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*Research Article*

# Analysis on Black Shale Sedimentary Paleoenvironment and Tectonic Setting of the First Member of Luzhai Formation of Lower Carboniferous, Rongshui Area of Guangxi, China

**Juan Li**[1,2] **Yinglun Qin**[3] **Huanpeng Chi**[1] **Yukun Tian**[4] **Yufang Wang**[1] **and Liyun Kong**[1]

[1]*Oil & Gas Survey, China Geological Survey, Beijing 100083, China*
[2]*China University of Geosciences (Beijing), Beijing 100083, China*
[3]*China Guangxi Investment Group Energy Group CO., LTD, Guangxi 530000, China*
[4]*Command Center of Natural Resources Comprehensive Survey, China Geological Survey, Beijing 100055, China*

Correspondence should be addressed to Yukun Tian; tyksango@gmai.com

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In order to promote the discovery of new shale gas exploration areas in Guangxi, based on the latest drilling data, through detailed observation and description of logging data and cores, this paper selects high-quality shale samples of the target layer for X-ray diffraction analysis and testing of clay minerals and whole rock, major and trace elements (including rare-earth elements), TOC, and other related analysis and testing. The study shows that the total amount of rare-earth elements in the first member of Lower Carboniferous Luzhai Formation in Rongshui area, Guangxi, is low; $\delta$EU and $\delta$CE show negative abnormality. The average value of $w(V/(V+Ni))$, Th / U ratio, and Mo-TOC covariant model diagram of the first member of Luzhai Formation show that it was the condition of anoxic reduction at that time. At the same time, Ba-Sr diagram, Sr/Cu ratio, and total rare-earth elements reflect that the area was in an arid, hot, and marine salt water paleoenvironment during the sedimentary period. Most of the sample parent rocks of the first member of Luzhai Formation are in shale area, and some samples are close to felsic igneous rock area, which is of mixed origin. The tectonic background of the source area is mainly continental island arc and active continental margin, indicating that the sedimentary environment was unstable and highly active under the background of extensional rifting at that time.

## 1. Introduction

In recent years, many scholars have carried out a series of basic geological research work in stratigraphy, petrology, and paleontology for marine shale in southern China, especially for the Lower Cambrian Niutitang Formation and the Lower Silurian Longmaxi Formation [1–6]. Through the implementation of a series of advanced technologies such as fine processing of seismic data, detailed analysis of hydraulic fractures, and updating of horizontal well drilling technology [7, 8], predecessors have made important breakthroughs in local areas, realized large-scale development of shale gas in southern China, and confirmed the huge shale gas exploration and development potential in southern China [9–11]. However, most of these breakthroughs are concentrated in Sichuan, Chongqing, and Guizhou Province, while researches on shale in Guangxi Province are relatively lagging behind. Guangxi is a favorable area for shale gas exploration in southern China, but due to special geological and geographical conditions, the degree of basic geological research is relatively low [12–15].

Based on samples collected from the field profiles and well drillings, the predecessors conducted preliminary studies on the surrounding areas of Rongshui in Guangxi, such as Luzhai, Hezhou, and Tiane. It is believed that since the early Carboniferous in Guangxi, shale mainly existed in basin facies, slope facies, and platform shoal facies.

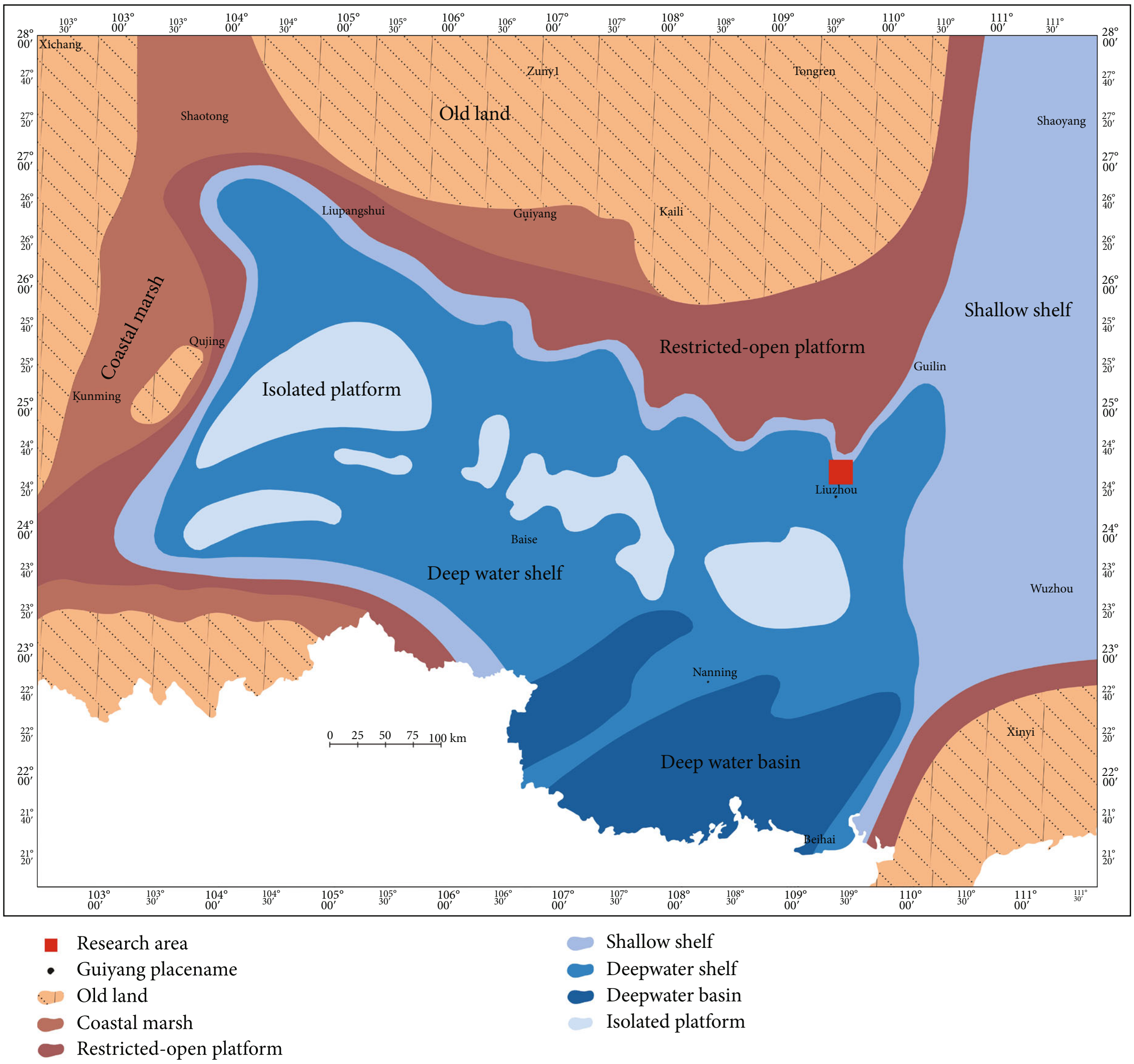


Figure 1: Early Carboniferous sedimentary paleogeographic map of Nanpanjiang area [18].

Carbonaceous shale is generally developed in the basin facies, with large thickness. Carbonaceous mudstone is also generally developed in slope facies, but there are many interbeds of silty mudstone. Shale of shoal facies in the platform is thin, with poor hydrocarbon generation capacity [16, 17]. In view of the strong heterogeneity of the Luzhai Formation shale in northern Guangxi and the rapid change of the sedimentary environment, the research on the paleoenvironment of the Lower Carboniferous shale in the Rongshui area is still insufficient. This research is based on the shale gas parameter well of Well Guirong Ye1 (hereinafter referred to as GRY1). The main purpose of GRY1 is to explore the shale sequence, sedimentary characteristics, and gas bearing characteristics of Luzhai Formation in the target layer; obtain shale gas evaluation parameters; and determine the exploration potential of shale gas resources. The well was drilled to a depth of 3305.00 m. Core samples of the first member of the Lower Carboniferous Luzhai Formation were obtained, and important discoveries of shale gas in the Lower Carboniferous Luzhai Formation were made, opening up a new area for shale gas exploration in Guangxi. Based on the latest drilled well GRY1, through detailed observation and description of cores, this paper selects high-quality shale samples of the target layer for relevant analysis and testing and carries out the geochemical and sedimentary environment analysis of the Lower Carboniferous Luzhai Formation shale in Rongshui area, Guangxi Province, in order to provide necessary geological basis for the exploration and development of shale gas in this area.

## 2. Geological Setting

The study area is located in the northern part of Liuzhou City, Guangxi Province, China. And the secondary structural unit is Guizhong Depression which is an important part of Nanpanjiang-Youjiang Basin.

The complex sedimentary pattern of Guizhong Depression from late Paleozoic to early Mesozoic is mainly reflected in the gradual transformation from shallow-marine

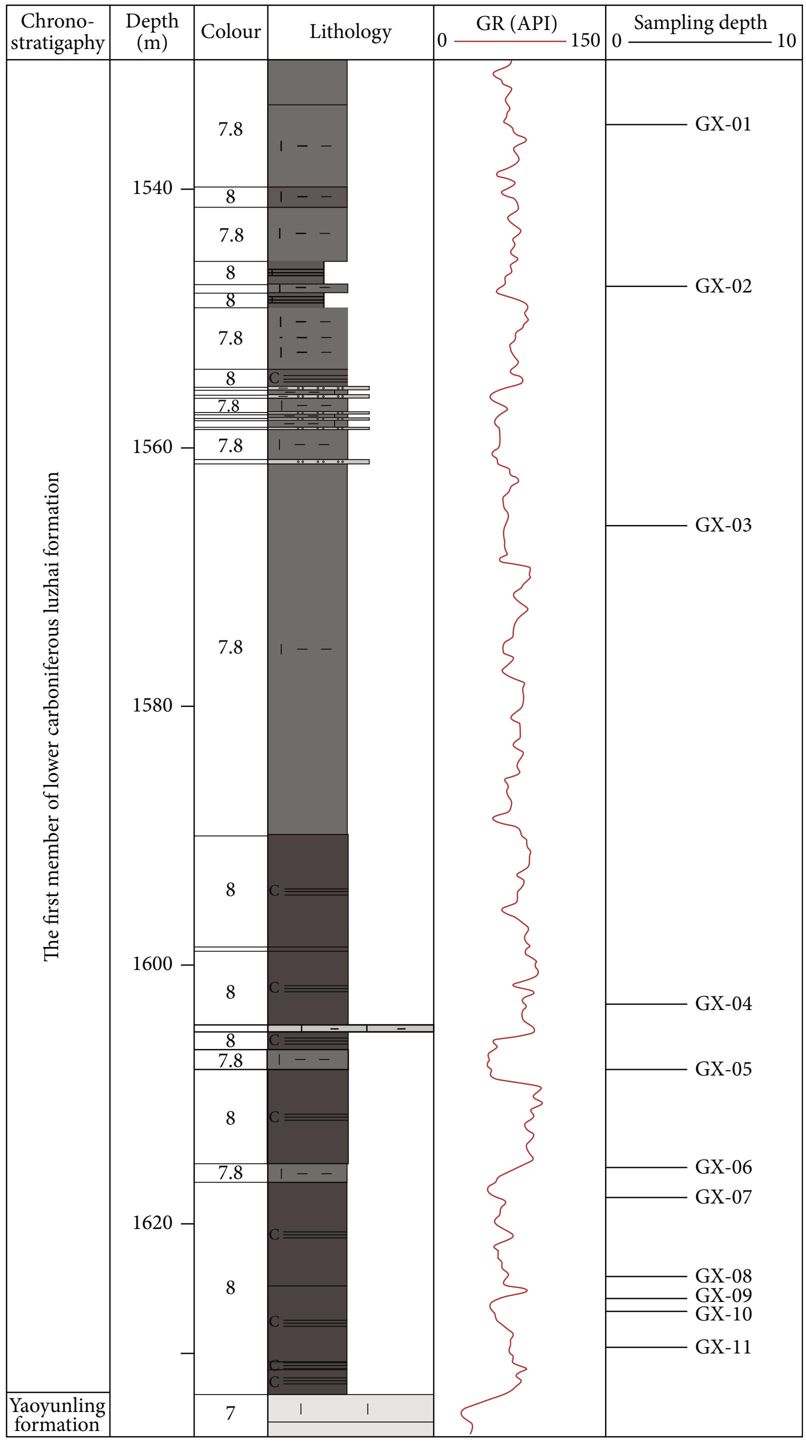


FIGURE 2: Comprehensive histogram and sampling location of the first member of the Carboniferous Luzhai Formation.

carbonate rock deposition to deep-water clastic rock deposition. The overall performance is the frequent changes of platform facies and basin facies (Figure 1) [18, 19]. The stratum from the Proterozoic to the Quaternary can be found except Ordovician, Silurian, Jurassic, and Tertiary in this area. And the most widely distributed strata are Cambrian, Devonian, and Carboniferous [20, 21].

The research target of this paper is the first member of the Luzhai Formation of the Lower Carboniferous, with a depth range of 1345.00 m-1633.50 m and a thickness of 288.50 m. It has an integrated contact relationship with the upper and lower strata. The main lithology of the upper part of the first member of the Luzhai Formation is dark gray limestone mudstone with a thin layer of dark gray marlstone. Horizontal bedding is seen, and local


(a) Depth of 1630.38~1635.30 m

(b) Depth of 1548.68 m

(c) Depth of 1617.58 m

(d) Depth of 1619.27~1619.41 m

Figure 3: Core characteristics of shale in the first member of Luzhai Formation: (a) the boundary between grey marl of Yaoyunling Formation and black mudstone of Luzhai Formation; (b) slightly developed foliation, 0.1~0.2 mm thick; (c) black carbonaceous shale, rich in carbon; (d) black carbonaceous shale with dark grey marl lamina.

fractures are developed, which are completely filled by calcite. The middle part is gray black mudstone mixed with black carbonaceous shale and dark gray marlstone. The bottom is black carbonaceous shale, with developed foliation (Figures 2 and 3).

## 3. Samples and Methods

The samples in this study are from GRY1 implemented by Oil & Gas Survey, China Geological Survey in Rongshui, Guangxi Province, in 2020. The depth range of the first member of Luzhai Formation in the target layer of the well is 1345 m to 1633.5 m. This sampling starts from 1535 m, and a total of 11 samples are taken. Dense sampling is conducted at the bottom of the key research section (Figure 2). As a comparative analysis, the sample with a depth of 1626.75 m is composed of calcareous bands in black carbonaceous shale. The samples were sent to Sichuan Keyuan Engineering Technology Testing Center for clay mineral and whole rock X-ray diffraction analysis and testing and major element and trace element (including rare-earth elements) testing.

The major elements are determined by an X-ray fluorescence spectrometer Axios-mAX in accordance with Methods for Chemical Analysis of Silicate Rocks-Part 28: Determination of 16 Primary and Secondary Components (GB/T 14506.28-2010). Trace elements (including rare-earth elements) are determined by inductively coupled plasma atomic emission mass spectrometry (ICP-MS PE NexION 350X) according to Chemical Analysis Methods of Silicate Rocks-Part 30: Determination of 44 Elements (GB/T 14506.30-2010).

## 4. Results

*4.1. Major Elements.* The content of $SiO_2$ in GRY1 is 21.1%-64.43%, with the highest average content of 50.36%; the second is CaO, whose content is 2.29%-35.17%, with an average content of 13.53%; the content of $Al_2O_3$ is 4.48-18.91%, and the average content is 12.92%. The average proportion of these three types of elements is more than 70%. Other contents are relatively low, with an average $K_2O$ content of 1.51%, average $Fe_2O_3$ content of 2.27%, and average MgO content of 0.78% (Table 1). The organic carbon content changes from top to bottom, with an average content of 1.63%.

*4.2. Trace Elements and Rare-Earth Elements.* Compared with the element abundance of the upper crust [22], the trace element analysis results of black shale samples from the first member of the Carboniferous Luzhai Formation in GRY1 in Rongshui area show that the concentration coefficients of Li, Sr, Mo, Cd, Sb, U, and Cs are 4.47, 3.26, 4.91, 7.12, 3.75, 1.95, and 2.03, respectively, showing the characteristics of moderate enrichment. The concentration coefficients of Co and Cu are 0.51 and 0.63, respectively, showing strong deficit characteristics. The abundance of other elements is similar to that of the upper crust, showing weak enrichment or weak depletion.

Table 1: Results of trace elements of Lower Carboniferous black shale in Rongshui, Guangxi.

| Depth (m) | Content of major elements and TOC (%) | | | | | | | | | | | Loss on ignition (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TOC | $SiO_2$ | $Al_2O_3$ | $TFe_2O_3$ | MgO | CaO | $Na_2O$ | $K_2O$ | $TiO_2$ | MnO | $P_2O_5$ | |
| 1535.00 | 0.95 | 42.11 | 10.32 | 3.74 | 0.76 | 20.12 | 0.52 | 0.9 | 0.44 | 0.09 | 0.09 | 20.84 |
| 1547.50 | 1.07 | 64.43 | 17.24 | 2.18 | 0.59 | 2.93 | 0.7 | 1.79 | 0.68 | 0.02 | 0.06 | 8.84 |
| 1566.00 | 1.01 | 55.63 | 12.76 | 2.91 | 0.65 | 11.27 | 0.53 | 1.28 | 0.5 | 0.05 | 0.04 | 13.81 |
| 1603.10 | 1.50 | 62.3 | 15.34 | 2.99 | 0.58 | 5.07 | 0.58 | 1.86 | 0.51 | 0.02 | 0.07 | 10.63 |
| 1608.10 | 1.49 | 62.85 | 18.91 | 2.46 | 0.72 | 2.29 | 0.65 | 2.5 | 0.61 | 0.02 | 0.04 | 8.69 |
| 1615.60 | 1.39 | 54.56 | 16.51 | 2.43 | 0.73 | 9.14 | 0.53 | 1.99 | 0.53 | 0.02 | 0.05 | 13.33 |
| 1617.98 | 1.51 | 55.39 | 10.64 | 1.81 | 0.68 | 13.16 | 0.34 | 1.43 | 0.49 | 0.015 | 0.045 | 15.34 |
| 1624.06 | 1.27 | 41.83 | 6.91 | 1.85 | 1.26 | 23.09 | 0.27 | 0.88 | 0.33 | 0.015 | 0.059 | 22.89 |
| 1625.80 | 1.86 | 38.1 | 11.74 | 1.85 | 0.95 | 21.5 | 0.58 | 1.3 | 0.36 | 0.02 | 0.06 | 22.72 |
| 1626.75 | 1.34 | 21.10 | 4.47 | 0.74 | 0.92 | 35.17 | 0.20 | 0.56 | 0.16 | 0.011 | 0.11 | 35.81 |
| 1629.50 | 4.53 | 55.62 | 17.33 | 2.04 | 0.78 | 5.08 | 0.43 | 2.11 | 0.62 | 0.0073 | 0.058 | 15.90 |
| Average | 1.63 | 50.36 | 12.92 | 2.27 | 0.78 | 13.53 | 0.48 | 1.51 | 0.48 | 0.03 | 0.06 | 17.16 |

The content of rare-earth elements in black shale in the study area has little difference with the abundance of upper crust, and the overall trend is basically consistent. See Table 2 for rare-earth element analysis results of samples in the study area. Light rare-earth elements (hereinafter referred to as LREE) contain La, Ce, Pr, Nd, Sm, and Eu. Heavy rare earth (hereinafter referred to as HREE) contains Tb, Dy, Ho, Er, Tm, Yb, and Lu. The average total amount of rare-earth elements is $128.39 \times 10^{-6}$, of which the average light rare earth is $114.58 \times 10^{-6}$ and $13.81 \times 10^{-6}$ for heavy rare earth. The total rare-earth element content of samples in the study area ($128.39 \times 10^{-6}$) is significantly lower than the content of the upper crust (UCC) ($148.14 \times 10^{-6}$) [23, 24]. $\delta$Eu is a reflection of the abnormal degree of Eu [25, 26]. In the shale sample of the first member of Luzhai Formation, the content of $\delta$Eu is 0.62-1.15, with an average value of 0.73, indicating a negative anomaly. $\delta$Ce content is 0.70-0.93, showing negative abnormality.

## 5. Discussion

*5.1. Paleoenvironment Analysis.* Based on the element geochemical data of the shale of the first member of the Carboniferous Luzhai Formation in GRY1, this paper analyzes the ancient environment of the Rongshui area from the aspects of the ancient redox environmental conditions, ancient salinity, and ancient climate.

*5.1.1. Paleoredox Conditions.* Many scholars have fully discussed how to select geochemical elements to judge ancient redox conditions and have effectively verified them through a large number of examples. Under different environmental conditions, the oxyphilic or thiophilic elements will be separated or their valence changes, resulting in enrichment or loss. Currently, wV/(wNi + wV), V/Sc, Th/U, $\delta$U, and so on are used to characterize the change of redox environment of water body.

Previous studies [27] believed that the ratio of wV/(wNi + wV) can indicate the change of sedimentary environment. When the ratio is less than 0.46, it is an oxidizing environment; between 0.46 and 0.57, it is a secondary oxidizing environment; between 0.57 and 0.85, it is a reducing environment; and more than 0.85, it is a sulfide environment. The average value of wV/(wNi + wV) in the first section of Luzhai Formation is 0.80, the minimum value is 0.74, and the maximum value is 0.87, indicating the restoration environment.

The uranium element in the sediment is relatively active, and $U^{4+}$ will be oxidized into $U^{6+}$ in the oxygen rich environment and dissolved in water, resulting in the loss of U element in the sediment; on the contrary, U element will be enriched in the anoxic environment. Th is an inert element, which is stably adsorbed in the sediment and will not change due to the change of redox environment. Research shows $\delta U = U/[0.5^{*}(Th/3 + U)]$. When the value of $\delta$U is less than 1, it generally represents normal water environment; when the value of $\delta$U is greater than 1, it indicates anoxic reduction environment [28, 29]. According to the trace element results in this paper, the average value of $\delta$U of the first member of Luzhai Formation is 6.26, indicating an anoxic reducing environment. When the ratio of Th/U is less than 2, it indicates an anoxic environment; when it is between 2 and 8, it indicates an oxygen deficient environment; when it is greater than 8, it indicates an oxidizing environment. The Th/U ratio of the first member of Luzhai Formation in Rongshui area is between 0.91 and 5.5, which is generally characterized by the transition from hypoxia to oxygen deprivation from bottom to top.

The rare-earth element Ce anomaly can also indicate the change of redox environment in water. Generally, Ce element has two valence states which are $Ce^{3+}$ and $Ce^{4+}$. If it is oxidized, stable $Ce^{3+}$ in the water will be converted into unstable $Ce^{4+}$ and hydrolyzed in the water, resulting in the loss of Ce in the water. Use the formula $\delta Ce = 2CeN/(LaN + PrN)$ which represents the change of element Ce, in which $N$ represents the chondrite normalized value of measured value of corresponding element [30]. Some scholars [31, 32] found that the negative anomaly of $\delta$Ce often appears at the redox interface of seawater when studying the relationship between the degree of abnormality of $\delta$Ce

Table 2: REE characteristic parameters of Lower Carboniferous black rock shale in Rongshui, Guangxi.

| Sample number | Depth (m) | Content of REE ($10^{-6}$) La | Ce | Pr | Nd | Sm | Eu | Gd | Tb | Dy | Ho | Er | Tm | Yb | Lu | Y | ΣREE | ΣLREE | ΣHREE | ΣLREE/ΣHREE | LaN/YbN | δEu | δCe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GX-01 | 1535.00 | 31.05 | 58.64 | 6.52 | 25.06 | 4.87 | 0.99 | 4.68 | 0.74 | 3.97 | 0.73 | 2.28 | 0.33 | 2.25 | 0.35 | 19.40 | 142.46 | 127.13 | 15.33 | 8.29 | 9.33 | 0.63 | 0.93 |
| GX-02 | 1547.50 | 39.52 | 67.98 | 7.62 | 27.11 | 4.75 | 0.91 | 3.69 | 0.54 | 2.80 | 0.57 | 1.95 | 0.30 | 2.29 | 0.37 | 14.14 | 160.40 | 147.89 | 12.51 | 11.82 | 11.66 | 0.64 | 0.87 |
| GX-03 | 1566.00 | 28.47 | 51.82 | 5.67 | 21.04 | 3.73 | 0.74 | 3.18 | 0.50 | 2.76 | 0.57 | 1.78 | 0.27 | 1.98 | 0.29 | 14.00 | 122.80 | 111.47 | 11.33 | 9.84 | 9.72 | 0.64 | 0.91 |
| GX-04 | 1603.10 | 29.94 | 46.15 | 5.59 | 21.28 | 3.92 | 0.81 | 3.47 | 0.56 | 3.08 | 0.66 | 2.09 | 0.32 | 2.35 | 0.38 | 17.37 | 120.60 | 107.69 | 12.91 | 8.34 | 8.61 | 0.66 | 0.79 |
| GX-05 | 1608.10 | 36.44 | 64.79 | 7.11 | 25.81 | 4.35 | 0.79 | 3.16 | 0.45 | 2.84 | 0.64 | 2.29 | 0.38 | 3.00 | 0.48 | 15.35 | 152.53 | 139.29 | 13.24 | 10.52 | 8.21 | 0.62 | 0.90 |
| GX-06 | 1615.60 | 32.26 | 60.39 | 6.85 | 26.21 | 4.72 | 0.96 | 3.96 | 0.60 | 3.72 | 0.76 | 2.55 | 0.40 | 2.96 | 0.46 | 18.32 | 146.80 | 131.39 | 15.41 | 8.53 | 7.36 | 0.66 | 0.92 |
| GX-07 | 1617.98 | 24.59 | 46.99 | 6.35 | 23.06 | 4.49 | 1.08 | 3.63 | 0.65 | 3.64 | 0.76 | 2.16 | 0.34 | 2.17 | 0.30 | 18.76 | 120.20 | 106.54 | 13.66 | 7.80 | 7.64 | 0.79 | 0.87 |
| GX-08 | 1624.06 | 20.15 | 36.19 | 5.06 | 18.73 | 3.87 | 1.07 | 4.03 | 0.73 | 4.12 | 0.82 | 2.23 | 0.34 | 2.31 | 0.30 | 23.26 | 99.93 | 85.07 | 14.87 | 5.72 | 5.89 | 0.82 | 0.82 |
| GX-09 | 1625.80 | 26.34 | 42.30 | 5.25 | 19.65 | 3.70 | 0.86 | 3.52 | 0.58 | 3.44 | 0.71 | 2.30 | 0.34 | 2.35 | 0.37 | 19.37 | 111.71 | 98.10 | 13.61 | 7.21 | 7.57 | 0.72 | 0.80 |
| GX-10 | 1626.75 | 14.82 | 22.40 | 3.66 | 14.33 | 3.27 | 1.23 | 3.19 | 0.56 | 3.16 | 0.66 | 1.77 | 0.27 | 1.64 | 0.22 | 17.38 | 71.18 | 59.71 | 11.47 | 5.21 | 6.11 | 1.15 | 0.70 |
| GX-11 | 1629.50 | 38.12 | 60.56 | 8.89 | 31.87 | 5.55 | 1.07 | 4.06 | 0.74 | 4.32 | 1.00 | 2.99 | 0.49 | 3.50 | 0.50 | 27.14 | 163.67 | 146.06 | 17.61 | 8.29 | 7.36 | 0.66 | 0.75 |
| Average | | 29.24 | 50.75 | 6.23 | 23.10 | 4.29 | 0.96 | 3.69 | 0.61 | 3.44 | 0.72 | 2.22 | 0.34 | 2.44 | 0.37 | 18.59 | 128.39 | 114.58 | 13.81 | 8.32 | 8.13 | 0.73 | 0.84 |

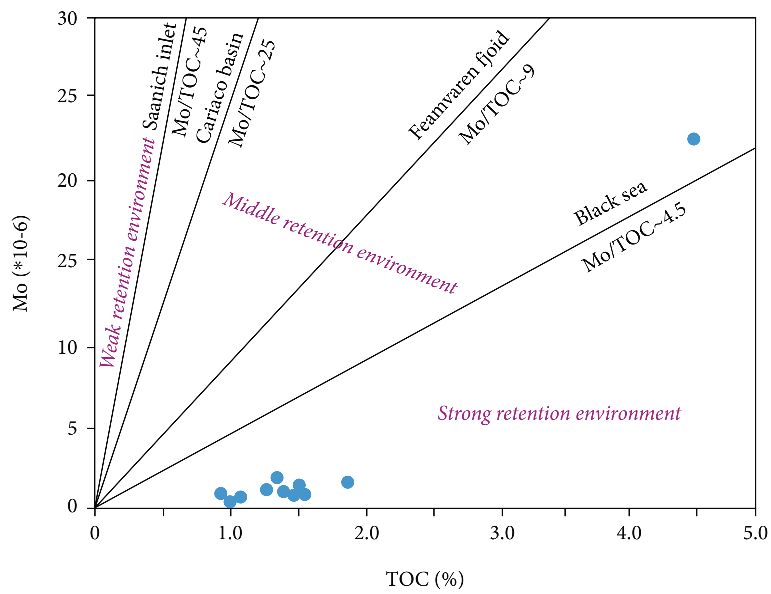


Figure 4: The relationship between Mo and TOC of the first member of Luzhai Formation in Rongshui area [31].

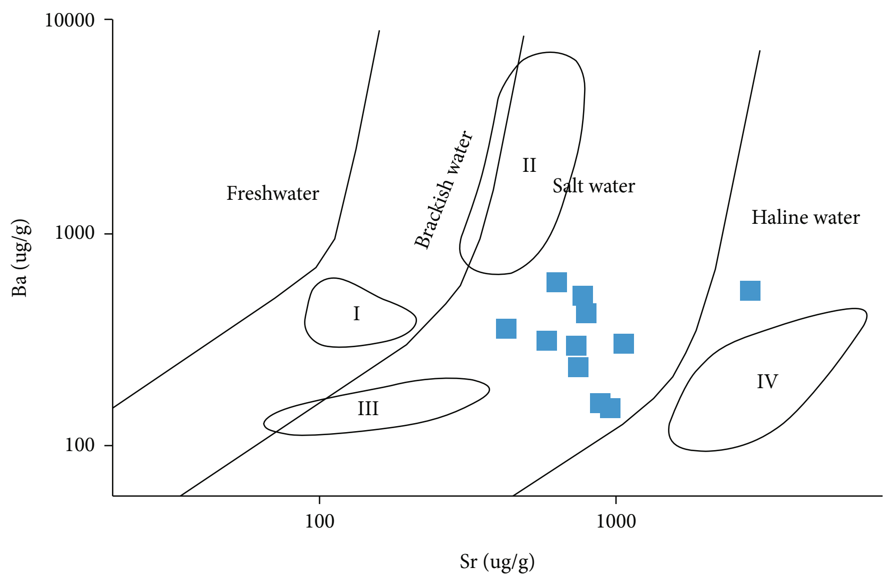


Figure 5: Ba-Sr map of shales in the first member of Luzhai formation in Rongshui area [35]: I stands for modern delta brackish clay area; II represents the Pacific offshore sediment area; III represents marine carbonate rock area of different ages in Russian platform; IV represents modern high salt water sediment area.

in modern seawater and dissolved oxygen in seawater. When the depth of seawater changes, the position of the negative anomaly of $\delta$Ce changes accordingly. The $\delta$Ce anomaly in sediment also changes correspondingly at the same time. In this way, it can be understood that the increase of negative $\delta$Ce anomaly represents the rise of sea level, while the increase of positive $\delta$Ce anomaly represents the decline of sea level. In the sample of the first section of Luzhai Formation in Rongshui area, $\delta$Ce is characterized by negative anomaly, the value of $\delta$Ce varies from 0.7 to 0.93, with a small vertical change, representing a certain fluctuation of sea level.

The Mo-TOC covariant model map can be used to judge the retention degree of anoxic ancient marine water [33]. When the ratio of Mo/TOC is greater than 45, it is a weak retention environment. With the enhancement of water retention, the ratio of Mo/TOC in the sediment also decreases. When the ratio of Mo/TOC is less than 4.5, it represents a strong retention environment. The element geochemical test data of the first member of the Luzhai Formation shale on the projection of the Mo-TOC covariant model map shows that there was a strong detention environment at that time (Figure 4).

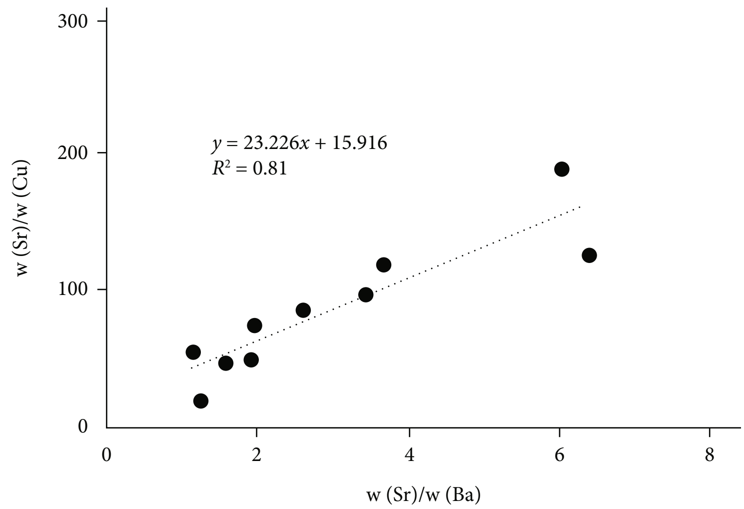


FIGURE 6: w(Sr)/w(Ba) and w(Sr)/w(Ba) relationship of the first member of Luzhai Formation in Rongshui area.

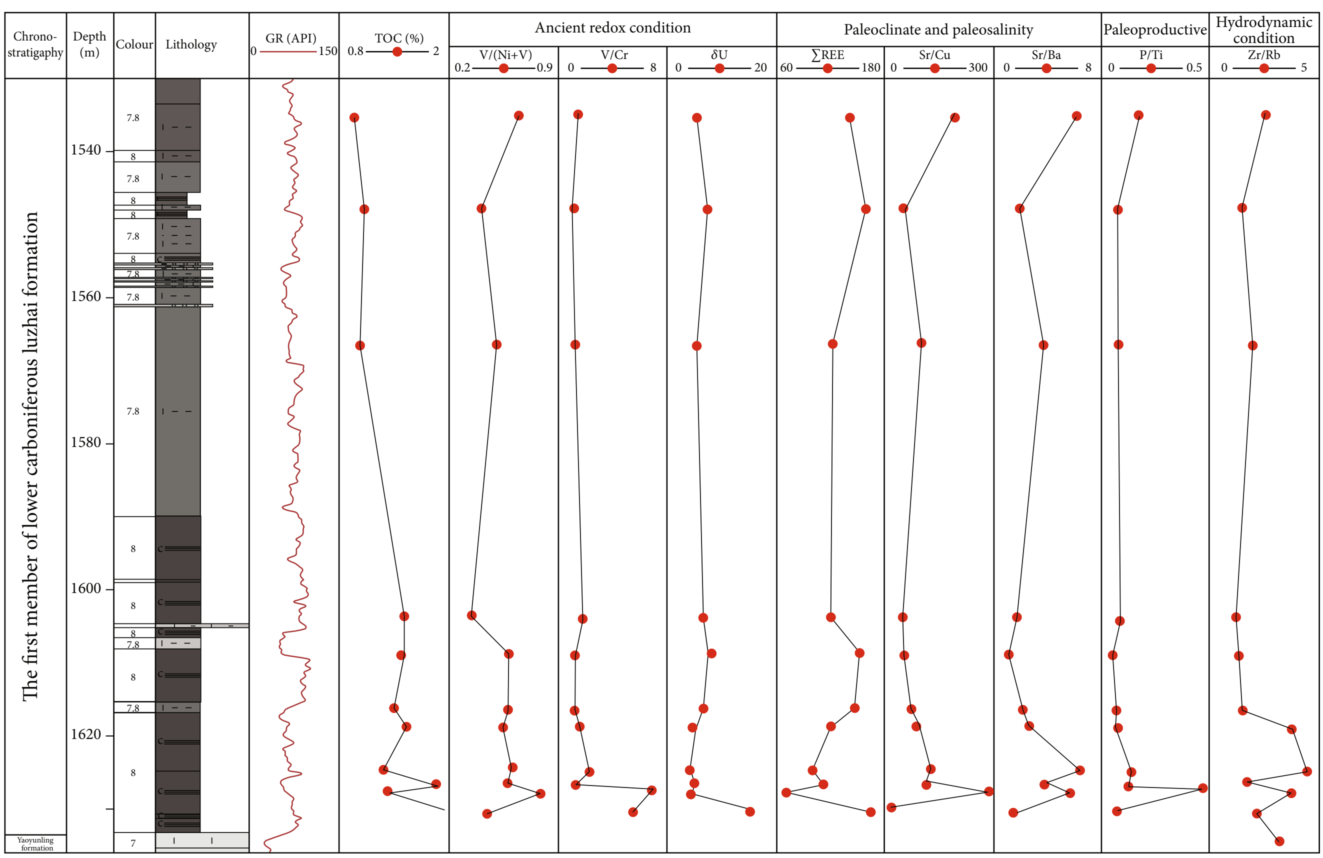


FIGURE 7: Paleoenvironment and paleoproductivity distribution of the first member of the Carboniferous Luzhai formation in the well GRY1 in Rongshui area, Guangxi.

*5.1.2. Paleosalinity and Paleoclimate.* Trace elements Sr and Ba are widely distributed in the crust, and the ratio of Sr/Ba can be used to reflect the change of water salinity during sediment deposition. The solubility of Sr is greater than that of Ba; if the salinity of the water body increases, Ba will preferentially precipitate from the water body in the form of sulfate, leading to the gradual increase of Sr/Ba. If the ratio is greater than 1.0, it represents marine saline water; if it is less than 0.6, it represents fresh water; if the ratio is between 0.6 and 1.0, it represents brackish water environment [34]. Based on the analysis of trace elements in the sample of the first section of the Luzhai Formation, the ratio of Sr/Ba is greater than 1.0, and the ratio fluctuates from the bottom to the top, indicating that it is marine salt water, but the salinity of the water body changes to some extent internally.

When studying clays of different origins in different sedimentary periods, some scholars found that ancient salinity or sedimentary origin can be distinguished according to the content difference of Sr, B, Ba, and other elements and proposed Ba-Sr diagrams to reflect the degree of ancient salinity of sediments and sediments formed in different sedimentary environments [35]. It can be seen from the Sr-Ba diagram (Figure 5) of the samples in the first section of the Luzhai Formation that most of the samples are scattered in the range of salt water, and some samples at the bottom of the first section of the Luzhai Formation are in the haline water environment.

Previous studies [36] show that the ratio of Sr/Cu can reflect the ancient climate. When the ratio of Sr/Cu is less than 10, it represents a warm and humid climate environment; when the ratio is greater than 10, it represents a dry and hot climate environment. The samples' ratio of Sr/Cu from the first section of the Luzhai Formation in Rongshui area is between 19.12 and 513.92, with an average of 124.74, reflecting the dry and hot climate at that time.

The total amount of rare-earth elements can indicate the changes of the ancient climate. The warm and humid environment is conducive to the enrichment of rare-earth elements. On the contrary, the dry and cold or dry and hot environment is not conducive to the preservation of rare-earth elements [37]. The average total amount of rare-earth elements in shale samples of the first member of Luzhai Formation in Rongshui area is $128.39 \times 10^{-6}$, obviously lower than that of the post-Archean Australian shale (PAAS) ($184.44 \times 10^{-6}$) and upper crust (UCC) ($148.14 \times 10^{-6}$), which reflects that the study area was in a dry and hot climate during the deposition period.

Correlation analysis of w(Sr)/w(Ba) and w(Sr)/w(Cu) of shale samples from the first member of Luzhai Formation in Rongshui area (Figure 6) shows that w(Sr)/w(Ba) and w(Sr)/w(Cu) are positively correlated, which can infer that the paleosalinity environment of marine saline water in the study area is closely related to the dry and hot paleoclimatic conditions at that time. In the arid and hot climate, strong evaporation and less rainfall could cause the increase of paleosalinity. On the whole, the shale of the first member of the Lower Carboniferous Luzhai Formation in the Rongshui area was formed in a dry, hot, marine salt water paleoenvironment.

*5.1.3. Evolution of Sedimentary Environment.* Through the vertical analysis of the samples from the first member of the Carboniferous Luzhai Formation in GRY1, it is believed that the paleoredox environment, paleoclimate, paleosalinity, and paleoproductivity reflect certain sedimentary evolution laws. $\delta$U and V/Cr of the first member of Luzhai Formation in Rongshui area are generally characterized by the transition from hypoxia to oxygen deprivation from bottom to top. The ratio of Sr/Ba fluctuates from the bottom to the top, indicating that it is marine salt water, but the salinity of the water body changes to some extent internally. At the bottom (depth of 1625 m-1630 m) of the first member of the Luzhai Formation, the paleoenvironment inherited the characteristics of the late Devonian. The climate was warm and humid, and the salinity of seawater was relatively low. The rising sea level was conducive to the propagation of algae, while preventing the input of a large number of terrigenous debris. The anaerobic sulfurization environment was conducive to the preservation of organic matter and the formation of organic rich intervals. Therefore, the TOC content of carbonaceous shale at the bottom of the Luzhai Formation was the highest. In the middle and lower part (depth of 1580 m-1625 m) of the first member of the Luzhai Formation, the paleoenvironment has changed to a certain extent. The salinity of the seawater has increased, the climate is dry and hot, the paleoproductivity has gradually decreased, the hydrodynamic conditions have increased, the algae reproduction has weakened, and at the same time, a certain amount of terrigenous debris input has led to the reduction of shale purity and TOC content. In the upper part (depth of 1530 m-1580 m) of the first member of Luzhai Formation, the paleoproductivity was further reduced under the relatively weak reduction environment, which was not conducive to the production and preservation of organic matter (Figure 7).

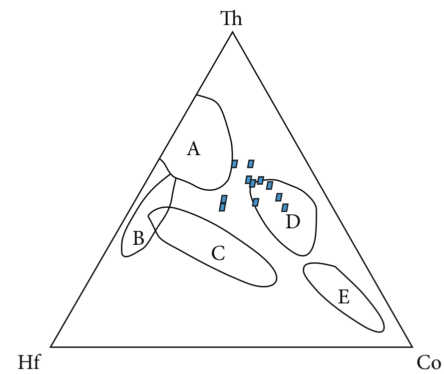


Figure 8: Th-Hf-Co provenance discrimination diagram [38]: A—felsic volcanic rocks; B—quartzite from cratonic basin; C—feldspar sandstones; D—shale (average upper continental crust); E—graywackes (arcs).

### *5.2. Analysis of Tectonic Background*

*5.2.1. Provenance Analysis.* In the process of migration, although the sediment will be sorted under the action of hydrodynamic forces, resulting in different minerals and grain sizes of the sediment, the activity of rare-earth elements is weak and the relative mobility is small. The rare-earth elements in sedimentary rocks generally inherit the characteristics of the parent rock. Therefore, some characteristic parameters and distribution patterns of rare-earth elements are widely used in judging the source of materials.

Condie [38] proposed Th-Hf-Co provenance discrimination diagram for analysis. It can be seen from the figure (Figure 8) that most of the parent rocks of the samples in the first section of the Luzhai Formation are located in the shale area, and some samples are close to the felsic igneous rock area. It shows that the study area has the

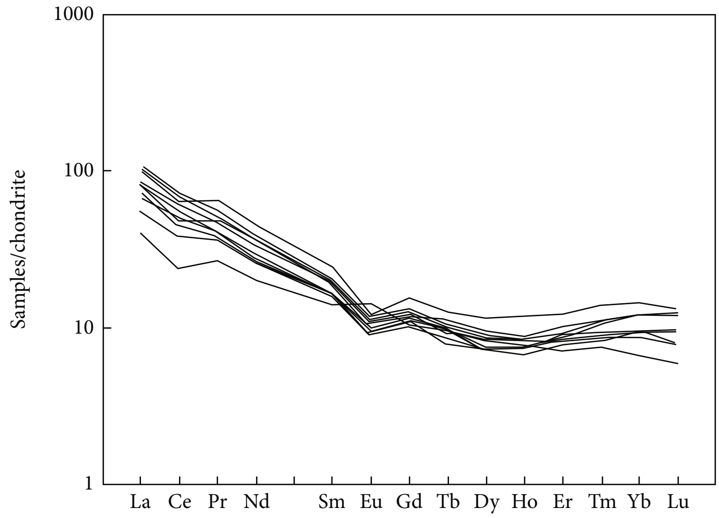


Figure 9: The chondrite-normalized REE patterns in shale samples of the first member of Luzhai Formation in Rongshui area.

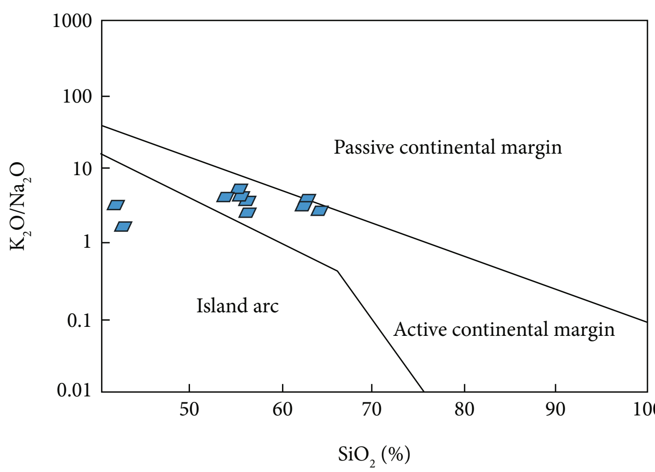


Figure 10: $SiO_2$-($K_2O/Na_2O$) tectonic discrimination diagram in Rongshui, Guangxi [41].

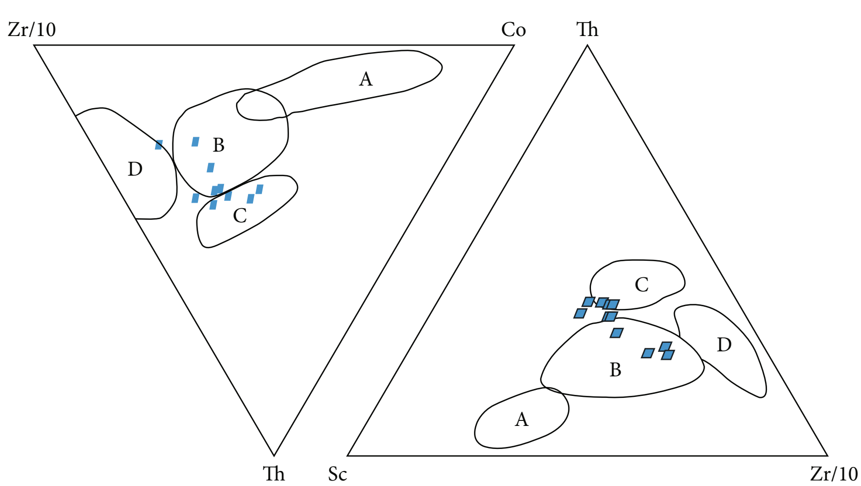


Figure 11: La-Th-Sc and Th-Sc-Zr/10 tectonic discrimination diagram [42]: A—oceanic island arc; B—continental island arc; C—active continental margin; D—passive continental margin.

provenance characteristics of active continental margin and felsic island arc.

The total amount of rare-earth elements is often used to judge the original rock characteristics and distinguish rock types. The chondrite-normalized rare-earth distribution pattern [39] of shale samples from the first segment of Luzhai Formation is shown in Figure 9. In REE distribution patterns, the chondrite-normalized REE partition curves incline to the right, indicating that they are enriched in LREE. Most samples show the same trend, and some samples show a small deviation, indicating that the samples taken have similar provenance. The maximum ratio of light and heavy rare earths is 11.82, the minimum is 5.21, and the average is 8.32, showing the characteristics of crust mantle source material deposition.

$\delta$Eu is used to represent the degree of Eu anomaly, which can generally be used as one of the parameters to identify the source of parent rock materials. If the parent rock is a medium acid felsic rock (such as granite and rhyolite), the ratio of light and heavy rare earths in sedimentary rocks is high, light rare earths are enriched, and most of them have negative Eu anomalies. If the parent rock is basalt, the ratio of light and heavy rare earths in the sedimentary rock is low, and most of them are without Eu anomaly [40]. In the study area, $\delta$Eu varies from 0.62 to 1.15, with an average of 0.73, indicating that the parent rock of the first member of the Luzhai Formation sample in the Rongshui area is of mixed origin.

*5.2.2. Tectonic Analysis.* Under different geotectonic backgrounds, the distribution characteristics of major elements in rocks are different. Therefore, the ratio diagram of major elements can be used to distinguish the source area property and tectonic background of sedimentary rocks. Rose and Korsch (1988) [41] proposed to use $K_2O/Na_2O$-$SiO_2$ for tectonic background discrimination. The samples of the first member of Luzhai Formation in Rongshui area fall on the active continental margin and island arc area as shown in Figure 10.

Th, Zr, Ti, Co, Sc, and other inactive trace elements have good stability, so they can be used to analyze the tectonic environment. In Th-Co-Zr/10 discrimination map (Figure 11(a)), the samples of the first member of Luzhai Formation in Rongshui area fall in the continental island arc and active continental margin area. In Th-Sc-Zr/10 discrimination diagram (Figure 11(b)), samples also fall in the continental island arc and active continental margin area, which are mutually verified.

The predecessors [42] summarized the data of eastern Australia and believed that the sediments with low total rare earth, weak enrichment of light rare earth, and weak positive anomaly of europium mostly came from the tectonic background of oceanic island arc. Most of the sediments in the tectonic setting of continental island arc are characterized by high REE content and weak europium negative anomaly. The average values of sample parameters of the first member of Luzhai Formation in Rongshui area mostly fall between the continental island arc and the active continental margin, indicating that the sedimentary environment was unstable and highly active under the background of extensional rifting at that time. This is consistent with the regional understanding of sedimentary characteristics. In the early Carboniferous, Guangxi had basin facies or slope facies deposits with platform basin facies alternating. On the plane, the thickness of organic-rich shale in the Luzhai Formation changed rapidly. In the vertical direction, although the first section of the Luzhai Formation is thick, the lithology of well GRY1 changed frequently from top to bottom, which is the embodiment of the changes in the sedimentary environment.

## 6. Conclusions

Through the analysis of the sedimentary paleoenvironment and tectonic background of the shale of the first member of the Carboniferous Luzhai Formation in GRY1, the following conclusions can be made:

(1) The samples from the first member of the Lower Carboniferous Luzhai Formation in Rongshui area are mainly quartz and feldspar minerals. The trace elements Li, Sr, Mo, Cd, Sb, U, and Cs are relatively rich, while Co and Cu are strongly depleted. The total amount of rare-earth elements is obviously lower than that of the upper crust

(2) The average values of $V/(V+Ni)$, Th/U, and Mo-TOC of the first member of the Luzhai Formation indicate that it was an anoxic reduction paleoenvironment. The Ba-Sr diagram, Sr/Cu, and total amount of REE of the samples reflect that the study area was in a dry and hot marine saline water paleoenvironment during the deposition period

(3) The vertical sedimentary evolution of the first member of the Carboniferous Luzhai Formation can be divided into three sections: at the bottom, the climate is warm and humid, the seawater salinity is low, and the TOC is high; the upward reduction conditions are weakened, and the paleoproductivity is reduced, which is not conducive to the production and preservation of organic matter

(4) Most of the parent rocks of the first member of the Luzhai Formation are located in shale area, and some samples are close to felsic igneous rock area, which shows mixed origin. The samples were located in the continental island arc and active continental margin, indicating that the sedimentary environment was unstable and active under the background of extensional rifting at that time

## Data Availability

The data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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