A 3D Geological Model Constrained by Gravity and Magnetic Inversion and its Exploration Implications for the World-class Zhuxi Tungsten Deposit, South China

YAN Jiayong1,2, LÜ Qingtian1,2,*1, QI Guang1,2, FU Guangming1,2,3, ZHANG Kun1,2, LAN Xueyi4, GUO Xin5, WEI Jin5, LÜO Fan1,2,3, WANG Hao1,2 and WANG Xu1,2

1 Chinese Academy of Geological Sciences, Beijing 100037, China
2 China Deep Exploration Center, China Geological Survey & Chinese Academy of Geological Sciences, Beijing 100037, China
3 School of Geophysics and Measurement-control Technology, East China University of Technology, Nanchang 330013, China
4 Geological Exploration Technology Institute of Anhui Province, Hefei 230031, China
5 No. 912 Geological Surveying Team of Jiangxi Bureau of Geology and Mineral Exploration and Development, Yingtan, Jiangxi 335001, China

Abstract: The Zhuxi tungsten deposit in Jiangxi Province, South China, contains a total W reserve of about 2.86 Mt at an average grade of 0.54 wt% WO₃, representing the largest W deposit in the world. Numerous studies on the metallogeny of the deposit have included its timing, the ore-controlling structures and sedimentary host rocks and their implications for mineral exploration. However, the deep nappe structural style of Taqian–Fuchun metallogenic belt that hosts the W deposit, and the spatial shape and scale of deeply concealed intrusions and their sedimentary host rocks are still poorly defined, which seriously restricts the discovery of new deposits at depth and in surrounding areas of the W deposit. Modern 3D geological modeling is an important tool for the exploration of concealed orebodies, especially in brownfield environments. There are obvious density contrast and weak magnetic contrast in the ore-controlling strata and granite at the periphery of the deposit, which lays a physical foundation for solving the 3D spatial problems of the ore-controlling geological body in the deep part of the study area through gravity and magnetic modeling. Gravity data (1:50000) and aeromagnetic data (1:50000) from the latest geophysical surveys of 2016–2018 have been used, firstly, to carry out a potential field separation and WANG Xu

© 2020 Geological Society of China

1 Introduction

The recent discovery of the Zhuxi tungsten deposit (ZTD) in Jiangxi Province was a major exploration success because it represents the world’s largest tungsten (W) deposit. Located in the Taqian–Fuchun metallogenic belt in the Leping and Wuyuan sub-provinces, previous studies on the regional geological survey and mineral investigation had discovered the basic structural pattern of the study area, and discussed the diagenetic and metallogenic mechanism and evolutionary law of the magmatic rocks exposed in the area; the ore-controlling structure, ore-bearing horizon and ore-prospecting patterns of various minerals in the area were also studied (Ouyang et al., 2019). The discovery of the Zhuxi super large-scale W deposit with a resource of 3.44 Mt W and an average grade of 0.54% WO₃ shows that the Taqian–Fuchun metallogenic belt has great greenfields exploration potential. Tracing the deep extension of the metallogenic belt and finding new metallogenic space in the deep are the directions to achieve breakthroughs in deep prospecting in the future (Wang X et al., 2014). In recent
years, with further exploration of the ZTD, the boreholes have gradually been concentrated and the recognition degree gradually increased. However, in terms of the exploration work around the deposit, the boreholes are still few and scattered, and the large-scale, i.e., 1:50,000, geophysical survey is insufficient. The ore-forming intrusions and ore-controlling strata in this area are covered by Neoproterozoic strata with multi-stage nappe structure. We could infer the deep structure from the surface geology but with a high degree of uncertainty, which restricts our understanding of the deep geological structure, and thus also restricts the discovery of new deposits.

Three-dimensional (3D) geological modeling is a technique of integrated information geological interpretation that uses a variety of geophysical, borehole, geochemical, and other comprehensive information, through inversion technology and 3D visualization technology, to obtain a certain depth of underground structure, intrusions, strata and fault spatial shape (Joly et al., 2015). In recent years, 3D geological modeling has become an important tool of exploration for deep and concealed orebodies. It can be used to trace the deep extension of a known ore belt, or to judge the features of important ore-forming anomalies, so as to realize deep ore-body location prediction (Chen, 2014). The traditional 3D geological modeling is mainly based on borehole data and experience of and interpretation by geologists. On the premise of densely placed boreholes, such as the deposit under consideration, the established model is relatively reliable, and can objectively reflect the underground situation and provide information for mineral exploitation. However, at the stage of prospecting and exploration, there are few and scattered or even no boreholes, so it is impossible to use them to build accurate models. If only the surface geological map is relied upon to infer its deep extension, in the established 3D geological model, the geological units are mostly in the form of “straight up and straight down”, and these geological units distribution in the deep cannot verify its reliability, which restricts the correct understanding of the deep geological structure (Chen and Yan, 2014). In order to overcome the shortcomings of conventional geological modeling, gravity and magnetic inversion were introduced into 3D geological modeling. Through the comparison of gravity and magnetic response of the geological model with actual measured anomalies, the shape of the model is modified until it fits to the acceptable range of accuracy, thus greatly improving the reliability of the modeling. For example, the modeling of gravity and magnetic 3D inversion in the Shizishan Copper deposit (Tongling), the Nihe iron deposit (Luzong), the Jiurui ore concentration area and other areas in the metallogenic belt in the middle and lower reaches of the Yangtze River (Lü et al., 2012; Qi et al., 2012; Deng et al., 2013) realize 3D visualization display of a series of sections and blocks by using software platforms such as Modelvision, EncomPA, thus greatly improving the reliability of the 3D geological model, which is one of the effective methods for deep mineral resource prediction.

The clear density differences and weak magnetic susceptibility differences in the ore-controlling strata and the granite in the periphery of the ZTD provide a physical foundation for solving the 3D spatial problems of the ore-controlling geological body in the deep part of the study area through gravity and magnetic modeling. In this study, gravity data (1:50,000) and aeromagnetic data (1:50,000) were obtained through the latest geophysical survey. Under the constraints of surface geology and borehole data, 18 sections were examined for human–computer interactive gravity and magnetic inversion. Through these sections, we established a new 3D geological model of the ZTD and its periphery, as well as the spatial shape of the intrusions and the strata with a depth of 5-km underground; the “transparency” for the main ore-controlling bodies is investigated for the first time. Based on the analysis of the 3D model and geological information, we offer a prediction of five new prospecting targets surrounding the ZTD.

2 Geological Settings

The ZTD is located in the northeast of Jiangxi Province, southern China, and, tectonically, in the eastern part of the Qinhang junction belt where the Yangtze Block (YB) and the Cathaysia Block (CB) are connected. The Qinhang junction belt is not only the boundary of the YB and CB but also the most important structural, magnetic, and metallogenic belt in South China (Zhao et al., 2018). This metallogenic belt extends from Qinzhou Bay, Guangxi Province, in the southwest, to the eastern Hunan Province and middle of Jiangxi Province, to Hangzhou Bay, Zhejiang Province, with a total length of nearly 2000 km (Shu et al., 2008).

Mineral resources, such as copper, gold, tin, tungsten, lead, iron and others, are very abundant in the metallogenic belt, with great opportunities of prospecting, making it the most important non-ferrous metal production area in China (Yan et al., 2019). Northeastern Jiangxi Province is an important part of the Qinhang metallogenic belt and also a well-known mineral concentration area in China (Fig. 1). Here the rich mineral resources are mainly W, Cu, Au, Zn, Ag, Mn, Ta, and Nb, including the Dexing porphyry copper deposit, Yinshan lead–zinc deposit, Jinshan gold deposit, Songshugang antalum–niobium deposit, Lehua manganese deposit, and so on (Wang et al., 2018). In recent years, with the development of regional mineral exploration, the super large-scale ZTD deposit was found. The rich mineral resources make this area a ‘hot spot’ for the study of geology and mineral resources (Chen et al., 2014).

The NE-trending Taqian–Fuchun nappe belt controls the formation and distribution of W and Cu polymetallic deposits in the study area. The ZTD is located in the middle of the nappe structural belt. The geochemical-element background values of Cu, W, Mo, Pb and Zn in the Upper Carboniferous Huanglong and Chuanshan formations and the Permian Maokou Formation (Fm.) are all high, and these are the main ore-bearing horizons of W and Cu polymetallic deposits (Wei et al., 2019). There are several ca. 146–149 Ma granitic intrusions of biotite granite, granitic porphyry, granodiorite, and monzonite
intruding the Carboniferous–Permian Huanglong and Chuanshan Formations (Su, 2014; Wang X G et al., 2014; Hu, 2015; Chen et al., 2015).

The mineralization in the ZTD is mainly hosted by skarn developed in carbonate rocks of the Carboniferous Chuanshan and Huanglong formations, which are in structural contact with the Neoproterozoic Shuangqiaoshan Group (Gp) consisting of phyllite and sandy phyllite (Yuan et al., 2019). The skarn is not limited to the contact zone between carbonates and granite intrusion, but rather extends along the carbonate strata >1 km away from the intrusion, and is surrounded by a marble zone. Small bodies of granite, likely branches of an intrusion, truncate the boundary between the Neoproterozoic and overlying Carboniferous rocks and extend into the latter. Part of the granite has been altered to greisen. The W orebodies mostly follow the skarn, and minor mineralization also occurs in the greisen and in the...
phyllite of the Shuangqiaoshan Gp. The Cu mineralization is also mainly developed within the skarn, overprinting the W orebodies, and locally extends into the granite. The primary ore minerals are mainly scheelite, chalcopyrite, pyrrhotine, sphalerite and galena, and the gangue minerals include garnet, diopside, actinolite, epidote, calcite and fluorite.

3 3D Geological Model Construction

3.1 Methodology

The dispersion inversion modeling method was used in this study. The 2.5D human–computer interactive gravity and magnetic inversion were carried out for each section, 18 in all, in the study area, and then all sections were coordinated to calculate the fitting misfit between gravity and magnetic response and the anomalies of all sections. If the fitting misfit did not meet the accuracy requirements, we modified the shape of geological model units in sections until the necessary requirements are achieved. Finally, all sections were imported into a 3D modeling software to build a 3D solid model. This method makes full use of physical property data and borehole geological information. The modeling process is shown in Fig. 2, including mainly modeling area definition, prior geological information processing, 2D geological model construction, 2.5D/3D inversion simulation, visualization and interpretation, and other steps (cf. Lü et al., 2012).

Modeling area definition: according to the research objectives, the modeling range and depth were first determined, and then the spacing of the 2D section was determined. Generally, the spacing is the same as that of the exploration section in the modeling area.

A priori geological information and processing mainly includes: simplification of the surface lithologic or geological unit, collection of borehole and chronological data, measurement of rock physical properties, analysis of the corresponding relationship between lithology and physical properties, data preprocessing, such as editing, gridding, filtering, and local field separation, etc., and seismic section interpretation. It is particularly important to simplify the lithologic units in the areas with complex structural geology and lithologic changes, as this can reduce the difficulty of inversion simulation. The borehole information provides the boundary depth of the main stratigraphic units at depth, which is generally used as an important constraint on gravity and magnetic inversion and remains unchanged. The separation of the regional field and local anomaly is very important. The separated local anomaly is a basis to consider whether the model is reasonable or not.

2D geological model construction: according to the section spacing determined in step one, based on the analysis of existing geological and borehole data, all 2D geological sections in the modeling area were inferred and drawn successively. Each section consists of several closely related model bodies (geological bodies), which roughly reflect the understanding of the spatial distribution of strata, structures, intrusions and ore bodies in the area where the section passes. The understanding of geologists who are familiar with the mining area and regional geology is very important in the creation of this 2D geological section. The subsequent inversion simulation is actually the revision and improvement of the geological model.

2.5D/3D inversion simulation mainly includes 2.5D and 3D gravity inversion simulation. The initial model of 2.5D simulation comes from the 2D geological model in step 3. Each model body is assumed to be long enough along the strike, with the section a polyhedron of any shape, and then the approximate conditions of 2.5D

![Fig. 2. Workflow of 3D geological modelling constrained by gravity and magnetic inversion (modified after Lü et al., 2012).](image-url)
Gravity and magnetic anomaly calculation are achieved. Then, each model body is given an initial density and magnetization intensity, and the model based on the 2D section is modified by human–computer interaction, i.e., ‘trial and error’, until a reasonable geological model and satisfactory data fitting are achieved (Li and Oldenburg, 1996, 1998). The modification range of the physical property and spatial shape of the model body is determined by physical property data and geological rationality. The gravity simulation of all 2D sections in the modeling area is completed according to the above method, and then the model strike length of each 2D section is shortened to the section spacing, and the 2.5D model is transferred into the 3D model according to the spatial order of the section. Finally, the theoretical anomalies of the 3D model are calculated and compared with the actual anomalies, and, where the fitting error is large, we return to the 2D section for modification. At this time, although the model is modified in the 2D section, the calculated anomalies are the anomalies of all 3D models and so, it is actually a 3D inversion progress. All the places with large fitting errors are modified until satisfactory results are obtained. In the whole simulation process, the corresponding relationship between physical properties and lithology remains in an unchanged range.

**Visualization and interpretation is the last step.** The 3D model is output to the 3D visualization platform for spatial analysis. If regional scale 3D modeling is desired, then deep metalliclogenic information can be extracted and combined with the metallogenic model to initiate deep metalliclogenic predictions. If we wish 3D modeling of a deposit scale, this can be analyzed comprehensively on the spatial relationship of ore-controlling strata, ore body, and intrusions, to establish a metallogenic model, calculate reserves, design mines, and predict ore bodies at depth or on flanks, and so on.

### 3.2 Potential field data

#### 3.2.1 Gravity data

We used a surveying grid with a line spacing of 500 m and point spacing of 250 m (1:50,000), with a CG-5 gravimeter gravity acquisition instrument and a Trimble R8 dual frequency differential GPS positioning instrument. In an area of altered artificial terrain, a multi-rotor unmanned aerial vehicle was used to measure the actual terrain, combined with collected high-precision terrain data, and then terrain correction was carried out to improve the accuracy of terrain correction in the near zone. Based on the analysis of the correlation between the Bouguer gravity anomaly value and the topography, the density value of 2.60 g/cm³, which is the least affected value by the elevation change (uncorrelated with terrain), was selected as the density for stone slab correction.

The Bouguer gravity anomaly (Fig. 3b) covering the ZTD and its periphery was obtained by topographic correction, stone slab correction, and height correction. The total accuracy of the Bouguer gravity anomaly is ±0.091×10⁻³ m/s². The gravity anomaly shows a pattern of high gravity in the southwest and low gravity in the northeast and gradually then it decreases from the southwest to the northeast in a bench style, with the northeast trend of the anomaly. Three gravity low anomaly areas in the northeast of the study area, i.e., Dayuan village–Chen village, Ehu, and Zhushan, reflect the distribution range of any large-scale low-density concealed intrusions. There are also the three large-scale concealed intrusions that divide the NE-trending gravity anomaly of the study area into two, i.e., the southwest high gravity and northeast low gravity blocks.

The gravity anomaly is a comprehensive reflection of the underground physical heterogeneity. It is necessary to separate the regional field from the background field, and extract the gravity anomaly corresponding to the depth range of 3D modeling. In this paper, four potential field separation methods, i.e. upward continuation, moving average, matched wave filtering, and wavelet transform, were used to separate the gravity field. The frequency of the regional field is different from that of the shallow field. The matched wave filtering method can separate the potential field by extracting the fields with different frequency components. The ZTD is a nappe structure and the density difference between the upper and lower wallrocks is obvious (Guo et al., 2020). The density difference between the large and small buried depth intrusions and the surrounding intrusions is also obvious, and the whole is a double-layer density structure. The matching wave filtering method has a good effect on the separation of the vertical superposition field source with large buried depth and difference in scale, which just meets the goal of differentiating ore-forming intrusions and surrounding rock (Fig. 3c). Analytic continuation is to calculate the value of the potential field on one plane and another plane according to the value of the potential field on the other plane. As shown in Fig. 3d, the analytical continuation method can be used to better distinguish low-density intrusions, low-density Upper Paleozoic, and high-density Neoproterozoic in this area, which is more suitable to decompose the abnormal body in the horizontal direction, but it is not clear for internal local anomalies. The moving average method takes the average value of the data in the window with the regional field value at the center. The effect of separating the anomalies depends on the size of the moving average window, which cannot always reflect well the trend in a large range. As shown in Fig. 3e, the amplitude change of the remaining anomalies calculated by the sliding average method is not obvious in the Ehu intrusions (northeast corner of Fig. 3a). Wavelet transform can reflect well the shape and trend of the strip anomaly, which can be used as the basis for selecting local anomalies with large area and simple shape, but it cannot clearly reflect the details of secondary local anomaly (Fig. 3f). By comparison, it was considered that the local gravity anomaly map of the gravity Bouguer anomaly (1:50,000) after matched wave filtering reflects more detailed gravity anomaly characteristics of the NE-trending structure and concealed shape of intrusions. Therefore, the residual anomaly extracted by this method is used as the input data of gravity interactive inversion.

#### 3.2.2 Magnetic data

The aeromagnetic data (1:50,000) was provided by the Aerial Geophysical Remote Sensing Center of China.
Fig. 3. Comparison of residual gravity anomaly by different methods of ZDT and its periphery.
(a) Geological map; (b) Bouguer gravity anomaly; (c) residual gravity anomaly obtained by the 4.75km × 4.75km window moving average as the regional field; (d) first order approximation of first order details of wavelet transform; (e) residual anomaly of matched wave filtering; (f) remaining anomalies calculated from the 2-km extension as the regional field.
Geological Survey with a grid spacing of 500m × 250 m. Reduction-to-the-pole (RTP) of magnetic anomalies has played a key role in their interpretation, and so, here, we did an RTP filter with magnetic inclination 42.63°, declination 3.53°, and the RTP aeromagnetic shown in Fig. 4b.

As with the gravity anomaly, the magnetic anomaly is also the underground comprehensive response of the magnetic body at different depths. This anomaly not only has deep and regional magnetic body information, but also shallow and local magnetic body information. The high value of magnetic anomalies is distributed like a 'string of beads' and this cannot reflect the shape of the magnetic anomaly of the ore body, and thus anomaly separation is needed. We chose the methods of upward continuation, sliding average, matched wave filtering, and other potential field separation. From the polarization anomaly and residual abnormal maps, it can be seen that the magnetic anomaly in this area is relatively disordered. The main reason is that the amplitude of the aeromagnetic data in this area is small, and the variation range of magnetic amplitude in the range of 2700 km² is only ~11.8 to 2 nT. Comparing different methods of anomaly separation (Fig. 4), they all removed the background field of the measurement area, retained the local field information, and the separation results are well controlled. Based on this, it can be inferred that the characteristics of the aeromagnetic field in the survey area, the positions of the remaining zero contours of the anomalies obtained by the four methods basically coincide; that is, there is no major change in the position of the boundary of the reflected anomaly. Among them, the shapes of the anomalies obtained by moving average, matching wave filter and upward continuation methods are similar. The local anomalies are prominent and the details are obvious (Figs.4c-f), the details of the local anomalies obtained by moving average method are the most abundant, followed by those of matching wave filter. The local anomalies obtained by the continuation method are relatively low in amplitude and more prominent in the low value anomaly area due to the large field value obtained by this method.

Thus, these three methods are more conducive to the fine analysis of geological conditions. Wavelet transform has a better response to large-scale and simple local anomalies, which makes it easy to identify and analyze the shape and trend of the overall anomaly. Because the small amplitude of the aeromagnetic anomaly and most of the detailed changes are beyond the modeling accuracy, according to comprehensive factors such as modeling scope, geological unit division and modeling accuracy, combined with the regional geological data, it was considered that the local anomaly data is more conducive to two-dimensional analysis and interpretation. The aeromagnetic pole anomaly is more suitable for inversion modeling work, so this inversion modeling work will use the RTP aeromagnetic anomaly as the basic inversion data, and then the inversion process is mainly gravity data, supplemented by aeromagnetic data.

3.3 Physical properties and 3D model units

The density and magnetic susceptibility of borehole and surface samples (Tables 1–2) suggest that the density and other characteristics of rock physical properties change with the depth. It is very important for comprehensive research to analyze the change rule of the main lithology density with the burial depth. In the surface measurement results, the basic law of density change is as follows: granodiorite porphyry and monzogranite ≈ quartz sandstone and siliceous rock (P2-3) < granite and granite porphyry ≈ siltstone (T1-P1) < metatuffaceous fine sandstone (Pt3) < limestone < metamorphic debris greywacke (Pt1). In the borehole core results, the correlation is adjusted as follows: siltstone (T1-P1) ≈ quartz sandstone and siliceous rock (P2-3) < granite < limestone < metamorphic debris greywacke (Pt1). The physical properties of the rocks (ores) in the study area have the following characteristics using comprehensive statistics (Tables 1–2):

1. granite and granite porphyry are always characterized by low magnetism and low density;
2. the densities of granodiorite porphyry, monzogranite and sandstone are similar, but they can be distinguished by

Table 1 Stratigraphy and intrusions with average density and magnetic susceptibility surface of samples from the study area

<table>
<thead>
<tr>
<th>Strata and intrusions</th>
<th>Code</th>
<th>Lithology</th>
<th>Density (10^3 kg/m³)</th>
<th>Susceptibility (10^5 SI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary</td>
<td>Q</td>
<td>Sand, clay, gravel</td>
<td>1.80</td>
<td>0</td>
</tr>
<tr>
<td>Cretaceous and Upper Triassic</td>
<td>K-T1</td>
<td>Argillaceous siltstone and conglomerate</td>
<td>2.56</td>
<td>13</td>
</tr>
<tr>
<td>Lower Triassic and Upper Permian</td>
<td>T1-P1</td>
<td>Microcrystalline limestone and dolomite</td>
<td>2.67</td>
<td>0</td>
</tr>
<tr>
<td>Upper and Middle Permian</td>
<td>P2-3</td>
<td>Silicous rock and fine sandstone</td>
<td>2.47</td>
<td>9</td>
</tr>
<tr>
<td>Middle Permaan and Upper Carboniferous</td>
<td>P2-3</td>
<td>Biotite granite</td>
<td>2.67</td>
<td>0</td>
</tr>
<tr>
<td>Lower Carboniferous and Devonian</td>
<td>P1-2</td>
<td>Quartz conglomerate, gravel bearing quartz sandstone</td>
<td>2.59</td>
<td>15</td>
</tr>
<tr>
<td>Lower Chengyuan Fm. and Niutouling Fm.</td>
<td>P1t(1-3), P1tp</td>
<td>Metamorphic debris greywacke and slate</td>
<td>2.70</td>
<td>26</td>
</tr>
<tr>
<td>Anlelin Fm., Jilan Fm. and Chengyuan Fm.</td>
<td>P1tr, P1tl, P1tc</td>
<td>Metatuffaceous fine sandstone and metasedimentary tuff</td>
<td>2.61</td>
<td>23</td>
</tr>
<tr>
<td>Biotite granite</td>
<td>γ</td>
<td>Biotite granite</td>
<td>2.55</td>
<td>0</td>
</tr>
<tr>
<td>Fine-grained granite</td>
<td>γ</td>
<td>Yellowish brown fine grained granite</td>
<td>2.57</td>
<td>0</td>
</tr>
<tr>
<td>Biotite Biotitemonzonitic granite</td>
<td>K1γβ</td>
<td>Biotitemonzonitic granite</td>
<td>2.52</td>
<td>120</td>
</tr>
<tr>
<td>Zhanjianguan granodiorite porphyry</td>
<td>Zγηγπ</td>
<td>Granodiorite porphyry</td>
<td>2.43</td>
<td>115</td>
</tr>
<tr>
<td>Yanguaogang granodiorite porphyry</td>
<td>Yγηη</td>
<td>Biotitegranodiorite porphyry</td>
<td>2.59</td>
<td>361</td>
</tr>
<tr>
<td>Quartz albitic porphyry</td>
<td>ληη</td>
<td>Quartz albitic porphyry</td>
<td>2.59</td>
<td>7</td>
</tr>
<tr>
<td>Northwest granite porphyry</td>
<td>γp</td>
<td>Granite porphyry</td>
<td>2.62</td>
<td>8</td>
</tr>
<tr>
<td>Zhenzhushan granite porphyry</td>
<td>γp</td>
<td>Granite porphyry</td>
<td>2.53</td>
<td>3</td>
</tr>
</tbody>
</table>

Abbreviation: Fm. = Formation
Fig. 4. Comparison of residual anomalies obtained by different methods of ZDT and its periphery.
(a) Geological map; (b) aeromagnetic pole anomaly; (c) residual anomaly obtained by window sliding average (8.75 km × 8.75 km) as regional field; (d) first order approximation of first order details of wavelet transform; (e) residual anomaly of matched wave filter; (f) remaining anomalies calculated from the 2-km extension.
magnetism;
(3) there is a density difference of $0.03 \times 10^3 \text{ kg/m}^3$ between the sandstone of the Middle and Upper Permian and the limestone of the underlying Middle Permian and Upper Carboniferous. There is a density difference of $0.03 \sim 0.05 \times 10^3 \text{ kg/m}^2$ between the limestone of the Middle Permian and Upper Carboniferous and the metamorphic rock of the underlying Neoproterozoic. Therefore, the widely distributed Upper Paleozoic belt structure in the area is easy to distinguish by gravity anomaly or density structure.

The stratigraphic units in the study area in descending order are mainly Quaternary, Devonian, Carboniferous, Permian, Triassic, Jurassic, and Mesoproterozoic shallow metamorphic strata. The intrusions are mainly acid rock masses, mainly of granite and monzogranite. Based on the comprehensive analysis of geological and physical data, and considering the scale and modeling accuracy of the geological units, 12 types of modeling units were finally subdivided (Table 3). The reference thickness and display color of each modeling unit are given in Table 3.

3.4 2.5D/3D gravity and magnetic forward modeling

**First step: Initial geological model build.** Based on the revision of the geological map (1:50,000), the characteristics of lithology, composition, texture and structure, sedimentary characteristics, basic sequence, and thickness, the lateral changes of important strata in the study area are identified through targeted measured geological sections and field geological survey. It is considered that a thrust nappe structure is the main structural framework of the study area, as noted above. The basic parameters of the model are as follows: the dip angle is 0°, the azimuth angle is 45°NW, the thickness of the model is 12 km, and the depth range is 5 km from the surface to the underground. The nappe structure is involved in the Neoproterozoic basement strata, and then spreads upward into the Carboniferous to Jurassic strata and even affects Cretaceous strata. The structure is mainly composed of a series of rock sheets or nappes that are stacked in imbrication from northwest to southeast, and thrust faults that are distributed in parallel in a general northeasterly direction. There is a multi-layer stacking structure in the vertical direction and an imbrication arrangement in the horizontal direction. Therefore, combined with the surface geological map and borehole data of the study area, the stratigraphic units were systematically compiled, the stratigraphic interface was inferred, the thickness of strata, and the thickness and spatial position of the rock and ore bodies was identified. 18 geological sections were set up as the initial geological model sections of the 3D human–computer interactive gravity and magnetic inversion (Fig. 5).

**Second step: 2.5D interactive gravity and magnetic inversion.** The Encom ModelVision (MV) software was used for human–computer interactive gravity and magnetic inversion. The software uses the dispersion modeling method. Different model bodies are used to represent different geological units. Each model body has a fixed density value range. For a geological unit with large physical property differences in different regions, it can be divided into multiple connected model bodies and given corresponding physical property values, respectively. Taking line 0 as an example, the 2.5D geological model was established based on the drawn 2D geological section, as noted above. The basic parameters of the model are as follows: the dip angle is 0°, the azimuth angle is 45°NW, the thickness of the model is 12 km, the background density is 2.60 g/cm³, and the depth range is 5 km from the surface to the underground. In order to eliminate the influence of the boundary, the model

<table>
<thead>
<tr>
<th>Strata and intrusions</th>
<th>Depth (m)</th>
<th>Code</th>
<th>Lithology</th>
<th>Density ($10^3 \text{ kg/m}^3$)</th>
<th>Susceptibility ($10^{-5} \text{ SI}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cretaceous and Upper Triassic</td>
<td>80–120</td>
<td>K-T</td>
<td>Argillaceous siltstone and conglomerate</td>
<td>2.69</td>
<td>3</td>
</tr>
<tr>
<td>Lower Triassic and Upper Permian</td>
<td>30–740</td>
<td>T1-T3</td>
<td>Microcrystalline limestone and dolomite</td>
<td>2.72</td>
<td>0</td>
</tr>
<tr>
<td>Upper and Middle Permian</td>
<td>820–870</td>
<td>P2-C2</td>
<td>Siliceous rock and fine sandstone</td>
<td>2.70</td>
<td>2</td>
</tr>
<tr>
<td>Middle Permian and Upper Carboniferous</td>
<td>15–1570</td>
<td>Pt1</td>
<td>Bioclastic limestone and dolomite</td>
<td>2.72</td>
<td>0</td>
</tr>
<tr>
<td>Neoproterozoic (shallow)</td>
<td>5–300</td>
<td>Pt1</td>
<td>Metasiltstone, slate, phyllite</td>
<td>2.73</td>
<td>3</td>
</tr>
<tr>
<td>Neoproterozoic (shallow alteration)</td>
<td>50–300</td>
<td>Pt1</td>
<td>Metasiltstone, slate, phyllite</td>
<td>2.75</td>
<td>6</td>
</tr>
<tr>
<td>Neoproterozoic (deep)</td>
<td>1800–1900</td>
<td>Pt1</td>
<td>Metasiltstone, slate, phyllite</td>
<td>2.77</td>
<td>2</td>
</tr>
<tr>
<td>Biotite granite</td>
<td>500–600</td>
<td>γ</td>
<td>Biotite granite</td>
<td>2.60</td>
<td>0</td>
</tr>
<tr>
<td>Biotite granite</td>
<td>700–2000</td>
<td>γ</td>
<td>Biotite granite</td>
<td>2.70</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
<th>Reference thickness</th>
<th>Color</th>
<th>Code</th>
<th>Name</th>
<th>Reference thickness</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>Permian</td>
<td>&gt;435m</td>
<td></td>
<td>C-D</td>
<td>Devonian to Carboniferous</td>
<td>&gt;336m</td>
<td></td>
</tr>
<tr>
<td>C-D</td>
<td>Devonian to Carboniferous</td>
<td>&gt;336m</td>
<td></td>
<td>P_C</td>
<td>Chengyu Formation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P_{TS}</td>
<td>Niutouling Formation</td>
<td>2200–5400m</td>
<td></td>
<td>P_{TS}</td>
<td>Anline Formation</td>
<td>&gt;2000m</td>
<td></td>
</tr>
<tr>
<td>P_{TJ}</td>
<td>Jilin Formation</td>
<td>2318–2870m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The body is extended 10 km to the southeast and the northwest, as shown in Fig. 6.

Then, as recorded in Table 1, each model body was given corresponding density parameters. For the same strata or intrusions and orebodies with a large density difference, the model body was divided into several parts, and the model was established separately to make the density change closer to the actual situation and to improve the accuracy of inversion model. The forward calculation was carried out and the model was modified repeatedly until the curve fitting degree was satisfied. The modification range of the physical property and spatial shape of the model body is determined by physical property data and geological rationality. The final fitting situation of the 2.5D model is shown in Fig. 7.

**Third step: 3D inversion simulation.** The strike length of the model bodies of all 18 sections was adjusted to the line distance (5 km), and all 2.5D models were integrated into 3D model bodies according to the spatial location of the sections (Fig. 8). At this time, the model was integrated into the 3D environment to calculate the theoretical anomalies of the 3D model, and compared with the actual anomalies, where the fitting error is large, returning to the 2D section for modification. Although the
Fig. 6. Schematic diagram of 2.5D inversion model (L0 as an example).

Fig. 7. Line 0 as an example showing the 2.5D joint gravity and magnetic interactive inversion (Geological model legend as Table 3; for location see Fig.1).

Fig. 8. 3D solid model constructed gravity and magnetic interactive inversion from 18 sections (Topo is geological map draped on DEM).
model is modified in the 2D section, the calculated exception is that of all 3D models, i.e., the modification of any point will affect the theoretical value of the model at any point in the whole region. All parts with a large fitting error were modified until the fitting errors met the modeling requirements.

In the whole simulation process, the corresponding relationship between physical properties and geological units remains unchanged. The final 3D model forward calculation anomalies, measured gravity and magnetic anomalies and their fitting errors are shown in Fig. 9. Generally, the forward modeling response of the model is basically consistent with the measured gravity and aeromagnetic anomalies. The main anomaly shapes and amplitudes are very similar, with only some local differences in detail. The root mean square error (RMSE) for the fitting of the input gravity anomaly is \(0.64399 \times 10^{-5}\) m/s and that for the magnetic anomaly is 2.74 nT. These 2 RMSEs are less than the survey errors meaning that the 3D geological model we constructed has high reliability.

3.5 3D geological model of the Zhuxi tungsten deposit

The model was further optimized to promote its efficiency in spatial analysis and 3-D view. Based on the result section of the 3D inversion, the GeoModeller software was used to import the cross-inversion section, and the 3D geological model of the study area was established by the interpolation method (Fig.10). The model directly depicts the 3D spatial morphology and interrelationship of the ZTD and its adjacent strata, intrusions and other geological bodies.

According to the results of 3D inversion modeling, the distribution of the geological units in the study area is relatively complex with a large fold. The Neoproterozoic Qingbaikou Fm. is widespread in the area, and the rest of the formation is relatively small and many regional strata have an unconformable contact. The Cretaceous strata are mainly distributed in the northwest corner of the study area (Fig. 11a). From the 3D model, it can be seen these strata unconformably cover the Neoproterozoic strata, with a relatively complex shape. The main body is located at the western boundary, distributed in the northeast direction, and then they gradually disappear. The thickness of the Cretaceous strata is mainly between 500 m and 1000 m.

The Jurassic strata are located in the southwest of the study area (Fig. 11b), and distributed along the northeast direction. The main part is divided into two nearly parallel strips. The strata are complex but the dip is relatively gentle. The boundary is mainly controlled by the fault structure, with thicknesses mainly between 500 m and 1500 m, and the maximum depth of the downward extension is about 1800 m.

The Triassic is located in the middle of the study area (Fig. 11c), distributed along the northeast direction, mainly in three strips. The thickness of the northern strip is relatively small, mainly concentrated in 100 m to 500 m, inclined to the northwest, with a gentle dip angle, mostly between 10° and 45°. There are obvious folds in the middle of the strip, and the surface is mostly covered by the Quaternary. The strata in the middle part of the belt are discontinuous, with little thickness and scattered distribution. The southern strip has a steep dip angle and extends to a maximum depth of about 4000 m. The two sides of the strata are controlled by faults. In addition, the surface is also completely covered with Quaternary.

In the Paleozoic, the Permian is distributed in a NE-trending belt, overlain by Triassic strata (Fig. 11d). Generally, it is a monoclinal structure inclined to the NW, and the stratal thickness is generally low, mainly between 100 m and 500 m. The Carboniferous and Devonian rocks (Fig. 11e) are distributed in NE-trending belts, four in total. They are the same as the Permian and Triassic with the dip angle of the strata on the north side relatively low. The strata in the middle and southern belts are relatively steeply dipping, and the boundary position is controlled by NE-trending faults.

The Neoproterozoic Qingbaikou system is the most exposed and widely distributed, mainly including the Anlelin Formation (Fig. 11f) and the Jilin Formation, Shuangqiaoshan Gp, and the Chengyuan Fm. and Niutouling Fm., Wannian Gp. The Jilin Fm. is relatively thick (Fig. 11g), and in the northwest corner of the area is relatively thin, thickening to the southeast, with a thickness of 1000 m to 5000 m. The strata of the Chengyuan Fm. and Niutouling Fm. are most widely distributed in the southeast of the study area, with the Chengyuan Fm. (Fig. 11h) overlying in conformable contact with the Niutouling Fm. (Fig. 11i), in complex shapes and varying greatly in thickness. The strata in the southeast of the study area are the thickest, divided into several belts because of the influence of faults, and spread in the northeast direction.

From the 3D model, it can be seen that there is a large area of acid intrusions (Fig. 11j) at depth in the study area. The main petlogies are granite (red) and monzogranite (pink); the granite is widely distributed, with complex morphology and large-scale changes. Also, it can be seen that the rock body is mainly intruded into volcanic rock, generally distributed in the northeast direction, mostly in the form of rock bed and branch. The intrusions are mainly located in the deep fault structure, indicating that they are controlled by deeply hidden faults. In addition, the 3D model shows that the main body of the granite has five parts, and the northwestern corner intrusion is spherical and extends outward. The middle of the intrusions is generally NE-trending, with obvious NW–SE dislocation at line 10. The intrusions in the southeast of the study area are diamond-shaped, with a certain burial depth. The intrusions in the southeast, middle and northeast of the study area have a trend to joined at depth. The monzonic granite is mainly located in the northeast corner of the study area, extending outside of the area, with complex shapes. Part of the area is stepped, concave to the southwest, and the downward extension depth of the intrusions is large. Other rocks are scattered in the study area, with relatively small volumes.

4 Exploration Implications

According the analysis of geophysical, geochemical and 3D geological model characteristics of the ZTD, first we
Fig. 9. Comparison between the (a) observed and (b) calculated gravity responses from the 3D forward modeling and (d) observed and (e) calculated magnetic responses from 3D forward modeling as shown in Fig. 8. Data differences between (c) observed and (f) calculated 3D gravity and magnetic responses, respectively. A general agreement of the major gravity and magnetic anomalies can be seen between the observed and calculated 3D responses.
summed up three principles for prospecting and prediction in the area and then are able to propose five new exploration targets based on our 3D geological model.

4.1 Geophysical, geochemical characteristics of the Zhuxi tungsten deposit and prospecting principles

Characteristics of gravity anomaly: on the Bouguer gravity anomaly map, the deposit is located in the gradient zone of transition from high gravity in the NE trend to low gravity. The extreme value of the gradient zone is the boundary between Permian sandstone and Carboniferous limestone. The low-density intrusions and low-density Permian together cause the low gravity in the NE trend. In the northwest of the mine area, the middle of the low gravity area is cut off because of the northwest-trending limestone alteration and the increase of density value. This feature is clearly seen in the gravity section (Fig. 12). In the south of the deposit, a saddle-shaped gravity with NE strike is formed, which is caused by concealed intrusions. In the depression zone with high gravity in the saddle shape, there is local high gravity in the middle of low gravity, which can be used as a sign to search for ore-induced anomalies.

Characteristics of the magnetic anomaly: according to the measured geomagnetic data (Fig. 12), the overall amplitude of the magnetic anomaly along the survey line has little change, only a local high magnetic anomaly occurring at 3 km to 4 km, which is a high-density high-magnetic intrusion in the intrusive metamorphic rock. The rock body closely related to the formation of ZTD is not very magnetic.

Geochemical anomalies: the stream sediment geochemical survey shows the high geochemical anomalies of the ZTD in the area. The concentration of main ore-forming elements is generally Cu 50 to 700 ppm, Pb 50 to 800 ppm, Zn 150 to 800 ppm, Mo 2 to 25 ppm, and As 50 to 500 ppm. The assemblage anomaly is a concentric ellipse or a long strip, and the concentration distribution of the three main ore-forming elements is obvious. The soil geochemical survey (1:200,000) found the anomalies of Cu, Au, Ag, Pb, Zn, Sb, As, Sn, W in the ZTD. It can be seen from Fig. 14 that the geochemical anomaly is in good agreement with the deposit and mineralization point, which is an ore-induced anomaly.

Through the analysis of the above-mentioned geophysical and geochemical prospecting indicators of typical deposits, we determine the main basis for ore prospecting prediction:

(1) low gravity and high geomagnetism are the most favorable local anomaly combination for finding large and medium-sized ore deposits. The lower gravity is mainly caused by rock mass and the Upper Paleozoic, while higher geomagnetism reflects the granodiorite closely related to mineralization. Secondly, the combination of lower gravity and lower geomagnetic anomalies near low gravity and high geomagnetism is also a favorable local abnormity combination for the exploration of ore deposits, while the physical field effect of ore (mineralized) bodies is often superimposed on the gradient belt at the upper edge of low gravity and high geomagnetism. The geophysical and geochemical anomalies with the above two kinds of combination characteristics are the preferred objects of the key geophysical and geochemical anomalies.

(2) The contact zone and its vicinity between the concealed intrusions and the late Paleozoic carbonate strata.

(3) There are geochemical ore-forming element anomalies, especially the combination anomalies with a large range, high intensity and good zoning; these are more favorable for ore-forming.

4.2 Targets prospecting

According to the analysis above, the contact zone between the intrusions and the carbonate formation is a key prospecting position, which is directly described by the 3D geological model. As shown in Fig. 13, the Carboniferous and Triassic rocks are in an imbricated structure. According to the analysis, the contact zone between the imbricated structure and the intrusions of the ZTD is a favorable location for ore body exploration. According to the 3D geological model, gravity and magnetic field characteristics, and geochemical characteristics, five prospecting targets can be predicted;
Fig. 11. 3D shape of wallrock strata and intrusions around the Zhuxi tungsten deposit and its periphery.
(a) Cretaceous; (b) Jurassic; (c) Triassic; (d) Permian; (e) Devonian–Carboniferous; (f) Chengyuan Formation; (g) Anlelin Formation; (h) Jilin Formation; (i) Niutouling Formation; (j) Intrusions.
Fig. 12. Typical joint gravity and magnetic inversion section of the Zhuxi tungsten deposit.

Fig. 13. Cartoon illustrating the evolution of the carbonate formation and intrusions around the Zhuxi tungsten deposit and its periphery.

(a) Triassic and intrusions; (b) Permian and intrusions; (c) Carboniferous and Devonian and intrusions; (d) Triassic and Devonian and intrusions.
their location is shown in Fig. 14. The selection basis and prospecting prospect of each target are as follows:

### 4.2.1 T1 Target

The T1 target is located near Jingdezhen in the modeling area (Fig. 14). The exposed strata are the Neoproterozoic Niutouling and Chengyuan formations, and a NE-trending banded granite porphyry vein that can be seen in the Ma'anling area.

According to the metallogenic model (Mao et al., 2010), the Daxing copper deposit is located in the front of the Wannian thrust nappe terrane, the composite part of the NE-trending imbricate fault and the NW-trending transverse fault on the hanging wall of the Northeast Jiangxi deep fault zone. The granodiorite porphyry intrudes into the core of the anticline, and the ore body occurs in the contact zone inside and outside the metallogenic porphyry. The T1 target is also located in the hanging wall of the imbricated fault, and concealed intrusions are developed in the fold axis (Fig. 13), and a Cu–Mo–Au point has been found in the Hujialing area. The T1 target structure is similar to the Daxing copper deposit, which is located at the edge of gravity and high magnetic anomalies. The characteristics of gravity and magnetic anomalies are similar to those of the Daxing Copper deposit. Therefore, we consider that the T1 target is a favorable area for further exploration of the Daxing copper type deposit.

### 4.2.2 T1 Target

The T2 target is located in the west direction of the ZTD (Fig. 14). The exposed strata are the Neoproterozoic Niutouling and Chengyuan formations, and lithologies comprise mainly slate, phyllite, meta-residual sandstone, and meta-siltstone. In the Ma'anling area, a NE-trending banded granite porphyry vein is exposed.

On the residual gravity anomaly map, T2 corresponds to a low gravity anomaly. The anomaly shape is elliptical, with a northeast trend (Fig. 14a). A very low value is located in the center of the ellipse, with a minimum amplitude of $-2.1 \times 10^{-5}$ m/s$^2$. On the aeromagnetic residual anomaly map, there is a NE-trending aeromagnetic positive anomaly, with two anomaly centers on both sides of Dawoli, which is a combination of lower gravity and lower magnetic anomalies. The geochemical anomaly is obvious, and is very similar to that of the Mo–W deposit in Taqian from the perspective of gravity and geomagnetic anomaly. We consider that the deep T2 target is a favorable prospect for the exploration of the skarn-type deposit, with the main target lying in the contact zone between the imbricated structure and Upper Paleozoic intrusions.

### 4.2.3 T3 Target

The T3 target outcropping strata are the Neoproterozoic Chengyuan Fm. and Carboniferous Huanglong Fm. Structurally, the target area is located in the core of the Xiajiawu–Lingang reverse anticline, where two NE-trending reverse faults are developed (Fig. 14).

The Huanglong Fm. is distributed in a synclinal shape. The low gravity strip turns at the T3 target, indicating that the trend of the Upper Paleozoic has changed here. These turning zones are the release areas of compressive stress. The T3 Target develops reverse faults, which together form a weak strata zone. Intrusions intruded upward along the fault, with developing fractures, breaking the surrounding rock, which was a favorable area for contact metasomatism. Therefore, it may be inferred that a ZTD-type skarn deposit is formed here. According to analysis of the 3D geological model, the buried depth of the top surface of the contact zone is $\sim 1000$ m.

### 4.2.4 T4 Target

The T4 target is located in the Zhenzhushan anticline in the southeast corner of the modeling area (Fig. 14). Only the northwest flank of the inversion is exposed in this area. After subsequent napping, an inversion fold with its axis inclined to the southeast was formed. The surface shows NE- and NW-trending granite porphyry walls.

It can be seen from the gravity inference map that the T4 target is shallowly buried and located in the northeast section of the Upper Paleozoic belt of the Liujiatan–Zhenzhushan area. Carboniferous strata make up the lower part of the nappe. There are two NE-trending faults on the north and south sides of the T4 target. When intrusions intruded upward along the faults on both sides, a depression was formed in the prospective area. Fractures developed, the surrounding rock broke easily and so ore fluid was often easily concentrated; rocks were fully metasomatized with favorable surrounding rock for mineralization. Besides, the surrounding rock near the thrust cover was easily broken, and the lithology difference between the upper and lower parts is large, which is also conducive to mineralization. According to the 3D model, we speculate that the buried depth of the top surface of the Carboniferous and Permian is $\sim 500$ m, with a large batholith at depth, and the shallow rock body tends to dip to the northwest. Therefore, we infer that the T4 target may form a ZTD-type skarn deposit.

### 4.2.5 T5 Target

The T5 target is located in the Longtan area in the northwest of the modeling area (Fig. 14). The Niutouling and Chengyuan formations are exposed on the surface, and located on the northwest flank of the Shantian–Huihua syncline. No intrusion is exposed on the surface and the NE Xianghu–Zhentou fault passes through here.

As shown on the gravity inference map (Fig. 14), the T5 target is located on the NE-trending fault and there are NE-trending intrusions along the fault, all of which provides an important source of ore for mineralization. As shown on the inversion section map (Fig. 7), there is Carboniferous limestone under the Shantian–Huixia syncline. The Carboniferous and Permian in the T4 target are the main ore-forming rocks. Through a NE-trending fault, there is a good contact relationship between the intrusions and the Upper Paleozoic rocks, and there are Ag, As, and B geochemical anomalies on the river sediment anomaly map (Fig. 14). According to the 3D geological model (Fig. 13), the lower part of Shantian–Huixia syncline are Carboniferous and Triassic rocks and intrusions in the upper part of the Zhushan segment nappe.
Fig. 14. Comprehensive anomalies and exploration targets around the Zhuxi tungsten deposit.
(a) Residual gravity anomaly; (b) residual aeromagnetic RTP anomaly; (c) geochemical anomaly; (d) geological interpretation based on gravity and magnetic anomalies and 3D geological model.
The shallowest burial depth of the Carboniferous top is ~425 m, the northern burial depth of the intrusions is ~500 m, and the southern burial depth is ~750 m. It was speculated that the rock body intruded upward along the fault and interpenetrated into the Triassic and Carboniferous limestone in the upper of the Zhenzhushan–Duanxin nappe. The surrounding rock near the nappe face was easily broken, and there is a large difference between the upper and lower lithology, which is also conducive to mineralization. Therefore, we can conclude that the TS target is favorable for the ZTD-type skarn.

5 Conclusions

(1) In this study of the Zhuxi tungsten deposit (ZTD), gravity data (1:50,000) and aeromagnetic data (1:50,000) were obtained by the latest geophysical survey. Based on the analysis of physical properties and lithologies, under the constraints of surface geology and borehole data, human–computer interactive gravity and magnetic inversion for 18 cross-sections were completed. Through these 18 sections, the new 3D geological model of the ZTD and its periphery was established, and the spatial shape of the intrusions and strata with a depth of 5 km underground was obtained, and the ‗transparency' of the main ore-controlling geological bodies in the ZTD and its periphery were realized.

(2) According to the integrated analysis of geophysics, geochemistry, and geology of the ZTD, the low gravity anomaly is mainly caused by intrusions and Upper Paleozoic strata, whereas the high magnetic anomaly mainly reflects granodiorite closely related to mineralization. The combination of low gravity anomaly and high magnetic anomaly might indicate the contact zone between the concealed intrusions and the Upper Paleozoic carbonate strata. If the geochemical ore-forming element anomaly is in the contact zone, then especially the combination of anomalies with a large range, high intensity, and obvious zoning is more favorable for mineralization.

(3) Based on the 3D geological model, the spatial location relationship between granodiorite and Carboniferous and Triassic strata was analyzed, and five prospecting targets were predicted in the periphery of the ZTD.

(4) Using 3D geological modeling based on the constraints of gravity and magnetic inversion can greatly reduce the multiplicity of inversions and thus improve the reliability of the model. It has proved an effective method for prospecting prediction at the ore-concentration scale.

Acknowledgements

We present this paper for the 90th birthday celebrations of Professor Chang Yinfo, in honor of his contribution to Chinese geological science promotion, especially in metallogeny, 3D geological mapping and advising Chinese geological management throughout his career. This study was jointly supported by the National Key R&D Program of China (Grant No. 2016YFC0600201), China Geological Survey project (Grant Nos. DD20190012, DD20160082) and the National Natural Science Foundation of China (Grant Nos. 92062108, 41630320, 41574133).

Manuscript received May 12, 2019 accepted Dec. 2, 2019 associate EIC: XU Jifeng edited by FEI Hongcai

References


Su, X., 2014. Geology, Geochemistry of Zhuxi tungsten deposit...


About the first author

YAN Jiayong, male, born in 1977 in Lijiang City, Yunnan Province; Ph.D.; graduated from the Institute of Geology and Geophysics, Chinese Academy of Sciences; professor of Chinese Academy of Geological Sciences. He is now interested in the study of mineral system exploration and deep earth exploration. Email: yanjy@163.com; phone: 13552350590

About the corresponding author

LU Qingtian, male, born in 1964 in Tongbai County, Henan Province; Ph.D.; graduated from China University of Geosciences, Beijing; professor of Chinese Academy of Geological Sciences. He is now interested in the study of deep earth exploration. Email: lqt@cags.ac.cn; phone: 13910406919