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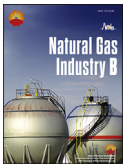
Natural Gas Industry B xx (2016) 1−12



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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

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Received 31 December 2015; accepted 16 March 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

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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 $\times$ 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).

Please cite this article in press as: Chen ZQ, et al., 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, Natural Gas Industry B (2016), http://dx.doi.org/10.1016/j.ngib.2016.03.006