ABSTRACTS

Research and industrial application of efficient structural interpretation technology based on deep learning. YANG Ping[1], SONG Qianggong[1], ZHAN Shifan[1], TAO Chunfeng[1], GUO Rui[1], and ZHU Donglin[1]. Oil Geophysical Prospecting, 2022, 57 (6): 1265-1275.

Deep learning technology has given strong impetus to the development of interpretation technology for traditional seismic data, which has spawned a large number of intelligent interpretation technologies. However, limited research achievements can be applied in large-scale production. This study focuses on the industrial implementation of intelligent interpretation technologies based on deep learning for low-to-medium signal-to-noise ratio (SNR) data. Upon the development of the intelligent software development platform, an intelligent horizon interpretation and fault detection technology with strong data adaptability is formed, which plays an important role in the horizon interpretation of large-scale continuous survey data and the fine description of complex fault blocks. The efficiency of horizon interpretation by this method is increased by a factor of 9-21 compared with that of the traditional automatic interpretation techniques, and the accuracy of fault identification is significantly improved in comparison with that of classic techniques such as coherence and curvature. It can completely replace the original automatic interpretation modules and achieve the intelligent transformation of structural interpretation.

Keywords: deep learning, intelligent structural interpretation, horizon tracking, fault identification, quality and efficiency improvement

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Intelligent recognition method of low-grade faults based on VNet deep learning architecture. LU Pengfei[1], DU Wenlong[2], LI Li[3], CHENG Danhua[4], and GUO Aihua[1]. Oil Geophysical Prospecting, 2022, 57(6): 1276-1286.

The recognition of low-grade faults is an important link in oil and gas exploration and development. Coherent volume, spectral decomposition, curvature, aunt body, edge detection, and other traditional methods have greatly improved the effect and accuracy of fault recognition, but they cannot effectively recognize low-grade faults with small fault distances. However, as an artificial intelligence technology, the deep learning method based on a full convolution neural network provides a new way for low-grade fault recognition. Based on UNet, the proposed VNet deep learning architecture can increase the receptive field of signals during the up and down sampling, extract large-scale fault information as much as possible, yet retain and extract small-scale fault information at the same time. Furthermore, this paper uses forward modeling data and actual seismic data to test UNet and VNet models, selects appropriate loss function, iteration times, and model weight parameters to compare the effects of model training and fault recognition. The results show that the VNet-based method can extract rich information and is more effective in low-grade fault recognition.

Keywords: seismic data, fault recognition, low-grade faults, deep learning, VNet

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Low frequency compensation of pre-stack seismic data based on improved CNN and double constrained loss function. DAI Yongshou[1], GAO Qianqian[1], SUN Weifeng[1], WAN Yong[1], and WU Shasha[1]. 2022, 57(6): 1287-1295.

Due to the lacking low frequency information and the low resolution of seismic data for deep or ultra-deep land layers, the accurate interpretation of subsequent seismic data is affected. Model-driven low frequency compensation methods have dependence on strict assumptions and inflexible parameter adjustment. The convolutional neural network (CNN) has limited feature extraction ability for subtle changes and no obvious gradient changes, and the network is easy to fall into local optimum, resulting in low frequency undercompensation or low compensation accuracy. Therefore, a low frequency compensation method for pre-stack seismic data combining improved CNN and double constrained loss function is proposed. On the premise of not increasing the computational complexity of CNN, residual blocks network units that can directly learn residual features between input and output are added to solve gradient disappearance. Additionally, batch normalization is adopted to make the network more sensitive to subtle changes, to improve network training efficiency. Since

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the gradient changes are not obvious, the network convergence is premature. To address the problem, this paper takes the difference and the correlation between the network output and original seismic record as optimization objectives and establishes the loss function by the weighted sum of the mean square error and Pearson distance to calculate the compensation error under double constraints. Finally, the gradient changes become more evident and ensure that the local optimal can be jumped out during gradient descent, so as to improve the low frequency compensation accuracy. The synthetic data and the low frequency compensation results of the real pre-stack seismic data in X area of western China verify the feasibility and effectiveness of the proposed method. Compared with the low frequency compensation method based on CNN and that based on deconvolution combined with broadband Yu low-pass filter, the proposed method can compensate the low frequency components without destroying the original medium and high frequency information.

Keywords: pre-stack seismic data, residual block, Pearson distance, low frequency compensation, convolutional neural network (CNN)

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Comparative analysis of three seismic impedance inversion methods based on deep learning. WANG Zefeng[1], LI Yonggen[2], XU Huiqun[1], YANG Mengqiong[1], ZHAO Yasong[1], and PENG Zhen[1]. Oil Geophysical Prospecting, 2022, 57(6): 1296-1303.

The difference in neural network structure leads to different deep learning effects. Hence, upon the comparison of the fully convolutional neural network (FCN), convolutional recurrent neural network (CRNN), and time-domain convolutional neural network (TCN), this study uses the forward model tests to comparatively analyze the accuracy and computational efficiency of seismic impedance inversion methods based on the above three deep learning methods. Moreover, the three methods are applied to actual data for further comparison. The experimental results show that the computational efficiency and accuracy of TCN-based wave impedance inversion are relatively high. For wave impedance inversion based on TCN, FCN, and CRNN, the inversion time is 82 s, 68 s, and 264 s, respectively, and the inversion accuracy is 99.15%, 97.84%, and 98.14%, respectively. The actual data application reveals that the results of TCN-based wave impedance inversion match better with the logging data. This conclusion can provide a reference for the optimization and selection of intelligent wave impedance inversion methods.

Keywords: deep learning, seismic wave impedance inversion, FCN, CRNN, TCN

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Application of comprehensive fault detection technology combining deep learning with edge enhancement in detecting ultra-deep strike-slip faults in Shunbei block. CHEN Jun'an[1], CHEN Haidong[2], GONG Wei[1], and LIAO Maohui[1]. Oil Geophysical Prospecting, 2022, 57(6): 1304-1316.

Karst fracture-cave reservoirs are well-developed in the Shunbei block of the Tarim Basin, and high-productivity wells have emerged in recent years. A large number of studies have confirmed that the development of strike-slip faults with high angles plays a decisive role in the migration and accumulation of oil and gas reservoirs. Due to the deep burial of fault-controlled reservoir small fault throws, and hard closure, the SNR of seismic data in the Shunbei block is low, and the characteristic of fault planes is not clear, which make the detection and spatial interpretation of strike-slip faults difficult. Given the difficulties faced by studies on ultra-deep strike-slip fault detection, this paper proposes a comprehensive detection technology combining deep learning with edge enhancement for multi-scale faults. Specifically, the paper divides the strike-slip faults into main faults, associated secondary faults, and small-scale fractures by scale and carries out targeted studies. According to the seismic response characteristics of different fracture modes including forward main faults, associated secondary faults, and small-scale fractures and method experimental tests, it is believed that U-Net convolutional neural network deep learning technology can be used to identify main faults, and amplitude gradient vector disordered detection technology can be applied to identify associated secondary faults. In addition, the Aberrance enhancement attribute can be adopted to identify small-scale fractures. The proposed technology has been applied to detect strike-slip faults in the Shunbei block and achieved remarkable effects.

Keywords: ultra-deep strike-slip fault, seismic pattern identification, deep learning, disordered detection, Aberrance enhancement

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Multi-streamer positioning algorithm based on curvilinear integral for seismic exploration. DUAN Chufeng[1], ZHANG Haonan[1,2,3], KUANG Cuilin[1], YU Wenkun[1], RUAN Fuming[2,3], and DAI Wujiao[1]. Oil Geophysical Prospecting, 2022, 57(6): 1317-1324.

Streamer positioning is a key step of offshore seismic exploration, and an accurate streamer model and positioning algorithm are the core of high-precision streamer positioning. The application of the existing streamer positioning algorithm to the multi-streamer exploration scene is exposed to problems such as the loose mathematical model of streamers and the inadequate use of the observation values of positioning networks. Therefore, a multi-streamer positioning algorithm based on curvilinear integral is proposed in this paper. Firstly, a rigorous mathematical model of streamers based on curvilinear integral is built. Then, with the model, the error equation of each positioning observation value is derived. Finally, the experimental verification is carried out by simulation and measured data. The experimental results show that the accuracy of the shape and position of the streamer estimated by the new algorithm is better than that of the traditional algorithm. Specifically, the precision of the along-line direction is better than 1 m, and that of the across-line direction is better than 3 m, which can meet the needs of offshore seismic exploration and subsequent seismic data analysis.

Keywords: offshore seismic exploration, streamer positioning, curvilinear integral model, error equation, multi-streamer positioning

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High-resolution processing method based on matching pursuit algorithm. LIU Hanqing[1], LUO Ming[1], SUN Hui[1], and CHEN Weitao[1]. Oil Geophysical Prospecting, 2022, 57(6): 1325-1331.

Conventional seismic data processing methods have various disadvantages, such as window effect, poor energy focusing performance, and mutual restriction between resolution and signal-to-noise ratio, that limit their processing ability. For this reason, a new high-resolution processing method is proposed on the basis of expounding the basic principle of the matching pursuit algorithm and the construction method for relative-amplitude-preserving amplitude-versus-frequency (AVF) profiles. The proposed technology starts with decomposing the signal and constructing a relative-amplitude-preserving AVF profile. Then, energy is redistributed in the time-frequency spectrum to highlight the high-frequency component of the original data. The spectral value of each time-frequency atom at a given frequency determines the contribution of the atom. Finally, the seismic signal is reconstructed in an amplitude-preserving manner. The actual data processing results show that after reconstruction, the seismic signal obtains a more prominent dominant frequency, a wider frequency band, and a relatively improved resolution, which indicates that the proposed processing method improves the ability to identify small geological bodies with seismic data and paves the way for subsequent reservoir identification and fluid detection.

Keywords: matching pursuit, relative amplitude preservation, AVF profile, time-frequency analysis, high-resolution processing

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Radon transform based on greedy fast iterative shrinkage threshold and its application in multiple suppression. ZHANG Quan[1,2,3], LEI Qin[1], LIN Baiyue[1], PENG Bo[1,2], and LIU Shuyan[1,2]. Oil Geophysical Prospecting, 2022, 57(6): 1332-1341.

In seismic exploration, multiples seriously affect the interpretation accuracy of seismic data, and effective suppression of multiples is important in seismic data processing. The parabolic Radon transform is a common method to suppress multiples. The iterative shrinkage thresholding algorithm (ISTA) is the most widely used method in the industry to obtain the solution to the inverse problem of the parabolic Radon transform. It has excellent computational accuracy and efficiency, but for massive seismic data, the processing efficiency still needs to be improved. To improve the convergence rate of the parabolic Radon transform, this study proposes greedy fast ISTA (Greedy FISTA) to processing of inversion problem for Radom transform suppressing multiple, and constract an accelerated sparse time-invariant Randon transform in the mixed frequency-time domain based on fast interative shrinkage-thesholding algorithn (SRTG-FIS). Unlike ISTA, Greedy FISTA takes the weighted sum of the results of the previous two iterations as the iteration starting point, and it introduces restart conditions and convergence conditions to reduce the oscillation period in the iteration process and accelerate the calculation. The multiple suppression experiments with synthetic and real data show that compared with ISTA and FISTA, the proposed algorithm has a great improvement in convergence efficiency and a slight improvement in convergence accuracy.

Keywords: multiple suppression, Radon transform, ISTA, FISTA, greedy FISTA

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Adaptive equalization of synthetic aperture sonar image under local background variational iteration. **LI Gengxiang[1,2,3], LIU Jiyuan[1,3], LI Baoqi[1,3], WEI Linzhe[1,3], and GONG Wenjing[1,2,3].** **Oil Geophysical Prospecting, 2022, 57(6): 1342-1351.**

Aiming at the problems of local gray distortion, low contrast, and target masking in synthetic aperture sonar images, this paper proposes an adaptive equalization enhancement method. Firstly, a non-equilibrium time evolution model in the image domain is established by the variational theory. Then the local information of the sonar image and the difference relationship between the images at adjacent moments in the equalization evolution process are used to construct the equalization function by means of exponential weighting. The weight coefficient is automatically updated, and the background component is estimated during the iteration. Finally, the equalization outcome is obtained by background equalization and dynamic range adjustment. According to the verification and analysis of actual data, the background of the sonar image after equalization becomes more uniform, and the contrast is improved. In addition, the target and texture are enhanced, and the noise interference is effectively suppressed. Compared with other algorithms, the local equalization, equivalent view, peak signal-to-noise ratio, and local structure similarity of the image are optimal, and the practicability and effectiveness are guaranteed.

Keywords: gray distortion, variational theory, time evolution model, exponential weighting, iterative update

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Numerical simulation of first-order velocity-dilatation-rotation elastic wave equation with staggered grid. **WANG Hui[1,2], HE Bingshou[1,2], SHAO Xiangqi[3].** **Oil Geophysical Prospecting, 2022, 57(6): 1352-1361.**

Elastic wave forward modeling plays an important role in seismic wave propagation mechanism research and the acquisition, processing, interpretation, and inversion of multi-wave seismic data. Present forward modeling of elastic wave equations often numerically solves first-order velocity-stress equation or second-order displacement equation to only obtain three particle vibration velocity components or displacement components containing P- and S-wave. The wave-field decoupling operator should be employed to separate P- and S-wave for a more intuitive recording of pure P- and S-wave components. Therefore, the accuracy of the wave records simulated by the methods is subject to the accuracy of both the simulation algorithm and the wavefield decoupling algorithm. This paper derives the higher-order finite-difference scheme of the first-order velocity-dilatation-rotation elastic wave equation in three-dimensional staggered grid space and gives the corresponding stability conditions. The PML absorbing boundary conditions adapted to the equation are derived, and the forward modeling of the first-order velocity-dilatation-rotation elastic wave equation is realized. The physical meaning of each component in the simulation results is analyzed. The equation not only contains the vibration velocity vector of the particles but also explicitly includes the P- and S-wave vibration velocity vectors. Additionally, an volumetric strain and a rotation vector are also involved. Therefore, in addition to the three particle vibration velocity components, the decoupled P- and S-wave components can be obtained directly by the equation. This avoids the influence of the decoupling algorithm on decoupling accuracy, and model trials prove he validity and superiority of the proposed method.

Keywords: first-order velocity-dilatation-rotation equation, staggered grid, forward modeling, finite-difference, PML absorbing boundary condition, P- and S-wave separation

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Elastic wavefield decomposition in 3D TTI media. **ZUO Jiahui[1,2,3], ZHANG Lele[3], SHUAI Da[3], ZHU Chenghong[1,2,4], XU Weiya[1,2,4], and ZHAO Yang[3].** **Oil Geophysical Prospecting, 2022, 57(6): 1362-1374.**

According to the geometric relationship between the tilted symmetry axis of 3D TTI media and the observation coordinate system, the TTI media can be regarded as 3D VTI media through coordinate rotation. The wavefield decomposition method for VTI can be applied to TTI media. Therefore, on the basis of the 3D anisotropic elas-

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tic wave equation, this paper built a 3D VTI wavefield decomposition operator by solving the eigenvectors of the Christoffel equation. Then a 3D TTI decomposition operator is derived by coordinate rotation. Finally, the elastic wavefield decomposition of 3D TTI can be realized by Poisson's equation. An improved fast algorithm is introduced to avoid solving Poisson's equation directly. The derived decomposition operator is suitable for the complex 3D TTI media because it considers the varying elastic parameters and tilted symmetry axis with space. When the anisotropic parameters and tilted angle of the symmetry axis are zero, this operator can be degraded into isotropic form. Numerical results show the derived TTI operator can obtain more accurate decomposition results than isotropic or VTI operators, and efficiently realize 3D anisotropic vector elastic wave field decomposition.
Keywords: reverse time migration, elastic wavefield decomposition, 3D TTI media, Poisson's equation, eigen analysis
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Joint imaging method of primaries and internal multiples. QIN Ning[1], WANG Changbo[1], LIANG Hongxian[1], LI Zhina[2], LI Zhenchun[2], and DING Yixuan[2]. Oil Geophysical Prospecting, 2022, 57(6): 1375-1383.

The internal multiples generated by strong reflection interfaces have bothered the oil and gas exploration for a long time because of their complicated propagation paths and high costs in difficult suppression. Since internal multiples are also real reflections from the underground interfaces and reverse time migration can realize the imaging of multiples, a joint imaging method of primaries and internal multiples is studied to reduce calculation cost and improve imaging accuracy. First, the imaging conditions based on the separation of up-going and down-going wavefields are introduced by analyzing the joint imaging process to improve imaging accuracy. Then, the generation mechanism of crosstalk artifacts that are introduced in the joint imaging process is analyzed, and the corresponding solution based on missing boundary matching and compensation is put forward. The matching factor is obtained by matching the upper boundary of forward-extrapolation with the real seismic data and then employed to the forward-extrapolation boundaries to compensate for the missing boundaries. As a result, the fidelity of reverse time extrapolation is realized, which can effectively avoid the crosstalk artifacts. Finally, the feasibility, effectiveness, and applicability of the method are verified by numerical tests.
Keywords: primaries, internal multiple, joint imaging, imaging condition, boundary compensation, migration artifact
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Source wavefield reconstruction based on a new finite-difference stencil and infinity norm. BAO Qianzong[1,2], DAI Xue[1], and LIANG Xue[3]. Oil Geophysical Prospecting, 2022, 57(6): 1384-1394.

The adjoint-state method is widely used in migration imaging and full waveform inversion. The image or gradient of the model can be obtained by the interaction between source and adjoint wavefields. The two wavefields, however, propagate in forward and backward time directions, respectively, and cannot be accessed at the same time. To avoid the storage of the source wavefield, we can use boundary wavefields to reconstruct the source wavefield in the backward time direction, but the existing reconstruction methods still cannot balance the requirements of accuracy and storage. Hence, this paper develops a new staggered-grid finitedifference (FD) source wavefield reconstruction method. The method stores the N-layer wavefields and a linear combination of $(M-N)$-layer wavefields in the boundary area to reconstruct the internal source wavefield, where M denotes the length parameter of the FD operator, and $0 \leqslant N \leqslant M$. On the basis of the new FD stencil, we derive the dispersion relation, construct an infinite-norm-type objective function, and optimize the reconstruction coefficients by the Remez exchange algorithm. Moreover, we analyze the accuracy and stability of the proposed method and apply it to acoustic reverse time migration and elastic full waveform inversion. Numerical results reveal that the new method can obtain sufficiently accurate reconstructed wavefields, migration profiles, and inversion results, and its memory usage is only $(N+1)/M$ of that of the traditional method.
Keywords: source wavefield reconstruction, finite difference, staggered grid, reverse time migration, full waveform inversion
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Study on Q pre-stack depth migration method in sea-land transition zone in Bohai Bay Basin. CHEN Jianwei[1], YE Yueming[1], ZHONG Shichao[1], and CHANG Shaoying[1]. Oil Geophysical Prospecting, 2022, 57(6): 1395-1399.

The sea-land transition zone in Nanpu Sag of Bohai Bay Basin has a complex surface structure. As surface and underground and viscoelastic media are absorbed, the seismic wave energy is seriously attenuated, which results in the loss of seismic signal strength and frequency bandwidth. In order to improve imaging accuracy, it is necessary to compensate for the attenuation of seismic wave energy in stratum. Inverse Q filtering and time-frequency analysis methods fail to consider the propagation path of seismic waves, but the energy attenuation of actual seismic waves is closely related to the propagation path. Therefore, the seismic imaging method based on Kirchhoff pre-stack depth migration is adopted. In the migration process, the energy attenuation of seismic waves propagating along different paths is considered, and the migration imaging quality is improved in terms of energy localization and attenuation compensation. In addition, Q pre-stack depth migration is utilized, and a Q model is obtained by using the Q tomography method. Furthermore, Kirchhoff pre-stack depth migration imaging is performed based on the Q model, which effectively compensates for amplitude and corrects phase distortion, improves the signal-to-noise ratio, fidelity, and structural interpretation accuracy of deep data, and provides a reliable basis for pre-stack inversion, lithology identification, and fluid detection.

Keywords: sea-land transition zone, amplitude attenuation, Q tomography, Q pre-stack depth migration

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Sparse seismic inversion method based on full-domain regularized fast matching pursuit. PEI Song[1], YIN Xingyao[1], and LI Kun[1]. Oil Geophysical Prospecting, 2022, 57(6): 1400-1408, 1426.

The matching pursuit (MP) algorithm has been widely applied to signal processing since it was proposed. This paper starts with constructing a redundant dictionary for MP by leveraging the initial model constraint and the convolution operator for the time-frequency (TF) domain. All possible matching atoms are then screened out from the whole TF domain to build an alternative atom dictionary. Subsequently, the subset with the highest energy is selected from the alternative atom dictionary by a regularization method to serve as the final matching atom dictionary. In other words, multiple matching atoms can be obtained in one iteration. The full-domain regularized fast MP algorithm thereby obtained offers the advantages of high computational efficiency and robustness. Furthermore, the initial model constraint and the TF-domain joint inversion method are introduced into the inversion framework, which effectively improves the accuracy of the inversion results. The proposed method is tested by 1D and 2D models and 3D field data, and the results indicate that the seismic inversion method based on full-domain regularized fast MP significantly outperforms those based on conventional MP in computational efficiency. The inversion results of the proposed method exhibit favorable horizon boundary fidelity in addition to high robustness.

Keywords: matching pursuit (MP), regularization, time-frequency domain, seismic inversion, sparse

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Seismic "blocky" acoustic impedance inversion based on $L_{1\text{-}2}$ regularization. GENG Weiheng[1,2], CHEN Xiaohong[1,2], LI Jingye[1,2], TANG Wei[1,2], WU Fan[1,2], and ZHANG Junjie[1,2]. Oil Geophysical Prospecting, 2022, 57(6): 1409-1417.

Although acoustic impedance inversion technology is quite mature, there are still some issues such as the ill-posedness of inverse problems, low resolution of inversion results, and the inability to delineate the stratigraphic boundaries. To this end, a seismic "blocky" acoustic impedance inversion method based on $L_{1\text{-}2}$ regularization is proposed. Based on existing research, this paper introduces $L_{1\text{-}2}$ regularization into the model-based acoustic impedance inversion and directly obtains the acoustic impedance inversion results from post-stack seismic data according to the idea of total variation regularization. First, the paper deduces a linearized forward modeling equation of acoustic impedance and analyzes its accuracy. Then, based on Bayesian theory, the paper constructs the objective function of the acoustic impedance inversion by the $L_{1\text{-}2}$ regularization and solves the function through an iterative reweighted least squares (IRLS) algorithm to obtain the acoustic impedance inversion results. Since the acoustic impedance inversion is a single-trace inversion method, when it is applied to multi-trace data inversion, there is a spatial discontinuity. Therefore, an f-x space predictive filtering method is used to alleviate the discontinuity caused by noise and single-trace inversion. The quantitative comparison of correlation coefficients proves that the inversion results obtained by the $L_{1\text{-}2}$ norm are better than those obtained by L_1 and L_2 norms, and synthetic and field data inversion examples demonstrate the effectiveness and feasibility of the proposed method.

Keywords: acoustic impedance inversion, $L_{1\text{-}2}$ regularization, Bayesian theory, iterative reweighted least

squares, objective function, resolution.
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Seismic identification method of ultra-deep strike-slip fault zones in Tarim Basin. **LI Xiangwen[1,2,3], LI Jingye[2,3], LIU Yonglei[1], TAO Chunfeng[4], ZHANG Liangliang[1], and ZHANG Guanqing[1].** **Oil Geophysical Prospecting, 2022, 57(6): 1418-1426.**

The ultra-deep (7500-9000 m) strike-slip fault zones (SFZs) are the important oil and gas enrichment zones in the Tarim Basin. The formation of ultra-deep heterogeneous reservoirs is closely related to the reformation and dissolution of SFZs, and SFZs are characterized by disordered seismic reflections with different energy. How to accurately identify SFZs in the ultra-deep tight limestone is one of the problems that need to be solved for higher productivity of oilfields. Therefore, a combined method for seismic identification of ultra-deep SFZs is proposed. Firstly, a transverse smoothing filter based on the seismic dip angle data is constructed by the introduction of the scanning results of formation dip angles, and the transverse smoothing filter is applied to the original seismic data to obtain the transverse trend data with local stratigraphic background characteristics. Then, the residual between the transverse trend data of the formation energy background and the original seismic data is calculated, and the enhanced response data of SFZs is finally obtained, which can guide the identification of SFZs. The model test and practical data application show that the seismic data produced by this method has significantly higher discrimination of heterogeneous geological bodies, which can effectively identify faults of different scales and distinguish fractures and cavities submerged in the background of formation energy. This method has strong applicability and is worth popularizing for the identification of similar geological bodies.
Keywords: Tarim Basin, ultra-deep, strike-slip fault zone, transverse smoothing filter, Fuman oilfield, seismic identification
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Pre-stack inversion method for frequency-dependent P-wave and S-wave attenuation parameters. **XU Bin[1,2], CHEN Xuehua[1,2], ZHANG Jie[2], JIANG Xiaomin[2], and LIU Junjie[2].** **Oil Geophysical Prospecting, 2022, 57(6): 1427-1435.**

As seismic exploration progress develops, effective fluid identification methods are required to meet the demands of increasingly improved reservoir prediction accuracy. In this paper, according to an initial model of a two-layer reservoir designed by dynamic equivalent medium theory, an optimal sinusoidal fitting analytical formula between the reciprocal of quality factor and velocity is established, and the frequency-dependent P-wave and S-wave attenuation parameters are defined. In addition, an algorithm adopting attenuation parameters of pre-stack angle gathers and rock modulus inversion is constructed and verified by model calculation and real data. The results show that the P-wave and S-wave attenuation parameters are highly sensitive to reservoirs with fluids, and the attribute inversion results of attenuation parameters indicate that reservoirs with high gas saturation can be effectively identified. Specifically, the P-wave attenuation parameter is less disturbed by the background and can accurately identify gas reservoirs. Therefore, the proposed algorithm provides a new way to effectively identify fluids by using attenuation attributes.
Keywords: reciprocal of quality factor, sinusoidal fitting, P-wave and S-wave attenuation parameter, reservoir prediction
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Application of high-angle-fault constrained azimuthal Fourier coefficient fracture prediction in M gas field. **FAN Tingen[1], DU Xin[1], MA Shufang[1], FAN Hongjun[1], HE Xinwei[2], and FAN Pengjun[1].** **Oil Geophysical Prospecting, 2022, 57(6): 1436-1444.**

The existing pre-stack wide-azimuth fracture prediction method is data-based, and the geological model cannot affect the prediction process. The Archaean buried-hill fractured reservoirs in the M gas field of Bohai Bay Basin (China) are mainly controlled by inside high-angle faults. To this end, based on the wide-azimuth seismic data of the M gas field, this paper proposes a high-angle-fault constrained azimuthal Fourier coefficient fracture prediction method with pre-stack inversion. Firstly, the *f-k* filtering and the Radon transformation with a high resolution are used to extract the high-angle fault information from post-stack seismic da-

ta, which is then converted as prior weights of the azimuthal Fourier coefficient inversion method, so as to develop the function of high-angle-fault constrained fracture prediction inversion targets and calculate the fracture density and azimuth estimation. The proposed method is applied in the M gas field, and the application effect shows that fracture prediction results are of geological significance and are in good agreement with fracture features interpreted from the electrical imaging well logging and the production and test data of each well. Therefore, the method can be applied to design and optimize the location of production wells.
Keywords: azimuthal anisotropy, fracture prediction, azimuthal Fourier coefficients, *f-k* filtering, Radon transformation, high-angle-fault constrained
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Multi-point geostatistical modeling with inversion constraints: a case study of continental oil fields in Daqing placanticline. HUANG Yong[1], XU Liheng[1], YANG Huidong[1], HE Qiuli[1], HE Yuhang[1], and YANG Qingjie[1]. Oil Geophysical Prospecting, 2022, 57(6): 1445-1452.

In view of the problems of rapid lateral change of sedimentation, small sand-body scale, and scattered distribution of remaining oil in continental oil fields, the multi-point geostatistical modeling method constrained by seismic inversion is adopted to realize the three-dimensional accurate representation of sand-body space and guide the remaining-oil potential tapping of old oil fields. Specific steps are as follows: Firstly, the "training images" are constructed for plane combination modes of three distributary channel sand bodies and two non-channel sand bodies of the river-delta facies. Secondly, the P-wave impedance characteristics of different sedimentary microfacies are defined. In other words, the channel sand body features low P-wave impedance, and the inter-river mud features high P-wave impedance, while that of inter-river sand is between the two. The P-wave impedance data volume is obtained by the waveform-indication inversion method. Finally, the training images are used to replace the variation function for mode guidance, and the inversion data volume of P-wave impedance is used as the inter-well trend control to achieve the fine modeling of multi-point geostatistical sedimentary microfacies. The results show that the multi-point geostatistics method (compared with the conventional modeling method) can clearly describe the geometric shape, width, and sand-body contact relationships of channels, and the connection relationship between sand bodies is more clear, with fewer invalid grids. The average prediction accuracy of channel sand bodies is improved from 79.6% to 86.1%. Given the modeling results, the potential positions of remaining oil in the study area are identified, and the measures to guide potential tapping have achieved good results. This indicates that the method in this paper can meet the needs of fine reservoir description and accurate potential tapping of remaining oil in continental oil fields.
Keywords: multi-point geostatistics, seismic inversion, modeling, training images, continental oil field, Daqing placanticline
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Key technologies for seismic exploration of Carboniferous volcanic rocks in Junggar Basin. GU Wen[1,2], YIN Xingyao[1], BIAN Baoli[3], YU Baoli[2], DENG Yong[2], and LIN Yu[2]. Oil Geophysical Prospecting, 2022, 57(6): 1453-1463.

Taking the Carboniferous primary rhythmic igneous rocks in the center and the weathered volcanic rocks at the northwestern margin of Junggar Basin as examples, this study discusses the key techniques for solving difficulties in seismic exploration. According to the research, for primary rhythmic volcanic rocks, the use of low-frequency vibroseis acquisition, well-controlled low-frequency compensation, and interlayer multiple suppression can greatly improve the fidelity and spatial resolution of deep seismic data with the idea of lithologic oil and gas reservoirs. Quantitative prediction of superior reservoirs can be achieved by post-stack facies-driven inversion with the constraints of volcanic lithofacies predicted by multi-attribute fusion. For weathered volcanic rocks, according to the idea of later stimulated reservoirs, the continuous wave suppression of strong reflection interfaces and the TTI pre-stack depth migration technology of the "true" surface can realize fine imaging of structure, formations, and faults. Ancient landform restoration and fine identification of multi-attribute faults are conducive to identifying favorable target areas. The bandwidth of seismic data for volcanic rocks in the central Junggar Basin is increased from 3～25 Hz to 8～46 Hz, and the average coincidence rate of reservoir drilling is raised from 65% to 81%. This method can provide a reference for the exploration of similar volcanic rock reservoirs at home and abroad.
Keywords: volcanic rock, Junggar Basin, primary rhythmic type, weathering crust, seismic prediction
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Evaluation of metamorphic reservoir effectiveness by array acoustic logging data. TAN Lihong[1,2], ZHANG Guoqiang[3], TAN Zhongjian[3], ZHANG Guibin[4], ZHANG Chengguang[1,2], and CAI Ming[1,2]. Oil Geophysical Prospecting, 2022, 57(6): 1464-1472.

At present, conventional logging is mainly used to identify the lithology of metamorphic rock and then evaluate the reservoirs, while array acoustic logging is seldom used to evaluate the effectiveness of metamorphic rock reservoirs. Therefore, given the logging data of metamorphic rock in Bozhong 19-6 (BZ19-6) gas field, the response characteristics of array acoustic logging are analyzed, and the average attenuation calculation method is proposed on the basis of the conventional acoustic parameter calculation. By the quantitative study of the correlation between various acoustic parameters and different reservoirs, nine acoustic parameters sensitive to effective reservoirs, such as the time difference of longitudinal wave, shear wave, and Stoneley wave, array attenuation, and average attenuation, are extracted, and the evaluation chart and scheme of reservoir effectiveness based on sensitive acoustic parameters are established. The new well data are processed by the proposed method, and the reservoir effectiveness is evaluated. The coincidence rate between the evaluation results and the test results is 91.43%, which meets the field application requirements.

Keywords: BZ19-6 gas field, metamorphic rock reservoir, array acoustic logging, sensitive acoustic parameters, reservoir effectiveness, chart

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Logging data reconstruction based on cascade bidirectional long short-term memory neural network. ZHOU Wei[1], ZHAO Haihang[1], JIANG Yunfeng[1], YI Jun[1], and LAI Fuqiang[1]. Oil Geophysical Prospecting, 2022, 57(6): 1473-1480.

As the basis for the development and evaluation of oil and gas fields, logging data is of great significance to determine the location of underground oil and gas reservoirs, and calculate and evaluate the oil and gas reserves. However, on the one hand, several logging data at some depths are often distorted or missing due to wellbore collapse and instrument failure during actual mining. On the other hand, the re-logging cost is too high with difficult construction. Therefore, this paper proposes a logging data reconstruction method based on a cascade bidirectional long short-term memory neural network (CBi-LSTM). This method fully considers the two-way correlation between the precursor and successor of missing data points and the correlation between logging curves without adding additional measurement cost. Firstly, the cascade system is applied to combine the estimated value and the known logging curve into a new input. Then, the iterative update strategy is employed to reconstruct the missing data block. Finally, the logging data of 4 wells in the Sulige gas field are supplemented and reconstructed. Experimental results show that the proposed method features high data reconstruction accuracy, and the model has better robustness and generalization abilities.

Keywords: logging curve, reconstruction, long short-term memory neural network (LSTM), cascade bidirectional long short-term memory neural network (CBi-LSTM)

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Numerical simulation of polarization effect in low-frequency interface of oil-gas reservoirs. XU Wei[1], WEI Ran[1], HUANG Hang[1], and KE Shizhen[2]. Oil Geophysical Prospecting, 2022, 57(6): 1481-1488.

Based on the pore capillary model of reservoir rock, this paper constructs the quantitative relationship between the macroscopic physical parameters of reservoirs and the conductivity and dielectric properties of microscopic pore fluids as well as an equivalent circuit model to quantitatively describe the polarization effect of low-frequency interface of reservoir rock. Compared with those of the traditional Cole-Cole equivalent circuit model, the parameters of the proposed equivalent circuit model show more explicit physical meaning and are more suitable for quantitatively characterizing the polarization effect of the low-frequency interface of the reservoir rock. The proposed equivalent circuit model is used to simulate the polarization effect of the low-frequency interface of rock samples saturated with saline water and oil-bearing rock samples, respectively, and the influence of pore-throat ratio, salinity, and water saturation of reservoir rock on resistivity dispersion of imaginary part is analyzed. The simulation results show that the modulus of the imaginary resistivity minimum is exponentially related to pore-throat ratio, salinity, and water saturation. Specifically, it increases as the pore-throat ratio improves and decreases as the salinity and water saturation rise. The numerical simulation results provide a theoretical and model basis for quantitatively evaluating the oil and gas in reservoirs by using the polarization effect of low-frequency rock interface.

Keywords: interfacial polarization, complex resistivity, induced polarization, numerical simulation

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Time-frequency electromagnetic data inversion and reservoir evaluation based on physical property analysis modeling: A case study of the Shibei structural belt on the northern margin of the Junggar Basin. WANG Youtao[1,2,3], HE Zhanxiang[4,5], CHEN Xueguo[2], LI Zhuqiang[2], WU Mengying[4,5], and CAO Yang[6]. Oil Geophysical Prospecting, 2022, 57(6): 1489-1497.

Time-frequency electromagnetic (TFEM) method plays an important role in oil and gas exploration. In addition, model accuracy in data inversion has a great impact on the inversion accuracy. In order to effectively reduce the non-uniqueness of inversion and improve the inversion accuracy, it is necessary to make full use of existing data for accurate modeling. Based on the actual exploration data of the Northern Junggar Basin, this paper uses Gaussian distribution to statistically analyze the electrical logging data of the study area and obtains characteristic electrical data of each stratum, such as the mean value of resistivity and deviation, so as to propose a layered electrical modeling method for the upper and lower structural layers and different strata in the study area. Through the rock dispersion test of igneous greservoirs, the dispersion characteristics of igneous rock with different oil and gas saturation in the study area are obtained. Furthermore, according to the TFEM oil and gas detection results and the oil and gas information during drilling, an identification template for oil and gas electromagnetic attributes is established. The case shows the resistivity and polarization profiles obtained through layered modeling and TFEM inversion, as well as the analysis and interpretation of profiles, have identified favorable targets for hydrocarbon exploration. The modeling method and hydrocarbon target interpretation idea in the paper can provide a valuable reference for hydrocarbon reservoir evaluation in similar areas.

Keywords: Time-frequency electromagnetic (TFEM) method, hysical property analysis, layered modeling, reservoir evaluation

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Magnetotelluric galvanic distortion correction based on amplitude-phase tensor decomposition. YU Caiguo[1], XIAO Xiao[1,2,3,4], TANG Jingtian[1,2,3,4], HUANG Xiangyu[1], and XU Jintong[1]. Oil Geophysical Prospecting, 2022, 57(6): 1498-1508.

In terms of magnetotelluric (MT) exploration, when the geometric size of the near-surface three-dimensional abnormal body with inhomogeneous electrical property is much smaller than the skin depth of the electromagnetic wave, the impedance tensor will be seriously distorted. If this effect continues, the electrical structural model obtained by inversion will deviate from the true tectonic model, which will further affect the subsequent geological interpretation. Most of the traditional distortion correction methods assume that the regional structure is one-dimensional or two-dimensional, while the actual regional structure is generally three-dimensional. Therefore, this paper starts from the amplitude phase tensor decomposition of impedance tensor, uses the feature that the amplitude tensor decomposition parameters without distortion are highly similar to the phase tensor decomposition parameters, and establishes an objective function according to the sum of the corresponding decomposition parameter differences. Furthermore, the paper searches for the distortion parameters by improving the particle swarm algorithm and takes the objective function value as the fitness of the particles. As a result, the MT galvanic distortion correction in which the regional structure is arbitrary in dimensions is realized. In addition, the paper proposes an MT galvanic distortion correction method that requires no assumption of the dimension of regional structure and has wider adaptability. Finally, the method is applied to calculate the three-dimensional model and filed data, and the results verify the effectiveness, correctness, and practicability of the method.

Keywords: Magnetotelluric (MT), impedance decomposition, distortion correction, particle swarm optimization

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