Proceedings of the 4th International Conference on Environmental Geoscience and Earth Ecology
DOI: 10.54254/2753-8818/2026.35731

A Review of Fractured Carbonate Reservoir Identification Techniques Based on Seismic Attributes

Yicheng Xia

Beijing Language and Culture University, Beijing, China
3059921650@qq.com

Abstract. Fractured carbonate reservoir is an important area of hydrocarbon exploration and development. Their reservoir spaces, formed through multiple phases of karst processes, having complex morphology and are highly interconnected. These make accurate identification and prediction particularly challenging. Seismic attribute analysis is a key method linking seismic reflection characteristics with subsurface geological features, and it can quantitatively extract response characteristics such as amplitude, frequency, and phase from large amounts of seismic data, and provides effective support for the identification of such reservoirs. This study systematically reviews the classification system of seismic attributes, proposes a three-class attribute classification based on geological target identification, and constructs a hierarchical progressive reservoir prediction technology chain. We also analyzes the limitations of applying single attributes using seismic attribute case studies. Furthermore, we summarizes the core concepts and practical achievements of multi-attribute fusion and anticipates the future directions of application trends and intelligent technologies in this field, which help to provide the systematic theoretical references and practical insights for the efficient identification and prediction of fractured carbonate reservoirs.

Keywords: Fractured carbonate reservoir, Seismic attributes, Effective identification

1. Introduction

Fractured carbonate reservoirs are widely distributed in hydrocarbon-bearing basins such as the Tarim and Sichuan basins, and represent a key focus and major challenge in current hydrocarbon exploration. These reservoirs have been shaped by multiple phases of karstification and tectonic movements; their storage spaces consist primarily of caves and fractures. They are characterised by diverse morphologies, uneven distribution and complex connectivity, posing significant challenges for the precise identification, spatial characterisation and assessment of fluid-bearing potential of these reservoirs.

Seismic attribute analysis is one of the core technologies in the field of geophysical exploration. It involves application of mathematical transformations to pre-stack and post-stack seismic data to quantitatively extract seismic parameters which can reflect the geometric morphology, lithological properties and fluid content of subsurface formations, as a result establishing a link between seismic reflection characteristics and subsurface geological structures. Compared with traditional seismic

DOI: 10.54254/2753-8818/2026.35731

interpretation methods, this method offers the advantages of quantification, efficiency and precision, becoming a key tool for addressing the challenges of identifying fractured carbonate reservoirs.

This study examines the geological characteristics and exploration requirements of fractured carbonate reservoirs, and provides a systematic review of the application of seismic attributes in the identification of such reservoirs. Firstly, establishing a classification system for seismic attributes based on geological targets, clarifying the geological significance and application scenarios of each attribute; Secondly, the physical principles, application cases and limitations of each attribute are elaborated in detail, with targeted optimization proposals put forward; Thirdly, the technical approaches and practical outcomes of multi-attribute fusion are summarized; Finally, it looks ahead to the application trends of intelligent technologies in this field, with a view to providing guidance for research and production practices in related areas.

2. Classification of core attributes and geological interpretation

Seismic attributes refer to quantifiable parameters derived from mathematical transformations of pre-stack or post-stack seismic data, which reflect quantifiable characterization parameters of seismic wave geometry, kinematics, and dynamics [1]. Essentially, they are quantifiable characteristics within seismic data that can indirectly describe geological information such as stratigraphic structure, lithology, physical properties and fluid content.

To meet the exploration requirements for fractured carbonate reservoirs, a geologically target-oriented classification system has been adopted. This system categorizes the vast array of seismic attributes into three main groups, each corresponding to a distinct core aspect of reservoir characterization. This approach enables a precise alignment between the physical significance of seismic attributes and geological interpretation objectives, thereby establishing a hierarchical and progressive chain of reservoir prediction techniques (Table 1).

Table 1. Three-category classification of attributes based on geological target identification

Classification	Definition and typical attributes	Main applications in carbonate reservoir prediction
Amplitude/Frequency Attributes	Used to reflect variations in lithology, physical properties and fluid content; typical attributes include root mean square amplitude, arc length, instantaneous frequency, effective bandwidth.	Identify of carbonate reservoirs: Large-scale karst caves often manifest as bead-like high-amplitude anomalies; frequency attenuation characteristics may indicate reservoir fluid content.
Geometric/Structural Attributes	Used to characterise stratigraphic discontinuities and lateral variations; typical attributes include coherent volumes, curvature volumes, dip angles and ant-tracking volumes.	Identify of fractures and faults: highlight fracture zones, faults and boundaries of karst caves, accurately delineate the spatial contours and distribute of reservoirs.
Absorption/Attenuation Attributes	Used to reflect the attenuation characteristics of seismic wave energy, which are closely related to the degree of fracture development and fluid content in the reservoir. Typical attributes include absorption coefficient, quality factor Q.	Determine reservoir fluid content: when fractures or karst caves contain fluids, attenuate high-frequency components of seismic waves is more pronounced, serve as an important indicator for detecting hydrocarbon presence.

The first reason for using this division of types is that the three kinds of attributes have been divided in accordance with the geological problems of reservoir prediction, and different main

DOI: 10.54254/2753-8818/2026.35731

application objectives have been set for these groups, such as amplitude and frequency attributes are used to detect storage space (e.g., karst caves), geometric/structural attributes refer to the distribution of connecting pathways (e.g., fractures), and absorption/attenuation attributes are used to determine the amount of fluid contained in the storage space. The division method is based on the physical characteristics of attributes and also meets the practical requirements for exploration; therefore, it can be used to selectively and efficiently apply these attributes to lay the foundation for the next development of reservoir identification technology.

2.1. Amplitude/frequency attributes

The physical reason for amplitude/frequency characteristics is a change in the dynamic properties of seismic waves. It is a general idea to record the sudden changes in the amplitude and frequency of seismic waves that occur when there are unusual changes in physical properties and fluid content. Among them, the most commonly used are Root-mean-square amplitude, arc length, instantaneous frequency and effective bandwidth. The root-mean-square amplitude of the seismic impedance contrast can fluctuate, and at the same time, the instantaneous frequency is very sensitive to heterogeneity and changes in fluid.

Amplitude/frequency properties have been used to find fractured carbonate reservoirs, and the main purpose of doing so is to locate and describe these reservoirs. If there are karst caves or solution zones underground, the seismic impedance in the filling material (fluid or sediment) is different from that in the surrounding rock; therefore, it will have a high-amplitude anomaly in the seismic profile and is generally a beaded reflection pattern. At the same time, if there are fractures or fluids in the reservoir, the high-frequency components of seismic waves will be preferentially absorbed; thus, there will be a local decrease in the frequency or attenuation of high frequencies. It can be used to determine how good the reservoir is.

The Ordovician reservoirs in the S67 block of Tahe are a good representative case [2], and therefore, researchers have selected the seismic amplitude spectral gradient attribute to predict small-scale fractures and pores. This attribute is the change rate of the amplitude of seismic reflection waves, which shows how the amplitude of seismic reflectivity varies with frequency in the effective frequency range of the seismic data and integrates the response characteristics of different frequencies and amplitudes. It has the characteristics of different frequencies and amplitudes, can reduce the interference of the rock matrix on seismic response, and enhance the accuracy of small-scale fracture and cavity identification. It reduces the interference from the rock matrix on seismic response and improves the accuracy of small-scale fracture identification. Due to the lack of good data, a distribution model for the small near-surface fractures and cavity system of the carbonate fracture system was constructed by means of sequential simulation, and the amplitude spectral gradient attribute and the vertical probability volume and probability density distribution were used. A karst property model was also built by way of sequential Gaussian simulation (Figure 1). The model is to set the distribution of space and the parameters for surface karst fractures and pores, as well as the properties of porosity. As shown in Figure 1a, the main features of the surface fractured reservoir are small fractures and pores that have good lateral continuity; Figure 1b shows that the overall distribution of porosity is uniform, and there is a relatively high porosity in karst caves and karst residual hills, indicating good connectivity. The results of the simulation are in line with the geological observations.

DOI: 10.54254/2753-8818/2026.35731

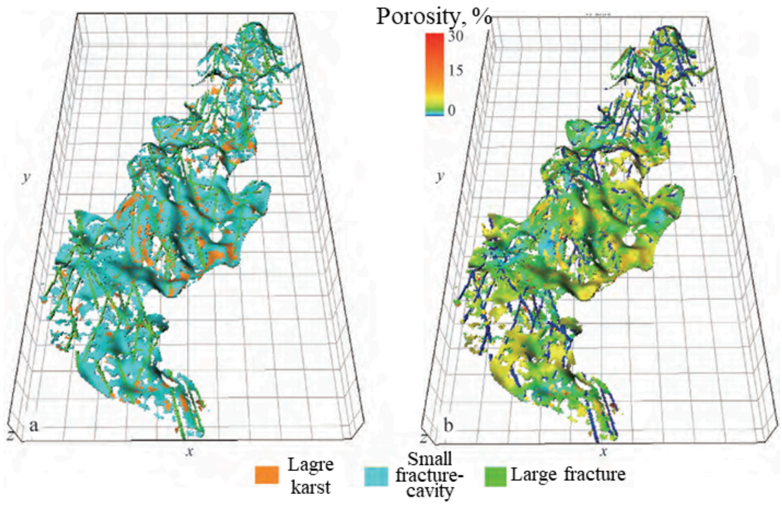

Figure 1. 3D geological model of epikarst reservoir in Block S67, Tahe Oilfield, Tarim Basin, modelled by fracture-cavity distribution (left side), and porosity (right side)

The primary deficiency of amplitude/frequency attributes is that they have various ways of interpretation; thus, there is no direct correspondence between the seismic attribute and the geological target. A single amplitude or frequency anomaly can be caused by many reasons in the geological environment (for instance, strong amplitude may be due to the presence of karst caves, lithology changes, structural disturbances, etc.). To solve the problem mentioned above, the two optimization methods are as follows: First, pre-stack attributes such as pre-stack amplitude and angle gradient will be added; Second, machine learning technology will be used for attribute dimension reduction and combination to reduce interference caused by the uncertainty of individual attributes and improve the accuracy of fracture porosity detection.

2.2. Geometric/structural attributes

The physical foundation of geometric/structural properties is the lateral discontinuity of seismic phase axes; at the core, one needs to capture changes in the waveform of adjacent seismic traces to infer the distribution pattern of underground geological discontinuities, such as faults, fractures and karst caves. Among them, the most frequently employed are coherence volume, curvature volume, dip angle and inverse tracking volume techniques. Coherence volume technology can be used to easily determine the suddenness of strata; curvature volume technology is used to determine the range and direction of fracture development, and inverse-tracking volume technology is employed to obtain details of small faults and fractures.

To predict the type of fracture in a carbonate reservoir, core values for geometric and structural attributes are employed to describe the fracture and fault; thus, it can provide an approximation of the geometric constraints for space description in the reservoir. A fracture zone or small-scale fault will cause a relatively large deformation in the seismic wave shape of the adjacent seismic trace. Coherence volume analysis is a sensitive method to observe changes in coherence and can clearly present the direction, density, range, etc., of fracture zones and accurately determine the orientation, density and extent of these zones; thus, it is used to know the spatial distribution of the reservoir.

Taking the main oil layer of the super-deep carbonate reservoir in Well X of the Tarim Oilfield as an example [3], scholars have begun to study the prediction of the spatial shape of the fractured

DOI: 10.54254/2753-8818/2026.35731

reservoir using coherence attributes. The reservoir has the characteristic of pearl-like reflection in the seismic section (Figure 2a), and the center of this pearl-like reflection zone is related to the center of the fractured reservoir. The size of the pearl-like reflection zone is related to the size and physical quality of the reservoir. Figure 2b is the coherence profile at Well W11. Layered strata are shown in green, and they have higher coherence attribute values; Areas with lower coherence attribute values are the flanks of the fractured reservoir. The reservoir core is located in the middle of these two sides and has a clear boundary; it is a relatively precise indication of the location of the reservoir.

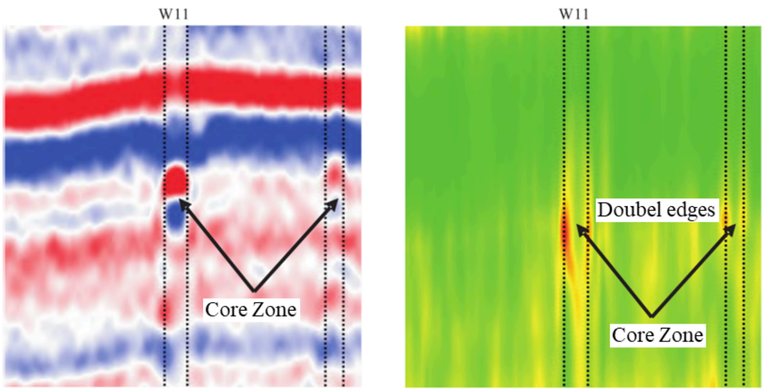

Figure 2. Coherence characteristic analysis of fracture-cavity reservoirs based on the original full-angle section (left) and coherence full-angle section (right)

The first problem with geometry and structure is that although they can indicate the position and shape of cracks, karst caves, and fissures, they fail to determine their interconnectedness or efficiency. It is relatively obvious in the case of oil and gas migration pathways, karst channels, and fault networks. Therefore, a way to improve the problems mentioned above is to use both the geometry and structure of the system in a stress-field model. Stress-field models can help us determine the causes of the development of karst channels, identify which areas are controlled by stress or closed within the fracture-porosity system, and predict the space and internal structure, connectivity and efficiency of fractured carbonate reservoirs in all weather conditions; thus, they can enhance the all-encompassing characteristics and accuracy of reservoir identification.

2.3. Absorption and attenuation attributes

The physical basis of the absorption and attenuation properties is that energy is lost during propagation of seismic waves. When seismic waves are in a reservoir for oil and gas or in a fractured area with good well development, the high-frequency component can be more easily attenuated; therefore, there will be a relatively small decrease in high-frequency energy. Generally speaking, these are the parameters that show how much seismic wave energy is lost in a certain area, such as absorption coefficient and quality factor Q. They can be used to study the propagation characteristics of seismic waves in viscoelastic materials and thus derive information about the magnitude of reservoir fractures and fluid storage ability in the reservoir.

In identifying fractured carbonate reservoirs, the core value of absorption/attenuation properties lies in two aspects: first, they are sensitive indicators for detecting reservoir fluid content; second, they can indirectly characterize the degree of fracture development. When fluids (especially hydrocarbons) are present in fractures or karst caves, the high-frequency attenuation of seismic

DOI: 10.54254/2753-8818/2026.35731

waves is significantly enhanced. By extracting absorption/attenuation properties, the fluid content of the reservoir can be quickly assessed. Simultaneously, fractured areas exacerbate the attenuation of seismic wave energy; therefore, this property can also serve as an auxiliary indicator for assessing the degree of fracture development.

In studies of fissured carbonate reservoirs in the Tazhong region, researchers employed Seismic wave absorption and attenuation technology based on non-orthogonal wavelet transform in the TZ45 well area to analyze the fissure and cavity system of the Ordovician Lianglitag Formation and to predict hydrocarbon-bearing reservoirs, achieving favorable results [4] (Figures 3–4). A comparison with drilling data revealed a strong correlation between the developed sections of the carbonate fracture-cavity reservoirs in each well and abnormal high-frequency amplitude decay gradient.

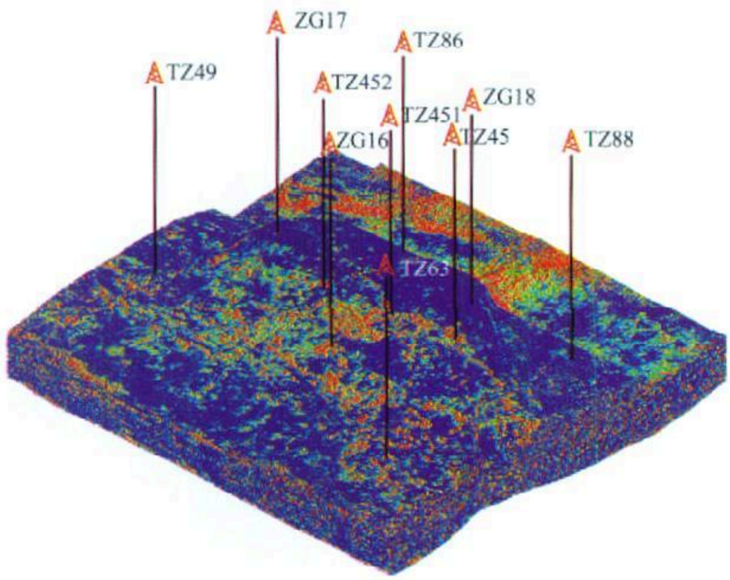

Figure 3. Frequency-domain amplitude attenuation gradient data volume of the Ordovician in Well Block TZ45

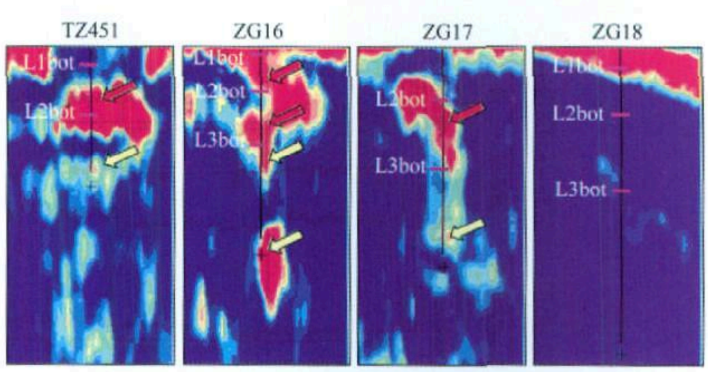

Figure 4. Well-crossing sections of frequency-domain amplitude attenuation gradient data volume in Well Block TZ45(Red arrows indicate oil and gas producing intervals of each well; yellow arrows mark reservoir intervals interpreted by well logging)

The first reason that absorption/attenuation attributes are insufficient is that high-frequency attenuation is not only caused by fluids; moreover, there are many other sources of interference,

DOI: 10.54254/2753-8818/2026.35731

such as multi-path interference. In addition to the fluid factor, some particular lithologies naturally have high absorption properties, and sometimes the scattering attenuation of seismic waves due to structural fractures and viscoelastic attenuation caused by fluids are difficult to distinguish clearly in seismic data. To solve this problem, a time-frequency transformation can be employed to extract the effective Q-value at different center frequencies and plot a Q-frequency (QF) curve; if the curve is monotonically smooth, it can be determined that the attenuation is mainly due to fluid effects; otherwise, if there are significant fluctuations or a sudden drop in the high-frequency range of the curve, it can be inferred that the cause of attenuation is tectonic fracture zones, and thus distinguish between attenuation anomalies of different origins.

3. Multi-attribute integration and comprehensive forecasting

Individual seismic attributes all have significant limitations and are unable to fully characterize the complex geological features of fractured carbonate reservoirs—amplitude/frequency attributes are highly multivalued, geometric/structural attributes cannot determine reservoir viability, and absorption/attenuation attributes struggle to distinguish the causes of attenuation. Consequently, integrating various single attributes for analysis to achieve complementary advantages is an inevitable trend for improving the accuracy of fractured carbonate reservoir identification.

The core concept of multi-attribute fusion is to identify reservoir-sensitive attributes based on geological understanding and drilling data, and then integrate the beneficial information from these attributes through appropriate fusion methods to suppress multiple solutions and interfering factors, thereby achieving accurate reservoir identification and prediction. Currently, common multi-attribute fusion methods can be broadly classified into two categories: traditional statistical fusion (such as cross-plotting and cluster analysis) and modern intelligent fusion (such as neural networks and support vector machines). Among these, cross-plotting is the most widely used in reservoir identification practice due to its simplicity and intuitiveness.

Taking the identification of fractured carbonate reservoirs in the Amu Darya region as an example [5], the oilfields in this region are affected by the overlying salt layer, resulting in poor identification of single attributes: in terms of amplitude attributes, the amplitude changes of the fracture zone corresponding to high-yield wells are obvious, but the tight carbonate reservoirs under the salt pit usually show medium or strong seismic wave amplitudes, which are difficult to distinguish effectively; in terms of frequency attributes, the fracture zone where the high-yield wells are located and the fracture zone near the fault show medium-high frequency characteristics, while the low-yield wells in the tight zone show low frequency characteristics. However, the tight zone under the salt basin shows medium-low frequency characteristics, which overlap with the medium frequency band of the fracture-pore zone, making accurate identification difficult.

To address the issues above, researchers combined drilling data with geological knowledge to develop a model for identifying carbonate oil and gas reservoirs. Using the instantaneous frequency–instantaneous amplitude cross-plot method, they comprehensively utilized both amplitude-based and frequency-based attributes to distinguish between reservoir types(see Figure 5). The results show that fractured reservoirs in the Amu Darya region exhibit typical "medium-to-high frequency, high amplitude" seismic response characteristics. Through multi-attribute fusion, fracture zones and various tight zones, it is possible to effectively distinguished, significantly improving the accuracy of reservoir identification.

DOI: 10.54254/2753-8818/2026.35731

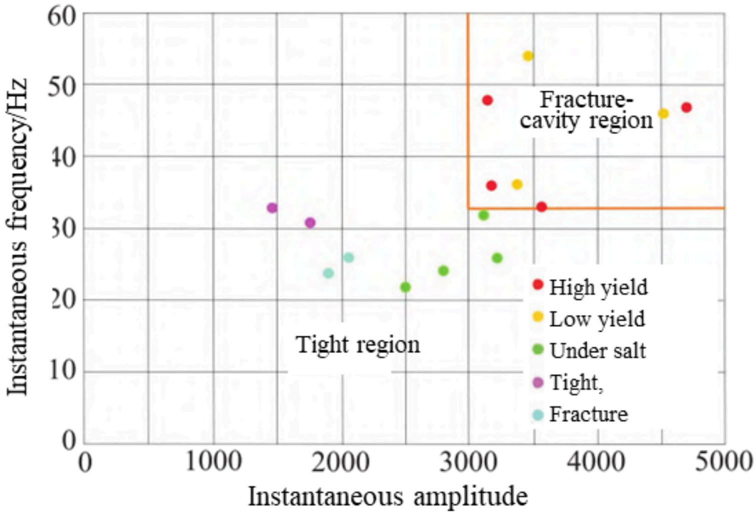

Figure 5. Instantaneous versus instantaneous amplitude crossplots

4. Trends in intelligent development

Traditional multi-attribute fusion methods typically rely on human experience to determine attribute weights, making it difficult to capture the complex nonlinear mapping relationship between attributes and reservoir characteristics, thus limiting prediction accuracy. With the rapid development of artificial intelligence, intelligent methods such as neural networks and deep learning have been widely applied in seismic attribute analysis. By automatically learning the intrinsic relationship between attributes and reservoir characteristics, these methods significantly improve the accuracy and efficiency of reservoir prediction, becoming an important direction for identifying fractured carbonate reservoirs.

Although artificial intelligence technology has great potential in seismic attribute analysis, its application in predicting fractured carbonate reservoirs still faces many challenges: First, the performance of deep learning models is highly dependent on large-scale, high-quality labeled data, which is very scarce in actual exploration. Although a large amount of synthetic data can be generated through forward modeling, there are differences between the simulation results and the actual seismic data, which can easily lead to the problem of effective modeling but failing field measurements [6]; Second, most existing models are purely data-driven "black box" models that fail to combine geological models with geophysical principles, which means that their predictions may contradict basic geological knowledge.

In the future, the development of intelligent technologies in this field will focus on the deep integration of 'geology, engineering, and algorithms. On the one hand, geological knowledge—such as sedimentary facies and fault development patterns—will be transformed into model constraints, guiding AI models to learn features consistent with geological understanding and preventing predictions result from deviating from actual geological patterns. On the other hand, forward modeling technology will be optimized to improve the consistency between synthetic data and real seismic data, thereby addressing the problem of the scarcity of labeled data. Simultaneously, research into lightweight and interpretable AI models will be pursued to overcome the "black box" dilemma, thereby enhancing the models' practicality and reliability and driving the development of fault carbonate reservoir identification technology towards greater precision and intelligence.

References

[1] Zhou, Y. (2017). *Application of seismic reservoir prediction in oil and gas exploration: A case study of Chang 81 member in Zhenjing block* [Doctoral dissertation, Yangtze University]. Hubei: Yangtze University.

[2] Lü, X., Sun, J., Wu, X., et al. (2021). Internal architecture characterization of fractured-vuggy carbonate reservoirs: A case study on the Ordovician reservoirs, Tahe Unit S67, Tarim Basin. *Oil & Gas Geology, 42*(3), 728-737.

[3] Gui, Z., Zhang, J., Zhang, Y., et al. (2025). Fine identification of deep carbonate fracture-cavity reservoirs using angle domain information. *Oil Geophysical Prospecting, 60*(4), 998-1006.

[4] Liu, L., & Sun, Z. (2009). Application of seismic wave absorption and attenuation technology in predicting fracture-vug carbonate reservoir. *Oil Geophysical Prospecting, 44*(S1), 121-124+168+2.

[5] Sun, Y., Chai, H., Wei, X., et al. (2023). Multi-attribute fusion fracture-cavity description technique and application based on deep learning: A case study of H gas field on the right bank of Amu Darya River. *Oil Geophysical Prospecting, 58*(S1), 1-5.

[6] Peng, D., Xi, C., Long, L., et al. (2019). Prediction method for carbonate fracture-cavity bodies based on neural network and multi-information fusion of well and seismic data. In *Proceedings of the 2019 Annual Academic Conference on Oil and Gas Geophysics*. Nanjing.