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A comparative study of oil shale-bearing intervals in the Lower Cretaceous Jiufotang Formation in the Beipiao Basin, Northeast China based on sedimentary organic-facies theory

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Abstract. *In this paper, the sedimentary organic facies is defined as a stratigraphic unit that not only contains organic matter (OM) of particular abundance, genetic type and spatial distribution, but also is influenced by its sedimentary environment and preservation conditions. This study aims to reveal the characteristics of OM accumulation in sediments. In the current work, three sedimentary organic facies of oil shale (OS) in the Lower Cretaceous Jiufotang Formation in the Beipiao Basin, Northeast China were distinguished on the basis of OM content, source and sedimentary environment. The accumulation conditions and characteristics of oil shale in different sedimentary organic facies are divergent. Deep-lake sapropelic oil shale with a high alginate-originated total organic carbon (TOC) content is deposited in a strongly reducing environment and is featured by high oil yield, medium-high calorific value, medium to low ash content, and low sulfur content. Deposited in a moderately reducing environment and having a medium alginate- and sporinite-derived TOC content, deep-to-semi-deep-lake sapropel–humic sapropelic oil shale is characterized by medium oil yield, medium calorific value, high ash content, and medium sulfur content. Semi-deep-lake humic-sapropelic oil shale with a medium-low terrigenous and alginate-mixed originated TOC is deposited in a weakly reducing environment and is characterized by low oil yield, low calorific value, high ash content, and high sulfur content. The current study of sedimentary organic facies also contributes to predicting high-quality oil shale. The quality of oil shale is controlled by organic matter content and sedimentary environment. Strongly reducing deep lake water with abundant alginate is an ideal environment for the accumulation of high-quality oil shale.*

Keywords: *oil shale characteristics, sedimentary organic facies, organic matter enrichment model, Beipiao Basin.*

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1. Introduction

The theory of sedimentary organic facies was developed from the concept of organic facies [1, 2]. Compared with organic facies, the study of sedimentary organic facies puts more emphasis on the sedimentary environment and spatial distribution of organic matter (OM). Therefore, this study represents a great possibility for elucidating the origin of OM in organic-rich mudstone and for predicting energy and mineral resources in shale [3, 4].

Previous studies have shown that oil shales in the continental basins of China are of different types [5–8]. The genetic types of oil shale are closely related to the abundance, type and source of organic matter in sediments. However, the original sedimentary organic facies control the formation of biological assemblages. Meanwhile, the biological assemblages control the source of OM, while the sedimentary and diagenetic environments govern its formation and evolution. Therefore, there is a close relationship between sedimentary organic facies and the types of oil shale.

In this paper, the sedimentary organic facies is determined from three aspects: organic matter content, source and sedimentary environment. Compared with the traditional classification of sedimentary facies, which only takes into account the sedimentary environment, we also consider the organic geochemical characteristics of rock. The quality of oil shale of the Lower Cretaceous Jiufotang Formation in the Beipiao Basin is variable, with oil yield ranging from 3.35 to 12%. The sedimentary environments and organic geochemical characteristics of the oil shales with different qualities are also quite divergent. This contribution aims to study the sedimentary organic facies of oil shales in the Beipiao Basin, using the petrology, industrial quality, organic geochemistry, sedimentary environment and preservation criteria.

2. Regional geological background

The Beipiao Basin is located in the western part of Liaoning Province, Northeast China. It is adjacent to the Chifeng-Kaiyuan Fault in the north and the Taohuatu Uplift in the Jianchang Basin in the south. The basin extends in a north-easterly direction with an area of 1200 km^2. The study area contains abundant oil shale and coal resources [9]. The maximum cumulative thickness of oil shale may reach 350 m, with an average cumulative thickness of 170 m. Nine layers of industrial quality oil shale have developed (Fig. 1). The basement of the Beipiao Basin is composed of Archean metamorphic rock series, and the overlying deposits are represented by Paleozoic-Carboniferous sandstones, Jurassic coal-bearing series, Cretaceous sandy conglomerate and oil-bearing shale series, and Quaternary strata. The Lower Cretaceous Jiufotang Formation is the main basin filling stratum in this area. According to the tectonic evolution and sedimentary assemblage characteristics, the

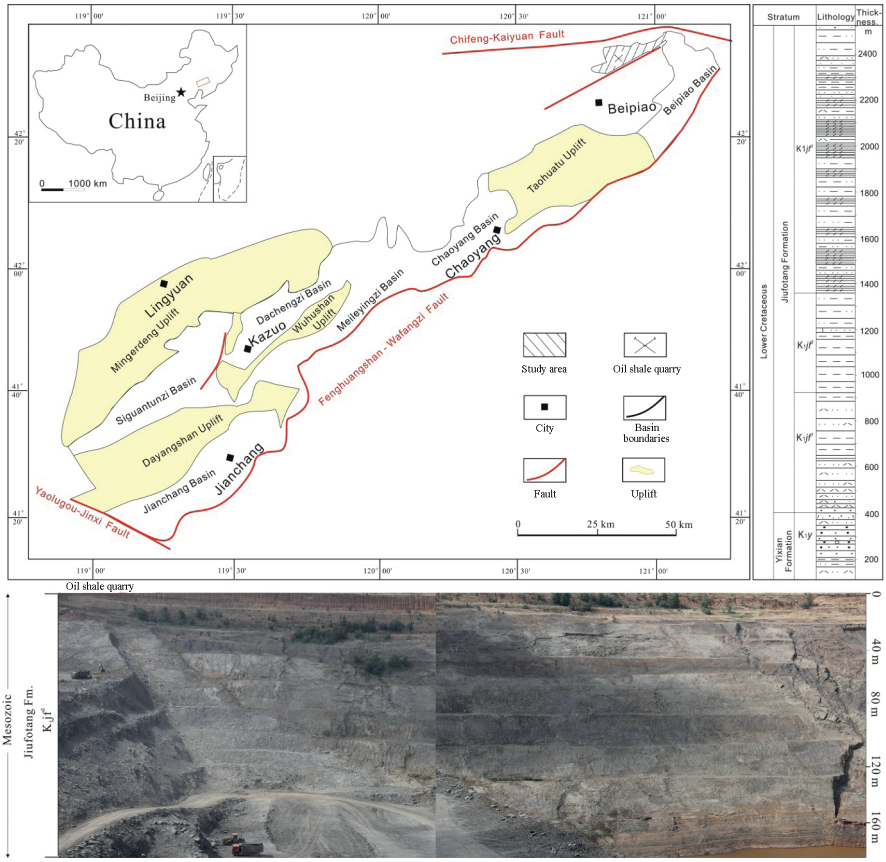

Fig. 1. Geological structure and sampling location in the Beipiao Basin, western Liaoning Province. (Abbreviation: Fm. – Formation.)

Jiufotang Formation is divided into three members: the pale yellow tuffaceous conglomerate was deposited during the initial subsidence stage, the grey-white tuffaceous conglomerate with the largest distribution area is in the middle, and the oil shale with the greatest cumulative thickness of 350 m is in the upper part.

The Beitazi Quarry is located in the Fangshen-Falaidianzi Syncline in the north of the Bapiao Basin. From Fangshen Village to Falaidianzi Village, the syncline is about 20 km long and 3.0–4.0 km wide. The gently folded Jiufotang Formation exposed in the quarry shows a local maximum dip angle of 24 degrees. In the core of the syncline, the deposits belonging to the third member of the Jiufotang Formation (K_1jf^3) are exposed. Because of the undulating basement topography in the eastern part of Wushu Tulu (near the Hechenghao), the sedimentary changes of the Jiufotang Formation stratum have resulted in the formation of two depocenters with oil-bearing shale strata in the whole Beitazi area.

3. Sampling and methods

Fresh oil shale and mudstone samples were collected from the exploited open-pit oil shale quarry of Beitazi, which is 400 m long and 178 m deep. A total of 157 samples were collected at a sampling interval of about 1.0 m. The lithology of the study area is mainly grey-white tuffaceous siltstone, grey siltstone, dark-grey mudstone, grey-black oil shale and brown oil shale. All samples were analyzed for oil yield, calorific value, ash content, sulfur content and total organic carbon (TOC). Thirty-seven oil shale samples were selected for Rock-Eval pyrolysis analysis. In addition, 14 representative oil shale samples were selected for microscopic thin section observation and maceral identification.

Fischer assay (FA) oil yield (wt%), Rock-Eval parameters, TOC (wt%) and sulfur content (%) were determined and proximate analysis was performed at the Key-Lab for Oil Shale and Paragenetic Minerals of Jilin Province, Changchun, China. Oil yield gained from low-temperature carbonization at approximately 520 °C was measured with a Chinese Fushun retort, using the FA method. The mixture of oil and water was extracted from oil shale by heating, and the content of oil was obtained by weighting the water distilled from the mixture. Afterwards, the oil yield was calculated from the total weight. TOC was measured in samples pretreated with concentrated HCI, using a Leco CS-230 elemental analyzer. Rock-Eval pyrolysis was carried out employing a Rock-Eval 6 instrument. With this method, the quantity of pyrolyzate (mg HC/g rock) obtained from kerogen during gradual heating in a helium stream is normalized to TOC to give the hydrogen index (HI, mg HC/g TOC) and the oxygen index (OI, mg CO_2/g TOC). The temperature of maximum hydrocarbon generation (*T*max) serves as a maturity indicator. Ash yield, sulfur content, density and gross calorific value were determined following Chinese standard methods GB/T 212-2008 [10] and GB/T 213-2008 [11]. Maceral analysis was performed employing a single-scan method, with a Leica MPV microscope using reflected white and fluorescent light.

4. Characteristics of oil shale

Oil yield (FA) is an important index for the quality evaluation of oil shale. Liu et al. [12] and Song et al. [13] divide oil shale into three classes by oil yield: high-quality (FA $\geq$ 10 wt%), medium-quality (10 wt% > FA $\geq$ 5wt%), and low-quality (5 wt% > FA $\geq$ 3.5 wt%) oil shales. Based on this classification, the characteristics of Beipiao Basin oil shales of different qualities are studied in detail.

4.1. Industrial quality oil shale characteristics

Medium-quality oil shale is dominant in the studied area. Its FA varies between 5.6 and 8.6 wt%, accounting for 60.7% of total oil shale samples. The FA of low-quality oil shale ranges from 3.5 to 4.9 wt%, accounting for 34.2% of total oil shale samples. The FA of high-quality oil shale may reach 11.9 wt%, accounting for 5.1% of total oil shale samples (Table 1).

Table 1. Parameters of oil shales of different qualities

Oil shale quality	Oil yield, %	Calorific value, MJ/kg	Ash, %	Sulfur, %
High	10.02–11.91	9.31–9.54	64.52–75.39	1.51–2.07
Average	10.82	9.41	69.6	1.70
Medium	5.62–8.61	4.85–6.82	74.43–83.46	2.05–2.86
Average	7.21	5.22	78.42	2.67
Low	3.52–4.93	4.61–5.24	79.12–82.25	2.33–3.19
Average	3.93	4.72	81.78	2.88

The calorific value of oil shale is generally higher than 4.18 MJ/kg [13] and correlates with oil yield. Similarly, the ash content is inversely related to the quality of oil shale. Total sulfur content is an important indicator for evaluating the potential environmental pollution during the utilization of oil shale.

The high-quality oil shale in the Beipiao Basin has a medium-high calorific value (9.58–9.35 MJ/kg), a medium-low ash content (69.8–64.5%) and a medium-low sulfur content (1.51–2.07%). The medium-quality oil shale, as defined by oil yield, is characterized by a calorific value and ash content varying from 6.8 to 4.8 MJ/kg and from 78.2 to 83.4%, respectively. The sulfur content in this oil shale type ranges from 2.05 to 2.86%. The low-quality oil shale shows, as expected, a low calorific value (4.8–4.46 MJ/kg), a high ash content (79.2–87.4%) and a high sulfur content (2.33–3.19%) (Table 1).

4.2. Petrologic characteristics of oil shale

The high-quality oil shale in the Beipiao Basin is brown (Fig. 2a), with a density ranging from 1.67 to 1.89 g/cm^3 (average 1.78 g/cm^3). Microscopically, the sediment is composed of continuous and directional organic bands interbedded with clay layers rich in organic matter with some ostracod and plant fossil debris [14].

The medium-quality oil shale is typically grey-to-black (Fig. 2b), with a density ranging from 1.91 to 2.1 g/cm^3 (average 1.97 g/cm^3). This type forms

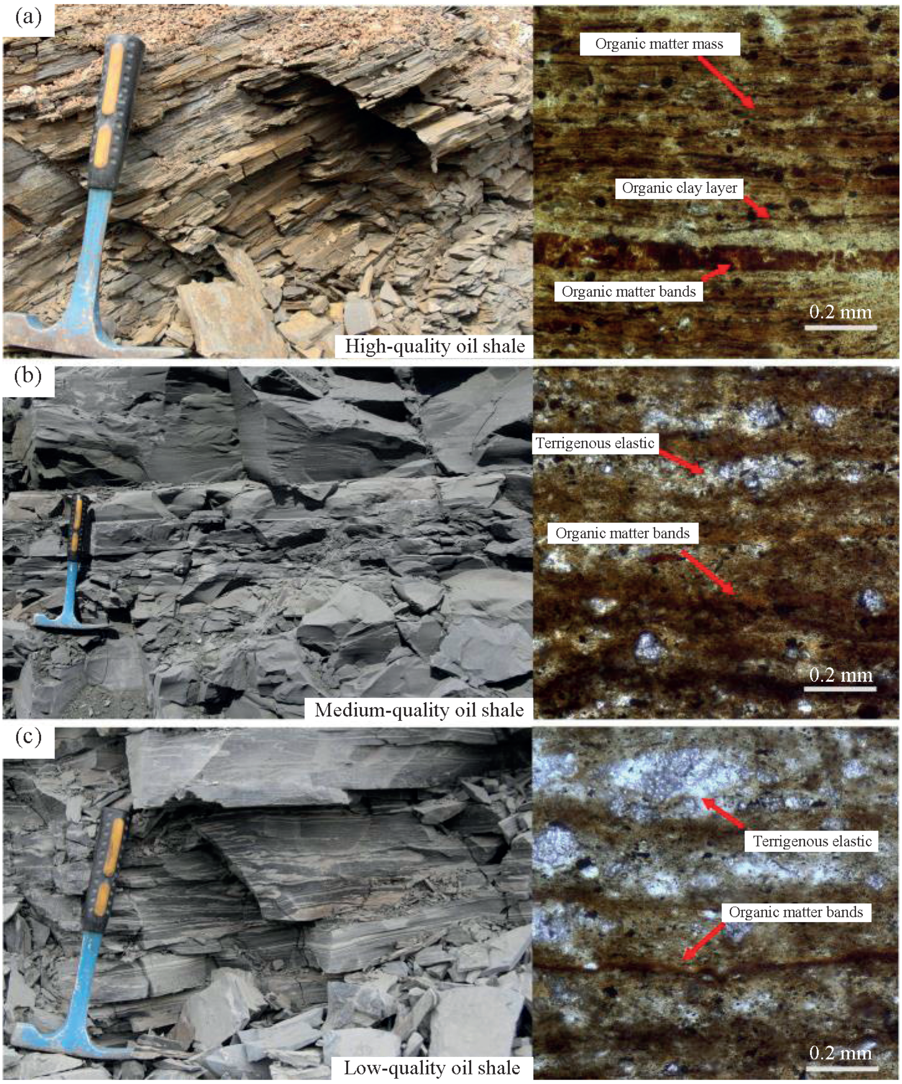

Fig. 2. Photographs of oil shale outcrops and thin sections in the Beitazi Quarry in the Beipiao Basin: a) bulk and thin section of high-quality oil shale at 165.7 m and 10.8% oil yield; b) bulk and thin section of medium-quality oil shale at 102.4 m and 8.2% oil yield; c) bulk and thin section of low-quality oil shale at 23.1 m and 4.3% oil yield.

massive to horizontal bedding with occasional ostracods and Lycoptera fossils. Microscopic observation shows that organic matter-rich bands with poor continuity are slightly thinner (about 0.1 mm) than in higher-quality oil shale and with remains of terrestrial and plant debris.

The low-quality oil shale is typically grey in appearance (Fig. 2c). Because of the increase of terrigenous material and the decrease of organic matter, the density of low-quality oil shale is relatively high, ranging from 2.01 to 2.23 g/cm^3, averaging at 2.12 g/cm^3. The low-quality oil shale units are characterized by wave bedding with locally occurring carbonaceous debris. Microscopically, the organic matter-rich bands are thin (about 0.05 mm thick), discontinuous, and interbedded with terrigenous clastic lamellas (about 0.1 mm thick). Terrigenous clastic grains are mainly quartz and also large-grained feldspar.

4.3. Organic geochemical characteristics of oil shale

4.3.1. Organic matter content of oil shale

The total organic carbon content of oil shale in the Beipiao Basin is relatively high and mainly ranges from 3.00 to 10.00 wt%, with the maximum 19.4% (Fig. 3). The oil yield (FA) has a good positive correlation with TOC content ($R^2 = 0.79$) (Fig. 4a). The TOC of low- and medium-quality oil shales generally ranges from 5.32 to 7.03 wt% (average 9.18 wt%) and from 7.14 to 12.75 wt% (average 6.19 wt%), respectively. The oil shale with high TOC contents (average 16.7 wt%) is termed high-quality oil shale.

Hydrocarbon potential ($S_1 + S_2$) is also an effective parameter for evaluating the abundance of organic matter in sedimentary rocks where free and residual hydrocarbon (S_1) and pyrolytic hydrocarbon (S_2) represent the contents of soluble hydrocarbons and pyrolysis hydrocarbons, respectively [15]. The correlation between FA and $S_1 + S_2$ is higher ($R^2 = 0.87$) than that between FA and TOC (Fig. 4b). According to the relationship, $S_1 + S_2$ ranges from 34.96 to 54.02 mg/g in low-quality oil shale, and from 54.02 to 117.1 mg/g in medium-quality oil shale, and when $S_1 + S_2$ is higher than 117.1 mg/g, oil shale is considered to be of high quality.

TOC and $S_1 + S_2$ can be used to explain the organic matter abundance in oil shale. All the samples of oil shales of different qualities in the studied area showed high organic matter abundance (Fig. 5).

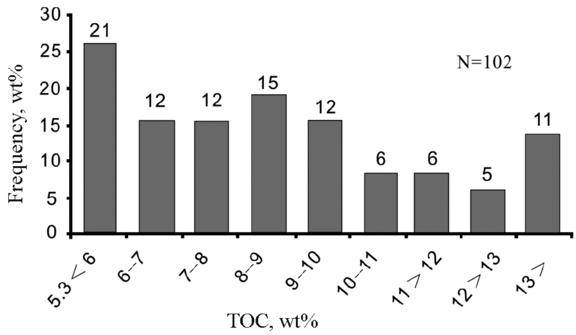

Fig. 3. TOC of oil shale of Beitazi Quarry in the Beipiao Basin.

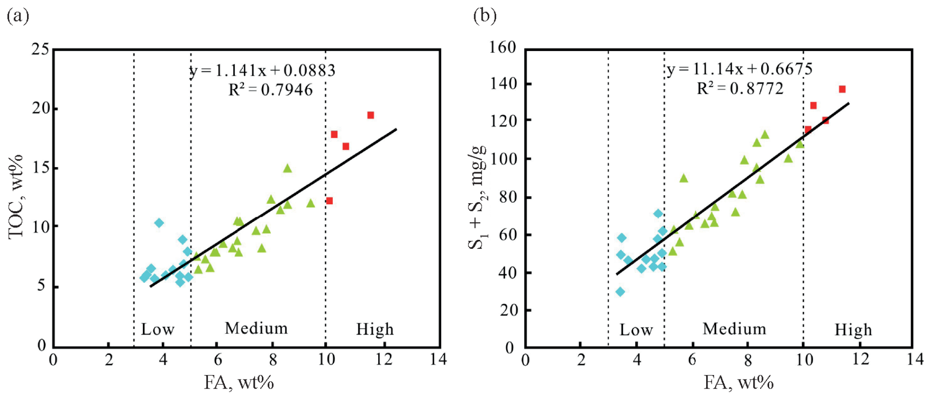

Fig. 4. Correlation between TOC and FA (a) and $S_1 + S_2$ and FA (b) of oil shale in the Beipiao Basin.

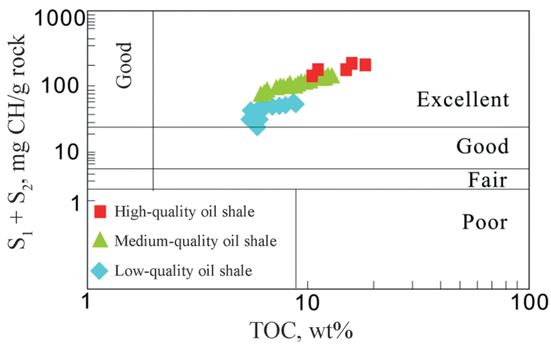

Fig. 5. The cross-plots of TOC content vs FA and $S_1 + S_2$ vs FA of oil shale in the Beipiao Basin. The threshold values for low-, medium- and high-quality oil shales (FA = 3.5 wt%, 5.0 wt%, 10.0 wt%, respectively) are marked by dashed lines.

4.3.2. Organic matter maceral of oil shale

The variation of terrigenous organic matter (the sum of vitrinite, inertinite, sporinite and cutinite) and alginate (the sum of lamalginite and telalginite) is seen from Table 2.

Alginite is the main source of organic matter in the oil shale in the studied area. The content of organic macerals representing higher terrestrial plants is relatively low [16].

The high-quality oil shale was characterized by the relatively high content of alginite (average 82 vol%) (Fig. 6a). Lamalginite (average 60 vol%) predominates over telalginite (average 22 vol%) in the majority of oil shale

Table 2. The maceral composition of oil shale in the Jiufotang Formation

Sample	Depth, m	Oil yield, %	Alginite, vol%, mmf, %				Exinite, vol%, mmf, %			Vitrinite, vol%, mmf, %			Ine, %	Kerogen type
			Lamalg	Telalg	Sum	Spor	Cut	Chi	Sum	Des.	Vit	Sum		
High-quality oil shale														
BT-1	168.7	12	65	20	85	5	1	2	8	4	3	7	0	I
BT-4	166.2	10.5	62	20	82	10	1	2	12	4	2	6	0	I
BT-9	162.1	11	56	25	81	5	1	5	11	3	4	7	1	I
Medium-quality oil shale														
BT-10	156.8	6.8	41	17	68	9	2	6	17	7	6	13	2	I
BT-31	147.2	7.66	65	12	77	8	1	7	16	4	1	5	2	I
BT-55	125.3	7.5	56	14	70	15	3	5	23	3	2	5	2	I
BT-61	105.7	6.75	61	12	73	11	2	7	20	2	4	6	1	I
BT-90	82.5	5	51	14	65	18	2	4	24	6	4	10	1	I
BT-97	62.3	5.9	54	12	66	20	1	4	25	2	6	8	1	I
Low-quality oil shale														
BT-35	60.4	4.5	46	11	57	19	3	5	27	3	11	14	2	II_1
BT-50	42.0	4.8	43	10	53	23	1	13	37	3	6	9	1	I
BT-52	35.5	4.0	41	12	53	20	1	10	31	3	2	15	1	I
BT-66	20.4	4.2	40	11	51	26	2	9	37	2	10	12	0	II_1
BT-98	10.6	3.5	38	12	50	26	2	12	40	4	5	9	1	II_1

Abbreviations: Ine – inertinite; Lamalg – lamalginite; Telalg – telalginite; Spor – sporinite; Cut – cutinite; Chi – chitin clastic; Des – desmocollinite; Vit – vitrinite; Sum – summary.

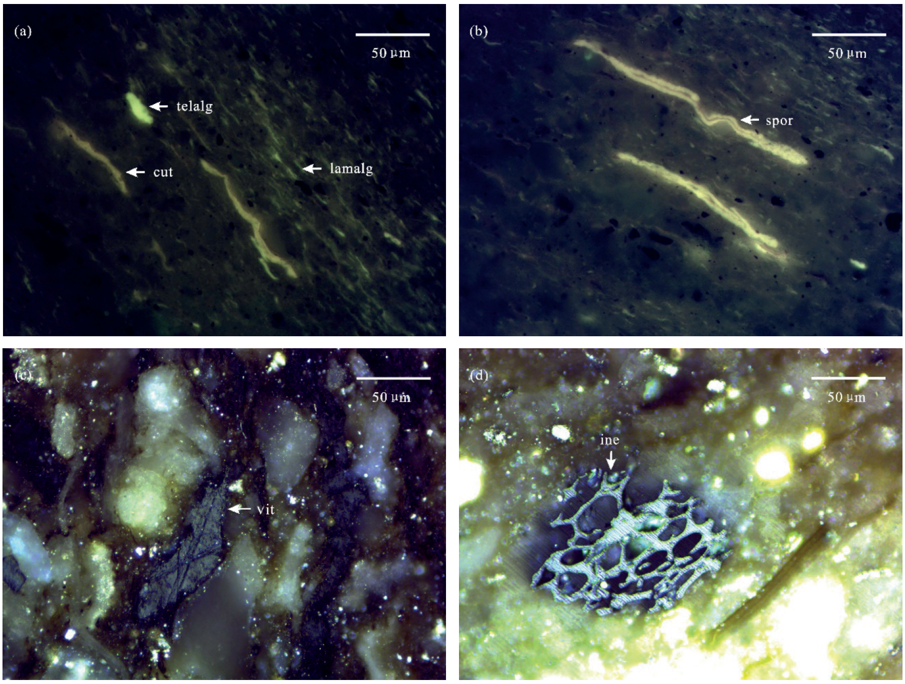

Fig. 6. Photomicrographs of Jiufotang Formation oil shale samples from the Beipiao Basin: (a) sample BT-1 under UV light; (b) sample BT-10 under UV light; (c) sample BT-35 under white light; (d) sample BT-50 under white light. (Abbreviations: telalg – telalginite; cut – cutinite; lamalg – lamalginite; spor – sporinite; vit – vitrinite; ine. – inertinite.)

samples [17]. The contents of exinite (Fig. 6b), vitrinite (Fig. 6c) and inertinite (Fig. 6d) were lower. The OM type is sapropel, which proves that aquatic organisms were the main primary producers of OM during the deposition of oil shale (Table 2).

The medium-quality oil shale was mostly composed of alginate (average 70 vol%) (Fig. 6a). The terrigenous OM consisted mainly of sporinite (average 15 vol%) (Fig. 6a) and vitrinite (average 9 vol%). The source of organic matter represents a mixture of aquatic and terrigenous OM but is dominated by aquatic organisms. The organic matter is of sapropel-humic sapropel type (Table 2).

Previous studies have shown that sporinite represents terrestrial organic matter and shallow water plants [18]. The share of sporinite increases in low-quality oil shale samples where sporinite (23%), cutinite (1%) and chitin clastic (9%) were detected. In addition, vitrinite and inertinite were detected (totalling 15%) in this oil shale type where the source of organic matter represents a mixture of aquatic and terrigenous OM that can be characterized as a humic sapropel (Table 2).

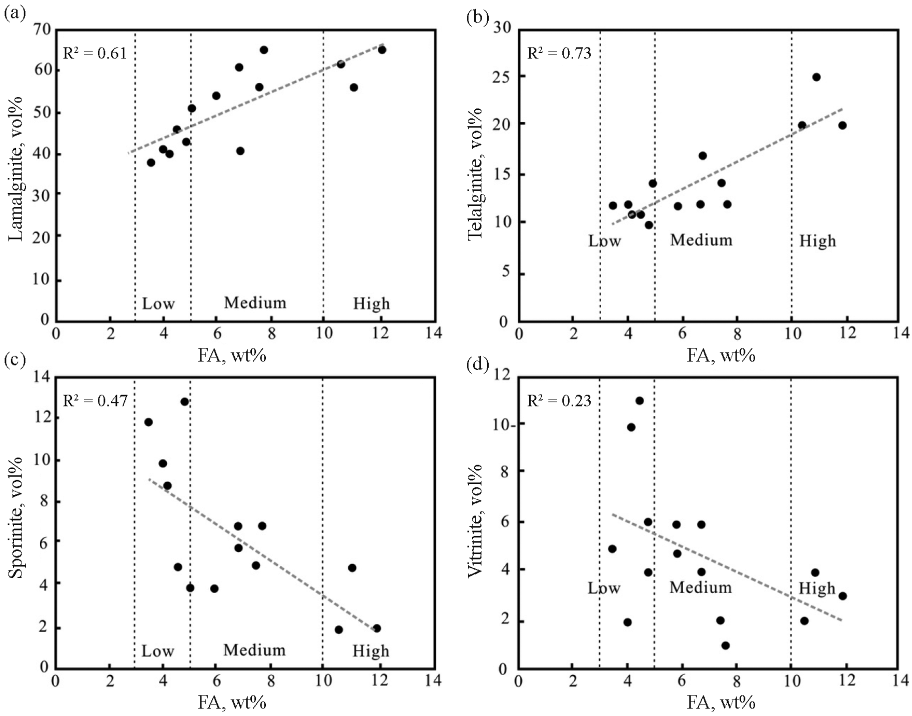

Fig. 7. Diagrams of correlation between main macerals and FA: a) lamalginite, b) telalginite, c) sporinite, d) vitrinite.

The diagram of the main organic macerals and FA (Fig. 7) shows that there is a positive correlation between the content of alginite and the quality of oil shale but a significant negative correlation between the content of sporinite and the quality of oil shale. This indicates that the input of terrestrial organic matter negatively impacts the quality of oil shale deposited in deep lakes. On the contrary, algae blooms improve the quality of oil shale.

4.3.3. Kerogen type and maturity of oil shale

Kerogen type is an important indicator for the classification of sedimentary organic facies. HI-*T*max, S_2-TOC, and HI-OI diagrams [19] identify two types of organic matter, type I and type II_1 (Fig. 8). The high- and medium-quality oil shales in the Beipiao Basin are plotted in the area of type I kerogen, whereas the low-quality oil shale is plotted in the domain of mainly types I and II_1 kerogen.

The *T*max values, which vary between 423 and 442 °C, indicate that the oil shale in the studied area is immature-low mature.

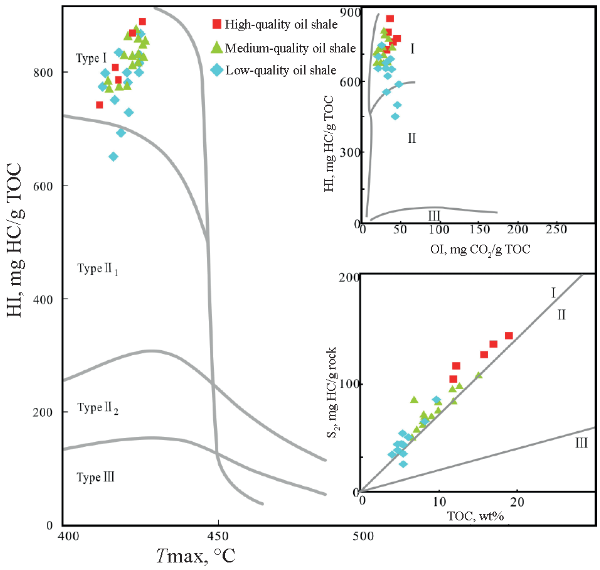

Fig. 8. Discriminant map of organic matter of oil shale in the Jiufotang Formation, Beipao Basin.

5. Sedimentary organic facies division scheme

The organic facies model was introduced by Rogers and Koons in 1971 [20]. Combining the hydrocarbon generating capacity, organic geochemistry and the input of original organic matter, Jones [21] proposed seven most widely used organic facies types: A–D, mainly for marine basins. The classification was based on organic geochemical parameters H/C, HI and OI (Table 3) [21]. According to Jones [21], the oil shales in the Beipiao Basin are divided into A, AB and B types. The high-quality oil shale mainly corresponds to type A, the medium-quality oil shale mostly to type AB, and the low-quality oil shale chiefly to types AB and B (Table 4).

Table 3. Quantitative classification of organic facies [21]

Organic facies type	H/C $R_o = 0.5\%$	Rock-Eval pyrolysis		OM and sedimentary environment
		HI	OI	
A	≥ 1.45	> 850	10–30	Alginite, sapropelic amorphous
AB	1.35–1.45	650–850	20–50	Sapropelic amorphous, terrigenous OM
B	1.15–1.35	400–650	30–80	Sapropelic amorphous, terrigenous OM
BC	0.95–1.15	250–400	40–80	Mixed type, dioxic
C	0.75–0.95	125–250	50–150	Terrigenous OM, dioxic
CD	0.60–0.75	50–125	40–150	Dioxic, alteration
D	≤ 0.6	≤ 0.6	20–200	Oxic, alteration

Table 4. Sedimentary organic facies types and characteristics of Jiufotang Formation oil shale in the Beipiao Basin

Sedimentary organic facies	Oil shale quality	Kerogen type	Source of OM	Sedimentary environment	Industrial quality	Type [21]
Semi-deep-lake humic sapropel facies	Low	I, II_1	Sapropelic amorphous, terrigenous	Weakly reducing, poor preservation conditions	Low calorific value, high ash content, high sulfur content	AB, B
Deep-to-semi-deep-lake sapropel–humic sapropel facies	Medium	I	Sapropelic amorphous, little terrigenous OM	Sub-reducing, medium preservation conditions	Medium calorific value, high ash content, medium sulfur content	AB
Deep-lake sapropel facies	High	I	Alginite, sapropelic amorphous	Anoxic and reducing, good preservation conditions	Medium-high calorific value, medium-low ash content, low sulfur content	A

Organic facies can be associated with sedimentary environment. When studying the sedimentary organic facies of coal and source rocks of the Triassic Yanchang Formation in the Ordos Basin, Yao et. al [22] put forward the classification of sedimentary organic facies based on OM macerals. The classification presented by the researchers contributes to the understanding of the theory of coal and petroleum genesis, as well as to the exploration of various energy minerals. Figure 9 shows that oil shales in the Beipiao

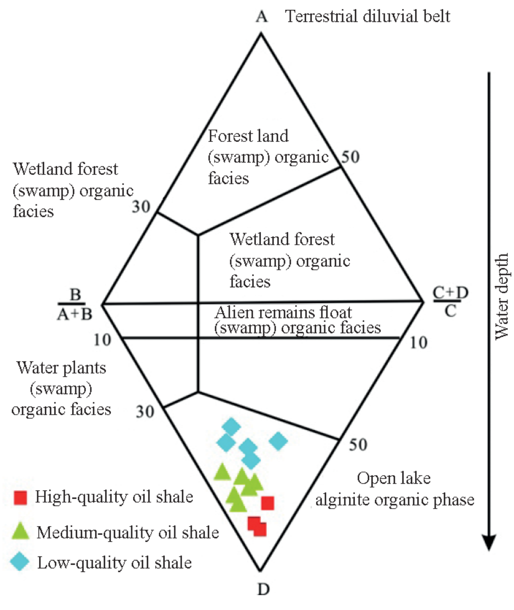

Fig. 9. Organic facies diagram of the oil shale maceral division in the Jiufotang Formation, Beipiao Basin, according to [22]: A – inertinite; B – vitrinite; C – sporinite; D – alginate. (The upper delta represents drier conditions towards A. When D is less than 10%, C and D merge in the triangle. The lower triangle represents the underwater environment, D direction indicates the deepening of the water body. When D is greater than 10%, A and B merge in the triangle.)

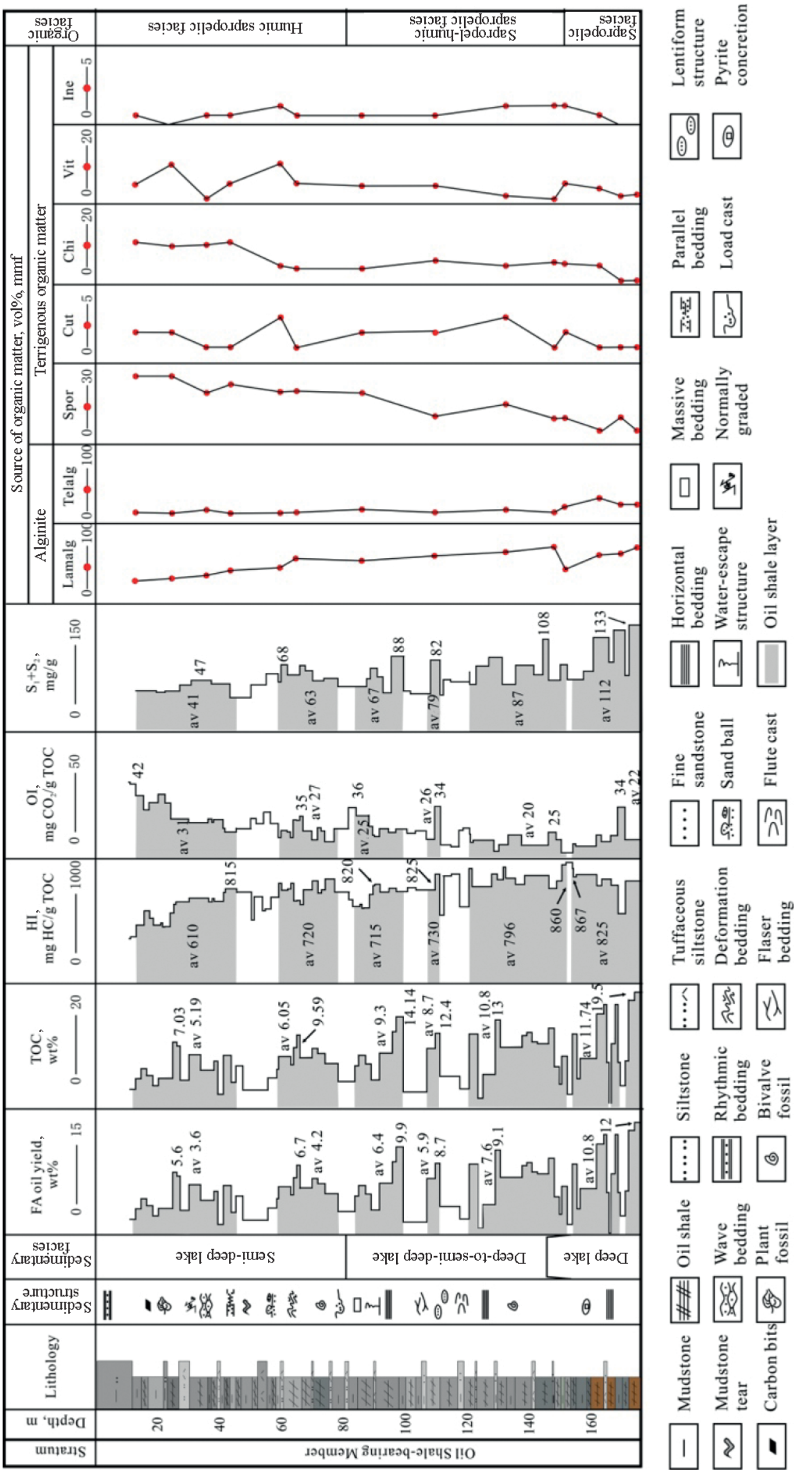

Fig. 10. Comprehensive analysis of formation conditions of oil shale in the Jiufotang Formation, Beipiao Basin. (Abbreviations: Lamalg – lamalginite; Telalg – telalginite; Spor – sporinite; Cut – cutinite; Chi – chitin clastic; Vit – vitrinite; Ine – inertinite.)

Basin belong to alginite organic facies deposited in the open lake basin, and with the deepening of the lake, their quality gradually improves. Based on combining sedimentary environments (i.e. sedimentary facies) with organic geochemical characteristics (i.e. organic matter type), sedimentary organic facies are divided into three types [23, 24]. According to this classification, the sedimentary organic facies types of oil shales of the Beipiao Basin are deep-lake sapropelic facies, deep-to-semi-deep-lake sapropel–humic sapropelic facies and semi-deep-lake humic sapropelic facies.

5.1. Deep-lake sapropelic facies

Deep-lake sapropelic oil shale with high industrial quality was developed in the lower part of the oil shale section in the studied area (Fig. 10), with locally visible pyrite. Lamalginite and telalginite are dominant in organic matter. The average hydrogen index of high-quality oil shale is 825 mg/g, the highest HI being 867 mg/g. The oxygen index is relatively low, averaging 22 mg/g, while the highest OI is 34 mg/g. Hydrogen index is an important indicator for determination of organic matter source and thermal degradation ability and can also be used to distinguish a sedimentary environment, especially the redox conditions of sedimentary OM [25–27]. Generally, the higher the HI, the stronger the reducing conditions of sedimentary organic matter deposition. Therefore, deep-lake sapropelic facies oil shale in the studied area was formed in a strongly reducing environment (Fig. 11).

5.2. Deep-to-semi-deep-lake sapropel–humic sapropelic facies

Deep-to-semi-deep-lake sapropel–humic sapropelic oil shale, usually of medium industrial quality (Fig. 10), developed in the middle of the oil shale section. It displays a horizontal bedding, layered distribution of conchostraca, and partial lycoptera. The average HI of medium-quality oil shale is 747 mg/g, with the highest value being 860 mg/g. The average OI is 29 mg/g, the highest value is 34 mg/g. Alginite is the main source of organic matter, but the content of sporinite is also increased. The study shows oil shale in this facies to be deposited in the transitional zone between deep and semi-deep water, which is a sub-reducing environment (Fig. 11).

5.3. Semi-deep-lake humic sapropelic facies

Semi-deep-lake humic sapropel facies oil shale, usually of low industrial quality (Fig. 10), developed in the upper part of the oil shale section in the studied area, and displays deformation bedding, wave bedding, and carbon debris, indicating an unstable sedimentary environment of shallow depth. Its organic matter is sourced from a mixture of alginite and terrigenous material. The average hydrogen index of low-quality oil shale is 610 mg/g, while the relatively high average oxygen index of 31 mg/g, with a maximum of 42 mg/g, indicates a low HI and a high OI, which suggests a weakly reducing environment (Fig. 11).

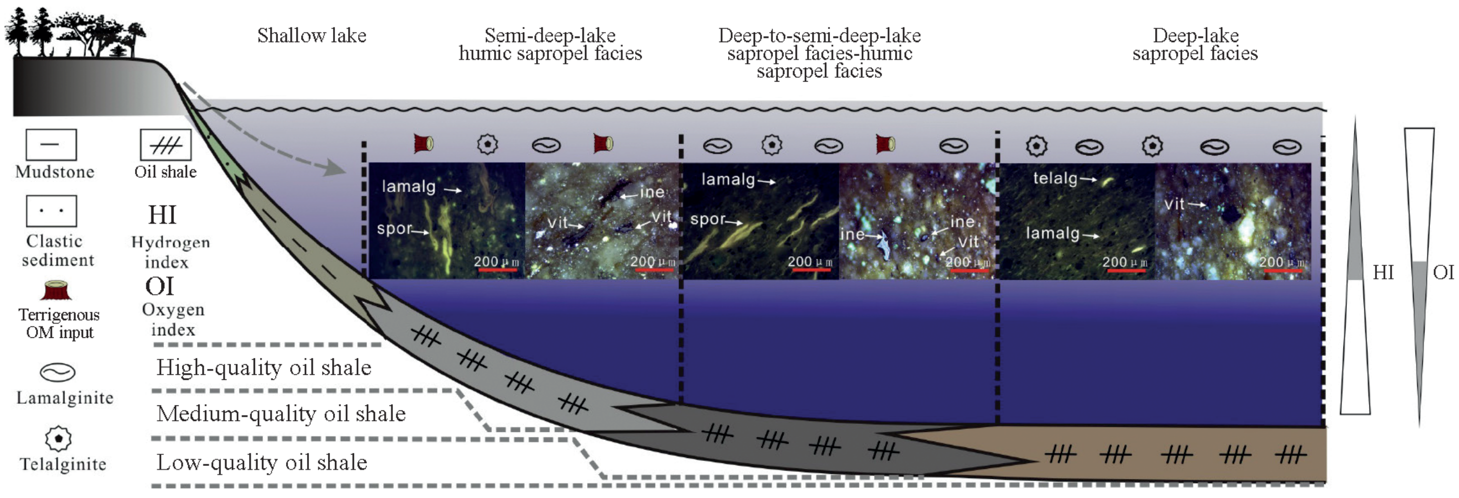

Fig. 11. Organic enrichment model of sedimentary organic facies and oil shale in the Jiufotang Formation, Beipiao Basin. (Abbreviations: lamalg – lamalginite; spor – sporinite; vit – vitrinite; telalg – telalginite.)

Thus, the high-, medium- and low-quality oil shales correspond well with the three sedimentary organic facies (Table 4), respectively. The oil shale of high quality and high hydrocarbon potential is mainly developed in a deep-lake sapropelic facies in a strongly reducing environment.

6. Conclusions

Three types of sedimentary organic facies of oil shale are identified in the Beipiao Basin, Northeast China: deep-lake sapropelic facies, deep-to-semi-deep-lake sapropel–humic sapropelic facies, and semi-deep-lake humic sapropelic facies. The high-, medium- and low-quality oil shales in this basin correspond well to the three sedimentary organic facies.

The results of study lead to the following conclusions:

1. High industrial-quality oil shale with a high alginite-originated total organic carbon (average value 16.7%) is mainly developed in a strongly reducing deep-lake sapropelic facies, and is marked by high oil yield, medium-high calorific value, medium-to-low ash content and low sulfur content.
2. Medium-quality oil shale having a medium alginate- and bituminite-derived TOC (average value 9.18%) is deposited in a moderately reducing deep-to-semi-deep-lake sapropel–humic sapropelic facies. Although its organic matter is dominated by alginate, the content of sporinite is significantly increased. This kind of oil shale is characterized by medium oil yield, medium calorific value, high ash content and medium sulfur content.
3. Low-quality oil shale with a low terrestrial-alginite mixed derived TOC (average value 6.19%) is deposited in a weakly reducing semi-deep-lake humic sapropelic facies, and has low oil yield, low calorific value, high ash content and high sulfur content.
4. The study of sedimentary organic facies helps to predict high-quality oil shale. Organic matter origin and preservation conditions (sedimentary environment) are the main factors that control the quality of oil shale. The strongly reducing deep lake water with abundant alginate contained is an ideal environment for the accumulation of high-quality oil shale.

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