Geochemical characteristics of the lower Jurassic black shales in the Jinyang Basin, northeast China: Implications for organic matter accumulation

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Abstract. The lower Jurassic Beipiao Formation is a significant set of hydrocarbon source rocks in Jinyang basin. Hydrocarbon generation potential and paleoenvironment conditions of Beipiao shale were investigated by utilizing organic and inorganic geochemistry data. The results show that the Beipiao shale contains a wide range of TOC and type II and type III organic matter. The Beipiao shale was deposited in a hot, humid and oxic climate. In addition, the salinity of the water column was low. Paleoenvironment parameters, such as the Sr/Ba ratios and V/Cr ratios show a strong positive relationship between TOC content. These correlation studies indicate that paleoenvironment conditions have a strong controlling effect on the accumulation of organic matter during early Jurassic time.

1. Introduction

Lacustrine source rocks usually display strong lateral heterogeneity due to the confined lake water size and sensitivity to changes in external environment [1-3]. To study the control factors, various geochemical parameters such as organic and inorganic proxies are commonly used [4, 5]. Of the many factors, influence of external factors, such as climate and tectonics, on lacustrine deposition had been much investigated [6-8]. Trace element geochemistry can provide useful information about climate, primary productivity and water properties. Therefore, the integration of organic and inorganic geochemical data is an effective way to characterize source rock depositional paleoenvironment and organic matter sources. Correlate source rock depositional environment with tectonic and climatic properties can help us better understand the process of source rock deposition.

The Jinyang basin, one of the Mesozoic volcano-sedimentary rifted basins in the southern peripheral area of the world famous Songliao basin, is a newly discovered petroliferous basin. It is a narrow and elongated basin trending from southwest to northeast (Fig. 1). The Jinyang basin is about 200km long, 40km wide and its total area is about 7400 km², make it the largest of the Mesozoic basins in this area. Preliminary stratigraphic correlations and other studies in this area prove that the black shale from early Jurassic Beipiao Formation is widely distributed and possibly have significant hydrocarbon resource potential [9-11]. In this study, a variety of organic and inorganic parameters were utilized to investigate the type of organic matter, sedimentary paleoenvironment, level of thermal maturation and potential for hydrocarbon generation (oil and/or gas) of the lower Jurassic Beipiao Formation.

2. Geological setting
The Jinyang Basin, tectonically bounded by the Nantianmen thrust fault to the west and Songlingmen uplift to the east, is a relatively new petroliferous basin in the peripheral area of the Songliao Basin, northeast China (Fig.1). The residual sedimentary series in Jinyang Basin are mainly composed of Jurassic deposits. The Beipiao Formation is early Jurassic coal measured terrestrial deposits mainly distributed in Jinyang basin and adjacent areas. The lithology of Beipiao Formation is represented by coarse grained and weakly cemented conglomerate, conglomeratic sandstone, siltstone and dark lacustrine mudstone interbedded with coal seams [12]. The sedimentary facies identified in Beipiao Formation including alluvial fans, braided river deltas and lake deposits. Depositional facies vary vertically from alluvial fans to braided river delta and then to lake facies and finally to delta [12]. These sediments unconformably overly the early Jurassic andesite or Precambrian carbonates. Previous studies indicate that Beipiao Formation was deposited as a result of subsidence that related to the formation of Yanshan orogeny during Mesozoic [13, 14]. Middle to late Jurassic intermediate volcanics were widespread across the eastern part of Jinyang basin and unconformably overlie Beipiao formation.

Figure 1. Geological outline map of Jinyang basin and adjacent areas (Modified from Sun et al. 2017)

3. Methods
The samples analyzed were from a profile named Kuntouyingzi profile on the western area of the Jinyang Basin (Fig. 1). A total of 11 samples were collected from this section, and all of the samples are dark-colored shales. These samples were collected from the profile from bottom to the up and covered the widespread layers.
A combined experimental program, including total organic carbon (TOC) contents, Rock-Eval pyrolysis, trace and main elements was conducted for all samples. Total organic carbon content is measured by LECO CS230 Carbon/Sulfur analytical instrument. Rock-Eval pyrolysis analyses were analyzed with OGE-VI Rock-Eval workstation at Yangtze University based on a standard procedure. The Rigaku X-ray Fluorescence (XRF) Spectrometer (model 3080E3) was used to analyse selected trace elements based on the Chinese national standard (GB/T14506.28—1993).

4. Results and discussions

4.1. Organic geochemistry

The TOC of the samples ranges from 0.65% to 3.27%, with an average of 1.55%, indicating fair to good organic source rocks. The HI value fall into a wide range of 20–341 mg HC/g TOC (average: 128 mg HC/g TOC). The Tmax-HI plot suggests that the organic matter type of shale sample includes type II₁, II₂ and III, showing that the OM type of shale samples in the same formation is heterogeneous. (Fig. 2). Generally, type II kerogen is oil prone and type III kerogen is gas prone. The type of hydrocarbon that could be generated for shale samples in the mature stage is related with the organic maceral composition of the shale samples. Therefore, the organic petrology of shale samples needs to be characterized. Except for one sample of which the Ro is larger than 1.3%, the thermal maturity of the samples ranges between 0.5 and 1.3%, which suggests that the samples are mainly in the mature stage. The value of S1+S2 of the samples is positively correlated with the TOC content, indicating that shale samples with higher TOC has larger hydrocarbon retention capacity and hydrocarbon generation potential.

![Figure 2. Rock-Eval plots of the samples from Beipiao Formation](image)

4.2. Paleoenvironment conditions

Paleoclimate and paleoredox conditions are key environmental factors that control source rock accumulation and properties. Numerous studies have demonstrated that certain trace elements, such as Sr, Ba, Cu, U, Th, V, Cr, Ni and Co in fine-grained shales can reveal the paleoclimate and paleoredox conditions during their deposition times [15-19].

The Sr/Ba and Sr/Cu ratios are widely used for reconstruction of the paleo-salinity and paleoclimate conditions. In the samples from Beipiao Formation, the Sr/Ba ratios vary from 0.17 to 0.63 (avg. 0.38), indicating the humid climate conditions. The Sr/Cu ratio is also a commonly used indicator to investigate paleoclimate conditions. The Sr/Cu ratios of shales from the Beipiao Formation vary from 3.15 to 10.05 (average 6.66), indicating a generally humid climate condition but with arid intervals. According to previous studies, the climate during early Jurassic in this area was
warm and humid but could be hot and even arid at short intervals [20, 21], which is consistent with the Sr/Ba and Sr/Cu ratios. It should be known that these elements are subject to more complex processes controlled by provenance, climate and depositional and diagenetic conditions, so these ratios should be used with caution.

![Lithological column of the Beipiao Formation in Kuntouyingzi profile with organic geochemical and trace elemental parameters](image)

**Figure 3.** Lithological column of the Beipiao Formation in Kuntouyingzi profile with organic geochemical and trace elemental parameters

Redox-sensitive elements, such as U, Th, V, Cr, Ni and Co are widely used as paleoenvironment proxies. The ratios of U/Th, V/Cr, and Ni/Co are considered as reliable redox indexes. A ratio of U/Th higher than 1.25 marks an anoxic environment, and 0.75–1.25 signals a suboxic to dysoxic environment, while a ratio lower than 0.75 indicates an oxic environment. For the V/Cr ratio, the range higher than 4.25, 2.0–4.25, lower than 2.0, respectively. For ratios of Ni/Co the ranges are higher than 7.0, 5.0–7.0 and lower than 5.0[22]. As Figure 3 indicates, all of the three redox proxies suggest an oxic environment, which is consistent with results from palaeontology and sedimentology [20]. All these inorganic and organic indicators suggest an oxic and humid water column. These results reveal that Beipiao shale was deposited in terrestrial oxic environments with relatively poor preservation conditions.

4.3. Correlations between paleoenvironment and organic matter accumulation

Many factors, including climate, water column conditions, weathering, plant availability and tectonic setting can substantially impact the accumulation of organic matter. Generally, good source rocks are
deposited in reducing and humid environments, while the Beipiao Formation was deposited in oxic conditions as indicated by the redox sensitive elements. To discern whether the climate and redox conditions had a controlling effect on organic matter accumulation, the relationship between TOC and climate and redox proxies were analyzed.

Low Sr/Ba ratios were found in Beipiao shale, and the ratios show a strong positive relationship to the TOC. Nevertheless, the Sr/Cu ratios show no correlation to TOC, indicating no controlling effect on organic matter accumulation. High V/Cr and Ni/Co ratios relate to increasingly deficient oxygen levels during deposition [22]. Low V/Cr and Ni/Co ratios are found within Beipiao shales, suggesting high oxygen regimes during deposition of Beipiao shale. Despite the high maturation levels of Beipiao shale, element ratios to TOC contents are relatively consistent suggesting no significant thermal maturity overprinting of the geochemistry has occurred. It should be noted that the V/Cr and Ni/Co ratio have negative correlations, although all of the ratios fall into the oxic range. That may be related to diagenetic processes which have slightly altered the elemental compositions. Generally, high-salinity and anoxic water are good conditions for the accumulation and preservation of organic matters during deposition. However, the results showed before indicate that the Beipiao Formation is deposited during a hot and oxic water column, which is unfavorable for the preservation of organic matters. So, it is of great importance to study the thermal evolution and preservation conditions of Beipiao Formation.

5. Conclusions
Our investigation on lower Jurassic Beipiao Formation in Jinyang Basin draw the following main conclusions:

(1) The TOC content of the thermally mature Beipiao shale varies in a wide range and the shale samples are heterogeneous in organic matter type including type II_1, II_2 and III.

(2) The paleoenvironment parameters of Beipiao shale present a humid and hot climate, and the water column is of low salinity. These proxies indicate that Beipiao shale was deposited in terrestrial oxic environments with relatively poor preservation conditions.

(3) The good correlation between the paleoclimate/paleoredox parameters and TOC content implies that paleoenvironment had a strong controlling effect on the accumulation and preservation of organic matter in Beipiao shale.

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