PRELIMINARY LONG-PERIOD MAGNETOTELLURIC INVESTIGATION AT THE EDGE OF ICE SHEET IN EAST ANTARCTICA

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ABSTRACT:

The lithospheric mantle structure of the Antarctic continent is of great significance of studying the polymerization and fragmentation mechanism of Gondwana and the plate movement law. Long-period magnetotelluric (LMT) is an important method to study the electrical structure of earth crust and mantle. However, been limited by the bad natural environment and logistics supply difficulties, there is no LMT record of Antarctica before. In 2018, China’s 34th Antarctic scientific expedition carried out the LMT survey at the eastern edge of the Antarctic continent with a frequency range of 0.00015 Hz to 0.1 Hz. After the processing and analysis, we get three points as fellow: (1) The lithospheric mantle of Antarctica has a three-dimensional resistivity structure; (2) There are low resistivity regions in the Antarctic mantle, which may be related to thermal activity. (3) It is possible to carry out LMT measurements in eastern Antarctic and more can be done in the future.

1. INTRODUCTION

The Antarctic continent are the central block of all the fragmented blocks of Gondwana, which is adjacent to other blocks (such as Africa, India, and Australia) before the disintegration of Gondwana in the late Mesozoic (An et al., 2015; Torsvik et al., 2010). Since the Mesozoic, the level of tectonic activity in the Antarctic continent is relatively low, especially in the stable craton in the east of the Antarctic continent which has no obvious tectonic deformation in the crust or lithosphere (An et al., 2015; Cande et al., 2000). The information on the aggregation and evolution of Gondwana ancient land may still be preserved in its crust and lithospheric mantle. Therefore, the lithospheric mantle structure of the Antarctic continent is of great significance of studying the polymerization and fragmentation mechanism of Gondwana and the plate movement law (Michaux, 2009; Sutherland and Cooper, 2008).

To research, the lithospheric mantle structure largely depends on geophysical methods (Darbyshire et al., 2018; Malleswari et al., 2019; Tien et al., 2016; Winberry and Anandakrishnan, 2004). Magnetotelluric (MT) is an important geophysical technique for investigating sub-ice structure of Antarctica, which has the advantages of wide detection frequency band, not easy to be shielded by high resistivity layer, high resolution to low resistivity abnormal body, simple field construction layout and minimal environmental impact (Peacock and Selway, 2016).

Hessler and Jacobs (1966) described the MT measurement in Antarctica first. Based on the analysis of two MT data collected from north Victoria Land, Antarctica, Beblo and Liebig (1990) believe that the non-plane wave field source of the polar region has little influence on the calculation of MT apparent resistivity. Wannamaker et al. (1996) overcome the problem of high contact resistance through preamplifier and obtained the high-quality MT data in the middle thick ice-covered area of Byrd subglacial basin in Antarctica at first time. In 2004, they also collected high-quality MT data onto the eastern Antarctica, which proved the feasibility of MT data collection of the whole Antarctic region (Wannamaker et al., 2004). After that, Armadillo et al. (2004), Murthy et al. (2013), Peacock and Selway (2016) also showed the excellent MT measurement at the eastern Antarctica (Figure 1). Long-period magnetotelluric (LMT) can be used to study the electrical structure of earth crust and mantle (Lizarralde et al., 1995; Mackie et al., 1988; Unsworth et al., 2005).

However, due to the fact that Antarctica is covered by ice and snow, limited by the bad natural environment and logistics supply difficulties, it is relatively difficult to carry out large-scale long-time MT measurement continuously. At present, the most detection depth is generally within 40 kms using MT method (Armadillo et al., 2004; Murthy et al., 2013; Peacock and Selway, 2016; Wannamaker et al., 2004). The geophysical research on the structure of the Antarctic plate crust and lithospheric mantle is still focused on imaging the broadband seismic base station data (An et al., 2015; Heeszel et al., 2016; Ritzwoller et al., 2001), processing and inversion of satellite gravity anomaly data (Haeger et al., 2019; Ji et al., 2018; Scheinert et al., 2016), and joint processing and interpretation based on gravity and seismic data (Baranov et al., 2017; Tenzer et al., 2018).

This paper introduces the LMT measurement of China’s 34th Antarctic expedition to 2018 at the edge of ice sheet in east Antarctica. The purpose of this work is to test the feasibility of LMT measurement of Antarctica. Using the LMT data, we can obtain the electrical structure of the upper mantle of the lithosphere and enriches the geophysical data set about the Antarctic lithospheric mantle structure. Considering the issue of logistics supplied, prior to the more challenging polar inland research, the area around the edge of the ice sheet in the east of Antarctica is relatively easy to access.
survey, the LMT sites were set near Zhongshan Station this time (Shown in Figure 1).

2. LMT METHOD

MT is a passive method that measures the Earth’s electrical response to natural, time-varying magnetic fields (Chave and Jones, 2012). And there is a key assumption that the magnetic field is a horizontally polarized plane wave propagating vertically to the earth in MT method. The plane waves electromagnetic field satisfies the Maxwell equations as follows:

\[
\begin{align*}
\nabla \times \mathbf{H} &= j + \frac{\partial \mathbf{D}}{\partial t} \\
\nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \\
\n\nabla \cdot \mathbf{B} &= 0 \\
\n\nabla \cdot \mathbf{D} &= q
\end{align*}
\]  

(1)

where \( \mathbf{H} \) = the magnetic field strength (A/m)  
\( \mathbf{E} \) = the electric field strength (V/m)  
\( \mathbf{D} \) = the electrical displacement (C/m²)  
\( \mathbf{B} \) = the magnetic induction intensity (Wb/m²)  
\( j \) = the conduction current density (A/m²)  
\( \frac{\partial \mathbf{D}}{\partial t} \) = the displacement current density.

Moreover, based on the Maxwell equation, the \( \mathbf{H} \) and \( \mathbf{E} \) measured at the surface satisfy the following relationship:

\[
\mathbf{E} = \mathbf{ZH}
\]  

(2)

where \( \mathbf{Z} \) is the impedance tensor, also been called the MT transfer function. \( \mathbf{Z} \) is a complex, frequency-dependent, rank two tensor that contains all the information about subsurface resistivity structure (Peacock and Selway, 2016).

In a 1-D Earth model, the diagonal components of \( \mathbf{Z} \) will be zero and the off-diagonal components will be equal but opposite in sign; In a 2-D Earth model, when the measured \( \mathbf{E} \) and \( \mathbf{H} \) fields are parallel and perpendicular to geoelectric strike, the diagonal components of \( \mathbf{Z} \) will remain zero while the off-diagonal components will decompose into the transverse electric (TE) mode and the transverse magnetic (TM) mode. In a 3D Earth model, all components of \( \mathbf{Z} \) will be nonzero (Booker, 2014; Peacock and Selway, 2016). Therefore, before the inversion of MT data, dimension analysis is needed to determine the correct earth model (Bahr, 1988; Martì, 2014).

There is no essential difference between the method of LMT and MT. In MT method, the penetration depth can be estimated by the skin depth, which increases with period and subsurface resistivity. Therefore, the LMT method can penetrate a deeper structure than the general MT method. Accordingly, in order to obtain long-period data, the LMT method requires a longer acquisition time, which is particularly difficult in Antarctica.

3. DATA RECORDING

From November 15, 2017 to February 5, 2018, Eight long-period magneto telluric survey points were sit by Polar Research Institute of China within 20 km south of Zhongshan station, Antarctica (Shown in Figure 2.). An Aether multi-functional acquisition system was used for data recording developed by Crystal Globe (Shown in Figure 3). Magnetic fields (\( B_x \), \( B_y \), \( B_z \)) were measured using three-component fluxgate sensor (Shown in Figure 3.c). Electric fields were measured using non-polarizing electrode (Shown in Figure 3.b). Horizontal electric (\( E_x \), \( E_y \)) and magnetic (\( B_x \), \( B_y \)) field components were recorded in N-S and E-W orientation. For each station, the total recording time was 144-168 hours. The control and detection of the acquisition status is completed by the acquisition software on the external PC (Shown in Figure 3.a).
Since the electromagnetic field time series recording by Aether are stored in blocks, before further processing, we used the Geotshub software matched with Aether to merge the time series blocks into a single time series file. Then, impedance tensors were estimated at time series using the proprietary prMT software from Crystal Globe with local electric field ($E$) reference. with a period range of 13-6700 s. According to Equation (4), the apparent resistivity can be calculated (Nam et al., 2007):

$$\rho_a^j = \frac{1}{\mu_0} \left| Z^j (\omega) \right|^2$$

(4)

where $\omega$ = the angular frequency
$\mu_0$ = the free space permeability
$Z^j$ = the impedance tensor element
$\rho_a^j$ = the apparent resistivity.

The geo-electrical strike can indicate the geological structure strike (Bibby et al., 2005). In 2D model, it's the best azimuth of rotating impedance tensor to decompose MT data onto TE mode and TM mode (Zhang et al., 1987). Although the 2D skewness indicates that the underground of the study area has a 3D electrical structure, the geo-electrical strike is still helpful for us to understand the characteristics of the lithospheric mantle structure. Figure 5 shows the geo-electrical strike of the 2th and 6th LMT station with frequency. Since we take the X direction as the north-south direction, the geo-electrical strikes shift to the east-west direction with depth.
As the underground cannot be approximately 2D geolectric model, the apparent resistivity of TE and TM modes cannot be separated. In this case, the equivalent impedance derived from the impedance invariants can better reflect the characteristics of the underground electrical structure than the single impedance to some extent (Rodríguez et al., 2001). Calculation formula for equivalent impedance:

\[ Z_{eff} = \sqrt{Z_{xx}Z_{yy} - Z_{xy}Z_{yx}} \]  

The equivalent apparent resistivity can be calculated by Equation (4) (Shown in Figure 6).

![Figure 6. Equivalent apparent resistivity section](image)

Figure 6. Equivalent apparent resistivity section

In this paper, 1D Occam inversion method is used for inversion of equivalent apparent resistivity (Shown in Figure 7) (Rodríguez et al., 2001). The most interpretation depth is 90km. In the inverted section, there is a high conductivity layer (C1) at the depth of about 20 kms which also was found in the MT exploration by Peacock and others at Antarctica (Armadillo et al., 2004; Murthy et al., 2013; Peacock and Selway, 2016). Armadillo et al. (2004) believed that this high conductivity layer is related to the thermal activities of the lower crust and upper mantle. In Figure 7, the thickness of high conductivity layer C1 is about 10 km, but it is not an isolated abnormal layer. The vertical zonal distribution of high conductivity region (C2) intersects with C1 and extend to the bottom of inverted section which may be a channel for upward transportation of thermal materials. We thought that the C1 high conductivity layer is related to the underground thermal activity, and the high temperature leads to the extremely low resistivity; the C2 high conductivity region is related to the mantle thermal supply, which provides the heat source guarantee for the C1 high conductivity layer to maintain a high thermal state. Objectively speaking, because of the frequency less than 0.1 Hz, there is a certain error in the burial depth of the high conductivity layer due to the lack of high frequency data.

5. CONCLUSIONS

In this paper, LMT measurement has been successfully carried at the eastern Antarctic by Polar Research Institute of China. The 2D skewness of LMT data indicates that the lithospheric mantle of Antarctica has a 3D resistivity structure. The geo-electrical strikes to rotate around north-south to east-west with depth. The inverted section shows that there are high conductive regions in the lower crust of the Antarctic plate which is related to the thermal activities of the lower crust and upper mantle. The LMT measurement is feasible at the Antarctic, and the LMT has great potential for the exploration of the Antarctic plate crust and lithospheric mantle structure. In the future work, we plan to supplement the high-frequency MT data and extend the LMT survey line of the Antarctic inland, so as to obtain more abundant data.

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