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Origin of organic matter and paleo-sedimentary environment reconstruction of the Triassic oil shale in Tongchuan City, southern Ordos Basin (China)

Delu Li [a,*], Rongxi Li [a,*], Zengwu Zhu [b], Xiaoli Wu [a], Jinghua Cheng [a], Futian Liu [a], Bangsheng Zhao [a]

[a] School of Earth Sciences and Resources, Chang'an University, Xi'an 710054, China
[b] Shaanxi Center of Geological Survey, Xi'an 710068, China

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ABSTRACT

Owing to the lack of conventional oil resources, oil shale from the Triassic Yanchang Formation in the southern Ordos Basin has attracted unprecedented attention. The origin of organic matter and the paleo-sedimentary environment of oil shale are discussed. Based on the results of total organic carbon (TOC), total sulfur (TS), rock pyrolysis, organic elements, vitrinite reflectance (Ro), biomarkers, major elements, and trace elements of oil shale from Yishicun Profile, Tongchuan City. The oil shale from the Chang 7 sub-unit has high TOC (0.29–24.68%) and low TS content (0.13–0.61%), exhibiting middle-grade criterion and extra-low sulfur quality. The Ro, together with discrimination diagrams of C_29steraneββ/(ββ + αα)-αααC$_2$9sterane20 S/(20 S + 20 R) and OEP-CPI, suggests that the oil shale has reached maturity. $C_{27}-C_{29}$ regular steranes distribution, (C_{19} + C_{20}tricyclic terpane)/C_{23}tricyclic terpane, and C_{23}tricyclic terpane/(C_{23}tricyclic terpane + C_{30}hopane) all indicate that the parent materials of the organic matter in the oil shale are algae, phytoplankton, and terrestrial plants. The Pr/Ph, V/Cr, V/(V + Ni), U/Th, δU, and TOC-TS-TFe$_2$O$_3$ ternary diagrams indicate that oil shale mainly deposits in reducing environment with a relatively poor preservation conditions. TS content, gammacerane/αβ-C_{30}hopane, gammacerane/0.5C_{31}αβ(22 R + 22 S), and Equivalent Boron accurately explain that marine transgression did not occur and the paleosalinity of the lake indicates predominantly fresh water. The paleoproductivity of the lake during oil shale sedimentation is very high in terms of U and Mo concentrations and Ba/Al ratio. After quantitative calculation, the lake is classified as an extremely eutrophic lake. The water depth of oil shale sedimentation varies from 26.00 to 108.6 m, indicating a semi deep- deep lake.

1. Introduction

Oil shale has been studied extensively because of its potential as an unconventional source of oil and gas [1–3]. Large Chinese oil shale deposits were found in the Songliao Basin, Junggar Basin, and Ordos Basin. Oil shale from the Triassic Yanchang Formation in the southern Ordos Basin contains estimated resources of 14159.04×10^8t of shale oil [4]. The main hosting stratum of the oil shale is at the bottom of the Chang 7 sub-unit. In early studies of oil shale, major controversy focused on the type and origin of the organic matter, the lake type and salinity at time of deposition of the oil shale [5–13]. Zhang et al. [5] performed pyrolysis experiments on individual oil shale samples and proposed that the organic material was primarily Type I, was high maturity, and came from a mixed source [12]. Other scholars argued that the organic matter was dominantly Type II, and was immature [11,13]. Sun et al. [9] calculated the productivity of the lake during deposition of oil shale, but because of the controversial nature of the organic matter, their results reflect the wrong lake type. Luo et al. [6] used saturate hydrocarbon biomarkers to determine that the lake water was fresh (low salinity), and that the redox state was euxinic. However, other studies presented faunal data, the presence of framboidal pyrite, and the ratio of organic carbon to total phosphorus to suggest that marine transgression occurred during oil shale sedimentation, and the redox condition was primarily oxidizing, with poor preservation of organic matter [14,15]. Deng et al. [7] hold the viewpoint that the oil shale was deposited in a semi-deep to deep lake based on organic geochemistry and geophysical log characteristics. In contrast, Bai et al. [10] believed that oil shale was mainly deposited in a shallow lake. Although numerous research efforts have been conducted on the

* Corresponding authors.
E-mail addresses: lidelu322@126.com (D. Li), rongxi99@163.com (R. Li).

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oil shale from the Chang 7 sub-unit in the southern Ordos Basin, many unresolved issues remain. This confusion appears to result from over-reliance on single analytical methods and too widespread distribution of samples across the basin, which has obstructed oil shale exploration in the Ordos Basin.

Here, we systematically present total organic matter (TOC), total sulfur content (TS), rock pyrolysis data, vitrinite reflectance (Ro), biomarkers distribution, organic elements, major elements and trace elements of oil shale outcrops of the Yishicun profile in Tongchuan City to provide a more thorough understanding of the type and source of its organic matter and the formation of the paleoenvironment.

2. Geological setting

Located in central China, the Ordos Basin is predominantly a Mesozoic depressed basin developed in the Palaeozoic North China Craton with a Proterozoic crystalline basement [16,17]. The north and the south of the basin are adjacent to the Hetao Basin and Fenwei Graben, with an irregular rectangular area of 25×10^4 km^2 (Fig. 1(a)) [18]. Originally part of Huabei Block, the basin gradually separated and evolved into a continental basin in the late Mesozoic Era [19]. Influenced by Indosinian orogeny, during the period of Yanchang Formation, the southern Ordos Basin proved to be an intracontinental foreland basin [20,21] and developed a fluvial-lacustrine sedimentary system. According to sedimentary cycles and lithological assemblages, the Yanchang Formation (T_3y) is divided into ten sub-units, appointed as Chang 10 to Chang 1 (from bottom to top) [22,23]. The whole formation is an integrated record of progradation- aggradation- retrogradation cycle and the most extensive lake transgression occurred during the Chang 7 period with tectonic orogeny and paroxysmal eruption in the south, producing the famous "Zhangjiatan Oil Shale" [24,25].

Yishicun Profile is located in Tongchuan City, southern Ordos Basin, with clear oil shale outcrops at the bottom of the Chang 7 sub-unit (Fig. 2), and the occurrence of oil shale is nearly horizontal. The lithologies of oil shale section are composed of oil shale and mudstone with thin tuff intercalations.

3. Samples and methods

A total of 14 samples, including two mudstone samples and 12 oil shale samples, were collected from the oil shale section in the Yishicun Profile. Details of the rock assemblages and numbers of samples are shown in Fig. 3. All samples were collected and stored in plastic bags until they were used in experiments to ensure minimal contamination and oxidation.

For analyses of TS, samples were crushed to less than 100 μm and heated to 1250 °C with N_2 as carrier gas after being mixed with WO_3. The SO_2 generated was absorbed by diluted hydrochloric acid with starch and potassium iodide. The test methods were in accordance with GB/T 6730.17-2014 [28]

For analyses of TOC and rock pyrolysis, samples were crushed to powder and the inorganic carbon in samples was removed by diluted hydrochloric acid. After being burnt in high temperature oxygen flow, organic carbon could be tranformed to CO_2 and tested using a Multi EA2000. Pyrolysis analysis was conducted on powder samples using Rock-Eval equipment. Samples of mass 30 mg were heated to 600 °C in a helium atmosphere and S_1, S_2, S_3 and Tmax were measured. The test methods were in accordance with GB/T 19145-2003[29] and GB/T 18602-2012 [30].

For analyses of the organic elements, samples were ground homogeneously in agate mortar and dried at 60 °C for four hours, Then, a high temperature cannular burner was used to calculate the carbon and hydrogen concentrations. Oxygen is tested using an infrared detector in a cracking tube. The test method was in accordance with GB/T 19143-2003 [31].

The selected oil shale samples were tested by gas chromatography (GC) and gas chromatography-mass spectrometry (GC–MS). GC analyses were conducted on a SHIMADZU GC-2010, equipped with a 30 m × 0.25mm × 0.25μm HP-5 fused silica capillary column, with He as the carrier gas. Then, the gas was boosted at a rate of 1.0 mL/min. The testing standard used was GB/T 18340.5-2010 [32].

GC–MS analyses were performed on an Agilent 6890GC/5975i MS with a 60 m × 0.25 mm × 0.25 μm HP-5MS fused silica capillary column, with He as the carrier gas. Then, the gas was boosted at a rate of 1.0 mL/min. The testing standard used was GB/T 18606-2001 [33].

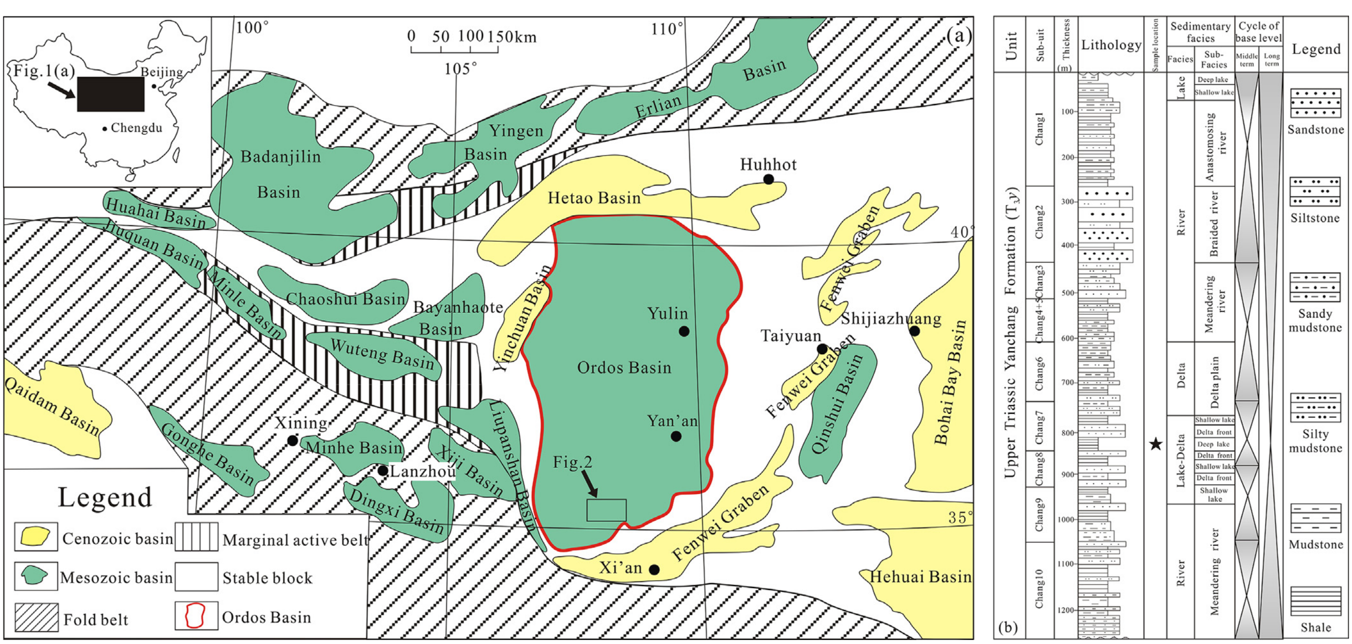

Fig. 1. (a) Mesozoic and Cenozoic sedimentary basins distribution and tectonic setting map (modified after Liu [26]). (b) Stratigraphic column of Upper Triassic Yanchang Formation (modified after Qiu et al. [27]).