

Article

Hydrocarbon-Generating Assemblages and Organic Matter Accumulation Patterns from the Basal Silurian Renheqiao Formation in Western Yunnan, China

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Abstract

The organic-rich shales of the Upper Ordovician–Lower Silurian Renheqiao Formation in Yunnan, China, represent a valuable target for understanding marine hydrocarbon systems and offshore oil and gas exploration. To decipher its organic matter (OM) accumulation patterns and offer perspectives relevant to the assessment of marine resources, this study employs an integrated petroleum geological, sedimentological, and palynological approach. Our findings indicate that organic-rich intervals (cumulative thickness 74–84.5 m) are concentrated in the R1–lower R6 and upper R6–R9 graptolite biozones, exhibiting high total organic carbon (TOC) content and graptolite reflectance values indicative of high to post-maturity thermal evolution, which confirms significant shale gas potential. Sedimentary evolution shows broad similarities with the Yangtze region’s Longmaxi Formation but with finer-scale differences. Due to its restricted paleogeographic setting on the Sibumasu Block, the Baoshan region responded to global sea-level changes with a lag, favoring sustained OM accumulation. Palynological analysis identified microphytoplankton, acritarchs, macroalgae, and animal-derived OM. Hydrocarbon-generating assemblages are divided into three stages: the first (R1–lower R6) and third (upper R6–R9) stages are favorable intervals with high TOC, dominated by microphytoplankton and acritarchs; the second stage (middle R6) shows lower enrichment, with increased macroalgae/animal-derived debris. Our analysis indicates that high abundances of primary producers (microphytoplankton/acritarchs) are strongly associated with organic enrichment. In contrast, higher abundances of secondary consumers (e.g., graptolites) show a significant negative correlation with TOC, suggesting their presence may coincide with conditions less favorable for accumulation or that they actively inhibit it.



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1. Introduction

The evolution of the Proto-Tethys Oceanic realm holds keys to understanding marine hydrocarbon systems and offers valuable analogues for modern marine offshore hydrocarbon exploration. The Ordovician–Silurian black rock series is extensively developed

in China. The Renheqiao Formation (Fm.) represents a thick sequence of organic-rich, graptolitic black mudstone/shale deposited during this period [1,2]. Tectonically, it belongs to the Sibumasu Block (also known as the Shan–Thai–Malay Block), which was situated near the northern margin of the Gondwana continent during the Late Ordovician to Early Silurian, positioned along the periphery of the Proto-Tethys Ocean between the Arabian Craton and South China [3]. Its paleogeographic location aligns with globally significant hydrocarbon source rock depositional settings and occupied a low-latitude region highly favorable for source rock deposition [4–6]. Current research on organic matter enrichment in the Renheqiao Fm. indicates that its depositional environment can be characterized by a warm and humid paleoclimate, which promoted intense chemical weathering. This weathering process delivered abundant terrigenous nutrients to the ocean, stimulating high primary productivity and thereby providing a substantial source of organic material. Concurrently, a persistently anoxic sedimentary environment effectively inhibited the degradation of organic matter, creating essential conditions for its enrichment and preservation, and the kerogen is primarily composed of Type I to II₁ organic matter, indicating substantial shale gas potential [7,8]. However, comprehensive geological evaluation of the Renheqiao Fm. for shale gas exploration remains incomplete, and fundamental geological research is still in its nascent stages.

Hydrocarbon-generating organisms, as the original source material for petroleum generation, serve as a robust proxy for analyzing hydrocarbon generation potential [5,9]. Variations in hydrocarbon contributions from different organisms render the analysis of hydrocarbon-generating organism assemblages crucial for evaluating highly mature source rocks [10,11]. Over the past decade, significant breakthroughs in the exploration and development of the graptolite-bearing black mudstones/shales of the Wufeng–Longmaxi (WF–LM) Fm.s around the Sichuan Basin have been achieved [12]. Extensive geobiological research on the WF–LM Fm.s has revealed diverse life forms and hydrocarbon-generating organism assemblages during this period [11,13,14], leading to new perspectives on primary hydrocarbon deposition [15,16]. Therefore, systematically analyzing the types of hydrocarbon-generating organism assemblages within the Renheqiao Fm. black mudstones and investigating OM sources have significant implications for precise petroleum resource assessment.

Post-extinction ecological recovery following the end-Ordovician mass extinction was a complex process. Environmental changes have triggered significant shifts in biogeographic distribution. Biodiversity began a gradual recovery during the early Silurian, marked by the emergence of new biological groups and ecological niches [17]. The primary focus of hydrocarbon-generating organism research lies in identifying biological individuals or fragments within source rocks [18,19]. Palynofacies analysis traces the biological origins of maceral components based on the organic petrographic classification of source rocks. Over the past three decades, integrating palynofacies with other datasets has significantly contributed to analyzing hydrocarbon-generating assemblages, interpreting paleoenvironments, and evaluating energy potential [19]. The widely adopted classification of palynological OM relies on observations under transmitted light and fluorescence microscopy. Similar to kerogen analysis, the morphology, texture, and structure of organic macerals serve as key classification criteria [20–22]. The positive correlation between various producers and primary productivity is well-proved [23–25]. However, regarding animals as significant components of hydrocarbon-generating organisms, current research has not yet clearly determined whether secondary productivity substantially contributes to the final quantity of buried OM [26]. This issue requires further investigation through multi-faceted approaches and diverse methodologies, thus highlighting the necessity of focusing on the characteristics and distribution patterns of hydrocarbon-generating or-

ganism assemblages. From an ecological structure perspective, phytoplankton not only serves as primary producers but also provides food sources for zooplankton, filter feeders, and scavengers. Its diversity profoundly influences the enrichment of OM associated with secondary productivity [27]. For instance, in some study areas, a significant portion of primary productivity is consumed by animals such as radiolarians, sponges, and foraminifera, resulting in lower OM enrichment in intervals where primary producers (e.g., acritarchs and algae) are relatively abundant [28,29].

Furthermore, this study adopts an integrated approach that combines the identification and classification of palynomorphs—direct indicators of OM origins—with a comprehensive evaluation of diverse particulate organic components, including amorphous organic matter (AOM) and structured organic matter (SOM). This methodology provides deeper insights into hydrocarbon-generating organisms and allows for a more precise reconstruction and delineation of hydrocarbon generation potential across distinct stratigraphic intervals.

In summary, as a source rock deposit situated along the Proto-Tethys margin under distinct paleogeographic and depositional environments, the composition, interrelationships, and distribution patterns of hydrocarbon-generating organisms within the Renheqiao Fm. are expected to differ from those of the Ordovician-Silurian black rock series (Longmaxi Fm.) in South China. Given that interactions between paleo-oceanic physicochemical and biological environments fostered unique ecosystems fundamentally controlling hydrocarbon-generating organisms and potential, this study analyzes the characteristics of hydrocarbon-generating organism assemblages in the Renheqiao Fm., their distribution patterns, and their interactions with the environment.

2. Geological Settings

The study area is situated within the Baoshan Block (Figure 1), the Chinese segment of the Sibumasu Block (also known as the Shan–Thai–Malay Block), which is a well-known stable continental block [30]. The Sibumasu Block extends from northern Sumatra through western Malaysia and Thailand to the Shan Plateau of Myanmar, and continues northward to the Baoshan Block in China, where it connects with the South Qiangtang Block of Tibet [3,23]. Our investigated strata are located in the central part of the Baoshan region [31]. Paleozoic and Mesozoic strata are well-developed in this area, characterized by abundant fossils and a complete stratigraphic sequence. The Upper Ordovician–Lower Silurian systems are divided, in ascending order, into the Pupiao Fm., Renheqiao Fm., and Lichaiba Fm., all of which exhibit good development.

The Renheqiao Fm. has outcrops in the Baoshan, Lushui, Fengqing, Shidian, and Zhenkang areas of Yunnan Province. It consists of a set of black, graptolite-rich, slope-basin facies rocks deposited in a deep-water environment, displaying well-developed horizontal bedding. Positioned between the Upper Ordovician Pupiao Fm. and the Middle–Upper Silurian Lichaiba Fm., the Renheqiao Fm. therefore provides favorable structural conditions for shale gas development. The Pupiao Fm. comprises variegated marlstones, mudstones, and fine-grained clastic rocks with considerable thickness. The Lichaiba Fm. is dominated by marlstones and limestones, approximately 200 m thick. The Renheqiao Fm. primarily consists of gray, gray-black, and yellowish-brown Graptolite-bearing shales and arenaceous shales. It exhibits well-developed horizontal bedding, contains abundant pyrite grains or lenses, is rich in graptolite fossils, and possesses high OM content, making it a regionally significant source rock. The Renheqiao Fm. can be broadly divided into two members: the lower member consists of black organic-rich siliceous mudstone (shale), and the upper member comprises gray and gray-green silty mudstones and fine-grained detrital rocks. Based on high-resolution graptolite fossil investigations [31–33], nine graptolite biozones, ranging from the Upper Ordovician Hirnantian Stage to the Telychian Stage of

the Silurian Llandovery Series, have been identified within the Renheqiao Fm. These were documented at the Chadi and Banpo sections, located in Renheqiao Town (24°43′48″ N, 99°10′48″ E) [34]. In ascending order, these are the *Metabolograptus persculptus* Zone (R1), *Akidograptus ascensus* Zone (R2), *Parakidograptus acuminatus* Zone (R3), *Cystograptus vesiculosus* Zone (R4), *Coronograptus cyphus* Zone (R5), *Demirastrites triangulatus* Zone (R6), *Lituigraptus convolutus* Zone (R7), *Stimulograptus sedgwickii* Zone (R8), and *Spirograptus guerichi* Zone (R9) [34]. Comparison with the graptolite biostratigraphy of the Longmaxi Fm. in the Yangtze region revealed that these nine graptolite zones in the Baoshan Block's Renheqiao Fm. correspond well to the LM1–LM9 graptolite zones of the Longmaxi Fm. (Figure 1). Consequently, the principal part of the black organic-rich siliceous mudstone (shale) in the Renheqiao Fm. can be correlated with sub-members 2–8 of the lower Longmaxi Fm., equivalent to the primary target interval for shale gas exploration and development in the Fuling area [35,36]. However, the Renheqiao Fm. lacks deposits equivalent to the black siliceous mudstone (shale) of the Wufeng Fm. developed in the Middle-Upper Yangtze region. Instead, the variegated mudstone at the top of the Pupiao Fm. in the Shidian area is stratigraphically equivalent to the Wufeng Fm. of the Middle-Upper Yangtze region.

System	Series	Stage	Formation	South China (Xu et al., 2000)	Formation	Chadi Section (Zheng et al., 2025)	Banpo Section (Zheng et al., 2025)	CPT drill core (this study)	SLJ drill core (this study)				
Silurian	Llandovery	Telychian	Longmaxi	N2	Renheqiao								
				LM 9/N1		<i>Spirograptus guerichi</i>	R9	<i>Spirograptus guerichi</i>	R9	<i>Spirograptus guerichi</i>			
		Aeronian		LM 8		<i>Stimulograptus sedgwickii</i>	R8	<i>Stimulograptus sedgwickii</i>	R8	<i>Stimulograptus sedgwickii</i>			
				LM 7		<i>Lituigraptus convolutus</i>	R7	<i>Lituigraptus convolutus</i>	R7	<i>Lituigraptus convolutus</i>			
				LM 6		<i>Demirastrites triangulatus</i>	R6	<i>Demirastrites triangulatus</i>	R6	<i>Demirastrites triangulatus</i>			
				LM 5		<i>Coronograptus cyphus</i>		R5	<i>Coronograptus cyphus</i>	R5	<i>Coronograptus cyphus</i>		
				LM 4		<i>Cystograptus vesiculosus</i>		R4	<i>Cystograptus vesiculosus</i>				
				LM 3		<i>Parakidograptus acuminatus</i>		R3	<i>Parakidograptus acuminatus</i>				
				LM 2		<i>Akidograptus ascensus</i>		R2	<i>Akidograptus ascensus</i>				
		Ruddanian											
		Ordovician		Upper Ordovician		Hirnantian	Guanyinqiao	LM 1	Pupiao	R1	<i>Metabolograptus persculptus</i>		
								WF4		<i>Normalograptus extraordinarius</i>			
						Katian	Wufeng	WF3	<i>Paraorthograptus pacificus</i>				
WF2	<i>Dicellograptus complexus</i>												
	WF1		<i>Foliomena-Nankinolithus</i>										

Figure 1. Graptolite zone comparison between the Renheqiao Fm. and the Longmaxi Fm [12,34].

The Chadi section is administratively located approximately 3 km west of Renheqiao Town, Shidian County, Baoshan City, Yunnan Province, China (Figure 2). It is a freshly exposed artificial roadcut profile with excellent outcrop conditions, clear stratigraphic sequences, and abundant graptolite fossils. The Ordovician-Silurian strata in the section

comprise, in ascending order, the Pupiao Fm. and the Renheqiao Fm. The contains six graptolite biozones (Figure 3): the R1 Zone corresponds to the Late Ordovician Hirnantian Stage, the R2–R5 zones correspond to the Silurian Rhuddanian Stage, and the R6 Zone corresponds to the Aeronian Stage [34]. The section is divided into 10 lithologic beds. Bed 1 belongs to the Pupiao Fm. and consists of yellowish-green, thin- to medium-bedded, bioclastic calcareous mudstone containing calcareous concretions. Its overall field character is characterized by alternating purplish-red silty mudstone and grayish-green mudstone representing the Katian age. Beds 2–3 represent the Hirnantian strata: Bed 2 is a paleocrust of weathering showing parallel unconformity with the overlying and underlying strata, and Bed 3 consists of argillaceous siltstone. Beds 4–10 belong to the Renheqiao Fm., dominated by black thin-bedded carbonaceous mudstone and black thin-bedded silty mudstone (Figure 3).

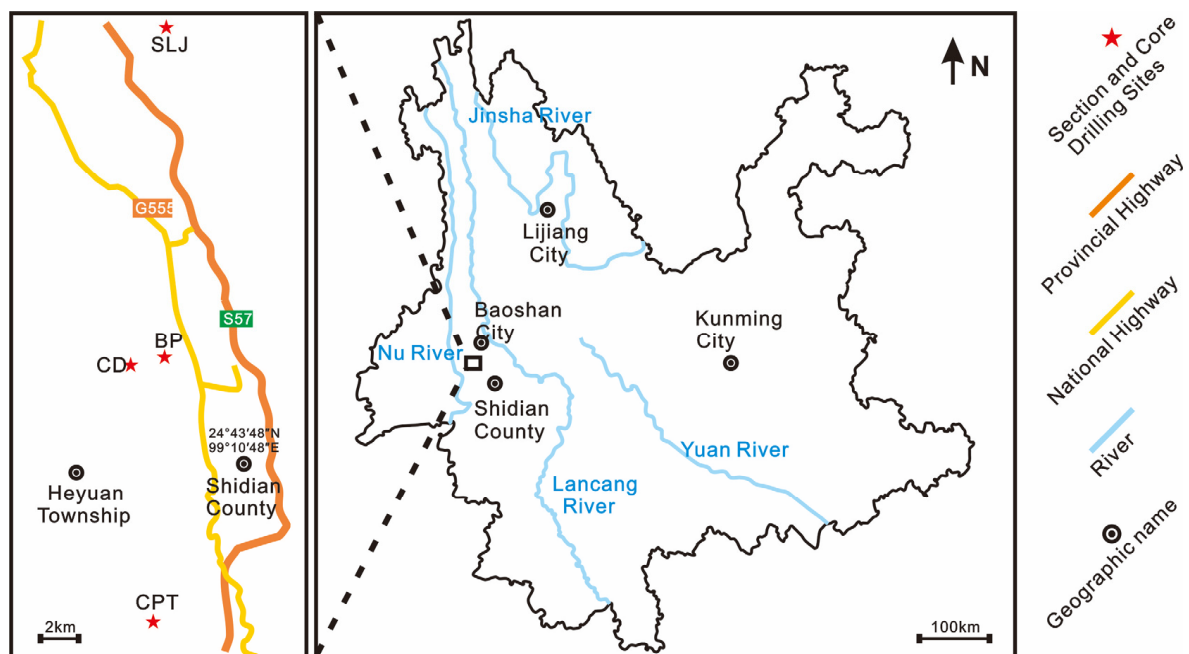


Figure 2. Location maps of the investigated area (CD = Chadi section, BP = Banpo section, CPT = Changputang borehole; SLJ = Shanglongjing borehole).

The Banpo section is located west of Banpo Village, approximately 3 km west of Renheqiao Town and about 1.8 km from the Chadi section (Figure 2). It serves as the type section for the Renheqiao Fm. This section is a freshly exposed artificial roadcut profile with excellent outcrop conditions, a clear stratigraphic sequence, and abundant graptolite fossils. The entire section, from base to top, belongs to the Silurian Renheqiao Fm. It contains four graptolite biozones: the R6, R7, and R8 zones correspond to the Aeronian Stage of the Llandovery Series, and the R9 Zone corresponds to the Telychian Stage (Figure 3). Lithologically, it is divided into eight beds. Beds 1–2 are dominated by gray carbonaceous silty mudstone, locally interbedded with thin siltstone layers. Weathering surfaces appear light yellow, while fresh surfaces are grayish-black. Starting from Bed 3 upwards, the carbon content increases, dominated by silty carbonaceous mudstone.

The Changputang borehole is situated 14.3 km south of Banpo Village (Figure 2). The strata of the Renheqiao Fm. in this area exhibit a relatively horizontal attitude, making it highly suitable for drilling and coring. This borehole penetrated starting from the overlying Lichaiba Fm., reaching the underlying Renheqiao Fm. (Figure 3). Graptolite fossils are abundant, allowing the identification of five graptolite biozones: the R5 Zone corresponds to the Silurian Rhuddanian Stage, the R6–R8 zones correspond to the Aeronian Stage, and the R9

Zone corresponds to the Telychian Stage. The core is divided into seven lithostratigraphic units. Bed 1 is characterized by light gray and yellowish-gray thick-bedded argillaceous siltstone. Beds 2 to 7 form the main part of the section, corresponding to the Renheqiao Fm. The lower part (Beds 2–4) consists mainly of black and gray carbonaceous silty shale and mudstone. The upper part (Beds 5–7) comprises primarily gray and grayish-white thin-bedded argillaceous siltstone and silty mudstone; well-developed horizontal bedding and lamellation are present (Figure 3).

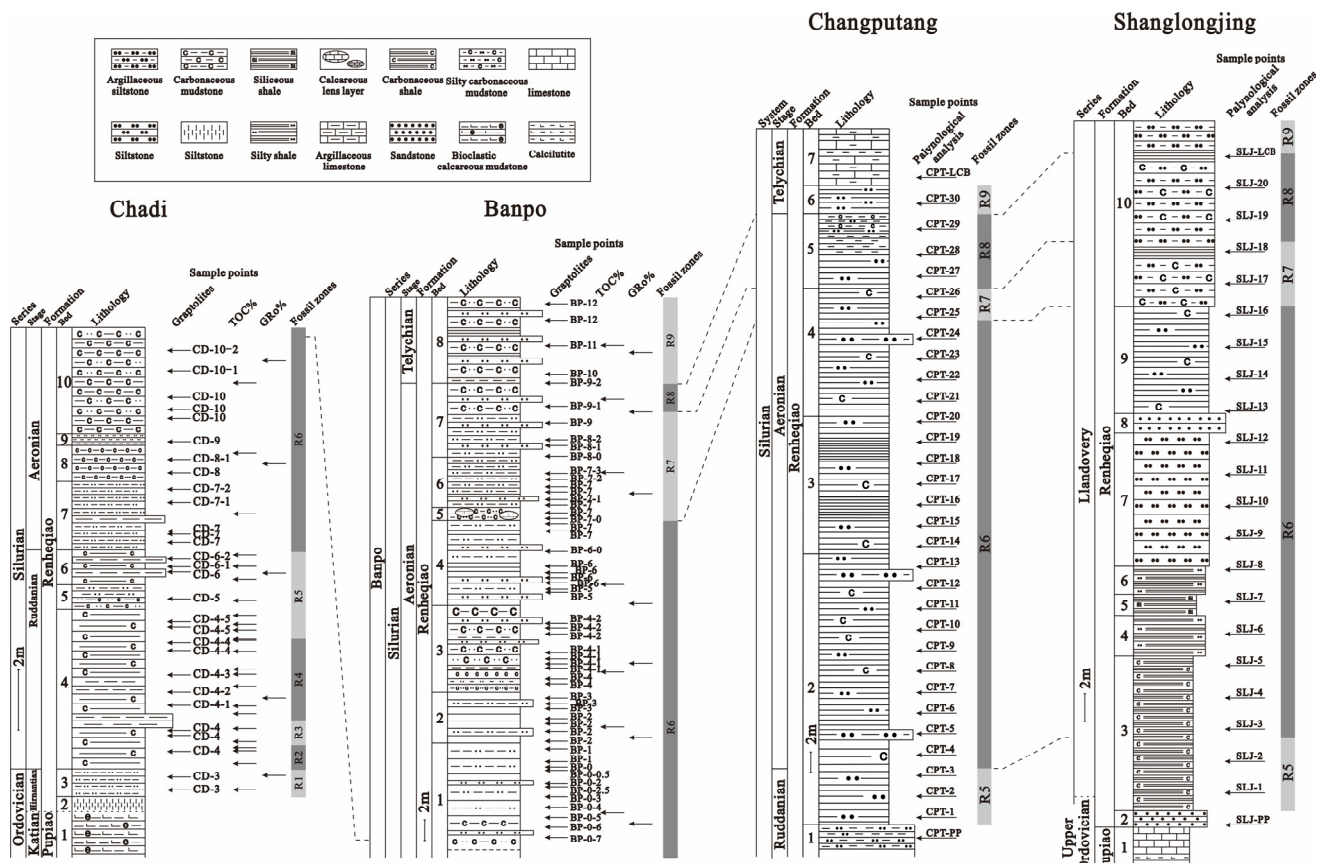


Figure 3. Stratigraphic correlations and sample points of the investigated sequences.

The Shanglongjing borehole is located near Shanglongjing Village, Laomai Township, approximately 18.1 km north of Banpo Village. The core sampling condition is excellent. The boundary between the Renheqiao Fm. and the underlying Pupiao Fm. is distinct, while the boundary with the overlying Lichaiba Fm. is less clear. Five graptolite biozones were identified: the R5 Zone corresponds to the Silurian Rhuddanian Stage, the R6–R8 zones correspond to the Silurian Aeronian Stage, and the R9 Zone corresponds to the Telychian Stage (Figure 3). The core is divided into 10 lithologic beds. Bed 1 consists of silty limestone with mud crystals and calcilutite, featuring horizontal bedding and containing shelly bioclastic as well as calcite veins. This bed corresponds to the Upper Ordovician Pupiao Fm. Bed 2 marks the entry into the Renheqiao Fm., composed of dark gray sandstone interbedded with thin marl layers. Beds 3 to 6 comprise grayish-black to black carbonaceous shale with well-developed horizontal bedding and abundant graptolites. Beds 7 to 10 show an increase in silt content, dominated by silty carbonaceous mudstone, occasionally displaying horizontal or lenticular siltstone layers; minor pyrite is developed and graptolite fossils are present (Figure 3).

3. Materials and Methods

3.1. Graptolite Sampling

To determine the geological ages of the four investigated sequences, systematic graptolite sampling was conducted following the principle of representative coverage across all lithologies. Collected samples were subsequently identified in the laboratory. The sampling quantities were as follows:

Changputang core: 470 samples.

Shanglongjing core: 441 samples.

For the Chadi and Banpo sections where graptolites are well-preserved and reported [34], statistical analyses of graptolite abundance and diversity were performed using a vertical sampling interval of 1.6 m.

3.2. TOC and Graptolite Reflectance Analysis

TOC abundance analyses were conducted relatively on 7 samples from the Banpo section and 20 samples from the Chadi section distributed uniformly throughout the Renheqiao Fm. (sample points shown in Figure 3). TOC abundance was determined by a Carbon/Sulfur Analyzer CS-2000 (LECO Corporation, St. Joseph, MI, USA) after dissolution of powdered samples in 10% HCl and subsequent air drying. This was performed at the Wuxi Research Institute of Petroleum Geology, China, with an analytical precision better than $\pm 0.2\%$.

Samples for reflectance measurement were collected from the Renheqiao Fm. The sampling quantities were as follows: 5 samples from the Chadi section, 7 samples from the Banpo section, data from the Changputang and Shanglongjing borehole cores are cited from [2] (Table 1). Samples were gently crushed using a jaw crusher and sieved to obtain particles ranging from 10 to 20 mesh (2–0.9 mm). These particles were mounted with epoxy resin into cylindrical blocks approximately 1 cm in diameter. After grinding and polishing, a smooth surface containing numerous fine rock particles was prepared. Reflectance measurements were conducted under oil immersion using a Leica DM4500P polarizing microscope (Leica Microsystems, Wetzlar, Germany) with a 50 $\times$ objective, and random reflectance values were recorded. Due to the fine-grained nature of bitumen particles in the shale, a grayscale-based method for OM reflectance calculation was employed [9,37]. Graptolite reflectance (GRo) is a well-established proxy for thermal maturity assessment in Silurian strata lacking vitrinite. To calculate an equivalent vitrinite reflectance (EqVRo), we applied the conversion formula $\text{EqVRo} = 0.99 \times \text{GRo} + 0.08$ [38], with results summarized in Table 1. It is important to note the inherent constraints of this approach: (1) the conversion is empirical, and EqVRo may diverge from true vitrinite reflectance, particularly at thermal maturity extremes; and (2) for outcrop samples, surficial weathering may have caused minor oxidation or alteration of the graptolite periderm, potentially leading to a slight underestimation of GRo and, consequently, EqVRo. The graptolites in the Renheqiao Fm., though often fragmented and variably preserved within the mineral matrix, provided consistent material for measurement, primarily derived from their cortical tissues [39,40]. The potential implications of these constraints for data interpretation are addressed in the Discussion (Section 5.1).

Table 1. Graptolite reflectance and equivalent vitrinite reflectance in the investigated sequences (data from the Changputang and Shanglongjing borehole cores are cited from [2]).

Sampling Location	Sampling Quantity	Graptolite Reflectance GRo (%)	Equivalent Vitrinite Reflectance EqRo (%)
Chadi	5	1.16	1.23
Banpo	7	1.54	1.60
Changputang	10	1.77	1.83
Shanglongjing	16	1.86	1.92

3.3. Palynological Analysis

To investigate hydrocarbon-generating organisms and OM composition, fresh core samples from the Changputang and Shanglongjing boreholes were selected for experimental analysis (sample points shown in Figure 3). Sample processing followed standard palynological preparation techniques as outlined by Tyson (2000) and Traverse (2007) [41,42]. All samples were first cleaned to eliminate potential contamination by mechanically removing weathered surfaces with a chisel and hammer, then crushed into 2–5 mm fragments. Subsequently, 25 g aliquots of each sample were subjected to sequential chemical treatments: carbonates were dissolved using 37% HCl (18 h), followed by silicate removal with 40% HF (24 h), to concentrate acid-insoluble organic components for analysis.

To quantify the OM content in each sample, a tablet containing a fixed concentration of *Lycopodium* spores (27,637 spores/tablet) was dissolved in acid, allowing the spores to disperse uniformly in the solution for statistical normalization of particle counts. Between processing steps, samples were rinsed with distilled water until the rinse water reached pH neutrality. Following this procedure, a mixed solution of ZnI₂ and KI (density: 2.15–2.25 g/cm³) was added, stirred, and centrifuged to separate the OM. The material floating on the surface was carefully extracted, washed, and transferred to distilled water. Finally, strew slides were prepared using the concentrated organic residue.

Quantification of organic particles was conducted using strew slides. Each slide was studied and photographed under transmitted white light with a Leica DM5500 biological microscope (Leica Microsystems, Wetzlar, Germany) at the State Key Laboratory of Biogeology and Environmental Geology, China University of Geosciences (Wuhan). Palynomorphs were identified and recorded based on their occurrence in each slide, as quantitative analysis of palynomorph types is inherently subject to depositional and preservation biases [42]. For each sample, counting was terminated once exactly 70 *Lycopodium* spores were tallied. AOM and SOM were quantified by counting discrete particles, with a particle defined as any organic fragment whose approximate area was equivalent to a circle 45 µm in diameter.

The raw counts were subsequently extrapolated to the whole-sample scale using Formula (1):

$$OM_{CON} = \frac{N \times C_{ly}}{N_{ly}} \quad (1)$$

where OM con: OM concentration (pieces/25 g), N: counted OM numbers (pieces), C_{ly}: *Lycopodium* spore concentration (27,637 pieces/25 g), and N_{ly}: counted *Lycopodium* spore numbers (pieces). *Lycopodium* spores were used as a normalization factor of each kind of OM. All figured specimens are stored in specimen room 812 in the main building in China University of Geosciences (Wuhan).

4. Results

4.1. The Abundance and Diversity of Graptolites

4.1.1. Abundance

To quantify graptolite abundance, specimen counts per unit area (1600 cm²) were measured in the Chadi and Banpo sections. Statistical analysis of 18 sampling bins (3.3 m each) revealed significant vertical variation in abundance within the Renheqiao Fm., showing an overall downward trend from base to top. Peak abundance (>200 specimens/1600 cm²) occurred at the lower part of Aeronian in R6 Zone, while the R7 Zone recorded the minimum (six specimens/1600 cm²) (Figure 4).

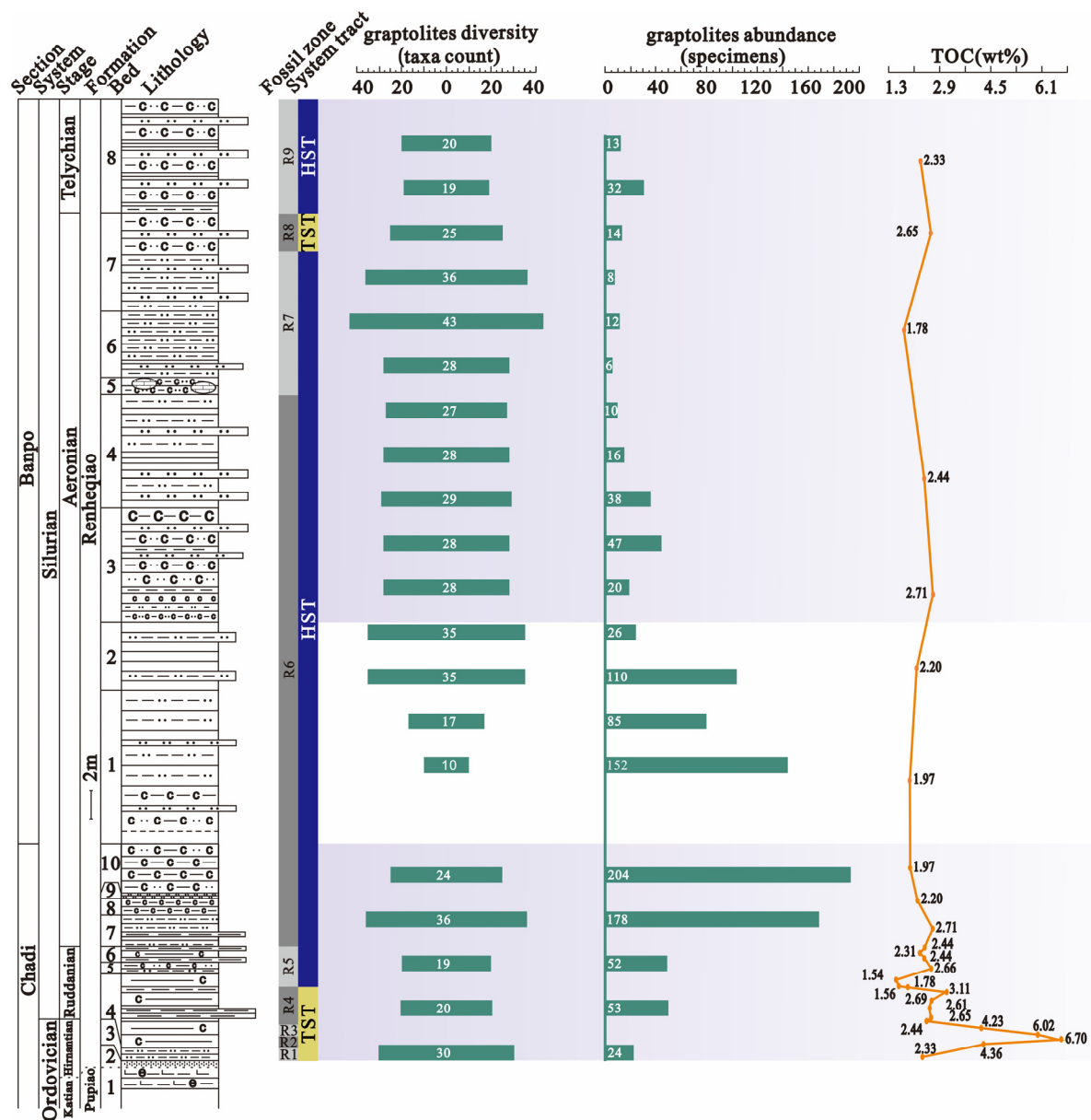


Figure 4. Composite column of the Chadi and Banpo sections, showing graptolite abundance, diversity, and TOC% (Legend same as in Figure 3).

In the lower Hirnantian strata of the Chadi section (Bed 3), lithologically dominated by gray-black thin-bedded silty mudstone, the interval yields graptolites including *Metabolograptus persculptus*, *M. ojsuensis*, *M. extraordinarius*, and *Normalograptus xainzaensis* [32], and the graptolite abundance is 24 specimens per unit area, representing moderate values within the section. In the overlying Rhuddanian strata (Beds 4–6), lithologically dominated by black thin-bedded carbonaceous shale intercalated with thin (3–5 cm) mudstone layers, the interval exhibits upward-increasing silt content and well-developed horizontal laminae. It yields graptolites including *Akidograptus ascensus*, *Metabolograptus wangjiawanensis*, *Parakidograptus acuminatus*, *Normalograptus scalaris*, *Cystograptus vesiculosus*, *N. similis*, and *Coronograptus cyphus* [34]. Graptolite abundance averaged 52.5 specimens per unit area, indicating an increase compared to underlying beds (Figure 4). In the Aeronian strata (Beds 7–10), lithologically dominated by black thin-bedded silty mudstone with silt laminae, the interval yields graptolites including *Demirastrites triangulatus*, *Petalolithus minor*, *Normalograptus crassus*, *Oktavites communis juvenis*, *Monograptus xizangensis*, *Pernerograptus*

revolutus gracilentus, *Demirastrites magnificus*, and *Rastrites guizhouensis* [34]. Graptolite abundance reaches its maximum in this interval, averaging 191 specimens per unit area.

Beds 1–2 of the Banpo section represent the lower R6 Zone, lithologically dominated by gray carbonaceous silty mudstone with locally interbedded thin siltstone layers, showing higher clay content than the upper beds of the Chadi section. The interval yields graptolites including *Emirastrites magnificus*, *Rastrites distans*, *Diplograptus changningensis*, *Monograptus rhynchophorus*, *Streptograptus runcinatus*, *Euclimacograptus hastatus*, *Oktavites spiralis*, *Pristiograptus sichuanensis*, and *Pernerograptus raphidos* [34]. Graptolite abundance remains substantial in this interval, averaging 93.25 specimens per unit area (Figure 4). Beds 3–4 of the Banpo section represent the R6 Zone, dominated by gray-black laminated carbonaceous mudstone with laminae composed of alternating white silty and black clayey layers. This interval yields graptolites including *Pristiograptus concinnus*, *Climacograptus scalaris*, *Rastrites guizhouensis densus*, *Demirastrites denticulatus*, *Oktavites gansuensis*, and *Pernerograptus qijiangensis* [34]. Graptolite abundance shows a marked decline here, averaging 26.2 specimens per unit area (Figure 4). Beds 5–8 of the Banpo section encompass the R7–R9 graptolite zones. Lithologically dominated by gray laminated silty mudstone with laminae composed of alternating white silty and black clayey layers, the interval exhibits upward-increasing clay content. It yields graptolites including *Pristiograptus sichuanensis*, *Demirastrites triangulatus*, *D. decipiens valens*, *Pernerograptus galaensis*, *Monograptus gemmatus*, *Lituigraptus convolutus*, *Rastrites linggispinus*, *Streptograptus cf. nanshanensis*, *S. crisptus*, and *S. linearis* [34]. Graptolite abundance is notably low in this interval, averaging 14.17 specimens per unit area (Figure 4).

4.1.2. Diversity

Based on graptolite taxonomic data from Zheng et al. [34], diversity was calculated at 3.3 m intervals for both the Chadi and Banpo sections. This investigation reveals that graptolite diversity remained relatively stable throughout the Renheqiao Fm. In the Chadi section, diversity shows an upward-increasing trend, peaking at 36 species in Beds 7–8, coinciding with the base of the Aeronian Stage. Similarly, the Banpo section exhibits an upward-increasing diversity pattern: minimum diversity (10 species) occurs in the basal Bed 1, while maximum diversity (43 species) is recorded in Bed 6, corresponding to the mid-R7 Zone (Figure 4).

4.2. Graptolite Reflectance

Thermal maturity in the study area was assessed based on published core data and our own measurements. For the Changputang and Shanglongjing cores, the literature data ([2], Table 1) show G_{Ro} values ranging from 1.53% to 1.89% (average 1.77%) and 1.52% to 2.13% (average 1.86%), respectively, with corresponding average E_{qV}R_o values of 1.83% and 1.92%. Our new measurements from the Chadi and Banpo sections yielded lower G_{Ro} ranges of 1.12–1.20% (avg. 1.16%) and 1.51–1.57% (avg. 1.54%), with calculated average E_{qV}R_o values of 1.23% and 1.60%, respectively (Table 1). It should be noted that the G_{Ro} values from the Chadi and Banpo outcrop sections are slightly lower than those from the borehole cores, which is consistent with the expected effect of surficial weathering (see Section 3.2). Nevertheless, the overall thermal maturity pattern—with the Shanglongjing core showing the highest values and the Chadi section the lowest—remains internally consistent and interpretable.

4.3. TOC Content

As shown in Figure 4, analysis reveals that TOC% in the Chadi section ranges from 1.54% to 6.70% (mean: 2.87%), exhibiting higher values in lower beds and lower values in upper beds. Within the carbonaceous shale interval from the base to the upper part of Bed 4,

TOC% remains high (2.33–6.70%; mean: 3.71%), corresponding to the lower part of biozones R2–R5. From the upper Bed 4 to the top of the section, where silty carbonaceous mudstone or silty mudstone dominates, TOC% decreases significantly (1.54–2.71%; mean: 2.11%), corresponding to the lower R5 Zone through R6 Zone. The average TOC% for the entire Banpo section is 2.24%. The minimum value of 1.78% occurs in Bed 7, corresponding to the R7 zone, while the maximum value of 2.71% is found in Bed 3, which belongs to the R6 zone. Within the R6 zone (Beds 1–4), the average TOC% is 2.33%. From Bed 1 to the lower part of Bed 3, TOC% gradually increases to 2.71%, after which it begins to show a downward trend. Within the R7 zone (Bed 5 to the lower part of Bed 8), the TOC% is 1.78%, representing the lowest value in the section. The R8 Zone corresponds to the upper part of Bed 7, where TOC% increases to 2.65%. The R9 Zone corresponds to Bed 8, with a TOC% of 2.33%.

Previous studies indicate that TOC% content in the Changputang borehole ranges from 0.51% to 2.14%, averaging 0.76%. The Shanglongjing borehole shows an overall TOC% range of 0.91% to 8.21%, with an average content of 4.27% [2].

4.4. Organic-Walled Microfossils and OM Abundance in Palynological Analysis

To explore hydrocarbon-generating organisms in the Renheqiao Fm., microscopic examination was performed on the experimental results of palynological OM from the Changputang and Shanglongjing borehole core. The palynological OM was classified into three categories: ① Organic-walled microfossils are collectively termed palynomorphs, primarily composed of phytoplankton and acritarchs, along with fungal spores (Figures 5 and 6), which were microscopically observed, photographed, and identified. ② Under transmitted light microscopy, SOM comprises dark-colored, opaque fragments characterized by sharp margins and well-defined internal structures, including cuticular sheets and cellular remnants (Figures 7–9). While these particles exhibit distinct morphological organization, their specific internal structures often remain unidentifiable at the observed scale. The advanced degradation stage imparts a dark brown to black color with fragment dimensions variable between 25 and 220 μm . They are mainly derived from macroalgae and animals [20]. Others are some gelified homogeneous masses, the product of the gelification of late-stage diagenesis [26], presenting as rounded or polygonal plates or foam-like structures, with conchoidal or irregular fractures, and appearing colorless, yellow, or orange-red. They are typically brighter than other macerals (Figure 7E–G). ③ Under transmitted light, AOM is transparent or opaque, flocculated or gelatinous, and shows no identifiable biological structure or stable contour (occasionally cell-structure remnants are observed; Figure 10). The opaque AOM (Figure 10a,c) corresponds to black structureless aggregates, and gelatinous transparent amorphous organic matter (TOM), which consists of flocculent or spongy aggregates (Figure 10b,c), most likely corresponding to cyanobacterial mats [20,41,43]. Mixed opaque and (TOM) is abundant in the measured sequences (Figure 10c).

Standardized quantification of the three categories of OM was conducted using the lycopodium-based quantification method (a lycopodium spore, Figure 10c). Palynological OM in both core samples is dominated by AOM, accounting for approximately 97–99% of the total, with minor SOM and diverse palynomorph assemblages.

4.4.1. Changputang

In the Changputang borehole core, the palynomorphs are predominated by micro planktonic algae, notably *Leiosphaeridia*, *Shuiyousphaeridium*, and *Baltisphaeridium*, while specific intervals contain abundant fragments of SOM. The distribution of these components reveals systematic stratigraphic patterns: organic-walled fossil assemblages form three distinct intervals, each characterized by peak abundances of micro phytoplankton and

acritarchs, with subsidiary contributions from macroalgae and fungal spores. Based on vertical variations in fossil types and AOM abundance, three hydrocarbon-generating organism assemblages are defined for this borehole, with their OM content concisely documented.

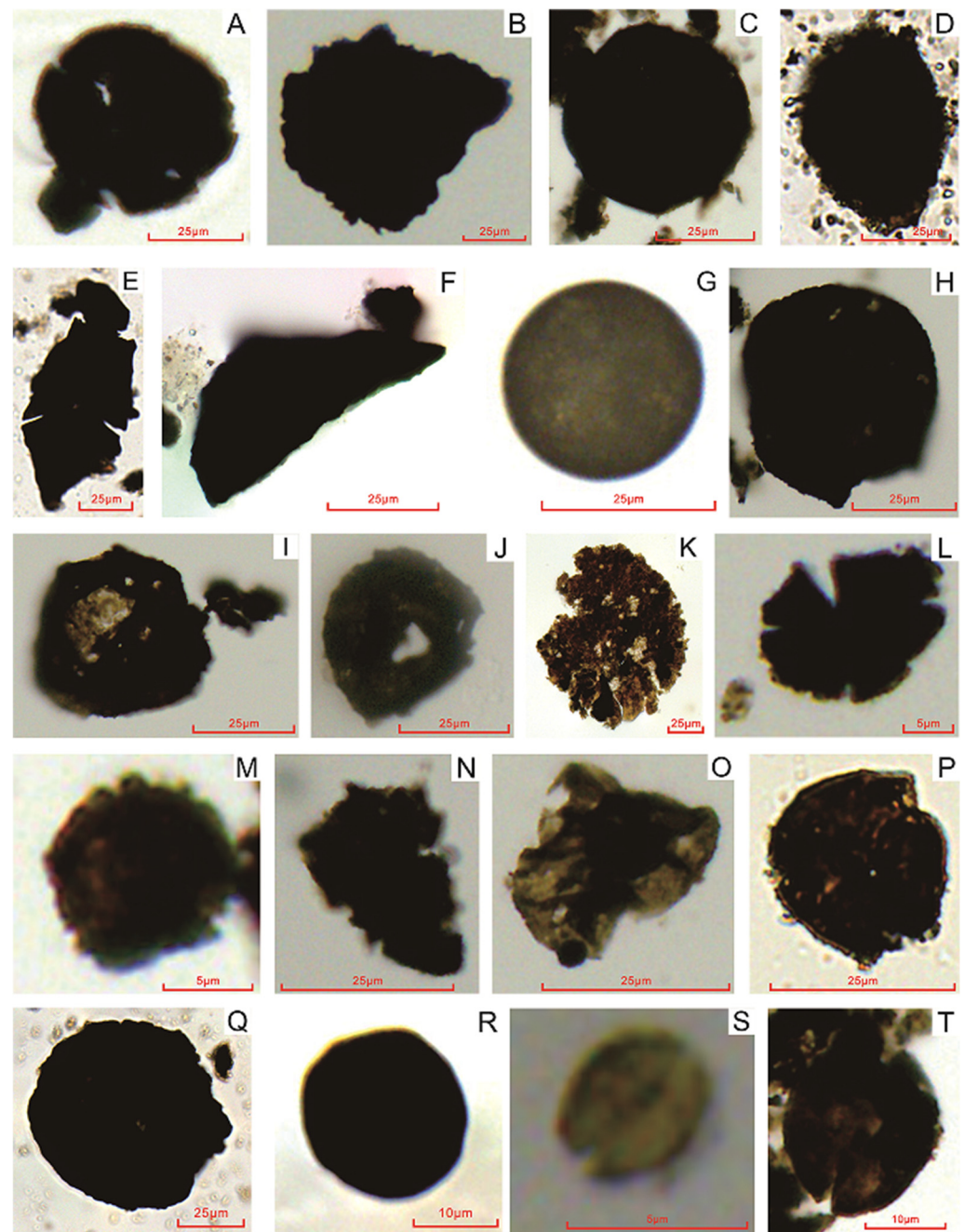


Figure 5. Organic-walled microfossils from the palynological slides of the Renheqiao Fm. in the Changputang core. (A), *Leiosphaeridia atava* from Bed 2 (CPT-11); (B), *Pireia sinensis* Li from Bed 2 (CPT-07); (C), *Leiosphaeridia* sp. from Bed 2 (CPT-11); (D), *Leiosphaeridia* sp. from Bed 4 (CPT-24); (E), *Shuiyousphaeridium macroreticulatum* from Bed 4 (CPT-25); (F), *Triceratium* sp. from Bed 6 (CPT-LCB); (G), fungal spore from Bed 2 (CPT-05); (H,I,K) *Leiosphaeridia* spp. from Bed 2 (CPT-10); (J), *Leiosphaeridia* sp. from Bed 2 (CPT-6); (L), *Protosphaeridium pusillum* from Bed 2 (CPT-12); (M), *Baltisphaeridium* sp. from Bed 3 (CPT-15); (N), *Leiosphaeridia anquensis* from Bed 3 (CPT-15); (O), *Tetrahedraletes medinensis*. from Bed 3 (CPT-15); (P), *Retisphaeridium* sp. from Bed 4 (CPT-25); (Q,R), fungal spore from Bed 3 (CPT-15); (S), *Classopollis monostraitus* from Bed 5 (CPT-27); (T), *Classopollis monostraitus* from Bed 5 (CPT-25).

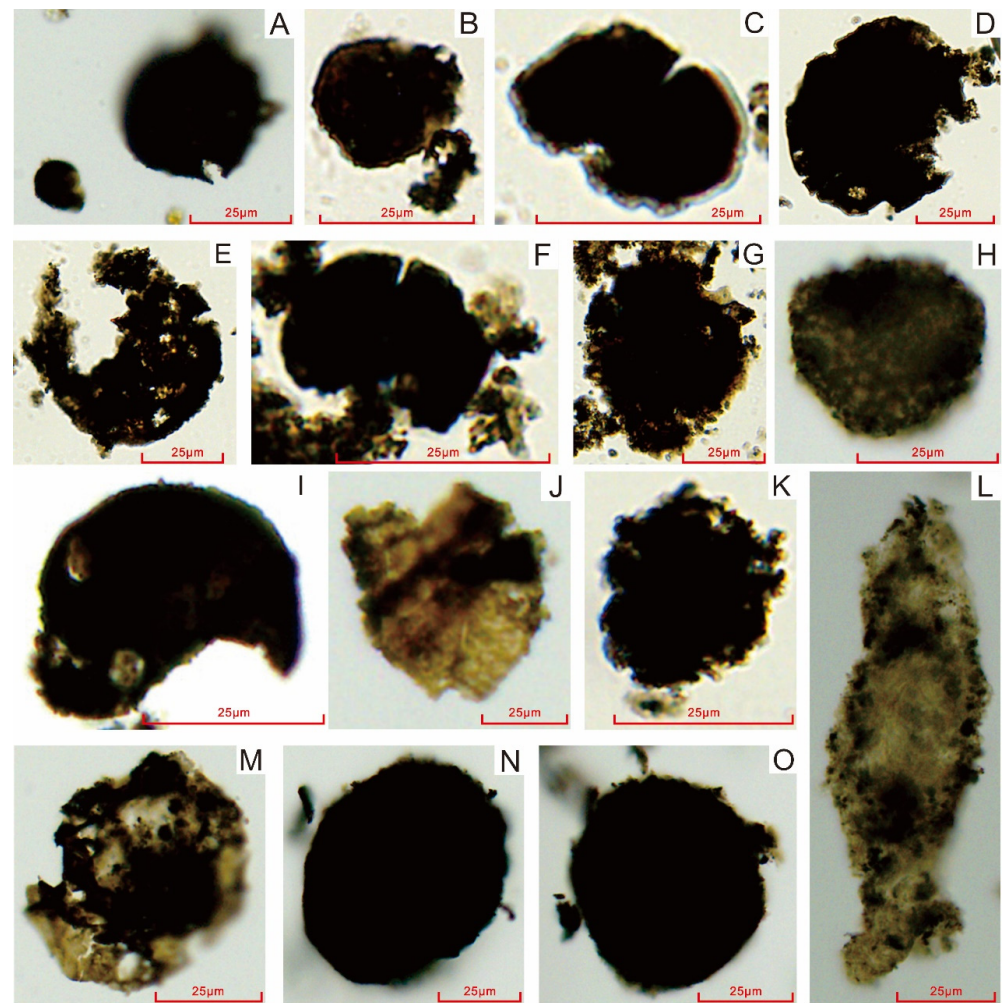


Figure 6. Organic-walled microfossils from the palynological slides of the Renheqiao Fm. in the Shanglongjing core. (A), *Leiosphaeridia* sp. from Bed 3 (SLJ-2); (B), *Visbysphaera microspinosus* from Bed 3 (SLJ-3); (C), subordinate multicellular sporangial fragments from Bed 3 (SLJ-3); (D), *Baltisphaeridium* sp. from Bed 9 (SLJ-15); (E), *Dictyosphaera delicata* from Bed 7 (SLJ-9); (F), *Leiosphaeridia* sp. from Bed 7 (SLJ-10); (G), *Baltisphaeridium* sp. from Bed 10 (SLJ-17); (H), *Arctacellularia ellipsoidea* from Bed 7 (SLJ-11); (I), *Pseudozonosphaera densa* from Bed 7 (SLJ-10); (J), *Meghystriospheraidium? densum* from Bed 9 (SLJ-14); (K), *Acrosphaeridium sensum* from Bed 9 (SLJ-14); (L), *Shuiyousphaeridium macroreticulatum* from Bed 5 (SLJ-7); (M), *Tetrahedraletes medinensis* from Bed 9 (SLJ-15); (N), *Leiosphaeridia* sp. from Bed 3 (SLJ-4); (O), *Leiosphaeridia* sp. from Bed 3 (SLJ-4).

(1) Interval 1 (samples CPT-01 to CPT-07): Designated as the *Leiosphaeridia* Zone.

This interval corresponds to the lower part of lithologic Bed 2 and is primarily composed of silty shale. Palynomorphs are dominated by black smooth-walled sphaeromorphs (*Leiosphaeridia*, Figure 5), exhibiting bilaterally symmetric circular or elliptical forms with smooth or wrinkled surfaces. Diameters (long axis) range 25–40 µm, occasionally showing monolet structures. Most specimens are indeterminate to species level, though *Leiosphaeridia atava* (Figure 5A) and *L. anquensis* (Figure 5N) were identified, predominantly preserved in a black to dark brown color. Only four genera and five species were documented. This zone is characterized by overwhelming *Leiosphaeridia* dominance, with subordinate occurrences of *Pireia sinensis* (Figure 5B). Palynomorph concentration averages 1464 pieces/25 g of sediment (variation curve shown in Figure 11).

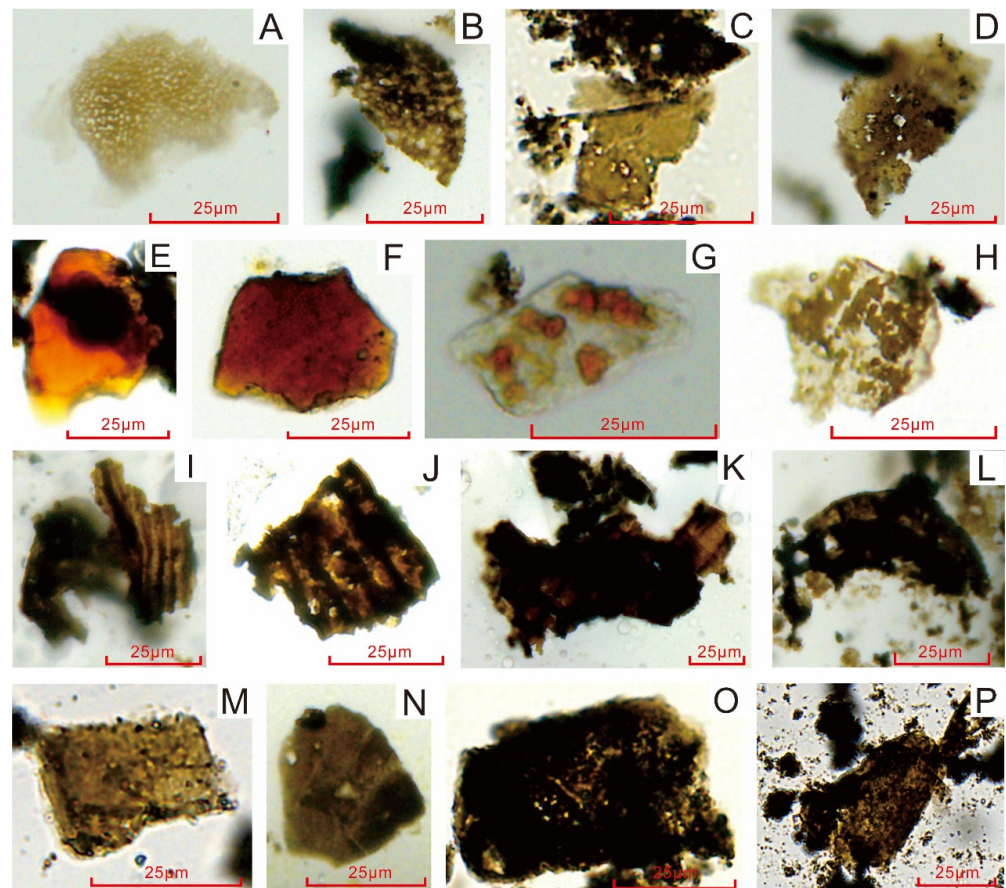


Figure 7. SOM from the palynological slides of the Renheqiao Fm. in the Changputang core. (A), fragment of *Visbysphaera microspinosa* from Bed 2 (CPT-3); (B), fragment of *Baltisphaeridium coolibahense* from Bed 5 (CPT-27); (C), light brown porous organic fragment from Bed 5 (CPT-27); (D), light brown porous organic fragment from Bed 4 (CPT-24); (E,F), homogenized gelified masses from Bed 3 (CPT-17); (G), homogenized gelified masses from Bed 4 (CPT-25); (H), light brown porous organic fragment from Bed 3 (CPT-15); (I,L), light brown porous organic fragment from Bed 3 (CPT-14); (J,P), light brown porous organic fragment from Bed 3 (CPT-20); (K,N), brown membranous biostructured sheets from Bed 2 (CPT-11); (M), light brown porous organic fragment from Bed 4 (CPT-24); (O), light brown porous organic fragment from Bed 4 (CPT-25).

Palynological OM content in this interval is moderate throughout the sequence (Figure 11). AOM primarily consists of flocculent opaque material with minor TOM, averaging 9,097,582.57 pieces/25 g. SOM appears as black or brown fragments, mostly well-defined blocks 70–320 µm in length (Figure 7K,N). Distinct porous structures are observable, featuring pore diameters of 0.8–2 µm (Figure 7A), indicative of macroalgal debris. SOM averages 8935 pieces/25 g.

- (2) Interval 2 (samples CPT-08 to CPT-18): Designated as the *Protosphaeridium-Baltisphaeridium* Assemblage Zone.

This interval spans from the upper part of lithologic Bed 2 to the lower part of Bed 3, and the lithology is dominated by silty shale interlayered with argillaceous shale. Micro-phytoplankton fossil diversity and abundance show a modest increase compared to the underlying interval 1. A total of seven genera and seven species were identified, dominated by *Protosphaeridium* and *Baltisphaeridium*, with common occurrences of *Shuiyousphaeridium macroreticulatum*, *Baltisphaeridium* sp. (Figure 5M), *Leiosphaeridia anquiensis* (Figure 5N), *Protosphaeridium pusillum* (Figure 5L), and *Tetrahedraletes medinensis* (Figure 5O). This zone also features rare fungal spores (Figure 5Q,R). The assemblage is characterized by abundant

animal-derived SOM (Figure 9E), light brown porous fragments of macroscopic algae (Figure 7H,I,L), brown membranous biostructured sheets (Figure 7K,N), and homogenized gelified masses (Figure 7E,F). Palynomorph concentration decreased to 952 pieces/25 g (variation curve shown in Figure 11).

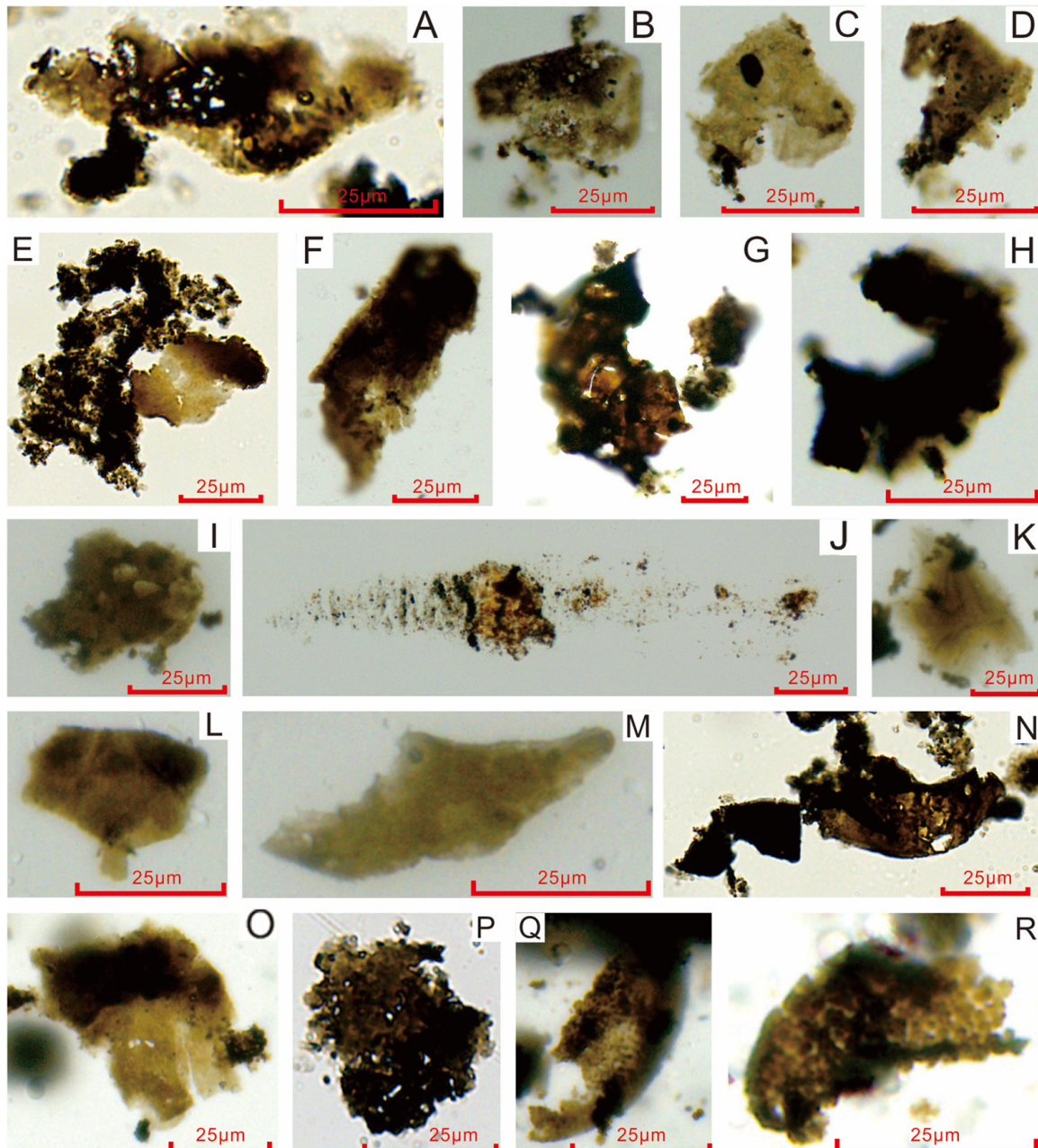


Figure 8. SOM from the palynological slides of the Renheqiao Fm. in the Shanglongjing core. (A), light brown porous organic fragment from Bed 3 (SLJ-2); (B,C), light brown porous organic fragment from Bed 3 (SLJ-4); (D), light brown porous organic fragment from Bed 4 (SLJ-6); (E), filamentous and granular OM fragments from Bed 10 (SLJ-20); (F), brown rod-shaped OM fragment from Bed 7 (SLJ-10); (G), irregular organic fragments from Bed 7 (SLJ-12); (H), brown, curved organic fragment from Bed 9 (SLJ-15); (I), light brown porous organic fragment from Bed 9 (SLJ-14); (J), cylindrical organic fragment with biological structures from Bed 9 (SLJ-14); (K,P), organic fragment with biological structures from Bed 7 (SLJ-12); (L), organic fragment with biological structures from Bed 10 (SLJ-17); (M), organic fragment with biological structures from Bed 10 (SLJ-20); (N), cylindrical OM fragments from Bed 7 (SLJ-11); (O), brown porous organic fragment from Bed 10 (SLJ-17); (Q,R), irregular organic fragments from Bed 10 (SLJ-18).

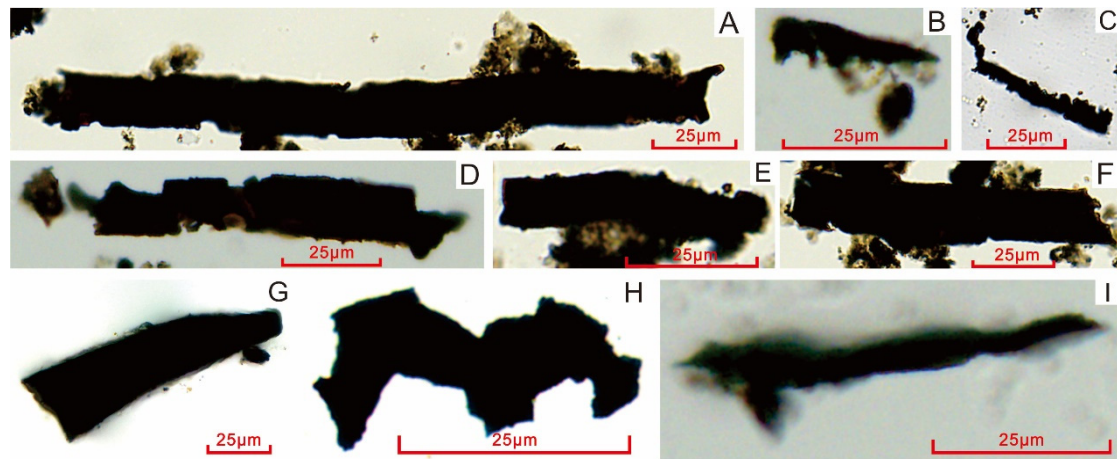


Figure 9. Animal-derived SOM from the Renheqiao Fm. in the Changputang and Shanglongjing cores. (A,D), animal organic lining from Bed 3 (CPT-15); (B), organic inner lining of sponge spicule from Bed 3 (SLJ3); (C,G), organic inner lining of sponge spicule from Bed 3 (CPT-20); (E), animal organic lining from Bed 2 (CPT-11); (F), animal organic lining from Bed 3 (CPT-16); (H,I), animal organic lining from Bed 4 (CPT-24).

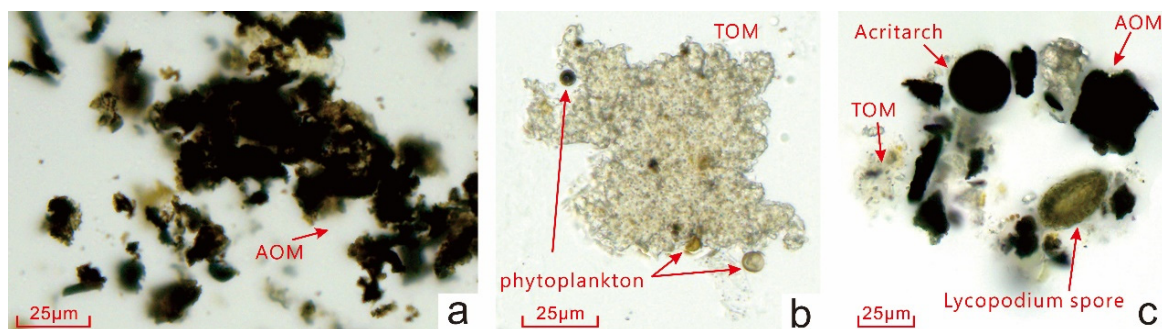


Figure 10. AOM from the Renheqiao Fm. in the Changputang and Shanglongjing cores. (a), opaque AOM from Bed 2 (CPT-3); (b), flocculated TOM from Bed 4 (CPT-23); (c), a mixture of opaque AOM, TOM acritarchs, and lycopodium spores.

In this interval, AOM content decreases significantly, reaching the lowest level in the entire sequence (Figure 11). It is dominated by flocculent and granular opaque material with minor TOM, averaging 5,098,245.36 pieces/25 g. SOM content shows no marked changes, maintaining an average concentration of 14,538 pieces/25 g.

(3) Interval 3 (samples CPT-19 to CPT-30): Designated as the *Shuiyousphaeridium* Zone.

This interval spans from the upper part of lithologic Bed 3 to Bed 6. The lithology of this interval primarily consists of silty shale, with total organic carbon content increasing upward through the sequence, exhibiting the highest microphytoplankton fossil diversity in the borehole, with eight genera and 12 species identified. It is characterized by abundant *Shuiyousphaeridium macroreticulatum* (Figure 5E), accompanied by *Leiosphaeridia* sp., *Visbysphaera microspinosa* (Figure 7A), *Baltisphaeridium* sp., *Meghystrichosphaeridium?* *densum*, *Acrosphaeridium sensum*, and *Baltisphaeridium coolibahense* (Figure 7B), alongside multicellular sporangial fragments, fungal spores, and *Classopollis monostriatus* (Figure 5S). Palynomorph concentration averages 1120 pieces/25 g (variation curve shown in Figure 11).

In this interval, AOM content displays an upward-decreasing trend, showing a significant decline within the R8 Zone (Figure 11). It is dominated by granular opaque material with minor TOM, averaging 13,581,837.38 pieces/25 g. SOM content exhibits no significant change, maintaining an average concentration of 13,251 pieces/25 g.

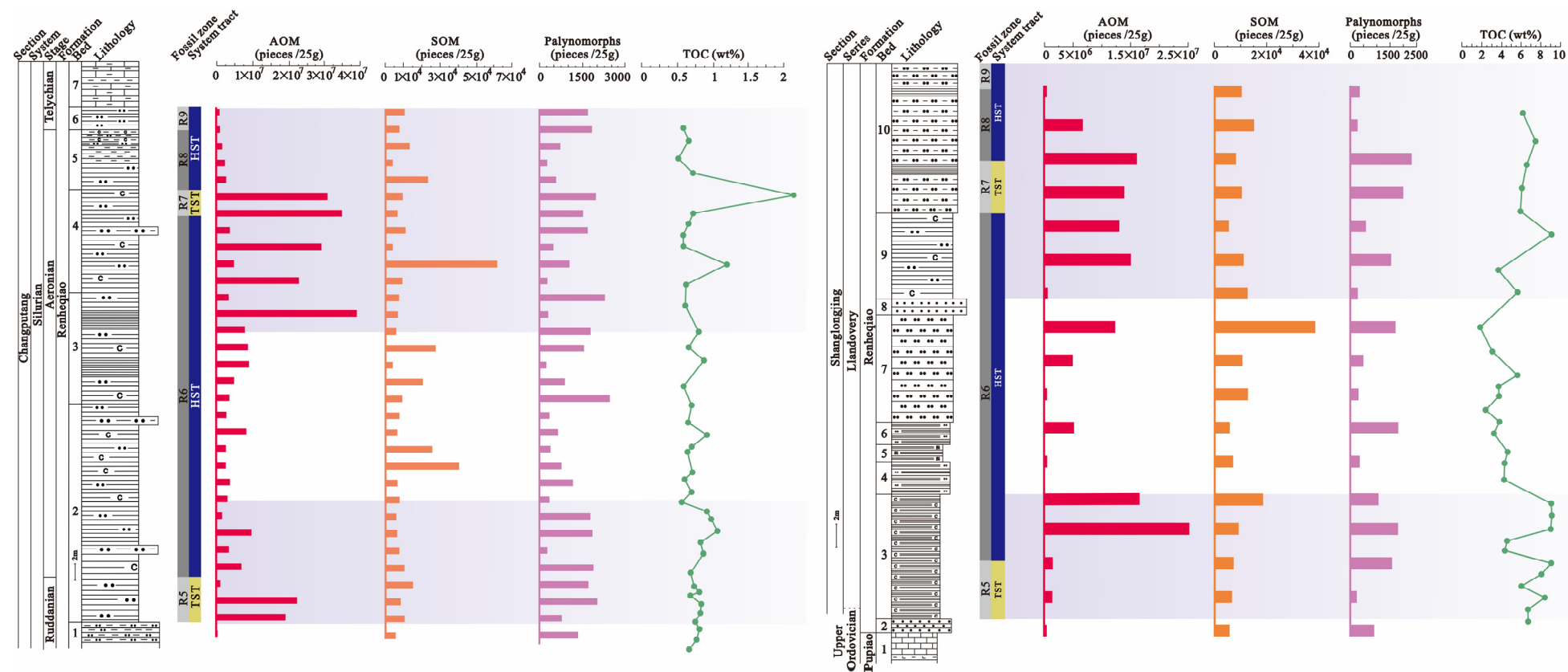


Figure 11. Palynological OM content and TOC% content of the Changputang and Shanglongjing cores (Legend same as in Figure 3. TOC% data cited from [2].).

4.4.2. Shanglongjing

The Shanglongjing borehole core exhibits abundant organic-walled fossils, with microphytoplankton dominated by *Leiosphaeridia*, *Baltisphaeridium*, and *Shuiyousphaeridium*. Significant fragments of macroalgae and animal-derived organic debris occur in specific intervals. Their distribution follows discernible stratigraphic patterns, featuring three distinct palynomorph assemblage and AOM abundance. This trend corresponds to three low-to-high preservation cycles of AOM and shows clear correlation with lithological transitions.

(1) Interval 1 (samples SLJ-01 to SLJ-05): Designated as the *Leiosphaeridia* Zone.

This interval corresponds to lithologic Bed 3, dominated by carbonaceous shale. Palynomorphs are overwhelmingly dominated by black smooth-walled sphaeromorphs (*Leiosphaeridia*), exhibiting bilaterally symmetric circular/elliptical forms, smooth or wrinkled surfaces, and occasional monolet structures, diameters (long axis): 25–40 µm. Most specimens are indeterminable to species level. Microphytoplankton fossils show low abundance and diversity, predominantly preserved in black to dark brown color. Identified taxa include *Leiosphaeridia* sp. (Figure 6A,N,O), *Visbysphaera microspinosa* (Figure 6B), and subordinate multicellular sporangial fragments (Figure 6C). Palynomorph concentration averages 966 pieces/25 g (variation curve shown in Figure 11).

In this interval, AOM content exhibits an abrupt upward-increasing trend (Figure 11). It primarily occurs as flocculent opaque material with minor TOM, constituting the primary organic facies, averaging 7,514,966.5 pieces/25 g. SOM appears as black or brown, well-defined blocks (80–300 µm long) with good preservation. Distinct porous structures are observable (pore diameters: 0.8–2 µm), interpreted as macroalgal debris and the organic inner lining of sponge spicule (Figure 9B), averaging 8939 pieces/25 g.

(2) Interval 2 (samples SLJ-06 to SLJ-12): Designated as the *Baltisphaeridium* Zone.

This interval corresponds to lithologic Beds 4–8, dominated by silty shale and siltstone with decreasing clay content. The fossil abundance of phytoplankton in this interval shows no significant difference from those in interval 1. A total of five genera and four species were identified, primarily featuring *Baltisphaeridium* sp., with common occurrences of *Dictyosphaera delicata* (Figure 6E), *Leiosphaeridia* sp. (Figure 6F), *Arctacellularia ellipsoidea* (Figure 6H), *Pseudozonosphaera densa* (Figure 6I), *Meghystrichosphaeridium? densum* (Figure 6J), and rare fungal spores. Palynomorph concentration averages 896 pieces/25 g of sediment (variation curve shown in Figure 11).

In this interval, AOM content exhibits a second low-to-high upward-increasing cycle (Figure 11). It is dominated by flocculent and granular opaque material with minor TOM, showing no significant change in average concentration at 4,605,809.6 pieces/25 g. The SOM assemblage in this interval is characterized by abundant macroalgae fragments and animal-derived fragments, including light brown porous fragments (Figure 8D), filamentous and granular fragments (Figure 8E), brown rod-shaped OM fragment (Figure 8F), cylindrical OM fragments (Figure 8N), and so forth (Figure 8). SOM content displays no marked variations, maintaining an average of 15,932 pieces/25 g.

(3) Interval 3 (samples SLJ-15 to SLJ-20): Designated as the *Shuiyousphaeridium* Zone.

This interval corresponds to lithologic Beds 9 to most of Bed 10, excluding the top part, dominated by silty carbonaceous mudstone with upward-increasing clay content. Microphytoplankton fossil diversity and abundance show a moderate increase compared to interval 2. A total of three genera and two species were identified, primarily featuring *Shuiyousphaeridium* sp., with common occurrences of *Acrosphaeridium sensum*, *Shuiyousphaeridium macroreticulatum*, and *Tetrahedraletes medinensis* (Figure 6M). Palynomorph concentration averages 1154 pieces/25 g of sediment (variation curve shown in Figure 11).

In this interval, AOM is dominated by flocculent and granular opaque material with minor TOM, showing an increase in average concentration at 10,824,266.67 pieces/25 g. This interval contains a low amount of animal-derived SOM, mostly composed of sponge spicule linings with minor amounts of brown biostructured membranous sheets. SOM decreased to an average of 9955 pieces/25 g (variation curve shown in Figure 11).

5. Discussion

5.1. Vertical Distribution of Organic-Rich Deposits in the Renheqiao Fm

The exploration and development of Upper Ordovician to Lower Silurian hydrocarbon source rocks have achieved significant success globally. Notably, the geological characteristics and research methodologies of shale gas in the Yangtze region have become exemplary models in China, providing valuable references for shale gas evaluation in other areas [35,44,45]. The Baoshan Block, situated on the southeastern margin of the Tibetan Plateau between the Gaoligong and Chongshan shear zones, shares the same Palaeo-Tethyan tectonic system as the southern Sichuan region (Yangtze Platform). Under the Palaeo-Tethyan Ocean tectonic framework, the Baoshan and Yangtze blocks exhibit similar tectonic-sedimentary evolutionary processes [46]. During the 480–380 Ma period, blocks such as South China, Sino-Indian, Songpan, and Qaidam continuously drifted northward. As the Palaeo-Tethyan Ocean opened, the Baoshan Block was briefly adjacent to the South China Block, leading to the contemporaneous deposition of similar organic-rich shales [23,47]. Graptolite biozone correlation confirms that the Late Ordovician to Early Silurian Renheqiao Fm. in the Baoshan Block is contemporaneous with the Longmaxi Fm. in southern Sichuan, with the R1–R9 graptolite zones of the Renheqiao Fm. being isochronously correlated to the LM1–LM9 zones of the Longmaxi Fm. (Figure 1; [34]).

Influenced by global sea-level fluctuations, the Yangtze region experienced an initial fall followed by a rise in sea level during the Katian–Aeronian, leading to the deposition of the graptolitic shale facies of the Wufeng Fm., the shell limestone facies of the Guanyinqiao Bed, and the graptolitic shale facies of the Longmaxi Fm. [48]. The Baoshan area underwent a similar sea-level fluctuation pattern during the Katian–Aeronian, sequentially depositing the calcareous mudstone facies of the Pupiao Fm., a palaeo-weathering crust, and the graptolitic shale facies of the Renheqiao Fm. During the Katian, the Pupiao Fm. was deposited in a relatively shallow-water environment, characterized by mudstones containing abundant calcareous nodules. Subsequent sea-level fall led to subaerial exposure, and the development of a weathering and denudation crust with associated stratigraphic hiatus. By the middle to upper Hirnantian (i.e., the R1 Zone), the area was re-submerged, depositing graptolitic mudstone facies under rapidly deepening marine conditions. During the Rhuddanian, the graptolitic shale facies of the Renheqiao Fm. developed, accompanied by substantial OM deposition that formed the material basis for hydrocarbon source rocks [49,50]. Therefore, to further understand the spatiotemporal distribution and OM enrichment characteristics of the organic-rich black mudstones/shale in the Renheqiao Fm. within the study area, comparisons were made with well-studied equivalent strata from the periphery of the Sichuan Basin in the Yangtze region and the Yongshan area in Yunnan (Table 2).

Previous studies indicate that the organic-rich shales of the Renheqiao Fm. in the Baoshan area are generally within the mature to post-mature gas-generation window [49–52]. Due to the absence of vitrinite derived from higher plants in Lower Paleozoic sedimentary rocks, graptolite reflectance measurements conducted across the sequences in the study area suggest that the bitumen in the Renheqiao Fm. samples likely originates primarily from graptolites or organic sources with similar structures, exhibiting comparable maturity characteristics. Therefore, to accurately determine the maturity level while accounting for some degree of weathering in the samples, graptolite reflectance—being well-defined in ori-

gin and showing good convergence—was selected as the reference parameter for maturity assessment [53]. Measurements reveal no significant vertical variation in maturity across the four sequences in the study area. Laterally, the highest random graptolite reflectance (GRo) is observed in the Shanglongjing core, reaching up to 1.86%, while the lowest value is recorded in the Chadi section, at only 1.16%. The EqVRo follows a distribution trend consistent with the GRo values (Table 1). Graptolite reflectance values from outcrop samples are lower than those obtained from the two borehole cores, likely due to varying degrees of weathering in the outcrop samples. In contrast, the borehole cores provided a larger number of samples, enabling more measurement points under microscopic examination [2], and generally contained better-preserved graptolites. The random GRo values measured from individual samples predominantly followed a normal distribution, demonstrating robust statistical significance. For example, in the Shanglongjing core, GRo values are 1.86% on average [2]. Therefore, assuming the thermal maturity is comparable between the outcrop and core samples, the GRo data from the Shanglongjing and Changputang wells are highly reliable indicators of OM thermal maturity, though inherent maturity differences between the selected outcrops and the two boreholes cannot be entirely ruled out. Before proceeding to the stratigraphic distribution of organic-rich intervals, it is necessary to consider the potential impact of the methodological constraints outlined in Section 3.2 on our thermal maturity assessment. First, the empirical conversion from GRo to EqVRo [37] may introduce some uncertainty, particularly at the high-maturity end of the spectrum. However, the consistency between our GRo measurements and published data from the same region [2] suggests that any systematic bias is likely minor and does not affect the relative maturity ranking among the studied sections. Second, the slightly lower GRo values obtained from the Chadi and Banpo outcrop sections compared to the borehole cores are consistent with the expected effect of surficial weathering. Crucially, the maturity trend among the four sequences—with Shanglongjing > Changputang > Banpo > Chadi in terms of both GRo and EqVRo—is coherent and geologically plausible, regardless of the absolute values. Therefore, the conclusion that the Renheqiao Formation has reached high to post-maturity, comparable to the Longmaxi Formation in the Yangtze region, remains robust.

Regarding the favorable depositional period of organic-rich shales, previous studies indicate that high-TOC intervals in the Fuling JY-1 and Changning N211 wells of the Yangtze region are predominantly confined to three graptolite biozones (LM2–LM4) within the lower Rhuddanian of the early Silurian [35]. Petrological and organic geochemical analyses further confirm that the corresponding black shales in these intervals represent significant hydrocarbon-producing zones [54–56]. However, the favorable depositional period varies across the Yangtze region, with the Longmaxi Fm. terminating at different levels ranging from LM7 to LM9 biozones. Consequently, the upper boundary of the black shales is diachronous. In some areas, the most prospective intervals are predominantly distributed from the middle-upper Wufeng Fm. to the lower Longmaxi Fm., corresponding to the WF2–LM6 biozones, with a composite thickness of approximately 66.25 m [10,35,45,57].

The TOC% content from the four sequences in the study area generally exhibits the following characteristics: Although the four sequences show significant differences in TOC% content, in the order of Shanglongjing > Chadi > Banpo > Changputang, the favorable intervals display relatively consistent depositional timing distributions. In the Chadi section, the R1–R6 zones all show high TOC%, representing favorable intervals; thus, Beds 2 to 10, with a total thickness of 15.7 m, can be considered as high OM content zones. In the Banpo section, Beds 1–2 (middle R6 Zone) exhibit relatively low TOC%, while the remaining intervals constitute favorable depositional zones for organic-rich mudstones, with a cumulative thickness of 42 m (Figure 4). Both the Changputang and Shanglongjing boreholes show lower TOC% and AOM content in the middle R6 Zone, which does not

belong to the favorable intervals, while the remaining zones are prospective, with 42.5 m in Changputang and a cumulative 32 m in Shanglongjing. Therefore, the favorable intervals in the Renheqiao Fm. can be defined as the lower R1–R6 zones and the upper R6–R9 zones, with a total thickness of approximately 74–84.5 m (Figure 11), which is not inferior to the favorable depositional areas in the Yangtze region.

Table 2. Graptolite biozones, thickness, sedimentary rate, and TOC% comparison between the Chadi and Banpo sections, Xindi 2, and Jiaoye 1 boreholes. (Biozone durations are calibrated to the Geologic Time Scale 2012 [58]; sedimentation rate ranges are calculated assuming a conservative $\pm 10\%$ uncertainty in biozone duration).

System	Series	Stage	Fossil Zone	Duration of Deposition ($\pm 10\%$ Ma)	Chadi Section (This Study)			Banpo Section (This Study)			Xindi 2 Borehole [35]			Jiaoye 1 Borehole [10,59]		
					Thickness (m)	Deposition Rate (m/Ma)	TOC (%)	Thickness (m)	Deposition Rate (m/Ma)	TOC (%)	Thickness (m)	Deposition Rate (m/Ma)	TOC (%)	Thickness (m)	Deposition Rate (m/Ma)	TOC (%)
Silurian	Llandovery	Telychian	R9 (LM9)	0.36				>8.8 (Top unexposed)	>24.44 (22.22–27.16)	2.33						
			R8 (LM8)	0.27				2.3	8.52 (7.74–9.47)	2.65	52.99	196.26	0.74	>44.19	>163.67	1.43
		Aeronian	R7 (LM7)	0.45				9.4	20.88 (18.99–23.21)	1.78	40.65	90.33	1.31	4.03	8.96	2.40
			R6 (LM6)	1.56	>7.25 (Top unexposed)	>4.64	2.29	>33.5 (Base unexposed)	>21.51 (19.52–23.86)	2.33	36.53	23.42	2.76	19.21	12.31	1.99
			R5 (LM5)	0.8	3.48	4.35 (3.95–4.83)	2.04				2.10	2.62	3.94	23.15	28.94	2.59
		Ruddanian	R4 (LM4)	0.9	1.87	2.07 (1.89–2.31)	4.46				9.20	10.22	5.85	13.69	15.21	3.66
			R3 (LM3)	0.93	0.79	0.84 (0.77–0.94)	6.02									
			R2 (LM2)	0.43	0.85	1.97 (1.80–2.20)	2.82				12.40	9.12	3.79	3.49	2.57	4.67
Ordovician	Upper Ordovician	Hirnantian	R1 (LM1)	0.6	0.85	1.42 (1.29–1.57)	2.33				1.07	1.78	6.16	4.34	7.23	3.22
			wf4	0.73												

5.2. Relationship Between Sedimentation Rate and Depositional Environment of the Renheqiao Fm

To further analyze the relationship between sedimentation rate and depositional environment in the Renheqiao Fm. within the study area, sedimentation rates were calculated based on graptolite biozone age data calibrated to the Geologic Time Scale 2012 (GTS2012) [58] and Sedimentation Rate (m/Ma) = Formation Thickness (m)/Biozone Duration (Ma). These calculations involve two key assumptions: (1) that compaction has not significantly altered the original thickness, and (2) that the mean age durations of the graptolite biozones are accurate. Uncertainties associated with these assumptions imply that the calculated rates are best interpreted as generalized estimates. According to GTS2012 ([58] Table 1), the 95% confidence uncertainty for Silurian stage boundaries ranges from ± 1.1 to ± 1.5 Ma. Given that our graptolite biozones are subdivisions of these stages, a conservative $\pm 10\%$ uncertainty in biozone duration is well within the range of uncertainty acknowledged by the international time scale community. The acknowledgment and quantification of uncertainty in geological time scaling and resource assessment are widely recognized as essential practices in unconventional hydrocarbon studies (e.g., [60]). Our approach (using a conservative $\pm 10\%$ uncertainty in biozone duration to calculate sedimentation rate ranges) is fully consistent with this principle. These rates were compared with data from the Xindi 2 and Jiaoye 1 wells in the Yangtze region (Table 2).

Since the R1–R5 biozones are only exposed in the Chadi section, data from this section were used for calculations in these intervals. For the R6–R9 biozones, the Banpo section was selected for sedimentation rate calculations due to its abundant graptolite preservation, de-

tailed research, and high reliability of stratigraphic thickness, as the three sequences (Banpo, Changputang, and Shanglongjing) show similar thickness variations in each graptolite biozone and consistent TOC% and AOM trends. Although TOC% content varies among the four study areas, the general variation patterns remain consistent. Thus, the Banpo section, which shows closer characteristics to the two Yangtze region wells, was selected as representative for discussing the impact of sedimentation rate on OM enrichment, while also considering data from the Changputang and Shanglongjing sequences.

The results show that the cumulative thickness of the R1–R4 graptolite biozones in the Chadi section is relatively small, measuring only 2.49 m, which aligns with previous descriptions of stratigraphic thickness variations in the Baoshan area [32,51]. In terms of sedimentation rate, the mean value for the R1–R4 biozones in the Chadi section is 1.41 m/Ma, which is 6.9–7.7 times lower than that of the Xindi-2 and Jiaoye-1 wells in the Yangtze region. However, the average TOC% content reaches 4.27%, comparable to the mean TOC% of 4.56% in the LM1–LM3 biozones of the Xindi-2 and Jiaoye-1 wells [10,59]. Analysis suggests that, during this period, the Yangtze region was significantly influenced by marine regression, leading to a substantial increase in sedimentation rate, greater stratigraphic thickness, and OM enrichment. In contrast, the Baoshan area experienced a more gradual marine regression, resulting in relatively thinner strata but conditions highly conducive to OM enrichment and preservation.

In the R6 Zone, the Banpo section, Changputang borehole, and Shanglongjing borehole all span substantial stratigraphic thicknesses of approximately 33.5 m, 44.7 m, and 42.7 m, respectively, reflecting the relatively stable variation characteristics of the Baoshan Block. This is consistent with the 36.53 m thickness of the LM6 Zone in the Xindi-2 well from the Yangtze region. During this stage, the sedimentation rate in the Banpo section exceeds 21.51 m/Ma, showing a magnitude and degree of influence comparable to the 23.42 m/Ma rate in the Xindi-2 well, both characteristic of high sedimentation rates. Despite clear regression influences, TOC% values at both locations remain at averages of 2.29% and 2.76%, without significant decline under the dilutive effect of high sedimentation rates, demonstrating acceptable OM enrichment. Therefore, in the Baoshan area, the R5 Zone represents only the initial phase of marine regression, whereas, in the Yangtze region, the Jiaoye-1 well experienced concentrated regression effects during the LM5 stage and the Xindi-2 well showed more pronounced regression influence by the LM6 stage.

Starting from the R7 Zone, the thickness of this zone across all studied locations in the Baoshan area is relatively thin, with an average of 5.7 m, a trend consistent with the LM7 Zone in the Jiaoye-1 well. In the Banpo section, the R7 Zone exhibits a sedimentation rate of 20.88 m/Ma, remaining high and indicating a continued regression process. Overall, a transgression occurred across the Baoshan area after the R7 Zone, though with minor local variations. This is most evident in the R8 Zone of the Banpo section, which reflects a sediment-starved state during the maximum flooding stability period, characterized by minimal thickness and slow deposition over 0.27 Ma. During this interval, TOC% shows some recovery. In contrast, the Changputang and Shanglongjing cores recorded this process earlier, within the R7 Zone.

Unlike the LM7–LM8 zones in the Jiaoye-1 well in the Yangtze region, which were influenced by maximum flooding [35], the Baoshan area experienced a later regression during the R9 Zone. Notably, TOC% did not decrease significantly despite increased sedimentation rates, indicating sustained OM enrichment. During the regression cycle, changes in the depositional environment and the shift from reducing to oxidizing conditions affected nearshore areas earlier. This distinct pattern, characterized by comparable or greater cumulative thicknesses of organic-rich intervals despite differing sedimentation rates, is consistent with a delayed response of the Baoshan Block to regional sea-level

fluctuations due to its more distal paleogeographic setting on the Sibumasu Block [61–64]. This pattern of sustained organic enrichment in a distal, slope-related setting is consistent with the “continuous accumulation” model for unconventional hydrocarbon systems described by Kokkinos et al. [60], who emphasized the importance of basin-center and basin-slope settings for long-term organic matter preservation.

5.3. Characteristics of Hydrocarbon-Generating Organism Assemblages and Their Correspondence with OM Distribution

The investigated sequences exhibit strong consistency in TOC%, AOM content, and distribution characteristics of organic-walled fossils, with minimal variation in the thickness of each fossil zone. Based on these characteristics, the hydrocarbon-generating organisms and OM distribution in the Renheqiao Fm. can be divided into three stages (Figure 12).

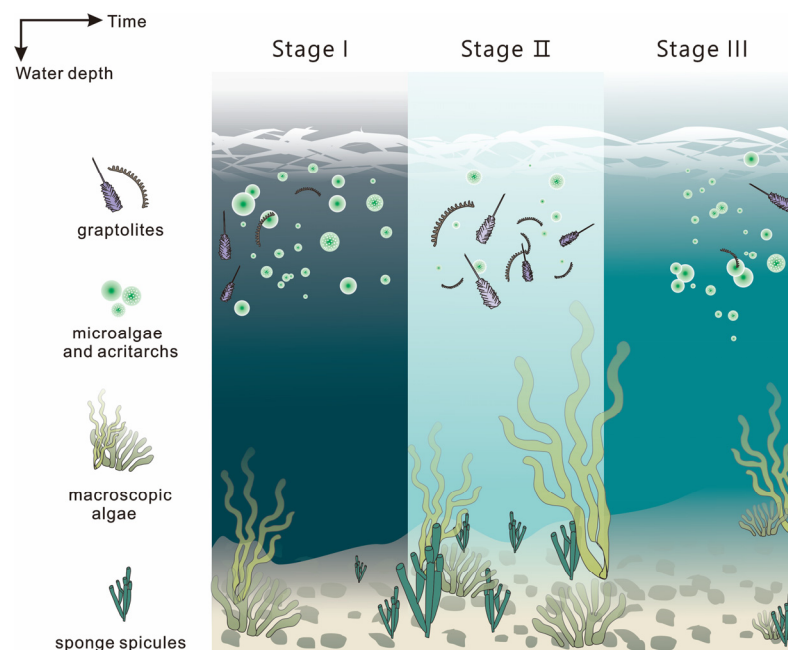


Figure 12. A schematic diagram showing the three-stage hydrocarbon-generating organism assemblages of the Renheqiao Fm. (legend indicates types, not actual sizes).

Stage I spans the R5 Zone to the lower R6 Zone, with an average thickness of 11.9 m across the four sequences. Including the 5.2 m thickness from the R1–R4 zones in the Chadi section, the total thickness reaches 17.1 m. This stage corresponds to the *Leiosphaeridia* Zone identified in the Changputang and Shanglongjing boreholes, characterized by high TOC%, high palynomorph content, and high AOM, indicating organic-rich conditions. The hydrocarbon-generating organisms in this stage are primarily microalgae and acritarchs, with some macroscopic algae and minor sponge spicules (Figure 12). Graptolite content shows an increasing trend, contrasting with the declining TOC% curve (Figure 4). Furthermore, the relatively low sedimentation rate during this stage favored OM accumulation.

Stage II corresponds to the middle R6 Zone, with an average thickness of 17.9 m across the four sequences. This interval is equivalent to the *Protosphaeridium-Baltisphaeridium* Assemblage Zone in the Changputang borehole and the *Baltisphaeridium* Zone in the Shanglongjing borehole. Decreases in TOC%, palynomorph content, and AOM are observed, indicating poor OM enrichment. The composition of hydrocarbon-generating organisms during this stage shows a notable increase in macroalgae and animal-derived OM, while microplanktonic algae and acritarchs decrease (Figure 12). Additionally, correlation analysis further confirms the negative relationship between graptolite abundance and TOC%,

with the analysis yielding a moderate negative correlation with a correlation coefficient of $R = -0.54$. This relationship is statistically significant, with a p -value of $p = 0.038$ ($p < 0.05$) (The raw data are provided in the Supplementary File). The quantitative evidence now provides clear and testable support for our interpretation of a negative relationship between graptolite abundance and TOC enrichment. This supports the interpretation that higher graptolite abundances are associated with lower OM enrichment. This association could be explained by graptolites acting as consumers of primary productivity, and by environmental conditions favoring graptolite communities (e.g., better-ventilated water masses) being less favorable for OM preservation.

It is certain that the overall lower TOC% levels in the R6 Zone are influenced by dilution from increasing terrestrial input, as demonstrated in Section 4.2. At the same time, the decline in TOC% during this stage is clearly controlled by changes in palynological OM content and hydrocarbon-generating assemblage. Therefore, it can still be demonstrated that the OM enrichment is affected by the hydrocarbon-generating assemblage, rather than being unidirectionally diluted solely due to the increase in sedimentation rate.

Stage III spans the upper R6 Zone to the R9 Zone, with an average thickness of 27.1 m across the four sequences. This stage corresponds to the *Shuiyousphaeridium* Zone identified in both the Changputang and Shanglongjing boreholes. During this interval, TOC%, palynomorph content, and AOM all increased significantly, indicating excellent OM enrichment. The composition of hydrocarbon-generating organisms in this stage shows an initial marked decline in macroscopic algae, with animal-derived OM limited to minor sponge spicules, while microplanktonic algae and acritarchs become more abundant (Figure 12). Persistently low graptolite content coincides with rising TOC% (Figure 4). Although the overall sedimentation rate during this stage remained high, OM accumulation was not strongly diluted, indicating that depositional conditions remained favorable.

Therefore, the high-quality hydrocarbon-generating organisms in the Renheqiao Fm. are microphytoplankton such as algae and acritarchs, rather than macroscopic algae. Animals exert a negative impact on productivity; for instance, both animal-derived debris and graptolites are associated with reduced productivity, likely due to their role as secondary consumers that deplete primary productivity.

6. Conclusions

The Renheqiao Fm. in the Baoshan region (western Yunnan, China) accumulated on the central Sibumasu Block, a setting that was located farther offshore in the Proto-Tethys Ocean. Understanding such depositional systems in ancient oceanic margins provides a critical analogue for evaluating hydrocarbon potential in modern, similarly situated marine basins away from major terrigenous input. Based on the results, the following conclusions can be drawn:

1. The vertical distribution of organic-rich shales in the Renheqiao Fm. is well-defined, with the thickness and duration of its high-quality intervals effectively comparable to those of the Longmaxi Fm. in the Yangtze region. The depositional timing of favorable intervals is highly consistent: they are primarily concentrated in the lower R1–R6 and upper R6–R9 graptolite biozones, with a cumulative thickness of 74–84.5 m, which is not less than that of the main intervals in the Yangtze region.
2. Graptolite reflectance values (1.16–1.86%) and equivalent vitrinite reflectance values (1.23–1.92%) from the Renheqiao Fm. indicate a high to post-maturity stage of thermal evolution. This maturity range is broadly comparable to that of the productive Longmaxi Formation in the Yangtze region, suggesting that the formation has entered the late hydrocarbon generation window and holds significant potential for shale gas.

3. The Renheqiao Fm. exhibits a sedimentary pattern characterized by an apparent delayed response to regional regressive trends yet sustained organic enrichment, which differs in detail from the sequences of the Yangtze Plate. This distinctive pattern is best explained by its more distal tectonic setting on the Sibumasu Block, which likely buffered it from the immediate effects of marine regression. We interpret that this setting was conducive to prolonged and enhanced OM accumulation.

4. The hydrocarbon-generating organism assemblages in the Renheqiao Fm. can be divided into three stages: The first stage (lower R1–R6 zones) is dominated by micro phytoplankton and acritarchs, corresponding to high TOC% and AOM content, representing the most favorable hydrocarbon-generating assemblage; the second stage (middle R6 Zone) shows an increase in macro algae and animal-derived debris, a decrease in micro phytoplankton, and a significant reduction in TOC%; the third stage (upper R6–R9) marks a recovery of micro phytoplankton and renewed OM enrichment. These assemblages indicate that primary producers (microphytoplankton/acritarchs) are associated with high-quality hydrocarbon generation potential. In contrast, secondary consumers (e.g., graptolites, sponges) are linked to conditions less favorable for OM preservation and/or may have played an inhibitory role in net accumulation.

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Abbreviations

The following abbreviations are used in this manuscript:

Fm.	Formation
TOC	total organic carbon
OM	organic matter
AOM	amorphous organic matter
SOM	structured organic matter
TOM	transparent amorphous organic matter
GRo	graptolite random reflectance
EqVRO	equivalent vitrinite reflectance

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