Integrated Geophysics-Geology-Engineering Technology in Mountainous Shale Gas Exploration and Development: A case study in southern Sichuan, China
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Summary

This paper highlights the crucial role of integrated geophysical and geological engineering technology in mountainous shale gas exploration and development. By integrating multi-disciplinary knowledge from seismology, geology, and engineering, this technology provides solid data support for shale gas resource evaluation and development decisions. Practice has proven that it significantly improves the prediction accuracy of mountainous shale gas reservoir characteristics and optimizes exploration and development strategies under complex geological conditions. The study emphasizes the importance of high-precision seismic imaging data, based on which detailed resource evaluation, accurate and precise well trajectory design, and scientific fracturing design are carried out. The successful application of these techniques not only supports drilling and fracturing engineering design but also provides a scientific basis for efficient resource development and utilization. Through a case study in southern Sichuan, the paper confirms the significant value of integrated technology in enhancing exploration efficiency and development effectiveness. Looking forward, with further research and widespread application of this technology, it is expected to drive shale gas exploration and development towards safer and more efficient practices.

Introduction

Against the backdrop of surging global demand for clean energy and increasingly stringent carbon reduction targets, shale gas has gradually become a focal point as a key alternative energy source. Despite the remarkable progress in shale gas exploration and development worldwide, it remains challenging to conduct these activities in complex mountainous regions (Bellani et al., 2021). The intricate surface topography, drastic variations in subsurface structures, and the heterogeneous stress fields intensify the difficulty and uncertainty associated with the exploration and development of shale gas resources, limiting the effectiveness of traditional technologies. Facing these challenges, there is an urgent need to enhance and innovate technical methods to adapt to the unique requirements of mountainous shale gas exploration and development.

This study focuses on the pivotal role of integrated geophysics, geology, and engineering technology (Wu et al., 2023) in shale gas exploration and development under complex terrain conditions, such as mountainous areas. By integrating knowledge and techniques from multiple disciplines, including geophysics, geology, and engineering (Yue et al., 2023), it provides solid data support for shale gas resource assessment and development decision-making. Practical application has proven that this integrated approach significantly enhances the precision of predicting the characteristics of shale gas reservoirs in mountainous areas and optimizes exploration and development strategies under complex geological conditions (Liang et al., 2016). The study particularly emphasizes the importance of high-resolution seismic imaging data, based on which detailed resource evaluation, accurate and high-quality block prediction, precise well trajectory design, and scientific fracturing operation planning are implemented (Zhang et al., 2022; Xie et al., 2018).

Through a case study of shale gas development in the mountainous areas of southern Sichuan, this paper demonstrates how integrated technology plays a crucial role in addressing technical challenges in complex geological settings and provides new insights and methodologies for the efficient development of mountainous shale gas resources.

Technique and/or Solutions

To tackle the numerous challenges in the exploration and development of shale gas reservoirs in mountainous areas, this study adopts an integrated approach combining geophysics, geology, and engineering. This multidisciplinary integration enables precise analysis throughout the entire process from data acquisition to fracturing design, significantly improving the precision and efficiency of exploration and development (Liang et al., 2021). The specific methods and steps are as follows:

- Optimization of Seismic Data Acquisition:
  1) Adopting wide-azimuth acquisition technology (Long et al., 2006) that is tailored to the geological characteristics of mountainous shale gas reservoirs, such as multiset fractures and complex stratigraphic combinations, to comprehensively capture seismic signals from the target layers.
  2) Utilizing low-frequency, high-precision controllable seismic source vehicles to enhance the bandwidth and uniformity of the signal.
  3) Deploying wireless seismic nodes to ensure the consistency of data sampling and effectively reduce data gaps caused by urban areas and complex terrain.

- High-Precision Seismic Imaging with Pre-stack Depth Migration (Lecomte, I., 1999; Deng et al., 2007):
1) Suppressing seismic noise using noise reduction technology with multi-attribute analysis cross-validation, preserving effective signals. (Figure 1).
2) Applying well-constrained deterministic Q-compensation technology along the actual path to compensate for attenuation effects and improve thin-layer resolution (Figure 3).
3) Utilizing multi-information fusion for true surface velocity modeling to accurately correct the depth migration velocity model, ensuring high-precision imaging of the target layer (Figure 3).

- Establishing a High-Precision Seismic Evaluation System:
  1) Constructing a high-precision seismic evaluation system that is progressively refined, used to identify favorable depositional zones, structural unit boundaries, and geological sweet spots in enrichment areas (such as fracture development zones, organic-rich zones, etc.),
  2) Precisely delineate oil and gas reservoir units, achieving a detailed description of the distribution and reserve potential of shale gas resources.

- Deep Coupling of Multi-source Data:
  1) The integration of three-dimensional seismic data with drilling, logging, and rock mechanics, and other geological engineering information provides a comprehensive description of the reservoir’s geological characteristics (Liu et al, 2022).
  2) On this basis, the design of the horizontal well trajectory is optimized to locate the most advantageous drilling positions and directions, providing accurate data support for directional drilling guidance (Figure 4).

- Guiding Fracturing Design:
  1) Continuously updating the integrated geological-engineering model based on newly acquired exploration and development data, such as logging, well testing, and production data.
  2) Dynamically adjusting the actual drilling data on the updated model to maximize economic benefits. Based on the model, a scientific design is conducted for the fracturing scale, number of stages, and cluster spacing to ensure the optimal effect of horizontal well fracturing operations. This significantly enhances the initial production rate and the long-term stable production capacity of individual wells, thereby boosting development benefits (Liu et al, 2022).

Figure 1: a comparison of slices before and after denoising, with the average signal-to-noise ratio increasing from 1.127 to 2.038, effectively suppressing the noise.

Figure 2: After high-resolution processing, the bandwidth is increased from 8-64Hz to 5-78Hz, significantly improving the apparent resolution of the target layer.

Figure 3: The actual drilling depth at point A is exactly equal to the seismic prediction.
Examples

The Ordovician Wufeng-Longmaxi shale gas reservoirs in the Luzhou area of South Sichuan are buried at depths between 3500-4500 meters and exhibit well-developed structures and fractures. The reservoir quality varies greatly across different structural units and structural locations, and the in-situ stress field is highly complex due to the influence of these fractures, making engineering implementation challenging (He et al, 2023). Based on high-quality three-dimensional seismic data, the integrated geophysical, geological, and engineering technology has been used to finely evaluate the favorable zones and resource quantity of deep shale gas in the Southern Sichuan area, clarifying the regions for exploration and development of deep shale gas.

By utilizing wide-azimuth acquisition techniques and low-frequency, high-precision slim controllable source vehicles, the resolution and characterization capabilities of seismic imaging in complex mountainous terrain have been significantly enhanced (Figure 5). This is crucial for accurately pinpointing the target layers and providing high-precision descriptions of geological and engineering sweet spots.

Resource rolling fine evaluation refers to the continuous updating and refining of resource assessments as new data become available. This approach has been applied to the LZ area by constructing a step-by-step refined high-precision seismic evaluation system. It has successfully identified favorable depositional zones, structural unit boundaries, and geological sweet spots with high gas production potential, significantly improving the accuracy of resource evaluation. Figure 6 illustrates that the rolling evaluation has expanded the identified favorable zones, whose buried depth is less than 4000m, in the mid-deep and deep layers of the LZ area.

Deep coupling of seismic, geological, and engineering data has been employed to accurately depict engineering sweet spots under geological structural conditions, providing accurate guidance for directional drilling. Seismic steering technology is used to dynamically optimize well trajectories and adjust the position of the casing shoe (Figure 7). The average depth error rate for hitting the target has been reduced to within 10 meters, achieving a 0.33% error rate. The average stratigraphic attitude prediction match rate has increased to 87%, precisely locating the reservoir position. This optimization of well trajectories has effectively supported an increase in the average length of horizontal sections to over 2200 meters, with the length of the target zone encountered by drilling increased to 2195m (Figure 8). Through the optimized design of the fracturing plan, the average daily production rate per well has increased from 110,000 cubic meters to 239,000 cubic meters. The first-year average daily production rate per well has increased from 46,000 cubic meters to 100,000 cubic meters, and the average estimated ultimate recovery (EUR) per well has improved from 0.51 billion cubic meters to 0.98 billion cubic meters (Figure 9).
Figure 7: Seismic results were used to guide drilling through a complex underground section, crossing distortions horizontally or at low angles (e.g. areas ①, ② and ④) to ensure wellbore integrity and smooth trajectory. This achieved a high 90% drilling encounter rate.

Figure 8: The application of rotary steerable drilling technology has led to an annual increase in the length of horizontal wells and the drilling encounter rate of reservoirs.

Figure 9: Comparison Chart of Production Effectiveness Over Different Periods

Conclusions

This paper is based on the application of integrated geophysics, geology, and engineering technology in the exploration and development of mountainous shale gas and deeply discusses the revolutionary results brought about by this technology. By integrating high-precision seismic imaging, resource evaluation, geological and engineering data analysis, as well as real-time monitoring and evaluation technologies, the precision, efficiency, and cost-effectiveness of mountainous shale gas exploration and development have been comprehensively improved.

In the complex environment of mountainous shale gas, the application of this technology has not only enhanced the level of detail in the exploration phase but also promoted the practice of precision management during the development process. Case studies have confirmed that this technology can effectively deal with complex and variable geological structures and geostress environment issues, ensure the accuracy of drilling positioning and fracturing operations, and significantly increase shale gas production and return on investment. This interdisciplinary integrated technical strategy provides an innovative approach for the exploration and development of mountainous shale gas and other deep unconventional hydrocarbon resources, indicating the vast development potential of this field in the future.

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References


