Enrichment Mechanism of Lithium in Late Permian Coals in the Bijie Area, Guizhou, China

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ABSTRACT: Research on the enrichment mechanism of lithium in coal can increase its economic value. We applied a series of techniques such as X-ray diffraction and ICP-MS to analyze the coal samples collected in the Bijie area and studied the enrichment mechanism of lithium in coal based on the theory of mineralogy and sedimentology. The results show that (1) the highest abundance of lithium in coal is 222 μg/g, the lowest 33.2 μg/g, and the average 87.05 μg/g. Among them, the abundance of lithium in coal samples from Xinhua coalfield and Wenjiaba coalfield reached 136 and 222 μg/g, respectively, which reached the minimum industrial grade (120 μg/g). (2) Lithium in coal was positively correlated not only with ash (0.46) and clay minerals (0.41) but also with total organic matter (0.38) and volatile matter (0.58) in coal, indicating that lithium in coal in the Bijie area has both inorganic and organic origins. (3) The ratio of TiO₂/Al₂O₃, a geochemical index, shows that the maximum ratio is 0.37, and the average is 0.09, indicating that the metal elements are a product of volcanic eruption, and the paleogeographic environment also shows that igneous rocks are exposed in the western provenance area of this study area. (4) The enrichment of lithium in coal is not closely related to the pure marine environment but is closely related to the marine–land transitional environment. In the past, there was a lack of relevant research on lithium in coal in the Bijie area, and the proposal of organic and inorganic coupling causes is of great significance for the development and utilization of lithium in coal.

1. INTRODUCTION

The discovery and research of lithium in coal can greatly increase the added value of coal resources¹,² and alleviate the shortage of industrial lithium to a certain extent.³–⁵ Its research can also provide scientific theoretical support for later development and utilization to carry out basic theoretical research on the enrichment of lithium in coal, such as provenance analysis, enrichment processes, and occurrence state research that can guide the selection of extraction techniques.⁶,⁷

The content of lithium in China varies greatly among coals from different regions or different ages.⁸ Existing reports on its enrichment factors show that lithium in coal is mainly related to inorganic components in coal but also related to organic matter in coal.⁹–¹² Finkelman⁹ speculated that clay minerals in coal are the main carriers of lithium. Tang et al.¹⁰ and He et al.¹¹ believed that the clay minerals such as illite, kaolinite, smectite, etc., had adsorbed lithium. Tang et al.¹⁰ also assumed that lithium had an affinity for clay minerals in coal. Yi et al.¹¹ and Liu et al.¹² further believed that the concentration of lithium in coal was not very closely related to organic substances. The leaching experiments also show that, whether in high-rank coal or low-rank coal, lithium has a great relationship with silicate.¹⁰,¹³,¹⁴ However, in the Longyearbyen coal mine in Norway, it was found that 72% of the lithium in the coal is combined with organic matter.¹⁵ Dai et al. found that, in addition to the two aforementioned types, it was partially enriched in mica and tourmaline.¹⁶ In fact, the reasons for the enrichment of lithium in coal are complex. The migration and enrichment of associated elements in coal are the result of the combined action of multiple geological factors.⁷ That is to say, the enrichment of trace elements in coal is mostly caused by coupling operations.¹⁷ It is probably related to inorganic minerals or organic matter or controlled by a single factor.¹⁸ The enrichment mechanism of lithium needs to be specifically analyzed in conjunction with specific field characteristics.

In Bijie City, as the main energy base of Guizhou’s "West-to-East Power Transmission",¹⁹ the discovery of lithium in coal has important economic significance for increasing the additional benefits of coal resources. However, due to the previous studies only focusing on the coal resource and its harmful elements in this area, there is a lack of research on beneficial elements in coal;²⁰–²² in particular, there are few
studies on the enrichment mechanism of lithium in coal. This Article uses mineralogy and sedimentary environment theories to discuss the spatial distribution and enrichment mechanism of lithium in coal in the Bijie area, which can lay a good foundation for subsequent development and utilization.

2. GEOLOGICAL BACKGROUND

The Late Permian coal-accumulating basin in the Bijie area of Guizhou is situated on the western edge of the Yangtze quasishelf. During the coal formation period, it was a part of the epicontinental depression basin in the Late Permian in South China. In the course of the Dongwu movement in Guizhou, it was mainly manifested in the pseudointegrated or unconformable contact relationship between the Wujiaping formation and the Maokou formation in the Middle and Late Permian, which further contributed to the paleogeographic pattern of Guizhou high in the northwest and low in the southeast. During the Yanshan movement, there was a development of folds in Guizhou. Therefore, the coal fields are dominated by equipotential folds and short-axis folds, followed by troughlike folds. Therefore, in the Bijie coal-bearing area, the fold structure basically controls the preservation and occurrence of the coal-bearing strata (Figure 1A). The subsequent Himalayan movement was mainly manifested as faults. Large-scale faults were large in scale and extended, which controlled the occurrence of current coal fields and constituted the natural boundary of the mine.

Most of the coal-bearing strata in the coalfield are the Upper Permian Longtan Formation (Xuanwei Formation), dominated by marine—terrestrial alternate deposits. Frequent regressive and transgressive events have resulted in significant multilevel cycles and have also caused a large number of coal seams, generally 15—35 layers, and the measured mineable and partially mineable coal seams amounted to 20 layers (Figure 1B), especially within 1.0—2.0 m of the thin coal seams and medium thick coal seams. These coals have established Bijie’s important energy supply position in southwestern China. It is especially known for its high-quality anthracite coal. The identified resource reserves are 42.087 GT, accounting for more than 45% of the province’s discovered coal resources. This paper only selects the principal coal seams in the study area and exploration area as the research object.

3. EXPERIMENTAL SECTION

3.1. Sample Collection Methods. The collected samples are all taken from the working faces of the mined coal seams from 11 coal mines (Figure 1A). A total of 17 samples were collected (Figure 1B). The samples were all collected from the main coal seams with simple geological structures. At the same time, it was also required to conduct scattered sampling of the same coal seam at different locations and to sample at different levels at the same location. Before sampling, the stripped surface of the coal seam was carefully cleaned to remove the oxidized and contaminated parts of rock dust, and grooves were cut according to the specification of 25 mm × 15 mm. Among them, if there is stratification in the coal seam, in order to avoid intermixing of samples, the stratified samples were taken from the top to the bottom in order, and the stratified samples are numbered sequentially from top to bottom.

During the sampling process, the characteristics of the coal seam structure, physical properties, and macroscopic coal rock
types at the sampling points need to be set out in detail. At the same time, it is required to ensure the sample weight as much as possible on the premise of ensuring the quality of coal samples, in order to facilitate the composite test and comparison between coal samples.

### 3.2. Analytical Methods

#### 3.2.1. Chemical Test of Coal

According to the national standard GB47421996,31 the coal samples were crushed; large particles (>0.2 mm) were discarded, and only samples with particles less than 0.2 mm were retained and divided into several parts. The total sulfur and form sulfur content in the coal samples were determined according to the national standard GB/T 215-2003,32 and the proximate analysis was based on the national standard GB/T 212-2008 industrial analysis.33

#### 3.2.2. Coal Rock Identification and Major Elements Test

The method for the determination of the microscopic components and minerals of coal is implemented according to GB/T 8899-2013.34 The method for the measurement of the vitrinite reflectance of coal is implemented according to GB/T 6948-2008.35 The method for the determination of clay minerals in coal is implemented according to SY/T163201029,36 and the determination method of major elements in coal is based on MT/T 1086-2008.37 The testing unit entrusted the testing center of China General Administration of Coal Geology to implement these methods.

#### 3.2.3. Test Method for Lithium in Coal

The preferred test method for lithium, Ga, Nb, etc., in coal is the ICP-MS method.38 The test methods for lithium in coal are as follows: In the first step, weigh the sample and place it in a PTFE crucible; moisten it with a few drops of water, and then, add HCl and HNO₃. In the second step, cover the crucible lid and place it on an electric hot plate with a temperature control of 150 °C for 24 h. The third step is to open the lid of the crucible, add HF and HClO₄, close the lid, continue heating at 150 °C for 12 h until the perchloric acid fumes are dissipated, and then cool. In the fourth step, repeat steps one, two, and three until the sample is completely dissolved. In the fifth step, evaporate the sample in the fourth step, add concentrated HCl to airtight vessels and heat until the solution becomes clear. In the sixth step, evaporate the sample after the fifth step, move it to a plastic colorimetric tube, and add 1 mL of 0.67 mol/L HNO₃ and 30% CH₃OH (v/v), measured by inductively coupled plasma mass spectrometry after shaking. The testing unit also entrusted the testing center of China General Administration of Coal Geology to implement this method.

### 4. RESULTS

#### 4.1. Coal Chemistry and Coal Rock Identification

The coal samples collected were all located in the upper Permian Longtan Formation, which is the most important coal-bearing formation in Guizhou Province.23–26 The test results are shown in Tables 1 and 2.

#### 4.2. Major Elements

The test results of lithium and major element oxides in coal are given in Table 3. It can be seen that the main element in coal ash is SiO₂, followed by Al₂O₃, Fe₂O₃, etc.; the content of other major elements is relatively low. Compared to average values for Chinese coals,38,39 Na₂O, K₂O, SiO₂, MgO, and TiO₂ are enriched in the Bijie area. According to the geological survey specification for placer (metallic minerals) (DZ/T0208-2002),40 the content of TiO₂ in coal ash is slightly higher than the lowest industrial grade percentage of rutile placer 1% (about 2 kg/m³ abundance). If it is to be used, further research is needed.
The average value of SiO$_2$/Al$_2$O$_3$ in coal ash is 1.75, which is slightly greater than the theoretical value in kaolinite, 1.18.\textsuperscript{41,42} Especially in coal seam 4 and coal seam 9, the SiO$_2$/Al$_2$O$_3$ ratio is higher than 2. In addition, the ratio of TiO$_2$/Al$_2$O$_3$ in coal ash is between 0.012 and 0.368. Among them, the ratio of TiO$_2$/Al$_2$O$_3$ in coal seam 15 reaches 0.36, and the ratio of TiO$_2$/Al$_2$O$_3$ in coal seam 9 also reaches 0.306.

### 4.3. Lithium and Other Trace Elements (U, Nb, Ga, Cu)

The abundance of lithium in coal is shown in Table 2 and Figures 2 and 3. The highest abundance of lithium in coal is 222 \( \mu \text{g/g} \), the lowest 33.2 \( \mu \text{g/g} \), and the average 87.05 \( \mu \text{g/g} \), which is much larger than the statistical average value (19 \( \mu \text{g/g} \) proposed by Sun et al.\textsuperscript{43} and 31.8 \( \mu \text{g/g} \) proposed by Liu et al.\textsuperscript{47}).

| sample ID | vitrinite (%) | inertite (%) | total organic | clay (%) | carbonate (%) | sulfide (%) | maximum reflectivity (%) |
|-----------|---------------|--------------|---------------|----------|---------------|-------------|--------------------------|
| LH-9-1    | 93.42         | 6.58         | 96.61         | 1.91     | 0.64          | 0.64        | 2.52                    |
| YS-8-1    | 90.35         | 9.65         | 94.67         | 2.53     |               |             | 2.49                    |
| YX-15-2   | 87.35         | 12.65        | 99.4          | 0.6      |               |             | 2.18                    |
| XD-15     | 94.23         | 5.77         | 95.71         | 2.45     | 1.23          | 0.61        | 2.06                    |
| WJB-6     | 85.72         | 14.28        | 60.49         | 30.25    | 9.26          |             | 2.34                    |
| QJ-4-1    | 90.58         | 9.42         | 97.7          | 1.15     |               | 1.15        | 2.37                    |
| YL-12     | 96.99         | 3.01         | 95.95         | 3.47     | 0.58          |             | 2.31                    |
| PC-3      | 97.08         | 2.92         | 98.28         | 1.72     |               |             | 2.3                     |
| YS-8-2    | 92.77         | 7.23         | 99.4          | 0.6      |               |             | 2.01                    |
| LH-9-2    | 87.2          | 12.8         | 89.14         | 9.78     | 0.54          | 0.54        | 2.49                    |
| QJ-4-2    | 84.93         | 15.07        | 76.83         | 20.53    | 0.53          | 2.11        | 2.4                     |
| KY-9      | 91.67         | 8.33         | 96.89         |          |               | 3.11        | 2.5                     |
| GG-6      | 93.59         | 6.41         | 98.11         | 1.89     |               |             | 2.06                    |
| GG-7      | 90.74         | 9.26         | 91.01         | 5.06     |               | 3.93        | 2.3                     |
| GG-16     | 87.92         | 12.08        | 88.69         | 1.19     |               | 10.12       | 2.3                     |
| XH-4      | 97.5          | 2.5          | 91.43         | 6.29     | 0.57          | 1.71        | 2.45                    |
| YX-15-1   | 94.38         | 5.62         | 98.17         | 0.61     | 0.61          | 0.61        | 2.4                     |

It can be seen from Figures 4 and 5 that there is a positive correlation between lithium and ash, and lithium and clay, in coal, and the correlation coefficients are 0.46 and 0.41, respectively, indicating that clay minerals play a role in promoting the enrichment of lithium in coal. Regarding the relationship between lithium and inorganic minerals in coal, Ling et al.\textsuperscript{48} pointed out that the lithium in coal is from the lithium-rich clay-altered volcanic ashes of the Late Permian Emeishan Emeshan formation. Liu et al.\textsuperscript{49} studied the Zhijin-Nayong coalfield in the Bijie area; they also suggested that the lithium in coal was derived from the felsic-alkaline Emeshan magmas and further inferred that lithium also has a relatively high proportion of illite/smectite, respectively, probably indicating a clay affinity for lithium. Moreover, target areas studied by Ling et al.\textsuperscript{50} and Liu et al.\textsuperscript{47} are close to this study area. With this taken into account, it can be inferred that lithium in coal is stored in clay minerals in the form of adsorption.\textsuperscript{51}

At the same time, it can be seen from Figures 6 and 7 that lithium in coal is also positively correlated with total organic matter and volatiles, and the correlation coefficients are 0.38 and 0.58, respectively, suggesting that lithium in coal is also closely related to organic matter and the strong adsorption of organic matter. This property is beneficial to the enrichment of lithium in coal. The relationship between lithium and organic matter in coal has been found by some scholars\textsuperscript{15} using laser microprobe mass spectrometry in the Longyearbyen coal mine in Norway. The content of lithium in silk is significantly higher than other microscopic components. Dai et al.\textsuperscript{18} found a highly mixed organic–inorganic material in the coal seam of the Zhijin mining area, which was formed by the codeposition of organic and inorganic materials in a certain proportion, and named it sedimentary-carbo-volcanic material. From the above, it can be seen that the source of lithium in coal in the Bijie area is mostly caused by coupling operations.

### 5. DISCUSSION

#### 5.1. Occurrence Analysis

The occurrence form of trace elements in coal refers to whether it is combined with organic matter, inorganic matter, or exists as a simple matter.\textsuperscript{44} Research on the occurrence state of lithium in coal is of great importance for evaluating whether it has development and utilization value.\textsuperscript{15,45}
### Table 3. Major Element Oxides and Trace Elements in Coal Samples in the Bijie Area

| items     | K₂O   | Na₂O  | SiO₂  | Al₂O₃ | Fe₂O₃ | CaO   | MgO   | SO₃   | TiO₂ | MnO₂ | Li    | Cu    | Ga    | Nb    | U    | SiO₂/Al₂O₃ | TiO₂/Al₂O₃ |
|-----------|-------|-------|-------|-------|-------|-------|-------|-------|------|------|-------|-------|-------|-------|------|-----------|-----------|
| LH-9-1    | 1.34  | 3.09  | 51.57 | 33.31 | 3.67  | 0.70  | 0.87  | 2.31  | 0.58 | 0.00 | 92.50 | 24.90 | 10.00 | 22.10 | 1.94 | 1.55      | 0.02      |
| YS-8-1    | 1.26  | 1.80  | 51.30 | 29.35 | 6.62  | 1.45  | 1.86  | 2.23  | 1.23 | 0.03 | 96.70 | 42.50 | 14.90 | 47.70 | 2.89 | 1.75      | 0.04      |
| YX-15-2   | 1.88  | 2.18  | 42.50 | 29.91 | 13.80 | 2.26  | 1.44  | 1.40  | 2.05 | 0.02 | 70.00 | 19.60 | 21.10 | 67.40 | 5.43 | 1.42      | 0.07      |
| XD-15     | 1.98  | 1.34  | 43.27 | 24.13 | 6.52  | 9.37  | 1.51  | 1.21  | 8.90 | 0.13 | 36.30 | 18.50 | 10.70 | 40.00 | 20.20 | 1.79      | 0.37      |
| WJ-6-6    | 1.16  | 2.48  | 48.78 | 30.03 | 9.30  | 0.97  | 1.43  | 3.18  | 0.36 | 0.01 | 222.00| 156.00| 33.60 | 72.50 | 4.10 | 1.62      | 0.01      |
| QJ-4-1    | 0.96  | 1.84  | 53.67 | 24.08 | 13.60 | 0.48  | 1.64  | 1.69  | 0.44 | 0.00 | 104.00| 27.60 | 6.99  | 12.70 | 2.06 | 2.23      | 0.02      |
| YL-12     | 1.80  | 1.37  | 49.12 | 31.21 | 5.34  | 2.05  | 1.90  | 2.49  | 1.82 | 0.04 | 96.80 | 27.00 | 11.80 | 37.50 | 2.49 | 1.57      | 0.06      |
| PC-3      | 0.46  | 1.58  | 49.98 | 33.20 | 5.94  | 0.65  | 1.94  | 2.91  | 0.43 | 0.01 | 35.70 | 32.10 | 8.24  | 18.60 | 1.51 | 1.51      | 0.01      |
| YS-8-2    | 0.88  | 0.88  | 49.63 | 34.07 | 5.68  | 1.00  | 1.49  | 2.16  | 0.88 | 0.01 | 94.80 | 15.10 | 8.82  | 23.90 | 2.13 | 1.46      | 0.03      |
| LH-9-2    | 1.90  | 2.15  | 54.63 | 29.63 | 4.05  | 1.02  | 1.55  | 2.26  | 0.92 | 0.01 | 54.50 | 52.20 | 18.60 | 68.80 | 3.25 | 1.84      | 0.03      |
| QJ-4-2    | 1.24  | 2.09  | 55.81 | 25.38 | 7.05  | 0.48  | 1.25  | 3.84  | 0.70 | 0.01 | 78.10 | 79.00 | 19.10 | 57.10 | 2.89 | 2.20      | 0.03      |
| KY-9      | 0.92  | 1.44  | 55.25 | 19.15 | 8.08  | 3.38  | 2.64  | 1.25  | 5.86 | 0.09 | 53.20 | 20.80 | 7.86  | 23.10 | 1.96 | 2.89      | 0.31      |
| GG-6      | 1.28  | 1.74  | 52.64 | 26.58 | 10.30 | 0.91  | 1.16  | 1.31  | 1.66 | 0.02 | 98.30 | 23.20 | 7.26  | 6.63  | 2.99 | 1.98      | 0.06      |
| GG-7      | 1.58  | 1.84  | 47.49 | 25.52 | 15.64 | 0.70  | 1.06  | 2.04  | 1.53 | 0.02 | 97.80 | 53.00 | 11.30 | 20.00 | 4.31 | 1.86      | 0.06      |
| GG-16     | 0.96  | 1.14  | 29.65 | 19.84 | 41.74 | 0.10  | 1.31  | 1.44  | 1.07 | 0.00 | 33.20 | 32.40 | 5.26  | 8.71  | 1.67 | 1.49      | 0.05      |
| XH-4      | 0.78  | 2.02  | 39.11 | 28.51 | 17.17 | 1.32  | 2.02  | 4.32  | 2.25 | 0.04 | 136.00| 36.50 | 14.70 | 28.00 | 3.28 | 1.37      | 0.08      |
| YX-15-1   | 1.08  | 2.12  | 33.08 | 26.88 | 18.77 | 6.06  | 1.08  | 1.08  | 6.60 | 0.02 | 80.00 | 19.80 | 20.40 | 15.10 | 2.76 | 1.23      | 0.25      |
| average value | 1.26  | 1.89  | 47.50 | 27.69 | 11.37 | 1.94  | 1.54  | 2.20  | 2.19 | 0.03 | 87.05 | 40.01 | 13.57 | 33.64 | 3.87 | 1.75      | 0.09      |
| maximum value | 1.98  | 3.09  | 55.81 | 34.07 | 41.74 | 9.37  | 2.64  | 4.32  | 8.90 | 0.13 | 222.00| 156.00| 33.60 | 72.50 | 20.20 | 2.89      | 0.37      |
| minimum value | 0.46  | 1.14  | 29.65 | 19.15 | 3.67  | 0.10  | 0.87  | 1.21  | 0.36 | 0.00 | 33.20 | 15.10 | 5.26  | 8.63  | 1.51 | 1.23      | 0.01      |
| China/world | 0.19  | 0.16  | 8.47  | 5.98  | 4.67  | 1.23  | 0.22  | nd   | 0.33 | 0.02 | 14.00*| 17.50*| 6.53* | 9.44* | 2.43*| 1.42      | 0.06      |

**Note:** Average values of major-element oxides for Chinese coals and average values (data with *) of trace elements for world hard coals are from Dai et al.38 and Ketris and Yudovich,39 respectively.
coal-forming period of the Qianbei coalfield, confirming to a certain extent that volcanic hydrothermal fluid is an important source of lithium enrichment in coal. Dai et al.,49,50 in their study of the Late Permian coal tonsteins in the Songzao area, Chongqing, noted that this tuff layer is closely related to the volcanic ash erupted from the Emeishan Basalt. Regarding this view, as early as 2007, when Dai et al.47 were studying the Nantong coal field, they had already inferred that the tectonic zone was volcanically active; the hydrothermal fluid released by the volcanic eruption entered the coal seam, and the volcanic hydrothermal fluid may contain metallic elements. The enrichment of metal elements provides the source.49 In more detail, during the Dongwu and Qiangui tectonic movement, a considerable scale of faulting took place in the western part of the coalfield, and basalt eruption and diabase intrusion occurred along the faulted structural belt. At the same time, the topography became higher in the west and lower in the east. Late Permian transgression was from east to west, resulting in strong erosion activities in the western uplift area. The western uplift area should be Kangdian Upland.47,51,52 Therefore, the detrital material from the west laid the provenance for the formation of the coal-bearing rock series in Longtan (Figure 8). In fact, the previous geological results indicate that, in the lithology composition of the coal-bearing rock series in the Bijie area, in addition to clastic rocks, argillaceous rocks, carbonate rocks, etc., there is indeed a small amount of volcanic clastic rocks.47,46,53

In coal seams or other sedimentary strata, the ratio of TiO₂/Al₂O₃ is considered to be an important parameter,47,56 and it is also a sign to identify the type of volcanic ash in coal and coal-measure strata.57 Successive researchers, such as Addisom,56 Hayashi et al.57 and Bueger et al.,58 agreed that the ratio of TiO₂/Al₂O₃ in acidic pozzolans is less than 0.02 and that, in alkaline pozzolans between 0.02 and 0.08, the ratio of basic volcanic rocks is greater than 0.08. In coal ash in the Bijie study...
area, the ratio of TiO$_2$/Al$_2$O$_3$ is between 0.01 and 0.37. Among them, the ratio of coal seam 15 is the largest, reaching 0.368, and the ratio of coal seam 9 also reaches 0.306, which again suggests that the lithium in the coal seam of the Longtan group is likely to have come from the basalt eruption caused by the western fault.

In addition, the trace element Nb content in this study area is between 8.63 and 72.50 $\mu$g/g, with an average value of 32.89 $\mu$g/g, which is 3.5 times and 8.9 times higher than that of Chinese coal, 9.4 $\mu$g/g, and the world coal, 3.7 $\mu$g/g, respectively. Figure 2 also shows that its average value is located in the upper part of the data distribution interval, indicating that the distribution of Nb in the coal in this study area is concentrated. Nb is widely used for source rock prediction due to its low solubility and essentially constant characteristics during weathering, transport, and deposition. According to the research of Nie et al., compared with other basalts, Emeishan basalt is significantly enriched in Cu and Nb. The abundance of Nb in this study area is very high, and the CC value of Cu also reaches 8.91, which indicates that the trace elements in coal in this study area are closely related to the Emeishan basalt.

### 5.3. Enrichment Mechanism

The structure (Figure 1, Ziyun-Shuicheng fault) and topography facilitate the enrichment of lithium in coal. Related studies have revealed that the structure not only generates magmatic activity but also forms an environment conducive to coal formation. Therefore, near the ancient weathering crust or denudation zone, the abundance of lithium in coal is relatively high. Figure 8 shows that the abundance of lithium in coal at several sampling points close to the provenance area is generally higher than the abundance far away from the provenance area. The specific reasons are as follows: First, the Dongwu movement caused large-scale deep faults in the Bijie coal-bearing area, and magma moved out of the surface along with the faults. The hydrothermal fluid released by the volcano may have entered the coal measures and provided a source for the enrichment of metal elements in the coal measures. Second, the Guizhou-Guangxi movement and the Dongwu movement formed paleogeographic topography with high west and low east areas. The uplift area in the west was eroded to form clastic materials that were carried into the Late Permian coal-forming basin by surface water. The abundance of lithium in coal in this study area is higher than the background value (0.026 $\mu$g/g) in the southwestern region where Guizhou is located, and it is low in the upper and lower parts and high in the middle (Figure 9). The characteristics indicate that the lithium in coal comes from the same depositional stage, that is, from the detrital material produced by the denudation of the provenance area. In fact, in China,
most of the numerous mining areas with higher lithium abundance in coal are of syn-sedimentary origin. In the northern part of the study area, Dai et al. performed a study on the coal seams in the Zhijin Mining Area, Guizhou, and believed that syn-sedimentary volcanic ash was the root cause of the geochemical variation of coal elements and the formation of special fabrics in the mining area. The depositional environment is helpful to the accumulation of lithium in the coal in the Bijie area. Previous studies by scholars believe that the abundance of lithium in coal is highest in the transitional or interactive environment between land and sea, while the pure marine sedimentary environment is lower. According to the study by Huang et al. in Baode, this is related to the salinity of seawater, and the trace elements in coal are relatively easy to enrich under the conditions of salt water deposition with Sr/Ba greater than 1. The specific reason is that, because of the large evaporation in the local trap area at the transition between the land and the sea, the salinity of seawater is also higher. At this moment, the Sr/Ba exceeds 1, so the lithium in the coal is relatively high. Under this situation, it also shows that the lithogenic element in coal is derived from terrestrial debris, because the transition between land and sea is located at the edge of the water storage area, close to the source area; it is also possible that local seawater traps are easily formed on barrier islands or sand dams, and seawater salinity is correspondingly higher, which is beneficial to the accumulation of lithium in coal. In fact, the high-value areas of the distribution of lithium in the coal in the Bijie area do follow this rule. The sample WJB-6 with the high-value areas of the distribution of lithium in the coal is derived from terrestrial debris, because the transition between land and sea transitional environment provide chemical and hydrodynamic conditions for the enrichment of lithium in coal. In this study, the highest lithium abundance in coal was 222 μg/g, the lowest 33.2 μg/g, and the average 87.05 μg/g. The lithium in two coal samples had reached the minimum recoverable requirement. Because the coal samples taken are located in the main coal seam, the resource reserves of lithium in the coal are considerable.

This area has a complex tectonic background and intense geological effects, and the previous research foundation is relatively weak, which meant many difficulties regarding the research of this paper. This Article is only a preliminary discussion, with the hope to have the opportunity to have further discussions with relevant scholars.

Table 4. Parameters of Ash Compositions for the Coal-Accumulation Environment

| Sedimentary Environment                  | Sdaf/% | FeO + CaO + MgO/% | SiO2 + Al2O3/% | (FeO + CaO + MgO)/(SiO2 + Al2O3) |
|------------------------------------------|--------|------------------|---------------|----------------------------------|
| Peat environment affected by seawater   | >1     | >20              | <75           | ≥0.23                            |
| Terrestrial peat environment            | <1     | 5–20             | >75           | ≤0.22                            |

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6. CONCLUSION

This study believes that the enrichment of lithium in the coal in the Bijie area has both inorganic and organic origins, and lithium enriched most likely in the syn-sedimentary stage. The volcanic eruptions that occurred during the Dongwu movement provided the source, and the paleogeographic features were shaped by the Qian-Gui movement and the Dongwu movement. Moreover, the sea–land transitional environment and the lagoon–tidal flat environment provide chemical and hydrodynamic conditions for the enrichment of lithium in coal. In this study, the highest lithium abundance in coal was 222 μg/g, the lowest 33.2 μg/g, and the average 87.05 μg/g. The lithium in two coal samples had reached the minimum recoverable requirement. Because the coal samples taken are located in the main coal seam, the resource reserves of lithium in the coal are considerable.

This area has a complex tectonic background and intense geological effects, and the previous research foundation is relatively weak, which meant many difficulties regarding the research of this paper. This Article is only a preliminary discussion, with the hope to have the opportunity to have further discussions with relevant scholars.

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Notes

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