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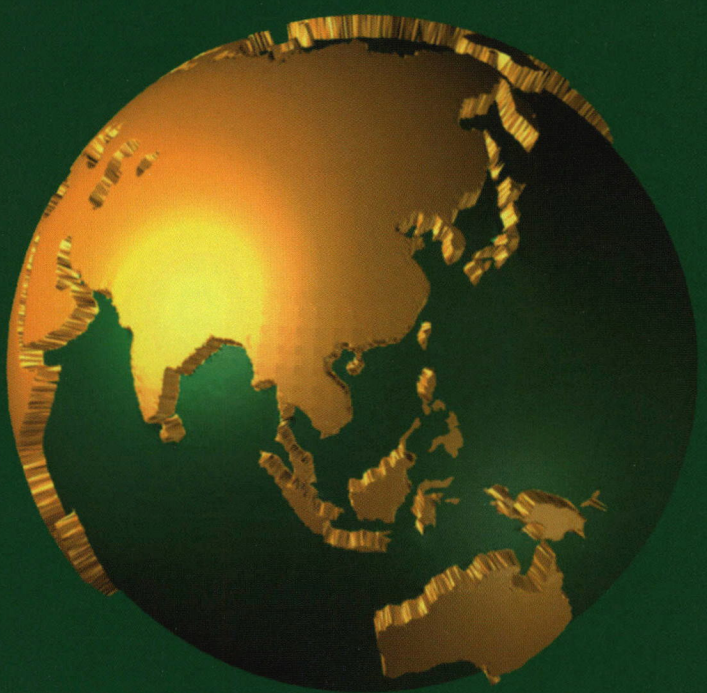

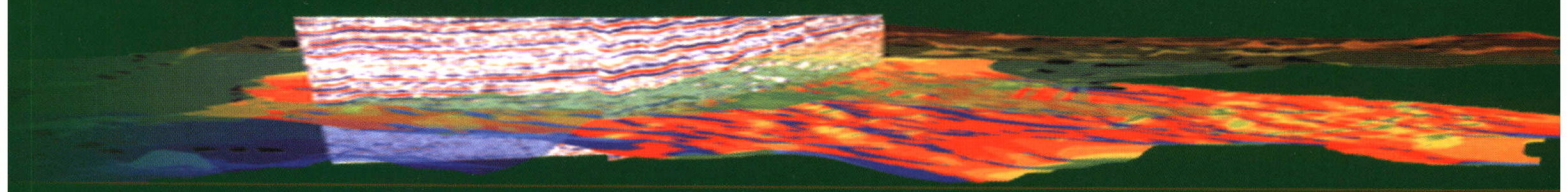

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ABSTRACTS

Random Forests lithology prediction method for imbalanced data sets. WANG Guangyu[1], SONG Jianguo[1], XU Fei[1], ZHANG Wen[2], LIU Jiong[3], and CHEN Feixu. Oil Geophysical Prospecting, 2021, 56(4):679-687.

For the lithology prediction method depending on a supervised machine learning classifier, if the data set has too few samples of target lithology while too many samples of non-target lithology, the classifier trained on this imbalanced data set will cause the prediction results be biased toward the non-target lithology, resulting in poor prediction accuracy of target lithology. With regard to this problem, a Random Forests lithology prediction method for imbalanced data sets is proposed. Firstly, a lithology data set is constructed with lithological logging data as sample labels and seismic attributes and elastic parameters of rock at the uphole trace as sample features. Secondly, the NM-SMOTE algorithm integrating near miss (NM) and synthetic minority over-sampling technique (SMOTE) is employed to balance the lithology data set. Then a Random Forests classifier is trained on the balanced data set to build a nonlinear relationship of lithology with various seismic attributes and elastic parameters. Finally, the seismic attributes and elastic parameters of the target exploratory area are input into the Random Forests classifier which will predict lithology according to the above nonlinear relationship obtained during training. The actual data test results demonstrate that too many samples of non-target lithology will affect the prediction accuracy of the Random Forests classifier, and the prediction accuracy of lithology is only 38%. After the training data set is balanced with the NM-SMOTE algorithm, the prediction accuracy of lithology rises up to 83%, and a data volume of lithology is obtained, which is more consistent with seismic data.

Keywords: lithology prediction, machine learning, Random Forests classification, imbalanced data sets, class balancing techniques

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Seismic data fault detection based on U-Net deep learning network. YANG Wuyang[1,2], YANG Jiarun[2,3], CHEN Shuangquan[2,3], KUANG Liqin[2,3], WANG Enli[1,2], and ZHOU Chunlei[1,2]. Oil Geophysical Prospecting, 2021, 56(4):688-697.

Fault interpretation is one of the key links in seismic data interpretation. With the development of artificial intelligence technology, automatic and rapid fault recognition has become a research hotspot in the application of machine learning methods in geophysics. At present, intelligent fault recognition is faced with problems, such as difficult model training and the unsatisfactory prediction results of actual data. Therefore, a fault detection method of seismic data based on a U-Net deep learning network is proposed, which combines U-Net and residual module Res-50 in the network structure to construct a new network: ResU-Net. ResU-Net uses the $1\times1\times1$ convolution kernel to process the channel number of feature images. It not only reduces the time complexity but expands the depth of the network based on the original U-Net, effectively improving the operation efficiency and learning ability of the network and identifying faults in a quick and accurate manner. Training and testing of synthetic data sets prove that ResU-Net has less time complexity and solves the problems of fault detection in the case of an irregular data volume by appropriate network input, data expansion, and weighted overlapped boundaries. The application results of actual data show that the ResU-Net training model has strong anti-noise capability, remarkable generalization ability, as well as high prediction accuracy and good continuity of faults.

Keywords: fault detection, U-Net, residual module, machine learning, data interpretation

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Characterization of fractures and vugs by electrical imaging based on image region segmentation and convolutional neural network. ZHANG Hao[1,2], WANG Liang[2,3], SIMA Liqiang[1,2], FAN Ling[4], GUO Yuhao[1,2], and GUO Yifan[1,2]. Oil Geophysical Prospecting, 2021, 56(4):698-706, 735.

The processing and interpretation of electrical imaging are confronted by problems including the difficulty in characterizing fractures and vugs and the dependence on manual operation. Manual ope-

ration is not only inefficient but also introduces human errors which are difficult to eliminate. Therefore, this paper proposes a electrical imaging approach based on image region segmentation and the convolutional neural network to automatically identify fractures and vugs. It relies on electrical imaging data and combines with the Otsu algorithm and the average segmentation threshold to separate the fractures and vugs from the stratum background. Also, the independent fracture and vug individuals in connected domains are extracted with the connected domain pixel labeling method. Then, the automatic recognition of fractures and vugs is realized by building and training the improved LeNet-5 network model with the training sample sets based on the image features of various geological structures. Finally, according to the conventional logging curves, the recognition results of the trained model are employed to classify the images, and quantitative evaluation parameters, including effective surface porosity; are calculated accurately on the basis of identified and extracted fractures and vugs. The applicability and rationality of the proposed method are verified by the test model and actual data. At the same time, compared with the manual processing method of electrical imaging, this method can improve the accuracy (by avoiding human errors) and processing speed (15s/m), and the prediction accuracy of the training model for the test set reaches 97.8%, providing an algorithm for the fine logging interpretation of fractured-vuggy reservoirs.

Keywords: image region segmentation, convolutional neural network, electrical imaging, fracture, vug

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Application of data augmentation and active learning to seismic wave impedance inversion. YI Xiaodie[1], WU Bangyu[1], MENG Delin[1], and CAO Xiangyong[1]. Oil Geophysical Prospecting, 2021, 56(4): 707-715.

For an effective deep learning based seismic impedance inversion strategy, a deep convolutional network is trained by massive data-driven models to obtain the mapping between seismic data and impedance. After the network is pre-trained by substantial synthetic data, a small amount of real data is required for transfer learning of the network. In this paper, we propose a new method based on data augmentation and active learning for seismic wave impedance inversion. First, the original single-trace wave impedance data is augmented by resampling at the same frequency, and then the reflectivity and random kernel are calculated to generate the seismic data after augmentation. The augmented seismic and wave impedance data is taken as training sets, and the maximum-error samples are selected to train the network iteratively considering active learning. The proposed method can avoid seismic wavelet estimation, while training the network with higher accuracy using a small amount of label data. The test results from the Marmousi 2 model demonstrate that this method only needs one tenth of label data and iteration times to achieve the prediction accuracy similar to that of iterative random training, with the prediction errors distributed more evenly on the profile.

Keywords: seismic wave impedance inversion, convolutional residual network, data augmentation, deep learning, active learning

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Deep learning seismic impedance inversion based on prior constraints. SONG Lei[1], YIN Xingyao[1], ZONG Zhaoyun[1], LI Bingkai[1], QU Xiaoyang[1], and XI Xiaoping[2]. Oil Geophysical Prospecting, 2021, 56(4): 716-727.

We propose a deep learning seismic impedance inversion method based on constraints of prior information. Different from traditional deep learning inversion methods, the inversion area is segmented based on the category of seismic face and segmentation regions are applied as an explicit spatial constraint to constrain the inversion process of the network model. Then the initial model is set as a label to enrich the low-frequency information of the inversion result. Finally, a strong anti-noise activation function is used to improve the adaptability of the network model to noisy data. To reduce the difficulty of acquiring label data and ensure the inversion accuracy of the network, semi-supervised learning is adopted to train the network model. The proposed method is tested on the Marmousi2 model, and the test results indicate that it has a good inversion effect and anti-noise performance. Subsequently, it is successfully applied to the real exploration data of an oilfield.

Keywords: deep learning, semi-supervised learning, prior constraints, anti-noise, impedance inversion

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Quality control method for secondary location of OBN data. WANG Zhongcheng[1], TONG Siyou[1,2],

ZHOU Huawei[1,3], FANG Yunfeng[4], SUN Yunsong[4], and XU Xiugang[1]. Oil Geophysical Prospecting, 2021, 56(4):728-735.

During ocean bottom node (OBN) survey, geophones need to be placed on the seafloor. However, due to the complex marine environment, the actual implantation position of OBN on the seafloor usually deviates from the design position and needs to be relocated. At present, a variety of secondary location methods have been developed, but their proposers focus on the principle and application effect of a secondary location method; there is little systematic description of effective quality control in field application. With this regard, based on the equivalent velocity method of secondary positioning, this paper studies the factors that affect the secondary positioning accuracy of OBN receiver points, including the accuracy of picked direct wave travel time, geometry, and time shift. The results show that the accuracy of picked direct wave travel time has a crucial impact on the secondary positioning accuracy; if the shot points and the receiver point are projected to the x-axis, y-axis, and z-axis respectively, the distribution of the shot points will be more uniform and more symmetrical relative to the receiver point, and the positioning accuracy will be higher in this direction; the systematic error of travel time is difficult to identify, but it has a great impact on the positioning accuracy in the z direction. Finally, this paper provides methods and suggestions for quality control of secondary positioning of OBN data. Firstly, the first-break travel time is sifted to ensure the accuracy of picked first-break travel time. Then the time shift is introduced as an additional variable to calculate the possible shift of first-break travel time, and the first-break travel time of shot points in a symmetrical distribution relative to the receiver point is selected for calculation. Finally, the processor can monitor the secondary positioning quality artificially according to the comparison between the shapes of the direct wave after NMO, the spatial distribution of travel time errors, mathematical statistics, and other aspects of the common detector gathers before and after secondary positioning.

Keywords: OBN, secondary positioning, travel time, quality control

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High resolution Radon transform based on the reweighted-iterative soft threshold algorithm. XUE Yaru[1], GUO Mengjun[1], FENG Luyu[1], MA Jitao[2], and CHEN Xiaohong[2]. Oil Geophysical Prospecting, 2021, 56(4):736-744,757.

The resolution of Radon transform is the key to seismic data processing. The iterative weighting method based on Bayes inversion improves the resolution of Radon transform, but its convergence rate is low. In light of the strong correlation between Radon transform spaces, the convergence rate of the iterative soft threshold algorithm applied to Radon transform inversion is also low, and the resolution is poor. In this paper, the iterative reweighted least squares algorithm is embedded into the iterative soft threshold algorithm to form a reweighted-iterative soft threshold algorithm. The idea of weighted matrix in high-resolution Radon transform is introduced, and the prior information of Radon parameters is employed to constrain the inversion error function, overcoming the disadvantages of slow convergence and low resolution of the iterative soft threshold algorithm. Synthetic records and real seismic data processing show that this method improves the resolution of Radon transform and achieves good performance in multiple separation and noise suppression.

Keywords: Radon transform, high resolution, iterative reweighted least squares, iterative soft threshold algorithm

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Rayleigh wave dispersion curve inversion based on adaptive weight dragonfly algorithm. GAO Xu[1], YU Jing[2], LI Xueliang[3], HU Tianyue[1], HE Chuan[1], and YUE Yongqiang[4]. Oil Geophysical Prospecting, 2021,56(4):745-757.

Rayleigh wave exploration is an effective means to explore the near-surface S-wave velocity structure. However, the inversion of Rayleigh wave dispersion curves is nonlinear, with multiple extremums. Traditional nonlinear algorithms, such as the genetic algorithm, are subject to difficult convergence and poor stability when solving such problems. The dragonfly algorithm is a novel nonlinear algorithm introduced lately. Based on this algorithm, this paper proposes an adaptive weight dragonfly algorithm, highlighting the idea of early "exploration" while later "development" of the nonlinear algorithm. According to the fitness difference of dragonflies in the iterative process, it introduces adaptive weights, and the weight para-meters of dragonflies' cohesion, separation, and alignment can perform self-adjustment according to fitness. This algorithm is examined by multiple test functions as well as theoretical and actual surface wave data. Compared with traditional nonli-near algo-

rithms, the proposed algorithm can significantly improve the accuracy and stability of the inversion results of Rayleigh wave dispersion curves.

Keywords: Rayleigh wave, dispersion curve, nonlinear algorithm, dragonfly algorithm, adaptive weight

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Analysis of elastic wave simulation accuracy with discontinuous Galerkin finite element method based on triangular meshes. HAN Dechao[1,2], LIU Weihua[1,2], and SI Wenpeng[1,2]. Oil Geophysical Prospecting, 2021, 56(4): 758-770.

Accuracy analysis is the foundation for numerical simulation of seismic waves. With regard to the numerical stability, dispersion, and dissipation of the discontinuous Galerkin finite element method (DGFEM) based on triangular meshes, a triangular periodic mesh model is constructed, which can be used to study the effects of different triangular elements on simulation accuracy. The theoretical and numerical results show that the stability condition of the DGFEM based on the Runge-Kutta time scheme is related to the shape of triangle elements. The maximum time step for stable modeling has a linear relationship with the radius of the inscribed circle of the element, and the equilateral triangle element has the least rigorous stability condition. Meanwhile, the wave field from DGFEM simulation based on the local Lax-Friedrichs flux shows weak dispersion but strong dissipation, and both dispersion and dissipation present directivity in the periodic mesh. In addition, the logarithm of the modeling error has a linear relationship with that of the mesh size. The numerical experiments compare the influence of different mesh shapes on the wave field and verify the theoretical directional difference. The results of this paper can provide a theoretical basis for the triangular mesh division, parameter setting, and selection of numerical flow in DGFEM.

Keywords: discontinuous Galerkin finite-element method, Runge-Kutta time scheme, triangular mesh, stability analysis, numerical dispersion, numerical dissipation

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Time-domain adaptive focused beam migration for viscous and VTI media. GAO Xue[1,2], HUANG Jianping[1,2], LI Zhenchun[1,2], LYU Qingda[3], LI Shengya[1,2] and WANG Zhaozhong[4]. Oil Geophysical Prospecting, 2021, 56(4): 771-781.

The adaptive focused beam operator relies on the dynamic initial beam parameters and focuses adaptively based on the velocity drive in the process of ray tracing. The operator has great flexibility, which is suitable for the region with drastic changes in velocity. Therefore, the idea of adaptive focused beam migration was extended to viscous and VTI media. By modifying the beam ray tracing equation and correcting the travel time information, we derived the viscous Green's function represented by adaptive focused beams and proposed a new beam migration method suitable for both viscous and VTI media. Beam migration in the frequency domain follows the single-trace input mode of Kirchhoff migration, with low efficiency. This paper introduced Fourier transform and Hilbert transform to reduce the migration integral dimension and changed the calculation in the frequency domain to that in the time domain, realizing the fast time-domain adaptive focused beam migration for viscous and VTI media. Comparing the processing results of viscous VTI sag model, viscous VTI SEG/Hess model and actual data based on the procedural method, we find that 1) when the viscosity and anisotropy cannot be ignored, this method can concurrently deal with the influence of both of them, thereby improving the image quality significantly; 2) compared with the frequency-domain adaptive focused beam migration, the proposed method has higher computational efficiency while ensuring the imaging accuracy; 3) the new method can improve the results of actual data processing.

Keywords: Gaussian beam, adaptive focused beam, time domain, anisotropy, viscosity

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Joint tomography for foothills seismic imaging. WANG Yanguang[1], SHANG Xinmin[1], ZHAO Shengtian[1], TENG Houhua[1], YAN Grace[2], and ZHU Xianhuai[2]. Oil Geophysical Prospecting, 2021, 56(4): 782-791.

Foothills seismic imaging has been a challenging problem for oil and gas exploration for many decades due to the complexity of both near-surface and subsurface conditions. The key issue is velocity model building. This paper illustrates a workflow with joint tomography as a key component for

improved foothills seismic imaging, including the following four steps: ①complex wavelet transform (CWT) for noise attenuation, which is with the robust for aliased noise suppression with fidelity of keeping signal, especially low-frequency signals, while removing noise; ② turning-ray tomography for near-surface velocity estimation using picked full-offset first arrivals; ③joint tomography starting from a robust and seamless initial velocity model, constrained by well logs and geologic interpretation, for velocity model building; and ④TTI anisotropic prestack depth migration from true topography for imaging steep-dip faulting structures. The application of the proposed methodologies and workflow to Miquan foothills 3D seismic survey from the south rim of Junggar Basin, northwestern China, has demonstrated that linear and scattering noise has been effectively suppressed; low-frequency signal has been preserved, which is important for reservoir characterization. More accurate velocity model has resulted in better focusing and more continuity of seismic images after migration, and better tie with wells. Images in target zones have been improved, starting to show meaningful faulting structures with a regional anticline. This is significant for seismic exploration in foothills regions not only in China, but also elsewhere around the world.

Keywords: foothills area, noise attenuation, complex wavelet transform (CWT), joint tomography, prestack depth migration, TTI anisotropy, Miquan Block

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Self-adaptive rock physics modeling method for tight sandstone reservoirs. ZHANG Jinqiang[1,2,3], LIU Zhenfeng[1,2,3], LIU Xiwu[1,2,3], and Han Lei[1,2,3]. Oil Geophysical Prospecting, 2021, 56(4): 792-800, 808.

In traditional rock physics modeling, the mineral components are known, and the equivalent elastic modulus of the rock matrix is solved with the Voigt-Reuss-Hill model. In the practice of rock physics modeling for tight sandstone reservoirs, accurate mineral component interpretation cannot be provided due to incomplete logging data. As a result, the accuracy of conventional rock physics modeling is affected. To tackle the problem, we propose a self-adaptive method for the rock physics modeling of tight sandstone reservoirs. The method uses both the Gassmann equation and the critical porosity model to estimate the elastic modulus of the rock matrix. According to the interpreted shale content curves, the upper and lower bounds of elastic moduli of shale and sandy components are estimated with the least square method and Voigt and Reuss models. A simulated annealing algorithm is employed to find the approximate elastic moduli of shale and sandy components. The values are fine-tuned according to the principle of constant P-wave modulus, and finally, the reasonable parameters for rock physics modeling are obtained. Area M in the southern Ordos Basin is subject to rock physics modeling with this method and the results show that the elastic parameters of shale and tight sandstone can be well distinguished. Shale is characterized by a high P-wave/S-wave velocity ratio and a low P-wave velocity. For sandstone, the P-wave/S-wave velocity ratio and the P-wave velocity decline as the porosity increases.

Keywords: tight sandstone, self-adaptive rock physics modeling, Gassmann equation, critical porosity model, Voigt-Reuss-Hill model

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Analysis of physical characteristics of shale rock based on ultrasonic testing. MA Xiaoyi[1], LI Chengcheng[1], BAI Jun[1], and MA Zhonggao[1]. Oil Geophysical Prospecting, 2021, 56(4): 801-808.

Given the development of shale bedding in Tonghua, Northeast China, tri-axial compression experiments and P & S wave velocity (v_P and v_S) tests in two directions are carried out to analyze the variation of elastic modulus, Poisson's ratio, v_P, and v_S of shale in different directions. Relevant experiment data show that the shale anisotropy parameters ε and γ are linearly correlated under different confining pressure and the empirical formula built by linear regression can provide references for their prediction or testing. The anisotropy of favorable reservoir samples is much higher than that of unfavorable ones. As the confining pressure gets higher, both v_P and v_S increase and ε and γ become smaller. The v_P/v_S of shale is positively correlated to density and therefore negatively to total organic carbon (TOC). The v_P/v_S of favorable reservoirs with high TOC is much lower than 1.7, while the ratio of unfavorable reservoirs with low TOC is higher than this value, which can be taken as a marker to distinguish unfavorable reservoirs. With the increase in porosity, the elastic modulus of shale parallel to the bedding direction rises but declines vertical to the bedding direction. Our findings can lay a foundation for the seismic quantitative prediction of shale brittleness and sweet spots.

Keywords: shale, v_P/v_S, anisotropy, TOC

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Improved window parameter optimized S-transform and its application in channel detection. ZHANG Fu-ai[1], CHEN Xuehua[1,2], LUO Xin[2], ZHANG Jie[2], and XU He[2]. Oil Geophysical Prospecting, 2021, 56(4):809-814,881.

Time-frequency analysis, which can process non-stationary signals, is an important tool for seismic signal analysis. The resolution of time-frequency is the key to high-precision reservoir prediction. The time-frequency focusing of conventional S-transform is difficult to fulfill the high-precision prediction of reservoirs. Therefore, an improved window parameter optimized S-transform method is proposed. According to the amplitude spectra of actual signals, the scale parameters of the window function are adaptively solved and then the window parameters are further improved with new optimization parameters. The comparative analysis of the synthetic signals indicates that the proposed method has better time-frequency focusing performance and higher resolution at both high and low frequency bands. The results of channel detection from the actual seismic data show that this method can better highlight the characteristics of channels, depict their details, and display their continuity. It can provide favorable method support for the fine reservoir description of seismic data.

Keywords: S-transform, time-frequency analysis, window parameter optimization, channel detection

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Identification of bioclastic beach, Maokou Formation of Langzhong area, northern Sichuan Basin. LI Suhua[1], SHI Guoshan[1], JIANG Nengchun[1], HU Hao[1], LI Rong[1], and YU Yang[1]. Oil Geophysical Prospecting, 2021, 56(4):815-825.

Due to multi-stage superposition, small thickness, and complex and varied seismic reflection structures of bioclastic beaches in Maokou Formation of Langzhong area, northern Sichuan Basin, conventional seismic interpretation and prediction methods are not suitable for the identification of bioclastic beaches and the fine characterization of their internal structures. Therefore, with the facies-sequence combination of a single well as the basis, drilling and seismic data are combined to finely calibrate and divide the development stages of bioclastic beaches and determine the seismic reflection characteristics of bioclastic beaches at different stages. The main factors affecting the internal reflection characteristics of bioclastic beaches are analyzed by forward modeling. The global automatic scanning interpretation technique based on sequence stratigraphy is used to accurately depict the internal reflection structure of bioclastic beaches. The seismic attributes that can characterize the distribution characteristics of the bioclastic beaches are selected and combined with the seismic facies to determine the development zone of bioclastic beaches. The sedimentary evolution of clastic beaches at different stages is analyzed in combination with isochronous stratigraphic slicing properties, and the spatial distribution of multi-stage bioclastic beaches is intuitively displayed. The results show that three stages of bioclastic beaches are mainly developed, manifested with "superposed, oblique, cluttered, and weak-amplitude" reflection characteristics. Horizontally, they are distributed in the NW-SE direction; vertically, they are deposited by coating and aggradation from the northeast to the southwest direction in the study area. Dolomite reservoirs are mainly developed in the stage-Ⅲ bioclastic beach. The above results are consistent with the actual drilling results and can provide a basis for future oil and gas exploration.

Keywords: bioclastic beach, internal structure, formation scanning, Maokou Formation, Langzhong area, Sichuan Basin

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Automatic fault separating method based on tensor voting. LIU Xuming[1]. Oil Geophysical Prospecting, 2021, 56(4):826-832.

In geological modeling, manual fault separating is cumbersome and time-consuming, and the accuracy of fault separating is restricted by subjective factors. Especially in complex fault blocks, wrong separating results may be induced. In addition, due to different geological problems in different work areas, the interpretation accuracy requirements are also inconsistent, making it extremely difficult to automatically separate faults. In this paper, we propose a method to separate faults automatically based on tensor voting. The direction information about the original fault point set is calculated with the tensor voting algorithm. Then, according to the current geological knowledge, the spatial location and fault stick number in the fault files are employed to realize automatic fault separating. The specific process is as follows: ① All the scattered points are encoded and displayed as ball tensors; ② the tensor fields of all the scattered points are calculated according to the scale parameters and then tensor voting is performed; ③ the eigenvalues of the tensor fields after voting are decomposed to obtain the normal vectors of all the scattered points, and then the instantaneous angle inclination and direction are calculated; ④ the faults are preliminarily separated according to the direc-

tion and spatial location information of the fault point set; ⑤ the faults are finely separated in combination with the geological knowledge. Simulation and actual data demonstrate that the proposed method can greatly improve the efficiency and accuracy of fault separating.

Keywords: tensor voting, fault point set, automatic fault separating, fault stick, occurrence

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Depiction of superimposed volcanic edifices in detail by high-density seismic techniques. LIANG Hailong[1] and CHEN Zhide[1]. Oil Geophysical Prospecting, 2021, 56(4):833-844.

The Anda area is located in the Xujiaweizi fault depression, and there are two large erupting periods (yc32 and yc33) in volcanic edifices in the third member of Yingcheng Formation, each consisting of multiple secondary erupting periods. Because volcanic edifices are characterized by a large burial depth, high concealment, special provenance, variable formation mechanisms, and fast lithofacies change, their internal structures are complex. The conventional seismic data in the Anda area have low vertical resolution and amplitude fidelity, and thus the stratigraphic distribution in each erupting period is hard to be accurately identified and depicted. Therefore, based on high-density seismic data, near-surface compensation and pre-stack time migration with stationary phases in the viscoelastic medium are used to greatly improve the vertical resolution and amplitude fidelity of the imaging results. Seismic interpretation techniques such as coherence analysis, layer flattening, and fine waveform comparison are applied to finely describing superimposed volcanic edifices. Well logging and seismic data are combined to accurately divide the erupting periods of volcanic edifices. To be specific, yc32 is divided into three periods (yc32-1, yc32-2, and yc32-3) and yc33 into two periods (yc33-1 and yc33-2). Finally, the following results are obtained: ① Acidic rocks, dominated by volcanic breccia, are mainly developed in yc33; in yc32, intermediate-basic volcanic edifices are mainly developed, dominated by andesite in the upper part and basalt in the lower part. ② Two basalt masses (with a respective area of 2 and 22km^2) and three andesite masses (with a respective area of 1.6, 6.5, and 22.6km^2) are identified. The above achievements lay a foundation for predicting the gas reservoirs of volcanic edifices.

Keywords: high-density seismic technique, near-surface compensation, pre-stack time migration with stationary phases, Anda sag, Yingcheng Formation, superimposed volcanic edifices

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Seismic response characteristics and prediction of fractured reservoir inside metamorphic buried hill of Bozhong 19-6 oilfield. ZHANG Zhijun, XIAO Guangrui, and LI Yao. Oil Geophysical Prospecting, 2020, 56(4):845-852.

The BZ19-6 Archean metamorphic buried hill is divided into a weathered fracture zone, a relatively dense zone, an inner fracture zone and a dense zone in sequence from the top surface. The weathered fracture zone and the inner fracture zone enable reservoir development, and the fractured reservoir is characterized by low velocity and density. There are three types of seismic reflection structures inside the Archean metamorphic buried hill: ① continuous, high and steep reflections from fault plane with a low frequency and a medium strength; ② intermittent, high and steep network with a low frequency; ③ local disorder with a medium-strength anomalous amplitude under the background of blank reflection. The complex geological and seismic characteristics of fractured reservoirs inside buried hills lead to multiple solutions and the uncertainty of reservoir prediction results. For this reason, the fractures inside the buried hill are divided into three scales (large, medium and small) according to logging data and seismic response characteristics. Forward modeling indicates that the high and steep reflection is a direct indicator of the development of large-scale fractures inside the buried hill, while the diffraction wave energy is an important feature indicating the development of medium-and small-scale fractures. The normalized fusion is performed on the data of high and steep reflection inside the buried hill which is enhanced by the curvelet transform and the diffraction wave data extracted with the principal component analysis. The comprehensive multi-wave field information effectively predicts the multi-scale fractured reservoir inside the buried hill.

Keywords: inside metamorphic buried hill, fracture scale, seismic reflection structure, curvelet transform, principal component analysis, reservoir prediction

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Quantitative interpretation and application of progradational reflection in the fourth member of Dengying Formation in the Moxi area, Sichuan Basin. GU Mingfeng[1], ZHU Mao[1], LIANG Feng[2], TIAN Han[3], LI Wenzheng[1,4], and HAO Yi[1,4]. Oil Geophysical Prospecting, 2021, 56 (4):853-868.

A large mound shoal zone is developed on the east platform margin of the Deyang-Anyue rift trough, which is a favorable area for reservoir development. Plenty of intra-platform progradational reflection structures are found in the three-dimensional (3D) seismic data of the study area. The progradation is roughly distributed along the plat-

form margin, which is different from the conventional progradation direction of carbonate platforms. These progradational reflection structures are less reported previously. Therefore, this study uses the 3D seismic data of the Moxi area and the calibration of drilling data to compare and trace the multi-stage progradational seismic reflection structures in the 3D area. Quantitative analysis helps to establish the filling sequence of the fourth member of the Dengying Formation in the deposition period, and the controlling effect of the Deyang-Anyue rift trough activity on deposition in this period is analyzed. The following conclusions are drawn: ① The multi-stage progradation, mainly transverse progradation, occurs in the fourth member of the Dengying Formation, which is mainly controlled by the slow decline of the relative sea level in the highstand stage and continuously migrates along the platform-margin slope break. ② The progradational slope break and the development of algal-bound thrombolitic dolomite and algal-bound arenaceous dolomite on the continental side are favorable reservoir facies, which provide the material basis for high-quality reservoirs. ③ On the basis of intra-platform seismic reflection structures, the progradational slope break of each stage is identified, and the facies zones of reservoir rock development can be found. The superposition of the karst paleogeomorphology with these zones has the potential to reveal new gas enrichment areas. The proposed reservoir prediction method based on seismic reflection structures is of great reference significance for the exploration of other deep carbonate basins in China.

Keywords: Moxi area, Dengying Formation, rift trough, progradation, platform-margin slope break, reflection structure

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Genesis of mass transport deposits and their effect on gas hydrate accumulation in the Qiongdongnan Basin. DU Hao[1], SHI Wanzhong[1], LIANG Jinqiang[2,3], WANG Ren[1], HE Yulin[2,3], and XU Litao[1]. Oil Geophysical Prospecting, 2021, 56(4):869-881.

The deep-water area of the Qiongdongnan Basin has considerable gas hydrate resources and has developed multi-stage mass transport deposits (MTDs). However, the influence mechanism of MTDs on hydrate accumulation remains to be fully elucidated. In view of this, this study comprehensively analyzes the various factors that affect hydrate accumulation with core, drilling, logging, seismic and regional geological data, taking into account the main characteristics of MTDs. Further, with the coupling relationship of MTDs having different backgrounds as the starting point, the genesis of MTDs and their effect on gas hydrate accumulation in the Qiongdongnan Basin are explored. The following results are obtained. ① The difference between MTDs and in-situ sediments is significant. MTDs are denser and have much lower porosity. The log curves have low interval transit time and high resistivity. Biological detritus, gravel particles, etc. can be observed in the MTDs section. The seismic profiles of the MTDs section show a chaotic reflection structure. ② Since 5.5Ma, the rapid subsidence of the Qiongdongnan Basin has led to the proliferation of provenance and the increases in the accommodating space and the gradient of continental slope, which provide prerequisites for the formation of MTDs. The MTDs developed on the northern continental slope are mainly controlled by sea level change, provenance, and slope gradient and triggered by magmatic activity. Those developed on the flanks of the submarine volcano in the southern uplift are directly controlled by magmatic activity. There is an isochronous coupling relationship among magmatic activity, MTDs of the southern uplift, and MTDs of continental slopes. ③ The deep gas source migrates to the stable zone for gas hydrate along the diapir and its derived channels and is covered by shallow MTDs to form a gas hydrate reservoir under suitable temperature and pressure conditions.

Keywords: mass transport deposits, gas hydrate, magmatic activity, sea level change, isochronous coupling relationship, Qiongdongnan Basin

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Post-processing algorithm based on superconvergence for nodal 3D finite element modeling. TANG Jingtian[1,2], LIAO Taoshan[3], CHEN Huang[1,2], HUANG Xiangyu[2], ZHOU Feng[1,4], and ZHANG Lincheng[5]. Oil Geophysical Prospecting, 2021, 56(4):882-890.

In the nodal finite element forward modeling of geophysical electromagnetic methods, the finite element solution of the main field needs to undergo numerical differentiation to derive the auxiliary field or the finite element calculation of potentials is necessary to yield the components of the electromagnetic field. To tackle the problem of low accu-

racy of traditional post-processing methods, we propose a method based on the superconvergent patch recovery (SPR) for the post-processing of nodal finite element forward modeling, which is applicable to the controlled-source electromagnetic method. First, on the basis of the curl-curl equation of the secondary electric field, the electric field (primary field) is solved with the Galerkin finite element method involving structured hexahedral grids and nodes. Then, given the superconvergence of the nodal finite element method, all adjacent elements at a certain node are used to form a patch. The electric field gradients are subjected to the least-squares surface fitting with Gauss points as sampling points on the patch so that the electric field gradients of nodes on the patch can be recovered. Finally, a high-precision magnetic field is achieved according to the recovered electric field gradients, and the high-precision apparent resistivity and phase responses are then obtained. The results show that the SPR-based post-processing algorithm can improve the accuracy of magnetic field components greatly and maintain good stability with slight increases in the memory and calculation time, compared with the conventional shape function differentiation (SFD), Lagrange interpolation (LI), and moving least-squares interpolation (MLSI).

Keywords: electromagnetic method, nodal finite element modeling, post-processing, superconvergent patch recovery

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Three-dimensional CSEM forward modeling using edge-based finite element method based on unstructured meshes and divergence correction. TANG Wenwu[1,2], DENG Juzhi[2], and HUANG Qinghua[1]. Oil Geophysical Prospecting, 2021, 56(4): 891-901.

The iterative computation with a system of linear equations derived from the three-dimensional (3D) controlled-source electromagnetic (CSEM) forward modeling of the electric field equation suffers from slow convergence. Moreover, unstructured meshes can make the system of linear equations more ill-posed. In view of this, we propose an algorithm for finite element forward modeling based on unstructured tetrahedral meshes and divergence correction. Starting from the divergence equation of current density, we derive the corrected divergence equation of the potential on geo-electrical interfaces. Solving the system of linear equations is accelerated with the preconditioned quasi-minimal residual (QMR) method and the alternate divergence correction during the iteration. A three-layer medium model is subjected to the forward modeling under two conditions (with/without divergence correction) to verify the reliability of the proposed algorithm. The iterative convergence and the accuracy of numerical solution of the system of linear equations indicate that the divergence correction is effective to accelerate the iteration and improve the forward modeling accuracy. On this basis, a 3D geo-electric model is built, the electromagnetic response of which is employed for the comparison of numerical solutions between the proposed algorithm and the forward modeling based on the quadratic coupling potential equation. It further confirms the high accuracy of the algorithm in this study. The modeling of a complex oil and gas monitoring system demonstrates the application potential of the CSEM method in oil and gas monitoring.

Keywords: three-dimensional controlled-source EM, unstructured meshes, divergence correction, forward modeling

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Two-dimensional magnetotelluric smooth focusing inversion based on optimization strategy. BAI Ningbo[1], ZHOU Junjun[2], and HU Xiangyun[1,2]. Oil Geophysical Prospecting, 2021, 56(4): 902-909.

On the basis of previous studies, this paper proposes a new inversion objective functional with the purposes of realizing rapid and stable inversion and obtaining clear geological interfaces. It adopts the smoothest model and the minimum support gradient model functional to constrain the data objective functional. Solved by the Gauss-Newton method, the new inversion objective functional enables the smooth focusing inversion of two-dimensional magnetotelluric data. The smooth focusing inversion can not only present clear geological interfaces but also avoid the distortion of structural morphology caused by focused inversion to a certain extent. In the process of inversion iteration, we adopt the optimization strategy of improving the Morozov discrepancy principle with the Nelder-Mead optimization algorithm to obtain the appropriate regularization factor, which greatly accelerates the inversion convergence. Finally, the pro-

posed inversion method is verified with a typical model and real data and also compared with other inversion strategies. The inversion results show that for typical model inversion, the algorithm in this paper outperforms the others in agreeing with the model, with the convergence curve decreasing rapidly and the geological body interface being clear. The inversion results of real data further verify the reliability and effectiveness of this algorithm.

Keywords: Gauss-Newton method, Nelder-Mead optimization algorithm, Morozov discrepancy principle, minimum support gradient

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Experimental research on NMR response characteristics of hydrates. TANG Kexuan[1,2], LI Zhenyu[2], WANG Hongyu[3], ZHANG Wenbo[2], and PAN Jianwei[4]. Oil Geophysical Prospecting, 2021, 56(4): 910-921.

Studying the nuclear magnetic resonance (NMR) response characteristics of gas hydrate in frozen soil region is of great significance for the classification of permafrost structure and the identification of hydrate reservoir. This study explores the NMR signal variation characteristics of the test samples during the formation and decomposition of tetrabutylammonium bromide (TBAB) hydrate. There are three obvious peaks (main peak, secondary peak and attached peak) in the transverse relaxation (T_2) time spectrum during freeze-thaw of the hydrate, which are attributed to the H nuclei of free water, bound water and water-soluble organic matter, respectively. Utilizing the distribution, amplitudes, areas and their variation of peaks, we can study the physicochemical state change of hydrate samples. In particular, the significance of the secondary peak and the attached peak can be employed to directly judge whether the hydrate exists and clarify its content. The decomposition of TBAB hydrate is divided into three stages: dispersion stage, decomposition stage and stable stage. Also, the relations of NMR signals with temperature and time are derived, which are applicable as the basis for the quantitative analysis of the content and storage conditions of the hydrate.

Keywords: nuclear magnetic resonance (NMR), gas hydrate, tetrabutylammonium bromide(TBAB), physical properties experiment, temperature

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Borehole seismic: A bridge connecting multiple oil and gas exploration methods. CAI Zhidong[1,2,3]. Oil Geophysical Prospecting, 2021, 56(4): 922-934.

With the research deepened in oil and gas exploration and development, continuous progress is made in a variety of exploration technologies in aspects of geology, drilling, geophysics, etc. The comprehensive application of many methods has become an inevitable trend. However, there are data and descriptive scale differences between different exploration methods. Borehole seismic technology plays an important role in the joint application of various exploration methods owing to the high signal-to-noise ratio, wide frequency band and rich wave-field information of its data. Based on the characteristic analysis of borehole seismic data, this paper summarizes the bridge role of borehole seismic technology in various exploration methods. Firstly, it can be used for resolution compensation, fine horizon calibration and logging curve correction between drilling and seismic methods. Secondly, its well-controlled time-to-depth conversion, prediction of formation depth and physical properties of reservoirs play a crucial part between time- and depth-domain exploration methods. Thirdly, it provides technical supports in the joint P-and S-wave seismic exploration methods via the study of seismic wave properties, the transformation between P-and S-wave domain, the calculation of fitting S-wave acoustic velocity, and the P- and S-wave joint inversion. Fourthly, it has been applied in the process of seismic exploration extending to fine reservoir development, functioning for seismic geological guidance, fine structure interpretation, well-controlled formation attribute optimization and reservoir fracturing monitoring. Finally, it builds a bridge for the joint research of reservoir static description and dynamic monitoring, especially the time-shifting borehole seismic technology and optical fiber sensing technology, which have shown good application prospects in this field.

Keywords: borehole seismic, VSP, oil and gas exploration, comprehensive research, bridge role

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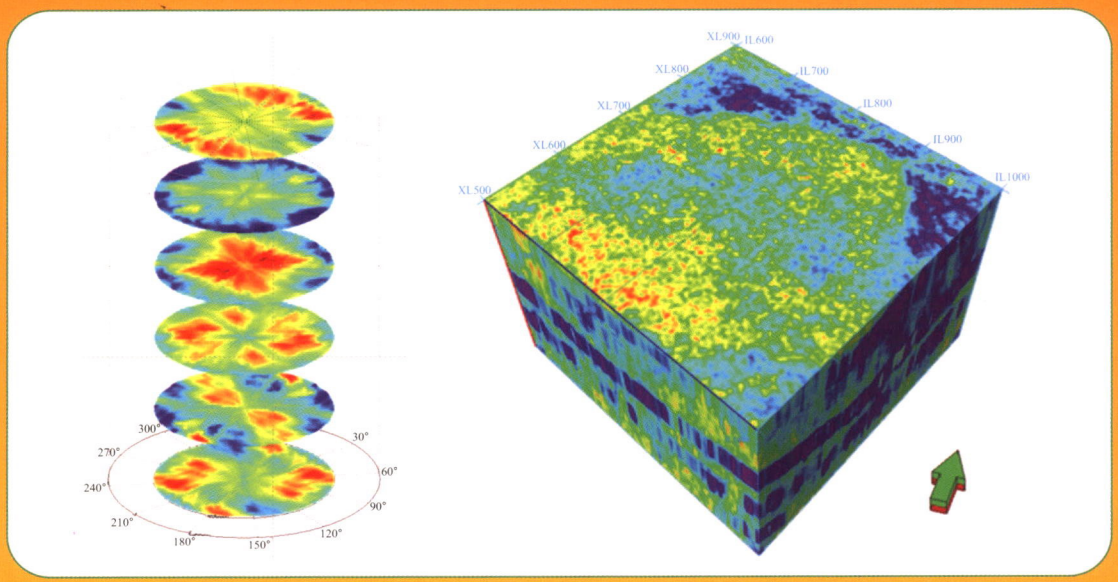

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