The 4th member of Shahejie Formation in Liaohe Western Depression had experienced rapid subsidence, which resulted into massive shale with the characteristics of high organic matter abundance and sapropelic kerogen. Most shale samples have the total organic carbon (TOC) over 2%, and the value can excess 4% for dolomitic shale in Leijia area. The thickness on organic-rich shale ranges from 30 m to 150m and increasing from northwest to southeast. The shales are now experiencing hydrocarbon generation peak due to high organic matter abundance and moderate thermal maturity. The shales have favorable geological condition for lacustrine shale oil accumulation according to the quantitative calculation, and the favorable areas for prospecting are Leijia, Shuguang and Dujiatai.

1 Introduction

Shale oil refers to the non-gaseous hydrocarbons which accumulate in shale formations or adjacent intervals as free, adsorbed or dissolved states with economic exploitation value. Shale oil is one of important unconventional hydrocarbons and have the characteristics of "self-generation and self-accumulation" (Zhang et al., 2012).

In North America, it had produced lots of shale oil in Bakken Formation in Willston Basin and Eagle Ford Formation in Texas state, which reveals good shale oil resource potential (Stephen, 2009; Ursula, 2011). As the increasing energy need, the geological conditions and resource potential for shale oil gain more attentions in China. Marine shale formations in China locates in Yangtze Plate and Tarim Plate with the characteristics of high thermal maturity. They are likely to produce shale gas rather than shale oil.

In Songliao Basin, Bohai Bay Basin and Ordos Basin, massive lacustrine shales were deposited in Mesozoic and Cenozoic era. The shales have the characteristics of shallow burial and younger sedimentary period and the thermal maturity reaches low to mature stage, which trends to generate shale oil. What's more, previous research works on conventional oil offered abundant geological date for shale oil exploration. At present, Well Shugu 165 and Leiping 2 in Liaohe Depression, well Anshen 1, Biye HF1 and Biye HF2 in Biyang Depression, well Nieye 1 in Jiyang Depression had produced commercial shale oil in Cenozoic formations (Chen et al., 2011; Zhang et al., 2014).

This paper studies on shale distribution and geochemistry of 4th member of Shahejie Formation (S4) and the shale oil accumulation geological conditions are analyzed. Through quantitative analysis on different geological factors on shale oil development, the accumulation coefficient are calculated and favorable area are selected. This study may also contribute to the theory regarding unconventional shale oil and is useful as a reference for other regions with similar geological conditions.

2 Shale Sedimentary and Distribution

The Liaohe western depression is located in the northeastern part of the Bohai Bay Basin, which is the largest depression in the Liaohe subbasin with an area of 2560 km² and is bounded by the western uplift in the west and the central uplift in the east. Variation in the Eogene formation exists between north and south, and the differences are observed in the aspects of the thickness of the formation (Li et al., 2007; Liao et al., 1996).

At the end of the Mesozoic, magma intrusion resulted in the thinning of the crust and created huge tensile stress. In the Fangshenpao period, the basalt formation was formed by volcanic eruptions that developed along large faults (Liao et al., 1996). Many rifted sags throughout the study
area provided excellent conditions for organic-rich shale in S4 period.

In the northern region, coastal and shallow lacustrine facies were developed, while mud platform and lime platform facies were formed in the middle areas. At the end of the S4 period, the Chenjia sag was the center of subsidence and sedimentation because of structural movement, which increased the thickness of the strata and enlarged the areas of the paleolake, resulting in the deep lacustrine environment that was beneficial for dark shale deposition. The S4 strata was distributed unevenly throughout the entire area. Sandstone and dolomitic limestone interbedded with shales were developed in the Niuxintuo area and were overlain upward by the shale formation. In the Gaosheng region, thin oil shale, dolomite, lime shale and dolomitic shale were widely developed because of the influence of the adjacent southern paleohigh that caused still water environments. In the southern region, conglomerate, sandstone and shale were alternately developed due to the input of abundant material sources.

When kerogen generate hydrocarbon, it usually needs high organic matter richness and moderate thermal maturity. So, the study on shale thickness focuses on intervals with rich organic matter. The selection criteria mainly are logging reveals, gas survey, geochemistry parameters, et al. The thickness on S4 shale ranges from 30m to 150m generally, increasing from northwest to southeast. In west slope area, the shale poorly developed. While, in Panshan sag, it has the largest thickness with over 200m ((Fig. 1).

3 Shale Oil Accumulation Geological Condition

3.1 Shale geochemistry characteristics

3.1.1 Types and abundance of organic matter

Organic matter type is a critical parameter for determining the hydrocarbon products in different thermal maturities. Based on experimental analyses of the organic elements, the type of organic matter was determined according to the relationship of H/C and O/C. The results showed that type I and type II1 are well-developed and type III is seldom developed.

The deposition rate was rapid during S4 period, which created the deep water column and restricted water flow. Thus, a semi-deep or deep lacustrine environment is beneficial for sapropelic kerogen development due to the massive plankton reservation.

Abundant organic matter forms the foundation for shale oil accumulations. After a volcano eruption, the shale that developed in the transgression environment had high organic matter abundance. In the study area, the TOC content of the shale from the S4 formations ranges mainly from 1 to 4% with an average of 2.55% (Fig. 2a).

The lateral distribution of organic matter abundance is significant for the exploration of shale oil and can indicate

![Fig. 2. Values and relationships of (a) TOC and (b) Ro content with buried depth in S4 shales in the study area.](image)
the favorable areas for exploration. Contour lines of the TOC content was mapped. Most samples of the S4 shales have a TOC larger than 2%, and shale with a TOC of > 5% is present primarily in the Chenjia and Panshan sags. In addition, TOC of > 2% is present in Niuxintuo sags and the western Qingshui sag because of the favorable conditions for the accumulation and preservation of organic matter (Fig. 3).

3.1.2 Thermal maturation
Experimental data on the thermal maturity of the Shahejie shales show that Ro mainly ranges from 0.4 to 0.9% (Fig. 2b). The thermal maturity is largely determined by the buried depth. The shallow buried depth in the S4 formations results in low Ro. The averages of Ro is 0.42%. There are also several shale samples with Ro values of more than 0.5% (maximum value is 0.66%). Commercial light oil was produced in the dolomitic formation in the Gaosheng regions where the Ro of the source rock is less than 0.5%; therefore, thermal maturity may be not the decisive parameter for oil production in the study area.

The thermal maturity of organic matter is low because of its shallow burial depth, and Ro values increase eastward in the S4 shales from 0.3%-0.7% (Fig. 4). In southeast area, the thermal maturity is high with the hypothetical Ro over 0.8%.

3.2 Shale oil accumulation coefficient
The shales in S4 strata have high organic matter richness, moderate thermal maturity and sapropelic kerogen. Based on multi-factor superposition method, This paper tries to select the favorable area for shale oil accumulation with accumulation coefficient method.

The calculation of shale oil accumulation coefficient base on quantification of single geological parameter. Weight analysis of every factor influencing shale oil accumulation is studied depend on importance, then sum the weight to evaluate the accumulation probability. In the calculation process, different geological parameters are mathematical standardized at first. Some parameter, which can benefit for shale oil accumulation, are positive parameter, and negative parameter if vice versa. The mathematical standardization formula are \( p_i = \frac{X_i - X_{\min}}{X_{\max} - X_{\min}} \) and
respectively, which $P_x$ is accumulation favorable degree of single parameter, $X$ is value of every parameter, $X_{\text{min}}$ is minimum value of every parameter and $X_{\text{max}}$ is maximum value of every parameter. The calculation formula of shale oil accumulation coefficient is $P=a_1P_1+a_2P_2+\ldots+a_iP_i+\ldots+a_nP_n+k$, which $P$ is accumulation coefficient ($0 \leq P \leq 1$), $P_i$ is favorable degree, $a_i$ is weight of parameter $P_i$, $k$ is correction coefficient and $n$ is parameter member.

For S4 strata, the calculation parameter is TOC, $R_o$ and shale thickness ($H$). Based on the exploration practice and geological condition, the weight is 0.4, 0.3 and 0.4 respectively. Therefore, the calculation formula on accumulation coefficient is $P=0.4P_{\text{TOC}}+0.3P_{R_o}+0.4P_H$. The larger on coefficient, the better on accumulation condition. In S4 period, massive shale deposited in several sags, such as Chenjia, Panshan et al. Contour lines of shale oil accumulation coefficient were mapped base on every parameter calculation (Fig. 5). The accumulation coefficient over 0.2 is common and it exceed 0.6 in Shuguang, Gaosheng and Leijia area, which reveals good geological condition for shale oil accumulation. Besides, Niuxintuo area in northern part and well Shuang202 in southern part have the accumulation coefficient over 0.4%, is also the favorable area for shale oil exploration.

4 Conclusions

(1) The S4 strata had experienced rapid subsidence, resulting into massive shale with the characteristics of high organic matter abundance and sapropelic kerogen. the average TOC value is exceed 2% and 4% for dolomitic shale.

(2) The thickness on organic-rich shale for S4 strata ranges from 30m to 150m and increasing from northwest to southeast,which is now experiencing hydrocarbon generation peak due to high organic matter abundance and moderate thermal maturity.

(3) The shales have favorable geological condition for lacustrine shale oil accumulation according to the quantitative calculation, and the favorable areas for prospecting are Leijia, Shuguang and Dujiatai.

Acknowledgements

This study was supported by the National Natural Science Founds (Grant No. 41272167) and China Huaneng Group science and technology project(Grant No. HNKJ14-H25). We also thank Dr. Li Junqian from China University of Petroleum for

References