A method of identifying effective source rocks and its application in the Bozhong Depression, Bohai Sea, China

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Abstract: Research on effective source rocks directly affects the accuracy of identifying hydrocarbon resources, and indirectly affects the exploration decisions in petroliferous basins. Although the previous evaluation methods of effective source rocks vary relatively widely, a complete quantitative evaluation approach has not yet been developed. For that reason, we redefined the concept of effective source rocks based on the existing research results. Surrounding this definition, and guided by the hydrocarbon expulsion theory, the quantitative model called “two stages and three steps” method is established to predict effective source rocks. Its application in the Bozhong Depression indicates that among the four sets source rocks in the Bozhong Depression, the Member 3 of the Shahejie Formation (E_3) has the largest effective source rock thickness, and the Member 1–Member 2 of the Shahejie Formation (E_{1+2}) is the second largest. The effective part of dark mudstone is only 30%-80% of the total volume and with the increase of buried depth and improvement of quality, the effective part increases. Comprehensive analysis indicates that the “two stages and three steps” method is a practical technique for effective source rock prediction.

Key words: Source rock, effectiveness, hydrocarbon expulsion threshold, Bozhong Depression, Bohai Sea

1 Introduction

Study of effective source rocks is needed for an accurate understanding of petroleum resources potential in the research field. Therefore, a lot of research has been done and some recognition has been achieved, but a complete quantitative assessment system for effective source rocks has not yet been established. In this paper, based on previous research results and the theory of the hydrocarbon expulsion threshold, a set of new methods for identification of effective source rocks are proposed.

2 Research status of effective source rock

2.1 Definition of effective source rock

Source rock is the first requirement for hydrocarbon accumulation, and the field has been studied by many scholars. Tissot and Welte (1978) put forward the concept of source rock and defined it as the rock that had generated

or used to be able to generate petroleum. Momper (1978) defined effective source rock as the mother rock which can generate and expel commercial petroleum. Jones (1981) deemed that effective mother rock is the source for a commercial reservoir determined by reliable oil-source correlation. In the natural environment, any kind of fine-grained sediment that has generated and expelled enough hydrocarbons to form a commercial oil and gas accumulation could be reckoned as source rock (Hunt, 1979). Sheng (1989) classified effective source rock as that part of mature source rock that can expel or diffuse generated hydrocarbon. Li et al (1999) defined effective gas source rock as the sedimentary rock that can generate enough gas under suitable thermal maturation conditions and expel gas to form gas pools after the pore and surface of the source rock had been completely saturated. Jin (2001) defined effective source rock as the strata that had generated and expelled oil and gas, and to some extent controlled the distribution of hydrocarbon accumulations in sedimentary basins. Jiang et al (2002) proposed that source rock was effective only when it could expel enough hydrocarbons to compensate for all kinds of losses in the process of reservoir formation and form commercial hydrocarbon accumulations. Rao et al (2003)

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thought that effective source rock should be source rock that has been shown by reliable oil-source correlation to have formed commercial hydrocarbon accumulations. Wang et al (2003) defined effective source rock as the rock that could both generate and expel hydrocarbon.

In this paper, the core of effective source rock identification is focused on whether hydrocarbon had been generated and expelled or not. Whether the expelled hydrocarbon is enough to form a commercial hydrocarbon pool or not must be determined by exploration degree and is hard to identify. Moreover, when there were several sets of source rocks, although some source rocks did not expel a large amount of hydrocarbon, which was thoroughly dispersed during secondary migration but which protected against further losses of hydrocarbon expelled from other source rocks, they should also be taken as effective source rocks for their contribution to hydrocarbon accumulation. Therefore, the concept of effective source rock should be defined as the strata that have generated and expelled hydrocarbon in the process of geologic evolution.

2.2 Traditional research methods

Geochemical index correlation is generally adopted for studying effective source rocks, and organic matter abundance is usually used as an identification yardstick. Organic matter abundance is often indicated by the total organic carbon (TOC) content, chloroform asphalt A and total hydrocarbon, among which the organic carbon content controls the characteristics of the other two factors. So organic carbon content is often taken as the minimum value of effective source rock (Barker, 1974; Cheng, 1982; Xia and Dai, 2000; Li, 2003; Teng et al, 2004; Chen et al, 2004; Chen, 2005; Zhang et al, 2006; 2007). The minimum value of organic matter abundance for an effective source rock differs from 0.05% to 1% according to previous research (Barker, 1974; Tissot and Welte, 1978; Hunt, 1979; Cheng, 1982; Fu et al, 1983; Xia and Dai, 2000), which is artificially limited by practical measurements and brings great uncertainty on effective source rock identification and assessment. In addition, other methods such as the physical simulation method (Lewan and Williams, 1987; England et al, 1987; Wang and Wang, 1999; Jin et al, 2001; Xiong, 2001) and observation of hydrocarbon content from close sampling are also applied to study source rock effectiveness (Leythaeuser et al, 1988; Zhou and Zhang, 1999). However, restrained by coring, experimental expense, sample amount and experiment conditions, the research results of all the above methods differ a lot with the practical geological conditions. Moreover, due to differences in sedimentary environments and later evolution, source rock can be very heterogeneous (Bertrand et al, 1994; Derenne et al, 2000; Carroll and Bohacs, 2001; Zhu et al, 2003; Zhu and Jin, 2002), which will also affect the research results. As well, the inorganic geochemistry index is also adopted to explore the formation environment of effective source rock. Because a large number of parameters are required in this method, it is hard to use (Teng et al, 2005).

To sum up, the identification of effective source rock still relies upon qualitative identification of a minimum value of organic abundance, and identification methods are

mostly proved by practical measurement data and simulation experimental results. A set of quantitative assessment system has not yet been established.

3 New methods of identifying effective source rocks

A source rock could be defined as effective, only when hydrocarbon has been generated and expelled to reservoir strata. So simply identifying the minimum value of organic abundance is not enough to define the characteristics of effective source rock. Besides, even if the source rock has generated hydrocarbon, but it is still residual in the source rock and has not been expelled outside, the source rock is not effective at all. All the problems above can not be solved by previous research methods. In view of the problems, a set of effective source rock identification methods are explored in this paper, which is temporarily called "two stages and three steps" method. The main process is as follows:

(1) Stage 1: Geological statistics stage

Step 1: In this stage, the main task is to collect statistics on the thickness of dark mudstone (shale) from exploration wells (Fig. 1(a)), and establish a database in the study area. The distribution characteristics of dark mudstone can be mapped horizontally from exploration well logs combined with sedimentary facies, organic facies or seismic inversion data (Zhang et al, 2007).

(2) Stage 2: Geological analysis stage

In this stage, on the basis of geological statistics, geochemical methods are applied to assess the quality of source rock and to identify the thickness of effective source rock from dark mudstone, which can be accomplished in two steps:

Step 2: According to hydrocarbon expulsion threshold theory (Pang, 2003), the effective dark mudstone thickness can be estimated by eliminating that part of the dark mudstone which has not entered the hydrocarbon expulsion threshold.

The hydrocarbon expulsion threshold is a critical geological condition in the burial history, when a separate hydrocarbon phase can be expelled from the source rock, whose hydrocarbon generation amount is more than all that adsorbed by the source rock itself, dissolved in the pore water, dissolved in the oil and retained by capillary forces (Pang, 1995). Only when the dark mudstone enters the hydrocarbon expulsion threshold can hydrocarbon be expelled. The hydrocarbon generation potential method can be adopted to identify the dark mudstone. The theoretical basis of the hydrocarbon generation potential method is material balance, which means the quantity of organic matter in source rock before hydrocarbon generation and expulsion equals to that remained in the source rock plus the part that has evolved into hydrocarbon which is later expelled from the source rock after it enters the hydrocarbon generation and expulsion threshold during the increase of the burial depth (Zhou and Pang, 2002; Jiang et al, 2007). As for the organic matter which could be transformed into hydrocarbon in the source rock, the total amount of material should be constant if no material exchange happened in geological history. During the quantitative assessment of source rock pyrolysis, the

sum of dissolved hydrocarbon (S_1) and cracked hydrocarbon (S_2) is usually adopted to represent the generation potential of the source rock. In practical application, the hydrocarbon generation potential is represented by the hydrocarbon generation potential index $(S_1+S_2)/\text{TOC}$, the decrease of which demonstrated the expulsion of hydrocarbon (Fig. 1(b)). So a dark mudstone that has not entered the hydrocarbon expulsion region can be easily eliminated after the hydrocarbon expulsion threshold is identified.

Step 3: Comprehensive analysis of the effectiveness of dark mudstones which have entered the hydrocarbon expulsion region according to the hydrocarbon expulsion threshold chart.

Because of the high heterogeneity of the organic matter in source rocks, some dark mudstone with low organic matter abundance can not expel hydrocarbon although it has reached the hydrocarbon expulsion threshold. So the hydrocarbon expulsion threshold chart can be applied to calibrate the abundance of organic matter. That is, according to the relation between organic matter abundance and evolution degree, the thickness of effective source rock can be obtained by eliminating the poor quality dark mudstone which is unable to expel hydrocarbon even after it has entered the hydrocarbon expulsion region (Fig. 1(c)). The horizontal distribution of effective source rock thickness can be obtained by calibrating and mapping of the data in the whole area using the ratio of the thickness of obtained effective source rocks to the formation thickness from exploration wells. In this paper, the Source Rock Index (SRI) chart is mainly adopted (Pang et al, 2005). The geological meaning of SRI is the percentage of practical expulsion quantity of hydrocarbon from the source rock compared to that from total high quality source rocks. The SRI value that is less than zero, equals to zero, and is more than zero respectively corresponds to non-hydrocarbon source rocks, threshold source rocks and effective source rocks. The larger the SRI value, the better quality the source rock (Fig. 1(c)). The related calculation approach is described by Pang et al (2005).

4 Prediction of the thickness of effective source rock in the Bozhong Depression

4.1 Regional geological setting

The Bozhong Depression, the largest depression enriched in hydrocarbon in the Bohai Sea area (Zhang, 2000), lies in the major deep place of the Bozhong sub-basin and extends in a north-east direction with an area of about 8,660 km². Presently the largest burial depth of the depression basement has exceeded 12,000 m. There are about 38×10^8 m³ oil and $2,500 \times 10^8$ m³ gas in geological reserves discovered in the Bohai Sea area, which shows a favorable exploration future (Zhu et al, 2000; Zhu and Ge, 2001). Most of the discovered oil and gas fields are distributed in the zone surrounding the Bozhong Depression (Gong et al, 2000). As the largest hydrocarbon generation and enrichment depression of the Bohai Sea area, the resource potential of the Bozhong Depression will directly affect exploration prospects and programs. Accurate identification of source rocks will undoubtedly be the basic guarantee for the understanding of

resource evaluation.

4.2 Prediction of the thickness of effective source rocks

There are four main sets of source rocks developed in the Bozhong Depression. These are Member 2 of the Dongying Formation (Ed_2), Member 3 of the Dongying Formation (Ed_3), Member 1–Member 2 of the Shahejie Formation (Es_{1+2}) and Member 3 of the Shahejie Formation (Es_3) in the Paleogene. According to previous work, the thickness of source rock in the Shahejie Formation is much thinner than that of the Dongying Formation, while the reserves of the Shahejie Formation is much larger than that of the Dongying Formation. Whether this is right or not will directly affect exploration directions. In this paper, the “two stages and three steps” method is adopted to initially predict the effective thickness of the four sets of source rocks.

4.2.1 Distribution characteristics of the dark mudstone thickness

According to the principles of the “two stages and three steps” method to identify effective source rocks, the thickness statistics of dark mudstone are firstly collected from all the exploration wells in the Bozhong Depression and its surrounding uplifts (Table 1). From the thickness distribution of the dark mudstone in the typical wells, the average thickness of the Ed_2 is 115 m, and the maximum thickness in a single well is 430 m. The average thickness of the Ed_3 is 150 m. The thickness of the Es_{1+2} is 10–230 m and the average value is 65 m. The thickness of the Es_3 is 5–200 m and the average value is 55 m.

For the area in the center of the depression without exploration wells drilled, the corresponding relationship between the ratio of dark mudstone thickness to strata thickness and sedimentary facies is adopted, on the basis of source rock prediction mapping in the low-explored area (Zhang et al, 2007), to horizontally predict the thickness of dark mudstone (Fig. 2). From the overall distribution trend of dark mudstone, the thickness of Ed is significantly more than that of Es , as the sedimentation center of the Bohai Bay Basin migrated during the sedimentation period of Es and Ed (Hou et al, 2000).

4.2.2 Horizontal distribution characteristics of effective source rock thickness

Step 1: Analysis of dark mudstone thickness exceeding the hydrocarbon expulsion threshold

According to the basic theory of hydrocarbon generation potential to identify the expulsion threshold, 546 pyrolysis data points from the exploration wells and complementary well test samples were gathered to obtain the expulsion threshold of each interval (Fig. 3). On the basis of the hydrocarbon expulsion threshold depth, the part of the dark mudstone which has not yet entered the hydrocarbon expulsion region is directly omitted, thus the part of dark mudstone which has entered the hydrocarbon expulsion region is acquired in each interval. According to the depth of the hydrocarbon expulsion threshold, the thickness of the dark mudstone which has not entered the hydrocarbon expulsion threshold can be directly eliminated, and then the thickness of mudstone within the hydrocarbon expulsion region can be

Fig. 1 Chart of “two stages and three steps” method to predict effective source rocks

calculated.

Step 2: Identification of dark mudstone without hydrocarbon expulsion using the hydrocarbon expulsion threshold chart

Statistics on typical wells with overall geochemical data and lithological profile can be used to set up a practical identification chart for hydrocarbon expulsion in different intervals (Fig. 4), and to identify all dark mudstone intervals

which have reached the hydrocarbon expulsion depth. Combined with the dark mudstone data exceeding the hydrocarbon expulsion threshold in Step 1, the ratio of the effective source rock thickness to the dark mudstone thickness in different intervals can be obtained (Table 2). According to the distribution characteristics of dark mudstone, the planar distribution characteristics of effective source rock in the Bohai Sea area can be identified (Fig. 5).

Table 1 Ratio of dark mudstone thickness to formation thickness of different sedimentary types in the Bozhong Depression and its periphery

Formation name	Sedimentary type	Ratio of dark mudstone thickness to formation thickness, %			
		Minimum value, m	Maximum value, m	Average value, m	Number of samples
Ed ₂	Braided river delta	6.8	64.5	39.4	5
	Shore and shallow lake	5.7	90.9	47.6	21
	Deep lake	53.6	94.7	78.3	9
	Meandering river delta	0.7	52.5	29.4	5
Ed ₃	Braided river delta	4.3	53.4	42.9	8
	Shore and shallow lake	35.7	80.9	48.6	12
	Deep lake	55.2	97.6	88.6	6
	Meandering river delta	0.7	22.5	12.4	3
Es ₁₊₂	Braided river delta	7.9	61.3	38.5	4
	Shore and shallow lake	56.2	98.6	52.7	6
	Deep lake	55.2	97.6	88.6	6
Es ₃	Braided river delta	12.5	85.6	53.7	3
	Shore and shallow lake	58.4	92.5	88.5	3
	Deep lake	66.2	66.2	66.2	1

Fig. 2 Contour diagram of dark mudstone thickness of all intervals in the Bozhong Depression

Fig. 3 Depth map of the hydrocarbon expulsion thresholds of Eocene source rocks in the Bozhong Depression

SRI<0, Non-hydrocarbon source rocks; 0-25, Poor source rocks; 25-50, Medium source rocks; 50-75, Good source rocks; >75, Best source rocks

Fig. 4 Identification chart of hydrocarbon expulsion thresholds of source rocks

Table 2 Ratio of effective thickness to dark mudstone thickness of the source rocks in each interval in the Bozhong Depression and its periphery

Formation name	Effective thickness/dark mudstone thickness			Number of exploration wells
	Minimum value, m	Maximum value, m	Average value, m	
Ed ₂	0.32	0.77	0.68	34
Ed ₃	0.37	0.89	0.75	23
Es ₁₊₂	0.25	0.93	0.84	21
Es ₃	0.65	1.00	0.92	12

From the distribution characteristics of effective source rock, the maximum values of effective thickness of Ed₂ and Ed₃ are both about 240 m and mainly located in the deep depression belt of the Bozhong Depression. The effective thicknesses of the members are much less than those of the actual dark mudstone of 700 m and 750 m. The maximum value of effective thickness of Es₁₊₂ is 280 m, and that of dark mudstone is 550 m, which is almost twice the former. The effective source rock thickness of Es₃ is 400 m. Compared with the maximum value of dark mudstone thickness of 550 m, most (80%) of the Es₃ dark mudstone is effective.

Fig. 5 Contour diagram of effective source rock thicknesses in the Bozhong Depression

5 Discussion and conclusions

5.1 Discussion

Applying the “two stages and three steps” method to distinguish effective source rocks is simple to operate and various kinds of data are comprehensively used. Relatively the method has a better accuracy compared to the previous methods, however, deficiencies also exist. Firstly, restrained by the scarcity of data, it is hard to apply this method in low-exploration areas. Secondly, in the second step of this method, geochemistry data like pyrolysis data are thoroughly used, which requires rich and evenly distributed analytical information in this area. Thirdly, during the process of mapping planar thickness of effective source rocks, sedimentary facies and organic facies data are required, which is highly affected by operators, so careful thought should be given to ensure the accuracy of results.

5.2 Conclusions

1) The “two stages and three steps” method obtained the effective source rock thickness mainly by eliminating the part that was unable to expel hydrocarbon, from the total dark mudstone (oil shale).

2) Four sets of source rocks developed in the Bozhong Depression. These are Member 2 of the Dongying Formation (Ed_2), Member 3 of the Dongying Formation (Ed_3), Member 1–Member 2 of the Shahejie Formation (Es_{1+2}) and Member 3 of the Shahejie Formation (Es_3) in Paleogene. The ratio of effective source rocks to dark mudstone is between 30% and 80%, while the Member 3 of the Shahejie Formation (Es_3) has the highest ratio.

3) The “two stages and three steps” method is a practical and accurate technique for predicting effective source rocks.

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