1 Introduction

Clay minerals are main components in shale and mudstone, different components including montmorillonite, Illite/montmorillonite (I-S) mixed layer, illite and chlorite in shale have different gas sorption capacity. Therefore, further analysis and evaluation on the components of clay minerals is necessary for evaluating the mechanism of shale gas existence. Clay minerals are composed by various elements, and different element contents reflect different minerals. The distribution of different element varies with the transportation, sedimentation and diagenesis of sediments, and many inorganic element ratio parameters have been used to recover sedimentary environment and ancient climate. Therefore, inorganic element geochemistry as well as mineralogy and microbiology, is increasingly important in the research and exploration in unconventional shale gas. However, sufficient clay mineral and inorganic element information is difficult to obtain through actual measurement, and the prediction of clay mineral and inorganic element using logging data to is necessary for evaluating the mechanism of shale gas existence.

The lower part of Member 3 of Paleogene Shahejie Formation (Es3) were one of the main source rock intervals with relative large burial depth in Dongying sag, eastern China (Chen and Zha, 2006). The Es3 source rocks deposited in lacustrine brackish water condition with semi-deep to deep lacustrine facies, and the main lithology were massive mudstone, grey brown oil shale and pure shale. This interval reached moderate maturity to high maturity thermal evolution stage, therefore, not only oil was abundant, but also considerable natural gas was generated, which formed coexisted situation of oil and gas. This article is mainly to describe classification, distribution of this Paleogene Es3 mudstones, and use logging data to predict elements in mudstone.

2 Classification and Distribution of Mudstone

2.1 classification of Mudstone

Based on characteristics of microscopic laminae and mineral compositions of mudstone, the Paleogene Es3 mudstones in Dongying depression were classified into five types.

oil shale

Oil shale was defined as the rocks that there is high kerogen abundance and is able to yield sufficient petroleum which met industrial value. Beddings were developed in oil shale with the component of organic-rich laminae and calcareous laminae (Liu et al., 2001). Double-layer structure was a significant sedimentary characteristic of oil shale in the study area. The white, fine-grained calcite laminae mainly consisted of pure carbonates, with slight thickness than organic laminae. The oil shale was observed by transmission electron microscopy and only found that light laminae was calcareous nannofossil with the characteristics of tight superposition, clear shapes and single species (Wang, 2012).

calcareous laminated shale

The main color of calcareous laminated shale was black-gray, dark-gray, gray-yellow, gray-white. Beddings were developed in this type of mudstone with higher clay content, relative lower carbonate content (general within 50%). Besides, pyrite was frequently found in the calcareous laminated shale. Generally, couplet was consisted of the distinctive light laminae layer and dark layer which are corresponding to cryptocrystalline carbonate laminae and organic-rich laminae under microscope. Besides, clay laminae was also developed in the calcareous laminated shale. The components of light...
laminae are micron to millimeter-cryptocrystalline carbonate, occasionally mixed with faint clay laminae. Dark laminae is consisted of organic-rich clay layers. They even formed medium-thick calcareous laminated shale interval. Terrigenous clastic was rare, sometimes silt lamination and clay lamination could also be observed. In general, bottom boundary of laminae manifested mutant which represented detrital materials with rapid progradation seasonality. Clay laminae generally located in the lowermost of lamina couplet, and upward contacted cryptocrystalline carbonate laminate that has very few organic matter and clay mineral. This suggested that rapid deposition of cryptocrystalline might be caused by rapid growth of algae, large amounts of carbon dioxide that was absorbed in carbonate deposited. Organic lamina was mainly derived from amorphous organic matter, which was the decomposition product of algae.

**calcareous mudstone**

For calcareous mudstone, the components were hybrid lamina of carbonate and clay, as well as a small amount of organic laminae. Carbonate mineral content was high with contents from 40% to 50%. While, as calcite and clay formed laminae together, calcium laminae was not obvious and was uneasy to recognize.

**laminated marlrite**

For laminated marlrite, the mostly observed color was grey white and light grey, and the carbonate content was high (up to more than 60%) and the content of organic matter as well as clay and siltstone was low. Lamellatio was not obvious, and the boundary between light and dark layer was not clear. In terms of rock composition, laminated marlrite showed laminate structure that was transitional between calcareous laminated shale and calcareous mudstone.

**massive mudstone**

Massive mudstone usually showed dark-gray and gray color, and non-laminated structure on the core, with high content of clay and relatively low content of carbonate (generally less than 30%). The content of organic matter was moderate and the content of terrigenous silt was between 10% and 25%. Massive mudstone generally formed in an environment with the following characteristics: deep water, moderate volatility, close to source, no water stratification and rapid sedimentation rate.

2.2 Distribution of Mudstone

In Dongying sag, the thickness of Paleogene E3\(^1\) clay rock was mostly over 100 meter (fig.1), and the thickness of mudstone depocenter in the Minfeng sub-sag was from 100 m on the edge to 280 m in the central. The close distribution of thickness isoline reflected relatively large gradient, which indicated that during the same geological period and deposition process, the sedimentation environment was in deep water condition with fast rate of water transgression. The thickness of clay rock in the Lijin sub-sag was from 100m to 150m, and displayed
decreasing trend along the northwest-southeast direction. The thickness of clay rock in the Niuzhuang sub-sag was from 80m to 220m and displayed decreasing trend from the north to south. The thickness of clay rock in the Boxing sub-sag was minimum, with the thickness from 60m to 80m.

In general, the clay rock was mainly distributed in the northeast. The difference in the thickness of clay rock was quite remarkable among four the sub-sags (Lijin, Minfeng, Niuzhuang and Boxing). The thickness isolines of total clay rock in the Lijin and Minfeng sub-sags were generally stretching along the northeast-southwest direction. While, for the Boxing and Niuzhuang sub-sags, they were generally stretching along the northwest-southeast direction. This difference was relevant to different water environment and structural geological background.

The thickness of the $E_{3}^{1}$ calcareous mudstone was less than clay rocks in Dongying sub-sag (fig. 2), and the maximum thickness was up to 110 m. The thickest was in the Minfeng sub-sag, where was from 10m to 30m and showed increasing tendency from the south to the north. The thickness of calcareous mudstone was large in the Niuzhuang sub-sag, and the thickness isoline displayed dumbbell-shaping in east-west direction with two depocenters. The thickness isoline of the Boxing sub-sag stretched in the northwest-southeast direction, with the thickness of 10m-70m. On the whole, the $E_{3}^{1}$ calcareous mudstone in the Dongying sag mainly distributed in southeast and showed decreasing tendency from the southeast to the northwest.

On the whole, the calcareous laminated shale was just distributed in local area with little amount. It was mainly distributed in the east and the maximum thickness was up to 29m. The difference in the thickness of calcareous laminated shale was remarkable in the north-eastern of the Lijin sub-sag, with maximum thickness of 30m and minimum thickness of 2m. In the Niuzhuang sub-sag, the thickness of calcareous laminated shale was mainly distributed between 2m and 10 m. In Boxing and Lijin sub-sags it was rare.

Oil shale was widely distributed in the study area (fig. 2), and there is a big depocenter in the west of Minfeng.
sun-sag with the maximum thickness of 85m. comparatively, the oil shale was relatively less distributed in the Niuzhuang sub-sag.

3 Prediction of Element and Clay Mineral Content in Mudstone

The contents of clay minerals in the N-38 Well (2750-3400m) and HK1 Well (3780-4450m) in the Dongying Depression, eastern China were intensively measured by X-ray diffractometer. Chlorite and kaolinite contents are limited (< 5% and < 10%, respectively) in the mineral composition of the studied intervals. Illite content is distributed between 16% and 53% and consists mainly of a mixed layer of illite and smectite, with this layer generally comprising 50% of the content. The characteristics of this mixed layer, which dominates representative mudstone and shale samples, are shown in Fig. 3. Meanwhile, the element energy spectrum and element content of four points in the sample from 3291.4 m (the sample for I–H in Fig. 3) are shown in Fig. 4.

A few samples in the Es1 have a mixed layer of illite and smectite content distributed between 40% and 50%. The mixed layer exhibits a significant decrease, whereas illite presents an obvious increase with depth increasing.

Geophysical well logging was widely used in the sequence division and reservoir evaluation in the petroleum industry. In addition to this direct application, the well logging can be combined with other geological data to establish a prediction model to forecast the unknown region geological and geochemical characteristics. The method of fitting regression equation was used to predict the element and clay mineral content in this study.

The following steps show the steps in the prediction.

1) We first make a correlation between each element/clay mineral and different well logging parameter, and the logging parameters in the higher correlation were selected as predicted parameters.

2) The LINEST function was used make a regression fitting. According to distribution of independent variables in the EXCEL table, the functions were brought up, the dependent variable arrays and the independent variables were selected, and the required values of regression were achieved.

3) In order to make the prediction model is more scientific and reasonable, some transformation on the data in the process of application function fitting was necessary. Because the LINEST function was resulted in multivariate linear regression equations, to reach higher order or nonlinear equation, the parameters of the array arguments can be transformed with the methods of exponentiate, logarithmic and ascending power.

4) Observe the changes of determination coefficient, and establish a good correlation regression equation from the results. In order to optimize the regression equation, it is necessary to eliminate parameters that show little effects on the dependent variable. In order to verify the validity of the prediction models, inspection the match of measured and predicted values is necessary (Fig. 5).

Combining with logging data resistivity (RT), acoustic time (AC), natural gamma (GR), prediction models of clay minerals and elements were established based on the minimum square method of fitting and regression using the computer system function LINEST. Several models related to clay minerals are as follows:

1) Illite = 114.39 + 2.88 × RT0.5 - 9.7 × AC0.5 (R=0.8);
2) Kaolinite = 35.49 - 0.0468 × RT0.5 - 2.95 × AC0.5 (R=0.63);
3) I-M = 10.48 - 0.00716 × RT2 + 0.0083 × AC2 (R=0.73);
4) Total Clay Mineral = 84.9 - 1.49 × RT0.5 - 13.8 × AC0.5 (R=0.73);
5) Ca = -6.17 + 0.104 × 10^-1 RT2 + 0.955 × 10^-1 AC2 (R=0.85);
6) Sr = -267.48 + 2.11 × 10^-2 GR2 + 7.0 × 10^-2 AC2 + 262.72 × lnRT (R=0.82);
7) K = 2.56 - 3.7 × 10^-6 RT - 1.62 × 10^-3 AC2 - 0.13 GR2 (R=0.81);
8) Na = 2.62 - 0.13 × 10^-4 RT - 1.56 × 10^-4 AC2 (R=0.88);
9) Zn = -4.06 - 6.9 × 10^-2 RT2 + 0.94 × 10^-2 AC2 (R=0.71);
10) Ba = 5083.3 - 6.09 × 10^-2 RT - 7.6 × 10^-2 AC2 (R=0.78);
11) V = 95.8 - 9.58 × 10^-2 RT2 + 5.57 × 10^-2 AC2 (R=0.77);
12) Mn = 2477.28 + 7.08 × 10^-2 RT2 + 3.1 × 10^-1 AC2 (R=0.76);
13) Ni = -3.61 - 9.84 × 10^-3 RT2 + 5.82 × 10^-1 AC2 (R=0.81);
14) Fe = -13.06 + 4.63 × lnRT (R=0.77).

4 Conclusions

Based on characteristics of microscopic laminae and mineral compositions of mudstone, the Paleogene Es1 mudstones in Dongying depression were classified into five types: oil shale, calcareous laminated shale, calcareous mudstone, laminated marlite and massive mudstone.

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Acknowledgements

This study was co-supported by the National Natural Science Foundation of China (Grants No. 41272140), the Fundamental Research Fund for the Central Universities.

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