Genesis and petroleum geological significance of calcareous mudstone in Beier Sag

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Abstract. Beier sag is one of the most oil-rich sags in the south of Hailaer Basin in China. The purpose of the study is to clarify the identification characteristics and geological origin of calcareous mudstone strata in Nantun Formation of Beier sag, so as to provide new ideas for the identification and evaluation of high-quality source rocks, and to provide effective support for efficient exploration of oil and gas in the basin. The comparative analysis of logging curves and seismic reflection characteristics shows that the calcareous mudstone layer has the "three high and one low" logging response with high GR (Natural Gamma Ray), high LLD (Deep Investigate Induction Log), high AC (Acoustic) and low DEN (Rock Density), showing continuous and strong seismic reflection characteristics. Through the comparative analysis of experimental data of rock thin slice and microscopic image and organic geochemistry, the layer lithology is mainly gray-black mudstone, locally mixed with oil shale and marl, rich in calcium and algae. The layer has the high abundance of organic matter, good organic matter type (II-1), high hydrocarbon-generating potential and high hydrocarbon-exhausting efficiency. It is the highest quality source rock found in Beier sag, and is the material base to form the large scale oil and gas accumulation. The formation of calcareous mudstone formed in the brackish water and wide lake basin by a wide range, represents the anoxic event early in Cretaceous period and is the significant stratigraphic correlation marker bed of the sag. In addition, this layer and the fan-delta front sand widely distributed in the lower part of Nantun Formation form the most favorable reservoir combination, which controls the plane distribution of oil and gas reservoirs. Above and below the calcareous mudstone strata, oil and gas are very rich.

1. Introduction

There is a good correlation between the high-quality source rock distribution and reservoir distribution [1-3], the theory of high-quality source rock controlling reservoir distribution has become an important theoretical basis for petroleum geologists to carry out oil and gas exploration. The high-quality source rock in Beier sag is located in the lower part of Nantun Formation, gray-black calcareous mudstone with oil shale and marl in some areas. About distribution and genesis of calcareous layer, O’ Brien G W[4], Ezat H[5], et al. considered that the genesis of calcareous layer is related to hydrocarbon related diagenetic zones (HRDZs). These studies mainly focus on calcareous reservoirs rather than calcareous mudstone. In this study, the data of core, logging, well logging and seismic are comprehensively applied. The calcareous mudstone layer has the "three high and one low" logging response with high GR (Natural Gamma Ray), high LLD (Deep Investigate Induction Log), high AC (Acoustic) and low DEN (Rock Density), showing continuous and strong seismic reflection characteristics. Compared with the...

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ordinary mudstone layer, the difference is obvious. This study systematically analyzed the sedimentary water, biological composition, climate and oxidation-reduction environment, and elucidated the geological origin of calcareous mudstone strata. It is the best source rock in Beier sag, which controls the enrichment and horizontal distribution of oil and gas, and provides support for efficient exploration of oil and gas.

2. Geological outline
Beier sag is located in the south of the central fault depression zone of Hailaer Basin. It connects Wuerxun Sag in the north with South Beier sag of Tamtsag Basin in the south. Beier sag is a typical dustpan fault depression and the largest secondary tectonic unit of the basin, with an area of 3010 km². Beier sag experienced three stages of tectonic evolution, rifting stage and rifting-subsiding stage and subsiding stage. The Nantun Formation deposited in the rifting stage is the main exploration layer, and most of the discovered reserves occur in this layer. The accumulated thickness of calcareous mudstone strata reaches about 80 m.

3. Lithologic characteristics
The lithology of the calcareous mudstone is mainly black mudstone, partly mixed with thin interbed marl and oil shale, and the thickness of single mudstone is 0.15m–0.50m. Brittle fractures are commonly developed, which are oil-bearing, oil-immersed or oil-spotted, and fill calcite veins. The pores are mainly cemented by carbonate minerals, mainly composed of iron calcite, partly of clay and powdery dolomite, and some of them are bioclastic with high calcium content, high mass fraction of carbonate and acid dripping foaming. The results of thin section identification and analysis in the laboratory show that the layer is an argillaceous structure with a small amount of silt-grade debris, which is distributed in a directional way. Due to the fine grain size, it is impossible to identify the composition of rock blocks [6]. Occasional, a small amount of volcanic ash is mixed with mud, part of the clastic particles are all metasomatized by carbonate, presenting a pseudomorphic appearance. Ostracoda fragment, with a mass fraction of about 8%, are distributed in the rocks in a directional arrangement (Fig.1), mixed microporphy carbonate in the mud.

The results of carbonate mass fraction analysis show that the carbonate mass fraction of ordinary mudstone ranges 0.2% ~ 5.1%, with an average of 1.4%. The carbonate mass fraction of sandstone ranges 0.2% ~ 2.9%, with an average of 0.5%. The carbonate mass fraction of calcareous mudstone ranges 1.3% ~ 20.3%, with an average of 9.8%, which is about 7 times that of ordinary mudstone and 20 times that of sandstone.

4. Electrical characteristics
The well logging curve is tooth uniform and distinguishes clearly from the flat electrical characteristics of conventional mudstone. The calcareous mudstone layers are fine grained deposits with large specific surface area, strong adsorption and high content of radioactive elements in the rocks. The natural gamma number generally ranges 70~197API, with an average of 135API, indicating high natural gamma. The calcareous mudstone layer is located in the lower part of Nantun Formation, and the burial depth is generally greater than 1800m. The mudstone is mature and has hydrocarbon generation and expulsions. The pores inside the mudstone are filled with hydrocarbons, resulting in high resistivity. The LLD (Deep Investigate Induction Log) ranges 5~110Ω•m, with an average of 15Ω•m. Compared with other longitudinal mudstone sections (LLD, 3~5Ω•m), the average resistivity is 3~5 times higher. Due to the high content of organic matter, the rock structure loose, the ability of transmitting sound wave is poor. The AC (Acoustic) ranges 80~132μs/ft, with an average of 95μs/ft, which is higher than that of other longitudinal mudstone segments (AC, 70~90μs/ft). The rocks are rich in algae. Since the density of organic matter is between 1.03g/cm³ and 1.10g/cm³ and the density of rock skeleton is between 2.30g/cm³ and 3.10g/cm³, the overall lithologic density of calcareous mudstone layers is lower, between 2.35g/cm³ and 2.45g/cm³. However, the rock density of the conventional mudstone section ranges from 2.40g/cm³ to 2.60g/cm³ (Fig. 1).

The calcareous mudstone has the characteristics of "three high and one low" logging response with high GR (Natural Gamma Ray), high LLD (Deep Investigate Induction Log), high AC (Acoustic) and low DEN.
(Rock Density). The logging curve presents positive cycle, showing abrupt contact with overlying reverse cycle, which is easy to identify and calibrate. The seismic event is characterized by medium-high frequency, medium-strong reflection and medium-good continuity. The thick dark mudstone developed above and below this layer is characterized by low frequency, weak reflection and poor continuity.

**Figure 1.** Identification diagram of calcareous mudstone strata of B70 well

5. Thickness and distribution characteristics
The sedimentary thickness of this layer is generally between 30m and 50m, and the thickest of a single well is up to 80m, accounting for about 15% of the total thickness of the dark mudstone of Nantun Formation. On the plane, this layer is distributed in the whole area, with a certain regularity in thickness and scale distribution. It is mainly found in Beixi sub-sag, Huonan trough, Beizhong sub-sag and Beidong sub-sag, and a certain size and distribution are also found in the residual trough group of northern Beidong sub-sag, which is well matched with the discovered oil and gas reservoirs (Fig. 2).

**Figure 2.** Composite map of calcareous mudstone strata and oil reservoirs in Beier sag
6. Geological origin

The calcareous mudstones in Beier Sag are different from ordinary mudstones mainly by high abundance of organic matter and high content of calcareous matter. The high abundance of organic matter depends on the high production and preservation of organic matter, and the high content of calcareous matter depends on the paleosedimentary environment. The distribution, quantity and quality of organic matter, especially the composition and distribution of biomarkers, are closely related to the depth and salinity of sedimentary water, the addition of aquatic or terrestrial organisms, regional climatic conditions, and the redox conditions of sedimentary water.

The calcareous mudstone strata were formed in the period of strong extension development of Hailaer Basin. The basin subsided rapidly, the sedimentary water was deepened (the paleosedimentary water between 200m and 300m). The accommodation space increased sharply, and the source supply was far less than the sedimentary capacity of the basin. In the subsidence center of the basin, undercompensated sediments are formed. The layer is a condensation layer, with slow deposition rate, wide and stable deposition range, riching in organic matter and shell and other biological fossils which is conducive to the formation and preservation of organic matter. In short, it is key to the formation of high-quality source rock.

High-quality source rocks in salinized lake basins often coexist with carbonate, sulfate and chloride deposits in deep water [7]. The GC-MS (gas chromatography-mass spectrometry) show that the calcareous mudstone strata contain trinorhopanes, steranes and β-carotanes, which confirm that the water is a strong reducing and anaerobic sedimentary environment of brackish water [8]. In addition, Pr/Ph (the ratio of pristane to phytane ) mainly distributed from 0.65 to 0.91, the content of TS (M/Z=191) significantly higher than TM, gammacerane also be found, shows that it is a deep water restoration environment. On the sterane chromatogram, that the calcareous mudstone contains pregnanes and rearranged steranes with asymmetric inverted "V" distribution, is also confirmed to be a salinized environment (Fig. 3).

The development of aquatic microorganisms and algae coincides with the growth of algae and other organisms after salinization in the lake basin. The algal blooms also induced extensive deposition of calcareous laminar mudstone. After a large number of algae deposited, amorphous organic matter lamina was formed under the degradation of deep-water microorganisms.

![Figure 3. GC-MS of calcareous mudstone strata](image_url)

In terms of biological composition, the analysis of kerogen macerals by transmission light-fluorescence shows that the calcareous mudstone is rich in organic matter, mainly laminar algae, sapropel amorphous (up to 280), and a small amount of unstructured vitrinite and inertinite filaments. The organic matter in this layer mainly comes from lower aquatic organisms, aquatic microorganisms and algae, such as ostracods, gastropods, dinoflagellates and lamellar algae.

The Nantun Formation is a period of frequent volcanic activities in Hailaer Basin. During this period, the rise of temperature and lake level accelerated the development of water invasion system tract. Volcanic activities provide a variety of growth elements for algae and other organisms, have the effect of "fertilizing"
or "adding nutrition", promote algae to flourish [9], increase the salinity and calcium content of the water, and lead to the formation of water stratification and bottom reduction environment. The concentrated occurrence of calcareous mudstone and marl and oil shale represents a global anoxic event. The calcareous mudstone formed by anoxic events in Hailaer Basin can be compared with the anoxic event sedimentary layers in Belias and Vanlan. According to the characteristics of calcareous mudstone, it can connect the Hailaer Basin with the Cretaceous faulted basins in Northeast Asia (such as Yin-E Basin and Erlian Basin), and forms a unified regional geological knowledge.

7. Geological Significance
Calcareous mudstone is the best source rock in Beier sag. The type of organic matter is \( \text{II}_1-\text{I} \) (Fig. 4-Types of organic matter), and the type and abundance of organic matter are better than that of ordinary mudstone. Lu Shuangfang et al. recommended the TOC mass fraction of 2.0% as the lower limit standard for high-quality source rocks when studying the evaluation standard of high-quality source rocks in Hailaer Basin, and the average TOC mass fraction of calcareous mudstone samples in Beier Sag is more than 2.0%. In addition to TOC, other hydrocarbon generation index scores (S1+S2, Chloroform Asphalt “A”, Vitrinite Reflectance “Ro”) are also better than those of ordinary mudstone (Table 1).

As can be seen from Table 2, HI (Hydrogen Index), degradation potential, hydrocarbon expulsion factor and aggregation factor are more than 1.5-3.0 times of those of ordinary mudstone. If the product of one of the first three indexes and hydrocarbon expulsion and aggregation factor is taken as the ratio of hydrocarbon generation potential, the hydrocarbon generation potential of calcareous mudstone strata will reach more than 6 times of those of ordinary mudstone (Fig. 4-Hydrocarbon generation potential).

Oil source correlation shows that the crude oil in Beier Sag belongs to mature crude oil, which is closest to the samples of calcareous mudstone (w(TOC)>2.0%) of Nantun Formation, showing a good genetic relationship (Fig. 4-Source correlation of oil in Nantun Formation). Using chloroform asphalt "A" method to calculate the resource of Beixi sub-sag, the hydrocarbon generation amount of calcareous mudstone strata accounts for 40% of the total hydrocarbon generation amount of Nantun Formation, which is 3-8 times of those of other hydrocarbon generation units.

![Figure 4. Comparison diagram about types and hydrocarbon potential of the organic matter between calcareous mudstone strata and ordinary mudstone in Beier sag](image)

| Table 1. Comparison of hydrocarbon index between calcareous mudstone and ordinary mudstone |
|-----------------------------------------------|
| rock stratum                        | TOC (mg g\(^{-1}\)) | S1+S2 (mg g\(^{-1}\)) | Chloroform Asphalt “A” (\%) | Kerogen type | Vitrinite Reflectance, Ro (\%) | conclusion |
| calcareous mudstone                 | 4.73 / 0.16 | 2.45 / 38 | 0.8351 / 0.0077 | \( \text{II}_1-\text{I} \) | 0.80~1.26 | good |
| ordinary mudstone                  | 4.19 / 0.05 | 1.79 / 520 | 0.4711 / 0.0011 | \( \text{II}_2-\text{II}_1 \) | 0.40~1.20 | moderate |

Remarks: \( \text{Max} / \text{Min} \), \( \text{Avg} / \text{Qty} \)
Table 2. Ratio of hydrocarbon generation potential between calcareous mudstone and ordinary mudstone in three sub-sags of Beier sag

| sub-sag | Toc  | HI    | Degradation Potential | Hydrocarbon Expulsion Factor | Aggregation Factor | Hydrocarbon Generation Potential |
|---------|------|-------|------------------------|------------------------------|-------------------|----------------------------------|
| Beixi   | 2.91 | 2.54  | 2.40                   | 1.7                          | 1.6               | 6.5~7.9                          |
| Beizhong| 3.23 | 2.06  | 1.89                   | 1.8                          | 1.7               | 5.7~9.8                          |
| Beidong | 3.01 | 2.33  | 1.86                   | 1.6                          | 1.4               | 4.1~6.7                          |

Exploration practice shows that Hailaer Basin has the characteristics of multi-layer oil-bearing, and the distribution of mature source rocks controls the distribution range of oil reservoirs. The calcareous mudstone has the greatest hydrocarbon generation potential, makes the most favorable reservoir combination with the above and below sandstone. Self-generated and self-contained reservoir is the main form of oil and gas accumulation. The proved reserves controlled by this combination account for 67% of the total amount of Beier sag, which is the main exploration target. Based on the theory of calcareous mudstone, we have found several high-yield well areas in Beier sag, for example H3-6 well, which has a high-yield industrial oil flow of 382t/d.

8. Conclusion
The calcareous mudstone has the characteristics of "three high and one low" logging response, and its seismic reflection characteristics are continuous and strong. It is easy to identify in logging curve and seismic profile. The lithology of this layer is mainly gray-black mudstone, locally mixed with oil shale and marl, rich in calcium and algae. The layer has the high abundance of organic matter, good organic matter type (Ⅱ1-Ⅰ), high hydrocarbon-generating potential and high hydrocarbon-exhausting efficiency. All of these are the material base to form the large scale oil and gas accumulation. The formation of calcareous mudstone formed in the brackish water and wide lake basin by a wide range, represents the anoxic event early in Cretaceous period and is the significant stratigraphic correlation marker bed of the sag. In addition, this layer and the fan-delta front sand widely distributed in the lower part of Nantun Formation form the most favorable reservoir combination which controls the plane distribution of oil and gas reservoirs. Above and below the calcareous mudstone strata, oil and gas are very rich. This study can provide new ideas for the identification and evaluation of high-quality source rocks, and also provide effective support for efficient exploration in the basin.

References
[1] Zhang Wenzheng. Yang Hua, et al. Leading effect of high-class source rock of Chang 7 in Ordos Basin on enrichment of low permeability oil-gas accumulation-Hydrocarbon generation and expulsion mechanism [J]. Petroleum Exploration and Development, 2006, 33(03):289-293.
[2] Wang Weiming, Lu Shuangfang, Cao Ruicheng, et al. High-quality hydrocarbon source rock identification and hydrocarbon migration and accumulation characteristics in the Wudong slope zone of the Hailer Basin[J]. Oil & Gas Geology, 2011, 32(54):692-697.
[3] Jiu Kai, Ding Wenlong, Huang Wenhui, et al. Analysis of geological condition of the formation of Shahejie shale gas in Jiyang Depression in Bohai Bay Basin[J]. Journal of Northeast Petroleum University, 2012, 36(2):65-70.
[4] O’Brien G W, Lisk M, Duddy I, et al. Plate convergence foreland development and fault reactivation: Primary controls on brine migration, thermal histories and trap breach in the Timor sea, Australia[J]. Marine and petroleum Geology, 1999, 16(6):533-560.
[5] Ezat H, William J M. Massive recrystallization of low Mg calcite at high temperatures in hydrocarbon source rocks: Implications for organic acids as factors in diagenesis[J]. AAPG Bulletin, 2002, 86(7):1285-1303.
[6] Li Cai, You Li, Zhu Jitian. Distribution and controlling factors of calcareous layer on the lower section of the first member of Zhujiang formation in Shenhua uplift[J]. Journal of Northeast Petroleum University, 2014, 38(1):37-44.
[7] Jin Qiang, Zhu Guangyou. Progress in Research of Deposition of Oil Source Rocks in Saline Lakes and Their Hydrocarbon Generation[J]. Geological Journal of China Universities, 2006, 12(4):483-492.

[8] Ma Ning, Hou Dujie, Shi Hesheng. Analysis of the main controlling factors of source rocks of Huizhou sag in the Pearl River Mouth Basin[J]. Journal of Northeast Petroleum University, 2012, 3(36):19-24.

[9] Liu Chiyang, Zhao Junfeng, Ma Yanping, et al. The advances and problems in the study of the characteristics and formation of hydrocarbon-rich sag[J]. Earth Science Frontiers, 2014, 21(1):75-85.