

Article

Three-Dimensional Electrical Structure and Metallogenic Background of the Southeastern Hubei Ore Concentration Area

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Abstract: The Southeastern Hubei Ore Concentration Area (SHOCA) is located in the west section of the Middle and Lower Yangtze River Metallogenic Belt in China, and it is a significant copper and iron mining region in China. Here, 117 pieces of magnetotelluric array data were used to obtain a three-dimensional resistivity model of the SHOCA and to investigate the relationship between the deep electrical features and the genesis of mineral deposits. The model shows that the Qinling-Dabie Orogenic Belt exhibits high-resistivity characteristics, representing Mesozoic granites and high-pressure to ultra-high-pressure metamorphic rocks. There are several low-resistivity anomalies in the upper crust of the SHOCA, which are connected to the widespread low-resistivity anomaly in the middle-lower crust. Near the Yangxin-Changzhou Fault, there is evidence of an electrical gradient zone. The Xiangfan-Guangji Fault, located at the south margin of the Qinling-Dabie Orogenic Belt, also exhibits distinct high- and low-resistivity boundaries at the upper crust. However, the Yangtze Fault and the Tancheng-Lujiang Fault manifest as resistivity gradient zones at the lithospheric scale. These faults are connected the low-resistivity anomaly in the middle to lower crust, possibly serving as upwelling channels of deep thermal fluids, exerting control over shallow diagenesis and mineralization processes. The low-resistivity anomaly in the middle to lower crust of the SHOCA is explained as partial melting resulting from the mixing of crustal and mantle materials. These low-resistivity anomalies play a role as source components in the mineralization system, where mineral-rich hydrothermal fluids migrate upward along intra-basin faults, exerting control over the distribution of shallow mineral deposits.

Keywords: Southeastern Hubei Ore Concentration Area; magnetotellurics; three-dimensional resistivity model; mineralization; partial melting; gravity



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1. Introduction

Metallic minerals, which are critical metals, have become strategic mineral resources. The middle and lower Yangtze River Metallogenic Belt is one of the most significant polymetallic mineralization belts for gold, copper, and iron in the eastern region of China. There are seven mineralization clusters in this belt, namely, Southeastern Hubei (Fe-Cu), Jiurui (Cu-Au), Anqing-Guichi (Cu), Ningzhen (Cu-Fe-Zn-Pb), Ningwu (Fe), Lu'an-Zongxiu (Fe-Cu), and Tongling (Cu-Au). The SHOCA, located in the western section of the middle and lower Yangtze River Metallogenic Belt, is an essential copper and iron mining area in

China. It hosts multiple deposits rich in iron and copper. These deposits are vital to China's copper and iron mining industry [1].

Researchers have been studying why there is such a considerable accumulation of metals within a limited area, what dynamic processes have occurred in the deep subsurface, what the structure of the lithosphere is, and how metal deposits are transported from the deep to the shallow regions. In the past decade or so, extensive studies in the mineralization district have been conducted, including geophysical investigations [2], geochemical analyses [3], and research on mineralization processes [4], significantly contributing to our understanding of the deep structure and mineralization processes in the mineralization district. In the academic community, there are three main theories regarding the deep dynamics and magmatic activity mechanisms of the middle and lower reaches of the Yangtze River region:

1. The continental extension model [5]: This suggests that the large-scale magmatic activity in the middle and lower reaches of the Yangtze River region is related to the continental collision between the Yangtze and North China Cratons, followed by extensional events.
2. The plate subduction model [6]: This proposes that the large-scale magmatic activity in the middle and lower reaches of the Yangtze River region is associated with the subduction of the Paleo-Pacific Plate.
3. The delamination model [2,7]: This suggests that during the collision process between the Yangtze Craton and the North China Craton, the eastern part of the Yangtze Craton collided and squeezed into the North China Craton, forming the Tancheng-Lujiang Fault on the western side of the intrusion. The ore-bearing belt in the middle and lower reaches of the Yangtze River is located on the western side of the Tancheng-Lujiang Fault. This region's subsequent large-scale magmatic activity is attributed to lithospheric mantle delamination and asthenospheric upwelling caused by the relative rotation between the North China Craton and the Yangtze Craton.

The enrichment of metallic ore deposits is typically associated with the migration of deep-seated hydrothermal fluids and their subsequent accumulation in shallow regions. This process can result in electrical conductivity variations between the ore-bearing rocks and the surrounding rocks. Additionally, the ascent and intrusion of magma often exhibit distinct electrical characteristics [8].

The magnetotelluric (MT) method measures the natural electromagnetic field signals in the time domain at the Earth's surface. The response curves of apparent resistivity and phase variation with frequency are obtained through signal processing. A resistivity model that extends to the upper mantle can be derived by analyzing the different penetration depths of signals at different frequencies. The MT method is widely used in ore-forming background studies with successful results [9–11]. This study used an array of MT data collected in the SHOCA and its adjacent areas (Figure 1). A crustal electrical structure model was obtained by performing three-dimensional inversions, providing constraints for studying the ore-forming background and material sources in the SHOCA.

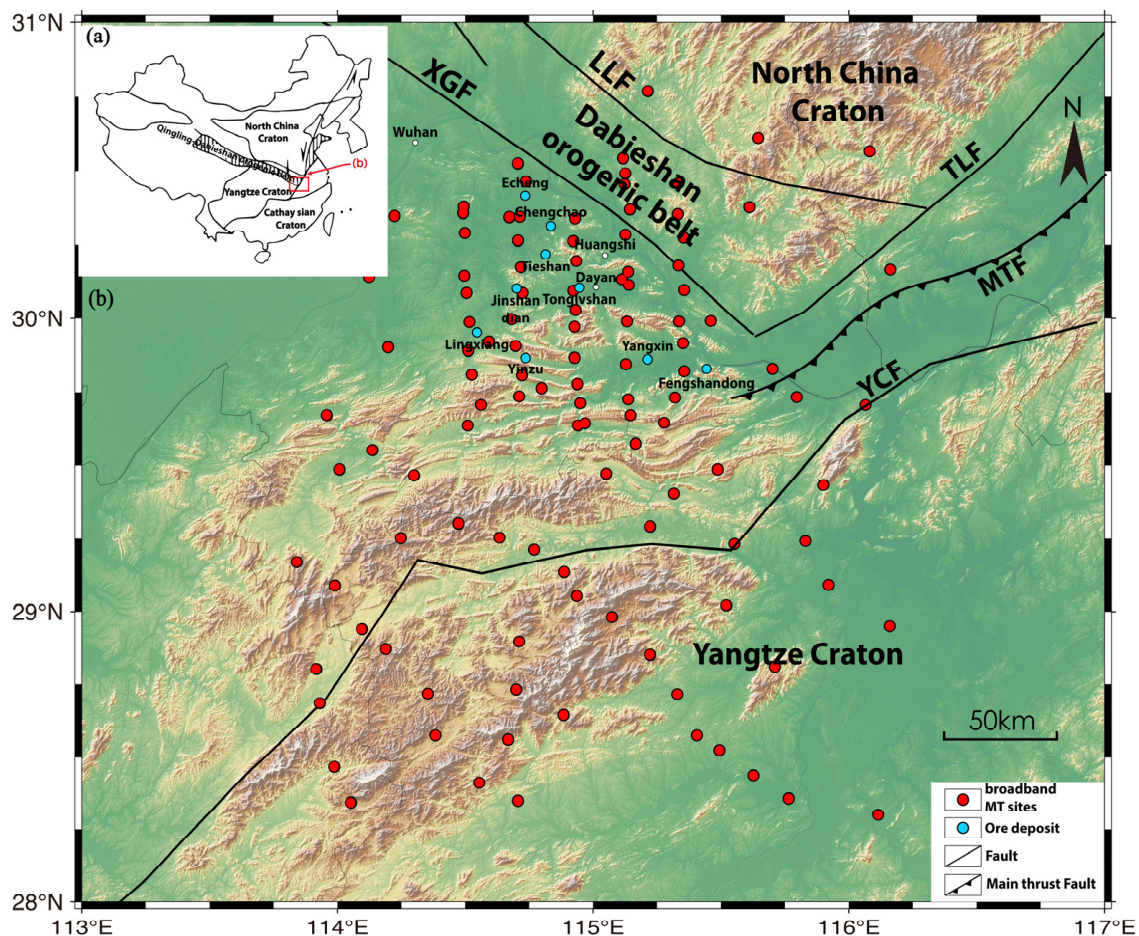


Figure 1. (a): The position of (b). (b): Topography map showing major tectonic structures and MT station locations in the survey area. TLF: Tancheng-Lujiang Fault, XGF: Xiangfan-Guangji Fault, YCF: Yangxin-Changzhou Fault, LLF: Luonan-Luanchuan Fault, and MTF: Main Thrust Fault.

2. Geological and Geophysical Background

The SHOCA is located in the western segment of the middle and lower reaches of the Yangtze River metallogenic belt. Structurally, it belongs to the southeastern part of the Qinling-Dabie orogenic belt and the junction area of the Mufushan passive margin basin of the middle and lower Yangtze Block.

The geological strata in this mineralization district are well developed, with exposures ranging from the Ediacaran to the Quaternary (from 533 Ma to present). The only missing formations are the Lower and Middle Devonian (420–338 Ma) and Lower Carboniferous (338–295 Ma). The magmatic activity in the SHOCA is intense. Among the magmatic bodies related to mineralization are six intermediate-acidic intrusions: Tieshan, Echeng, Jinshandian, Lingxiang, Yangxin, and Yinzu [12]. Numerous smaller intermediate-acidic rock bodies, such as Tongsankou and Fengshandong, are also present in the area.

During the Yanshanian Period (150–115 Ma), magmatic intrusions and volcanic eruptions had significant impacts on the regional geology, resulting in the following [13]:

1. Large- and medium-sized skarn-type iron and copper deposits, such as Jinshandian, Chengchao, Tieshan, and Tonglushan deposits, were formed. These deposits are characterized by silicate-carbonate rocks and host significant iron and copper mineralization.
2. Silicate-carbonate and porphyry-type copper-molybdenum deposits, such as Fengshandong, were generated. These deposits are associated with intrusive rocks and are rich in copper and molybdenum mineralization.

3. Magmatic-hydrothermal and volcanic-hydrothermal iron and copper polymetallic deposits were formed. These deposits resulted from the interaction between magmatic and hydrothermal fluids associated with volcanic activities.

Furthermore, during the late Yanshanian Period, volcanic eruption activities formed two continental volcanic eruption basins, namely, the Jinniu and Huahu basins. These basins represent depositional environments where volcanic materials were deposited.

The geological structure of the SHOCA is characterized by the superimposition of the Yanshanian (NNE) and Indosinian (NW) tectonic events [14]. The ore deposit cluster in southeastern Hubei can be divided into two distinct periods of magmatic activity and mineralization during the Mesozoic era (254~66 Ma), with 137 million years ago serving as a boundary [13].

The Yanshan early-stage intrusive rocks intruded between 150 and 137 million years ago, with the primary phase of copper ore formation predominantly occurring from 145 to 137 million years ago. This period witnessed the development of skarn-type copper-iron-gold deposits and porphyry-type copper-gold deposits. The early-stage intrusions affected major rock masses in the eastern part of Tieshan, Yinzhu, Lingxiang, and Yangxin, forming a northwest-oriented magmatic belt along the Daye-Jiujiang area. Additionally, smaller intrusions, such as Coppershankou, Baiyunshan, Fengshandong, and Ruanjiawan, were also established during this phase.

During the late stage, intrusive activities occurred broadly between 133 and 127 million years ago, representing the iron-forming stage. Late-stage intrusions extended to the eastern side of the Liangzihu depression zone, forming rock bodies like Echeng, Tieshan West, Jinshandian, and Lingxiang West. The volcanic eruptions during the late Yanshanian period, approximately 130 to 115 million years ago, formed the Hua Lake and Jinniu volcanic basins. However, no significant mineralization associated with this volcanic activity has been identified to date. Only in the Wangbaoshan area, sporadic occurrences of small-scale volcanic hydrothermal deposits and partial gold mineralization have been observed.

The characteristics of the copper-iron mineralization zones in the SHOCA are related to the deep T-shaped mantle uplift and the shallow structural pattern [15].

The geological structures in the southeastern part of Hubei Province can be divided into three categories according to depth and scale: (1) northwest-trending lithospheric faults, such as the Xiangfan-Guangji Fault; (2) northwest-trending crustal faults, for example, the Bao'an-Taogang Fault; and (3) northeast-trending basement faults (such as the Jinniu-Daye-Huangshi Fault), east-west trending basement faults (such as the Maopu-Liangjianqiao Fault), and north-northeast trending basement faults (such as the Tuan-Ma Fault and Tancheng-Lujiang Fault).

The Jinniu-Daye-Huangshi Fault, which trends northeast, is particularly significant. The northern side of the fault, including the Jinshandian, Echeng, and Tieshan areas, is mainly associated with skarn-type iron deposits formed through contact metasomatism. The southern side of the fault, including the Yangxin and Daye areas, is primarily related to skarn-type copper deposits formed through contact metasomatism.

Xie et al. [16] summarized the southeastern Hubei region's main mineralization events, ore-forming processes, and rock associations. They proposed that the porphyry-type gold deposits in the area are related to the Yangxin and Tieshan intrusions. In contrast, the skarn-type copper-iron-gold deposits are associated with the diorite-quartz diorite. The porphyry-skarn-type copper-molybdenum-tungsten deposits are related to the granite diorite. Zhou et al. [17] suggested that the Shanshan-Fenglin supra crustal fault is a pathway for deep-seated material upwelling in the SHOCA. Zhang et al. [18] believed that the triangular thrust-reverse fault zones control the Daye-Yangxin polymetallic copper-iron-gold deposits, the Tieshan-Huangjinshan thrust-reverse fault zone controls the Ezhou-Huangshi deposits, and the Yinzhu-Yaoshan thrust-reverse fault zone controls the Daye-Yangxin deposits. The Damo-Fenglin thrust fault zone controls the Fengshandong deposit.

In summary, the SHOCA is primarily characterized by endogenous metallic minerals, with copper-iron ores being the most abundant, followed by gold, silver, zinc, lead, tungsten,

molybdenum, and other ores. The distribution of metallic deposits exhibits the following characteristics [19]:

1. Copper-iron deposits are influenced by the distribution of magmatic rocks. The deposits are closely associated with intrusive bodies, and the main distribution area is in the contact zone between Mesozoic intermediate-acidic igneous rocks and carbonate sandstone shale. Some deposits are also found in the residual bodies and xenoliths of carbonate rocks.
2. Copper-iron deposits are distributed along the Ezhou-Damushan superimposed folding zone. Along the EW direction, the deposits can be divided into iron ore deposits, copper-iron ore deposits, and copper (tungsten, molybdenum) mineralization belts.

Geophysical exploration is an effective means of studying the deep subsurface structure. Previous studies have been conducted in the SHOCA using satellite gravity [20] and magnetic anomaly [21] data. Based on the satellite Bouguer gravity anomaly (Figure 2), it can be observed that the northeastern side of the Qinling-Dabie orogenic belt and the area between the Tancheng-Lujiang Fault Zone and the Yangxin-Changzhou Fault Zone exhibit high gravity anomalies (100–130 mGal). The area between the Xiangfan-Guangji Fault and the Yangxin-Changzhou Fault exhibits a gravity anomaly, with lower values to the south (40–80 mGal) and higher values to the north (90–100 mGal). The Yangtze block south of the Yangxin-Changzhou Fault displays high (100–130 mGal) gravity anomalies, with low values (60–90 mGal) on both sides. The North China Craton exhibits the most inferior gravity anomalies in the region, with positive anomalies ranging from 40 to 80 mGal. These anomaly distributions correspond well to the tectonic units, and the transitional zones align with the fault structures.

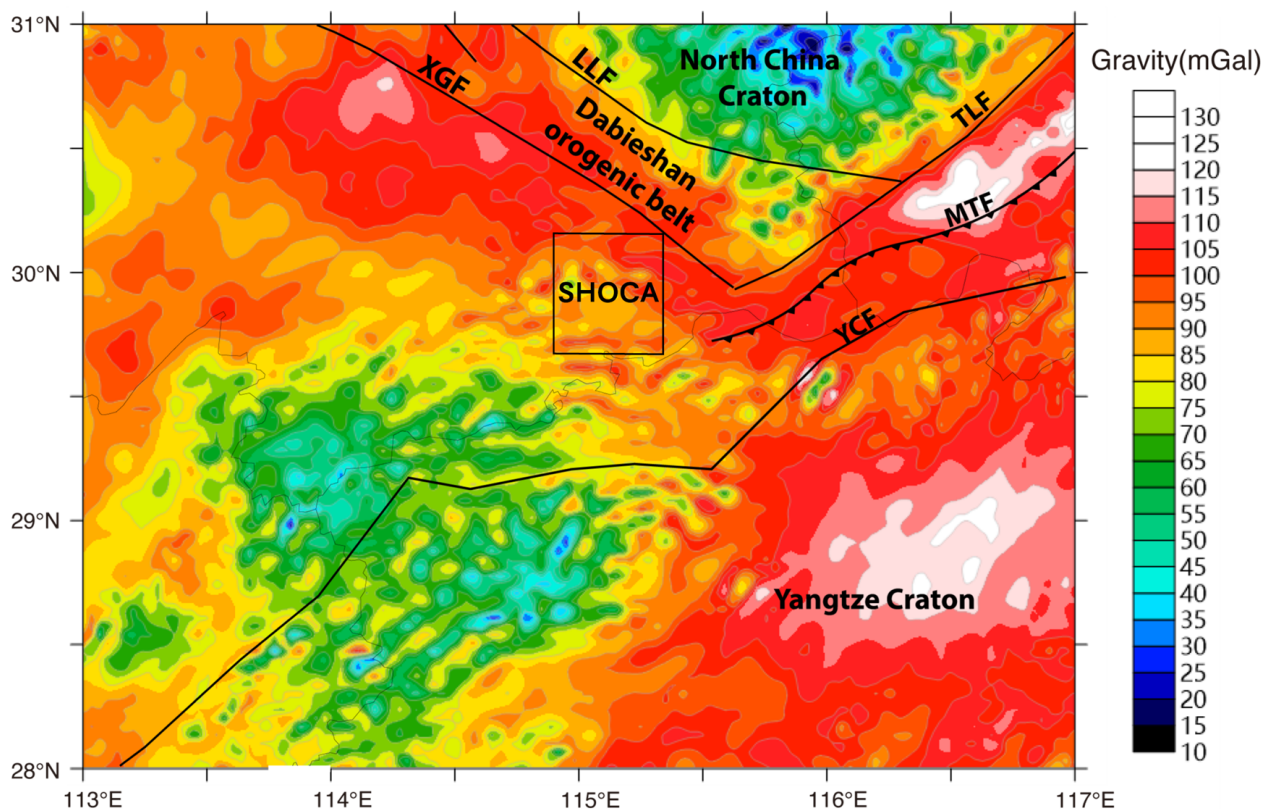


Figure 2. The satellite Bouguer gravity anomaly map in the southeastern Hubei region. TLF: Tancheng-Lujiang Fault, XGF: Xiangfan-Guangji Fault, YCF: Yangxin-Changzhou Fault, LLF: Luonan-Luanchuan Fault, and MTF: Main Thrust Fault.

According to Gao [19], based on 1:500,000 Bouguer gravity anomalies and aeromagnetic anomalies, the mineralized intrusions in the SHOCA are considered composite intermediate-acidic intrusions that have undergone multiple intrusions. These intrusions exhibit complex gravity and magnetic anomaly characteristics. They are characterized by solid magnetism, resulting in strong magnetic anomalies. On the other hand, slightly acidic intrusions tend to form lower magnetic anomalies, and acidic rock bodies generally do not generate significant magnetic anomalies. In other words, the stronger the acidity, the weaker the magnetic anomaly reflection. Gravity anomalies primarily reflect the acidic portions of the rock bodies, and different sedimentary layers and the basement can influence gravity anomalies, leading to their complexity.

Furthermore, some electrical exploration work has also been conducted in the SHOCA. However, these efforts have mainly focused on smaller areas within individual mining districts. No crustal-scale electrical structure models cover the entire region for studying deep-seated mineralization backgrounds or providing further guidance for exploration activities.

3. Data Collection, Processing, and Analysis

3.1. MT Data Acquisition and Processing

As shown in Figure 1, the survey area is located in the southern region of Hubei Province, east of the Yangtze River. It covers the south margin of the North China Craton, the southeastern segment of the Qinling-Dabie orogenic belt, the SHOCA, and a portion of the southern area of the mineralized zone. Field data were collected in 2021, with 117 broadband magnetotelluric (MT) stations deployed. The data were acquired using the MTU-5A/C Earth's electromagnetic depth sounder produced by Phoenix Geophysics Ltd. of Canada. The acquisition time at each station was at least 40 h. The polarization direction was defined with true north as the positive X-axis direction, east as the positive Y-axis direction, and vertically downward as the positive Z-axis direction. A pair of orthogonal horizontal electric field components (E_x and E_y) and three mutually orthogonal magnetic field components (H_x , H_y , and H_z) were recorded at each station.

The data were processed using SSMT2000 and EMPower software [22]. The remote referencing technique [23] and Robust estimation were applied at each station. Power spectral density was carefully examined, and data from interference time intervals were removed. Despite numerous mines and significant anthropogenic interference in the study area, these technical measures improved data processing quality. The reliable period range for each station was 0.003 to 2000 s, and the detection depth could reach the Moho interface.

Figure 3 shows the average apparent resistivity section of the study area overlaid on topography for six different periods. The most prominent feature of the average apparent resistivity in the study area is a distinct low-resistivity anomaly in the central part. At shorter periods (0.01 s, 0.1 s, and 1 s), it exhibits an alternating distribution with high-resistivity anomalies. However, at more extended periods (100 s and 1000 s), it appears as a large-scale low-resistivity anomaly, with its center located north of the Yangxin-Changzhou Fault and extending northeastward towards the area between the Tancheng-Lujiang Fault Zone and the Yangxin-Changzhou Fault. Apart from this low-resistivity anomaly, there are only large-scale low-resistivity anomalies observed at shorter periods (0.01 s and 0.1 s) in the Yangtze Block and the southwestern side of the Xiangfan-Guangji Fault, which correspond to the locations of surface sedimentary basins. Overall, the remaining areas exhibit a characteristic of high resistivity.

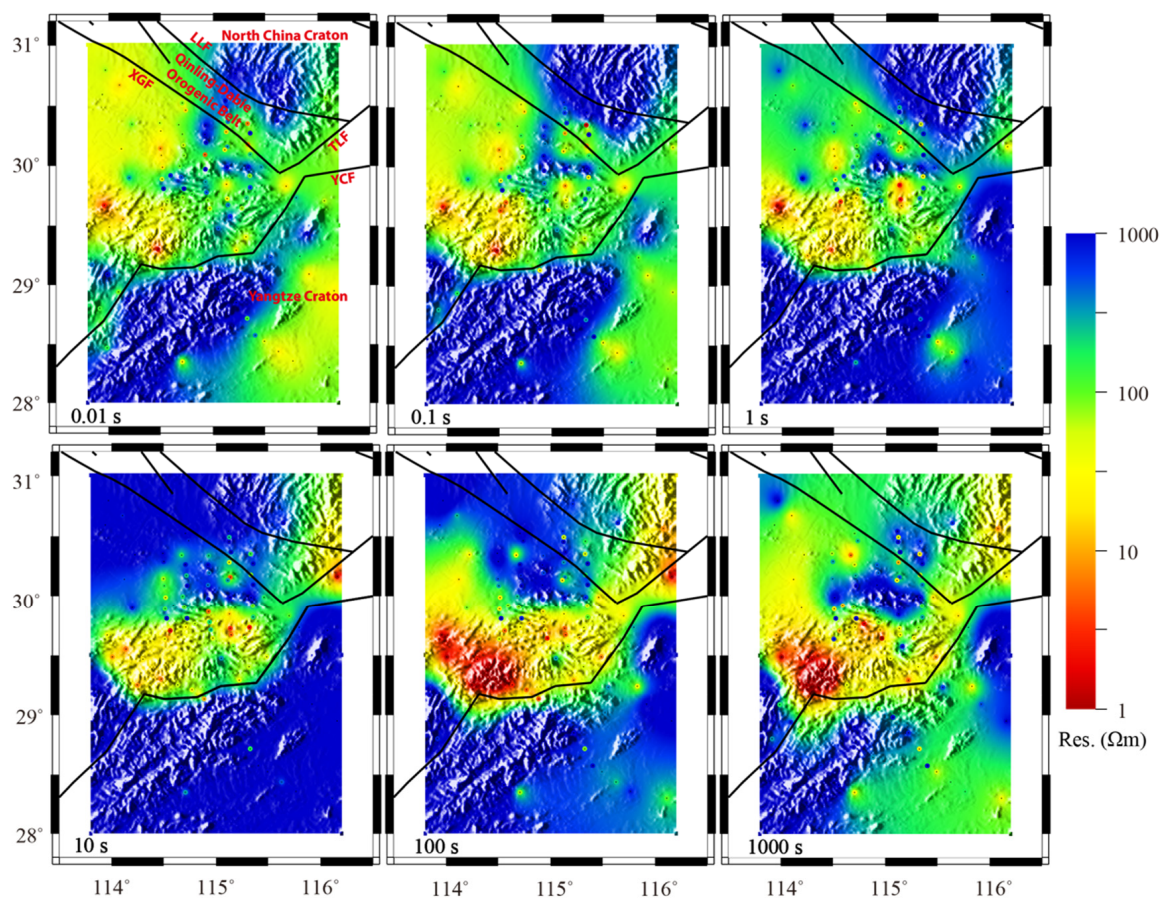


Figure 3. The planar distribution map of the average apparent resistivity at different periods in the southeastern Hubei region. TLF: Tancheng-Luijiang Fault, XGF: Xiangfan-Guangji Fault, YCF: Yangxin-Changzhou Fault, LLF: Luonan-Luanchuan Fault.

3.2. Data Analysis

Before inversions, the data underwent dimensionality analysis to determine the dimensionality of the subsurface structures. The most commonly used method for dimensionality analysis is phase tensor analysis [24]. This method does not require a predefined structural strike angle and is unaffected by distortion effects. The phase tensor is defined by the maximum phase angle, minimum phase angle, and skew angle, visualized using the lengths of the major and minor axes of an ellipse and color. Generally, when the skew angle is less than 3° , the subsurface medium can be regarded as a two-dimensional structure [25]. In this case, the direction of the major or minor axis represents the structural strike direction, and when their lengths are equal, the subsurface medium is considered one-dimensional. Figure 4 shows the results of phase tensor analysis for four periods. The skew angles are mostly less than 3° , and some are even less than 1° with equal lengths of major and minor axes, indicating a two-dimensional structure in the shallow portion, with some stations exhibiting one-dimensional features within specific basins. However, at more extended periods (10 s, 100 s, and 1000 s), approximately half of the stations have skew angles more significant than 3° [26], indicating pronounced three-dimensional characteristics, especially at the intersection of the Qinling-Dabie Orogenic Belt and the Yangtze Block, where clear three-dimensional structures are observed. These pronounced three-dimensional features may be related to the interaction of the Cathaysia tectonic system and the Yangtze-North China Block compression, as well as the convergence of the Paleo-Pacific Plate towards the Eurasian continent in the northeastern direction. Therefore, three-dimensional inversions are necessary for the study area.

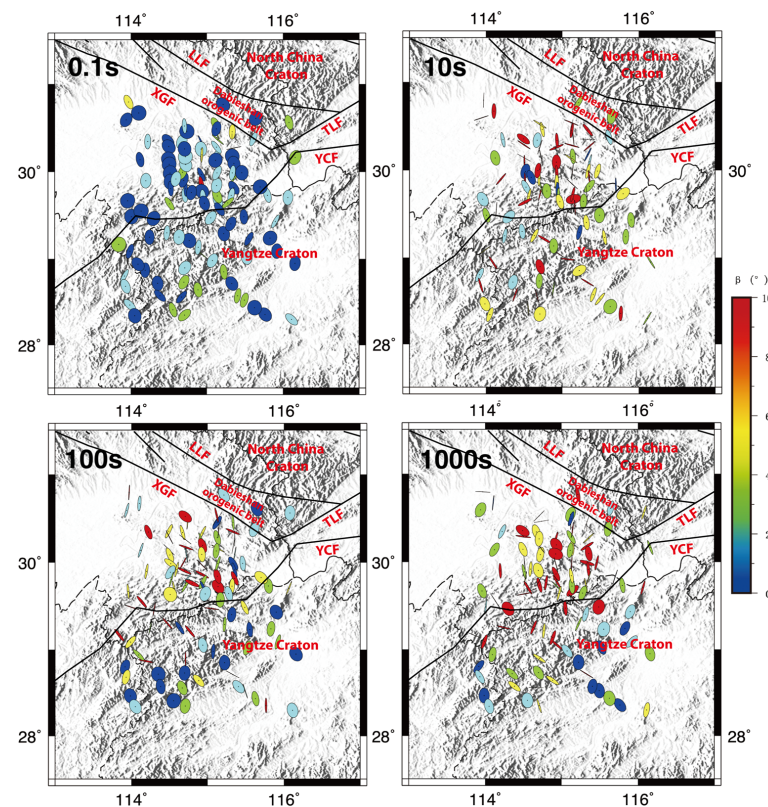


Figure 4. Phase tensor distribution at four periods of MT stations in the study area (0.1 s, 10 s, 100 s, and 1000 s). TLF: Tancheng-Lujiang Fault, XGF: Xiangfan-Guangji Fault, YCF: Yangxin-Changzhou Fault, LLF: Luonan-Luanchuan Fault.

3.3. 3D Inversions

Three-dimensional inversions were performed using ModEM software, developed by Professor Gary Egbert and his team, based on the nonlinear conjugate gradient algorithm [26]. One hundred eleven MT stations were selected for 3D inversions out of the total one hundred seventeen MT stations acquired. In the 0.001–5000 s period range, the full impedance tensor data at 31 periods were selected for 3D inversions. The error floor of the diagonal elements of the impedance, Z_{xx} and Z_{yy} , was $|Z_{xy} \cdot Z_{yx}|^{1/2} \cdot 10\%$, and the error floor of the off-diagonal components, Z_{xy} and Z_{yx} , was set to $|Z_{xy} \cdot Z_{yx}|^{1/2} \cdot 5\%$. The study area was horizontally divided into a 5 km $\times$ 5 km grid based on the distribution of stations, resulting in a 63 $\times$ 53 grid. To approximate the boundary conditions at infinity, an additional 12 grids were added outward in each of the four horizontal directions, with a step size of one-and-a-half times. In the vertical direction, the first layer had a thickness of 10 m, and a total of 60 layers were divided with a step size of 1.1 times. Three additional layers were added with a step size of one-and-a-half times, and five air layers were included. As a result, a final grid of 87 $\times$ 77 $\times$ 68 was obtained. The initial model for inversions was set as a homogeneous half-space with a resistivity of 100 Ω m. After 130 iterations, the normalized RMS misfit was reduced to 2.9.

Based on the three-dimensional inversion results of the magnetotelluric (MT) data in the SHOCA, we have extracted and analyzed eight horizontal slices at different depths (labeled as a–h in Figure 5). Overall, the electrical structure characteristics in the southeastern Hubei region exhibit significant variations at different depths.

Based on the resistivity models of the horizontal slices (Figure 5), we observe that the electrical structure of the shallow crust in the study area is quite complex. The eastern part of the Qinling-Dabie orogenic belt exhibits high-resistivity electrical characteristics (Figure 5), with a resistivity value exceeding 100 Ω m. This indicates the electrical characteristics of Mesozoic granites and the high-pressure to ultra-high-pressure metamorphic rock series

in the Qinling-Dabie orogenic belt. In contrast, the near surface of the SHOCA shows a predominantly high-conductivity feature, with resistivity values less than $10\Omega\text{m}$. This high-conductivity feature is related to the distribution of mineral deposits in the SHOCA. However, this high-conductivity anomaly is only present in shallow subsurface layers above 2 km (Figure 5a). As the depth increases, this high-conductivity anomaly diminishes, as shown in Figure 5b. We attribute the occurrence of the high-conductivity feature in the shallow subsurface to the distribution of mineral deposits in the SHOCA and the sedimentary layers in the upper crust.

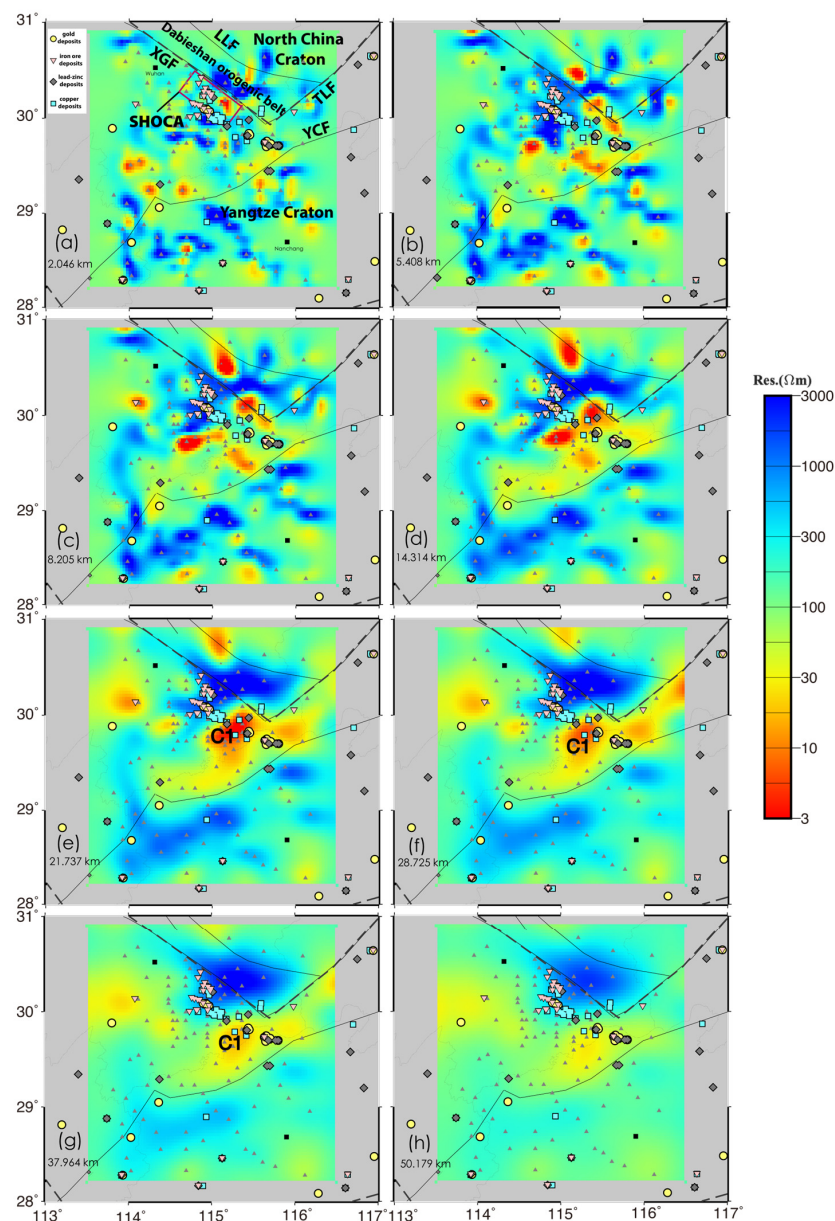


Figure 5. Horizontal slices of the 3D resistivity model at different depths (a–h) and the distribution of mineral deposits. Gray triangles represent MT stations. TLF: Tancheng-Lujiang Fault, XGF: Xiangfan-Guangji Fault, YCF: Yangxin-Changzhou Fault, LLF: Luonan-Luanchuan Fault. C1: High-conductivity anomaly.

The high-conductivity and high-resistivity anomalies in the shallow layers of the Yangtze Block exhibit sporadic and alternating distributions. However, on the southern side of the Yangxin-Changzhou Fault, they are predominantly reflected as high-resistivity anomalies, whereas on the northern side, they are reflected as high-conductivity anomalies.

The electrical gradient zone between the high-conductivity and high-resistivity anomalies may be associated with the electrical response of the Yangxin-Changzhou Fault. With increasing depth, it becomes evident that the high-resistivity anomalies, distributed in a necklace-like pattern on the southern side of the Yangxin-Changzhou Fault (Figure 5b), gradually converge into a coherent feature (Figure 5f).

Of particular interest is the gradual convergence of the dispersed high-conductivity anomalies (Figure 5c) distributed in the SHOCA and the northern side of the Yangxin-Changzhou Fault into a large-scale high-conductivity anomaly C1 (Figure 5e) with increasing depth. The sensitivity test of the model confirms that the high-conductivity anomaly C1 is reliable at depths greater than 50 km (Figures S1 and S2 in the Supplementary Materials). From the vertical slice of the three-dimensional resistivity model (Figure 6), it can be observed that this high-conductivity anomaly essentially occupies the deep space of the mineralized area. High-conductivity anomaly C1 is connected to a low-resistivity zone in the upper crust (electrical characteristics of main faults in the study area), indicating that it may serve as a pathway for deep-seated thermal fluids and play a controlling role in the diagenesis and mineralization processes in the shallow layers.

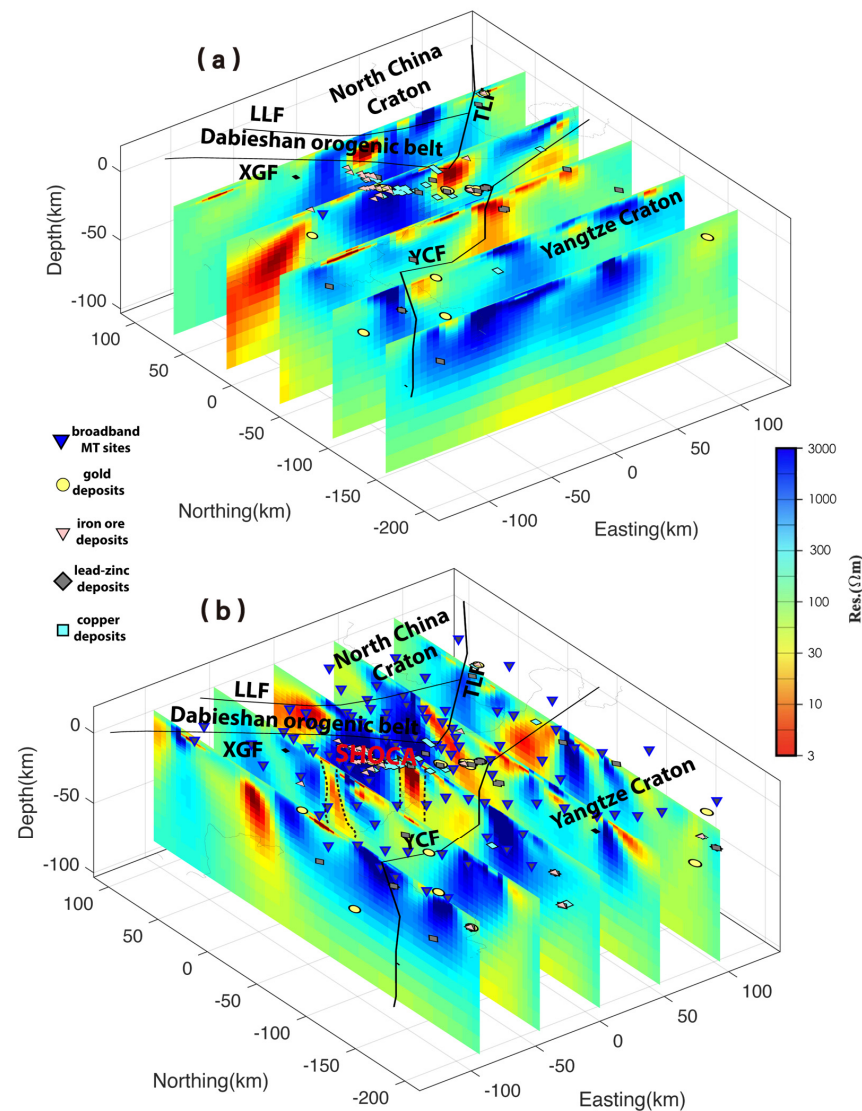


Figure 6. Cross-sectional views of the 3D resistivity model (a) The east–west direction. (b) The north–south direction. Reversed blue triangles are the MT stations. TLF: Tancheng-Lujiang Fault, XGF: Xiangfan-Guangji Fault, YCF: Yangxin-Changzhou Fault, LLF: Luonan-Luanchuan Fault. C1: High-conductivity anomaly. SHOCA: The Southeastern Hubei Ore Concentration Area.

4. Interpretation and Discussion

4.1. The Composition of Crustal Materials

In the SE135° cross-sectional profile shown in Figure 7, we observe a range of high-resistivity anomalies in the northwestern part of the SHOCA. Within these high-resistivity anomalies, there are several small-scale high-conductivity anomalies. The mineral deposits are primarily distributed near the electrical boundaries between high-conductivity and high-resistivity regions. For example, the Echeng-Jinshandian-Lingxiang skarn-type iron deposits and the Fengshandong-Wushan-Chengmenshan porphyry-type copper-gold polymetallic deposits are in the western part of the mineralized area. These electrical boundaries may be formed by intrusive bodies rich in minerals that have intruded into carbonate rocks, high-resistivity volcanic rocks, and sedimentary formations near the shallow crustal layers, creating contact zones [19].

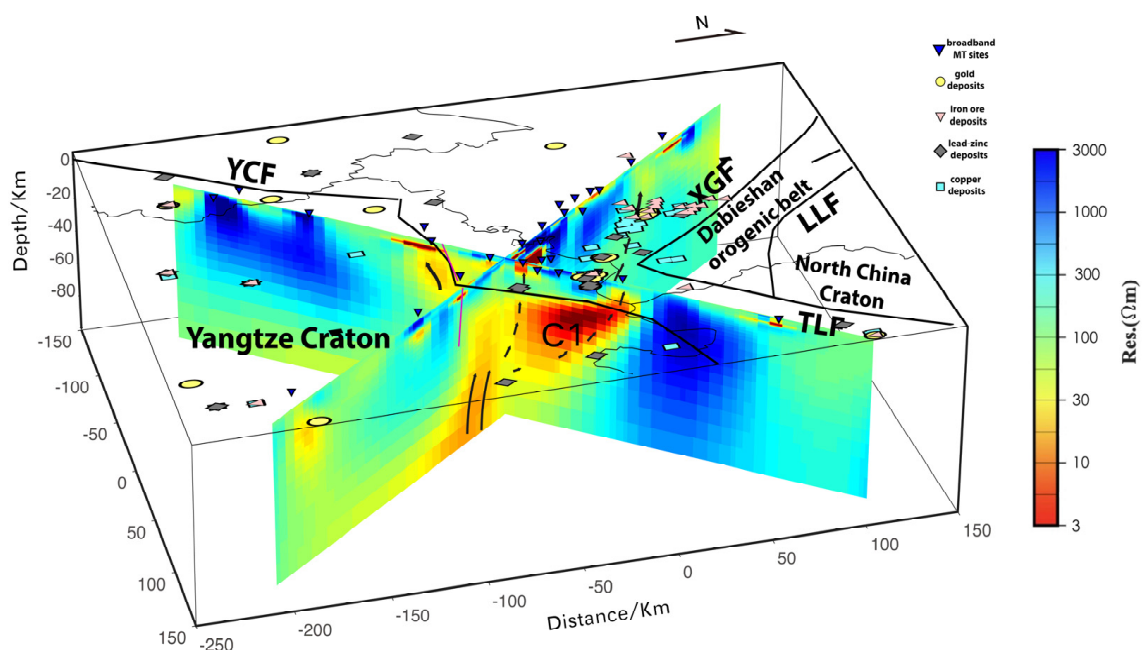


Figure 7. Two cross-sectional profiles of the three-dimensional electrical structure model across the mineralized area in southeastern Hubei Province. TLF: Tancheng-Lujiang Fault, XGF: Xiangfan-Guangji Fault, YCF: Yangxin-Changzhou Fault, and LLF: Luonan-Luanchuan Fault. C1: High-conductivity anomaly.

In Figure 7, it can be observed that there is a high-conductivity anomaly (C1) in the middle and lower crust of SHOCA, with a top boundary interface at 10 km, and it exhibits a continuous downward trend. Combining the geochemical studies conducted by previous researchers, the nature of adakitic rocks is found in the Mesozoic acidic magmatic rocks in the mining district. Moreover, there are numerous crust–mantle hybrid materials [27,28]. Additionally, based on previous research [29], large amounts of water are generated during processes such as metamorphic dehydration, magma differentiation, and hydrothermal melting, leading to the manifestation of low-resistivity characteristics. This aligns with the presence of a high-conductivity anomaly in the lower crust of the ore-forming zone, suggesting that the high-conductivity anomaly is indicative of partial melting of the lower crust, contamination of crust–mantle materials, and the electrical characteristics associated with the ascent of aqueous fluids. The upper crust in the ore-forming zone serves as a relatively ideal cap rock, facilitating the storage of deep-seated aqueous fluids [11]. High-conductivity anomaly C1 may also be attributed to deep conductors with high skew, as due either to anisotropy [30] or solid-state conductors [31].

The major faults in the study area, including the Tancheng-Lujiang Fault, the Yangxin-Changzhou Fault, and the Xiangfan-Guangji Fault, are reflected in the resistivity model as electrical gradient zones connected to high-conductivity features in the middle and lower crust of the mineralized belt. Previous studies have identified these faults as the main controlling structures for mineralization in the study area [32]. They exert control over the distribution of shallow copper-iron deposits, and the enrichment and migration of sulfur are closely related to the mineralization process. The presence of abundant sulfur and the release of water during hydrothermal alteration processes can significantly reduce the resistivity of the surrounding rocks [11,33]. Therefore, the fault zones primarily exhibit low-resistivity characteristics.

According to previous studies, the Xiangfan-Guangji Fault has been proposed as a lithospheric-scale fault [34], which differs from the results shown in the resistivity model of this study. Figure 5 shows that the Xiangfan-Guangji Fault does not appear as a lithospheric-scale electrical boundary in the resistivity model; it is only evident in the upper crust. Therefore, we consider the Xiangfan-Guangji Fault to be a crustal-scale fault. Combining the Bouguer gravity anomaly and aeromagnetic anomaly in the study area [19], as shown in Figure 2, it can be seen that the Xiangfan-Guangji Fault does not exhibit a prominent Bouguer gravity anomaly or aeromagnetic anomaly gradient zone. This further supports the notion that the Xiangfan-Guangji Fault is not a deep-seated fault but rather a crustal-scale fault.

4.2. The Deep-Seated Background of the Magma-Mineral System

The mineralization system is located at the southern margin of the Yangtze-North China collisional orogeny. This area has undergone two major tectonic events since the Mesozoic. During the Indosinian–Yanshanian early stage, the dominant stress background was compression. The Yangtze Craton was the first to collide and intrude into the North China Craton [2,35], followed by intracontinental subduction events [36]. In the subducted slab, rocks underwent metamorphism, deformation, and dehydration, melting under high-temperature and high-pressure conditions [37]. During the Yanshanian period, the dominant stress background shifted to extension due to the detachment and sinking of the intracontinental subducted slab, converting the study area from a compression stress background to an extension stress background [5]. Modifying the overlying “mantle wedge” by dehydration and melting the subducted slab enriched the metallic substances during this period. With the upwelling of deep-seated thermal materials (asthenospheric upwelling) to the crust–mantle boundary, copper-iron-rich primary ore-forming magmas formed through the MASH process (melting, assimilation, storage, and homogenization) [3,38]. This process led to the development of the high-conductivity C1 feature in the lower crust of the mineralization zone. Petrochemical studies suggest that the Late Mesozoic intermediate-acidic magmatic rocks in the study area have characteristics of adakitic rocks, indicating a mixture of mantle-derived magma and lower crustal materials [3,28]. Therefore, it can be inferred that large-scale melting of the lower crust, upwelling of the asthenospheric material, and mixing of crust–mantle materials are deep-seated sources of the mineralization zone.

Deep-seated faults play a significant controlling role in the spatial distribution of mineral deposits and serve as primary factors controlling the migration and intrusion of magma/fluids [39]. They act as conduits in the mineralization system. The Olympic Dam deposit in South Australia is the world’s fourth-largest copper deposit and the largest known uranium deposit. Graham Heinson et al. (2018) conducted a study using 110 wide-band magnetotelluric (MT) stations along a 200 km transect across the Olympic Dam deposit. The research found that the pathways of crustal fluids originating from the lower crustal source are mapped as conductive “finger-like” structures, similar to the electrical reflections of ore-bearing hydrothermal upflow channels discussed in this paper.

In Figure 6b, it can be seen that beneath the SHOCA, there is also a finger-like high-conductivity structure connected to the deep high-conductivity zone C1.

The study area includes three major faults: the Tancheng-Lujiang Fault, the Yangxin-Changzhou Fault, and the Xiangfan-Guangji Fault. By combining the electrical structure model presented in this study, it can be observed that all three faults are connected to the high-conductivity C1 feature in the middle and lower crust, serving as pathways for the upwelling of mineral-bearing hydrothermal fluids and controlling the distribution of shallow deposits. Furthermore, since these three faults almost cover the entire mineralization belt in the middle and lower reaches of the Yangtze River, it can be inferred that various mining districts within the belt have a relatively unified mineralization system and deep background [11,32]. Previous studies using reflection seismic profiles in the mineralization belt have discovered a giant magma chamber in the middle crust at a depth of approximately 18 km [40], which corresponds to the high-conductivity feature in the middle and lower crust in the electrical structure model of this study. After the crust–mantle boundary undergoes the MASH process (melting, assimilation, storage, and homogenization) [3,7] to form ore-forming magmas and fluids, these migrate upward through chimney-like conduits to the middle crust. Due to the brittle upper crust acting as a barrier, a secondary magma chamber is formed in the middle and lower crust, corresponding to the high-conductivity C1 feature in Figure 7.

5. Conclusions

This paper utilizes magnetotelluric data from the southeastern Hubei region to construct a three-dimensional resistivity model of the crust, covering the SHOCA and surrounding areas. Based on previous research on the metallogenic system in the middle and lower reaches of the Yangtze River, the relationship between deep structures and the distribution of shallow ore deposits is discussed, providing constraints on the metallogenic background and material sources in the SHOCA. The main conclusions are drawn as follows:

1. The high-conductivity anomaly in the middle and lower crust of the metallogenic belt indicates the occurrence of partial melting and crust–mantle material mixing in the subsurface. During the Indonesian to early Yanshanian period, plate collisions and subsequent intracontinental subduction events occurred under compressional stress, resulting in metamorphic deformation and dehydration melting of the upper crustal rocks of the subducting plate. In the late Yanshanian period, deep-seated materials upwelled and mixed with the crust under the extensional stress regime, forming primary ore-forming magmas through the MASH process. This is reflected in the electrical structure model as the widespread high-conductivity anomaly C1.
2. The major faults in the study area, including the Tancheng-Lujiang Fault, the Yangxin-Changzhou Fault, and the Xiangfan-Guangji Fault, are manifested as boundaries between high and low resistivity in the electrical structure model. They are connected to the high-conductivity anomaly C1 in the middle and lower crust of the study area. These faults serve as pathways for the upward migration of deep-seated hydrothermal fluids and control the distribution of shallow mineral deposits. The deep-source elements in various ore clusters of the middle and lower Yangtze River Metallogenic Belt are inferred to have a certain degree of homogeneity.
3. By analyzing the resistivity model and integrating it with the Bouguer gravity and aeromagnetic anomalies in the study area, we conclude that the Xiangfan-Guangji Fault is a crustal-scale fault.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/min14060558/s1>, Figure S1: Sensitivity test was conducted on the low-resistivity anomaly C1 by replacing it with a high-resistivity block (3000 Ωm) at depths greater than 50 km. The model responses were compared with the original inversion model responses; Figure S2: Comparisons of the RMS misfit between the original model and the edited models.

Author Contributions: G.Y. (Gaofeng Ye), D.X. and Y.Z. (Yiwu Zhang) inverted the data and wrote the manuscript; B.T. and G.Y. (Guolong Yan) performed the original literature reviews; B.L., J.D. and

Y.Z. (Yiming Zhang) participated in the model investigation and discussion. All authors have read and agreed to the published version of the manuscript.

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