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Advances in Integrated Prediction Methods for Complex Volcanic Reservoirs and Their Applications

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Abstract. Volcanic reservoirs represent a significant domain in global hydrocarbon exploration, characterized by substantial resource potential yet considerable exploration challenges. These reservoirs exhibit diverse storage types, complex pore structures, highly variable fracture development, and strong heterogeneity, which render conventional exploration methods inadequate for effective prediction. This paper provides a systematic review of recent advances in the study of volcanic reservoirs, focusing on rock physical characteristic analysis, well-log interpretation, seismic inversion techniques, and integrated prediction using multi-scale data. The applications and limitations of existing technologies are summarized. Research indicates that the identification of sensitive parameters based on rock physical analysis offers a theoretical foundation for reservoir prediction. Techniques such as pre-stack geostatistical inversion have significantly enhanced the accuracy of volcanic reservoir characterization. Moreover, the integration of multi-disciplinary data and facies-controlled modeling has considerably improved the reliability of reservoir predictions. Nevertheless, current research still suffers from insufficient understanding of reservoir formation mechanisms, limited integration of multi-scale data, and a lack of generalizability in predictive models. Future studies should focus on developing intelligent prediction technologies leveraging interdisciplinary approaches and deepening quantitative evaluation and geological modeling of volcanic reservoirs to facilitate efficient exploration and development.

Keywords: Volcanic Reservoir, Rock physics Characteristics, Seismic Inversion, Integrated Multi-Scale Prediction, Reservoir Prediction

1. Introduction

Volcanic rock reservoirs, as a type of unconventional hydrocarbon reservoir, are widely distributed around the world and possess significant resource potential, making them an important domain in oil and gas exploration. In recent years, hydrocarbon discoveries have been successively made in volcanic rocks across various basins in China—such as the Songliao Basin, Sichuan Basin, Bohai Bay Basin, and Pearl River Mouth Basin—demonstrating promising exploration prospects [1,2]. However, due to their complex formation mechanisms, rapid variations in lithology and facies, diverse storage spaces, and strong heterogeneity, predicting hydrocarbon accumulations in volcanic reservoirs remains highly challenging. These challenges are mainly reflected in the following

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aspects: 1) Volcanic reservoirs are generally deeply buried and often exhibit low porosity and low permeability, leading to unsatisfactory drilling outcomes; 2) The multitude of volcanic rock types, rapid lateral and vertical facies changes, and multi-phase volcanic stacking result in complex seismic response characteristics, making reservoir prediction difficult; 3) The diversity of pore spaces—including primary gas pores, secondary dissolution pores, and fractures—coupled with multi-factor controls such as tectonics and diagenesis, complicates the identification and prediction of effective reservoirs [3,4]. In addition, limitations inherent in traditional inversion methods further exacerbate the difficulty of predicting volcanic reservoirs [5].

In response to these challenges, extensive research has been conducted in recent years, focusing mainly on rock physics characterization of volcanic rocks, seismic inversion prediction methods based on well-log data, and integrated prediction approaches incorporating well-log, seismic, and geological multi-scale data. Significant progress has been achieved in these areas [6,7]. This paper will first introduce the fundamental principles and application examples of rock physics studies in volcanic reservoirs. It will then elaborate on seismic inversion prediction methods based on well-log data, with a focus on pre-stack geostatistical inversion techniques. Subsequently, the integrated use of multi-scale data—combining well-log, seismic, and geological information—will be discussed along with its practical applications. Finally, the paper concludes with a summary and future outlook.

2. Rock physics characteristics of volcanic reservoirs

2.1. Basic theories

Following clastic and carbonate rocks, volcanic rocks have emerged as another critical type of hydrocarbon reservoir, attracting significant attention in exploration [8]. The study of rock physics characteristics of volcanic reservoirs serves as the theoretical foundation for reservoir prediction. Its primary objective is to identify sensitive rock physics parameters that reflect reservoir properties by analyzing the relationships among lithology, physical properties, electrical properties, and elastic parameters of volcanic rocks. This enables the establishment of connections between reservoir attributes and elastic parameters or seismic responses, thereby providing a basis for selecting appropriate reservoir prediction methods.

Volcanic reservoirs typically exhibit low porosity and low permeability characteristics. However, they display diverse types of storage spaces, including primary gas pores, secondary dissolution pores, fractures, and various pore-fracture combinations. Moreover, different genetic types—such as volcanic mudflows, basalts, and tuffs—may exhibit distinct rock physics characteristics.

2.2. Application cases of rock physics-based S-wave velocity prediction

Shear wave velocity (S-wave) is a critical parameter for pre-stack seismic inversion. However, due to the frequent absence of S-wave logging data in many wells, rock physics methods are often employed to predict S-wave velocity.

In a study of volcanic reservoirs in Block X of the Xujiaweizi Fault Depression in the Songliao Basin, the research team led by Xiang Yangchen conducted systematic rock physics analysis using available well-log data from the area [6]. In the absence of direct S-wave measurements, S-wave velocity was predicted through S-wave curve reconstruction techniques, providing essential input parameters for pre-stack inversion. By integrating multiple elastic parameters—such as resistivity, natural gamma ray, P-wave to S-wave velocity ratio (Vp/Vs), P-wave impedance, S-wave

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impedance, and density (see Figure 1, which is modified from modified from [6])—the team identified rock physics indicators sensitive to reservoir properties and gas-bearing characteristics. Furthermore, lithology-specific impedance parameters were constructed to improve gas detection.

The prediction of S-wave velocity compensated for the lack of elastic parameters in the evaluation of volcanic reservoirs, significantly enhancing the inversion accuracy of key properties—including density, P-wave impedance, and S-wave impedance—in pre-stack geostatistical inversion. This approach provided a reliable foundation for effective identification and gas-bearing prediction in complex volcanic reservoirs, thereby supporting the forecast of favorable reservoir distribution and guiding exploration and development strategies in the study area [9].

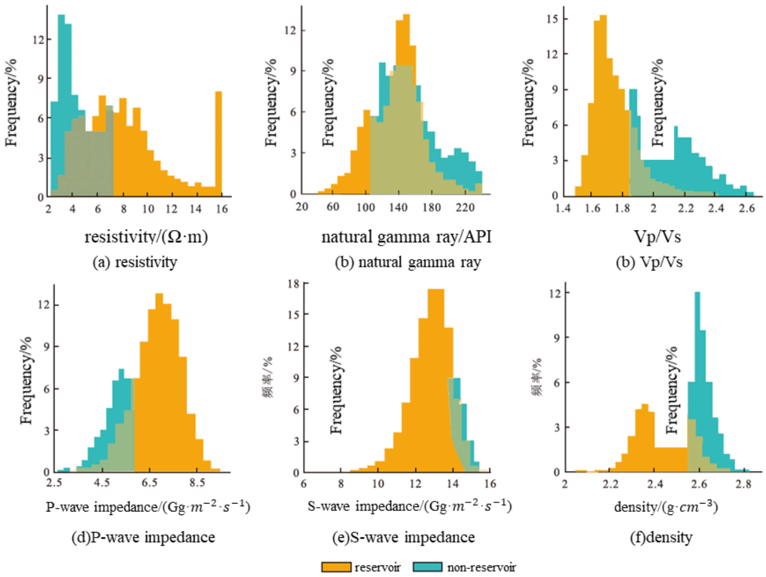

Figure 1. Well-log curves of multiple parameters in Block X. (a) resistivity, (b) natural gamma ray, (c) Vp/Vs, (d)P-wave impedance, (e) S-wave impedance, and (f) density

In a study of the Dongling area of the Songnan Gas Field within the Changling Fault Depression of the Songliao Basin, the research team led by Cang Zhengyi integrated well-log data with core experimental measurements to develop a conversion model between P-wave and S-wave velocities using empirical relationships [1]. Based on reservoir classification, separate regression models were fitted for different volcanic lithologies to improve the accuracy of S-wave velocity prediction. This approach compensated for the lack of direct S-wave logging data, thereby enhancing the reliability of seismic inversion and comprehensive reservoir evaluation. For complex volcanic reservoirs, this rock physics-based S-wave prediction method aids in identifying favorable reservoir zones and provides valuable guidance for subsequent exploration [10].

In another study focusing on the volcanic reservoirs of the Yingcheng Formation in the Xingshan area of the Songliao Basin, the rock physics analysis to address the challenges posed by complex lithology and the absence of S-wave logs is employed. Using a nonlinear multi-parameter regression method, S-wave velocity was predicted based on conventional log curves such as P-wave velocity and density. The empirical model established between P-wave and S-wave velocities achieved a correlation coefficient of 0.85 with actual S-wave log data, indicating a high degree of consistency. This rock physics-driven S-wave prediction method effectively supported pre-stack inversion and comprehensive reservoir characterization in the absence of measured S-wave data, improving the

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reliability of complex volcanic reservoir prediction and providing enhanced guidance for exploration.

3. Seismic inversion for reservoir prediction based on well-logging data

3.1. Basic theories

Volcanic rocks and sedimentary rocks differ significantly in their geological origins and reservoir formation mechanisms. Volcanic reservoirs are characterized by complex structures, rapid lateral lithological variations, and poor stratification, making their distribution patterns difficult to predict. Most volcanic rocks formed during the early stages of basin development and are deeply buried. Their geophysical properties often exhibit unclear lithological boundaries and complex wavefields, further increasing the difficulty of reservoir identification and prediction [11].

Seismic inversion based on well-log data serves as a core technique for characterizing volcanic reservoirs. The fundamental principle involves using pre-stack or post-stack seismic data, combined with information from well logs—such as P-wave impedance, S-wave impedance, and density—to infer lithology, physical properties, and even hydrocarbon potential of subsurface formations through various inversion algorithms. For complex reservoirs like volcanic rocks, pre-stack seismic inversion offers distinct advantages over conventional post-stack methods, as it utilizes amplitude variation with offset (AVO) information to derive a wider range of elastic parameters (Figure 2 that is modified from [12]). Among these techniques, pre-stack geostatistical inversion integrates deterministic inversion with stochastic modeling. This approach leverages both the lateral continuity of seismic data and the high vertical resolution of well-log data, enabling more accurate characterization of the strong heterogeneities typical of volcanic reservoirs.

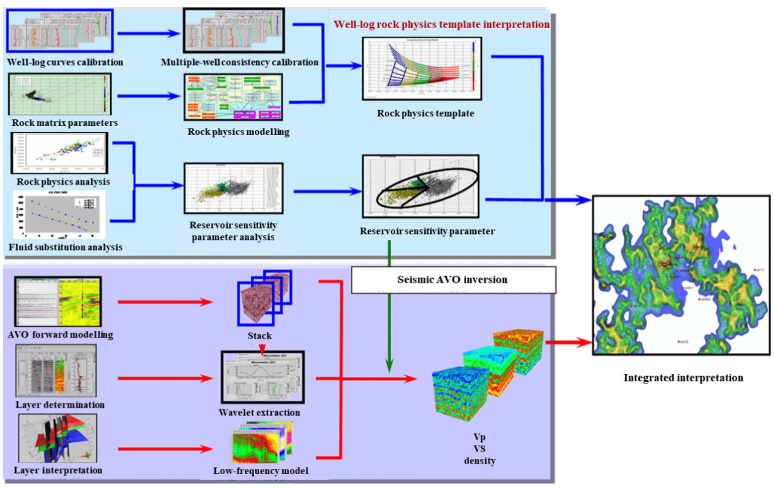

Figure 2. Integrated seismic inversion process

3.2. Research approach and technical workflow

In a study on seismic prediction of effusive volcanic reservoirs in the Yingcheng Formation in the Xuxi area, Luo Cong adopted an integrated multi-method approach combining geological, seismic, and well-log data to achieve detailed interpretation of volcanic strata, particularly targeting challenging-to-identify effusive facies. By dividing the volcanic sequences into different eruption episodes and using these episodes as a temporal framework, fine-scale subdivision and interpretation of volcanic eruptive bodies were carried out. Post-stack inversion was employed for preliminary

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reservoir prediction, while rock physics sensitive parameter analysis was integrated with pre-stack inversion to further enhance the accuracy of lithological and reservoir quantitative prediction. By optimizing reservoir sensitivity parameters of lithological units and combining seismic attributes with volcanic facies classification, favorable reservoir zones within effusive facies were ultimately identified, thereby improving prediction accuracy and exploration effectiveness for complex volcanic reservoirs [13].

In a study on seismic interpretation and reservoir prediction of the Yingcheng Formation in the Xingshan area, Zhang Zhiming utilized integrated seismic, well-log, and geological data, applying principles of detailed sequence stratigraphy, structural geology, and reservoir prediction theory, along with methods such as seismic attribute analysis and waveform clustering [12]. He proposed a well-log-based volcanic reservoir prediction approach. First, fine interpretation of volcanic eruption episodes and their stacking patterns was conducted to establish a stratigraphic framework and characterize the structural features of volcanic formations. Second, combined with rock physics analysis, cross-plotting of elastic parameters was used to optimize reservoir-sensitive parameters, and pre-stack elastic parameter inversion was performed to achieve detailed prediction of volcanic reservoirs. Furthermore, the identification of different lithologies and reservoir types provided effective technical support for predicting reservoir distribution.

3.3. Application cases

In the seismic prediction study of effusive volcanic reservoirs in the Yingcheng Formation in the Xuxi area, the proposed seismic inversion technology for volcanic reservoirs demonstrated its effectiveness through an application case in the Xujiaweizi Fault Depression. By integrating post-stack and pre-stack inversion techniques with rock physics sensitive parameter analysis, the study successfully predicted volcanic reservoirs, particularly those within effusive facies. Specific applications included optimizing reservoir-sensitive parameters through cross-plot analysis of elastic parameters, quantitatively classifying reservoirs using pre-stack CRP gather data, and identifying favorable effusive volcanic reservoir zones by combining seismic attributes and lithofacies classification. These applications significantly improved reservoir prediction accuracy and provided precise guidance for exploration planning [14].

In the seismic interpretation and reservoir prediction study of the Yingcheng Formation in the Xingshan area, the well-log-based seismic inversion method was successfully applied to volcanic reservoirs, achieving detailed reservoir characterization. By finely subdividing volcanic eruption episodes and lithofacies, combined with rock physics analysis and pre-stack elastic impedance inversion, the study effectively predicted the distribution and thickness of volcanic lithologies. Additionally, multi-attribute analysis was used to predict fracture development zones and gas-bearing potential. Integrating structural interpretation, volcanic facies, and fracture characteristics, the research accurately identified favorable reservoir zones, providing a reliable basis for subsequent exploration. These application examples demonstrate the significant advantages of this technology in identifying and predicting complex volcanic reservoirs.

4. Integrated prediction based on multi-scale logging, seismic, and geological data

4.1. Basic theories

The strong heterogeneity of volcanic reservoirs leads to inherent ambiguity and uncertainty in predictions based on any single data source or technique. The core concept of integrated multi-scale

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prediction methods is to combine multi-source information—such as geological, well-log, seismic, and dynamic production data—to leverage their complementary strengths, reduce interpretive uncertainty, and improve the accuracy of reservoir prediction [15].

Well-log data provide precise information about lithology and physical properties at the borehole location, but are limited to discrete points. Seismic data offer extensive coverage of subsurface structures, yet at a relatively low resolution. Geological data contribute a macro-scale understanding of regional tectonic settings and depositional environments, supplying essential context for integrated interpretation.

4.2. Research approach and technical workflow

The workflow begins with the collection of comprehensive logging, seismic, and geological data from the study area. On the geological side, regional tectonic settings and volcanic activity history are analyzed to develop a geological model of volcanic edifices and lithofacies. Well-log data are processed and interpreted in detail to identify key lithology and facies characteristics, enabling the establishment of a log-based lithofacies model. For seismic data, conventional processing is followed by seismic attribute analysis, extracting attributes such as amplitude, frequency, and phase, with subsequent screening to identify those most sensitive to volcanic reservoirs.

Next, the volcanic edifice and lithofacies geological model are integrated with the log-derived facies model to establish relationships among lithofacies, seismic response, and physical properties. Using the geological model and seismic attribute volumes as constraints, stochastic modeling or deterministic interpolation methods are applied to predict the spatial distribution of key reservoir parameters—such as lithofacies, porosity, and fluid saturation—in three dimensions. The prediction results are iteratively validated and optimized through drilling data, reducing interpretation uncertainties caused by strong reservoir heterogeneity (see Figure 3). This process provides a reliable geological basis for well placement planning.

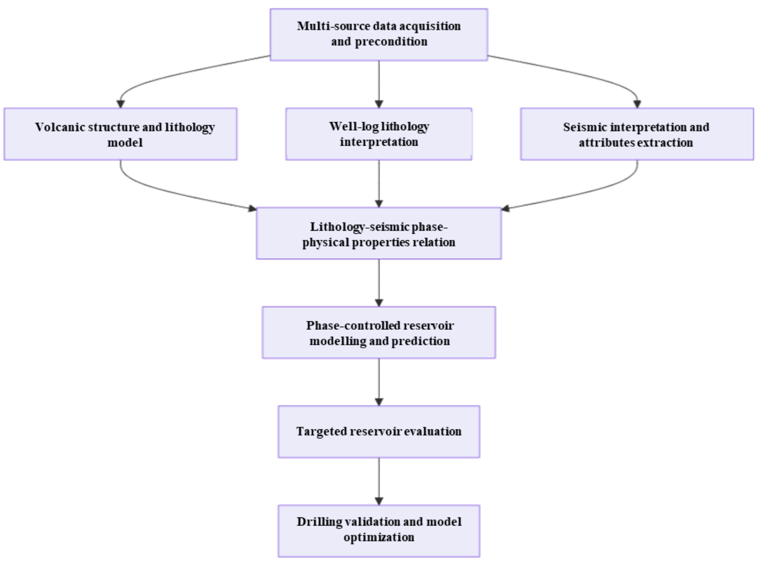

Figure 3. Workflow of integrated prediction for volcanic reservoirs

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4.3. Application cases

In the prediction of Permian volcanic reservoirs in the Jianyang area of southwestern Sichuan, the research team led by Zou Qin developed an integrated technical framework based on multi-scale data from well logs, seismic surveys, and geological studies. This system encompassed the identification of volcanic eruption patterns, characterization of facies belts, and prediction of reservoir thickness and spatial distribution. Specifically, well-seismic integration was used to identify volcanic edifices and favorable facies zones—such as Class I and Class II explosive facies. Facies-controlled reservoir prediction was then conducted using seismic inversion and well-log-derived physical property constraints, enabling detailed mapping of high-quality reservoirs with porosity ranging from 9% to 13% and thickness exceeding 120 meters. This approach successfully guided the deployment of multiple exploration wells, including Yongtan 1, Tianfu 1, and Tianfu 7, resulting in high industrial gas flow rates and demonstrating the reliability and applicability of the methodology [16,17].

Regarding the reservoir characteristics and main controlling factors of Permian volcanic rocks in the western Sichuan Basin, the correlations between volcanic lithofacies types and physical properties by integrating well logs, seismic inversion, rock physics analysis, and geological depositional background are established, building on well-seismic combined interpretation. Seismic attributes and facies-controlled inversion were then applied to predict the spatial distribution of reservoirs. Specifically, within the study area, well-log data were first used to identify volcanic lithofacies and reservoir thickness characteristics. Three-dimensional seismic data were subsequently employed to delineate volcanic edifices, eruption channels, and lithofacies zone distributions. Finally, a 3D geological model was constructed through seismic inversion constrained by well logs to quantitatively predict reservoir porosity and physical property distribution. This method has been applied in multiple well areas in western Sichuan, successfully predicting the distribution of high-quality reservoirs such as Class I explosive facies, guiding drilling deployment, achieving industrial gas flow, and validating the accuracy and practicality of the prediction results.

5. Conclusion and future outlook

5.1. Conclusion

This paper systematically reviews recent advances in rock physics characterization, seismic inversion techniques, and integrated multi-scale prediction methods for complex volcanic reservoirs. The main conclusions are as follows:

1) Fundamentals of Rock Physics Analysis

Volcanic reservoirs typically exhibit low porosity and low permeability, with complex pore systems. Identifying elastic parameters sensitive to reservoir properties and fluid content—such as density and lithology impedance—along with their threshold values, provides a physical basis for effective reservoir prediction.

2) Effectiveness of Pre-Stack Geostatistical Inversion

By integrating the lateral continuity of seismic data and the vertical resolution of well logs, this technique significantly improves the characterization of strong heterogeneities in volcanic reservoirs.

3) Necessity of Multi-Information Integration

Combining multi-scale data from geology, well logs, and seismic surveys under a volcanic lithofacies framework reduces uncertainties inherent in single-method approaches and enhances the reliability of prediction results.

4) Continuous Improvement of Integrated Prediction Mechanisms

The application of theories and methods such as lithofacies sequence analysis, geostatistics, and multi-source data fusion has led to the development of more comprehensive prediction workflows and visual models, which have been successfully applied in multiple basin cases.

5.2. Future outlook

Despite significant progress in prediction techniques for volcanic reservoirs, several challenges remain, warranting further in-depth research in the following directions:

1) Development of interdisciplinary intelligent prediction technologies

Advances in seismic acquisition, well logging, computer technology, and data science should be leveraged to promote deeper integration across disciplines. For example, machine learning and deep learning techniques can be employed to efficiently process and intelligently interpret massive multi-source datasets, uncover hidden patterns, and achieve more precise and intelligent prediction of volcanic reservoir parameters.

2) Enhancement of quantitative evaluation and geological modeling of volcanic reservoirs

Current classification and evaluation standards for volcanic reservoirs lack uniformity, and the accuracy of 3D geological models requires improvement. Future work should focus on developing more refined quantitative evaluation methods and constructing detailed 3D geological models that better represent volcanic architectures, spatial lithofacies distribution, and reservoir parameter trends. Such models will provide a more reliable geological foundation for numerical reservoir simulation and development strategy optimization.

In summary, the exploration and development of complex volcanic reservoirs require close collaboration among disciplines such as geology, geophysics, petrophysics, and engineering. Through continuous technological innovation and theoretical advancement, the resource potential of volcanic reservoirs can be effectively unlocked.

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