Inspiration of magma source and intrusion of Niukutou polymetallic ore area: evidence from audio frequency magnetotelluric (AMT)

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Abstract. Niukutou research area is located in the north slope of Qimantage mountain in the east Kunlun, which is an important part of the lead, zinc, copper and iron metallogenic belt. The regional mineralization is inseparable from Indosinian magmatism. However, the research area is covered by Quaternary stratum area and the trace of magmatic activity is difficult to find. In order to further understand the underground structure, the spatial distribution characteristics of magmatic rocks and the relationship with polymetallic mineralization of the research area, the audio-frequency magnetotelluric (AMT) survey is deployed. Through the comprehensive analysis based on the electrical structure, we found that the granites encountered in the research area are from the magma source corresponding to the deep F3 channel, the granites are occurred as the veins from multi-channels. There are no granites base in the profiles and the regional metallogeny are controlled by the magma activity and the fault F3. In geologic modeling process of groundwater system, block modeling needs to be established.

1. Introduction
Niukutou research area is located in the north slope of Qimantage mountain in the east Kunlun, and its structural position is located in the early Paleozoic magmatic arc. It belongs to the Yemaquan-Kaimuqihe Variscan lead, zinc and cobalt metallogenic sub belt (IV) of the Qimantager-Dulan Variscan iron, cobalt, copper, lead zinc and tin metallogenic belt (III), which is an is an important part of the lead, zinc, copper and iron metallogenic belt in the central part of east Kunlun [1,2,3,4] (Figure 1a). Based on the characteristics of magnetic anomalies, large-scale polymetallic deposits have been found in the adjacent area of the research area. The lead, zinc, copper and iron polymetallic deposits in the area are all related to magmatic hydrothermal activity or later transformation. In order to further understand the underground structure, the spatial distribution characteristics of magmatic rocks and the relationship with polymetallic mineralization of the research area, the audio-frequency magnetotelluric (AMT) survey is deployed and the regional magmatic source and intrusion mode are interpreted. The AMT survey arrangement are shown in Figure 1b.
2. Methods

2.1. MT Data Acquisition and Processing

5 AMT profiles accounting for 116 AMT sounding are acquired. The V8 multi-functional electrical method workstation of Phoenix geophysics is used for field observation. The offset of the AMT sites is 50m. The effective frequency range is 10000 ~ 1Hz. In the process of data processing, SSMT2000 and MTeditor software system are used to process the original time series, and high-quality apparent resistivity, impedance phase and other data are obtained. In the process of processing, robust estimation, remote reference processing, power spectrum selection and other processing methods are used to ensure the credibility of the original data.

2.2. Impedance tensor decomposition and strike analysis

Before the 2-D inversion of magnetotelluric sounding data, it is necessary to analyze the data to determine the strike of each profile. Multisite, multifrequency tensor decomposition technology [5] are used to determine the regional strike. The azimuths of the five exploration lines are all concentrated at 0° or 90°, that is to say, the direction of the electrical principal axis in the observation area is north-south or east-west. According to the results of the existing geomagnetic and aeromagnetic data, the magnetic anomalies in the work area spread in the east-west direction. The study of geological structure also shows that the NW trending fault in the working area is the most developed, and the extension scale is relatively large, which is the main large structure in the area. The electrical principal axis direction obtained by impedance tensor decomposition is consistent with the prior information.

2.3. 2D inversion

Some text. The L-curve method is used to evaluate the selection of regularization factors. The L-curve is drawn with the fitting error RMS as the vertical axis and the model roughness as the horizontal axis. The corresponding inversion model of regularization factors at the inflection point of the curve comprehensively considers the fitting degree and smoothness of the model, and corresponds to the best regularization factor \( \tau \). The data inversion of 5 profiles is evaluated respectively. Because the quality of TM mode data is better than that of TE mode data, and the apparent resistivity and the phase of TE mode are not easy to fit in the process of joint inversion, which will lead to large fitting error, so the inversion error threshold of TE mode apparent resistivity and phase position should be properly increased when the inversion parameters are set. The inversion parameters of 2D inversion are as follows:

- Inversion algorithm: nonlinear conjugate gradient inversion (NLCG)
- Inversion frequency band: 0.1Hz ~ 10000Hz
- Minimum fitting error: 1.5
- Maximum number of iterations: 200
Apparent resistivity inversion error of TE mode: 30%
TE mode phase inversion error: 5.8 °
Apparent resistivity inversion error of TM mode: 10%
TM mode phase inversion error: 2.9 °

The inversion of resistivity profile by AMT soundings is the basic map for interpretation and inference, which mainly reflects the variation of resistivity with depth in the measured profile. According to the above inversion process and determined inversion parameters, the inversion profiles of 5 profiles are obtained through multiple iterations, and each profile fits well. The inversion profiles from east to west are L23, L7, L8, L24, L40, as shown in the following figure 2.

![Figure 2. The 2D inversion results of each profile.](image)

L23 is located in the east end of research area. 21 AMT soundings are involved in the inversion of the profile. The final inversion RMS is 4.71. According to the 2-D inversion resistivity structure, the underground electrical structure of this profile can be roughly divided into two layers. The resistivity of the upper layer is generally low, the resistivity is less than 100 Ω · m, and the buried depth is gradually deeper from northeast to southwest, about 150-300m. There are two low resistivity bodies in the upper layer, and the resistivity is less than 1 Ω · m. The resistivity of the lower part is greater than 100 Ω · m, which is a high resistance area. There is a high resistance body R1 in the northeast side, and the resistivity is higher than 1000 Ω · m. It is speculated that there are two faults F1 and F2 in the upper layer, and the two faults control the upper low resistivity bodies C1 and C2.

L7 is located in the east of research area. 21 AMT soundings are involved in the inversion of the profile. The final inversion RMS is 3.64. According to the 2-D inversion resistivity structure, the underground electrical structure of this profile can be roughly divided into two layers. The resistivity of the upper layer is generally low, the resistivity is less than 100 Ω · m, and the buried depth is gradually deeper from southwest to northeast, ranging from 200-500m. There are two low resistivity bodies C1 and C2 in the upper layer, which correspond to the two low resistivity bodies of L23, and the resistivity is within 1 Ω · m. C1 is a near horizontal low resistivity body, C2 tends to wedge into the lower high resistivity layer in the northeast. The resistivity of the lower part is greater than 100 Ω · m, which is a high resistance area. R2 is located in the southwest corner of the profile, which is different from L23, and the resistivity of which is higher than 1000 Ω · m. It is speculated that there are three faults F1, F2 and F3 in the upper layer. F1 and F2 are traceable, and the two faults control the upper low resistivity bodies C1 and C2, which are consistent with L23. F3 is located in the northeast side of the profile, separating R1 and C2. It is a gradient zone of resistivity change, inclined to the northeast, with an inclination of about 45 ° and a cutting depth of more than 300m.
L8 is located in the middle east of research area, with 18 survey points participating in inversion. The final inversion RMS is 5.69. The 2-D inversion resistivity structure shows that the whole underground electrical structure of this profile can still be divided into two layers. The resistivity of the upper layer is generally low, with the resistivity less than 100 Ω · m, wedged from southwest to northeast, and the buried depth gradually becomes shallow from southwest to northeast, ranging from 100-500m. The upper two low resistivity bodies C1 and C2 are traceable, corresponding to the two low resistivity bodies of L7 and L23, and the resistivity is within 1Ω·m. Among them, C1 is larger, while C2 is smaller. The lower part is a relatively high resistance area, which is composed of two high resistance bodies R1 and R2. The resistivity is about a few hundred Ω·m. R1 and R2 are relatively low resistivity belts, which are speculated to be fault related zones or fracture development areas. It is speculated that there are three faults F1, F2 and F3 in L8, among which F1 is located near site 37, inclining to the northeast, with a large dip angle of about 65 °, and the cutting depth is more than 300m; F2 is shallowly cut, separating C1 and C2; F3 is steeply inclined to the northeast, with a dip angle of about 60 °, and the cutting depth of the profile is at least 850m, with the shallow part separating C1 and C2, and the deep part separating R1 and R2. F2 overlaps F3 shallowly, so the profile only identifies F3.

L24 is located in the central and western part of research area, with 21 survey points participating in inversion. The final inversion RMS is 5.86. The 2-D inversion resistivity structure shows that the layered characteristics of the underground electrical structure of the profile are not obvious, and there are high and low resistivity gradient zones in the profile, corresponding to F3. F3 fault is a gentle dip fault at L24, with an inclination of about 45 °. The southwest side of F3 is the high resistence area and the northeast side is the low resistence area. The high resistivity area is located in the depth of the profile, which is composed of R2 and R3. The resistivity of R2 is high, which is higher than 1000 Ω·m. The resistivity of R2 is relatively low, which is about several hundred Ω·m. The low resistence area is located in the upper part, and the burial depth gradually increases from southwest to northeast, ranging from 50-600m. The low resistivity body C2 is located in the shallow part with a buried depth of about 50-200m, which is cut by F4.

L40 is located on the west side of research area, and 21 survey points participate in inversion. The final inversion RMS is 4.19. The 2-D inversion resistivity structure shows that this profile can be divided into three layers. The upper high resistance and low resistence occur alternately, among which the low resistivity body C3 has a large scale, with a transverse extension of about 400m and a longitudinal extension of about 200m, which may be related to fracture or joint development. There is a high resistance body on both sides of C3, F4 and F5 separate C3 from the high resistance body on both sides. F4 inclines to the northeast with an angle of about 40 °, the cutting depth is about 300m, F5 also inclines to the northeast with an angle of about 40 °, and the cutting depth is about 400m. A high resistivity body R3 is developed in the northeast of F4, but its authenticity is questionable because there is no other control point above C3. The middle layer is the transition layer, and the resistivity is about dozens of Ω·m. The lower part of the middle layer is R2, which is a high resistance layer. The control range of R2 in L40 becomes larger, and the resistivity is still a few hundred Ω·m.

3. Discussion

According to the statistics of electrical physical property measurement results in the research area, the magnetic (Pyrite) ore and polymetallic ore are of low resistance, while skarn, marble and granodiorite are of high resistance. Because the resistivity distribution reflected by the inversion electrical structure is not only influenced by the resistivity of the rock and ore itself, but also influenced by many factors such as the joint development level, fracture/void development degree, structural change, water content and distribution of the rock under the actual conditions. Drill holes are distributed in some profiles. The distribution of granite, granodiorite, diorite, monzonite, etc. in the drilling data is extracted. The production location of skarn and lead-zinc mine is compared with the electrical structure profile (if a well is located between two AMT profiles, the well data is projected to the electrical profiles on both sides). According to the limit of drilling data, the high resistance and low
resistance anomalies reflected by electrical structure are transformed into the inference of lithology and structure distribution, and the interpretation figures of 5 profiles including L23, L7, L8, L24 and L40 are obtained, as shown in the Figure 3.

Table 1. Statistics of electric physical property measurement results in research area

| Name                  | Number | Resistivity ρ (Ω·m) | Polarizability η (%) |
|-----------------------|--------|---------------------|----------------------|
|                       |        | minimum             | maximum              | minimum | maximum | average |
| Magnetite (Pyrite)    | 11     | 7                   | 18                   | 15.6    | 44.4    | 64      | 54.5    |
| Skarn                 | 16     | 2062                | 5638                 | 3427.9  | 0.25    | 1.85    | 1.11    |
| Polymetallic ore      | 14     | 38                  | 3069                 | 504.9   | 1.86    | 44.44   | 18.27   |
| Carbonaceous limestone| 12     | 740                 | 4589                 | 2669    | 0.18    | 6.46    | 1.6     |
| Marble                | 21     | 708                 | 6340                 | 2457.7  | 0       | 1.35    | 0.32    |
| Carbonaceous marble   | 10     | 768                 | 2596                 | 1864    | 0.74    | 6.70    | 3.5     |
| Granodiorite          | 18     | 12275.0             | 4511.8               | 7942.8  | 2.07    | 0.47    | 1.42    |

Through the analysis of the drilling data in the research area, it is found that the granite occurs in multiple layers in the same drilling well, the multi-layer granites are mostly metamarble, and there is no large profile of granite base. The deep high resistivity body in the research area may not be the reflection of granite. Due to the limitation of low resistivity and frequency of audio frequency magnetotelluric in the general survey area, it is impossible to determine the deeper electrical structure combination and characteristics of the inversion profile, and there is no working method of large depth in the research area, so the source of magmatic material is not clear at present.

The electrical structure of 2D inversion can be divided into five faults: F1, F2, F3, F4 and F5. Among them, F3 is a deep fault in the research area, which can be traced at L7, L8 and L24. F3 may be a channel for the upwelling of deep magma. The characteristics of F3 in the research area are: steep dip in the north-east, gentle dip in the south-west; large cutting depth in the south-west direction, up to 800m, small cutting depth in the north-east direction, and visible cutting to 300m depth in the inversion profile of L7. F3 corresponds to the major faults in the general survey area delineated by the regional gravity data.

When ZK0801 is drawn to L8, it is found that the distribution of granitoids is related to F3, and it is distributed at the boundaries of R1 and R2, with medium resistivity, about tens to 100 Ω·m. Two sets of granites are encountered in ZK0801, and the upper layer is drilled intermittently in layers of 275m
thick granites, corresponding to R1; the lower part encountered granites with a thickness of tens of meters, corresponding to F3. By projecting well ZK0005 and ZK0006 to profile L0 to L8, it is found that two sets of granites are encountered in ZK0006, and multi-layer granite with thickness of 350 m is encountered in the upper intermittent drilling, corresponding to R1; two layers of granite are encountered in the lower drilling, corresponding to F3. According to the drilling data of ZK0005, the core area of R2 is not granite, but marble. The granites appear at the boundary of R2.

By projecting ZK0005, ZK0006 and ZK1501 to L7, it is found that the distribution of ZK0006 granites may be related to R1, ZK1501 and ZK0005 and ZK0006 granites are related to the R2, and the vertical position has a good geometric correspondence with R2. Two sets of granites are drilled in ZK0006, and the upper layer is intermittently drilled with multiple layers of granite up to 350 m thick, corresponding to R1; two layers of granite are found in the lower part. According to the drilling data of ZK0005, the core area of R2 of L8 is not granite, but marble. The granite appears at R2 boundary.

ZK2401 is drawn on L24, ZK2801 and ZK3201 are projected on L24, and it is found that the granite encountered in ZK2401 drilling is at the upper boundary of R2, the resistivity is about 100 Ω·m, while R2 is not granite base, ZK3201 does not encounter granite, and the granite encountered in ZK2801 drilling is at the boundary of R3.

In addition, ZK0004 found 14 m thick lead-zinc ore body with Pb+Zn grade of about 11% was found at the depth of about 520 m, which corresponding to the F3 channel[2]. The thick lead-zinc ore body indicated that the fault F3 is the key factor for the polymetallic mineralization. The magmatic water invaded into the upper stratum and ore-forming elements enriched and mineralized in favorable position.

4. Conclusions

(1) The granites encountered in the research area are all from the magma source corresponding to the deep F3 channel, and the main branch of granites intrudes along the main channel of the fault, forming the multi-layer thick granite at the upper part of ZK0006 and ZK0801; the branch intrudes along R2 boundary to the southwest at the bottom of the fault, forming the thin granite at the lower part of ZK1501, ZK0005 and ZK0006.

(2) The granites are occurred as the veins from multi-channels. The multilayer thick granites in the upper part of ZK0006 and ZK0801 are from the side related to R1, that is to say, there are still large-scale and deep granites in the north of R1, with large scale; while the thin-layer granites in the lower part of ZK1501, ZK0005 and ZK0006 are from the magma intrusion of F3 channel. In addition to the above-mentioned F3 channel, R3 may also be granite, and the magma may come from the southeast trending channel under R3. Through verifying the properties of R1, the magma source can be inferred.

(3) The regional metallogeny are controlled by the magma activity and the important tectonic structure, such as F3, which served as fluid migration pathway. The magmatic water invaded into the upper stratum and ore-forming elements enriched and mineralized in favorable position.

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