

Identification and hydrocarbon expulsion history simulation of the effective source rocks in the Dongying Formation, Paleogene, Bohai Sea area, eastern China

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ABSTRACT

This paper discusses a new method for identification and simulation of the hydrocarbon expulsion history of Effective Source Rocks (ESR) in the Dongying Formation (E_3d), Bohai sea area, Bohai Bay basin, eastern China. This new method enables us to reliably identify the distribution and quantitatively determine the hydrocarbon expulsion history of ESR in petroliferous basins. ESR are the material basis for hydrocarbon accumulation, having important implications for oil and gas exploration prospects. The Bohai Bay basin is one of the most petroliferous basins in China, with nearly one third of the total oil production of the country. However, insufficient research on the ESR in the Dongying Formation (E_3d), Bohai sea area, Bohai Bay basin obstructs further exploration. In this paper, ESR of E_3d are identified with the new "two-stage and three-step" method, and their planar distribution is predicted by combining well data with sedimentary facies, and structure distribution. On that basis, the hydrocarbon expulsion history of ESR in the 2nd Member (E_3d_2) and 3rd Member (E_3d_3) of E_3d was systematically simulated by using the hydrocarbon generation potential method. The results show that the ESR of E_3d_2 are distributed in four sags of Bohai Sea area, while the ESR of E_3d_3 occur in seven sags. Hydrocarbon expulsion from the ESR of E_3d_2 began during the deposition period of the Minghuazhen Formation (N_m) (12 Ma) with a hydrocarbon expulsion quantity of 42×10^8 t. The hydrocarbon expulsion centers were located in the Bozhong, Huanghekou, Qikou and Bodong sags. Hydrocarbon expulsion from the ESR of E_3d_3 began around 16.6 Ma ago (hydrocarbon expulsion quantity of 84×10^8 t), and the hydrocarbon expulsion centers were located in the Bozhong, Qinnan, Huanghekou, Liaozhong, Nanpu and Qikou sags. In conclusion, the hydrocarbon expulsion centers of the ESR of E_3d are mainly located in Bozhong, Huanghekou, Qikou and Bodong sags, with late-stage hydrocarbon expulsion (16.6–2 Ma), which is advantageous to hydrocarbon accumulation and preservation. The uplifts and slope belts around the hydrocarbon expulsion centers would be favorable exploration targets.

Key words: effective source rocks (ESR), hydrocarbon expulsion threshold, Dongying Formation, Paleogene, Bohai Sea, Bohai Bay basin, China.

RESUMEN

En este artículo se discute un nuevo método para la identificación y simulación de la historia de expulsión de hidrocarburos de la Roca Madre Efectiva (RME) en la Formación Dongying (E_3d), área del Mar de Bohai, cuenca de la Bahía de Bohai, este de China. Este nuevo método permite identificar de manera confiable la distribución y determinar cuantitativamente la historia de expulsión de hidrocarburos de las RME en cuencas petrolíferas. Las RME son la base material para la acumulación de hidrocarburos y tienen implicaciones importantes para prospectos de exploración de petróleo y gas. La cuenca de la Bahía de Bohai es una de las más ricas en petróleo de China, con cerca de un tercio de la producción total de petróleo en el país. Sin embargo, la investigación de las RME de la Formación Dongying (E_3d) en la cuenca de la Bahía de Bohai es aún insuficiente, lo que ha obstruido el avance de la exploración. En este trabajo, se indentifican las RME de E_3d con el nuevo método de “dos etapas y tres pasos”, y su distribución planar se predice por medio de la combinación de datos de pozos con facies sedimentarias y distribución de estructuras. Con base en lo anterior se simuló sistemáticamente la historia de expulsión de hidrocarburos de las RME en el 2° Miembro (E_3d_2) y el 3er Miembro (E_3d_3) de E_3d por medio de la aplicación del método de potencial de generación de hidrocarburos. Los resultados muestran que las RME de E_3d_2 están distribuidas en cuatro depresiones (“sags”) del área del Mar de Bohai, mientras que las RME de E_3d_3 se presentan en siete depresiones. La expulsión de hidrocarburos de las RME de E_3d_2 inició en el periodo de depósito de la Formación Minghuazhen (N_1m) (12 Ma) con la expulsión de 42×10^8 t. Los centros de expulsión se localizan en las depresiones de Bozhong, Huanghekou, Qikou y Bodong. La expulsión de hidrocarburos de las RME de E_3d_3 inició a ~ 16.6 Ma con la expulsión de 84×10^8 t, y los centros de expulsión se localizaron en las depresiones Bozhong, Qinnan, Huanghekou, Liaozhong, Nanpu y Qikou. En conclusión, los centros de expulsión de hidrocarburos de las RME de E_3d se localizan principalmente en las depresiones Bozhong, Huanghekou, Qikou y Bodong, con expulsión de hidrocarburos tardía (16.6–2 Ma), lo cual es ventajoso para la acumulación y preservación de hidrocarburos. Los levantamientos (“uplifts”) y cinturones de talud que rodean a los centros de expulsión de hidrocarburos serían blancos de exploración favorables.

Key words: roca madre efectiva, umbral de expulsión de hidrocarburos, Formación, Dongying, Paleógeno, Mar de Bohai, cuenca de la Bahía de Bohai, China.

INTRODUCTION

The study of effective source rocks (ESR) relates to the accuracy of estimates of hydrocarbon resources and directly affects the exploration prospects in petroliferous basins. Tissot and Welte (1978) defined source rocks as rocks that already generated or have the ability to generate petroleum. Momper (1978) proposed the concept of ESR, defined as the rocks that could generate and expel commercial petroleum. Since then, many definitions of these rocks have been proposed, which can be divided into two major types: (1) source rocks that have already generated and expelled hydrocarbons (Sheng, 1989; Wang *et al.*, 2003), and (2) source rocks that already expelled hydrocarbons and also have formed commercial hydrocarbon reservoirs via oil-source correlation (Hunt, 1979; Jones, 1981; Li *et al.*, 1999; Jin, 2001; Jiang *et al.*, 2002; Rao *et al.*, 2003). Due to different cognition and research methods (Fu *et al.*, 1983; England, 1987; Lewan and Williams, 1987; Leythaeuser, 1988; Chen *et al.*, 2004; Chen, 2005), certain differences also occur in the definitions of ESR. However, generating and expelling hydrocarbon is the precondition of ESR, and whether they can form commercial hydrocarbon reservoirs needs to be

verified by exploration, which is difficult as it is affected by exploration progress and late-stage preservation. In addition, in the situation of the coexistence of multiple source rocks, although the amount of hydrocarbon expelled from some source rocks can be relatively small and is lost during secondary migration, this process can effectively avoid loss of hydrocarbon expelled from other source rocks, so those source rocks also make a contribution to hydrocarbon accumulation and can be considered to be ESR as well.

The Bohai Bay basin is one of the most petroliferous basins in China, with an exploration area of approximately 4.2×10^4 km² (Li, 1980), accounting for nearly one third of the total oil production of China. Oil and gas exploration in the Bohai sea area began in 1966; seven oil and gas fields have been successively confirmed in this area, including PL19-3, SZ36-1, among others. So far, 48 oil and gas fields and 100 hydrocarbon bearing structures have been discovered in the Bohai Sea area with proven OOIP (original oil in place) of about 24×10^8 m³ and OGIP (original gas in place) of about 500×10^8 m³. With its cumulative production exceeding 50×10^6 t oil equivalent (Zuo *et al.*, 2010), the Bohai Sea area is still the main oil and gas exploration target in eastern China. Currently discovered oil and gas

movements, the Bohai Sea area was uplifted and underwent weathering and denudation over a long geological time. During the Cenozoic sedimentation period, influenced by Himalayan movement, the structural evolution of hydrocarbon-bearing areas in Bohai is characterized by polyphase rifting, multicycle superimposition and polygenous mechanism, and is divided into a Paleogene rifting stage and a Neogene—Quaternary post-rifting thermal subsidence stage (Hou *et al.*, 2000; Gong and Wang, 2001; Gong, 2004; Sun *et al.*, 2008). The rifting stage can be further divided into four evolution phases: I, period from the Kongdian Formation (E_1k) to the 4th Member of the Shahejie Formation (E_2s_4) (55–42 Ma); II, period of the 3rd Member of the Shahejie Formation (E_2s_3) (42–38 Ma); III, period of the 1st and 2nd

Member of the Shahejie Formation (E_2s_{1+2}) (38–32.8 Ma); and IV, period of Dongying Formation (E_3d) (32.8–24.6 Ma). The post-rifting thermal subsidence stage can be further divided into phase I corresponding to the sedimentation period from Guantao Formation (N_1g) to the 2nd Member of the Minghuazhen Formation (N_1m_2) (16.6–5.1 Ma), and phase II from the 1st Member of the Minghuazhen Formation (N_1m_1) to the Quaternary (5.1–0 Ma) (Figure 2; Gong, 2004).

Correlated with the tectonic evolution, the sedimentation and subsidence center of the Bohai Bay basin migrated from land to sea, forming a structural framework of land depressions intersecting in the sea area. The thickness of sediment increased gradually from the Paleogene to the Neogene in the sea area (Xu *et al.*, 2008).

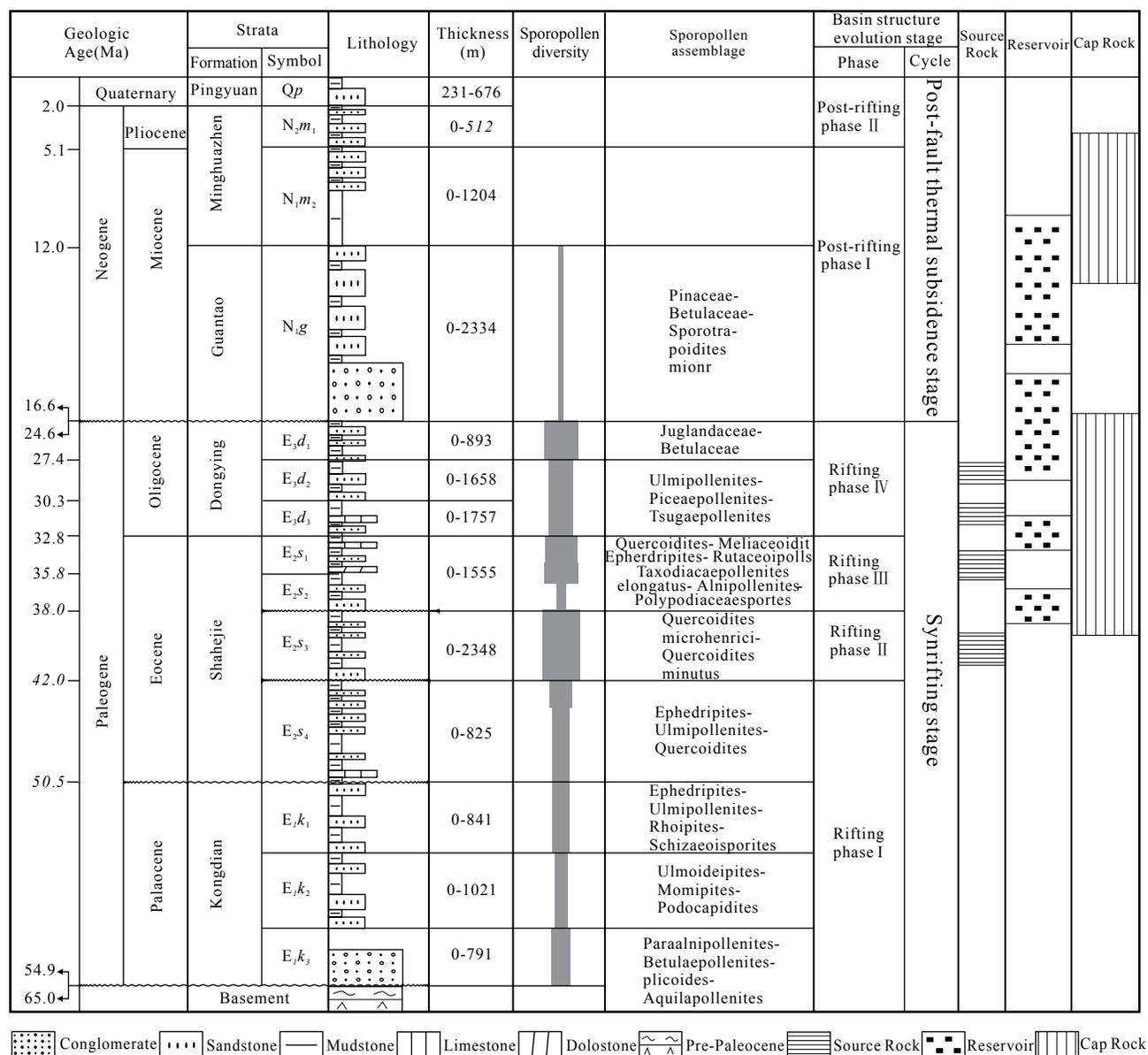


Figure 2. Sedimentary strata, tectonic evolution and combination of source rocks, reservoirs and cap rocks in the Bohai Sea area (Gong, 2004).

Sedimentary strata

The sedimentary formations in the Bohai sea area mainly include Paleogene, Neogene and Quaternary sediments from bottom to top (Figure 2; Gong, 2004). Rift valley sedimentation is preserved in the Paleogene strata, which indicate that lake basins with lacustrine sedimentation were well developed. In the Neogene, lakes basically disappeared, and deposition was characterized by fluvial plain and shore-shallow lake environments. Quaternary strata are mainly marine deposits. According to lithologic features, the whole Cenozoic basin-filling sequence can be divided into six formations from the bottom up (Figure 2, Gong, 2004): Kongdian(E_1k), Shahejie (E_2s) and Dongying formations (E_3d) of Paleogene age, Guantao (N_1g) and Minghuazhen formations ($N_{1+2}m$) of Neogene age, and the Pingyuan Formation (Qp) of Quaternary age (Figure 2, Gong, 2004).

Introduction to oil and gas geology, and characteristics of source rocks

Reservoirs in the Bohai Sea area are mainly distributed around Bozhong, Huanghekou and Liaozhong sags, and the biggest offshore reservoir PL19-3 is situated at the Bonan lower uplift between the Bozhong and Huanghekou sags (Figure 1). Industrial oil flows have been found in Shahejie, Dongying, Guantao and Minghuazhen formations, and they are mainly in the 1st Member of the Dongying Formation and in the Guantao Formation, where the discovered oil and gas reserve is roughly 50% of total discovered reserve (Zuo *et al.*, 2010). The distribution of main source rocks, reservoirs and caprocks in the Bohai Sea area is shown in Figure 2.

Four sets of source rocks are developed in the Bohai Sea area: the 3rd Member of the Shahejie Formation (E_2s_3), the 1st and 2nd Members of the Shahejie Formation (E_2s_{1+2}), the 3rd Member of Dongying Formation (E_3d_3), and the 2nd Member of Dongying Formation (E_3d_2) (Figure 2, Gong, 2004). So far, due to its deep burial depth, 58 wells have been drilled in the source rocks of E_2s_3 , and the bottom boundary is deepest in the Bozhong sag (8000 m) and it exceeds 3000 m in most of the sea area.

The source rocks of E_2s_{1+2} are extensively distributed, but their thickness is rather low with an average thickness less than 200 m. The lithology of the source rocks of E_2s_{1+2} is mainly dark mudstone deposits, and their maximum burial depth can reach 6000 m in the Bozhong sag.

The dark mudstones of E_3d have a large thickness and a wide distribution range. The sedimentary facies include fan delta, braided river delta, sublacustrine fan, and lake (Xu, 1981). Lacustrine deposit systems are widely distributed and two main subsidence centers formed in the Bozhong and Liaozhong sags (Deng *et al.*, 2011). The lithology is thick dark gray-blackish mudstone interbedded with thin sandstone. Deep and semi-deep lake deposits were developed in the deep depressed part of all sags, and shore-

shallow lake deposits were distributed in the slope part of lake basins. The maximum strata thickness is 1080 m, with an average of about 600 m. The maximum burial depth is 5500 m in the Bozhong sag. The sedimentary facies of E_3d_2 correspond to fan delta, braided river delta, meandering river delta, reticular river delta, sublacustrine fan, and lake. Semi-deep to deep lake deposits developed in the deep depressed part of sags. The lithology assemblage contains mainly thick-bedded, grayish-black and black mudstone interbedded with thin sandstone; the subsidence center was located in the Bozhong sag. The maximum strata thickness is 1650 m with an average thickness of about 800 m, and on the whole, the burial depth is around 1000 to 4500 m.

Many studies of source rocks of the Shahejie Formation have been conducted (Chi, 2001; Hu *et al.*, 2001; Wang and Zhang, 2003; Jiang *et al.*, 2010a), while systematic and further research on the source rocks of E_3d is rare (Li *et al.*, 2001; Huang and Li, 2002). With recent exploration practices, oil and gas discoveries in E_3d has increased greatly (Wang *et al.*, 2006). Therefore, the comprehensive study of the effectiveness and hydrocarbon supply capacity of the source rocks in E_3d and their variation in different sags is of great geologic significance for furthering the recognition of oil and gas sources and expanding the exploration extent in the Bohai Sea area. Especially, with the development of seismic exploration in recent years, plenty of geologic and geochemical data of source rocks have been obtained, enabling systematic evaluation of source rocks. Aiming at the existing problems in exploration, combining with the new recognition of the regional structural evolution history and sedimentary facies distribution, by systematically analyzing drilling data and geochemical data, in this paper the ESR of E_3d are identified and their hydrocarbon expulsion history is outlined. The study provides reference information on oil and gas resource potential to guide exploration directions in the Bohai Sea area.

METHODS

Determination of ESR

Many methods for determining ESR have been proposed, including identification through simulation experiments, identification based on a lower limit of organic carbon content, and identification using analysis of the hydrocarbon content in closely sampled core samples (Jiang *et al.*, 2010b). However, the applications of these methods are limited by core availability, experimental analysis cost, sample amount and experiment conditions, which leads to poor maneuverability and lopsided results. This paper discusses a new method for identification of the ESR in E_3d , named the "two-stage and three-step method" (Jiang *et al.*, 2010b). This new method enables us to reliably determine distribution of ESR in petroliferous basins. The process of this method is as follows:

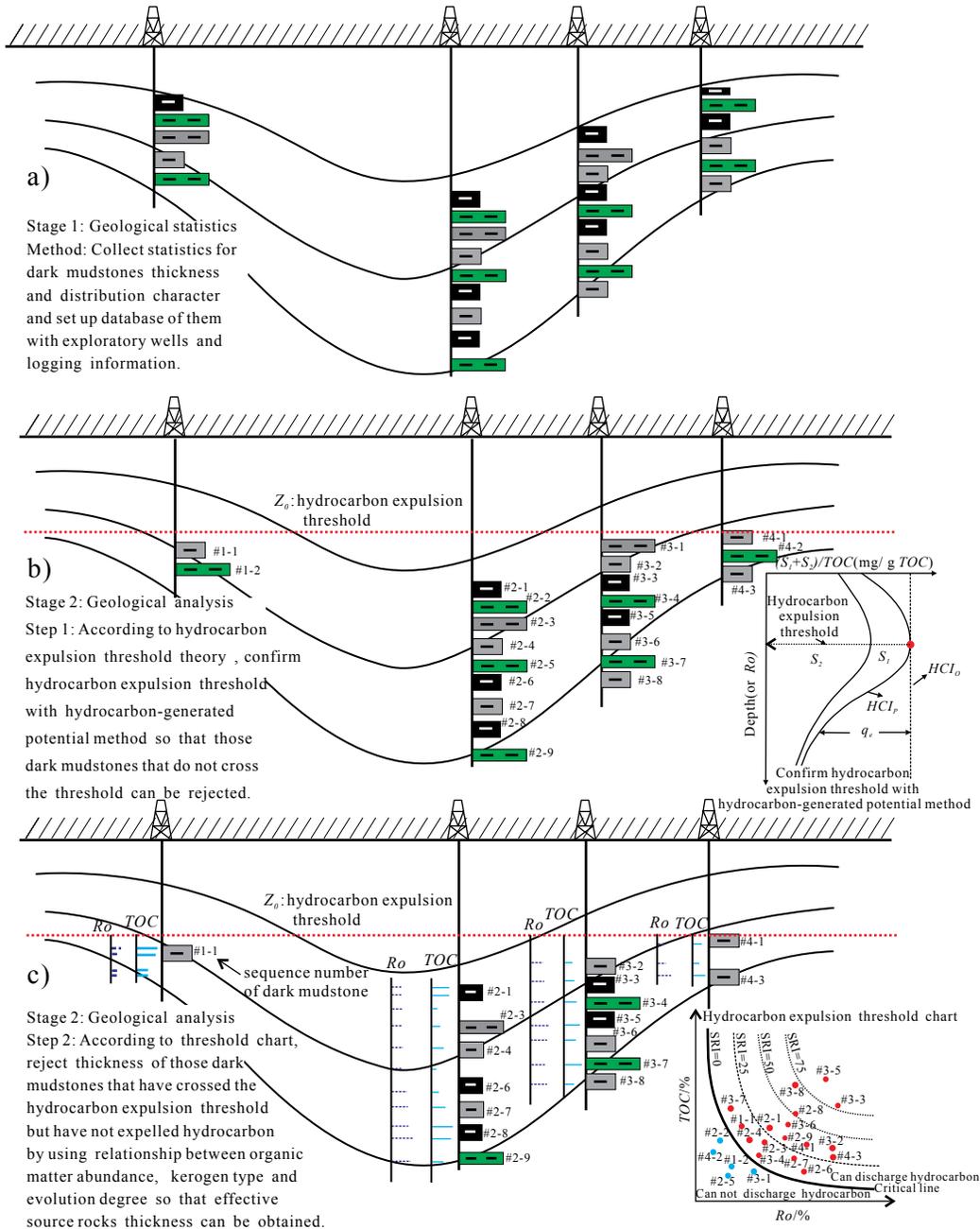


Figure 3. Workflow for applying the “Two-stage and Three-step Method” to determine the effective source rocks (ESR).

Stage 1: Geological statistics

Step 1. Collect thickness data for dark mudstones from wells in the study area, set up a database of dark mudstone thickness (Figure 3a), then extrapolate to the areas with less or no wells, on the basis of sedimentary facies, seismic facies data, etc., and finally, obtain the planar distribution of the dark mudstone in the study area (Zhang et al., 2007).

Stage 2: Geological analysis

On the basis of stage 1 results, determine the thickness of ESR in bulk dark mudstone by means of geochemical

analysis. Stage 2 can be further divided into two steps: step 2 and step 3.

Step 2. Apply the hydrocarbon expulsion threshold theory (Pang, 1995) to identify the hydrocarbon expulsion threshold of source rocks and eliminate the dark mudstones that have not crossed the hydrocarbon expulsion threshold.

Basic approach. The hydrocarbon expulsion threshold refers to the critical geologic condition at which the amount of hydrocarbon generated satisfies the residual needs for hydrocarbon in various processes, including

self-adsorption, interstitial water dissolution, oil dissolution (gas), capillary blockage, etc. Consequently, lots of oil and gas can be expelled and can migrate in separate phases during the burial process (Pang, 1995). It is obvious that only dark mudstones that had crossed the hydrocarbon expulsion threshold could possibly expel hydrocarbons, and the hydrocarbon generation potential method can be used for discrimination (Zhou and Pang, 2002; Jiang *et al.*, 2007). The method is theoretically based on the principle of conservation of matter, namely that the amount of organic matter in the source rocks remains constant before and after hydrocarbon generation and migration. A decrease in the amount of the organic matter can occur as result of substance exchange between the source rocks and the surroundings. In terms of Rock-Eval pyrolysis, S_1 represents free volatile hydrocarbons thermally flushed from a rock sample at 300 °C, S_2 represents products of cracking during standard Rock-Eval pyrolysis temperatures (300–600 °C), and the sum (S_1+S_2) is generally used to signify the content of hydrocarbon in source rocks (Espitalie *et al.*, 1977; Tissot and Welte, 1978, 1984). Thus, the (S_1+S_2)/

total organic content (TOC) ratio could be used to delineate the potential of source rocks to generate hydrocarbons. In other words, it could reflect volumes of hydrocarbons generated by *per unit* of TOC in the source rocks. Zhou and Pang (2002) called the (S_1+S_2)/TOC ratio as Hydrocarbon Generation Potential Index. Hydrocarbon expulsion begins (Figure 3b) when the index starts to decrease and the critical geologic condition is defined as the hydrocarbon expulsion threshold. Those dark mudstones that have not crossed the hydrocarbon expulsion threshold could be reasonably eliminated after determining the hydrocarbon expulsion threshold.

Different types of organic matter in source rocks will result in differences in hydrocarbon generation potential and hydrocarbon expulsion (Pang, 1995). The organic matter types of source rocks in the study area can be classified into three groups: Type I kerogen is mainly located in the center of the sag, Type III is distributed in the edge of the sag, and type II is located between them (Li *et al.*, 2001; Chi, 2001; Wang *et al.*, 2004). Thus, in this paper, three hydrocarbon expulsion geological models are established. The models are

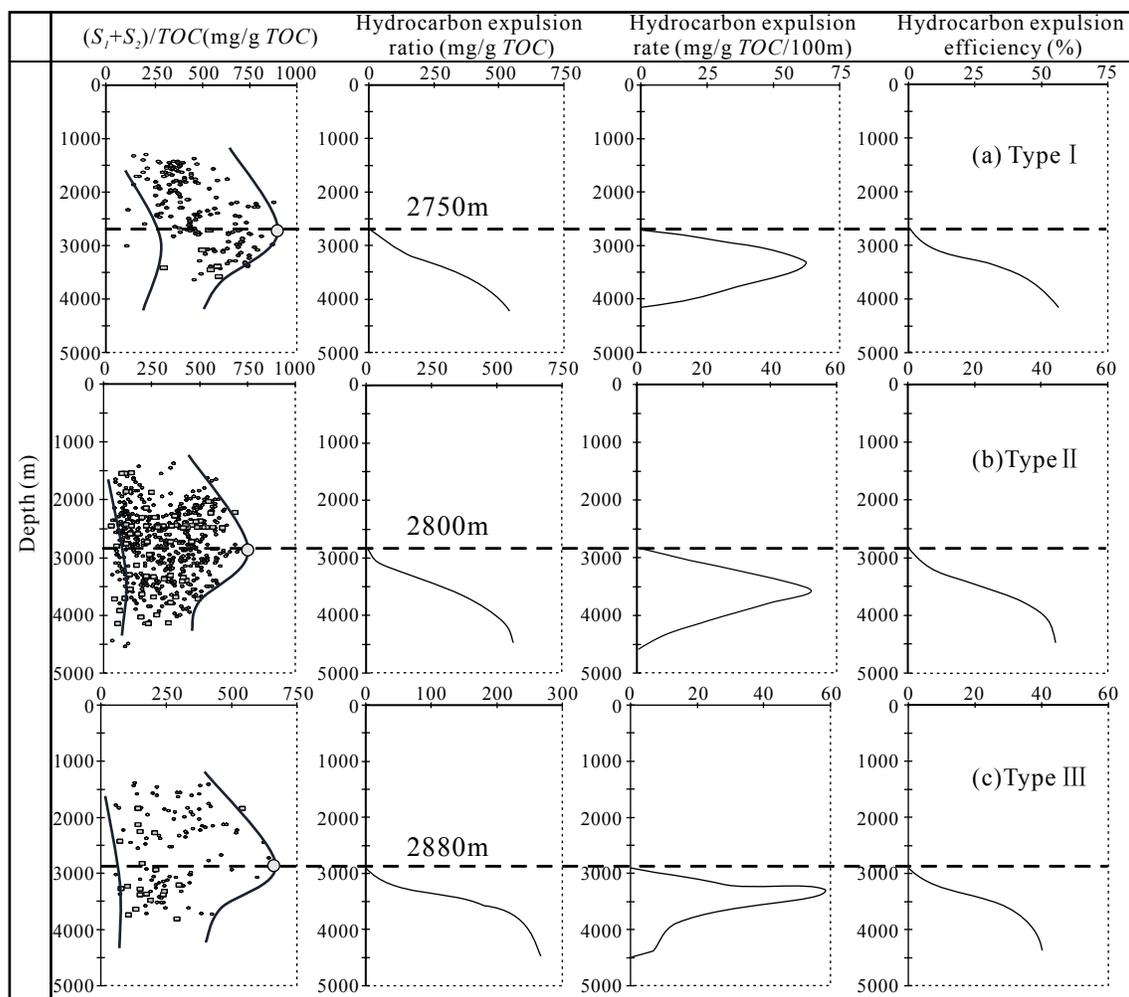


Figure 4. Hydrocarbon expulsion models of different types of organic matter in E_3d in the Bohai Sea area.

Table 1. Rock-Eval pyrolysis of source rocks in the Dongying Formation, Bohai Sea area. S₁+S₂: hydrocarbon content; TOC: total organic carbon.

Layer	S ₁ +S ₂ (mg/g)	TOC (%)	(S ₁ +S ₂)/TOC (mg/g TOC)	Number of samples
	min – max average	min – max average	min – max average	
E ₃ d ₂	0.51 – 46.8 6.48	0.50 – 4.15 1.74	65 – 876 358	765
E ₃ d ₃	0.67 – 50.3 7.56	0.50 – 5.51 2.32	87 – 913 496	469

based on the type of kerogen (Figure 4), using a database of 1234 Rock-Eval pyrolysis analysis of samples from the Dongying Formation, Bohai Sea area (Table 1).

Step 3. Determine the ESR that have crossed the hydrocarbon expulsion threshold using the hydrocarbon expulsion threshold chart.

Basic approach. The abundance of organic matter in source rocks is strongly heterogeneous. Therefore, the bulk dark mudstone which has crossed the hydrocarbon expulsion threshold may still contain some parts that cannot expel hydrocarbons due to poor quality. These kinds of dark mudstones can be calibrated using a hydrocarbon expulsion threshold identification chart. The effective thickness of source rocks can be determined by using the correlation chart of organic matter abundance, kerogen type and thermal evolution degree, which can get rid of the dark mudstone that cannot expel hydrocarbon due to their poor quality (Figure 3c). Data calibration and mapping are performed to get the planar thickness distribution of ESR by using the ratio of the obtained ESR to the formation thickness in wells. Hydrocarbon Source Rock Index (SRI) charts are used in this paper (Pang, 2003). The SRI represents the percentage of the actually expelled hydrocarbon compared to the amount of hydrocarbon that would be expelled from optimal source rocks. Source rocks of the semi lacustrine to deep lacustrine facies of the Qing Shankou Formation, deposited in Songliao Basin, are considered to be the best ones in the China eastern continental sedimentary basin because they have the highest organic matter abundance and high to very high organic matter maturity. Therefore, source rocks of Qing Shankou Formation were utilized as a standard in the evaluation of source rocks, being termed as the optimal source rocks. The equation to calculate the SRI is as follows:

$$SRI = (Q_p - Q_{rm}) / Q_{em} \times 100 \quad (1)$$

Where Q_p and Q_{rm} represent the hydrocarbon generation amount of source rocks and the critical saturation amount of residual hydrocarbons, respectively; Q_{em} represents the amount of hydrocarbon expulsion from optimal source rocks.

Values of SRI < 0 mean that the amount of hydrocarbons

generated in rocks is less than the critical saturation amount of residual hydrocarbons, and thus the rocks are non-source rocks; on the contrary, rocks are considered source rocks when SRI > 0. The larger the SRI, the better the quality of source rocks (Figure 3c). A statistical analysis of numerous geologic data undertaken by Pang (1995) shows that the hydrocarbon generation, retention and expulsion amount is determined by TOC, vitrinite reflectance (Ro) and source rock type. Based on this recognition, Pang (1995) established the relation chart of SRI versus the above three parameters to distinguish source rocks from non-source rocks.

Method for hydrocarbon expulsion history simulation

The hydrocarbon generation potential method (Zhou and Pang, 2002; Pang et al., 2005) is used for the reconstruction of hydrocarbon generation and expulsion processes. When no hydrocarbon has been expelled, the hydrocarbon potential of source rocks is known as initial hydrocarbon generation potential index (HCI_o); when hydrocarbon expulsion begin, the hydrocarbon potential decreases gradually and the hydrocarbon potential can be known as residual hydrocarbon generation potential index (HCI_p). The differentials between the maximum hydrocarbon generation potential index and the residual hydrocarbon generation potential index is the hydrocarbon expulsion ratio q_e , which is the hydrocarbon amount expelled per unit of organic carbon, since source rocks crossed the hydrocarbon expulsion threshold, in mg/g. Q_e represents the cumulative hydrocarbon expulsion amount of source rocks in geological history, Q_r represents the residual hydrocarbon amount in source rocks (unit: g), and Q_p is the hydrocarbon generation amount of source rocks (unit: g) (Pang et al., 2005, Figure 5).

The hydrocarbon generation potential index represents the hydrocarbon expulsion ratio of source rocks, and the profile area represents the cumulative hydrocarbon expulsion amount of source rocks in geological history. Based on this principle, the equations for calculating the hydrocarbon

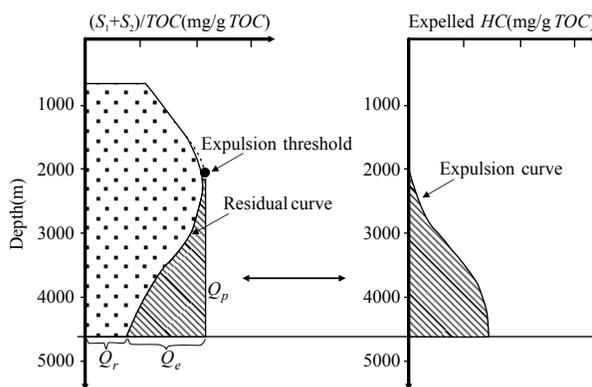


Figure 5. Operational models for the quantification of hydrocarbon expulsion (Pang et al., 2005).

expulsion intensity and hydrocarbon expulsion amount are as follows:

$$E_{hc} = \int_{z_0}^z 10^{-1} \cdot q_e(z) \cdot H \cdot \rho(z) \cdot TOC \cdot dz \quad (2)$$

$$Q_e = \int_1^n \int_{z_0}^z 10^{-5} \cdot q_e(z) \cdot H \cdot S(n) \cdot \rho(z) \cdot TOC \cdot dzdn \quad (3)$$

Where E_{hc} represents the hydrocarbon expulsion intensity in t/km^2 ; $q_e(z)$ represents the hydrocarbon expulsion ratio per unit of organic carbon in mg/g ; Q_e represents the hydrocarbon expulsion amount in t ; Z represents the burial depth in m ; Z_0 represents the hydrocarbon expulsion threshold; $\rho(z)$ represents the density of source rocks in g/cm^3 ; TOC represents the organic carbon mass fraction in $wt\%$; H represents the thickness of source rocks in m ; $S(n)$ represents the area of source rocks in m^2 .

The hydrocarbon potential evolution of source rocks in each geological epoch can be simulated by combining the hydrocarbon generation potential index of source rocks with the burial history results. Combined with organic matter abundance, organic matter type, as well as evolution degree, the hydrocarbon expulsion process of source rocks in each geological epoch can be simulated.

RESULTS

Distribution of ESR in the E_3d in the Bohai Sea area

Distribution of dark mudstone and source rocks in E_3d

So far, 165 wells have been drilled in the E_3d_2 and 36 wells have been drilled in the E_3d_3 of the Bohai Sea area. The results show that the dark mudstone thickness of E_3d_2 ranges from 2 to 814 m, averaging 180 m, and that the thickness

of E_3d_3 ranges from 3.5 to 496 m with a mean thickness of 143 m. Considering that these unevenly drilled wells are mainly located on uplifts, the relationship between the dark mudstone thickness and sedimentary facies is obtained by evaluating the ratio of the dark mudstone thickness to the formation thickness in wells and sedimentary facies (Figure 6). For the area of the dark mudstone with less wells, thickness can be predicted from sedimentary facies and strata thickness. Finally, the map view distribution of the dark mudstone of E_3d can be derived (Figure 7).

The results suggest that the dark mudstone in E_3d_2 is widely distributed throughout the area. The maximum thickness is 700 m in Bozhong sag, much thicker than that of 500 m in Liaozhong sag, 400 m in Qikou sag and about 400 m in Huanghekou sag (Figure 7a). Compared with that in E_3d_2 , the distribution of dark mudstone in E_3d_3 is relatively limited in some regions. It is distributed mainly in Bozhong and Liaozhong sags, with maximum thicknesses of 700 m and 600 m respectively. The thickness of E_3d_3 dark mudstone is relatively small or only appears in deep depressions of other sags (Figure 7b). As a whole, although the dark mudstone thickness in E_3d is large, the percentage of ESR, which is of great importance for the further exploration, remains unclear.

Determination whether the dark mudstone has crossed the hydrocarbon expulsion threshold. According to the hydrocarbon expulsion threshold depth (Figure 4), the dark mudstone that has not crossed the hydrocarbon expulsion threshold can be directly eliminated, thus the dark mudstone thickness which has crossed the hydrocarbon expulsion threshold can be determined.

Determination of the dark mudstone that cannot expel hydrocarbon using the hydrocarbon expulsion threshold chart. Typical wells with sufficient geochemical data and

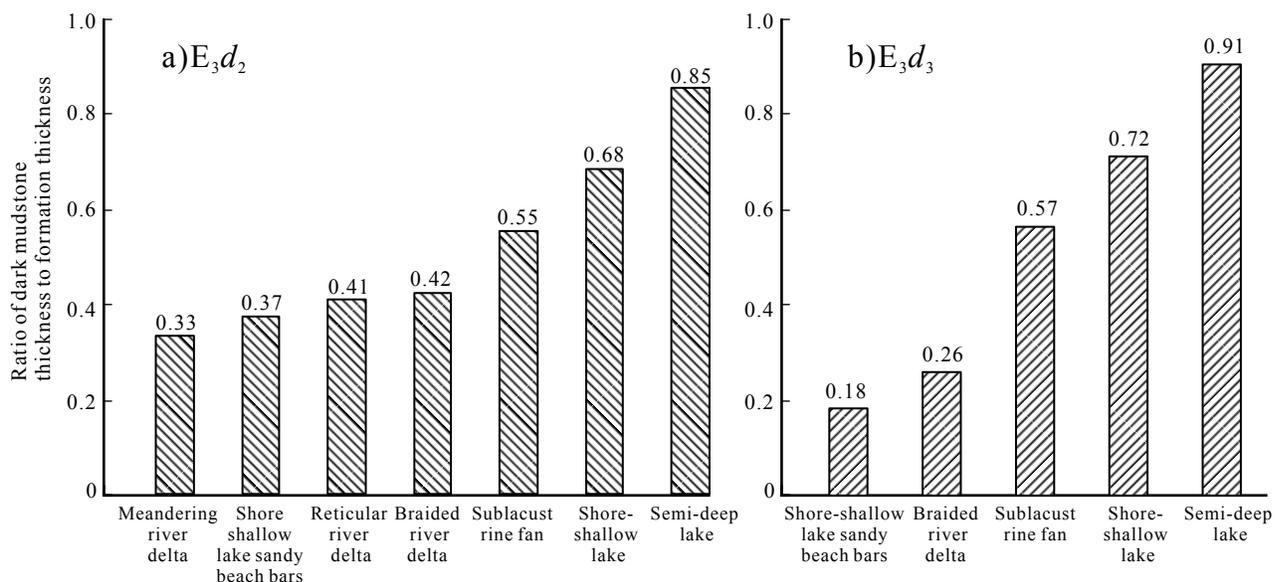


Figure 6. Relationship between the ratio of dark mudstone thickness to formation thickness and sedimentary facies in E_3d_2 and E_3d_3 in the Bohai sea area.

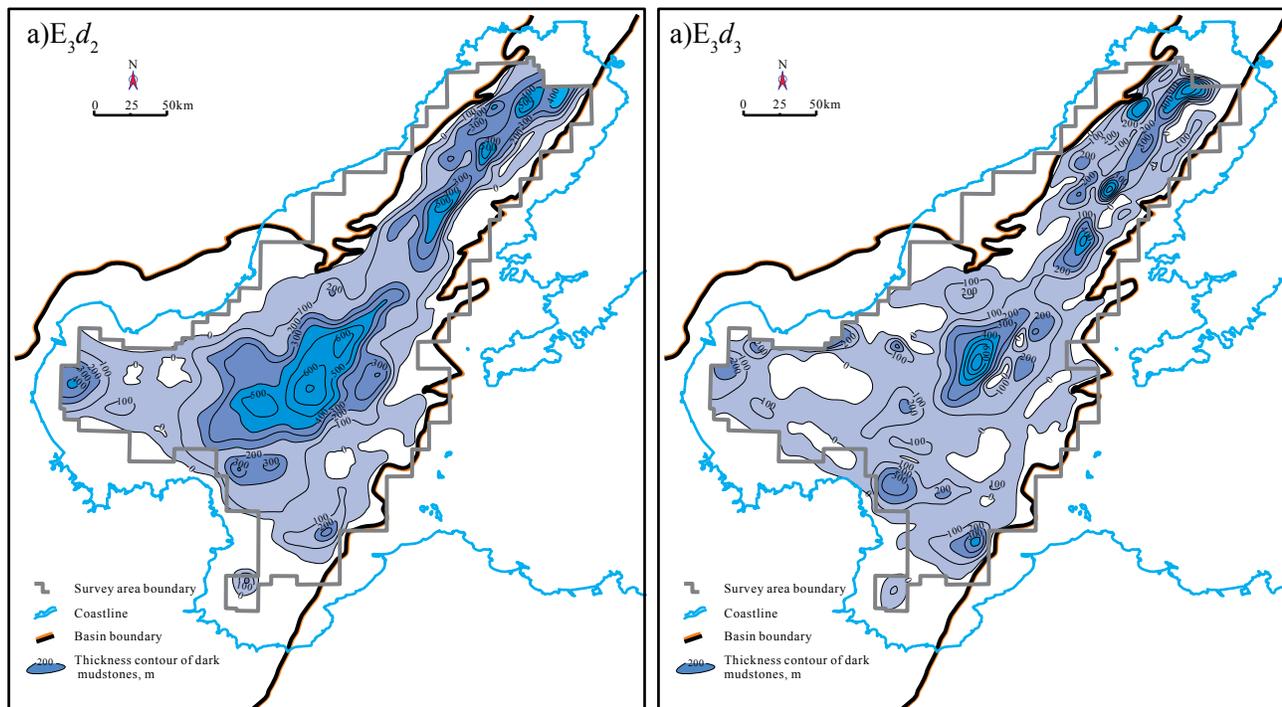


Figure 7. Thickness distribution of dark mudstone of E_3d in the Bohai Sea area.

lithologic profiles were selected for statistical analysis, and actual hydrocarbon expulsion determination charts of typical wells in different strata were established (Figure 8) to discriminate whether dark mudstones have crossed the hydrocarbon expulsion threshold. In addition, combining the results of the dark mudstone that have not crossed the hydrocarbon expulsion threshold as described above, a comprehensive data table (Table 2) of the percentage of ESR in the bulk dark mudstones in each stratum can be obtained. Based on the distribution of dark mudstone, the distribution characteristics of the ESR in E_3d can be determined in map view (Figure 9).

The ESR in E_3d_2 is distributed in Bozhong, Huanghekou

and Qikou sags (Figure 9a). In other sags, there is no ESR in E_3d_2 due to the relatively shallow burial depth in most cases. In addition, although have crossed the hydrocarbon expulsion threshold, a part of source rocks still cannot expel hydrocarbon due to the relatively low organic matter abundance and low evolution degree, which limits the distribution of ESR. The ESR thickness in E_3d_2 has a maximum of 500 m in Bozhong sag and 300 m in Huanghekou sag. Although the maximum ESR thickness in Qikou sag is 400 m, it has a relatively limited distribution. The distribution of the ESR in E_3d_3 is relatively wider in Bozhong, Huanghekou, Liaozhong and Qikou sags. The maximum thickness is 600 m in Bozhong sag and 400 m in the north of Liaozhong sag.

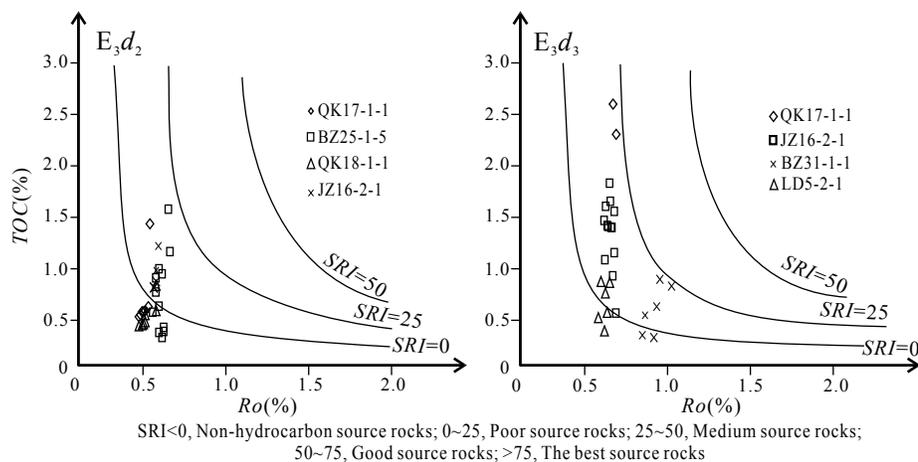


Figure 8. Hydrocarbon expulsion discrimination chart of typical single wells in E_3d in the Bohai sea area.

Table 2. Ratio of effective source rock thickness to dark mudstone thickness of Dongying Formation, Bohai Sea area. ESR: Effective source rocks.

Formation	Thickness of ESR / Thickness of dark mudstone			Number of wells
	Minimum value	Maximum value	Average value	
Ed ₂	0.00	0.51	0.35	165
Ed ₃	0.12	1.00	0.56	36

The maximum thickness is 300 m in both Huanghekou and Qikou sags (Figure 9b).

Hydrocarbon expulsion history of source rocks in E₃d

After recognizing the hydrocarbon expulsion threshold and the relationship between hydrocarbon expulsion ratio and depth in different organic matter types, based on the data of source rock thickness, current buried depth, organic matter abundance and organic types, etc., the hydrocarbon expulsion intensity and hydrocarbon expulsion amount of source rocks can be calculated by using the hydrocarbon generation potential method (Equations 2 and 3). In addition, the hydrocarbon generation potential curve of source rocks, reflecting the hydrocarbon expulsion evolution at different burial depths, is a function of the effects of various geologic factors. Therefore, on the basis of ascertaining the burial history of source rocks, defining the extent of ESR by

hydrocarbon expulsion threshold, determining the evolution of the hydrocarbon generation potential curve, combined with data on effective source rock thickness, organic matter abundance and organic matter type, etc., the hydrocarbon expulsion history of source rocks and the hydrocarbon expulsion amount during each period can be derived.

Evolution of hydrocarbon generation kitchens

Hydrocarbon expulsion history of source rocks in E₃d₂

Source rocks of E₃d₂ began to expel hydrocarbons at around the end of Minghuazhen Formation sedimentary period (12–2 Ma), with corresponding burial depth of 2800 m, and were mainly restricted to Bozhong and Qikou sags. In that period, source rocks in Qikou sag just crossed the hydrocarbon expulsion threshold and had a limited hydrocarbon expulsion extent and low hydrocarbon expulsion intensity of less than 40×10^4 t/km² (Figure 10a). Source rocks of E₃d₂ in Bozhong sag reached the maximum hydrocarbon expulsion intensity of 80×10^4 t/km² at the burial depth of 3400 m (Figure 10a). At present, the maximum expulsion rate of source rocks is 550 mg/g (type I), and its expulsion extent has been gradually increased. The maximum hydrocarbon expulsion intensity has reached 40×10^4 t/km² and 160×10^4 t/km² in Qikou and Bozhong sags, respectively (Figure 10b).

Hydrocarbon expulsion history of source rocks in E₃d₃

Source rocks of E₃d₃ began to expel hydrocarbons around the end of Guantao Formation sedimentary period (12 Ma), with corresponding burial depth of 2800 m, and were mainly restricted to Bozhong and Qinnan sags. During this period,

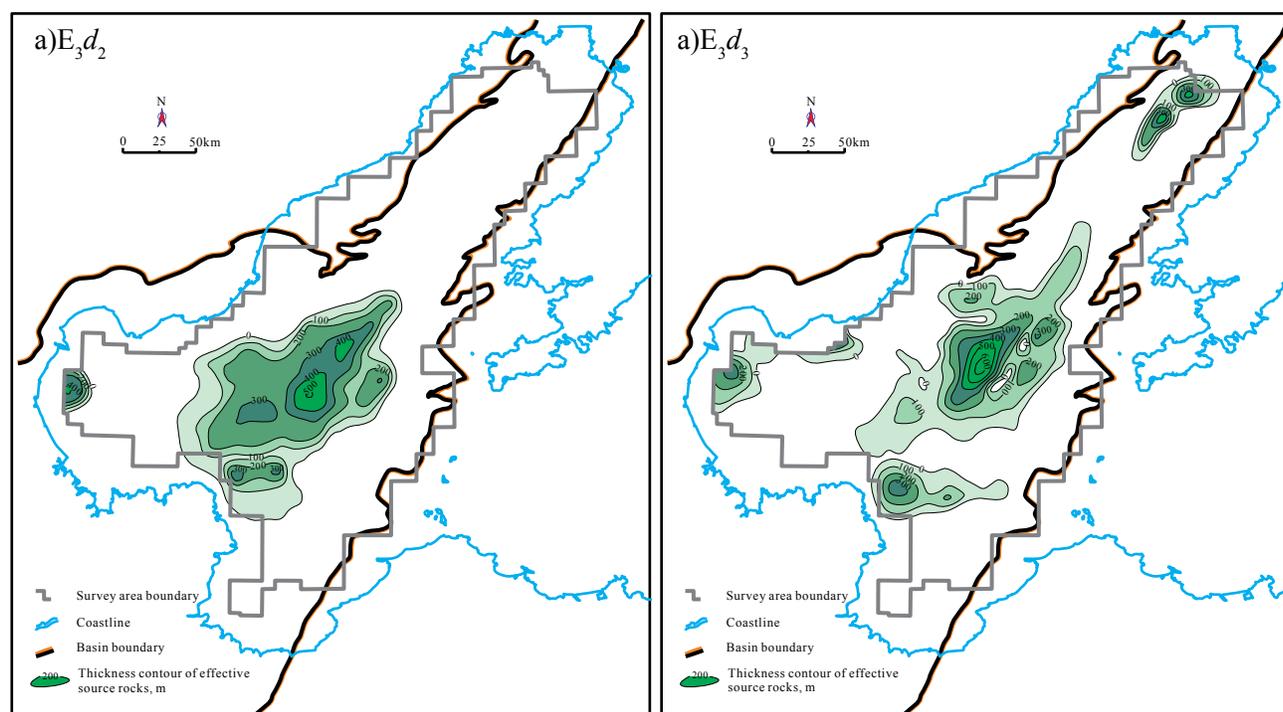


Figure 9. Thickness distribution of effective source rocks (ESR) in E₃d, Bohai Sea area.

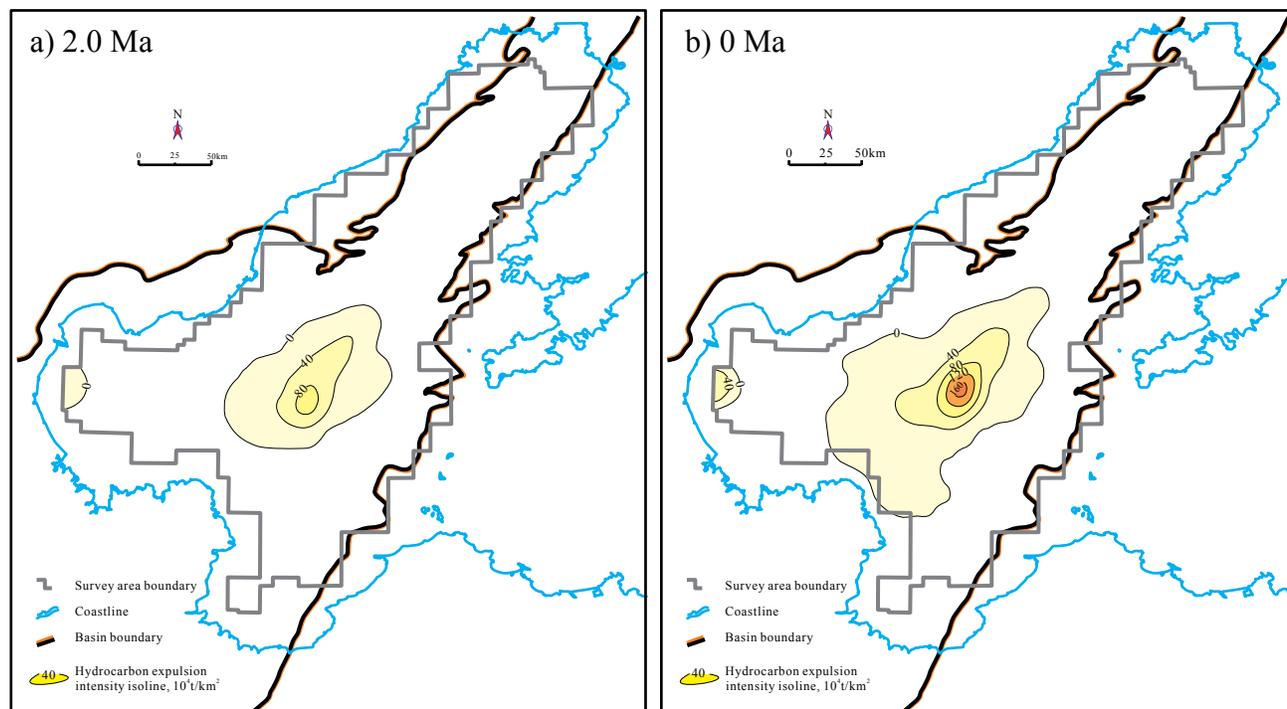


Figure 10. Evolution of hydrocarbon expulsion intensities of source rocks of E_3d_2 , Bohai Sea area.

the maximum hydrocarbon expulsion intensity was 160×10^4 t/km² in the Bozhong sag and 40×10^4 t/km² in the Qinnan sag (Figure 11a). By the end of Minghuazhen Formation sedimentary period, when the average burial depth was around 3400 m, source rocks reached their maximum hydrocarbon expulsion rate and their extent was increasing. There was hydrocarbon expulsion in the Bozhong, Qinnan, Qikou, and Huanghekou sags and in the northern part of the Liaozhong sag, and the maximum hydrocarbon expulsion intensity in Bozhong sag was 200×10^4 t/km². A small difference of the maximum hydrocarbon expulsion intensity existed in other sags with a maximum hydrocarbon expulsion intensity range of 40×10^4 – 80×10^4 t/km², whereas their hydrocarbon expulsion extents were slightly different (Figure 11b). The source rocks of E_3d_3 have expelled hydrocarbons in large areas, and Bozhong, Bodong and Qinnan sags are characterized by continuous hydrocarbon expulsion, with a hydrocarbon expulsion rate of 550 mg/g (type I). The accumulative maximum hydrocarbon expulsion intensity was 280×10^4 t/km² in Bozhong sag and 80×10^4 t/km² in Bodong and Qinnan sags. Hydrocarbon expulsion in Qikou, Liaozhong and Huanghekou sags also occurs over wide areas, but their maximum hydrocarbon expulsion intensity varies little and mainly ranges from 40×10^4 to 80×10^4 t/km² (Figure 11c).

Evolution of hydrocarbon expulsion amount variation

Hydrocarbon expulsion intensity reflects the migration evolution of hydrocarbon expulsion centers of source rocks in each period, and the expelled amount is the best indicator of the amount of hydrocarbons supplied from

source rocks. Through volume integration of hydrocarbon expulsion intensity of source rocks in each period, total amount of hydrocarbons expelled from these two sets of source rocks in E_3d was obtained. Accumulative average thickness, accumulative areas of hydrocarbon expulsion, and expelled volume of hydrocarbons for source rocks of E_3d in different geological times are reported in Table 3.

Evolution of hydrocarbon expulsion amount of source rocks in E_3d . The hydrocarbon expulsion amount of source rocks of E_3d_2 was 27×10^8 t during about 12–2 Ma, with 25×10^8 t hydrocarbon derived from the Bozhong sag, making up 90% of the total expulsion amount. The amounts of hydrocarbon expulsion in Bodong and Qikou sags were only 0.65×10^8 t and 1.0×10^8 t, respectively, indicating that the expulsion center of the source rocks in E_3d_2 was Bozhong sag during this period. Influenced by sedimentary environment and burial conditions, the source rocks of E_3d_2 in Bozhong sag had a relatively high evolution degree and a large expulsion extent. During the sedimentation period of 2.0–0 Ma, the total hydrocarbon expulsion amount was 15×10^8 t, including 8×10^8 t in Bozhong sag, 2.5×10^8 t in Huanghekou sag, 4×10^8 t in Qikou sag, and 0.6×10^8 t in Bodong sag. These results suggest that the hydrocarbon expulsion of the source rocks in E_3d_2 was relatively scattered in this period, and the expulsion amount remarkably increased in Qikou and Huanghekou sags (Figure 12). The evolution of the expulsion amount indicate that the source rocks of E_3d_2 began to expel hydrocarbons in the Minghuazhen Formation sedimentary period, and that the hydrocarbon expulsion center was mainly located in Bozhong sag. Due

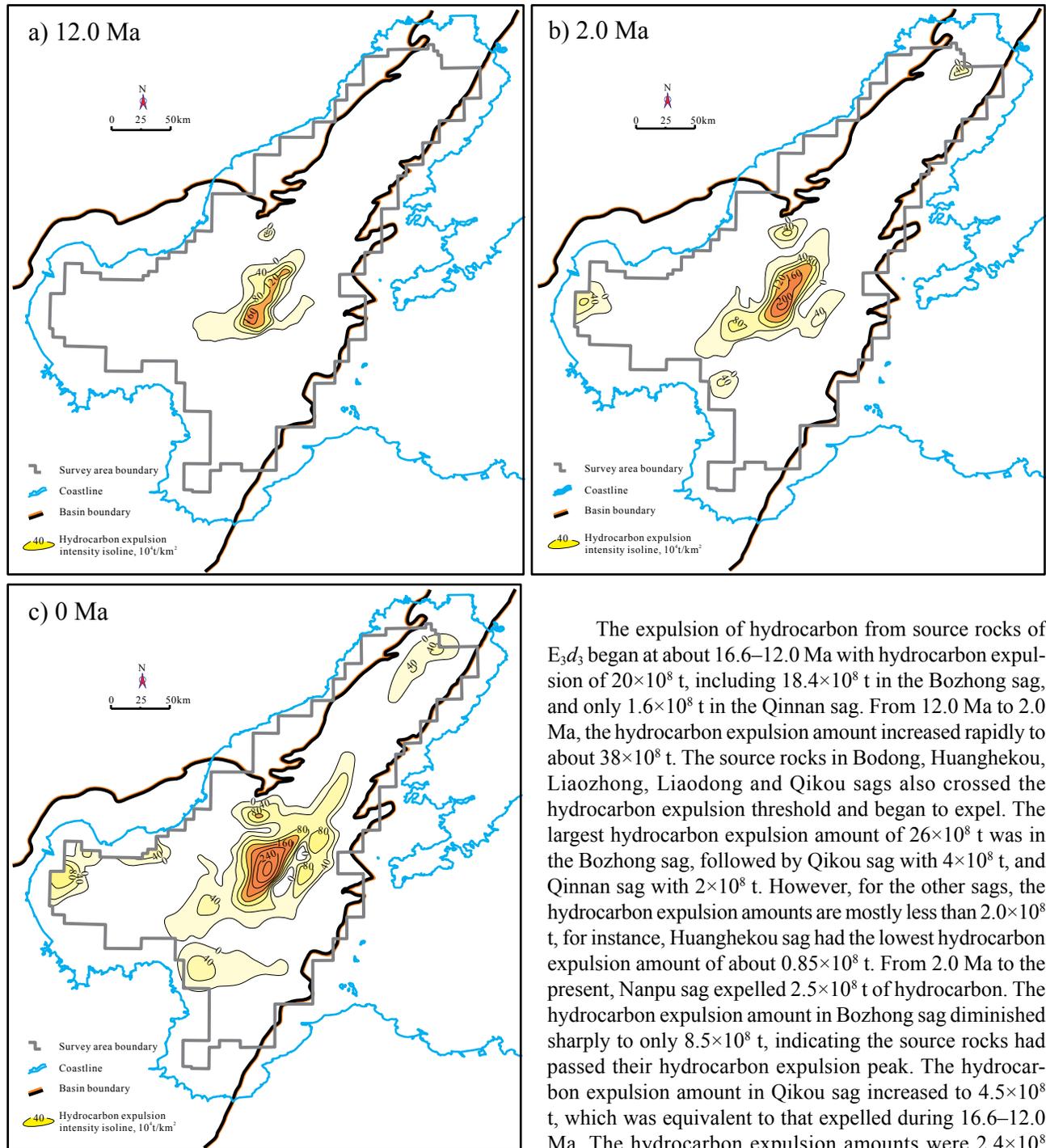


Figure 11. Evolution of hydrocarbon expulsion intensities of source rocks of E_3d_3 , Bohai Sea area.

to long term sedimentation and thick sediments, the source rocks reached hydrocarbon expulsion peak rapidly. From 2 Ma to present, the hydrocarbon expulsion amount was reduced significantly, but the expulsion extent increased slightly. For other sags, because of the relatively shallow burial depth, source rocks have not expelled hydrocarbons until now.

The expulsion of hydrocarbon from source rocks of E_3d_3 began at about 16.6–12.0 Ma with hydrocarbon expulsion of 20×10^8 t, including 18.4×10^8 t in the Bozhong sag, and only 1.6×10^8 t in the Qinnan sag. From 12.0 Ma to 2.0 Ma, the hydrocarbon expulsion amount increased rapidly to about 38×10^8 t. The source rocks in Bodong, Huanghekou, Liaozhong, Liaodong and Qikou sags also crossed the hydrocarbon expulsion threshold and began to expel. The largest hydrocarbon expulsion amount of 26×10^8 t was in the Bozhong sag, followed by Qikou sag with 4×10^8 t, and Qinnan sag with 2×10^8 t. However, for the other sags, the hydrocarbon expulsion amounts are mostly less than 2.0×10^8 t, for instance, Huanghekou sag had the lowest hydrocarbon expulsion amount of about 0.85×10^8 t. From 2.0 Ma to the present, Nanpu sag expelled 2.5×10^8 t of hydrocarbon. The hydrocarbon expulsion amount in Bozhong sag diminished sharply to only 8.5×10^8 t, indicating the source rocks had passed their hydrocarbon expulsion peak. The hydrocarbon expulsion amount in Qikou sag increased to 4.5×10^8 t, which was equivalent to that expelled during 16.6–12.0 Ma. The hydrocarbon expulsion amounts were 2.4×10^8 t in the Bodong sag, 3×10^8 t in Qinnan sag, 2.2×10^8 t in Liaozhong sag, 1.6×10^8 t in Liaodong sag, and 1×10^8 t in Huanghekou sag. Hydrocarbon expulsion amounts in these sags increased slightly compared with previous expulsion periods (Figure 12).

The results of hydrocarbon expulsion amount evolution suggest that the source rocks in E_3d_3 began to expel hydrocarbons at about 16.6–12 Ma ago, and the hydrocarbon expulsion center was located in the Bozhong sag. From 12 Ma to 2 Ma, source rocks in the Bozhong sag reached the hydrocarbon expulsion peak, and the hydrocarbon expulsion

extent increased to seven hydrocarbon expulsion sags. From 2 Ma to present, although the amount of hydrocarbon expulsion diminished sharply in the Bozhong sag, it increased slightly in other sags, indicating that the source rocks in medium to small sags just entered their hydrocarbon expulsion peak during this period.

CONCLUSIONS

Dark mudstones of E₃d in Bohai Sea area are widely distributed with large thickness, being the thickness of E₃d₂ dark mudstone larger than that of E₃d₃. However, the effective source rocks of E₃d have a limited distribution. ESR of E₃d₂ are mainly located in Bozhong, Huanghekou, Qikou and Bodong sags, with an average thickness of 200 m; while ESR distribution of E₃d₃ is relatively broad, mainly in Bozhong, Bodong, Huanghekou, Liaozhong, Qinnan, Qikou and Nanpu sags, with an average thickness of 230 m.

The hydrocarbon expulsion history simulation results indicate that the source rocks of E₃d₂ began to expel hydrocarbons at around 12–2 Ma (Minghuazheng Formation sedimentary period). So far, the cumulative hydrocarbon expulsion amount is 41.95×10⁸ t, with the hydrocarbon expulsion center mainly located in the Bozhong sag, from where the hydrocarbon expulsion accounts for over 90%,

Table 3 Characteristics of hydrocarbon expulsion for source rocks of the Dongying Formation in the Bohai Sea area in different geological times.

Category	E ₃ d ₂	E ₃ d ₃
<i>23 – 12 Ma</i>		
Cumulative average expulsion thickness (m)	0	51
Cumulative expulsion area (km ²)	0	3879
Expelled volume of hydrocarbons (10 ⁸ t)	0	20.03
<i>12 – 2 Ma</i>		
Cumulative average expulsion thickness (m)	120	105
Cumulative expulsion area (km ²)	7914	8190
Expelled volume of hydrocarbons (10 ⁸ t)	26.68	38.03
<i>2 – 0 Ma</i>		
Cumulative average expulsion thickness (m)	211	146
Cumulative expulsion area (km ²)	14167	16282
Expelled volume of hydrocarbons (10 ⁸ t)	15.27	25.69
Total expelled volume of hydrocarbons (10 ⁸ t)	41.95	83.75

whereas the hydrocarbon expulsion amount is very small in Bodong, Huanghekou and Qikou sags. Source rocks of E₃d₃ began to expel hydrocarbons at about 16.6–12 Ma (Guantao Formation sedimentary period). So far, the cumulative hydrocarbon expulsion amount has been 83.75×10⁸ t. In addition to the hydrocarbon expulsion center of Bozhong

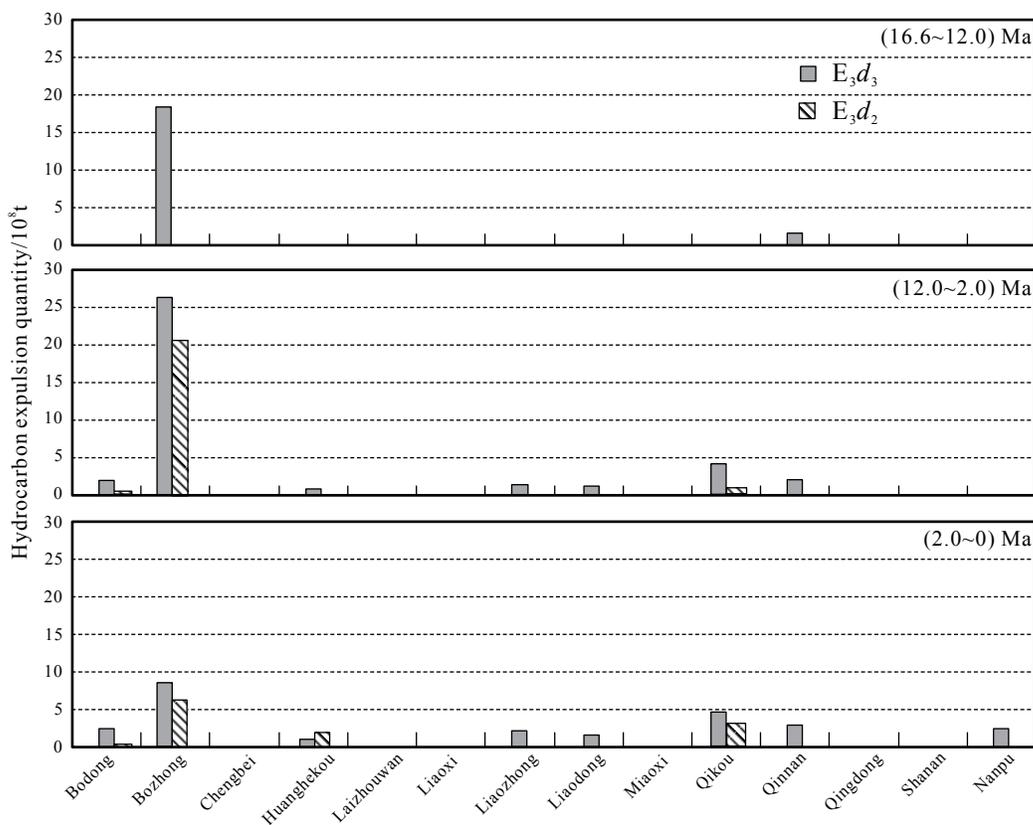


Figure 12. Evolution of hydrocarbon expulsion amount from the effective source rocks (ESR) of Dongying Formation in different sags.

sag, hydrocarbons are also expelled from source rocks in Liaozhong, Qinnan, Qikou and Huanghekou sags. Source rocks of E_3d_3 make greater contribution to hydrocarbon accumulation than those of E_3d_2 in Bohai Sea area.

Comprehensive analysis reveals that the Minghuazhen Formation sedimentary period was the main hydrocarbon accumulation stage. Source rocks are still expelling hydrocarbon, which is very significant to hydrocarbon accumulation, advantageous for oil and gas gathering, and favorable for the preservation of oil and gas.

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