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Electrical Structure beneath the Schirmacher Oasis, East Antarctica, from Magnetotelluric Measurements

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ABSTRACT

Geophysical investigations were carried out in East Antarctica during 24th Indian Antarctic Scientific Expedition program to know the deep electrical properties of the area around the Indian station, Maitri. The already available data sets (Gravity, magnetic, electromagnetic etc.) have provided information of the basement and sub-basement. In our study, magnetotelluric (MT) data have been acquired to delineate the crustal electrical structure of the Schirmacher Oasis. Deep structural information from the results of our study gave more details about the tectonics of the region. MT has the advantage of depth resolution as the data acquisition covers a wide frequency band of 10-3 to 103 Hz, permitting penetration depths of at least 100 km. The modeling results indicate the presence of high resistive upper crust (8,000-10,000 Ohm.m.) with a thickness of 10-15 km followed by conductive (500-600 Ohm.m.) layer. The high resistive upper crust is thinning towards western part of the Schirmacher Oasis.

INTRODUCTION

Antarctica has been broadly divided into eastern and western parts by transantarctic mountains (Gregory, 1901). West Antarctica encompasses the Scotia arc region, the Antarctic peninsula, Ellsworth Land, the Ellsworth mountains and Marie Byrd Land, while East Antarctica consists of Dronning Maud Land, Enderby and Kemp Lands. An approximately 95 per cent of its surface is covered with thick (1–3 km) ice, and so crust and mantle structure must be deduced geophysically. Geophysical deductions must make use of only a handful of physical properties of the Earth, one of which is its electrical resistivity. The geophysical method that can provide images of resistivity to deep crustal or upper mantle depths is magnetotellurics (MT) (Vozoff, 1991; Harinarayana et al., 2003, Wannamaker et al., 2004). This physical property in turn can provide information on primary structures (sedimentary distributions, lithologic contrasts, major fault offsets), geochemical fluxes (hydrothermal alteration, remobilized graphite and sulphides) and thermal regime (prograde or melt-exsolved fluids, crustal or upper mantle melts, mineral semi-conduction). We have acquired good-quality MT data along E-W transect in Schirmacher Oasis, Dronning Maud Land, East Antarctica.

East Antarctica has been accepted as a stable cratonic block of Pre-Cambrian rocks, but more recently is thought to have been a component of a Late Proterozoic supercontinent Rodinia (e.g. Dalziel 1991; Borg and DePaolo 1994; Rodgers *et al.*, 1995; Satish-Kumar et al., 2008). West Antarctica has been assembled to East Antarctica from accreted blocks and subduction-related plutonism since lower Paleozoic time (Storey & Alabaster, 1991).

EARLIER STUDIES

Crustal thickness of West Antarctica varies between 20 and 30 km in contrast to ~40 km in East Antarctica, derived on the basis of seismic refraction profiles near its NE coast, and gravity interpretations region-wide (Bentley, 1991). However, the Moho depth in Schirmacher Oasis region has been interpreted to ~35 km on the basis of geomagnetic data (Wagner and Lindner, 1991). Surface wave studies confirm separateness of East and West Antarctica, with the former showing more craton-like velocities on an average and with the highest lateral gradient in model velocities (Bentley, 1991; Danesi and Morelli, 2000; Ritzwoller et al., 2001; Harley, 2003). Seismicity throughout Antarctica is low, which is consistent with a slow moving plate almost entirely surrounded by mid-ocean ridges. However, the western part is approximately 10 times more active than the east (Bentley 1991; Hole and Lemasurier, 1994). Electromagnetic measurements have been conducted for bed rock investigation (Bhattacharya and Majumdar, 1997; Bhattacharya et al., 1987). The influence of mantle plume in Antarctica has been reported by many authors (Wannamaker et al., 2004). The upwelling mantle plume, in general, tries to pass through mobile belts, which are relatively thin as compared to relatively thick cratonic parts (Raval and Veeraswamy, 2000). However, particularly the study of plume-related magmatism by Sushchevskaya et al. (2008) within Antarctica proves the spreading of the Karoo-Maud plume, which determined the split of the Gondwana continent and formation of the Indian ocean, to the east – from Queen Maud land towards Schirmacher Oasis. Isotopic compositions of dolerite dykes of Schirmacher Oasis clearly indicate the crustal contamination processes which took place during the plume upwelling and emplacement into the continental crust. The earth's most extensive orogen, i.e. Mozambique belt that was formed during the collision of east and west Gondwana seems to extend from South Africa in the north to Dronning Maud land in the south (Jacobs, 1999; Ravikant et al., 2004, 2007). According to Satish-Kumar et al. (2008) the Schirmacher Oasis could be part of SE Africa, where as the inland mountains were part of crust formed during the final amalgamation of East Gondwana.

GEOLOGICAL SETTING OF SCHIRMACHER OASIS

"Schirmacher Oasis" is located near the Princess Astrid Coast, Central Queen Maud Land, East Antarctica (**Fig. 1**). This area (70044'-70047'S and 11025'-11055'E) of about 35 km^2 is situated parallel to the E-W trending coast line between the inland ice and the shelf ice (Tingey, 1991). The Precambrian crystalline basement of Schirmacher Oasis is part of the East Antarctic shield. The rocks of Schirmacher Oasis were affected by an initial granulite facies metamorphism in Proterozoic times (Sengupta and Bose, 1997; Hoch and Tobschall, 1998). The main deformation was followed by an amphibolites facies metamorphism which was accompanied by migmatization and isoclinal folding of the rocks (Kampf and Stackebrandt, 1985). The formation of east-west striking overthrusts took place subsequently. The Pan-African thermotectonic activation at the time of Precambrian-Phanerozoic (600-450 Ma) overprinted the crust and caused faulting, dynamometamorphism under amphibolite facies P-T conditions

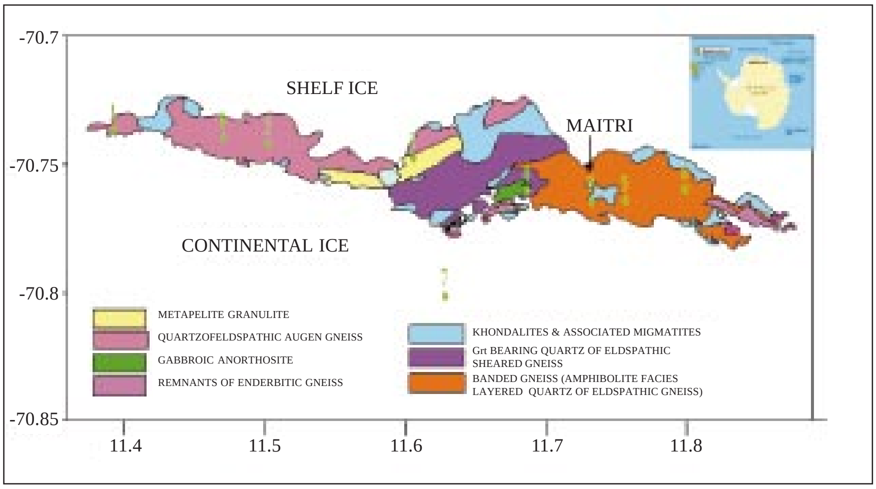

Fig. 1 : Geological map with MT sites in Schirmacher Oasis, East Antarctica

and dyke intrusions (Ravich and Krylov, 1964). The youngest fault event is connected with the formation of cataclasites and greenschist facies metamorphism in the area of faults (Kampf and Stackebrandt, 1985). The metamorphic complex of Schirmacher Oasis is intersected by numerous lamprophyre, basalt, pegmatite and aplite dykes. On the basis of field observations it has been indicated that the minettes of Schirmacher Oasis are younger than the pegmatites and older than the basalt dykes. Kaiser and Wand (1985) and Wand et al. (1988) distinguished two age groups of basalts, Palaeozoic and Mesozoic. Conventional K-Ar isotope age determinations yielded isochrons of 223 and 354 Ma. Potassium feldspars fiom pegmatites gave Pb-Pb ages between 600 and 865 Ma (Bielicki et al., 1991). The studied minettes are obviously older than 354 Ma, but younger than the pegmatites. Whole rock-biotite Rb-Sr isotope isochrones indicate ages of 430 Ma and 703 Ma for the minettes (Hoch and Tobschall, 1998).

MAGNETOTELLURICS

In Magnetotelluric (MT) method, naturally occurring electromagnetic (EM) wave fields have been used as sources for imaging the electrical resistivity structure of the Earth (Vozoff, 1991). The incident EM waves propagate vertically downward and usually are treated as planar in geometry.

In the conducting Earth, EM waves at typical frequencies of the method (<1000 Hz, for example) travel diffusively, such that high frequency (short period) waves penetrate a relatively short distance while low-frequency (long period) waves can reach the mantle depths. The electric (**E**) and magnetic (**H**) vector fields scattered by buried structure and measured at the surface may have arbitrary polarization relative to the incident fields. This requires a tensor relationship between the measured fields as a function of frequency (or period T, its inverse) denoted for the horizontal components through

$$[\mathbf{E}] = [\boldsymbol{Z}][\mathbf{H}],$$

where $\boldsymbol{Z}$ is the 2×2 complex impedance. The individual impedance elements typically are transformed into an apparent resistivity (ρa) and an impedance phase (ϕ) for presentation and modelling. On a uniform half-space of resistivity ρ, ρa = ρ and $\phi = 45^{o}$. For more complex structures, ρa versus T approximates a smoothed version of ρ versus depth below the measurement. The phase ϕ tends to be proportional to slope of ρa versus T, and thus is more reflective of spatial gradients in the subsurface resistivity. These primary data in turn are transformed to constrained resistivity models through the process of inversion, specified in the model construction section below.

Over 2-D structures where one of the measurement axes is parallel to geoelectric strike (*x* here by convention), the diagonal entries of ***Z*** are zero (Vozoff, 1991). In this situation, the MT response separates into two independent modes. These are the transverse electric (TE) mode, where Ex = ZxyHy and electric current flows parallel to strike (*x*-axis), and the transverse magnetic (TM) mode, where Ey = ZyxHx and current flows perpendicular to strike (*y*-axis). Additionally, a 1×1 tensor ***K****z* relates the vertical and horizontal magnetic fields through

$$[Hz\ ] = [\boldsymbol{K}z\ ][\mathbf{H}].$$

For a 2-D Earth, Kzx = 0 and Kzy reflects cross-strike changes in current flowing along strike (TE mode).

MT STUDIES IN ANTARCTICA

Hessler and Jacobs (1966) recorded analogue, long period ($T > 1$ min) **E**-fields over glacial ice at Vostok with 200 m bipoles and copper screen electrodes buried in brine-soaked firn. Correlations were visible with simultaneous magnetic records, but large spike noise was common and no MT impedances were estimated. MT measurements were taken by Fournier (1994) on the Antarctic peninsula but electrical contact either was on exposed earth or sea ice of similar resistivity (1000 ohm m) and so not characteristic of the continental interior. This appears to have been the case as well in the surveys of Kong et al. (1993, 1994) on the Fildes peninsula of West Antarctica and near the Larsmann Hills of East Antarctica. Good-quality MT data at relatively long periods (20–2000 s) has been acquired by Beblo and Liebig (1990) over thin glacial ice cover in North Victoria Land. They used copper screens as electrodes over a 25 m bipole span and an electrometer of very high input impedance. Signals in this longer period range are due to high amplitude ionospheric micropulsations, but the lack of shorter period data makes it difficult to quantify resistivity of most of the crustal column. However, Wannamaker et al. (2004) did show that sounding results during both low- and high-activity times of the polar electrojet were very similar, from which they concluded that non-plane-wave source effects were not a serious issue. The first high-quality broadband MT soundings over the thick interior ice sheet of Antarctica were obtained by over Whitmore Mountains–Ross Embayment transitional crust (Wannamaker et al., 1996) A total of nine tensor soundings in the period range 0.001–1000 s approximately were taken in a profile along an approximately east-west oriented Schirmacher Oasis (Fig.1). Out of nine stations, one station (MT 7) has been occupied over polar ice sheet which is situated at 4 km towards south of Schirmacher Oasis. However, it may be noted that the profile acquired is 18 km in length and may not be representative of other areas of East Antarctica. Data from two MT sites (8, 9) could not be recovered due to problems with instrument and logistic support. Also, the data from MT site 9 has been very noisy, being very close to Maitri and hence has not been considered.

MT SURVEYING AT SCHIRMACHER OASIS

MT data was collected using the GMS-05 and ADU-06 systems of Metronix, Germany with a station spacing of ~2-3 km. The average recording time per site was approximately 3-4 days. This is slow compared with most MT surveys on land because of the additional logistical requirements of Antarctica. Despite difficulties, patient surveying led to the acquisition of good quality MT sites. The apparent resistivity and impedance phase response for all the soundings, after robust processing is shown in **Figs 2-5**. The most striking feature is the variation of apparent resistivity in both TE and TM modes, i.e. high resistive layer (at short periods) followed by conductive layer at long periods.

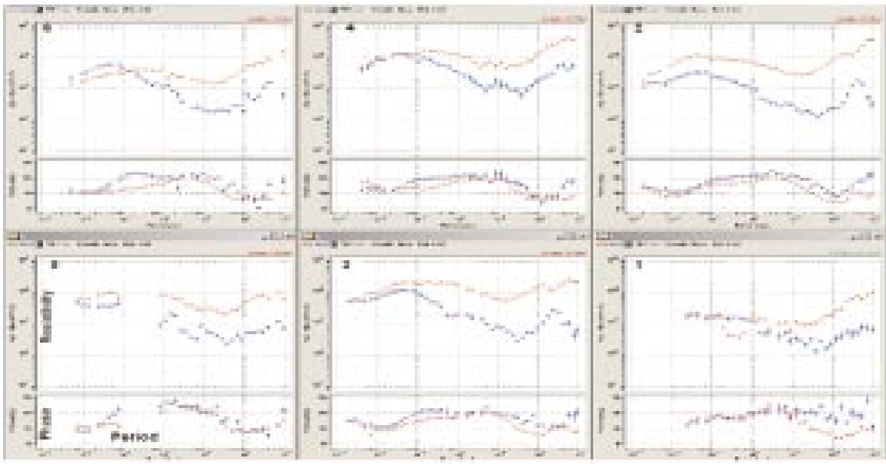

Fig. 2 : Apparent resistivity and phase response for MT sites

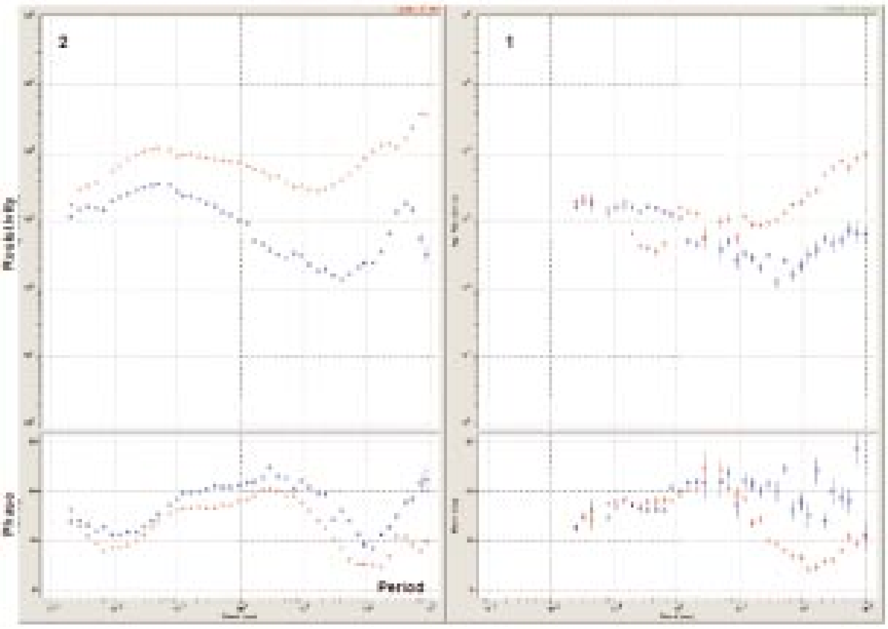

Fig. 3 : Apparent resistivity and phase response for MT sites

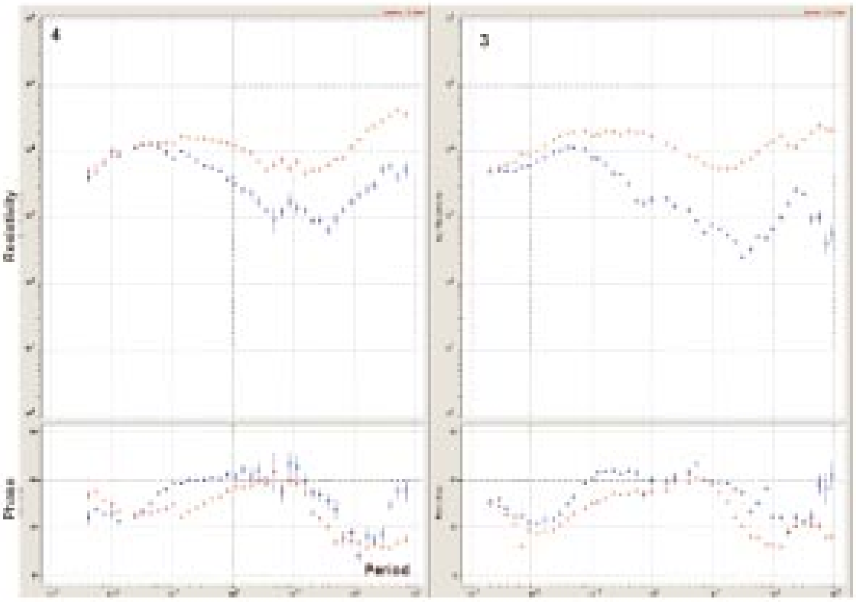

Fig. 4 : Apparent resistivity and phase response for MT sites

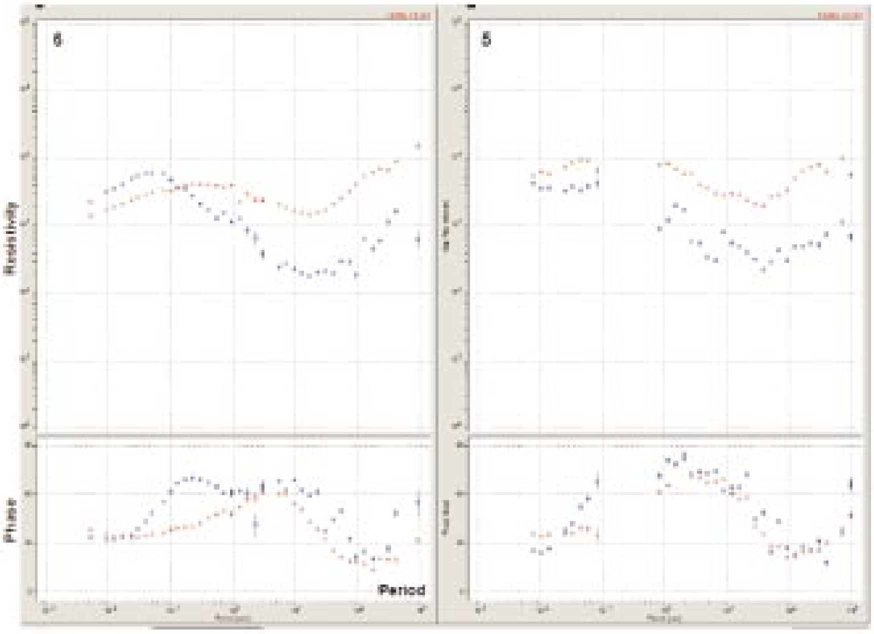

Fig. 5 : Apparent resistivity and phase response for MT sites

Forward modeling

Schirmacher Oasis is an exposure surrounded by ice with shelf ice towards Northern side and continental ice on the southern side. Possibility of sea water on the northern side intruding into the Oasis has been reported (IAE volumes). The effect of this intrusion of sea water on the response of MT curves is a matter of debate. Information from bore wells on the northern shelf has been taken into account and MT response modeled using forward modeling. The initial model used for forward modeling is shown in **Fig. 6. Figures 7 & 8** show the forward response with and without seawater intrusion. Forward response brings out clear evidence of the effect of underlying subsurface seawater intrusion and the MT responses in the Oasis. This needs to be taken care properly. TM component is affected by the underlying subsurface seawater layer. Accordingly, only the TM component is considered here for 2D modeling.

Resistivity models

Because the propagation of EM waves in the Earth at the periods of interest is diffusive, MT fields cannot resolve sharp structure in the subsurface without additional constraints (Parker, 1994). One way to

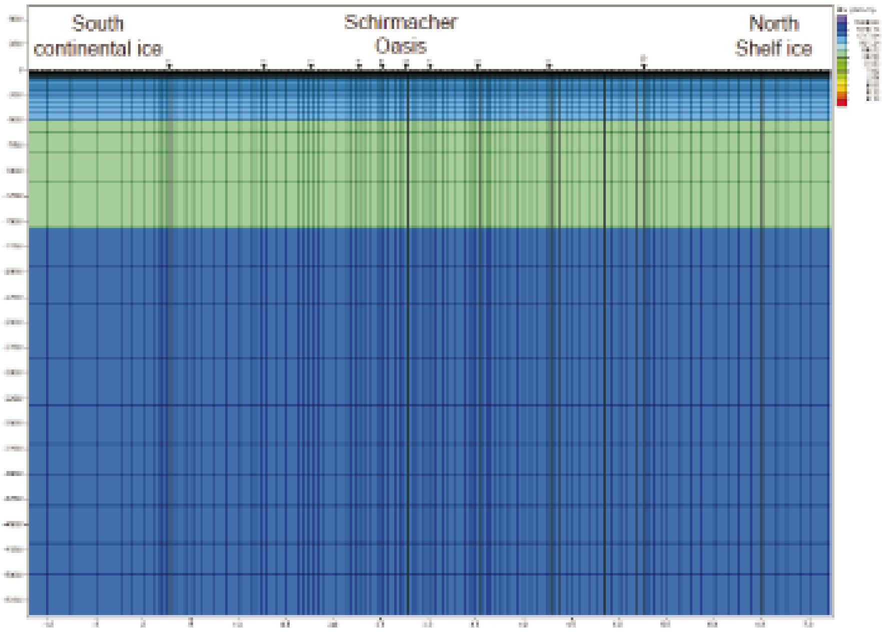

Fig. 6 : Numerical grid for forward response in the Oasis upto 50 Km

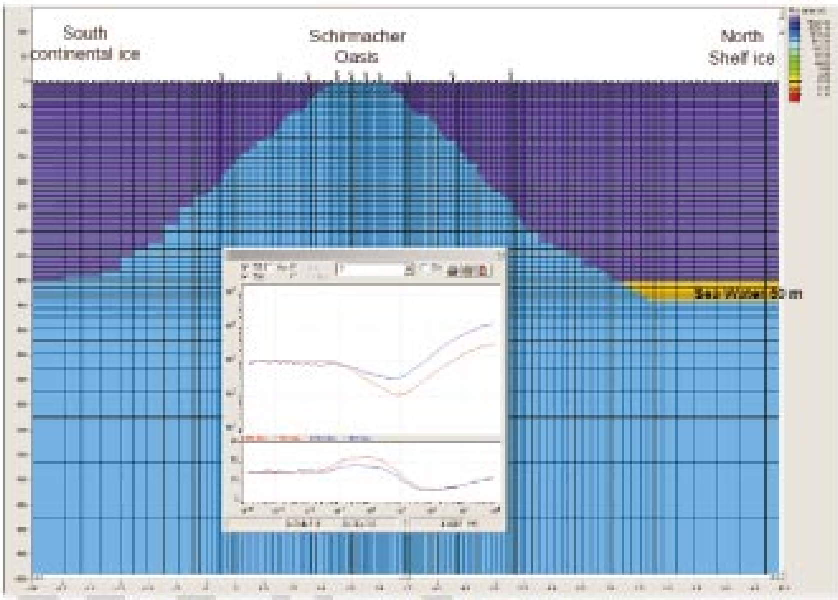

Fig. 7 : Model with sea water (50 m thickness) below the shelf ice on northern side-starting from 4 Km from Oasis and forward response in the Oasis at Site 7

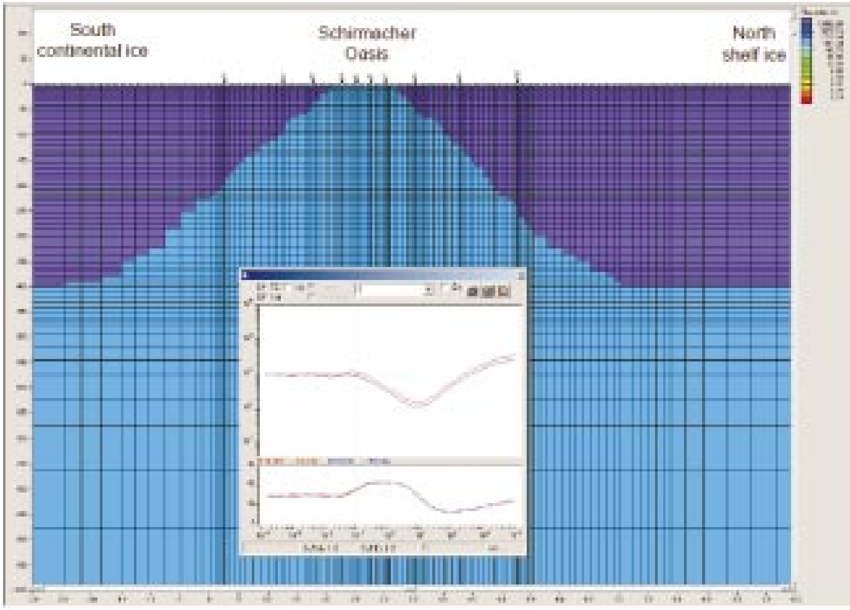

Fig. 8 : Model without sea water below the shelf ice on northern side-forward response in the Oasis at Site 7

proceed is by solving for a limited number of resistivity parameters, such as in a discrete layered model, in a least-squares sense (e.g. Petrick et al., 1977). Alternately, the Earth model can be divided into several thousand incremental parameters or 'pixels', constrained as an ensemble to produce conservative model variations (de Groot-Hedlin and Constable, 1990) and is often referred to as a minimum structure model. We consider both approaches. Given the first-order similarity of all the sites, a quick initial interpretation is carried out by integrating the nominal TM (yx) mode impedance along the profile (results not shown here). The nominal error bars for the integrated impedance are smaller than those of any individual sounding because each original sounding contains independent information concerning the regional average profile. Although a physical basis for such integration is established only for the TM mode, we apply it to the TE mode and show that there is a single model of resistivity variation which is consistent with all the quantities.

A data set of six sounding (MT sites) has been considered here for 2-D modeling. The profile is oriented in East-West direction and is about 18 km. in length. MT site 6 falls towards the eastern end of Schirmacher Oasis close to the Russain station, Novolazareyskaya. MT site 1 is close to a nunatek on the Western side. Geological strike for the sites along the profile has been computed using McNiece program (McNiece and Jones, 2001) and a strike of N150W deduced for all the sites.

All the six MT sites have been considered here without rotation as the strike of N150W is a gentle one. TE= YX has been considered after detailed analysis and forward modeling of the geological situation in Schirmacher Oasis. MT Data is subjected to 2-D modeling using NLCG program implemented on latest version 2.20 WinGlink platform (Rodi and Mackie, 2001). A model with half space resistivity of 100 Ohm.m. is considered and model subjected to 250 iterations. Both TM and TE data with six decades (0.001 to 1000 Hz) is considered here with an error floor of 5% for resistivity and phase.

A Tau of 3, which indicates smoothness for the model, has been used here. The 2-D inversion is called off when misfit reductions per iteration reach less than 0.05 percent. The obtained model is then studied for different parameters of Tau, starting from 3 to 50. Variation of rms error with roughness for the model is plotted and an optimum value of eight for tau is obtained from this L curve. The resulting model for Tau of eight is presented in **Fig.9** and represents the 2-D geo-electric section for the profile. The

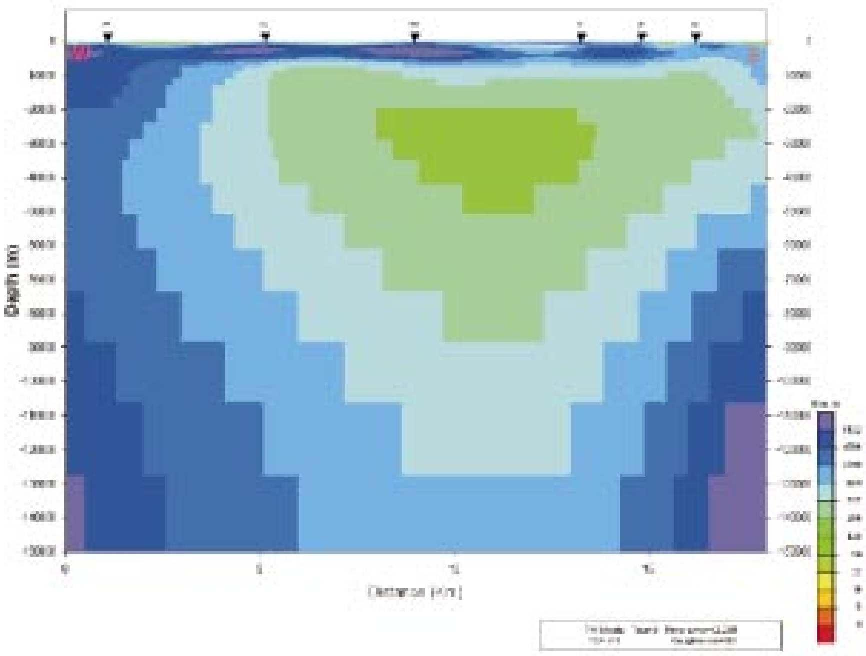

Fig. 9 : 2D Geoelectric section over Schirmacher Oasis

computed response has an rms misfit of 2.24. The electrical structure of the Schirmacher Oasis up to a depth of 150 km is shown here. 2 D Geoelectric structure for tau of eight and both TE and TM modes for different depths is shown in **Fig. 10a, b & c**.

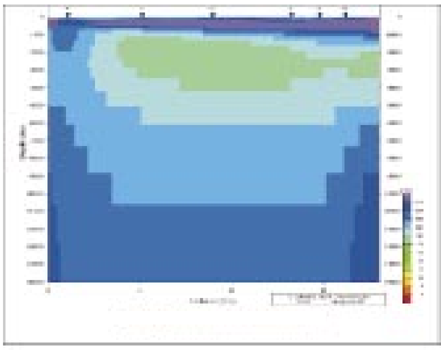

Fig. 10a : 2D geoelectric section over Schirmacher Oasis

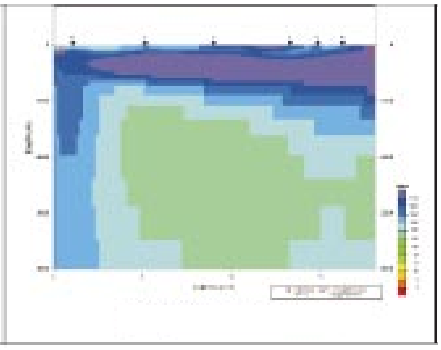

Fig. 10b : 2D geoelectric section over Schirmacher Oasis (40 Km)

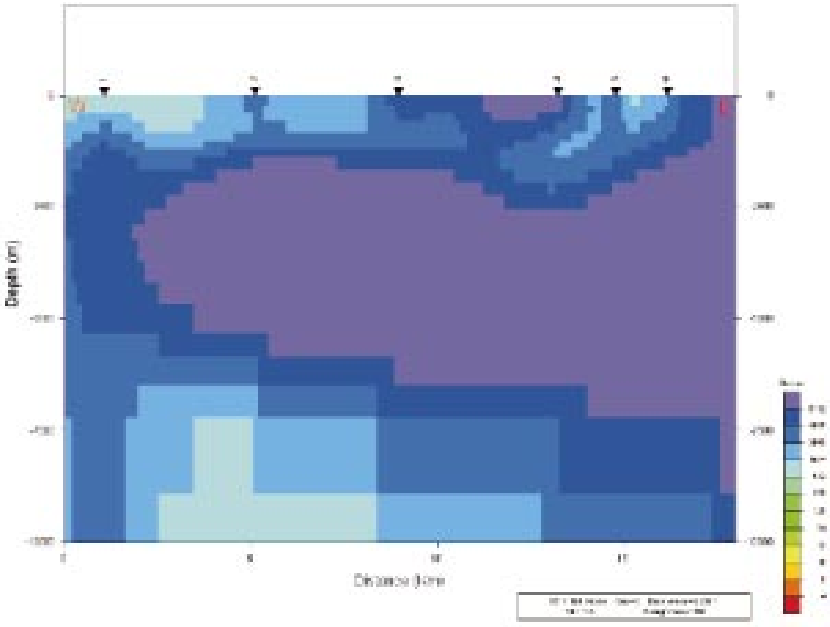

Fig. 10c : 2D gepelectroc section over Schirmacher Oasis (10 Km)

Average thickness layer of 13 km with resistivity of 8000 Ohm.m. is quite evident throughout the profile (Fig.10b). The thickness of the layer varies over the length of the profile, being 15 km on the eastern side of Maitri and 10 km on the western side. Thus thinning of upper crust towards the West is prominent from the 2-D model. The upper high resistive layer is overlain by a layer of 7 km thickness (resistivity of 6000 Ohm.m.), followed by a layer of thickness 8 km (resistivity of 2000 Ohm.m.). The lower crust is conductive with resistivity of 600 Ohm.m. and extends to deeper level. The general trend of thinning of the layers is markedly seen through the profile.

In our study, apparent resistivity and phase data for both TE and TM modes have been considered. An example of fit between the observed and computed data for this profile in the form of apparent resistivity and phase pseudo sections is presented in **Fig. 11** and **Fig. 12** for TM and TE modes respectively. A reasonably good fit is observed for all stations. The fit may be further improved by considering 3-D model for the subsurface.

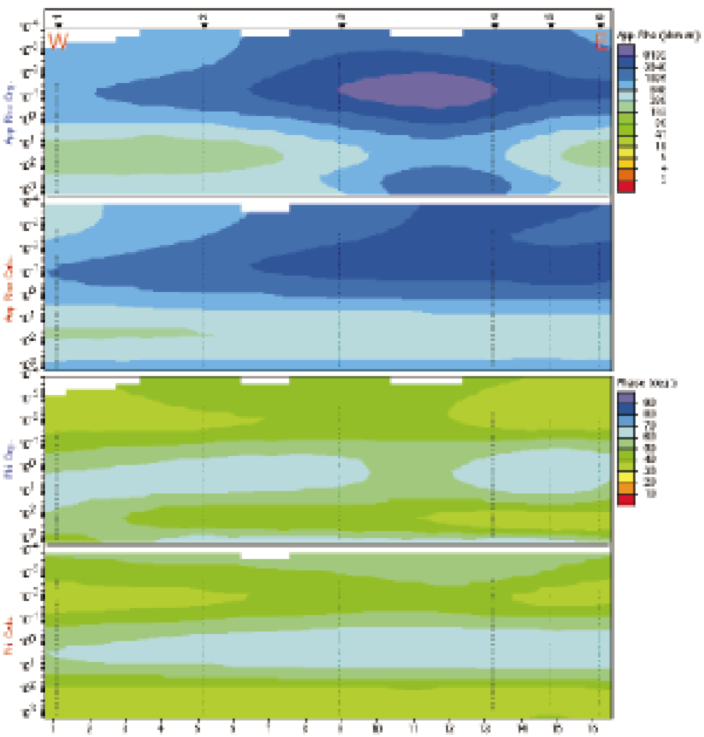

Fig. 11 : Observed and modeled apparent resistivity and phase Pseudo sections with TM fit for TE + TM data

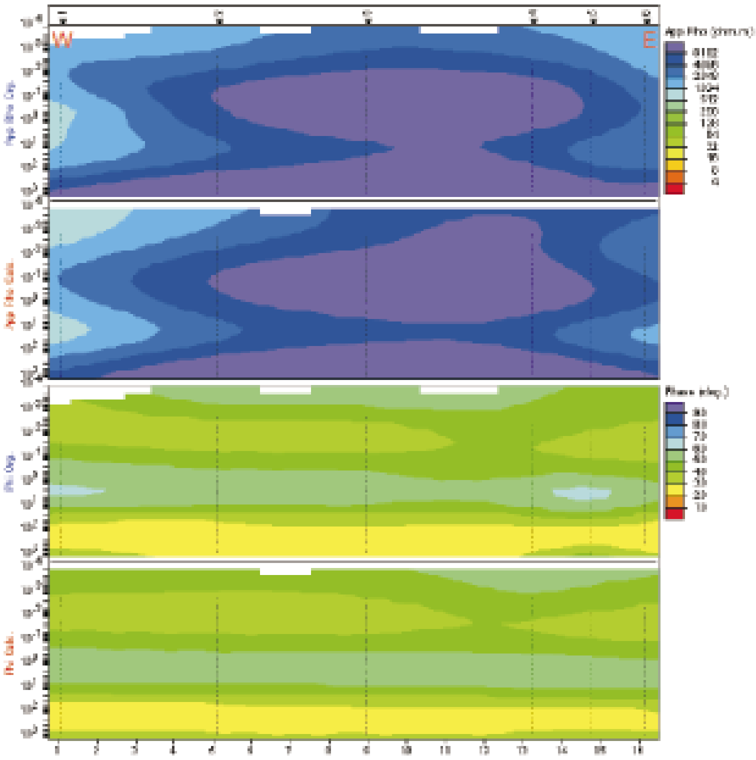

Fig. 12 : Observed and modeled apparent resistivity and phase Pseudo sections with TE fit for TE + TM data

MT MEASUREMENTS OVER ICE-COVER

On polar ice one site has been occupied, which is situated at 4 km south of Schirmacher Oasis. Here, the conventional electric field sensors are not suitable for measurements. So, Titanium sheet (60 cm × 60 cm × 3 mm) has been used as an electric field sensor, and it has been buried in the ice in vertical direction. Bentonite powder has been used for better contact between the titanium sheet and ice. High strength electric cables (multi-standard) were used to avoid breakup/cracks of wire at low temperatures (<-50 C). Field photos in **Figs. 13&14** demonstrate the logistics used for MT survey in Antarctica. The data was acquired for a period of 5 days, and the variation in resistivity and phase with period is shown in **Fig. 15**. 1-D modeling provides information about the horizontal layers at subsurface depths. The best fitting 1-D model parameters of a fivelayer model earth are interpreted using Marquardt (1963) algorithm and the results are tabulated in **Fig**. **15**.

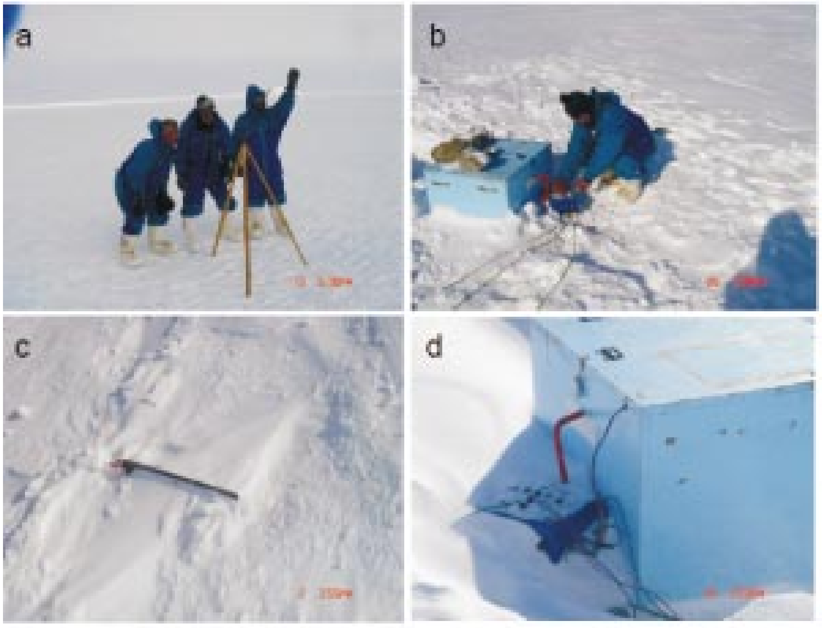

Fig. 13 : (a) Fixing layout on ice station (b) Inspection of equipment durng the recording (c) Titanic sheet as electrode and (d) ADU-06 covered with ice after 6 days

Fig. 14 : (a) Induction coil, porous pot assembly (b) Fixing of Cd C12 Porous Pot at MT site (c) Leveling and positioning induction coil (d) Signal Detection Box during data acquisition

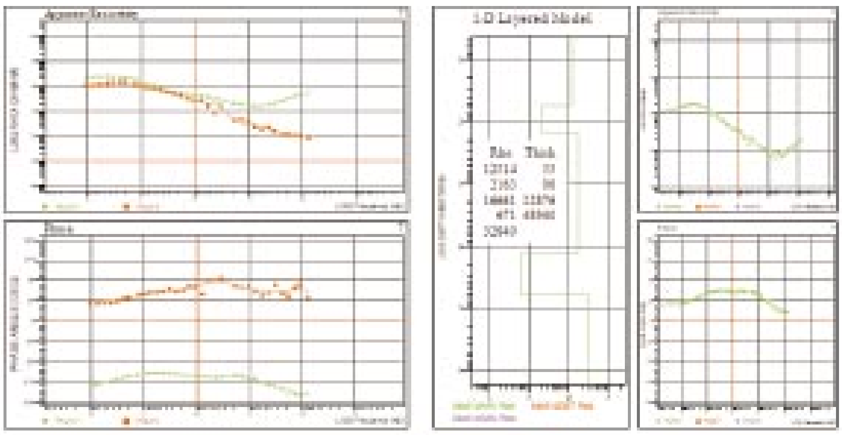

Fig. 15 : Apparent resistivity and phase response for a stateion (MT7) on ice-cover, 1-D layered model and fit for the arithmetic average

The modeling results indicate the presence of resistive top layer up to 55m (12500 ohm m) and ~100 m thick (~2200 ohm.m) sequentially corresponds to ice and sediments below ice-cover. The sedimentary layer is overlain by resistive basement of resistivity ~16,000 ohm m. Conductive lower crust (~600 ohm m) of ~50 km thick, has been identified from a depth of 13 km and it is followed by a resistive layer of resistivity ~33,000 Ohm-m.

GEOLOGICAL IMPLICATIONS OF RESISTIVITY STRUCTURE

The conductive layer directly under the ice sheet is strongly suggestive of sedimentary rocks of substantial porosity or of clay or organic matter content (e.g. Wannamaker and Doerner, 2002). The resistivity of the lower crust is low while the resistivity of upper mantle beneath the Schirmacher Oasis region is high. Siegert (2000) proposed that heat flow through much of the East Antarctic lithosphere could be ~50 mWm”2 or more. The degree of extensional activity in Antarctica today is limited, perhaps related to its being surrounded by oceanic ridges, so that the volcanism and thermal processes are hypothesized to stem from mantle plume processes (Hole & LeMasurier 1994). Continents are estimated to migrate over ~5 hotspot plumes every 150 Myr on average that may contribute up to one-third of lower crustal material (Condie, 1999; Johnston & Thorkelson, 2000). Plume fronts are modelled to interact with lithospheric basal ‘topography’, thereby localizing zones of melting and thermal processes (Ebinger and Sleep, 1998;

Maza *et al.*, 1998), which may explain regionalized East Antarctic uplifts such as the Gamburtsev–Vostok areas.

CONCLUSIONS

High-quality MT measurements may be gained from the Antarctic icy-continent with proper attention to instrument design and time-series processing. Incorporation of non-reactive electrodes can yield electric field records of high fidelity over ice cover. The principal impediment to acquire high quality MT data that we experienced was electric field contact. Signal-to-noise ratio may be improved by lengthening the E-field bipoles and also by using titanium sheet electrodes in addition to using bentonite power for better contact. Magnetic field recording appeared to present no special problems relative to surveying in temperate climates, although calibration factors appropriate to low operating temperatures should be ensured.

MT results have provided some of the first definitive indications of both exposed and sub-ice structure. A substantial and widespread basement of granitic gneiss has been inferred just below the ice sheet, corroborating earlier conjecture from geological and resistivity data. Deep resistivity structure of the Schirmacher Oasis region appears to differ from that typical of cratonic lithosphere worldwide in exhibiting low resistivity in the lower crust. We believe thermal activity generating high-temperature fluids or melts is more likely than solid phases for explaining the low resistivity, although the interpretation is not unique.

ACKNOWLEDGEMENTS

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