

Article

Origin of Suspected Solid Bitumen in Mesoproterozoic Jixian System in Tongcheng Outcrops, Southwest Ordos Basin

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Abstract

To clarify the composition and origin of the suspected solid bitumen, which is found in the fractures of the Jixian System in Tongcheng outcrops, the suspected solid bitumen samples, as well as dolomite samples, were collected from the Jixian System in Tongcheng and Qishan outcrops for various tests. The results show that the suspected solid bitumen samples are mainly composed of clay minerals. No solid bitumen was found in the pores and microcracks of the dolomite samples by microscope and Raman spectroscopy. The total organic carbon content of the solid bitumen ranges from 0.59% to 1.15%, revealing that the suspected solid bitumen is dark mudstone powder, rather than solid bitumen. The R_b values range from 2.59% to 2.77%, and the $T_s/(T_s + T_m)$ values mostly approach 0.5, indicating that the organic matter in the suspected solid bitumen is in the mature to over-mature stage. The $V/(V + Ni)$, Sr/Cu , and Sr/Ba values of the suspected solid bitumen indicate that it was deposited in a warm, humid, anoxic sedimentary environment. The slightly right-inclined rare earth element pattern of the suspected solid bitumen samples implies the sedimentation rate was slow or they were affected by weathering and leaching processes. Through a comparison of trace elements and hierarchical clustering analysis of rare earth elements, the suspected solid bitumen manifests the closest correlation with the mudstone source rocks of the Cambrian Zhangxia Formation. Early Devonian period, the Cambrian mudstone source rocks in the Tongcheng area were uplifted; then weathered, leached, and fragmented into powder; and then filled the fractures of the underlying Mesoproterozoic Jixian System. Of course, another geological scenario has not been ruled out: that some of the fractures in the Jixian System may be filled with solid bitumen, which may be the result of the destroyed paleo-oil reservoirs near the ancient uplift in the Tongcheng area.

Keywords: Jixian system; Tongcheng outcrops; suspected solid bitumen; trace element distribution; rare earth element; southwest Ordos Basin

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1. Introduction

The discovery of Precambrian primary oil–gas reservoirs in Oman, India, Australia and Russia proved that Precambrian strata, including Meso-Neoproterozoic strata, could include potential effective source rocks and primary oil–gas reservoirs [1–4]. In China, the successful exploration of the Ediacaran Weiyuan gas field and the Cambrian

Anyue gas field in the Sichuan Basin enhanced geologists' exploration confidence in Precambrian oil and gas resources [5–7]. Since 1950, a large amount of solid bitumen and oil seedlings in Mesoproterozoic Jixian System outcrops have been found [8] in the North China Craton (NCC), which is an ancient craton with a series of sedimentary basins in it, including the Ordos Basin. The discovery of solid bitumen has promoted extensive research on primary oil reservoirs from the Ediacaran to the Mesoproterozoic [7,9,10].

The Ordos Basin is situated in the west of the NCC and in the peripheral outcrops; Well Tao 19 confirmed the existence of the source rocks of the Mesoproterozoic Changcheng system [9], and Well Jin 13 in the north Ordos Basin obtained a high yield of gas in Mesoproterozoic strata [11,12]. Whether the Meso-Neoproterozoic developed large-scale and effective source rocks has become a significant issue, and the Meso-Neoproterozoic source rock in the south Ordos Basin has increasingly attracted geologists' attention [6,7,12]. Numerous studies have focused on the sedimentary characteristics and evaluation of the quality potential of Mesoproterozoic source rocks [10–13].

Simultaneously, oil seep outcrops potentially related to deep hydrocarbon reservoirs were also noticed by researchers. In the Tongcheng, Chongxin, Gansu, Qishan, and Shanxi areas, some dark loose substances were found to occur in Mesoproterozoic Jixian System outcrops, which were considered to be solid bitumen originating from palaeo-oil reservoirs [7,12]. Li analyzed the hydrocarbon group compositions and biomarker compounds of the solid bitumen in the Mesoproterozoic Jixian System [7] and inferred that the solid bitumen in the Jixian System stemmed from laminated algal dolostone of the Jixian System [7]. Yet, whether the Jixian System has effective source rocks is controversial [7,9]. Overall, the research associated with the Mesoproterozoic Jixian System in the Ordos Basin so far focuses on the sedimentary and paleoenvironment characteristics [11,13]. Meanwhile, the mineral compositions and the origin of the solid bitumen in the Jixian System remain unclear. Herein, we call them suspected solid bitumen. To clarify the petroleum geological conditions of deep oil and gas, it is significant to figure out the mineral composition, geochemical characteristics, and the formation process of the suspected solid bitumen in the Mesoproterozoic Jixian System. This article aims to (1) analyze the composition and geochemical characteristics of the suspected solid bitumen occurring in the fractures of the Jixian System in Tongcheng outcrops, (2) provide insight into the origin of solid bitumen, and (3) analyze the possible formation process of suspected solid bitumen. The conclusions will deepen the exploration potential of the Mesoproterozoic in the Ordos Basin.

2. Geological Setting

The Ordos Basin can be divided into six tectonic units, named Yimeng Uplift, Jinxi Knitebelt, Yishan Slope, Weibei Uplift, Tianhuan Depression, and Xiyuan Knitebelt [14], respectively (Figure 1a). Before the Paleozoic, the Ordos Basin had a similar tectonic and sedimentary background to the other areas in the NCC, which all developed the Mesoproterozoic as the bottommost sedimentary cover layers. During the Mesoproterozoic, the topography of the Ordos Basin was monoclinic, meaning it was high in the northeast and low in the southwest. The northeast part manifested as an ancient uplift area and the southwest part manifested as a sedimentary area (Figure 1a). During the early Mesoproterozoic, accompanied by the global breakup of the Columbia supercontinent, a series of rifts occurred in the NCC [15]; the Changcheng System was deposited, respectively, in neritic, littoral, and fluvial-deltaic environments from southwest to northeast [11]. During the late Mesoproterozoic, the Jixian System was subsequently deposited in a tidal flat sedimentary environment in the south Ordos Basin within a stable passive continental margin, with the ancient Kuanping Sea in the southwest and the ancient Qinqi

Sea in the south [11,16]. Due to the influence of ancient uplift and depression [15], the thickness of the Jixian System in the south Ordos Basin varies greatly. The studied Tongcheng outcrops, where the suspected solid bitumen was sampled, are situated near the Qingyang uplift in the southwest Ordos Basin (Figure 1a), where the Mesoproterozoic Jixian System is relatively thin in thickness, controlled by the persistent Qingyang ancient uplift.

Except for the studied Tongcheng area, the Jixian System is also exposed in the Helan Mountain area in the west of the Ordos Basin, as well as in the Qishan and Lunan areas in the south margin of the Ordos Basin [11]. The Jixian System exposed in these outcrops is mainly composed of gray-white, flesh pink mud-powder crystal laminar dolomite, interbedded with a siliceous interlayer and gray argillaceous dolomites [11], rarely developing mudstone and shale. The Jixian System can be divided into four formations, named Longjiayuan Formation, Xunjiansi Formation, Duguan Formation, and Fengjiawan Formation, from the bottom to the top [16], with a total thickness ranging from 0 m to 1000 m [11]. In Tongcheng outcrops, Jixian System is directly covered by the Cretaceous Luohandong Formation (Figure 1b).

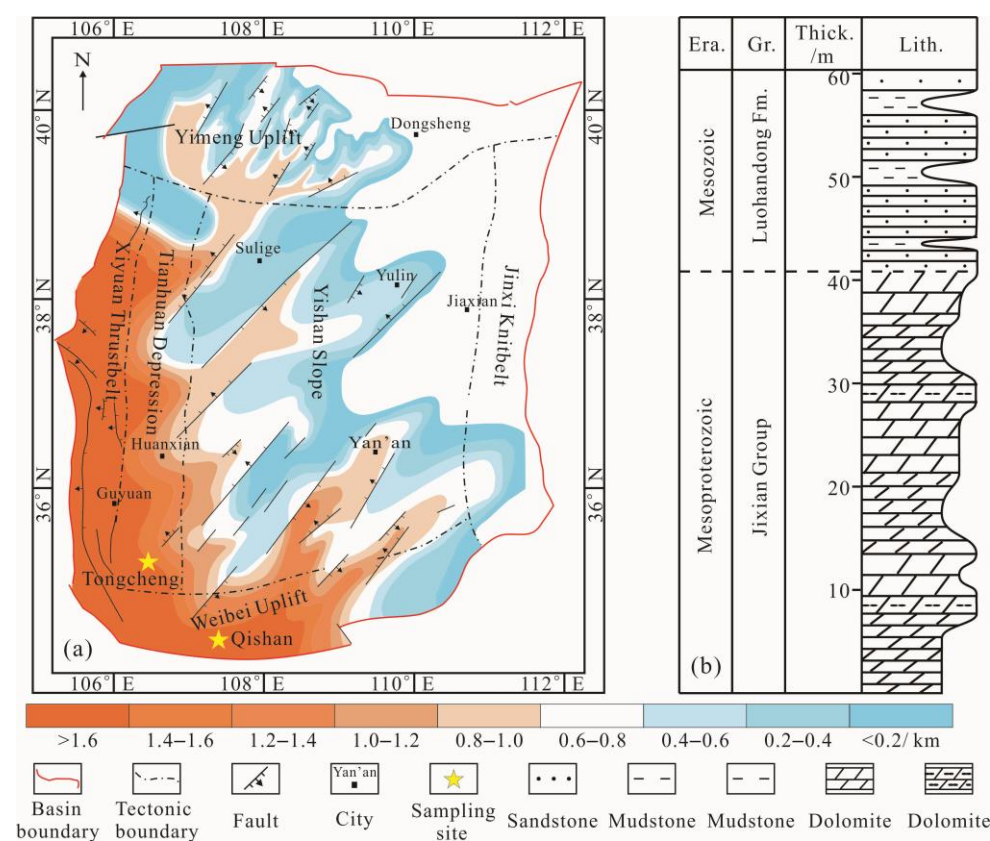


Figure 1. (a) The position of the study area and contour map of thickness of Mesoproterozoic strata in the Ordos Basin (modified from [16]). (b) The section of the Jixian System in Tongcheng outcrops (modified from [17]).

3. Sampling and Methods

A total of twenty-five samples were used for testing in this study, including fourteen suspected solid bitumen samples, which appear as dark, loose, powdery materials in the fractures of the Jixian System, and eleven block-shaped dolomite samples of the Jixian System. Most samples were collected in Tongcheng outcrops, and three dolomite samples were also collected in Qishan outcrops. During the sampling process, the exposed surface was excavated, and fresh samples with relatively low weathering were

selected. To clarify the petrology and geochemical characteristics of the suspected solid bitumen samples, a series of tests were conducted on these samples, such as total organic carbon content (TOC) test, X-ray diffraction (XRD), the gas chromatography-mass spectrometry (GC-MS) analysis, thin section microscopic observation, Tescan Field Emission Electron Microscope (F-SEM) examination, inductive coupling plasma mass-spectrometric (ICP-MS) test, etc. The organic geochemical tests, such as TOC, GC-MS, and bitumen reflectance (Rb) measurement, were completed in the Geochemistry Laboratory of Changjiang University; other tests were completed in the Geological Test and Analysis Center of Xi'an Shiyou University (Table 1).

Table 1. The sampling site and lithology of the test samples in this research.

Testing Institution	Type of Testing	Sample No.	Sampling Site	Lithology
Geochemistry Laboratory of Changjiang University	XRD, GC-MS, TOC, hydro-carbon components	HY29, HY35, HY37, HY54	Tongcheng outcrops	Dark loose power
	Rb	HY29, HY35		
the Geological Test and Analysis Center of Xi'an Shiyou University	Thin section observation	HY29, HY37,	Tongcheng outcrops	Dolomite
	SEM	HY30-1, HY30-3, HY37-1		
	Laser Raman test	HY29-1, HY29-4, HY39-1		
	ICP-MS	HY26, HY28, HY29-1, HY29-2,	Qishan outcrops	Dark loose power
		HY30, HY34, HY35-1, HY35-2, HY37-1, HY37-2, HY40		
		HY51-1, HY52, HY32	Qishan outcrops	Dolomite

3.1. Microscopic Component Identification and Raman Spectroscopy

Dolomite samples were prepared into thin rock slices with a thickness of approximately 0.03 mm and then were observed with a DM4500 microscope under orthogonal light and single polarization. Simultaneously, to clarify the microscopic morphology and compositions of dolomite samples, a Tescan MIRA3 Field Emission Electron Microscope (Tescan Corporation, Brno, Czech Republic) and Xplore30 Energy Spectrometer System (Oxford Instruments plc, Oxfordshire, UK) were used; the testing temperature was 25 °C and the humidity was 43%.

Dolomite samples were analyzed on a LabRAM HR Evolution Laser Raman Spectrometer (HORIBA France SAS, Longjumeau, France) to detect the composition of dark materials in microfractures and inclusions in minerals. The wavelength of the He-Ne laser used in the experiment is 632.8 nm, the slit width of the spectrometer is 10 µm, and the experimental temperature and humidity are 20 °C and 43%, respectively.

3.2. Mineral and Elemental Composition Tests

The XRD test used a D8AA25 X-ray diffractometer (Bruker AXS SE, Karlsruhe, Germany), with a copper target characteristic X-ray Cu Ka and ceramic-wrapped metal X-ray tube, Lynx Eye™ semiconductor array detector (Bruker AXS SE, Karlsruhe, Germany). Each sample was dried for 48 h in an oven below 80 °C, then ground to a particle size of less than 40 µm, and made into a test piece with a flat surface. The XRD test was operated at a temperature of 21 °C and a humidity of 70%.

To analyze the elemental composition of these samples, an Agilent Technologies 7700 Series (Agilent Technologies, Inc., Santa Clara, CA, USA) was used for ICP-MS analysis. The experimental temperature was 25 °C and the humidity was 43%. During the experiment, 10 ng/mL Rh solution was used as the online internal standard, and the repeated measurement of the laboratory rock standard sample was used to control the analysis accuracy. The analysis accuracy of trace elements is better than 5%, and the analysis accuracy of rare earth elements is better than 10%.

3.3. Organic Composition and Thermal Maturity Tests

The TOC tests were operated with a LECO-CS230 high-frequency infrared carbon-sulfur analyzer (LECO Corporation, St Joseph, MI, USA). Before measurement, each suspected solid bitumen sample was crushed to below 100 mesh, and the carbonate in the sample was removed with dilute hydrochloric acid. The ratio of hydrochloric acid was 1:10, the temperature for heating the crucible was 60–80 °C, and the time for dissolving carbonate in the sample was 2 h.

To obtain the hydrocarbon group components, the suspected solid bitumen samples were Soxhlet-extracted for 24 h with CHCl_3 , the n-hexane solvent fractionation was conducted through a silica gel alumina chromatography column, the saturated hydrocarbons, aromatic hydrocarbons, and non-hydrocarbons were sequentially washed out, and weighed using an AE240 balance (Mettler-Toledo GmbH, Greifensee, Switzerland).

To figure out the biomarker characteristics, the suspected solid bitumen samples were analyzed on an Agilent 6890/5975 desktop mass spectrometer (Agilent Technologies, Inc., Santa Clara, CA, USA) for GC-MS analysis, and on a solid phase chromatography column with silica gel/alumina (3:2) for component separation, after Soxhlet extraction and petroleum ether dissolution. The biomarker content was calculated using peak areas from the various chromatograms.

A Leica MPV-SP Microphotometer (Leica Microsystems GmbH, Wetzlar, Germany) was used to measure Rb values of the suspected solid bitumen samples. The asphaltene component extracted from the samples was encapsulated in epoxy resin, cured after vacuum degassing, and polished to a thickness of 30 μm . The wavelength of the incident light is $546 \text{ nm} \pm 5 \text{ nm}$; the standard sample is cubic zirconia with a reflectivity of 3.08%.

4. Results

4.1. Petrological Characteristics

In the studied Tongcheng outcrops, the Cretaceous Luohandong Formation and the underlying Jixian System are both exposed. The Luohandong Formation is mainly composed of yellow-brown thick-layered sandstone (Figure 2A), and the Jixian System is mainly composed of fine-crystalline to micritic dolomite and siliceous dolomite, interbedded with siliceous bands (Figure 2B,C). The Jixian System developed bedding and oblique bedding fractures, filled with a dark powdery substance. According to previous research, when a paleo-oil reservoir is destroyed, the solid bitumen within the reservoir trap range may be preserved. The sandstone reservoirs are usually black to dark gray in color [17], and the carbonate reservoirs generally contain solid bitumen in dissolved pores, caves, and fractures [5,12,18]. The Jixian System in the Tongcheng outcrops is tight, rarely develops secondary dissolution pores or cavities, and the suspected solid bitumen appears as dark powder lacking luster and hardly dirties hands. Some dolomite samples have dark stripes and spotted dark material in rock specimens (Figure 2D,E); the composition of these dark stripes in siliceous dolomite is not yet clear.



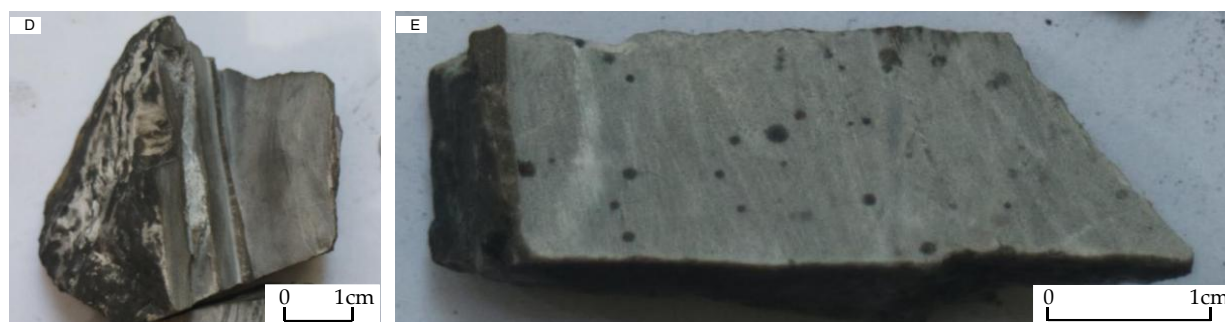


Figure 2. The photographs of the solid bitumen in the Jixian System in Tongcheng outcrops, Chongxin County, southwest Ordos Basin. (A) The unconformity contact interface between the Cretaceous Luohandong Fm. and the underlying Jixian System. (B) Banded siliceous dolomite of the Jixian System in Tongcheng outcrops; a large amount of loose granular dark material occurring in the fractures of the Jixian System. (C) A large amount of loose granular dark material filled in the fractures of gray-white siliceous dolomite. (D) Sample HY37, dark stripes in gray micritic dolomite of Jixian System in Tongcheng outcrops. (E) Spotted dark material in gray siliceous dolomite of Jixian System in Tongcheng outcrops.

4.2. The XRD and TOC Test

The TOC values of the suspected solid bitumen range from 0.59% to 1.15% (Table 2), equivalent to a medium level of oil source rock according to the evaluation criteria of Chinese terrestrial oil source rocks [19]. Due to the result of the XRD test, these dark loose sample materials are mainly composed of silicate minerals; the content of clay minerals ranks the highest with mass percentage ranging from 34.7% to 48.3%, followed by quartz with mass percentage ranging from 11.6% to 41.1% (Table 2). Solid bitumen should be composed of aromatic hydrocarbons or carbon rather than inorganic minerals. Therefore, the suspected solid bitumen is not solid bitumen, but mudstone powder.

Table 2. The mineral compositions of rock samples of the Jixian Group in Tongxiang outcrops.

Sample No.	Mineral Compositions/%							TOC/%
	Quartz	K-Feldspar	Plagioclase	Calcite	Dolomite	Pyrite	Clay Minerals	
HY-29	31.8	2.8	12.8	10.5	5.4	2.0	34.7	0.98
HY-35	41.1	1.4	6.0	3.7	4.8	4.7	38.3	0.59
HY-37	33.7	1.9	4.9	3.3	4.9	3.0	48.3	1.15
HY-54	11.6	0.6	4.7	20.0	8.6	9.5	45.0	0.63

4.3. Thin Section Observation and SEM Examination

Under an optical microscope, dark material was observed to occur in the microcracks of the micritic dolomite samples of the Jixian System in Tongcheng outcrops (Figure 3A–C), and this dark material does not fluoresce under long-wavelength ultra-violet light excitation (Figure 3C), implying it may be carbonized bitumen, which underwent a high-degree thermal evolution process, or it may be metal minerals. Previous research suggests that solid bitumen is usually in the shape of crusts, spheres, polygons, and thin-skinned under SEM [18]. While no substance with these features was found in this research, according to the observation and energy spectrum measurement of the dolomite samples of the Jixian System in Tongcheng outcrops, some powdery substances similar to solid bitumen were observed to fill in the pores; however, these were identified as not containing C atoms (Figure 3D). Some blocky substances were found with an atomic ratio of C and O close to 1:3, implying they are probably carbonate (Figure 3D–F). Therefore, no solid bitumen characteristics were found in the dolomite samples of the Jixian System under SEM.

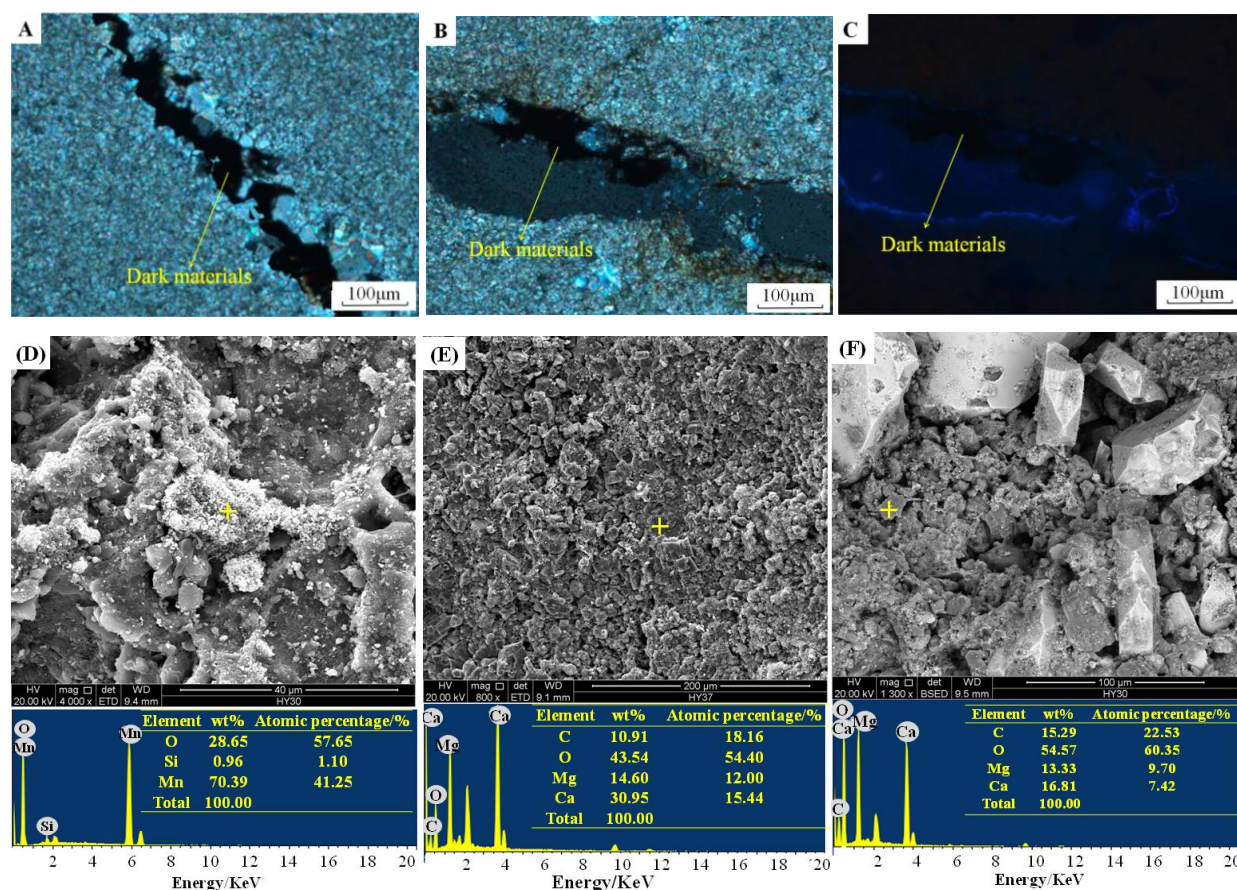


Figure 3. The photos of micritic dolomite of the Jixian System from Tongcheng outcrops under the optical microscope and SEM. (A): Sample HY29, microcracks in the micritic dolomite; the dark materials are opaque under plane-polarized light. (B): Sample HY37, microcracks in the micritic dolomite; the dark materials are opaque under plane-polarized light. (C): Sample HY37, the dark materials filling the microcracks are opaque under perpendicular-polarized light. (D): Sample HY30-1, SEM photo and the energy spectrum of the speculative solid bitumen. (E): Sample HY37-1, the SEM photo and the energy spectrum of the speculative solid bitumen in micritic dolomite. (F): Sample HY30-3, the photo of siliceous dolomite and the energy spectrum of the speculative solid bitumen under SEM.

4.4. Laser Raman Tests

Bitumen generally has two pairs of Raman peaks (1360 and $1620\text{ cm}^{-1} \pm$), which are called “D” and “G” absorption peaks, respectively [20]. In this research, no bitumen was found through the Laser Raman test. Instead, the inclusions captured in the mineral particles or the microcracks of the dolomite samples were found. The weak absorption peaks of the banding dark opaque materials in Sample HY-29-4 are located at 1099 cm^{-1} and 2899 cm^{-1} , corresponding to ethane and water (Figure 4A). The absorption peaks of lumpy dark opaque materials appearing in the absorption spectrum in Sample HY-29-4 are located at 301 cm^{-1} , 466 cm^{-1} , 1099 cm^{-1} , 2899 cm^{-1} , and 3729 cm^{-1} , corresponding to dolomite, quartz, dolomite, C_2H_6 and H_2O , respectively (Figure 4C). The absorption peaks of dark opaque materials filling in the microcracks of Sample HY-29-4 are located at 301 cm^{-1} , 798 cm^{-1} , 1099 cm^{-1} , and 2084 cm^{-1} , corresponding to dolomite and alkane (Figure 4B). The absorption peaks of inclusions within the mineral particles of Sample HY-29-1 are located at the spectrum intervals of $2040\text{--}2060\text{ cm}^{-1}$ and $2910\text{--}2970\text{ cm}^{-1}$, corresponding to mixed hydrocarbons (Figure 4D).

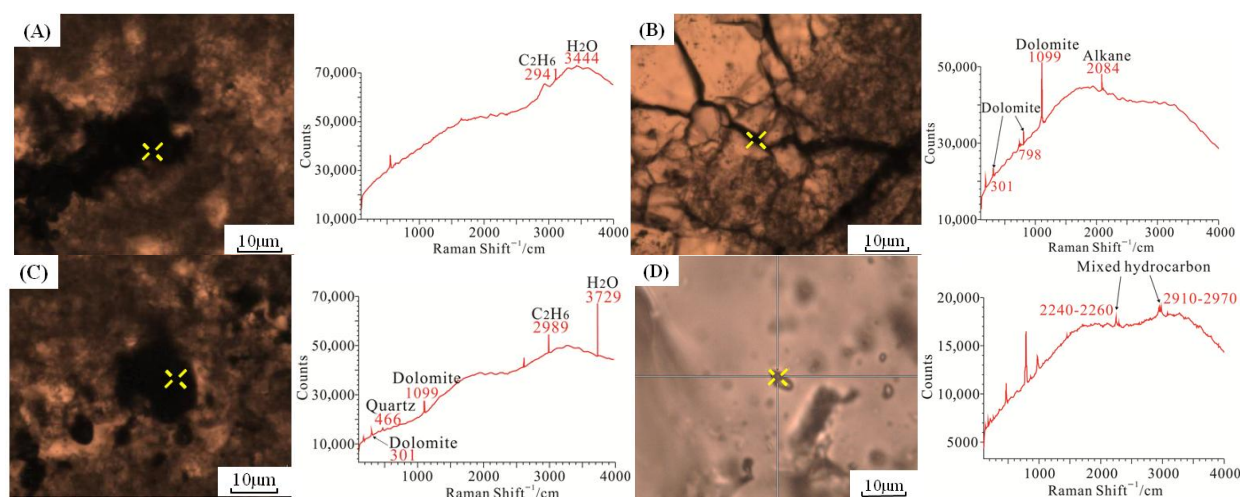


Figure 4. The microscopic photos and Raman absorption spectrum of the dolomite samples of the Jixian System in Tongcheng outcrops. (A): Sample HY-29-4, the absorption peaks of dark materials within dolomite particles; (B): Sample HY-39-1, the absorption peaks of dark materials filled in the microcracks of dolomite; (C): Sample HY-29-4, the absorption peaks of dark materials within dolomite particles; (D): Sample HY-29-1, the absorption peaks of inclusions within dolomite particles.

4.5. Elemental Composition Derived from ICP-MS Test

It shows that the values of Ba, Mn, Sr, Pb, and Cu of the suspected solid bitumen samples, which are usually above 1000 ppm (Table 3), are overall higher, while those of the dolomite samples are overall lower, which may be due to the fact that carbonate minerals in dolomite have a weaker ability to adsorb trace elements [21]. The abnormally high content of Ba, Mn, Sr, Pb, and Zn may be owing to the hydrothermal fluid activity [22]. Previous research has confirmed that, during the Early Cretaceous, the Ordos Basin experienced strong tectonic movements accompanied by magma intrusion [14], which have been found to develop around the Jixian System in the Tongcheng outcrops [7]. Besides the influence of hydrothermal fluids, the content of trace elements may also be affected by sedimentary environmental factors. The high content of Ba may be caused by the concentration of green alga or higher salinity of the palaeosedimentary environment [21–23]. High values of Mn and Cu indicate a deeper water, saline sedimentary environment (Table 3, Figure 5). Except for Sample HY30, the V/Ni ratios of the suspected solid bitumen samples are relatively high (1.89–5.03) ppm, and the U/Th ratios of all the suspected solid bitumen samples are also higher (1.39–18.08) ppm, indicating an anoxic sedimentary environment (Table 3).

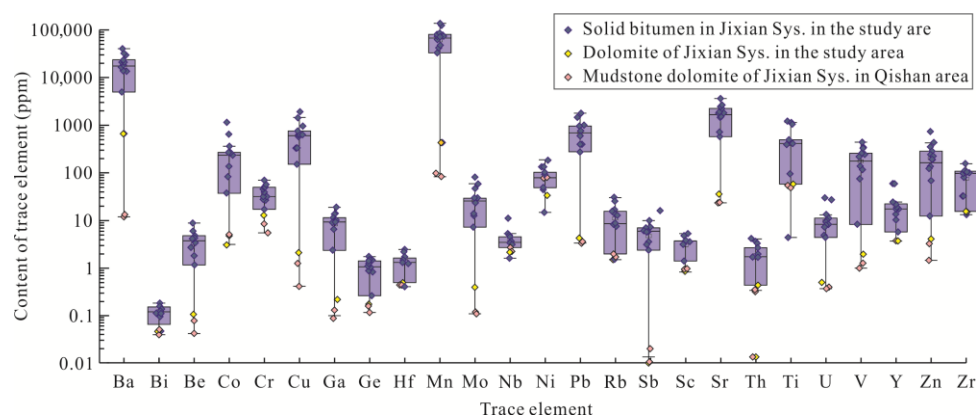


Figure 5. The trace element content of the suspected solid bitumen, as well as the dolomite of the Jixian System in Tongcheng outcrops and Qishan outcrops.

Table 3. The trace element and rare earth element data of the dark mudstone powder samples and dolomite samples of the Jixian Sys. in Tongcheng and Qishan outcrops.

Trace Element	Content of Trace Element (ppm)													
	HY26	HY28	HY29-1	HY29-2	HY30	HY34	HY35-1	HY35-2	HY37-1	HY37-2	HY40	HY51-1	HY52	HY32
Ba	13,615.66	13,949.68	23,457.99	20,932.33	29,772.87	21,103.48	18,353.81	16,540.15	40,592.80	32,490.47	4964.93	12.03	13.60	664.30
Be	8.90	2.75	4.88	4.17	4.32	1.85	4.09	3.41	6.05	4.84	1.18	0.08	0.04	0.11
Bi	0.13	0.18	0.15	0.18	0.15	0.10	0.14	0.13	0.11	0.11	0.05	0.07	0.04	0.05
Co	242.85	137.66	270.30	263.70	362.32	83.60	260.65	229.35	1155.92	650.92	37.73	5.10	4.80	3.09
Cr	69.78	31.84	39.60	50.79	27.77	31.77	57.01	45.58	26.70	49.81	17.24	8.57	5.56	12.90
Cu	967.19	333.95	637.02	635.67	759.78	331.14	665.97	573.49	1920.10	1430.13	150.80	1.26	0.42	2.13
Ga	13.65	8.83	9.29	9.27	11.55	6.63	10.21	9.48	19.04	14.11	2.38	0.09	0.13	0.22
Ge	1.43	1.05	1.09	0.84	1.49	0.89	1.25	1.11	1.74	1.54	0.27	0.16	0.12	0.18
Hf	2.42	2.14	1.61	1.30	1.70	1.29	1.35	1.46	1.30	1.22	0.40	0.44	0.43	0.49
Mn	62,920.00	42,260.00	71,200.00	75,680.00	79,670.00	47,850.00	86,120.00	73,900.00	137,800.00	124,800.00	32,600.00	98.57	83.33	433.10
Mo	46.75	13.51	29.64	29.08	29.47	12.56	27.75	23.40	80.31	58.55	7.15	0.12	0.11	0.39
Nb	4.57	4.94	3.58	3.17	3.74	11.18	3.17	5.29	3.36	3.58	1.62	2.26	2.71	2.17
Ni	103.39	44.34	79.19	78.43	133.91	49.02	93.30	77.56	184.20	134.13	14.91	81.17	77.76	33.80
Pb	597.66	398.15	937.74	953.44	988.24	396.53	902.50	762.48	1785.13	1459.65	272.92	3.59	3.30	4.21
Rb	25.50	30.82	7.80	7.60	15.76	17.07	8.30	8.96	12.96	13.66	1.53	2.00	1.73	1.55
Sb	9.86	3.06	6.86	7.27	6.16	3.52	6.79	5.62	6.89	6.77	2.37	0.00	0.02	0.00
Sc	5.21	4.75	3.50	3.70	3.61	3.11	3.78	3.58	3.33	3.63	1.40	0.89	0.83	0.82
Sr	1778.00	1451.00	3638.00	2470.00	2256.00	717.90	1907.00	1533.00	2675.00	1831.00	577.90	23.58	23.93	36.14
Th	2.66	4.05	1.94	1.81	3.31	3.55	1.79	1.65	1.66	1.65	0.43	0.32	0.34	0.38
Ti	1136.00	1195.00	415.90	386.40	4.31	1051.00	414.90	429.00	400.30	491.40	94.27	53.19	48.33	56.83
U	11.26	8.48	13.27	10.15	7.31	4.92	9.42	8.03	30.02	27.33	4.43	0.37	0.40	0.51
V	441.10	138.70	255.60	247.80	8.31	117.30	257.50	218.50	349.00	329.70	75.06	1.28	1.00	1.97
Y	24.33	17.44	18.96	19.13	10.31	13.63	22.56	17.47	59.54	59.45	5.77	3.71	3.78	3.71
Zn	741.75	137.26	283.79	242.37	12.31	124.25	224.19	191.54	432.23	351.14	68.78	3.28	1.45	4.14
Zr	155.95	97.43	98.26	105.91	13.31	81.06	111.19	100.42	111.79	108.44	32.89	15.04	15.00	15.56
V/Ni	4.27	3.13	3.23	3.16	0.06	2.39	2.76	2.82	1.89	2.46	5.03	0.02	0.01	0.06
U/Th	4.23	2.09	6.84	5.61	2.21	1.39	5.26	4.87	18.08	16.56	10.30	1.16	1.18	1.34
La	90.84	79.94	98.51	97.17	94.71	80.17	98.12	83.80	132.43	124.45	22.97	3.33	3.45	2.79
Ce	39.77	28.62	16.57	15.02	19.28	34.58	14.82	12.94	18.16	16.78	3.47	0.63	0.75	0.21

Pr	40.02	38.66	42.66	43.62	44.50	45.42	48.16	40.06	78.34	72.93	14.30	3.48	3.51	3.11
Nd	33.07	31.93	34.37	35.62	36.78	36.70	39.22	32.79	67.13	64.13	11.91	0.97	0.93	0.93
Sm	16.79	18.73	18.58	19.47	20.19	19.70	20.82	17.98	45.26	41.94	6.29	0.74	0.75	0.78
Eu	90.93	88.64	144.99	128.82	180.82	128.19	116.82	105.88	273.93	227.37	31.43	0.26	0.29	16.59
Gd	15.35	14.05	15.22	15.81	15.76	13.58	17.05	14.31	40.58	38.26	5.04	0.36	0.37	0.36
Tb	13.72	12.38	13.79	13.51	27.85	12.17	14.94	12.83	35.00	31.64	4.28	0.72	0.72	0.72
Dy	13.24	10.36	11.52	11.85	12.00	8.93	13.00	10.97	30.62	29.04	3.80	0.35	0.41	0.40
Ho	13.25	9.26	10.81	11.11	11.17	8.40	12.08	10.11	27.90	26.67	3.59	0.65	0.70	0.71
Er	12.24	8.52	10.09	10.21	10.31	7.71	11.09	9.34	23.38	22.48	3.44	0.50	0.52	0.52
Tm	12.72	8.55	9.66	9.94	194.72	7.75	10.49	8.61	20.28	19.88	3.21	1.17	1.17	1.45
Yb	13.06	9.68	10.56	10.59	54.11	9.47	11.49	9.73	18.54	18.15	4.56	0.72	0.66	0.07
Lu	14.22	10.59	12.83	12.17	13.23	10.81	12.55	10.65	22.55	20.19	3.85	2.20	2.11	0.40
δEu	5.66	5.46	8.62	7.34	10.14	7.84	6.20	6.60	6.39	5.68	5.58	0.50	0.54	31.52
δCe	0.61	0.48	0.23	0.21	0.28	0.55	0.20	0.21	0.17	0.17	0.19	0.19	0.21	0.07
La _N /Yb _N	6.96	8.26	9.32	9.17	1.75	8.46	8.54	8.61	7.14	6.86	5.04	4.61	5.23	41.66
ΣREE	419.21	369.92	450.15	434.91	735.44	423.56	440.65	379.99	834.08	753.91	122.14	16.08	16.35	29.04
ΣLREE/ΣHREE	2.89	3.44	3.77	3.57	1.17	4.37	3.29	3.39	2.81	2.65	2.84	1.41	1.45	5.27

The subscript N represents the ordinary chondrites normalized rare earth element values. δEu: $Eu_N \cdot \sqrt{Sm_N \cdot Gd_N}$; δCe: $2Ce_N/(La_N + Pr_N)$; ΣREE: Total concentrations of rare earth elements. ΣLREE: The sum of light rare earth elements La, Ce, Pr, Nd, Sm and Eu; ΣHREE: The sum of heavy rare earth elements Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu; La_N/Yb_N: Chondrite-normalized ratio of La to Yb.

Normalized to ordinary chondrites [24], the REE patterns of all the samples are slightly inclined to the right, manifested as high La_N/Yb_N ratios ranging from 1.75 to 41.66 (Table 3). The enrichment of light rare earth elements may be due to the slow deposition rate or the granite-derived sediments [25]. The suspected solid bitumen samples have total rare earth element values (ΣREE) ranging from 122.14 to 834.08 ppm (Table 3), generally higher than the average total amount of rare earth elements in the continental crust (146.4 ppm) [24]. The ΣREE values of the dolomite samples are quite low (Figure 6), which is related to the low adsorption capacity and the fast depositing rate of carbonates for the rare earth elements [26]. The suspected solid bitumen samples have slightly positive anomalies in Eu values and negative Ce values, implying the influence of weathering and hydrothermal processes on most of the samples (Table 3, Figure 6).

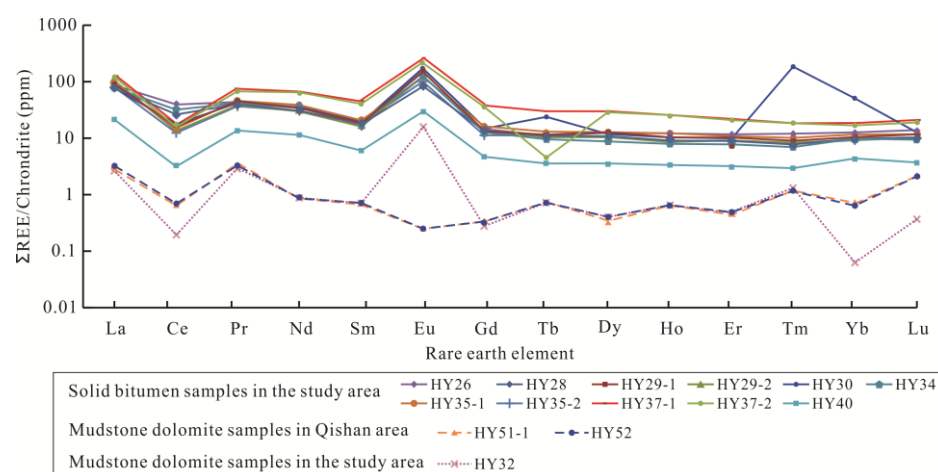


Figure 6. The chondrite-normalized REE distribution patterns of the suspected solid bitumen in the fractures of the Jixian System in Tongcheng outcrops. The lithology and sampling location of each sample are shown in Figure 6.

4.6. The Hydrocarbon Group Component Test and R_b Measurement

The solvent-extracted group components of the suspected solid bitumen were found to be mainly composed of asphaltene, with a content from 56.34% to 82.65%. The aromatic hydrocarbons ranked second, ranging from 6.51% to 18.31%. The saturated hydrocarbons are lower than 10%, ranging from 5.42% to 9.86%, and the chloroform asphalt “A” is the lowest, ranging from 0.0255% to 0.0602% (Table 4). The higher content of aromatics and asphaltenes indicates high thermal evolution [12].

Table 4. The hydrocarbon components and R_b of the suspected solid bitumen of the Jixian System in the study outcrops.

Sample No.	Chloroform Asphalt “A” (wt.%)	Asphaltene (wt.%)	Saturated Hydrocarbon (wt.%)	Aromatic Hydrocarbon (wt.%)	Non Hydrocarbon (wt.%)	R_b (%)
HY-35	0.0602	79.21	6.93	8.91	4.95	2.77
HY-37	0.0341	82.65	5.42	6.51	5.42	-
HY-29	0.0255	56.34	9.86	18.31	15.49	2.59
HY54	0.0316	70.27	8.11	12.16	9.46	-

Note: “-” represents that this sample has not been tested.

4.7. The Biomarker Analysis Based on the GC-MS Test

Figures 7 and 8 exhibit the distribution of the $M/z191$ and $M/z217$ mass fragmentograms of saturated hydrocarbon fractions, which show that the suspected solid bitumen

samples (HY-35, HY-37, HY-29 and HY-54) have higher values of $Ts/(Ts + Tm)$, ranging from 0.39 to 0.52. Simultaneously, the ratios of C_{29} sterane to $20S/(20S + 20R)$ are in the range of 0.50–0.52, approaching 0.5 (Table 5, Figure 7), indicating that the organic matter in the suspected solid bitumen has a high to over-mature thermal degree.

Samples HY-35, HY-37, and HY-29 have a certain amount of tricyclic terpane (Figure 8), indicating a salinized, sulfur-rich, and anoxic sedimentary environment. The higher content of hopane indicates bacteria-derived organic matter and an anoxic sedimentary environment. The (Pregnane + homopregnane)/ C_{27} regular sterane of all the samples except HY-35 is generally lower, with values in the range of 0.06–0.15 (Table 5), indicating weak biodegradation, while that of Sample HY-35 is 1.19, implying strong biodegradation. Simultaneously, the C_{27} , C_{28} , and C_{29} regular steranes of these samples exhibit a “V” distribution (Figure 8), implying that the organic matter partially originated from algae and bacteria. The high values of C_{29} regular steranes may not necessarily be caused by organic matter sources from higher plants [7]; they may be related to the priority degradation of C_{27} regular steranes and C_{29} regular steranes from green algae sources.

Table 5. Biomarker parameters of the suspected solid bitumen in fractures of the Jixian Sys. in the study area.

No.	$Ts/(Ts + Tm)$	$C_{31}22S/(2S + 22R)$	Gammaceran $e/\alpha\beta C_{30}$ -hopane	$C_{29}\alpha\alpha\alpha 20$ $S/(20S + 20R)$	(Pregnane + Homopregnane)/ C_{27} Regular Sterane	C_{27} Regular Sterane (%)	C_{28} Regular Sterane (%)	C_{29} Regular Sterane (%)
HY-35	0.51	0.57	0.12	0.50	1.19	0.33	0.25	0.42
HY-37	0.52	0.61	0.04	0.52	0.06	0.38	0.16	0.46
HY-29	-	0.97	0.06	0.51	0.10	0.44	0.13	0.43
HY-54	0.39	0.58	0.03	0.40	0.15	0.29	0.27	0.44

Note: “-” represents that the indicator has not been detected.

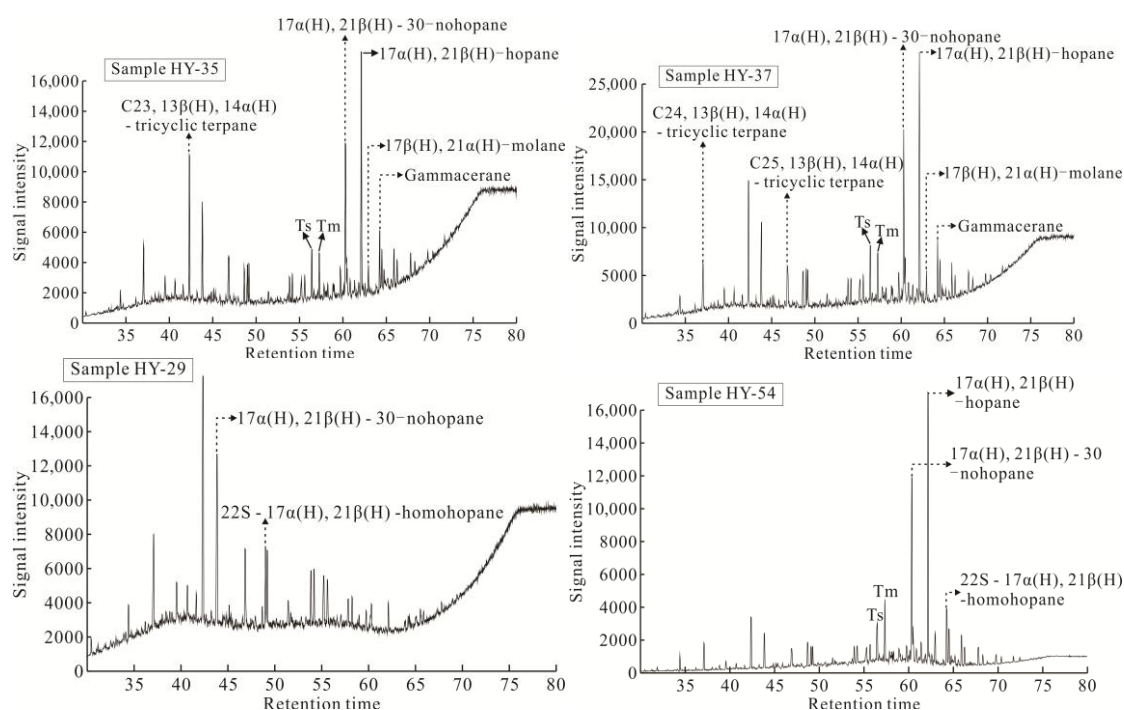


Figure 7. M/z191 mass fragment grams of saturated hydrocarbon fractions of the suspected solid bitumen occurring in the Jixi System in Tongcheng outcrops.

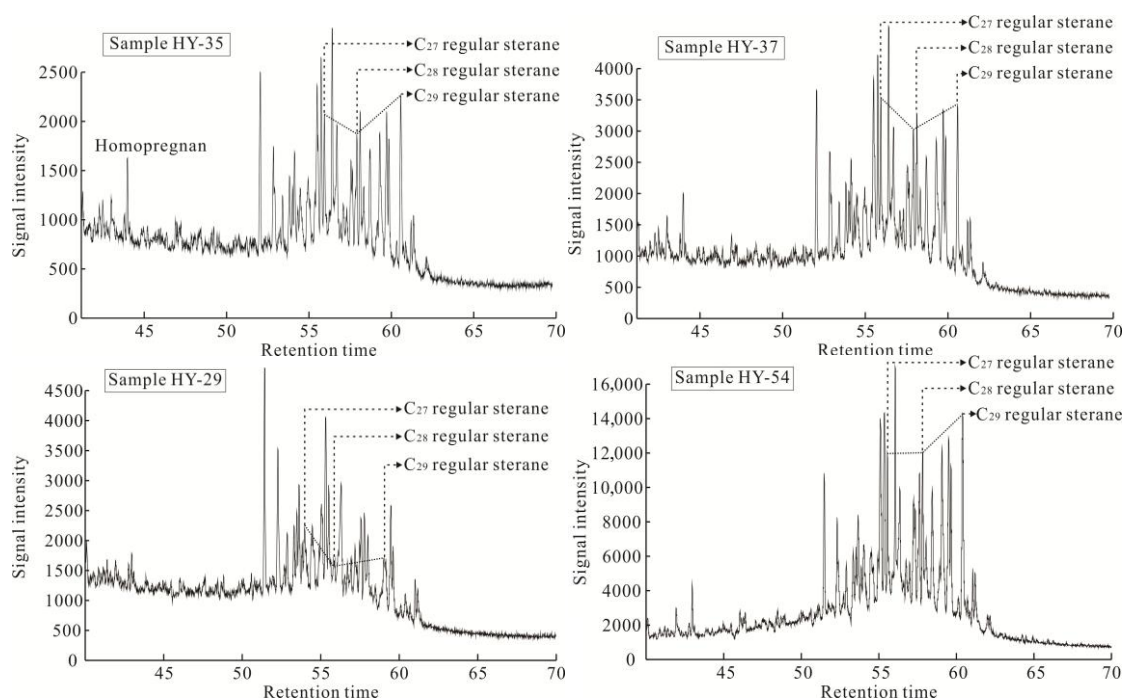


Figure 8. M/z217 mass fragment grams of saturated hydrocarbon fractions of the suspected solid bitumen occurring in the Jixi System in Tongcheng outcrops.

5. Discussion

5.1. The Origin of the Suspected Solid Bitumen

Although Li confirmed the existence of bitumen veins filled in fractures of the Jixian System in the Tongcheng outcrop [7], this research found that at least some of the suspected solid bitumen filled in the fractures is not solid bitumen, but rather dark mudstone. These suspected solid bitumens filled in the fractures are similar to the traces left on the leached surface by the overlying dark root soil layers, which we can see on the bared rock section in mountainous areas. Therefore, these suspected solid bitumens are probably leaching products from overlying dark mudstone source rock. The high Rb values (2.59–2.77%) and the Ts/(Ts + Tm) values approaching 0.5 reveal that the related source rock may be Precambrian, which generally has an Ro value higher than 1.8% [9].

The confirmed potential Precambrian source rocks in the Ordos Basin include the Mesoproterozoic Cuizhuang Fm., the Ediacaran Luoquan Fm., the Cambrian Dongpo Formation and Xuzhuang Formation [9,12], which are more developed in the southern part of the basin (Figure 9). The Mesoproterozoic Cuizhuang Formation developed dark mudstone and shale with a thickness exceeding 100 m in the western and southern margins of the Ordos Basin [9]. The Ediacaran Luoquan Formation has been identified as developing dark mudstone in the Luonan area, on the southern edge of the Ordos Basin, with poor hydrocarbon generation potential [12]. The lower Cambrian Dongpo Formation and the middle Cambrian Xuzhuang Formation have been confirmed as developing potential dark mudstone source rocks by outcrops and drilling, respectively [6]. The thickness of Cambrian Dongpo muddy source rock layers in Luonan outcrops is up to about 40 m [9,12]. It is controversial whether or not the Jixiannian source rock exists in the Ordos Basin and its periphery [6,7,9]. The laminated algal dolostones were considered potential valid source rocks in the south Ordos Basin [7]. While, due to the stable tectonic condition during the Jixian period, the Ordos Basin was a tidal flat sedimentary environment, and dolomite, stromatolites, and siliceous interlayer deposited [11,16], which is unfavorable for forming muddy hydrocarbon source rock layers. Consequently,

the most closely related overlying Precambrian muddy source rocks may be the Cambrian and Ediacaran mudstone source rocks.

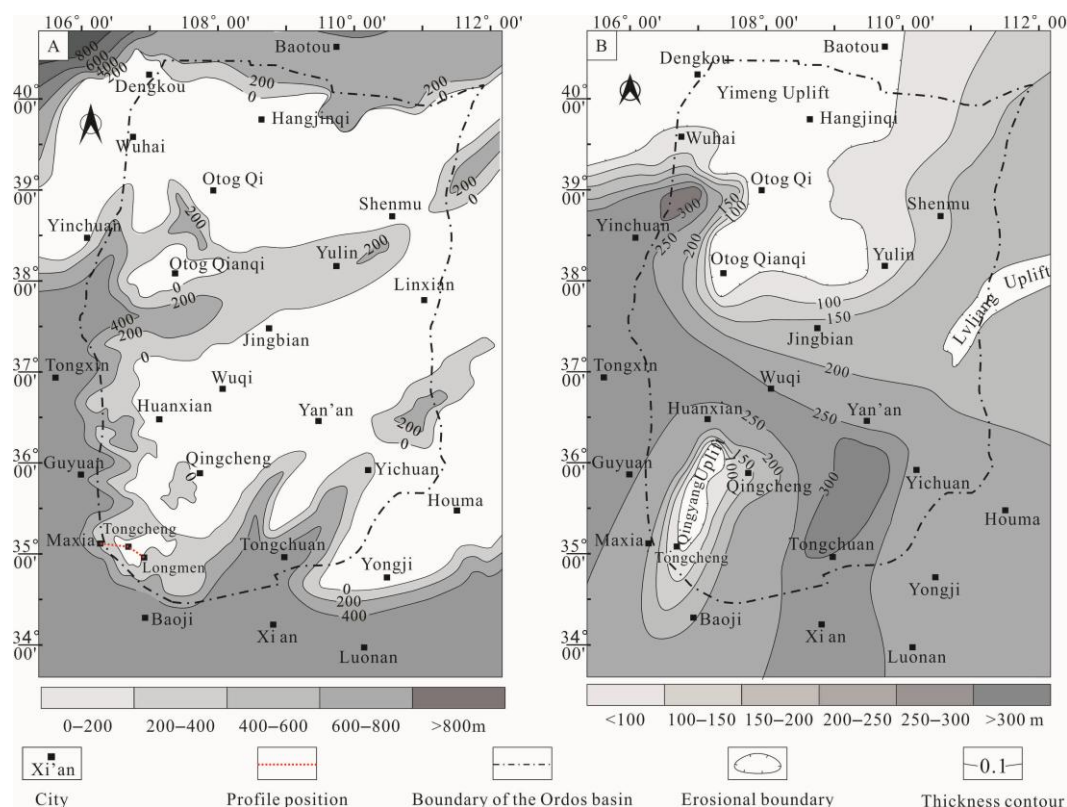


Figure 9. The thickness contour of the Changcheng Sys. muddy source rock in the Ordos Basin and its periphery (A) and that of the lower Cambrian (B), modified from [9].

5.2. The Element Tracking Comparison

The $V/(V + Ni)$, Zr/Rb , Sr/Cu , and Sr/Ba of the suspected solid bitumen samples and those of the potential Precambrian source rocks in the south Ordos Basin were compared. It shows that the suspected solid bitumen samples in the fractures of the Jixian System in Tongcheng outcrops have higher values of $V/(V + Ni)$, similar to the samples of Ediacaran Luoquan Formation in Luonan outcrops and of the Mesoproterozoic Changcheng system in Zhongtiaoshan outcrops, indicating an anoxic sedimentary environment. Simultaneously, they have higher values of Sr/Cu , similar to the samples of Cambrian Zhangxia Formation in Luonan outcrops and of the Mesoproterozoic Jixian system in Zhongtiaoshan outcrops (Figure 10), indicating they deposited in a warm and humid sedimentary environment. Additionally, the suspected solid bitumen has lower values of Sr/Ba (Figure 10), significantly different from the compared source rock samples, which may be related to the effect of mudstone leaching on the Sr/Ba ratio (Figure 6).

Hierarchical cluster analysis is employed to compare the similarities of rare earth element distribution between solid bitumen and Precambrian source rocks. It shows that most of the suspected solid bitumen samples are similar to samples of the Cambrian Zhangxia Formation in Luonan outcrops and of the Mesoproterozoic Jixian system in Qishan outcrops (Figure 11). Simultaneously, three suspected solid bitumen samples (HY30, HY37-1, HY37-2) exhibit poor correlation with these source rock samples (Figure 11), and this may be due to the different degree of weathering and leaching experienced. Additionally, the rare earth element characteristics of the suspected solid bitumen samples show significant differences from the Cambrian Dongpo Formation (Figure 11); this

is probably owing to the limited distribution of the Dongpo Formation [9,12]. Considering that the samples of the Jixian system are mainly algal dolomite rather than mudstone, the suspected solid bitumen may probably originate from the Cambrian Zhangxia mudstone source rocks.

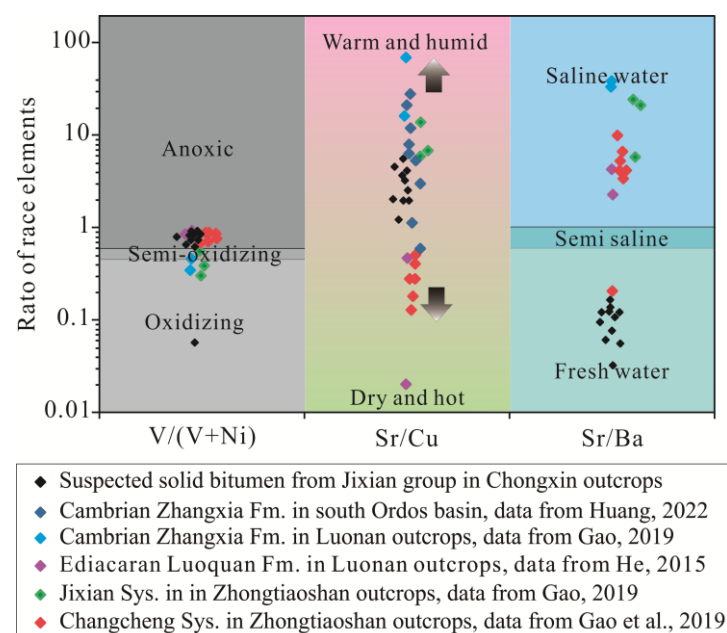


Figure 10. The values of $V/(V + Ni)$, Sr/Cu , and Sr/Ba of the suspected solid bitumen in Tongcheng outcrops, compared with the mudstone source rocks of the Ediacaran System, Jixian System, and Changcheng System source rocks in Luonan and Zhongtiaoshan outcrops, south Ordos Basin; the trace element data used as a reference are cited from [12,27,28].

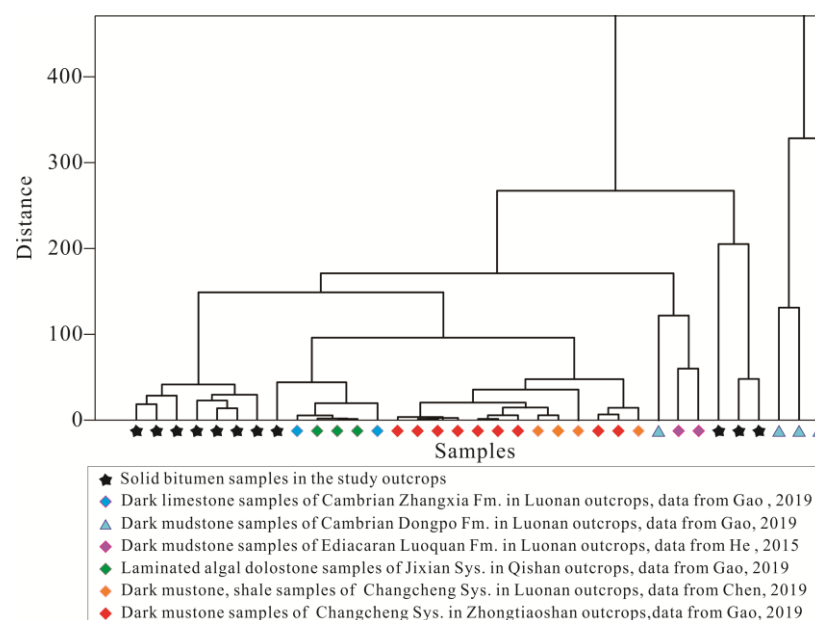


Figure 11. Cluster diagram of rare earth elements of solid bitumen occurring in the Jixian Sys. and Precambrian source rocks; the rare earth element data used as a reference are cited from [27–29].

5.3. The Possible Formation Process of the Suspected Solid Bitumen

A northeast-trending stratigraphic structural evolution profile shows that the studied Tongcheng area underwent uplift on the east side and continuous subsidence on the west side, forming the ancient Qingyang uplift since the Late Paleozoic (Figure 12). Af-

ected by the Caledonian and Hercynian tectonic movements, the Tongcheng area, like most parts of the basin, was not deposited during the Early Paleozoic [16,30]. Since the Late Jurassic, the differential tectonic uplift and subsidence movements in the Tongcheng area were more significant (Figure 12). From the Late Early Cretaceous to the present, the Mesoproterozoic Jixian System in the Tongcheng area and its overlying strata were exposed to the surface (Figure 12). Long-term exposure at a high structural location makes the Tongcheng area favorable for hydrocarbon migration and accumulation and probably developed palaeo-oil reservoirs [30].

According to the buried and thermal evolution of the south Ordos Basin, in the early Devonian, the Cambrian mudstone source rocks and the underlying Mesoproterozoic Jixian system were uplifted to the surface (Figure 13). Due to weathering and leaching, the dark mudstone of the Cambrian system may then fill into the fractures of the underlying Jixian system (Figure 13). Due to the long-term location of the research area at a high tectonic position, oil and gas generated in later stages may also enter the Jixian system fractures through faults and unconformities. This is also the reason why biomarker compounds of Sample HY-54 show higher plant sources (Figure 7, Table 5).

Additionally, the mudstone source rocks of the Changcheng System in the north and south Ordos Basin first entered the oil generation window in the Late Permian and Late Ordovician periods, respectively [31]. The Tongcheng area might develop palaeo-oil reservoirs, which are composed of Changchengian porous sandstone reservoirs and cap rocks of the tight dolomite of the Jixian system. From the Late Jurassic to Early Cretaceous, strong tectonic and magmatic activities occurred [11,31]; the source rock of the Mesoproterozoic Jixian system entered an oil-cracking gas period (Figure 13). Consequently, the palaeo-oil reservoirs might be destroyed by strong thermal evolution or tectonic movement. The solid bitumen vein in the Jixian System fractures discovered by predecessors might form during the destruction of ancient oil reservoirs [11].

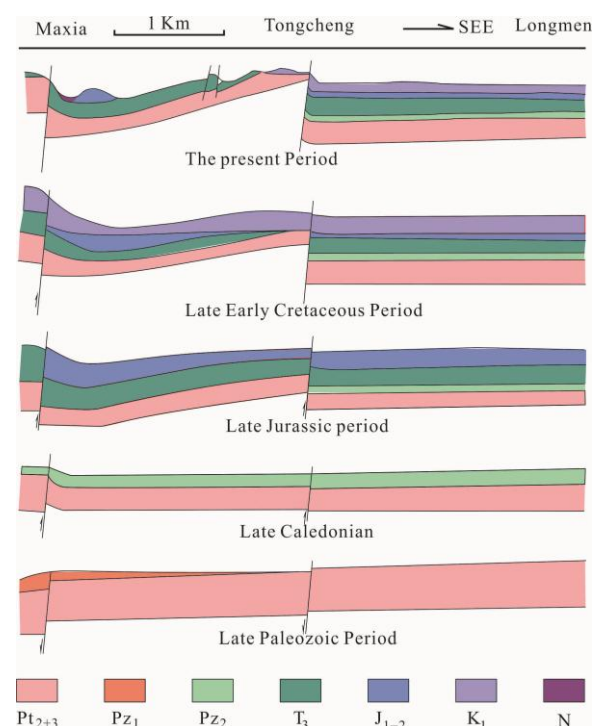


Figure 12. SEE trending simplified geological profiles of the Meso-Neoproterozoic in Tongcheng outcrops, south periphery of Ordos Basin during the Late Paleozoic to the present; modified from Ma's research [30]. The position of the profile is shown in Figure 9A.

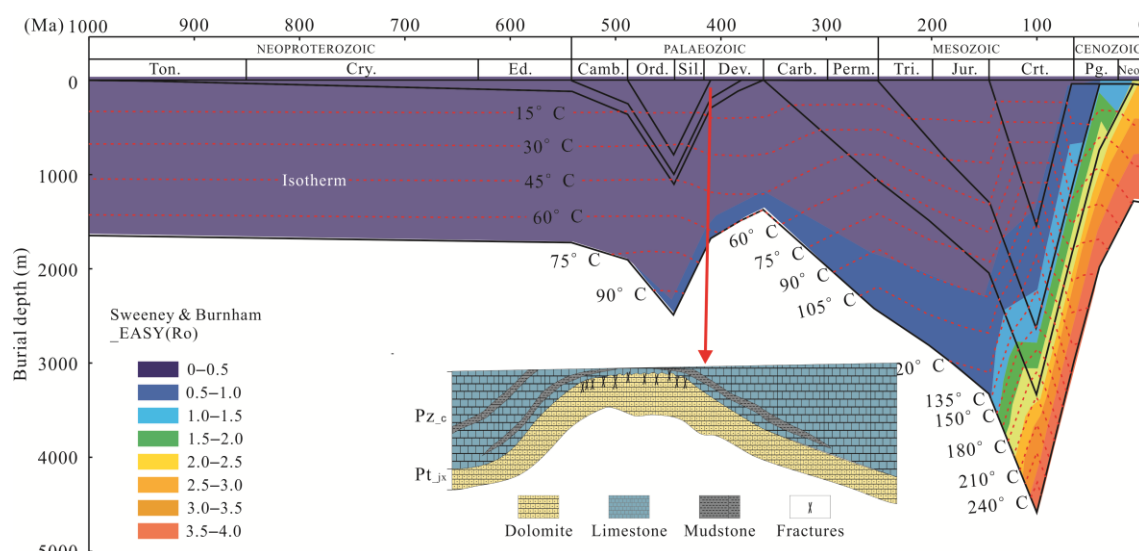


Figure 13. The burial history and thermal evolution history of the Jixian system in the Tongcheng area [32].

6. Conclusions

- (1) The suspected solid bitumen filling in the fractures of the Jixian System in the Tongcheng outcrops has been found to be mainly composed of clay minerals; therefore, they are not solid bitumen but mudstone powder. Laser Raman spectroscopy and scanning electron microscopy did not detect solid bitumen in the pores and microcracks of Jixian dolomite samples. The TOC values of the suspected solid bitumen range from 0.59% to 1.15%, the Rb values are 2.59% and 2.77%, and the $T_s/(T_s + T_m)$ values are approaching 0.5, indicating that these suspected solid bitumens are mature source rocks.
- (2) The suspected solid bitumens in the studied Tongcheng outcrops have lower Sr/Ba ratios and higher Sr/Cu and $V/(V + Ni)$ ratios, indicating a warm, humid, and anoxic sedimentary environment. They have similar $V/(V + Ni)$ values to those of the dark mudstone of the Ediacaran Luoquan Formation and Mesoproterozoic Changcheng system. On the other hand, these suspected solid bitumens have similar Sr/Cu values to those of the source rocks of the Cambrian Zhangxia Formation and Mesoproterozoic Jixian system. Simultaneously, the suspected solid bitumen samples have a similar rare earth element distribution to that of the Cambrian Zhangxia Formation and Mesoproterozoic Jixian system. Comprehensively, the suspected solid bitumen may originate from the mudstone source rocks of the Cambrian Zhangxia Formation.
- (3) In the Early Devonian, the Cambrian mudstone source rocks in the Tongcheng area were uplifted, weathered, leached, fragmented into powder, and filled into the fractures of the Mesoproterozoic Jixian system. Therefore, some of the suspected solid bitumens are Cambrian mudstone source rocks. Of course, another situation cannot be ruled out: the paleo-oil reservoirs near the ancient uplift in the Tongcheng area might have been destroyed by strong Cretaceous tectonic movement. Further comprehensive research is needed on the source of the suspected solid bitumen.

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References

1. Gupta, S.N.; Arora, Y.K.; Mathur, R.K.; Iqballuddin Prasad, B.; Sahai, T.N.; Sharma, S.B. The precambrian geology of the Aravalli region, southern Rajasthan and northeastern Gujrat. *Mem. Geol. Surv. India* **1997**, *123*, 1–262.
2. Grosjean, E.; Love, G.D.; Stalvies, C.; Fike, D.A.; Summons, R.E. Origin of petroleum in the Neoproterozoic-Cambrian South Oman Salt Basin. *Org. Geochem.* **2009**, *40*, 87–110. <https://doi.org/10.1016/j.orggeochem.2008.09.011>.
3. Suslova, E.A.; Parfenova, T.M.; Saraev, S.V.; Nagovitsyn, K.E. Organic geochemistry of rocks of the Mesoproterozoic Malgin Formation and their depositional environments (southeastern Siberian Platform). *Russ. Geol. Geophys.* **2017**, *58*, 516–528. <https://doi.org/10.1016/j.rgg.2016.09.027>.
4. Grosjean, E.; Jarrett, A.J.M.; Boreham, C.J.; Wang, L.; Johnson, L.; Hope, J.M.; Ranasinghe, P.; Brocks, J.J.; Balley, A.H.E.; Butcher, G.A. Resource potential of the Proterozoic–Paleozoic Carrara depocentre, South Nicholson region, Australia: Insights from stratigraphic drilling. *Org. Geochem.* **2023**, *186*, 104688. <https://doi.org/10.1016/j.orggeochem.2023.104688>.
5. Chen, Z.H.; Yang, Y.M.; Wang, T.G.; Cheng, B.; Li, M.J.; Li, B.; Luo, B.; Chen, Y.; Ni, Z.Y.; Yang, C.Y.; et al. Dibenzothiophenes in solid bitumens: Use of molecular markers to trace paleo-oil filling orientations in the Lower Cambrian reservoir of the Moxi-Gaoshiti Bulge, Sichuan Basin, southern China. *Org. Geochem.* **2017**, *108*, 94–112. <https://doi.org/10.1016/j.orggeochem.2017.03.013>.
6. Zhao, W.Z.; Hu, S.Y.; Wang, Z.H.; Zhang, S.C.; Wang, T.S. Petroleum geological conditions and exploration importance of Proterozoic to Cambrian in China. *Pet. Explor. Dev.* **2018**, *45*, 1–14. [https://doi.org/10.1016/S1876-3804\(18\)30001-6](https://doi.org/10.1016/S1876-3804(18)30001-6).
7. Li, R.X.; Liang, J.W.; Weng, K. Paleo reservoir bitumen of the middle Protozoic Jixian System in the southwest margin of the Ordos Basin, China. *Pet. Explor. Dev.* **2011**, *38*, 168–173. [https://doi.org/10.1016/S1876-3804\(11\)60024-4](https://doi.org/10.1016/S1876-3804(11)60024-4).
8. Zhang, T.; Peng, P.A.; Li, Y.F.; Sun, S.L.; Guo, H.J.; Pang, H.M. Molecular and carbon isotopic evidence for the possible origin of 13 α (n-alkyl)-tricyclic terpanes in Mesoproterozoic bitumens from the Yanliao Rift, North China. *Org. Geochem.* **2024**, *190*, 104766. <https://doi.org/10.1016/j.orggeochem.2024.104766>.
9. Du, J.H.; Li, X.B.; Bao, H.P.; Xu, W.L.; Wang, Y.T.; Huang, J.P.; Wang, H.B.; WanYan, R.; Wang, J. Geological conditions of natural gas accumulation and new exploration areas in the Mesoproterozoic to Lower Paleozoic of Ordos Basin, NW China. *Pet. Explor. Dev.* **2019**, *46*, 866–882. [https://doi.org/10.1016/S1876-3804\(19\)60246-6](https://doi.org/10.1016/S1876-3804(19)60246-6).
10. Li, J.Z.; Tao, X.W.; Bai, B.; Huang, S.P.; Jiang, Q.C.; Zhao, Z.Y.; Chen, Y.Y.; Ma, D.B.; Zhang, L.P.; Li, N.X.; et al. Geological condition, reservoir evolution and favorable exploration directions of marine ultra-deep oil and gas in China. *Pet. Explor. Dev.* **2021**, *48*, 60–79. [https://doi.org/10.1016/S1876-3804\(21\)60005-8](https://doi.org/10.1016/S1876-3804(21)60005-8).
11. Bai, J.L.; Zhao, J.F.; Ren, Z.L.; Li, W.H.; Wang, K.; Li, X. Paleographic and sedimentary evolution of Meso-Neoproterozoic Strata in the Ordos Basin, western North China Craton. *J. Pet. Sci. Eng.* **2022**, *215*, 110600. <https://doi.org/10.1016/j.petrol.2022.110600>.
12. Huang, J.P.; He, W.X.; Lin, J.F.; Li, X.B.; Xu, Y.H.; Wang, Y.T.; Wang, H.B. Geochemical characteristics of bitumen from the Cambrian reservoir in the Ordos basin, Northern China: Insights into bitumen classification and origin. *J. Asian Earth Sci.* **2022**, *230*, 105168. <https://doi.org/10.1016/j.jseaes.2022.105168>.
13. Pan, X.; Wang, Z.L.; Li, Q.Y.; Gao, J.; Zhu, L.W.; Liu, W.H. Sedimentary environments and mechanism of organic matter enrichment of dark shales with low TOC in the Mesoproterzoic Cuizhuang Formation of the Ordos Basin: Evidence from petrology, organic geochemistry, and major and trace elements. *Mar. Pet. Geol.* **2020**, *122*, 104695. <https://doi.org/10.1016/j.marpetgeo.2020.104695>.

14. Yang, Y.T.; Li, W.; Ma, L. Tectonic and stratigraphic controls of hydrocarbon systems in the Ordos basin: A multicycle cratonic basin in central China. *AAPG Bull.* **2005**, *89*, 255–269. <https://doi.org/10.1306/10070404027>.
15. Peng, H.; Wang, J.Q.; Liu, C.Y.; Zhao, H.G.; Huang, L.; Zhao, X.C.; Zhang, S.H.; Liang, C.; Wang, Z.; Cattò, S.; et al. Long term and multiple stage exhumation of the Ordos Basin, western North China Craton: Insights from seismic reflection, borehole and geochronological data. *Earth-Sci. Rev.* **2023**, *238*, 104349. <https://doi.org/10.1016/j.earscirev.2023.104349>.
16. Liu, X.G.; Li, S.Z.; Zhang, J.; Li, X.Y.; Zhao, S.J.; Dai, L.M.; Wang, G.Z. Meso-Neoproterozoic strata and target source rocks in the North China Craton: A review. *Precambrian Res.* **2019**, *334*, 105458. <https://doi.org/10.1016/j.precamres.2019.105458>.
17. Liu, Y.; Zhong, N.; Tian, Y.J.; Qi, W.; Mu, G.Y. The oldest oil accumulation in China: Meso-proterozoic Xiamaling Formation bituminous sandstone reservoirs. *Pet. Explor. Dev.* **2011**, *38*, 503–512. [https://doi.org/10.1016/S1876-3804\(11\)60050-5](https://doi.org/10.1016/S1876-3804(11)60050-5).
18. Jacob, H. Classification, structure, genesis and practical importance of natural solid oil bitumen (“migrabitumen”). *Int. J. Coal Geol.* **1989**, *11*, 65–79. [https://doi.org/10.1016/0166-5162\(89\)90113-4](https://doi.org/10.1016/0166-5162(89)90113-4).
19. SY/T 5735-2019; Geochemical Method for Source Rock Evaluation; Standard for the Petroleum and Natural Gas Industry of the People’s Republic of China; Petroleum Industry Press: Beijing, China, 2019.
20. Kelemen, S.R.; Walters, C.C.; Kwiatek, P.J.; Freund, H.; Afeworki, M.; Sansone, M.; Lamberti, W.A.; Pottorf, R.J.; Machel, H.G.; Peters, K.E.; et al. Characterization of solid bitumens originating from thermal chemical alteration and thermochemical sulfate reduction. *Geochim. Cosmochim. Acta* **2010**, *74*, 5305–5332. <https://doi.org/10.1016/j.gca.2010.06.013>.
21. Walker, C.T. Evaluation of boron as a paleosalinity indicator and its application to offshore prospects. *AAPG Bull.* **1968**, *52*, 751–766. <https://doi.org/10.1306/5D25C45D-16C1-11D7-8645000102C1865D>.
22. Jones, B.; Manning, D.A.C. Comparison of geochemical indices used for the interpretation of palaeoredox conditions in ancient mudstone. *Chem. Geol.* **1994**, *111*, 111–129. [https://doi.org/10.1016/0009-2541\(94\)90085-X](https://doi.org/10.1016/0009-2541(94)90085-X).
23. Tribouillard, N.; Algeo, T.J.; Lyons, T.; Riboulleau, A. Trace metals as paleoredox and paleoproductivity proxies: An update. *Chem. Geol.* **2006**, *232*, 12–32. <https://doi.org/10.1016/j.chemgeo.2006.02.012>.
24. Boynton, W.V. Cosmochemistry of the Rare Earth Elements: Meteorite Studies. In *Development in Geochemistry*; Elsevier: Amsterdam, The Netherlands, 1984; pp. 63–114. <https://doi.org/10.1016/B978-0-444-42148-7.50008-3>.
25. Hitchon, B.; Filby, R.H. Use of trace elements for classification of crude oils into families-example from Alberta, Canada. *AAPG Bull.* **1984**, *68*, 838–849. <https://doi.org/10.1306/ad461435-16f7-11d7-8645000102c1865d>.
26. Mongenot, T.; Tribouillard, N.P.; Desprairies, A.; Lallier-Vergès, E.; Laggoun-Defarge, F. Trace elements as palaeoenvironmental markers in strongly mature hydrocarbon source rocks: The Cretaceous La Luna Formation of Venezuela. *Sediment. Geol.* **1996**, *103*, 23–37. [https://doi.org/10.1016/0037-0738\(95\)00078-X](https://doi.org/10.1016/0037-0738(95)00078-X).
27. Gao, J. Geochemical Characteristics and Distribution Prediction of Precambrian Source Rocks in the Southern Margin of Ordos Area. Master’s Thesis, Northwest University, Xi’an, China, 2019.
28. He, J.Z. Sedimentation and Geochemistry of Potential Source Rocks in Pt₂₋₃-E₁ Around Ordos Region. Master’s Thesis, China University of Petroleum (East China), Qingdao, China, 2015. (In Chinese).
29. Chen, Y.Z.; Zhu, W.M. Geochemical characteristics of Mesoproterozoic sedimentary rock in the Southern margin of Ordos Block. *Geol. Sci. Technol. Inf.* **2019**, *38*, 81–87. (In Chinese) <https://doi.org/10.19509/j.cnki.dzkg.2019.0308>.
30. Ma, Q. Tectonic Evolution and Middle-Upper Proterozoic Petroleum Geological Setting in South-Western Ordos Basin. Master’s Thesis, Northwest University, Xi’an, China, 2020. <https://doi.org/10.27405/d.cnki.gxbdu.2020.000045>.
31. Tian, G.; Song, L.J. Thermal evolution modeling of Mesoproterozoic source rocks in the Ordos Basin. *Pet. Geol. Exp.* **2017**, *39*, 520–526. (In Chinese) <https://doi.org/10.11781/sydz201704520>.
32. Sweeney, J.J.; Burnham, A.K. Evaluation of a simple model of vitrinite reflectance based on chemical kinetics. *AAPG Bull.* **1990**, *74*, 1559–1570. <https://doi.org/10.1306/0C9B251F-1710-11D7-8645000102C1865D>

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