A NOTE ON THE PETROPHYSICAL PROPERTIES AND GEOLOGICAL INTERPRETATION IN SCHIRMACHER OASIS, EAST ANTARCTICA

N. SUNDARARAJAN and B. MADHUSUDAN RAO
Centre of Exploration Geophysics, Osmania University, Hyderabad-500 007, A.P.
Email: sundararajan_n@yahoo.com

Vertical magnetic measurements were carried out along three chosen profiles to have an insight and inference about the subsurface geology and structures of Schirmacher region of east Antarctica. The interpretation of magnetic profiles based on amplitude analysis using the Hilbert transform and traditional Fourier spectral analysis in frequency domain reveal certain structural features such as faults/contacts at shallow depth. Depths from modeling of the magnetic anomalies agree well with the interpreted depths particularly in the case of profiles II and III. Measured densities and magnetic susceptibilities of the rock samples are found to be marginally high in some cases in comparison with those of the Indian Peninsula.

Introduction

Geophysical methods continue to play a significant role in deciphering the bedrock topography and subsurface structure of the not so easily accessible and ice covered continent — Antarctica. Though geophysical investigations were carried out in Antarctica during the early 1930s, the systematic geo-investigations employing seismic reflection and refraction, ground and airborne magnetic and gravity surveys were realized only since the 1950s (Behrendt and Wold, 1963).

Several geophysical measurements including magnetometrics were initiated in the first Indian scientific expedition to Antarctica (1981-82). The results have clearly demonstrated the utility of magnetic anomalies in delineating structural features of the Antarctica margin (Arora et al. 1985). During the second expedition (1982-83), magnetic measurements were carried out across Princess Astrid coast, which threw light on magnetic characteristics and structures below the ice cover in the region (Mittal and Mishra, 1985). Results of the magnetic mapping over the Schirmacher region during the third expedition (1983-84) is characterized by low amplitude fluctuations implying low magnetizations (Gupta and Verma, 1986). Major thrust was placed for geophysical surveys during the fourth expedition in which bedrock elevation studies from magnetic anomalies (Bhattacharya and Mazumdar, 1987), geochronological studies, electrical and electromagnetic studies, seismic investigations and radioactive measurements were carried out. Thus, geophysical investigations have become an important and integral scientific component of successive Indian expeditions to Antarctica.

In this context, during the 13th expedition to Antarctica (1993-94), various geophysical surveys such as magnetic, radiometric measurements etc. were carried out to assess the physical properties of major rock types in the Schirmacher region with an objective of establishing a correlative study with the petrophysical data obtained from rock types of the Indian peninsula. The results clearly indicate the lithological variations and structural details of Schirmacher Oasis (Chandra Reddy, 1994). In continuation, the authors carried out vertical magnetic field measurements for structural investigations in the Schirmacher hills and measurements of the petrophysical properties such as density and magnetic susceptibility of major rock types of the area during the 14th expedition (1994-95) and the results are presented here.

Geology of the Schirmacher Range

The Precambrian basement of the east Antarctica shield is mostly covered with ice but there are restricted outcrops along the coastline. The Schirmacher Range emerges as a rock oasis between the continental ice sheet and the coastal ice shelf, occupying an approximate area of 35 sq. km bounded by 70°44'30"S - 70°46'30"S latitudes and 11°24'4"E -11°54'E longitudes. The major mountain of Queen Maud land runs for about a thousand kilometres approximately parallel to the coast. The Schirmacher Range which runs roughly east-west belongs to the "East Antarctica Charnockite Province", the largest area of granulite facies rocks in the world and it is situated approximately halfway between the main mountain range and the present coast line. Here, the rocks have undergone polyphase metamorphism, magmatism and deformation (Sengupta, 1986).

Banded gneiss is the major lithological unit of the Schirmacher Range; the compositional variation of gneisses is due to the non-uniformity of the metamorphic rocks. The rock sequences, intrusives and tectonites of the Schirmacher hills have been classified (Chandra Reddy, 1994) as: (a) Banded gneiss (thin and thick bands), (b) Augen

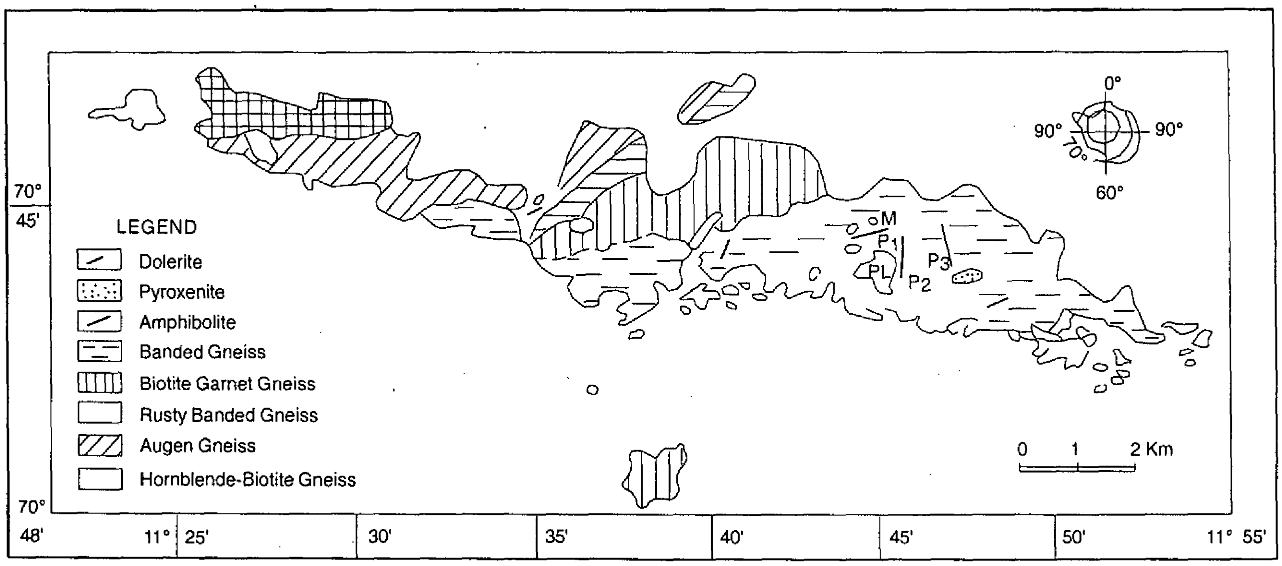

Fig.1. Geological sketch map of Schirmacher area, East Antarctica showing location of magnetic traverses (P1, P2 and P3).

gneiss, (c) Biotite gneiss, (d) Pyroxene granulites, (e) Amphibolites, (f) Calc-silicates, (g) Dolorites, (h) Basalts, (i) Vein quartz, and (j) Pegmatites are shown in the geological map of Schirmacher area (Fig.1).

Vertical Magnetic Survey

Though the total magnetic field measurements were carried out in the continental shelf around the first Indian station Dakshin Gangothri (approximately 30 km from the shelf) to assess the basement features and geology of the Schirmacher hills (Mittal and Mishra, 1985, Arora et al. 1985, Gupta and Varma, 1986; Jain et al. 1988) the vertical component measurements were started only from the 13th expedition (1993-94). The preference of vertical magnetic measurements over total component measurements is partly attributed to the simplicity of interpretation of such anomalies with fairly good accuracy and also that at polar regions the magnetic induction will be nearly vertical. Chandra Reddy (1994) has reported, based on the vertical magnetic surveys in the Schirmacher region, that the contacts/shears/faults deciphered from magnetic surveys may be of some help in locating economic mineral zones besides defining the lithological variations and structural details. However, the country rocks here are characterized by low magnetization as evidenced from low magnetic susceptibility values.

The objective of the magnetic survey undertaken was to map the structural features and accordingly the vertical magnetic surveys were carried out along three traverses of each approximately one km length (Fig. 1) at an interval of 20 m to know the magnetic response of the shallow features. A fluxgate magnetometer (Scintrex) with a sensitivity of 1 nT was used for the investigation. The measurements were made only on quiet magnetic days and adequate repetitions were made to monitor the diurnal variations. For simplicity, magnetic anomalies were referred to different local base stations instead of one as in usual practice. Profile-P1 is located approximately 300 m behind Maitri station [(M), 70°45'56"S, 11°43'52"E (Fig.1)] and runs approximately E-W. The entire profile lies in the biotite gneissic terrain with sharp changes varying from –80 to 350 nT (Fig.2a). Profile-P2 runs approximately N-S adjacent to Priyadarshini Lake (PL). This anomaly ranges from –15 to 170 nT (Fig.2b) with some sharp variations. Profile-P3 is located 500 m east of Maitri station and also runs N-S; it features four sharp peaks of which two are of 180 nT at the ends while the other two being 120 nT in the middle of the profile and the profile ranges from –30 to 190 nT (Fig. 2c).

Amplitude Analysis

The interpretation is based on the assumption that the magnetization of the anomalous body is caused by induction in the earth's field and that the direction of magnetization is uniform throughout the body. Further, the remnant magnetization, if any, is also in the direction of earth's field or is negligible. The amplitude analysis of the magnetic anomalies under discussion involves computation of the Hilbert transform of the magnetic profiles and then the amplitude of the analytic signal as discussed by Nabighian,

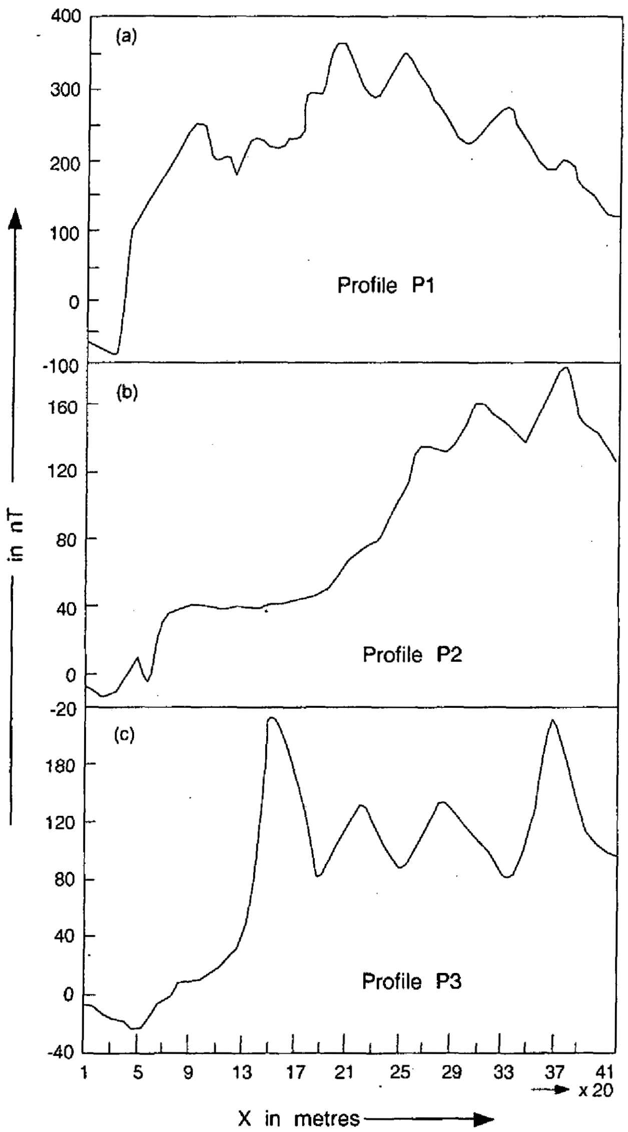

Fig.2. Magnetic profiles, Schirmacher Oasis, East Antarctica. Vertical magnetic anomaly (a) P1 along E-W. (b) P2 along N-S. (c) P3 along N-S.

(1972), Mohan et al. (1982), Sundararajan, (1982) and Sundararajan and Chary (1993). If m(x) and h(x) are the vertical magnetic anomaly and its Hilbert transform, then the analytic signal is expressed as:

$$a(x) = m(x) - i\, h(x) \quad (1)$$

Further, the amplitude of the analytic signal is given as:

$$aa(x) = \sqrt{m(x)^2+h(x)^2} \quad (2)$$

The amplitude defined above is of paramount importance in locating precisely the origin of the causative bodies besides being useful in the interpretation.

The magnetic anomaly, the Hilbert transform and the amplitude of these profiles are shown in Figs. 3a, b and c respectively. The amplitude of the analytic signal analysis clearly indicates the presence of multiple bodies. From the abscissa of the points of intersection of the anomaly and its Hilbert transform, the depth to the contact can be estimated. Alternatively, the shape, size and width of the amplitude of the analytical signal can be related empirically with the depth of the causative bodies. Based on such an analysis, for profile-P1, the depth is estimated to be between 170 and 180 m, for profile-P2 the depth ranged between 90-160 m, whereas profile-P3 yields the depth between 80 and 150 m. Intrusives or the contacts with different magnetic susceptibility might be the cause for the localized peaks or fluctuations in the magnetic anomalies.

Spectral Analysis

The Fourier spectral analysis is one of the well known tools for the interpretation of potential field anomalies. Accordingly, the magnetic anomalies m(x) are subjected to spectral analysis for depth estimation. The spectrum of the magnetic anomalies can be expressed by the relation:

$$M(w) = |M(w)|\, e^{i\Phi(w)} \quad (3)$$

where $|M(w)|$ is the amplitude and $\Phi(w)$ is the phase spectra respectively of the magnetic anomalies and w is the angular frequency expressed in radians per meter. Using the fast Fourier transform (FFT) algorithm, the real and imaginary components of all the three magnetic profiles were computed and then their amplitudes (Famp) and logarithmic amplitudes (Flogamp) were obtained and shown in Figs. 4a, b and c respectively. The slope of the linear plots of the logarithmic amplitude yields the depth to the top of the structures (Mohan, 1978 and Sundararajan and Rama Brahmam, 1998). The approximate depth from profiles P1, P2 and P3 were estimated to be 160 m, 140 m and 125 m respectively and found to be similar to the amplitude analysis and the results are presented in Table 1.

Modeling

Complex problems which do not yield analytical solutions can sometimes be modeled with some degree of similarity to field data. Accordingly, the magnetic profiles

Table 1. Interpreted depths from magnetic anomalies, Schirmacher Oasis, East Antarctica

Profiles	From amplitude analysis (in m)	From spectral analysis (in m)	From modeling (in m)
P1	170-180	160	120
P2	90-160	140	120
P3	80-150	125	120

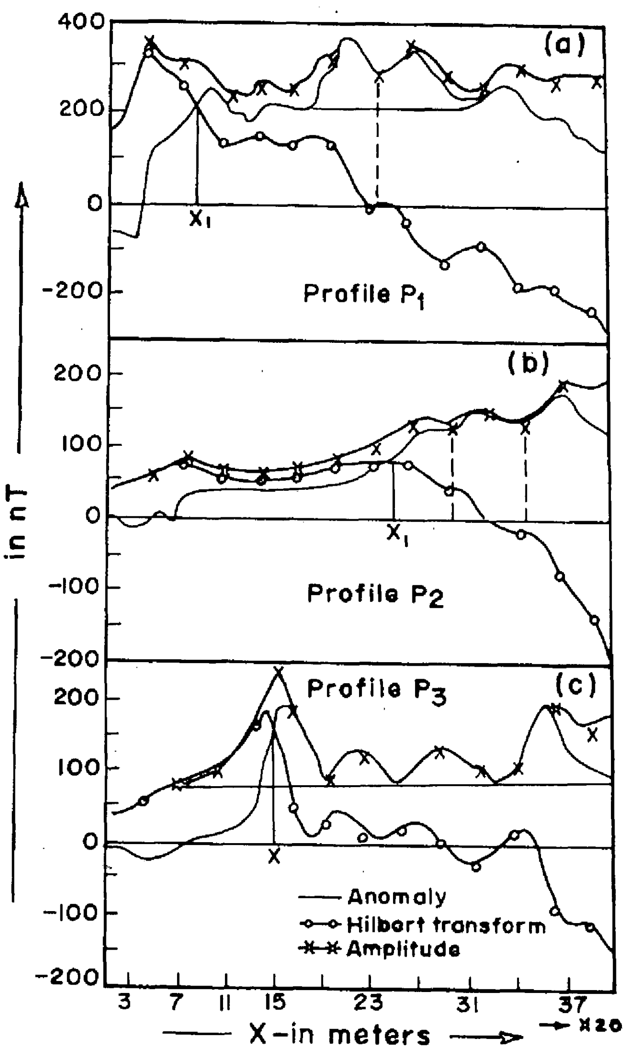

Fig.3. Amplitude analysis of magnetic profiles, Schirmacher Oasis, East Antarctica. Vertical magnetic anomaly, Hilbert transform and the amplitude of analytic signal (a) Profile-P1. (b) Profile-P2. (c) Profile-P3.

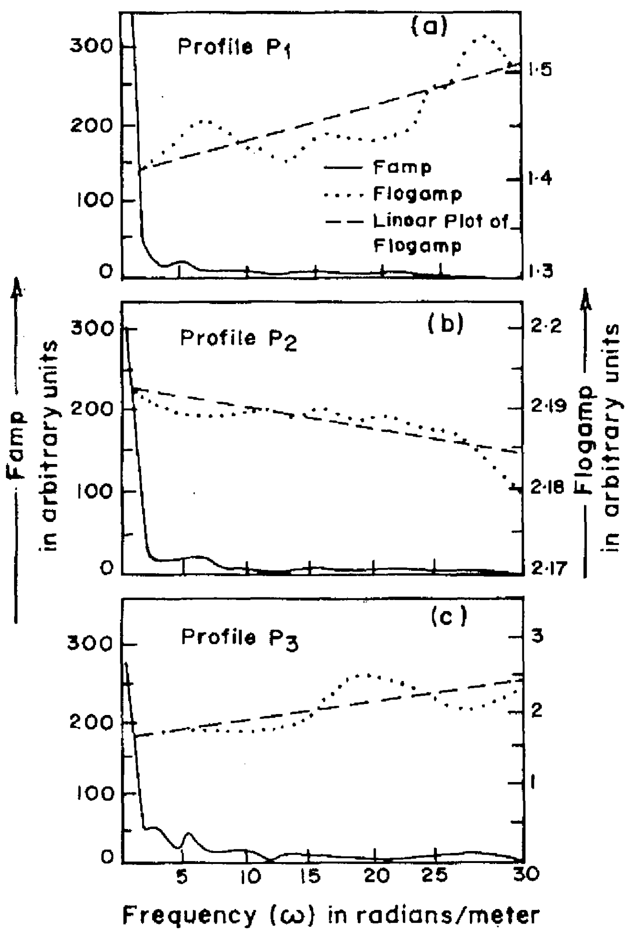

Fig.4. Fourier amplitude spectra. Fourier and logarithmic amplitude of magnetic profile (a) Profile-P1, (b) Profile-P2, (c) Profile-P3.

are subjected to qualitative interpretation by way of modeling using GMPAC software. The lateral disposition and depths of the individual sources are obtained through forward modeling. The regional gradient in both the N-S profiles (profiles P1 and P2) is attributed to the deep seated magnetic sources with higher magnetic susceptibility. While such a regional gradient is absent in profile P1, profiles P2 and P3 show excellent correlation between computed and observed data with regional gradients. The objective function which is the sum of the squares of the differences between the observed and computed in both cases are convergent after as many as fifteen iterations. Profile-P1 which is along E-W is not so easily amenable to inversion. This could be due to the fact that the E-W bodies resulting in the interpretation of the magnetic data along N-S traverses cut the traverse at an angle giving rise to composite or overlapping anomalies. Further, it is possible that there exists a deep seated source below these bodies at an average depth of 120 m. Figs.5a, b and c show the modeling of the magnetic profiles P1, P2 and P3 respectively. After, as many as fifteen iterations, the average depth of the shallow bodies are obtained approximately as 100-150 m which very well agree with the depths (Table 1) obtained from other methods as discussed in the earlier sections.

Petrophysical Properties

Density and Susceptibility Measurements

The density of a rock is primarily dependent on its mineral and chemical composition. To study the variations of density among the various rock types, a large number of samples were collected and identified along the traverses and then the densities were determined using

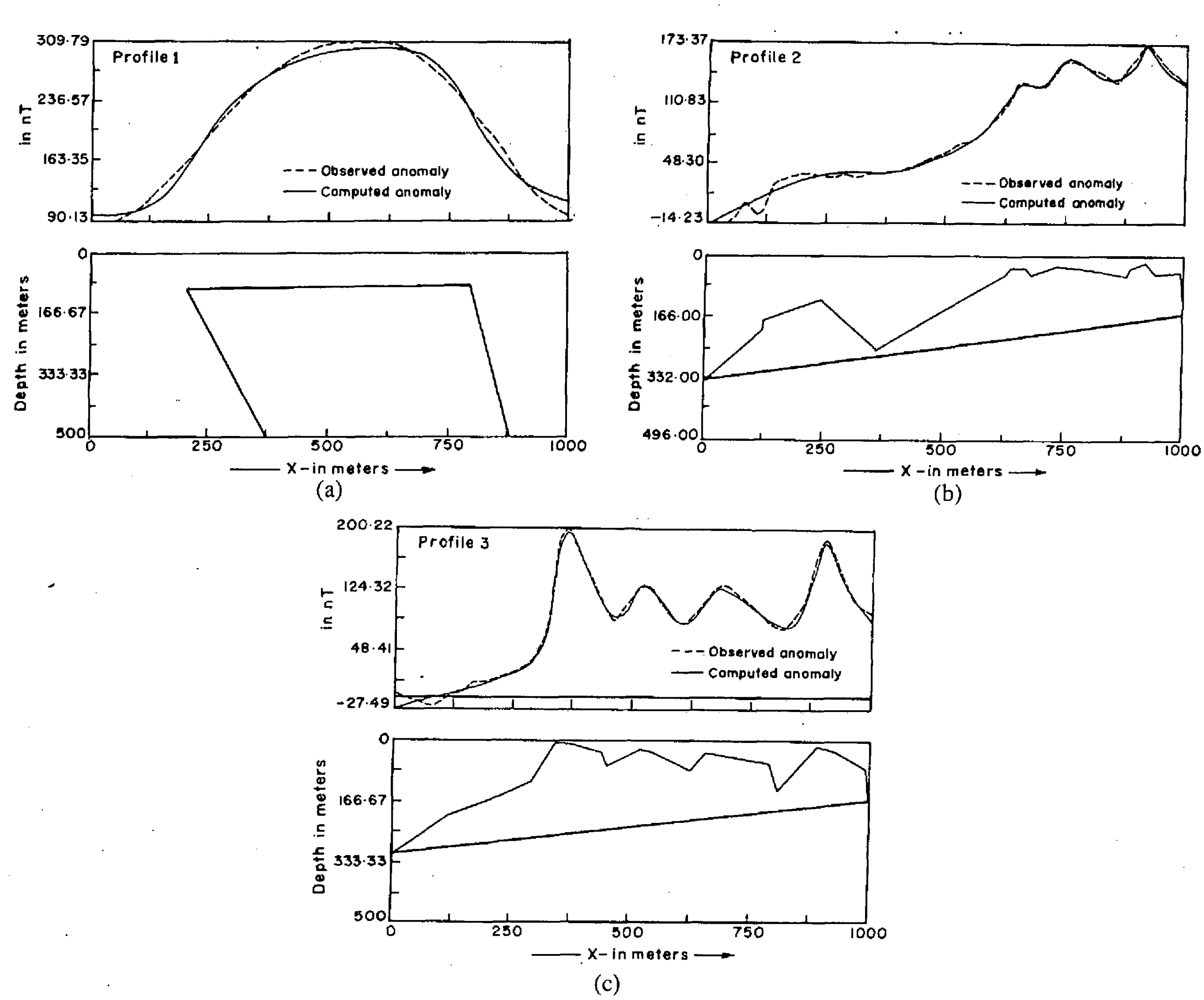

Fig.5. Optimised damped approximate inversion modeling of magnetic profile (a) Profile-P1, (b) Profile-P2 and (c) Profile-P3.

Samsanov's density balance. For each type of rock, several measurements were made and then the average was computed. It is observed that the density values measured for various rock types vary from 2.00 to 2.97 gm/cc (Table 2). It is to be noted that the samples collected were very likely transported ones rather than *in-situ* ones.

On the other hand, the magnetic susceptibility of a rock sample depends on the presence of ferrimagnetic minerals, chief among them being magnetite and members of the titanomagnetite series. Using a direct reading portable K-2 Kappameter, magnetic susceptibility values for all the above samples were determined in the laboratory. It is observed that for certain type of rock the range in susceptibility varies significantly whereas for other types the variations are within the normal range. The over all values of susceptibility lie in the range 0 to 82×10^{-6} CGS units (Table 2).

The average density and magnetic susceptibility values of some rock types in south India which were reported earlier have been cited here for comparison (Subbarao et al. 1983, Subramaniam and Verma, 1981 and Varaprasada Rao and Bhimashankaram, 1982). For rock types like biotite gneisses, migmatite, quartz and pegmatite, the density values were reported as 2.68 gm/cc, 2.89 gm/cc, 2.65 gm/cc and 2.59 gm/cc respectively. However, for the corresponding rocks from Antarctica, the computed density values vary marginally (Table 2). On the other hand, the magnetic susceptibilities of biotite gneisses, migmatite, garnet-biotite gneisses and pegmatite were reported as 25, 18, 12 and 5×10^{-6} CGS units respectively. While the susceptibility values of migmatite and garnet-biotite gneisses from Indian samples are within the average limit of those from Antarctica, the value for biotite gneisses is rather higher in comparison with the corresponding rocks from Antarctica. However, the average susceptibility values of pegmatite from

Table 2. Petrophysical properties of rock samples, Schirmacher Oasis, east Antarctica and south India

S.No.	Rock Type	No.of Samples	Density (s) in gm/cc		Susceptibility (K) in 10^{-6} CGS units	
			Antarctica	India	Antarctica	India
1.	Augen gneiss	15	2.25-2.90	-	0-10	-
2.	Banded gneiss	20	2.0-2.95	-	10-82	-
3.	Garnet banded gneiss	02	-	-	10-50	-
4.	Biotite gneiss	10	2.50-2.95	2.68	0-13	25
5.	Pyroxene granulites	9	2.68-2.69	-	5-40	-
6.	Leucocratic gneiss	3	2.45-2.85	-	<1	-
7.	Migmatite	3	2.76-3.11	2.89	10-21	18
8.	Quartz	4	2.66-2.73	2.65	0-10	-
9.	Garnet-Biotite gneiss	18	2.50-2.97	-	0-21	12
10.	Pegmatite	2	2.60	2.59	0-10	5
11.	Graphic granite	2	2.45	-	<1	-

Antarctica is the same as that of corresponding samples from south India (Ramachandran, 1990). It is to be noted from Table 2, that out of 11 samples from Antarctica, the values of density and magnetic susceptibility are compared only with 4 samples from south India which perhaps is inadequate to draw any significant inference between the physical properties of rocks between these two regions.

Conclusions

Despite the low magnetic character of the rocks, the vertical magnetic surveys in Schirmacher Oasis were found to be useful in geological and structural mapping. The deciphered structural features such as faults/contacts from the magnetic anomalies were found to be of shallow origin. The variations of the field in the magnetic profiles may be attributed to the variation in the thickness of surface biotite gneisses.

In Schirmacher region of Antarctica, for rock types like augen gneiss, biotite gneiss, garnet gneiss, the range in density and for other rock types like banded gneiss, garnet banded gneiss and pyroxene granulites the range in magnetic susceptibility are found to be marginally high. Thus, it may be concluded that while the petrophysical properties of some rock types in Schirmacher region are marginally high in comparison with those of Indian peninsula and however it is difficult to generalize for all types of rocks.

Acknowledgements: Authors record their profound thanks to the Dept. of Ocean Development (DOD), Govt. of India for giving us an opportunity to visit the icy continent. Dr. A. Mitra, the then senior scientist (DOD), New Delhi and Mr. Bhaskar Rao, Scientist (NCAOR-DOD), Goa are profusely acknowledged and appreciated for their cooperation and help during the expedition. The reviewers are sincerely thanked for their constructive suggestions to improve the manuscript. Prof. B.V.S. Murthy, the then Head, Department of Geophysics deserves lots of thanks for his initiative, cooperation, encouragement and suggestions all through. All the colleagues particularly, Prof. P. Jettaiah, Messrs. T. Chandrashekar, Y. Venu Gopal Rao and K. Ram Reddy Lab Assts. Dept of Geophysics are acknowledged, for their help.

References

Arora, B.R, Wahgmare, S.Y. and D'Cruz, L.A. (1985) Magnetometrics in the study of subsurface structures of Antarctica margin. Tech. Publ. 2, Dept. Ocean Development, New Delhi, pp.69-73.

Behrendt, J.C. and Wold, R.J. (1963) Depth to magnetic basement in west Antarctica, Jour. Geophys. Res., v.68, pp.1145-1153.

Bhattacharya, B.B. and Majumdar, T.J. (1987) Bedrock elevation studies in Queen Maud Land, Antarctica. Tech. Publ.4, Dept. Ocean Development, New Delhi, pp.35-41.

Chandra Reddy, P. (1994) Measurement of *insitu* petrophysical properties, VLF-EM and vertical component magnetic surveys in Schirmacher hills, East Antarctica. XIII ISEA, Report submitted to Dept. Ocean Development, New Delhi.

Gupta, H.K. and Verma, A.K. (1986) Magnetic characteristics in Antarctica over geological contact in Schirmacher hill region and the ice shelf near Dakshin Gangotri. Tech. Publ.3, Dept. Ocean Development, New Delhi, pp.231-239.

Jain, S.C, Dhar, R. and Reddy, K.N.S. (1988) Geophysical investigations in Schirmacher land mass. Tech. Publ. 5, Dept. Ocean Development, New Delhi, pp.145-150.

Mittal, G.S. and Mishra, D.C. (1985) Magnetic characteristics of Princess Astrid Coast of Antarctica 70°S, 12°E north of

Dakshin Gangotri. Tech. Publ. 2, Dept. Ocean Development, New Delhi, pp.47-51.

MOHAN, N.L. (1978) Interpretation techniques in exploration geophysics using the Fourier Transform. Ph.D. Thesis submitted to Osmania University, India.

MOHAN, N.L., SUNDARARAJAN, N. and SESHAGIRI RAO, S.V. (1982) Interpretation of some of two-dimensional magnetic bodies using Hilbert Transforms. Geophysics, v.47, pp.376-387.

NABIGHIAN, M.N. (1972) The analytical signal of two-dimensional magnetic bodies with polygonal cross section: Its properties and use for automated anomaly interpretation. Geophysics, v.37, pp.507-517.

RAMACHANDRAN, C. (1990) Metamorphism and magnetic susceptibilities in South Indian granulite terrain. Jour. Geol. Soc. India, v.35, pp.395-403.

SENGUPTA, S. (1986) Geology of Schirmacher Range (Dakshin Gangotri), East Antarctica, Tech. Publ.3, Dept. Ocean Development, New Delhi, pp.187-217.

SUBBARAO, D.V., SHARMA, J.R.K. and KRISHNA BRAHMAM, N. (1983) Densities of Geological Formations of Peninsular India. Geoviews, v.11, pp.371-407.

SUBRAMANIAM, C. and VERMA, R.K. (1981) Densities and magnetic susceptibilities of Pre Cambrian rocks of different metamorphic grade rocks (southern Indian shield). Jour. Geophys. v.49, pp.101-107.

SUNDARARAJAN, N. (1982) Interpretation techniques in geophysical exploration using Hilbert transform: Ph.D thesis, Osmanai University, Hyderabad.

SUNDARARAJAN, N. and CHARY, M.N. (1993) Direct interpretation of SP anomalies due to spherical structures- A Hilbert transform technique: Geophysical Trans., v.38, pp.151-165.

SUNDARARAJAN, N. and RAMA BRAHMAM, G. (1998) Spectral analysis of gravity anomalies caused by slab like structures: A Hartley transform technique: Jour. Applied Geophysics, v.39, pp.53-61.

VARAPRASADA RAO, S.M. and BHIMASANKARAM, V.L.S. (1982) Geophysical investigations for Barite at Gopalpur, Khammam district, A.P. Jour. Geol. Soc. India, v.23, pp.32-38.

(Recieved: 31 January 2003; Revised form accepted: 29 October 2004)