Electrical Resistivity Structure of Changbai Volcanic Mountain: Results from Magnetotelluric Exploration Methods

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Abstract: To address the foreign media's comments that the Tianchi Volcano in Changbai Mountain is likely to erupt in the near future, we collected a magnetotelluric (MT) observation profile approximately 120 km in length in the area to detect the deep electrical structures of magma chamber. Because electromagnetic noise from an unknown source is very strong in the research area, we used remote-referencing and robust processing, rhoplus analysis, impedance tensor decomposition, and a mutual approximate calculating method between apparent resistivity and phase for MT data processing. These techniques resulted in relatively reliable electromagnetic response data in the strong electromagnetic noise area. The results show that there is a clear magma channel beneath Tianchi Volcano, at a depth of approximately 10 km. An obvious abnormal body of low resistance, where resistivity is less than 10 Ω•m connects with the magma channel at 7 km deep and north of the existing crater, suggesting a developing magma chamber in the shallow surface. There are two nearly vertical low resistivity zones at 7-17 km in depth, one between stations C07-C09 and the other between stations C04-C05, that connect directly to the low resistance body directly; these low resistivity zones are likely active fault zones. Crustal low resistivity anomaly bodies are widely developed at depths of 13 – 30 km about 20 km south of Tianchi Volcano, suggesting an active magma chamber. The MT sounding method results indicate that Changbai Mountain has a high risk of volcanic eruption, and the MT method performed well detecting the state of current volcanism.

1 INTRODUCTION

In 2012, Taniguchi Hiroshi stated that the probability of a volcanic eruption at Changbai Mountain was 99% over the next 20 years based on a "3-11" earthquake that occurred in 2011. To address the foreign scholars' claims that Changbai Mountain volcano may erupt in coming years, China's Changbai Mountain Administrative Committee official responded based on data from the China Earthquake Administration, the Seismological Bureau of Jilin Province. The Tianchi Volcano monitoring station was established at Changbai Mountain in 1997, and all observations since then have indicated that Changbai Mountain shows no active volcanism. Although the most recent eruption of the Changbai Mountain volcano remains unconfirmed, the active period of the Northeast Asian geological plate has attracted the attention of many scientists.

Changbai Mountain is located at the border of northeast China and North Korea. The middle of the crater is Tianchi Lake, with half belonging to China and the remaining half belonging to North Korea. The water surface is 2150 m above sea level and the average water depth is 204 meters. It is the deepest lake in China and the border lake between China and Korea; its storage capacity is more than 2 billion cubic meters. Tianchi Volcano at Changbai Mountain is the most comprehensive Cenozoic composite volcano preserved in China (Liu et al., 1995). In geological structure, Changbai Mountain is located above the deep subduction zone of the Western Pacific Ocean and a series of network faults composed of NE and NW faults are developed in the area. There have been several eruptions of this volcano in history, with three credible volcanic eruptions in 1668, 1702 and 1903 (Jin and Xi, 1994). Changbai Mountain is one has some of the most intense Quaternary volcanic activity in China

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and is also one of the most dangerous volcanoes in recent years in China (Liu et al., 1995).

Because magma has clear characteristics of low resistance, magnetotelluric (MT) exploration in the volcanic area can provide important constraints on volcanism. The MT sounding method is sensitive to low resistivity structures and is an important method for deep exploration. It has been widely applied in deep structure detection and resource exploration (Jin et al., 2010; Wei, 2002). Tang Ji and others completed five umbrella lines and one North-West line around Changbai crater and nearby areas. Sixty-one stations were installed for broadband magnetotelluric sounding data, and their detection results showed that at Changbai Mountain Lake and the north and east regions, there is very low resistivity at depths of about 12 km; the resistivity of abnormal body is ten to dozens of Ω•m, indicating a probable crustal magma chamber (Tang and Liu, 1997; Tang and Li, 2001; Tang et al., 1999). The purpose of this study is to investigate underground volcanic magma chamber system and electrical characteristics of the crust and upper mantle to provide a geophysical basis for hazard prediction and disaster evaluation of volcanic eruptions.

2 DATA ACQUISITION

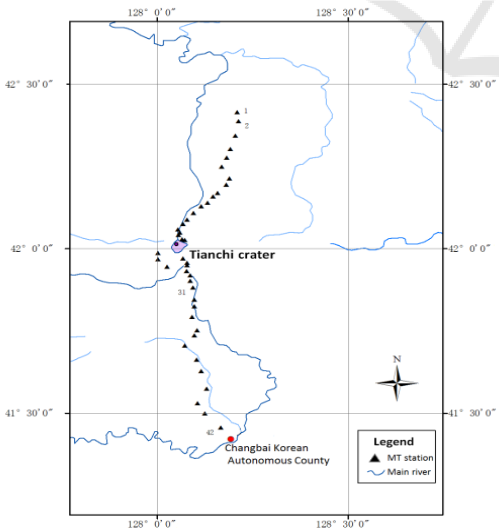

Figure 1: Distribution of MT stations at the Tianchi Volcanic area at Changbaishan Mountain. The center of the survey line is Tianchi Lake. The length of the measuring line is approximately 120 km.

Changbai Mountain scenic area is a key 5A level tourist attraction in China. With the development and utilization of the scenic area, various large electromagnetic interference sources are spread across the study area. Therefore, data acquisition and data processing were two major key technical problems for this project. Based on prior working characterizing the geological deep structures in the Tianchi Volcanic Area of Changbai Mountain, the area shows two dimensional structures at NW and NNW (Tang et al., 1999; Li et al., 1995). There are also three dimensional anomalous bodies corresponding to the regional tectonic background. Most of the work area is covered by virgin forest , vegetation flourishes, and the terrain is undulating; therefore, it is impossible to arrange a straight line survey. For the convenience of comparative analysis to the results from previous studies, we designed one north-easterly MT observational profile with a length of 120 km (Figure 1). Forty-two stations were arranged along the line for broadband MT and long-period MT measurements at a spacing interval of about 2.5 km. For the strong electromagnetic noise, wide frequency and long period data were acquired simultaneously, which improves the data quality of the low frequency signal

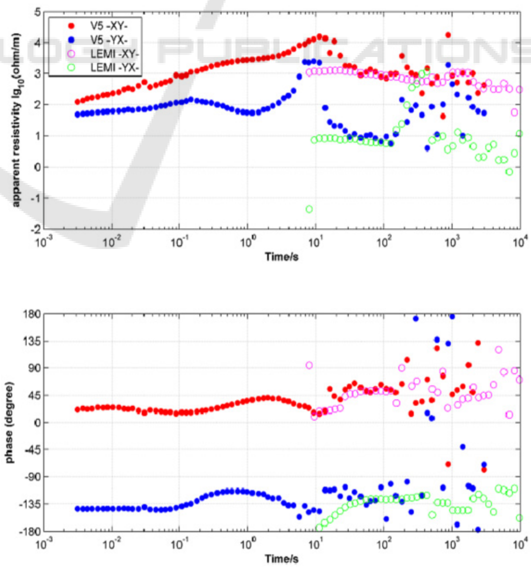

Figure 2: Magnetotelluric sounding curves for station No. C03. The closed points represent observation data acquired using the wide-band magnetotelluric sounding instrument MTU-5A/P, and open symbols represent the observation data acquired using the long period magnetotelluric sounding instrument LEMI417M.

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At each station, an induction type MTU - 5p broadband MT sounding instrument and flux-gate type LEMI417M MT sounding instrument were deployed for combined observations. Usually, the low frequency signal obtained using the long period instrument is better than the wide-band MT sounding instrument (Ye et al., 2013). The observational frequency range of the broadband MT instrument is 320-1/1000Hz, and the range of the long period MT sounding is 1/500-1/10000Hz. The data acquisition time for each wide-band MT station was 30 hours, while the data acquisition time for the long period MT station was 90 hours. Figure 2 shows the MT sounding response data for station No.C03, where both sets of instruments were deployed. The curve quality in the low frequency section, acquired by LEMI417M, is better than that of MTU-5P. With the combined observations from two sets of instruments at the same station, the data quality in the low frequency section can be improved.

3 DATA PROCESSING

During field data collection, we tested consistency with two mechanisms and repeated measurements to control data quality. Changbai Mountain is located at the border of northeast China and North Korea, where there is strong electromagnetic noise. Reliable electromagnetic response data was obtained after remote-reference and robust processing, rhoplus analysis, impedance tensor decomposition and applying a method for mutual approximate calculations between apparent resistivity and phase.

3.1 Remote Reference Technology

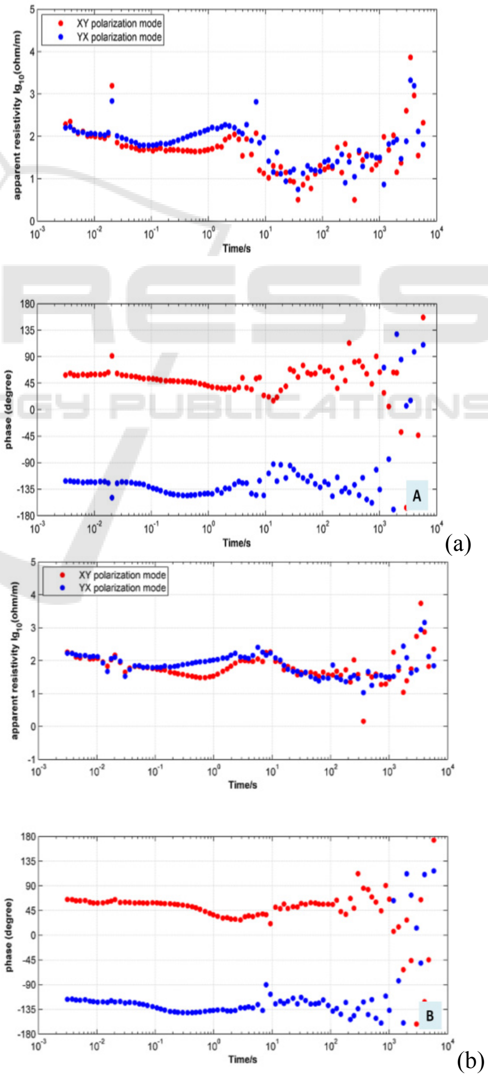

Figure 3: Data from station No.C14 before (a) and after (b) processing by remote reference technology.

Remote reference technology is based on the principle that the magnetic field signal changes little at over a short time in a certain range, but the noise between the measurement and reference stations is generally unrelated over a certain distance. Therefore, the method has the effect of suppressing interference (Yan and Hu, 1998; Edwards and Hastie, 1997). Due to the strong electromagnetic noise in the work area, we chose a flat terrain with little noise 40 km away from the working area to build a long-term reference station during field data collection. All station data were processed by magnetic remote reference technology, and the data quality from most stations was improved after reference processing. Figure 3 compares the results collected at station No.C14 before and after processing by remote reference technology. It is clear that remote reference processing technology in Changbai Volcanic Mountain has a certain suppression effect on electromagnetic noise.

3.2 Static Shift Correction

The additional electric field produced by the accumulation of charge around local inhomogeneous bodies usually results in an offset in the overall curves, which easily produces false geological anomalies if the curves are uncorrected. In the case of transverse homogeneous media, the high frequency segments of two apparent resistivity curves at one station should have consistent data values according to the principle of adjacent station similarity and regional similarity. The high frequency section of the apparent resistivity curve of an adjacent station should be almost identical (Chen et al., 2004; Weidelt and Kaikkonen, 1994; deGroot-Hedlin, 1991; Zhang et al., 2015). Using a unified analysis of all stations in the work area, a manual static shift correction was made to the apparent resistivity curve based on the static shift having a great influence on apparent resistivity and little influence on phase.

3.3 Mutual Approximate Calculation Method between Apparent Resistivity and Phase

Because the MT impedance is the minimum phase response function in one-dimensional media, for the minimum phase response function, the relationship between amplitude and phase angle is provided from the Hilbert transform formula (Fu, 1983; Fu, 198)

$$\theta(f) = -\frac{1}{\pi}\int_{-\infty}^{\infty} \frac{\lg|\mathbf{Z}(g)|}{f-g} dg \tag{1}$$

The approximate formula can be obtained from:

$$\theta(\omega) \approx \frac{\pi}{4} + \frac{\pi}{4}\frac{d \lg \rho_T}{d \lg \omega} \tag{2}$$

Concurrently, the following relationship can be obtained:

$$\frac{d \lg \rho_T}{d \lg \omega} = \frac{4}{\pi}\theta - 1 \tag{3}$$

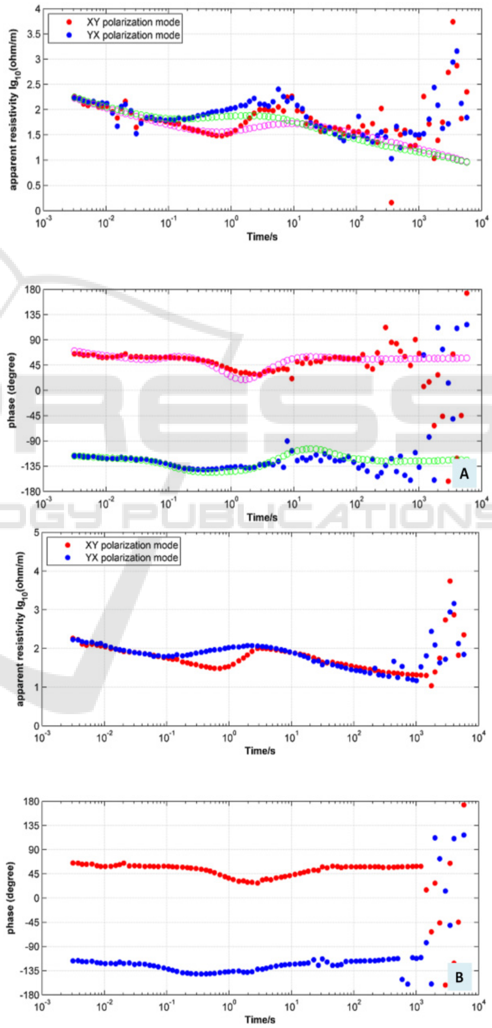

Figure 4: Results for station No.C14 based on the mutual approximate calculation method between apparent resistivity and phase curves. As shown, the quality of the low frequency signal is poor for strong electromagnetic noise. (a) Measured curves and calculated theoretical curves and (b) results for station No.C14 after correction.

The apparent resistivity and phase curves can be calculated using Equations 1-3, and some noise influence can be corrected with this method. Figure 4 shows the processing results for station No.C14 based on the apparent resistivity and phase mutual calculation technology method. The curve with open symbols indicates the results calculated using the trend in apparent resistivity and phase data. As shown in Figure 4(b), the MT data acquired is closer to the theoretical data when after modifying the apparent resistivity and phase data at a noise frequency while referencing the theoretical calculations value.

3.4 Other Processing Techniques

In addition to the described methods, there are additional advanced processing technologies, such as robust processing, rhoplus analysis, impedance tensor decomposition and others (Egbert and Booker, 1986; Chave et al., 1987). We ultimately obtained relatively reliable electromagnetic response data in the strong electromagnetic noise area using these different techniques.

4 DATA ANALYSIS AND QUALITATIVE EXPLANATION

A qualitative estimate of underground electrical structure in the Tianchi Volcanic area was obtained using 2D skewness and the analysis of the real induction vector. The profile was generally characterized using the 2D structure. The tectonic direction is primarily northwest. In addition, there is a 3D low resistivity body localized at shallow and deep depths.

4.1 Analysis of Two-Dimensional Characteristics

The two-dimensional deviation S (skewness) of the MT sounding impedance is a parameter reflecting the 2D dimension characteristics (Chen and Wang, 1990). For one dimension and the ideal two-dimensional structure, S=0. Generally speaking, smaller S values results in a more two-dimensional underground medium. It is generally believed that when the S value is less than 0.3 ~ 0.4, the underground structure can be considered a two-dimensional feature. Finally, S values greater than 0.5 indicate a three-dimensional medium in the corresponding depth underground. The MT result data after editing was used to calculate skewness along the profile (Figure 5). As shown, most of the stations along the profile show 2D structure characteristics in shallow space and strong three-dimensional characteristics at depth. Affected by strong electromagnetic noise, the low frequency skewness may be influenced and unreliable.

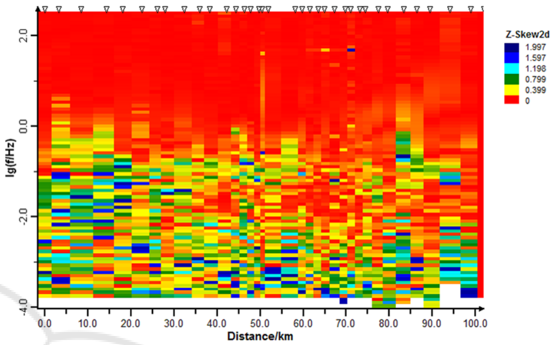

Figure 5: Analysis of 2D skewness along the observation profile. Most stations show 2D structure characteristics at shallow depths and three-dimensional characteristics deeper. The 2D skewness value is larger at low frequency (less than 0.1 Hz), which is likely to be affected by noise and unreliable.

4.2 Analysis of Two-Dimensional Tectonic Direction

Due to the continuous subduction of the Western Pacific plate toward mainland China, Northeast China has been squeezed. The direction of maximum principal compressive stress in the study area is NEE - SWW, and the main fault shows strike slip movement. The results from satellite photographs and gravitational field interpretation show that a group of NW westward faults are distributed parallel at the Tianchi volcanic crater and its vicinity (Li et al., 2006). Groom and Bailey proposed the tensor decomposition theory to manage the local surface current distortion near the surface, which is called GB decomposition. The theory decomposes the impedance tensor into a distortion tensor and regional two-dimensional tensor. This restores the undistorted region two-dimensional impedance tensor data, providing the regional tectonic direction angle, and solving the distortion factors, such as shear and distortion in the local distortion effect (McNeice and Jones, 2001). In this study, the method for impedance tensor GB decomposition was used to analyze all station tectonic trends. Figure 6 is a statistical analysis diagram of tectonic trend showing that the tectonic trend for most stations is primarily northwest.

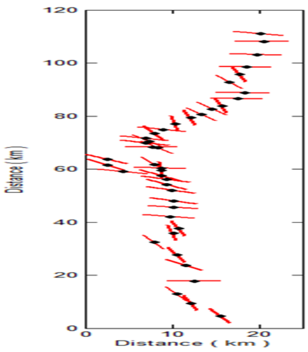

Figure 6: Analysis of the 2D tectonic direction using the impedance tensor GB decomposition method.

4.3 Induction Vector Analysis

The induction vector for MT sounding was obtained through the transfer function of the magnetic field. The induction vector is an important vector constructed by tilting data. It plays an important role in delineating low resistivity anomaly bodies and analyzing structural trends and deep dimensional characteristics. Its greatest advantage is that it can provide lateral electrical information about the corresponding depth below, which is mainly used to reflect large scale structural features. In addition, the magnetic field is almost unaffected by local distortion, and there are no static MT curve shifts. The induction vector is divided into the real induction vector and virtual induction vector. The real induction vector has been widely recognized and applied because of its clear directivity and stability. In this study, the direction of the induction vector is directed to high resistance. If the underground resistivity varies with depth alone without lateral variation (one dimensional medium), the magnetic induction vector is zero.

According to the distribution map of induction vectors at different frequencies, the approximate position and distribution range of the inhomogeneous medium in the underground medium can be determined. The relevant relationship is that lower frequencies correspond to deeper reactions. Due to serious electromagnetic noise in the work area, the induction vector analysis in this study can only analyze the characteristics of the macroscopic electrical change. Figure 7 shows the distribution of real induction vectors along the observed profile, in the map upward direction towards west.

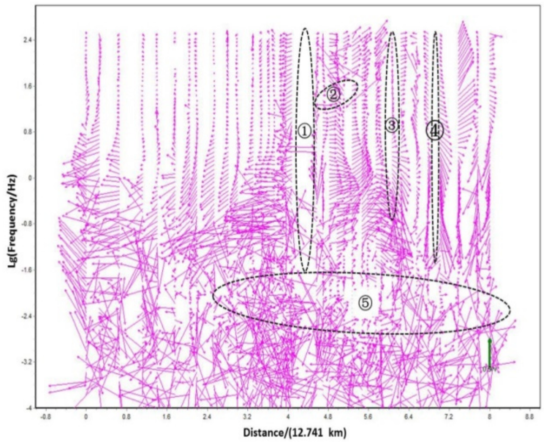

Figure 7: Analysis of the real induction vector; here, up indicates west. In this paper, the direction of the induction vector is directed to high resistance. The whole profile contains five abnormal zones with low resistivity.

From the regular direction of the real induction vector, from shallow to deep, the whole profile contains five abnormal zones with low resistivity. The No.1 low resistivity zone is located at the bottom of the Tianchi Volcano and below, and the real induction vectors on both sides are all away from the direction of the crater. This direction may represent the Tianchi water body and magma channel. The No.2 low resistivity zone is located in the north direction of the Tianchi volcanic crater. There is a local solid induction vector pointing northwest, indicating that there is a local low resistivity anomaly in the southeast direction. The No.3 low resistivity zone is located between stations C07 and C09, which is also located near the Changbai Mountain gate. From the morphology of the real induction vector, the anomalous area is approximately vertical. The No.4 low resistance zone is located between stations C04 and C05, and is also an approximately vertical strip. As the frequency decreases, the real induction vector begins to change, and gradually loses obvious regularity. The No.5 low resistivity zone is located in the deep part of the earth's crust. The real vector direction deviates from the position 20 km south of Tianchi Volcano, suggesting that the range of the deep and low resistance abnormal body is large, and the anomaly area may correspond to a deep magma capsule. With a further reduction in frequency, the direction of the real induction vector becomes disordered and its directivity may be influenced by strong electromagnetic noise.

5 ANALYSIS OF 2D INVERSION RESULTS

According to direction of the profile, we can obtain corresponding accurate TE and TM polarization mode data by rotating the impedance tensor -90 degrees. A large body of research has shown that a more accurate inversion result is usually obtained using the TM polarization mode for the two-dimensional inversion. Especially in complex geological conditions, the inversion results from the TM polarization mode are more reliable than other inversion results using other polarization mode data (Dong et al., 2012; Cai and Chen, 2010; Rodi and Mackie, 2001). The two-dimensional electrical structure model for the Changbai Mountain igneous area is obtained through nonlinear conjugate gradient two-dimensional inversion and regularization "L curve" factor analysis (Figure 8). Figure 9 shows the apparent resistivity and phase of the inversion result fitting. As shown, the calculated values of the model are in good agreement with the observed values, and the inversion results are more reliable.

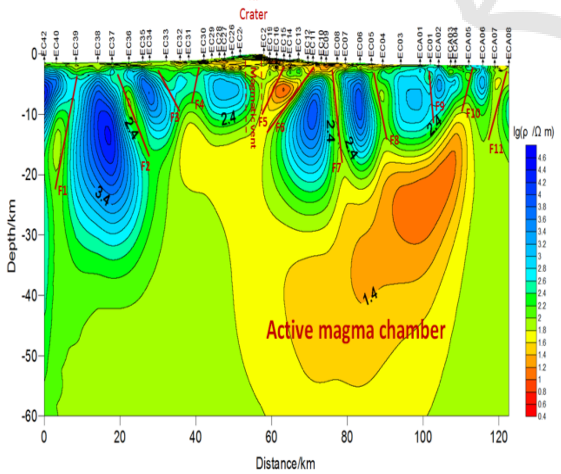

Figure 8: MT 2D inversion result for the volcanic area at Changbai Mountain. From the diagram, there are clear low resistivity anomalies below the Changbai Mountain volcanoes.

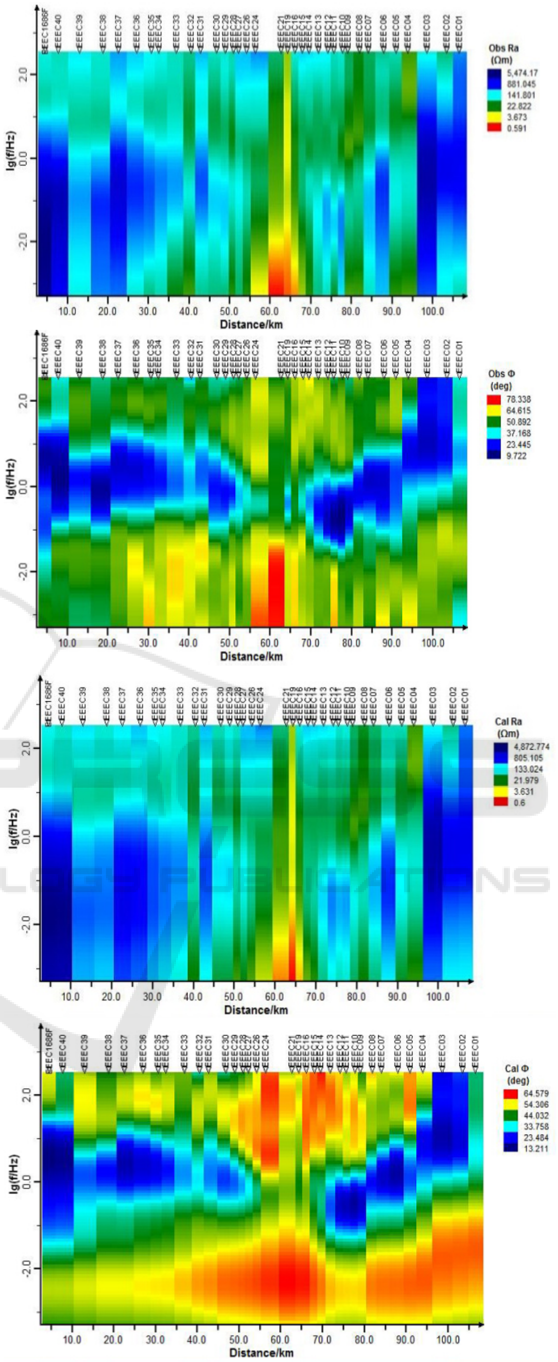

Figure 9: Fitting the inversion result. The calculated values of the forward model are in good agreement with the observed values, and the inversion result is reliable. Note that the left side shows the apparent resistivity map and right side shows the phase map. The top panels are observed data, and bottom panels are the calculated values from the 2D inversion result model.

From the two-dimensional inversion results in Figure 8, there are clear low resistivity bodies and electrical gradient zones at depth along the profile, which correspond to low resistivity abnormal bodies and fault structures at different depths. Because Tianchi Volcano at Changbai Mountain is located on the subduction zone of the Western Pacific Ocean, and is affected by the compression of the Western Pacific plate, the subduction produces tension in the back arc area, and a series of northern oblique faults developed near the shallow surface of the working area. According to the characteristics of large variation gradient and dense contour line, 11 fracture structures are deduced along the profile. Most of the shallow surface of the working area is covered by volcanic debris and Quaternary sediments, which are characterized by low resistance in the inversion results. At depth (~20 km), the profile is characterized by low resistance in the middle region and high resistance at the south and north areas. The high resistivity body corresponds to the relatively high deep resistivity of the crystalline matrix rock mass, and the middle low resistance corresponds to the magma channel and the low resistivity anomaly body. The magma channel located beneath Tianchi Volcano is an erect structure and closed at about 10 km. At the bottom of the crater, the position approximately 7 km north shows a clearly abnormal body of low resistance, resistivity < 10Ω•m, which connects with the magma channel. Based on these characteristics, we propose that it may be a developing magma chamber in the shallow surface. The abnormal regions between C07 and C09 stations and between C04 and C05 stations show two clear nearly vertical low resistivity zones at a depth of about 7 – 17 km, directly connecting with the below low resistance body, suggesting that the low resistivity zone is an active fault zone. With increasing depth, the crust low resistivity anomaly bodies are widely developed at depths of 13 – 30 km approximately 20 km south of Tianchi Volcano, suggesting that it may be active magma chamber. There have been differing opinions about the formation mechanism of volcanoes in northeast China. A variety of viewpoints have been proposed by prior researchers, and Tang Ji and others believe that the modern volcanic activity in the northeast region is closely related to the dewatering of the subduction plate of the Western Pacific plate (Hu et al., 2007; Tang et al., 2006). From the two-dimensional inversion result model presented in this study, we can see that the eruption of Changbai Mountain volcano is closely related to the Western Pacific plate.

6 CONCLUSIONS

Evaluating the possibility of an eruption of the Changbai Mountain Tianchi Volcano has become an important research topic in recent years. In this study, the MT sounding method was applied to detect deep electrical structures at Changbai Mountain, and a nearly north-south observation profile was surveyed across Tianchi Volcano. A two-dimensional electrical structure model was constructed, and the following conclusions obtained.

The electrical resistivity structure of Changbai Mountain clearly shows the presence of a magma channel beneath Tianchi Volcano; the magma channel is closed at a depth of 10 km.

There is an obvious abnormal body of low resistance, resistivity < 10Ω•m, which connects to the magma channel. It lies about 7 km north from the bottom of the crater, suggesting that it may be a developing magma chamber in the shallow surface.

There are clearly two nearly vertical low resistivity zones at a depth of 7 - 17 km located between stations C07 and C09 and between stations C04 and C05, directly connecting with the low resistance body, suggesting that these low resistivity zones are active fault zones.

With increasing depth, the crust low resistivity anomaly bodies are widely developed at depths of 13 – 30 km approximately 20 km south of Tianchi Volcano, suggesting that it may be an active magma chamber.

A number of fault structures have developed in the working area. According to the electrical resistivity structure along the profile, 11 fracture structures were deduced. Due to the extrusion influence of the Western Pacific plate, a series of extensional fracture structures inclined toward the northwest have developed. The heat energy deep underground is transmitted through the fault to shallower depths, and a number of hot springs have formed in the shallow space.

The exploration results obtained using the MT sounding method show that Changbai Mountain has a high potential eruption risk. Furthermore, the MT sounding method performed well detecting the spatial distribution and active state of the magma capsule below the crater.

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