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Research Article

Isotopic Age of the Xiong'er Group Volcanic Rocks and Its Geological Significance in Western Henan, China

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The Xiong'er Group is mainly distributed in western Henan, southern Shanxi, and southeastern Shaanxi. As a set of low-grade metamorphic and low-deformation volcanic rocks formed in the transition period during the tectonic evolution of the North China Craton in the Precambrian, the tectonic and magmatic evolution information of this period are well recorded. The accurate isotopic dating of the Xiong'er Group has great significance to the study of the stratigraphic division and formation of volcanic rocks in the Xiong'er Group and the improved cognition of regional tectonic magmatism. In this study, through the SHRIMP (sensitive high-resolution ion microprobe) zircon uranium-lead (U-Pb) isotope dating of the volcanic rocks of the Xiong'er Group in the Xiong'er Mountain, the research results showed that the age data were separated into two intervals, the magmatic zircon ages from 1836 to 1711 Ma and the inherited zircon ages from 2415 ± 19 to 2193 ± 34 Ma. The isotopic age of magmatic zircon was considered to represent the formation age of the Jidanping Formation in the Xiong'er Mountain, and the isotopic ages of the inherited zircons were consistent with the formation ages of the Taihua Group supracrustal rocks in the lower Xiong'er Group. Combined with previous studies on isotope and rock geochemistry of volcanic rocks in the Xiong'er Group, it was believed that the formation ages of the volcanic rocks of the Xiong'er Group are between 1874 and 1618 Ma, among the ages of the Xushan Formation, Jidanping Formation, and Majiahe Formation, which were concentrated between 1874 and 1800 Ma, 1836 and 1711 Ma, and 1780 and 1618 Ma, respectively. The age of inherited zircon in the volcanic rocks of the Xiong'er Group indicated that the formation of the volcanic rocks of the Xiong'er Group had the addition of stratigraphic materials from the Taihua Group.

1. Introduction

During the Proterozoic era, the Columbia supercontinent experienced a series of continent-continent collision orogenic evolution and plate breakup processes on a global scale, and a series of rift basins were formed at the edge of the supercontinent, such as the Calvert basin, Isa basin, Yanliao rift basin, and the North China Craton Xiong'er rift basin [1, 2]. In the process of plate breakup, extensive magmatic activity occurred, such as the Chaiskii basic rock wall, Tarak A-type granite, and Xiong'er group volcanic rocks [3, 4]. The Xiong'er Group is a set of low-grade metamorphic and low-deformation volcanic rocks with the widest distribution in the southern margin of the North China Craton. It was formed during the transition period [5] and has an extensive record of the southern margin of North China craton Precambrian tectonomagmatic evolution. Therefore, scholars have carried out more research on it. Hu et al. [6] used the rubidium-strontium (Rb-Sr) method to date the tuff in the Xiong'er Group and obtained an isotopic age of 1780 ± 25 Ma; Zhao et al. [7] conducted zircon uranium-lead (U-Pb) dating of rhyolites in the Xiong'er Group in Song county and obtained an isotopic age of 1761 ± 16 Ma; Huyan and Lu [8] conducted zircon U-Pb dating of andesite from the Xiong'er Group in the Xiaoqinling and obtained an isotopic age of 1810 ± 41 Ma; Sun et al. [9] obtained the isotopic ages of the top boundary (1400 Ma) and the bottom boundary (1710 Ma) of the Xiong'er Group using the Rb-

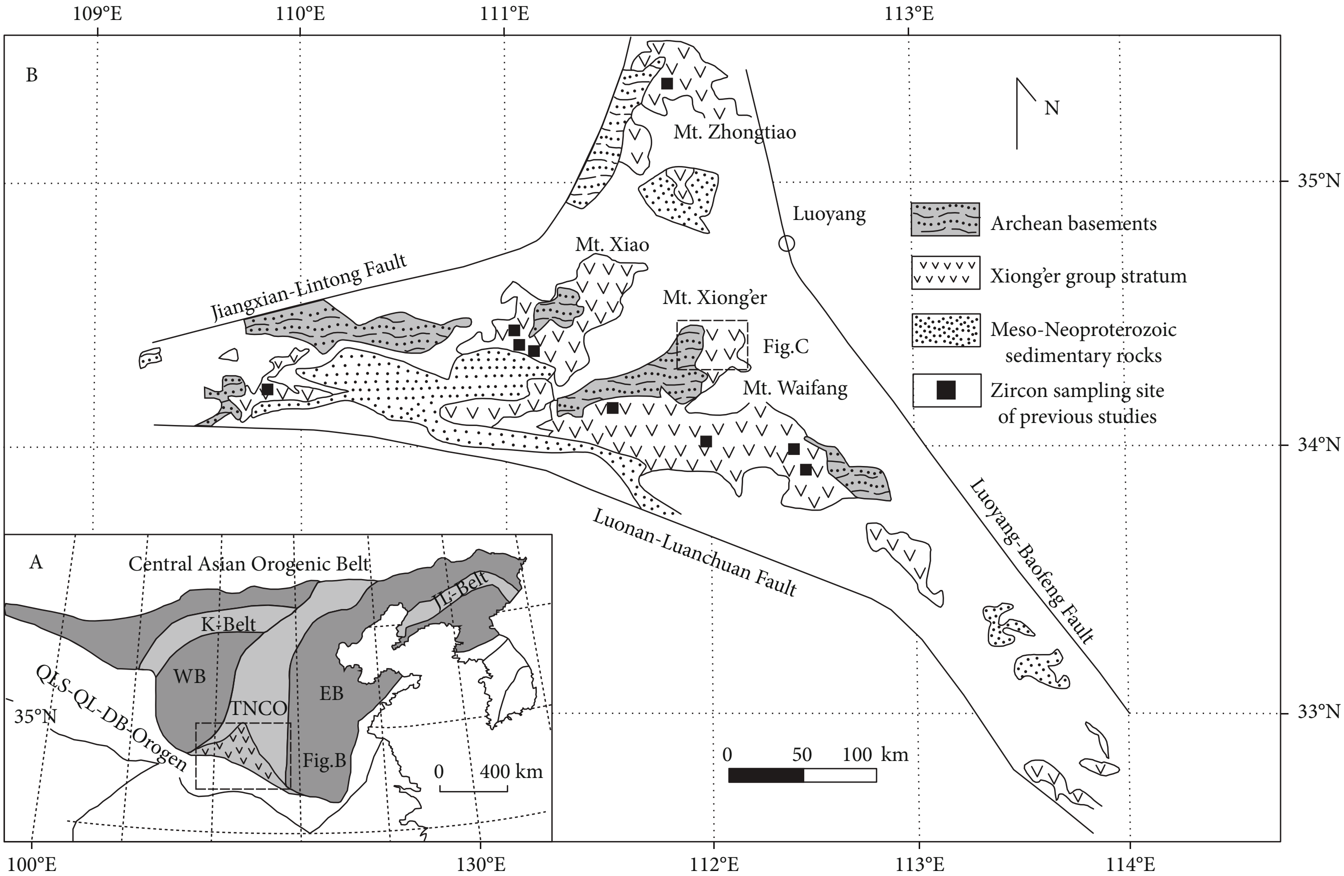

Figure 1: Distribution map of volcanic rocks in the Xiong'er Group. (after He et al. [1]). WB: Western Block; EB: Eastern Block; TNCO: Trans-North China Orogen; K-Belt: the Khondalite Belt; JL-Belt: the Jiao-Liao Belt; QLS-QL-DB Orogen: Qilianshan-Qinling-Dabie Orogen.

Sr isotope dating method. According to the previous research results, the research has mostly concentrated on Xiaoqinling, Zhongtiao Mountain, Xiao Mountain, Waifang Mountain, etc., and there are few reports on the volcanic rocks of the Xiong'er Group exposed in the Xiong'er Mountain. In addition, some of the test methods themselves have large errors, so there is a large controversy over the formation age of the Xiong'er Group volcanic rocks. At the same time, Zhao et al. [10, 11] believe that the Xiong'er Group experienced multiple eruptive cycles during its formation; thus, it is obviously flawed to use a single isotopic age to represent the whole formation age of the Xiong'er Group. In this paper, the SHRIMP (sensitive high-resolution ion microprobe) zircon U-Pb isotope dating of the volcanic rocks from the Jidanping Formation of the Xiong'er Group in the Xiong'er Mountain was taken as the objective to investigate the age of their formation and provide the basis for the study of regional theory.

2. Geological Background Overview

The North China Craton is composed of the Eastern Plate (EB), the Central Orogenic Belt (TNCO), and the Western Plate (WB). It experienced tectonic evolution, magmatic activity, and metamorphism and finally completed cratonization before 1.85 Ga, making it the oldest craton in China [12]. The study area is located in the southern margin of the North China Craton, the northern part of the Qinling orogenic belt, with the Waifang Mountains to the east and the Xiaoshan Mountains to the west, showing typical craton edge characteristics (as shown in Figure 1). The middeep metamorphic rocks of the Taihua Group constitute the bottom of the regional strata, and the volcanic rocks of the Xiong'er Group and the coastal sedimentary rocks of the Guandaokou Group are the main sedimentary caprocks. The area has experienced long-term and complex tectonic-magmatic evolution. The fault structure is extremely developed, and due to frequent magmatic activity, a large number of magmatic rocks have developed; magmatism has occurred throughout the entire geological evolution of the region [13].

The Xiong'er Group is mainly distributed in western Henan, southern Shanxi, and southeastern Shaanxi. It is a set of basic, intermediate-basic, and intermediate-acid volcanic rocks, with a total outcrop area of about 6000 km^2 and a thickness of 3000–8000 m. In the Xiong'er Mountain area, the Xiong'er group is distributed in the south and northeast of the area in a planar shape, and the outcropping area accounts for about 47% of the total area in the region (as shown in Figure 2). The Xiong'er Group is a volcanic-sedimentary rock series developed after the consolidation

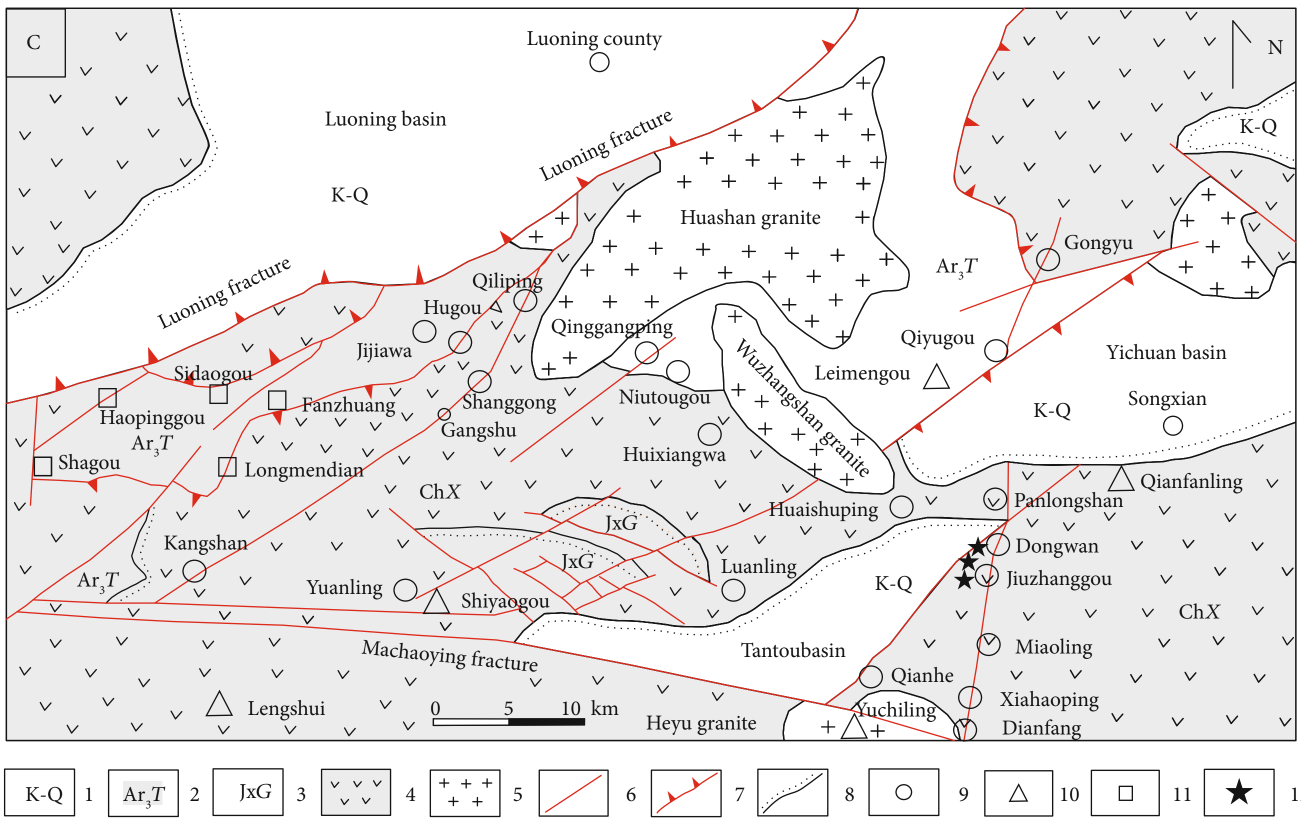

Figure 2: Regional geological map of the Xiong'er Mountain Area. (after Pang et al. [14]). 1: quaternary sediments; 2: Taihua Group; 3: Guandaokou Group; 4: Xiong'er Group; 5: magmatic of Yanshanian; 6: faults; 7: detachment faults; 8: unconformity geological boundary; 9: gold deposit; 10: Mo deposit; 11: Ag-Pb-Zn deposit; 12: zircon sampling site.

of the North China Craton, and its lithology is dominated by volcanic lava, with partial sedimentary interlayers and volcanic clastics. The lavas are dominated by basalt-andesite and andesite, followed by quartz and rhyolite. According to the regional geological background and lithological assemblage characteristics, the Xiong'er Group is divided into Xushan Formation, Jidanping Formation, and Majiahe Formation from bottom to top.

The Xushan Formation is composed of basic and intermediate-basic volcanic rocks; the main lithology is large porphyry andesite, andesite porphyry, basalt-andesite, and so on, with a small amount of volcanic clastics in some parts, and the stratum thickness varies greatly, from 600 to 3000 m. The Jidanping Formation is a set of intermediate-acid volcanic rocks; the local interlayer is intermediate and acid volcanic rock, as well as tuff. From the bottom to the top, the proportion of acidic rocks increases gradually, the proportion of intermediate-basic rocks decreases gradually, and the number of layers of volcanic clastics also increases gradually. The lithology is mainly dacite, andesite, tuff, etc. It is mainly distributed in southern Song county, with a thickness of about 1800–2500 m. The Majiahe Formation is dominated by acid and intermediate-acid volcanic rocks, locally interbedded with tuff and siltstone; the lithology is mainly rhyolite and basalt. There is in an unconformable contact with the underlying strata of the Jidanping Formation and the overlying strata of the Guandaokou Group, with a thickness of about 2500 m. The sampling object of this study is the dacite of the Jidanping Formation, which is gray and gray-green, with a porphyritic texture and massive structure (as shown in Figure 3). The porphyritic crystal is short columnar, the particle size is 1–2 mm, the content is about 30%, and the main component is intermediate plagioclase, followed by orthoclase and quartz. The intermediate plagioclase is short columnar, with a particle size of 1.5–2 mm, albite twin crystals, local occurrence of calcitization, silicification, sericitization, and so on. The quartz is mostly granular, with a particle size of about 1 mm, and calcitization develops along the crack. The orthoclase is short columnar, with a particle size of 1.5–2 mm and the development of fine microcrosshatch twinning. The matrix is mainly composed of intermediate plagioclase and quartz, and a small amount of chlorite, epidote, and apatite. The main features are vitreous structure, vitreous-basis pilotaxitic texture, and felsitic texture.

3. Samples and Methods

3.1. Samples. In this study, we selected three dacite samples (CM5, 1314-1, and CM3-5) from the Jidanping Formation of the Xiong'er Group. The sampling location is the Jiuzhanggou gold mine in Song county. The sample test and analysis results are presented in Table 1. In order to reflect the geochronology characteristics of zircon isotopic age in

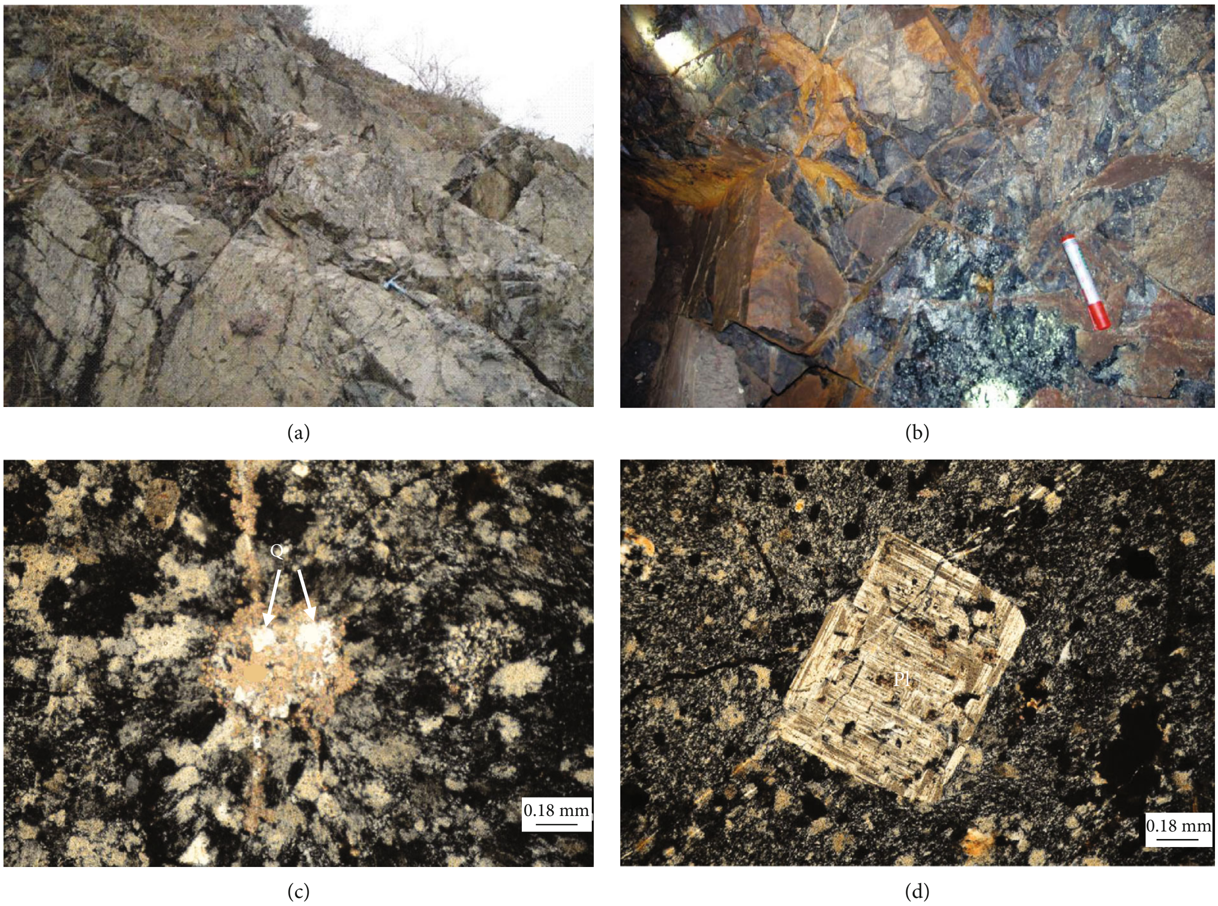

Figure 3: Field and micrographs of the Jidanping Formation in the Xiong'er Group. (a) Field surface outcrop of dacite. (b) Dacite outcrop in Jiuzhanggou gold mine. (c) Micrograph of dacite. (d) Feldspar phenocryst of dacite.

different samples, the zircons in the study samples were divided into two types. One type was magmatic zircon generated in the process of magma crystallization; its U-Pb isotope system has good stability and sealing, and the zircon vibration band is clearer. Compared with other isotope systems, it better recorded the time of zircon formation, representing the age of the magmatism origin, such as magmatic intrusion or magmatic exhalation. The other type was inherited (captured) zircon, and these ages reflected the source rock characteristics, the history of crustal accretion, and the age of crystallization basement evolution [15]. Different types of zircons had little difference in thorium (Th) and U contents, and the Th/U ratios of zircons range from 0.06–1.19. The average U content of magmatic zircons was 227.55 ppm, and the average Th/U was 0.65. The inherited zircon U content was 127.00 ppm, and the average Th/U is 0.86. Our selected zircon samples showed automorphic and half-automorphic characteristics, and the color was snuff color, light yellow, or colorless. The zircon shape included a long column and a short column, with an aspect ratio of 1.05 : 1–2.3 : 1, some of which were strongly abraded. Most zircons had an obvious vibration band in the main body or part (as shown in Figure 4).

3.2. Methods. SHRIMP zircon U-Pb isotope analysis was completed at the Institute of Geology, Chinese Academy of Geological Sciences, Beijing Shrimp Center. The biggest advantage of the SHRIMP test method is that it can be used for the in situ dating of zircons; in other words, direct dating analysis of different parts of the same zircon was carried out. The samples were manually broken apart, cleaned, screened, reselected, and magnetically separated. Then, we selected the zircon with better transparency and representativeness under binoculars, stuck the sorted zircon particles, RSES reference sample SL13 on the double-sided tape, fixed with epoxy resin, and waited for the resin to fully consolidate, grinding and polishing to expose the zircon center to make a zircon sample target. The cathode fluorescence spectrometer was used to perform the zircon cathodoluminescence (CL) image microphotography on the sample target and analyze the zircon characteristics. Finally, the U-Pb isotope data of the zircon were determined. The original test data were processed with the Ludwig SQUID software [16], where the ordinary ^{204}Pb correction method referred to [17], and ^{206}Pb-^{238}U-weighted average age and the Concordia diagram were obtained by the ISOPLOT software [18].

4. Results

4.1. Zircon U-Pb Age of CM3-5. The CM3-5 samples were tested at a total of 11 points for a single particle zircon. These analysis points were all located in regions with a

Table 1: Zircon U–Pb isotope test results.

Number	Th (ppm)	U (ppm)	Th/U	$^{206}Pb_c$ %	Age (Ma) $^{206}Pb/^{238}U$	σ	$^{207}Pb^*/^{206}Pb$	σ	$^{206}Pb^*/^{238}U$	σ
1314-1										
1	173	160	1.11	0.26	1760 ± 17	0.77	0.11	0.9	0.31	1.1
2	125	115	1.12	0.70	1769 ± 27	0.80	0.11	1.3	0.31	1.8
3	38	42	0.92	0.81	1808 ± 27	0.66	0.12	1.7	0.32	1.8
4	110	216	0.53	0.11	2279 ± 20	0.85	0.14	0.6	0.42	1.1
5	262	503	0.54	0.02	2415 ± 19	0.91	0.15	0.4	0.45	0.9
6	94	121	0.80	0.07	2294 ± 23	0.82	0.14	0.8	0.43	1.2
7	300	313	0.99	0.03	2206 ± 19	0.87	0.13	0.5	0.41	10
8	62	131	0.49	0.20	2212 ± 22	0.82	0.14	0.8	0.41	1.2
9	67	129	0.54	0.10	2292 ± 23	0.82	0.14	0.8	0.43	1.2
10	134	214	0.65	0.04	2330 ± 33	0.94	0.15	0.6	0.44	1.7
11	93	159	0.61	0.07	2368 ± 22	0.72	0.15	1.0	0.44	1.1
12	252	364	0.72	0.01	2293 ± 19	0.89	0.14	0.5	0.43	0.9
13	97	384	0.26	0.54	1643 ± 14	0.83	0.13	0.5	0.29	0.9
14	141	128	1.13	0.37	1768 ± 19	0.74	0.11	1.0	0.32	1.2
15	32	39	0.84	1.18	1754 ± 63	0.72	0.11	3.6	0.31	4.1
16	62	96	0.67	0.12	2193 ± 34	0.84	0.14	1.2	0.41	1.8
CM3-5										
1	34	41	0.85	0.87	1825 ± 27	0.69	0.11	3.1	0.32	1.7
2	18	27	0.68	0.00	1721 ± 30	0.64	0.12	2.2	0.31	2.0
3	30	38	0.83	24.22	1720 ± 95	0.13	0.11	45.0	0.31	7.0
4	34	41	0.84	0.73	1811 ± 27	0.66	0.11	2.8	0.32	1.7
5	20	29	0.69	0.74	1711 ± 29	0.65	0.11	4.0	0.30	2.0
6	113	99	1.19	0.34	1751 ± 20	0.73	0.11	1.5	0.31	1.3
7	70	73	0.99	1.26	1781 ± 24	0.66	0.12	3.2	0.32	1.5
8	33	41	0.83	4.67	1737 ± 37	0.58	0.13	10.0	0.31	2.6
9	51	51	1.04	1.63	1746 ± 25	0.53	0.11	4.1	0.31	1.6
10	258	239	1.11	1.54	1834 ± 18	0.46	0.12	2.9	0.33	1.1
11	43	45	0.99	21.44	1711 ± 44	0.27	0.13	15.0	0.30	3.0
CM5										
1	115	191	0.62	0.05	2339 ± 22	0.86	1.10	1.7	0.44	1.1
2	36	598	0.06	0.48	1970 ± 17	0.71	2.30	1.0	0.36	0.9
3	46	46	1.03	0.44	1801 ± 26	0.68	3.30	2.0	0.32	1.6
4	199	877	0.24	2.92	1398 ± 18	0.17	2.40	2.6	0.24	1.5
5	88	109	0.84	4.06	1648 ± 26	0.18	4.10	2.3	0.29	1.8
6	33	41	0.85	—	1809 ± 31	0.73	1.80	5.0	0.32	1.9
7	129	122	1.09	0.09	1836 ± 20	0.75	3.05	1.7	0.33	1.2
8	24	32	0.78	0.77	1712 ± 33	0.71	3.26	1.9	0.30	2.2
9	50	49	1.05	0.50	1809 ± 26	0.70	3.19	1.3	0.32	1.7
10	49	48	1.06	0.38	1788 ± 26	0.68	3.10	1.5	0.32	1.6
11	31	40	0.81	0.22	1714 ± 64	0.92	3.06	1.9	0.31	4.2
12	138	128	1.11	0.09	1825 ± 21	0.79	3.16	1.6	0.33	1.3
13	23	32	0.76	0.83	1807 ± 30	0.63	2.98	1.1	0.32	1.9

Table 1: Continued.

Number	Th (ppm)	U (ppm)	Th/U	$^{206}Pb_c$ %	Age (Ma) $^{206}Pb/^{238}U$	σ	$^{207}Pb^*/^{206}Pb$	σ	$^{206}Pb^*/^{238}U$	σ
14	96	162	0.61	0.11	2338 ± 22	0.84	1.48	1.6	0.44	1.1

Note: Pbc and Pb* indicate the common and radiogenic portions, respectively. σ indicates the error.

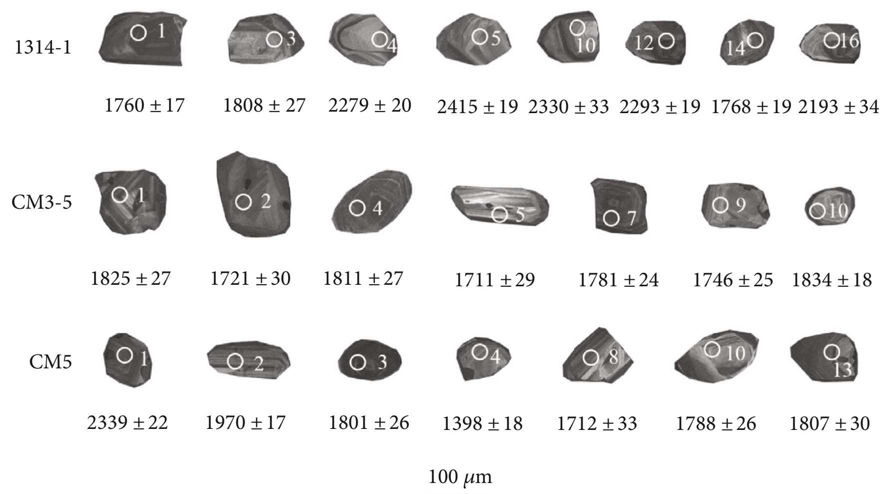

Figure 4: Cathodoluminescence (CL) images of selected zircon grains from the studied sample.

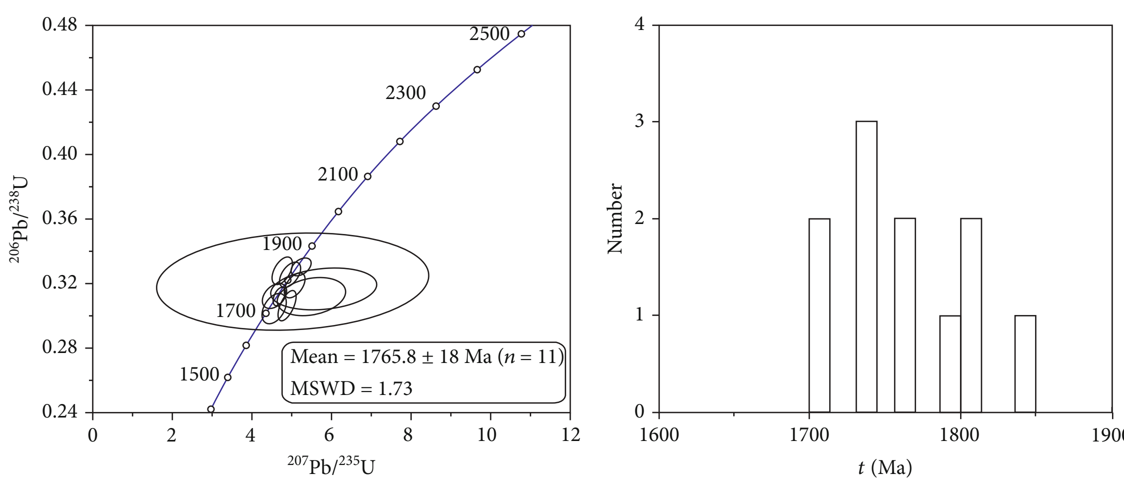

Figure 5: The zircon U-Pb age Concordia diagram and histogram of CM3-5.

typical vibration band. The U content of the 11 magmatic zircon analysis points ranged from 27 to 239 ppm, with an average of 65.82 ppm. The Th/U ratio ranged from 0.68 to 1.19, with an average of 0.91. On the zircon U-Pb age Concordia diagram and histogram (shown in Figure 5), the 11 ages were relatively concentrated, the 207Pb/206 Pb age ranged from 1834 ± 18 to 1711 ± 29 Ma, and the weighted average age was 1765.8 ± 18 Ma (MSWD = 1.73).

4.2. Zircon U-Pb Age of CM5. The CM5 samples were tested at a total of 14 points for a single particle zircon, and these analysis points were all located in regions with a typical vibration band or core part of a tabular band. The U content of the 12 magmatic zircon analysis points ranged from 32 to 877 ppm, with an average of 176.83 ppm. The Th/U ratio ranged from 0.06 to 1.11, with an average of 0.81. The U content of the two inherited zircon analysis points ranged from 162 to 191 ppm, with an average of 176.50 ppm. The Th/U ratio ranged from 0.61 to 0.62, with an average of 0.62. On the zircon U-Pb age Concordia diagram and histogram (shown in Figure 6), the age data of the magmatic and inherited zircon displayed two intervals. Among them, the age of $^{207}Pb/^{206}Pb$ at point 4 was 1398 ± 18 Ma, which is similar to 1450 ± 31 Ma measured by [1], which represented the age of the most recent magma eruption. The remaining magmatic zircon $^{207}Pb/^{206}Pb$ age ranges were concentrated

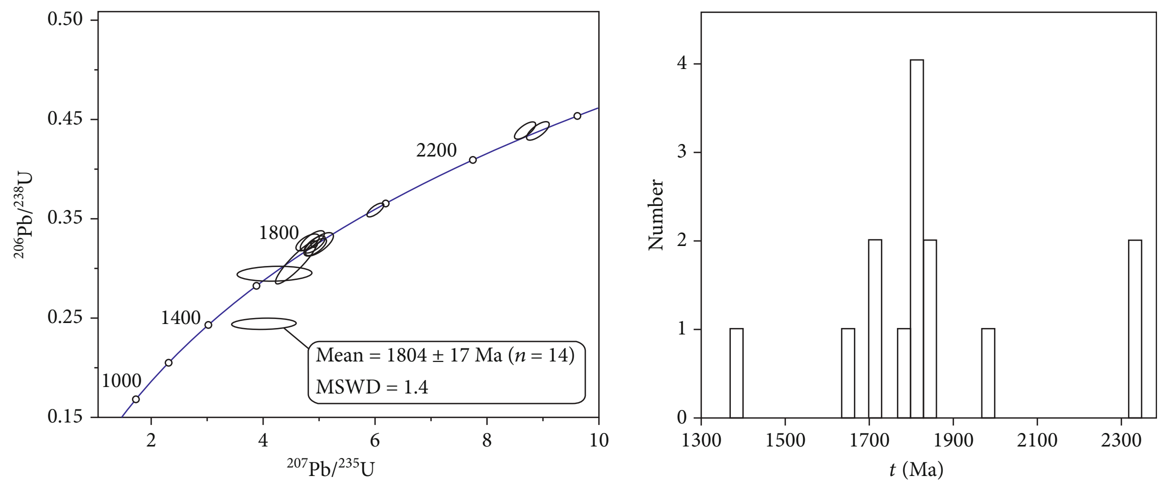

Figure 6: Zircon U-Pb age Concordia diagram and histogram of CM5.

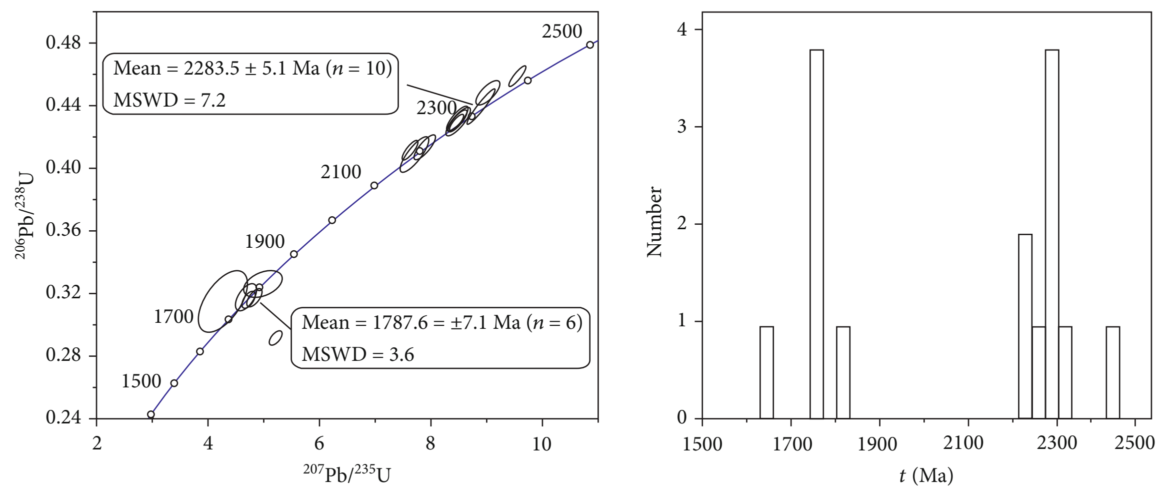

Figure 7: Zircon U-Pb age Concordia diagram and histogram of 1314-1.

between 1836 ± 20 and 1712 ± 33 Ma, the weighted average age was 1804.3 ± 17 Ma, and the two inherited zircon $^{207}Pb/^{206}Pb$ weighted average age was 2338.5 ± 22 Ma.

4.3. Zircon U-Pb Age of 1314-1. The 1314-1 samples were tested at a total of 16 points of a single particle zircon, and these analysis points were all located in regions with a typical vibration band or core part of a tabular band. The U content of the 6 magmatic zircon analysis points ranged from 39 to 384 ppm, with an average of 144.67 ppm. The Th/U ratio ranged from 0.26 to 1.13, with an average of 0.90. The U content of the 10 inherited zircon analysis points ranged from 96 to 503 ppm, with an average of 224.60 ppm. The Th/U ratio ranged from 0.49 to 0.99, with an average of 0.65. The zircon U-Pb age Concordia diagram (as shown in Figure 7) shows that most analysis points were located on the Concordia line, and a few points were located outside the Concordia line, displaying that the zircon had experienced the influence of metamorphic disturbance in the later period. The age data of the magmatic and inherited zircon showed two intervals on the histogram. Among them, the age datum at point 13 was far away from the Concordia line, and the age of $^{207}Pb/^{206}Pb$ was 1643 ± 14 Ma. The remaining 6 magmatic zircon $^{207}Pb/^{206}Pb$ age ranges were concentrated between 1808 ± 27 and 1754 ± 63 Ma, and the weighted average age was 1787.6 ± 7.1 Ma. The 10 inherited zircon $^{207}Pb/^{206}Pb$ age ranges were concentrated between 2415 ± 19 Ma and 2193 ± 34 Ma, and the weighted average age was 2334.7 ± 25 Ma.

5. Discussion

5.1. The Formation Age of Jidanping in Xiong'er Group. A significant amount of prior research has been performed on the volcanic rocks of the Xiong'er Group in Henan, Shanxi, and Shaanxi. Due to the different sample collection locations and test methods, the resulting ages of the volcanic rocks of the Jidanping Formation were different, but their main ages were limited to the Early Proterozoic [19]. Zhao et al. [20] used the SHRIMP zircon U-Pb method to analyze the Jidanping Formation in the Ruyang area and obtained an age between 1800 and 1750 Ma. He et al. [1] used the

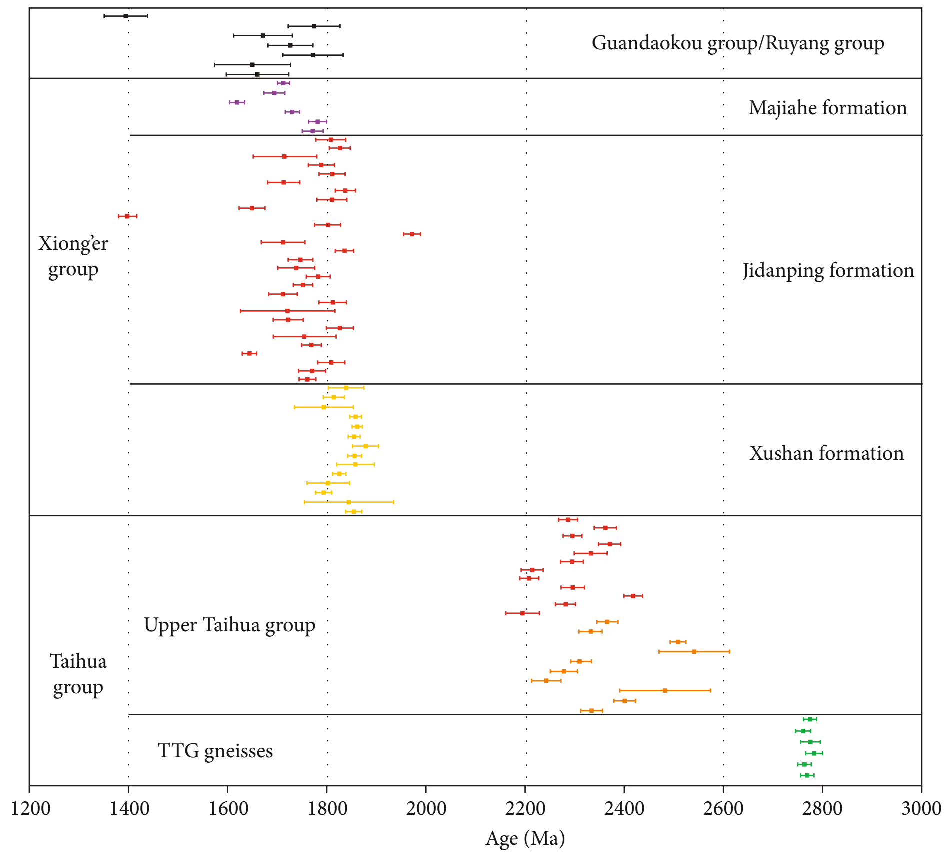

FIGURE 8: Formation age pedigree chart of volcanic rocks in the Xiong'er Group. Data source: this paper, [1, 8, 22–24]. Note: the southern margin of the North China Craton is divided by Sanmenxia-Fangcheng-Xinyang. The west is the Ronan Basin, and the upper strata of Xiong'er Group are the Guandaokou Group. The eastern is the Ruyang Basin, and the upper strata of Xiong'er Group are the Ruyang Group.

SHRIMP method to analyze zircon U-Pb dating on dacite samples from the Jidanping Formation in the Xiao Mountain and obtained an age between 1783 and 1778 Ma; He et al. [21] used the SHRIMP zircon U-Pb dating method to analyze samples of the Jidanping Formation in the Waifang Mountain and obtained an age of 1751 Ma. According to the results of previous studies, in the absence of data from the Xiong'er Mountain area, there were some differences in the Jidanping Formation age data in different regions, but the overall limit was between 1800 and 1750 Ma. In this study, by using the SHRIMP zircon U-Pb dating to test and analyze three samples from the Jidanping Formation in the Xiong'er Mountain, the CM3-5 samples magmatic zircon age limit was between 1834 ± 18 and 1711 ± 29 Ma; the CM5 samples magmatic zircon age limit was between 1836 ± 20 and 1712 ± 33 Ma; and the 1314-1 samples magmatic zircon age limit was between 1808 ± 27 and 1754 ± 63 Ma. The data showed that the age of the Jidanping Formation in the Xiong'er Mountain had a larger time span than the Jidanping Formation in the Ruyang, Xiao Mountain, and Waifang Mountain, with breakthroughs in the upper and lower time limits, which were concentrated between 1836 and 1711 Ma. The data represented the formation age of the Jidanping Formation in the Xiong'er Group on the southern margin of the North China Craton.

5.2. Sequence Stratigraphic Age of Volcanic Rocks in the Xiong'er Group. The volcanic rocks of the Xiong'er Group are mainly composed of basic, intermediate-basic, acid, and intermediate-acid rocks, and researchers have different opinions on the stratigraphic division. Zhao et al. [7] based on lithological characteristics, divided the Xiong'er Group from bottom to top: Dagushi Formation, Xushan Formation, Jidanping Formation, and Majiahe Formation; Pirajno [11] studied the volcanic eruption cycles of the Xiong'er Group and divided them into the following: (1) the eruption cycle of the Xushan Formation, mainly composed of intermediate-basic and basic magmatic rocks; (2) the eruption cycle of the Jidanping Formation, mainly composed of intermediate and acid magmatic rocks; and (3) the eruption cycle of the Majiahe Formation, where the magmatic rocks are mainly formed by alternating and mixing of intermediate and acidic magmatic rocks. He et al. [1], based on the distribution characteristics of the Xiong'er Group volcanic rocks, divided them into the Xushan, Jidanping, and Majiahe Formations. Previous studies and field geological surveys found that (1) the lithology of the Dagushi Formation was composed of sandstone, mudstone, and conglomerate, which was quite different from the volcanic rocks of the Xiong'er Group; (2) the Dagushi Formation sporadically emerged on the southern margin of the North China Craton and only

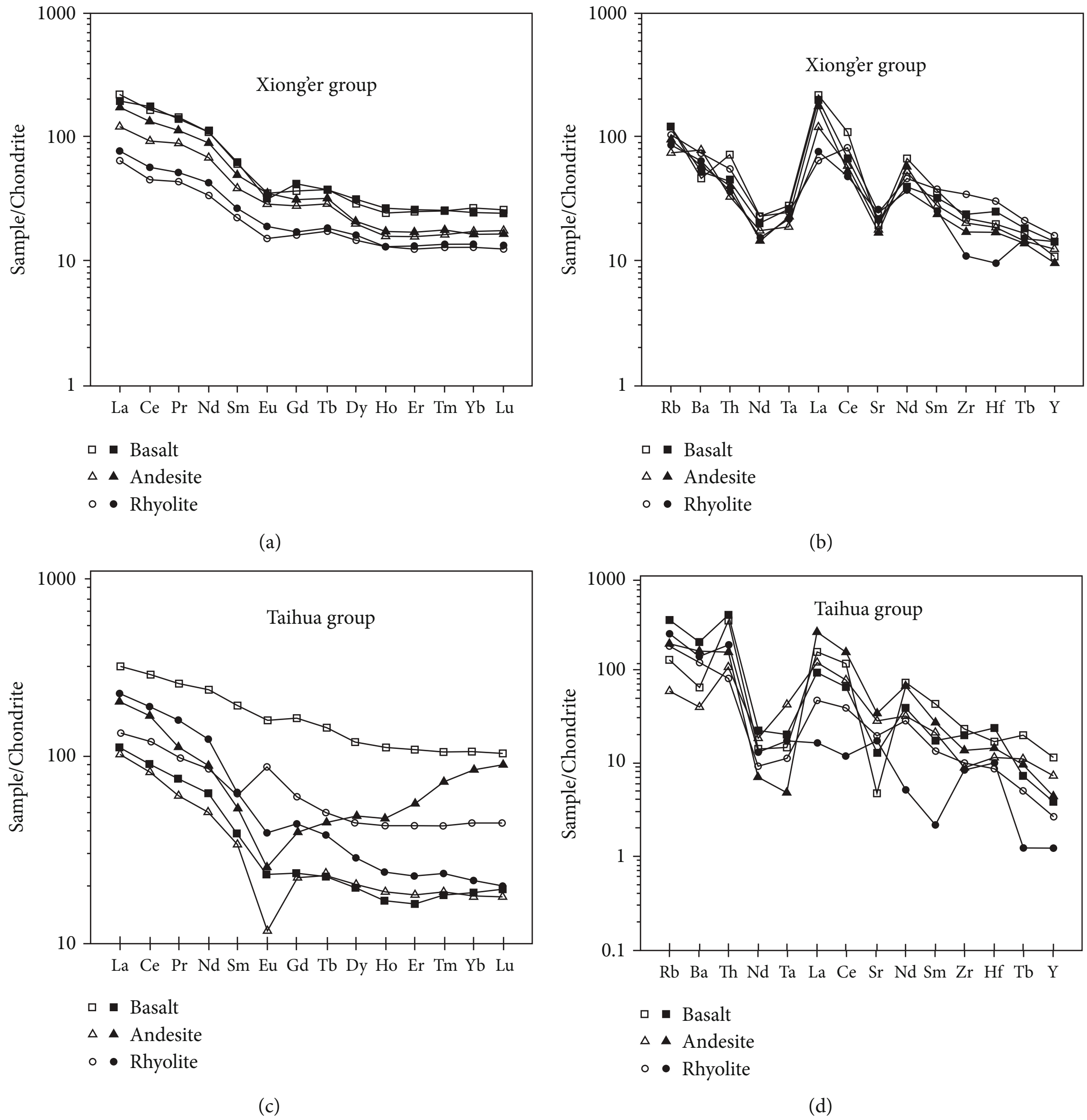

Figure 9: (a, c) Chondrite-normalized REE patterns and (b, d) trace element spider diagram of the Xiong'er Group and Taihua Group. Data source: [1, 8, 14, 25, 26].

emerges in Xiayu, Xinghua, and so on. Different interpretations of the volcanic strata division of the Xiong'er Group by previous scholars are due to differences in lithology and distribution range. This study mainly focused on the volcanic rocks of the Xiong'er Group and did not discuss the Dagushi Formation.

Based on the isotopic ages obtained in this study, combined with previous studies on the Xiong'er Group volcanic rocks in the Qinling, Zhongtiao Mountain, Xiao Mountain, Waifang Mountains, etc., we completed the formation age pedigree chart of volcanic rocks in the Xiong'er Group (as shown in Figure 8), concluding that the age of volcanic rocks in the Xiong'er Group was between 1874 and 1618 Ma. Among them, the age of the Xushan Formation was limited to 1874–1800 Ma, and the lithology was mainly basalt; the age of the Jidanping Formation was limited to 1836–1711 Ma, and the lithology was mainly andesite. The age of the Majiahe Formation was limited to 1780–1618 Ma, and the lithology was mainly rhyolite. The formation ages of the TTG gneisses at the bottom of the Taihua Group were limited to 2800–2700 Ma, the age of the upper supracrustal rock of the Taihua Group was limited to 2415–2193 Ma. The formation ages of the Ruyang Group/Guandaokou Group in the upper strata of the Xiong'er Group were limited to 1771–1394 Ma.

5.3. Contribution of the Taihua Group to the Provenance of the Xiong'er Group. Through the SHRIMP zircon U-Pb isotopic dating of the Jidanping Formation, the formation ages of magmatic zircon and inherited zircon were obtained. The formation age of magmatic zircon represents the formation age of the volcanic rocks in the Jidanping Formation, and the age of the inherited zircon should be the formation age of the Taihua Group in the lower part of the Xiong'er Group.

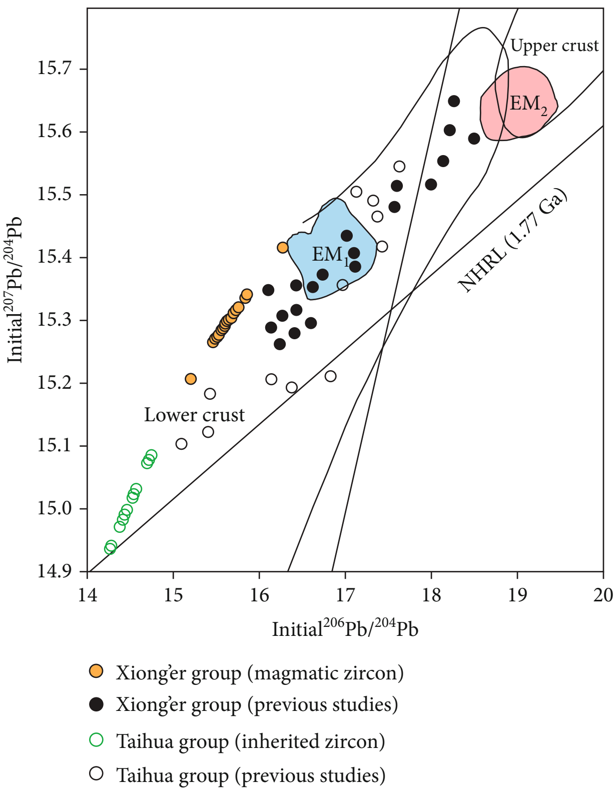

Figure 10: The ^{206}Pb/^{204}Pb-^{207}Pb/^{204}Pb diagram of the Xiong'er Group and Taihua Group in the North China Craton. Data source: this paper; [1, 29]; NHRL: northern hemisphere reference line [31]; EM$_1$ and EM$_2$: the mantle endmember [32].

We came to this determination based on the following: (1) inherited zircon was zircon captured from surrounding rock during magmatic processes, representing the formation age of the captured strata. Both the Taihua Group and Xiong'er Group were relatively ancient strata in the area, and in terms of the formation time limit, inherited zircons cannot come from the rock strata formations formed later; (2) the age of inherited zircons was earlier than the age of the Xushan Formation at the bottom of the Xiong'er Group, which is consistent with the isotopic age of the supracrustal rock of the Taihua Group; and (3) the rare earth element (REE) patterns curve showed that the REE patterns of the Xiong'er Group and the Taihua Group had some similar characteristics (as shown in Figure 9), suggesting that they are genetically related to a certain degree. Therefore, the inherited zircons in the volcanic rocks of the Xiong'er Group were derived from the early formation of the Taihua Group, and part of the Taihua Group was fused during the formation of the Xiong'er Group volcanic rocks. In other words, the Taihua Group provided part of the provenance for the formation of the Xiong'er Group volcanic rocks.

The REE patterns curves of basalt, andesite, and rhyolite in the volcanic rocks of the Xiong'er Group were relatively consistent; the results showed that the total light REEs (ΣLREE) were enriched and the total heavy REEs (ΣHREE) were deficit. The enrichment degree of ΣLREE was much higher than the ratio of mantle and chondrite, indicating that the volcanic rocks of the Xiong'er Group were formed shallowly [14]. At the same time, the REE pattern curve of the Xiong'er Group was relatively flattened, showing deep source fluid, which indicated that part of the provenance of the volcanic rocks came from the deep source fluid [27, 28]. This is consistent with the Pb isotopic characteristics of the volcanic rocks in the Xiong'er Group: in the ^{206}Pb/^{204}Pb-^{207}Pb/^{204}Pb diagram, the cast points of the Xiong'er Group and the Taihua Group are located in the lower crust, partly in the EM$_1$ mantle (as shown in Figure 10). He et al. [29] believed that the EM$_1$ mantle originated from the lithospheric mantle, indicating that the lower crust and the lithospheric mantle were involved in the formation of the Xiong'er Group volcanic rocks. The trace elements of basalt, andesite, and rhyolite in the Xiong'er Group had the same tendency of enrichment and deficit, relative enrichment of elements such as Rb, Th, La, Ce, and Nd; relative deficit of elements such as Nb, Ta, and Sr (as shown in Figure 9(b)). This characteristic was similar to the potash basalt series, and it indicated that the volcanic rocks of the Xiong'er Group may have formed in a continental rift environment [29, 30].

6. Conclusions

(1) The dacite dating results of the Jidanping Formation of the Xiong'er Group in the Xiong'er Mountain showed two age ranges: the magmatic zircon ages of 1836–1711 Ma and the zircon ages of inherited zircon of 2415 ± 19–2193 ± 34 Ma. The isotopic age of magmatic zircon was considered to represent the formation age of the Jidanping Formation in the Xiong'er Mountain, combined with the results of previous studies on the isotopes of Jidanping Formation in Ruyang, Xiao Mountain, and Waifang Mountain. It is believed that the age of formation of the Jidanping Formation in the Xiong'er Group on the southern margin of the North China Craton was limited to 1836–1711 Ma

(2) Based on previous studies of the Xiong'er Group in Qinling, Zhongtiao Mountain, Xiao Mountain, Waifang Mountain, and other areas, it is believed that the volcanic rocks of Xiong'er Group were formed in the Early Proterozoic, and their formation age was limited to 1874–1618 Ma. The three main eruptive stratigraphic units are from bottom to top, Xushan Formation, Jidanping Formation, and Majiahe Formation, with ages of 1874–1800 Ma, 1836–1711 Ma, and 1780–1618 Ma, respectively

(3) The isotopic ages of the inherited zircons are consistent with the formation ages of the Taihua Group supracrustal rocks in the underlying layer of the Xiong'er Group. Combined with the study of geochemical characteristics in the area, our results indicated that the Taihua Group provided part of the provenance during the formation and evolution of the Xiong'er Group volcanic rocks

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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