Very-low-frequency electromagnetic (VLF-EM) measurements in the Schirmacheroasen area, East Antarctica

P. Gnaneshwar, A. Shivaji¹, Y. Srinivas², P. Jettaiah, N. Sundararajan*

Centre for Exploration Geophysics, Osmania University, Hyderabad 500 007, India

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Abstract

To assess the feasibility of the very-low-frequency electromagnetic (VLF-EM) method in the Schirmacheroasen area of East Antarctica, and to investigate its response, VLF-EM measurements were performed along four traverses. The preliminary results reveal the locations of geological boundaries and shear zones/faults, which may indicate that VLF anomalies are due to shear zones or alteration zones located along contacts between different rock types. The strength of the VLF anomaly decreases over the polar ice cap. The inphase component of the VLF anomaly, when processed and interpreted with an analytic signal approach, yields a depth range of 15–30 m, whereas Fraser and Hjelt filter analyses yield a depth range of 25–60 m. The VLF-EM responses along all four traverses, along with their interpretations, are presented here as a case study.

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1. Introduction

The recent availability of geochronological data and geological observations has led to a revision of our understanding of the geological setting of East Antarctica as the central continent of Gondwana (Ravikant, 2006; Reading, 2006; Santosh et al., 2009). For example, Reading (2006) linked the seismic structure of the Lambert Glacier region to the surface geology of the area. McLean et al. (2009) studied geological exposures in the Lambert Rift region and utilized airborne magnetic, gravity, and ice radar data to interpret the distribution and architecture of tectonic terranes that are largely buried beneath a thick ice sheet. Although the free-air and Bouguer gravity anomaly data for East Antarctica are strongly influenced by the sub-ice and mantle topography, the interpretation of these geophysical data provides an insight into the distribution and geometry of four tectonic blocks (McLean et al., 2009), supported by surface observations (e.g., lithological descriptions, isotopic data, and structural mapping).

More than 95% of Antarctica is covered by a thick ice sheet, meaning that electromagnetic (EM) surveys play a vital role in unraveling the complexities of the subsurface geology, including the bedrock topography and

¹ Corresponding author. Present address: Department of Earth Science, Sultan Qaboos University, Post Box 36, Postal Code 123, Al Khod, Muscat, Oman.
E-mail address: sundararajan_n@yahoo.com (N. Sundararajan).
² Present address: Centre for Marine Living Resources & Ecology, Cochin 682 037, India.
¹ Present address: Centre for Marine Living Resources & Ecology, Cochin 682 037, India.
2 Present address: Centre for GeoTechnology, Manonmaniam Sundaranar University, Tirunelveli 627 012, India.

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subsurface structure (Behrendt and Wold, 1963; Bormann et al., 1986). Although many factors may hamper the propagation of a very low frequency (VLF) signal (including the presence of highly resistive ice sheets, wind-induced electrostatic noise, magnetic storms, and disturbed ionosphere activity), Wannamaker et al. (2004) provided a new view of the geology and geophysics below the South Pole region, based on high-quality magnetotelluric (MT) data acquired using specialized hardware. In addition, Pfaffling et al. (2007) developed an algorithm that enables sea-ice thickness inversion of helicopter-borne EM data; the accuracy and applicability of this algorithm were validated by synthetic data and drillhole data from East Antarctica.

The Indian scientific expeditions to Antarctica in the early 1980s focused on the utility of magnetic anomalies in delineating structural features across areas such as the Princess Astrid Coast (Arora et al., 1985). Magnetic mapping over the Schirmacheroasen (Schirmacher Oasis) region revealed low-amplitude fluctuations, indicating weak magnetization and little spatial variation in the elevation of bedrock (Bhattacharya and Majumdar, 1987; Gupta and Verma, 1986; Mittal and Mishra, 1985; Shikhar et al., 1988).

Although the VLF-EM method has been primarily used to map conductive ore deposits (Paal, 1965) it is useful in investigating the nature of shallow geological features at high resolution (e.g., Aina and Emofurieta, 1991). Hence, the 13th and 15th Indian expeditions to Antarctica performed VLF-EM measurements in the Schirmacher Oasis region with the aim of establishing the utility (and understanding the response) of the VLF signal in this region, which is known to experience frequent magnetic storms. Accordingly, these expeditions performed VLF-EM measurements (inphase and quadrature components) along four traverses around the permanent Maitri research station (India) in East Antarctica. These data are analyzed in the present study.

2. Geology of the Schirmacher Range

The Precambrian basement of the East Antarctic shield is largely covered by ice, although limited outcrops occur along the coastline. The Schirmacher Range is a rock oasis between the continental ice sheet and the coastal ice shelf, occupying an area of approximately 35 km² (70°44′30″S—70°46′30″S latitude, 11°24′4″E—11°54′E longitude). The major mountains of Dronning Maud Land run for about 1000 km approximately parallel to the coast. The Schirmacher Range, which trends roughly east—west, belongs to the East Antarctic Charnockite Province, which is the largest area of granulite facies rocks in the world, situated approximately half way between the main mountain range and the present coastline. The rocks of the Schirmacher Range have undergone multiple episodes of metamorphism, magmatisation, and deformation (Sengupta, 1986). Banded gneiss is the dominant rock type in the Schirmacher Range; compositional variation in the gneisses reflects the non-uniformity of the metamorphic rocks. The rock sequences, intrusives, and tectonites of the Schirmacher Range have been classified into banded gneiss (thin and thick bands), augen gneiss, biotite gneiss, pyroxene granulites, amphibolites, calc-silicates, dolerites, basalts, vein quartz, and pegmatites (Sundararajan and Rao, 2005), as shown in a geological map of the Schirmacher Oasis area (Fig. 1).

3. VLF-EM measurements

The theory that underlies the VLF-EM technique is well described in the literature (Paterson and Ronka, 1971; Phillips and Richards, 1975). The VLF-EM technique is a passive method that uses radiation from ground-based military radio transmitters (used for navigation, of which there are about 42 worldwide) operating in the VLF band (15—30 kHz) as the primary EM field. These transmitters generate plane EM waves that can induce secondary eddy currents, particularly in electrically conductive elongate 2-D targets. Although this range is very low for radio transmission, it is higher than that used in standard low-frequency EM methods (1—3 kHz). Paal (1965) observed that radio waves at VLFs could be used to prospect for conductive mineral deposits. Subsequently, VLF transmitters situated at several locations worldwide have been widely used as EM sources for near-surface geological mapping (Ramesh Babu et al., 2007).

The VLF method generally yields considerable EM anomalies, even over poor conductors such as sheared contacts, fracture zones, and faults. Hence, this method has been the most popular tool for the rapid mapping of near-surface geological structures (Parker, 1980; Phillips and Richards, 1975; Saydam, 1981; Sundararajan et al., 2006). The VLF-EM unit is a sensitive receiver, covering the frequency band of the VLF-transmitting stations and capable of measuring the vertical components of the secondary field generated by lateral changes in conductivity in earth materials. Herein, that part of the vertical field which is inphase with the horizontal field is called the ‘inphase component’; that part which is out-of-phase with the horizontal magnetic field is called the ‘out-of-phase (quadrature) component’.
The equipment used for our survey was a VLF-R Meter (Geonics Ltd, Canada). The device was tested in terms of reception of a clear VLF response when operated in the Antarctic environment, which is known for frequent magnetic storms that may hinder the transmission of VLF signals. To minimize contamination of the VLF band by natural high-frequency radio noise from the ionosphere or aurora, measurements were repeated twice. Use of the VLF-EM unit revealed that the Australian broadcasting signal (NWC, frequency 22.3 kHz) was clear enough to conduct a VLF-EM survey in the Schirmacher Oasis region. We performed measurements of inphase and quadrature components of the VLF-EM response along four profiles (Fig. 1). During the survey, frequent repetitions of the measurements were made to assess the repeatability of the observations. In the following sections, we briefly describe and interpret the measured inphase and quadrature components of VLF anomalies along the four traverses.

3.1. Traverse-I

Traverse-I crosses a hill of olivine-bearing norite located adjacent to Taatvanett Lake (TL) (the Indian name for this lake is Priyadarshini Lake) (Fig. 1). The width of the norite body [dyke like body dominated by orthopyroxene (hypersthene), calcic plagioclase and small grains of ilmenite (Simpson and Aslund, 1996). Norite is medium-coarse grained and is characterised by a subhedral granular texture.] along the traverse is about 35 m. The traverse trends approximately N–S and is 400 m long. The raw data profiles of the inphase and quadrature components are shown in Fig. 2(a). The data show two main cross-overs in the inphase and quadrature profiles. The cross-over towards the southern end of the traverse (peak-to-peak amplitude of 40% of the inphase component) falls in a depression zone, possibly indicating a fault, as fault-related depression zones are sometimes recognized as shear bands (Bormann et al., 1986). The other cross-over occurs near the middle of the profile (240–280 m), corresponding to the southern margin of the norite body. At the northern end of the profile, the inphase signature and quadrature component show a large negative amplitude over an area of banded gneisses.

3.2. Traverse-II

Traverse-II trends NE–SW across a narrow shear zone located adjacent to a lake at a site 1 km west of Maitri station (M in Fig. 1). The shear zone, 1.5 m wide, is mylonitized. The inphase signature shows a cross-over at approximately 130 m along the traverse, coincident with the shear zone (as indicated by the arrow in Fig. 2(b)). The imaginary signature (quadrature component), on the other hand, shows an inverse relationship with topography, probably reflecting the terrain effect.

3.3. Traverses-III and -IV

Traverse-III (Fig. 3(a)) trends approximately NE–SW and crosses a fault located near Trishul Hill (TH in Fig. 1, 4 km west of Maitri). The fault has displaced a 2-m-wide pegmatite vein that occurs within the banded...
gneissic rock. The pegmatite ends abruptly against the fault plane; the pegmatite on the other side of the fault cannot be seen because of ice cover. Traverse-IV (Fig. 3 (b)) was located in an ice-covered area, upon the polar ice cap near ‘Dozer Point’ at Maitri station (DP in Fig. 1).

The level of the VLF signal on the polar ice cap is markedly reduced compared with that in areas of bare rock. The inphase signature indicates that the traverse crosses the boundary of the depression zone identified in Traverse-I.

4. Filtering procedure

To overcome the effect of temporal variations in the magnetic field (e.g., due to changes in the wave guided by the surface and bottom of the ionosphere), Fraser (1969) devised a simple numerical filter (the Fraser filter) that converts cross-over of the current polarity into peaks by differencing successive values of the inphase component along the profile. The Fraser filter shifts the data by 90°; i.e., it transforms the anomaly such that those parts with the maximum slope appear with the maximum amplitude. As a sequence of consecutive readings of inphase data (Nabighian, 1982), referred to as M1, M2, M3 and M4, the term (M2 − M1) not only shifts the dip angle but also attenuates the spatial wavelengths. Numerical averaging of the weighted values of three adjacent sets of such differences [i.e., (M2 − M1)/4 + (M3 − M2)/2 + (M4 − M3)/4, which reduces to (M3 + M4) − (M1 + M2)] results in a reduced noise level.

Karous and Hjelt (1983) made use of linear filtering in analyzing VLF inphase data, which is an extension of the Fraser filter. The authors described the magnetic field

![Fig. 2. (a) VLF-EM inphase and quadrature components (Traverse-I). (b) VLF-EM inphase and quadrature components (Traverse-II).](image)

![Fig. 3. (a) VLF-EM inphase and quadrature components (Traverse-III). (b) VLF-EM inphase and quadrature components (Traverse-IV).](image)
arising from a subsurface 2-D current distribution assumed to be located in a thin horizontal sheet of varying current density situated everywhere at a depth equal to the distance between measurement stations. This approach involves filtering the same dataset for various depths and indicates the change in current density with depth. The areas with high current density correspond to good conductors. In the absence of numerical modeling, this filtering technique has found wide popularity because it provides a simple, readily implemented scheme for semi-quantitative analysis and target visualization (Ramesh Babu et al., 2007; Sundararajan et al., 2006). The apparent current density pseudo-section should provide a pictorial indication of the depths of various current concentrations and hence the spatial distribution of subsurface geological features (Ogilvy and Lee, 1991). Over conductors, the inphase part of the equivalent current distribution has only positive values. Negative parts on both sides of the conductor can be caused either by the length of the filter or by a decrease in current density due to current gathering, which is not present in 2-D structures (Nabighian, 1982).

In its simplest form, the Fraser filter can be expressed as

\[
\left(\frac{\Delta z}{2\pi}\right)I_x(\Delta x/2) = -0.205H_{-2} + 0.323H_{-1} - 1.446H_0 + 1.446H_1 - 0.323H_2 + 0.205H_3I_a(\Delta x/2)
\]

where \(\Delta z\) is the assumed thickness of the current sheet, \(I_a\) is the current density, and \(\Delta x\) is the distance between data points (and also the depth to the current sheet). The values of \(H_{-2}\) through \(H_3\) are the normalized vertical magnetic field anomaly at each of the six data points. The location of the calculated current density is beneath the center of the six data points.

Fig. 4. (a) Analytic signal analysis of the VLF-EM inphase component (Traverse-I). (b) Analytic signal analysis of the VLF-EM inphase component (Traverse-II).
5. Processing and interpretation

Although the VLF method has been widely used in recent decades to map shallow subsurface structures, VLF anomalies are mainly interpreted based on anomaly curves and monograms (e.g., Kaikkonen, 1979; Saydam, 1981). Filtering and subsequent contouring of the observed responses are commonly employed to derive qualitative information about the subsurface (Fraser, 1969; Karous and Hjelt, 1977, 1983). Multidimensional numerical modeling and inversion are needed to determine quantitatively the geometrical and physical subsurface parameters from VLF anomalies. Because there are no well-defined quantitative methods for interpreting VLF data, we employ an analytic signal approach (Sundararajan, 1983), and the Fraser filter or Hjelt filter, which are semi-quantitative in nature. Freely available MATLAB-based software (Sundararajan et al., 2006) was used to process the measured components of VLF-EM signals. In the following sections, these methods are briefly discussed and the inphase component of VLF data (for all the traverses) is interpreted and presented.

5.1. Amplitude analysis

Amplitude analysis of the VLF anomalies under discussion involves computation of the Hilbert transform of the inphase component of VLF profiles and then the amplitude of the analytic signal, as discussed previously (Nabighian, 1972; Sundararajan, 1983; Sundararajan and Srinivas, 1996; Sundararajan et al., 2000). If \( v(x) \) and \( h(x) \) are the inphase component and its Hilbert transform, respectively, then the analytic signal can be expressed as

\[
a(x) = v(x) - ih(x).
\]

Furthermore, the amplitude of the analytic signal can be given as

\[
aa(x) = \sqrt{[v(x)^2 + h(x)^2]}.
\]

The amplitude defined above is a key factor in precisely locating the origin of the causative in the interpretation. The VLF anomaly (inphase component), the Hilbert transform, and the amplitude of Traverses-I and -II are shown in Fig. 4(a) and (b), respectively; the data for Traverses-III and -IV are shown in Fig. 5(a) and (b), respectively. The amplitude of the analytic signal analysis clearly indicates the presence of multiple bodies. The depth of the contact can be estimated from the abscissa of the points of intersection of the anomaly and its Hilbert transform. Alternatively, the shape, size, and width of the amplitude of the analytical signal can be related empirically to the depth of the causative bodies. In the case of traverses I—IV, the evaluated depths range from 15 to 30 m, which differ from the depths evaluated based on magnetic data (Sundararajan and Rao, 2005).

5.2. Fraser filter and Hjelt filter analyses

An additional interpretative tool based on pseudosections of the filtered outputs is applied in the present analysis. This tool is obtained by processing a single data profile by either the Fraser filter or the Hjelt filter (Karous and Hjelt, 1977), or by both at various lengths or spans. With increasing length of the filter, the responses from increasing depths become increasingly pronounced. Therefore, if the outputs are arranged on a section so that greater depths correspond to longer
filters, the section should approximately resemble the current pattern in the ground. However, it must be emphasized that this is only an approximation of the section (Wright, 1988). Thus, construction of the pseudo-section consists of a number of steps, like processing profiles with as many as number of levels (approximately 5 or 6); at each level, in terms of integer multiples of the station spacing ($n\Delta x$; where $n$ is the number of levels and $\Delta x$ is the station spacing). Finally, the results separated by $n\Delta x$ at each level are plotted one below the other, thereby forming a section.

The inphase components of all the traverses are subjected to both Fraser filtering and Hjelt filtering, using interactive MATLAB-based software (Ramesh Babu et al., 2007; Sundararajan et al., 2006). The corresponding pseudo-sections (plots of station interval vs. depth) are shown in Figs. 6–9. The inferred depth from the pseudo-sections ranges from 25 to 60 m, thereby partially correlating with depths obtained from analytic signal analysis, as discussed earlier.

Although it is known theoretically that the conductor lies at the maximum of the negative gradient (inflexion) of the VLF inphase component, we prefer the cross-over of the inphase and quadrature components as an indicator of a conductor (Sundararajan et al., 2006), based on our earlier VLF-EM study of groundwater (Sundararajan et al., 2007). The interpretation of VLF data may be difficult because the transmitted frequency may give rise to secondary fields from many geological features. However, VLF data are useful for obtaining a qualitative view of the structure, particularly after filtering the data and analyzing the current density across the section. For a more reliable interpretation, VLF data alone are not sufficient;
however, they can be appropriately used with other available geophysical data to reduce the non-uniqueness of estimation of depth to conductors.

6. Discussion

In general, the inphase and quadrature components of all four traverses are relatively weak, due to the presence of the highly resistive ice sheet, wind-induced electrostatic noise, magnetic storms, and disturbed ionosphere activity, among other factors. The sudden commencement of geomagnetic storms is related to high-latitude electron precipitation, in which case VLF anomalies are weak and small in size. Despite the poor signal quality, the norite body and the shear zone are apparent from the respective inphase components in Traverses-I and -II. In Traverse-III, the location of the fault is apparent from the inphase component. The inphase component of Traverse-IV is relatively strong, whereas the quadrature is weak, due to either the presence of ice cover along the profile or malfunction of the equipment as a consequence of the low temperatures. The inferred depth of the contact based on the amplitude of analytical signal analysis, ranges from 15 to 30 m for all the traverses, whereas the depth inferred from Fraser and Hjelt filtered analyses is in the range of 20–60 m.

7. Conclusions

Although there are several factors that hamper VLF propagation, VLF-EM surveys in the ice-covered Schirmacher Oasis region proved to be useful in terms of geological mapping in a polar region. Although the signal level of VLF anomalies was weak, various geological bands were apparent. Analytic signal analysis of the VLF-EM inphase component yields a depth range of geological structures of 15–30 m. Fraser and Hjelt filtered analyses of the inphase component yield a deeper depth range. The VLF-EM method is a useful tool, although with some limitations, for rapid and economical mapping of geophysical structures. The analysis of VLF-EM signals from more than one transmitter may enhance the reliability of the results.

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