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Oil and gas resource potential of the lower members of E_{h3} in the lower Tertiary of the Biyang Depression, China

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Abstract: The lower Tertiary E_{h3} is divided into two sections: the upper members of E_{h3} and the lower members of E_{h3} in the Biyang Depression. The first section is generally regarded as a key target of oil and gas exploration, but the resource potential of the lower members of E_{h3} has been neglected. We have obtained new knowledge about E_{h3} from comprehensive geological research. The lower members of E_{h3} are high-quality and main source rocks, which have good oil and gas resource potential. This is a new direction for oil and gas exploration. The geochemistry characteristics of source rocks of the lower members of E_{h3} in the lower Tertiary of the Biyang Depression were analyzed in detail. A basin modeling method was applied to hydrocarbon generation of the lower and upper members of E_{h3} source rocks, the oil and gas resource potential was comparatively analyzed, and then favorable tectonic zones were pointed out. In the lower members of E_{h3}, a set of semi-deep lake to deep lake high-quality source rocks occurs rich in algae organisms, mainly of type II_1, with a high abundance of organic matter. Most of the source rocks are just in the peak stage of hydrocarbon generation, which is a favorable foundation for forming abundant oil and gas resources in the Biyang Depression. The comparative analysis of the hydrocarbon-generation quantities between lower and upper members of the E_{h3} source rocks shows that the lower members of E_{h3} have good oil and gas resource potential, and the hydrocarbon-generation quantity accounts for 51% of the total in E_{h3}. Specifically, the oil-generating quantity accounts for 50% of the total and the gas-generating quantity accounts for two thirds of the total. Therefore, source rocks in the lower members of E_{h3} of the Biyang Depression have good oil and gas resource potential, which is a key factor for future deep oil and gas exploration.

Key words: Geochemistry, source rocks, hydrocarbon-generation potential, Biyang Depression

The Biyang Depression is a relatively independent secondary structural unit in the Nanxiang Basin located between Tanghe and Biyang counties of Henan province, China. It is a down-faulted basin formed in the Mesozoic-Cenozoic Eras. It covers only 1,000 km^2 but its oil and gas reserves are abundant. The main oil and gas reserves are found in the Eogene Hetaoyuan Formation and the main exploration layer is E_{h3} (Qiu et al, 2005b; Yu et al, 2007; Sun et al, 2008; Luo, 2003; Luo et al, 2008).

Achievements have been gained due to the high exploration degree and detailed research on the upper members of E_{h3} (Wen et al, 2006; Qin et al, 2005; Zeng et al, 2005). However, relatively little study has been done on the lower members of E_{h3} and more attention is needed. For deep hydrocarbon targets formed by the lower members of E_{h3} source rocks in the Biyang Depression, the density of drilling is not adequate, and the exploration degree is relatively low. Many reservoirs are subtle reservoirs (Yu et al, 2007). Besides, information such as time and space distribution of the lower members of E_{h3} source rocks, organic types, organic matter abundance, maturity and hydrocarbon generation history is not clear. Neglecting the existence of high quality hydrocarbon source rocks of the lower members of E_{h3} leads to an underestimate of the deep-seated hydrocarbon resource potential.

Therefore, based on the geochemical characteristics of the E_{h3} source rocks, we compare the potential of oil and gas resource of the upper members of E_{h3} with that of the lower members of E_{h3}, and clarify its distribution to provide guidance for future exploration.

1 Geological background

According to stratigraphic sequence, tectonic characteristics and development history, the Biyang

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Depression is divided into south abrupt slope area, deep depression area and north downslope area (Fig. 1) (Yu et al, 2007; Qin, 2004). The Hetaoyuan Formation is the main hydrocarbon reservoir assemblage, with a thickness of 2,000 to 3,000 m. There are three geological units in the Hetaoyuan Formation, namely E_{h1}, E_{h2}, and E_{h3}. The E_{h1} is only 400 to 500 m thick, mainly composed of grey−grey green mudstone interbedded with oil shale and sandstone. The E_{h2} is 700 to 800 m, mainly composed of grey−dark grey mudstone and argillaceous dolomite and a small amount of grey brown−light brown dolomite, oil shale, sandstone and evaporites with the grey−grey green mudstone increasing from bottom to top. Grey black−dark grey mudstone is the main lithology of E_{h3} which also contains argillaceous dolomite, dolomite and sandstone. There are evaporites, oil shale and calcareous shale in the upper layer of E_{h3}. The E_{h3} Formation has the main oil and gas reserves in this basin, which includes two sub-formations and eight sand groups according to cyclic sedimentation and electrical differences. The upper members of E_{h3} include four sub members E_{h3-1}, E_{h3-2}, E_{h3-3}, E_{h3-4}, the lower members of E_{h3} include four sub members E_{h3-5}, E_{h3-6}, E_{h3-7}, E_{h3-8}.

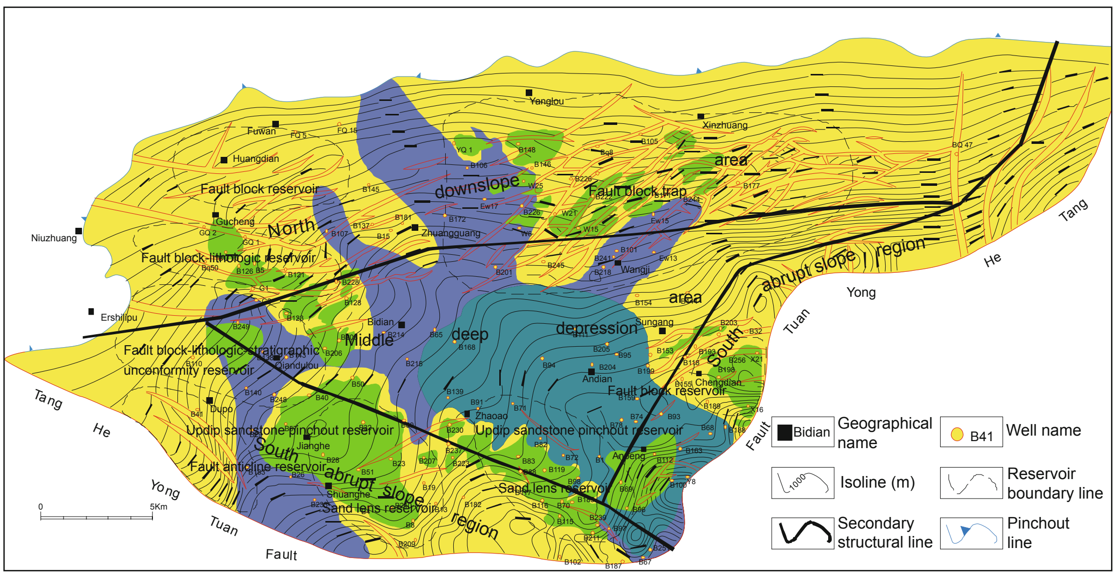

Fig. 1 Structural units of the Biyang Depression

2 Correlation of crude oil and source rocks

The Biyang Depression is a Meso-Cenozoic down-faulted lake basin with abundant oil and gas resources, and a thick hydrocarbon storage system of the lower Tertiary E_h formation. Nine oil & gas fields have been found so far, and reservoirs are concentrated in the E_{h3} formation. Many scholars have published results on oil and source rock correlation of the Biyang Depression (Zhou and Wu, 2004; Yang et al, 2005). Luo et al (2008) used biomarkers and carbon isotopes to analyze the geochemical characteristics of the upper and the lower members of E_{h3} source rocks and the oil source differences between them, and suggested that the crude oil in the upper members of E_{h3} was originated from those members, and the crude oil of the lower members of E_{h3} was from the lower members of E_{h3} source rocks. This result indicates that oil and gas origin in the Biyang Depression is very simple, and it is a typical self-generated and self-contained reservoir where the lower members of E_{h3} source rocks are effective.

3 Geochemical characteristics of the lower members of E_{h3} source rocks

3.1 Types of the lower members of E_{h3} source rocks

In the early E_{h3} deposition period, the Biyang Depression continued to subside, then the lake deepened and water expanded as the environment became warm and humid which resulted in abundant aquatic organisms. At the same time, the Biyang Depression was a semi-deep to deep water strongly reducing environment, which was favorable for the preservation of organic materials, so a set of typical continental lacustrine pelitic source rocks formed. The lower members of E_{h3} source rocks were mainly deposited in lacustrine facies, and the effective source rocks in E_{h3} mainly consist of dark mudstone, oil shale and argillaceous dolomite that were formed in a semi-deep to deep lake environment. The basis of the rich oil and gas resources in the Biyang Depression is the great potential and high efficiency of E_{h3} source rocks for hydrocarbon generation as well as their wide distribution and large thickness.

3.2 Distribution and development characteristics of the lower members of E_{h3} source rocks

The lower members of E_{h3} source rocks mainly deposited in a semi-deep to deep lake sedimentary environment. Fig. 2 shows that the depocenter is in the Anpeng-Andian area with a thickness of over 120 m. Generally, the location of the depocenter remained unchanged, and the source rocks are widespread and have a large thickness. Each sand group in the lower members of E_{h3} is thicker than 100 m, and the distribution areas of pelitic source rocks from E_{h3-8} to upper E_{h3-5} show a variation from small to large, which agrees with the change of sedimentary facies of the Biyang Depression.

The Biyang Depression started to subside in the E_{h3-8} sedimentary period, and developed a deep lake in the northwest of the Anpeng-Andian area due to humid climate and increased rainfall. The source rocks which are thicker than 100 m relatively occurred in a small area. In E_{h3-7} sedimentary period, the sedimentary center was still in Anpeng-Andian with a lower subsidence rate. The lake area reduced and the pelitic source rocks have the same characteristics as the E_{h3-8} source rocks. In the E_{h3-6} sedimentary period, the subsidence rate of the Biyang Depression became higher again, and the lake area became larger. Widespread thick pelitic source rocks developed, and the depocenter extended to the Bidian-Zhaoao area. In the E_{h3-5} sedimentary period, abundant and thick pelitic source rocks developed due to the larger and deeper lake, and this was also the biggest lake erosion period in the lower E_{h3} sedimentary history. In summary, the pelitic source rocks were affected by the subsidence rate of the depression and the change of sedimentary facies, which also determined the size and quality of source rocks.

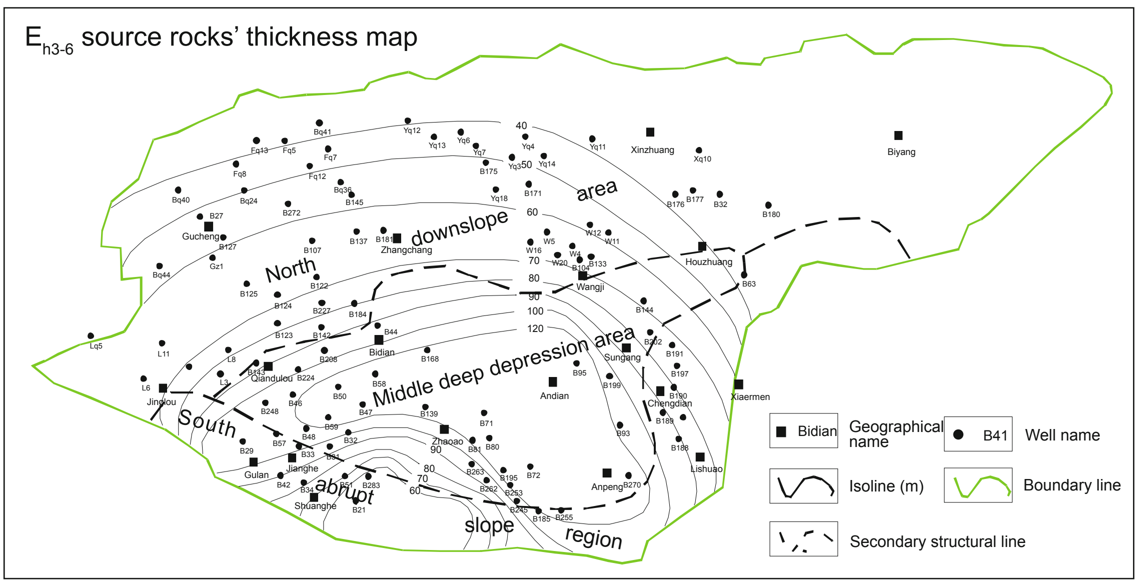

Fig. 2 Contour map showing the thickness of the E_{h3-6} source rocks in the Biyang Depression

3.3 Organic matter types and abundance of the lower members of E_{h3} source rocks

The E_{h3} source rocks are mainly dominated by algae, Type I organic matter. According to the H/C and O/C atomic comparison chart (Fig. 3), the source rocks are mainly dominated by Type II_1 and secondarily by the Types I and II_2 kerogen.

In addition, the kerogen maceral results show that the organic matter in the lower members of E_{h3} source rocks was mainly amorphous sapropelinite and amorphous huminite of sapropelinite. Vitrinite accounts for less than 10%, and inertinite accounts for less than 5%. So both the organic matter maceral analysis and the organic matter type index agree with the above conclusion (Table 1). Furthermore, HI indexes of the lower E_{h3} source rocks in well BQ31, YQ3, B145, B224 and B227 are all more than 470 mg/g.TOC and lower than 670 mg/g.TOC, and all of the evidence indicates that the source rocks belong to the Type I and Type II_1.

Fig. 4 is a total organic carbon contour map of the lower members of E_{h3-6} source rocks. We can find that the high organic abundance areas mainly occur in the semi-deep to deep lake area and the edge of the lake basin. The highest

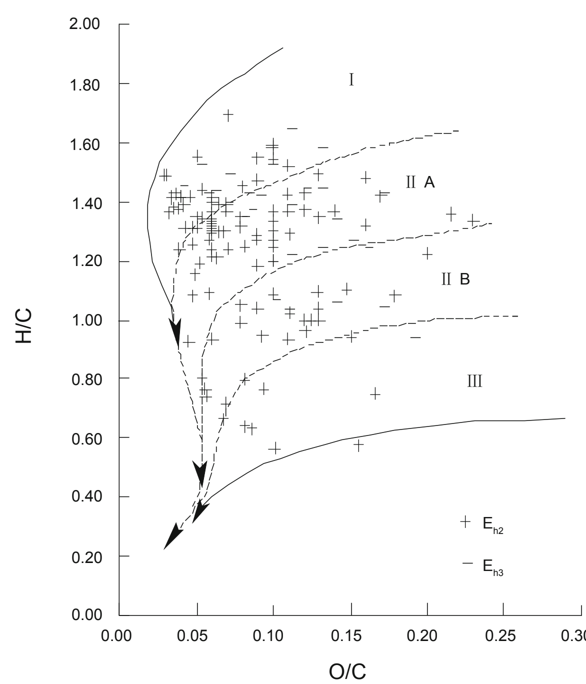

Fig. 3 Map showing the kerogen H/C-O/C of the Lower Tertiary Hetaoyuan Formation source rocks in the Biyang Depression

Table 1 Kerogen macerals and types of organic matter in the lower members of E_{h3} in the Biyang Depression

Well	Depth m	Layer	Sapropelinite			Exinite							Vitrinite			Inertinite	Type index	Organic matter type
			Alginite	Amorphous sapropelinite	Total	Cutinite	Suberin	Resinite	Sporopollenin	Amorphous huminite	Liptodetrinite	Total	Normal vitrinite	Hydrogen -rich vitrinite	Total			
BQ31	310.4	$E_{h3\text{-}5}$	5	35	40					54		54	2		2	4	62	II_1
BQ31	448	$E_{h3\text{-}6}$	2	8	10					75		75	8		8	7	35	II_2
YQ3	842.5	$E_{h3\text{-}6}$			0					95		95	2		2	3	43	II_1
YQ3	782.5	$E_{h3\text{-}5}$	3	17	20				3	62	1	65	10		10	5	40	II_1
B145	936.4	$E_{h3\text{-}5}$	5	30	35					59	1	60	2		2	3	60	II_1
B224	1563	$E_{h3\text{-}6}$		5	5					87	1	88	5		5	2	43	II_1
B227	1427	$E_{h3\text{-}6}$			0					91	1	92	5		5	3	39	II_2
B270	3647	$E_{h3\text{-}5}$			0					90		90	7		7	3	37	II_2
B270	4010	$E_{h3\text{-}6}$			0					92		92	6		6	2	39	II_2
B270	4185	$E_{h3\text{-}7}$			0					93		93	5		5	2	40	II_1
B270	4288	$E_{h3\text{-}8}$			0					93		93	4		4	3	40	II_1

organic abundance areas concentrate around the edge of the lake basin, and the abundance reduces from the edge to the center and falls to 1.0% in deep lake area due to the high maturity of source rocks in the deep lake. There are many explanations for this observation. The lake (lacustrine facies) in the Biyang Depression was mainly dominated by algae, and it is true that the delta front and prodelta had a great amount of algae, but the deep lake area was lacking in algae. The delta front and prodelta were close to the estuary so the lake brought abundant nutrient and luxuriant organisms, resulting in a high sedimentary rate so that the organic matter can be well preserved. The deep lake reducing environment is favorable for the preservation of organic matter, whereas the deep lake source rocks occur widely, algae of the deep lake is good for hydrocarbon generation. The Wangji-Zhangchang-Qiandulou-Shuanghe areas have high organic abundance with an average around 2.0%, and these areas were all in the delta front. The abundance of organic matter in the Biyang Depression is mostly above 0.5%, but this index is low in the eastern Xinzhuang-Houzhuang area, which reveals that the whole depression has a high level of organic abundance which is good for hydrocarbon generation.

3.4 Maturity of the lower members of E_{h3} source rocks

The lower members of E_{h3} source rocks are all mature due to the high geothermal gradient (4.1°C/100m) and deep burial depth (Fig. 5), with R_O over 1.2% in the Anpeng-Andian area that is located in the middle deep depression, indicating that this area reached the mature stage and is entering gas condensate and natural gas phase, which is consistent with exploration results. R_O is about 0.5% in Gucheng-Xinzhuang which is located in the north shelf, showing that most of the lower members of E_{h3} source rocks are mature. It is discovered that R_O is between 0.5% and 1.0% in the north shelf by contrasting each group of the lower E_{h3}, because this shelf was exposed to strong uplift and denudation in the Liaozhuang group period, and the biggest denudation thickness was about 1,000 m. The source rocks in this area became mature because of the thermal evolution before denudation, so the maturity remained the same as the period before denudation, which can be testified by the thermal evolution history of the source rocks. According to the R_O contour map, the E_{h3} source rocks are all mature. The source rocks which are at the oil peak stage (R_O=1.0%) and the gas condensate–wet gas stage (R_O>1.2%) enlarged with the increasing depth, but always in the Anpeng-Andian area.

4 Potential of the E_{h3} source rocks

4.1 Hydrocarbon-generation quantity contrast between the upper members and the lower members of E_{h3} source rocks

Based on the first order chemical reaction kinetics and the Arrhenius law, we select geothermal gradient parameters (Qiu et al, 2005a), denuded thickness of each layer, chemical kinetics parameters and hydrocarbon accumulation coefficient in the Biyang Depression, according to the chemical dynamics hydrocarbon-generating history model (Shi, 2004; Pepper and Corvi, 1995a; 1995b; Pepper and Dodd, 1995; Pang et al, 2010), the oil-generating quantity of the E_{h3} source rocks is 2.33 billion tonne, and the gas-generating quantity is 199.48 billion m^3 and the total hydrocarbon-generation quantity is 2.53 billion tonne. For the lower members of E_{h3} source rocks, the oil-generating quantity is 1.17 billion tonne, the gas-generating quantity is 136.60 billion m^3 and the total hydrocarbon-generation quantity is 1.30 billion tonne. For the upper members of E_{h3} source rocks, the oil-generating quantity is 1.16 billion tonne, the gas-generating quantity is 62.88 billion m^3, and the total hydrocarbon-generation quantity is 1.22 billion tonne.

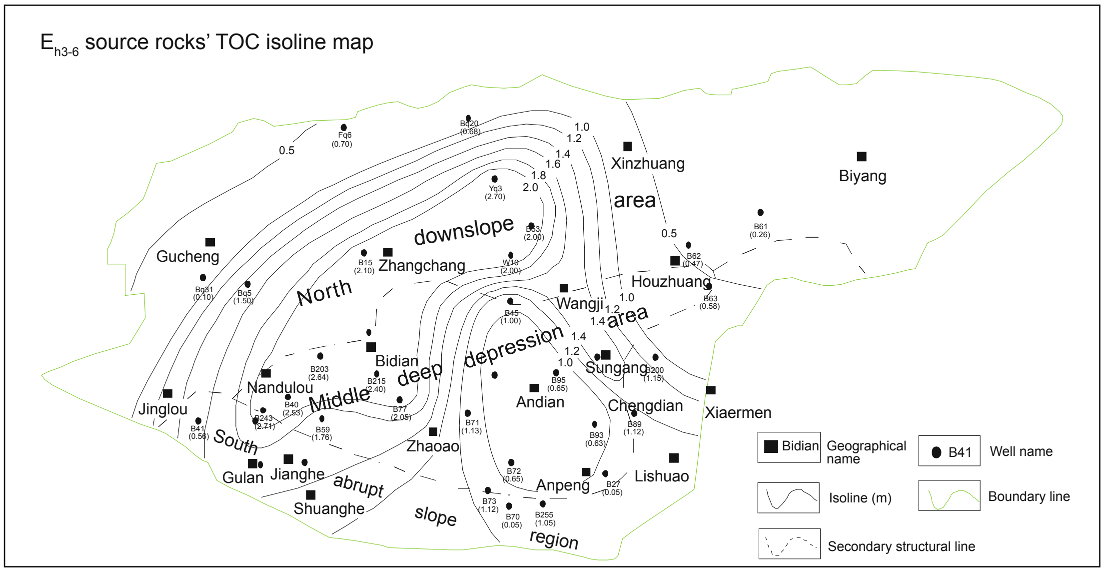

Fig. 4 Contour map showing the TOC of the E_{h3-6} source rocks in the Biyang Depression

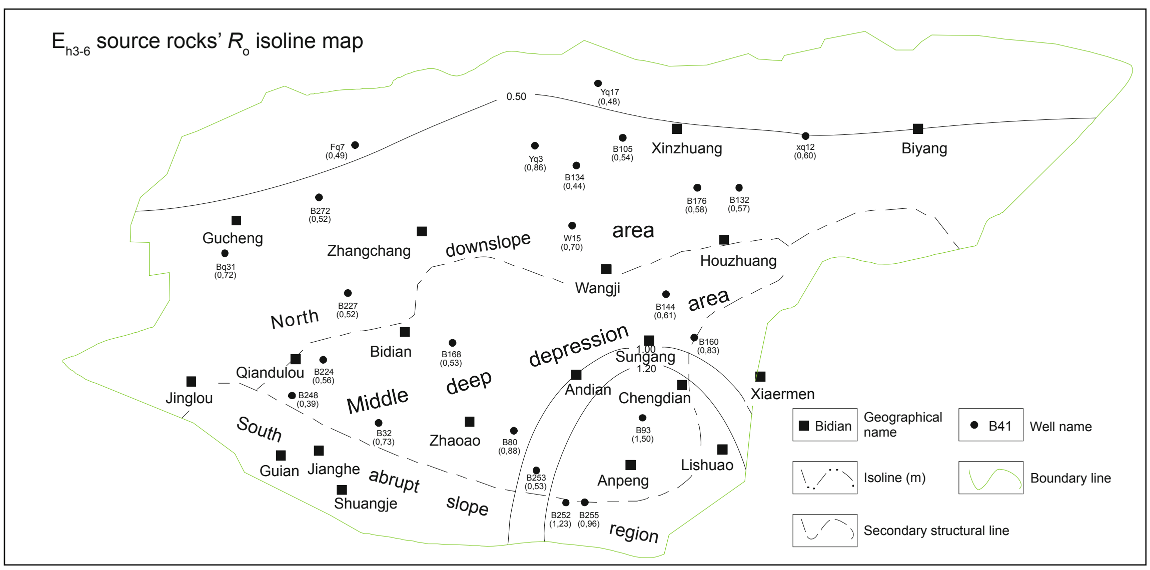

Fig. 5 Contour map showing R_O of the E_{h3-6} source rocks in the Biyang Depression

According to Fig. 6, the E_{h3-2} sand group has the highest oil-generating quantity of all the E_{h3} source rocks; the E_{h3-6} sand group has the highest oil-generating quantity of all the lower members of E_{h3} source rocks, and the E_{h3-7} sand group has the lowest oil-generating quantity. Every sand group's oil-generating quantity is similar to each other. The gas-generating quantity rises from the E_{h3-1} sand group to the E_{h3-8} sand group, but the gas-generating quantity plays little part in the total E_{h3} resource quantity, so the E_{h3-2} sand group still has the highest total resources, and the E_{h3-6} sand group has the most resource quantity of all the sand groups of the lower members of E_{h3}. From E_{h3-5} to E_{h3-8}, the sand groups account for 13%, 14%, 12%, 12% of the total hydrocarbon-generation quantities, respectively, collectively 51% of the total.

4.2 Comparison of hydrocarbon-generation quantity of E_{h3} of every structural belt

The Biyang Depression is divided into six structural belts, namely Shuanghe-Anpeng, Jinglou-Gucheng, Xiaermen, Wangji-Xinzhuang, Fuwan and Dawuzhuang.

Fig. 7 is a comparison chart of the estimated oil & gas resources of E_{h3} in each of the structural belts. From this figure, the E_{h3} source rocks of the Shuanghe-Anpeng structural belt are estimated to have produced 0.21 billion tonne of oil and gas in situ, the highest of all the belts, so it has the best prospect for petroleum exploration. The E_{h3} source rocks of the Jinglou-Gucheng structural belt have produced estimated 0.069 billion tonne of oil and gas, the E_{h3} source rocks of the

Xiaermen structural belt 0.080 billion tonne of oil and gas, and the E_{h3} source rocks of the Wangji-Xinzhuang structural belt 0.087 billion tonne of oil and gas. The three structural belts' total oil and gas resources are similar, so they all have good prospect for petroleum exploration. The Fuwan and Dawuzhuang structural belts are likely to have produced few resources, so they have little prospect for petroleum exploration.

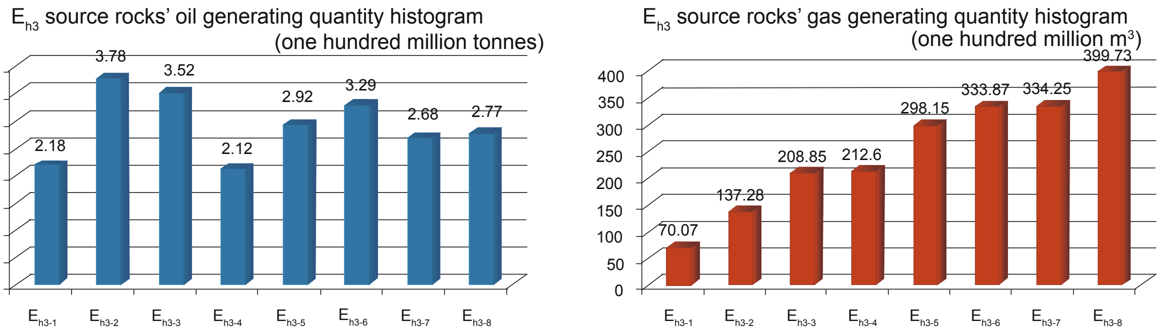

Fig. 6 Oil & gas generating quantity histogram of the E_{h3} source rocks in the Biyang Depression

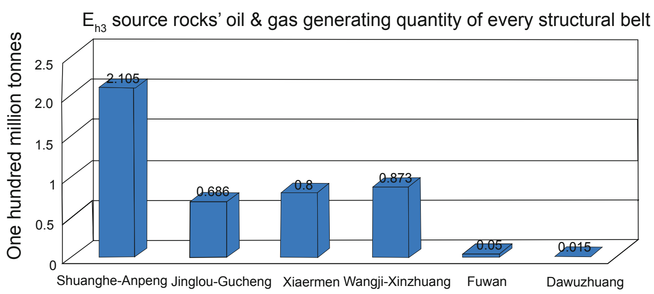

Fig. 7 Comparison chart showing the oil & gas generation potential of E_{h3} source rocks of every structural belt in the Biyang Depression

5 Conclusions

The lower members of E_{h3} source rocks of the Biyang Depression are typically continental lacustrine facies deposits. The climate was warm and wet, so lacustrine aquatic algae were luxuriant, and the source rocks are mainly of the Type II_1, secondarily the Type I and II_2, which is good for hydrocarbon generation. Due to the lacustrine transgression-regression cycle, dark mudstone and oil shale of the semi-deep to deep lake facies developed, and these efficient source rocks were mainly distributed in the Anpeng-Andian and Bidian-Zhaoao areas. The river brought nutrient materials, and the delta front and prodelta located in Jinglou-Shuanghe-Gucheng-Zhangchang were full of aquatic organisms, so the abundance of organic matter was high. Most of the source rocks in the Biyang Depression are mature, especially those of the semi-deep to deep lake facies that are at the peak of hydrocarbon generation. In conclusion, the systematic study of the geochemical characteristics of the lower members of E_{h3} source rocks confirms that the lower members of E_{h3} source rocks are widespread, and their kerogen type is better and in the mature stage, so they have good material basis to produce oil and gas.

Comparing the lower members of E_{h3} source rocks with the upper members of E_{h3}, the former have higher hydrocarbon-generation potential. The hydrocarbon-generation quantity accounts for 51% of the total, specifically, the oil-generating quantity accounts for 50% and the gas-generating quantity accounts for two thirds. In addition, from the comparison among E_{h3} oil & gas resources of every structural belt, Shuanghe-Anpeng, Xiaermen and Wangji-Xinzhuang structure belts will be the key exploration areas, and Fuwan and Dawuzhuang structure belts have little hydrocarbon-generation potential.

To sum up, comprehensive geological study and geochemical analysis, qualitative analysis and quantitative analysis, have together proved that the source rocks of the lower members of E_{h3} are high-quality hydrocarbon source rocks and have a good potential of hydrocarbon resource. Recently, the lower members of E_{h3} have shown commercial oil in the well of E-wang 25, confirming that the lower members of E_{h3} source rocks are good prospects for exploration for primary hydrocarbon reservoirs and deep-basin gas.

References

Luo J Q. Reservoiring patterns of oil and gas in the deep layer of the Biyang Depression. Oil & Gas Geology. 2003. 24(1): 55-57 (in Chinese)

Luo J Q, Gan H J, Cai J, et al. Source differences and geochemical characteristics of the upper and lower members of E_{h3} in the lower Tertiary of the Biyang Depression. Journal of Oil and Gas Technology. 2008. 30(2): 20-24 (in Chinese)

Pang X Q, Meng Q Y, Jiang Z X, et al. A hydrocarbon enrichment model and prediction of favorable accumulation areas in complicated superimposed basins in China. Petroleum Science. 2010. 7(1): 10-19

Pepper A S and Corvi P J. Simple kinetic models of petroleum formation. Part I: oil and gas generation from kerogen. Marine and Petroleum Geology. 1995a. 12(3): 291-319

Pepper A S and Corvi P J. Simple kinetic models of petroleum formation. Part III: Modelling an open system. Marine and Petroleum Geology. 1995b. 12(4): 417-452

Pepper A S and Dodd T A. Simple kinetic models of petroleum formation. Part II: oil-gas cracking. Marine and Petroleum Geology. 1995. 12(3): 321-340

Qin W J. Reservoiring factors of large structural-lithologic composite oil reservoirs in the Biyang Depression. Oil & Gas Geology. 2004. 25(4): 433-436 (in Chinese)

Qin W J, Lin S Q, Cheng Z, et al. Hydrocarbon accumulation and reservoiring pattern in the Biyang Depression, Nanxiang Basin. Oil & Gas Geology. 2005. 26(5): 668-673 (in Chinese)

Qiu N S, Puckette J, Jin Z J, et al. Geothermal regime, thermal history and hydrocarbon generation types of sedimentary basins in the continental area of China. Petroleum Science. 2005a. 2(2): 1-11

Qiu R H, Lin S Q and Tu Y F. Features of hydrocarbon accumulation and analysis on exploration potential in the Biyang Depression. Journal of Oil and Gas Technology. 2005b. 27(2): 158-162 (in Chinese)

Shi G R. Numerical Methods of Petroliferous Basin Modeling, Version 3. Beijing: Petroleum Industry Press. 2004 (in Chinese)

Sun C, Ren Y L, Wu G S, et al. Main controlling factors of hydrocarbon accumulation of the complex fault-block group in the north slope of the Biyang Depression. Journal of Oil and Gas Technology. 2008. 30(3): 29-36 (in Chinese)

Wen Z X, Wang H M, Chen C Q, et al. Formation and distribution of subtle reservoirs in the southern steep slope zone in the Biyang Sag of the Nanxiang Basin. Petroleum Geology & Experiment. 2006. 28(2): 117-122 (in Chinese)

Yang D Q, Lin S Q, Zhu J X, et al. Characteristics of hydrocarbon accumulation assemblage in the north slope of the Biyang Depression. Journal of Oil and Gas Technology. 2005. 27(1): 14-16 (in Chinese)

Yu G M, Wang D F, Zhang S H, et al. The hydrocarbon accumulation system and its resource potential in the Biyang Depression of Nanxiang Basin. Fault-Block Oil & Gas Field. 2007. 14(1): 27-29 (in Chinese)

Zeng X Y, Zhao D L and Kong F J. Analysis of the structural controlling oil pattern in the Biyang Depression. Journal of Oil and Gas Technology. 2005. 27(S3): 422-424 (in Chinese)

Zhou X J and Wu X Y. Analysis of the exploration potential of E_{h2} immature and low-mature oil in the Biyang Depression of the Nanxiang Basin. Petroleum Geology & Experiment. 2004. 26(5): 457-461 (in Chinese)

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