Application of 3D fine seismic interpretation technique in Dawangzhuang Area, Bohai Bay Basin, Northeast China

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Abstract One of the major problems in subsurface seismic acquisition, procession, and exploration we are facing today is the uncertainty in geologic interpretation because of the complexity of subsurface geology and the limited dimension of the subsurface data available (including drilling data, well logging, and core samples). Case studies from worldwide exploration projects indicate that an integrated, three-dimensional seismic volume visualization and interpretation workflow contributes greatly to resolving the problems we mentioned by extracting critical geologic information from within 3D seismic datasets. Over the last decade, with the increasing employment and improvement of geophysical technology and following 3D seismic data acquisition and processing, the subsurface seismic interpretation workflow is composed of four integrated stages from data selection and procession, to structures, stratum, and facies characterization; to prospect prediction and evaluation; and to well-bore planning. In the data selection and pre-procession phase, the most favorable and frequently used datum is the full and limited angle and limited azimuth post-stack amplitude with significant structures, stratum, and facies enhancements. Signal-to-noise ratio, color scheme, dynamic range, bit resolution, and visual contrast all affect the visibility of features of interest. During the structures, stratum, and facies characterization phase, vertical slicing along arbitrary traverses demonstrates structure styles, stratigraphic architecture, and reservoir geometry in the cross-sectional view. Time/depth slicing defines lateral and vertical variability in the structural trend and areal extent in the map view. Stratal slicing and fault slicing suggest chronostratigraphic seismic facies, associated depositional information, and cross-stratal, along fault seismic signature. Volume flattening and structure restoration aid in unraveling paleo-structural framework, stratigraphic architecture, evolution, and filling histories. In the prospect prediction and evaluation phase, a combination of volume trimming, core-rendering, transparency, attribute analysis, and attribute body detection is instrumental in delineating volumetric extent and evaluating spatial connectivity of critical seismic features. Finally, in the well-bore planning phase, decision making relies on the integration of all the information and knowledge extracted from 3D seismic datasets. Most importantly, interpreters' geologic insights and employments of geophysical technology are crucial to optimal well-bore planning with high geologic potential and low economic risk. The structure of the study area, which is poorly understood to be primarily due to the complexity of subsurface geology and the limited dimension of the subsurface data available, and therefore, we design the integrated workflows and use some of the methods mentioned above to carry out fine seismic interpretation in an analysis of high-resolution 3D seismic data and other...
geological data in the study area. Finally, we finished the fine interpretation of 3D seismic data and achieved a series of success and good application results. The evolution of tectonics resulted in sub-tectonic units containing the sequences of Ek, Es, Ed, Ng, and Nm. Interpretation reveals that tectonic transition zone which controlled the evolution of the sequences because of its strength, and also, the structural pattern resulted in types of fault (such as “Y” type). The seismic interpretations provide new information on subsurface geology, including the recognition of complex structural patterns in rift lacustrine basin and the presence of a tectonic transition zone at the structural center. The interpretation of these seismic reflection profiles provides new insights into the structure, geological evolution, and petroleum potential of the study area.

**Keywords** Seismic attribute · Visualization · Slices · Horizon flattening

**Introduction**

The key problems in basin analysis are: What is the hydrocarbon volume and how is the hydrocarbon distributed in the basin? The ability to answer these questions and to provide evidence for hydrocarbon exploration and exploitation is critical for deciding whether to produce a field and to develop a production plan. Well drilled during the appraisal phase provides well and other related data, which are combined with structural and stratigraphic knowledge from seismic surveys to map the extent of the field and generate a reservoir model. The cost is usually too high for onshore drilling, not to mention the offshore drilling, and it is desirable to obtain the information required with fewer wells if possible. The fine seismic interpretation of modern 3D seismic data provides us much geological information we need between well locations and can therefore reduce the exploration costs. Traditional 2D seismic displays of limited numerous seismic lines or maps often distort the interpretation of tectonic deformation, sediment deposition, and hydrocarbon occurring in three dimensions easily. With the improvement of computer processing and display, three-dimensional seismic imaging technology provides geologist a continuous volumetric seismic coverage of the survey area that makes it possible to interpret seismic structure, stratigraphic distribution, hydrocarbon migration, and accumulation from a three-dimensional perspective (Dom et al. 1995; Dorn 1998; Walla and Edward 2003; Jiang et al. 2006; Al-Zahrani and Neves 2008; Wu et al. 2010; Amogu et al. 2011; Yan et al. 2013; Wang 2013). Although the 3D seismic data offer a unique opportunity to make seismic observations and geologic interpretations in 3D space, most 3D seismic data are displayed and interpreted in a 2D manner, leaving the critical advantage and potential value of 3D seismic data underused. High-performance 3D digital computing and state-of-the-art volume visualization and interpretation technologies have played an important role in facilitating a 3D seismic volume interpretation in an interactive manner (Dorn et al. 1995; Dorn 1998). There is extensive documentation on various seismic volume visualization and interpretation techniques; however, these techniques have been largely used as individual, independent functions in routine seismic interpretation applications (Jiang et al. 2005a, b; Li 2012; Gorodnitskiy et al. 2013). Due to the poor understanding of the subsurface structure and stratigraphy of the study area, we plan to relate structures to the broader tectonic framework of Dawangzhuang Area. This paper presents and implements the key seismic
volume visualization and interpretation modules in an integrated workflow beginning with data selection and pre-processing, through structures, stratum, and facies characterization; prospect prediction; and evaluation. Using case studies of worldwide exploration projects, this study demonstrates that the integrated workflow helps interpreters unravel and understand structural, stratigraphic, and reservoir systems that are of geologic and economic significance. The workflows should have general applicability in seismic exploration projects in diverse geologic settings (Yang et al. 2012; Zhang et al. 2012). The interpretation of seismic reflection data reveals a pattern of faults, linked by different tectonic settings, making the distribution and characteristics of faults clear.

**Geological overviews**

The Dawangzhuang Area is mainly located in the central part of Raoyang Sag, Jiyang Depression, Bohai Bay Basin (Fig. 1) and adjacent to several tectonic zones including Liuxi, Liuchu, Suning, and Zhaohuangzhuang. The area covered by 3D seismic survey in the study area is about 200 km². The strata here from the bottom to top include pre-Cenozoic deposits, the Paleocene Kongdian Formation deposits, the Eocene Shahejie Formation deposits, the Oligocene Dongying Formation deposits, the Miocene and early Pliocene Guantao Formation deposits, and the mid-late Pliocene Minghuazhen Formation deposits. Due to the petrolierous reservoirs and low-quality seismic datasets, it is a serious impediment to fine evaluating process of the study area. In order to further reveal the geologic structure, to understand the fault assemblage relationships, and to study the potential traps, it aims to make deeper studies about fine 3D seismic interpretation to get all these issues mentioned above clear.

**General workflows**

The subset of seismic data employed in this study is provided by the No.3 Oil Plant, Huabei Oilfield, which is composed of

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*Fig. 2* The tiny changes observed on seismic profile (see Fig. 1 for location from line B) with flattening technique in Dawangzhuang Area, Bohai Bay Basin (as for the color column, it can be seen from Fig. 2)
a 350-km² grid of a post-stack, time-migrated 3D volume, with a bin spacing of 25×50 m and a two-way travel time trace length of 4 s. The 3D seismic data quality in the survey at the target stratigraphic interval is good, with 25–30 Hz in the main frequency width; furthermore, there are some kind of well logs, such as density logs, sonic logs, natural gamma ray logs, and spontaneous logs. Except those data above, a wide variety of sedimentological, paleontological, biostratigraphic, and oil–gas production data are collected. The well data we employed are used to calibrate seismic interpretations mainly for horizon tracing. Because the resolution of seismic dataset is far more ambiguous in vertical profile than that of well data, however, the horizontal resolution of well data is much worse than that of seismic data. The application of well data, especially the fact that interpretation of well logs such as SP curve and GR curve, can help us identify sequence stratigraphy and systems tract and build sequence stratigraphic framework.

With the development of oil exploration technology constantly, the research work on Dawangzhuang Area gradually formed a set of 3D fine seismic interpretation technique and achieved wonderful results in the studied area.

The comparison of traditional seismic interpretation methods and seismic geological interpretation in integration platform

Processes for the traditional seismic interpretation are data loading, well-seismic calibration, structural

Fig. 3 The seismic attribute extraction based on the strata slices in Dawangzhuang Area, Bohai Bay Basin (the seismic attribute is used for looking for fault features, i.e., inclination, azimuth. The best seismic attribute results are obtained by slicing as near as possible to the target interval and parallel to a well-mapped structural horizon.)
interpretation, mapping, and favorable target analysis (Jiang et al. 2005a, b; Hong et al. 2008; Hao et al. 2012). There are some disadvantages for this process: (1) it is a linear process which is in lack of lateral interactivity, (2) the soft architecture is single, and (3) there are too many modules which are difficult to transfer. While in integration platform, all the disadvantages mentioned above are gone, and instead, there are some obvious advantages of the seismic geological interpretation: (1) it can take an advantage of a variety of data to make seismic geological interpretation fully merged and interpretation process clearer, concise, and practical; (2) it can give full play to the advantage of the integration platform and integrate interpretation into the interpretation process; and (3) all the processing results can be shared and updated in the platform.

Several key technologies and its application in the integration platform

Fine structural interpretation techniques

1. To make full use of the workstation characteristics of stretch and strong amplification technology and also convenient, flexible, and interactive features to observe all events with tiny changes, and to explain the small faults

Fig. 4 The seismic attributes of faults interpretation in Dawangzhuang Area, Bohai Bay Basin (the upper right is inclination seismic attribute, and it can be seen from the map that the dark linear distribution of northeast strike is clearly displayed which indicates faults. The upper left is the azimuth seismic attribute, and also, the faults can be identified. The lower seismic cross volume testifies the spatial distribution of faults on the plane section including fault strike and trend. The color map on the left is for the upper left figure, and the color map on the right is for the lower right and the lower one.)
and small amplitude structure, and finally, to meet the requirements of shallow low-amplitude trap identification (Fig. 2).

2. To use time slices, horizon-parallel slices (i.e., strata slices), and proportional slices to identify fault inclination and azimuth on both sides of faults and to verify the fault plane assemblage and its structural types (Fig. 3) (Dorn 1998; Zeng et al. 2001; Zeng 2005).

3. To employ variable density, variable area displays, various seismic attributes (such as inclination and azimuth seismic attributes), and the observation of seismic events in view of phase, amplitude, and other properties to improve the correctness of interpretation and to test its rationality (Fig. 4) (Todorov 2000; Zeng 2005).

4. To use a comparison of fault block moving and sliding and so on to further deepen the relationship between fine structural interpretation and comparison of wave groups and to achieve full visualization, wonderful paleogeomorphology, and good geology information (Fig. 5).

5. To employ a flattening technique to examine the rationality of fault interpretation and to analyze the tectonic evolution history (Fig. 6). By flattening all the reflection surfaces in the study area by inline direction, the evolution of faults and stratum can be understood better (Fig. 7a, b).

All the techniques mentioned above have been applied in Dawangzhuang Area, and they overcame the difficulties of traditional 2D seismic datasets and achieved good results.

The application of three-dimensional coherence technique in fault and strata interpretation

Three-dimensional coherence technique which is a highly effective technology is fully used to utilize the computer functions to pick up automatically three-dimensional seismic geological information to identify the continuous variation of faults and the formation. The methods of using three-dimensional coherent data for fault interpretation could decrease the influence of human factors and reduce the multiplicity. That is because the coherent data were used to employ the similarity of seismic waves to identify its continuity (Todorov 2000; Jiang et al. 2005a, b; Posamentier et al. 2007). All these advantages can be summarized in three aspects:

1. The application in identifying the faults parallel to the strike of strata

   The normal time slicing played an important role in studying the faults which were vertical to the strata. However, it is difficult to identify the faults when they are parallel to the strata. Due to the fact that the coherent data can avoid the characteristics of horizontal compatibility and the effects of bedding, therefore, it can reveal the faults of arbitrary direction.

2. The application in improving efficiency and accuracy of seismic interpretation
The coherent interpretation is not based on the traditional manual interpretation, but to the reflected real subsurface seismic reflection records, and therefore, it can reduce the interpretation of time consumed and increase the effects needed.

The coherent data can meet the needs of various actual regions with different geologic backgrounds. It can be designed to characterize the complex sand bodies in special tectonic settings or along the strike of strata. It can also be calculated in a special way to co-render the inner structure of seismic dataset within visualization using dip or azimuth seismic attributes, which makes interpretation more reliable and simple.

3. The application in auto faults interpretation
   Based on the previous references (Jiang et al. 2005a, b; Hao et al. 2012), the accuracy of auto faults interpretation with coherent data can be as high as 60–70 % which is also proved by practices.
The spatial continuity of the coherent data could reduce the chances of missing smaller faults. Practice has proven that the use of coherent data on faults identification and faults spatial distribution and its assemblage relationship is very effective. Here is an example, in shallow tectonic breaks zone in Dawangzhuang Area where lots of faults were developed, it is easy to interpret the faults, understanding the evolution and spatial distribution of these faults reasonably with coherence technique (Fig. 8). In addition, from the coherence data, it can be seen that an obvious dislocation appears in the center of studied area which is regarded as the structure transition zone based on the comprehensive analysis of the characteristics of plane and cross section (Lomask et al. 2009).

Three-dimensional visualization technique

The three-dimensional visualization technique is not only the basis of full visualization interpretation but also the trend of technological development for hydrocarbon exploration and exploitation. Firstly, the interpreter will quickly scan through a 3D seismic volume to get a better idea of strata framework, reservoir heterogeneity and depositional characteristics by inline, crossline, and arbitrary line. The objective is to identify spatial distribution of volume of different attributes. All the
information from this phase can be a guide to the interpreter to analyze the seismic and geological information (Fig. 9).

Another reconnaissance approach consists of opacity rendering, whereby the 3D seismic volume is rendered
transparent except for specific amplitude values associated with a particular target, such as a river channel infill (Zeng et al. 2001; Zeng 2005; Zhao 2012). Commonly, it is the amplitude extremes that are rendered opaque, thus allowing the targeted opaque features to stand out (Fig. 10).

Conclusions

In summary, through the application of fine 3D fine seismic interpretation in Dawangzhuang Area, the integrated interpretations provide insights into the structures and stratigraphy of the study area. New observations include the recognition of tectonic fault types and graben structures, the recognition of transformation zone and its identification methods, and the presence of tectonic and stratigraphic evolution.

1. Structural pattern recognition, including the interpreter being able to identify geologically significant features in plane and cross-section view on the 3D seismic dataset, is crucial to the fine seismic interpretation, especially for the fault and horizon interpretation and visualization. During the fault interpretation, the type of fault assemblage appeared as Y type in graben settings. The horizon interpretation and flattening technique reveal the deposition and erosion of the strata changed with the tectonic evolution. In the initial stage, with the strong tectonic movements, there were many deposits in the gentle and escarpment of the study area. However, with the tectonic stress increased, the strata were erased by exposure during the deposition of Ed and Es1 and Es2. In the last stage, the strata were preserved well due to the weak tectonic movements.

2. To ensure that the results from this paper have broader applicability to other similar geological settings and to aid with the calibration necessary for this more general usage, this method should focus more on issues related to the following: (1) erecting a stratigraphic hierarchy, (2) differentiating between internal and external controls, (3) integrating outcrop and core samples and other micro subsurface data, (4) making fairway and reservoir prediction, and (5) studying the evolution of sequence stratigraphy and its systems tracts which could be able to predict the reservoir elements. If we took all those things mentioned above into consideration, we might come up with a better understanding of the geology and geophysics in the study area.

Fig. 10 The opacity render display in Dawangzhuang Area, Bohai Bay Basin
3. The method used in the study area achieved good results for the structural interpretation and provided a new blueprint for future development in fine seismic interpretation. Processing and fine interpretation of 3D seismic data from the similar area is an economically reasonable decision that provides additional information about the geological structure of a region. With the new knowledge, theory, and techniques taken into consideration, one can manage future geophysical works.

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