

Article

Paleoenvironmental Evolution and Its Dominant Controls on Organic Matter Enrichment: Insights from the Lower Cambrian Qiongzhusi Formation Shale

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Abstract

Based on data from core observations, thin-section petrography, scanning electron microscopy, whole-rock X-ray diffraction, organic geochemical analysis, and element analysis, in this study, we characterized the mineralogical–petrological features and sedimentary environment of the Lower Cambrian Qiongzhusi Formation shale in Western Hubei Province, and we clarified their relationships with organic matter enrichment. The results are as follows: (1) Five dominant rock types were identified in the Qiongzhusi Formation, namely, siliceous shale, argillaceous–siliceous mixed shale, argillaceous–calcareous shale, calcareous–siliceous shale, and calcareous shale. Vertically, the lithofacies transition follows the sequence of siliceous shale facies → mixed shale facies → calcareous shale facies. Laterally, from the marine trough to the trough margin, the thicknesses of the siliceous shale, argillaceous–siliceous mixed shale, and calcareous–siliceous mixed shale gradually decrease, whereas the thickness of the argillaceous–calcareous mixed shale increases progressively. (2) From the early to late sedimentary periods of the Qiongzhusi Formation and from the marine trough to the trough margin, a consistent evolutionary trend can be observed: gradual shallowing of the water depth, intensified hydrodynamic conditions, increased dissolved oxygen content of the bottom water, weakened upwelling currents, reduced paleoproductivity in the surface water, enhanced water mass stagnation, increased terrigenous input, and a corresponding gradual decrease in the total organic carbon (TOC) content. (3) The formation of the late-stage organic-rich shale was comprehensively controlled by the terrigenous input, redox conditions, paleoproductivity, water mass stagnation, and upwelling activity. Among these factors, the redox conditions, water mass stagnation, and paleoproductivity were the primary drivers responsible for the difference in the TOC contents in the Western Hubei marine trough and its margin, while the terrigenous input played a secondary role.



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conditions of the [Creative Commons](https://creativecommons.org/licenses/by/4.0/)[Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.**Keywords:** Qiongzhusi Formation; shale; mineralogical–petrological characteristics; sedimentary environment; organic matter enrichment; controlling factors

1. Introduction

The Lower Cambrian Qiongzhusi Formation represents a principal stratigraphic unit for marine-shale gas exploration and development in southern China [1]. It is characterized by a wide geographic distribution, substantial sedimentary thickness, high organic-matter abundance, and advanced thermal maturation of its source rocks. At present, shale gas drilling in this formation is mainly concentrated in the Upper Yangtze Sichuan Basin, and wells such as We201, Jinye1, and Jinshi1 in the Weiyuan-Qianwei area have produced industrial gas flows [2], representing a major breakthrough in exploration [3]. However, exploration of the Qiongzhusi Formation in the Central Yangtze Western Hubei region remains in the early stage. Nevertheless, recent flows reported for wells such as Eyangye1 and Eyiye1 [4] indicate promising prospects for shale gas exploration in western Hubei. Prior investigations of the Qiongzhusi Formation in Western Hubei have emphasized the geochemical characteristics, shale gas pore structure and gas storage capacity, and the geological features of shale gas accumulation; however, studies addressing the linkage between paleoenvironmental evolution and organic-matter enrichment remain limited. The conditions of the sedimentary environment fundamentally regulate the formation and preservation of organic matter in marine shales; therefore, reconstructing the depositional environments provides a scientific basis for predicting the distribution of high-quality shale intervals and identifying exploration sweet spots.

Previous studies indicate that the variability in the mineralogy, sedimentary structures, organic-matter content, fossil assemblages, and lithological abundances reflects the combined influences of the basin architecture, hydrodynamics, terrigenous input, climatic variability, and eustatic sea-level changes during deposition [5,6]. Classifying shale lithotypes and reconstructing their depositional environments are therefore fundamental to understanding the sedimentation of black shale and identifying shale gas sweet spots.

Therefore, in this study, we focused on the Qiongzhusi Formation shale in Western Hubei by selecting representative outcrop profiles and wells in the region. We integrated core samples, thin sections, whole-rock X-ray diffraction, organic geochemical analysis, and element geochemical analysis. We analyzed the development characteristics of the shale facies, reconstructed the sedimentary paleoenvironment, investigated its relationship with organic matter enrichment, and established a sedimentary evolution model. The results provide geological constraints for predicting and mapping the distribution of high-quality shale reservoirs in the Qiongzhusi Formation in Western Hubei.

2. Regional Geological Overview

The Sinian–Cambrian transition constitutes a pivotal geological interval in Earth’s evolution, coinciding with a suite of major global and regional geological events, including the breakup of the Rodinia Supercontinent, the Cambrian Explosion, Snowball Earth episodes, and global anoxic events [7,8]. At the end of the Late Sinian Dengying Period, the Middle Yangtze Platform underwent tectonic uplift associated with the Huiting Movement. The central Hubei region was elevated, forming the Central Hubei Old Land, which is predominantly composed of carbonate rocks and distinctly differs from the clastic-dominated old land in the Upper Yangtze Platform [9–11].

During the Early Cambrian, inheriting the Late Sinian paleogeographic framework and controlled by regional extensional rifting, rapid global sea-level rise occurred. Against this tectono-sedimentary backdrop, a widespread sequence of organic-rich black shales was deposited across the Middle Yangtze Platform [12,13]. The stratigraphic nomenclature for this Early Cambrian black shale succession remains inconsistent across different subregions of the Middle Yangtze Platform. For the sake of research consistency, this study collectively refers to it as the Qiongzhusi Formation. The Qiongzhusi Formation in the study area was

deposited primarily in a shelf depositional environment. Proximal to the Central Hubei Old Land, the sedimentary facies are dominated by shoreline–shallow-water shelf deposits. Toward the southwest, the water depth gradually increases, and the sedimentary facies transition sequentially to semi-deep-water shelf–deep-water shelf facies (Figure 1).

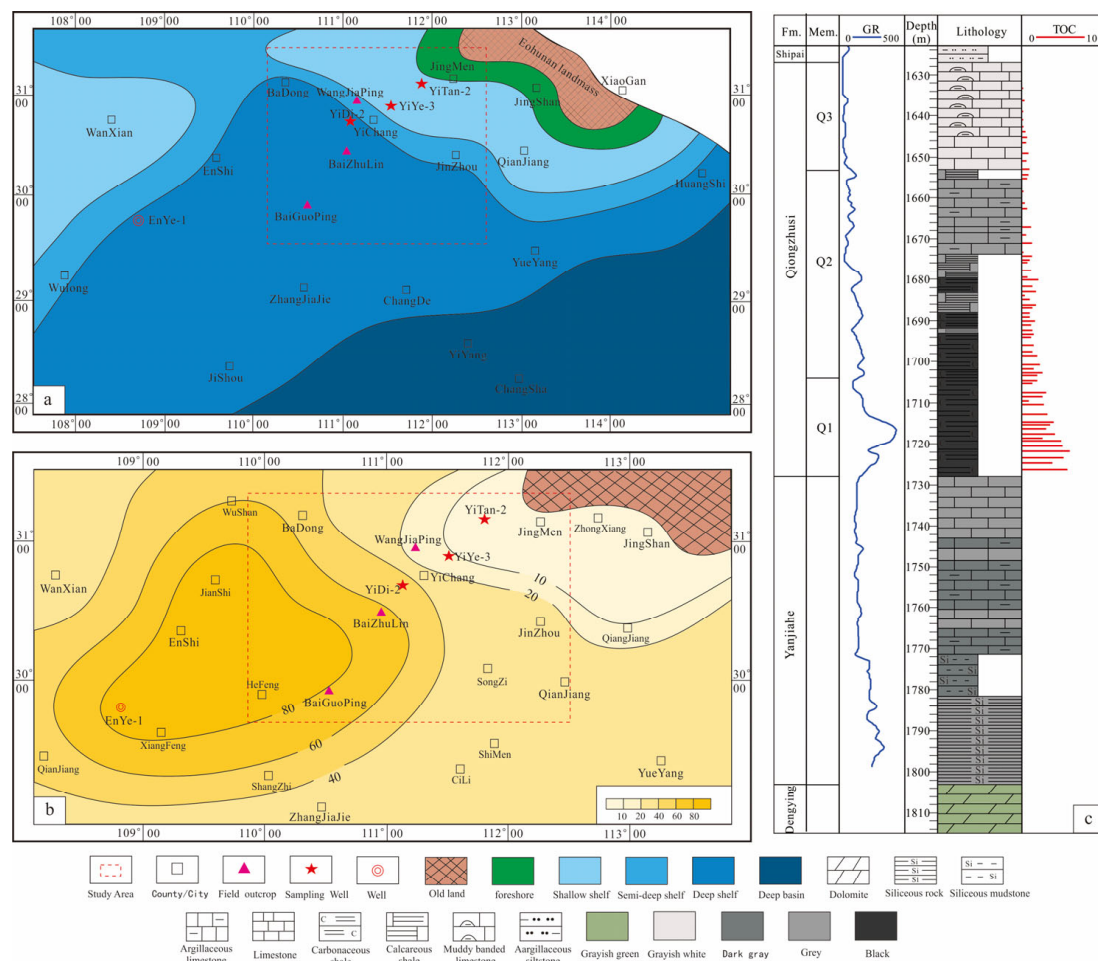


Figure 1. (a) Lithofacies paleogeography of the Lower Cambrian Qiongzhusi Formation in the Central Yangtze region. (b) Planar distribution of the thickness of the organic-rich shale in the study area. (c) Stratigraphic column of the Qiongzhusi Formation in Well Yidi 2.

The stratigraphic succession in the study area, from bottom to top, comprises the Upper Sinian Dengying Formation, Lower Cambrian Yanjiahe Formation, Qiongzhusi Formation, and Shipai Formation. The Dengying Formation is dominated by gray to light gray dolomite and is in unconformable contact with the overlying Yanjiahe Formation. The Yanjiahe Formation has a restricted distribution, primarily occurring on the southern and western flanks of the Huangling Anticline and in the core of the Changyang Anticline [14,15], and its extent was strongly controlled by rifting. Vertically, the Yanjiahe Formation can be divided into two members: the lower member mainly consists of grayish-black siliceous mudstone and dark gray siliceous rock, while the upper member is dominated by grayish-black argillaceous limestone and gray limestone. The Qiongzhusi Formation overlies the Dengying Formation paraconformably or the Yanjiahe Formation conformably, and it is in conformable contact with the overlying silt-bearing mudstone of the Shipai Formation. The sedimentary thickness of the Qiongzhusi Formation varies significantly laterally across the study area. In the Enshi-Xianfeng-Sangzhi area, which is dominated by the Western Hubei Trough, the thickness of high-quality organic-rich shale ranges from 60 to 100 m. In

contrast, in the Jingmen-Zhongxiang-Jingshan area, which is strongly influenced by the Central Hubei Old Land, the thickness of the organic-rich shale is relatively thin, generally less than 20 m. Overall, the thickness of the organic-rich shale in the Qiongzhusi Formation exhibits a gradual thinning trend from southwest to northeast (Figure 1).

Based on lithological observations and logging response characteristics, the Qiongzhusi Formation in the study area can be vertically subdivided into three lithological members from bottom to top (Figure 1):

- Member 1 (Qiong-1) is dominated by black siliceous shale and is characterized by high natural gamma (GR) values (150–600 API, average of 349 API), making it the interval with the highest GR values among the three members of the Qiongzhusi Formation.
- The base of Member 2 (Qiong-2) is dominated by black carbonaceous shale, which transitions upward to calcareous shale interbedded with argillaceous rocks of unequal thickness. The GR values are significantly lower than those of Member 1, showing a medium-low amplitude funnel-shaped logging curve (96.2–280.5 API, average of 146.7 API).
- Member 3 (Qiong-3) is mainly composed of limestone or calcareous mudstone, and its GR values rapidly decrease and exhibit a weakly serrated box-shaped logging curve (17.2–100 API, average of 79.8 API).

3. Materials and Methods

In this study, a total of 155 samples were collected from the black shale section of the Qiongzhusi Formation, including 52 from well Baizhuling, 67 from well YiDi2, 23 from YiYe3, and 13 from YiTan2. The samples were analyzed to determine their organic carbon contents, mineral compositions, and lithological characteristics and micropaleontological identification was conducted. Based on the analysis results, 13 and 17, of the samples from well YiYe3 and Baizhuling, respectively, were selected for elemental analysis.

All of the analyses conducted in this study were performed in the Geological Laboratory of the PetroChina Southwest Oil and Gas Field Company. The organic carbon content was measured using a CS-344 carbon and sulfur analyzer (LECO Corporation, St. Joseph, MI, USA), with an analytical accuracy of $\pm 0.5\%$. The thin sections of the samples were stained with a mixture of alizarin red and potassium ferricyanide (Aladdin, Shanghai, China). The X-ray diffraction analysis was performed using a Phillips Xpert-MPD X-ray diffractometer (Malvern Panalytical, Almelo, The Netherlands). The major elements were analyzed using a Rigaku 100e wavelength dispersive X-ray fluorescence spectrometer (XRF) (Rigaku, Nagano, Japan) after sample treatment using the alkali fusion method. The trace and rare earth elements were analyzed using a Thermo Scientific Element XR inductively coupled plasma mass spectrometer (Thermo Fisher Scientific, Wilmington, DE, USA), with an accuracy better than 5%.

4. Lithofacies Development and Distribution Characteristics

4.1. Lithofacies Classification

Based on whole-rock X-ray diffraction data, the shale lithofacies in the study area were classified with reference to the ternary diagram classification scheme for siliceous minerals (quartz + feldspar)–carbonate minerals–clay minerals [16]. The classification system is defined as follows:

- Siliceous shale facies (siliceous mineral content $> 50\%$, both carbonate and clay mineral contents $< 50\%$);
- Argillaceous shale facies (clay mineral content $> 50\%$, both siliceous and carbonate mineral contents $< 50\%$);

- Calcareous shale facies (carbonate mineral content > 50%, both siliceous and clay mineral contents < 50%);
- Mixed shale facies (all three mineral groups range from 25% to 50%), further subdivided into argillaceous–siliceous mixed shale facies, calcareous–siliceous mixed shale facies, and argillaceous–calcareous mixed shale facies.

Using 25%, 50%, and 75% as the critical mineral content thresholds, the aforementioned lithofacies were further refined into nine specific shale lithofacies types. The details of the classification criteria are provided in Figure 2 and Table 1.

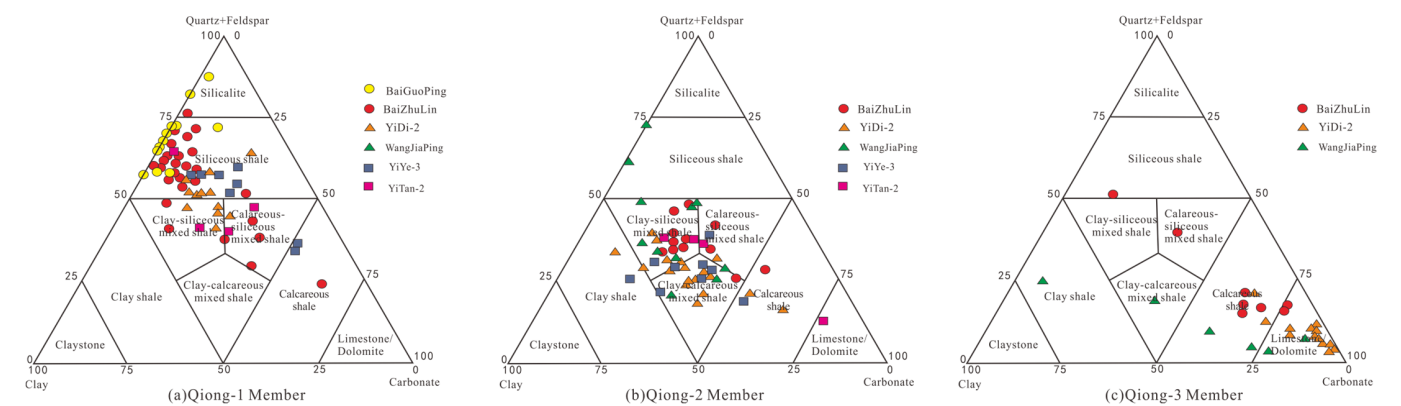


Figure 2. Ternary diagram for shale lithofacies classification of the Qiongzhusi Formation in the study area.

Table 1. Classification scheme of the marine shale lithofacies types.

Lithofacies Type	Mass Fraction of Rock Mineral Components (%)		
	Quartz + Feldspar	Calcite + Dolomite	Clay
Siliceous shale facies	50–75	<30	10–50
Clay shale facies	25–50	<30	50–75
Calcareous shale facies	<30	50–75	25–50
Clay like siliceous mixed shale facies	30–50	<33	30–50
Clay calcareous mixed shale facies	<33	30–50	30–50
Calcareous siliceous mixed shale facies	30–50	30–50	<33

4.2. Development Characteristics of the First Section of the Qiongzhusi Formation

The first member of the Qiongzhusi Formation (hereafter referred to as the Qiong-1 Member) is dominated by deep-water shelf subfacies, and the siliceous shale facies are the dominant lithofacies. Core observations and field outcrop surveys reveal that this siliceous shale facies occurs as thin- to medium-bedded intervals and is predominantly grayish-black to black. The rocks are rigid and brittle and are characterized by well-developed horizontal bedding, pyrite bands, and siliceous concretions (Figure 3a–c). Locally, black calcareous mudstone is present in the Well Yiye-3 block at the trough margin.

Microscopic analyses indicate that the Qiong-1 Member siliceous shale in the study area is characterized by high organic matter abundance and poor light transmittance. The matrix particles are dominated by flocculent microspheres and biogenic framework grains, which are mostly rounded pellets with a particle size range of 9–75 μm, dispersed within the clay matrix (Figure 3d). It is enriched in siliceous fossils, primarily consisting of sponge spicules and radiolarians, which have relatively simple morphologies (predominantly spherical or ellipsoidal; Figure 3e,f). Comprehensive investigations revealed that the quartz in the Qiong-1 Member siliceous shale is predominantly of biogenic siliceous origin, indicative of deposition in a deep-water, low-energy, and stable reducing environment.

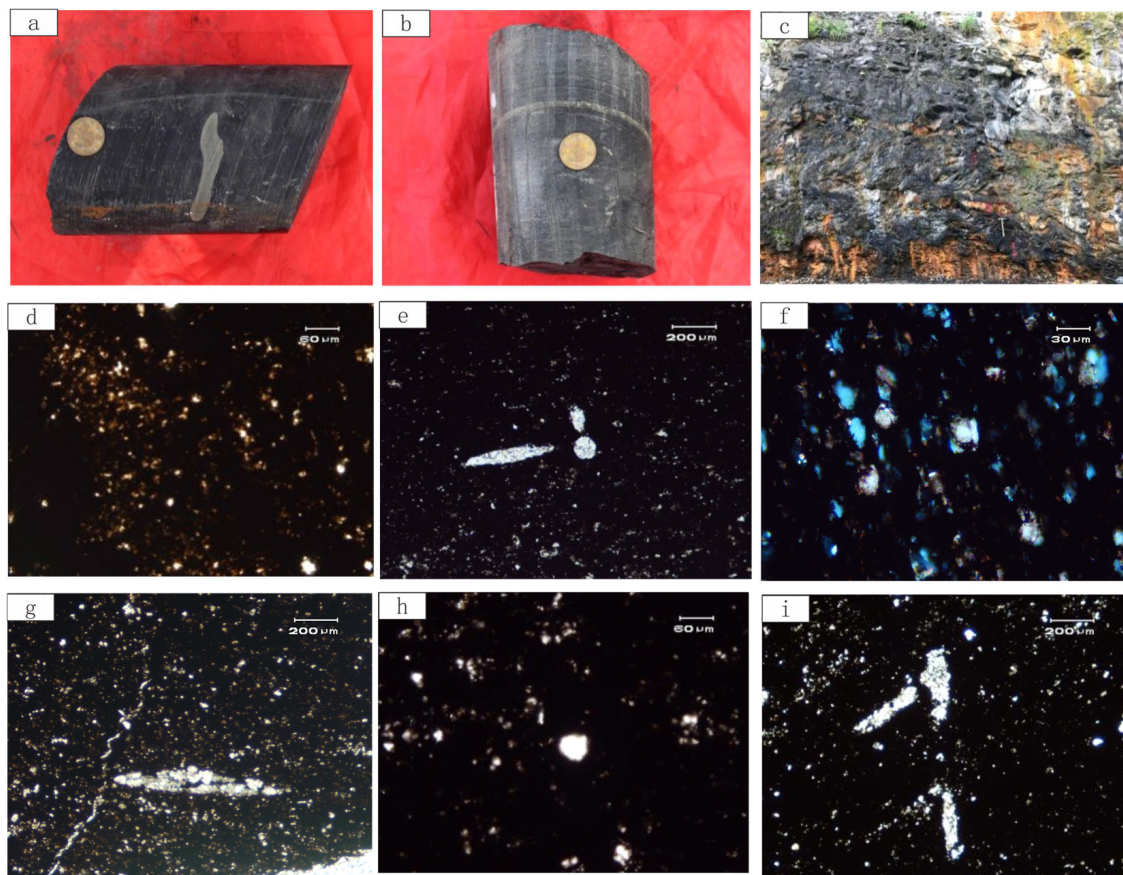


Figure 3. Characteristics of lithofacies in the first section of the Qiong Formation. (a) Gray black siliceous shale with horizontal bedding and pyrite clusters, suitable for exploration in two wells, 5056 m. (b) Gray black siliceous shale with pyrite bands, suitable for exploration in two wells, 5059.1 m. (c) Black carbonaceous shale, with a large number of siliceous nodules visible at the top of three layers, Baizhuling. (d) Siliceous shale, developed siliceous organisms, Baizhuling. (e) Siliceous shale with visible sponge bone needles, high TOC content, Baizhuling. (f) Siliceous shale with visible radiolarians, Yiye 3 well, 3048.8 m. (g) Siliceous shale, siliceous spicules replaced by calcite, well Yiye 3, 3052.8 m. (h) Siliceous shale with high content of siliceous organisms, suitable for exploration in two wells, 3059.95 m. (i) Siliceous shale, visible bone needles, Baiguoping.

The shales at the center of the trough (Baizhuling and Baiguoping areas) are enriched in siliceous minerals (quartz + feldspar), with an average content of 65%. Specifically, the average quartz content is 39.2%, the average feldspar content is 8%, clay minerals account for 23.3% on average, the average carbonate mineral content is 18%, and pyrite is the least abundant (average of 3%). The total organic carbon (TOC) content ranges from 1.5% to 15.1%, with a mean value of 4%. In contrast, in the trough margin area (well blocks Yidi-2, Yitan-2, and Yiye-3), the average siliceous mineral content decreases to 40%, the carbonate mineral content increases to 30% on average, and the mean TOC content is 3%—exhibiting a vertical trend of gradual reduction from bottom to top (Figure 4). These features illustrate that the siliceous mineral (quartz + feldspar) and TOC contents of the siliceous shale facies are significantly higher at the center of the trough than in the trough margin (Central Hubei Old Land) area, whereas the carbonate mineral content is notably lower. These lateral differences in the mineral composition and TOC content are strongly governed by variations in the sedimentary environments and are consistent with the material distribution patterns of deep-water sedimentary systems.

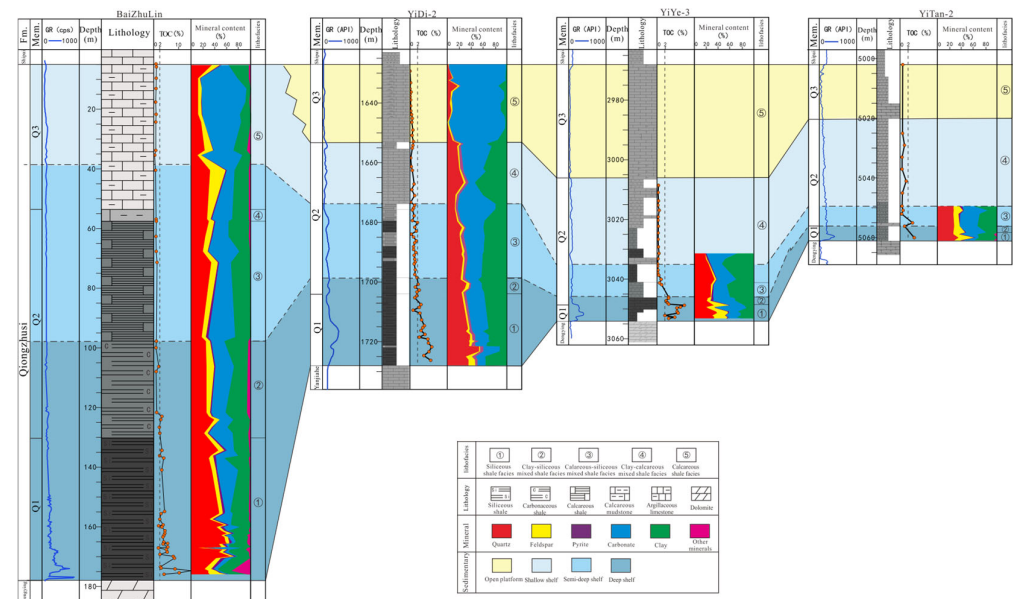


Figure 4. Cross-well correlation profile of the Qiongzhusi Formation along the trough-to-old land transect: Changyang Baizhuling–Well Yidi-2–Well Yiye-3–Well Yitan-2.

4.3. Development Characteristics of the Second Section of the Qiongzhusi Formation

The lower interval of the second member of the Qiongzhusi Formation (hereafter designated as the Qiong-2 Member) is dominated by deep-water shelf subfacies, and the lithology predominantly consists of grayish-black carbonaceous shale, locally interbedded with calcareous shale interlayers. Vertically, it exhibits a continuous depositional transition from deep-water shelf to semi-deep-water shelf and shallow-water shelf subfacies upward (Figure 4), and the dominant lithofacies shifts to mixed shale facies, including argillaceous–siliceous mixed shale and argillaceous–calcareous mixed shale. Overall, the depositional conditions were less favorable during the deposition of the Qiong-2 member than during the deposition of the Qiong-1 Member.

Field outcrop investigations revealed that the mixed shale of the Qiong-2 Member is characterized by spheroidal weathering (Figure 5a). The rocks are rigid and exhibit intense effervescence upon contact with dilute hydrochloric acid, indicative of an elevated calcareous component content. Microscopic observations revealed the occurrence of well-developed horizontal laminations, manifested as alternating low-transmissivity organic-rich mudstone and low-transmissivity calcareous layers. The degree of development of the lamination in the Qiong-2 Member is notably greater than that in the Qiong-1 Member (Figure 5b). In comparison to the Qiong-1 Member, the Qiong-2 Member has a substantially lower biogenic silica content, with grains showing irregular morphologies and smaller individual dimensions. The calcareous components are significantly enriched and occur as granular aggregates scattered sporadically within the claystone matrix. Siliceous biogenic fossils (e.g., radiolarians) are scarce (Figure 5c–f).

Comprehensive analysis of the lithological, textural, and biotic fossil characteristics indicates that the water depth was significantly shallower during the deposition of the Qiong-2 Member than during the deposition of the Qiong-1 Member. The depositional environmental stability decreased, and the water column oxygenation increased. These features are consistent with the evolutionary trajectory of shelf facies deposits under a background of eustatic sea-level fall.

Vertical correlation analysis revealed the occurrence of substantial differences in the shale mineral assemblages between the Qiong-2 Member and the Qiong-1 Member. Specifically, the average quartz content declines to 28.4%, exhibiting a pronounced downward

trend relative to the Qiong-1 Member. In contrast, the average feldspar content (7.4%) and pyrite content (2%) do not exhibit statistically significant deviations from those of the Qiong-1 Member. In addition, the average clay mineral content increases to 28.3%, while the average carbonate mineral content increases to 31.3%, with both showing marked enrichment compared to the Qiong-1 Member (Figure 4).

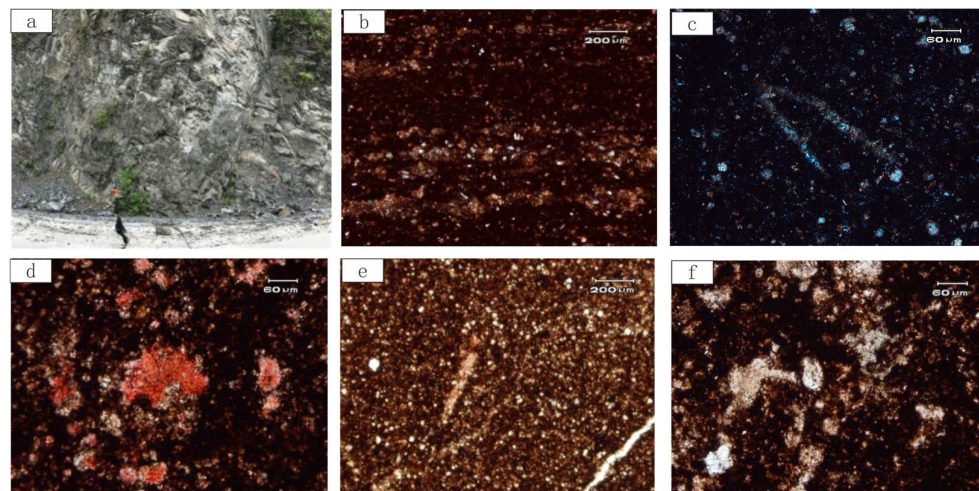


Figure 5. Characteristics of lithofacies in the second section of the Qiong formation: (a) Gray calcareous siliceous mixed shale, locally interbedded with calcareous shale, developed spherical weathering, Baizhuling. (b) Calcareous siliceous mixed shale, with calcareous fine silt and calcareous source rocks developed along the bedding planes, Baizhuling. (c) Clay mixed with siliceous shale, with poor transparency and visible siliceous organisms, suitable for well 3, 3041.3 m. (d) Limestone mudstone, sporadic calcareous debris, Yiye 3 well, 3046 m. (e) Clay calcareous mixed shale with scattered calcareous debris and low content of siliceous organisms, suitable for well 3, 3040.09 m. (f) Clay calcareous mixed shale, low content of siliceous organisms, irregular solidification resembling bone needles, suitable for well 3, 3046 m.

These systematic variations in the mineral composition were primarily governed by the evolution of the regional dynamic sedimentary regime during the deposition of the Qiong-2 Member. During this interval, gradual eustatic sea-level fall triggered a progressive forced regression. This tectono-sedimentary event induced southwestward contraction of the sedimentary center within the Western Hubei Trough and sustained shallowing of the depositional water column [13–15]. Against the backdrop of this regression, the paleotopography of the Central Hubei Old Land underwent relative uplift, leading to a significant increase in the flux of terrigenous clastic materials, including a substantial increase in the carbonate-bearing terrigenous input. These observations align with the typical sedimentary response pattern of regressive sequences, characterized by reductions in the siliceous components and enrichment of terrigenous clays and carbonates, thereby reflecting the dominant control of the evolution of the depositional environment on the mineralogical composition of the shale.

4.4. Development Characteristics of the Third Section of the Qiongzhusi Formation

The dominant lithofacies of the third member of the Qiongzhusi Formation (hereafter referred to as the Qiong-3 Member) are calcareous shale facies and limestone facies, and there is pronounced lateral heterogeneity of the sedimentary facies zonation. The central part of the Western Hubei Trough is predominantly composed of shallow-water shelf subfacies, which are underlain by a basal interval of semi-deep-water shelf subfacies. In contrast, the trough margin is dominated by open platform facies, which is stratigraphically characterized by light gray argillaceous limestone at the base, interbedded argillaceous

limestone and dolomitic limestone in the middle section, and light gray limestone in the upper part section (Figure 6a–c). Petrographically, the limestone is primarily classified as muddy grainstone according to the Dunham carbonate texture classification system, and the grain content ranges from 65% to 80%. The grain fraction is dominated by bioclasts, and intense effervescence occurs upon contact with dilute hydrochloric acid, indicative of enrichment of the significant calcareous component.

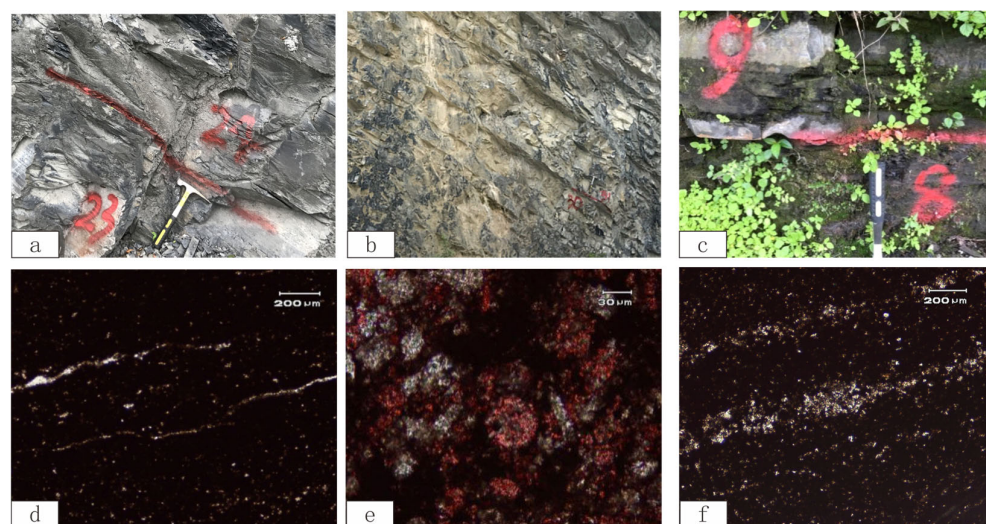


Figure 6. Characteristics of lithofacies in the third section of the Qiong formation: (a) Gray white calcareous shale with high calcium content, acid dripping and foaming, Baizhuling. (b) Gray white mudstone with high calcium content, acid dripping and foaming, Baizhuling. (c) Gray white middle layer mudstone, interbedded with a small amount of siliceous shale, Wangjiaping. (d) Calcareous shale, calcareous fine silt and calcareous sediment along the page, Baizhuling. (e) Calcareous shale, calcareous fine silt and calcareous cohesive source along the bedding plane, Baizhuling. (f) Gray mudstone, gray sediment with good translucency interbedded with clay rock with poor translucency, developed horizontal bedding, Baizhuling.

Microscopic petrographic analysis revealed that the Qiong-3 Member rocks exhibit excellent light transmittance and well-developed horizontal bedding, and the amount of silty components is negligible. Relative to the Qiong-2 Member, the content of calcareous bioclasts is substantially higher, whereas siliceous fossils (e.g., radiolarians) are virtually absent (Figure 6d–f). The geochemical data indicate that the TOC content of the Qiong-3 Member shale is generally less than 1%, and it locally declines to below 0.5%. Comprehensive analysis of the sedimentary facies, lithological, and geochemical characteristics revealed that the Qiong-3 Member was deposited in an overall shallow-water shelf–open platform depositional setting. Markedly enhanced hydrodynamic conditions and improved water mass circulation resulted in elevated paleo-oxygenation levels. This oxic depositional environment was unfavorable for the preservation of organic matter, ultimately leading to the notably low TOC content of this member.

Vertical comparative analysis of the mineral composition revealed the existence of distinct evolutionary trends in the shale mineral assemblages of the Qiong-3 Member. The average quartz content is 19.6%, and the average clay mineral content is 19.7%, both showing significant decreasing trend compared to the Qiong-2 Member. In contrast, the average feldspar content (8.7%) and pyrite content (1.2%) are not statistically significant from those of the Qiong-2 Member. Conversely, the average carbonate mineral content increases sharply to 49.1%, representing substantial enrichment relative to the Qiong-2 Member (Figure 4). Driven by sustained global eustatic sea-level fall, the Western Hubei Trough entered a phase of progressive regression, characterized by continuous shallowing

of the depositional water depth and a transition in the sedimentary environment from a deep-water, low-energy setting to a shallow-water, relatively high-energy regime. During this regressive episode, the paleotopography of the Central Hubei Old Land provenance underwent relative uplift, which significantly enhanced the flux of terrigenous clastic materials—particularly a substantial increase in the carbonate-bearing terrigenous input. This process dominated the evolutionary trajectory of the shale mineral assemblages, which is highly consistent with the typical sedimentary response pattern of regressive sequences, namely, carbonate enrichment coupled with attenuation of the siliceous and clay components.

5. Sedimentary Environment Analysis

5.1. Changes in Ancient Sea Level

Previous studies have well established that the cerium (Ce) anomaly is a robust geochemical proxy for reconstructing depositional water redox conditions and paleo-sea-level fluctuations [17,18]. The underlying response mechanism is as follows: under oxic conditions, Ce (III) is oxidized to Ce (IV), which readily precipitates due to its low solubility, resulting in relative depletion of Ce in sediments and the manifestation of a distinct negative Ce anomaly. In contrast, under reducing conditions, Ce predominantly exists in the soluble Ce (III) state and thus undergoes mobilization and enrichment. This process weakens the negative Ce anomaly or even changes it to a positive anomaly. As the paleo-water depth varies, the redox interface within the water column migrates synchronously. Consequently, the Ce anomaly can be employed to indirectly infer the processes of paleo-sea-level transgression and regression.

The geochemical analysis results for the Qiongzhusi Formation samples from Well Yiye-3 in the Western Hubei region reveal the following characteristics (Table 2): the δCe values of the Qiong-1 Member range from 0.66 to 0.81, demonstrating a significant negative anomaly. This geochemical signature indicates that the depositional environment was characterized by anoxic bottom water during this period. Regionally, this interval was dominated by rapid transgression, accompanied by a marked rise in sea level, which caused the redox interface to synchronously migrate upward and become decoupled from the sediment-water interface. Upon transitioning to the Qiong-2 Member, the negative Ce anomaly weakened significantly and stabilized, with δCe values distributed between 0.85 and 0.94. This transition reflects a gradual sea-level fall trend, but the overall sea level remained at a relatively high stand (Figure 7).

Table 2. Statistical Table of Rare Earth Element Content in Yiye-3 Well.

Sample No.	Depth (m)	La ($\mu\text{g/g}$)	Ce ($\mu\text{g/g}$)	Nd ($\mu\text{g/g}$)	δCe
YY3-29	3034.9	52.646	102.632	43.428	0.92
YY3-27	3035.7	53.460	104.303	44.980	0.92
YY3-25	3037	50.182	94.021	40.698	0.89
YY3-21	3038.7	50.952	99.734	39.999	0.94
YY3-19	3040.09	35.843	69.173	30.847	0.91
YY3-17	3041.3	44.857	83.061	34.569	0.89
YY3-13	3046	37.056	65.643	27.941	0.85
YY3-11	3047.3	38.762	75.646	33.235	0.92
YY3-14	3048	34.901	63.427	27.794	0.87
YY3-8	3048.8	28.766	45.721	21.357	0.77
YY3-6	3049.68	25.527	44.729	24.435	0.81
YY3-4	3051.4	34.641	53.252	27.161	0.74
YY3-2	3052.8	35.124	46.567	20.866	0.66

Note: $\delta\text{Ce} = \text{Ce}/\text{Ce}^* = 3\text{CeN}/(2\text{La}_\text{N} + \text{Nd}_\text{N})$.

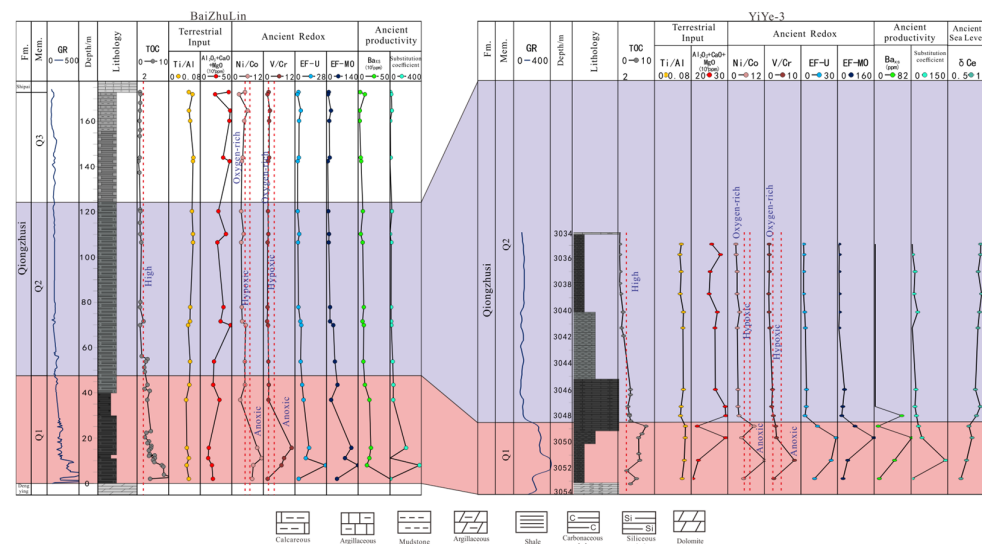


Figure 7. Standard stratigraphic column of depositional environments for the Qiongzhusi Formation, from the Baizhuling section (Changyang) to Well Yiye-3. The red dashed line is the threshold value for classification.

The rapid sea-level rise during the deposition of the Qiong-1 Member exerted two key controls on the depositional system. First, upwelling currents transported substantial fluxes of nutrients (e.g., phosphate and sulfate) into the basin, providing a fundamental material basis for the explosive proliferation of plankton and algae. This biological bloom substantially enhanced the marine primary productivity, which is a critical prerequisite for organic matter accumulation. Second, the massive mortality of thriving organisms in the surface water column led to continuous sedimentation of organic matter on the seafloor. The subsequent decomposition of this organic matter consumed large quantities of dissolved oxygen from the bottom water, ultimately giving rise to a stratified, anoxic, or even sulfidic reducing environment at the seafloor. This reducing setting provided favorable conditions for the preservation of sedimentary organic matter.

5.2. Terrestrial Input

Aluminum (Al), potassium (K), and rubidium (Rb) are transported to sedimentary basins via fluvial or aeolian processes and are primarily associated with aluminosilicate minerals. Due to their inherent chemical stability and resistance to post-depositional alteration, these elements are widely recognized as robust proxies for quantifying the terrigenous input to sedimentary systems [17,18]. The terrigenous input, typically manifested as the clastic flux, is predominantly governed by relative sea-level fluctuations: during transgressive phases, clastic depocenters migrate landward, whereas regressive episodes drive progradation of these depocenters toward the interior of the basin [19]. Therefore, the Al_2O_3 content and Ti/Al ratio are commonly used to assess terrigenous input into sediments. Specifically, Al_2O_3 content is positively correlated with the degree of terrigenous influence, whereas the Ti/Al ratio exhibits an inverse relationship [19–21].

Within the study area, the Baizhuling section (Changyang) and Well Yiye-3 are proximal to the Central Hubei Old Land, and the terrigenous material supply was dominated by carbonate detritus. The geochemical data for the Qiong-1 Member reveal that it has low $(\text{Al}_2\text{O}_3 + \text{CaO} + \text{MgO}) \times 10^4$ values (averages of 19.31 for the Baizhuling section and 23.06 for Well Yiye-3) and relatively high Ti/Al ratios (averages of 0.048 for the Baizhuling section and 0.062 for Well Yiye-3). These signatures collectively indicate the occurrence of a low-intensity terrigenous input regime, which is attributed to eustatic sea-level rise driven by seafloor spreading and consequent deepening of the depositional water column.

During the deposition of the Qiong-2 Member, the intensified tectonic activity triggered a gradual eustatic sea-level fall. Corresponding geochemical proxies record a notable increase in the average $(\text{Al}_2\text{O}_3 + \text{CaO} + \text{MgO}) \times 10^4$ values (33.64 for the Baizhuling section and 26.66 for Well Yiye-3) and a consistent Ti/Al ratio of 0.056 for both localities. This transition signifies a substantial increase in the terrigenous input relative to the underlying Qiong-1 Member, reflecting the tectonically driven reorganization of the sediment routing systems.

During the deposition of the Qiong-3 Member, the tectonic activity intensified further, and this was accompanied by sustained shallowing of the depositional environment. The Baizhuling section exhibits a markedly high average $(\text{Al}_2\text{O}_3 + \text{CaO} + \text{MgO}) \times 10^4$ value of 39.99, indicative of a substantial terrigenous flux. Overall, the terrigenous input intensity was low during the deposition of the Qiong-1 Member in the western Hunan-Hubei region, and it gradually increased upward through the Qiong-2 and Qiong-3 Members, reflecting a long-term regressive trend (Figure 7).

Extensive research has demonstrated that the terrigenous input exerts three primary modulating effects on organic matter enrichment: (1) dilution of organic matter by terrigenous clastic particles, directly reducing its concentration in the sedimentary record; (2) attenuation of organic matter sedimentation rates, prolonging exposure to oxidative degradation in the water column; and (3) weakening of the organic matter burial efficiency, disrupting the sequestration of organic carbon in seafloor sediments. Geochemical correlation analyses within the study area revealed that the TOC content is generally positively correlated with the Ti/Al ratio (Figure 8a) and is strongly negatively correlated with both the Al_2O_3 content and $(\text{Al}_2\text{O}_3 + \text{CaO} + \text{MgO}) \times 10^4$ values (Figure 8b). These relationships indicate that the intervals in the Qiong-1 Member that are characterized by a low terrigenous input are associated with elevated TOC contents. Conversely, the intensified terrigenous input during the deposition of the Qiong-2 Member resulted in extensive organic matter dilution, leading to a discernible decrease in the TOC content compared to the Qiong-1 Member.

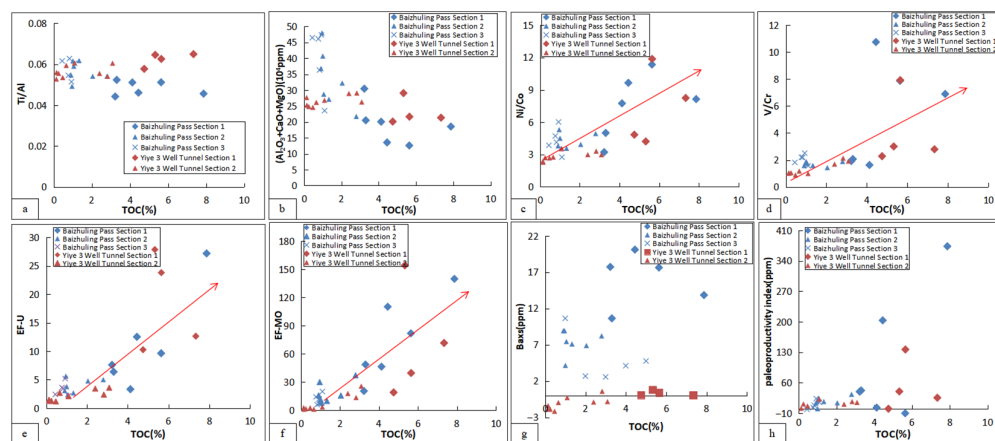


Figure 8. Correlation diagram of sedimentary environment indicators: (a,b) are the correlations between terrestrial input indicators and TOC, (c–f) are the correlations between paleoredox indicators and TOC, and (g,h) are the correlations between paleoproductivity indicators and TOC. The red arrow indicates a positive correlation.

5.3. Ancient Redox Conditions

Redox-sensitive elements (RSEs) such as uranium (U) and molybdenum (Mo) are widely employed as proxies for reconstructing marine redox conditions [20]. Generally, the concentrations of U and Mo exhibit positive correlations with the anoxia intensity. In oxic environments, U and Mo occur in high-valence states and remain dissolved in the water

column, leading to low accumulation in sediments. Conversely, under reducing conditions, these elements precipitate as low-valence authigenic minerals and become enriched in sediments [21]. In this study, three diagnostic indices were adopted: the Ni/Co, V/Cr ratio and the terrigenous input-corrected enrichment factor (X_{EF}), which was calculated as follows: $(X/Al)_{\text{sample}}/(X/Al)_{\text{PAAS}}$ [22]. Specifically, in anaerobic environments, Ni/Co is greater than 7, V/Cr is greater than 4.25, whereas in oxygen-rich environments, Ni/Co is less than 5 and V/Cr is less than 2.0 [22–24].

The vertical variation patterns of the Ni/Co and V/Cr ratios in the study area are highly consistent. During the deposition of Member 1 of the Qiongzhusi Formation, the average values of Ni/Co, V/Cr, the uranium enrichment factor (U_{EF}), and the molybdenum enrichment factor (Mo_{EF}) in the Baizhuling section were 7.52, 5.19, 11.11, and 74.46, respectively, while those in Well Yeye-3 were 7.29, 4.00, 18.63, and 71.00, respectively. The maximal enrichment of U and Mo confirms that the water column was anaerobic during this period, which favored the accumulation of redox-sensitive U and Mo. During the deposition of Member 2, the Ni/Co ratios in Baizhuling were predominantly < 5 (with only one exception of 5.31 at the base), all of the V/Cr ratios were < 2 , and the average U_{EF} and Mo_{EF} values were 3.91 and 18.10, respectively. In Well Yeye-3, all of the Ni/Co ratios were < 5 , all of the V/Cr ratios were < 2 , and the average U_{EF} and Mo_{EF} values were 2.50 and 7.68, respectively. The significant reductions in U and Mo enrichment compared to Member 1 reflect gradual weakening of the reducibility of the bottom water from the Exi Trough to the Exi Old Land, exhibiting a redox transition sequence of dysoxic–oxic (Baizhuling) $\rightarrow$ oxic (Well Yeye-3). During the deposition of Member 3, the Ni/Co ratios in Baizhuling were mostly < 5 , the V/Cr ratios ranged from 1.57 to 2.50 (average of 2.06), and the enrichment factors of U and Mo were 3.37 and 11.75, respectively. The continuous decreasing trends of the U and Mo enrichments indicate that the water column was persistently oxic throughout this interval.

The redox proxies (U_{EF} , Mo_{EF} , Ni/Co, and V/Cr) exhibit strong positive correlations with the TOC content (Figure 8c–f), suggesting that the redox conditions exerted a significant control on the organic matter preservation. Consequently, (1) Member 1 in the study area was characterized by an anaerobic environment, which facilitated excellent organic matter preservation and resulted in relatively high TOC contents; (2) at the base of Member 2, the environment gradually transitioned to dysoxic, with the middle-upper part shifting to oxic conditions, leading to a notable decrease in the TOC content; and (3) during the deposition of Member 3, the study area was dominated by oxic conditions, which were unfavorable for U and Mo enrichment, thus resulting in low TOC contents.

5.4. Degree of Water Retention

The molybdenum/total organic carbon (Mo/TOC) ratio serves as a reliable proxy for evaluating water mass stagnation in anoxic marine basins [23,24]. Low Mo/TOC ratios indicate a strong water retaining environment, and vice versa (Figure 9). However, this method is only suitable for anaerobic environments with certain water parameter constraints [25–28]. All of the samples from the second member of the Qiongzhusi Formation in Well Yeye-3 were deposited under oxic conditions, so these data were only utilized as a reference for the variation trend of the water mass stagnation (Figure 9).

Molybdenum (Mo) and uranium (U) exhibit high mobility under aquatic anoxic conditions, which facilitates their enrichment in sediments. The covariation pattern of the Mo enrichment factor (Mo_{EF}) and U enrichment factor (U_{EF}) can also be employed to assess the degree of water mass stagnation [28]. In non-stagnant, relatively dysoxic (weakly reducing) environments, U enrichment precedes Mo enrichment, with Mo_{EF}/U_{EF} ratios ranging from 0.1 to 0.3 times that of normal seawater. As the reducing conditions intensify, the rate of Mo enrichment surpasses that of U enrichment, and the Mo_{EF}/U_{EF}

ratio increases to 1–3 times the value of normal seawater. In anaerobic, weakly stagnant environments, Mo enrichment is further enhanced, leading to Mo_{EF}/U_{EF} ratios as high as 3–10 times that of normal seawater. In strongly stagnant environments, enhanced water mass confinement limits the supplies of Mo and U. Under anoxic conditions, the rate of Mo uptake and consumption exceeds that of U, resulting in Mo_{EF}/U_{EF} ratios below that of normal seawater (i.e., <1 times) [29,30].

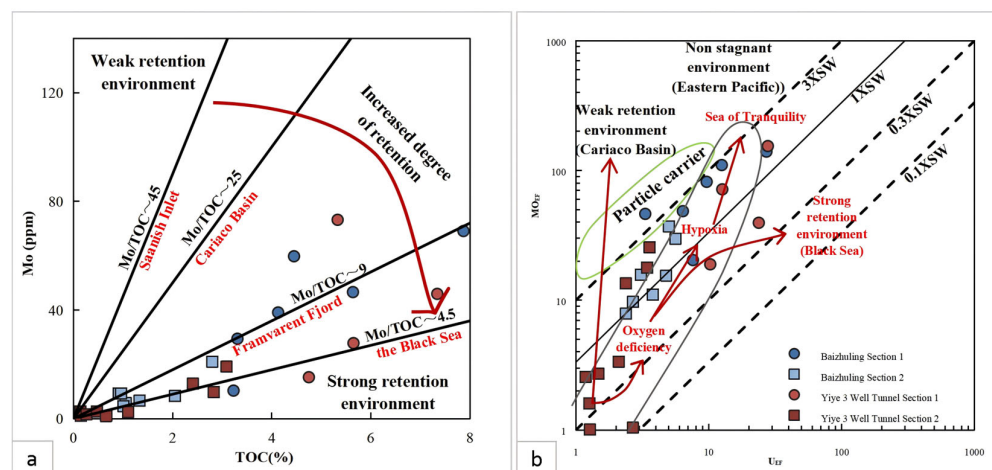


Figure 9. Mo/TOC relationship diagram and Mo_{EF}/U_{EF} covariance diagram in western Hubei region: (a) The solid line in the Mo/TOC relationship graph represents the Mo/TOC ratio of four modern ocean basins. (b) The solid line in the $Mo_{EF}-U_{EF}$ covariance plot represents the Mo/U molar concentration ratio (SW = 7.9) in seawater, while the three dashed lines represent Mo/U ratios that are 0.1 times, 0.3 times, and 3 times higher than seawater, respectively.

In the western Hubei region, the Mo/TOC ratios generally range from 4.5 to 25 (average of 6.94), which is close to the semi-stagnant environment threshold. This infers that the Qiongzhusi Formation was deposited in a semi-stagnant marine basin (Figure 9a). For the Baizhuhling Section, the average Mo/TOC ratios are 8.67 for the first member of the Qiongzhusi Formation (Qiongzhusi 1 Member) and 6.63 for the second member (Qiongzhusi 2 Member). For Well Yiye-3, the average Mo/TOC ratios are 7.03 for the Qiongzhusi 1 Member and 6.29 for the Qiongzhusi 2 Member, indicating that the degree of water mass stagnation was stronger during the deposition of the Qiongzhusi 2 Member than during the deposition of the Qiongzhusi 1 Member.

As shown in Figure 9b, the Mo_{EF}/U_{EF} ratios in the western Hunan-western Hubei region range from $0.3\times$ to $3\times$ that of seawater. With increases in these enrichment factors, the Mo_{EF}/U_{EF} ratio remains essentially constant. This differs from the continuous increase in the Mo_{EF}/U_{EF} ratio in open marine basins, thus deviating from the non-stagnant marine range. The Mo/U ratios of the Qiongzhusi Formation shale are only $0.3\times$ – $3\times$ those of seawater, which are lower than the ratios affected by Mo adsorption onto manganese-iron oxide particles (Mo/U ratios: $3\times$ – $10\times$ that of seawater). For high enrichment factors, there is no trend of decreasing Mo/U ratios with increasing enrichment factors, indicating that it does not belong to the strong stagnation basin model. Therefore, the Qiongzhusi Formation was deposited in a semi-stagnant marine basin. This setting resulted in low Mo concentrations in seawater, limiting the continuous increase in the Mo/U ratio, as observed in non-stagnant basins. In addition, the incomplete isolation of the basin allowed a certain amount of replenishment of U and Mo in the seawater, unlike the situation in a strong stagnation environment where the Mo in seawater was transferred to the sediments without subsequent replenishment, leading to a decrease in the Mo/U ratio. This inference that the organic-rich shale of the Qiongzhusi Formation formed in a semi-stagnant marine

basin is consistent with the conclusion derived from the Mo/TOC ratios. Furthermore, the Mo_{EF}/U_{EF} covariation diagram for the western Hubei region shows that the Mo_{EF}/U_{EF} ratios of most of the samples from the Qiongzhusi 2 Member are less than $1 \times SW$, further confirming that the degree of water mass stagnation was significantly stronger during the deposition of the Qiongzhusi 2 Member than during the deposition of the Qiongzhusi 1 Member.

The degree of water mass stagnation is closely related to tectonic activities and sea-level fluctuations, which in turn affect the exchange of nutrients in the water column and play vital roles in organic matter enrichment [19]. Overall, the western Hubei region was dominated by a semi-stagnant environment during the deposition of the Qiongzhusi Formation. During the deposition of the Qiongzhusi 1 Member, the tectonic activity was stable, the sea level was rising, the sedimentary water depth was relatively large, and the degree water mass stagnation was weak. After entering the deposition period of the Qiongzhusi 2 Member, the tectonic activity intensified, the sea level fell, the sedimentary water depth became shallower, and the degree of water mass stagnation increased. This led to weakened seawater exchange, which affected the redox conditions and paleoproductivity, resulting in a slight decrease in the TOC content.

5.5. Upwelling

Upwelling currents are typically anoxic, nutrient-rich, silica-enriched marine currents, and they can fuel intense biological productivity in surface waters. Elevated nutrient fluxes and subsequent organic matter degradation consume substantial amounts of dissolved oxygen, thereby establishing conditions of high organic matter productivity and facilitating the accumulation and preservation of organic matter [20]. According to Sweere et al. [21], cobalt (Co) and manganese (Mn) exhibit analogous distribution patterns but show pronounced variability across distinct depositional environments. In upwelling systems, deep-water-sourced nutrient supplies are characteristically depleted in Co and Mn, and the authigenic enrichment of these elements is limited by insufficient availability. In contrast, within restricted basin settings, Co and Mn inputs are governed by Co- and Mn-rich fluvial discharge, making it improbable for the authigenic enrichment to become supply-limited. Thus, the geochemical proxy $Al-CO_{EF} \times Mn_{EF}$ can be employed to discriminate between upwelling systems and restricted environments. In this study, the cobalt enrichment factor (CO_{EF}) and manganese enrichment factor (Mn_{EF}) were utilized to negate the effects of clastic input and dilution. As a general discriminant criterion: $CO_{EF} \times Mn_{EF}$ values > 2 indicate a restricted environment; values < 0.5 correspond to an open/upwelling environment; and values of 0.5–2 indicate an unstable seasonal upwelling environment [31].

In Figure 10a, the samples from the Qiongzhusi 1 Member in the western Hubei region—characterized by weak watermass restriction—cluster around a $Co \times Mn$ value of 0.4, which approximates the discriminant boundary between restricted and open/upwelling environments. The robust positive correlation between $Co \times Mn$ and aluminum (Al) implies that the $Co \times Mn$ values are predominantly controlled by terrigenous clastic minerals, and these samples are therefore inferred to have been influenced by seasonal upwelling. This weak water mass restriction also reflects a certain degree of connectivity between the western Hubei region and open marine realms. The samples from the Qiongzhusi 2 Member and Qiongzhusi 3 Member in the Baizhuling Section and Well Yiye-3—proximal to the Central Hubei Old Land—mostly plot within the restricted environment field (with the exception of three samples from the Baizhuling Section), indicating an increase in the degree of water mass restriction. In Figure 10b, the Co and Mn enrichment factors were calculated to effectively eliminate the confounding effects of clastic input and dilution. Consistent with the observations in Figure 10a, the samples from the

Qiongzhusi 1 Member in the Baizhuling Section and Well Yiye-3 were primarily influenced by open/upwelling conditions, whereas the Qiongzhusi 2 Member and Qiongzhusi 3 Member reflect intensified water mass restriction. The samples with $Co_{EF} \times Mn_{EF}$ values of 0.5–2.0 (predominantly from the Qiongzhusi 2 Member and Qiongzhusi 3 Member in the Baizhuling Section and Well Yiye-3) could not be precisely delineated into a specific water mass environment. This ambiguity is presumably attributed to the influence of unstable seasonal upwelling.

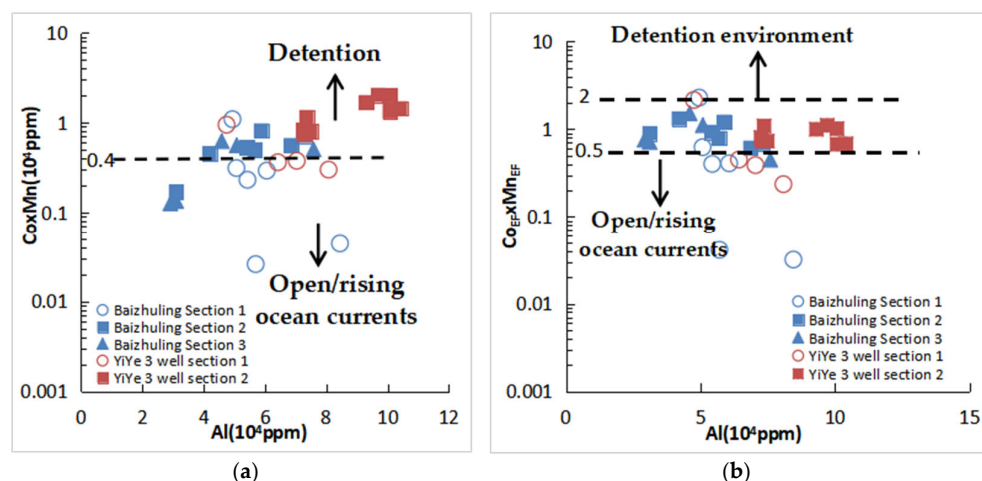


Figure 10. Plots of Al vs. $Co \times Mn$ and Al vs. $Co_{EF} \times Mn_{EF}$: (a) Plot of Al vs. $Co \times Mn$: $Co \times Mn$ values > 0.4 indicate a restricted environment, while values < 0.4 indicate an open/upwelling environment. (b) Plot of Al vs. $Co_{EF} \times Mn_{EF}$: Values > 2 correspond to a restricted environment, values < 0.5 denote an open/upwelling environment, and values of 0.5–2 represent an unstable seasonal upwelling environment.

Collectively, these geochemical results demonstrate that the Qiongzhusi 1 Member in the western Hubei region was influenced by open/upwelling currents, which sustained a high level of paleoproductivity. In contrast, the Qiongzhusi 2 Member and Qiongzhusi 3 Member experienced enhanced water mass restriction, diminished open/upwelling influence, reduced paleoproductivity, and a consequent decrease in organic matter content. This interpretation is consistent with inferences based on the Mo/TOC ratios and the Mo_{EF}/U_{EF} covariation pattern, providing consistent evidence of the evolution of the depositional environment and its control on the organic matter enrichment.

5.6. Ancient Productivity

Organic matter enrichment in shales requires sustained high productivity in seawater to provide a robust source of organic carbon. Paleoproductivity variations are typically inferred using proxies such as excess barium (Baxs), the Ba/Al ratio, and the composite paleoproductivity index (Y) [32,33]. The excess barium is calculated with aluminum (Al) correction via the formula $Baxs = Basample - Alsampl \times (Ba/Al)_{PAAS}$. It should be noted that sulfate reduction and iron oxide dissolution under anoxic conditions will lead to the decomposition of $BaSO_4$ in organic matter, respectively, which distorts the Ba indicators [32–35].

In contrast, copper (Cu), nickel (Ni), and zinc (Zn) exhibit more reliable behavior, Chen et al. [35] developed a composite paleoproductivity index (Y) using these elements: $Y = 0.593955 \times Cuxs + 0.523396 \times Nixs + 0.610962 \times Znxs$. Excess values (Cuxs, Nixs, and Znxs) are calculated relative to the Post-Archean Australian Shale (PAAS) standard and with titanium (Ti) correction: $Elementxs = Elementsample - Tisampl \times (Element/Ti)_{PAAS}$.

During deposition of the Qiongzhusi 1 Member in western Hubei, elevated proxy values were recorded in both the Baizhuling Section (average Baxs = 3381.30; average Y = 108.65) and Well Yiye-3 (average Baxs = 34.86; average Y = 50.64), indicating high paleoproductivity. For the Qiongzhusi 2 Member, a significant decline occurred: the Baxs (416.19–893.48) and Y (average of 17.03) values in the Baizhuling section and the Baxs (0–58.79) and Y (average of 6.92) values in Well Yiye-3 are substantially lower than those in the Qiongzhusi 1 Member. Similarly, the Qiongzhusi 3 Member in the Baizhuling section exhibits even lower values (average Baxs = 495.25; average Y = 9.80). Overall, the paleoproductivity was the highest during the deposition of Qiongzhusi 1 Member, and it progressively weakened upward through the stratigraphic succession.

The results of this study confirm that paleoproductivity exerts a critical control on organic matter enrichment. This is supported by strong positive correlations between the TOC and both Baxs and Y in the study area (Figure 8g,h). From the Qiongzhusi 1 Member to the Qiongzhusi 3 Member, the consistent decline in paleoproductivity—accompanied by decreasing nutrient availability in the surface waters—resulted in a gradual reduction in organic matter content.

6. Sedimentary Environment Evolution Model

Early Depositional Stage of the Qiongzhusi Formation (Qiongzhusi 1 Member): This stage corresponds to a period of rapid sea-level rise followed by an early phase of sea-level fall. It was characterized by relatively deep depositional water depths and the development of marine water column stratification. Owing to inadequate oxygen circulation, anoxic to hypoxic conditions prevailed in the bottom waters of the western Hubei Trough, as evidenced by the intense enrichment of RSEs. The Mo/TOC ratios and Mo_{EF}/U_{EF} values indicate that the study area was characterized by a semi-confined environment during this interval, which was influenced by seasonal upwelling currents. These currents transported nutrients from the Paleo-South China Ocean to the study area, enriching the surface waters with nutrients and sustaining a high level of paleoproductivity. Furthermore, sea-level rise displaced the Yangtze Basin farther from its provenance areas, resulting in reduced terrigenous input. The reduced dilution effect of the terrigenous detritus on the organic matter, coupled with the high organic matter abundance, created favorable conditions for the enrichment and preservation of organic matter (Figure 11a).

Middle Depositional Stage of the Qiongzhusi Formation (Qiongzhusi 2 Member): With the uplift of the ancient lands surrounding the Middle-Upper Yangtze region, the extensional intensity of the rift basin decreased and the sea level fell. This transition led to an increase in the dissolved oxygen content of the water column, disrupting the anoxic bottom-water conditions and establishing a predominantly hypoxic environment. Deposited in this paleoenvironmental setting, the Qiongzhusi 2 Member in the western Hubei Trough is dominated by semi-deep-water shelf facies deposits. From the western Hubei Trough to the Central Hubei Old Land, the facies transition from semi-deep-water shelf to shallow-water shelf is associated with a gradual decrease in the reducibility of the bottom-water, shifting from hypoxic to oxic conditions. Concurrently, the degree of water mass restriction intensified, the influence of open/upwelling currents waned, the surface water nutrient availability declined progressively, the terrigenous input increased, the paleoproductivity decreased, and the TOC content decreased accordingly (Figure 11b).

Late Depositional Stage of the Qiongzhusi Formation (Qiongzhusi 3 Member): During the late depositional stage of the Qiongzhusi Formation, the ancient lands surrounding the Middle-Upper Yangtze region underwent sustained uplift, which further accelerated the infilling rate of the rift basin. The western Hubei area was dominated by a shallow-water, oxic depositional environment. There was a continued increase in the terrigenous

clastic input, which intensified the dilution effect on the organic matter. Concurrently, the paleoproductivity level persistently decreased, culminating in the lowest organic matter content across the entire Qiongzhusi Formation stratigraphic succession.

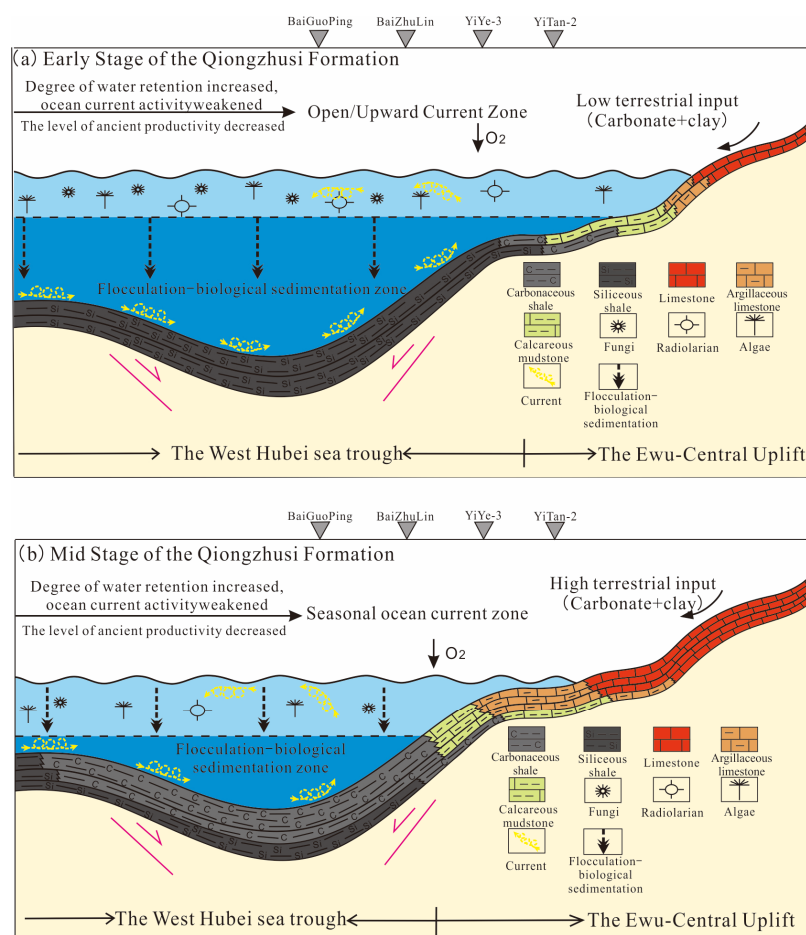


Figure 11. Schematic diagram showing the shale formation and evolution during the Early Cambrian Qiongzhusi Period: Western Hubei Trough–Central Hubei Old Land.

7. Conclusions

- (1) The TOC content in the western Hubei area exhibits a consistent decreasing trend both vertically and laterally from the center of the trough to its margins. Specifically, the TOC content of the Qiongzhusi 1 Member generally exceeds 3% (regarded as an excellent source rock quality), is primarily between 1.13% and 3% in the Qiongzhusi 2 Member, and is mostly less than 1% in the Qiongzhusi 3 Member, reflecting a progressive deterioration of the organic matter enrichment potential upward through the stratigraphic sequence.
- (2) The Qiongzhusi Formation in the western Hubei area is characterized by strong vertical heterogeneity, with a distinct lithofacies transition sequence from siliceous shale facies → mixed shale facies → calcareous shale facies from bottom to top. Laterally and areally driven by the sustained uplift of the ancient lands surrounding the Middle–Upper Yangtze region, the thicknesses of the siliceous shale, argillaceous–siliceous mixed shale, and calcareous–siliceous mixed shale gradually thin toward the northeast. In contrast, the thickness of the argillaceous–calcareous mixed shale progressively increases, which is closely linked to the intensified terrigenous clastic input from the northeast paleo-provenance.

- (3) From the early to late depositional stages of the Qiongzhusi Formation in the western Hubei area, a systematic paleoenvironmental transition occurred: the water depth gradually shallowed, the hydrodynamic energy intensified, the dissolved oxygen content of the bottom waters increased progressively, the upwelling current intensity weakened continuously, the surface-water paleoproductivity declined steadily, the degree of water mass restriction increased gradually, and the terrigenous clastic input increased consistently. This suite of coeval environmental changes collectively governed the vertical evolution of the organic matter enrichment conditions.
- (4) The formation of the organic-rich shale in the study area was predominantly controlled by the synergistic effects of the terrigenous input, redox conditions, paleoproductivity, water mass restriction, and upwelling currents. Favorable conditions for organic matter enrichment include a low terrigenous clastic input (minimizing dilution), anoxic bottom-water environments (enhancing preservation), high paleoproductivity (increasing organic matter supply), semi-confined water mass, and active upwelling currents (transporting nutrients). Among these factors, the redox conditions, degree of water mass restriction, and paleoproductivity were the primary drivers responsible for the differences in the TOC contents at the center and margins of the western Hubei Trough, while the terrigenous input was the secondary controlling factor.

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