

Article

Geochemical Characteristics of the Minghuazhen Formation in the Cangdong Sag, Bohai Bay Basin: Implications for Provenance, Paleoclimate, and Hydrocarbon Exploration

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Abstract: The Minghuazhen Formation in the Cangdong Sag of the Bohai Bay Basin is a key sedimentary unit for investigating regional provenance evolution, paleoclimate variations, and hydrocarbon potential in Eastern China. This study integrates mineralogical and geochemical analyses to explore sedimentary characteristics. Techniques include X-ray diffraction (XRD), major/trace element compositions, rare earth element (REE) distributions, and organic carbon content. XRD data and elemental ratios (e.g., Al/Ti, Zr/Sc) suggest a predominant felsic provenance, sourced from acidic magmatic rocks. The enrichment with light rare earth elements (LREE: La–Eu) and notable negative Eu anomalies in the REE patterns support the interpretation of a provenance from the Taihangshan and Yanshan Orogenic Belts. Geochemical proxies, such as the Chemical Index of Alteration (CIA) and trace element ratios (e.g., U/Th, V/Cr, Ni/Co), indicate a warm and humid depositional environment, characterized by predominantly oxic freshwater conditions. Organic geochemical parameters, including total organic carbon (TOC), total nitrogen (TN), and C/N ratios, suggest that organic matter primarily originates from aquatic algae and plankton, with C/N values predominantly below 10 and a strong correlation between TOC and TN. The weak correlation between TOC and total carbon (TC) indicates that the organic carbon is mainly biological in origin rather than carbonate-derived. Although the warm and humid climate promoted the production of organic matter, the prevailing oxic conditions hindered its preservation, resulting in a relatively low hydrocarbon generation potential within the Minghuazhen Formation of the Cangdong Sag. These findings provide new insights into the sedimentary evolution and hydrocarbon potential of the Bohai Bay Basin.

Keywords: provenance; paleoclimate; geochemistry; organic carbon; hydrocarbon potential; Minghuazhen Formation; Cangdong Sag



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1. Introduction

The geochemical composition of sediments provides critical insights into sedimentary processes, diagenetic evolution, and paleoclimate variations [1–3]. Geochemical signatures also play a pivotal role in hydrocarbon exploration by aiding the characterization of reservoirs and assessing their hydrocarbon generation potential [4,5]. The distribution of elemental composition and organic matter in sedimentary basins reflects the characteristics of source areas and serves as a key record of paleoclimatic conditions, weathering intensity, and the accumulation of organic matter [6,7].

Provenance has a significant influence on sediment geochemistry, directly affecting reservoirs and source rocks of hydrocarbons. Major element ratios (e.g., Al/Ti, Fe/Ti, K/Na) and trace element proxies (e.g., Th/Sc, La/Sc, Cr/Zr), as well as rare earth element (REE) distributions, are commonly used to infer source lithology, weathering intensity, and tectonic settings [8,9]. These factors are crucial for evaluating reservoirs' quality and hydrocarbon accumulation potential. The degree of chemical weathering in source regions, which is largely climate-controlled, impacts sediment mineralogy and geochemical signatures. In warm, humid climates, intense weathering enriches immobile elements such as Si and Al, while leaching mobile elements like Ca and Na [7]. This process can enhance porosity and permeability, facilitating hydrocarbon migration and improving reservoirs' quality. In contrast, arid climates typically result in weaker weathering and the preservation of primary minerals, which may reduce reservoirs' quality [10,11].

Paleoclimate plays a dominant role in shaping sediments' geochemistry and source rocks' development. The Chemical Index of Alteration (CIA) is frequently employed to infer past climatic conditions, distinguishing between humid and arid environments [12,13]. Higher CIA values indicate strong chemical weathering in humid climates, which favor the deposition of organic-rich mudstones, while lower CIA values are associated with arid conditions, less conducive to the preservation of organic matter [14,15]. Additionally, trace elements such as Sr, Rb, and REE ratios serve as valuable climatic proxies, distinguishing between warm-humid and cold-arid conditions [16,17].

The quantity and origin of organic matter are critical for evaluating the hydrocarbon potential of source rocks. Parameters such as total organic carbon (TOC), total nitrogen (TN), and the carbon-to-nitrogen (C/N) ratio are commonly used to differentiate between terrestrial and aquatic sources of organic matter [18,19]. High C/N ratios (>20) typically indicate terrestrial plant-derived organic matter, while lower values (<10) are more suggestive of algal or planktonic contributions, which are often associated with higher-quality source rocks [20,21]. Redox-sensitive elemental proxies such as V/Cr and V/Ni ratios provide further insights into depositional oxygen conditions and hydrocarbon generation potential [22]. A V/Cr ratio greater than 2.0 suggests anoxic conditions, which favor the preservation of organic matter, while ratios below this threshold indicate more oxygen-rich environments, which are less favorable for the accumulation of organics [23].

The Cangdong Sag, located in the Southern Bohai Bay Basin (Figure 1), is a significant hydrocarbon-rich depression within the Huanghua Depression [24]. Its Cenozoic sedimentary succession plays a crucial role in reconstructing the tectonic evolution and hydrocarbon accumulation patterns of Eastern North China. The Minghuazhen Formation (5.33–2.58 Ma [25]), a widespread stratigraphic unit in this region, consists primarily of siltstones, mudstones, and fine-grained sandstones [26]. The geochemical characteristics of these sediments are influenced by provenance, climate, and depositional conditions, making them valuable archives for understanding sedimentary evolution and assessing hydrocarbon potential [24,27]. This study systematically investigates the major and trace element geochemistry and TOC content of Minghuazhen Formation sediments to explore their provenance, diagenetic evolution, paleoclimate, and hydrocarbon generation potential. By integrating elemental ratio analysis, weathering indices, paleoclimate proxies, and organic geochemical parameters, this research aims to refine the understanding of sedimentary evolution in the Cangdong Sag, offering new insights into the region's paleoclimate history and for hydrocarbon exploration.

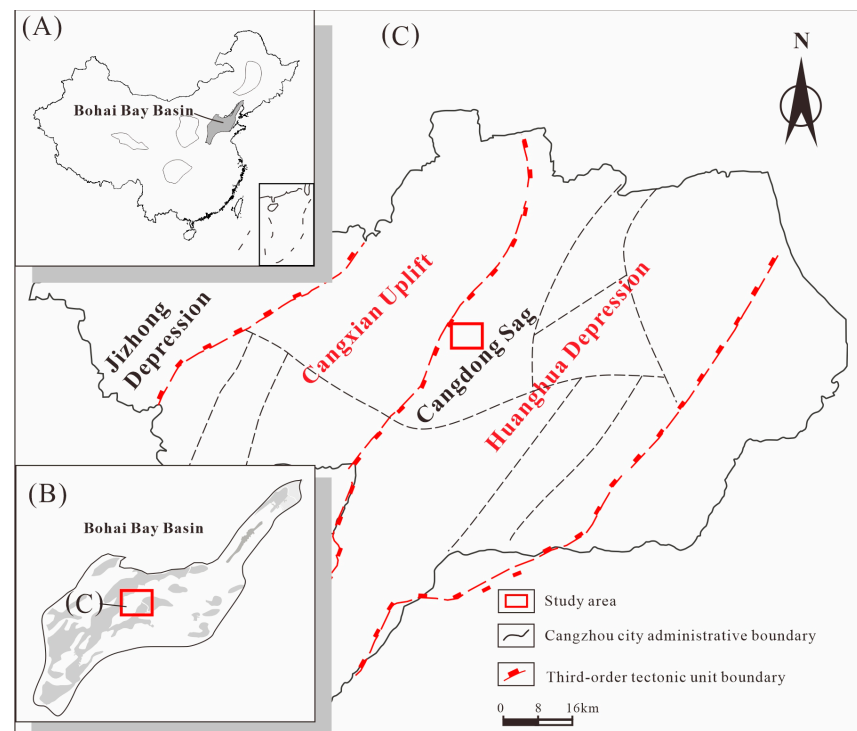


Figure 1. Tectonic sketch map of the study area. (A) Simplified map of mainland China. (B) Regional map of the Bohai Bay Basin. (C) Tectonic map of the Cangzhou Area.

2. Materials and Methods

Thin sections of rock samples from borehole core CZKZ01 were prepared at the Cores and Samples Center of Land and Resources, China Geological Survey (CGS), and petrographic observations were conducted using a GTSC-YQ-83 polarizing microscope (Sunny Optical, China). In the pretreatment stage of the thin section preparation, 95% ethanol is employed for the dehydration treatment of rock and mineral samples to eliminate residual moisture and clean the surface. Its temporary consolidation effect effectively maintains the structural integrity of loosely consolidated samples, providing technical support for subsequent resin impregnation and precision grinding/polishing processes. X-ray diffraction (XRD) analysis was performed at the Microstructure Analytical Laboratory in Beijing. For the XRD analysis, appropriately ground rock powder was loaded into quartz sample holders. The powder was gently leveled and compacted with a flat glass plate to ensure a smooth and uniform surface. Excess powder was removed from the glass surface, ethanol (95%) was added to aid adhesion, and the sample was dried prior to measurement. XRD patterns were obtained using a D8 Advance (Bruker, German). Mineral identification was based on crystal lattice parameters, and the mineralogical composition of sedimentary rocks was determined by comparing the diffraction data with standard references using MDI Jade software (Livermore, CA, USA).

TN and TC concentrations were determined using an elemental analyzer based on oxidative combustion–gas chromatography (OC–GC). TOC was measured using a high-frequency combustion infrared carbon–sulfur analyzer (HF-IR C–S)(CS-580A, Eltra, German). Major oxides and trace elements, including REEs, were determined using X-ray fluorescence (XRF) and inductively coupled plasma mass spectrometry (ICP-MS) (iCAP Qc, Thermo Fisher, USA). Quality control was ensured through the use of duplicate samples and certified reference materials GSD10, GSD17a, GSS3a, and GSS43. The detailed analytical procedures for major and trace element analyses follow the methodology described by [28]. The relative standard deviation (RSD) values for most elements, based on replicate

analyses, ranged from 1% to 7%, while the RSD for S reached up to 17%. Deviations in certified reference materials were better than 5–15% for most elements, with Cr, S, Zr, La, Lu, and TOC showing deviations better than 17%.

3. Results

3.1. Petrographic Characteristics of Representative Samples

3.1.1. CZ1-b52: Fine to Medium Sandstone

Sample CZ1-b52 is primarily composed of sand and silt (95%), with subangular to subrounded grains (Figure 2A). The sand fraction is mostly fine sand (0.06–0.25 mm), followed by medium sand (0.25–0.5 mm) and occasional coarse sand (0.5–1 mm), primarily consisting of sheet-like minerals. The silt fraction (0.004–0.06 mm) is sparsely distributed among the sand grains. The main constituents are quartz, feldspar, and lithic fragments, with the quartz being predominantly monocrystalline, exhibiting slight undulatory extinction. The feldspar includes both potassium feldspar and plagioclase, some of which show kaolinization and sericitization. The lithic fragments include carbonates (mainly dolomite), claystones, siliceous rocks, rhyolites, schists, and various mineral fragments, such as biotite, muscovite, chlorite, amphibole, epidote, and garnet. The clay content (5%) is characterized by light yellowish-brown, fine-grained, cryptocrystalline to micaceous minerals, typically <0.004 mm, filling intergranular pore spaces. Minor opaque minerals, with sizes < 0.8 mm, are scattered throughout the sample.

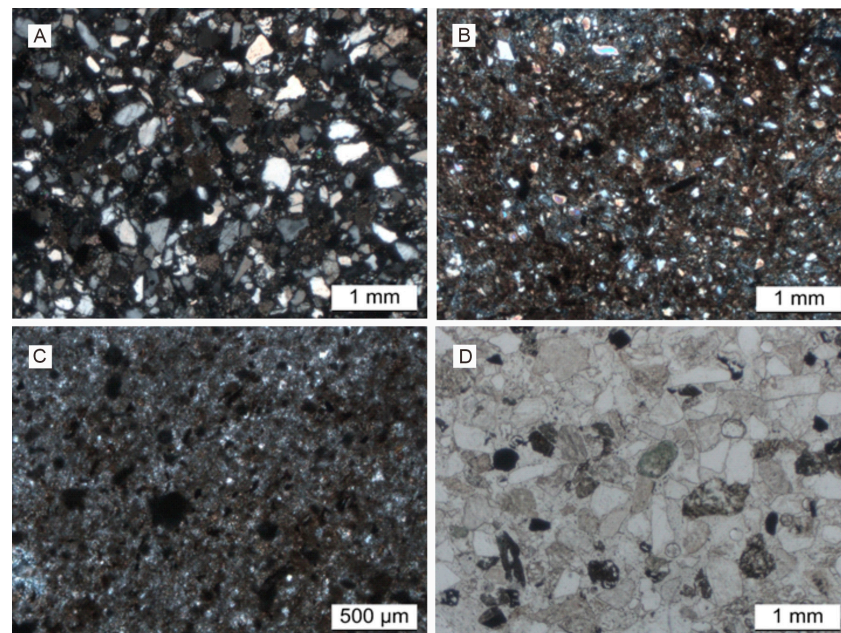


Figure 2. Typical petrographic features of Minghuazhen Formation: (A) CZ1-b52, Sandstone, 514 m; (B) CZ1-b54, Clay, 556 m; (C) CZ1-b67, Mudstone, 773 m; (D) CZ1-b80, Sandstone, 1284.7 m.

3.1.2. CZ1-b54: Calcareous Core, Silty Fine Sand with Clay

Sample CZ1-b54 consists of clay and minor organic matter (45%), predominantly yellow-brown, with the clay fraction made up of cryptocrystalline to micaceous minerals (<0.004 mm), distributed irregularly (Figure 2B). The sand and silt fraction (45%) contains subangular to subrounded grains, mainly fine sand (0.06–0.25 mm), with smaller amounts of medium sand (0.3–0.4 mm) and silt (0.004–0.06 mm). The composition includes quartz (monocrystalline with slight undulatory extinction), feldspar (potassium feldspar and plagioclase, some altered to kaolinite and sericite), and lithic fragments, such as claystone and siliceous rocks. The calcareous core (10%) consists of irregular particles (0.5–8 mm),

mainly carbonate minerals with minor clay, sand, and iron-rich materials. Minor opaque minerals (<1.05 mm) and trace zircon are also present.

3.1.3. CZ1-b67: Mudstone

This semi-consolidated sediment comprises approximately 90% clay and iron oxide, with the remainder being sand, silt, and calcareous nodules (Figure 2C). The clay and iron oxide fraction consists mainly of cryptocrystalline to micro-foliated clay minerals (<0.004 mm), forming clump-like aggregates in certain areas. The sand and silt fraction (~5%) is predominantly fine silt (0.004–0.06 mm), with minor fine (0.06–0.25 mm) and medium sand (0.25–0.35 mm). The mineral components are chiefly quartz and feldspar. Elliptical calcareous nodules (<5%), ranging from 1.2 to 7 mm, are sporadically distributed and primarily composed of carbonate minerals, with minor clay, silt, and iron oxide.

3.1.4. CZ1-b80: Medium Sandstone

This sample consists mainly of sand (85–90%), with calcareous nodules (10–15%) and minimal clay. Sand grains are subangular to subrounded, predominantly medium-sized (0.25–0.5 mm), with minor coarse (0.5–0.9 mm) and fine sand (0.06–0.25 mm), exhibiting a heterogeneous distribution (Figure 2D). Quartz occurs as monocrystals with a slight undulose extinction. Feldspars, mainly potassium feldspar and plagioclase, show kaolinitization and sericitization. The rock fragments include calcareous sandstones, claystones, granites, rhyolites, sericitic quartzites, and andesites. Irregularly shaped calcareous nodules (1.1–9 mm) are dispersed throughout, primarily composed of micritic calcite, with minor clay, sand, and opaque minerals. The minimal clay fraction comprises cryptocrystalline to micro-foliated clay minerals (<0.004 mm) filling intergranular pore spaces.

3.1.5. Overall Petrographic Characteristics

The reservoir rocks of the Minghuazhen Formation exhibit a low maturity, with clastic grains uniformly arranged and predominantly subangular to subrounded, with some angular grains. Grain size sorting is moderate. The intergranular material mainly consists of clay and calcite, with blocky and pore-filling cementation. The rock is relatively loose, with minor clay minerals and matrix filling intergranular pore spaces and visible clay mineral aggregates between grains.

3.2. XRD Analysis

The XRD results are shown in Figure 3. The analysis indicates that quartz is the dominant mineral, accounting for 40–60% of the total mineral content throughout the depth profile, which suggests a significant terrigenous input. Feldspar, primarily in the forms of plagioclase and microcline, is present in smaller amounts but exhibits localized increases at certain depths, such as 514 m (CZ-52) and 826.5 m (CZ-70). These variations imply changes in the depositional environment. Additionally, the calcite content is notably enriched at specific intervals, particularly at 490 m (CZ-51) and 917 m (CZ-73), where concentrations reach up to 75% at 917 m. This enrichment points to episodic carbonate deposition, indicating a carbonate-dominated sedimentary environment at these depths.

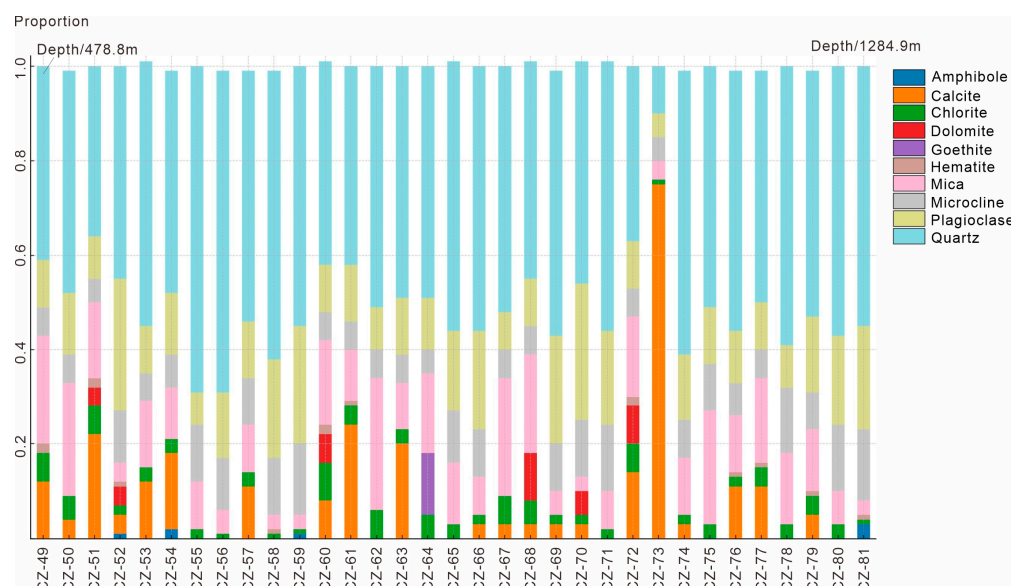


Figure 3. Stratigraphic mineral composition of the Minghuazhen Formation.

3.3. Major and Trace Elements

3.3.1. Major Element Characteristics

The major elemental composition of the Minghuazhen Formation sediments is predominantly characterized by SiO_2 (21.5–76.3%), Al_2O_3 (5.73–19.2%), TFe_2O_3 (2.20–32.0%), and CaO (0.69–38.5%) (Table 1). SiO_2 exhibits the highest abundance, averaging 61.2%, followed by Al_2O_3 at an average of 15.2%, indicating a primarily siliceous and aluminous nature. The concentrations of MgO (0.76–3.69%), Na_2O (0.44–3.26%), and K_2O (0.79–3.10%) are relatively low. TC and TOC content range from 0.04% to 8.10% and from 0.04% to 0.49%, respectively, with limited variation among samples. Compared to sediments from the Bohai Bay cores (Table 1), the Minghuazhen Formation samples from our study area exhibit a broadly similar major element composition but with a slightly lower SiO_2 and Al_2O_3 content and higher CaO concentrations. These differences may reflect the relatively lower degree of chemical weathering and sedimentary maturity of our samples.

Table 1. Statistical distribution of major and trace element characteristics of Minghuazheng Fomation.

		SiO_2	Al_2O_3	TFe_2O_3	MgO	CaO	Na_2O	K_2O	CIA	ICV	TC
Minghuazheng Formation (n = 32)	mean	61.2	15.2	6.33	1.96	4.82	1.56	2.34	67.4	1.30	0.96
	min	21.5	5.73	2.20	0.761	0.685	0.435	0.785	49.2	0.49	0.04
	max	76.3	19.2	32.0	3.69	38.5	3.26	3.23	78.8	7.88	8.10
G 2 borehole in Bohai Bay (n = 573) [29]	min	35.3	9.23	1.08	0.82	0.71	0.53	1.18	50	/	/
	max	74.38	25.34	27.16	4.07	23.12	3.49	3.86	88.1	/	/
UCC		66.62	15.40	5.04	2.48	3.59	3.27	2.80			
Minghuazheng Formation		B	Co	Cr	Hf	Mn	Nb	Ni	Rb	Sc	Sr
	mean	43.2	16.0	70.0	5.42	721.8	12.9	30.1	97.4	13.2	179.3
	min	12.90	3.41	15.60	2.20	137.7	5.84	12.06	33.10	4.01	101.6
UCC	max	65.6	46.5	117.0	14.7	3699.0	18.0	63.1	134.3	20.6	308.5
		17	17.3	92	5.3	774.5	12	47	84	14.0	320
Minghuazheng Formation		Ta	Th	Ti	U	V	Zr	N	P	S	TOC
	mean	1.11	12.7	4074.5	2.54	90.2	185.8	151.6	402.8	166.1	0.10
	min	0.37	4.12	1251.2	1.00	27.2	80.6	27.7	99.9	48.8	0.04
UCC	max	1.53	20.6	5448.0	6.64	191.0	517.7	302.2	744.2	1428.3	0.49
		0.9	10.5	3835.7	2.7	97	193	83	654.7	621	

CIA values calculated as $\text{CIA} = 100 \times (\text{Al}_2\text{O}_3 / (\text{Al}_2\text{O}_3 + \text{CaO}^* + \text{Na}_2\text{O} + \text{K}_2\text{O}))$, where Al_2O_3 , CaO^* , Na_2O , and K_2O are molecular proportions, and CaO^* represents the silicate-derived fraction of CaO [30]; $\text{ICV} = (\text{Fe}_2\text{O}_3 + \text{K}_2\text{O} + \text{Na}_2\text{O} + \text{CaO} + \text{MgO} + \text{TiO}_2) / \text{Al}_2\text{O}_3$ [31]. UCC (upper continental crust) values are from Gao and Rudnick (2014) [32].

3.3.2. Trace Element Characteristics

The samples have relatively high concentrations of Cr (15.6–117 µg/g), V (27.2–191 µg/g), and Zr (80.6–518 µg/g) compared to the lower concentrations of other trace elements such as Ta (0.37–1.53 µg/g), Hf (2.2–14.7 µg/g), and U (1.00–6.64 µg/g) (Table 1). Notably, Zr exhibits a marked accumulation in certain samples. Transition elements such as Co (3.41–46.5 µg/g) and Ni (12.1–63.1 µg/g) exhibit a relatively uniform distribution, resembling the characteristics of terrigenous clastic materials. The negative correlation observed between Rb (33.1–141 µg/g) and Sr (102–221 µg/g) ($r = -0.36$, $p < 0.05$) suggests a differential weathering of feldspar minerals.

3.3.3. Rare Earth Element Characteristics

The Σ REE ranges from 75.0 to 372 µg/g, with an average of 251 µg/g (Table 2). This value is notably higher than the average Σ REE of the UCC (183.14 µg/g) [32], North American shale (229.48 µg/g) [33], and Post-Archean Australian Shale (PAAS) (183.0 µg/g) [6]. LREEs range from 58.5 to 313 µg/g, averaging 202 µg/g, whereas heavy rare earth elements (HREE: Sm–Dy) range from 6.07 to 30.6 µg/g, with an average of 20.4 µg/g. The LREE/HREE ratio varies between 8.17 and 12.3, with an average of 10.0, indicating significant LREE fractionation. The Eu anomaly ($\delta\text{Eu} = \text{Eu}_N/(\text{Sm}_N \times \text{Gd}_N)^{0.5}$, normalized to chondrite, ranges from 0.61 to 1.10, with an average of 0.70, suggesting a weak negative anomaly. This most likely indicates source characteristics, particularly the presence of residual plagioclase in the provenance.

Table 2. Rare earth element composition of the Minghuazhen Formation.

	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Y	Σ REE
CZ-49	55.8	112	13.3	48.9	8.88	1.73	8.13	1.33	7.51	1.58	4.25	0.67	4.26	0.68	43.1	312.1
CZ-50	60.9	117	14.2	51.6	8.78	1.57	6.99	1.10	5.87	1.18	3.28	0.53	3.61	0.56	27.8	305.4
CZ-51	53.6	104	12.5	46.0	8.48	1.64	7.57	1.25	6.95	1.45	3.97	0.62	3.88	0.62	39.9	292.9
CZ-52	42.5	84.4	10.0	37.1	6.53	1.25	5.56	0.88	4.84	0.98	2.69	0.44	2.89	0.46	25.1	225.8
CZ-53	36.7	76.5	8.92	32.9	6.07	1.20	5.09	0.84	4.69	0.96	2.69	0.44	2.91	0.46	23.9	204.3
CZ-54	54.3	105	12.9	48.2	8.72	1.79	7.75	1.26	7.10	1.46	3.94	0.61	4.00	0.62	38.4	295.6
CZ-55	28.4	50.1	5.88	20.3	3.53	0.72	2.88	0.48	2.72	0.56	1.60	0.26	1.71	0.28	15.9	135.3
CZ-56	22.8	41.4	5.25	18.0	3.10	0.77	2.44	0.39	2.07	0.41	1.10	0.18	1.17	0.19	11.3	110.6
CZ-57	62.5	110	14.8	55.5	10.3	2.06	9.12	1.47	8.14	1.63	4.42	0.69	4.45	0.69	44.0	329.8
CZ-58	22.9	42.2	5.38	19.8	3.55	0.92	3.00	0.50	2.78	0.55	1.50	0.24	1.56	0.25	15.4	120.6
CZ-59	14.6	25.9	3.25	12.0	2.05	0.68	1.75	0.27	1.59	0.32	0.89	0.14	0.96	0.15	10.5	75.02
CZ-60	55.3	112	13.1	47.0	8.41	1.54	6.66	1.07	5.75	1.14	3.12	0.50	3.24	0.52	29.3	289.0
CZ-61	52.1	102	12.5	46.9	8.71	1.68	7.56	1.24	7.07	1.45	3.91	0.62	4.04	0.64	39.2	289.2
CZ-62	51.7	104	11.9	41.9	6.93	1.26	5.38	0.82	4.51	0.89	2.49	0.41	2.71	0.43	21.7	257.1
CZ-63	52.5	108	12.6	47.1	8.45	1.69	7.12	1.18	6.42	1.31	3.48	0.55	3.52	0.56	32.2	286.3
CZ-64	56.8	117	13.4	49.5	9.03	1.74	8.03	1.34	7.75	1.67	4.81	0.77	5.08	0.89	48.0	326.1
CZ-65	55.0	111	12.8	46.7	8.12	1.62	6.62	1.05	5.68	1.16	3.15	0.49	3.29	0.52	29.1	285.9
CZ-66	44.7	90.1	10.7	39.5	7.13	1.45	5.92	0.95	5.23	1.07	2.85	0.46	2.93	0.48	27.7	241.1
CZ-67	46.2	90.5	10.8	40.2	6.96	1.29	5.30	0.84	4.73	1.00	2.84	0.48	3.19	0.52	24.7	239.6
CZ-68	53.4	108	12.7	46.8	8.35	1.71	7.04	1.12	6.15	1.25	3.39	0.54	3.42	0.55	33.8	288.6
CZ-69	33.9	63.9	8.12	30.2	5.36	1.22	4.50	0.72	3.95	0.80	2.16	0.35	2.27	0.36	20.7	178.4
CZ-70	34.0	62.4	8.03	29.8	5.33	1.20	4.36	0.70	3.80	0.78	2.12	0.34	2.23	0.36	19.3	174.8
CZ-71	69.6	146	17.6	65.6	11.8	2.44	9.04	1.39	7.20	1.37	3.68	0.58	3.99	0.61	31.2	372.2
CZ-72	70.2	140	16.2	59.0	10.2	1.84	8.34	1.30	7.13	1.41	3.82	0.60	3.92	0.63	35.6	360.3
CZ-73	62.3	98.5	11.8	45.0	7.92	1.63	7.93	1.27	7.17	1.53	4.23	0.64	3.98	0.67	53.6	308.2
CZ-74	49.2	96.4	11.4	42.5	7.37	1.58	5.95	0.94	5.02	1.00	2.69	0.43	2.79	0.45	25.9	253.7
CZ-75	48.9	97.2	11.3	41.0	7.00	1.36	5.49	0.85	4.44	0.88	2.37	0.38	2.49	0.41	21.5	245.6
CZ-76	42.0	89.6	9.84	36.0	6.18	1.28	4.91	0.77	4.10	0.82	2.21	0.36	2.33	0.37	20.1	220.9
CZ-77	57.3	115	13.8	51.9	9.26	1.98	7.81	1.25	6.62	1.33	3.53	0.54	3.42	0.54	34.5	308.4
CZ-78	39.2	72.0	8.93	31.9	5.50	1.15	4.22	0.67	3.66	0.75	2.07	0.34	2.31	0.37	18.1	191.3
CZ-79	56.4	111	13.4	49.0	8.58	1.71	7.09	1.14	6.08	1.23	3.37	0.53	3.45	0.54	30.7	294.4
CZ-80	39.3	75.9	9.32	34.8	6.42	1.36	5.38	0.86	4.69	0.93	2.54	0.40	2.65	0.42	23.9	208.9
CZ-81	47.0	92.1	10.6	39.4	6.54	1.58	5.51	0.85	4.50	0.89	2.33	0.35	2.20	0.35	25.2	239.4

4. Discussion

4.1. Provenance of the Minghuazhen Formation

The geochemical composition of sedimentary deposits reflects source characteristics, reservoir properties, and the quality of hydrocarbon source rocks. Elemental analysis provides insights into the source characteristics, though potential modifications due to recycling and diagenesis must be considered [12,34]. The Index of Composition Variability (ICV) is widely used to assess the extent of sediment recycling. An $ICV > 1$ indicates a dominance of non-clay silicate minerals, suggesting low degrees of recycling and primary deposition under active tectonic conditions, whereas an $ICV < 1$ signifies higher maturity and increased clay mineral content, indicative of substantial recycling or intense chemical weathering [12].

The Minghuazhen Formation exhibits an average ICV of 1.30 (Table 1), suggesting a limited influence of recycling. This interpretation is supported by petrographic observations, which reveal abundant detrital material, and XRD data, which indicate a weak transport-related modification of clastic components [35]. Th/Sc and Zr/Sc ratios align with values characteristic of PAAS and the UCC (Figure 4A) [36]. However, isolated samples exhibit elevated Zr concentrations, likely due to the introduction of zircon grains at a later stage [37], which is consistent with our lithofacial observations. Despite these variations, the overall geochemical signature suggests a minimal influence of recycling.

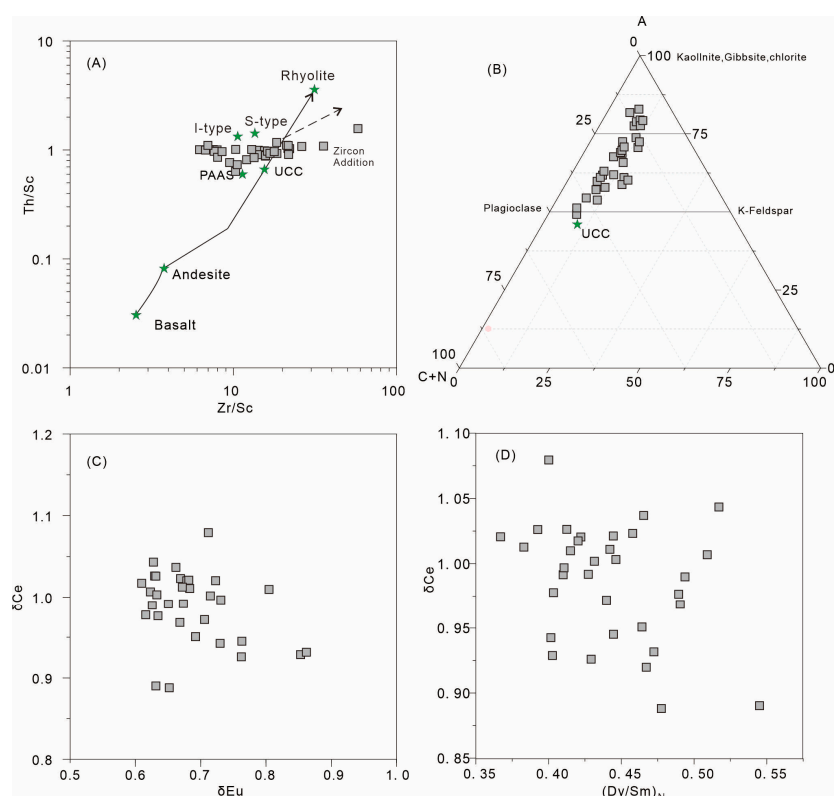


Figure 4. Geochemical characteristics of rocks of the Minghuazhen Formation: (A) Th/Sc vs. Zr/Sc [36]; (B) A-CN-K diagram showing the proportions of Al_2O_3 , $CaO^* + Na_2O$, and K_2O , where CaO^* represents CaO corrected for carbonate content [7]; (C) δCe vs. δEu ; (D) δCe vs. $(Dy/Sm)_N$.

Further evidence from the A-CN-K ternary diagram demonstrates that all samples plot along the A-CN connection line (Figure 4B), indicating the absence of potassium alterations [38]. Additionally, the lack of significant correlations between δCe ($\delta Ce = Ce_N / (La_N \times Pr_N)^{0.5}$), δEu , and $(Dy/Sm)_N$ in samples from the Cangdong Sag (Figure 4C,D) suggests minimal diagenetic modification, as diagenesis typically enhances such correlations [39].

Collectively, these findings indicate that the geochemical composition of the Minghuazhen Formation sediments remains largely unaltered by recycling and diagenesis, affirming their suitability for provenance analysis.

In igneous rocks, Al_2O_3 is primarily associated with feldspar, while TiO_2 is predominantly found in ferromagnesian minerals. Both elements exhibit a low solubility and mobility during weathering, preserving the geochemical signature of the source rock and serving as reliable indicators for sediments' provenance [40]. The $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratio in the Minghuazhen Formation sediments consistently falls within an intermediate range, averaging 23.6 ± 6.6 , positioning the sediments within the felsic igneous rock domain (Figure 5A). Additionally, trace elements such as Zr, Sc, and Co provide further constraints on the sediment source characteristics. The TiO_2/Zr ratio averages 40.0 ± 15.2 , with most values below 55 (Figure 5B), indicative of a predominantly felsic source. The Co/Th - La/Sc and La/Th - Hf diagrams (Figure 5C,D) corroborate this interpretation, confirming a felsic provenance [6,41].

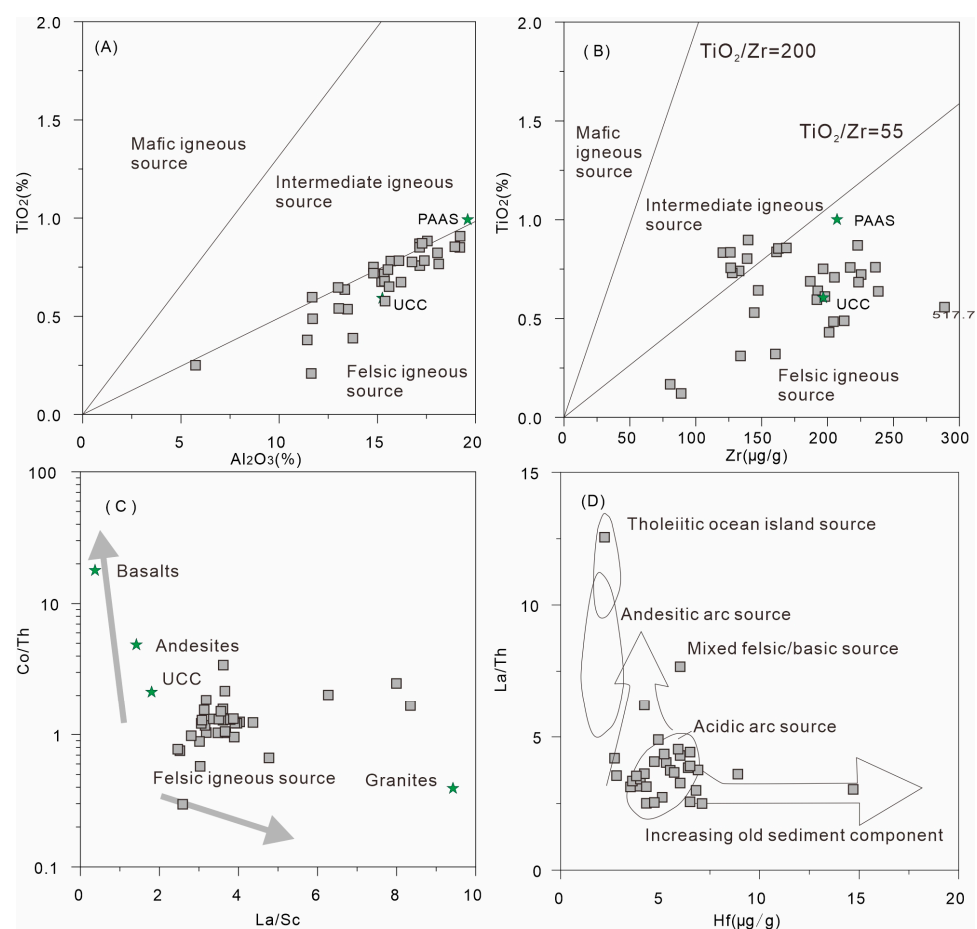


Figure 5. Sediment provenance discrimination diagrams: (A) TiO_2 - Al_2O_3 distribution diagram [42]; (B) TiO_2 -Zr distribution diagram [43]; (C) Co/Th vs. La/Sc distribution diagram [41]; (D) La/Th vs. Hf distribution diagram [6].

REEs provide robust constraints on the sedimentary basin's provenance. The REE distribution in the upper crust is marked by LREE enrichment, relatively stable HREE concentrations, and a distinct negative Eu anomaly [32]. Chondrite-normalized REE patterns from the Minghuazhen Formation sediments closely resemble those of the upper crust, reinforcing the inference that the sediments were sourced from upper crustal material, consistent with the major and trace element data. The Eu anomaly (δEu) in sedimentary rocks reflects the composition of their parent rocks [8], with granitoid sources typically

exhibiting negative anomalies, while basaltic sources show minimal Eu depletion. The δEu values in the studied sediments range from 0.61 to 1.10, averaging 0.70, indicating a negative Eu anomaly characteristic of granitic source rocks. The REE-La/Yb diagram (Figure 6A) for Cangdong Sag mudstones places the samples within the granite–sedimentary rock field [38], suggesting a mixed provenance of granitic and sedimentary sources.

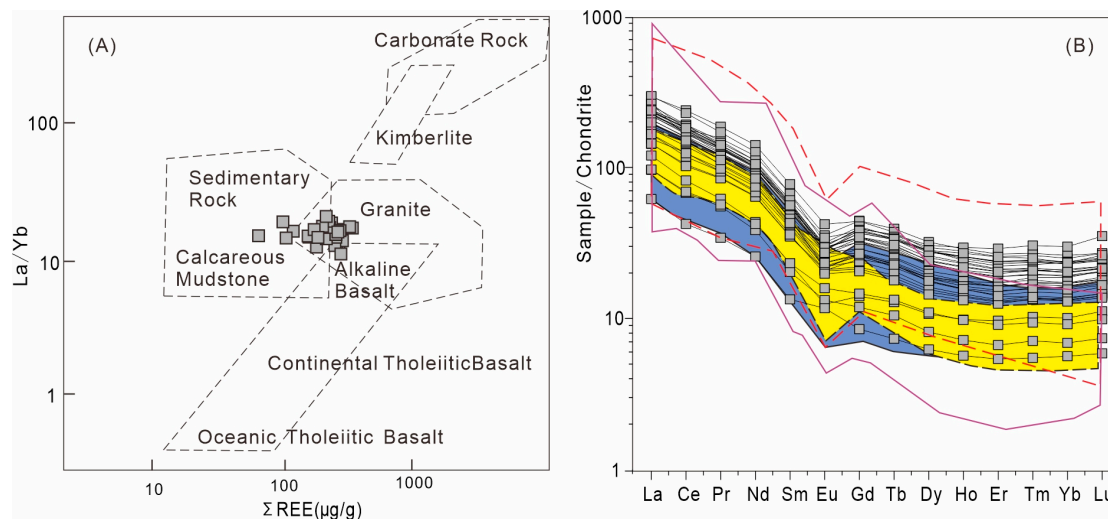


Figure 6. Rock geochemical diagrams of the study area: (A) (REEs-La/Yb) Diagram (base map after Allègre and Michard (1974) [44]). (B) Rare earth element distribution diagram (blue region represents acidic volcanic rocks from the Yanshan Orogen, yellow region represents granitoids from the Yanshan Orogen; after Reference [26]. Purple solid and red dashed lines represent Mesozoic magmatic and metamorphic–sedimentary rocks from the Taihang Mountains, after Reference [45]).

Petrographic and XRD analyses confirm that the Minghuazhen Formation sediments are dominated by quartz, feldspar, and mica, which are common minerals in granite. The southern portion of the study area, within the Luxi Uplift, exhibits a greater influence from mafic sources [46], contrasting with the felsic-dominated Cangdong Sag. The northern region is influenced by the Taihangshan–Yanshan Orogenic Belt, which experienced multiple episodes of intermediate to felsic magmatism, serving as a major sediment source for the Bohai Bay Basin [26,47]. A comparison of REE distribution patterns between the Minghuazhen Formation sediments and intermediate to felsic volcanic rocks and granites from different periods in the central and Eastern Taihangshan–Yanshan Orogenic Belt reveals a strong similarity with intermediate to felsic volcanic rocks and granites (Figure 6B). This geochemical signature distinguishes the sediments from Archean, Proterozoic, and Paleozoic Hercynian granites. Furthermore, the total REE content in the Minghuazhen Formation sediments closely matches that of Taihangshan–Yanshanian volcanic and granitic rocks, differentiating it from other lithologies. Similarly, Neogene strata from the Nandoukou Sag in the Northeastern Cangdong Sag exhibit a comparable REE composition [26], indicating a shared provenance. Thus, the Cangdong Sag sediments are primarily sourced from the Taihangshan–Yanshan Orogenic Belt, with dominant contributions from intermediate to felsic volcanic rocks and granitic intrusions, along with a minor input from sedimentary sources.

4.2. Paleoenvironment Reconstruction

Paleoclimatic changes influence hydrocarbon source rock's development by altering the geochemical composition of sediments. During deposition, elemental solubility and mobility vary under different redox and salinity conditions, making specific elemental ratios useful for paleoenvironmental reconstructions.

4.2.1. Paleoclimate Characteristics

The CIA is a widely applied metric for assessing paleoclimate and weathering intensity [1,31]. The degree of chemical weathering is primarily governed by temperature and precipitation, with high CIA values indicative of warm, humid climates conducive to intense weathering, while lower values correspond to cold, arid conditions. Specifically, CIA values between 50 and 60 reflect a low weathering intensity, typical of cold, arid environments; values between 60 and 80 indicate moderate weathering under warm, humid conditions; and values exceeding 80 suggest intense weathering in hot, humid climates [7,48].

REEs also exhibit climate-dependent enrichment behaviors. REE values tend to increase in warm, humid climates and decrease in cold, arid conditions [49]. The differential mobility of HREEs and LREEs during weathering results in preferential HREE migration, while LREEs accumulate in residual material, making the REE composition valuable for paleoenvironmental reconstructions [16]. The CIA values for the Minghuazhen Formation sediments range from 49.2 to 78.8, with an average of 67.6, suggesting a predominantly warm and humid paleoclimate. A high carbonate mineral content, particularly in mixed shales, along with elevated REE concentrations and LREE/HREE ratios further support the inference of a warm, humid environment conducive to the accumulation of organic matter and hydrocarbon source rock's development.

4.2.2. Paleosalinity Characteristics

Paleosalinity serves as a crucial indicator of past aquatic environments and significantly influences the formation and accumulation of organic matter and hydrocarbons. Due to the high solubility and mobility of borates, increased salinity correlates with elevated boron concentrations in sediments. Boron concentrations below 60 $\mu\text{g/g}$ indicate freshwater conditions, values between 60 and 80 $\mu\text{g/g}$ suggest brackish to semi-saline environments, and concentrations exceeding 80 $\mu\text{g/g}$ signify saline conditions [50]. In addition to boron, other geochemical proxies, such as Sr, Ca, and Fe, also provide insights into past salinity fluctuations. Sr concentrations above 100 $\mu\text{g/g}$ and a $\text{Ca}/(\text{Ca} + \text{Fe})$ ratio below 0.4 are typical of freshwater environments, while Sr concentrations between 40 and 100 $\mu\text{g/g}$ and $\text{Ca}/(\text{Ca} + \text{Fe})$ ratios between 0.4 and 0.6 are associated with brackish conditions. Saline environments are characterized by Sr concentrations below 40 $\mu\text{g/g}$ and $\text{Ca}/(\text{Ca} + \text{Fe})$ ratios above 0.6 [51–53].

In the Minghuazhen Formation sediments, boron concentrations range from 12.9 to 69.1 $\mu\text{g/g}$, with an average of 43.2 $\mu\text{g/g}$. Sr concentrations vary from 102 to 309 $\mu\text{g/g}$, with an average of 179 $\mu\text{g/g}$ (Figure 7A); excluding the influence of carbonate minerals formed during diagenesis, which may affect the salinity signal, samples with CaO concentrations less than 7% yielded $\text{Ca}/(\text{Ca} + \text{Fe})$ ratios ranging from 0.03 to 0.67, with an average value of 0.34. These geochemical parameters suggest that the dominant depositional environment was freshwater, with intermittent brackish water influences. The development of fluvial–deltaic depositional facies during the Minghuazhen Formation in the Bohai Bay Basin further supports these findings.

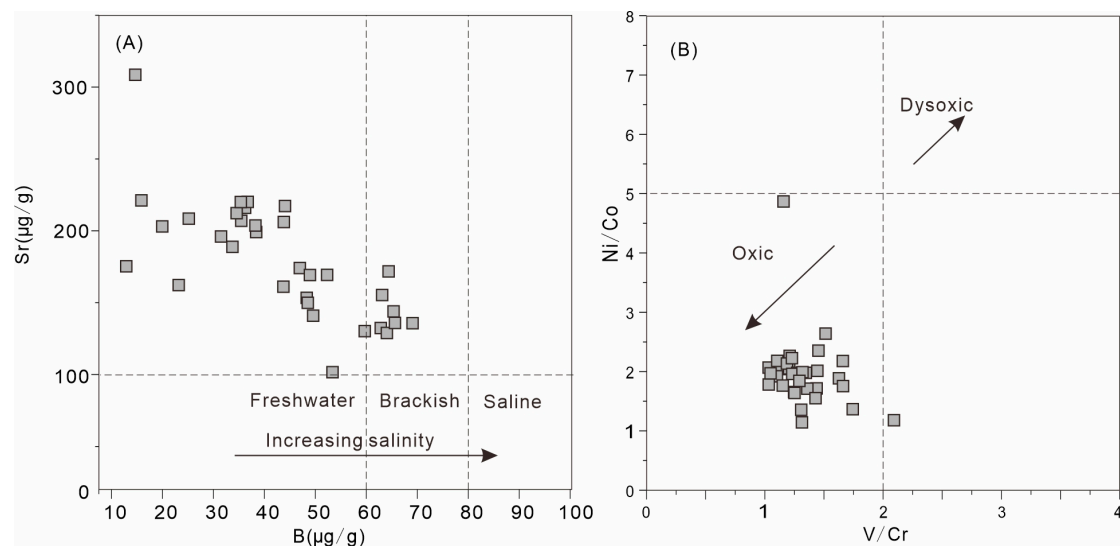


Figure 7. Sedimentary rock diagrams of the study area: (A) Salinity (Sr-B distribution). (B) Paleo-redox environment (Ni/Co vs. V/Cr distribution).

4.2.3. Redox Conditions

The redox conditions of basin sediments can be assessed using trace element ratios and Ce anomalies within REEs [23,39]. Elements such as U, V, Cr, and Co tend to be insoluble under reducing conditions, while Ni, Zn, and Cd commonly exist in the form of sulfide precipitates. Under oxidizing conditions, all of these elements become more soluble. Geochemical proxies, including the δU ($\delta U = 2 \times U/(U + Th/3)$), U/Th, V/Cr, and Ni/Co ratios, provide valuable insights into redox environments [23,54].

In the Minghuazhen Formation, the δU ranges from 0.6 to 1.3, with an average of 0.75, which is below 1, indicating an oxidizing environment. The U/Th ratio varies from 0.14 to 0.62, with an average of 0.21, which is significantly lower than the anoxic threshold of 0.75, further suggesting predominantly oxidizing conditions. The V/Cr ratio ranges from 0.85 to 2.37, with an average of 1.26 (Figure 7B), indicating an environment that varies from weakly reducing to oxidizing. Similarly, the Ni/Co ratio remains below 5 (Figure 7B), which further supports an oxygenated depositional setting.

The distribution of REEs in sedimentary rocks offers valuable insights into the redox conditions of ancient water bodies during sedimentation. Cerium, in particular, serves as an important redox-sensitive indicator. Under oxidizing conditions and specific pH values, Ce^{3+} is oxidized to Ce^{4+} , leading to a decrease in the concentration of Ce^{3+} . In contrast, under anoxic conditions, Ce^{3+} tends to accumulate. To quantify cerium anomalies, Elderfield and Greaves (1982) [55] proposed the index $Ce^* = \lg(3Ce_N/[2La_N + Nd_N])$, where $Ce^* > 0$ indicates cerium enrichment and reflects anoxic conditions, while $Ce^* < 0$ suggests cerium depletion in an oxidizing environment. In the Minghuazhen Formation sediments, Ce^* values range from -0.11 to 0.007 , with an average of -0.034 , reinforcing the interpretation of an oxygen-rich water column. These geochemical indicators, in conjunction with lithological characteristics, paleontological evidence, and additional paleo-oxygenation proxies, collectively suggest that the Minghuazhen Formation of the Cangdong Sag was deposited under oxygenated fluvial conditions.

4.3. Paleoclimatic Implications for Hydrocarbon Generation During the Sedimentation of the Minghuazhen Formation in the Cangdong Depression

Paleoclimatic conditions play a crucial role in the development of source rocks and reservoir layers. Warm and humid climates enhance chemical weathering, increase the input of terrestrial materials, and promote the accumulation of organic matter [56], which

is conducive to the formation of source rocks. In the Bohai Bay Basin, the reducing strata of the lower Minghuazhen Formation in the Nanbao Sag and Bozhong Sag provide favorable conditions for the development of high-quality source rocks [57]. Additionally, the sediments of the Minghuazhen Formation in the study area reflect a warm and humid environment that also promotes organic productivity.

However, the TOC content of the Minghuazhen Formation sediments in the Cangdong Depression ranges from 0.04% to 0.49%, indicating a relatively low organic matter content. Meanwhile, the TC content shows significant variation (0.04% to 8.10%), with the high values in some samples potentially attributed to localized carbonate deposition. The low organic carbon content is likely due to the depositional environment's limited ability to preserve organic matter.

The correlation between organic carbon and other elements can reflect the preservation mode of organic matter to some extent. A significant positive correlation was observed between TOC and S (Table 3), suggesting that the accumulation of organic matter is closely related to sulfur-rich reducing environments. However, strong oxidation conditions during the deposition of the Minghuazhen Formation in the Cangdong Sag hindered the preservation of organic matter, as evidenced by the low TOC content. Furthermore, high hydrodynamic conditions may accelerate organic matter degradation, while shallow water depositional environments limit effective burial. These characteristics are consistent with the extensive development of braided river and deltaic sediments in the Minghuazhen Formation [58]. Therefore, the Minghuazhen Formation in the study area serves only as a regional cap rock rather than a high-quality reservoir.

Table 3. Correlation matrix of TOC, TC, and major elements in the sedimentary rocks of the study area.

	TOC	TC	S	N	P	SiO ₂	Al ₂ O ₃	TFe ₂ O ₃	MgO	CaO	Na ₂ O
TC	−0.128										
S	0.855 **	0.103									
N	0.527 **	−0.281	0.372 *								
P	−0.028	0.149	−0.117	0.191							
SiO ₂	0.196	−0.809 **	−0.001	−0.022	−0.236						
Al ₂ O ₃	0.128	−0.553 **	0.0001	0.711 **	0.085	0.111					
TFe ₂ O ₃	−0.083	−0.128	−0.099	0.281	0.016	−0.399 *	0.327 *				
MgO	−0.164	0.057	−0.069	0.347 *	0.621 **	−0.401 **	0.556 **	0.288			
CaO	−0.173	0.998 **	0.057	−0.308 *	0.125	−0.808 *	−0.565 **	−0.127	0.030		
Na ₂ O	0.039	−0.383 *	0.027	−0.450 **	−0.091	0.716 *	−0.477 **	−0.393 *	−0.508 **	−0.378 *	
K ₂ O	0.201	−0.620 **	0.081	0.129	0.095	0.698 *	0.081	−0.165	−0.100	−0.630 **	0.625 *

(* $p < 0.05$; ** $p < 0.01$).

Despite its relatively low organic carbon content, the Minghuazhen Formation may still possess some hydrocarbon generation potential. Studies have shown that sediments with a low TOC content can generate natural gas under favorable thermal maturation conditions, particularly when the C/N ratio is low (indicating that the organic matter is derived from aquatic environments) [20]. The correlation between TOC and N (Table 3) indicates the contribution of aquatic biogenic sources to the organic matter. The C/N ratio of the Minghuazhen Formation sediments ranges from 2.78 to 18.2, with an average of 7.32. Some samples fall within the typical range for aquatic organic matter (below 10), suggesting that hydrocarbon generation may still occur under specific thermal conditions [59].

Although the warm and humid paleoclimatic conditions of the Cangdong Depression during the deposition of the Minghuazhen Formation facilitated terrestrial input, the strong oxidation and shallow water depositional environment suppressed the preservation of organic matter, resulting in a relatively low organic carbon content in the source rocks. Given the low TOC content and oxidizing conditions in the Minghuazhen Formation,

hydrocarbon resources in the Cangdong Sag likely derive from other formations with a higher preservation potential.

5. Conclusions

The geochemical and petrographic characteristics of the Minghuazhen Formation in the Cangdong Sag offer critical insights into its sedimentary environment, paleoclimatic conditions, and source rock potential. The dominance of terrigenous material, alongside its major and trace element composition, suggests limited sediment recycling and a primary depositional setting. Geochemical signatures point to a felsic provenance, primarily derived from acidic magmatic rocks of the Northern Taihangshan–Yanshan Fold Belt.

Paleoclimatic reconstructions indicate warm and humid conditions during deposition, as reflected by a high CIA, which signals intense chemical weathering. However, prevailing oxidizing conditions and a shallow depositional environment limited the preservation of organic matter, resulting in a low TOC content. Despite this, certain samples show C/N ratios indicative of aquatic organic matter contributions, suggesting potential for hydrocarbon generation under favorable thermal conditions.

The highly oxidative depositional environment likely restricted the accumulation and burial of organic material, thereby limiting the formation of high-quality source rocks. Consequently, while the Minghuazhen Formation has some hydrocarbon potential, its overall capacity as a source rock is limited.

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