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FORMATION CONDITIONS OF JIMUSAER OIL SHALE AT THE NORTHERN FOOT OF BOGDA MOUNTAIN, CHINA

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Abstract. *The Jimusaer oil shale, located in the northern foot of Bogda Mountain, was deposited in the Lucaogou Formation in the Upper Permian. In this paper the effect of paleostructure, paleoclimate and sedimentary environment on the mineralization of oil shale in the study area was investigated. The results show that the Jimusaer oil shale was developed in the stable paralic lacustrine basin formed in the Late Middle Permian, and cropped out with the uplift of Bogda Mountain during the Himalayan orogeny. The Lucaogou Formation, which is composed of six lithologic segments, was deposited in a warm humid to dry hot climate and fresh to brackish water environment indicated by values of Sr/Cu, Sr/Ba and Mn/Fe ratios, which vary segment by segment. There are also similar variety regularities shown, which implicate that the changes of paleoclimate influenced directly water salinity in the study area. The Lucaogou Formation includes two oil shale segments which were developed respectively in the shallow to semi-deep lake and semi-deep to deep lake, and the environment of large-area, moderate saline deep water provided favourable conditions for generation and preservation of oil shale.*

Keywords: *Jimusaer oil shale, paleostructure, paleoclimate, sedimentary environment.*

1. Introduction

With increasing demand for energy and reduction in the amount of petroleum resources, oil shale has drawn wide attention in recent years as an important substitute energy resource for conventional oil and gas. Oil shale, also called oil-forming shale, is a kind of combustible organic rock with high

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ash and low metamorphic grade, which is derived from algae and unicellular lower eukaryote or remains as a result of the processes of putrefaction and coalification. China's widely distributed oil shale resources are abundant [1]. The Junggar Basin is one of the largest oil shale basins and has great development prospects, the resources being mainly located in the northern foot of Bogda Mountain, including Yaomoshan, Shuimogou, Lucaogou, Dongshan, Sangonghe, Donggou, Dadonggou, Sigonghe, Wugonghe, Xigou, Dahuangshan, Ergonghe, Shichanggou, Mutasi, Wujiawan, and Baiyanghe mining areas from west to east (Fig. 1). The last four mining areas are located in Jimusaer county, after which the oil shale is called. While oil shales of most mining areas have been studied quite profoundly in recent years [2–7], the Jimusaer oil shale has received almost no attention, and the few studies view differently the sedimentary environment of oil shale in the study area [8–10]. Based on analysis of sedimentary and geochemical characteristics of selected oil shale samples, this paper summarizes the sedimentary environment and mineralization pattern of the study area, and provides a reference to the metallogenic mechanism of Jimusaer oil shale.

2. Geological setting

The Jimusaer oil shale is located in the east of the Bogda Mountain oil shale belt on the southern margin of the Junggar Basin, which is in the front of the tectonic system of thrust nappe structure in the north of the Meso-Cenozoic depression in Urumqi. The study area is a kind of monoclinal structure inclined to southwest on the whole (Fig. 1).

Strata of Carboniferous, Permian, Triassic, Jurassic, Paleogene, Neogene and Quaternary age are the main outcropping units in the study area, among which the Permian and Triassic systems are predominant. These are the Permian Lucaogou (P_2l), Hongyanchi (P_2hy), Quanzijie (P_2q) and Wutonggou (P_2w) formations, from the oldest to the youngest.

Oil shales mainly occur in the Permian Lucaogou Formation in the study area, which outcrop in the Shichanggou to Baiyanghe mining area from west to east. The Lucaogou Formation manifests an apparent sedimentary rhythm, and from bottom to top six segments can be distinguished according to lithologic character: dolostone (P_2l^1), dolostone interbedded with siltstone (P_2l^2), lower oil shale (P_2l^3), sandstone (P_2l^4), upper oil shale (P_2l^5) and shale (P_2l^6). Except the fourth and fifth lithologic segments, most outcrop incompletely due to the coverage by the Quaternary sediment or destruction in fault zones.

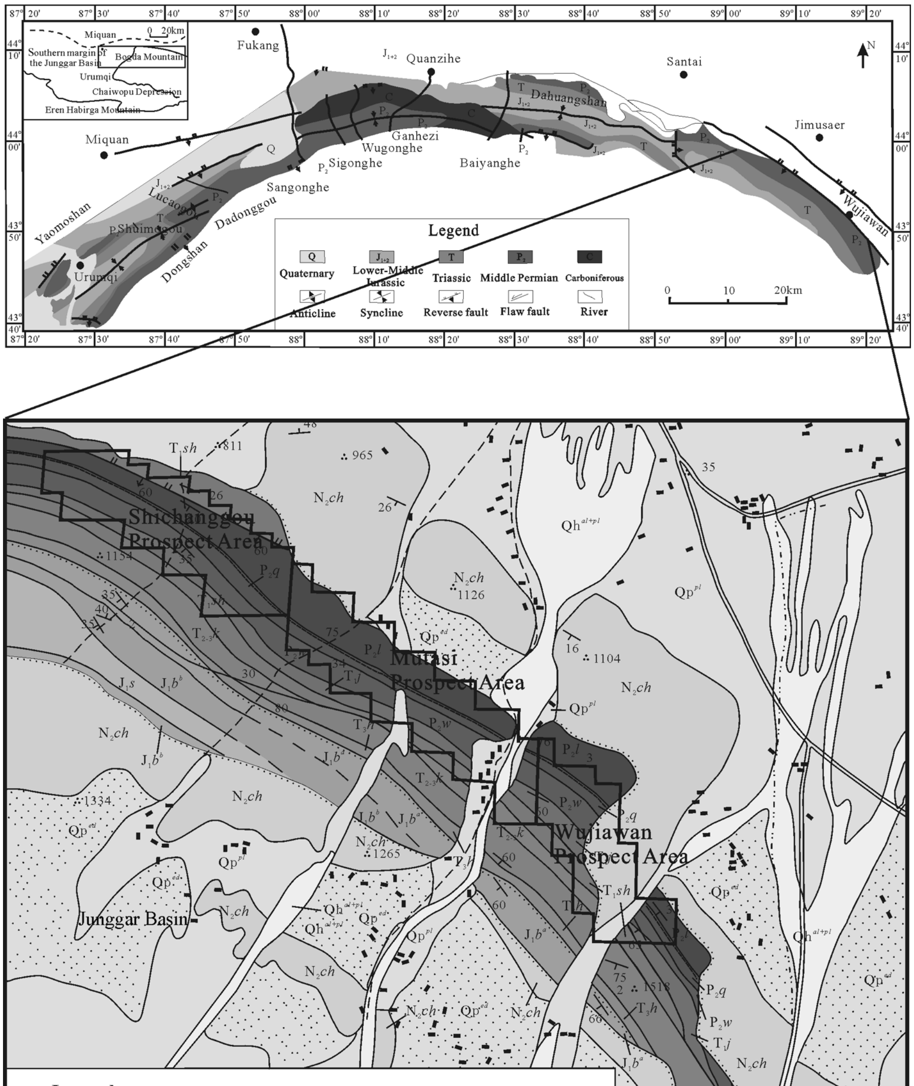


Fig. 1. Simplified geological map and location of the studied outcrops.

3. Samples and tests

A total of 285 oil shale samples were collected from Shichanggou, Mutasi and Wujiawan mining areas as follows: 65 samples from 4 outcrop profiles and 220 samples from 37 drilling sites. The samples were selected and crushed for Gray-King low-temperature dry distillation and major and trace element analysis.

Gray-King low-temperature dry distillation of 273 samples was conducted in the Xinjiang Coal Science Research Institute, following the Chinese National Standard methods GB/T 1341-2007. The purpose of the tests was to determine the tar yield of samples to study the quality of oil shales.

Based on lithologic segments division, 25 oil shale samples were selected for major and trace element content determination to study the environment characteristics of segments. Element content was tested respectively by AB-104L, PW2404 X-ray Fluorescence Spectrometer (XRF) and Element inductively-coupled plasma mass spectrometer (ICP-MS) in the CNNC Beijing Research Institute of Uranium Geology, following Chinese GB/T14506.14-2010, GB/T14506.28-2010 and GB/T14506.30-2010 standards of the Methods for chemical analysis of silicate rocks.

4. Results and discussion

4.1. Paleostructure

Paleostructure controlled the development of basins and distribution of sedimentary facies, which further influenced the depocenter of oil shale and the center of the prolific zone.

Bogda Mountain transformed from an early rift to an early foreland basin during the Carboniferous-Early Permian period. The main geological structure events were the closure of the Eren Habirga Ocean and the uplift of Tianshan Mountain caused by the collision of the Junggar and Tarim plates in the Middle-Late Carboniferous. Then the Eren Habirga Mountains uplifted rapidly and a restricted bay developed in Bogda and Tianshan mountains in the Early Permian [11]. During the early stage of the Middle Permian, the crustal activity was enhanced in Bogda Mountain, and in the late stage of the Middle Permian (Lucaogou and Hongyanchi formations), the study area underwent a significant transformation from an epicontinental marine basin to a lacustrine basin as a result of crustal uplift and marine regression, and Bogda Mountain became the depocenter. During the depositional period of the Lucaogou Formation, steady deep-water lacustrine basin conditions were favorable for generation and preservation of oil shale. In the period of Himalayan orogeny, the Permian oil shale cropped out with the uplift of Bogda Mountain due to large-scale thrust faults, which inhibited the organic thermal evolution, a significant structural condition for oil shale formation.

4.2. Paleoclimate

Paleoclimate affected the primary productivity of lakes, and also had an effect on water environment such as alkalinity, acidity, salinity and oxidizing/reducing conditions, which further influenced the generation and enrichment of organic matter.

The geochemical data for selected major and trace elements in 25 Jimusaer oil shale samples of six lithologic segments are tabulated in the Table.

Table. Geochemical data for selected major and trace elements in 25 Jimusaer oil shale samples

Segment	Sample No.	Sr, μg/g	Cu, μg/g	Ba, μg/g	Fe, %	Mn, %	V, μg/g	Ni, μg/g
P_2l^6	O-1	213	62.9	332	4.37	0.096	154	42.1
	O-2	251	46.48	400	4.21	0.063	93	34.8
	O-3	226	55.9	493	5.01	0.084	87.4	25.3
	O-4	261	48.79	676	5.43	0.027	120	46.6
	O-5	454	68.27	200	2.04	0.100	33.3	17.3
	O-6	694	45.39	304	4.28	0.163	43.8	19.4
	O-7	460	24.66	161	1.38	0.048	16.7	9.37
P_2l^5	O-8	297	56.46	277	5.69	0.079	96.9	22.5
	O-9	407	79.96	369	5.03	0.112	129	43
	O-10	476	82.21	405	4.41	0.129	120	32.6
P_2l^4	O-11	836	71.88	393	3.85	0.185	36.2	51.3
	O-12	388	44.19	219	3.32	0.139	102	16.9
P_2l^3	O-13	243	55.9	346	4.68	0.122	105	40.5
	O-14	223	54.8	376	4.75	0.094	123	38.4
	O-15	338	83.01	307	4.27	0.111	157	43.3
	O-16	423	83.93	327	4.45	0.113	118	41.8
	O-17	358	71.17	332	4.2	0.148	90.2	36.3
	O-18	472	89.73	263	4.05	0.130	112	38.2
	O-19	143	72.19	284	3.78	0.087	63.8	32.4
	O-20	183	63.1	261	3.46	0.066	63.4	39.9
	O-21	207	58.81	355	4.47	0.089	57.6	34.1
	O-22	213	46.2	317	4.16	0.096	86.5	40.4
	O-23	252	63.09	312	4.02	0.076	86	43.8
P_2l^2	O-24	493	81.76	260	3.82	0.099	85.2	44.9
	O-25	150	28.63	429	4.97	0.06	68.5	48.1

4.2.1. Sr/Cu

Sr is of high activity and is easily dissolved from weathered rock, the high content of Sr usually denotes salinization of lake water resulting from an arid climate in lacustrine sedimentation without seawater intrusion [12–13]. Cu is one of sulfophile elements, Cu^{2+} can be reduced to Cu_2S and precipitates in a reducing organic-rich environment. In addition, as a certain amount of Cu occurs in an organism, Cu tends to accumulate in the combustible organic rock deposited in a warm humid climate. Sr/Cu ratio is usually used to reflect paleoclimatic conditions: a warm humid climate is indicated by Sr/Cu ranging from 1.3 to 5.0, whereas Sr/Cu > 5.0 suggests a dry hot climate [14–15].

Sr/Cu shows an increasing trend from bottom to top in the study area (Fig. 2). The Sr/Cu ratio of most samples from P_2l^3 is lower than 5, which represents a warm humid climate. Samples from P_2l^4 have a high Sr/Cu ratio exceeding 10, which shows changes of paleoclimate conditions. The Sr/Cu ratio of samples from P_2l^5 is between 5 and 10, which corresponds to a slightly dry hot climate. P_2l^6 deposited in dry hot climatic conditions with high values of the Sr/Cu ratio. It can be inferred from Figure 2 that warm humid and slightly dry hot climates are favorable for the deposition of oil shale.

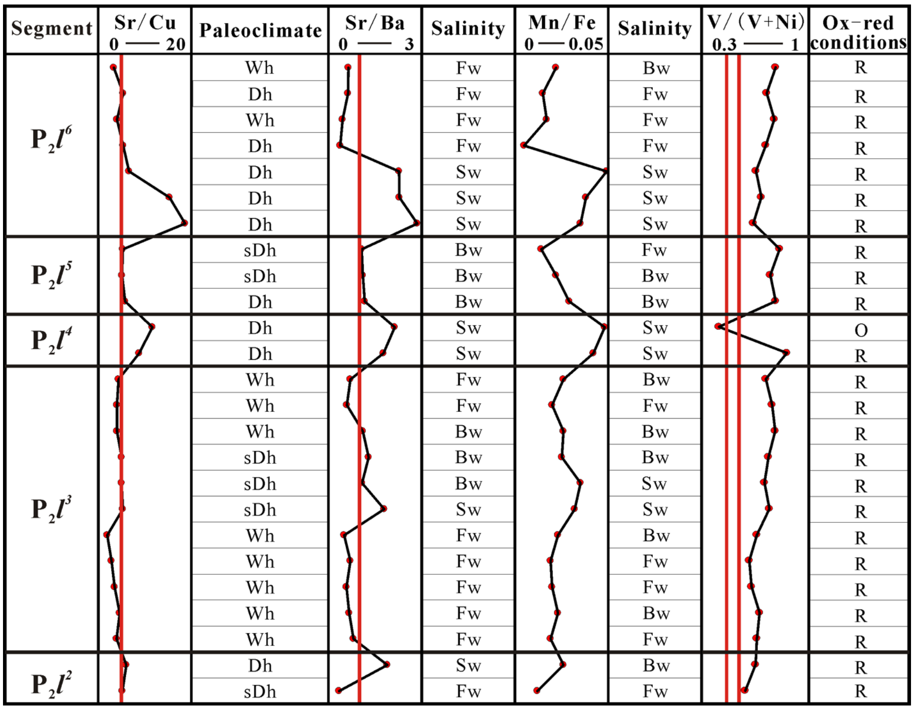


Fig. 2. Vertical variabilities map of paleoclimate and water salinity of the Lucaogou Formation; Wh – warm humid, Dh – dry hot, sDh – slightly dry hot, Fw – fresh water, Bw – brackish water, Sw – saline water, R – anaerobic environment, O – aerobic environment.

4.2.2. Sr/Ba

Sr and Ba are both trace alkaline earth metals and have similar chemical properties, but barium salts have a relatively lower solubility and the radius of a barium ion is much larger. As a result, Ba is inclined to be adsorbed by clay mineral, colloid or organic matter. Ba precipitates first with increasing salinity, while Sr precipitates when the salinity is high enough. So water salinity can be interpreted from the ratio of Sr/Ba. Sr/Ba > 1 indicates the saline water environment, whereas Sr/Ba < 1 implies the fresh water environment [12–14, 16–17].

As shown in Figure 2, the Sr/Ba ratio of most samples from P_2l^3 is lower than 1, which denotes the fresh water environment. The respective ratio of samples from P_2l^4 increases obviously and the water salinity may be very high. The Sr/Cu ratio in samples from P_2l^5 is a little higher than 1, which corresponds to the brackish water environment. In samples from P_2l^6, this ratio increases again and the brackish water environment turns into saline water.

4.2.3. Mn/Fe

Mn and Fe are both iron group elements and have two main valence states: Fe^{2+}, Fe^{3+} and Mn^{2+}, Mn^{4+}, respectively. Fe is inclined to precipitate because Fe^{2+} tends to be oxidized more easily than Mn^{4+} and Fe can precipitate in a colloidal form in low salinity, while Mn is relatively stable in the form of Mn^{2+} and precipitation takes place only when the salinity is high enough [14, 18]. As a result, values of the Mn/Fe ratio in the saline water environment are usually significantly higher than those in the fresh water environment.

As seen from Figure 2, the Mn/Fe ratio exhibits similar variations to the Sr/Ba ratio: P_2l^3 is mainly a fresh-water deposit; P_2l^4 was deposited in saline water; brackish water is indicated in P_2l^5. The salinity increased again in P_2l^6, and the Jimusaer oil shale was deposited in fresh or brackish water.

4.2.4. Paleoclimate and water salinity

As shown in Figure 2, the curves of Sr/Cu, Sr/Ba and Mn/Fe demonstrate similar trends of change: the respective values increase from P_2l^3 to P_2l^4, then decrease from P_2l^4 to P_2l^5, and increase again from P_2l^5 to P_2l^6. Low values only appear in both the oil shale segment and the late P_2l^6; the values in P_2l^3 are lower than in P_2l^5. In other words, the relationship between paleoclimate and water salinity is significant: warm humid, dry hot and slightly dry hot climates correspond to fresh water, saline water and brackish water environments, respectively, which demonstrates that the paleoclimate influenced directly the water salinity in the study area and an intensive evaporation of the lake due to the dry hot climate is the main reason of the increase of salinity.

4.3. Sedimentary environment

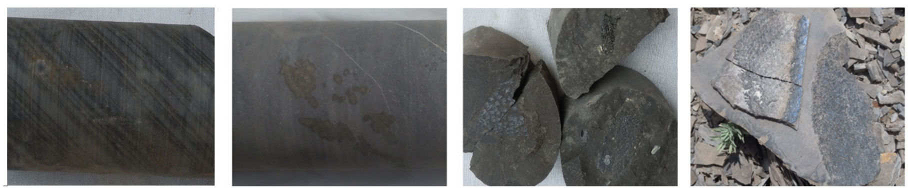
Sedimentary environment influences water depth, hydrodynamic conditions and ecological elements and further controls the abundance and preservation of organic matter as well as thickness of single oil shale layers.

V/(V+Ni) ratio is a commonly-used parameter of paleo-oxygenation facies, V/(V+Ni) > 0.54 indicates an anaerobic environment and V/(V+Ni) < 0.46 indicates an aerobic environment [14, 16, 19–22]. The Table demonstrates that the values of V/(V+Ni) range from 0.414 to 0.858, implicating a reducing depositional environment with only one exception, which favors the preservation of oil shale.

In sandstone and siltstone layers in the Permian Lucaogou Formation, horizontal, current and deformation beddings are well-developed. In addition, pyrite and tuffaceous composition are common, which show typical characteristics of lacustrine sedimentation in the reducing environment and eutrophic conditions. The Lucaogou Formation oil shales were mainly deposited in shallow to semi-deep and semi-deep to deep lake environments.

4.3.1. Semi-deep to deep lake facies

The semi-deep to deep lake facies is an organic-rich reducing environment below the wave base wherein the lower oil shale segment (P_2l^3) was deposited, which refers to the major sedimentary period of oil shale formation in the Lucaogou Formation, with stable lateral distribution, great thickness and relatively high oil yield values. The semi-deep to deep lake facies is deposited by suspension and the sediments generally feature fine grain size, dark color, organic richness and horizontal beddings (Fig. 3 (a)). The main rock assemblage in this segment is dark-black argillaceous rock containing organic matter (silty claystone, oil shale) interbedded with sandy dolostone and dolomitic siltstone of approximately isopachous type. Oil shales of medium to high quality with laminated structure are developed in this segment. Pyrite is a common authigenic mineral and is widely dispersed in argillaceous rock (Fig. 3 (b)), along with fish scale and skeletal fossils, which are abundant in oil shale (Fig. 3 (c), (d)).

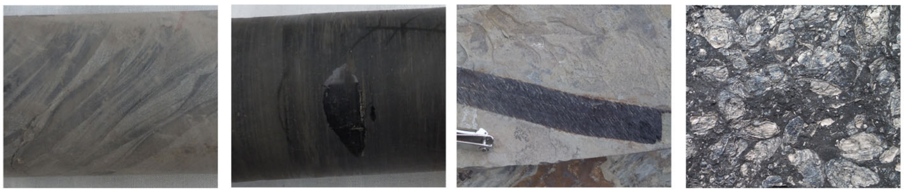


(a) (b) (c) (d)

Fig. 3. Lithologic features of semi-deep to deep lake facies: (a) horizontal bedding, (b) pyrite, (c) fish scale fossils, (d) fish skeleton fossils.

4.3.2. Shallow to semi-deep lake facies

The shallow to semi-deep lake facies lies between the surface and minimum water level in low water season, and formed deposits in a reducing environment with abundant aquatic life, wherein coal seams are not developed, which distinguishes it from the paludal facies. The upper oil shale segment (P_2l^5) was deposited in the shallow to semi-deep lake facies and terrigenous clastic grains are the major sediments. The main rock assemblage in this segment is dark-black silty shale, oil shale interbedded with dark-gray argillaceous siltstone, dolomitic sandstone and dolostone. Meanwhile, linsen, horizontal and fine current beddings were developed (Fig. 4 (a)), whereas large-scale cross beddings have not been discovered. Siderite and pyrite, as well as small amounts of plant debris, plant stem fossils and lamellibranchiate fossils can be found (Fig. 4 (b), (c), (d)). The lateral distribution of oil shale in this segment is inconsistent in the whole mining area, and oil yield values vary over a wide range from low to high grade, which shows that the quality and abundance of organic matter are inferior to those in the lower oil shale segment.



(a) (b) (c) (d)

Fig. 4. Lithologic features of shallow to semi-deep lake facies: (a) linsen bedding, (b) siderite concretion, (c) plant stem fossils, (d) lamellibranchiate fossils.

5. Conclusions

The Jimusaer oil shale can be divided from bottom to top into six segments according to lithologic character: dolomite, dolomite interbedded with siltstone, lower oil shale, sandstone, upper oil shale and shale segments.

A stable lacustrine basin formed in the late stage of the Middle Permian and large-scale thrust faults in the period of Himalayan orogeny are significant structural conditions for the generation and preservation of oil shale.

The Permian Lucaogou Formation was deposited in a warm humid to dry hot climate, and oil shale was deposited in a warm humid to slightly dry hot climate. The paleoclimate influenced directly the water salinity in the study area: warm humid, dry hot and slightly dry hot climates correspond respectively to fresh water, saline water and brackish water conditions.

The Lucaogou Formation was formed in a large-scale paralic lacustrine basin with very high organic matter productivity in a reducing water environment favorable to preservation of organic matter. Oil shale was mainly developed in shallow to semi-deep and semi-deep to deep lake environments; the semi-deep to deep lake was a favorable environment for the development of rich oil shale.

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REFERENCES

1. Liu, Z. J., Liu, R. Oil shale resource state and evaluating system. *Earth Science Frontiers,* 2005, **12**(3), 315–323 (in Chinese).
2. Tao, S., Tang, D. Z., Li, J. J., Xu, H., Li, S., Chen, X. Z. Indexes in evaluating the grade of Bogda Mountain oil shale in China. *Oil Shale,* 2010, **27**(2), 179–189.
3. Tao, S., Tang, D. Z., Xu, H., Cai, J. L., Gou, M. F., Chen, Z. L. Retorting properties of oil shale found at the northern foot of Bogda Mountain, China. *Oil Shale,* 2011, **28**(1), 19–28.
4. Jiao, Y. Q., Wu, L. Q., He, M. C., Roger, M., Wang, M. F., Xu, Z. C. Occurrence, thermal evolution and primary migration processes derived from studies of organic matter in the Lucaogou source rock at the southern margin of the Junggar Basin, NW China. *Science in China Series D: Earth Sciences,* 2007, **50**, 114–123.
5. Tao, S., Wang, Y. B., Tang, D. Z., Xu, H., Zhang, B., He, W., Liu, C. Composition of the organic constituents of Dahuangshan oil shale at the northern foot of Bogda Mountain, China. *Oil Shale,* 2012, **29**(2), 115–127.
6. Tao, S., Wang, Y. B., Tang, D. Z., Wu, D. M., Xu, H., He, W. Organic petrology of Fukang Permian Lucaogou Formation oil shales at the northern foot of Bogda Mountain, Junggar Basin, China. *Int. J. Coal Geol.,* 2012, **99**(1), 27–34.
7. Tao, S., Wang, Y. B., Tang, D. Z., Xu, H., Zhang, B., Deng, C. M., He, W. Estimation of the mineable oil shale amount in West Fukang at the Northern Foot of Bogda Mountain, Zhunggar Basin, China. *Energ. Source., Part A,* 2012, **34(**19), 1791–1800.
8. Wu, S. Z., Qu, X., Li, Q. Paleoclimatic conditions of Lucaogou and Huangshanjie formations in Junggar. *Xinjiang Geol.,* 2009, **20**(3), 183–186 (in Chinese).

9. Li, C. B., Guo, W., Song, Y. Q., Du, J. F. The genetic type of the oil shale at the northern foot of Bogda Mountain, Xinjiang and prediction for favorable areas. *Journal of Jilin University (Earth Science Edition),* 2006, **36**(6), 949–953 (in Chinese).
10. Carroll, A. R. Upper Permian lacustrine organic facies evolution, Southern Junggar Basin, NW China. *Org. Geochem.,* 1998, **28**(11), 649–667.
11. Gao, Z. L., Kang, Y. S., Liu, R. H., Bai, W. H. Geological features and developmental controlling factors of Lucaogou oil shale in the southern margin of Junggar basin. *Xinjiang Geol.,* 2011, **29**(2), 189–193 (in Chinese).
12. Couch, E. L. Calculation of palaeosalinities from boron and clay mineral data. *Am. Assoc. Petr. Geol. B.,* 1971, **55**, 1829–1839.
13. Department of Geology, Nanjing University. *Geochemistry.* Science Press, Beijing, 1987 (in Chinese).
14. Chen, H. J., Liu, Z. J., Liu, R., Guo, W., Xiao, G. P., Wu, Y. B., Fu, Z. R., Shi, J. Z., Hu, X. F., Meng, Q. T. Characteristics of oil shale and paleoenvironment of the Bayingebi formation in the lower Cretaceous in Yin'e basin. *Journal of Jilin University (Earth Science Edition),* 2009, **39**(4), 669–675 (in Chinese).
15. Abraham, L. (ed.). *Lakes – Chemistry, Geology, Physics.* Geological Publishing House. Springer-Verlag, Berlin, 1978.
16. Liu, Z. J., Meng, Q. T., Liu, R. Characteristics and genetic types of continental oil shales in China. *Journal of Palaeogeography,* 2009, **11**(1), 105–114 (in Chinese).
17. Miknis, F. P., McKay, J. F. (eds.). *Geochemistry and Chemistry of Oil Shales*. ACS symposium series 230, Washington, D. C., 1983.
18. Song, M. S. Sedimentary environment geochemistry in the Shasi section of southern ramp, Dongying depression. *Journal of Mineralogy and Petrology,* 2005, **25**(1), 67–73 (in Chinese).
19. Finkelman, R. B. Trace elements in coal: environmental and health significance. *Biol. Trace Elem. Res.,* 1999, **67**(3), 197–204.
20. Hatch, J. R., Leventhal, J. S. Relationship between inferred redox potential of the depositional environment and geochemistry of the Upper Pennsylvanian (Missourian) Stark Shale Member of the Dennis Limestone, Wabaunsee County, Kansas, U.S.A. *Chem. Geol.,* 1992, **99**(1–3), 65–82.
21. Lewan, M. D. Factors controlling the proportionality of vanadium to nickel in crude oils. *Geochim. Cosmochim. Ac.*, 1984, **48**(11), 2231–2238.
22. Lewan, M. D., Maynard, J. B. Factors controlling enrichment of vanadium and nickel in the bitumen of organic sedimentary rocks. *Geochim. Cosmochim. Ac.*, 1982, **46**(12), 2547–2560.

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