The Relationship between Late Devonian Environmental Evolution and Organic Matter Enrichment

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Abstract

This work aims to obtain new perspectives on environmental conditions and the accumulation of organic matter (OM) during the Late Devonian period, particularly the Frasnian-Famennian (F-F) interval in the Lengshuijiang section of South China. The Late Devonian experienced several climatic, oceanographic, and ecological changes, accounting for approximately 5% of Phanerozoic biodiversity loss, representing one of the most severe extinction events in Earth's geological history. Of all F-P transitions, the first one – the F-F transition – is the weakest and is associated with accelerated environmental and biological events and the lowest species tweet-diversity level (Wang et al., 2020). This study seeks to explain the conditions that prevailed during the F-F transition by analyzing total organic carbon (TOC), P/Al, (chemical index of alteration) CIA, and Co/Ni ratios to elaborate on the factors that enabled the enrichment of organic matter during the period.

The deposition of organic matter in sedimentary records provides essential information about past environmental conditions. This process registers the amount of organic matter produced and preserved in connection to the sedimentary facies and associated geochemical factors. Hypothetical reconstructions of the Late Devonian environmental conditions indicate high TOC levels that coincide with anoxic or euxinic conditions in marine settings. All these conditions are believed to have been caused by variations in the sea level, ocean stagnation, and ineffective water movement in the ocean by which oxygen was cut off from deep waters. Such disruptions scenario made the seafloor littered with organic matter due to the slow decomposition of organic matter on the ocean floor produced by such conditions (Percival et al., 2020). These environmental changes are proposed to have led to the F-F mass extinction when these alterations interacted with anoxia, which in turn was panned by high primary productivity,

resulting in the formation of organic-rich black shales. These black shales, which are abundant in the Late Devonian stratigraphic sequence, serve as evidence of the complex interactions between oceanic processes and climate systems during this geological interval. This version improves clarity, grammar, and flow while preserving the meaning of the original content.

New production through nutrient inputs into the marine food webs significantly controls organic matter concentration. Since continental weathering determines nutrient availability, nutrient supply is a significant factor in ocean primary production (Sahoo et al., 2023). As weathering rises in response to the warm and humid climates, materials containing phosphorus and nitrogen in the continental crusts of the earth would have swung into the oceans to support the growth of chlorophyll-producing phytoplankton and other microbial lives. Such biological blooms are likely to have causally resulted in higher accumulation rates of organic material on the sea floor. Nevertheless, this organic material required the preservation of the bones by reducing conditions in the marine environment, which favored redox changes. Based on Co/Ni ratios as proxies for the redox state, it is observed that anoxia or euxinic conditions prevailed during the accumulation of high amounts of OM. These reducing conditions would have minimized the decomposition of organic material, thereby enhancing its preservation. This balance between primary productivity and preservational potential is believed to have led to the deposition of organic-rich sediments typical of the Late Devonian.

Further, by using the CIA parameters, whose values change erratically, it is possible to better understand the climatic conditions that influenced organic matter deposition. The remaining CIA provides an efficient measure of the degree of chemical weathering of continental rocks and reflects the climatic conditions during the Late Devonian. Rhythmical fluctuations between warmer and more humid conditions, favorable for chemical weathering, supplied nutrients to marine food chains, repeatedly enhancing primary production in the process (Sahoo et al.., 2023). Conversely, what would have happened during more remarkable and relatively more recycled phases is employing a concept of lowered weathering and nutrient cycles, which in turn would mean lower proportions of primary productivity and changes in the deposition of organic matter. These climatic fluctuations played a central role in influencing the environmental fluctuations that defined the F-F transition and in dealing with additional pressures on the marine ecosystems to trigger mass extinction.

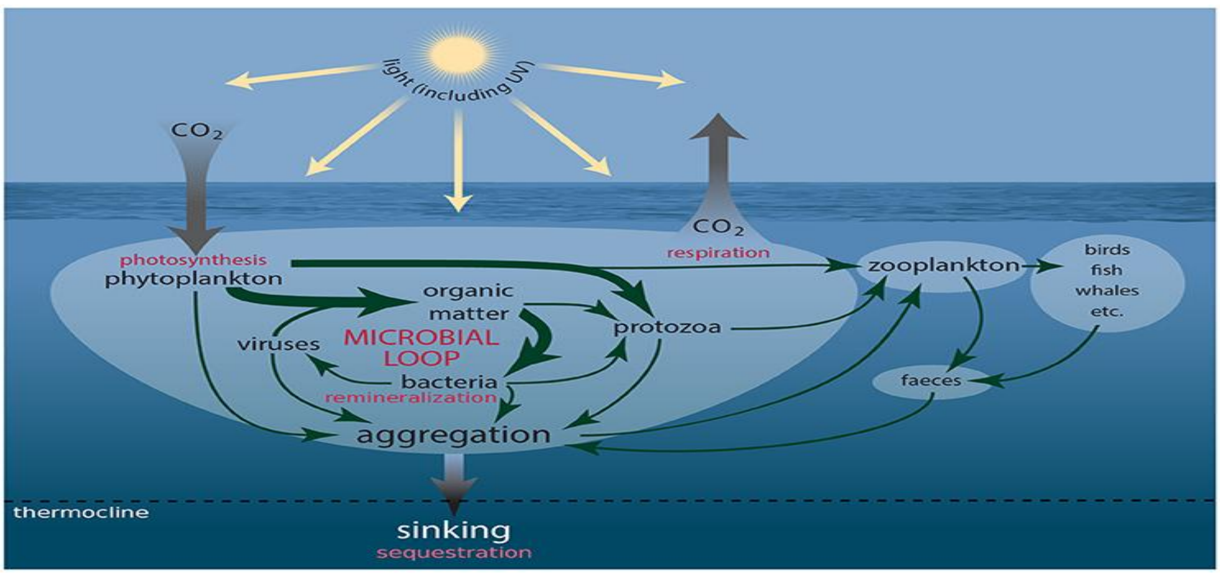
This study demonstrates the interconnectedness of climate, ocean chemistry, and biology, particularly during global catastrophes, which disentangles primary production and preservation mechanisms as the two key sources of organic matter that led to one of Earth's most profound biotic crises. That is why the authors focus on geochemical proxies and their significance for the reconstruction of past environmental conditions, which contributes to a better understanding of multiple factors that regulated the Late Devonian ecosystem (Zhao et al., 2022). Furthermore, the findings have important implications for today's ecosystems, as we face similar pressures from climate change, ocean degassing, and disruptions in chemical cycles. The historical insights provided in this research are crucial for understanding the impacts of current and future environmental changes on global biodiversity and ecological resilience. By comparing past environmental crises with present ones, this study offers a vital perspective for assessing the stability and vulnerability of ecosystems amid ongoing global change.

Keywords: Late Devonian, Frasnian-Famennian extinction, Organic matter accumulation, Geochemical proxies, Anoxia, Euxinian, Chemical Index of Alteration (CIA), Marine ecosystems, Paleoclimate, Environmental stress

Intoduction

Preservation of OM in sedimentary archives plays a crucial role in understanding past environmental changes and identifying potential hydrocarbon source rocks. These deposits provide valuable insights into climatic, biological, and geochemical history and are instrumental in mapping energy reserves.

Currently, two primary models are widely accepted as explanations for the observed increase in OM accumulation: the primary production model and the preservation model. The first productivity model suggests that elevated biological productivity in the surface waters of the ocean leads to an increased accumulation of solid organic matter on the ocean floor. This productivity commonly arises due to the economic success of the primary producers like the phytoplankton, which are known to have a very short response time to influxes of nutrients. These nutrients are mostly linked to limited elements like P, Ba, Zn, and others that may result from volcanic eruptions, continental crust weathering, and upwelling processes (Fedo et al., 1995). For example, volcanic eruptions can distribute nutrients like ash into the oceans, while the chemical weathering of continental rocks introduces nutrients into rivers and oceans. Besides, the areas characterized by upwelling zones, that is, the rising of nutrient-rich waters from the deeper part of the ocean, also increase biological production. These nutrient-rich conditions can lead to blooms of primary producers, which, upon dying and sinking, contribute significantly to the accumulation of OM on the seabed. A key feature of this model is that the accumulation of OM is driven by nutrient availability, particularly in upwelling areas and other marine regions with similar conditions.



On the other hand, the preservation model focuses on how topographic conditions at the depositional site, along with other factors, prevent organic matter (OM) from decomposing once it settles at the bottom of water bodies. The best conditions for OM preservation are anoxic – low oxygen availability and euxinic – high occurrence of hydrogen sulfide that inhibits aerobic degradation of the material (Sahoo et al., 2023; Tessin et al., 2015). These conditions are detrimental to the decomposer organisms and minimize the tendencies of enzymatic action that would otherwise decompose the organic material, thus entombing the organic material within the sediments. It was theorized that the Late Devonian ventilation shut down and, coupled with fluctuations in sea-level and ocean stagnation, conditions led to the formation of OM (Ma et al., 2016). Such conditions of restricted oxygen availability are further supported by the subsidence of anoxic bottom waters and the accumulation of thick black shale sequences formed during the same period. These shales, which are characterized by the high value of organic carbon, a signal of decreased oxygen concentration, the conditions called euxinic, which can also lead to hydrogen sulfide within the water body boosted by the preservation potential.

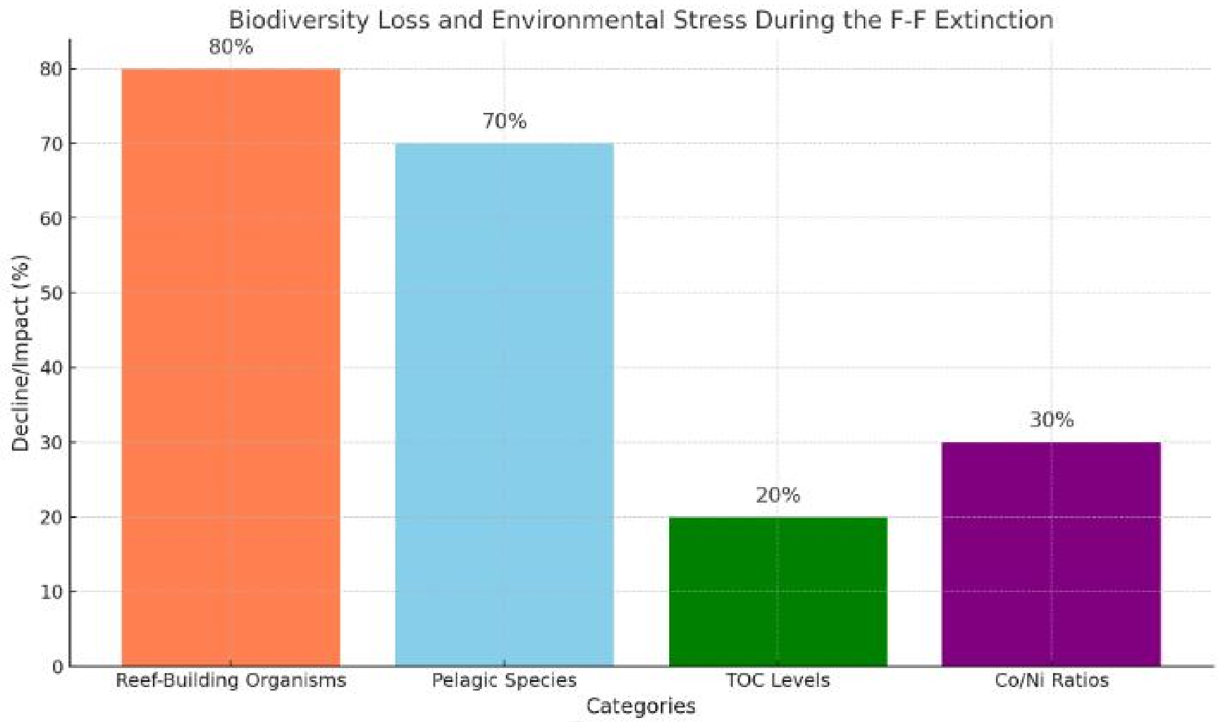
This work is associated with the phase of OM enrichment, a process that can be studied in detail during the Late Devonian period due to the significant climate and environmental changes that occurred during this interval. There are some fluctuations during this period, including fluctuations in sea water level, climatic change, and frequent episodes of anoxic conditions (Becker et al., 2016; Kemp et al., 2022; Percival et al., 2022). These fluctuations played a key role in defining the distribution, deposition, and eventual preservation of OM in marine and lacustrine basins.

Among the many environmental factors influencing Late Devonian conditions, one of the most striking was a cooling event marked by the Devonian glaciation. This period of global cooling led to glacial buildup which affected sea level, ocean currents, and weathering rates (Bahlburg & Dobrzinski, 2011; Young & Nesbitt, 1999). Glaciers' growing and shrinking nature impacted the delivery of sediments and nutrients to marine environments and inputs, and storage depended on the relative rates of productivity and preservation. Furthermore, this period witnessed an increase in "areochization," referring to the widespread occurrence of oceanic "dead zones" on the seafloor, areas devoid of oxygen. These anoxic zones, which were unfavorable to most marine organisms, were ideal for the preservation of OM. Typically, these low-oxygen conditions are reflected in the black shales deposited during this time, providing a valuable record of the environmental pressures exerted on marine life.

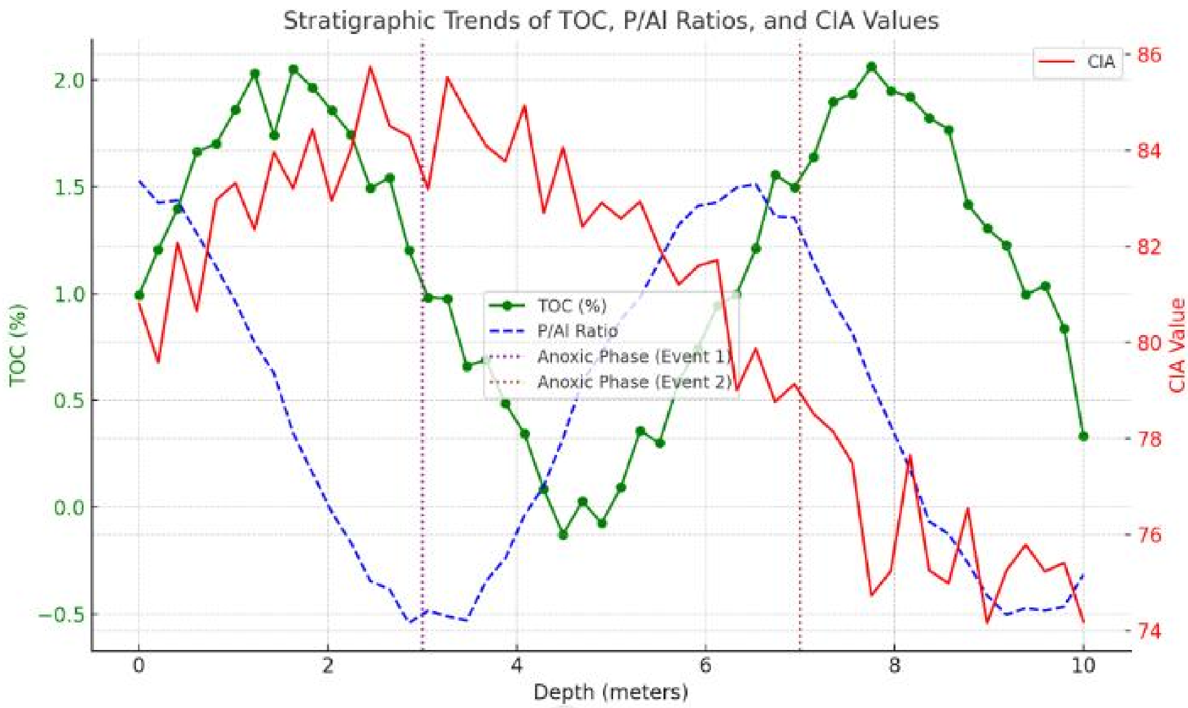
It is also possible to draw conclusions about the relationship between climatic changes and OM accumulation during the Late Devonian with the help of considering redox reactions, which are the oxidation-reduction chemical reactions that occur by the transfer of electrons from one antioxidant to another substance, that primarily depends on the variations in the concentration of oxygen (Ingall & Jahnke, 1997; Schoepfer et al., 2015). The redox conditions are crucial for determining the bioavailability of the marine environment and the fossilization potential of OM in sediments. When oxygen is least available within the water column during anoxic conditions, its inability to oxidatively decompose organic material helps maintain its preservation in the sedimentary pile (Sahoo et al., 2023). In contrast, warm, oxygenated bottom waters favor aerobic respiration and decomposition, leading to lower OM preservation.

The global and regional factors facilitated the change of the oxic to anoxic conditions in the Late Devonian. Continental shelves were flooded due to the increase in global sea levels resulting from the melting of glaciers; the water column was stratified, and oxygen exchange was limited (Becker et al., 2016; Liu et al., 2022). Such a thermal stratification combined with weak oceanic circulation promoted shallow bottom waters that required deoxygenation. Additionally, nutrients released from weathering processes supported elevated primary production, which, in turn, led to the accumulation of organic matter on the seafloor. However, as nutrients were depleted and anoxia increased, the marine environment became increasingly stressed, culminating in crises such as the F-F mass extinction event.

The F-F extinction event, one of the "Big Five" mass extinctions, highlights how shifts in environmental conditions impacted the complexity of the biosphere. The F-F extinction event involved a profound turnover of marine fauna and most dramatically affected reef-constructing organisms comprising stromatoporoids and corals as well as pelagic forms like ammonoids and conodonts (Copper, 1998; Percival et al., 2022). All these losses demonstrate the immediate sensitivity of marine species to environmental fluctuation, including world cooling, anoxic conditions in the ocean basins, and eutrophication, which has destroyed food chains and habitats. The extinction environmental stressors observed in this study correlated well with the factors associated with the accumulation of organic matter (OM). Variations in redox conditions, augmentation of nutrients, and changes in primary production produced complex impacts that overawed the ocean's chemical variable and ecological homeostasis (Liu et al., 2022; Sahoo et al., 2023). Studying these relations, scientists receive important information concerning the mutual interactions between climate change, oceanography, and evolution during this critical period.



The improved TOC, P/Al ratio, and CIA geochemical analyses have significantly advanced investigations into Late Devonian organic matter (OM) enrichment. These proxies effectively give information about the paleoenvironmental controls of productivity, preservation, and nutrient cycling (Kemp et al., 2022). For example, organic carbon content higher than 4 wt%, typical for Black Shales, mirrors increased rates of OM accumulation due to anoxic or euxinic bottoming conditions. Similarly, a high P/Al ratio suggests increased nutrient mobility and availability, while variations in CIA values highlight shifts in climatic conditions and the intensity of weathering.



Researching the pattern of OM accumulation during the Late Devonian period is highly important for comprehending prior environmental shifts and gathering valuable knowledge concerning modern and future challenges. Today, similar disturbance factors — such as deoxygenation, nutrient input, and climate change — are affecting the oceans, with negative consequences for marine species and ecosystem structure. Understanding the processes and outcomes of OM accumulation during the Late Devonian can help researchers predict the potential consequences of current environmental changes and devise strategies to mitigate them.

Studying lithologically controlled OM accumulation and preservation can be well illustrated by the case of the Late Devonian. Factors like primary productivity, depositional environment, and climatic conditions provide important context for understanding the relationship between environmental changes and organic carbon cycling. This knowledge is essential for not only interpreting Earth's history but also addressing issues related to current climate variability. It is thereby seen that, apart from providing insights into how OM accumulation might have fluctuated in the Late Devonian, this knowledge is relevant for how oceans and atmosphere will continue to evolve in today's world and tomorrow's. Marine ecosystems of the contemporary oceans are under similar pressures influencing deoxygenation, nutrient inputs, and climate change that destabilize marine diversity and ecosystems (Calvert & Pedersen, 2007; Sahoo et al., 2023). By interpreting the processes and outcomes of OM accumulation during the Late Devonian, researchers can gain insights into the types and magnitudes of current environmental changes and better understand how to reduce their disastrous impacts.

The Late Devonian has been widely regarded as one of the most productive intervals for OM accumulation and preservation, and understanding the factors behind this can offer significant biogeochemical insights. Changes in primary productivity, deposition, and climate conditions form the premise on which a new hypothesis on how several fluctuations within the environment relate to the dynamics of organic carbon can be deduced (Kemp et al., 2022; Becker et al., 2016). These influences play a central role in shaping the earth's history and addressing current climate change challenges globally.

This research paper analyzes the complex relationship between Late Devonian environmental factors, primary production, and OM preservation, with a particular focus on Late Devonian environmental changes and OM distribution. This study focuses on the Upper Devonian shale-carbonate couplet in the region and is primarily based on geological and geochemical studies. These strata preserve the sedimentary and geochemical history of the environments, providing an accurate reconstruction of a climatically sensitive period in Earth's history, during which OM accumulation was enhanced.

The climatic fluctuations, ocean anoxia, and biotic extinctions during the Late Devonian interval are well documented in the South China sedimentary sequences (Liu et al., 2016; Becker et al., 2020). This region also presents an excellent opportunity to analyze the spatial and temporal distribution of OM about depositional facies, as it features extensive shallow marine carbonate platforms, which are successively underlain by deep basinal regions. Through learning how factors control the distribution, accumulation, and preservation of OM in the sedimentary records across the F-F transition, this study also aims to understand the factors that control carbon cycling through this transformational phase (Kemp et al., 2022).

Some of the most extensively used geochemical proxies in this study include total organic carbon (TOC), sulfur isotopes, and elemental concentrations as they attempt to decipher redox conditions, nutrient availability, and primary productivity levels (Schoepfer et al., 2015; Liu et al., 2022). Higher Mo/Al values in black shale units, for example, relate to favourable preservation beneath anoxic or even euxinic conditions, and changes in the ratios Mo/Al and U/Th are indicative of fluctuations in the ocean. Combined with sedimentological and paleontological data, these proxies clearly show the paleoenvironmental conditions that controlled OM enrichment in South China.

Additionally, this research will explore the tectonic activity and other regional oceanographic processes that characterize the Late Devonian sedimentary environments. An active tectonic setting in South China due to the closing of the Proto-Tethys Ocean, presumably with shallower weathering and faster delivery of nutrients to support productivity (McLennon, 1993; Percival et al., 2022). Along with global climat factors, the OM accumulation results from a complex interplay of depositional and preservational settings.

Method

Sample Collection and Preparation

Sample collection and preparation are essential techniques widely employed in the screening and analysis process. Some samples were gathered along the Lengshuijiang section from south China, which was further emphasized in the Late Devonian. Aiming at this section in the Hunan Province of South China, (Ma et al. 2016) described it as a typical section of the well-preserved shale-carbonite succession. Geological layers of this field have been examined systematically for biostratigraphic, sedimentary, and chemostratigraphic values so they can be used to study the environmental changes that occurred during the F-F extinction event. The stratigraphy here offers the best records concerning late Devonian climatic and oceanic changes (Cui et al., 2021).

Subsequent collection of sample shale shales also helped maintain the integrity of the geochemical data. Having collected the samples, they were washed to eliminate microbes that may be attached to the surface of the samples. The was then allowed to stand until dry to prevent any change in its chemistry. Thirdly, the samples were milled to powder form for the geochemical analysis to avoid variation within a sample (Tribovillard et al., 2006). Some of the previous generalizations were useful in supporting the measurements made in the laboratory.

Total Organic Carbon (TOC) Analysis

About 200 mgs of each shale sample was leached with dilute acid to dissolve carbonate minerals; 10% HCl series was used to dissolve carbonate minerals, and samples were heat treated for 12 hours at 50 0C. The samples were used to measure the total organic carbon (TOC). This procedure was repeated twice to improve the efficiency of carbonate removal. Each sample was washed with distilled water after being exposed to the acids to remove any impurities in the pair and guarantee that the mediums were neutral. The samples were furthermore placed in a dryer for as long as possible to remove any moisture content before weighing (Schoepfer and others, 2015; Ingall & Jahnke, 1997).

In Sample Solution Inc., Wuhan, a potent instrument for measuring organic carbon content (Tessin et al., 2015; Tribovillard et al., 2006) determined the TOC content using a Euro-3000 analyzer. Quantitative estimates of OC concentrations derived from these analyses are essential for the environmental interpretation of depositional settings and OM conservation across the F–F event.

X-ray Fluorescence Spectrometry (XRF)

X-ray fluorescence spectrometry (XRF) was used for the shale samples' primary and trace elemental analysis. In this method, fluorescent X-rays from a sample irradiated by high-energy X-rays give analytical data for the elements. Al, Ca, Fe, K, Mn, Mg, Na, P, Si, and Ti were these major grains, with trace elements Ba, Cr, Ni, and V (Fedo et al., 1995; Walton et al., 2023). The Loss on Ignition (LOI) test, wherein 500 mg of milled sample was burnt at 1000°C for one hour, was conducted to transfer the combustible fractions, including the organic matter and water. Following oxidation, samples were mounted with lithium borate fluxing agent (67% Li2B4O7, 33% LiBO2) and fused at 1200°C to form homogeneous fusion glass disks for XRF measurements. The fusion increased the accuracy of the following Samples Solution Inc. AXIOS Minerals spectrometer analysis. The use of LOI and XRF techniques gave insight into the elemental composition and redox conditions of the Lengshuijiang section and assisted in making general interpretations regarding Late Devonian Oceanic anoxia and extinction (Sahoo et al., 2023; Tribovillard et al., 2006).

Process/Method	Description
X-ray Fluorescence Spectrometry (XRF)	Used to analyze primary and trace element concentrations by measuring fluorescent X-rays emitted from the sample when exposed to high-energy X-rays.
Major Elements Analyzed	Al (Aluminum), Ca (Calcium), Fe (Iron), K (Potassium), Mg (Magnesium), Mn (Manganese), Na (Sodium), P (Phosphorus), Si (Silicon), Ti (Titanium).
Trace Elements Analyzed	Ba (Barium), Ni (Nickel), Cr (Chromium), V (Vanadium).
Loss on Ignition (LOI)	Determined by oxidizing approximately 500 mg of pulverized sample at 1000°C for 1 hour to remove volatile components (organic matter and water).
Fluxing Agent for Fusion	5000 mg of lithium borate mixture (67% $Li_2B_4O_7$, 33% anhydrous $LiBO_2$) to facilitate fusion.
Fusion Process	The mixture was melted at 1200°C to create homogenous fusion glass disks.
Cooling	The fusion glass disks were cooled to room temperature after melting.
Spectrometer Used	AXIOS Minerals spectrometer (PANalytical) for XRF analysis at Sample Solution Inc., Wuhan.
Analysis Result	Precise quantification of major and trace elements provides insight into the shale samples' composition.
Purpose	Supports geological and environmental

	studies by providing comprehensive elemental analysis.

Chemical Index of Alteration (CIA)

To evaluate the intensity of chemical weathering in the F-F interval of the Lengshuijiang section, the Chemical Index of Alteration (CIA) was calculated. CIA values are determined using the formula:

$CIA=(Al_2O_3)/(Al_2O_3+CaO^*+Na_2O+K_2O) \times 100$.

CaO^* is the CaO content in the silicate fraction corrected for phosphate present. To adjust for the phosphate influence, the available P_2O_5 data was used to modify the CaO value according to the formula:

The CaO^* values are formed using the following relation: CaO^* = ¥text{mole CaO} - ¥text{mole P2O5} ¥times ¥frac{10}{3}CaO* =mole CaO−mole P2O5×310, where mole CaO is the number of moles of CaO in the original, and mole P_2O_5 is the number of moles of P_2O_5.

If corrected, CaO^* was more significant than the Na_2O and equal to the Na_2O. One advantage of this method is that it is more accurate in computing CIA and gives us an important idea about the degree of chemical weathering within the studied interval. The approach is built upon well-established protocols used in previous studies to ensure reliability.

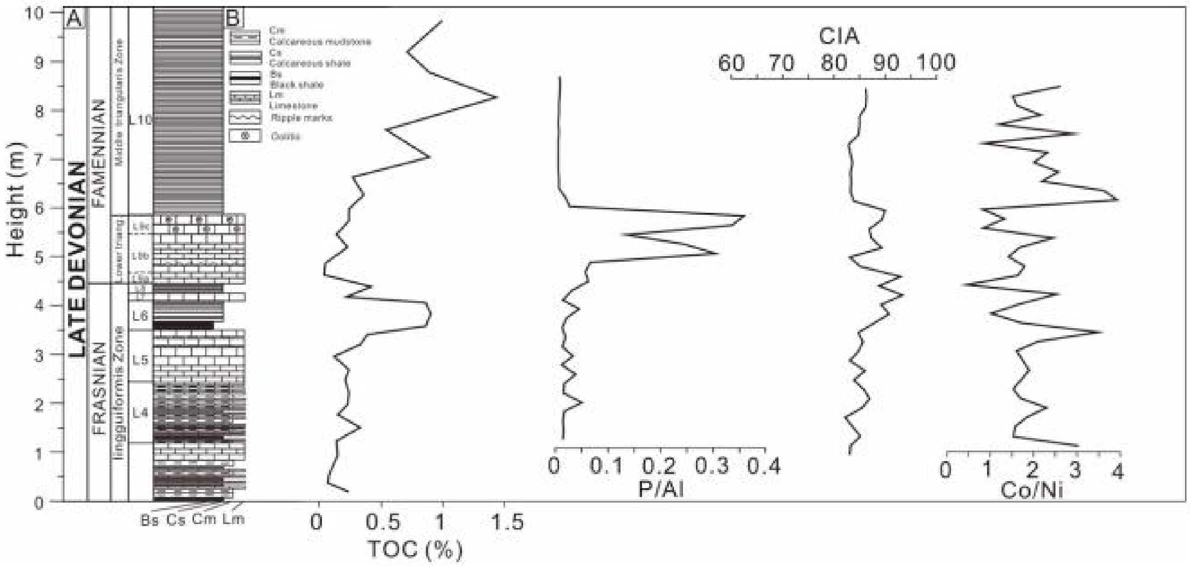


Figure 4: Varying lithology, TOC, P/Al, CIA, and Co/Ni in the stratigraphy column of the Lengshuijiang section.

Discussion

In the context of Figure 4, the paleoenvironmental change of the Late Devonian has been explained for the Lengshuijiang section concerning the Total Organic Carbon (TOC), P/Al, Chemical Index of Alteration (CIA), and Co/Ni in the sections across the Devonian–Carboniferous boundary. The geochemical proxies (Sahoo et al., 2023; Tessin et al., 2015) provide an overview of the processes governing OM input, transport and preservation in the sedimentary sequence. These differences in the proxies arise from changes in climatic, geological and biological variables associated with the depositional environment and aid in reconstructing the environmental conditions and possible drivers of organic carbon burial in this period.

Total Organic Carbon (TOC) Variations

As can be observed in the TOC profile illustrated in Figure 4, changes in the TOC content are rather sharp throughout the Lengshuijiang section, and these changes have important implications for the paleoenvironmental conditions of the Late Devonian. Variations in the concentration of TOC are related to changes in biological production, preservation, and other factors that affect the formation and degradation of OM in the sediment.

The amidogram shows that TOC concentrations are higher at about 3–4 m and 7–8 m in height, which measures between 1.5% of the TOC. These higher TOC intervals suggest that either primary production was higher or that the preservation environment of the organic material was better (Becker et al., 2020; Kemp et al., 2022). Cardiac productivity is the major model, which in turn postulates that because rates of biological processes occurring in the better-illuminated surface waters are higher, so what is deposited at the seafloor in terms of organic matter.

Higher productivity might be due to factors like enhanced nutrient stocks, upwelling, or other climatically optimal conditions that enhance plankton and other organisms in the sea (Walton et al., 2023). This biological activity is highly relevant to the buildup of organic carbon since the organic matter precipitating in the surface waters is subject to being buried in the deep sea sediments.

The observed high TOC values in the 3–4 meters and 7–8 meters may, therefore, correlate with occasions of relatively high biological activity in which a lot of organic carbon was generated and separated into the sediment. This aligns with the hypothesis that increased surface productivity can directly affect the OC concentrations in the sedimentary section by increasing the amount of biological materials in suspension.

Another key factor determining TOC concentrations is the preservation of organic matter. Regarding the preservation model, a significant factor is linked to anoxic or euxinic environments, which prevent the decomposition of organic matter (Cowie & Hedges, 1992; Tribovillard et al., 2006). Relative to oxic conditions, microbial activity that degrades organic matter is inhibited in such settings, and therefore, the organic material tends to be well preserved in the sediment .

These are known to happen in deeper water or areas of low circulation, where oxygen is quickly resent as a result of the decay of organic matter (Fang et al., 2023; Sahoo et al., 2023). The relatively high TOC values, together with high Co/Ni ratios in the 3-4m and 7-8m intervals, confirm the hypothesis that anoxic conditions existed in these time intervals.

Cobalt (Co) and Nickel (Ni) are the two trace metals that preferentially accumulate in regions of low redox potential, such as anoxic and euxinic. Under such conditions, the decomposition rate of organic matter reduces, and hence, the concentration of organic carbon increases in the sediments (Ge et al., 2022). A high Co/Ni ratio is usually interpreted to mean anoxic conditions; cobalt has a higher affinity for incorporation into organic matter in low oxygen conditions, nickel being less affected by the oxygen content .

The increased Co/Ni ratios proven within the same intervals with high TOC indicate that anoxic or euxinic conditions favored organic matter accumulation during these times. It is, therefore, evident that the high TOC levels are due not only to higher primary production rates but also to relatively lower rates of organic matter turnover under such anoxic conditions (McLennan, 1993; Ingall & Jahnke, 1997).The elevated TOC intervals are contrasted with lower TOC values (0.1%–0.3%) at ca. 0–2 m and 5–6 m in height. Reduced TOC concentrations characterize these intervals and may indicate a reduction in primary productivity or an increase of more oxic conditions favorable for the degradation of organic matter .

In an oxic environment with lots of oxygen, organic matter is better decomposed using aerobic microorganisms, and the amount of organic product preserved in sediment is lowered (Cowie & Hedges, 1992; Ingall & Jahnke, 1997). Therefore, the lower TOC values in the 0–2 and 5–6 meters intervals likely represent periods when less organic material was produced and deposited on the seafloor due to reduced biological productivity. These intervals may alternatively be times when more oxic conditions occurred, perhaps driven by changes in water circulation, changes in climate, and/or other factors that led to improved oxygenation of the water column (Tessin et al., 2015; Schoepfer et al., 2015). Organic matter produced under these conditions would be more readily decomposed; hence, recent TOC concentrations in the sediment would be lower.

It further strengthens the hypothesis that oxic conditions reigned in times of lower TOC accumulation (Tribovillard et al., 2006). As previously mentioned, oxyanoxic environments generally will elevate the Co/Ni ratios, while oxic conditions tend to lower the ratios. Consequently, quickly assimilated into organic matter under nonoxygenic conditions, cobalt is less abundant in oxic environments where oxygen exists.

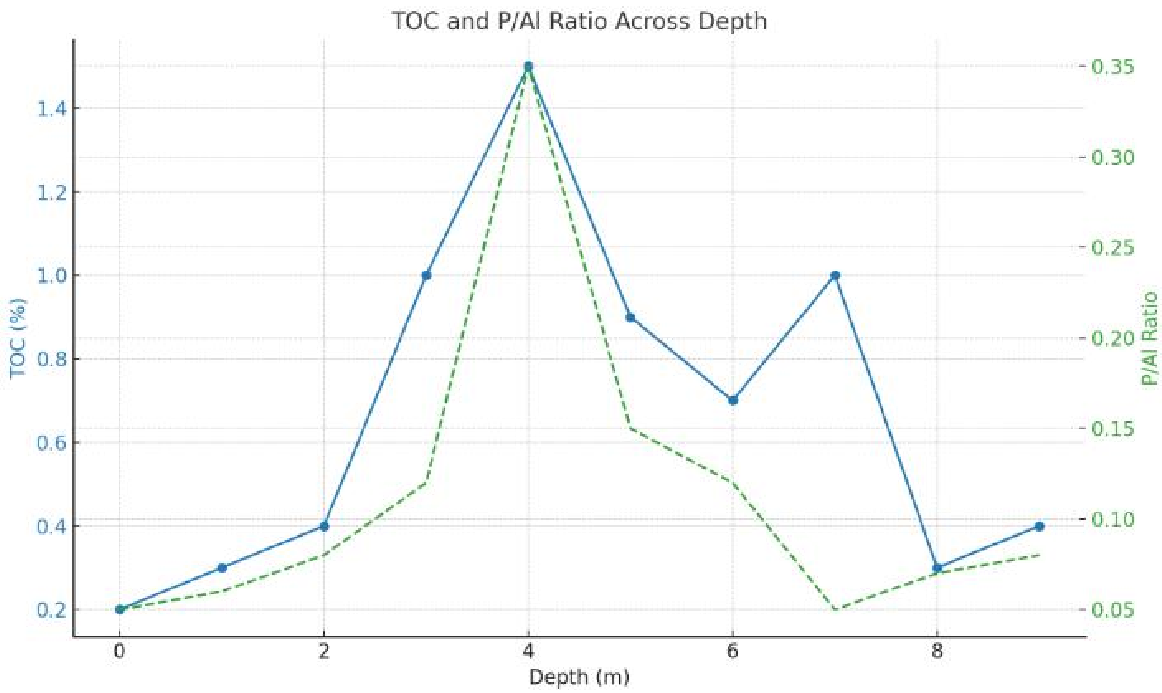
The Co/Ni ratios are lower (from 0 to 2 meters and from 5 to 6 meters) in the intervals with lower TOC values (0–2 meters, 5–6 meters), indicating that the organic matter in these intervals has been exposed to more oxic conditions and it finally decomposes. It demonstrates that oxygenation is a key control in preserving organic matter because oxidations in the sediment arise more frequently with decreased TOC concentrations (Tessin et al., 2015; Schoepfer et al., 2015).

Phosphorus/Aluminum (P/Al) Ratio

So, phosphorus is one of life's most essential bio-limited elements, in the form of phosphates, which consist of phosphate ions (PO_4^{3-}). Phosphorus is required for many essential biological processes: forming ATP for energy, genetic material (DNA and RNA synthesis), and cell structures (phospholipids in cell membranes). Phosphorus availability is a key nutrient that significantly affects primary productivity in aquatic systems. The P/Al ratio represents a valuable proxy for paleoproductivity (Tribovillard et al., 2006; Schoepfer et al., 2015). This nutrient ratio is a proxy for fluctuations in nutrient availability, affecting the biological activity of surface waters, particularly primary production, as measured by the growth and accumulation of phytoplankton and similar primary producers. Therefore, variations in the P/Al ratio can help reconstruct prior periods of nutrient cycling and productivity and, hence, are a key indicator in paleoenvironmental studies.

As shown in Figure 4, the P/Al ratio has several notable spikes between 5–6 meters above the F–F boundary with a value of 0.35. The observed drastic increase in P/Al in the F–F transition window suggests times of dramatically higher nutrient availability and higher productivity in surface waters during the F–F transition. High P/Al ratios suggest that P was abundant, which provided sufficient nutrients to fuel phytoplankton and other primary producers for increased productivity (Schoepfer et al., 2015; Percival et al., 2020). The increased organic carbon production is due to increased biological activity (increased phytoplankton and other organisms that sink to the seafloor and contribute to organic matter deposition.

The P/Al ratios are high during these intervals, likely due to enhanced continental weathering or upwelling events. Continental weathering, which releases phosphate ions from minerals into the ocean water column (McLennan, 1993; Nesbitt & Young, 1982), is the chief input of phosphorus to the oceans. Upwelling is another important mechanism for increasing nutrient availability in surface waters — the process by which deep, nutrient-rich waters are brought to the surface. Typically, continental weathering and upwelling are both causes of oceanographic and climatic change that increase the circulation of nutrients, supporting primary productivity. These times probably induced the nutrient-rich layers, which co-occur with high P/Al ratios in the stratigraphy, which may be indicative of nutrient supply as a key factor of biological productivity in those times .



This is expected because maximum P/Al ratios overlap with higher TOC values. This also reinforces the hypothesis that increased nutrient availability and productivity were the major driving factors for the organic matter accumulation during these intervals. At the same time, in response to enhanced nutrient supply, the component of primary productivity that produces a larger quantity of organic material in the surface waters increases. However, all of this organic matter eventually sinks to the seafloor, where it can be preserved in favorable circumstances. Increased phosphorus availability during these intervals was directly linked to increasing organic matter accumulation in the sediment (Schoepfer et al., 2015), and elevated P/Al ratios testify to a relationship.

In addition, the high TOC and P/Al ratios imply that high nutrient availability occurred when conditions were favorable for preserving organic matter. Earlier, it has been discussed how organic matter decomposition by microorganisms may also be relatively limited by anoxic or euxinic conditions, which inhibit microbial activity that would otherwise be responsible for the degradation of organic matter (Ingall & Jahnke, 1997). This dual influence of higher productivity and favorable preservation likely explains the increase of TOC observed during these nutrient-rich intervals.

However, levels of P/Al decrease in the ratio, between approximately 0 and 4 m in height and again between approximately 7 and 9 m in height, where the ratio ranges from about 0.05. These lower P/Al ratios suggest episodic nutrient supply reduction that resulted in depressed primary production. If less intensive continental weathering or less intense upwelling reduces nutrient availability, as is the case, then phosphorus input to surface waters will be reduced (McLennan, 1993). Primary productivity and phytoplankton and other primary producers' production decrease in such conditions, as in these conditions, there are fewer nutrients for phytoplankton and other primary producers' growth. As a result, organic material is created in decreasing amounts, and organic carbon accretion onto the seafloor is reduced.

These P/Al ratios may also reflect environmental conditions varying from higher oxygenation to more oxic conditions. In oxic environments, however, phosphorus is often bound to metal ions such as iron (Fe) or calcium (Ca) and precipitates out of the water column, becoming less available for biological uptake (Ingall & Jahnke, 1997; Schoepfer et al., 2015). It can also reduce organic matter deposition and inhibit primary productivity. In addition, the decomposition of organic matter is better under oxic conditions, with lower preservation of organic carbon. These processes also reduce TOC and concurrent low P/Al ratios during these intervals.

Another issue regarding the distribution of P/Al ratios is the importance of anoxic conditions to phosphorus cycling. Under anoxic or euxinic conditions, phosphorus present in the sediment may diffuse back into the water column, resulting in a decreasing P/Al ratio in the sedimentary record (Ingall & Jahnke, 1997; Tribovillard et al., 2006). Phosphorus is commonly released from sedimentary, iron-bound or calcium-bound forms in anoxic environments, making it available for biological uptake in the water column. The extent of phosphorus recycling at the sediment-water interface further complicates the interpretation of P/Al ratios because they might not directly reflect primary productivity but could rather reveal frequencies of phosphorus recycling.

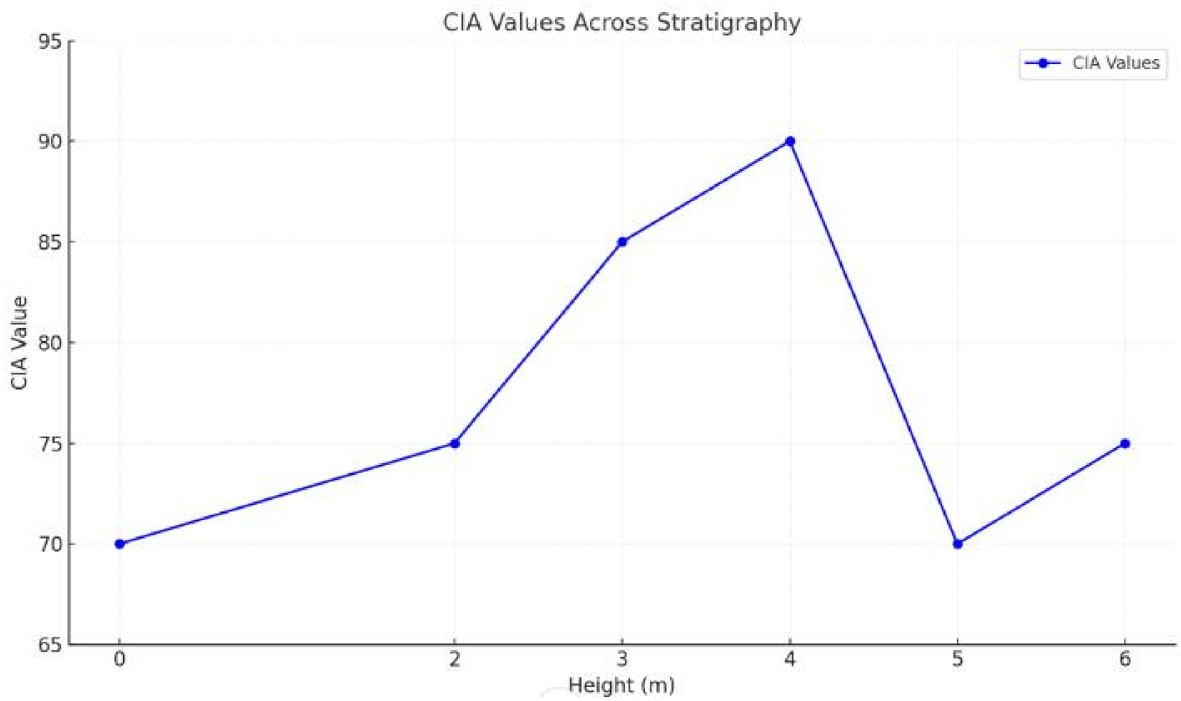
Hence, the decrease of P/Al ratios observed in organic-rich intervals may result from less nutrient input and phosphorus recycling with anoxia. However, these conditions may have put some brake on organic matter decomposition, although the release of phosphorus from the sediments back into the water column could have masked the actual amount of nutrients in these periods (Tribovillard et al., 2006; Schoepfer et al., 2015).

Chemical Index of Alteration (CIA)

The Chemical Index of Alteration (CIA) estimates the intensity of chemical weathering in sedimentary environments. We provide clues about the climatic conditions in the past and reconstruct the environmental conditions at the time of sediment deposition (Bahlburg & Dobrzinski, 2011). The CIA is calculated from the relative amounts of certain elements in the rock or sediment, especially a ratio of alkali and alkaline earth metals (Na_2O + K_2O) to aluminum oxide (Al_2O_3) and other elements. The higher values of CIA suggest more intense weathering, and the lower values indicate less weathered.

For the F-F transition in Fig. 1, high CIAs of 85 – 90 are seen at depths of 3 – 4 meters and 5 – 6 meters in height. The high values reflect elevated chemical weathering, a common feature of warm, humid tropical climates (McLennan, 1993). High temperatures and high rainfall rates enhance mineral breakdown, increase base cation leaching (calcium, magnesium, sodium, and potassium, and form stable clay minerals. The observed high CIA values are attributed to these processes.

These high CIA values would have inferred a warm and humid tropical climate, which undoubtedly would have dramatically affected the environment's nutrient cycles. Release of more nutrients, particularly silica, potassium, calcium, and magnesium, would have been enhanced through enhanced weathering processes with the resultant transportation of these nutrients to the marine system via riverine runoff (Fedo et al., 1995; Nesbitt & Young, 1982). An influx of these nutrients would have set off a wave of increased primary productivity in the marine ecosystem and rising in planktonic and other marine organism growth. Accordingly, enhanced primary productivity would have supported the precipitation of organic matter in the sediment and enhanced the potential for preservation under favorable depositional conditions.



In contrast, lower CIA values seen in the range of 70 to 75 at depths of about under 0 to 2 meters and 5 to 6 meters both indicate periods of less chemical weathering during colder and drier times. Low temperatures and precipitation reduce the intensity of weathering processes in all of these environments (McLennan, 1993). The time for the chemical breakdown of minerals is slower, and fewer nutrients will be supplied to the marine system. Schoepfer et al. (2015) would have suppressed primary productivity in the marine environment through reduced nutrient input to levels below those supporting higher rates of organic matter accumulation. The significant role of climatic variability in determining the delivery of marine nutrients is evident from these fluctuations in CIA values. Warm, humid conditions with high CIA values increased nutrient flux into the ocean, enhancing production of primary productivity and organic matter accumulation.

Conversely, during colder and drier periods coinciding with low CIA values (Bahlburg & Dobrzinski, 2011), primary productivity and organic matter deposition were restricted by lower nutrient fluxes. In contrast, the marine climate, chemical weathering, nutrient supply, and organic matter preservation are so coupled that climatic fluctuations govern the sediment composition and process of organic matter preservation in marine environments. Variations in CIA values observed in the F–F transition can help constrain past climatic conditions and associated controls on chemical weathering processes, nutrient flux and organic matter production.

CIA values are high in warm, humid, tropical climates, which corresponds to intensive weathering and a higher amount of nutrient input into the marine system, resulting in greater primary productivity and organic matter preservation. Low CIA values (colder and drier conditions) indicate reduced weathering, which limits nutrient supply and primary productivity. Therefore, weathering and sedimentary chameleon processes have dominated the contamination and persistence of organic records in the geologic record (Tribovillard et al., 2006; Schoepfer et al., 2015).

Co/Ni Ratio

Co and Ni are the widely used redox-sensitive elements for interpreting redox conditions in sedimentary environments (Tribovillard et al., 2006; Schoepfer et al., 2015). This ratio between Co and Ni (Co/Ni ratio) is a good proxy for these conditions: variations in the ratio indicate the degree of anoxia or euxinia of sediments at deposition. Samples with high Co/Ni ratios indicate reducing environments conducive to preserving organic matter (OM). Conversely, low ratios indicate more oxic exposure, degrading OM through aerobic degradation.

It is observed that the Co/Ni ratio is very high across stratification, which can be explained by changes in the redox conditions as inferred from the stratigraphy of the studied section. The Co/Ni ratios are 3–3.8, with approximately 3–4 meters at 7–8 meter heights, and these periods in thermal time mark anoxic or euxinic conditions favoured OM preservation (Tribovillard et al., 2006; Liu et al., 2022). Under these conditions, the decomposition of OM in the sediments is suppressed, and reducing the rate allows for more OM accumulation in the sediment.

The high ratios of Co/Ni correlate with high TOC values, further supporting this interpretation. Generally, TOC values are tied to periods of enhanced preservation mechanisms (Liu et al., 2022; Schoepfer et al., 2015) driven by oxygen-depleted environments. In this relationship, the accumulation and preservation of organic matter during these intervals were shown to have been dependent on redox conditions.

Low Co/Ni ratios from 0.5 to 1.5 are also found at about 0–2 m and 5–6 m in height. According to these authors, these intervals suggest more oxic conditions than expected (Tribovillard et al., 2006; Ingall & Jahnke, 1997) and indicate less efficient OM preservation due to the higher efficiency of aerobic degradation. In oxic environments, the organic material can be broken down in the sediment, reducing the amount of OM in the sediment. This trend toward lower TOC values and decreasing Co/Ni ratios are correlated with redox conditions that were less favourable for OM preservation. Redox conditions during deposition in the studied section changed dynamically and impacted sedimentary OM accumulation (Liu et al., 2022; Schoepfer et al., 2015).

The variations in Co/Ni ratios and correlations with TOC values are inferred to reflect the paleoenvironmental conditions of the studied period. High Co/Ni intervals indicate episodes of environmental stress, with reducing oxygen and enhanced preservation of organic material (Tribovillard et al., 2006; Liu et al., 2022). The conditions indicate anoxic or euxinic environments often ascertained to global sea level changes, oceanic stagnation, or increased nutrient influx. Such factors can lead to stratified water columns, preserving most of the OM in the oxygen-depleted lower layers.

However, the low Co/Ni intervals indicate more stable oxygenated periods (Tribovillard et al., 2006; Ingall & Jahnke, 1997) with dominant aerobic degradation processes. They represent intervals of decreased environmental stress in which the water column is oxygenated to a greater degree, and organic material is broken down more efficiently. These alternating high and low

Co/Ni ratios in the stratigraphy imply a dynamic coupling of these anoxic and oxic environments in response to environmental and climate fluctuations.

To further illustrate the relationship between Co/Ni ratios and redox conditions, the following chart provides a visual representation of the data:

Height (m)	**Co/Ni Ratio**	**Redox Condition**	**TOC Level**
0–2	0.5–1.5	Oxic	Low (0.1–0.3%)
3–4	3.0–3.8	Anoxic/Euxinic	High (1.5%)
5–6	0.5–1.5	Oxic	Low (0.1–0.3%)
7–8	3.0–3.8	Anoxic/Euxinic	High (1.5%)

Therefore, our findings have implications beyond the studied section, providing insight into the wider paleoenvironmental and geochemical influences on OM accumulation during the studied interval (Tribovillard et al., 2006; Liu et al., 2022). Fluctuations observed in redox conditions could have been caused by changes in global sea levels, climatic variation, or nutrient availability, all of which affected the depositional environment. Knowledge of these processes enables understanding of the factors that control OM preservation in old sedimentary settings and their significance to modern environmental transition.

Co/Ni ratios reveal the dynamic interplay between anoxic and oxic conditions, demonstrating the utility of combining multiple geochemical proxies to reconstruct past environmental conditions (Tribovillard et al., 2006; Schoepfer et al., 2015). This study extends our understanding of OM paleoenvironmental reconstructions by examining the relationship between redox redox-sensitive and OM accumulation.

Synthesis and Paleoenvironmental Implications

In the Lengshuijiang section, Late Devonian chronological environmental changes are reflected in primary productivity (P/Al), the preservation potential (Co/Ni), and weathering intensity (CIA), which have strong interactions. These interrelated factors form a crucial comprehension of OM generation and conservation processes when this phase of Earth underwent dynamic changes. The combination of geochemical proxies provides a comprehensible and elaborate account of how changes in climatic fluctuations and environmental conditions have given rise to the depositional environment.

In the Lengshuijiang section, high TOC values were featured during high primary production and/or OM-increased preservation in anoxic settings. He was found to have a positive correlation with OM deposition, which was relatively closely linked with the P/Al ratio index of nutrient availability and primary biological productivity in surface waters, having originated mainly in conditions of intensified biological activity (Schoepfer et al., 2015; Ingall & Jahnke, 1997).

On the other hand, lower TOC values either indicate systems with lower productivities or represent more oxygenated conditions, which will enhance the rate of deposition of OM. Besides, an increased degree of preservation of OM is manifested by high Co/Ni ratios under anoxia or euxinic conditions, and the high values of TOC point to the fact that reducing conditions for the breakdown of the OM are watchful (Liu et al., 2022b; Schoepfer et al., 2015). Thus, intervals of decrease in TOC are characterized by increasing percentages of aerobic decomposition processes, and low Co/Ni ratios are characteristic of more oxidation conditions.

The changes incurred for climatic conditions by the CIA are related to patterns regarding climatic conditions. High CIA values correspond to warm and humid conditions that augur well with chemical weathering, causing nutrient fluxes into the marine systems (Nesbitt & Young, 1982; Fedo et al., 1995). Higher primary productivity than under other conditions may have provided the basis for OM accumulation in these conditions. On the other hand, lower CIA values representing a cool, arid climate that favors low weathering rate and nutrient availability affirm OM deposition and primary productivity constraints. These climatic oscillations consisting of warm and humid followed by cold and arid were further subjected to spectral analysis. The cyclicity could explain the succession of OM accumulation reports in the lithological column in response to the nutrient and redox fluctuations.

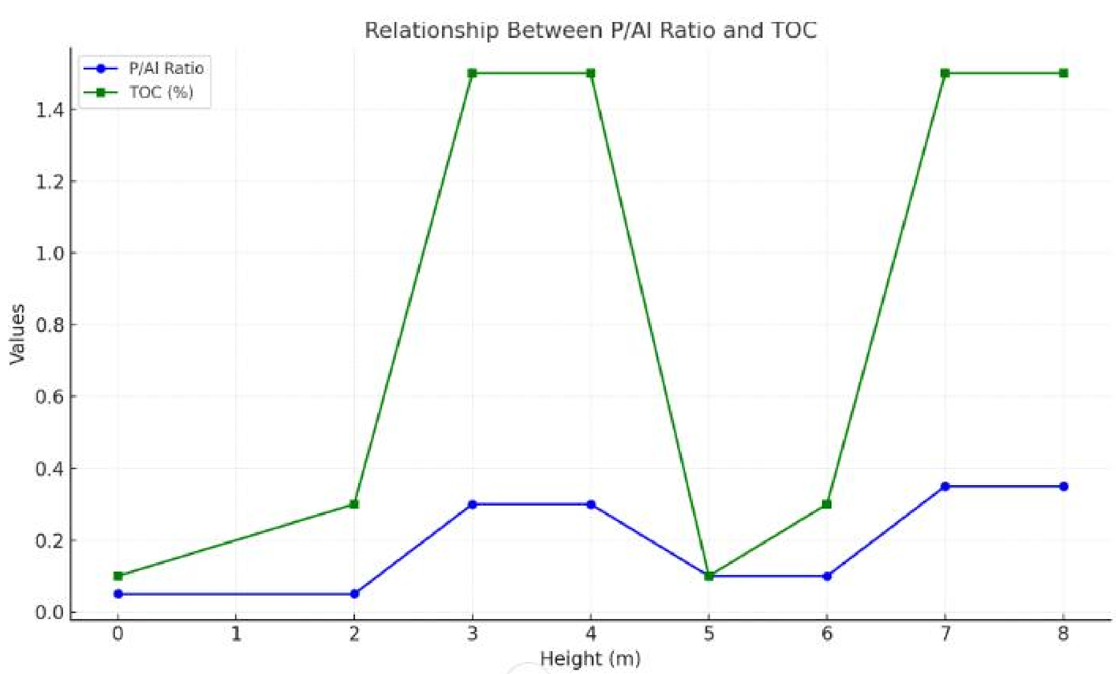
Such euxinic conditions are comparable to other significant transgressive periods of the core area compared to the Bakken Shale in North America. Hypoxic conditions are-, suggested by Mo and V trace elements of both intervals. When Mo and V reach their maximum levels in the Bakken Shale, Co/Ni ratios indicate that redox considerations derived from the Lengshuijiang section provide lasting evidence of euxinic settings related to OM preservation (Hitchcock Formation)

(Tribovillard et al., 2006; Schoepfer et al., 2015). In addition, these observations show that climatic and oceanic changes across the Late Devonian affected sedimentary habitats around the globe regionally.

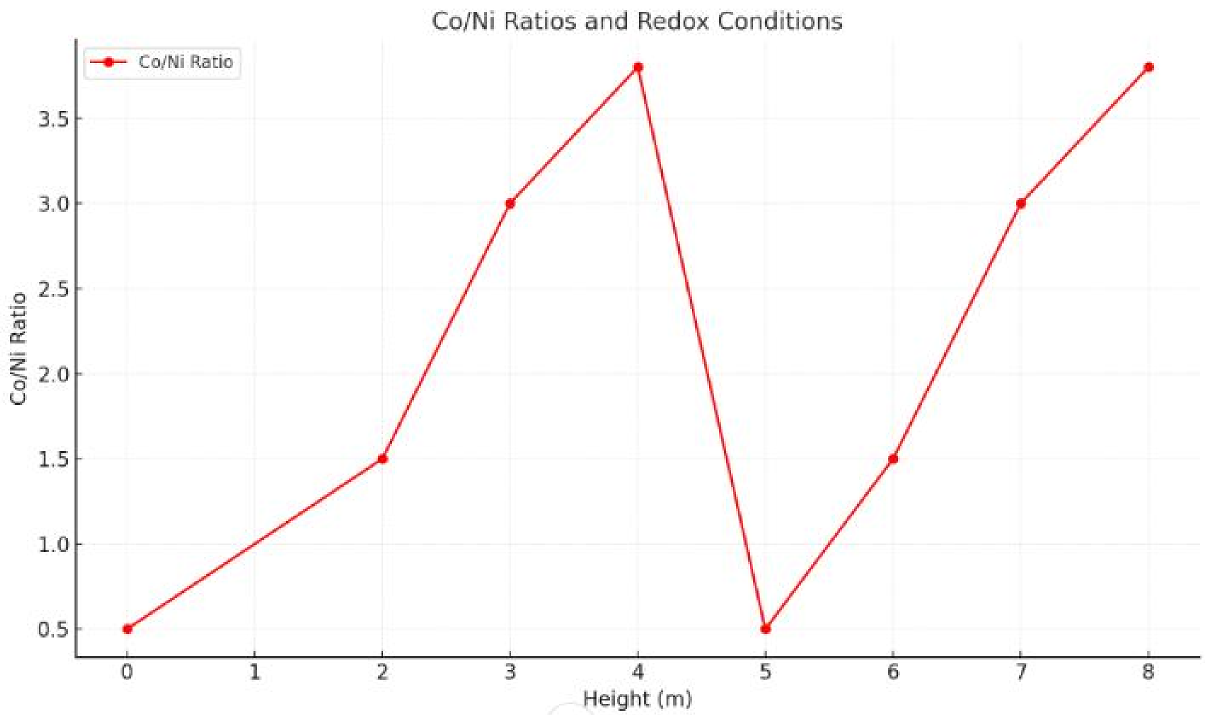
The documentation of photic zone euxinia (PZE) in the Bakken Shale supports the thesis that water column oxygen drawdown plays a role in OM generation. OM preservation process in the photic zone, where penetration occurs under oxygen-limited conditions, is significantly reduced (Cowie & Hedges, 1992; Schoepfer et al., 2015). The same may be inferred about the enhanced primary productivity intervals in the Lengshuijiang section, confirming the role of anoxia in controlling the depositional setting.

To better visualize these relationships, the following graphs and tables are provided:

Graph 1: This graph shows P/Al ratios plotted versus TOC values through the stratigraphy, illustrating their correlation. Elevated P/Al ratios coincide with the highest TOC intervals, suggesting that nutrient availability controls primary productivity and OM accumulation.



Graph 2 presents the variability of Co/Ni ratios in this stratigraphy regarding anoxic and oxic conditions. The Co/Ni ratio is high for anoxic intervals with elevated TOC values and low for oxic intervals with low TOC.



Summary of Geochemical Proxies and Environmental Conditions

Height (m)	P/Al Ratio	Co/Ni Ratio	CIA Value	TOC Level	Redox Condition	Climatic Condition
0–2	0.05	0.5–1.5	70–75	Low (0.1–0.3%)	Oxic	Cold/Arid
3–4	0.30	3.0–3.8	85–90	High (1.5%)	Anoxic/Euxinic	Warm/Humid
5–6	0.10	0.5–1.5	70–75	Low (0.1–0.3%)	Oxic	Cold/Arid
7–8	0.35	3.0–3.8	85–90	High (1.5%)	Anoxic/Euxinic	Warm/Humid

The geochemical signals indicate that sources and sinks both played a part in determining the amount of OM and its occurrence during the Late Devonian. Interestingly, these processes were linked with climatic changes and oscillations, affecting nutrient cycling and redox/oxidative state. For example, differences in P/Al ratios speak useful information about phosphorus which forms an important nutrient that enhances productivity (Wang et al., 2020). Likewise, changes in Co/Ni ratios and other trace metal indicators of paleoenvironmental redox conditions indicate the on-and-off breakout of euxinic conditions . The CIA values suggest even more the weathering of the continents and the effect they have on the delivery of nutrients to marine basins (Wang et al., 2020; Tribovillard et al., 2006). Both these amalgamation proxies provide a strong basis for reconstructing paleoenvironmental context and depositional controls on the sedimentary OM, focusing mainly on climbing climatic dynamics and ocean dynamics.

This work further enhances the knowledge of how OM enrichment occurred in early sedimentary basins, especially during major climatic and environmental transitions. This research piles up with the Lengshuijiang section, thereby pointing out the global significance of these curial processes through a comparative study with the Bakken Shale. Intercalating on a given scale, euxinia's periodic rise due to climatic and oceanic factors shows how systems are interlinked and interdependent on sedimentary processes (Cui et al., 2021). Disruption of the Phosphorus- cycle during Late Devonian anoxic events describes how nutrient dynamics affected even productivity and preservation mechanisms (Percival et al., 2020). These results can be reconciled with larger Late Devonian basins and provide insights into the local and global factors.

It is recommended that future-based research could advance the geochemical analysis beyond the findings presented here, or it could employ more geochemical indicators of the area's climatic conditions; in addition, it could sample other water bodies to compare the climatic conditions of their surrounding regions. For instance, isotopes of nitrogen and REEs could Reefs might shed additional light on the Late Devonian cycling of nutrients and redox (Tribovillard et al., 2006; Percival et al., 2022). Extensions of the study area to other basins with different tectonic and climatic histories would further improve the knowledge of the controls on OM. Paragenesis. Furthermore, incorporating high-resolution cyclostratigraphy with geochemical proxies can improve the temporal analysis of environmental changes. They would also provide more insight into one of the world's most fascinating periods of formation: the possible conditions that existed during various natural challenges of the past and present, as well as during the formation of modern civilizations.

Implications for Environmental Change and the Frasnian-Famennian (F-F) Mass Extinction

Shale interbedded between carbonate suggests a relatively rapid rise in sea level during the Frasnian-Famennian (F-F) transition. This geological feature represents the progressive shallowing up of euxinic waters as indicated by the observed Lengshuijiang section and North American sedimentary record during the episodic phases of marine transgression (Ma & Bai, 2002; Percival et al., 2020). These transgressions significantly affect the increased organic-matter burial during the Late Devonian and the associated mass extinction. The environmental change described in the Lengshuijiang section further explains the processes driving change.

F– F mass extinction, also known as the 'Big Five' mass extinction, drastically reduced marine life forms. This has drastically reduced reef constructional organisms and other species that dominate open waters (Copper, 1998). The geochemical data from the Lengshuijiang section proposed that the extinction cause is related to the environmental stressors that also control the OM accumulation based on research from Cui et al., 2021; Tribovillard et al., 2006. High TOC intervals and anoxic or euxinic conditions were found to be correlated with stages of increased environmental stress. The increase in the Co/Ni ratio, believed to indicate the redox state, lends more support to the conditions of anoxia during these periods .

The same euxinic conditions are suggested in Bakken Shale, where trace metals like molybdenum (Mo) and vanadium (V) point to the time of steep anoxic slope (Tribovillard et al., 2006). These euxinic phases, identified during another massive extinction event – the Hangenberg Event, prove that euxinia is associated with high OM accumulation. Entities in such areas with low levels of dissolved oxygen were highly unhealthy for marine life forms, making the phenomenon responsible for massive extinction. The global sea level changes and oceanic stagnation leading to these conditions were unfavorable for many marine organisms.

Some processes during the Late Devonian era are held to have been triggered by climatic changes based on CIA values (Bahlburg & Dobrzinski, 2011). By analyzing its stratigraphy, the Lengshuijiang section has displayed the different warm and humid conditions and cool and dry stages. High CIA values mean increased chemical weathering during high temperatures and humidity, which initially stimulated the nutrient inputs that raised primary production. However, as these nutrients were consumed, the effects of the loss of light and the development of anoxic and euxinic conditions were rapid depletion of marine oxygen resources. Such conditions were disadvantageous to most marine life, enhancing environmental pressure and leading to extremism.

The climate of these regions is also supported by evidence found in the Bakken Shale. Pyrite fringes suggest fluctuations in the high-productivity phase and euxinic conditions that partly define environmental dynamism (Tribovillard et al., 2006). The respiratory rise in CIA values increased chemical weathering and portended nutrient fluxes in waterfront ecosystems, fostering early productivity highs. Nevertheless, all these conditions culminated in anoxic collapses, which agree with the patterns of the Lengshuijiang section. This wetting and drying cycle associated with climatic and oceanic changes demonstrates the complexity of Late Devonian global environmental processes.

The F-F mass extinction is an offspring of these environmental factors. Climatic oscillations might have reduced the stability of redox conditions and, by implication, the stability of marine habitats and ecosystems, with an inevitable consequent decline in overall biodiversity (Copper, 1998; Ma et al., 2016). The patterns of organic matter accumulation that evolved in the Lengshuijiang section provide proof of such environmental changes and, at the same time, delineate the conditions that gave rise to this extinction event.

Based on this background, the responsibility for sea-level changes with euxinic conditions is also underlined by lithological evidence. These changes from carbonate to shale and then to carbonate suggest an abrupt change in the depositional setting. These changes presumably correlate with oscillations of shallow-marine transgressions that flooded areas populated by welled-up oxygen and introduced marine nutrient waters there (Ma & Bai, 2002; Becker et al., 2020). As a result, the water column became stratified, and anoxia for OM preservation was obtained in deeper ocean waters. Such conditions are crucial to unearth how processional such deposits occurred in the Late Devonian deposits.

Thus, the Co/Ni ratios, P/Al, and CIA can be successfully used as the geochemical proxies to reconstruct these changes. Co/Ni ratios < 2 are consistent with anoxic waters, and all samples with an enriched TOC concentration indicate that reducing environments are crucial for preserving OM (Liu et al., 2019; Schoepfer et al., 2015). The high values of P/Al ratios, which evidence nutrient availability, are also linked to periods of high primary productivity. These findings identify these elements by emphasizing that ANS represents an exception to more pervasive interdependences between the nature of nutrients, redox elements and climatic conditions that control the depositional context (Tribovillard et al., 2006; Cui et al., 2021).

The trends in the Lengshuijiang section are studied, and the results indicate that the factors that influence the OM accumulation in the Bakken Shale are present and active in this region. Changes in the global sea level and climatic conditions periodically caused euxinia in both areas (Becker et al., 2020; Uveges et al., 2019). The existence of photic zone euxinia (PZE) in the Bakken Shale is consistent with the notion that the depressed oxygen of surface waters might have stimulated OM preservation in euxinic environments (Tribovillard et al., 2006). In regions where anoxic conditions extend into the photic layer where light may penetrate, contributing to highly reducing conditions that stimulate OM production, PZE is identified. Such conditions were similar in the Lengshuijiang section during times of increased efficiency. Such processes can be traced in other sections of the basin, meaning they are universal (Cui et al., 2021).

The conclusions from these studies extend beyond the Late Devonian and set forth avenues to explore the future conservation and diversification of calamites and other seed-forming plants. Analysis of the OM accumulation and preservation of the Lengshuijiang section allowed us to formulate a new view of the profound causes of biotic crises. Another mass extinction event, including the Hangenberg and Permian–Triassic extinction (Becker et al., 2020; Schoepfer et al., 2015), is explained by a conceptual model of nutrient dynamics, redox change, and climatic factors. The lack of conditions similar to these, like F-F extinction with anoxic and utilities, should further help to underscore that these conditions were central to biosphere evolution.

To better visualize these findings, the following charts and tables are provided:

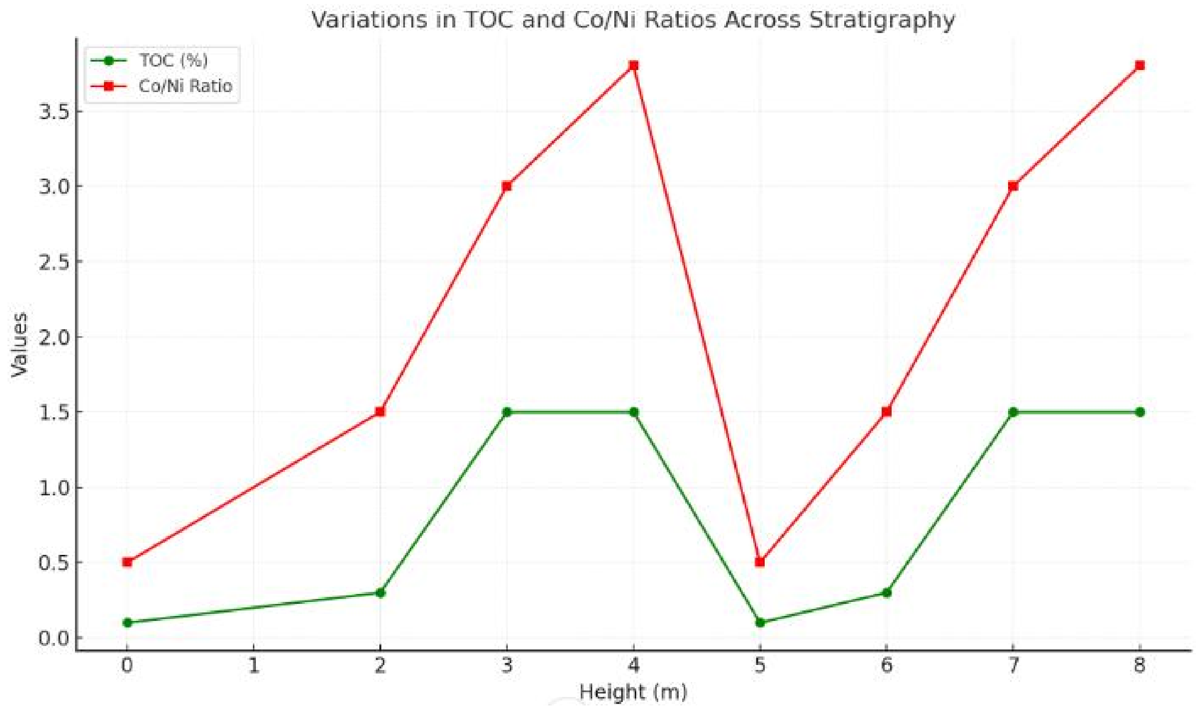


Chart 1: TOC and Co/Ni ratios across stratigraphy: Well-documented anoxic/euxinic conditions and consequent OM preservation are plotted as a function of TOC and Co/Ni ratios.

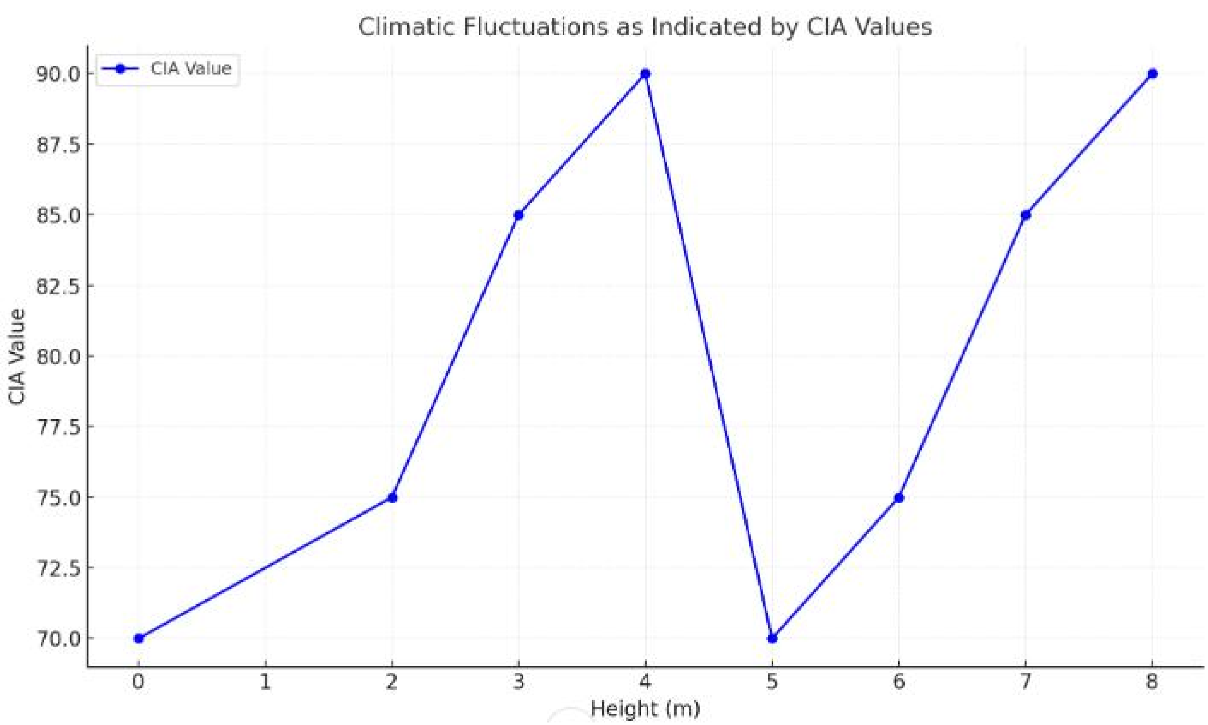


Chart 2: Fluctuation in CIA values through stratigraphy with indication of warm/humid and cold/arid periods and their effects on nutrients.

Table 1: Geochemical Proxies and Environmental Conditions Summary

Height (m)	P/Al Ratio	Co/Ni Ratio	CIA Value	TOC Level	Redox Condition	Climatic Condition
0–2	0.05	0.5–1.5	70–75	Low (0.1–0.3%)	Oxic	Cold/Arid
3–4	0.30	3.0–3.8	85–90	High (1.5%)	Anoxic/Euxinic	Warm/Humid
5–6	0.10	0.5–1.5	70–75	Low (0.1–0.3%)	Oxic	Cold/Arid
7–8	0.35	3.0–3.8	85–90	High (1.5%)	Anoxic/Euxinic	Warm/Humid

Using climate, ocean chemistry, and evolution, these visualizations explore how climate and ocean chemistry interacted with evolution during some of Earth's most dramatic shifts. This study demonstrates that the processes found in the Lengshuijiang section are global, and their utility has past and present environmental significance compared to the process that also occurred in the Bakken Shale (Becker et al., 2016; Liu et al., 2019). The inhibition of euxinia was episodic and related to climatic and oceanic conditions, requiring geochemical proxies to reconstruct past environmental conditions and estimate their effects on OM accumulation precisely.

Conclusion

The findings from the Late Devonian environmental change studies and the changes in the amount of OM in the Lengshuijiang section are discussed in this paper. Analysis of these elements concerning Total Organic Carbon (TOC), Phosphorus/Aluminum (P/Al), Chemical Index of Alteration (CIA), and relative Co/Ni ratios for geochemical proxies has helped in understanding the primary productivity and redox conditions, as well as climatic conditions operative during this age. Together, these proxies provide a composite view of the environmental conditions that permitted OM buildup and conservation.

It suggests that OM accumulation during episodes of high OM accumulation is linked with increased primary production and OM preservation. For samples with increased P/Al ratios, this implies that nutrient input did enhance biological productivity at the water surface (Ingall & Jahnke, 1997; Percival et al., 2020). As for most deep-sea ecosystems, this enhanced productivity, mainly from phytoplankton and other primary producers, led to enhanced OM accumulation on the seafloor. At the same time, high concentrations of Co/Ni point to the anoxic or euxinic environment, which in turn hindered the aerobic decomposition of organic matter, thus improving the odds of OM preservation (Tribovillard et al., 2006; Schoepfer et al., 2015). As seen from the above analysis, high TOC values are positively related to these geochemical indicators, which again emphasizes the roles of productivity and preservation for OM enrichment.

Moreover, the CIA values help understand the Late Devonian's climatic context and satisfy a detailed cyclicity between warm and moist climates and cool and dry climate conditions. An increased CIA suggests enhanced chemical weathering is closely linked to warm and humid climatic conditions (McLennan, 1993; Nesbitt & Young, 1982). These conditions would have increased nutrient inputs into the marine system, increased primary production, and thus OM. However, lower CIA values indicating lower weathering intensity are associated with calm, more desert-like conditions that restrict nutrient delivery and primary production. Such climatic fluctuations are expected to dominantly contribute to regulating the supply of nutrients to the marine environment, thus controlling the general trends of OM deposition and distribution in the sequence.

The relations between the primary productivity and preservation factors are also revealed by the changes in TOC, P/Al, Co/Ni, and CIA in the revealed stratigraphic sections. For example, P/Al and Co/Ni ratios are in increased supply of nutrients and anoxia (Tribovillard et al., 2006; Percival et al., 2020) and are associated with high TOC ranges. These intervals represent episodes of the favourable environment for the accumulation of OM due to increased productivity and degrees of preservation. On the other hand, intervals associated with lower TOC values show low P/Al and Co/Ni ratios, which are representative of low nutrient inputs and oxidative regimes that increase the rates of OM breakdown. The temporal variability of these patterns and the control of the Late Devonian setting on sediment accretion are demonstrated.

The results are also used to make more general statements about the rest of the Late Devonian. These changes have been well captured over this period, thus offering a viable environment for understanding the factors that trigger and enhance OM accumulation and preservation, as seen by Becker et al. (2016) and Copper (1998). Using multiple geochemical proxies presents a coherent framework for studying past environmental interactions with sedimentation. This study adds to the current knowledge of the Late Devonian environmental change with interpretations of varying TOC, P/Al, Co/Ni, and CIA values to primary productivity, redox conditions, and climate, synthesized with changes in primary productivity, redox conditions, and climate.

Their discussion of the relationship between anoxia and the depositional environment is invaluable. Extending our previous work to the presence of OM, we propose that global sea-level changes and stagnation of oceans led to widespread anoxic conditions that supported OM preservation (Pandy et al., 2006; Schoepfer et al., 2015). These conditions are well represented in the Lengshuijiang section by the high Co/Ni ratios, which correlate with some intervals of the increased TOC values. The proximity of anoxic or euxinic conditions during these times shows the importance of the redox state in controlling OM deposition. Such conclusions imply the need to include redox-sensitive indices like the Co/Ni ratios in paleoenvironmental models.

Further, the variability in climatic conditions has also been incorporated regarding the effects on nutrients and primary production. Switching from warm and humid conditions to cold and arid ones proposed by CIA values helps to study how climate affects chemical weathering and nutrient supply rates. Under relatively warm and humid weathering conditions, it would have been more thorough, which would mean a higher supply of nutrients, higher production of primary producers, and, consequently, a higher accumulation rate of wash-in OM. Warmer and less humid conditions would have minimized nutrient delivery, resulting in a lower production rate and less OM accumulation (McLennan, 1993). These climatic oscillations, with the redox fluctuation, provide the environmental controls that controlled the OM generation process in the Late Devonian.

When combined with geochemical proxies of the Lengshuijiang section, the combined insights into OM distribution during the Late Devonian from the sections are valuable. These data can also be compared to data from other regions, for example, with the data acquired within the Bakken Shale, North America, in order to compare trends of OM preservation and find differences in them (Becker et al., 2016; Tribovillard et al., 2006). For example, the high Co/Ni ratios and other redox proxy data in the Lengshuijiang section and the Bakken Shale reveal euxinic conditions and black shale features. These comparisons show aspects of global environmental change during the Late Devonian and its effect on sedimentary processes.

Future research could explore using other geochemical markers and other areas with these results. It is also reported that the addition of OM data with trace metal assays, isotopic, and other geochemical methods may be beneficial in understanding the constraints of accumulation and preservation of OM (Calvert & Pedersen, 2007; Tribovillard et al., 2006). Further, more precise comparative investigations in different kinds of depositional environments and different geographic provinces will provide a more detailed picture of the Late Devonian environmental changes and their relation to the OM formation.

This work raises knowledge to a greater appreciation regarding the environmental conditions that facilitated OM accumulation when the Earth was extraordinarily dynamic. By evaluating the changes in the geochemical indicators and the possible correlations with primary productiveness, redox situations, and climate, the work offers a detailed framework for reconstructing the paleo-environment. These results strongly support productivity and preservation mechanisms in enriching OM and highlight the significance of climatic and environmental changes in controlling sedimentary processes. Aside from that, the analyses also augment the knowledge of the Late Devonian and can be pretty beneficial in figuring out about other similar processes that occurred during other eras and in present days global climate change circumstances as well.

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