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A review of research on reservoir fracture extraction

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Abstract

Fractured oil and gas reservoirs occupy a very important position in the world's oil and natural gas production and reserves. On the one hand, natural fractures can significantly improve the permeability of the reservoir and even provide a certain storage space for oil and gas accumulation. On the other hand, they have an important impact on the fracturing stimulation of the reservoir and the optimization design of petroleum engineering plans. This article conducts a literature review on reservoir fracture information extraction, analyzes the advantages, disadvantages and development trends of existing technologies from three aspects: reservoir fracture characterization, technology, fracture extraction algorithms, and fracture image information extraction, and provides research for reservoir rock fracture image extraction for reference.

Keywords

Reservoir fractures; fracture characterization; extraction algorithm; image information extraction.

1. Preface

Rock cracks are a kind of fracture structure, which is caused by the cracking and deformation of rocks under the action of various stresses. Fractured reservoirs play an important role in oil and gas exploration and development. The storage body of fractured oil and gas reservoirs is tight rock mass, in which fractures are important storage spaces and diversion channels for fluids. Therefore, accurately identifying fractures in reservoirs is of extremely important significance to oil and gas development and the improvement of crude oil recovery [1].

For different reservoirs, there are differences in fracture identification and extraction. In unconventional oil and gas reservoirs, the influencing factors, formation mechanisms, grading combinations, distribution patterns, and control effects on oil and gas of fractures are all somewhat different from those in conventional reservoirs. Research on fracture identification and characterization has put forward higher standards. requirements. At present, fracture identification and characterization tend to develop in a refined and quantitative direction, and a multi-method, multi-scale, and multi-parameter comprehensive characterization of reservoir fractures has gradually formed. Comprehensive characterization of reservoir fractures is the basis for reservoir fracture prediction and modeling, and is also an important reference for reservoir engineering sweet spot selection and exploration and development plan formulation. Due to the complexity of crack formation mechanisms and influencing factors, it is difficult to accurately describe the three-dimensional distribution of cracks using a single method or single parameter. At present, fracture identification and characterization methods mainly include geological and petrological methods, logging methods, drilling and logging, and production dynamic data analysis methods. Therefore, this article summarizes the research results in the field of fracture information extraction and analyzes the advantages, disadvantages and development trends of existing technologies from three aspects: reservoir fracture characterization technology, fracture extraction algorithm, and fracture image information extraction.

2. Research on reservoir fracture characterization technology

2.1. Characterization of fractures by geological and petrological methods

Geological and petrological methods mainly directly observe the shape of fractures through field outcrops, cores and other samples. Combined with a small number of drilling holes, a continuous underground fracture network model can be constructed [2]. With the development of tomography machines, cathodoluminescence, UAV remote sensing technology, three-dimensional laser scanning technology and field three-dimensional fracture modeling [3-5], geological and petrological methods for characterizing fractures are becoming more microscopic, three-dimensional and more refined direction development.

2.2. Identify fractures from well logging data

The identification of fractures from conventional logging data is actually a process of extracting and amplifying weak signals [6]. At present, commonly used logging methods to identify fractures mainly include lithology logging, porosity logging, resistivity logging, sonic full wave train logging, formation dip angle logging, and imaging logging [7-11]. Usually fractures with different occurrences have different responses, so the logging response of fractures should consider the development type of fractures [12]. At present, the characterization of fracture parameters by well logging methods is developing in the direction of quantitative characterization and three-dimensional detection, that is, from "seeing in one hole" to "seeing in one hole" [13]. Starting from limited core data, Zhao Junlong et al. [14] used R/S variable scale analysis technology and gray correlation technology in modern mathematics to combine well logging, well logging and dynamic data to carry out the analysis of natural fractures in low-permeability sandstone reservoirs of identify work. Zerrouki et al. [15] improved the neural network method and used Messaoud oil field logging data to calculate natural fracture porosity, and pointed out that density logging has the greatest correlation with the calculated natural fracture porosity. Lyu et al. [16] summarized the logging responses of fractures in tight sandstone. When fractures develop in tight oil sandstone, there are fracture responses in caliber logging, sonic logging, compensated neutron logging, density logging and dual induction logging. ; However, in sandstones with low rock fracture strength, it is difficult for conventional logging to distinguish between fractured and non-cracked development sections. Xu et al. [17,18] established a fracture identification model based on the sensitivity characteristics of logging responses, and used the differences in logging responses to characterize the porosity of fractures. Che Shiqi [19] took the Wufeng Formation-Longmaxi Formation shale reservoir in the Fuling shale gas field in the Sichuan Basin as an example to construct a quantitative calculation model for shale fracture parameters. Tang Xiaoming et al. [13] creatively developed dipole shear wave remote detection imaging logging technology, and used corresponding imaging processing software to achieve precise characterization of the microstructure morphology and orientation within tens of meters around the wellbore. Pan Baozhi et al. [20] used resistivity data and conventional logging data to establish electrical imaging reservoir fracture identification factors and conventional reservoir logging fracture comprehensive identification factors, which provided a new method for reservoir fracture identification. Deng Shaogui et al. [21] systematically simulated the azimuthal lateral logging response of fractures based on the three-dimensional finite element method, and visualized the occurrence and development characteristics of fractures through wellbore imaging of the azimuthal resistivity logging response. Xiao et al. [22] improved the traditional R/S analysis method by introducing the finite difference method, and verified the reliability of the method through dynamic and static data.

2.3. Drilling and logging data characterize fractures

In terms of identifying fractures from drilling and logging data, Chen Qinggui et al. [23] proposed using three models of drilling time curve, formation drillability and drilling time regression parameters to identify fractured reservoirs. Norbeck et al. [24] proposed two evaluation parameters to obtain the location of natural fractures intersecting the wellbore during underbalanced drilling operations: (1) total gas concentration in mud logs; (2) mud volume. He Xinbing [25] systematically summarized the well logging response characteristics when drilling into a fracture development zone: (1) The phenomenon of bubbles and rising bubbles generated by overflow, logging groove surface and well leakage; (2) Gas detection of full hydrocarbon peak-type rises, and cyclical recurrence occurs; (3) the standard oil mass concentration is an abnormally high value; (4) the conductivity of the drilling fluid outlet is high. Sui Zedong et al. [26] proposed using work index to identify fracture development sections in igneous rock reservoirs. The decrease in work index can reflect the degree of fracture development. The intervals where cracks develop also affect the stability of the rock. The direction of the well wall collapse can usually reflect the direction of the fracture, but the influence of in-situ stress on the direction of the well wall collapse should be considered. Kan Liujie et al. [27] pointed out the response characteristics of mudstone fractures while drilling: abnormal formation drillability index (dc index) curve, high gas log curve, abnormally high GR curve, well wall instability during drilling and well The content of secondary minerals in leaks and cuttings increased.

2.4. Use production dynamic data to identify cracks

When using production dynamic data to identify cracks, attention should be paid to distinguishing whether water absorption, leakage, and water channeling are caused by cracks or pore throats. On the profile, the injected water will rush along the high-permeability sections where fractures develop or the high-porosity and high-permeability sections of the matrix, while the low-permeability sections absorb less or no water, forming a peak shape in the crack-developed sections in the water-absorbing profile. This layer with a sharp peak shape and large-scale water absorption is likely to be a fracture development section or a water-flooded layer [28]. Deng Hucheng et al. [29] found that the unimpeded flow rate of gas wells in the Xinchang gas field is correlated with the fracture opening in the test well section, reflecting that effective fractures near the wellbore have a controlling effect on productivity and output. Kim et al. [30] extracted virtual vertical seismic profiles and single well profile data from synthetic microseismic data, and performed prestack depth migration to accurately determine the spatial location of natural fractures.

3. Crack extraction algorithm

3.1. Well fracture extraction algorithm based on ultrasonic logging images

In oil and gas ultrasonic logging, fractures are an important reference in the study of oil reservoirs and reservoir heterogeneity. In order to effectively identify and extract well-travel fractures, there are currently many extraction algorithms for well-travel fractures. Zhang Xiaofeng et al. proposed a crack extraction algorithm based on wavelet analysis [31]. This method has good anti-interference performance, but the algorithm requires many parameters to be set, the degree of freedom is too large, and the algorithm is not stable enough. The team of not too good. Zhang Chengen et al. [32] proposed a logging fracture extraction algorithm based on ant colony edge detection [33], which achieved good results. However, due to the use of ant colony algorithm, this algorithm requires a large number of iterations and has high time complexity. Xie F et al. proposed a multi-scale pipe flow model for fracture identification and achieved good results. However, this algorithm is aimed at electrical imaging logging images.

Although there are currently a variety of fracture extraction algorithms, most of them are only suitable for In well-formed images, cracks with low contrast and low signal-to-noise ratio have poor extraction effects. Zhang Haojie [34] et al. proposed a well-passing fracture extraction algorithm based on edge detection in view of the poor anti-interference ability of the existing well-passing fracture extraction algorithms. The algorithm first improves the contrast of the logging image through limited contrast histogram equalization and improves the accuracy of edge detection. In order to further improve its anti-interference performance, adaptive filtering and morphological processing are performed on the detected edge images. Finally, cracks are extracted through Hough transform after dimensionality reduction.

3.2. Based on the improved UNet++ core image filling joint extraction algorithm

In recent years, with the rapid development of deep learning, algorithms based on deep learning have achieved certain results in the field of segmentation. Ronneberger et al. [35] proposed a UNet network with a similar U-shaped structure, using skip connections to splice shallow-level and deep-level features. This network has achieved good results in the field of medical image segmentation. Zhou et al. [36] proposed the UNet++ network, which added dense short connections based on UNet to improve the performance of the model. Liang Bo et al. [37] proposed a multi-task segmentation network based on a fully convolutional neural network, which achieved good segmentation results in actual scenarios. Liu Qi et al. [38] combined prior information with the UNet network for segmentation of land and sea images, which has good timeliness and segmentation accuracy.

3.3. Based on the improved MF-FDOG algorithm

The MF-FDOG algorithm [39] was first proposed by Zhang et al. in 2010. Its purpose is to solve the problem that the conventional MF algorithm cannot accurately identify blood vessel targets and edges in retinal images. This not only improves the accuracy of blood vessel extraction, but also provides reliable technical support for computer-aided diagnosis and treatment. In 2013, Stumpf et al. [40] successfully applied the MF-FDOG algorithm to monitoring by taking advantage of the commonalities between ground fissures in drone images and blood vessels in retinal images (that is, having dark tones and striped distribution characteristics). The ground fissures produced by landslides are being monitored, and ground fissures are extracted from drone images obtained at different times to infer the direction and extent of landslide expansion, thereby achieving the purpose of dynamic monitoring of landslides. However, when this algorithm adjusts the value range difference between the two response value images obtained by the MF algorithm and the FDOG algorithm, the sensitivity correction parameters introduced have the disadvantage of not being universal, and the method of using parameter empirical values has limitations; Secondly, the direction of ground fissures in the image is arbitrary. Ground fissures with unknown directions can be accurately extracted by using templates with multiple direction detection capabilities, and the selection of the number of template directions has an impact on the operating efficiency of the MF-FDOG algorithm and ground fissures. Extraction accuracy plays a decisive role, and the original algorithm does not involve the study of template directionality. Through a large amount of research, Wei Bowen [41] focused on a series of possible problems existing in the research. Starting from the principles of the MF-FDOG algorithm, he conducted research on the deficiencies in the algorithm. Through a large number of experiments and analysis, he finally proposed a An improved MF-FDOG algorithm. In order to enhance the theoretical basis of this algorithm, the following two important assumptions are first made: (1) Ground fissures are distributed along straight lines in a local area in the image, and the two edges are anti-parallel (i.e., the two edges of ground fissures Symmetrical about the central axis); (2) The vertical distribution curve of ground fissures satisfies the inverted Gaussian distribution.

4. Crack image information extraction

4.1. Core fracture image extraction based on image processing technology

Threshold segmentation is one of the simplest image segmentation methods. It uses the grayscale characteristics of the image to set a threshold in advance. According to this threshold, the image pixels are divided into two categories to achieve image binarization. Threshold segmentation has the advantages of simple calculation, high computational efficiency, and fast speed. Wang Renyi used digital image processing technology and used a large number of field core longitudinal (or plane) cleavage surface image data in the oil field to directly separate the fracture information on the core profile. The binarization algorithm of the maximum inter-class variance method is based on the inter-class variance Taking the maximum as the criterion, this method is used to obtain an ideal binary effect, and the fracture image information can be extracted from the core section more accurately. Oliveira et al. [42] applied the characteristics of darker crack areas and smaller pixel values, used two dynamic thresholds to detect the crack areas in the image, and used different image blocks of the image segmented by the first dynamic threshold to calculate entropy. The obtained entropy block matrix is subjected to the second dynamic threshold segmentation to segment image blocks containing crack pixels. Kirschke et al. [43] segmented the cracks into multiple image blocks based on the grayscale histogram of the crack image, and then set thresholds based on the parameters of the crack area image block and the background area image block histogram to determine whether the cracks contained cracks. Image blocks to segment out crack areas. Threshold segmentation achieves crack image segmentation through image grayscale values. The segmentation effect is poor for images where the grayscale difference between the background and cracks is not obvious, and threshold segmentation is sensitive to noise.

4.2. Fracture extraction based on three-dimensional digital core CT sequence images

Due to its unique advantages, digital cores have been widely used in the oil and gas industry in recent years. The two-dimensional batch processing process of core CT sequence images is a key step in the process of building a three-dimensional core model. Its purpose is to extract objects of interest from the complex core structure, such as core pore particles and fractures, etc., so as to facilitate three-dimensional Model construction and calculation of three-dimensional parameters. Xu Kang [44] proposed a batch extraction method of cracks based on crack translation. First, the crack area is manually marked in the first frame of the sequence diagram, and then the cracks are moved and changed according to the position of the crack in the next frame to achieve the purpose of extracting cracks. . Experimental results show that the method in this paper has two advantages: First, it removes the interference of noise after binary extraction, and also makes the extracted cracks more complete and without breaks. It has better performance in the scenario of extracting certain types of cracks in large quantities. application. Second, you can choose to extract fracture targets one by one, ignore some shallow cracks or inconspicuous cracks, and only retain the fracture targets in the area of interest, so that the three-dimensional structure of the target fracture can be reconstructed in a targeted manner. New crack extraction algorithm for rock 3D images. Deng Zhiqiu et al. [45] performed three-dimensional reconstruction of core CT sequence images and used the least squares method to obtain the fitting plane of the three-dimensional target. By calculating the ratio of the minimum circumscribed sphere radius of the three-dimensional target and the equivalent sphere radius, the shape factor and the approximate minimum circumscribed cuboid The ratio of the longest side to the shortest side enables automatic identification of core fractures. Experimental results confirm that this method can better identify cracks in three-dimensional images. There are already several algorithms dedicated to extracting cracks from a single 2D image. Miyamotod et al. [46] both binarized the two-dimensional image, extracted the targets with long and narrow features, and regarded them as cracks; Non-Member et al. [47] first established a seepage model based on the two-dimensional image, and then based on the image The connectivity of gray values and the shape characteristics of the seepage area identify cracks. The limitations of the above methods are that they only use two-dimensional image information of rocks (i.e., rock surface images or single rock CT images), and the two-dimensional morphological characteristics of rock fractures cannot fully characterize their characteristics in three-dimensional space. The above method can easily cause ordinary pores in the shape of long and narrow lines in the two-dimensional image to be misjudged as cracks; or cause cracks in the shape of non-long and narrow lines in the two-dimensional image to be misjudged as ordinary pores. In view of the possible shortcomings of the above methods, Xia Chenmu et al. [48] proposed a new crack extraction algorithm for three-dimensional rock images, which performs surface reconstruction and Laplacian grid smoothing on each connected component of the three-dimensional rock pore model ,grid simplification and other operations. Triangular meshes are divided into different categories based on the triangular mesh area and mesh unit normal vector direction characteristics. The shape factor is used to determine whether the three-dimensional space structure composed of each triangular mesh class has crack characteristics. Perform a morphological expansion operation on the voxel point set contained in the three-dimensional space structure with crack characteristics, and perform a logical AND operation with the voxel point set of the connected components of the original three-dimensional rock pore model, and the operation result is the rock crack.

5. Conclusion

Reservoir fracture characterization technology: Comprehensive analysis of several fracture characterization technologies currently mainly includes geological and petrological methods, logging methods, drilling and logging, and production dynamic data analysis methods. However, the above methods are still analyzing the static characteristics of the reservoir rock, or using actual data in the production process for comparative analysis of data, and lack the combination of static characteristics of the reservoir and dynamic data to achieve fracture characterization. In the future, we hope to further optimize and combine comparative analysis on the existing basis.

Crack extraction algorithm: With the development of extraction algorithms over the years, great progress has been made in crack information processing. However, although there are currently a variety of crack extraction algorithms, most of them are only suitable for images with better imaging. The extraction effect of cracks under contrast and low signal-to-noise ratio is poor. There is still a lack of more detailed calculation methods for the crack algorithm. In the future, more accurate algorithms can be proposed by combining professional fields from multiple aspects and directions.

In terms of information extraction of fracture images: At present, the information extraction of fracture images has been greatly improved. Whether it is characterizing fracture images through the basic characteristics of rocks, or combining three-dimensional digital cores, the extraction of fracture images through CT technology has great achievements. Great progress has been made. However, these methods only draw conclusions through the static characteristics of rock cores and experiments. In the future, fracturing and core processing methods can be combined to compare and analyze the dynamic data before and after rock processing to improve the generation of cracks and the fine characterization of cracks. All have great benefits. We also hope to completely solve the identification and characterization of fractures in complex reservoirs.

References

[1] Liu Jingshou, Ding Wenlong, Xiao Zikang, et al. Research progress on comprehensive characterization and prediction of reservoir fractures [J]. Exhibitions of Geophysics, 2019, 34(06): 2283-2300.

[2] Moein M J A ,Márk Somogyvári, Valley B ,et al.Fracture Network Characterization Using Stress-Based Tomography[J].Journal of Geophysical Research: Solid Earth, 2018.DOI:10.1029/ 2018 JB016438.

[3] Baytok S , Pranter M J .Fault and fracture distribution within a tight-gas sandstone reservoir: Mesaverde Group, Mamm Creek Field, Piceance Basin, Colorado, USA[J].Petroleum Geoscience, 2013, 19(3):203-222.DOI:10.1144/petgeo2011-093.

[4] Bisdom K , Bertotti G , Nick H M .The impact of in-situ stress and outcrop-based fracture geometry on hydraulic aperture and upscaled permeability in fractured reservoirs[J].Tectonophysics, 2016.DOI:10.1016/j.tecto.2016.04.006.

[5] Bogatkov D , Babadagli T .Fracture network modeling conditioned to pressure transient and tracer test dynamic data[J].Journal of Petroleum Science & Engineering, 2010, 75(1-2):154-167.DOI:10.1016/j.petrol.2010.11.004.

[6] Bisdom,Kevin,Bertotti,et al.A geometrically based method for predicting stress-induced fracture aperture and flow in discrete fracture networks[J].[2023-12-24].

[7] Zeng Lianbo. Fractures and seepage characteristics of low-permeability sandstone oil and gas reservoirs [J]. Geological Science, 2004, (01): 11-17.

[8] Sun Wei, Li Yufeng, Fu Jianwei, et al. Research progress on well logging and seismic fracture identification [J]. Progress in Geophysics, 2014, 29(03): 1231-1242.

[9] Lai Jin, Wang Guiwen, Sun Simian et al. Research progress on fracture logging identification and evaluation methods in tight sandstone reservoirs [J]. Progress in Geophysics, 2015, 30(04): 1712-1724.

[10] Qu Haizhou, Zhang Fuxiang, Wang Zhenyu, et al. Quantitative characterization method of fractures based on core-electronic imaging logging - taking the sandstone of the Cretaceous Bashkiqike Formation in the ks2 block of the Kuqa Depression as an example [J]. Petroleum Exploration and Development, 2016 ,43(03):425-432.

[11] Lai,Jin,Wang,et al.A review on the applications of image logs in structural analysis and sedimentary characterization[J].Marine & Petroleum Geology, 2018.

[12] Zhao Junlong, Li Zhaoming, Li Jianting, et al. Application of logging and identification technology for natural fractures in Z Oilfield [J]. Petroleum Geophysical Exploration, 2010, 45(04): 584-590+624+470-471. DOI: 10.13810/j.cnki .issn.1000-7210.2010.04.026

[13] Tang Xiaoming, Li Shengqing, Xu Song, et al. Research on horizontal logging fracture identification and acoustic imaging of shale gas reservoirs [J]. Logging Technology, 2017, 41(05): 501-505. DOI: 10.16489/j.issn.1004- 1338.2017.05.001

[14] Zhao Junlong, Zhu Guangshe, Ma Yongning, et al. Research on comprehensive identification of natural fractures in Area A of Ordos Basin based on multi-information [J]. Logging Technology, 2011, 35(06): 544-549. DOI: 10.16489/j.issn.1004 -1338.2011.06.012

[15] Zerrouki A A , A?Fa T , Baddari K .Prediction of natural fracture porosity from well log data by means of fuzzy ranking and an artificial neural network in Hassi Messaoud oil field, Algeria[J].Journal of Petroleum Science and Engineering, 2014, 115:78-89.DOI:10.1016/j.petrol.2014.01.011.

[16] Lyu W , Zeng L , Liu Z ,et al.Fracture responses of conventional logs in tight-oil sandstones: A case study of the Upper Triassic Yanchang Formation in southwest Ordos Basin, China[J].Aapg Bulletin, 2016, 100(09):1399-1417.DOI:10.1306/04041615129.

[17] Cao,Guangwei,Zhang,et al.Method for calculating the fracture porosity of tight-fracture reservoirs[J].Geophysics Journal of the Society of Exploration Geophysicists, 2016.

[18] Jingling,Zhang,Baoying,et al.Predicting the Porosity of Natural Fractures in Tight Reservoirs[J]. Arabian journal for science and engineering, 2018.

[19] Che Shiqi. Quantitative logging identification of shale fractures in Fuling area, Sichuan Basin [J]. Special Oil and Gas Reservoirs, 2017, 24(06):72-78.

[20] Pan Baozhi, Liu Wenbin, Zhang Lihua, et al. A method to improve the accuracy of reservoir fracture identification [J]. Journal of Jilin University (Earth Science Edition), 2018, 48(01): 298-306. DOI: 10.13278/j.cnki. jjuese.20160343

[21] Deng Shaogui, Yuan Xiyong, Wang Zhengkai, et al. Numerical simulation of azimuthal lateral logging response in fractured formations [J]. Acta Geophysica Sinica, 2018, 61(08): 3457-3467.

[22] Xiao Z , Ding W , Liu J ,et al.A fracture identification method for low-permeability sandstone based on R/S analysis and the finite difference method: A case study from the Chang 6 reservoir in Huaqing oilfield, Ordos Basin[J].Journal of Petroleum Science & Engineering, 2019, 174:1169-1178.DOI:10.1016/j.petrol.2018.12.017.

[23] Chen Qinggui, Pan Xiaodong. Research on comprehensive logging identification technology for fractures in tight sandstone reservoirs [J]. Logging Engineering, 2006, (03): 6-9+23+74.

[24] Norbeck J H , Fonseca E R , Griffiths D V ,et al.Natural Fracture Identification and Characterization While Drilling Underbalanced[J]. 2012.DOI:10.2118/154864-MS.

[25] He Xinbing. Analysis of differences in logging and logging interpretation of horizontal wells in the Chang 8 reservoir of Honghe Oilfield [D]. Northwest University, 2015.

[26] Sui Zedong, Hu Zhangming, Qin Baomai, et al. Interpretation and evaluation of logging work index ratio and fluid identification method in igneous rock fractured reservoirs in Zhongguai area, Xinjiang [J]. Logging Engineering, 2015, 26(01): 13-17+84-85.

[27] Kan Liujie, Chen Dingding, Zhu Guowei et al. Method of identifying mudstone fractures using well logging and logging data [J]. Logging Engineering, 2015, 26(02): 29-33+90-91.

[28] Bisdom,Kevin,Bertotti,et al.A geometrically based method for predicting stress-induced fracture aperture and flow in discrete fracture networks[J].[2023-12-25].

[29] Deng Hucheng, Zhou Wen, Zhou Qiumei, et al. Quantitative characterization method and application of natural fracture effectiveness in Xuer gas reservoir in Xinchang Gas Field [J]. Acta Petrologica Sinica, 2013, 29(03): 1087-1097.

[30] Kim M , Tak H , Byun J .Imaging pre-existing natural fractures using microseismic data[J].Geophysical Prospecting, 2015, 63(5):1175-1187.DOI:10.1111/1365-2478.12241.

[31] Zhang Xiaofeng, Pan Baozhi. Research on the application of two-dimensional wavelet transform in imaging logging to identify fractures [J]. Petroleum Geophysical Exploration, 2012, 47(01): 173-176+188+201. DOI: 10.13810/j.cnki. issn.1000-7210.2012.01.001

[32] Xavier A , Guerra C E ,Andrade, André.Fracture analysis in borehole acoustic images using mathematical morphology[J].Journal of Geophysics & Engineering, 12(3):492-501[2023-12-25].DOI:10.1088/1742-2132/12/3/492.

[33] Zhang Chengen. Research on imaging logging fracture identification and extraction and fracture parameter calculation methods [D]. Jilin University, 2012.

[34] Zhang Haojie, Zhou Luoyu. Research on extraction algorithm of well-crossing fractures in ultrasonic logging images [J]. Optoelectronics·Laser, 2019, 30(06): 654-658. DOI: 10.16136/j.joel.2019. 06.0349

[35] Ronneberger O , Fischer P , Brox T .U-Net: Convolutional Networks for Biomedical Image Segmentation[J].Springer, Cham, 2015.DOI:10.1007/978-3-319-24574-4_28.

[36] Zhou Z , Siddiquee M M R , Tajbakhsh N ,et al.UNet++: Redesigning Skip Connections to Exploit Multiscale Features in Image Segmentation[J].IEEE Transactions on Medical Imaging, 2020, 39(6):1856-1867.DOI:10.1109/TMI.2019.2959609.

[37] Liang Bo, Yu Lei, Li Shuang. Multi-task image semantic segmentation based on convolutional neural network [J]. Radio Engineering, 2019, 49(07): 575-580.

[38] Liu Qi, Zhang Xiaolei, Wang Yanan. A sea and land segmentation method for SAR images based on prior information and U-Net [J]. Radio Engineering, 2021, 51(12): 1471-1476.

[39] Wei Bowen. Extraction of ground fissures in loess areas based on improved MF-FDOG algorithm and drone images[D]. Southwest Jiaotong University, 2018.

[40] Stumpf A , Malet J P , Kerle N ,et al.Image-based mapping of surface fissures for the investigation of landslide dynamics[J].Geomorphology, 2013, 186(MAR.15):12-27.DOI:10.1016/j. geomorph. 2012.12.010.

[41] Wei Bowen, Liu Guoxiang, Wang Zhiheng. Extraction of ground fissures in loess areas based on improved MF-FDOG algorithm and drone images [J]. Surveying and Mapping, 2018, 41(02): 51-56+61.

[42] Oliveira H , Correia P L .AUTOMATIC ROAD CRACK SEGMENTATION USING ENTROPY AND IMAGE DYNAMIC THRESHOLDING[C]//2009 17th European Signal Processing Conference.IEEE, 2009.

[43] Kirschke K R , Velinsky S A .Histogram-Based Approach for Automated Pavement-Crack Sensing[J].Journal of Transportation Engineering, 1992, 118(5):700-710.DOI:10.1061/ (ASCE) 0733-947X (1992)118:5(700).

[44] Xu Kang, Teng Qizhi. Batch extraction of fractures from core CT sequence images based on fracture translation [J]. Modern Computer, 2021, 27(32): 46-53.

[45] Deng Zhiqiu, Teng Qizhi. Automatic identification of fractures in three-dimensional core images [J]. Computers and Digital Engineering, 2013, 41(01):98-100.

[46] Miyamoto A , Konno M A , Bruhwiler E .Automatic Crack Recognition System for Concrete Structures Using Image Processing Approach[J].Asian Journal of Information Technology, 2007. DOI: 10.1063 /1.1147123.

[47] Non-Member T Y , Non-Member S N , Non-Member R S ,et al.Image-Based Crack Detection for Real Concrete Surfaces[J].Ieej Transactions on Electrical & Electronic Engineering, 2008, 3(1):128-135.DOI:10.1002/tee.20244.

[48] Xia Chenmu, Teng Qizhi, Qing Linbo, et al. Crack extraction method from three-dimensional rock images [J]. Computer Engineering and Applications, 2018, 54(17): 186-191.