Identification and characterization of complicated lithological traps within sequence stratigraphic framework – A case study in Yacheng uplift, Qiongdongnan Basin

Anqi Li*, Yong Deng, Lin Hu, Qi Ye, Yu Qiu
Research Institute of CNOOC Ltd. Zhanjiang Branch, Zhanjiang, 524057, China

*Corresponding author e-mail: lianqi@cnooc.com

Abstract. With the increasing of lithologic reservoir reserve ratio, lithologic traps are playing an increasingly important role in worldwide oil and gas exploration. Focusing on the lithological traps in the Yacheng Uplift area, Qiongdongnan Basin, this paper introduces a workflow for identification and characterization of lithological traps within sequence stratigraphic framework. The first step is to divide the Miocene Meishan and Sanya formation in the Yacheng Uplift area into 2 third order sequences and 5 fourth order sequences (SQ1-SQ5), and to identify the type, characteristics and distribution of lithological traps, thus confirming the main type of lithological trap is muddy channel lateral-sealing traps which are concentratedly distributed in the highstand system tract (SQ3) of Sanya formation. The second step is to quantitatively characterize the shape, channel lateral-sealing effectiveness and oil-gas-bearing possibility of the traps by some geophysical methods such as seismic attributes, seismic slice, pre-stack and post stack acoustic inversion. By using the above techniques, a lot of channel lateral-sealing lithologic traps have been found and accurately evaluated, thus putting forward the new oil and gas exploration direction in the study area.

1. Introduction
Lithologic traps are the non-tectonic traps formed due to the change of reservoir lithology or property. In recent years, the proportion of lithologic reservoir has been a rapid increase, and has become an important part of petroleum and gas reserves in China. However, lithologic trap types and formation mechanisms are different, and it is not easy to identify and characterize by seismic data, so that the exploration difficulty is greatly improved compared with traditional structural oil and gas reservoirs. It is necessary to use a variety of new technologies and multiple exploring methods to improve the exploration success ratio.

Qiongdongnan basin is located at the northern part of South China Sea, with an area of about 6 × 104 km². It is a petrolierous basin developed on the pre-Cenozoic basement [1-3], and the first offshore large-scale gas field with a size of 100 billion square meters in China - the Yacheng 13-1 gas field has been discovered in the northern part [4-6]. However, with the development of oil and gas exploration, the quantity and size of structural traps in Qiongdongnan basin have been greatly reduced, and the direction of oil and gas exploration will change to lithologic traps [7-9]. As an attempt to find lithologic traps in traditional exploration blocks, based on the sequence stratigraphy theory the study tries to build regional sequence stratigraphic framework in the Yacheng Uplift area, and analyzing the characteristics
of sedimentary environment, lithologic trap types and favorable zones. Then through a variety of geophysical methods, the characterization and quantitative evaluation of lithologic traps are accomplished to search for favorable lithologic traps in Sanya formation in the Yacheng Uplift, and a better effect is achieved.

Figure 1. The structure location of Yacheng Uplift, Qiongdongnan Basin

2. Sequence stratigraphic framework and lithologic trap characteristics

2.1. Sequence stratigraphic framework

The critical key step of the exploration of stratigraphic and lithologic reservoirs is the establishment of high resolution sequence stratigraphic framework, that is, the analysis of isochronostratigraphic correlation between different sedimentary systems [10-13]. According to the seismic data, drilling core, logging data and well-seismic calibration, the Miocene Meishan and Sanya formation in the Yacheng Uplift area can be divided into 2 third order sequences and 5 fourth order sequences (SQ1-SQ5), including the transgressive and high stand system tract (SQ4 - SQ5) of Meishan formation, and the low stand, transgressive and high stand system tract (SQ1-SQ3) of Sanya formation. On this basis, the Miocene isochronous sequence stratigraphic framework is established in the study area, then the relationship between the sedimentary environment characteristics, sand body location and sea level fluctuation in each fourth order sequence is analyzed to determine the most favorable sequence to the development of lithologic traps, so as to clarify the most important sequence of oil and gas exploration. During the period of lowstand system tract (SQ1) of Sanya formation, the sea level curve showed a relatively low level of rapid rise. The higher part of the Yacheng uplift was exposed and the littoral facies deposits existed only in the lower part. With the early stable high and later slowly decline of sea level curve, the depositional accommodation was increased and the terrestrial sediment inputs were reduced during the period of transgression system tract of Sanya formation (SQ2). The sedimentary environment was mainly shallow marine facies, and the mudstone content in the sequence was increased, and there was a small amount of thin shallow marine sandbar sandstone and turbidite sandstone. In the high stand system tract (SQ3) period, the sea level curve showed rapid falling and coarse clastic material supply was continued to increase, and the delta facies sandstone with typical low angle procreation and lateral continuity was formed. The Yacheng 13-4 and Yacheng 13-6 gas reservoir is located in the high stand system tract (SQ3) of Sanya formation, which has revealed the good porosity and permeability of the delta facies reservoir sandstone, also reflects that the high stand system tract (SQ3) is the most
important reservoir sequence in the study area. During the period of transgressive system tract (SQ4) of Meishan formation the sea level curve was stable high after the rapid rising and the sedimentary environment in the study area was shallow water platform, characterized by lithology combination for mudstone, muddy limestone and a small amount of argillaceous siltstone. The sea level showed a trend of slow decline in high stand system tract (SQ4) of Meishan formation and clastic particle continuously pushed up to the sea, and the sediments were mainly shallow water platform limestone, shale at the bottom and thin layer of delta sandbar sandstone at the top.

2.2. Seismic reflection characteristics
Well-seismic calibration and logging-sedimentary-seismic facies comparative analysis have been carried out to summarize the seismic reflection characteristics of each four-level sequence in Meishan and Sanya formation in Yacheng Uplift area. The mudstone and lime mudstone in the lower part of the shallow platform facies (SQ4-SQ5) are generally characterized by the continuity of the seismic events, the low-frequency and chaotic medium-weak amplitude, and the delta sandbar sandstone in the upper part (SQ5) shows an obviously strong amplitude response. In addition, an incised channel is found in the transgression system tract (SQ4) of Meishan formation. The U-shaped channel can be seen in some seismic profiles, and its internal shows weak amplitude, poor continuity and chaotic reflection. The low stand, transgressive and high stand system tract (SQ1-SQ3) of Sanya formation mainly show good seismic events continuity, medium frequency and medium-strong amplitude characteristics. The regionally distributed delta sandstone at the top of high stand system tract (SQ3) has the characteristic of good continuity and strong negative amplitude, and shows low frequency locally, with typical delta seismic reflection such as low angle procreation and bidirectional downlap convergence, etc. Through the analysis of seismic reflection characteristics of sequences, the relationship between lithology combination and the corresponding seismic reflection has been cleared as an effective basis of seismic attributes analysis and detailed interpretation of lithologic traps.

2.3. Lithologic trap types
Based on the research on sequence stratigraphic framework and sedimentary characteristics, the delta sandstone in high stand system tract (SQ3) of Sanya formation is the most widely distributed reservoir
in the Yacheng Uplift, and is incised by the muddy channel in transgressive system tract (SQ4) of Meishan formation in some areas, thus forming channel lateral-sealing lithologic traps.

3. Identification and detailed description of complex lithologic traps

Yacheng Uplift area are now completely covered by high resolution 3D seismic data, with the effective bandwidth is 5-68 Hz, the dominant frequency is 35 Hz and the vertical resolution is about 29m, which provides a good condition for complex lithologic trap identification and description.

3.1. Muddy channel identification and description

The key to describe the channel lateral-sealing lithologic traps is to define the muddy channel interface accurately. Based on the rock physical parameter in the study area, 3 kinds of geological model of muddy channel incised to different lithology combination have been established. And then the seismic forward modeling has proved the bottom interface of muddy channel was characterized by medium-weak amplitude, negative phase reflection features in different models, providing an effective basis for the detailed seismic interpretation and attribute analysis. However, as the lithology combination of low stand system tract (SQ3) of Meishan formation is dominated by mudstone and limestone, the acoustic impedance difference between SQ3 mudstone and the muddy channel is relatively small, so that the erosion of the channel is not very clear in the seismic section, and it is difficult to describe precisely. To solve the problems mentioned above, taking the sequence stratigraphic framework and rock physics parameter as constraint, a variety of seismic attributes such as amplitude, frequency and post-stack inversion method have been applied to describe of the muddy channel accurately, and good effect obtained. It shows that the muddy channel is NW-SE trend, with the length of about 20 km, and is separated to 2 branch channels at the north of Yacheng 13-6 gas reservoir, and the overall shape is “Y” shape. The post-stack inversion also reveals that the internal of muddy channel shows high acoustic impedance characteristics, as a reflection of mudstone and lime mudstone filling.

![Figure 3. Correlation section of forwarding record of muddy channel](image)

3.2. Identification and quantitative evaluation of lithologic trap

Seismic slice and attribute analysis techniques are effective methods to search and analyze the spatial distribution of sand body rapidly, which can greatly improve the efficiency of lithologic trap identification. The work flow of channel lateral-sealing lithologic trap identification in Yacheng Uplift area is as follows: 1.well-seismic calibration to definite the seismic reflection characteristics of the favorable sand bodies; 2. search for favorable sand bodies by seismic slice in target system tract; 3. optimize seismic attributes to achieve qualitative identification of favorable sand bodies. Based on the well-seismic calibration results of Yacheng 13-4 and 13-6 gas reservoirs, the delta sandstone in high stand system tract (SQ3) of Sanya formation shows strong amplitude and low frequency “light spot” characteristics, and the seismic slices along the SQ3 with 20ms interval can easily find a lot of similar sand bodies. Seismic amplitude, frequency, bandwidth and post-stack inversion acoustic impedance...
property are tried to describe the plane characterization and quantitative sculpture of the sand bodies, and the difference between sand bodies and surrounding rock is extremely obvious in amplitude and acoustic impedance distribution maps, but is not very clear in frequency and bandwidth property. Through the above steps, 7 channel lateral-sealing lithologic traps are selected out to quantitatively analysis the trap effectiveness.

The geological model of channel lateral seal is established first. According to the model, there is only when the depth of the channel erosion is greater than the thickness of the nearby sand body, the channel lateral seal is reliable. So that post-stack inversion acoustic impedance property is used to quantitatively describe the sand body and the muddy channel, reveals that the northern part of the muddy channel can effectively seal oil and gas, but the southern part of the muddy channel tends to leak, thus 3 favorable traps are select out.

3.3. Lithologic trap hydrocarbon detection

The approximate formula of Zoeppritz equation is the basis of pre-stack elastic inversion. Through AVO forward modeling and property intersection analysis, the sensitive elastic parameters to fluid are determined, and then different elastic physical parameters are obtained by pre-stack seismic inversion, which can effectively improve the success rate of seismic hydrocarbon prediction [14-16].

Before the inversion, the seismic data is firstly analyzed and optimized to obtain the seismic data with high fidelity and high signal-to-noise ratio as much as possible, and then converted into angular gathers data. Then, the cross-well section angular gathers data is scanned and analyzed to obtain the minimum and maximum angle range of the superimposed body, and the wavelet of different angle are extracted. The second is the establishment of fine structure interpretation and initial simulation, and then the elastic parameters such as elastic impedance and Poisson’s ratio, Vp/Vs ratio are obtained through pre-stack inversion. By comparing the inversion results with the oil and gas discoveries revealed by drilling, it can be seen that the gas-bearing sandstone in Yacheng 13-4 and 13-6 gas reservoirs shows good low Vp/Vs response characteristics in the inversion profile, and are mostly located in the red and yellow regions, means the results of pre-stack inversion and drilling are in good agreement. Therefore the pre-stack inversion can be used to predict the hydrocarbon potential of the 3 above-mentioned favorable channel lateral-sealing lithologic traps, and finally 2 favorable traps with low Vp/Vs characteristics are thought to be with high probability of gas-bearing, and are the most advantageous prospects for the following exploration.

Figure 4. Acoustic Impedence and Vp/Vs attribute of channel lateral-sealing lithologic trap
4. Conclusion
The Miocene Meishan and Sanya formation in the Yacheng Uplift area can be divided into 2 third order sequences and 5 fourth order sequences (SQ1-SQ5). The delta sandstone in high stand system tract (SQ3) of Sanya formation is the most widely distributed reservoir in the Yacheng Uplift, and is incised by the muddy channel in transgressive system tract (SQ4) of Meishan formation in some areas, thus forming channel lateral-sealing lithologic traps. Taking the sequence stratigraphic framework as the constraint, the seismic forward modeling, seismic attributes analysis and seismic slice method can be used to quickly identify channel lateral-sealing lithologic traps in the Yacheng Uplift area. The post-stack and pre-stack seismic inversion are effective methods to evaluate channel lateral-sealing quantitatively and hydrocarbon detecting. By using the above techniques, a lot of channel lateral-sealing lithologic traps have been found and accurately evaluated, thus putting forward the new oil and gas exploration direction in the study area.

Acknowledgments
This work was financially supported by “National science and technology major projects-Formation conditions and exploration technology of offshore large and medium-sized oil and gas fields (2016ZX05024-005)” fund.

References
[1] ZHU Weilin, ZHANG Gongcheng, YANG Shaokun, et al. Gas Geology of Continental Margin in Northern South China Sea [M]. Beijing: Petroleum Industry Press, 2007: 101.
[2] HE Jiaxiong, LIU Hailing, YAO Yongjian, et al. The petroleum geology and the resource potential of the marginal basins in the Northern South China Sea [M]. Beijing: Petroleum Industry Press, 2008: 84 - 85.
[3] ZHANG Gongcheng, DENG Yunhua, Wu Jingfu, et al. Coal measure source-rock characteristics and gas exploration directions in Cenozoic superimposed faulted depressions, offshore China [J]. China Offshore Oil and Gas, 2013, 25 (6): 85 - 96.
[4] XIE Yuhong, TONG Chuanxin. Conditions and gas pooling modes of natural gas accumulation in the Yacheng 13-1 Gas Field. [J]. Natural Gas Industry, 2011, 31 (8): 1 - 5.
[5] GONG Zaisheng. The major oil and gas fields of China offshore [M]. Beijing: Petroleum Industry Press, 1997: 1 - 216.
[6] HU Zhongliang. Hydrocarbon source rocks and hydrocarbon accumulation dynamics research of Yanan Sag in the Qiongdongnan Basin [D]. Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, 2005.
[7] HE Jiaxiong, XIA Bin, SUN Dongshan, et al. Hydrocarbon accumulation, migration and play targets in the Qiongdongnan Basin, South China Sea [J]. Petroleum Exploration And Development, 2006. 33 (1): 53 - 59.
[8] WANG Zhenfeng, HE Jiaxiong, Miocene hydrocarbon's transferring and collecting condition and reservoir combination analysis in Qiongdongnan basin. [J]. Natural Gas Geoscience, 2010, 21 (5): 693 - 699.
[9] YANG Hongjun. Hydrocarbon carrier system types and accumulation models in Qiongdongnan basin [J]. China Offshore Oil and Gas, 2008, 20 (2): 87 - 91.
[10] JIA Chengzao, Zhao Wenzhi, Zou Caineng, et al. Two key technologies about exploration of stratigraphic / lithological reservoirs [J]. Petroleum Exploration and Development, 2004, 31 (3): 3 - 9.
[11] JIA Chengzao, Zhao Wenzhi, Zou Caineng, et al. Geological theory and exploration technology for lithostratigraphic hydrocarbon reservoirs. Petroleum Exploration and Development, 2007, 34 (3), 257 ~ 271.
[12] CAI Xiyuan. Continental High Precision of Sequence Stratigraphy Basis, Methods and Practice of Hidden Reservoir Exploration [M]. Beijing: Geological Press, 2003.
[13] JI Xuewu, Xia Yiping, Kang Nanchang, et al. Work steps identifying lithostratigraphic traps
and associated techniques [J]. Oil Geophysical Prospecting, 2008, 43 (1): 101 - 106.

[14] YU Yueyu, Yang Changchun, Wang Yanfei, et al. Application of pre-stack seismic elastic impedance inversion to gas reservoir [J]. Progress in Geophysics, 2009, 24 (2): 574 - 580.

[15] WANG Baoli, Yin Xingyao, Zhang Fanchang. Elastic impedance inversion and its application. Progress in Geophysics, 2005, 20 (1): 89 - 92.

[16] YIN Xingyao, Cao Danping, Wang Baoli et al. Research progress of fluid discrimination with pre-stack seismic inversion. Oil Geophysical Prospecting, 2014, 49 (1): 22 - 34.

[17] YIN Xingyao, Zhang Shixin, Zhang Fanchang, et al. Utilizing Russell Approximation based elastic wave impedance inversion to conduct reservoir description and fluid identification. Oil Geophysical Prospecting, 2010, 45 (3): 373 - 380.