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Audio Magnetotellurics Study of the Geoelectric Structure across the Zhugongtang Giant Lead–Zinc Deposit, NW Guizhou Province, China

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Abstract: Non-invasive geophysical exploration methods play a key role in the exploration of ore deposits. In the present study, the audio-frequency magnetotelluric (AMT) method was applied to metallic mineral exploration. The metallic mineral deposit targeted was the recently discovered super large lead–zinc deposit of the Zhugongtang mining area of Hezhang County in the northwestern Guizhou province in China. The main objectives of this study were to estimate the geoelectric strike and generate geoelectric models that estimate both the depth and distribution of resistivity structures across the deposit. To achieve the objectives, we deployed sixty-one (61) AMT survey sites with an interstation separation of 20 m on a 1280 m survey track perpendicular to the geological strike across the Zhugongtang deposit. We operated in fifty-three (53) frequencies in the range 1–10,400 Hz to record the resistivity distribution of subsurface to a depth of more than 1200 m. The results from the AMT data computations estimated the geoelectric strike that varies between NE285° and NE315°. This range of strikes suggested that structures across the deposit are oriented in the NW–SE direction. Obtained two-dimensional (2D) models elucidated a remarkably low resistivity body (<15 Ωm) at an elevation of less than 1600 m above sea level (>0.50 km depth), thus extending to great depth and were interpreted as lead–zinc mineralization. Furthermore, low resistivity (<63 Ωm) features were imaged both in superficial and deeper depths and interpreted as shale, sandstone, claystone, and silty mudstone units. Dolomite and limestone lithologies were found widely distributed with high resistivity (>1000 Ωm). Bioclastic limestone and dolomite limestone were inferred and characterized by moderate-high resistivity (>250 Ωm) and were not widely distributed. A unit of basalts was found with moderate resistivity (>63 Ωm). In addition, it was also found that regions with high number of faults tend to have low resistivity values compared to regions with a low fault number. In summary, this case study presents the results of applying an AMT approach to explore the conductivity characteristics of structures across the Zhugongtang deposit. The findings may contribute to the literature about this deposit.

Keywords: Zhugongtang deposit; lead–zinc; Sichuan–Yunnan–Guizhou Metallogenic Province (SYGMP); audio magnetotelluric; inversion

1. Introduction

In the modern era, mineral resources are being used at an unprecedented rate by humanity. Demand will continue to rise as a result of population growth, urbanization, and technological advancements such as the transition from fossil fuel dependency to

green technology [1,2]. For many years, industries and academia have implemented mineral resource development to meet the demand for mineral resources. In mineral resource development, exploration and characterization of mineralization have and continue to play key roles [3]. Furthermore, mineral studies and research projects have shifted from the conventional approach of recognition of surface mineralization (outcrop) as a preliminary indicator for a potential mineral resource [4], to the detection of deep-seated orebodies without surface manifestation [5,6]. In this approach, prospection methods such as geological, drilling, geochemical and geo-physical are used [7]. Among these prospection methods, the geophysical methods generally have the advantage of great detection depths and high resolution, which result in the provision of rich information for deep ore prospection [8]. Since the development of electromagnetic (EM) geophysical methods in the 1950s, the methods have been extensively applied to mapping lateral and vertical resistivity variation in the subsurface. For example, natural source audio magnetotelluric (AMT) and controlled source AMT (CSAMT) are widely applied to metallic mineral [9–15], groundwater [16–19], and geothermal system exploration [20–24], whereas the natural source broadband magnetotelluric (BBMT) method is widely used in the field of deep structure explorations, including lower crust and upper mantle structure [25–27]. The radio magnetotelluric (RMT) method has been applied in engineering investigations to aid urban infrastructure planning [28–31]. The RMT method is also gaining applications in land characterization, for cases such as waste sites, landslides, etc. [32,33].

In this paper, we investigate the recently discovered Zhugongtang lead–zinc deposit in the northwestern (NW) Guizhou province of China with the AMT approach. This deposit is the largest lead–zinc mineralization in the province and is buried in deep subsurface without significant outcrops. This lead–zinc deposit has potential economic value. Therefore, the development and utilization of its resources are expected to alleviate local poverty and provide strong mineral resource support for the development of the Yangtze River economic belt. Since commercial mining of the deposit has not yet started, we attempt to examine the electrical resistivity structures across the deposit with the following objectives: (i) approximate geoelectric strike distribution, (ii) estimate deposit minimum burial depth, and (iii) generate two-dimensional (2D) geoelectric models that estimate the resistivity of structures across the deposit. The formulated objectives above form a guide to better understand the conductivity characteristics of the deposit we studied.

2. Geological Setting

The Zhugongtang deposit is a member of the lead–zinc deposits (such as Nayongzhi, Shaojiwan, Tianqiao, Huize, Tianboashan, Daliangzi, Fule, etc.) of the Sichuan-Yunnan-Guizhou Metallogenic Province (SYGMP) (Figure 1b). The SYGMP is a mineral-rich region hosting world-class deposits and spans an area of about 170,000 km² of the southwest Yangtze Block in the South China Block (Figure 1a) [34,35]. The South China Block is reported to have undergone multiple tectonic episodes, including the amalgamation and remobilization of Yangtze and Cathaysia block, with a strength of approximately 950–900 Ma [36,37], and the collision with North China and Indochina blocks to the north and south, respectively [35]. It is generally suggested that this series of tectonic events was vital for the mineralization of thrust-hosted epigenetic zinc–lead (Zn–Pb) deposits in the region [38,39]. These thrust-hosted epigenetic Zn–Pb deposits in SYGMP generally have very high ore grades of Zn–Pb at > 10%, with a maximum of 30–35% [40]. The ore-forming fluids of these deposits have been reported to have characteristic low temperatures of 120–280°C. They exhibit spatial and genetic association with igneous activities of the Emeishan large igneous province (ELIP) [41]. The SYGMP region has the highest concentration of epigenetic hydrothermal Pb–Zn polymetallic deposits hosted in the Neoproterozoic to early Permian carbonate strata in thrust and fold systems [42]. About 17% of the known global lead and zinc resources are hosted in this

region and more than 440 deposits and mineral occurrences have been reported [40,43,44]. The SYGMP is bounded by three regional fault belts in the South West Yangtze Block: the NW-trending Kangding–Yiliang–Shuicheng fault (KYSF), the NS-trending Anninghe–Lvzhijiang fault (ALF), and the NE trending Mile–Shizong–Shuicheng fault (MSSF) (Figure 1a) [35,45]. These faults extend into the basement rocks and were continually activated by the multiphase orogenic activities, including the Wuyi–Yunkai orogeny that occurred between the Middle Ordovician (> 460 Ma) and the end of the Silurian (420–415 Ma) [46]. Indosinian orogeny, with an age estimate of 244 ± 7 Ma [47], and the Yanshanian orogeny that occurred during the Jurassic Period [48] in the South China Block. Regional stratigraphy includes a Mesoproterozoic folded meta-sandstone and slate basement overlain by Paleozoic to early Mesozoic submarine sedimentary sequences and Jurassic to Cenozoic terrigenous sedimentary sequences [35].

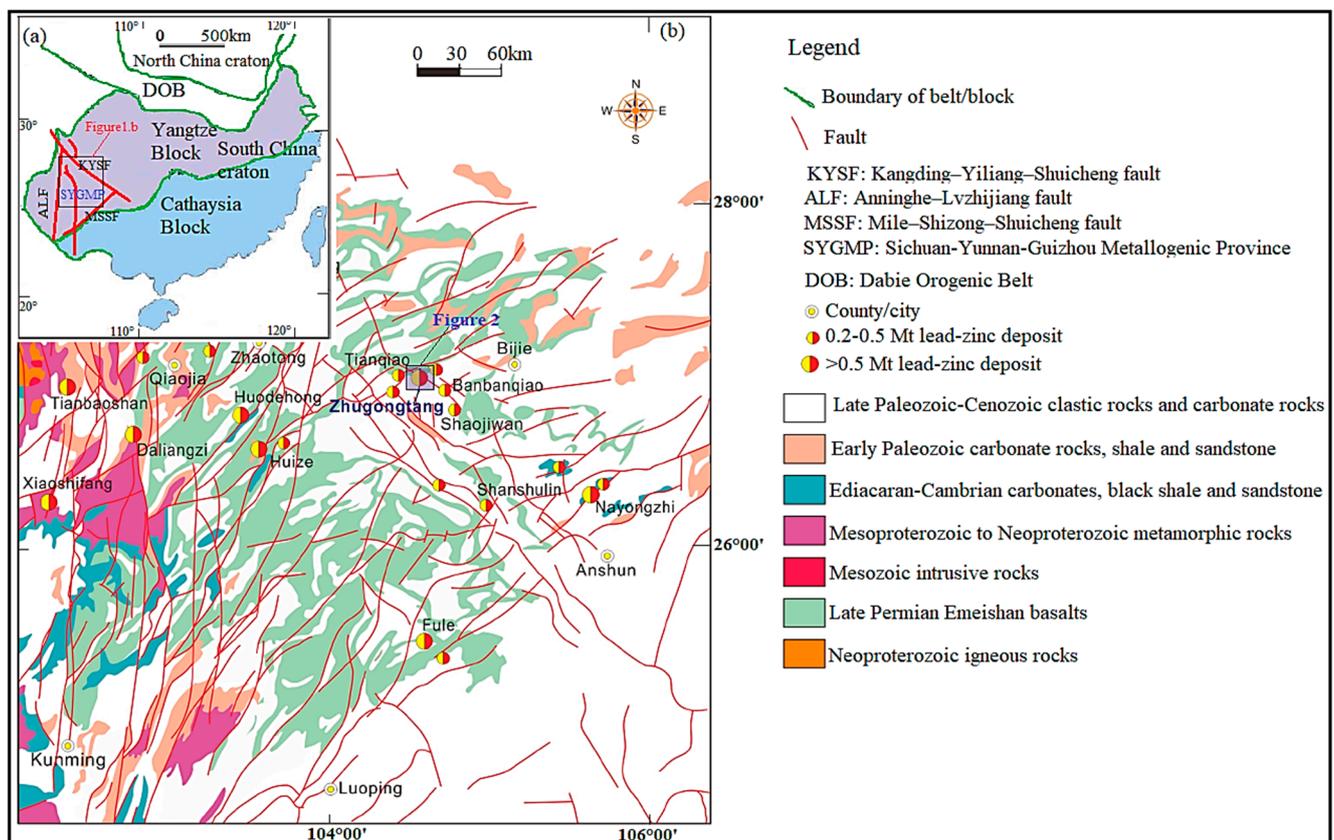


Figure 1. (a) Regional geological setting showing the location of the Sichuan–Yunnan–Guizhou Metallogenic Province (SYGMP) in South China; (b) geological sketch map of SYGMP showing regional structures, strata, and the distribution of lead–zinc deposits in the metallogenic province (modified from [35,45]).

3. Deposit Geology

The exposed rocks in the Zhugongtang orefield are predominantly sedimentary covers from the early Silurian to the late Permian periods (Figure 2) [49]. Early Silurian Hanjiadian Fm sandstone and silty mudstones are the oldest rocks in this region [35]. The Devonian Wangchengpo and Yaosuo Fms, which are made up of dolostone, siliceous dolostone, limestone, and dolomitic limestone, unconformably overlay the old rock formations [35]. The Carboniferous and Permian layers unconformably overlay the Devonian Yaosuo Fm [35]. The most prominent controlling structures include the NW and NE trending faults, as well as small interlayer fractures. Lead–zinc orebodies in this area occur as stratiform, lenticular, and steeply dipping veins inside the NW-trending F1 and F2 faults (Figures 2 and 3), as well as in the interlayer fracture zones [35,49]. The types

of ore textures are mainly disseminated, massive, and vein. Ore minerals include sphalerite, galena, and pyrite. Gangue minerals include dolomite, calcite, and minor quartz and K feldspar [35].

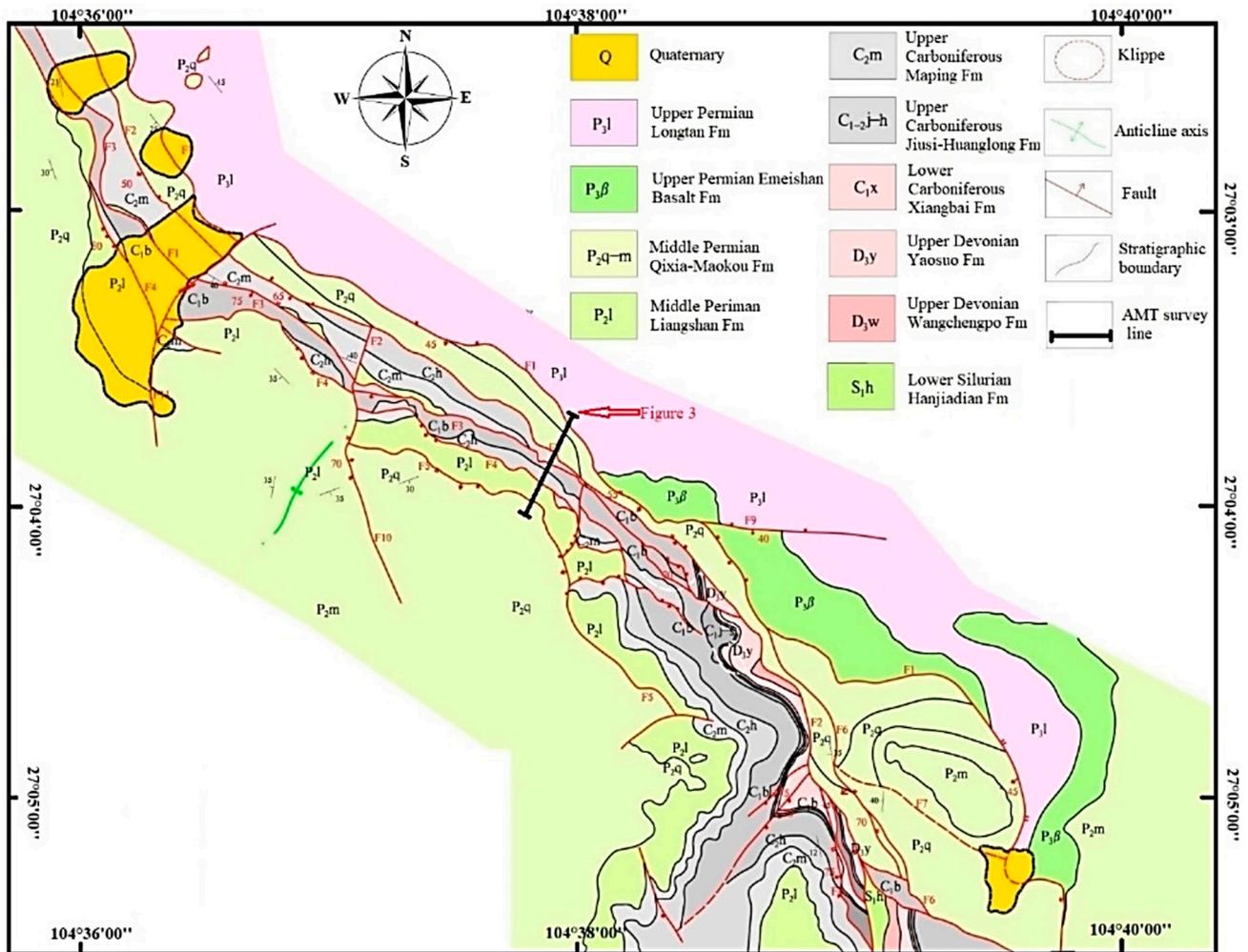


Figure 2. Geological map of Zhugongtang orefield with AMT survey line on top of an interpretation of the geology. Fm: Formation.

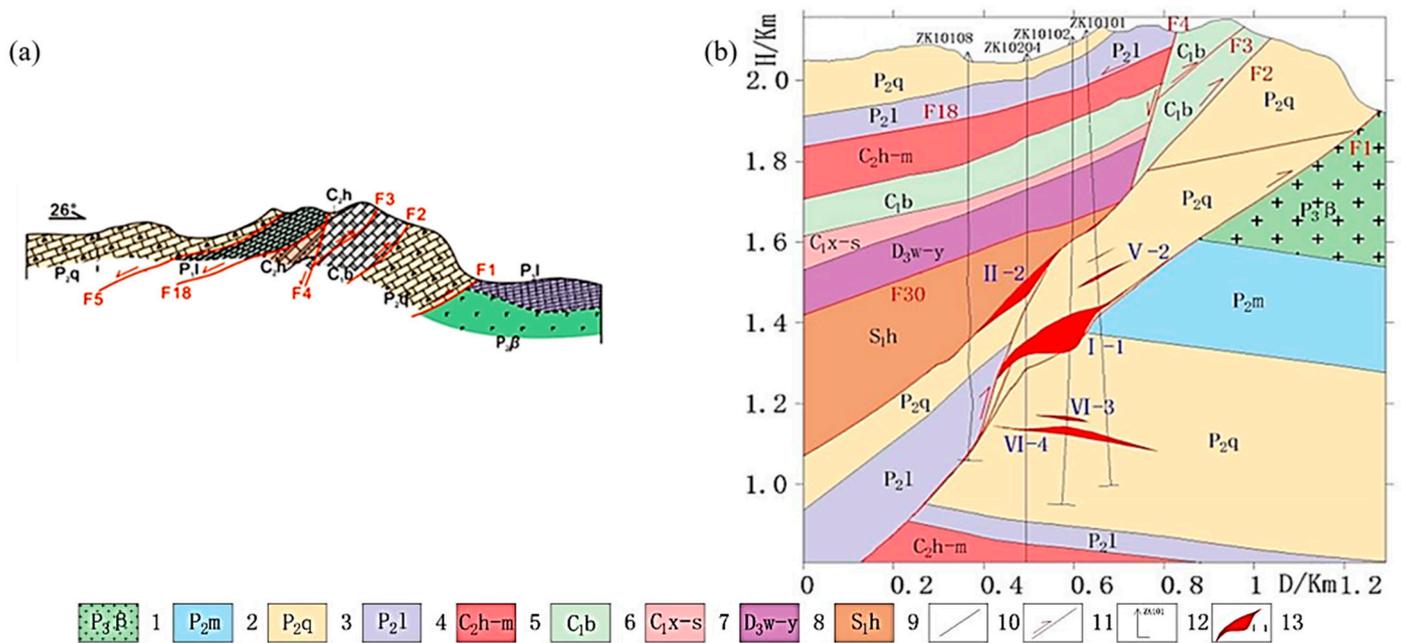


Figure 3. Geological cross-section of the Zhugongtang deposit on the AMT survey line: (a) showing the thrust system (adopted from [35]), (b) stratigraphic boundary and boreholes (from after [35]). H: elevation, D: distance, 1: upper Permian Emeishan basalt formation; 2: middle Permian Maokou formation; 3: middle Permian Qixia formation; 4: middle Permian Liangshan formation; 5: upper Carboniferous Huanglong–Maping formation; 6: lower Carboniferous Baizuo formation; 7: lower Carboniferous Xiangbai formation; 8: upper Devonian Wangchengpo–Yaosuo formation; 9: lower Silurian Hanjiadian formation; 10: stratigraphic boundaries; 11: faults; 12: drill holes and numbers; 13: orebody number.

4. Methods

In this investigation, the magnetotelluric method is applied to mineral exploration. The magnetotelluric method was first introduced by Andrey Nikolayevich Tikhonov in 1950 [50] and Louis Cagniard in 1953 [51]. Later, the method was further developed by Cantwell Thomas in 1960 [52,53] and Keeva Vozoff [54]. The method probes the electrical structure of the subsurface using either the artificial (controlled) or natural electromagnetic (EM) field as the field source [55]. In artificial or controlled magnetotelluric, the EM signals are generated by EM transmitters. The radio magnetotelluric (RMT) method, which uses civilian and military radio transmitters broadcasting in the frequency range of 10 kHz to 1 MHz, is an example of artificial source magnetotellurics [56]. In natural magnetotelluric exploration, the electromagnetic fields originate from global lightning or sferics (short period signals) and solar wind activities in the ionosphere (long-period signals). Based on frequency, the natural magnetotelluric fields can be clustered into audiomagnetotellurics (AMT) with frequencies $f = 1\text{--}10,000$ Hz and broadband magnetotelluric (BBMT) with $f = 0.001\text{--}300$ Hz [57]. In principle, the earth is viewed as a horizontal medium and the magnetotelluric fields as the plane electromagnetic waves are projected vertically onto the ground (earth) [21]. When these waves impinge the ground, large proportions of them are reflected, and a small fraction is transmitted into the subsurface [54]. Electromagnetic induction (i.e., the fluctuating magnetic field) causes telluric currents to flow into the subsurface. The magnitude depends on electrical conductivity [58]. Diffusive signal transmission occurs, resulting in signal attenuation/decay as the depth increases. The skin depth (δ), which is the depth (in meters) of electromagnetic wave decay in the subsurface when the amplitude diminishes to $1/e$ of its value at the surface, is given by the following expression [59]:

$$\delta = \sqrt{\frac{\rho}{\pi f \mu}} \approx 500 \sqrt{\frac{\rho}{f}} \quad (1)$$

where ρ is the resistivity (Ωm), f is the frequency (Hz), and μ is the magnetic permeability (H/m). The skin depth is controlled mainly by the conductivity (inverse of resistivity) of rocks and the operating frequency used. The most common sources for enhanced conductivity in the subsurface include graphite or carbon films, interconnected metallic minerals, aqueous fluid, partial melt, and any combination of these [60].

The above expression shows that the skin depth is inversely proportional to frequency. This implies that low frequencies penetrate to greater depths, and high frequencies are limited to shallow depths. On the ground, orthogonal electromagnetic field components are observed. The frequency response reflects the distribution of the electrical properties of the subsurface medium [61]. The variation of the magnetotelluric field component with time is converted into a frequency spectrum. Magnetotelluric frequency domain responses—such as apparent resistivity and the impedance phase—can be computed. Apparent resistivity is calculated using the following expression:

$$\rho = \frac{1}{5f} \left| \frac{E_x}{H_y} \right|^2 \quad (2)$$

where f is the frequency in Hz, ρ is the resistivity in Ωm , E_x is the electric field and H_y is the magnetic field.

5. Data Acquisition and Processing

In November 2021, we carried out an AMT survey comprising sixty-one (61) AMT stations distributed along a SW-NE striking profile across the Zhugongtang deposit (Figure 2). The length of the profile line was 1280 m, stretching perpendicular to the geological strike with an inter-AMT station separation of 20 m (Figure 2). Due to tough terrains (cliffs) in the north-east section of the profile, four (4) AMT sites were abandoned between the AMT-59 and AMT-60 sites. The AMT time-variant field or time series data were acquired using the GSEM-W10 system (developed by Giant Sequoia Artificial Intelligence Technology Co., Ltd., Changsha, China) (Figure 4) [62]. The AMT data were collected in fifty-three (53) frequencies in the range of 1 Hz to 10400 Hz for thirty-five (35) minutes at each station by measuring two horizontal components of the electric field (E_x and E_y) and the two orthogonal components of the magnetic field (H_x and H_y). The X- and Y- directions were assigned along the profiles toward the north (N) and east (E), respectively. Data for magnetic field variations were obtained using induction coil magnetometers (ICM) and data for electric field variations were obtained by two pairs of non-polarizable lead–chloride electrodes (Pb–PbCl₂). Prior to measurement, each electric field measurement point was soaked with water to reduce their contact resistivity. The condition of each station was recorded for sources of interference. Identified sources of interference included roads, high voltage power lines, and communication cables, many of which were observed in the middle of the survey lines. Utilizing the GSEM-pros software (that is provided with the acquisition unit) [63], the collected AMT time series field data were processed, transformed into frequency domain, and the cross-power spectra were computed. The cross-power spectra estimate the impedance tensor as a function of frequency. The impedance tensor contains information about the dimensionality and the strike of the subsurface structures. This is discussed in the next section. In general, the data quality was good at most sites, except for data collected at and near the interference (AMT23, Figure 5) sources mentioned above.



Figure 4. AMT field instruments used and the covers in the area. ICM: induction coil magnetometers.

6. Data Analysis

We performed data analysis and visualization of the processed AMT data for the properties of resistivity, phase, dimensionality, and geoelectric strike with the MTPy software package. The MTPy package is an open-source python library for magnetotelluric data analysis, developed by Geoscience Australia [64,65].

6.1. Apparent Resistivity-Phase Curves and Pseudo-Sections

Apparent resistivity and phase values for the off-diagonal components (Z_{xy} and Z_{yx}) of the impedance tensor and minimum phase tensor (Φ_{min}) ellipses are shown in Figure 5 for the stations AMT01, AMT07, AMT23, and AMT59, located at different geological units. It is observed that apparent resistivity values are high, ranging from ~ 100 – $10,000 \Omega m$ for stations AMT01 and AMT07, and ~ 10 – $2,000 \Omega m$ at AMT59. The resistivity range at AMT23 is comparatively low, with a maximum value of $100 \Omega m$. Stations AMT01 and AMT07 generally exhibit the same trends in the resistivity and phase curves. That is, high resistivity values are observed over a short period range, and low resistivities are observed for longer periods with phase angle above but asymptotic to 45° . The Φ_{min} values show low to high characteristics, suggesting of response from both resistive and fairly conductive geological units. The curves for station AMT23 show noise due to interference in the acquired data. The noise is depicted by a sharp change of the curve at the period of 10^{-3} s in the Z_{xy} component of the impedance tensor Z (Figure 5: AMT23 black circle). The corresponding Φ_{min} is characterized by high values over short periods, which decrease with period increase. The underlying geological units at this station can be inferred to constitute both resistive and conductive lithologies. At Station AMT59, the apparent resistivity curve for Z_{xy} increases while the phase curve drops for most periods (10^{-4} s– 10^{-1} s). The Φ_{min} values are high at all periods. Thus, the geological formations at AMT59 can be interpreted as being highly electrically resistive.

Figure 6 shows the apparent resistivity pseudo-sections for the Z_{xx} and Z_{yy} components of Z for all stations. In both sections, at least two different structures can be speculated. These are highly conductive formations bound by electrically resistive formations on either side. The phase angle corresponding to the conductive formation is generally above 45° for Z_{xx} data. A phase angle of $<45^\circ$ is evidently dominant for the Z_{yy} data along the profile.

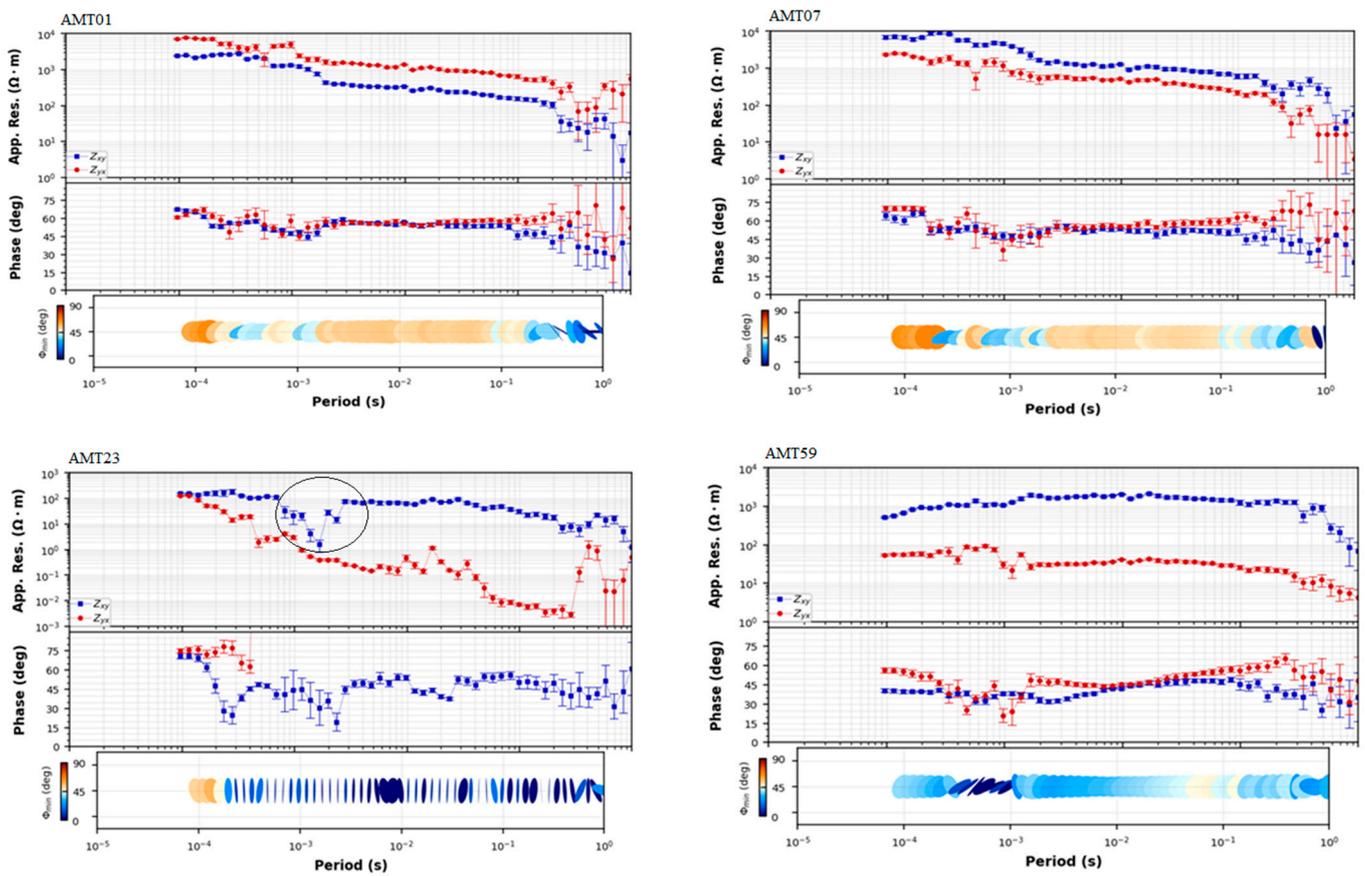


Figure 5. Observed apparent resistivity-phase curves and phase tensor ellipses for four representative AMT stations (AMT01, AMT07, AMT23 and AMT59). The black circle in AMT23 curve depicts interference in data.

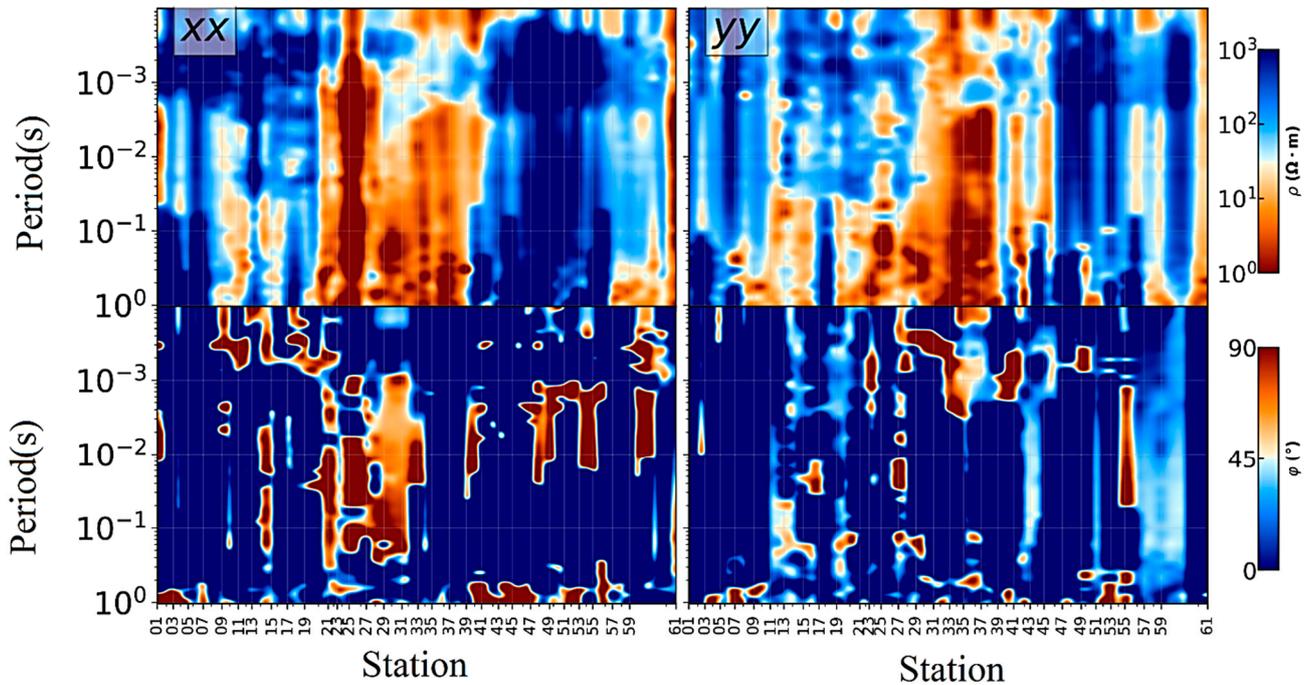


Figure 6. Apparent resistivity-phase pseudo-sections for Z_{xx} and Z_{yy} for an array of 61 stations across the Zhugongtang lead-zinc deposit. The upper panel shows resistivity and the lower panel represents phase, with Z_{xx} as xx and Z_{yy} as yy .

6.2. Dimensionality Analysis

We performed a dimensionality analysis of the AMT data prior to inversion to determine whether the computed impedance tensors, apparent resistivities, and phases at a specific frequency were related to one-, two-, or three-dimensional (1D, 2D or 3D) geoelectrical structures. Different researchers have proposed different dimensional tools to check the dimensionality of AMT data. In the present work, we analyzed dimensionality through the phase tensor method. Through the phase tensor method, no priori assumptions about the regional resistivity structure that we try to determine are made. In the phase tensor analysis, the relationship between the real and imaginary components of the impedance tensor of the observed data is described by the parameter skew (β) and is expressed as follows:

$$\beta = \frac{1}{2} \tan^{-1} \left(\frac{\phi_{xy} - \phi_{yx}}{\phi_{xx} + \phi_{yy}} \right) \quad (3)$$

The phase tensor skew (β) holds essential information about the dimensionality of the AMT data for the subsurface structure and its complexity [66]. For visual illustration, the phase tensor is graphically represented as an ellipse, and the value of the skew angle is represented by the color-coded ellipses as shown in Figure 7. For a 1D earth or a layered subsurface, the phase tensor is circular in shape, representing a small skew angle (β) [66]. In the case of a 2D regional resistivity structure, the phase tensor is elliptically shaped, with β becoming small. β is zero in data without errors [67]. For a 3D earth, the phase tensor is non-symmetric with β indicating large values. A rapid lateral change of the principal axes of the phase tensor also indicates 3D structures [66]. In our study, a threshold of $|\beta| \leq \pm 5$ is considered for a 2D structure [22,68–70]. The analysis of the phase tensor pseudo-section plotted at different periods reveals the dimensionality of the subsurface structure (Figure 7). In the period interval 10^{-4} to 10^{-3} s, the phase tensor ellipses are dominated by a skew angle of $|\beta| \geq \pm 5^\circ$, suggesting a 3D structure. However, the uppermost portion of the phase tensor pseudo section between AMT14–AMT20, AMT28–AMT39, and AMT52–AMT61 (except AMT56), the subsurface shows the skew angle of $|\beta| \leq \pm 5^\circ$, suggesting a 2D structure. For the period interval of 10^{-3} – 10^{-1} s, in the sections from AMT01–AMT11 and AMT27–AMT61, the skew angles are observed to have values $|\beta| \leq \pm 5^\circ$. This range of β -values and the shape of the ellipses (Figure 7) imply the presence of 1D structure for values close to zero and 2D feature for values far from zero. During the same period, the subsurface between AMT12–AMT26 is suggested to have 1D, 2D, and 3D structures, as the β -values vary from 0 up to $\pm 8^\circ$. For the period 10^{-1} to 1 s, all the AMT sites generally infer the existence of 2D and 3D structures. In summary, our AMT data have very large β -values and the phase tensors are elliptical and non-symmetric in shape. Therefore, we assume that the study area is characterized by 2D and 3D structures.

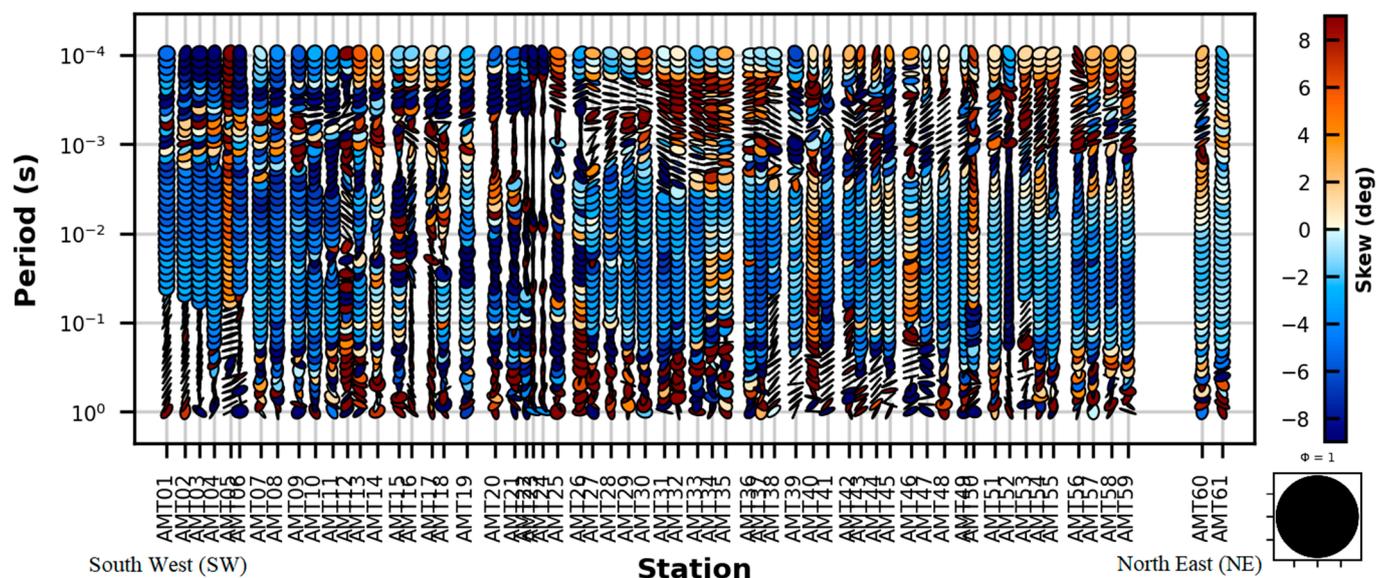


Figure 7. Phase tensor ellipses pseudo-section, color-coded by skew angle values along transect SW-NE. Four sites between AMT59 and AMT60 were neglected due the presence of cliffs.

6.3. Geoelectric Strike Estimation

The geoelectric strike is defined as the preferential direction representing the orientation of electric current flow in the subsurface [71]. The discussion from the previous subsection suggests that the study area has a 2D and 3D resistivity structure. Here, we have estimated the strike direction for the subsurface structures by the invariants of the impedance tensor (Z) and the phase tensor (PT) parameters. The obtained strikes are shown in Figure 8 as rose diagrams at different decades and all period ranges with the principal axis directions. A pair of dominant strikes were obtained by Z method observed to decrease from NE315° and NE40° at short period to NE285° and NE15° at long period respectively. A similar trend is exhibited for strikes obtained by PT approach which decrease from NE305° and NE35° to NE285° and NE17.5° respectively. At all periods, the Z pair of strikes converged to NE300° and NE27.5°, whereas the PT strikes converged to NE307° and NE35°. This strike analysis is inherently ambiguous by $\pm 90^\circ$, implying that the geology of this area must also be taken into consideration. Simplified geological and cross-sectional maps of the study area (Figures 2 and 3) show that the Zhugongtang deposit is mainly controlled by several NW-trending (nearly parallel) faults, exhibiting similar strikes of roughly NE315° as reported by other researchers [35,49,72]. Our results for the strike angle (at all periods) of NE300° and NE307° are in fairly good agreement with the NW–SE regional structure of the area. Therefore, in the AMT modelling, we used a strike direction of NE307° for the rotation of MT data. Strike angles of NE27.5 and NE35 were neglected, as they are not consistent with the structure in the study area.

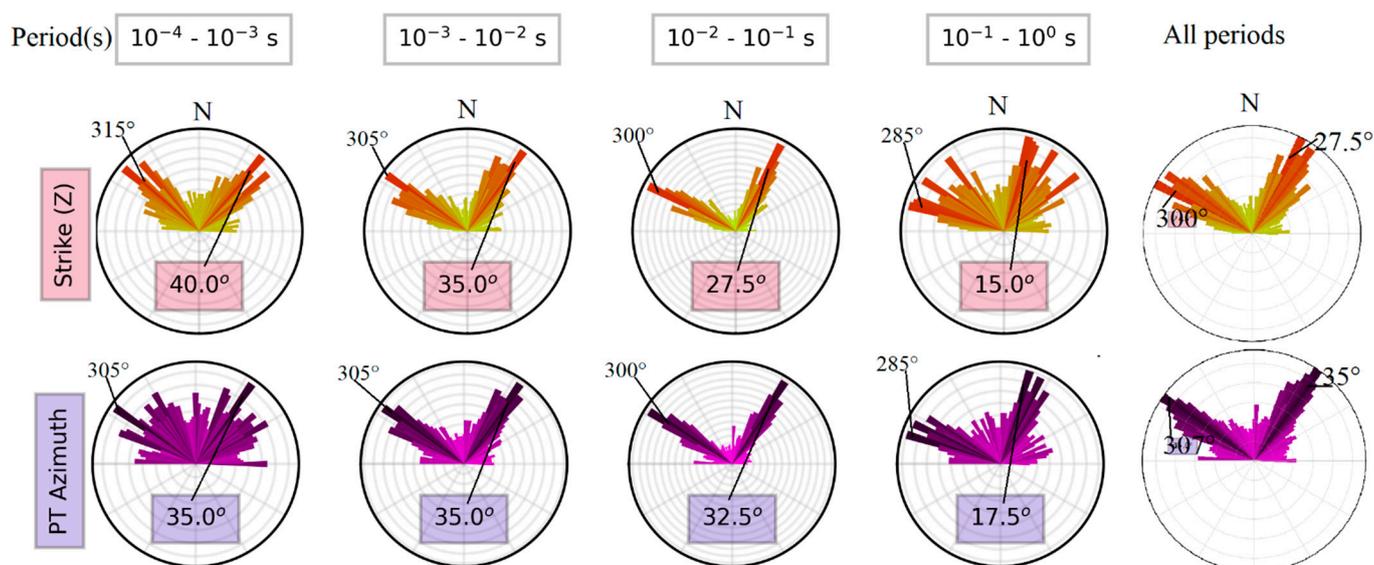


Figure 8. Multi-period rose diagrams of geoelectric strikes estimation at decade and at all periods from invariants of impedance tensor (Z) [73] and phase tensor (PT) [66]. North (N) is assumed to be 0 and the strike angle is measured clockwise positive.

7. Two-Dimensional Inversion

We inverted the rotated AMT data with the focused inversion algorithm contained in the ZONDMT2D software. This software package is designed for two-dimensional modelling and interpretation of MT data and was developed by Zond—a geophysical software developer in the Republic of Cyprus [74]. The focused inversion scheme uses the least square method with a smoothing operator and additional contrast focusing. As a result of this algorithm, piecewise smooth parameter distributions can be achieved. In other words, models which consist of blocks with constant resistivity can be obtained. Considering the high-elevation locations of 1.918–2.157 km (above sea level) of the study area, topographic relief was included in the 2D inverse modeling. This was done to reduce distortion in imaging based on acquired AMT data caused by rough topography. In the inversions, we considered transverse electric (TE), transverse magnetic (TM), and determinant or effective impedance (D) modes. The TE mode describes currents flowing parallel to strike, while the TM mode describes currents flowing perpendicular to strike. The determinant (effective impedance) mode describes the average of the impedance for all current directions. Prior to inverse modelling, we performed a static shift correction. This is because static shift is caused by near-surface inhomogeneities and noticeably complicate the interpretation of the apparent resistivity curves. This results in false geoelectric structures. The performed static shift correction was by done by identification and manually changing the curve level with reference to the adjacent curves using tools in ZONDMT2D. Additionally, an automatic static shift correction was also carried out on TE and TM data to suppress shifts by utilizing tools in the software (ZONDMT2D). We did not have access to TEM data that could be used to reliably correct the static shift. In the inversions process, we used 300 Ωm as an initial half-space value. For the inversion parameters, a smoothing factor of 1, depth smoothing of 1, smoothness ratio of 1, and focused threshold of 0.1 were set (more details on conditions of applying these factors can be found in [74]). Common model limits of 0.01 Ωm and 10000 Ωm were assigned to the minimum and maximum resistivity, respectively. The inversion was initially carried out for 30 iterations, then for 20 iterations, while adjusting the parameters for a better root mean square (RMS). The difference between modeled and measured datasets is captured in the RMS error and is usually presented as a percentage. RMS errors of less than 10% were considered acceptable in our 2D inverse modelling. After running the inversions, the final RMS error along the profile converged to 18.1% for TE, 9.7% for the TM mode and

9.1% for the D mode. The obtained models from the three inversion modes are further discussed in the next section.

8. Results and Discussion

The results of the 2D inversions in TE, TM, and D mode for AMT data collected across Zhugongtang deposit are shown in Figure 9, along with inversions error in RMS. The AMT models identify several regions of resistivity, which are also presented in Figure 10 and summarized in Table 1.

In the immediate SW section of the profile, the strata from the shallow to greater depths are observed to be highly resistive with variations between 250 Ωm and 10 000 Ωm . The three modes resolved a resistive section bound by an offset distance of 0–0.15 km, which were inferred to be dolomite and limestone dominated zones. A conductive zone (<63 Ωm) is evident in the subsurface and defined by offset distances of 0.15–0.30 km at approximately 400 m depth and extend deeper and are overlaid by inferred resistive dolomite and limestone units. We interpret that this conductive zone is due to silty mudstone, sandstone, shale, claystone, and siltstones, belonging to the Silurian Hanjiangdian(S_{1h}) and Permian Longtan(P_{2l}) Fm. The enhanced conductivity of this zone may be attributed to faults (Figure 10) and probable disseminated conductive minerals.

The central section of the profile has two distinct anomalous features, which are several small units of low resistivity features (<63 Ωm) imbedded in superficial depths and a significantly low electrical resistivity conductor (<15 Ωm) at a greater depth. The small units of low resistivity are confined by 0.30–1.28 km of distance and rest at a maximum depth of 0.10 km (above 1.9 km of elevation). The small units are thought to be associated with mudstones on the basis of their resistivity signatures and in reference to the geology of the area. The significantly low electrical resistivity of the conductor (<15 Ωm) is restricted by 0.3–0.8 km of horizontal distance and is evident from the minimum depth of 0.5 km, which extends into deeper strata. We deduce that this deep-seated low resistivity anomaly is due to mineralization of lead- and zinc-based metals. This is supported by a good overlap between obtained resistivity models and geological model for the location of the best conductor in the study area.

The subsurface materials in the NE section of the profile exhibit high resistivity values, ranging from shallow to greater depth, in the TE model. This is contrary to the results obtained by TM and D modes. The TM and D modes reveal moderate to high resistivity material in the shallow subsurface, and high resistivity material in the deep subsurface. The NE subsurface consists of four major faults: F1, F2, F3, and F4 (Figures 2 and 10), which are likely to exhibit low resistivity. According to Unsworth (1999), faults can increase permeability parallel to the faults line and inhibit the movement of materials perpendicular to the faults. In addition, faults can trap fluids in gouge- and fault- breccia [75]. Consequently, changing the electrical resistivity of the subsurface and influencing the preferred current flow direction [75]. In this work, the faults and their conductivity enhancing effects are not evident in the TE model, but rather evident in the TM and D mode. This demonstrates that TE and TM geoelectric models support the concept of information complementarity [76]. That is, structures missed by TE mode are defined in the TM mode, and those omitted by TM revealed in TE mode. We also observe that the TE mode is most responsive to conductors along the strike and the TM mode is better at identifying resistivity interfaces such as across faults and boundaries, owing to interface charge build-up [77]. In the TM geoelectric model, the NE upper area, with several faults bound between 0.8 and 1.28 km of distance and between 1.6 and 2 km of elevation are estimated to have resistivity that varies between 100–500 Ωm . This is more likely attributed to faults in dolomite and limestone units. Again, in the same distance (0.8–1.28 km) at elevations between 1.2 and 1.4 km, another moderate–high resistivity anomaly (>250 Ωm) is encountered. Through interpretation, it is associated with bioclastic limestone and dolomite limestone from the Permian Maokou Fm (P_{2m}). The subsurface outlined by a distance between 1.1 and 1.28 km, at an elevation between 1.4 and 1.9 km shows a low–

moderate resistivity zone ($>63 \Omega\text{m}$) revealed in TM and D mode. This is inferred to be basalt rock of the upper Permian Emeishan ($P_3\beta$) strata.

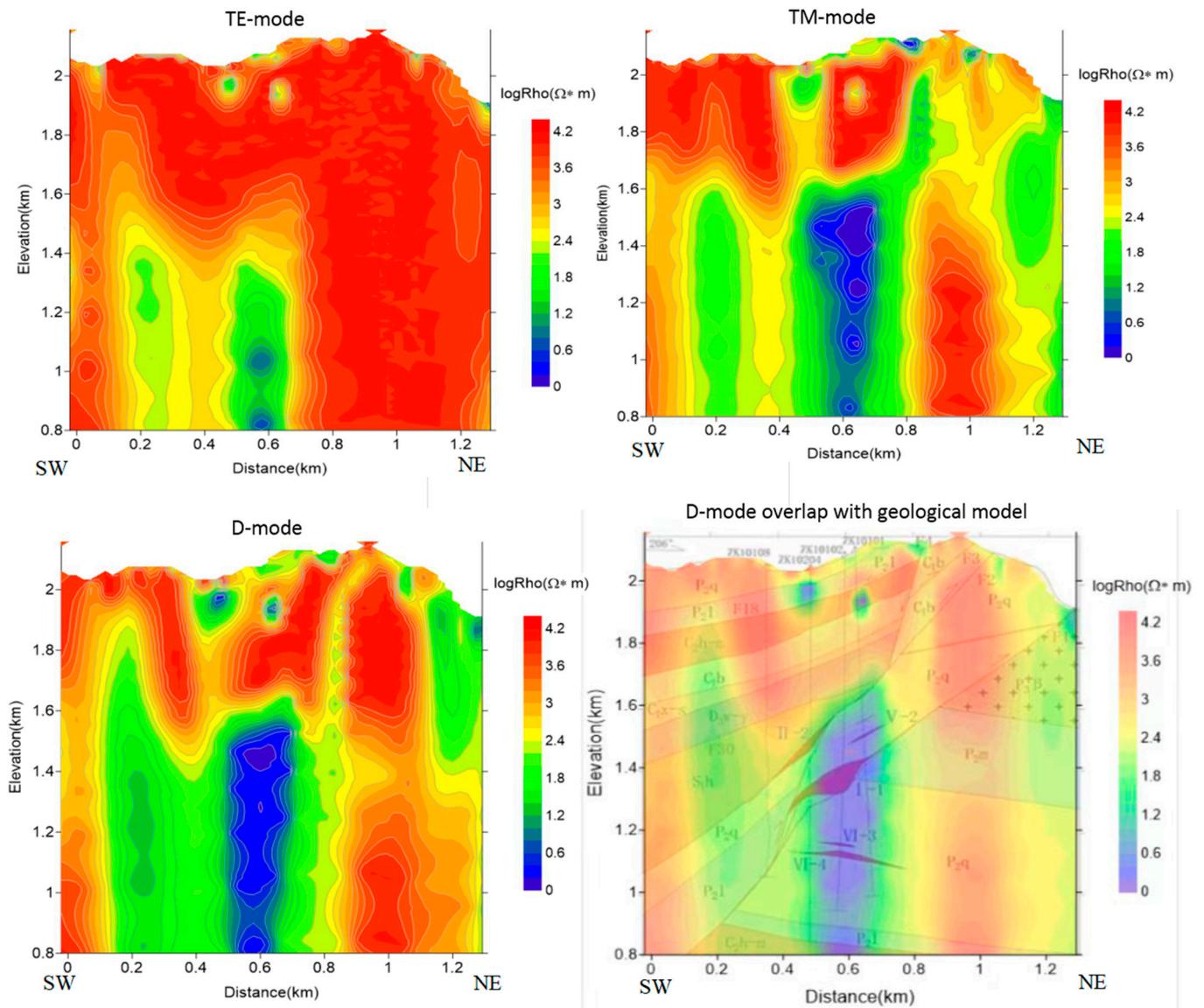


Figure 9. 2D inversion models of AMT data resolved by TE mode, TM mode, and D mode, obtained by ZondMT2D focused inversion and the overlap of the D- mode model with the geological model from Figure 3b. TE mode RMS=18.1%. TM mode RMS=9.7%. D-mode RMS=9.1%.

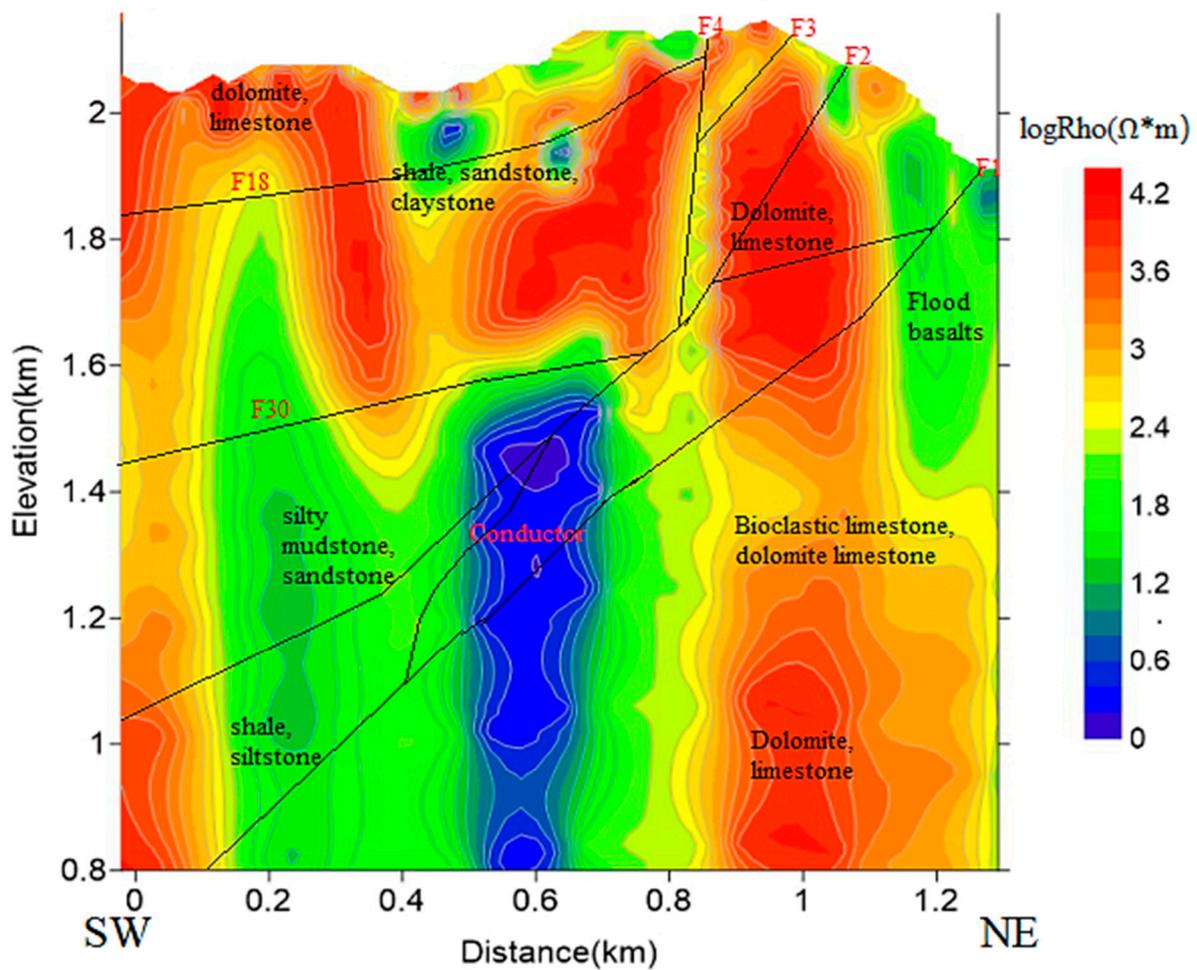


Figure 10. AMT resistivity cross-section across the Zhugongtang deposit showing inferred lithologic units and major faults.

Table 1. Rock and ore specimens resistivity comparison with AMT data in the study area.

Rock and Ore Specimens	Average Resistivity /Ω.m	Present Study: AMT Resistivity Range / Ω.m	
Dolomite and limestone	5 551–157 130	≥1 000	
Basalts	tuffaceous basalt massive basalt	517.3 2 384	>63 (flood basalts)
Shale, sandstone, claystone Silty mudstone	<100	4– 63	
Bioclastic limestone, dolomite limestone		>250	
Conductor (Pb-Zn)	69.4	<15	

9. Conclusions

In this study, the geoelectrical signature across the known location of lead–zinc mineralization in the Zhugongtang orefield was investigated by applying the AMT procedure to a single survey line. The results confirm the presence of conducting bodies: (a) small and large sized zones (<63 Ωm) in surficial depth (<0.10 km), and claystone, silty mudstone, shale and sandstone, to be more likely at deeper depths (>0.10 km), and (b) large sized conductors (<15 Ωm) at greater depths (≥0.50 km), which are inferred to be Pb–Zn mineralization. The geoelectrical strike estimated using the phase tensor and impedance tensor methods show satisfactory results and are in a good agreement with

the structure of the Zhugongtang mining area for the NW–SE direction. Two-dimensional resistivity models obtained for the study area could not clearly distinguish the boundaries between lithologic layers. However, the wide distribution of dolomite and limestone is evident in models and mineral-bearing geological formations are coincident with the low resistivity region. Furthermore, formation of flood basalts are also imaged in the study area. Moreover, rock and ore specimen data show fairly good agreement with AMT resistivity data. Likewise, regions with a high fault density were found to be fairly conductive compared to regions with low fault density. All in all, the 2D inversion with topography of AMT data can visually show the distribution of major structures across the lead–zinc deposit in a region with strong EM interferences and high elevations. Hence, these findings are a contribution to the current literature on Zhugongtang deposit and may be useful for future research work in the same or similar areas.

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