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标量拟解析近似方法模拟立方体的异常电场

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摘　要: 拟解析近似方法是一种求解积分方程的一种近似方法，它可以处理强散射或者大扰动的电磁散射问题，在计算过程中避免了传统微分数值方法解决问题时所遇到的大型矩阵或大型代数方程组的求解。孙建国[5]将其引入直流电场的积分方程中，并给出了求解异常电场积分方程的标量拟解析近似公式。在以前的研究中，已经验证了均匀场中异常球体的拟解析近似解的精度，这里对均匀场中的立方体异常体进行数值模拟，得到了直流电场中异常立方体模型的标量拟解析近似解。由于复杂地电模型可以用立方体的组合进行模拟，因此对立方体异常电场拟解析近似解的研究，为三维直流电场中复杂地电模型的快速正反演模拟打下了基础。

关键词: 积分方程; 拟解析近似; 直流电场; 立方体

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0　前言

近年来我国资源形势日益严峻，大规模的经济建设对金属矿的需求越来越大，对于资源的需求应该立足于国内，因此要加大国内金属矿勘探的力度。在金属矿勘探中，电法勘探占有重要地位，研究直流电场快速数值模拟，对于推进电法勘探的发展有着重要的意义。三维直流电场数值模拟的方法很多，大致可以分为微分方法和积分方法。在传统的数值方法中，都会遇到大型矩阵或求解大型线性代数方程组的问题，这对计算机硬件要求高，计算周期长。尤其是在复杂地质条件下，这些问题更为突出，所以寻求快速精确的数值模拟方法，一直是地球物理工作者的研究重点。积分方程法在解决三维直流电场问题中有其优点，如积分方程法只需对异常体进行计算，而不需要对背景区域进行计算，微分方程法在计算过程中存在误差累积并传递到下一次迭代中，而积分方程法不存在误差的累积和传递。基于这些优点，前人对积分方程法进行了很多的研究。T M Habashy 等[1]提出用局部非线性近似方法，对电磁场问题进行研究，但这种方法运算复杂不适于实际应用推广。Zhdanov 等[2]受到 T M Habashy 的局部非线性近似方法的启发，在遇电磁场散射场问题时提出了拟线性近似方法求解散射场的积分方程。这种方法通过假设异常电场 $E_a(r)$ 与正常电场 $E_0(r)$ 之间是由电反射张量 $\hat{\lambda}(r)$ 联系起来的拟线性关系，即: $E_a(r) = \hat{\lambda} \cdot E_a(r)$。简化了电磁散射的积分方程，从而可以提高计算速度，电反射张量 $\hat{\lambda}(r)$ 由最优化的方法求出。Zhdanov[3]在 2000 年将拟线性近似方法应用于电磁场反演，并用来反演美国新墨西哥州的 CSAMT 数据。由于拟线性近似时仍无法避开解线性代数方程组，因此 Zhdanov 经过研究后，提出假设电反射张量 $\hat{\lambda}(r)$ 在异常体内为缓变函数，由一

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种相对简单的替代方法确定$\hat{\lambda}(r)$，这种方法称为拟解析近似方法[4]，并提出了拟解析近似序列。孙建国[5、6]在通过电磁场中的拟线性近似方法和拟解析方法研究的基础上，先后提出将拟线性近似方法和拟解析近似方法的应用，扩展到直流电场模拟及声波散射模拟。孙建国[7~9]分别对2.5维直流电阻率正演和地球物理反演中拟线性近似方法的应用进行了讨论，接下来又研究了稳定电流场的电位反射函数。孙建国[10~12]2004年对稳定电流场中的拟线性近似方法进行了研究，给出了直流电位场数值模拟的拟解析方法。在2005年孙建国[13、14]研究了直流电场中的电反射张量，给出直流电场中的拟线性近似方法和拟解析近似方法的理论公式，并对电反射张量进行了详细的分析，对稳定电流场拟解析近似方法也进行精度分析。在2006年，孙建国[15]又对稳定电流场拟解析近似方法进行了数值评价。在2008年，张金会[17]用拟解析近似方法对均匀场中的异常球体进行了研究，并对拟解析近似方法的精度进行了分析和研究。

在2005年J. Sun推导出直流电场的标量拟解析近似的理论公式基础上，作者用标量拟解析近似对均匀场中的异常立方体进行研究。不同的立方体的组合，可以对复杂异常体进行模拟。当有多个异常体组合模拟复杂异常体时，异常立方体直接的异常电场会受到其它异常体所产生的二次场的影响，因此在进行模拟时，还要考虑异常体所产生的二次场之间的相互影响。作者对单独异常体的拟解析近似方法研究，为复杂地电模型的研究打下了基础，为三维直流电场中的复杂异常的正反演模拟奠定算法基础，可以加快三维电法勘探的进程，具有较高的实际意义。

1 基本方程及公式

J. Sun在其文章中给出标量拟解析近似方法的理论公式，作者利用其理论公式，推导得到拟解析近似方法在实现过程中的具体实现细节部份。在进行三维异常体数值模拟时，积分采用三维高斯积分进行计算，并对积分中出现的格林函数的奇异性进行了处理，采用处理方法简单，不增加运算量的挖去法[18]，在控制挖去小体积限度的基础上，得到了很好的计算效果，实现了拟解析近似方法在直流电场模拟中的应用。

一次场中异常体内部二次直流电场的积分方程[13]为：

$$E_a(r)=\int_{\Omega}\frac{\hat{G}(r',r)\cdot j_a(r')}{\mu\sigma_0(r')}\mathrm{d}r'-\frac{\sigma_a(r)}{\sigma_0(r)}E_0(r) \tag{1}$$

异常体外部的积分方程[13]为：

$$E_a(r)=\int_{\Omega}\frac{\hat{G}(r',r)\cdot j_a(r')}{\mu\sigma_0(r')}\mathrm{d}r' \tag{2}$$

在上面的方程中Ω表示异常体，$j_a(r)$为二次电流密度，由式(3)给出：

$$j_a(r)=\sigma_a(r)E(r)=\sigma_a(r)[E_0(r)+E_a(r)] \tag{3}$$

其中$\hat{G}(r',r)$为源在r'的并矢格林函数，令$E_a(r)=\hat{\lambda}(r)\cdot E_0(r)$，并将其同式(3)一起代入式(1)中并进行整理，可以得到[13]

$$\hat{\lambda}(r)\cdot E_0(r)=\frac{\sigma_0(r)}{\sigma(r)}E_{Ba}(r)-\frac{\sigma_a(r)}{\sigma(r)}E_0(r)+\frac{\sigma_0(r)}{\sigma(r)}L\nu\left[\frac{\sigma_a(r')\hat{\lambda}(r')\cdot E_0(r')}{\mu\sigma_0(r')}\right] \tag{4}$$

$$L\nu=\int_{\Omega}\mathrm{d}r'\hat{G}(r',r) \tag{5}$$

$$E_{Ba}(r)=L\nu\left[\frac{\sigma_a(r')}{\mu\sigma_0(r')}E_0(r')\right] \tag{6}$$

其中$E_{Ba}(r)$为$E_a(r)$的Born近似；$\hat{G}(r',r)$为并矢格林函数，由式(7)给出

$$\hat{G}(r',r)=\nabla\times\nabla\times\hat{G}_0(r',r) \tag{7}$$

其中$\hat{G}_0(r',r)$为下面矢量位方程并矢格林函数

$$\nabla^2A_a(r)=-\mu j_a(r') \tag{8}$$

推导出$\hat{G}(r',r)$的形式为式(9)。

$$\hat{\boldsymbol{G}}=\frac{1}{4\pi}\begin{bmatrix}-\frac{2}{r_s^3}-\frac{3(y-y')^2+3(z-z')^2}{r_s^5} & \frac{3(x-x')(y-y')}{r_s^5} & \frac{3(x-x')(z-z')}{r_s^5}\\ \frac{3(x-x')(y-y')}{r_s^5} & -\frac{2}{r_s^3}-\frac{3(z-z')^2+3(x-x')^2}{r_s^5} & \frac{3(y-y')(z-z')}{r_s^5}\\ \frac{3(x-x')(z-z')}{r_s^5} & \frac{3(y-y')(z-z')}{r_s^5} & -\frac{2}{r_s^3}-\frac{3(x-x')^2+3(y-y')^2}{r_s^5}\end{bmatrix} \tag{9}$$

式中　$r_s = [(x - x')^2 + (y - y')^2 + (z - z')^2]^{\frac{1}{2}}$

J. Sun[13] 于 2005 年通过假设电反射张量为 0 阶张量,令:

$$\hat{\lambda} = \lambda(r) I \tag{10}$$

其中　I 为单位张量,得到了方程(4) 的解:

$$\lambda(r) E_0(r) \approx \frac{\sigma_0(r)}{\sigma(r)} E_{Ba}(r) - \frac{\sigma_a(r)}{\sigma(r)} E_0(r) + \lambda(r) \frac{\sigma_0(r)}{\sigma(r)} E_{Ba}(r) \tag{11}$$

通过对式(11) 进行整理,可以得到:

$$\lambda(r) \approx \frac{g(r) - \dfrac{\sigma_a(r)}{\sigma(r)}}{1 - g(r)} \tag{12}$$

在式(12) 中

$$g(r) = \frac{\sigma_0(r)}{\sigma(r)} \frac{E_{Ba}(r) \cdot E_0(r)}{E_0(r) \cdot E_0(r)} \tag{13}$$

将式(12) 代入到式(1) 中,可以得到[13]:

$$E_a(r) \approx \int_\Omega \frac{1}{1 - g(r)} \frac{\sigma_a(r') \hat{G}(r',r) \cdot E_0(r')}{\mu\sigma(r')} dr' - \frac{\sigma_a(r)}{\sigma(r)} \frac{1}{1 - g(r)} E_0(r) \tag{14}$$

将式(14) 得到的 $E_a(r)$ 代入式(3) ,可以得到 $j_a(r)$,将 $j_a(r)$ 代入式(2) 中,即可得到异常体外部的异常电场:

$$E_a(r) = \int_\Omega \frac{\hat{G}(r',r) \cdot j_a(r')}{\mu\sigma_0(r')} dr' \tag{15}$$

通过方程(4) ,我们可以建立拟解析近似的迭代方程(16) [13]:

$$\hat{\lambda}^{m+1}(r) \cdot E_0(r) = \frac{\sigma_0(r)}{\sigma(r)} E_{Ba}(r) - \frac{\sigma_a(r)}{\sigma(r)} E_0(r) + \frac{\sigma_0(r)}{\sigma(r)} L\nu\left[\frac{\sigma_a(r') \hat{\lambda}^m(r') \cdot E_0(r')}{\mu\sigma_0(r')}\right] \tag{16}$$

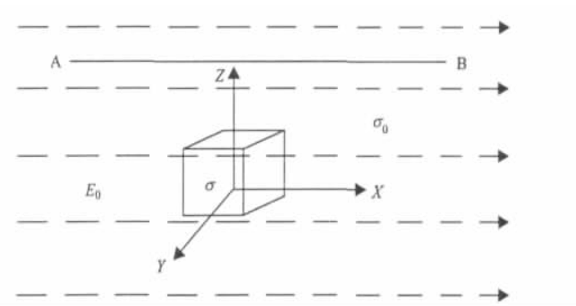
其中　m 是迭代数。令

$$\hat{\lambda}^0(r') = 0 \tag{17}$$

利用方程(16) ,当异常体电导率同围岩相比变化剧烈,即大扰动时,拟解析近似解不能得到想要的结果,我们可以通过式(16) 的拟解析近似的迭代解得到满意的结果。在一般情况下,迭代次数 m 在不超过 5 的情况下,我们就能得到满意结果。

2　标量拟解析近似立方体异常体电场值计算

很多矿体可以由立方体组合进行近似,选取立方体异常进行研究,得到的异常体为立方体时的异常电场。在研究中给定异常体为立方体,利用标量拟解析近似方法进行计算,求出异常电场的拟解析近似解,并与 Born 近似解进行比较,选取的均匀场场源中的异常立方体进行计算。立方体边长为 100 m,中心坐标为(0 m,0 m,0 m) ,通过背景介质和异常电导率变化,可以得到不同的模型。异常体外部异常电场计算点,关于立方体中心对称分布在 $z = 400$ m 处沿 x 方向。针对六种不同背景介质电导率与立方体异常电导率的模型,分别进行计算均匀场中不同电导率的外部电场。地电模型见图 1。



模型中电场 E_0(V/m) 沿 x 轴方向,大小为 (10,0,0) 。背景介质为均匀全空间,AB 为 $y = 0$ m、$z = 400$ m、$-2\,000$ m $< x <$ 2 000 m 处的测线

图 1　均匀场中异常立方体模型示意图

Fig. 1　Model of anomalous cube in the uniform field

针对于均匀场中的异常立方体,我们进行了下面几组不同电导率的模型的试算。

(1) 从下页图 2、图 3 可看出 Born 近似解与拟解析近似解相差很小,与异常球体表现出的现象相同。

(2) 后面的图 4、图 5 都是高阻立方体。由异常体引起的电场的 Born 近似解与拟解析近似解相差很大,这是由于 Born 近似解没有考虑二次电场对异常电场的影响。当二次电场对异常电场影响较大时,使得拟解析近似解的数值较 Born 近似解高。

(3) 图 2 至图 7(见后面) 中的曲线,给出了均匀场中不同背景的电导率,与异常电导率立方体模型的异常电场 E_a 的 x、z 分量。由均匀场中的球体的计算结果分析,可以得出图中的拟解析近似解比 Born 近似解更接近实际结果。

3 结论

积分方程法具有直接对异常体区域进行数值积分的优点，避免了传统数值方法解决问题时所遇到的求解大型矩阵或大型代数方程组。利用标量拟解析近似方法可以对直流电场的积分方程进行求解，作者在本文对异常体为立方体时的异常电场进行了标量拟解析近似数值模拟，该方法对于其它形状的异常体也同样可以适用，如椭球体、圆柱体等。作者通过对均匀场中的异常立方体进行的标量拟解析模拟，表明标量拟解析近似方法具有很强的适应性。当异常体电导率变化较大时，可以通过对标量拟解析近似解进行迭代仍可以达到很好的效果，这表明该方法可以用于大扰动问题的模拟。立方体异常体的空间组合可以用来模拟复杂分布的地下矿体，本文作者对立方体异常的拟解析近似研究，为解决复杂地电模型提供了借鉴，初步表明了该方法具有处理复杂地电结构的模型的能力。作者通过对直流电场标量拟解析近似方法实现的研究，为三维直流电场的快速正反演模拟，提供了快速的精确度高的数值模拟方法。

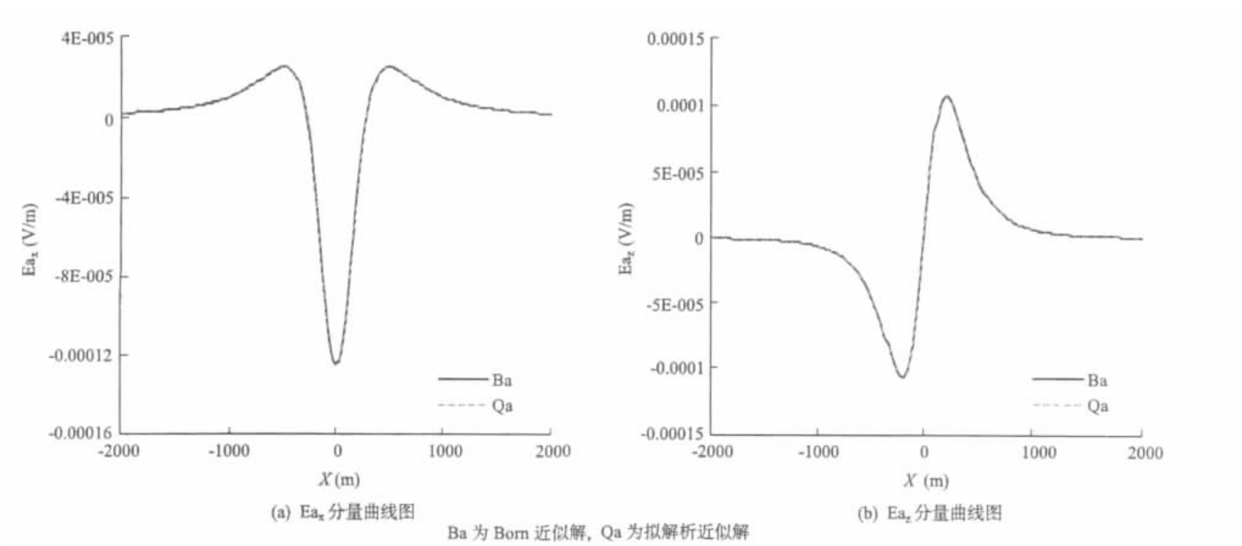


图 2 $\sigma_0 = 1.0$ S，$\sigma_a = 0.01$ S 时异常电场曲线图

Fig. 2 While $\sigma_0 = 1.0$ S, $\sigma_a = 0.01$ S, the anomalous electrical field curves

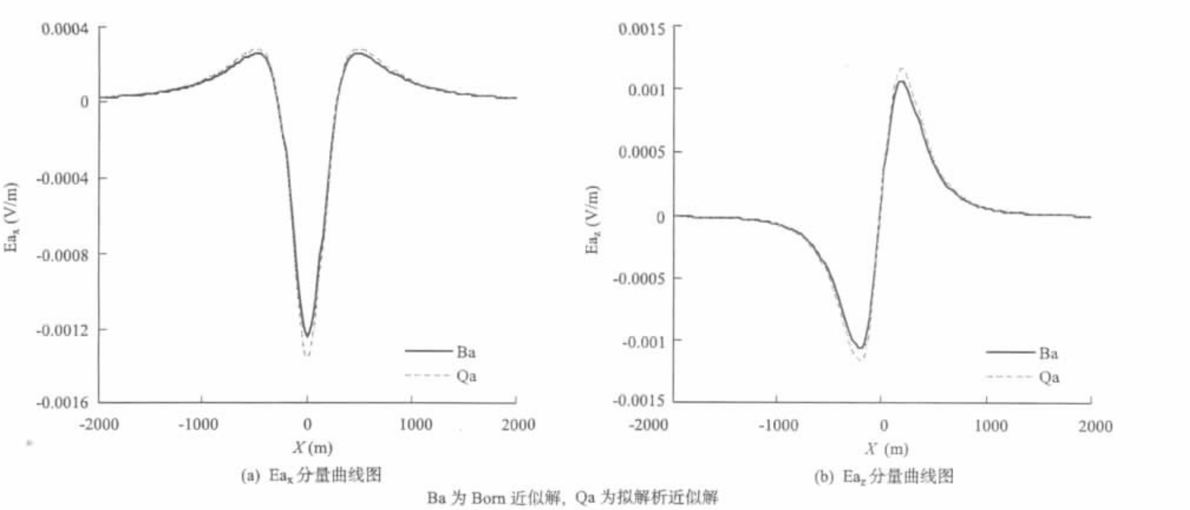


图 3 $\sigma_0 = 1.0$ S，$\sigma_a = 0.01$ S 时异常电场曲线图

Fig. 3 While $\sigma_0 = 1.0$ S, $\sigma_a = 0.1$ S, the anomalous electrical field curves

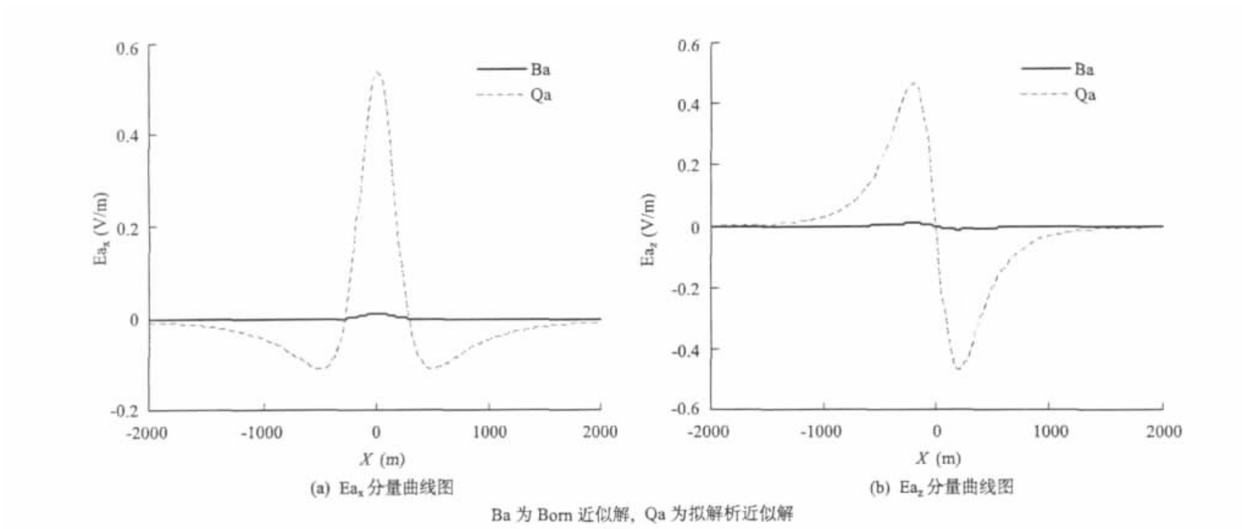


图 4　$\sigma_0 = 1.0$ S, $\sigma_a = -0.9$ S 时异常电场曲线图

Fig. 4　$\sigma_0 = 1.0$ S, $\sigma_a = -0.9$ S, the anomalous electrical field curves

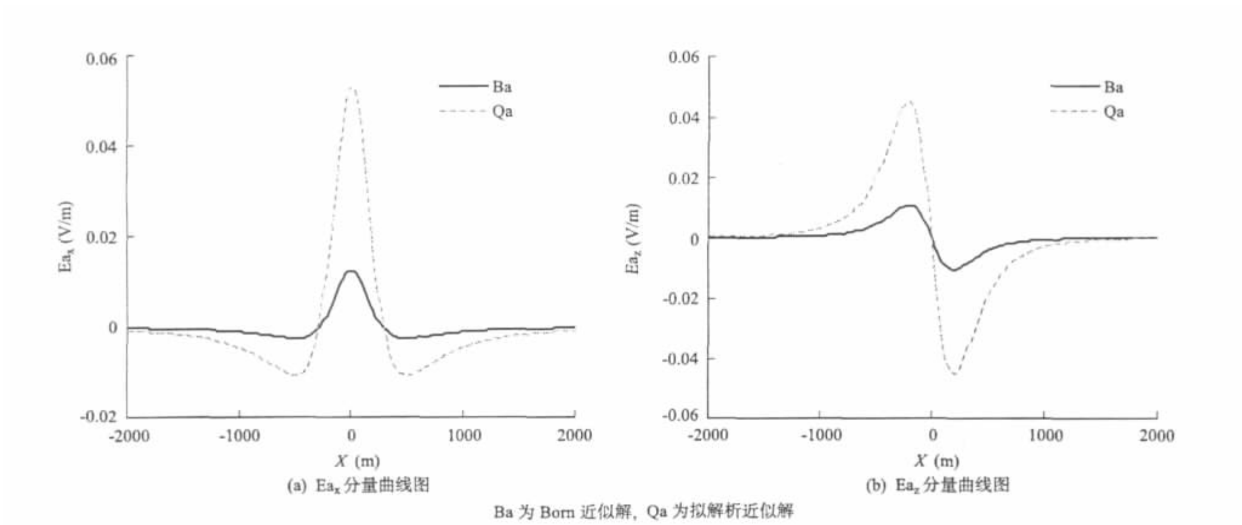


图 5　$\sigma_0 = 1.0$ S, $\sigma_a = -0.99$ S 时异常电场曲线图

Fig. 5　$\sigma_0 = 1.0$ S, $\sigma_a = -0.99$ S, the anomalous electrical field curves

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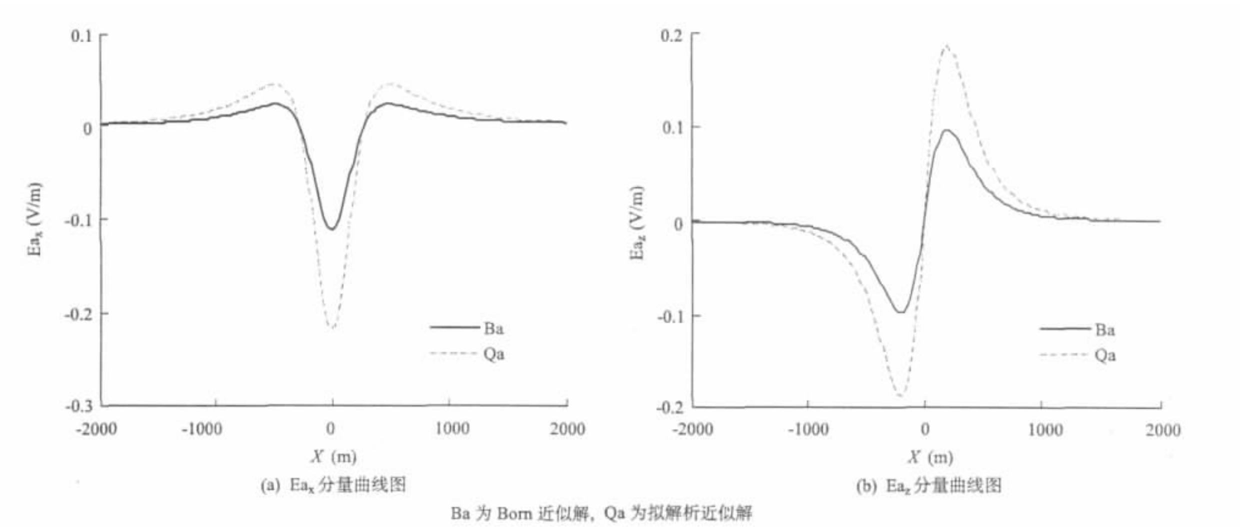

图 6 $\sigma_0 = 0.1$ S，$\sigma_a = 0.9$ S 时异常电场曲线图

Fig. 6 $\sigma_0 = 0.1$ S, $\sigma_a = 0.9$ S, the anomalous electrical field curves

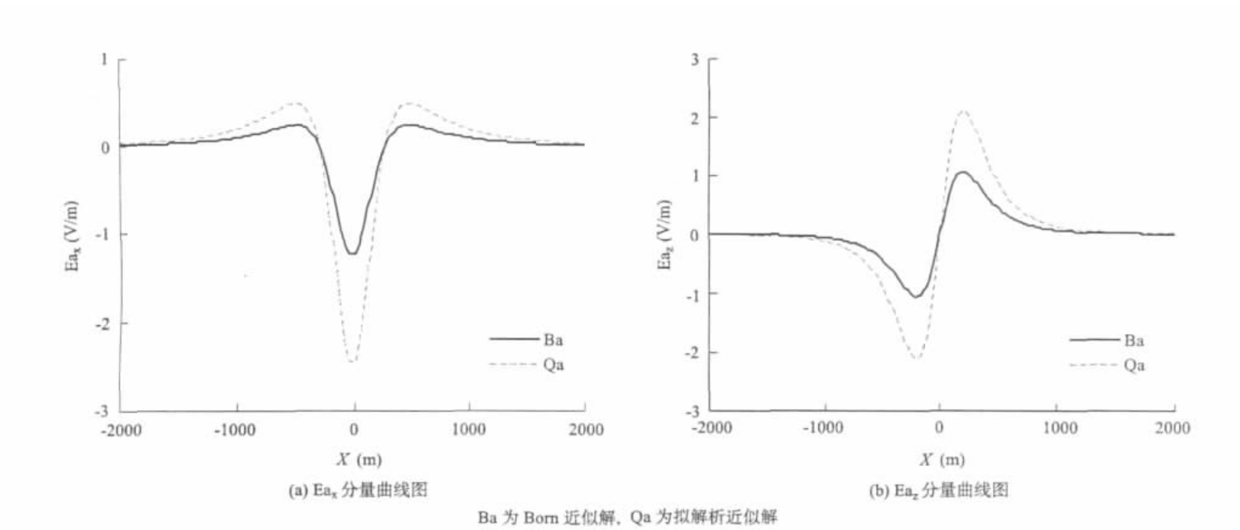

图 7 $\sigma_0 = 0.01$ S，$\sigma_a = 0.99$ S 时异常电场曲线图

Fig. 7 $\sigma_0 = 0.01$ S, $\sigma_a = 0.99$ S, The anomalous electrical field curves

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The reef identifying is significant to confirm the reservoir in the carbonate reservoir exploration. Variance Analysis Technology is an effective technique in checking the underground faults、the discontinuous stratum and abnormal geologic bodies. Firstly, this paper introduces the basic principles, and then focuses on analyzing the results in identifying reef and describing depositional facies, which confirm technical's advantages and good prospects.

Key words: variance cube; coherence technique; organic reef; depositional facies

EVENTS PICKING AND INTERPRETATION BASED ON COHERENCY SECTION

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Events picking on fault and sedimentary feature using the plane characteristics of coherency attributes has already been widely applied, but the characteristics of coherency attributes on sections are often neglected. The study shows that the features of coherent attributes on the sections can provide more sophisticated information on geological structures and sedimentary features besides the plane features. Particularly, we can use coherent attributes to track and interpret the horizons directly, moreover, we can get accuracy tracking and high resolution interpretation results with using of the characteristics of coherency on sections. This paper proposes the approaches of horizon tracking and interpreting using coherence attributes on the sections. With compared the steps and workflow with those using amplitude attributes, it is summarized that the advantages and disadvantages of horizon tracking and interpreting using coherency attributes on sections and the steps and workflow. The alternative method of horizon tracking and interpreting is provided in this paper, and good results are also achieved by applying the approaches in real data interpretation.

Key words: coherency attributes section; amplitude section; horizon tracking and interpretation

STUDY ON THE KEY PARAMETERS OF KIRCHHOFF PRE-STACK TIME MIGRATION

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Pre-stack time migration has become a routine means of seismic data processing, we could get a good imaging result in the circumstance of a complex structure and smooth lateral variation of velocity field by using pre-stack time migration. However, pre-stack time migration is a systematic approach, and the selection of a number of supporting techniques and some key parameters directly affect the imaging results. Based on the workflow of pre-stack time migration processing of OMEGA2 software, we summarize how to choose the supporting techniques involved in pre-stack time migration processing and the key parameters including pre-stack offsets , offset selected dip and aperture, RMS velocity modeling, and travel time. Combined g the test procedures of the study and discussion, The basic principles of selecting the key parameters are proposed, which has the high value for guiding the actual processing work.

Key words: kirchhoff pre-stack time migration; image by migration; key parameters

THE SCALAR QUASI-ANALYTICAL METHOD MODELING FOR ANOMALOUS ELECTRICAL FIELD OF THE ANOMALOUS CUBE

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The Quasi-analytical method is an approximation method for solving the integral equations which can deal with problems of strong scattering or large disturbing. In the process of calculation, it avoids the solving of the large matrix and the team algebraic equations, which was always encountered in the traditional differential coefficient methods. Sun J introduce this method into solving of the D. C. electric field integral equations, and he put forward the academic formulas. In the previous research, we had validated the precision of this method. In this paper we calculated the anomalous cube in the symmetrical field, got the Qua-

si-analytical solution of cube model. Due to the complex model decomposing into some cubes, the study of the cube model can pave way for the quasi-analytical method used in fast forward and inverse modeling of the complex model in the 3D D. C. electric field.

Key words: integration equation; the quasi-analytical method; D. C. electrical field; cube

DISCUSSION ON THE SENSITIVITY OF EACH MODE DISPERSION CURVES RAYLEIGH WAVE WITH THE SHEAR WAVE VELOCITY AND DEPTH OF STRATUM

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The exploration of Rayleigh surface wave aimed at effectively using dispersion curves to inverse the shear wave velocity and depth of stratum, but sensitivity of each mode with the shear wave velocity and depth of stratum are different. Frequency-phase velocity difference curve of each mode is obtained by subtracting the dispersion curve from the dispersion curve with one of the media parameter 10% changed. The sensitivity of each mode of Rayleigh wave with the shear wave velocity and depth of stratum of every layer is analyzed and discussed. Experimental results show that fundamental mode is more sensitive to the shear wave velocity and depth of stratum of shallow layer, and sensitive areas mainly concentrate on the narrow frequency range, while higher modes are more sensitive to the shear wave velocity and depth of stratum of deeper layer, and sensitive areas mainly concentrate on the wide frequency range, the distributions of frequency bands with strong sensitivity are scattered. The results can provide a theoretical basis for the multi-mode joint inversion of rayleigh surface waves.

Key words: dispersion curve of rayleigh wave; shear wave velocity; depth of stratum; sensitivity

APPLICATIONS OF STABILITY EXPLORATION WITH HIGH - DENSITY ELECTRICAL METHOD IN THE XILING SNOW MOUNTAIN RESERVOIR

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According to the shallow survey on the constructing working area in Snow Mountain reservoir, the study on the covering layer of working area and the electrical differences of bedrock, the abnormal characteristics of fracture and some comparing and correcting are carried out based on borehole data. The results show that there is obvious electrical differences among the bedrock, overburden rock and cracks and surrounding rock in working area. After the test line inversion of apparent resistivity anomalies and cross - section, a clear reflection of the up and down of bedrock and extension distribution of fracture underground rock and underground depth of the situation are showed, and thus the adverse geological scale can be delineated, and geological condition is provided to reservoir constructions.

Key words: high-density electrical method; cover layer thickness; crack

STUDY ON THE GEOLOGICAL CHARACTERISTICS IN THE PRIMARY MINING AREA OF SHARANG MOLYBDENUM DEPOSIT, TIBET

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Sharang molybdenum deposit is magmatic hydrothermal mineral deposit, the molybdenum orebodies mainly occur as veinlet and netted venation within the plagioclase granite-porphyry fracture zone, and the general strike of the orebody is EW. The industrial type of the ore is primary molybdenum sulfide, the main metallic mineral are molybdenite, pyrite, ilmenite. Molybdenite occur as schistose, granular and powdered in the ore, and the grain size of molybdenite single crystal ≤0. 1 mm ~ 2 mm, the content of molybdenite in the ore is 0. 1% ~ 3. 35%. Based on the petro-chemistry analysis, the paper indicates that in the collision process and post-orogenetic process, the magma hybridization is distinct from crustal matter, and the magmatic differentiation of anatectic magma is widely different. For that reason, the ore-bearing rock bodies in the Sharang deposit have the characteristic which is not only different from typical S-type granites, but also different from typical I-type granites.

Key words: granite-porphyry; primary sulfide deposit; geological character; sharang molybdenum deposit

STUDY OF CORRELATION OF FRACTURE CAUSED BY COAL MINE PRODUCTION AND RADON CONCENTRATION

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