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Application of Seismic Sedimentology in Oil and Gas Exploration and Its Deep Sea Technical Advantages and Case Studies

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Abstract

With the continuous advancement of geophysical technologies, seismic sedimentology, as an emerging discipline, has demonstrated remarkable advantages in the field of hydrocarbon exploration. This paper reviews the development background, fundamental principles, core methodologies, and applications of seismic sedimentology in hydrocarbon exploration, with a particular focus on its technical strengths and challenges in deep-sea hydrocarbon exploration. Seismic sedimentology integrates high-precision seismic data, well-logging data, and geological principles, employing techniques such as well-logging constrained inversion, stratigraphic slicing attribute analysis, and frequency decomposition interpretation to effectively identify sedimentary systems, reservoir distributions, and depositional environments. In deep-sea hydrocarbon exploration, despite facing complex challenges such as high temperature and pressure, seismic sedimentology significantly enhances exploration efficiency through high-precision imaging and 3D visualization technologies, demonstrating broad application prospects. Through case studies of hydrocarbon exploration in China's offshore areas, the potential of seismic sedimentology in complex geological conditions is illustrated. With innovations in technological equipment, seismic sedimentology will play an even more vital role in deep-sea hydrocarbon exploration, driving the efficient development of hydrocarbon resources.

Keywords

Seismic sedimentology; Oil and gas exploration; 3D seismic; Deep sea oil and gas; log constrained inversionn

1. Introduction

With the development of geophysical technology and its extensive application in petroleum geology research, seismic sedimentology, as an emerging discipline, has begun to attract people's attention. Research on utilizing seismic data for identifying sedimentary microfacies and stratigraphic lithology has been widely carried out both domestically and internationally [1]. Many fundamental principles of basin analysis originate from the development of 2D seismic technology [2]. Currently, 3D seismic data are increasingly being adopted in oil and gas exploration and development. Some 3D seismic work areas in basins have approached or even reached basin-scale dimensions (such as the Jiyang Depression), and the resolution and interpretation levels of 3D seismic data have also been continuously improved [3].

The rapid advancement of high-resolution 3D seismic processing, interpretation, and imaging technologies has provided powerful tools for the study of sedimentary systems and reservoirs. The close integration of these technologies with contemporary research on sedimentary system modeling has given rise to a new sub-discipline, namely seismic sedimentology. The concept of seismic sedimentology was only internationally proposed in recent years. It is based on the joint feedback of sedimentary environment models established from high-precision seismic data, outcrop data, and drilling core data, used to identify the 3D geometric shapes, internal structures, and sedimentary processes of sedimentary units. The core of its research is to establish a more detailed 3D configuration of sedimentary bodies. It should be noted that the development of 3D seismic visualization technology has played a crucial role in promoting the proposal and development of seismic sedimentology and has become an effective means for reservoir prediction [4]. It has been widely used on land and in offshore areas, particularly achieving good results in the identification and modeling of submarine fan reservoirs [5-7].

With the continuous development of oil and gas exploration technologies, seismic sedimentology, as an emerging geophysical exploration method, has gradually demonstrated its unique advantages in the field of oil and gas exploration. Seismic sedimentology utilizes seismic data to study sedimentary rocks and their formation processes. Through high-resolution seismic attribute pattern images [8], it helps exploration personnel identify sedimentary environments and facies, thereby enabling more effective discovery of oil and gas reservoirs. In deepwater oil and gas exploration, seismic sedimentology faces more complex challenges but also holds greater application potential.

2. Development of Seismic Sedimentology

In the study of high-frequency sequences in the Miocene Tiger Shoal area in the northern Gulf of Mexico, Zeng Hongliu et al. found that the seismic response of fourth-order sequences is a combination of a series of sedimentary interfaces, including the top and base of the sequences as well as internal interfaces that are difficult to identify on seismic profiles. The commonly used simple tracing method on seismic profiles can no longer delineate such fourth-order sequence boundaries and systems tracts. In response to this situation, Zeng Hongliu et al. proposed a high-frequency sequence interpretation method based on seismic sedimentology: Firstly, analyze high-resolution sedimentary elements within the low-order sequence (second- and third-order sequences) stratigraphic framework on a planar basis; then, study the high-frequency sequence stratigraphic context in both vertical and three-dimensional views.

In 1998, Zeng Hongliu, Henry, Riola, and others first used the term "seismic sedimentology," defining it as a discipline that utilizes seismic data to study sedimentary rocks and their formation processes. The core content of seismic sedimentology comprises seismic petrology and seismic geomorphology. The integration of geophysical techniques with sedimentological research, where the joint feedback of both is employed for sedimentary facies analysis, represents the most rapidly expanding technology in the application domain of seismic sedimentology in recent years; however, this is only one aspect of seismic sedimentology's applications. Seismic sedimentology is related to seismic stratigraphy, sequence stratigraphy, sedimentology, and other disciplines, but it differs from them in terms of concepts, research content, methodologies, and techniques.

From the perspective of research content, sedimentology covers a range from microscopic rock pore structures and diagenesis to macroscopic sedimentary facies and sedimentary system distributions. Seismic stratigraphy primarily studies sequence stratigraphic frameworks through the contact relationships of seismic events, whereas seismic sedimentology mainly focuses on the macroscopic study of stratigraphic rocks, sedimentary history, sedimentary architecture, sedimentary systems, and the planar distribution of sedimentary facies using seismic information and modern geophysical techniques under the guidance of geological principles (especially sedimentary environments and sedimentary facies models under different sedimentary environments) [9].

Seismic stratigraphy primarily focuses on studying reflection configurations on seismic profiles under the constraints of well-point information to obtain sequence stratigraphic data, with relatively singular research methods and content. Seismic sedimentology, guided by well data, fundamental geological research findings, and geological principles, makes more extensive use of seismic data and seismic research methodologies. Currently, the key technologies employed mainly include 90° phase rotation technology, stratal slicing technology, and frequency decomposition interpretation technology, among others [10-12].

3. The main methods and techniques of seismic sedimentology

3.1. Logging constrained inversion technique

In seismic reservoir prediction and sandbody description, logging-constrained inversion technology is an indispensable technique that plays a very important role in the description of sandstone lithologic reservoirs. Wave impedance inversion is the ultimate expression form of high-resolution seismic data processing. Currently, logging-constrained inversion processing has become a standard method for processing conventional targets.

3.1.1. Analysis of Reservoir Characteristic Parameters

The analysis of reservoir characteristic parameters is particularly important in distinguishing lithologies using seismic inversion. In commonly used recursive inversion methods, wave impedance derived from acoustic curves is mainly applied to differentiate or resolve lithologies. However, in some regions or intervals, wave impedance derived from acoustic curves cannot effectively distinguish sandstone from shale. In contrast, natural gamma, spontaneous potential, or resistivity clearly reflect lithological variations. Therefore, it is necessary to select curves that can effectively differentiate sandstone and shale for analysis and establish pseudo-acoustic curves for wave impedance inversion.

3.1.2. Synthetic seismic records and seismic wavelet extraction

The information from well logging, geology, and drilling is measured in depth, whereas seismic information is calibrated in time. Establishing a correlation between depth-domain well logging, geological, and drilling data and time-domain seismic data is of great importance. The bridge that establishes this relationship is the synthetic seismogram. By utilizing synthetic seismograms, precise calibration of reservoirs can be performed to ensure the coupling of seismic and well logging information, thereby establishing an accurate low-frequency wave impedance model. The wavelet is a critical factor in seismic inversion, as the convolution of the wavelet with model reflection coefficients generates synthetic seismic data, directly influencing the inversion results of wave impedance. In wavelet extraction, the most crucial aspect is the discrimination of wavelet polarity, which necessitates the integration of seismic and geological information to determine the wavelet polarity.

3.2. Comprehensive attribute analysis technology for stratigraphic slicing

Brown et al. first elucidated that horizontal imaging (time slices) through 3D seismic data can generate high-resolution sedimentary facies images. Since the 1990s, numerous studies have confirmed that seismic geomorphology is a powerful tool for sedimentary imaging research. Seismic geomorphologic imaging involves extracting various integrated attributes (average energy amplitude + average peak amplitude + maximum amplitude + root mean square amplitude + positive polarity amplitude) along isochronous sedimentary interfaces (geological time interfaces), and through attribute optimization, it can objectively reflect the distribution range of sedimentary systems within the seismic work area. Such seismic slices are known as stratigraphic slices, which are achieved through reasonable interpolation between two isochronous interfaces, similar to the proportional slicing method proposed by Posamentier in 1996. Commonly used slice types include time slices and horizon slices. Time slices are created by slicing the seismic data volume along a fixed seismic travel time, with the slicing direction perpendicular to the time axis, and they do not cut through a geologically significant horizon; horizon slices are made along or parallel to seismic horizons, and they are more inclined to have geophysical significance.

3.3. Frequency division interpretation and time-frequency analysis techniques

Research indicates that reflection events in low-frequency seismic data predominantly reflect lithological interface information, whereas those in high-frequency data mainly represent time interface information. Based on this understanding, a frequency-division interpretation method is employed, utilizing seismic data from different frequency bands for distinct geological objectives. The frequency-division interpretation used in seismic sedimentology is based on the principle that the frequency content of seismic data controls the dip angles of seismic reflection events and their internal reflection configurations. Generally, the higher the frequency of the seismic wavelet, the better the correspondence between the corresponding seismic data and well logging information, which serves as the fundamental basis for frequency-division interpretation. Therefore, the application of frequency-division interpretation technology reflects the understanding in seismic sedimentology that seismic frequency controls the dip angles of reflection events and their internal reflection configurations.

However, the continuous frequency variations within seismic data inherently contain abundant geological information, with different levels of geological sequence bodies corresponding to distinct frequency characteristics on seismic profiles. Simply employing frequency-division interpretation methods does not fully utilize this information, whereas time-frequency analysis methods precisely address this limitation. Time-frequency analysis, also known as frequency-time scanning, involves transforming time-domain seismic records into the frequency domain through fast Fourier transform. By utilizing time-frequency analysis techniques to conduct scanning analyses at different frequencies, it is possible to identify sequence bodies of varying scales, from large to small, thereby obtaining information not evident on seismic profiles. Since the directionality of longitudinal frequency changes represents variations in lithological coarseness, time-frequency analysis can not only be used for geological sequence interpretation but also for delineating sedimentary cycles and inferring patterns of water body changes and variations in sedimentary environments. Therefore, in the study of seismic sedimentology, frequency-division interpretation and time-frequency analysis techniques should be employed in conjunction.

4. Application of Seismic Sedimentology in Oil and Gas Exploration

4.1. Sedimentary Environment Interpretation

Seismic sedimentology can interpret the types and characteristics of sedimentary environments through the analysis of seismic data [13]. Different sedimentary environments have varying impacts on the formation and preservation of hydrocarbons; therefore, sedimentary environment interpretation can assist exploration personnel in identifying potential hydrocarbon exploration target areas.

4.2. Reservoir Prediction

Seismic sedimentology can predict the distribution and properties of reservoirs through the analysis of seismic data. By analyzing parameters such as sedimentary facies, lithology, and porosity, potential reservoir areas can be determined, and their reservoir capacities and fluid properties can be assessed, thereby aiding exploration personnel in identifying exploration targets.

4.3. Sedimentary System Analysis

Seismic sedimentology can reveal the evolutionary processes and characteristics of sedimentary systems through the analysis of these systems [14]. Different sedimentary systems have varying impacts on the formation and preservation of hydrocarbons; therefore, sedimentary system analysis can assist exploration personnel in identifying potential hydrocarbon exploration target areas.

4.4. Sedimentary Microfacies Research

Combining geophysical technology with sedimentological research for sedimentary facies analysis is a widely recognized and utilized method in the application domain of seismic sedimentology in recent years. There are primarily two categories of sedimentary facies identification techniques: one is based on slicing technology; the other is seismic facies identification technology based on attribute analysis.

The key aspects of sedimentary facies identification involve two aspects: first, calibrating seismic facies with single-well sedimentary facies to establish a connection between the two; second, inferring the sedimentary environment of the study area from single-well facies and establishing a general sedimentary facies model under this sedimentary environment. Under the guidance of the sedimentary facies model, the responses of seismic attributes are transformed into the planar distribution of sedimentary facies.

Based on the principles of seismic sedimentology, there is a good correlation between seismic microfacies and sedimentary microfacies distributions derived from well data (including logging facies), which fully illustrates the rationality and reliability of using seismic sedimentology theories and methods for sedimentary facies analysis.

4.5. Detailed Structural Interpretation

The accuracy of horizon tracking on seismic profiles is influenced by horizon picking errors and the resolution of seismic data, which cannot meet the requirements of detailed structural interpretation. The application of 90° phase conversion technology can enhance the accuracy of horizon picking caused by visual errors. After phase conversion, the position of the stratigraphic interface is shifted from within the blue axis (positive phase) to the zero-phase position, making horizon tracking more accurate. Additionally, seismic phases align more closely with lithological logging curves, granting seismic phases a lithostratigraphic significance.

For low-amplitude structural interpretation, vertical resolution is the primary factor affecting interpretation accuracy. The vertical resolution scale of seismic data is inversely proportional to frequency, so improving the resolution of seismic data can lead to more detailed interpretations.

4.6. Exploration Case Studies

The basic research approach to seismic sedimentology is "geology → seismic → geology". Expressed as "point → plane → cube", the approach stresses the calibration of geological data, which is also an effective way to resolve seismic ambiguity. The method can be summarized into four steps [15]:

(1)Build a time-equivalent stratigraphic framework. First, through detailed vertical analysis and horizontal correlation of outcrop, core and logging data, identify the high-order discontinuity surfaces, abrupt boundary changes in sedimentary facies and marine flooding or lake extension boundary resulting from changes in sea (lake) level or sedimentary base level, and, combined with the analysis of 3D seismic data, build a high-resolution stratigraphy sequence framework. The precision of sequence division depends on the data quality. When the geological and geophysical data are high in resolution, third- and fourth-order (or even higher) sequences and depositional system tracts can be recognized. Then, when time-equivalent analysis is conducted on divided seismic reflectors, adjust the diachronous horizons according to the analysis results. Finally, build the well-seismic tied time-equivalent stratigraphic framework.

(2)Analyze the sedimentary facies of coring intervals in a single well by using the surface outcrop data, coring data, and lab test results. Use the analysis results to calibrate the SP, GR, etc., logs of the coring intervals and represent the sedimentary facies in the form of logs. Then, use these logs to study the sedimentary facies of non-coring intervals, thus accomplishing the sedimentary facies analysis of the target interval (single-well facies division), and build the sedimentary facies model.

(3)Convert the seismic data cube into a lithological data cube with wave impedance, SP, and GR via seismic data conversion (i.e., reservoir parameter inversion or 90° phase shifting).

(4)Conduct time-equivalent stratal slicing or extract the time-equivalent unit's seismic attributes, and under the guidance of the sedimentary facies model, interpret these data cubes based on continuous vertical changes and relative spatial changes in the time-equivalent attributes. Obtain a relatively accurate sedimentary facies plan and profile, and finally build a 3D depositional system model based on modeling and 3D visualization (Figure 1)

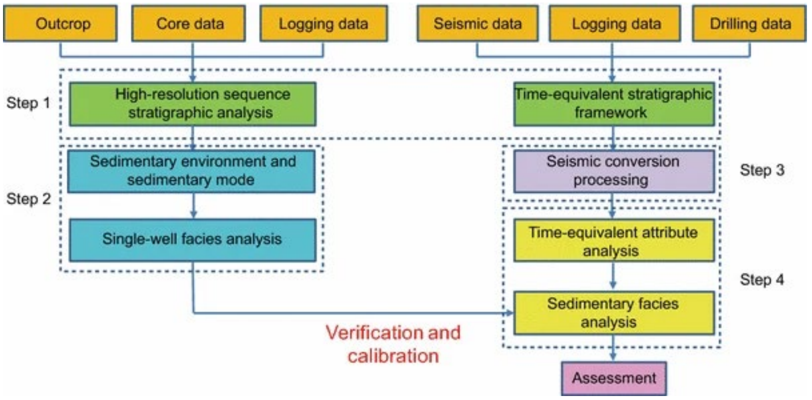

Figure 1: Seismic sedimentology research approach and method.

The study area is located in Mabei slope area of Mahu area at northwestern margin of Junggar Basin , and the target layer is the upper member of Triassic Karamay Formation. According to previous studies, the Karamay Formation in Mahu area is mainly composed of braided river delta deposits, in which the reservoirs are mainly delta front underwater distributary channel sand bodies.

The cross-well sand layer correlation (Figure 2) shows that sand bodies in the study area feature vertical superposition, thin thickness and fast lateral change. The cross well seismic profile after −90° phase shift (Figure 3) shows that the oil layer is close to the zero point. The top layer and bottom layer have good correspondence with the peak of event and good continuity[16]. These methods can more accurately predict the distribution of individual sand bodies in thin interbedded reservoirs.

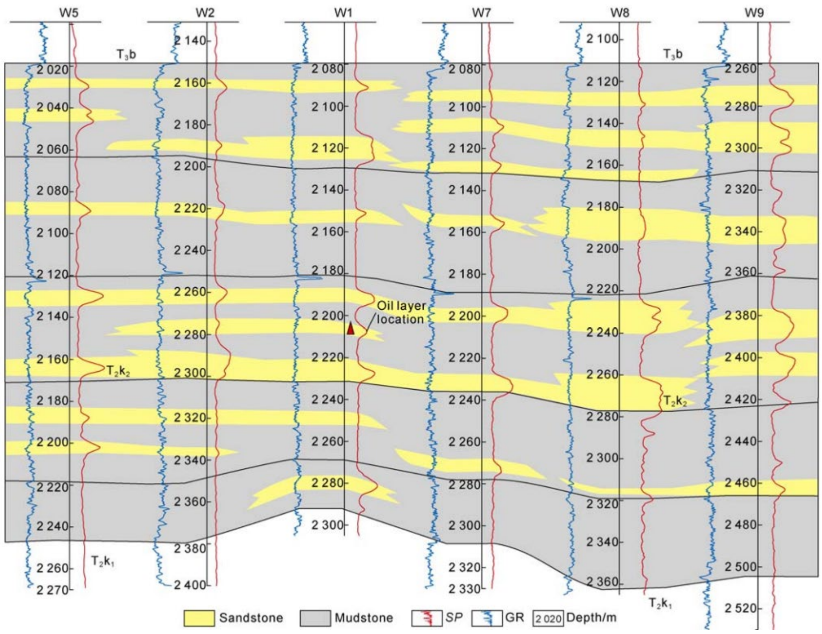

Figure 1: Cross-well sand layer correlation in the study area.

T2k—Middle Triassic Karamay Formation, T3b—Upper Triassic Baikouquan Formation.

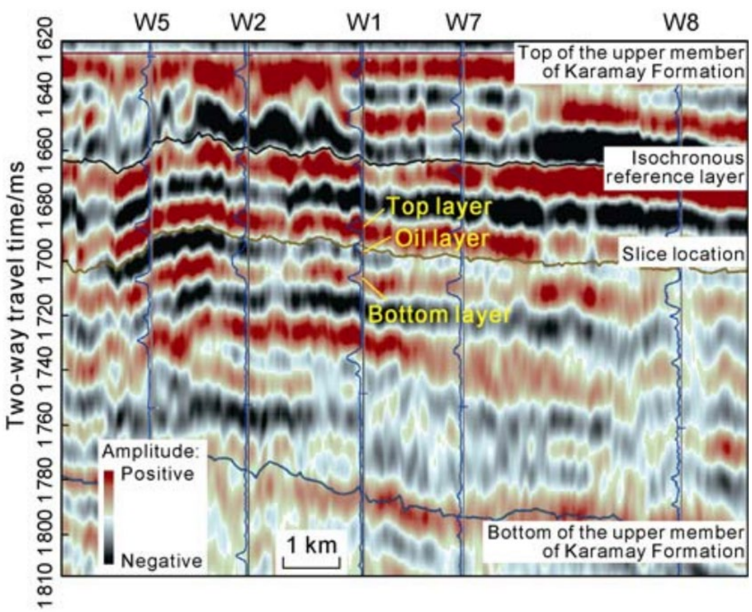

Figure 2: Cross-well seismic profile of −90° phase shift in the study area.

5. Application of Seismic Sedimentology in Deep Sea Oil and Gas Exploration

5.1. Differences between marine and continental basins

Oceanic basins and continental basins exhibit significant differences in terms of their major controlling factors as well as in their rock physical properties and seismic reflection characteristics (Table 1). In light of these constraints, new approaches and more detailed, effective technical methods are required to generate lithologic data cubes [15].

Table 1: Factors influencing seismic sedimentology research on marine and continental basins

Geologic factor	Ocean basin	Continental basin
Control factor	Changes in global sea level, basin subsidence, sedimentation rate, and climate	Structural subsidence, lake water level, water supply, paleoclimate, and paleotopography
Settlement range	Coastal zones, continental shelves, continental slopes, and deep seas, thousands of kilometers wide and tens to hundreds of kilometers or more thick	Alluvial fan, river, and lake sedimentary zones have relatively small sedimentary ranges and rapid facies changes
Sedimentary layers	Long horizontal extension and good continuity	Short horizontal extension and poor coherence
Sequences	The sequence is thick and stable	The sequence is thin and varied
Precipitation type	Relatively simple, large in area, stable in distribution, and includes mainly delta,coastal-shallow sea,and deep sea deposits	Relatively complex,small in area,unstable in distribution,and includes mainly fan delta, braided delta, delta, coastal-shallow lake and deep lake deposits

5.2. Challenges of Deep-sea Oil and Gas Exploration

Deep-sea oil and gas exploration faces multiple challenges brought about by high temperatures, high pressures, and complex fluids. Due to the complicated geological conditions in deep-sea environments, the technical difficulty and investment required for oil and gas exploration and development have surged exponentially. Consequently, there is a need for high-precision seismic acquisition technologies and equipment, as well as sophisticated data processing and interpretation techniques [17].

5.3. Technological Advantages of Seismic Sedimentology

In deep-sea oil and gas exploration, seismic sedimentology offers technological advantages such as high-precision imaging and three-dimensional visualization. By measuring and analyzing the propagation and reflection characteristics of seismic waves underground, it is possible to determine information about the location, thickness, properties, and structural features of subsurface oil and gas reservoirs. This information is crucial for deep-sea oil and gas exploration, as it can enhance the success rate of exploration efforts.

5.4. Case study of oil and gas exploration in Chinese waters

In China's maritime areas, self-developed marine seismic exploration equipment sets, such as the "Haijing" system, have been successfully utilized to complete 3D seismic surveys in multiple work areas. These equipment sets can penetrate nearly 10,000 meters of strata beneath the sea surface, providing reliable support for the evaluation of traps in complex structural belts. Additionally, the integration of AI technology has improved the signal-to-noise ratio of seismic data by 25%, significantly enhancing imaging clarity, and setting a new record for deep-sea deep-layer data processing.

6. Conclusion

Seismic sedimentology provides refined research methods for oil and gas exploration by integrating seismic data with sedimentological principles. Its core technologies, such as logging-constrained inversion, stratigraphic slicing attribute analysis, and frequency-decomposition interpretation, significantly enhance the precision of sedimentary environment interpretation, reservoir prediction, and sedimentary system analysis.

Logging and seismic waveform and curve patterns reflect the properties of subsurface rock layers. After removing interference, they can objectively represent various physical properties of the rock layers, including lithology, grain size, structure, porosity, and permeability. Therefore, effective processing and inversion of geophysical methods can truly reproduce the properties, morphology, and three-dimensional spatial distribution of sediments.

In deep-sea oil and gas exploration, despite complex geological conditions and high technical challenges, seismic sedimentology effectively overcomes obstacles such as high temperatures and pressures through its advantages in high-precision imaging and three-dimensional visualization, thereby improving exploration efficiency. In the future, with further innovations in technical equipment, seismic sedimentology will play an even more critical role in deep-sea oil and gas exploration, driving the efficient development of oil and gas resources.

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