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Integrated interpretation of dual frequency induced polarization measurement based on wavelet analysis and metal factor methods

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Abstract: In mineral exploration, the apparent resistivity and apparent frequency (or apparent polarizability) parameters of induced polarization method are commonly utilized to describe the induced polarization anomaly. When the target geology structure is significantly complicated, these parameters would fail to reflect the nature of the anomaly source, and wrong conclusions may be obtained. A wavelet approach and a metal factor method were used to comprehensively interpret the induced polarization anomaly of complex geologic bodies in the Adi Bladia mine. Db5 wavelet basis was used to conduct two-scale decomposition and reconstruction, which effectively suppress the noise interference of greenschist facies regional metamorphism and magma intrusion, making energy concentrated and boundary problem unobservable. On the basis of that, the ore-induced anomaly was effectively extracted by the metal factor method.

Key words: dual frequency induced polarization method; wavelet analysis; metal factor; Arabian−Nubian shield; volcanogenic massive sulfide deposit

1 Introduction

The induced polarization method (including frequency domain and time domain induced polarization method) is a conventional geophysical methods, and widely used in the exploration for mineral resources [1−3]. Due to the non-ore induced polarization anomaly caused by carbonaceous rocks, regional metamorphism, cleavage zone and other complex geological structure, the induced polarization anomaly becomes more complex. The use of apparent resistivity and apparent polarizability (or apparent frequency) parameters is difficult to effectively represent the anomaly source. So, how to suppress non-mineral anomalies and to distinguish them from mineral anomalies becomes an important problem for the induced polarization during the exploration of mineral resources. As to induced polarization method, the geophysicist has proposed and developed a variety of approaches. KHESIN et al [4] proposed the rapid interpretation method, which resolved terrain correction, qualitative and semi-quantitative interpretation of polarizability anomalies through approximate procedures. SAEIN et al [5] put forward the concentration−volume fractal method to separate high and moderate sulfide zones from low sulfide zone and barren wall rocks in the deposit based on the induced polarization and resistivity. LI et al [6] proposed the concept and applied program of the morphological interpretation of induced polarization anomalies based on the study of morphological characteristics of induced polarization anomalies from a lot of data tested in field. WENG et al [7] used the normalized total gradient method to explain induced polarization with the purpose of obtaining space information on anomaly sources. However, these methods are limited on the premise of no greater interference, and the processed results of methods above can hardly achieve the desired results as to induced polarization anomaly of complex geologic bodies.

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work. Firstly, taking advantage of wavelet multi-resolution and Mallat fast algorithm, the induced polarization data are processed by selecting the appropriate wavelet base and decomposition scale, then decomposition and reconstruction of original induced polarization are proceeded, by which the complex geological noise interference is effectively suppressed. On the basis of that, the metal factor method is used to extract ore-induced information and distinguish it from other anomalies by weighting the polarization data after processing with apparent conductivity. The results show that the integrated interpretation method of the wavelet analysis and metal factor is an effective process method, which has a good guidance meaning in the application of geophysics with the complex geological structure.

2 Theory and methods

2.1 Dual frequency induced polarization

The induced polarization method is one of the geophysical exploration methods which take the electrochemical properties of rocks and minerals as the physical premise. Dual frequency induced polarization method is an innovative frequency domain induced polarization technology invented by HE [8,9]. The basic idea of the dual frequency induced polarization method is to superimpose two frequency square wave currents to form dual frequency combinations of current (low and high frequency) into the ground at the same time, to accept the potential difference information of the induced polarization total field from the ground floor consisting of two main frequency induced polarizations.

After a series of steps, such as the amplification of the inner instruments, the frequency selection and the detector, a low-frequency potential difference and high-frequency potential difference can be obtained at the same time [10,11]. The apparent resistivity can be calculated by

$$\rho_{\mathrm{s}} = K\frac{\Delta V_{\mathrm{G}} - \Delta V_{\mathrm{D}}}{I} \tag{1}$$

and the apparent frequency is defined as

$$F_{\mathrm{s}} = \frac{\Delta V_{\mathrm{D}} - \Delta V_{\mathrm{G}}}{\Delta V_{\mathrm{G}}} \times 100\% \tag{2}$$

where ΔV_{G} is the high-frequency potential difference; ΔV_{D} is the low-frequency potential difference; I is supply current.

2.2 Wavelet analysis

2.2.1 Mallat fast algorithm

The wavelet transform which has the characteristic of multi-resolution is the time-scale (or time−frequency) analysis method of a signal, and it has the ability to characterize the local features of the signal in the two domains of time and frequency. So, it is a time−frequency localization analysis method with fixed window size but changeable shape and time−frequency window [12].

When $\forall f(t) \in L^2(R)$, continuous wavelet transform of $f(t)$ (sometimes refer to the integral wavelet transform) is as follows:

$$WT_f(a,b) = |a|^{-1/2}\int_{-\infty}^{\infty} f(t)\,\psi^*(\frac{t-b}{a})\mathrm{d}t, \quad a \neq 0 \tag{3}$$

where a is the scale factor; b is the translation factor.

Inverse transformation (recovery signal, or the reconstruction of the signal) is written as follows:

$$f(t) = C_\psi^1 \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \psi_{a,b}(t) WT_f(a,b)\mathrm{d}b\frac{\mathrm{d}a}{|a|^2} \tag{4}$$

In practical work, in order to use the Mallat pyramid fast algorithm, we use discrete wavelet transform mostly in the form of orthogonal wavelet transform, which requires the selected wavelet to be orthogonal wavelet. Selecting orthogonal wavelet to conduct discrete transform can avoid the redundancy of continuous wavelet transform. So, we can greatly reduce the amount of calculation without losing the original signal.

Any function $f(x) \in L_2(R)$ can be perfectly reconstructed according to the resolution 2^{-N} of the low-frequency section (approximate part) and the resolution $2^{-j}(1 \leq j \leq N)$ of the high-frequency section (detail section). Multi-scale analysis is only on further decomposition of the low frequency part regardless of the high frequency part [13]. The specific decomposition relation is

$$f(x) = A_n + D_n + D_{n-1} + \cdots + D_2 + D_1 \tag{5}$$

where $f(x)$ is data signal; A is the approximate low-frequency part; D is the high-frequency details section; n is the decomposition scale.

2.2.2 Selection of wavelet base and scale

With the development of wavelet theory, various wavelet bases are developed to meet the need of different industries. In general, each kind of wavelet base has different forms and functions, and all meeting the wavelet conditions can be used as wavelet base function. Some famous wavelet bases have Daubechies, Symlets, Coiflets, Morlet and Meyer etc [14,15]. In practice, the selection of wavelet base usually follows three principles [16]:

1) The self-similarity principle. For binary wavelet transform, the choice of wavelet base should have certain similarity with signal, the energy relatively concentrated after transforming, which can effectively reduce the computation cost.

2) The discriminant function. The discriminant

functions can be developed by extracting main technical indicators for particular problems. The substitution of wavelet functions into discriminant functions leads to an optimal function.

3) The support length. Generally, the choice of the support wavelet length is 5−9. If the support length is too long, it will cause the boundary problem; otherwise, the signal energy would not concentrate.

Different wavelets may get different results. Therefore, it is important to choose the wavelet base type to suit the induced polarization data. In practice, for specific data, it is difficult to find the corresponding mode, therefore wavelet analysis of the real data is required with a repeated comparison to the actual geological condition to choose wavelet base [17]. Based on the wavelet base selection principle, according to the different wavelet base processing analyses, Daubechies wavelet base (db) is chosen for induced polarization data, which indicates better applicability. Through the selection of different order number and scale for db wavelet, db5 wavelet basis is used to conduct two-scale analysis, which can better reflect the actual induced polarization anomaly with abilities of suppression of noise interference effect, energy concentration and unobservable boundary problem (Figs. 1 and 2).

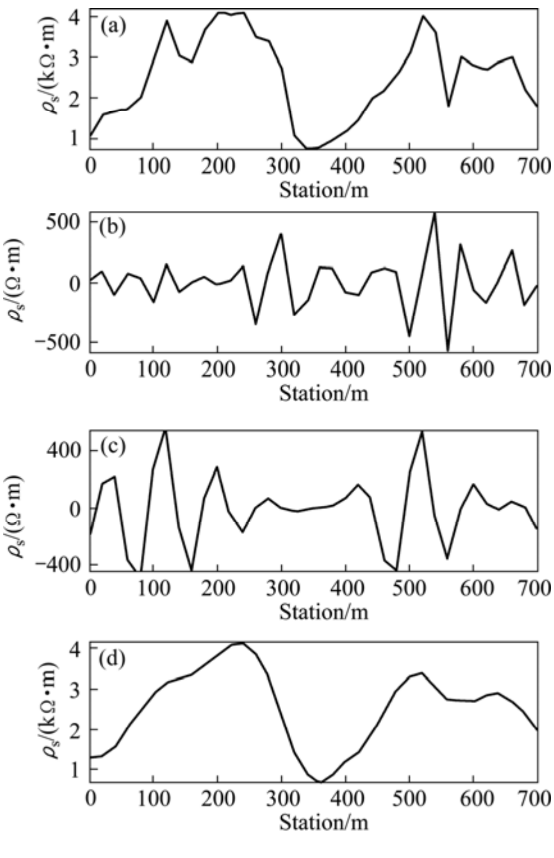

Fig. 1 db5 wavelet two-scale decomposition and reconstruction for ρ_s: (a) Original data; (b) High-frequency data (the first scale); (c) High-frequency data (the second scale); (d) Low-frequency data (the second scale)

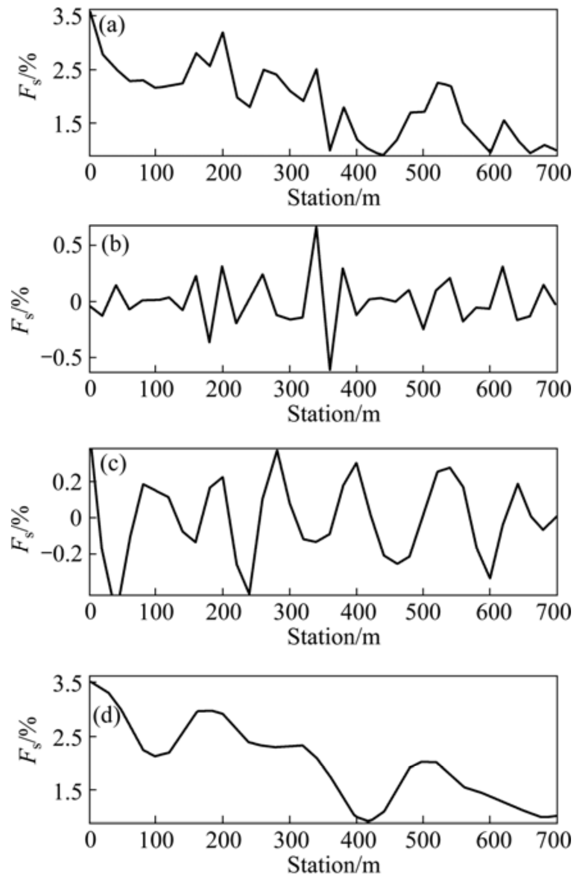

Fig. 2 db5 wavelet two-scale decomposition and reconstruction for F_s: (a) Original data; (b) High frequency data (the first scale); (c) High frequency data (the second scale); (d) Low-frequency data (the second scale)

2.3 Metal factor

In practice, people often directly use apparent resistivity and apparent frequency to explain the induced polarization anomalies. When the induced polarization anomaly is relatively complicated, it would be difficult to use these parameters to reasonably explain the nature of the anomaly source, also leading to wrong results [18]. The metal factor, secondary information of induced polarization method, can distinguish target anomaly and plays a good role in quantitative and qualitative explanation of anomaly [19]. The metal factor of dual frequency is as follows:

$$M_{\mathrm{F}}=\frac{\rho_{\mathrm{sD}}-\rho_{\mathrm{sG}}}{\rho_{\mathrm{sD}}\cdot\rho_{\mathrm{sG}}}=\frac{F_{\mathrm{s}}}{\rho_{\mathrm{sG}}}=F_{\mathrm{s}}\cdot\sigma_{\mathrm{sG}} \tag{6}$$

where ρ_{sG} is the high-frequency apparent resistivity; ρ_{sD} is the low-frequency apparent resistivity. Actually it weights apparent conductivity to the apparent frequency, which plays a role in highlighting good conductor anomaly and suppressing non-good conductor.

3 Application and analysis

The study area locates in the Shire region of

Ethiopia, which lies in a transition area between the northeast edge of western Gondwanaland and Mozambique ocean in the aspect of geological structure and is an important part of late Proterozoic arc hyperplasia belt of the Arabian-Nubian Shield [20−22]. The main exposed stratum is the late Proterozoic north-eastern trend metavolcanic rocks. It mainly consists of medium acidic volcanic and locally basic volcanic. Erupting face and flowing face are the main lithofacies of metavolcanic. Metavolcanic is main ore-bearing wall rock, VMS (volcanogenic massive sulfide) type ore body is mainly distributed in the conversion interface of the mid-basic−mid-acid lithology, and close to the Mid-acid volcanic rock. The ore bodies occur in bedded, stratoid and veined forms and are stable along strike and direction of dip. The pyritization has two types: one is primary massive sulfide mineralized belt, which is copper polymetallic mineralization belt; the other is formed by regional metamorphism and deformation, and appears in the subvolcanic, volcanic and pyroclastic rock, which is an interferential factor for induced polarization measurement because it does not form ore body.

Due to the influence that the volcanic rock has been suffered from greenschist facies regional metamorphism, tectonic deformation, magma intrusion, etc, the geological mineralization becomes more complex. Especially for the widespread pyritization of the metavolcanics acted by regional metamorphism, the induced polarization anomaly becomes more complex too. The Adi Bladia mine of research area has been carried out the induced polarization survey on grid of 100 m×20 m, with pole distance of power supply and reception of 1600 m and 40 m, respectively. Frequency of survey is 4/13 Hz. For integrated interpretation of induced polarization anomaly, the induced polarization data of the Adi Bladia are processed based on wavelet analysis and metal factor method.

The contours of original apparent resistivity and apparent frequency are shown in Figs. 3 and 4. The figures suggest that the curves of apparent resistivity and the apparent frequency are cluttered and local contour jumps significantly because of the interference of regional pyritization and local intrusive vein. It is difficult to explain anomaly shape and space distribution only from the original contours.

Figures 5 and 6 show the processed contours of apparent resistivity and apparent frequency by the wavelet multi-resolution method. Compared with the original contours, it can be seen that the processed

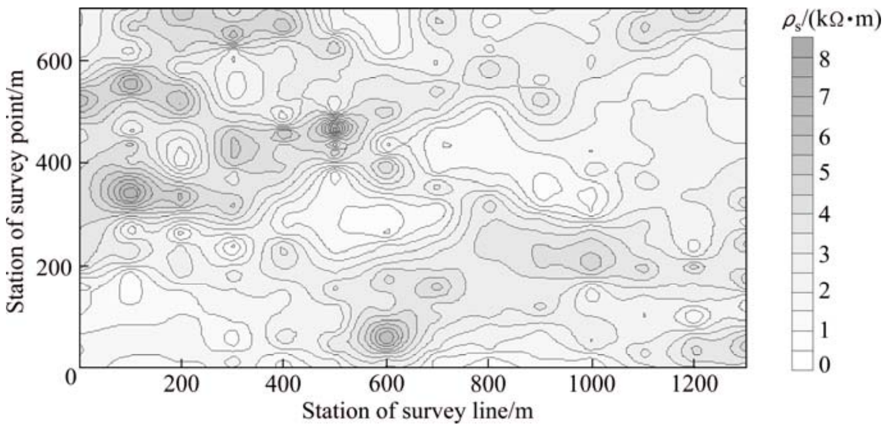

Fig. 3 Contour of original apparent resistivity

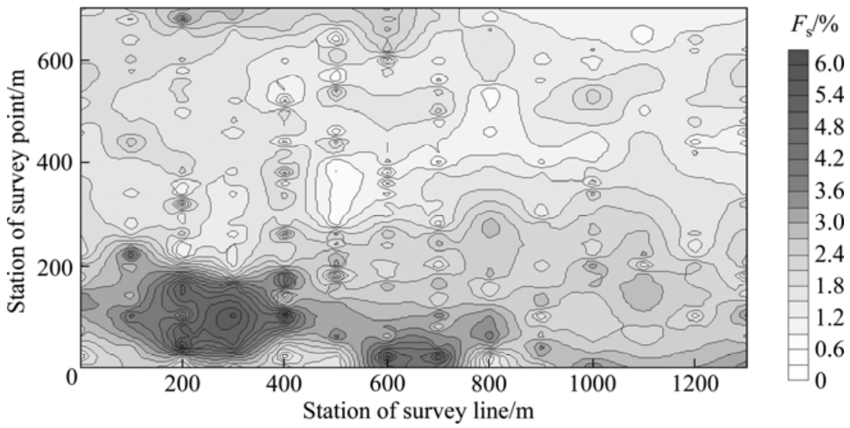

Fig. 4 Contour of original apparent frequency

contours have suppressed local interference and heterogeneity of surface physical properties. The contours of apparent resistivity and apparent frequency are effectively smooth; the fidelity is effectively obtained, and anomaly shape and space distribution are clear.

The metal factor is produced by the induced polarization data based on wavelet processing, and its contour is shown in Fig. 7. It can be clearly identified that there are five high metal factor anomalies from the figure, which are M_1, M_2, M_3, M_4 and M_5, respectively, and the anomaly range and degree of M_4 are the most obvious. The position of the metal factor anomaly is consistent with the one reflected by low resistivity and high apparent frequency. All of the metal factor anomalies are located in the sulfide zones of felsic metamorphic volcaniclastic strata, with the favourable geological conditions for Cu-polymetallic mineralization. The M_4 anomaly reflects massive sulphide ore bed. Others reflect disseminated sulfide ore bodies. Compared to the unprocessed contour, the metal factor method can

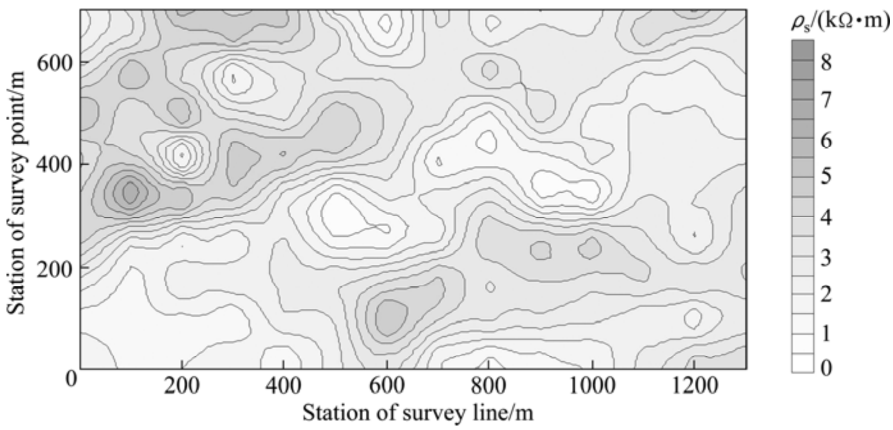

Fig. 5 Contour of apparent resistivity after processing by wavelet

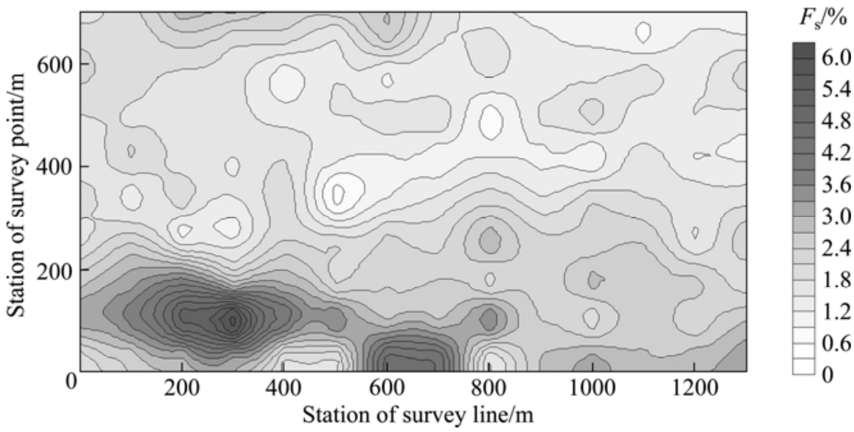

Fig. 6 Contour of apparent frequency after processing by wavelet

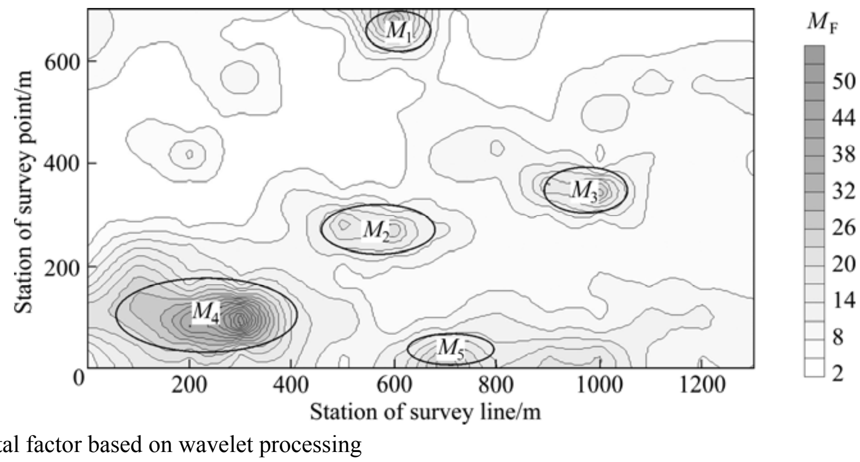

Fig. 7 Contour of metal factor based on wavelet processing

effectively separate the superimposed anomalies. The interpretation of the results is more intuitive and reliable.

In short, through wavelet analysis and metal factor method, the interference of regional pyritization and local intrusive vein is effectively suppressed, the target anomalies are effectively extracted too, which provides a favorable basis and foundation for the mineralized localization and the metallogenic prediction. This method is an effective process method, which can be extended to other geophysical problems. However, we must pay attention to the fact that there may be different geological conditions and distractive information, the choice of the wavelet basis and wavelet scale may be different. We should make the right choice related to the concrete data information.

4 Conclusions

1) Wavelet analysis method can effectively suppress local interference and heterogeneity of surface physical properties, making apparent resistivity and apparent frequency curve effectively smooth; the fidelity is effectively obtained, and anomaly shape and space distribution are clear.

2) Metal factor method can effectively separate the anomaly of superposition and distinguish the target anomaly from the complicated induced polarization data. As a result, the interpretation is more intuitive and reliable.

3) Based on the conventional induced polarization method, through integrated interpretation of the wavelet method and metal factor method, the pressing of interference anomaly, extracting effective anomaly and distinguishing target anomaly are effectively solved. This method can be well extended to other geophysical exploration under complex geological situation.

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基于小波分析和金属因子的双频激电综合解释

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摘　要：在矿产勘查中，人们常应用电阻率和极化率参数来解释激电异常。当地质体和激电异常较为复杂时，利用这些参数就难以对异常源的性质进行合理解释，还可能推断出错误结论。采用小波处理法和金属因子法综合解释阿迪布拉达矿区复杂地质体的激电异常，选择 db5 小波基对激电数据进行二尺度分解与重构，较好地压制了绿片岩相区域变质和岩浆侵入的噪音干扰，且其能量较集中，边界问题不明显。在此基础上利用金属因子法有效提取了激电矿致异常。

关键词：双频激电法；小波分析；金属因子；阿拉伯−努比亚地盾；火山成因块状硫化物矿床

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