Available online at www.sciencedirect.com

ScienceDirect

Natural Gas Industry B 3 (2016) 117–128

www.elsevier.com/locate/ngib

Research article

Application of high-precision 3D seismic technology to shale gas exploration: A case study of the large Jiaoshiba shale gas field in the Sichuan Basin

Chen Zuqing, Yang Hongfei*, Wang Jingbo, Zheng Tianfa, Jing Penggui, Li Suguang, Chen Chao

Sinopec Exploration Company, Chengdu, Sichuan 610041, China

Received 31 December 2015; accepted 16 March 2016
Available online 26 August 2016

Abstract

The accumulation pattern of the marine shale gas in South China is different from that in North America. The former has generally thin reservoirs and complex preservation conditions, so it is difficult to make a fine description of the structural features of shale formations and to reflect accurately the distribution pattern of high-quality shale by using the conventional 2D and 3D seismic exploration technology, which has an adverse effect on the successful deployment of horizontal wells. In view of this, high-precision 3D seismic prospecting focusing on lithological survey was implemented to make an accurate description of the distribution of shale gas sweet spots so that commercial shale gas production can be obtained. Therefore, due to the complex seismic geological condition of Jiaoshiba area in Fuling, SE Sichuan Basin, the observation system of high-precision 3D seismic acquisition should have such features as wide-azimuth angles, small trace intervals, high folds, uniform vertical and horizontal coverage and long spread to meet the needs of the shale gas exploration in terms of structural interpretation, lithological interpretation and fracture prediction. Based on this idea, the first implemented high-precision 3D seismic exploration project in Jiaoshiba area played an important role in the discovery of the large Jiaoshiba shale gas field. Considering that the high-quality marine shale in the Sichuan Basin shows the characteristics of multi-layer development from the Silurian system to the Cambrian system, the strategy of shale gas stereoscopic exploration should be implemented to fully obtain the oil and gas information of the shallow, medium and deep strata from the high-precision 3D seismic data, and ultimately to expand the prospecting achievements in an all-round way to balance the high upstream exploration cost, and to continue to push the efficient shale gas exploration and development process in China.

Keywords: Sichuan Basin; Southeast; Marine facies; Large Jiaoshiba shale gas field; Horizontal well; High-precision 3D seismic exploration; Stereoscopic exploration; Sweet spot prediction; Hydrocarbon information

In the initial stage, the exploration of shale gas in China, influenced by the shale gas exploration idea in North America, focused excessively on hydrocarbon generation conditions of source rocks, but neglected preservation condition of shale gas. As a result, many shale gas pools discovered were not commercially recoverable since they had been destroyed by tectonic processes [1–3]. Shale gas fields in North America are generally shallow-buried, with reservoir depth of 800–2600 m, and their high-quality shale layers are thick and uniformly distributed, presenting less challenge in fracturing treatment. Moreover, the overlying formations and surface tectonic conditions are simple, and the preservation conditions are favorable, which imply low technical difficulties and risks in exploration and development [4]. Even so, the success of shale gas exploration and development in the US benefited from advanced exploration and development technologies. For example, the 3D seismic and micro-seismic technologies were used to optimize the designs of development wells, which

* Corresponding author.
E-mail address: 9401734@qq.com (Yang HF).
Peer review under responsibility of Sichuan Petroleum Administration.

http://dx.doi.org/10.1016/j.ngib.2016.03.006

ensured high productivity and commercial values of shale gas [5–10]. However, the accumulation conditions of shale gas target layers in South China are very different from those in North America [1,11,12]. Specifically, the shale gas layers in China are deeply buried in areas between 2000 m and 4500 m. Under the action of multi-cycle stress, the high-quality shales change greatly in lateral thickness and distribute unevenly, thus presenting challenges to fracturing treatment. Furthermore, the surface and subsurface tectonic and preservation conditions are complex, so it is difficult to accurately obtain the geological parameters for evaluating shale gas enrichment law in South China by using the conventional 2D and 3D seismic exploration technologies. In other words, such technologies cannot meet the technical requirements of fine confirmation of shale gas "sweet spots", thus cannot efficiently support shale gas exploration. Available results of geological researches indicate that hydrocarbon generation and preservation conditions of shale formations must be emphasized if shale gas exploration in South China can obtain breakthroughs. In the aspect of hydrocarbon generation conditions, physical properties of source rocks must be identified. In the aspect of preservation condition, tectonic features of shale gas layers and their overlying cap rocks must be confirmed, and then preservation conditions of shale gas must be evaluated. According to the practices of staged fracturing development of shale gas horizontal wells in North America [13], it is known that the designed horizontal well trajectories should continuously pass through around 1500 m of high-quality shale layers, so as to maximize the productivity benefited from staged fracturing at horizontal sections. This raises higher requirements for the description of tectonic occurrences and the identification of small faults in shale layers and their adjacent rocks. Obviously, if the above geological tasks should be finished, high-precision 3D seismic prospecting technology [10] must be adopted to accurately find out the key factors (e.g. fine structures, thicknesses, organic matter content, brittleness index and preservation conditions of the high-quality shale layers) that can decide and influence the commercial exploration and development of shale gas.

Based on the above exploration idea, China Petroleum & Chemical Corporation ("Sinopec") carried out high-precision seismic acquisition, processing and interpretation in Jiaoshiba area in Fuling, SE Sichuan Basin, with features of wider azimuth angles, higher folds, smaller trace intervals, moderate array lengths and smaller transport distances. The obtained migration imaging data show that the Silurian inside is clear, and the Cambrian system has distinct reflections. In particular, the shale gas target layers (i.e. Lower Silurian Longmaxi Fm and Wufeng Fm) have clear and reliable reflections, good continuity and strong traceability, which lays an effective basis for the deployment of horizontal shale gas wells. Target processing and interpretation results indicate that the final fine processing and interpretation results of the high-precision 3D seismic data in Jiaoshiba area agree quite well with the drilling results in Wells Jiaoye 1 and Jiaoye 4 deployed in the major tectonic region, which proves the reliability of high-precision 3D seismic data in shale gas exploration. On this basis, several horizontal prospecting wells designed in stages followed all obtained important breakthroughs in gas testing, with the support of advanced shale gas sand hydraulic fracturing development technology in deep wells. In July 2014, the Jiaoshiba shale gas field booked 1067×10^8 m^3 of proved shale gas reserves, achieving commercial development of shale gas in Fuling, which unveiled the world's only large commercial marine shale gas field in the world, except for North America. The breakthrough of the large Jiaoshiba shale gas field marked the formation of marine shale gas exploration in South China [14], i.e., hydrocarbon generation condition and preservation condition of shale gas are equally important and indispensable. For the supporting seismic prospecting operations, a set of more complete technical ideas and technical processes have also been formed.

Starting from the geological characteristics of shale gas reservoirs in South China, the authors discussed the required high-precision 3D seismic prospecting technology for shale gas exploration. Taking the successful practice of the high-precision 3D seismic prospecting in the large Jiaoshiba shale gas field as an instance, the authors discussed how to utilize this technology to achieve the balance between cost and benefit of shale gas exploration and development, and to expand the final result of the high-precision 3D seismic prospecting.

1. Key technical requirements of shale gas exploration in South China

1.1. Key geologic problems

Shale gas reservoir is a typical "self-generation and self-storage" gas reservoir [15]. Obviously, its accumulation requires a sedimentary environment with organic-rich dark shale, which means abundant organic matter supply, quicker deposition condition and reductive environment with better sealing capacity. The Ordovician–Silurian systems and Lower Cambrian system in South China have such a sedimentary environment. Previous exploration results also indicate that two sets of high-quality source rocks (i.e. Upper Ordovician Wufeng Fm–Lower Silurian Longmaxi Fm and Lower Cambrian Qiongzhusi Fm) were widely developed in South China; particularly, the marine dark shales in the Longmaxi Fm within the Sichuan Basin and its periphery had higher organic matter content, higher organic thermal evolution degrees and relatively stable lithology distribution, providing basic conditions for forming large marine shale gas field [16]. The composite columnar section of source–reservoir–caprock in marine lower assemblage of the Sichuan Basin shows clearly that (Fig. 1), in addition to the two sets of high-quality source rocks (e.g. Wufeng Fm–Longmaxi Fm, Qiongzhusi Fm), there are another two sets of restricted platform reef flat reservoir beds in Cambrian Xixiangchi Fm, Longwangmiao Fm and Sinian Dengying Fm. This means that the lower marine assemblage in the Sichuan Basin has the stereoscopic exploration potential of conventional and unconventional gas (shale gas).

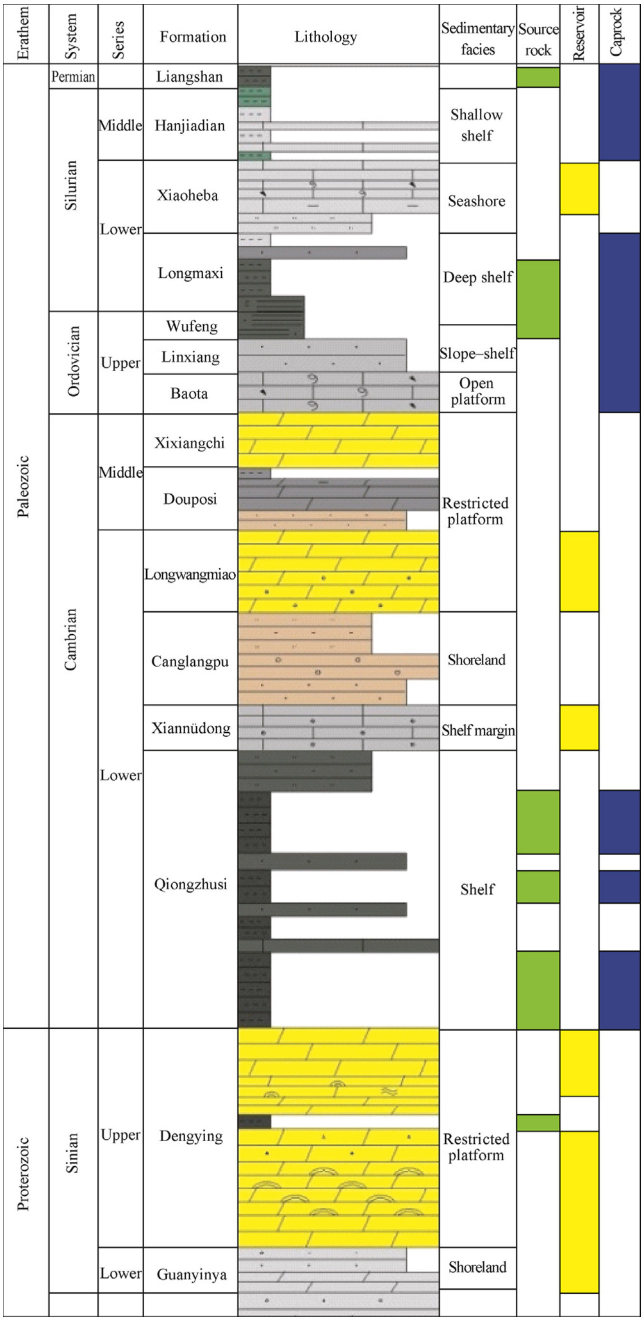


Fig. 1. Composite columnar section of source−reservoir−caprock in marine lower assemblage, Sichuan Basin.

Moreover, in shale gas pools, both free gas and adsorbed gas have positive correlation with pressures, and the pressure values control shale gas abundance and reserves [14]. Exploration practices in the past few years proved that fine preservation condition is the key factor for marine shale gas enrichment and high productivity. If the preservation condition is poor, shale gas pools are prone to be destroyed. If the formation pressures are normal or abnormally low, shale gas is hard to be preserved, or even completely dispersed.

Hence, the shale with high organic matter abundance does not always form shale gas pool with high gas content. Only when fine preservation condition is available, can shale gas pool with high enriching degree be formed. Therefore, the preservation condition is also a key factor for shale gas enrichment and high productivity.

Nevertheless, the Sichuan Basin is a superimposed basin in upper Yangtze massif. It experienced superimposition and reformation as a result of multiple tectonic movements (e.g. Caledonian movement, etc.), leading to violent fold deformation, uplift and erosion of the formations. Thus, the basin has a complex and versatile hydrocarbon preservation condition [14]. At the southeastern margin of the Sichuan Basin, influenced by the Qiyueshan large fault, the structural style is mainly composed of some deformed belts, such as the barrier belt inside the basin, “trough−barrier” transition belt at its margin, and barrier−trough belt outside the basin, leading to big differences of tectonic deformation of the formations in various tectonic belts and tectonic regions, and complicated hydrocarbon preservation conditions [17]. Therefore, in marine shale gas exploration in complex tectonic belts with high evolution degrees at the southeastern margin of the Sichuan Basin, fine description of the stratigraphic structure styles is the basis for studying the preservation condition of shale gas, and also the key to efficient shale gas exploration and development [14]. In view of the difference of accumulation pattern in marine shale gas in South China and North America, priority should be given to researches on both the hydrocarbon generation condition of source rocks and the preservation condition in actual explorations. The former is mainly to find out the physical properties of source rocks, while the latter is chiefly to confirm the tectonic patterns of shale gas layers and their overlying cap rocks.

1.2. Requirements for geophysical prospecting technologies

As the accumulation pattern of shale gas in South China is different from that in North America, some factors (e.g. tectonic occurrence, thicknesses, distribution law of organic matter content, brittleness index and preservation condition) of shale layers must be accurately confirmed to successfully predict shale gas “sweet spots” and to guide drilling horizontal well trajectories. Specifically, thicknesses, distribution law of organic matter content and brittleness index of shale are the physical properties of rock, falling into the category of lithological exploration. The preservation condition is generally controlled by geologic structures, and tectonic pattern of the overlying cap rocks must be confirmed, falling into the category of stratigraphic structural exploration. Clearly, it is necessary to use seismic exploration technology to complete the above two geological tasks in shale gas exploration. On the basis of seismic exploration results, combined with the theory and experiment of rock physical analysis, other physical properties (e.g. organic matter content, mineral composition, porosity, permeability, and brittleness index) of rocs can be further inferred. The work flow chart is shown in Fig. 2.

However, conventional 2D seismic prospecting can only be used to detect the geometric features of the 2D structural units and the simple lithological characteristics of the isotropic

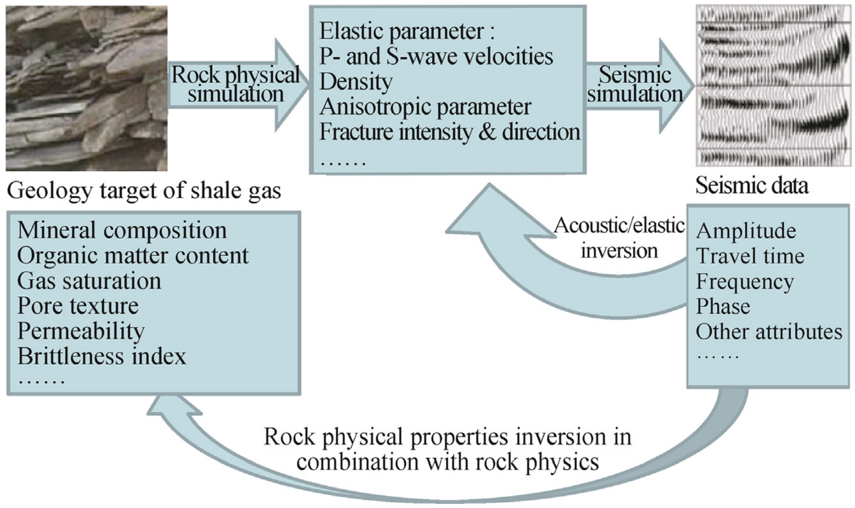


Fig. 2. Flow chart of applying seismic exploration and rock physics technologies in shale gas exploration [18].

medium, but not to make accurate imaging and lithological exploration of anisotropic (isotropic) medium of the 3D structural units [19]. Compared with single line 2D seismic prospecting, wide line 2D seismic or 3D seismic prospecting with narrower azimuth angles can be used to improve the imaging accuracy for simple 3D tectonic units to some extent, but it still cannot accurately describe the structural styles and lithological characteristics of complex structural zones. However, compared with the areas with well-developed shale gas in North American, the shale gas regions in South China generally have more complex surface and geologic conditions, dramatic terrain relief, rapid lateral lithology variation, having typical complex mountainous terrain features. Furthermore, subsurface structures in South China are also more complex than those in North America. The high-quality shale layers are thinner in South China – the high-quality shale layer in the Longmaxi Fm in Well Jiaoye 1 is only 38 m. For such complex 3D structural units, in order to ensure that the designed horizontal well trajectories can continuously drill more than 1000 m of high-quality mud layers and obtain commercial productivity, we must finish accurate imaging of the structures (especially the small faults) in target layers and accurate prediction of shale gas sweet spots. Apparently, high-precision 3D seismic prospecting is the prerequisite and foundation of accomplishing the above geological tasks.

Through years of studies and practices in shale gas exploration, Schlumberger recognized that high-precision 3D seismic prospecting technology played an irreplaceable role in predicting shale gas sweet spots (including distribution of thicknesses, organic matter content, brittleness index, fracturing development and pressure coefficient in 3D space) and horizontal well location design (including distribution of shale brittleness index, fracturing development and faults in 3D space) [6–10]. Experts of ExxonMobil affirmed the important role of the geophysical response characteristics of shale layers in evaluating their physical properties [18]. Liu Zhenwu et al. also clearly stated that geophysical technologies (especially the high-precision 3D seismic prospecting technology) were important in evaluating the physical properties and the stimulation treatment of shale layers [20].

The high-precision 3D seismic prospecting technology involves seismic acquisition, processing and interpretation. Acquisition is the base. If there is no original 3D seismic data with high-quality and abundant information, even the best processing and interpretation technologies cannot be utilized to accurately prove geology targets and finish geology exploration tasks. Therefore, considering the actual geological conditions of shale gas exploration in South China, the authors propose that high-precision 3D seismic acquisition is the prerequisite for implementing the high-precision 3D seismic prospecting technology.

When the high-precision 3D seismic prospecting technology is used in acquisition, depending on the features of the exploration targets, a 3D observation system with wide-azimuth angles, high folds, small trace intervals and long offsets should be designed. If cost and ground geological conditions are allowable, single point digital geophone receiving should be used too [21]. In this way, high-precision raw seismic data are provided for the accurate imaging of the underground structures and the accurate extraction of lithological and physical properties of the formations. The seismic data with wide-azimuth angles and long offsets contain relative complete information of lithological and physical properties of shale layers, providing data basis for lithological exploration; the seismic data with high folds, small trace intervals and long offsets contain relative complete features of dynamic and kinematic characteristics of effective reflected waves and interference waves, which is favorable for suppressing interference waves and utilizing effective waves, and can increase the signal/noise ratio, the fidelity of the effective waves and the imaging resolution of seismic data. Compared with the conventional 2D seismic and narrow azimuth 3D seismic acquisition, the high-precision 3D seismic acquisition technology provides more abundant effective information in lithological (physical) properties and structural form for shale gas exploration in complex areas. Therefore, the implementation of high-precision 3D seismic acquisition has become a necessity and a must in better completion of shale gas exploration in South China.

2. Successful application of high-precision 3D seismic prospecting in shale gas exploration in Jiaoshiba area

Exploration practices of unconventional oil and gas in southern and southeastern Sichuan Basin indicate that the Lower Silurian and Lower Cambrian series in this basin and its periphery have huge shale gas exploration potentials. Sinopec obtained commercial production of shale gas in Well Jiaoye 1 drilled in Jiaoshiba area. This breakthrough reveals a good exploration prospect in the Wufeng Fm (O_3w)–Longmaxi Fm (S_1l) in Jiaoshiba area. Though the previous 2D seismic data acquired in several periods ensured better stack imaging effect in the major part of the Jiaoshiba structure and better continuity in the Silurian system and overlying reflection horizons, the faults are hard to interpret, the structural details are not clear, the lateral variation of the O_3w–S_1l high-quality reservoir beds for shale gas is indistinct, the reflection horizons of the Cambrian and Silurian systems below *T*s have poor continuity, and the overall stack imaging effect in faulted belts and high-steep structures are poor. Subject to the restrictions of early acquisition methods and acquisition parameters, previous 2D seismic processing results cannot meet the exploration requirement of fine confirmation of shale gas "sweet spots" in the Silurian system, the top and bottom interfaces of Ordovician system are hard to trace, and it is difficult to confirm the structures in the Cambrian and Silurian systems (Fig. 3).

For further confirmation of the spatial distribution, shale gas enrichment law and its adjacent rocks of high-quality shale layers in the Longmaxi Fm to promote the overall deployment of marine shale gas exploration and development in Jiaoshiba area, the previous *Southern Branch of Sinopec* (now *Sinopec Exploration Company*) deployed high-precision 3D seismic acquisition in Jiaoshiba area in 2013. In the following sections, the successful application of high-precision 3D seismic prospecting in shale gas exploration in Jiaoshiba area will be discussed in terms of seismic acquisition, processing and interpretation effect.

2.1. Advantages of high-precision 3D seismic acquisition

Jiaoshiba area is dominated by hills and mountains, with seriously broken strata, bigger dip angle changes, serious seismic wave absorption and energy attenuation. Moreover, the outcrop rocks in the area are mainly limestone (about 90%). Compared with sandstone area, the excited and received original single shot records in the regions with complex surface condition (especially the areas with widely outcropped limestone) have apparently weaker effective reflecting energy and lower signal/noise ratio (Fig. 4). In order to meet the requirement of geologic task in shale gas exploration, improve seismic imaging quality in limestone regions, and meet the requirement of structural interpretation, lithological interpretation and fracture prediction, a high-precision 3D observation system was used in 3D seismic acquisition in this area. This system has features of wider azimuth angles, higher folds, smaller transport distances, smaller trace intervals and moderate array lengths. Furthermore, the receiving array of 6 shots and 24 lines was adopted, with width index of the observation system up to 0.83, folds up to 144 times, bin of 20×20 m^2, and the max vertical offset up to 4300 m. It can be seen from Fig. 5 that the high-precision 3D observation system can ensure the offsets and azimuth angles to be relatively uniform, and the azimuth angles of the target layers are wider, which

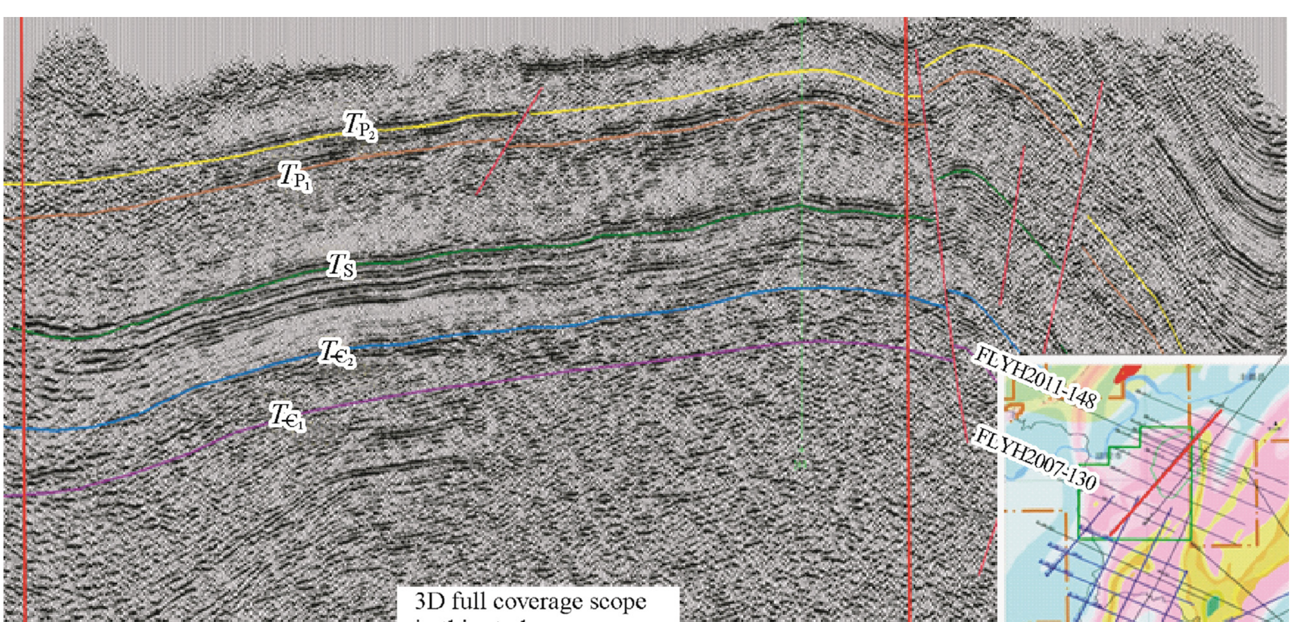


Fig. 3. Section of a 2D seismic line in Jiaoshiba area.

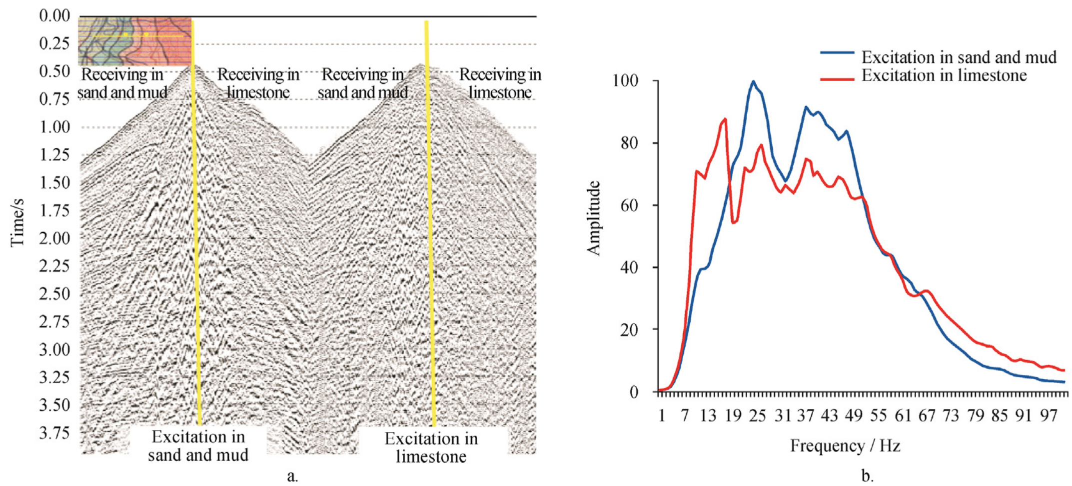


Fig. 4. Exciting and receiving single shot and its frequency distribution of various lithologies.

coincide with lithological exploration. In the following sections, this will be illustrated from two aspects (receiving line number and offset size) that the high-precision 3D observation system in Jiaoshiba area can ensure the imaging quality of the seismic data to meet the requirements of shale gas exploration.

2.1.1. *Influence of receiving line numbers on imaging effect*

Various receiving line numbers were extracted for degradation processing to the observation system. By comparing the imaging effect of 10–24 receiving lines (Fig. 6), it was found that with the increase of line number, the imaging (indicated by

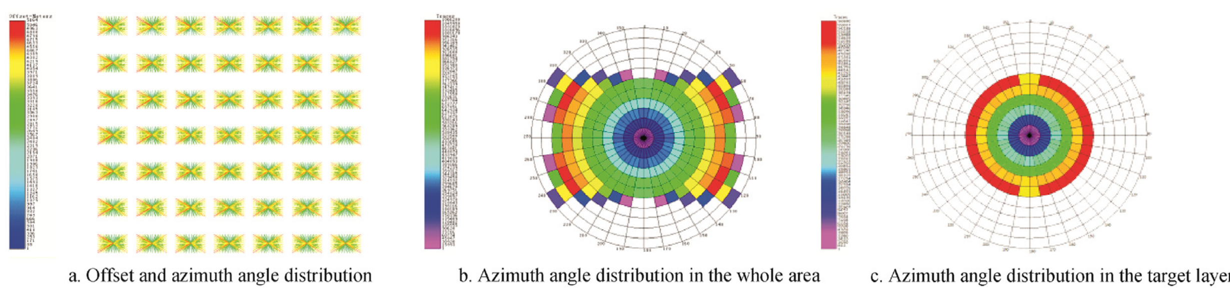


Fig. 5. Attribute analysis of the observation system.

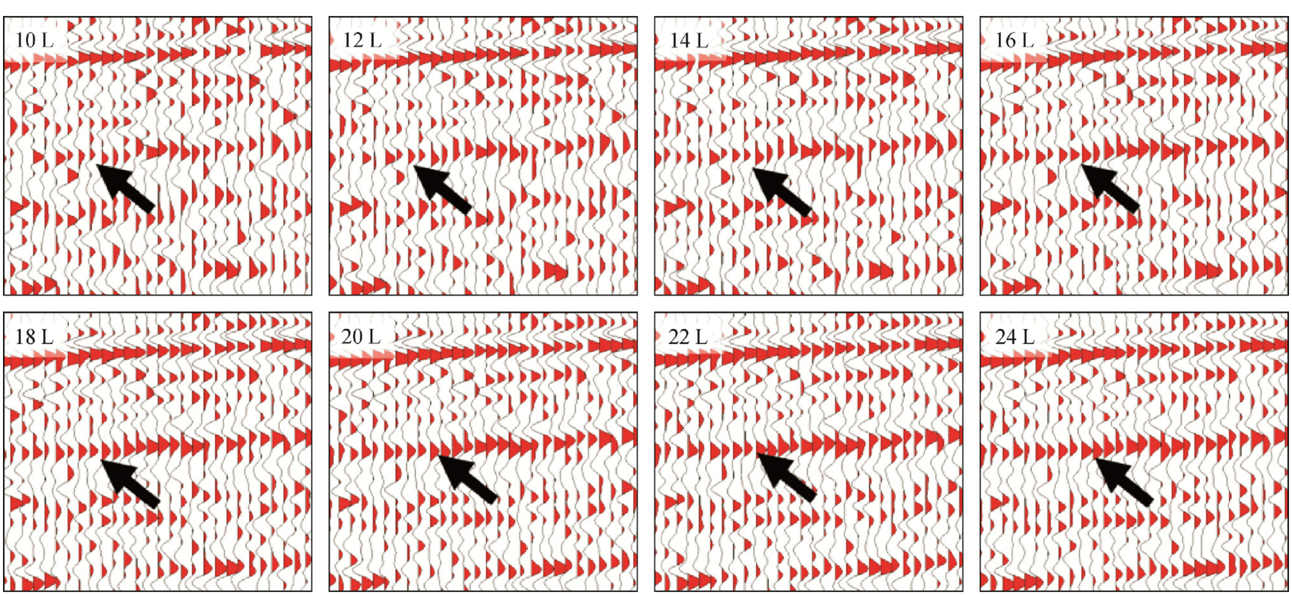


Fig. 6. Comparison of imaging effect of various receiving lines.

the black arrow in Fig. 6) signal/noise ratio and continuity of the subsurface marker bed are improved in a nonlinear style. Particularly, the imaging signal/noise ratio and event continuity of the 10 to 16 receiving lines are improved apparently. This means that within this scope, as the azimuth angles and folds increase, the acquisition effect mainly lies in the imaging signal/noise ratio. From 18 to 24 receiving lines, the improved amplitude of the signal/noise ratio becomes slow, but the concurrency and energy consistency between wave groups are further improved. Hence, it is reasonable to adopt 24 receiving lines in the 3D seismic acquisition in Jiaoshiba area.

2.1.2. *Influence of offsets on imaging effect*

By comparing the imaging effect of various offsets (Fig. 7), it can be seen that with the increase of offsets, the signal/noise ratio and continuity of the reflection events in shallow, medium and deep strata in the major part of the Jiaoshiba structure are improved. Especially, the minimum offset imaging (Fig. 8) implies that various offsets contribute to the Silurian (*T*s) shale gas layer (1400−1500 ms) in the major exploration strata. But, when the offsets are larger than 5000 m, its contribution to imaging becomes apparently smaller. In terms of shale gas exploration in *T*s, the design scheme with the maximum vertical offset of 4300 m can better meet the exploration requirement, i.e., it cannot only ensure the effective folds to the Silurian target layer, but also meet the need for exploring conventional hydrocarbons below the Silurian formations.

In summary, high-precision 3D seismic prospecting can make the acquisition of higher quality seismic data possible. It has been successfully used in structural interpretation, *TOC* prediction, shale brittleness index prediction, fracture

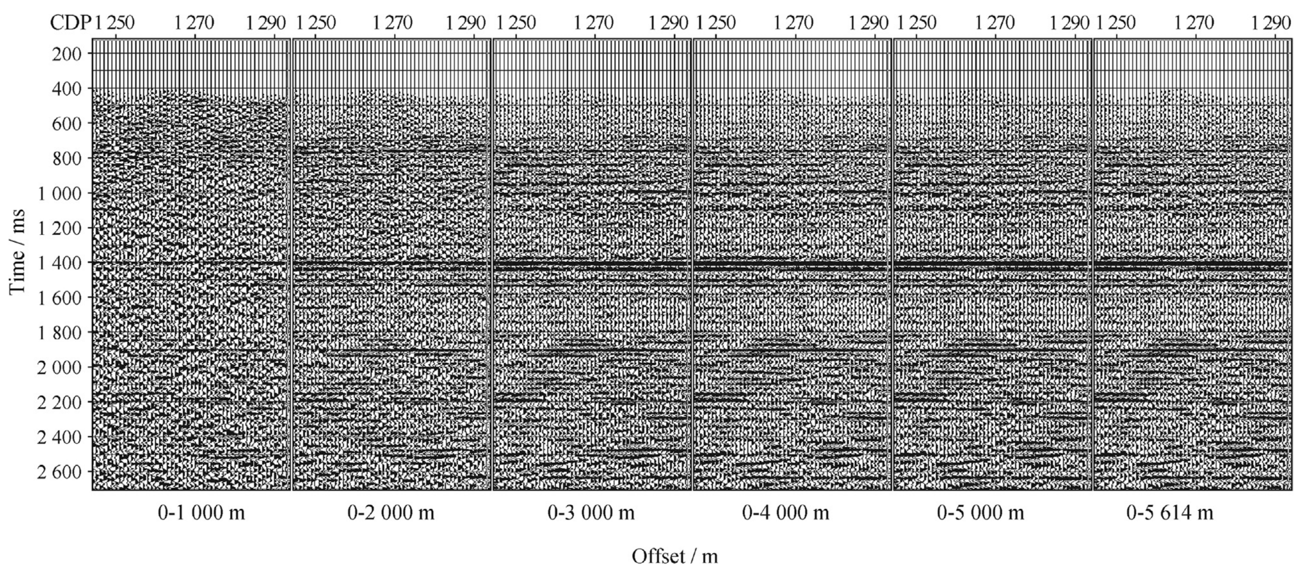


Fig. 7. Imaging section of the max offset.

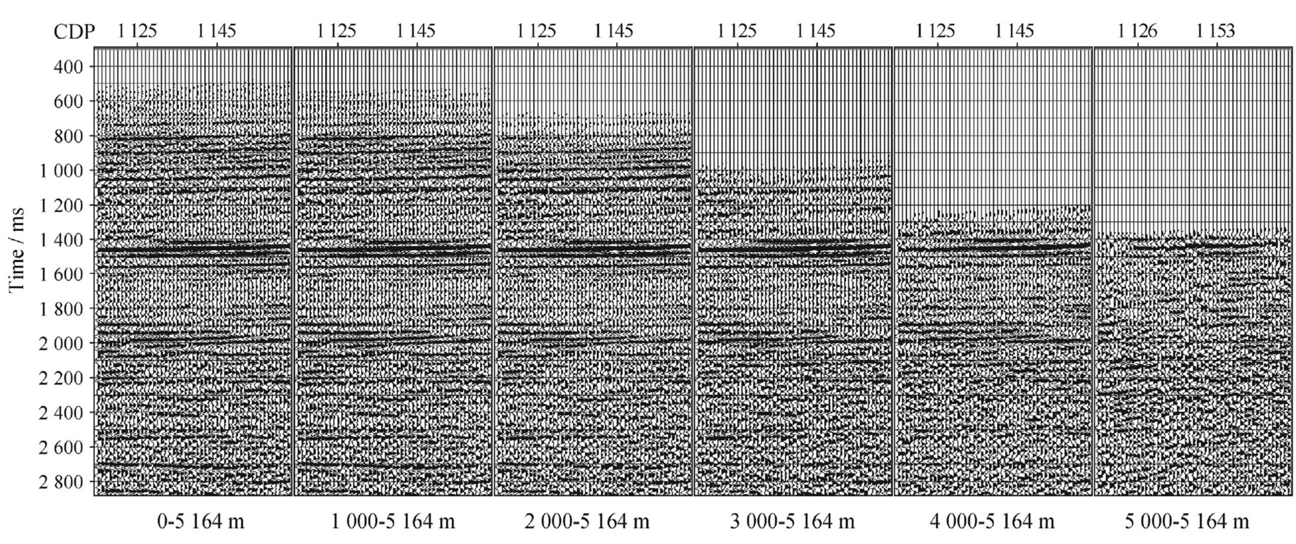


Fig. 8. Imaging section of the min offset.

prediction, and other aspects. Results in these aspects will be introduced below.

2.2. Structural interpretation

Fig. 9 shows the comparison of prestack time migration imaging sections between 2D seismic data and high-precision 3D seismic data at a certain location in Jiaoshiba area. Clearly, the continuity of the reflected wave event of the marker bed, signal/noise ratio and resolution of the 2D seismic data are worse than those of the 3D seismic data. Moreover, the 3D seismic data have much higher accuracy in the description of fault locations and their occurrences than the 2D seismic data. The 3D seismic data can also generate good images of the old basement formations. Thus, they can meet the need of structural interpretation in shale gas exploration in deep layers.

2.3. Prediction of organic matter content in shale layers

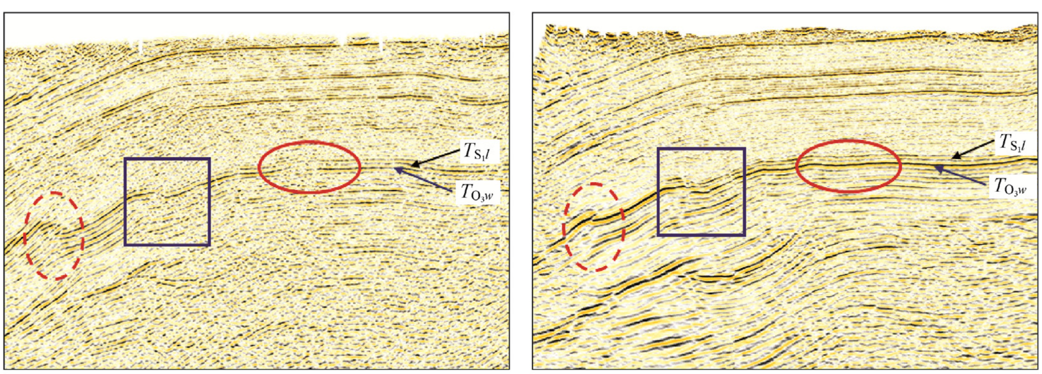
Fig. 10 shows the *TOC* section crossing Wells Jiaoye 1, Jiaoye 2 and Jiaoye 4, which were obtained by rock physical property inversion from high-precision 3D seismic data. It can be clearly seen that the measured *TOC* values in Wells Jiaoye 1, Jiaoye 2 and Jiaoye 4 have better coincidence with the 3D seismic data inversion result. This indicates that the *TOC* values of shale layers from high-precision 3D seismic data inversion can be used in evaluating high-quality shale layers, providing basis for well location optimization in the subsequent exploration and development.

2.4. Prediction of shale brittleness index

Fig. 11 shows the brittleness index section of high-quality shale obtained by rock physical property inversion from high-precision 3D seismic data. The black curve is the trajectory of Well Jiaoye 1DF obtained from early 2D seismic data interpretation. It can be seen that the well trajectory determined by the 2D seismic data is not in the layers with high brittleness index at the position delineated by the blue dashed box. This led to higher breakdown pressure in fracturing operation, increase of difficulty and cost in fracturing operation, and decrease of shale gas productivity. Compared with 2D seismic data, the brittleness index predicted by 3D seismic data can better guide the design of horizontal well trajectories.

2.5. Fracture prediction

It is well known that, in shale gas development, the compressibility of shale is the key to achieving commercial production of shale gas. The factors that affect the



a.2D seismic data　　b. High-precision 3D seismic data

Fig. 9. Comparison of prestack time migration imaging sections between 2D seismic data and high-precision 3D seismic data at a certain location in Jiaoshiba area.

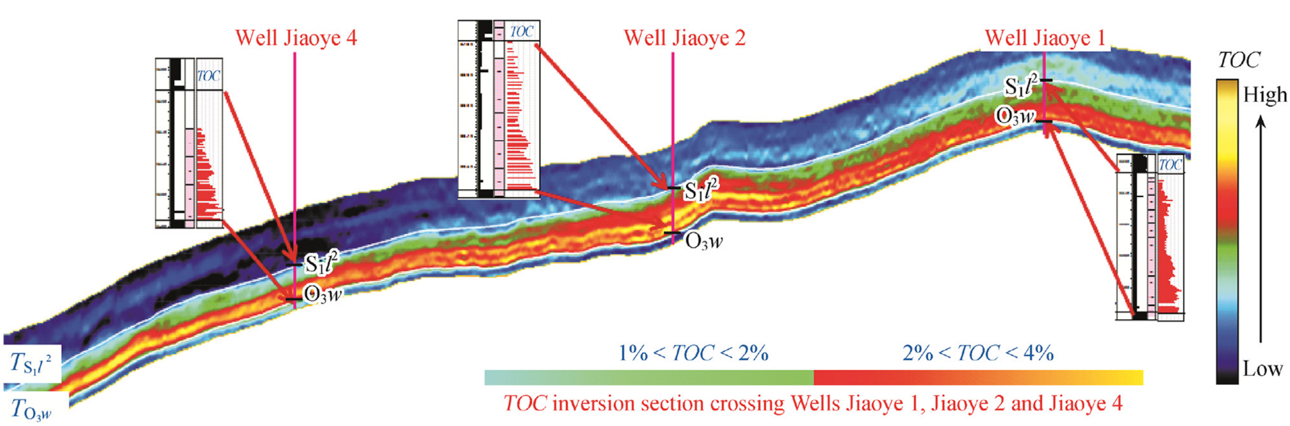


Fig. 10. *TOC* section crossing Wells Jiaoye 1, Jiaoye 2 and Jiaoye 4 obtained by rock physical property inversion from high-precision 3D seismic data.

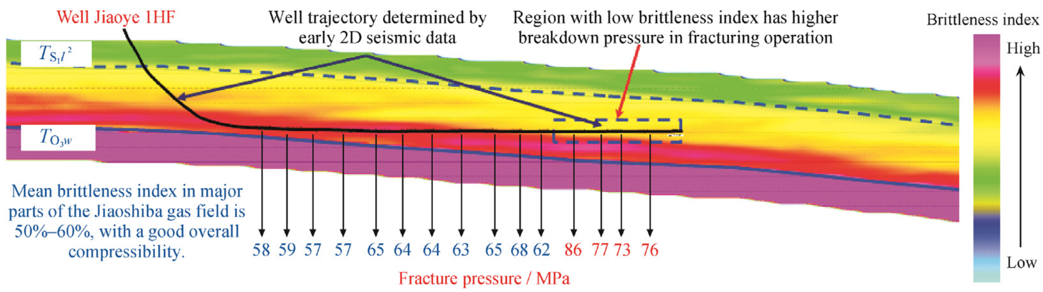


Fig. 11. Brittleness index section of high-quality shale obtained by rock physical property inversion from high-precision 3D seismic data.

compressibility include brittleness index and fracture development in shale layers. The higher the brittleness index is, the higher the fracture development degree is, and the better the compressibility of rock. Based on the wider azimuth angles in high-precision 3D seismic data, and through an analysis of anisotropy related to fracture development, the inverted intensity and major directions of the (high angle) fractures in shale layers can be obtained, guiding the optimum design of horizontal well trajectories and the confirmation of the optimum parameters in hydraulic fracturing operation. Fig. 12 shows the fracture development status in the Longmaxi Fm predicted by azimuth information from the seismic data.

It can be seen from Fig. 12 that the fracture strike and density have better coincidence with the measured values. There are more fractures near Wells Jiaoye 1 and Jiaoye 3, with a fracture density of 1.35–1.60 fract/m. There are fewer fractures near Wells Jiaoye 2 and Jiaoye 4 than other wells, with a fracture density of 1.10–1.30 fract/m. The predicted fracture densities generally show an increasing trend from southwest to northeast in the major region, which provides relatively reliable basis for the design of future exploration and development wells.

In summary, the implementation of high-precision 3D seismic prospecting can provide high-accuracy structure interpretation, lithology interpretation and fracture detection

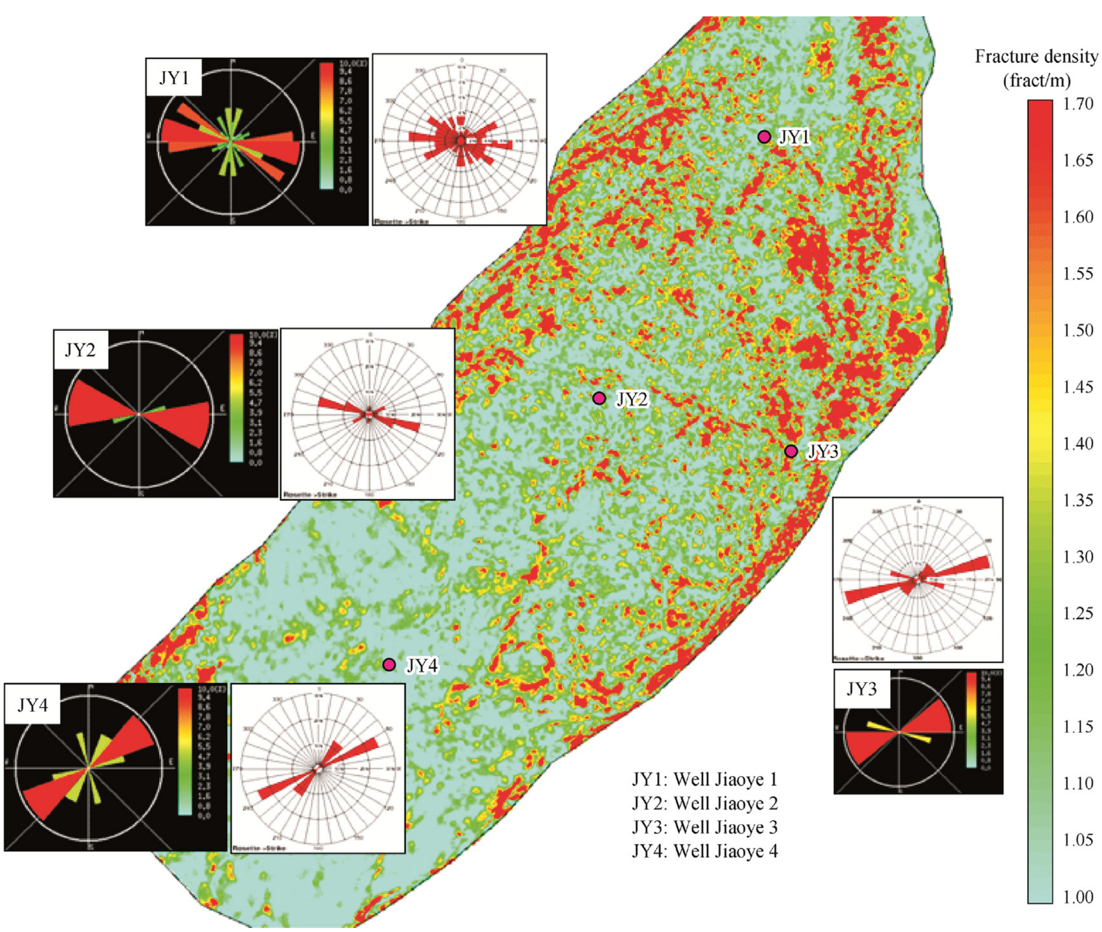


Fig. 12. Prediction result of prestack anisotropic fractures in Jiaoshiba area.

results for shale gas exploration and development, helping geologists know about the enrichment regularity of shale gas, and pointing out the direction for follow-up work.

2.6. Discussion on the cost and benefit of high-precision 3D seismic prospecting

2.6.1. High-precision 3D seismic prospecting reduces the design risk of horizontal shale gas wells

As we all know, for the reduction of shale gas exploration and development cost, inexpensive 2D seismic data were used in initial shale gas exploration within China to design horizontal well locations of the risk wells or appraisal wells. This is somewhat reasonable for the exploration and development of shale gas in North America with simple structures and thick shale formations. For the complex shale gas accumulation conditions in China, however, such exploration idea is worth discussing. Fig. 13 is the interpretation section of the high-precision 3D seismic data crossing Well Jiaoye 6 in Jiaoshiba area in 2013. The well trajectory pointed by the blue arrow in Fig. 13 was designed using 2D seismic data, for the high-precision 3D seismic data in Jiaoshiba area were acquired then. Therefore, this well penetrated the Ordovician Wufeng Fm and entered limestone layers, thus the designed horizontal well trajectory deviated from the target layer (S_1l–O_3w). Then, the drilling operation had to be stopped and the horizontal well location had to be designed again. This caused bigger loss in cost and effectiveness, and delayed the progress of efficient shale gas exploration. During later period, the high-precision 3D seismic data in Jiaoshiba area were used for fine imaging of the complex structure near Well Jiaoye 6, and the thrust fault in the target layer was accurately identified, and the horizontal well location was designed again (red arrow in Fig. 13). Up to now, more than 1000 m of high-quality shale layers in the Longmaxi Fm–Wufeng Fm have been drilled, showing high commercial production potential, and thus the exploration benefit of shale gas being greatly improved. This implies the necessity of implementing high-precision 3D seismic prospecting, even in the complex shale gas accumulation conditions in China. This technique can significantly reduce the design risk of horizontal well locations, improve shale gas exploration efficiency, and obtain exploration benefit that is much larger than the cost in high-precision 3D seismic prospecting.

2.6.2. High-precision 3D seismic data support the implementation of stereoscopic exploration strategy

The high-precision 3D seismic prospecting technology can provide precious “sweet spot” information for shale gas exploration, but its acquisition cost is much higher than that of conventional 2D or narrow azimuth 3D seismic acquisition (for exploration of conventional natural gas). If only the Silurian shale layer is the target, the array length and width can be reduced accordingly. For instance, the max vertical offset can be reduced to 3500 m. In this way, certain cost can be reduced, but conventional and unconventional oil and gas in other deeper layers cannot be well explored at the same time, so the technical benefit of high-precision 3D seismic prospecting has low utilization ratio, the exploration results cannot be further expanded, and the expensive composite cost in shale gas exploration and development cannot be balanced. Furthermore, under the situation that China has higher demand for clean energy resources but the supply is not enough, it is urgent to promote efficient natural gas exploration and development.

If the benefit of high-precision 3D seismic prospecting in Jiaoshiba area should be improved, its technical advantages in fine detection of shallow, medium and deep strata must be fully activated to implement stereoscopic exploration to unconventional gas and conventional gas. Furthermore, oil and

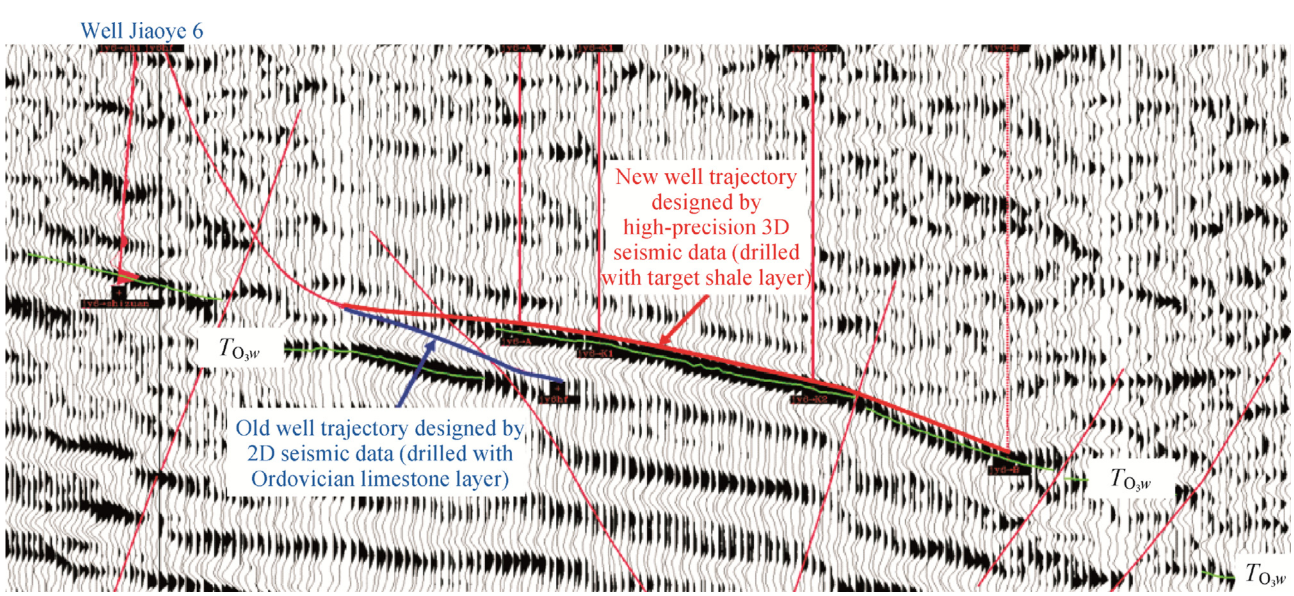


Fig. 13. Interpretation section of the high-precision 3D seismic data crossing Well Jiaoye 6 in Jiaoshiba area.

gas in other strata should be explored, so as to expand exploration achievements, increase natural gas productivity of the same block, finally to balance the expensive cost in shale gas exploration and development in single layer of the same block. According to the study of Zhang Jinchuan et al. [16], dark shales were widely developed in Lower Cambrian, Upper Ordovician−Lower Silurian in marine facies in the Sichuan Basin, with abundant organic matter and high thermal evolution maturity. Thus they were the most favorable layers for shale gas development in South China. Two sets of source rocks (i.e. Qiongzhusi Fm, and Wufeng Fm−Longmaxi Fm) were the major ones deposited in marine facies in this area. Furthermore, another two major sets of source rocks are developed in Lower Permian (Qixia Fm) and Upper Permian (Longtan Fm and Dalong Fm). These conclusions provide application prospect in implementing stereoscopic exploration of shale gas in the Sichuan Basin and its periphery.

The 24L6S216 T-1R144F observation system used in Jiaoshiba area in 2013 apparently increased array length in design. It can also explore deeper lower Cambrian, though its major target is the shale layers in the Silurian−Ordovician systems. Fig. 14 shows the vertical section of structural interpretation in Jiaoshiba area. It can be seen that the reflection feature and tectonic style in Lower Cambrian are reflected clearly, thus structural interpretation in the lower assemblage in marine facies can be made. Generally, the major part of Jiaoshiba area can be divided into two sets of deformed beds (upper and lower), bounded by the Cambrian gypsum layer (indicated in the purple area in Fig. 14). The upper deformed beds include Ordovician, Silurian, Permian and Triassic systems. There are few faults in the major part, and most faults are developed in the east and southwest edge of Jiaoshiba area. The tops and bottoms of the faults in the Wufeng Fm−Longmaxi Fm fault system disappear in the Silurian sand and mud layers and Cambrian gypsum slip layers. Most faults are small or tiny. Thus shale gas perseveration condition is good. The lower deformed beds include Sinian and Cambrian, with stronger tectonic deformation and more faults. The tops of these faults disappear in the Cambrian gypsum layers. Influenced by faults, these gypsum layers are violently deformed, forming typical gypsum slip event. Though the Lower Cambrian has relatively complex tectonic deformation, the existence of these gypsum layers provides a precious preservation condition for source rocks in the Lower Cambrian. Thus the Lower Cambrian also has exploration potential in forming large conventional or unconventional gas fields. This provides targets and directions for the implementation of stereoscopic exploration.

To be sure, the quality, event continuity and fault imaging accuracy of the seismic data in the Lower Cambrian are worse than those in the Silurian−Ordovician systems. The acquisition design at that time mainly targeted shale layers in the Silurian−Ordovician systems, thus the effective P/S ratios in the deeper target layers are lower. Besides, the high-precision 3D seismic prospecting acquisition scheme should be designed based on subsurface source rock exploration potential to explore multiple layers by optimizing the design of the observation system, provided that operation cost won't increase significantly. This can fully utilize the advantage of high-precision 3D seismic prospecting technology, and expand exploration achievement at the utmost.

To sum up, the future shale gas exploration should be guided by stereoscopic exploration. In designing a high-precision 3D seismic prospecting acquisition scheme, related parameters (folds and azimuth angles, etc.) of the major shale source rocks in shallow (Permian), medium (Silurian−Ordovician) and deep (Cambrian−Sinian) formations must be considered to meet the requirement of stereoscopic exploration for seismic data. This can lay a foundation for expanding the prospecting achievements, increasing shale gas productivity, and balancing the expensive exploration cost of shale gas.

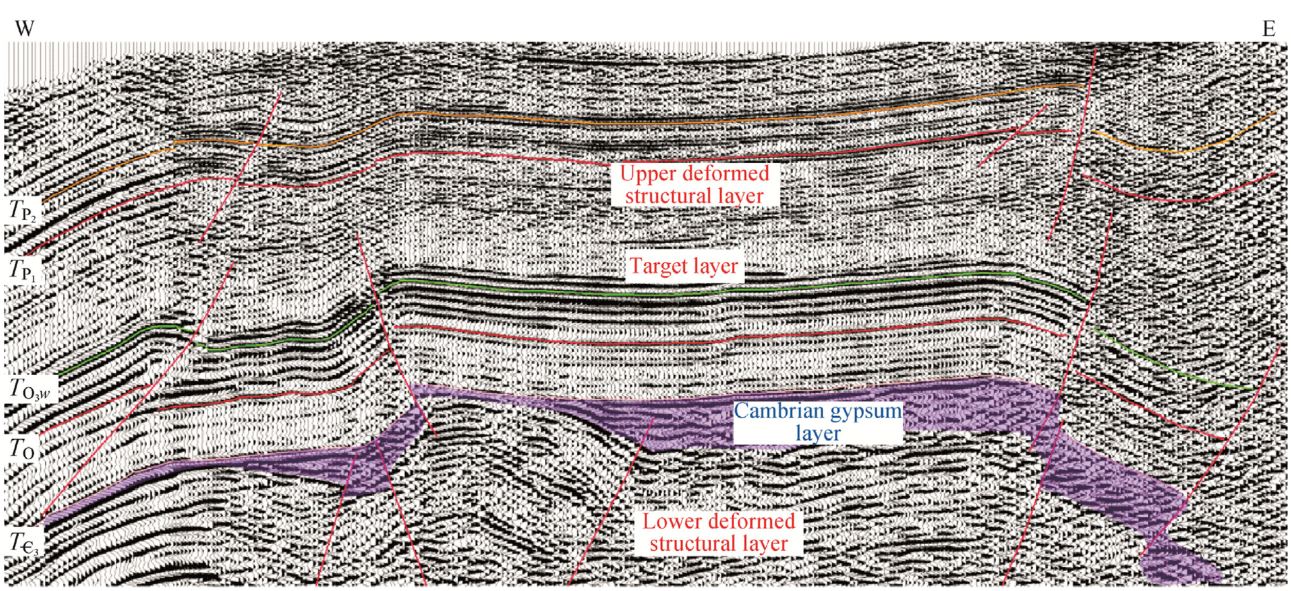


Fig. 14. Vertical section of structural interpretation in Jiaoshiba area.

3. Conclusions

1) Marine deposits were widely developed in South China from Sinian to Middle Triassic, forming several sets of source rocks with major lithology of black shale. There are two sets of high-quality source rocks in the Wufeng Fm−Longmaxi Fm in the Sichuan Basin and its periphery. The dark shales have higher organic matter contents, higher organic matter thermal evolution degrees, and relatively stable lithology distribution. Thus they have the basic accumulation conditions for forming large marine shale gas fields.
2) Geology study results show that the accumulation pattern of the marine shale gas in South China is different from that in North America. The former has generally thin reservoirs and complex preservation conditions. Hence, in shale gas exploration in South China, both hydrocarbon generation potential of the source rocks and preservation conditions should be stressed.
3) High-precision seismic acquisition with features of high folds, wide-azimuth angles and small trace intervals must be used to provide high-precision migration imaging data for fine study on the preservation conditions, to provide relatively reliable prestack imaging trace gathers for prestack high-precision elastic parameter inversion, and to lay a foundation for further shale gas "sweet spot" prediction and the design of horizontal well locations. Exploration results indicate that the implementation of the high-precision 3D seismic prospecting in Jiaoshiba area in 2013 effectively supported the exploration and development of shale gas field in Lower Silurian−Upper Ordovician in Fuling, greatly improved the rates of successful drilling of prospecting wells, appraisal wells and development wells, achieved great breakthroughs in shale gas exploration, and formed the world's first large commercial shale gas field (the Jiaoshiba gas field) except for North America.
4) From the view point of seismic exploration cost, it is really more expensive to implement high-precision 3D seismic prospecting just aiming at the Silurian shale gas layers. However, if the need for exploration accuracy can be met and the operation cost won't increase significantly, the acquisition design scheme must be optimized, and the Cambrian system with both accumulation conditions for conventional gas or unconventional gas must also be considered, to promote shale gas stereoscopic exploration process in medium and deep strata in lower assemblage in South China, to obtain more discoveries of conventional or unconventional oil and gas, and to achieve maximum benefit of high-precision 3D seismic prospecting technology. In this way, the shale gas exploration cost can be shared, and the exploration cost and benefit can be balanced, so as to continuously push the shale gas exploration and development in China.

References

[1] Guo Xusheng, Guo Tonglou, Wei Zhihong, Zhang Hanrong, Liu Ruobing, Liu Zhili, et al. Thoughts on shale gas exploration in southern China. Eng Sci 2012;14(6):101−5.
[2] Guo Tonglou, Liu Ruobing. Implications from marine shale gas exploration breakthrough in complicated structural area at high thermal stage: taking Longmaxi Formation in well JY1 as an example. Nat Gas Geosci 2013;24(4):643−51.
[3] Guo Tonglou, Zhang Hanrong. Formation and enrichment mode of Jiaoshiba shale gas field, Sichuan Basin. Petroleum Explor Dev 2014;41(1):28−36.
[4] Li Xinjing, Lü Zonggang, Dong Dazhong, Cheng Keming. Geologic controls on accumulation of shale gas in North America. Nat Gas Ind 2009;29(5):27−32.
[5] Liu Wei, He Zhenhua, Li Ke'en, Zhang Gulan, Rong Jiaojun, Ma Zhao, et al. Application and prospective of geophysics in shale gas development. Coal Geol Explor 2013;41(6):68−73.
[6] Johnson GM, Miller P. Advanced imaging and inversion for unconventional resource plays. First Break 2013;31(7):41−50. http://dx.doi.org/10.3997/1365-2397.2013020.
[7] Johnson GM, Miller P, Phillips D. Advanced imaging and inversion for oil production estimates in unconventional resource plays//Unconventional Resources Technology Conference, 12−14 August 2013, Denver, Colorado, USA. http://archives.datapages.com/data/urtec/2013/urtec-1579585-johnson.htm.
[8] Koesoemadinate A, El-Kaseeh G, Banik N, Dai Jianchun, Egan M, Gonzalez A, et al. Seismic reservoir characterization in Marcellus shale//2011 SEG annual meeting, 18−23 September 2011, San Antonio, Texas, USA. https://www.onepetro.org/conference-paper/SEG-2011-3700.
[9] Anon. Mississippian shale seismic reservoir characterization improves gas production. https://www.slb.com/~/media/Files/industry_challenges/unconventional_gas/case_studies/seismic_characterization_mississippian_shale.pdf.
[10] Meisenhelder J. Seismic for unconventional. E&P Magazine, June 2013. http://www.epmag.com/seismic-unconventionals-694971.
[11] Zhang Jinchuan, Jiang Shengling, Tang Xuan, Zhang Peixian, Tang Ying, Jing Tieya. Accumulation types and resources characteristics of shale gas in China. Nat Gas Ind 2009;29(12):109−14.
[12] Zhao Jingzhou, Fang Chaoqiang, Zhang Jie, Wang Li, Zhang Xinxin. Evaluation of China shale gas from the exploration and development of North America shale gas. J Xi'an Shiyou Univ Nat Sci Ed 2011;26(2):1−7.
[13] Li Qinghui, Chen Mian, Wang FP, Jin Yan, Li Zhimeng. Influences of engineering factors on shale gas productivity: a case study from the Haynesville shale gas reservoir in North America. Nat Gas Ind 2012;32(4):54−9.
[14] Guo Xusheng. Rules of two-factor enrichment for marine shale gas in Southern China − understanding from the Longmaxi Formation shale gas in Sichuan Basin and its surrounding area. Acta Geol Sin 2014;88(7):1209−18.
[15] Zou Caineng, Dong Dazhong, Wang Shejiao, Li Jianzhong, Li Xinjing, Wang Yuman, et al. Geological characteristics, formation mechanism and resource potential of shale gas in China. Petroleum Explor Dev 2010;37(6):641−53.
[16] Zhang Jinchuan, Xu Bo, Nie Haikuan, Wang Zongyu, Lin Tuo. Exploration potential of shale gas resources in China. Nat Gas Ind 2008;28(6):136−40.
[17] Yan Danping, Wang Xinwen, Liu Youyuan. Analysis of fold style and its formation mechanism in the area of boundary among Sichuan, Hubei and Hunan. Geoscience 2000;14(1):37−43.
[18] Zhu Y, Liu E, Martinez A, Michael A, Christophere H. Understanding geophysical responses of shale-gas plays. Lead Edge 2011;30(3):332−8.
[19] Lu Jimeng. Principle of seismic exploration (II). Dongying: China University of Petroleum Press; 2006. p. 55−61.
[20] Liu Zhengwu, Sa Liming, Yang Xiao, Li Xiangyang. Needs of geophysical technologies for shale gas exploration. Oil Geophys Prospect 2011;46(5):810−8.
[21] Zhao Diandong. Review and prospect on high-precision seismic exploration technique. Geophys Prospect Petroleum 2009;48(5):425−35.