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碳酸盐岩储集层模型数值模拟与分析

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摘 要:碳酸盐岩储层作为油气勘探领域中的重要研究目标,其波场特征变化极为复杂,为提高对该类储集层多波地震资料的认知度,高精度数值模拟是行之有效的方法之一。这里在各向同性弹性波方程基础上,推导了纵波、横波分离方程,运用高阶交错网格有限差分技术与PML边界吸收技术,高精度模拟地震波在碳酸盐岩储层中的传播,得到了该类储层模型中的弹性波全波场,也分离出纵波信息和转换波波场信息,并保留了各自能量信息。同时结合AVO技术分析了弹性波在碳酸盐岩储层中AVO响应特征,并通过对储层理论模型进行试算,分析研究该类储层中的波场响应特征及传播规律,为碳酸盐岩储层的识别与预测提供参考依据,更能满足复杂油气田勘探开发的实际需要。

关键词:碳酸盐岩;波场特征;AVO技术;PML;正演
中图分类号:TE 122.2+21 文献标识码:A

0 前言

碳酸盐岩储层是油气勘探领域中重要研究目标,研究其全波场响应特征对于储层的识别有着特别重要的意义。由于碳酸盐岩储层地层速度高,非均质性强,储层识别难度较大,究其原因,发现是由于碳酸盐岩储层的地震波场响应特征与其它类型储层不同,这将引起碳酸盐岩储层地震资料解释的多解性,因此储层所产生的复杂波场,增加了地震勘探难度。在多波资料解释过程中,要弄清碳酸盐岩储层的岩性与多波波场特征之间的关系,利用高精度数值模拟技术则显得尤为重要,它是联系地震、地质、测井以及油藏工程的纽带,其作用主要体现在提高人们对各种复杂介质中地震波传播规律的认知,并可为新技术、新方法提供试验数据,以满足方法技术研究的需要,同时也可以检验解释结果的正确性。因此,为了增强对该类储层复杂波场特征的识别,作者在本文通过理论模型研究地震波在碳酸盐储层中的传播规律与响应特性,利用地震正演全波场模拟和AVO分析技术,来识别碳酸盐岩储层的地震响应,可消除解释上的多解性,也为多波资料处理结果的判别提供理论依据。

1 高精度正演模拟方法原理

多波波场正演模拟是以弹性波方程为基础,其核心是研究高精度数值模拟技术。同时,结合边界处理技术,实现高精度、高效率正演。

1.1 各向同性介质中的一阶应力——速度弹性波方程

弹性波理论的研究基础是弹性体受力和应变的关系,根据各向同性介质表示的应力,即应变关系的本构方程和表示应变与位移的柯西方程,可以

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推导出各向同性介质中传播的一阶速度, 即应力弹性波方程[1]如式(1):

$$\begin{cases} \rho\dfrac{\partial v_x}{\partial t} = \dfrac{\partial \sigma_{xx}}{\partial x} + \dfrac{\partial \sigma_{xz}}{\partial z} \\ \rho\dfrac{\partial v_z}{\partial t} = \dfrac{\partial \sigma_{xz}}{\partial x} + \dfrac{\partial \sigma_{zz}}{\partial z} \\ \dfrac{\partial \sigma_{xx}}{\partial t} = (\lambda + 2\mu)\dfrac{\partial v_x}{\partial x} + \lambda\dfrac{\partial v_z}{\partial z} \\ \dfrac{\partial \sigma_{zz}}{\partial t} = \lambda\dfrac{\partial v_x}{\partial x} + (\lambda + 2\mu)\dfrac{\partial v_z}{\partial z} \\ \dfrac{\partial \sigma_{xz}}{\partial t} = \mu(\dfrac{\partial v_x}{\partial z} + \dfrac{\partial v_z}{\partial x}) \end{cases} \quad (1)$$

其中　λ、μ表示 Lame弹性常数; ρ为弹性体密度; σ_{xx}、σ_{zz}表示正应力; σ_{xz}表示切应力; v_x、v_z分别表示 x 方向、z 方向速度分量。

1.2　一阶应力——速度各向同性弹性波波场分离方程

在均匀各向同性介质中, 全弹性波的波场可分解为纯纵波和纯横波二部份[2]。通过分解全弹性波方程, 可以既得到完全弹性波方程, 又满足 P波和 S波方程的一阶应力, 即速度等价方程。

为构造等价方程, 在方程(1)的基础上, 引入混合波场新变量 $U = \{v_x, v_z\}$, P波波场新变量 $U_p = \{vp_x, vp_z\}$和 S波波场新变量 $U_s = \{vs_x, vs_z\}$, 并满足如下方程:

$$\begin{cases} \rho\dfrac{\partial vp_x}{\partial t} = \dfrac{\partial \delta p_{xx}}{\partial x} \\ \rho\dfrac{\partial vp_z}{\partial t} = \dfrac{\partial \delta p_{zz}}{\partial z} \\ \dfrac{\partial \delta p_{xx}}{\partial t} = \rho V_p^2(\dfrac{\partial v_x}{\partial x} + \dfrac{\partial v_z}{\partial z}) \\ \dfrac{\partial \delta p_{zz}}{\partial t} = \rho V_p^2(\dfrac{\partial v_x}{\partial x} + \dfrac{\partial v_z}{\partial z}) \end{cases} \quad (2)$$

$$\begin{cases} \rho\dfrac{\partial vs_x}{\partial t} = \dfrac{\partial \delta s_{xx}}{\partial x} + \dfrac{\partial \delta s_{xz}}{\partial z} \\ \rho\dfrac{\partial vs_z}{\partial t} = \dfrac{\partial \delta s_{xz}}{\partial x} + \dfrac{\partial \delta s_{zz}}{\partial z} \\ \dfrac{\partial \delta s_{xx}}{\partial t} = -2\rho V_s^2\dfrac{\partial v_z}{\partial z} \\ \dfrac{\partial \delta s_{zz}}{\partial t} = -2\rho V_s^2\dfrac{\partial v_x}{\partial x} \\ \dfrac{\partial \delta s_{xz}}{\partial t} = \rho V_s^2(\dfrac{\partial v_x}{\partial z} + \dfrac{\partial v_z}{\partial x}) \end{cases} \quad (3)$$

$$\begin{cases} v_x = vp_x + vs_x \\ v_z = vp_z + vs_z \end{cases} \quad (4)$$

其中　$vp_i\,(i = x, z)$、$vs_i\,(i = x, z)$分别为 P波、S波波场的速度分量; $\sigma p_{ij}\,(i, j = x, z)$、$\sigma s_{ij}\,(i, j = x, z)$分别为 P波、S波波场的应力分量; $v_i\,(i = x, z)$为混合波场的速度分量。

通过联立求解方程(2)、方程(3)和方程(4), 可得到 P波波场 $U_p = \{vp_x, vp_z\}$和 S波波场 $U_s = \{vs_x, vs_z\}$, 即可实现完全弹性波波场分离。

2　碳酸盐岩模型正演模拟与分析

(1)模型参数。碳酸盐岩储层模型(见图 1)分为五层: 第一层碳酸盐岩厚度 1 000 m; 第二层含气碳酸盐岩厚度为 500 m; 第三层含水碳酸盐岩厚度为 500 m; 第四层泥岩厚度为 500 m; 第五层硬石膏地层厚度为 500 m。

地层属性参数依次为: ①纵波速度 5 500 m/s, 横波速度 2 900 m/s, 密度 2.8 g/cm³; ②纵波速度 5 100 m/s, 横波速度 3 100 m/s, 密度 2.7 g/cm³; ③纵波速度 3 050 m/s, 横波速度 1 550 m/s, 密度 2.7 g/cm³; ④纵波速度 5 100 m/s, 横波速度 2 500 m/s, 密度 2.6 g/cm³; ⑤纵波速度 5 700 m/s, 横波速度 3 000 m/s, 密度 3.0 g/cm³。

(2)网格化参数。模型横向采样间隔为 10 m, 纵向采样间隔为 10 m; 横向网格数目为 300, 纵向网格数目为 300, 数值模拟时间采样间隔 1 ms, 记录长度 2 800 ms。

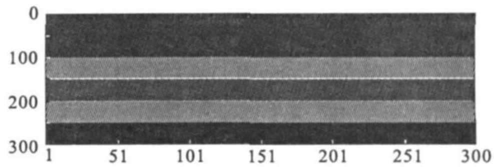

图 1　碳酸盐岩储层地质模型

Fig 1　Geological model of the carbonate reservoir

为了搞清楚地震波在该类碳酸盐岩储层模型中较为复杂的传播特性, 故作者采用了高精度数值模拟方法, 分别得到全波场记录、分离纵波和转换波记录, 并通过与 AVO 响应特征对比, 研究其传播规律及波场特征。下页图 2(a)、图 2(b)分别是碳酸盐岩储层模型全波场正演模拟水平分量记录和垂直分量记录。从图 2中可以看出, 水平分量和垂直分量都包含 P波反射信息和 S波反射信息, 这说明 Z 分量记录和 X 分量记录都是 P波和 S波的混合信息。转换波同相轴位于反射纵波的下方, 曲率

较大, 并且 P波和 S波的速度差异越大, 二者分得越开, 在单炮记录或零偏移距剖面上越容易识别。

图 3是在进行弹性波波场分离后得到的记录。其中图 3(a)为纵波分量, 图 3(b)为转换波分量。

图 4是对碳酸盐岩模型进行正演模拟得到的 AVO 记录 (图 4(a)是纵波分量, 图 4(b)是转换波分量)。

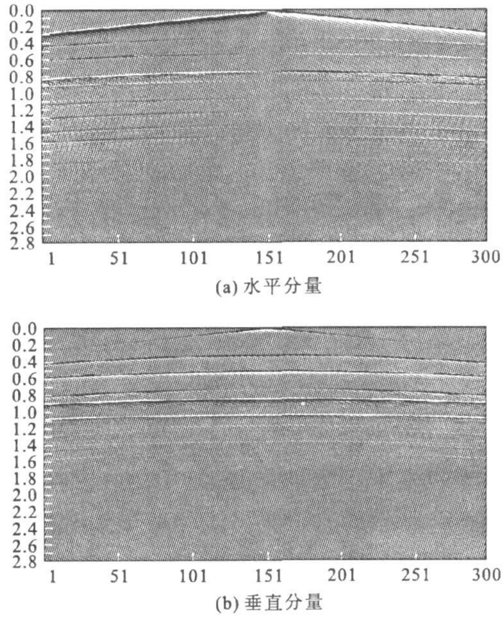

图 2 碳酸盐岩模型模拟单炮记录

Fig 2 Shot record of the carbonate rock model

(a horizontal component; b vertical component)

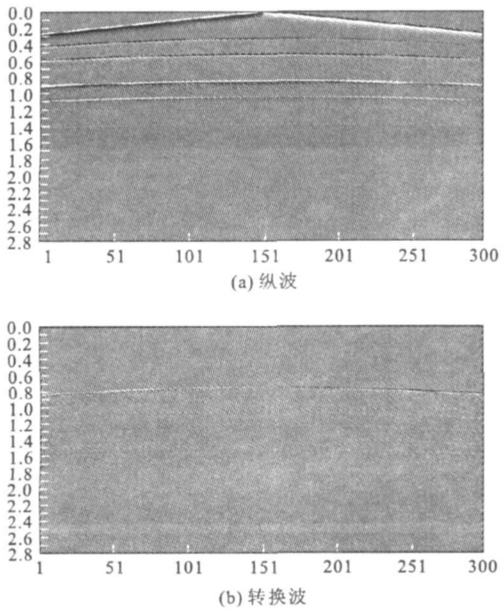

图 3 碳酸盐岩模型模拟单炮记录

Fig 3 Shot record of the carbonate rock model

(a P-wave; b converted wave)

图 5(a)、图 5(b)分别是碳酸盐岩模型中各界面纵波反射系数曲线和转换波反射系数曲线对比图。

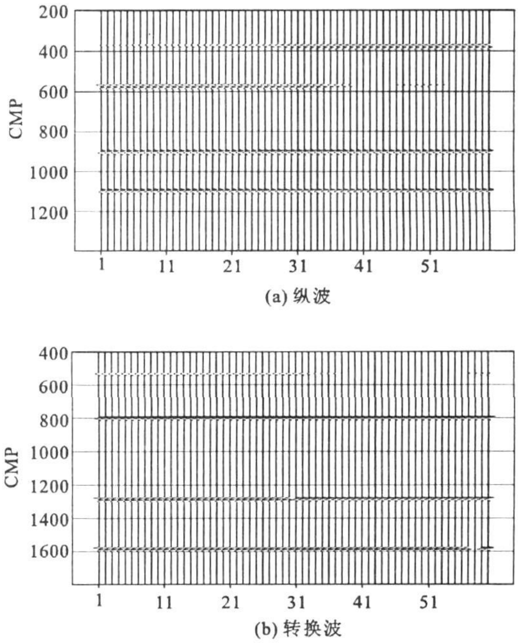

图 4 碳酸盐岩模型 AVO 响应

Fig 4 AVO response of the carbonate rocks model

(a P-wave; b converted wave)

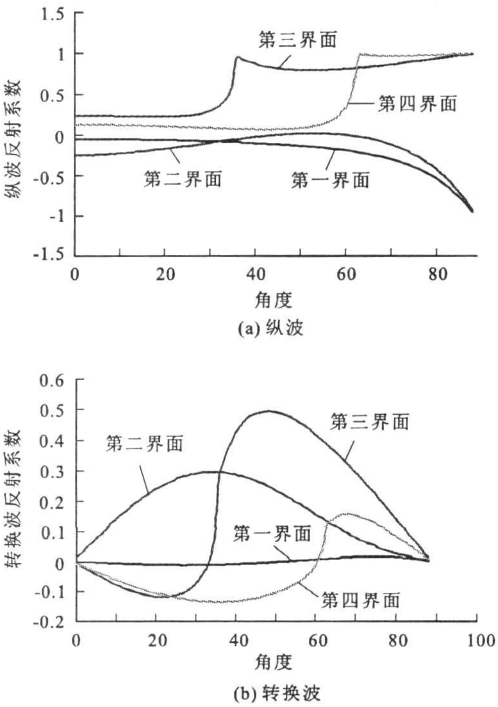

图 5 碳酸盐岩模型各界面反射系数曲线图

Fig 5 Reflection coefficient curve of the carbonate rock interface

(a P-wave; b converted wave)

通过正演模拟得到的单炮记录和 AVO 响应特性综合分析,可以得到几点该类碳酸盐岩储层波场特征:

(1) Z 分量记录的是质点的垂直震动,正偏移距和负偏移距都具有相同的极性,而 X 分量记录的是质点的水平震动,炮点二侧具有相反的极性。

(2) 同一岩性界面对应纵波分量和转换波分量,波场特征较为复杂。并且在到达同一界面的纵波旅行时比转换波旅行时要短,纵波同相轴曲率要比转换波同相轴曲率小,这说明 PP波比 P-SV 波传播速度快。

(3) P-SV 波的能量随偏移距的增加而增加,零偏移距处能量为零,即在炮点正下方不发生地震波的转换,只有反射和透射。

(4) 在含气碳酸盐岩层顶界面,垂直入射的纵波反射系数为负。随着偏移距的增加,反射系数绝对值逐渐增大,显示出该模型为“亮点”型气层模型。在零偏移距处,底界面反射系数为负。在小偏移距范围内,随偏移距增大而减小,然后发生极性反转,最后又随偏移距的增大,反射系数绝对值逐渐增大。

(5) 含气层顶界面转换波反射系数值较小,振幅强度相对较弱,并有极性反转现象发生。含气层底界面转换波反射系数为正,并随偏移距先增大后减小,没有发生极性反转。

3 结论与认识

(1)进行各向同性弹性波波动方程数值模拟,可以正确认识地震波在复杂介质中传播的运动学和动力学特征,准确分析油气储集体中的多波波场特征及其变化规律,进而指导多波资料的解释。

(2)正演模拟技术是研究多波波场特征的重要手段。在全波场弹性波波动方程数值模拟中,将高阶差分与交错网格技术相结合,同时采用 PML 边界吸收技术,可在模拟精度和效率上得到很大提高。但在同时,也要充分考虑正演精度、算法稳定性、计算效率和模型的适应性。

(3)通过数值模拟,可以得到地震波在碳酸盐岩储层模型中的响应结果,并结合 AVO 分析技术与之对比研究,可为多波地震资料解释提供最佳解决方案。

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ABSTRACTS

RESEARCH ON THE METHODOLOGY OF CARBONATE REEF-SHOAL RESERVOIR DESCRIPTION BY 3D SEISMIC DATA

HE Zhen-hua[1,2], JIA Yi-rong[2], JIANG Lian[2], et al. (1. State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Chengdu University of Technology, Chengdu 610059, China; 2. College of Information Engineering, Chengdu University of Technology, Chengdu 610059, China). *COMPUTING TECHNIQUES FOR GEOPHYSICAL AND GEOCHEMICAL EXPLORATION*, 2011, 33(1): 1

Predictions of reservoir pore-composition and pore-fluid on carbonate reef-shoal formation by using seismic data are very important and difficult. The problems of reservoir pore-composition and pore-fluid predictions can be solved partially by both optimal selection of hydrocarbon-sensitive parameters and an improved seismic porosity inversion. The hydrocarbon-sensitive parameter selection can be implemented through crossplot of elastic parameters and fluid factors which are constructed by compositing several reservoir parameters from well log data and/or petrophysics data. The calculations of improved seismic porosity inversion are divided in three steps: (1) simplification of Gassman-equation by $\beta_p - \beta_s \approx \beta_p$; (2) substituting Eshelby-Walsh pore-composition parameters into Gassman-equation; (3) implementing seismic porosity inversion using new equations above. Field data examples show that the improved porosity inversion is better than traditional ones.

Key words reef-shoal reservoir; fluid prediction; seismic porosity inversion; pore composition

THE NEW TREND AND APPLICATION EFFECT OF FIRST ARRIVAL INVERSION STATIC CORRECTION

JIANG Zai-chao, ZHANG Xu-jian, JIANG Lin, et al. (GRI, Exploration and Production Research Academe, Xinjiang Oilfield Company, Urumqi Xinjiang 830013, China). *COMPUTING TECHNIQUES FOR GEOPHYSICAL AND GEOCHEMICAL EXPLORATION*, 2011, 33(1): 6

In complex weathering areas, single static correction method is becoming harder to have good image and right structure, although those technologies ever played important roles. Accurate near-surface model base on integrated solution for visualization model and near-surface information interpretation is the new trend of static correction technology. It succeeds in Quan 1 area. The new techniques include different technologies applied to different layers and cases, integrated solution for visualization model and near-surface information applied as much as possible, and step by step iteration and mutual restriction. This method can not only improve seismic imaging accuracy and structure features, but also avoid excessive increase of drilling holes.

Key words integrated solution; mutual restriction; step by step iteration; comprehensive near-surface modeling

A PRESTACK INVERSION METHOD FOR COMMON REFLECTION POINT SEISMIC DATA

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Prestack seismic data contains the P-wave, S-wave velocity and density information of subsurface stratigraphy. If these parameters can be acquired from seismic data by prestack inversion, plenty of lithology and pore fluid information can be revealed. This paper derived the forward operator, which is generated by the plane wave propagation in stratified elastic media. A prestack three-term inversion method which is based on Brent algorithm is then proposed. This method did not need to compute the sophisticate first order and second order derivative matrix. By dealing the constraint conditions with adaptive annealing factor and penalty function, the inversion stability is improved. By introducing K-L transform in the direction substitution, the linear dependence of searching directions is effectively prevented. Application results in synthetic and real oil field data proved that this method is effective in reservoir prediction with prestack seismic data.

Key words prestack inversion; seismic gather; brent algorithm; forward operator; K-L transformation

NUMERICAL SIMULATION AND ANALYSIS BASED ON CARBONATE ROCK RESERVOIR MODEL

ZHOU Hua-lai, LI Lu-ming, LUO Sheng-xian, et al. (State Key Lab. of Oil Reservoir Geology and Develop Engineering, Chengdu University of Technology, Chengdu 610059, China). *COMPUTING TECHNIQUES FOR GEOPHYSICAL AND GEOCHEMICAL EXPLORATION*, 2011, 33(1): 20

As carbonate rock reservior is an important target of the oil-gas exploration fields, its change of wave fields characteristics are specialy complex. In order to improve the recognization degree of the reservior multi-wave seismic data, high-precision numerical simulation is one of the effective ways. Based on the isotropic elastic wave equation, this paper derived the P-S wave reparation equation, adopted the high-order staggered-grid finite-difference technology to simulate seismic wave propagation in the carbonate rock reserviormedia, acquired the total elastic wave feilds of the reserviormodel, deparated the P wave and S wavc information, and preserved the P-S wave energe information. This paper also combined with AVO techonology to analyze the elastic wave AVO response characteristics in this type of carbonate rock reservior; examined the simulation result based the resevior model, and analyzed and researched the wave fields response characteristic and the propagation law, which provided the reference for the carbonate rock reserivor identification and prediction, and better meeted the practical needs of complicated oilfield exploration and development.

Key words carbonate rock; wave field characteristics; AVO technique; perfectly matched layer; forward modeling

SEISMIC WAVEFORM SHAPE DESCRIPTION TECHNIQUE AND ITS APPLICATION IN SEISMIC FACIES ANALYSIS

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In seismic attributes, the general variation of waveform and its distributed rule is most important seismic parameter. Picking and identifying the waveform information is of benefits to reservoir prediction, reservoir description and improving drilling successful rate. Using waveform to create seismic facies is to use neural network technique to quantitatively describe the general variation of seismic signal. The core of this technologies is the wave shape description and characterization techniques. Taking Stratimagic for example, by the detailed analysis and comparison with the influence over waveform shape changes caused by the main parameters (amplitude, phase, and frequency) which make up of the waveform shape, this paper summarizes waveform shape variation and waveform shape description method which can be used and discusses the effect and significance wave shape classification in Seismic facies analysis.

Key words seismic facies; waveform classification; model trace; seed file

GROUND ROLL ATTENUATION IN TIME-FREQUENCY AND ITS APPLICATION

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Ground roll is a kind of strong noises in seismic data. Some methods are applied to attenuate ground roll such as frequency filter, F-K filtering, velocity filtering and so on, which have limitations because of the frequency dispersion of ground roll. A new method is proposed based on the ground roll's features that change with offsets, which includes (1) understanding the characteristics of ground roll with offsets by decomposing the zone data contained ground roll using Fourier or time-frequency analysis; (2) designing filters with different offsets and apply them to data; (3) Analyzing the removed noises by subtract them from raw data and research the filter parameters; (4) determining the optimal parameters in time-frequency and offset domain to ensure that we attenuate noise and preserve the low frequency signals. Good results are obtained when applying the method to high density seismic data.

Key words ground roll attenuation; time-frequency and offset domain; high density; single point receiver; filter

A TRUE AMPLITUDE SPLIT-STEP FOURIER PRE-STACK DEPTH MIGRATION BASED ON ONE-WAY WAVE EQUATION

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