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利用大地电磁测深法识别 EDA 地震电性变化前兆

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摘要 论述了起因于 EDA 现象的地球介质电导率各向异性特征,分析研究了地球介质电导率各向异性变化引起的大地电磁响应函数变化形态特征,简述了大地电磁测深法对 EDA 电性变化前兆的可识别性及大地电磁资料解释中考虑电导率各向异性的必要性,研究了对称各向异性层状介质大地电磁资料的反演问题。

主题词:地震前兆 大地电磁测深 电导率各向异性 膨胀各向异性

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USING MTS TO DISTINGUISH THE EARTHQUAKE PRECURSOR OF EDA ELECTRICAL CHANGES*

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Abstract

The characteristics of conductivity anisotropy of earth medium due to EDA phenomena were demonstrated, the pattern and characteristics of MT response function variations caused by the changes of conductivity anisotropy were analysed and studied, the distinguishability of MTS to the earthquake precursor of EDA electrical changes and the necessity of considering the anisotropy in the interpretation of MT data were explained, and the, inverse problem of MT data for the symmetrically anisotropic layered medium was discussed.

Key words: Earthquake precursor, Magnetotelluric sounding, Conductivity anisotropy, EDA

1 The Conductivity Anisotropy of the Earth's Medium due to EDA

The extensive-dilatancy anisotropy (EDA) is a microcrack activity phenomenon under lower stress level, and the microcracks in the rock are predominantly orientated along maximum compressive principal stress direction and opened along the minimum principal stress direction. In recent years the shear wave splitting phenomena were observed in some regions of Turkey, Canada, U. S. A., Japan, Russia and China, their physical mechanism was interpreted as the extensive-dilatancy anisotropy in the upper crust, at present the idea has been accepted by most of geophysicists (Crampin and Lovell, 1991). Since the differential stress causing the EDA phenomena is 1 or 2 orders of magnitude lower than stress causing the normal dilatancy, in the upper crust, especially in tectonic active regions, the EDA phenomena ought to be more general phenomena. The phenomena had not been noticed earlier only because of the restriction of the observation technique and theoretic method. In the upper crust shallower than 20 km, the maximum and minimum principal stresses are in the horizontal plane roughly, the EDA microcracks orientated along the maximum principal stress direction are vertical cracks. When shear waves with some given incident angles propagate in the medium with oriented cracks, they are splitted into the fast and slow waves, and the fast wave polarizes along the direction of the microcrack orientation.

Under the thermodynamic conditions in the upper crust, the resistivity of dry rock is above 10^6 ohm-m, but the volume resistivities in the upper crust rock obtained by the data inversion of MTS and other EM methods are 10^2-10^4 ohm-m, $2-4$ orders of magnitude lower than that of the dry rocks, so it is considered that there are cracks and porous water in

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the rock. The numerical simulation of the volume resistivity for two-phase medium showed that a few percent of the cracks containing water probably make the volume resistivity decrease by several orders of magnitude (Lin et al., 1989). Presently the existence of a few cracks and a little porous water in the upper crust has been accepted by most of geophysicists, even it was used for modelling the magnetotelluric and seismic reflection results of the lower crust in some regions (Hyndman and Shearer, 1989). The orientated microcracks due to EDA phenomena are the flat cracks with larger pore shape ratio, the self-consistent approximate calculation of the cracked medium shows that its volume conductivity is apparently directive, when there is the porous water in the cracks, the direction of the crack orientation is the direction of high conductivity (Hoening, 1978—1979). On condition that there are the orientated flat cracks in the rock, along the direction of the crack orientation the degree of connecting each other is higher, even some conductive paths form along it, thereby the direction becomes an apparent high conductivity direction. The numerical modelling of the volume conductivity for two-phase medium shows that its volume conductivity can be expressed as a weighted average of the volume conductivities for two ideal medium models in the field of the connective degree between cracks, the volume conductivity is affected very much by the connective weight factor. If the crack porosity in the upper crust was 0.03, the resistivity of the porous water was 0.4 ohm-m and the resistivity of the rock framework was 10^6 ohm-m, the increase from 0.4 to 0.8 of the connective weight factor results in the decrease from 10^4 ohm-m to 10^2 ohm-m of the effective volume resistivity (Lin et al, 1989). It is shown that the EDA cracks including porous water surely result in an apparent conductivity anisotropy of the earth's medium, and its principal characters approach those of the symmetrical anisotropic medium. In fact, the results of super deep drilling show that some layers in which the cracks developed better and the porous water was richer just were the layers with stronger anisotropy for the seismic wave. The oriented microcracks in some drill cores were certainly observed, they were considered relative to the stress state in situ (Wang and Sun, 1990).

2 The Precursor of EDA Electrical Changes in the Wide Regions around the Focal Zone

A great number of rock physics experiments, a variety of earthquake theories and a lot of numerical modelling calculations have predicted that during the macroseism-pregnant process the distribution of the stress field in the deep crust of an enough wide region around the focal zone would apparently change. A great number of the observed earthquake precursors have been imputed the changes of the stress field in the crust. The inversions of the earthquake process and precursor field for some strong earthquakes (for example, the Xingtai earthquake in 1966, the Tangshan earthquake in 1976) also inferred some changes of the crustal stress field distribution in enough wide region around the focal zone. The stress field changes in situ surely result in the electrical anisotropy changes of EDA, which can appear as the changes of the conductivity values along two principal directions or (and) the changes of anisotropic principal direction. Although few EDA precursors observed using S-wave splitting data have been reported because of the harsh observation condition and there are some controversies for the

EDA precursor observed using shear wave splitting data due to the complexity of the problem, we believe that to distinguish the EDA earthquake precursor by using S-wave splitting observations also has better prospects.

If MTS site is enough far from the future earthquake fault to neglect the influence of the lateral inhomogeneity in the focal zone on the MT response functions, a symmetrical anisotropic layered model can be used to describe the earth's medium conductivity distribution. In this condition the conductive property of the medium in the j-th layer is showed by a symmetrical tensor in the plane:

$$[\sigma_j]=\begin{bmatrix}\sigma_j^1\cos^2\theta_j+\sigma_j^2\sin^2\theta_j & (\sigma_j^2-\sigma_j^1)\sin\theta_j\cos\theta_j\\ (\sigma_j^2-\sigma_j^1)\sin\theta_j\cos\theta_j & \sigma_j^2\cos^2\theta_j+\sigma_j^1\sin^2\theta_j\end{bmatrix} \tag{1}$$

including three independent variates: σ_j^1 and σ_j^2 are the conductivities along principal directions, θ_j is angle between principal direction 1 and x-axis. It is easily deduced that for a symmetrical anisotropy homogeneous half-space the EM wave in the medium can be considered as the superposition of two EM waves polarizing along two principal directions and propagating independently, which are respectively equivalent to two waves propagating in two homogeneous isotropic half-spaces with the conductivities along two principal directions. For the homogeneous symmetrical anisotropic layered medium in which the principal direction of all layers are the same with each other, the mentioned case also occurs. When the principal directions of the layers are different, the case is more complex, the horizontal components of the EM field on the earth's surface can be calculated using the upward recursion from the top of the lowest half-space a layer by a layer (O'brien and Morrison, 1967). Using a series of complex metrix operation the tensor impedance on the earth's surface can be calculated, then various MT response functions can be calculated. The MT response functions of the symmetrical anisotropic layered medium have shown some apparent "non-one-dimensional characteristics" (Fig. 1). The apparent resistivity and phase curves along the measured directions separate each other, even different shape and character appear, and the two-dimensional judge coefficients and the dimensional weigh factors show that the model does not have ideal two-dimensional characteristics.

On the basis of a series of our studies about deep physics circumstance of seismicity (for example, Lin 1984; Lin et al, 1988), in some regions of the Nothwestern China, there is a high resistive layer in the upper crust about 5—30 km deep, the rock in it has higher strength and is more brittle, the accumulation and release of the stress and energy during the earthquake readiness and occurrence process take place mainly in it. The layer becomes one of main loaded layers for the regional tectonic stress field. During the earthquake readiness the stress and strain changes in the focal zone ought to result mainly in the stress field distribution changes in the layer around the focal zone, then EDA electrical changes probably take place mainly in the layer. The characteristics of MT response function changes due to the conductivity anisotropy coefficient changes and the changes of the principal axis direction angle in the layer are studied by us. In accordance with the earth's conductivity structures given by the

MTS results in and near the Gansu Province, four typical models are tested (Tab. 1), they are separately corresponding to Tianshui, Hexi corridor, southern Gansu and middle Gansu regions. The high conductive direction in the low resistive layers and the lower layers is the strike of the guessed deep shear zone, and the anisotropic principal direction of the earth's surface layer in some regions is guessed by the tectonic characters in the regions, the high conductive direction in the layers corresponding to EDA phenomena is the direction of the maximum principal compressional stress in the region, which is inferred using other geophysical data. On the basis of four background models, the anisotropic coefficient and principal axis direction angle of the corresponding layer medium were changed, and the variations of the apparent resistivities and phases of the principal impedance tensor elements along the measured direction (due to symmetry of the model conductive property, the magnitude of the auxiliary impedance tensor elements always is smaller than that of the principal impedance tensor elements very much) and the variations of the two dimensional judge coefficients (skew, ellipticity) and one-, two- and three-dimensional weight factors are studied. From the analysis of the obtained MT modelling results the following conclusions are given: a) When the conductivity anisotropy of the corresponding layer medium changed more clearly, the distinguishable variations of various MT response functions in varying degrees were produced, in some conditions the apparent resistivity and impedance phase curves underwent many variations, even their shape and characters changed largely; b) Depending on background models, for the same changes of medium anisotropy the different MT response function appears different characters of the variation, for example, for the models 1, 3, 4 the affection of the anisotropic coefficient on the mentioned MT response functions is larger than

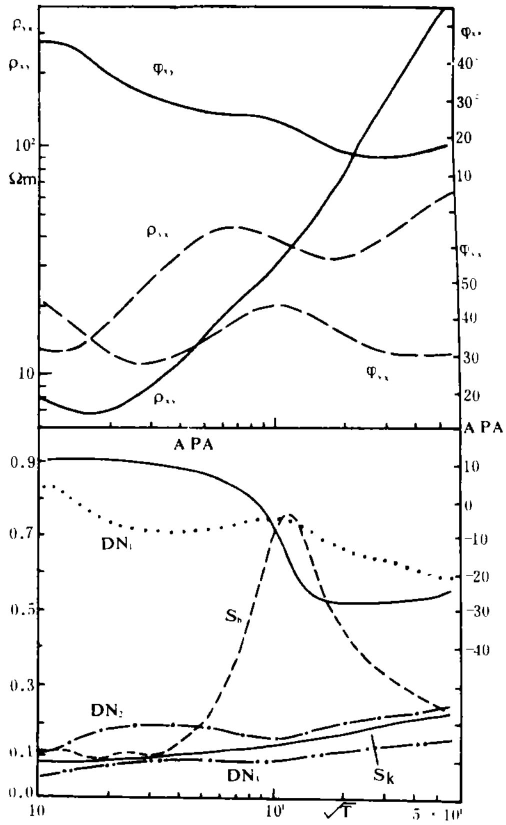

Fig. 1 Some MT response functions for a six-layer symmetrical anisotropic model. ρ_{xy}, ρ_{yx}, φ_{xy}, φ_{yx} are the normal apparent resistivity and impedance phase in the measured direction; APA is apparent direction angle of the principal axis; Sk and Sb are two-dimensional judge coefficients; DN1, DN2 and DN3 are one-, two- and three-dimensional weight factors. The model is the model 4 in Tab. 1, in which the conductivity anisotropic coefficients in the second and fourth layers are 5.0.

that of the principal directional angle changes apparently, but for model 2 the affection of the principal directional angle changes on the mentioned MT response functions is more apparent; c) If the layer in which the conductivity anisotropy undergoes changes outcrops at the earth's surface (model 3), various MT response functions will be affected by the anisotropy changes more apparently, otherwise the variations of the MT response function curves will occur within the middle and long period range; d) The two-dimensional judge coefficients and the dimensional weight factors all probably show apparent distinguishable variations due to conductivity anisotropy changes for the model 1 and 4, Sk is affected by anisotropy changes more apparently, Sb is affected by anisotropy changes apparently for the models 2 and 4, one-, two- and three-dimensional weight factors are affected by anisotropy changes more strongly for the model 3.

Tab. 1 Several tested models

Para.	model 1					model 3					
Res. 1j	12.0	800*	8.00	800*	8.00	120*	8.00	800*	5.00	250	5.00
Res. 2j	12.0	800*	12.0	800*	12.0	120*	12.0	800*	15.0	800	15.0
θ_j	0.00	65.0*	20.0	65.0*	20.0	85.0*	15.0	85.0*	15.0	15.0	15.0
hj	2.00	12.0	3.00	28.0		10.0	2.00	18.0	3.00	57.0	
Para.	model 2					model 4					
Res. 1j	12.0	800*	12.0	800*	12.0	8.00	400*	8.00	800*	5.00	400
Res. 2j	16.0	800*	8.00	800*	8.00	16.0	400*	12.0	800*	10.0	800
θ_j	45.0	50.0*	45.0	50.0*	45.0	10.0	55.0*	10.0	55.0*	10.0	10.0
hj	2.00	15.0	3.00	28.0		3.00	10.0	2.00	15.0	3.00	

Res. j—ohm-m; θ_j—degree; hj—km. * the layer whose conductivity anisotropy changes in modelling.

3 Magnetotelluric Inversion of Symmetrical Anisotropic Layered Medium

The observed MT data must be inversed and fitted by an anisotropic model to study the conductivity anisotropic property of earth's medium. We studied some problems about the MT inversion of symmetrical anisotropic layered medium. Since the anisotropic principal directions of layers in the model are not completely the same with each other, the apparent principal axis direction angle estimated using the observed MT data does not have clear meaning. It is not probable to estimate the apparent resistivity and phase values in the principal direction and to use them for the one- or two-dimensional inversion interpretations according to the mormal MT inverse interpretation. Here the principal impedance tensor elements in the measured direction are used as fitted MT response functions in the inversion, they are described separately using two pairs of real numbers: the normal apparent resistivity impedance phase (AP inversion), the impedance real part apparent resistivity-imaginary part apparent resistivity (RI inversion). Four sets of MT data in two measured directions are fitted at the same time (ρ_{xy}, ρ_{yx}, φ_{xy}, φ_{yx}, or ρ_{xyr}, ρ_{yxr}, ρ_{xyi}, ρ_{yxi}). We also tested the case in which the mensioned eight sets of the data were fitted at the same time (AP+RI inversion). The number of the model parameters for N-layer symmetrical anisotropic medium is 4N-1, i. e. two times as large as that for the isotropic model, the number of the fitted observed data also is two times as large as that for the isotropic model.

After the linearization of the inversion problem the following inversion normal equation can be formed:

$$[A][\Delta \ln \lambda]=[\Delta \ln \rho] \tag{2}$$

here $[A]$ is partial derivative matrix of the response functions for the model parameters, $[\Delta \ln \lambda]$ is the logarithm values of the parameter's corrected vector, $[\Delta \ln \rho]$ is the vector of the response function's difference values, which is expressed as the difference between the observed logarithm value and the calculated value for the model. Here SVD is used to calculate the generalized inversion matrix of $[A]$. In order to overcome the difficulty brought by the ill-condition of equation (2) as to make the inverse iteration converge steadily, in the inverse-iteration process a damping factor is added, which decreases gradually in the process.

The inverse tests for some theoretical models show that generally, when the primary model is enough different to the theoretical model, "the observed data" always can be fitted with higher accuracy, and the model whose parameters enough approach those of the theoretical model with the distinguishable level corresponding the fitted accuracy of the data can be found. After 3—5 times of the iterations in the early stages of the inversion the relative fitted difference descends by one order of magnitude, it is shown that for inverse fitting of the observed data with the error of several percent the inverse method is effective and suitable. In comparison with the isotropic model having the same number of layers, since the anisotropic model is more complex and its more parameters must be obtained by inversion, the ranges of the non-uniqueness of inverse resolution and the equivalence of model parameters are larger, the curved surface of the objective function in the model parameter's space is more complex, it is more difficult to find the minimum point of the objective function corresponding to the theoretical model, and inverse iteration is needed more times probably. For the isotropic medium models it was demonstrated that in the most conditions the RI inversion is more advantageous than the AP inversion apparently (Lin and Wu, 1991), the primary tests show that for the anisotropic medium the phenemona also existed.

Using the AP inversion of symmetrical anisotropic layered model the observed apparent resistivity and phase data along two measured directions at two sites basically are fitted in the observed error range (Fig. 2). Two sites are not far from each other, the conductivity structures obtained by the inversion of the anisotropic medium for two sites are analogous to each other (Tab. 2). The first electrical layered boundary of two models probably corresponds to the boundary between the Cretaceous and Jurassic layers given by the drill data here, is shallower than the latter a little, and the second layer with lower resistivity is guessed as the Jurassic J_3 layer (Lin and Wu, 1993). Except for the surface layer, the lower resistivity direction of the other layers, given by the inversion, is about N 0°—10° E which quite approaches the P-axis direction (N7° E) given by the focal mechanism solution of the Minqin earthquake in 1954 (it is not far from the site), the direction was inferred as the direction of the regional tectonic principal pressure stress in the area (Yan et al., 1979). It is shown that the MT inversion of anisotropic medium has better prospects for the research of the stress state in the deep crust.

Tab. 2 The results fitted for the MT observed data at two sites using AP inversion

Param.	ρ_1^1	ρ_2^1	ρ_3^1	ρ_4^1	ρ_5^1	ρ_1^2	ρ_2^2	ρ_3^2	ρ_4^2	ρ_5^2
site 1	6.63	1.46	36.3	1.49	7.52	27.6	3.37	118	1.16	1.36
site 2	5.02	1.77	51.2	1.65	13.8	35.4	2.92	139	0.79	2.01
Param.	θ_1	θ_2	θ_3	θ_4	θ_5	h_1	h_2	h_3	h_4	F.E.
site 1	47.3	9.88	7.02	88.2	81.0	0.84	0.45	4.29	6.32	4.5%
site 2	34.5	9.39	5.51	96.6	74.5	0.97	0.47	5.03	6.79	5.6%

Param. is model parameter; F.E. is the relative fitting error of the inversion.

4 The Characteristics of the MT Response Function's Variation at the Sensitive Locations of the EDA Precursor around the Focal Region

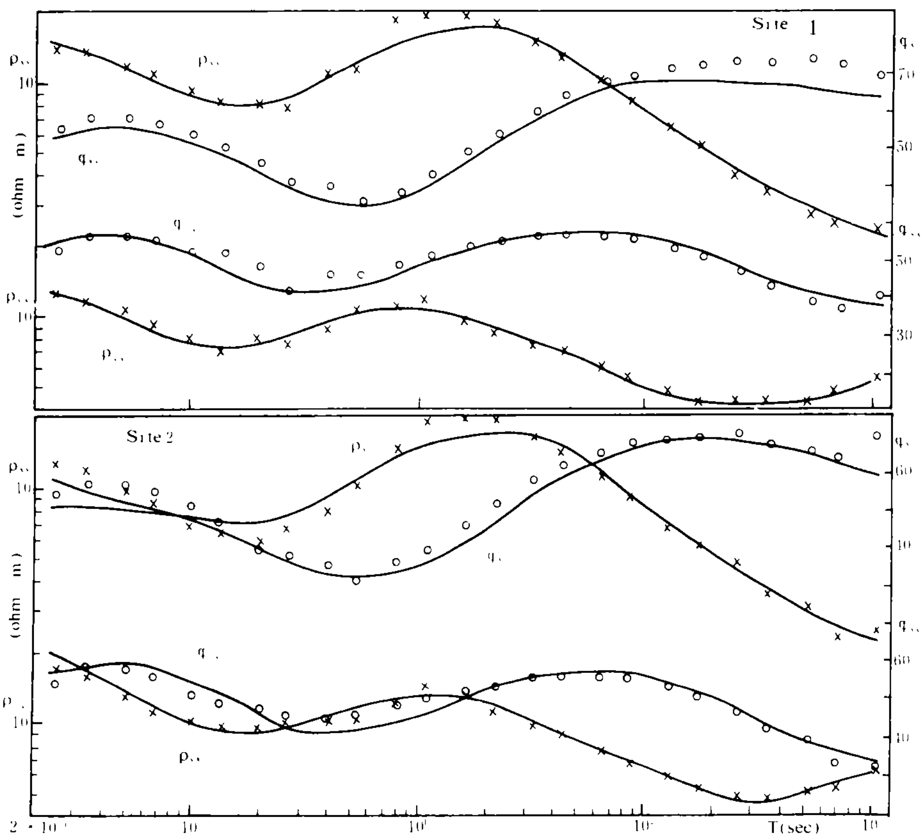

Fig. 2 The fitted results of the MT data at two sites by using AP inversion for the symmetrical anisotropic layered model.

The analysis and research of the observed earthquake precursors show that the space distribution of many precursors has more complex characters, some locations probably become the sensitive response points of some earthquake precursors, the precursor data observed in the locations include more useful informations, their background noise level is lower, to use these data for monitoring and predicting earthquakes is advantageous. Savage et al. analysed S-wave splitting data observed in California, U. S. A. during 1977—1988, and indicated that the EDA precursors observed at some sites mainly were from a smaller region near the site in the vicinity of an active fault. In the active fault belt a lot of the microcracks oriented along the fault strike were developed, the changes of the precursor stress field resulted in the variation of the crack porosity and shape ratio, and led up to more apparent EDA precursor variation which can be analysed and studied more easily by using S-wave splitting data (Savage et al., 1990). Thus the location in the vicinity of some active fault belt probably becomes the sensitive response location of the EDA precursor. The research of the Yamasaki active fault in Japan showed that its conductivity distribution appeared zonal characteristics clearly (Electromagnetic Research Group for the Active Fault, 1982). Generally, the active fault consists of a low resistive zone (or several zones), this is relative to the oriented microcracks including water along the fault strike.

To study the EDA electrical variation in the vicinity of an active fault using MTS is a MT anisotropic two-dimensional modelling problem. As an approximation, the electrical anisotropy around the fault belt is neglected. Since dominant direction of the microcrack orientation is always along the fault strike, i. e. low resistive direction of the conductivity anisotropy in the fault belt, and the lateral direction becomes the high resistive dircetion, here the EDA electrical anisotropy change mainly shows as change of the electrical anisotropic coefficient and there is no change of anisotropic principal direction. Because the fault belt has larger longwide ratio, the problem can be reduced to MT modelling for a symmetrical anisotropic two-dimensional medium, only the medium in the conductive zone is anisotropic, and low resistive direction is along the structure strike. In general MT two-dimensional anisotropic condition, TE and TM polarizations can not be separated and studied separately, the EM field components, Ex and Hx, along the strike couple each other, two nonhomogeneous partial differential equations are formed (Reddy and Rakin, 1975). However, in this problem one of the anisotropic principal directions coincides with the strike, let $\sigma_{xx}=\sigma_{yy}, \sigma_{xy}=\sigma_{yx}=0$, then two equations can be uncoupled and the following two partial differential equations are formed:

$$\partial^2 H_x/\partial Y^2+\partial^2 H_x/\partial Z^2+j\omega\mu k_y H_x=0$$
$$\partial^2 E_x/\partial Y^2+\partial^2 E_x/\partial Z^2+j\omega\mu k_x E_x=0 \qquad (4)$$

here $k_i=\sigma_i-J\omega\varepsilon, i=x,y$; σ_x and σ_y are the conductivities along the strike direction and its perpendicular direction separately. The equations (3) and (4) are analogous to the TM and TE polarizations for the isotropic two-dimensional medium. Thus the problem of MT modelling for the anisotropic two-dimensional medium can be resolved by the modelling for the isotropic two-dimensional medium, only the different conductivities σ_x and σ_y) are adopted in the TE and

TM calculations separately.

On the basis of the conductivity structure models of the crust in some seismic regions of Northwestern China a four-layer one-dimensional model is used as the background medel, it is representative. An anisotropic two-dimensional conductive zone included in the medel is used to model the fault belt. In the modelling, the conductivity anisotropic coefficient of conductive zone is changed (to change the conductivity value along a principal direction or to change two conductivity values along two principal directions at the same time), the variational characteristics of the apparent resistivities and phases at various locations on the earth's surface are studied. After analysis the following conclusions are obtained: a) When certain changes of the conductivity anisotropic coefficient in the conductive zone occur, the distinguishable variations of two apparent resistivity and phase values in a certain range on the earth's surface can be observed; b) If the conductivity only in a principal direction changes, the apparent resistivity and phase values only in the direction are affected; c) If the change of the conductivity anisotropic coefficient is due to the synchronous changes in two directions, above the conductive zone the response functions of TM mode are more sensitive to the change, and the space range in which the TE response are affected by the change is wider; d) The change of the conductivity anisotropic coefficient in an incline conductive zone affects MT response functions in wider range, the magnitude of the variations and the frequency band range which is affected by the change more apparently at a given site depend on the location of the site relative to the conductive zone; e) The existence of a surface overburden with low resistivity apparently reduces the influence of the conductivity anisotropy change in the conductive zone on various MT response functions.

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利用大地电磁测深法识别 EDA 地震电性变化前兆

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摘要　论述了起因于 EDA 现象的地球介质电导率各向异性特征，分析研究了地球介质电导率各向异性变化引起的大地电磁响应函数变化形态特征，简述了大地电磁测深法对 EDA 电性变化前兆的可识别性及大地电磁资料解释中考虑电导率各向异性的必要性，研究了对称各向异性层状介质大地电磁资料的反演问题。

主题词：地震前兆　大地电磁测深　电导率各向异性　膨胀各向异性