Sustainability in Environment
ISSN 2470-637X (Print) ISSN 2470-6388 (Online)
Vol. 11, No. 2, 2026
www.scholink.org/ojs/index.php/se

Original Paper

Trace Element Geochemistry and Sedimentary Environment Implications of the Lower Cambrian Qiongzhusi Formation in Qujing, Yunnan Province

Jing Jin[1,2] & Enlin Yang[1,2*]

[1] School of Geography and Environmental Sciences, Guizhou Normal University, Guiyang, Guizhou, China

[2] The State Key Laboratory Incubation Base for Karst Mountain Ecology Environment of Guizhou Province, Guiyang, Guizhou, China

[*] Corresponding Author

Received: February 01, 2026 Accepted: March 02, 2026 Online Published: March 11, 2026

doi:10.22158/se.v12n1p1 URL: http://dx.doi.org/10.22158/se.v12n1p1

Abstract

This study focuses on the black rock sequence of the Lower Cambrian Qiongzhusi Formation in the Qujing area of Yunnan Province. Using elemental geochemical methods, we investigate the characteristics of water salinity, climate, and redox conditions during the deposition of the Qiongzhusi Formation to reconstruct the paleoenvironmental conditions of the Lower Cambrian Qiongzhusi Formation in the Qujing area. The results indicate that Li concentrations ranged from 1.5 to 56.3 μg/g, and Sr/Ba ratios ranged from 0.09 to 0.56, indicating that the Qiongzhusi Formation in the study area was deposited in a predominantly freshwater environment; V/(V+Ni) values ranged from 0.66 to 0.91 (mean 0.79), U/Th values ranged from 0.75 to 15.45 (mean 4.33), and δU values ranged from 1.38 to 1.96 (mean 1.73), collectively indicating that the Qiongzhusi Formation deposition period was generally characterized by an anoxic-reducing environment; The paleoclimate index C ranges from 1.09 to 4.48, and the Sr/Cu ratio ranges from 1.16 to 9.30, indicating that the Qiongzhusi Formation was deposited under a warm and humid climate; the Babio value ranges from 200 to 1309.98, and the P/Ti ratio ranges from 1.59 to 62.5, indicating that the Qiongzhusi Formation deposits exhibited a high level of productivity overall; The concentrations of Ba, Ni, Co, and other elements, as well as the Mn/Fe ratio (average of 0.005) and Rb/Zr ratio (average of 2.27), indicate that the water depth during the Qiongzhusi Formation deposition period was generally shallow; the Sr concentration indicates that the average paleowater temperature of the Qiongzhusi Formation was 30.38°C, suggesting a relatively *high water temperature in the depositional environment.*

Keywords

geochemistry, trace elements, sedimentary environment, Qiongzhusi Formation, black shale series

1. Introduction

The black shale series is a multi-rock assemblage composed of dark gray to black siliceous rocks, carbonate rocks, mudstones (or tuffs), and their metamorphic counterparts. Characterized by relatively simple material composition and stable geochemical properties, it represents a significant product of the Earth's surface system evolution throughout geological history (Murray, 1994; Chen, Xia, Wan et al., 2007; Li, Qin, Liu et al., 2022). The trace element characteristics within black shale series effectively reveal paleo-oxidation/reduction conditions, paleo-productivity levels, and paleoclimate conditions during sedimentation, making them widely applied in paleo-sedimentary environment research (Liu, Gao, Zhu et al., 2024; Chen, Xu, Wang et al., 2023; Jiang, Yu, & Wang, 2025). The Early Cambrian represents a pivotal stage in geological history, marked by the convergence and breakup of the Gondwana supercontinent, global sea-level fluctuations, seafloor hydrothermal activity, the deposition of major metal deposits (Ni-Mo deposits, barite, vanadium deposits) and non-metallic deposits (phosphate deposits), as well as the emergence and flourishing of postbiotic organisms. These events profoundly influenced global paleogeography and ecosystem evolution. Against this backdrop, the Early Cambrian black shale series is extensively distributed across southern China, including Guizhou, Hunan, and Yunnan provinces. Their geochemical characteristics provide a comprehensive record of paleo-sedimentary environments and paleogeographic reconstructions from this period (Li, Qin, Liu et al., 2022). Consequently, investigating the geochemical features of these Early Cambrian black shale series holds significant importance.

In recent years, extensive research has been conducted on the Early Cambrian black shale series in Guizhou, Hunan, and other regions, covering aspects such as element enrichment mechanisms, material sources, and depositional environments (Fu, Zhou, Wang et al., 2021; Cheng & Wen, 2025; Tan, Du, Chen et al., 2025; Zhang, Wang, Cheng et al., 2025; Deng, Xu, Yang et al., 2025). Research on Early Cambrian black shale series in the Qujing area of Yunnan Province remains relatively limited, primarily confined to mineral prospecting and exploration, as well as stratigraphic classification studies. Detailed investigations into the sedimentary environment of this formation are still lacking, hindering the understanding of the mineralization mechanisms in this region (Chen, 2015). Therefore, this study systematically collected samples from the Early Cambrian Qiongzhusi Formation black shale series in the Qujing area of Yunnan Province. Elemental geochemical characterization of these samples was performed, and trace element signatures were analyzed to investigate the paleo-sedimentary environment of this black shale sequence.

2. Geological Background

During the Early Cambrian, the Yangtze Block evolved from a rift basin to a passive continental margin (Figure 1a). During this period, the paleogeographic pattern of the Yangtze Block was divided into three distinct zones from northwest to southeast: the shallow-water platform zone, the slope zone, and the deep-water basin zone (Figure 1b) (Zhou, Luo, Huff et al., 2008). Sedimentary sequences reveal that the inner shallow-water platform zone was dominated by carbonate and phosphorite deposits, while the deep-water slope and basin zones were characterized by carbonaceous shales and siliceous rocks (Zhou, Luo, Liu et al., 2013; Wang, 2020). The Early Cambrian stratigraphic sequence of the Yangtze Block's shallow-water platform comprises the Zhujiajing Formation and the Qiongzhusi Formation in chronological order. The Zhujiajing Formation consists primarily of siliceous rocks, phosphorite, and dolomite. The Qiongzhusi Formation is mainly composed of black shale and siltstone. The Early Cambrian strata developed in the slope and basin environments are, from oldest to youngest, the Liuchapo Formation and the Niutitang Formation. The Liuchapo Formation is predominantly siliceous rock throughout, while the Niutitang Formation is mainly black shale.

The Malong Section is located at Shilong Village, Nazhang Township, Malong County, Qujing City, Yunnan Province (103°36'42.20"E, 25°18'1.82"N). During the Early Cambrian, this section was situated in a shallow-water environment at the southwestern margin of the Yangtze Block. The exposed strata at the Malong Section belong to the Early Cambrian Qiongzhusi Formation (Figure 1c). Based on lithological assemblages, the Qiongzhusi Formation can be divided into the Shiyantou Member and the Yuanshan Member from bottom to top. The exposed strata in the study area consist of black shale and gray-black siltstone from the Shiyantou Member.

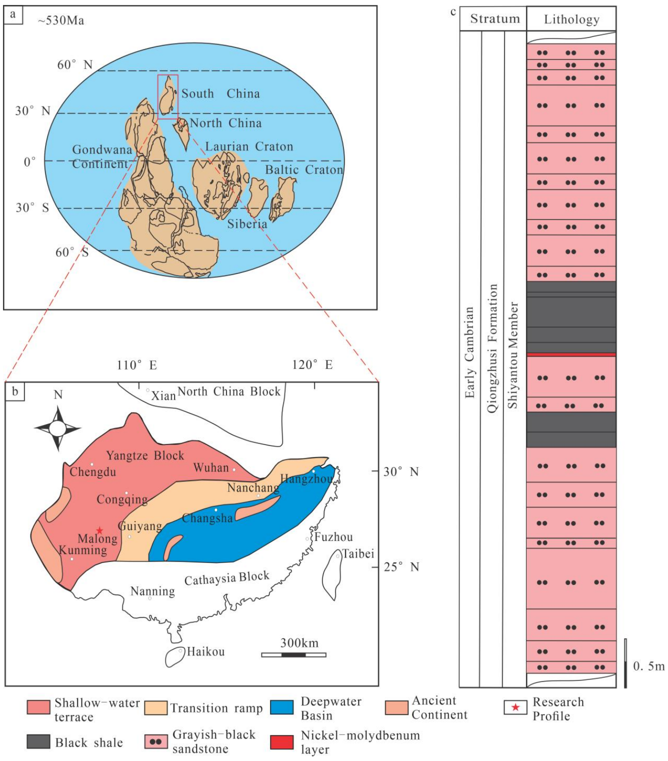

Figure 1. Global Paleogeography map of the Early Cambrian (a), Paleogeography Map of the Early Cambrian Yangtze Block (b), and Stratigraphic Map of the Qiongzhusi Formation at the Malong Section (c)

3. Sample Collection and Analysis Methods

A total of 11 samples were collected from the black shale series of the Qiongzhusi Formation at the Malong section, comprising gray-black siltstone and black shale. Samples were numbered sequentially from oldest to youngest as ML-1 to ML-11. During collection, fresh samples showing no alteration and minimal weathering were selected. Geochemical sample pretreatment involved rinsing with deionized water to remove surface impurities, followed by grinding to 200 mesh using an agate mortar and pestle to ensure uniformity. The ground powder was then dried, bagged, labeled, and sent to Guangzhou Ausil Mineral Laboratory for trace element testing.

Trace element analysis of black shale series was conducted using an Agilent 7700e Inductively Coupled Plasma Mass Spectrometer (ICP-MS). First, 50 mg of sample was weighed into a polytetrafluoroethylene (Teflon) digestion vessel. A 1:1 volume ratio mixture of HNO_3-HF was added, followed by placing the Teflon digestion pellet into a steel sleeve. The assembly was heated in an oven at 190°C for over 24 hours. After cooling, the sample was evaporated to dryness on a 140°C hot plate. Slowly add 1 mL of HNO_3 and evaporate to dryness again. Add a 1:1:1 volume ratio of HNO_3, ultrapure water, and internal standard In. Place the Teflon sample pellet back into the steel sleeve and heat at 190°C for over 12 hours. After cooling, transfer the solution to a polyethylene bottle and dilute to 100 mL with 2% HNO_3. Dissolve the diluted sample and analyze by ICP-MS. The analytical error for each element is less than 5%.

4. Test Results

The trace element test analysis results for the Qiongzhusi Formation samples are shown in Table 1. Significant variations were observed in the concentrations of different trace elements. Among them, Ba exhibited the highest content, ranging from 200 to 1310 μg/g with an average of 578.18 μg/g. V followed with a range of 33 to 212 μg/g and an average of 115.73 μg/g. Sr, Mn, Zr, and Pb followed, with ranges of 25.90~240 μg/g, 28~224 μg/g, 1.2~126.5 μg/g, and 27.2~78 μg/g, respectively, averaging 100.66 μg/g, 67.73 μg/g, 46.82 μg/g, and 44.94 μg/g, respectively. Comparison with upper continental crust (UCC) mean values (Taylor & Mclennan, 1985) indicates that the Qiongzhusi Formation exhibits enrichment in Mn, Co, Mo, Pb, and U, relative depletion in Sr, Zr, and Th, and V, Ni, Cu, and Ba contents comparable to the continental upper crust (Figure 2).

Table 1. Trace Element Content (μg/g)and Related Indicators of the Black Shale Serices in the Qiongzhusi Formation, Malong Section, Qujing City, Yunnan Province

Sample Number	ML-1	ML-2	ML-3	ML-4	ML-5	ML-6	ML-7	ML-8	ML-9	ML-10	ML-11	UCC
Lithology	Sandstone	Sandstone	Black shale	Black shale	Black shale	Sandstone	Sandstone	Sandstone	Sandstone	Sandstone	Sandstone	
V	100.00	87.00	119.00	86.00	212.00	157.00	153.00	191.00	62.00	73.00	33.00	60.00
Mn	94.00	67.00	32.00	47.00	34.00	30.00	31.00	28.00	224.00	78.00	80.00	600.00
Co	5.50	7.00	3.00	5.40	2.20	4.30	5.50	4.70	11.40	2.90	1.30	10.00
Ni	50.70	20.50	47.80	43.50	20.00	53.70	47.90	53.30	7.20	12.40	6.10	40.00
Cu	22.40	36.90	45.30	39.60	13.40	31.60	30.00	26.00	25.80	39.80	23.00	25.00
Rb	29.2	78.70	19.60	47.30	92.20	52.30	41.6	45	5.9	4.1	35.20	112.00
Sr	25.90	49.20	62.30	68.80	79.90	48.90	128.00	204.00	240.00	62.30	138.00	350.00
Zr	37.80	95.60	4.40	64.60	126.50	66.20	57.60	54.80	1.20	1.90	4.40	190.00
Mo	2.21	2.29	3.03	3.40	9.76	5.59	3.64	4.33	2.46	2.79	0.58	1.50
Ba	280.00	340.00	260.00	550.00	480.00	520.00	1190.00	1310.00	680.00	200.00	550.00	550.00
Pb	27.20	29.00	35.10	42.40	67.60	48.80	44.70	45.10	78.00	33.60	42.80	0.50
Th	3.47	10.30	2.44	6.24	12.30	6.17	5.30	5.37	1.12	0.66	3.65	10.70
U	12.20	7.70	5.80	10.60	21.20	12.30	14.40	18.00	17.40	10.20	3.40	2.80
Li	6.70	18.00	4.30	15.10	73.00	14.40	10.00	10.80	2.20	1.50	10.30	20.00
Sr/Ba	0.09	0.14	0.24	0.13	0.17	0.09	0.11	0.16	0.35	0.31	0.25	
V/(V+Ni)	0.66	0.81	0.71	0.66	0.91	0.75	0.76	0.78	0.90	0.85	0.84	

U/Th	3.52	0.75	2.38	1.70	1.72	1.99	2.72	3.35	15.54	15.45	0.93
δU	1.83	1.38	1.75	1.67	1.68	1.71	1.78	1.82	1.96	1.96	1.47
Ba_{bio}	279.99	339.97	259.99	549.98	479.97	519.98	1189.98	1309.98	680.00	200.00	549.99
P/Ti	4.34	4.81	11.75	5.37	3.75	1.59	3.08	3.61	40.00	62.50	14.93
C	1.09	1.83	1.18	2.71	1.52	1.83	4.48	4.45	2.60	1.13	4.76
Sr/Cu	1.16	1.33	1.38	1.74	5.96	1.55	4.27	7.85	9.30	1.57	6.00
Mn/Fe	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.01	0.01
Rb/Zr	0.77	0.82	4.45	0.73	0.73	0.79	0.72	0.82	4.92	2.16	8.00

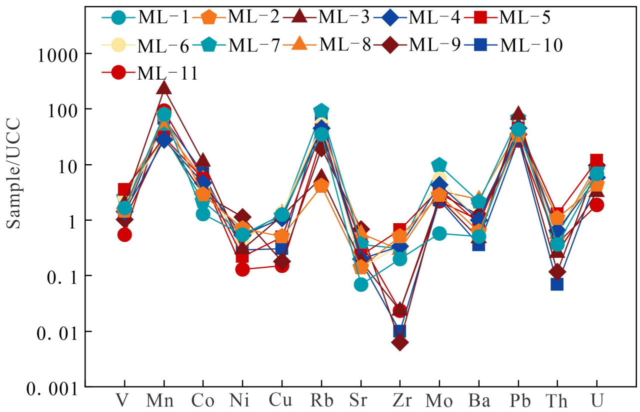

Figure 2. UCC-Standardized Spider Web Diagram of Trace Elements in the Qiongzhusi Formation, Malong Section, Qujing, Yunnan

5. Discussion

5.1 Paleosalinity

Paleosalinity analysis is a critical component in reconstructing ancient depositional environments. Currently, effective methods for determining the paleosalinity of depositional water bodies include biostratigraphic methods, major isotope techniques, and trace element discrimination methods (Zheng Rongcai, Liu, 1999; Tian & Zhang, 2016; Li & Chen, 2003). This study employs trace element content and trace element ratio methods to analyze the paleosalinity of the water body during the deposition of the black shale series of the Qiongzhusi Formation in the Malong area.

The trace element Li content exhibits a strong positive correlation with paleosalinity. Typically, Li concentrations below 90 μg/g indicate a terrestrial freshwater environment, while values exceeding 150 μg/g suggest a marine brackish environment (Xu, Diao, Wang et al., 2022). The Sr/Ba ratio method, due to its high technical maturity and widespread application, remains a primary technique for reconstructing paleosalinity.

Sr and Ba exhibit highly similar geochemical properties, but Sr demonstrates greater mobility than Ba. As water salinity increases, both Sr and Ba gradually precipitate from the water as sulfates. Ba preferentially precipitates as $BaSO_4$, while Sr only precipitates as $SrSO_4$ once salinity reaches a certain threshold (Li, Zhang, Shi et al., 2016; Xu, Xiao, Liu et al., 2022). Therefore, in terrestrial freshwater environments, Sr and Ba generally do not precipitate, resulting in a low Sr/Ba ratio in sediments. When terrestrial freshwater enters the ocean (or lake), a portion of Ba precipitates preferentially, while Sr does not precipitate at this stage, maintaining a low Sr/Ba ratio. As the water migrates to deep-sea (lake) environments, Ba content gradually decreases, and Sr begins to precipitate, causing the Sr/Ba ratio in sediments to increase sharply. Based on statistical analysis of extensive paleosalinity data, it is generally accepted that the Sr/Ba ratio is <0.6 in terrestrial freshwater environments, ranges from 0.6 to 1 in transitional brackish environments between land and sea, and exceeds 1 in marine saline environments. Li content in Qiongzhusi Formation samples ranged from 1.5 to 56.3 μg/g, averaging 18.6 μg/g, indicating a freshwater environment. The Sr/Ba ratio in Qiongzhusi Formation samples ranged from 0.09 to 0.56, averaging 0.22, also indicating a freshwater environment. Based on the combined analysis of these two paleosalinity indicators, the black lithology of the Qiongzhusi Formation is interpreted to have formed primarily in a freshwater environment (Figure 3).

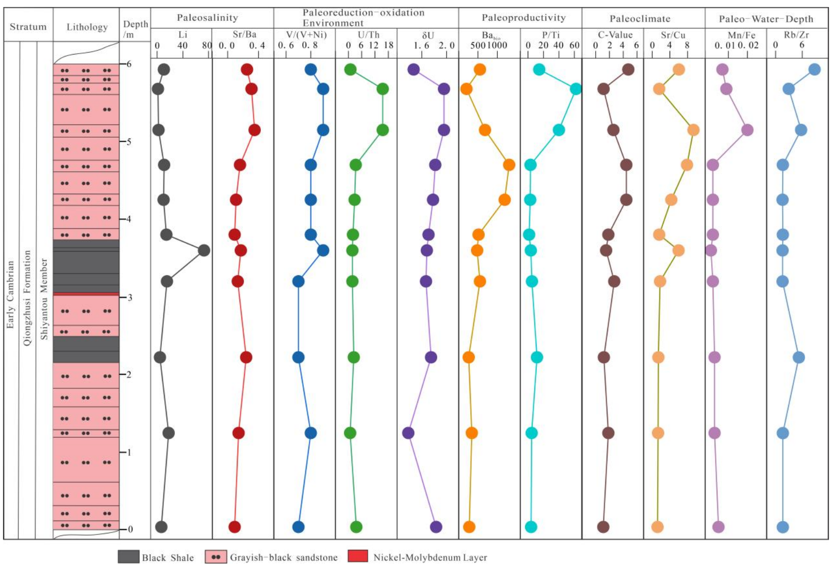

Figure 3. Vertical Variation Characteristics of Geochemical Indicators in the Black shale series of the Qiongzhusi Formation, Malong Section, Qujing, Yunnan

5.2 Paleoreduction-oxidation Environment

Redox-sensitive elements (such as V, Ni, Mo, etc.) exhibit unique geochemical behaviors that make them highly responsive to changes in redox conditions, rendering them ideal geochemical indicators for reconstructing the paleoreduction-oxidation environment of sedimentary water bodies (Chang, Chu, Feng et al., 2009). This study employs V/(V+Ni), U/Th, and δU as indicators for discerning paleo-reduction environments.

Both V and Ni tend to accumulate in reducing water environments, but V exhibits a significantly higher enrichment factor than Ni in strongly reducing conditions. Consequently, the V/(V+Ni) ratio increases with greater water reducing potential. Previous studies suggest that V/(V+Ni) > 0.6 indicates a reducing aquatic environment, 0.46~0.6 represents a redox transition zone, and <0.46 signifies an oxidizing aquatic environment (Hatch & Leventhal, 1992). The V/(V+Ni) values in the study area ranged from 0.66 to 0.91, with an average of 0.79, indicating that the Qiongzhusi Formation as a whole represents a reducing aquatic environment (Figure 3). U tends to accumulate in strongly reducing aquatic environments, precipitating out of seawater. In oxidizing environments, U remains soluble as ions. Thorium is a chemically inert element that typically remains insoluble regardless of redox conditions. Thus, U/Th ratios and δU values can be used to discern the redox state of sedimentary environments. Generally, U/Th values greater than 1.25 indicate a reducing aquatic environment, values between 0.75 and 1.25 indicate a redox transition environment, and values less than 0.75 indicate an oxidizing aquatic environment (Wignall & Twitchett, 1996). The U/Th values in the study area range from 0.75 to 15.45, with an average of 4.33. This indicates that the Qiongzhusi Formation as a whole exhibits a reducing aqueous environment, with locally transitional oxidizing-reducing conditions (Figure 3). The δU calculation formula is: δU = 2U/(U+Th/3). Typically, δU < 1 represents normal seawater conditions, while δU > 1 indicates a reducing water environment [33]. The δU values of samples from the study area ranged from 1.38 to 1.96, all exceeding 1, reflecting that the overall Qiongzhusi Formation was formed in a reducing water environment (Figure 3). The scatter plots of specific trace element ratios from the analyzed samples show consistent patterns across both plots, collectively indicating that the Qiongzhusi Formation formed in an anoxic, reducing aquatic environment (Figure 4).

Additionally, rock color serves as a crucial indicator for sedimentary environment assessment. Typically, red or brown rock colors indicate an oxidizing environment, while dark gray or black colors indicate a reducing environment (Lin, Chu, Shao et al., 2023). The black shale series in the study area predominantly exhibit grayish-black or black hues, indicating deposition in an anoxic environment, consistent with the results indicated by the preceding geochemical indicators. Comprehensive analysis reveals that the black shale series of the Qiongzhusi Formation in the Malong section were formed in an overall anoxic, reducing environment, with locally hypoxic conditions.

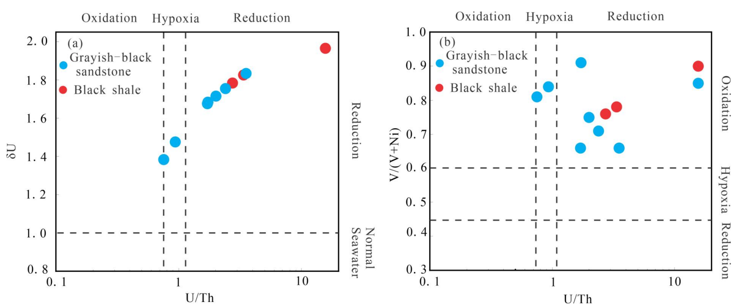

Figure 4. Geochemical Diagram of Ancient Redox Indicators in the Qiongzhusi Formation, Malong Section, Qujing City, Yunnan Province

5.3 Paleoproductivity

Paleoproductivity is crucial aspect in studying sedimentary paleoenvironments. Multiple geochemical indicators have been employed to reconstruct paleoproductivity. Since reconstructing paleoproductivity using a single indicator yields low accuracy and reliability, multiple indicators are typically used in combination to indicate paleoproductivity (Tribovillard, Algeo, Lyons, & Riboulleau, 2006).

The element Ba serves as a reliable indicator of paleo-oceanic productivity. Ba in sediments primarily originates from biogenic sources, terrestrial inputs, carbonate-bound Ba, and Ba adsorbed onto Fe-Mn oxides. Among these, biogenic Ba constitutes the major component of marine Ba and exhibits a strong correlation with productivity. Biogenic Ba combines with seawater SO_4^{2-} to form barite ($BaSO_4$) after organismal death, making it an effective proxy for paleoproductivity. The calculation formula is: $Ba_{bio} = Ba_{sample} - Al_{sample} \times (Ba/Al)_{PASS}$, where Ba_{sample} and Al_{sample} denote total Ba and total Al content in the measured sample, respectively, and $(Ba/Al)_{PASS}$ represents the average Ba/Al mass fraction ratio in Australian shales during the Late Archean, valued at 0.0077 (Xu, Xiao, Liu et al., 2022). Studies indicate that sedimentary paleoenvironments exhibit high productivity when Ba_{bio} values range between 1000~5000 μg/g; while Ba_{bio} values between 200~1000 μg/g indicate moderate productivity (Pi, Liu, Graham et al., 2013). Samples from the study area exhibited Ba_{bio} values ranging from 200 to 1309.98 μg/g, with an average of 585.82 μg/g, indicating overall high productivity during the Qiongzhusi Formation deposition (Figure 3).

P serves not only as an essential nutrient for life but also as a constituent of skeletal structures in numerous marine organisms. Upon organismal death, P is transferred into sediments alongside the remains, where it undergoes mineralization to form autochthonous phosphorus for preservation. Consequently, P can be utilized to assess paleo-oceanic productivity (Rimmer & Thompson, 2004).P mainly comes from two sources: biological phosphorus and detrital phosphorus from land-based sources. Biological phosphorus serves as an effective indicator of ancient productivity. When used as a productivity indicator, P is influenced by the redox conditions in seawater and the ability of iron compounds to adsorb P. The ratio of P to Ti provides a more accurate reflection of marine primary productivity (Yan, Wang, J. G., & Wang, Z. Z., 2009). Generally, $P/Ti > 0.79$ indicates high productivity, P/Ti between 0.34 and 0.79 represents moderate productivity, and $P/Ti < 0.34$ signifies low productivity. The P/Ti values for samples from the study area ranged from 1.59 to 62.5, with an average of 13.93, reflecting the overall high productivity level of the Qiongzhusi Formation (Figure 3).

In summary, analysis of Babio and P/Ti indices indicates that the Qiongzhusi Formation black shale series in the study area exhibited high productivity during its deposition period.

5.4 Paleoclimate

Different elements exhibit distinct migration and enrichment patterns in varying sedimentary environments. Therefore, the sensitivity of different elements to climate can be leveraged to reconstruct paleoclimate information. Under arid and hot climatic conditions, water evaporation increases the alkalinity of the aqueous medium, causing arid-preferring alkaline elements such as Cg, Mg, K, and Na to precipitate from the water and form various salts enriched in sediments. Conversely, under warm and humid climatic conditions, moisture-preferring elements such as Fe, Mn, Cr, and V accumulate in sedimentary rocks [40]. Thus, the paleoclimate index C = (Fe + Mn + Cr + Ni + V + Co) / (Ca + Mg + Sr + Ba + K + Na) serves as a crucial indicator for reconstructing past climate conditions. The C value is sensitive to climate change. Generally, C < 0.2 indicates arid climates, C 0.2~0.6 indicates semi-humid to semi-arid climates, and C > 0.6 indicates warm humid climates (Yu, Tian, Wang et al., 2022; Ma, Zhang, Zhou et al., 2023). Based on paleoclimate calculation formulas, the C values for the black shale series in the study area range from 1.09 to 4.48, with an average of 2.64—significantly exceeding 0.6. This reflects a warm-humid climate during the deposition of the Qiongzhusi Formation.

The ratio of moisture-favoring Sr to aridity-favoring Cu also serves as a crucial paleoclimate indicator (Lerman, 1979). Studies indicate that Sr/Cu values between 1 and 10 denote warm-humid climates, while Sr/Cu > 10 signifies arid conditions (Zhou, Chen, Zhang et al., 2021; Zhao, Shao, Hong et al., 2024). The Sr/Cu values of samples from the study area ranged from 1.16 to 9.30, with an average of 4.08, indicating a warm and humid climate during the deposition of the Qiongzhusi Formation. Combined with the C value and Sr/Cu intersection diagram (Figure 5), it is comprehensively concluded that the Qiongzhusi Formation was deposited under a warm and humid climate.

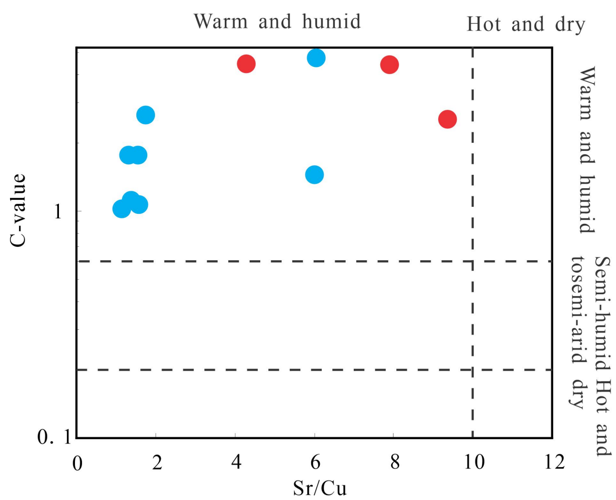

Figure 5. Sr/Cu-C Value Correlation Map of the Qiongzhusi Formation at the Malong Section, Qujing City, Yunnan Province

5.5 Paleo-Water Depth and Paleo-Water Temperature

The sedimentary fractionation of elements during deposition establishes a relationship between element accumulation/dispersion and water depth (Chen, Zhou, & Wang, 2004). In recent years, trace element concentrations and ratios have been widely applied to determine paleo-water depth (Zhang, Kang, Ding et al., 2023).

Previous studies suggest that when sediment trace element concentrations exceed the following thresholds:Ba > 1000 μg/g, Ni > 150 μg/g, Cu > 90 μg/g, Pb > 40 μg/g, Co > 40 μg/g, Mo > 50 μg/g, and especially U < 1 μg/g, the water depth during deposition may have exceeded 250 m [49]. The average Ba concentration in the Qiongzhusi Formation was 585.83 μg/g, Ni was 31.3 μg/g, Cu was 32.4 μg/g, Pb was 48.9 μg/g, Co was 4.8 μg/g, Mo was 3.64 μg/g, and U was 12.5 μg/g. All elements were below standard values, indicating that the depositional water body was shallow at the time.

Fe and Mn are sensitive to environmental changes. Fe readily oxidizes to form insoluble Fe^{3+}, whose compounds typically accumulate in shallow estuarine or coastal waters, while Mn exists more stably as Mn^{2+} in water bodies and generally accumulates in areas farther from the coast. Consequently, Mn/Fe ratios are lower in shallow-water environments and relatively higher in deep-water settings (Zhang, Wang, Liao et al., 2024). The Mn/Fe ratios in the Qiongzhusi Formation of the study area ranged from 0.001 to 0.007, with an average of 0.005, which is significantly low. This indicates that water depths were relatively shallow during the deposition of the Qiongzhusi Formation, consistent with the results indicated by trace element concentrations. Zirconium (Zr) primarily accumulates in shallow waters as stable minerals like zircon, which possess high density and resist long-distance migration with fine-grained materials such as clay. In contrast, rubidium (Rb) exhibits strong chemical weathering activity, often adsorbing onto clay minerals or migrating with mica minerals, leading to significant enrichment in deep-water zones. Therefore, the Rb/Zr ratio can distinguish water depth, with higher values indicating deeper water and lower values indicating shallower water (Liang & Cao, 2025). The Rb/Zr values in the study area ranged from 0.72 to 8.00, with an average of 2.27. This indicates significant fluctuations in water depth during the Qiongzhusi Formation deposition period, generally reflecting shallow water conditions, with a relative increase in depth from the base to the top of the formation (Figure 3).

Previous researchers developed an empirical formula to calculate paleotemperatures based on the relationship between trace element Sr and temperature through practical and experimental work.The calculation method is:

$$Y=(2578-Sr)/80.8$$

where Y represents the Sr content in the sample (μg/g) and T represents the paleotemperature of the depositional water body (°C) (Xu, Zeng, Diao et al., 2021). Substituting the Sr content from 11 samples in the study area into this formula yields an average paleowater temperature of 30.38°C for the Qiongzhusi Formation, with a maximum temperature of 31.59°C. Based on these indicators for paleowater depth and temperature, it is concluded that the Qiongzhusi Formation was deposited in a generally shallow water environment with relatively high water temperatures.

6. Conclusions

Through the study of trace element geochemical characteristics and sedimentary environments in black shale series samples from the Qiongzhusi Formation of the Early Cambrian in Qujing, Yunnan province, the main conclusions are as follows:

(1) Most test results from the Qiongzhisi Formation samples collected in the study area are consistent

with upper crustal element abundances. Mn, Co, Mo, Pb, and U show enrichment, while Sr, Zr, and Th exhibit relative depletion. The remaining elements are close to upper crustal abundances.

(2) The Li and Sr/Ba element combinations indicate that the paleosalinity during the deposition of the Qiongzhusi Formation was freshwater. The combined Ba_{bio} and P/Ti ratios indicate high productivity levels during the Qiongzhusi Formation deposition.

(3) Analysis of paleoclimate index C values, Sr/Cu ratios, V/(V+Ni), U/Th ratios, and δU values reveals that the Qiongzhusi Formation deposition occurred in an overall anoxic-reductive environment with a warm and humid climate.

(4) Analysis of trace elements Ba, Ni, Cu, Mn/Fe, Rb/Zr, and paleowater depth and temperature formulas indicates that the Qiongzhusi Formation was deposited in a generally shallow environment with an average water temperature of 30.38°C, reflecting a warm paleowater temperature during the deposition period.

Acknowledgments

This paper was supported by This research was supported by the National Natural Science Foundation of China (Grant No. 42362007).

References

Algeo, T. J., Kuwahara, K., Sano, H. et al. (2011). Spatial variation in sediment fluxes, redox conditions, and productivity in the Permian-Triassicpanthalassic ocean. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *308*(1-2), 65-83.

Chang, H. J., Chu, X. L., Feng, L. J. et al. (2009). Indicative Significance of Redox-Sensitive Trace Elements for Paleoceanic Sedimentary Environments. *Geological Review*, *55*(01), 91-99.

Chen, Y. X. (2015). *Geochemical Characteristics and Genesis of the Early Cambrian Black Rock Series in Qujing, Yunnan Province*. Kunming University of Science and Technology.

Chen, D. Z., Wang, J. G., Qing, H. R. et al. (2008). Hydrothermal venting activities in the Early Cambrian, South China:Petrological, geochronological and stable isotopic constraints. *Chemical Geology*, *258*(3-4), 168-181.

Chen, J. F., Xu, J., Wang, J. et al. (2023). Evolution of the sedimentary environment of the black shale series in the Yertus Formation at the northwestern margin of the Tarim Basin and its control on organic matter enrichment. *Frontiers of Earth Science*, *30*(06), 150-161.

Chen, J. Q., Zhou, H. R., & Wang, X. L. (2004). *Sedimentology and Paleogeography: A Tutorial* (pp. 32-33). Beijing: Geological Publishing House.

Chen, L., Xia, M. Q., Wan, Y. et al. (2007). Research Progress on Black Shales and Oceanic Anoxic Events. *Journal of Chongqing University of Science and Technology (Natural Science Edition)*, *9*(4), 1-4.

Cheng, Y., & Wen, Y. M. (2025). Analysis of the Mineralization Potential and Enrichment Mechanisms of Metal Elements in the Black Shale Series of the Zhalagou Group, Early Cambrian, Eastern Guizhou. *Mineral Exploration*, *16*(01), 44-54.

Deng Youguo, Xu Yanan, Yang Lifei, et al. Geochemical Characteristics and Sedimentary Environment of the Early Cambrian Hetang Formation Black Shale Series in the Jiujiang Basin, Lower Yangtze Block [J]. Acta Geologica Sinica, 2025, 1-20.

Fu, Y., Zhou, W. X., Wang, H. J. et al. (2021). Sedimentary Environment and Geochemical Response of the Early Cambrian Black Shale Series in Northern Guizhou. *Acta Geologica Sinica*, *95*(02), 536-548.

Hatch, J. R., & Leventhal, J. S. (1992). Relationship between Inferred Redox Potential of the Depositional Environment and Geochemistry of the Upper Pennaylvanian (Missourian) Stark Shale Member of the Dennis Limestone, Wabaunsee County, Kansas, U.S.A. *Chemical Geology*, *99*(1-3), 65-82.

Jiang, L. Y., Yu, Y., & Wang, L. (2025). Geochemical Characteristics and Genesis Analysis of the Black Shale Series in the Yanxi Formation of the Middle Ordovician System, Central-Southern Hunan Province. *Acta Geologica Sinica*, *46*(06), 1135-1148.

Lerman, A. (1979). Lakes:Chemistry, Geology, Physics. *Science*, *204*, 825-826.

Li, Z. X., Bogdanova, S. V., Collins, A. S. et al. (2007). Assembly, configuration, and break-up history of Rodinia: Asynthesis. *Precambrian Research*, *160*(1), 179-210.

Li, J. L., & Chen, D. J. (2003). Review of Quantitative Methods for Ancient Salinity Studies. *Oil and Gas Geology and Recovery Rate*, *10*(5), 1-3.

Li, L., Wang, Z. W., Wang, J. et al. (2025). Geochemical Characteristics and Sedimentary Paleoenvironment Analysis of the Xiaoli Formation Mudstone in the Southwest Margin of the Northern Qiangtang Depression, Middle Jurassic System. *Geochemistry*, *54*(04), 626-643.

Li, X., Zhang, L. Q., Shi, H. et al. (2016). Sedimentary Paleoenvironment Analysis of the Baikouquan Formation in the Mahu Depression, Junggar Basin: A Case Study of Well MA18. *Lithological Reservoirs*, *28*(2), 80-85.

Li, Z. X., Bogdanova, S. V., Collins, A. S. et al. (2007). Assembly, configuration, and break-up history of Rodinia: Asynthesis. *Precambrian Research*, *160*(1), 179-210.

Li, Z. X., Qin, M. K., Liu, X. Y. et al. (2022). Characteristics, Genesis, and Research Significance of Multi-Element Enrichmet Zones in Black Shale Series. *World Nuclear Geoscience*, *39*(01), 14-26.

Liang, F., & Cao, Z. (2025). Reservoir Characteristics, Forming Environments, and Enrichment Patterns of the Chang 7 Shale Oil Reservoir in the Huachi Area of the Ordos Basin, Triassic System. *Lithological Reservoirs*, *37*(1), 24-40.

Lin, J. Y., Chu, Q. Z., Shao, X. J. et al. (2023). Trace Element Geochemical Characteristics and Paleoenvironmental Implications of the Guzhuan Formation, Cambrian System, Liujiang Basin. *Science and Technology & Engineering*, *23*(7), 2749-2758.

Liu, L. H., Gao, Y. J., Zhu, G. Y. et al. (2024). Genesis of Siliceous Rocks in the Ediacaran-Cambrian

Transition Black Shale Series at the Northwest Margin of the Tarim Basin and Their Environmental Implications. *Acta Geologica Sinica*, *98*(02), 511-529.

Ma, D., Zhang, Z. J., Zhou, C. M. et al. (2023). Element geochemical characteristics and geological significance of mudstones from the Middle Jurassic Shaximiao Formation in Sichuan basin, Southwest China. *ACSOmega*, *8*(33), 29979-30000.

Marshall, C. R. (2006). Explaining the Cambrian "Explosion" of Animals. *Annu. Rev. Earth Planet. Sci*, *34*, 355-384.

Murray, R. W. (1994). Chemical Criteria to Identify the Depositional Environment of Chert: General Principles and Applications. *Sedimentary Geology*, *90*(3⁄4), 213-232.

Nicholls, G. D. (1967). Trace elements in sediments:an assessment of their possible utility as depth indicators. *Marine Geology*, *5*(5/6), 539-555.

Peng S, Babcock L, Cooper R. The Cambrian Period[J]. The geologic time scale, 2012, 2:437-488.

Pi, D. H., Liu, C. Q., Graham, A. et al. (2013). Trace and rare earth element geochemistry of black shale and kerogen in the early Cambrian Niutitang Formation in Guizhou province, South China: constraints for redox environments and origin of metal enrichments. *Precambrian Research*, *225*, 218-229.

Rimmer, S., & Thompson, J. (2004). Multiple controls on the preservation of organic matter in Devonian-Mississippian marine black shales: Geochemical and petrographic evidence. *Palaeogeography Palaeoclimatology Palaeoecology*, *215*(2), 125-154.

Sedimentary Environment and Hydrocarbon Geologic Significance of the Lower Triassic Baikouquan Formation on the Northern Slope of the Junggar Basin. (n.d.).

Steiner, M., Wallis, E., Erdtmann, B. D. et al. (2001). Submarine-hydrothermal exhalative ore layers in black shales from South China and associated fossils-insights into a Early Cambrian facies and bio-evolution. *Palaeogeography Palaeoclimatology Palaeoecology*, *169*(3-4), 165-91.

Tan, Z. D., Du, L. J., Chen, J. et al. (2025). Low-Temperature Mineralization Element Enrichment in the Early Cambrian Black Shale Series of Zhijin, Guizhou Province: Indications for Extensive Low-Temperature Mineralization. *Acta Geologica Sinica*, *99*(03), 830-844.

Taylor, S. R., & Mclennan, S. M. (1985). *The continental crust: its composition and evolution* (pp. 1-312) Oxford: Blackwell Scientific Publications.

Tian, J. C., & Zhang, X. (2016). *Sedimentary Geochemistry* (pp. 63-77). Beijing: Geological Publishing House.

Tribovillard, N., Algeo, T. J., Lyons, T., & Riboulleau, A. (2006). Trace metals as paleoredox and paleoproductivity proxies: An update. *Chemical Geology*, *232*(1-2), 12-32.

Wang, W. (2020). *High-Precision Zircon ID-TIMS U-P Geochronology of the Ediacaran-Cambrian Boundary in the Deepwater Area of South China*. University of Chinese Academy of Sciences.

Wang, Y., He, J., Kou, Y. L. et al. (2022). Causes of Low Resistivity in Shale Reservoirs of the Longmaxi Formation in the Changning Area. *Oil and Gas Geology and Recovery Rate*, *29*(3), 53-61.

Wignall, P. B., & Twitchett, R. J. (1996). Oceanic anoxia and the end Permian mass extinction. *Science*, *272*(5265), 1155-1158.

Xu, B., Diao, H., Wang, N. et al. (2022). Trace Element Geochemical Characteristics and Their Indicative Significance in the Paleocene System of the Lishui Depression, East China Sea Basin. *Frontiers of Marine Geology*, *38*(12), 64-74.

Xu, B., Zeng, W. Q., Diao, H. et al. (2021). Indicative Significance of Trace Rare Earth Elements in the Pinghu Formation of the Xihu Depression, East China Sea Basin, for Paleo-Production Environments. *Marine Geology and Quaternary Geology*, *41*(3), 72-84.

Xu, L., Xiao, J., Liu, D. M. et al. (2022). Geochemistry and Source Environment of Sandstones from the Qiaomo Cuo Formation, Middle Jurassic System, Jiangyumalo Area, Southern Qiangtang Basin. *Geology and Resources*, *31*(6), 738-747.

Yan, D. T., Wang, J. G., & Wang, Z. Z. (2009). Characteristics of Upper Ordovician-Lower Silurian Barium in the Yangtze Region and Their Implications for Paleoproductivity. *Journal of Xi'an Petroleum University: Natural Science Edition*, *24*(4), 16-19.

Yu, W., Tian, J. C., Wang, F. et al. (2022). Sedimentary environment and organic matter enrichment of black mudstones from the upper Triassic Chang-7 member in the Ordos basin, northern China. *Journal of Asian Earth Sciences*, *224*, 105009.

Zhang, H., Kang, Y., Ding, L. L. et al. (2023). Trace Element Characteristics of Lithium-Rich Claystone from the Liangshan Formation in Zhongxiang, Hubei Province and Their Implications for Sedimentary Environment. *Resources, Environment and Engineering*, *37*(4), 383-388.

Zhang, T., Wang, L. L., Liao, H. H. et al. (2024). Methods and Research Progress in Paleo-Water Depth Recovery of Sedimentary Basins. *Sedimentology and Tethyan Geology*, *44*(3), 582-599.

Zhang, X. Q., Wang, Y. Y., Cheng, G. F. et al. (2025). Geochemical Characteristics and Genesis of Uranium-Molybdenum-Nickel-Vanadium-PGE Black Shale Series in the Niutitang Formation, Yan Kong-Songlin Area, Northern Guizhou. *Gold*, *46*(11), 110-119.

Zhao, W., Shao, H. M., Hong, S. X. et al. (2024). Geochemical Characteristics of the Yanpi-Yanhuayuan Limestone and Their Paleoenvironmental Implications: A Case Study of the Maoyi Stage in Central Sichuan. *Block Oil and Gas Fields*, *31*(3), 478-486.

Zheng, R. C., & Liu, M. Q. (1999). Study on the Paleosalinity of Six Reservoir Formations in the Ordos Basin. *Petroleum and Natural Gas Geology*, *20*(1), 20-25.

Zhou, M. Z., Luo, T. Y., Huff, W. D. et al. (2008). Timing the termination of the Doushantuo negative carbon isotope excursion: Evidence from U-Pb ages from the Dengying and Liuchapo formations,South China. *Science Bulletin*, *63*(21), 1431-8.

Zhou, M. Z., Luo, T. Y., Liu, S. R. et al. Zircon SHRIMP Ages and Correlation Significance of the Top Member of the Laobao Formation, Jiangkou, Guizhou. *Science China: Earth Sciences*, *43*(07), 1195-206.

Zhou, J. Y., Chen, J. W., Zhang, Y. X. et al. (2021). Paleoenvironment and Tectonic Setting of the Mufushan Formation in the Lower Yangtze Region: Evidence from Elemental Geochemistry of Fine-Grained Conglomeratic Sedimentary Sequences. *Acta Geologica Sinica*, *95*(6), 1693-1711.

Zhu, M. Y., Zhang, J. M., Steiner, M. et al. (2003). Sinian-Cambrian stratigraphic framework for shallow- to deep-water environments of the Yangtze Platform: An integrated approach. *Progress in Natural Science*, *13*(12), 951-960.