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Research on Rock Physics and Seismic Inversion Methods for Deep- to Ultradeep- Strata Carbonate Reservoirs

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Abstract. Deep- to ultradeep-strata carbonate reservoirs are a crucial strategic area for increasing oil and gas reserves and production in my country. These reservoirs are characterized by their great depth, strong heterogeneity, and complex pore structure. The high-temperature and high-pressure environment makes the seismic response mechanism unclear, posing a severe challenge to traditional rock physics models and seismic inversion methods. This paper systematically reviews the recent research progress in rock physics and seismic inversion methods for deep-strata carbonate reservoirs. In rock physics, the paper focuses on the achievements in high-temperature and high-pressure experiments, pore structure characterization, and theoretical model improvements. In seismic inversion, the paper reviews the current development status of pre-stack inversion, multi-information constraints, and artificial intelligence-assisted methods. Based on this, the paper points out the shortcomings of current research in terms of theoretical foundation and prediction accuracy, and proposes development trends and key research directions of deep-strata integration, refinement, and intelligence.

Keywords: Deep-strata to ultradeep-strata, Carbonate reservoirs, Rock physics, Seismic inversion, Artificial intelligence

1. Introduction

Global carbonate formations contain abundant oil and gas resources and are key targets for deep- and ultradeep-strata oil and gas exploration [1-3]. With the successful discovery of industrial oil and gas flows at depths below 8200m in the Shunbei oil and gas area of the Tarim Basin and the Luntan 1 well in the Lunnan area, carbonate exploration is rapidly advancing into the deep- and ultradeep-strata realm. However, deep- and ultradeep-strata carbonate reservoirs are diverse in type, highly compacted, exhibit strong heterogeneity in their framework, and have complex pore and fracture structures [1]. Furthermore, the high-temperature and high-pressure environment contributes to the relatively low accuracy of reservoir seismic prediction and quantitative interpretation.

Seismic rock physics bridges the gap between reservoir properties and seismic characteristics, while seismic inversion is a crucial method for quantitatively extracting reservoir parameters from seismic responses [2]. In recent years, scholars both domestically and internationally have conducted extensive research on rock physics experiments, theoretical modeling, and seismic inversion algorithms for deep-strata carbonate rocks, achieving a series of significant advances. This paper

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aims to systematically review the current research status in this field, summarize key achievements and existing problems, and provide a reference for future research.

2. Reservoir characteristics and research challenges

Deep- to ultradeep-strata carbonate reservoirs possess distinct characteristics. While these reservoirs represent a crucial area for oil and gas exploration in my country, the inland surface conditions are complex, with fragmented subsurface structures and intricate deep-strata structural internals and fault systems. Due to the deep-strata burial depth of the target layer, long seismic wave propagation paths, and severe energy attenuation, the actual deep-strata seismic data acquired suffers from weak effective signals and low signal-to-noise ratios [4, 5]. Furthermore, deep-strata to ultradeep-strata carbonate reservoirs exhibit diverse types, with reservoir spaces dominated by fractures and dissolution cavities, strong heterogeneity, rapid lateral variations, and indistinct seismic response characteristics. Existing mature fracture prediction methods, such as pre-stack P-wave anisotropy and post-stack seismic attribute analysis, suffer from limitations in accuracy due to the scarcity and quality of pre-stack broad-azimuth data, as well as the high degree of method ambiguity. These methods are insufficient to effectively characterize the fracture development features of deep- to ultradeep-strata carbonate reservoirs. At depths greater than 4500m (ultra-deep layers > 6000m), formation temperatures exceed 150 ℃ and pressures exceed 70MPa. The reservoir exhibits a complex and diverse range of pore types, with dissolution pores, fractures, and cavities coexisting and unevenly distributed at varying heights. Multiple phases of diagenetic alteration (cementation, dissolution, compaction, and dolomitization) superimposed result in extremely strong heterogeneity and anisotropy in the reservoir.

These geological features present multiple challenges to seismic exploration: deep-strata reservoir burial leads to severe energy attenuation of seismic waves, resulting in lower signal-to-noise ratios and resolutions for deep-strata seismic signals; the development of pores, cavities, and fractures within reservoirs leads to complex seismic reflection characteristics, blurring the quantitative relationship between reservoir parameters and seismic attributes; the narrow range of effective signal incident angles at depth significantly impacts the accuracy of gas-bearing detection. For example, while dispersion analysis is simple and efficient for detecting gas-bearing properties in carbonate reservoirs, the AVO attribute is poorly applied at depth due to strong heterogeneity, and the single elastic parameter obtained from pre-stack inversion is insufficient to accurately predict the distribution of gas-bearing reservoirs, limiting the accuracy of gas-bearing detection [6]. While fluid identification factors constructed from $\mu\times\rho$ and Vp/Vs can more reliably predict gas-bearing carbonate reservoirs, they still face accuracy challenges posed by the complexity of deep-strata reservoirs; strong interference in thick desert areas leads to low signal-to-noise ratios; severe signal attenuation in ultradeep-strata layers; the shielding effect of igneous rocks causes imaging distortion of underlying targets; and quantitative prediction of highly heterogeneous reservoirs is extremely difficult [7]. These challenges render traditional petrographic models and inversion methods for shallow and intermediate clastic rocks ineffective in deep-strata carbonate rocks, necessitating the development of targeted theories and technologies.

3. Advances in rock physics research

The core objective of rock physics research is to establish a quantitative relationship between reservoir parameters (porosity, fluid saturation, fracture density, etc.) and seismic elastic parameters (P-wave velocity, S-wave velocity, density).

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1) In the area of high-temperature and high-pressure experiments, rock elastic parameter measurement systems for deep-strata formations have been developed in recent years, accumulating data on the variation patterns of parameters such as velocity and attenuation in carbonate rocks under high temperature and pressure. The HDI (Direct Hydrocarbon Detection) research consortium, jointly established by the University of Houston and the Colorado School of Mines, has systematically measured the elastic modulus, velocity, and density of multiphase fluid mixtures under different temperature and pressure conditions using a high-temperature and high-pressure experimental measurement system. This has yielded several regularities, and based on these findings, FLASH software has been developed for calculating the elastic modulus, velocity, and density of multiphase fluid mixtures under different temperature and pressure conditions. In practical applications, pore fluid types and their saturation parameters are obtained through sampling analysis. The elastic parameters of multiphase mixed pore fluids under formation temperature and pressure conditions are calculated using FLASH software, and fluid substitution studies are conducted in conjunction with rock physics models, thereby achieving reservoir prediction and fluid detection. The FLASH software is applicable under conditions below 200 ℃ and pressure below 100MPa. Based on nine limestone samples from the Ordovician ultradeep-strata layer (7203.96–7444.56 m) in the Tarim Basin, rock physics experiments were conducted under high-temperature and high-pressure conditions, reaching up to 200 °C and 137.9 MPa, to simulate the deep-to-ultradeep-strata temperature and pressure environment. The effects of temperature and pressure on P-wave and S-wave velocities and elastic modulus were systematically analyzed, and pore structure parameters were inverted using the Sun model. The results show that increasing temperature reduces P-wave and S-wave velocities and elastic modulus, mainly due to enhanced calcite lattice vibration, decreased pore aspect ratio, increased pore structure parameters, and weakened shear resistance. Increasing pressure promotes microcrack closure, increases pore aspect ratio, decreases pore structure parameters, and gradually restores rock stiffness and shear resistance. Low-porosity samples are more sensitive to temperature effects; the pressure effect evolves with the loading stage, and its overall effect is generally stronger than that of temperature [8]. The above experimental results further demonstrate that ultradeep-strata temperature and pressure conditions have a significant impact on the elastic characteristics of carbonate rocks, providing an experimental basis for subsequent analysis of the influence of supercritical fluid phase changes on fluid property calculations. Studies show that the effects of temperature and pressure on the elastic characteristics of carbonate rocks are not negligible, and the changes in fluid phase under supercritical conditions make fluid property calculations more complex.

2) In terms of pore structure characterization, significant progress has been made in multi-scale quantitative pore structure characterization techniques, represented by CT scans and nuclear magnetic resonance (NMR) [9]. Pore types can be classified into four categories: porous, fracture-porous, dissolution-cavitary, and fracture-dissolution-cavitary, with connectivity and permeability increasing sequentially. Pore structure is not solely determined by porosity; in tight carbonate rocks, altered by diagenesis and post-diagenesis, the variation in seismic elastic characteristics at the same porosity is primarily controlled by pore structure. Different types of reservoirs exhibit zoned distribution in the P-wave velocity (impedance)-velocity ratio cross-plot. Gas-bearing, fracture-bearing, or silica-bearing elements all reduce velocity and velocity ratio, and there is significant overlap in P-wave velocities between high-quality and low-quality reservoirs. Therefore, porosity and conventional elastic parameters alone are insufficient to effectively identify differences in pore structure; CT scans and NMR are necessary for detailed characterization. Researchers combined X-ray diffraction, cast thin sections, scanning electron microscopy, and multi-scale CT scanning

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techniques to successfully characterize multi-scale pore structures ranging from micrometers to centimeters. The application of digital core technology provides a new approach for pore structure identification and rock physical modeling.

3) Regarding theoretical model improvement, to address the limited applicability of traditional Gassmann equations and Wyllie time-averaged formulas in deep-strata carbonate rocks, the academic community has attempted to modify the theoretical framework by introducing measured data [3]. For example, Fang Chunhui et al. used the Gassmann equation as the core theoretical framework and constructed a gas saturation calculation model using elastic parameters obtained from acoustic logging inversion, achieving continuous quantitative evaluation of gas content. However, the practical application of these studies is still limited to some extent due to their reliance on a large number of difficult-to-measure rock skeleton and fluid acoustic parameters. Scholars have developed fracture-porous media rock physics models, and innovations in methods such as complex wavefield forward and inverse modeling, digital core rock physics analysis of carbonate rocks, and reservoir pore structure identification have provided key support for the development of new reservoir prediction technologies. The introduction of differential equivalent medium theory, self-consistent models, and pore shape factor correction schemes has initially achieved equivalent treatment of complex pore morphologies. However, due to the strong heterogeneity and rapid lateral changes in reservoirs, the selection of a unified rock physics model remains very difficult.

4. Advances in seismic inversion research

1) In terms of pre-stack inversion, AVO/AVA inversion and elastic impedance inversion have become relatively mature technical processes in conventional clastic rocks. For example, considering the characteristics of the Shunbei oil and gas field, such as deep-strata reservoir burial, strong heterogeneity, and complex oil and gas charging, a mature pre-stack AVO inversion technical process with reservoir characteristic constraints has been developed: First, based on well logging, core, and seismic data, the characteristics of three types of seismic reflections and AVO are analyzed. Forward modeling confirms that oil and gas-bearing reservoirs can cause significant changes in amplitude and AVO, laying the theoretical foundation for inversion; then, a stochastic model reflection coefficient relationship consistent with reality is established, and the reservoir characteristic-constrained AVO equation is derived to achieve the inversion of oil and gas sensitive attribute parameters. Applying this technology to the Shunbei study area shows that the AVO inversion prediction results are consistent with the actual well oil and gas situation, and can effectively identify ultradeep-strata carbonate oil and gas-bearing reservoirs and characterize oil and gas enrichment. Some authors [10] proposed an elastic wave impedance inversion method based on Bayesian theory, which improved the sparsity of the inversion. They also discussed the feasibility and reliability of this method in predicting heterogeneous carbonate reservoirs in practical applications. In deep-strata carbonate applications, the accuracy and stability of conventional inversion methods significantly decrease due to the low signal-to-noise ratio, small incident angle, and indistinct AVO characteristics of seismic data. Therefore, researchers have developed gas reservoir detection techniques based on pre-stack elastic parameter inversion and frequency-division attributes. This is of great significance for hydrocarbon detection in carbonate reservoirs and also improves fluid identification accuracy to some extent.

2) Regarding multi-information joint constraints, scholars both domestically and internationally are actively conducting theoretical research and methodological innovation in seismic prediction technology for deep-ultra-deep-strata carbonate reservoirs. Geostatistical stochastic simulation inversion and cloud transformation stochastic simulation are used for quantitative prediction of

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fracture-vuggy reservoirs. Through comprehensive analysis of the porosity and pore development zones of carbonate reservoirs, the prediction results matched the known distribution characteristics of dolomite, thus proving that geostatistical stochastic simulation inversion can be reliably used for quantitative prediction of fracture-vuggy reservoirs. This indicates that geostatistical inversion is currently one of the important methods for predicting strongly heterogeneous carbonate rocks. However, most methods that can effectively characterize the relationship between wave impedance and porosity are linear methods with low prediction accuracy, making it difficult to meet the needs of layer-by-layer quantitative prediction of fracture-vuggy reservoirs. Han Dong et al. proposed that a qualitative-quantitative uncertainty transformation model, namely the cloud theory model, can characterize the nonlinear relationship between wave impedance and porosity with high accuracy. Compared with linear fitting methods, this method uses the range of porosity values as a probability distribution reference, which can more objectively describe the heterogeneity characteristics of fractured-vuggy reservoirs, and is therefore more suitable for layer-by-layer quantitative prediction of strongly heterogeneous fractured-vuggy reservoirs. Combining well logging data, geological prior information, and seismic inversion can effectively reduce the ambiguity of inversion. Seismic gradient structure tensor technology has shown potential in the identification of small fractures [11, 12].

3) Artificial intelligence-assisted inversion is a cutting-edge field in recent years. Machine learning algorithms (such as BP neural networks, support vector machines, and random forests) have been successfully applied to seismic inversion and fracture prediction. For example, based on constrained sparse pulse, Bayesian seismic inversion, and seismic waveform indicator inversion, machine learning inversion based on random forest algorithms was introduced to solve the problem of identifying thin reservoirs in the Wujiaping Formation in a certain exploration area in northeastern Sichuan. The impedance inversion results are consistent with the drilling interpretation, with high vertical resolution and horizontal continuity. Finally, the seismic waveform indicator and random forest inversion results were selected for the study of thin reservoir distribution, demonstrating the significant application value of artificial intelligence-assisted inversion in thin reservoir seismic inversion. The deep-strata integration of seismic rock physics experiments and reservoir geology, as well as refined seismic prediction technology based on reservoir sensitive attributes (frequency, dispersion, and attenuation, etc.) of two-phase medium wave characteristics, and quantitative prediction and fluid detection technology of carbonate reservoirs using artificial intelligence are all important development directions. The development trend of reliable deep-strata seismic data, high-precision reservoir characterization through multidisciplinary collaboration, and deep learning artificial intelligence is very obvious. By establishing a nonlinear mapping relationship between well logging data and multiple seismic attributes, fracture development zones can be effectively predicted. Deep learning (such as convolutional autoencoders and deep neural networks) shows promising application prospects in multi-attribute fusion and reservoir parameter prediction.

5. Existing problems and development trends

The main shortcomings can be summarized as follows: 1) The low signal-to-noise ratio, weak effective signal, and unclear reservoir geophysical response mechanism of deep-strata seismic data restrict the improvement of inversion accuracy; 2) The petrographic research of carbonate rocks lacks a unified theoretical framework, and the understanding of wave dynamic characteristics such as strong heterogeneity, dispersion, and attenuation is still insufficient; 3) There are few studies on quantitative interpretation of pre-stack inversion, and the single elastic parameters obtained cannot

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accurately predict the distribution of gas-bearing reservoirs. The integration of petrographic parameters and inversion is still immature; 4) The training samples of artificial intelligence methods are insufficient, the interpretability is poor, and the generalization ability needs to be verified.

Regarding future development trends, existing research has clearly identified reliable deep-strata seismic data, high-precision reservoir characterization through multidisciplinary collaboration, and deep learning artificial intelligence as important development directions. Specific research areas include: strengthening refined seismic prediction techniques based on the wave characteristics (frequency, dispersion, and attenuation) of two-phase media; developing seismic prediction techniques for pore structure based on digital core rock physics analysis; improving comprehensive prediction methods for fracture-vuggy reservoirs based on multi-attribute analysis of pre-stack and post-stack seismic data; optimizing deep learning-based seismic prediction methods for fractures in deep-strata carbonate reservoirs based on optimized samples; and tackling key challenges in AI-based quantitative prediction and fluid detection technologies for carbonate reservoirs. Furthermore, the deep-strata integration of seismic rock physics experiments and reservoir geology, multi-scale data collaboration, and a comprehensive interpretation model that is pre-stack, multi-dimensional, integrated, unified, and intelligent will support the efficient exploration and development of deep- to ultradeep-strata carbonate reservoirs.

6. Conclusion and outlook

Significant progress has been made in the study of rock physics and seismic inversion of deep- to ultradeep-strata carbonate reservoirs, but core challenges remain, including weak theoretical foundations and insufficient prediction accuracy. Future development should follow a strategy of deep-strata integration, refinement, and intelligence, guided by geological objectives. This should comprehensively consider the influence of temperature and pressure conditions, matrix minerals, pore structure, and fluid properties on rock physics characteristics, developing adaptable seismic inversion methods with clearly defined physical constraints to provide theoretical support and technical assurance for deep-strata carbonate oil and gas exploration.

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