Research Article

Zircon U–Pb Dating and Lu-Hf Isotope of the Retrograded Eclogite from Chicheng, Northern Hebei Province, China

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We report zircon U–Pb ages and Lu-Hf isotopic data from two sample of the retrograded eclogite in the Chicheng area. Two groups of the metamorphic zircons from the Chicheng retrograded eclogite were identified: group one shows characteristics of depletion in LREE and flat in HREE curves and exhibit no significant Eu anomaly, and this may imply that they may form under eclogite facies metamorphic condition; group two is rich in HREE and shows slight negative Eu anomaly indicated that they may form under amphibolite facies metamorphic condition. Zircon Lu-Hf isotopic of $\varepsilon_{HF}$ from the Chicheng eclogite has larger span range from 6.0 to 18.0, which suggests that the magma of the eclogite protolith may be mixed with partial crustal components. The peak eclogite facies metamorphism of Chicheng eclogite may occur at 348.5–344.2 Ma and its retrograde metamorphism of amphibolite facies may occur at ca. 325.0 Ma. The Hongqiyingzi Complex may experience multistage metamorphic events mainly including Late Archean (2494–2448 Ma), Late Paleoproterozoic (1900–1734 Ma, peak age $= 1824.6$ Ma), and Phanerozoic (495–234 Ma, peak age $= 323.7$ Ma). Thus, the metamorphic event (348.5–325 Ma) of the Chicheng eclogite is in accordance with the Phanerozoic metamorphic event of the Hongqiyingzi Complex. The eclogite facies metamorphic age of the eclogite is in accordance with the metamorphism (granulite facies or amphibolite facies) of its surrounding rocks, which implied that the tectonic subduction and exhumation of the retrograded eclogite may cause the regional metamorphism of garnet biotite plagioclase gneiss.

1. Introduction

The tectonic evolution of the central part of the northern margin of the North China Craton has become a hot academic research focus in recent years. As a significant component of the dismembered ophiolite mélangé of the Hongqiyingzi Complex [1], the retrograded eclogite which recorded the evolution history of the Paleoasian Ocean has been attracting more and more attention [2–9].

The tectonic evolution of the Chicheng retrograded eclogite can be classified into four stages [10]: (1) the protolith formation stage, (2) the peak eclogite facies stage, (3) the granulite facies stage, and (4) the amphibolite facies stage. Previous chronology studies shows that the metamorphic age of the retrograded eclogite are still under disputes: 325 Ma of SHRIMP zircon U-Pb age was recommended as the peak metamorphic age by Ni et al. [10]; 355 Ma of SHRIMP zircon U-Pb age was proposed as the peak metamorphic age by Kong et al. [11]; 1847–1840 Ma of SIMS zircon U-Pb age was recommended as the peak metamorphic age by Liu et al. [1]; 1.85–1.80 Ga, 460–420 Ma, and 360–270 Ma of zircon U-Pb age was proposed as the peak metamorphic age, retrograded metamorphic age, and amphibolite facies metamorphic age, respectively, by Zhang et al. [8].

Because zircon geochemistry and chronology are very effective methods applied to metamorphism chronology research of the eclogite, this paper attempts to provide more zircon U–Pb and Lu-Hf isotopic composition of the eclogite and may be beneficial to solve these disputes.
2. Geological Background and Petrological Characteristics

The Chicheng area, including Zhenningpu, Luhepu, and Qilidun, is located on the north side of the Chongli-Chicheng Fault, northern margin of the North China Craton (NCC) (Figures 1(a)–1(c)). Retrograded eclogite, which occur as separate tectonic lenses within the Hongqiyinzhi Complex, range in size from 1–5 cm to 30–50 m and their elongation is consistent with regional schistosity or gneissosity (Figure 2(a)).

Based on the differences of the mineral assemblages and the degree of retrograde metamorphism, the retrograded eclogite from Chicheng can be divided into the weakly amphibolitized eclogite and the intensely amphibolitized eclogite [11]. The intensely amphibolitized eclogite are characterized by the existence of amphibole and plagioclase, very little or no omphacite and vermicular symplectite of Na-poor clinopyroxene and plagioclase; garnets are replaced completely by a granular symplectite of amphibole and plagioclase. The weakly amphibolitized eclogite are characterized by the existence of remnant omphacite and vermicular symplectite of Na-poor clinopyroxene and plagioclase.

3. Sample Descriptions

The weakly amphibolitized eclogite of sample 160601, from the east of Chicheng town, is fine-medium grained, with a mineral assemblage of omphacite (60 vol.%) + garnet (13 vol.%) + diopside (2 vol.%) + amphibole (5 vol.%) + plagioclase (15 vol.%) + quartz (5 vol.%). The weakly amphibolitized eclogite of sample 160602 from Luhepu, is medium grained, with a mineral assemblage of omphacite (63 vol.%) + garnet (12 vol.%) + diopside (2 vol.%) + amphibole (5 vol.%) + plagioclase (15 vol.%) + quartz (5 vol.%).

4. Sample Selection and Analytical Methods

Two samples (sample 160601 and 160602) of retrograded eclogite from Chicheng were used in this research and were performed by zircon ICP-MS U-Pb dating, zircon Lu-Hf isotopic analysis, and zircon trace element analysis. Combined with a Nu Plasma II ICP-MS (Wrexham, Wales, UK) at Nanjing FocuMS Technology Co. Ltd. The details of the analytical procedures and methods are similar to the dissertations elaborated by Griffin and Yuan [12, 13]. The diameter of the ion beam was approximately 32 μm at 8 Hz repetition rate, the depth of the ablation was 20–35 μm, and the duration of the ablation was 40 seconds. In the process of testing, 1 point of the standard zircons was measured after every 5 points of the purified zircons to control the stability and the accuracy of the ion counts. The uncertainty for each measuring point is ±1σ, and uncertainty of the final concordia ages is ±1σ. The isotope ages of 206Pb/238U were corrected by standard zircons 91500 (1064 Ma) [14]. Due to the small amount of 207Pb formed in the Phanerozoic zircons, the 206Pb/238U ages were used to constrain the metamorphic ages for the retrograded eclogite, and the detailed U-Pb isotopic dating data are shown in Table 1.

The zircon Lu-Hf isotopic analysis of sample 160601 and 160602 was conducted after the zircon U-Pb dating was finished. For instrumental mass bias correction, Hf isotope ratios were normalized to 176Hf/177Hf = 0.7325 and Yb isotope ratios to 172Yb/173Yb = 1.35274, and the mass bias behavior of Lu was assumed to follow that of Yb. Correction for the isobaric interferences of 176Yb and 176Lu with 176Hf utilizes 176Yb/172Yb = 0.796218 and 176Lu/172Lu = 0.02655 [15]. The Hf isotopic data process details were described by Vervoort et al. [16] and Vervoort [17]. The weighted mean 176Hf/177Hf ratio of standard zircon 91500 is 0.282303 ± 28 (2σ), which is indistinguishable with a weighted mean 176Hf/177Hf ratio of 0.282307 ± 31 (2σ) [18]. The weighted mean 176Hf/177Hf ratio of standard zircon GJ1 is 0.282017 ± 26 (2σ), which is indistinguishable with a weighted mean 176Hf/177Hf ratio of 0.282013 ± 19 (2σ) [19].

Calculation of Hf TDM1 ages is based on a depleted-mantle source with present-day 176Hf/177Hf = 0.283252, using the 176Lu decay constant 1.867 × 10−11 year−1 [20]. The zircon trace elements analysis of sample 160601 and 160602 were also performed by ICP-MS at the Nanjing FocuMS Technology Co. Ltd. The testing procedures and parameters are similar to zircon U-Pb dating and the analytical error is about ±10% for light rare Earth elements and ±5% for the other rare Earth elements.

5. Results

5.1. Zircon Trace Elements’ Analysis. The chondrite-normalized REE (rare-earth element) patterns of zircon from sample 160601 (Table 2) are characterized by flat HREE curves and no significant Eu anomaly, indicating that the zircon may form under eclogite facies metamorphic conditions (Figure 3(d)). Two groups of the zircon chondrite-normalized REE curves from sample 160602 can be distinguished: group one is similar to sample 160601 and characterized by flat HREE curves and exhibit no significant Eu anomaly, suggesting that the zircon may form under eclogite facies metamorphic conditions (Figure 3(e)); group two (including two spots, spot 1.1 and 3.1) exhibits steep HREE curves and slight negative Eu anomaly (Figure 3(f)) and has characteristics of metamorphic origin in CL images.
Figure 1: Geological sketch map showing the location of retrograded eclogite in the Chicheng area, North Hebei Province (modified after [3]). 1 denotes Quaternary cover; 2 denotes Jurassic; 3 denotes Hongqijingzi complex; 4 denotes Archean rocks; 5 denotes monzonitic granite; 6 denotes porphyritic granite; 7 denotes granitic gneiss-mylonite; 8 denotes metamafic rocks (retrograded eclogite); 9 denotes ultramafic rocks (serpentinized peridotite); 10 denotes Chongli-Chicheng Fault; 11 denotes schistosity; 12 denotes sample location.
Figure 2: Field photographs and photomicrographs of the retrograded eclogite. (a) The retrograded eclogite occurs as separate tectonic lenses within the Hongqiyingzi Complex. (b) Macrophoto of the symplectite of light-colored minerals around garnet. (c) Photomicrograph of minerals in sample 160602 (single-polarized light). (d) Photomicrograph of minerals in sample 160601 (single-polarized light). Omph: omphacite; Grt: garnet; Pl: plagioclase; Q: quartz.

Table 1: Zircon LA-ICP-MS U-Pb geochronological analyses of the eclogite (sample 160601 and 160602).

| Spot | Pb (ppm) | Th (ppm) | U (ppm) | Th/U | 207 Pb/235 U | 206 Pb/238 U | ±(1σ) | 207 Pb/235 U age (Ma) ± Ma | 206 Pb/238 U age (Ma) ± Ma |
|------|----------|----------|----------|------|--------------|--------------|-------|---------------------------|---------------------------|
| Sample 160601 |          |          |          |      |              |              |       |                           |                           |
| 1.1  | 6.2      | 3.1      | 108      | 0.029 | 0.4104       | 0.0203       | 0.0556 | 0.0009                    | 349.2 ± 14.6              | 348.6 ± 5.2               |
| 2.1  | 4.6      | 0.2      | 73       | 0.003 | 0.4387       | 0.0275       | 0.058  | 0.0012                    | 369.3 ± 19.4              | 363.7 ± 7.1               |
| 3.1  | 6        | 0.2      | 91       | 0.002 | 0.4724       | 0.0236       | 0.058  | 0.001                     | 392.9 ± 16.3              | 363.6 ± 6.0               |
| 4.1  | 16.1     | 1.7      | 280      | 0.006 | 0.4091       | 0.0133       | 0.0559 | 0.0007                    | 348.3 ± 9.6               | 350.7 ± 4.2               |
| 5.1  | 7.7      | 0.6      | 127      | 0.005 | 0.4156       | 0.0194       | 0.0568 | 0.0008                    | 352.9 ± 13.9              | 356.4 ± 5.0               |
| 6.1  | 3.4      | 0.4      | 57       | 0.006 | 0.4247       | 0.0219       | 0.0545 | 0.0008                    | 359.4 ± 15.6              | 342.1 ± 4.8               |
| 7.1  | 6.1      | 0.7      | 106      | 0.006 | 0.4121       | 0.0173       | 0.0561 | 0.0007                    | 350.4 ± 12.4              | 352.0 ± 4.1               |
| 8.1  | 11.7     | 1.4      | 205      | 0.007 | 0.4078       | 0.0112       | 0.055  | 0.0005                    | 347.3 ± 8.1               | 345.0 ± 2.9               |
| 9.1  | 3        | 0.7      | 48       | 0.014 | 0.402        | 0.0205       | 0.0552 | 0.0008                    | 343.1 ± 14.9              | 346.2 ± 5.0               |
| 10.1 | 2.5      | 0.3      | 40       | 0.009 | 0.4293       | 0.0232       | 0.0569 | 0.001                     | 362.7 ± 16.5              | 356.5 ± 5.9               |
| 11.1 | 5.2      | 0.4      | 92       | 0.004 | 0.4042       | 0.0133       | 0.0541 | 0.0006                    | 344.7 ± 9.6               | 339.4 ± 3.4               |
| 12.1 | 1.2      | 0.1      | 20       | 0.004 | 0.4452       | 0.0332       | 0.0569 | 0.0014                    | 373.9 ± 23.3              | 356.9 ± 8.3               |
| 13.1 | 6.2      | 0.8      | 111      | 0.007 | 0.398        | 0.0122       | 0.0543 | 0.0005                    | 340.2 ± 8.8               | 341.2 ± 3.1               |
| 14.1 | 2.6      | 0.4      | 39       | 0.01  | 0.4367       | 0.0243       | 0.0565 | 0.0009                    | 367.9 ± 17.2              | 354.4 ± 5.5               |
| 15.1 | 3.7      | 0.3      | 58       | 0.006 | 0.4577       | 0.021        | 0.0579 | 0.0008                    | 382.7 ± 14.6              | 362.6 ± 5.1               |
| 16.1 | 3.6      | 0.6      | 61       | 0.009 | 0.416        | 0.016        | 0.0556 | 0.0006                    | 353.2 ± 11.5              | 348.9 ± 3.5               |
| 17.1 | 3        | 0.1      | 50       | 0.002 | 0.4143       | 0.0184       | 0.055  | 0.0007                    | 352 ± 13.2                | 345.1 ± 4.2               |

Shock and Vibration
5.2. Zircon U-Pb Dating. The zircons from sample 160601 are colorless with subhedral to oval crystals, lengths ranging from 40 to 120 μm with length/width ratios of 1:1 to 2:1 (Figure 4(a)). Cathodoluminescence photos show cloudy zoned or unzoned features for metamorphic zircon. The 17 analytical points were made on this sample, which have similar low Th/U values (0.002–0.029) and yield mean ages of 348.5 ± 3.7 Ma (Figure 3(a)).

The zircons from sample 160602 are also colorless with subhedral to oval crystals, lengths ranging from 50 to 180 μm with length/width ratios of 1:1 to 2:1 (Figure 4(b)). Cathodoluminescence photos show metamorphic features of nebulos zoned or unzoned. The 9 analytical points of group one zircons have low Th/U values (0.005–0.091) and yield mean ages of 344.2 ± 7.3 Ma (Figure 3(b)). The 2 analytical points of group two zircons have low Th/U values (0.017–0.04) and yield mean ages of 325.0 ± 4.1 Ma (Figure 3(c)).

5.3. Zircon Lu-Hf Dating. Fifteen Lu-Hf spots on the zircon cores were obtained on zircon grains from sample 160601. On the basis of a metamorphic age of approximate 348.5 Ma, initial 176Lu/177Hf ratios and εHf(t) values are calculated by assuming t = 348.5 Ma (Table 3). The metamorphic zircons have a 176Lu/177Hf ratio of 0.000003–0.000013 and 176Hf/177Hf (348.5 Ma) of 0.282726–0.283025, corresponding to εHf (348.5 Ma) ranging from 6.0 to 16.6 (Figure 5).

Nine Lu-Hf spots on the zircon cores were obtained on zircon grains from sample 160602. On the basis of a metamorphic age of approximate 344.2 Ma, initial 176Hf/177Hf ratios and εHf(t) values are calculated by assuming t = 344.2 Ma (Table 3). The metamorphic zircons have a 176Lu/177Hf ratio of 0.000005–0.000059 and 176Hf/177Hf of 0.282921–0.283069, corresponding to εHf (344.2 Ma) ranging from 12.8 to 18.0 (Figure 5).

6. Discussion

6.1. The Protolith and Metamorphic Condition of the Eclogite. Previous studies show that the protolith of the Chicheng retrograded eclogite is tholeiitic oceanic crust with geochemical characteristics of midocean ridge basalt (MORB) or island arc tholeiite (IAT) [10] and experiences the peak eclogite facies metamorphism caused by the subduction of Paleo-Asian Ocean crust beneath the NCC and the granulite facies or amphibolite facies metamorphism resulted from its exhumation into the Hongqiyingzi Complex. The peak eclogite facies metamorphism is marked by the existence of a small amount of granular omphacite within the garnets (P > 1.40–1.50 GPa and T = 680–730°C) [10]. These features indicate that the Chicheng eclogite has the oceanic or mantle affinity, and thus, the protolith of the eclogite is of “foreign” origin [23, 24]. Zircon Lu-Hf isotopic εHf from the Chicheng eclogite has larger spans range from 6.0 to 18.0, which suggests that the magma of the eclogite protolith may mix with partial crustal components.

6.2. The Metamorphic Ages of the Eclogite. As presented above, the mineral assemblages from the retrograded eclogite are omphacite, garnet, amphibole, plagioclase, and quartz. Considering the low Th/U ratios and flat HREE curves with no significant Eu anomaly, the zircon age of 348.5 ± 3.7 Ma from sample 160601 and 344.2 ± 7.3 Ma from group one of sample 160602 are interpreted as the time of the eclogite facies metamorphism. Due to low Th/U ratios and steep HREE curves with slight negative Eu anomaly, the zircon age of 325.0 ± 4.1 Ma from group two of sample 160602 is interpreted as the time of the retrograde metamorphism of amphibolite facies. The eclogite facies metamorphic age of 348.5–344.2 Ma is older than the previous study of 325 Ma [10] and a little younger than the previous study of 355 Ma (Kong et al. [11]).

6.3. The Relationship of the Metamorphism between the Eclogite and Its Country Rock. According to previous studies, the Hongqiyingzi Complex may experience multistage metamorphic events (Figure 6), mainly including Late Archean (2494–2448 Ma), Late Paleo-protorozoic (1900–1734 Ma, peak age = 1824.6 Ma), and Phanerzoic (495–234 Ma, peak age = 323.7 Ma). The zircon U-Pb dating for retrograded eclogite shows that the peak eclogite facies metamorphism may occur at 348.5–344.2 Ma and its retrograde metamorphism of amphibolite facies may occur at ca. 325.0 Ma. Thus,

| Spot | Pb (ppm) | Th (ppm) | U (ppm) | 207Pb/235U | ±(1σ) | 206Pb/238U | ±(1σ) | 207Pb/235U age (Ma) ±(1σ) | ±(1σ) | 206Pb/238U age (Ma) ±(1σ) |
|------|----------|----------|----------|------------|------|------------|------|--------------------------|------|--------------------------|
| Sample 160601 |
| 1.1 | 3.9 | 1 | 59.4 | 0.017 | 0.4743 | 0.034 | 0.0559 | 0.0019 | 337.6 | 9.6 | 324.9 | 3.6 |
| 2.1 | 29.3 | 23.5 | 529.5 | 0.044 | 0.3702 | 0.0186 | 0.0525 | 0.0011 | 342.9 | 9 | 340.6 | 3.1 |
| 3.1 | 30.7 | 22.3 | 562.4 | 0.04 | 0.3714 | 0.0218 | 0.0512 | 0.0012 | 335 | 6.1 | 325.1 | 2.6 |
| 4.1 | 23.3 | 2.2 | 413.3 | 0.005 | 0.4263 | 0.0209 | 0.0554 | 0.0011 | 360.5 | 7.4 | 347.4 | 3.1 |
| 5.1 | 38.5 | 42.9 | 722 | 0.059 | 0.3989 | 0.0168 | 0.0517 | 0.0008 | 341.6 | 10.3 | 333.1 | 3.3 |
| 6.1 | 12.7 | 21.2 | 231.8 | 0.091 | 0.3945 | 0.0264 | 0.0517 | 0.0012 | 362.7 | 20.1 | 352.0 | 7.8 |
| 7.1 | 8.2 | 1 | 147.3 | 0.063 | 0.3999 | 0.0283 | 0.053 | 0.0011 | 365.2 | 17.7 | 358.3 | 5.8 |
| 8.1 | 13.2 | 2.4 | 240.6 | 0.01 | 0.4017 | 0.0248 | 0.0543 | 0.001 | 394.2 | 18.6 | 359.0 | 5.7 |
| 9.1 | 4.6 | 1.1 | 81.5 | 0.014 | 0.4146 | 0.0352 | 0.0539 | 0.0016 | 352.2 | 12.6 | 338.4 | 4.8 |
| 10.1 | 4.5 | 5.6 | 77.9 | 0.072 | 0.4168 | 0.0382 | 0.0532 | 0.0014 | 353.7 | 13.7 | 333.9 | 4.2 |
| 11.1 | 25.5 | 20.3 | 432.9 | 0.047 | 0.4388 | 0.0303 | 0.0556 | 0.0013 | 378.3 | 9.4 | 357.7 | 3.4 |
Table 2: Trace element concentrations of zircons in retrograded eclogite (ppm).

| Spot | La (ppm) | Ce (ppm) | Pr (ppm) | Nd (ppm) | Sm (ppm) | Eu (ppm) | Gd (ppm) | Tb (ppm) | Dy (ppm) | Ho (ppm) | Er (ppm) | Yb (ppm) | Lu (ppm) | Y (ppm) | ΣREE (ppm) | LREE (ppm) | HREE (ppm) | LREE/HREE | δEu | δCe |
|------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|--------|----------------|------------|----------------|-----------|------|-----|
| Sample 160601 |
| 1.1 | 0.001 | 0.066 | 0.000 | 0.035 | 0.170 | 0.313 | 3.74 | 1.37 | 7.75 | 1.07 | 2.05 | 0.33 | 2.60 | 0.40 | 34.11 | 19.90 | 0.59 | 19.32 | 0.03 | 0.56 | 2.30 |
| 2.1 | 0.010 | 0.098 | 0.007 | 0.047 | 0.225 | 0.390 | 3.79 | 1.04 | 5.50 | 0.86 | 1.73 | 0.25 | 1.78 | 0.23 | 24.20 | 15.96 | 0.78 | 15.18 | 0.05 | 0.68 | 2.78 |
| 3.1 | 0.004 | 0.073 | 0.002 | 0.020 | 0.194 | 0.324 | 2.77 | 0.96 | 5.38 | 0.62 | 0.98 | 0.14 | 0.91 | 0.13 | 18.07 | 12.50 | 0.62 | 11.89 | 0.05 | 0.76 | 6.26 |
| 4.1 | 0.001 | 0.146 | 0.001 | 0.048 | 0.276 | 0.322 | 3.22 | 1.10 | 6.69 | 0.79 | 1.56 | 0.21 | 1.71 | 0.18 | 23.24 | 16.25 | 0.79 | 15.45 | 0.05 | 0.64 | 27.37 |
| 5.1 | 0.000 | 0.065 | 0.001 | 0.019 | 0.321 | 0.370 | 4.68 | 1.92 | 12.21 | 1.62 | 2.49 | 0.30 | 2.23 | 0.31 | 46.56 | 26.53 | 0.77 | 25.76 | 0.03 | 0.51 | 33.37 |
| 7.1 | 0.003 | 0.132 | 0.001 | 0.046 | 0.482 | 0.573 | 6.05 | 1.49 | 6.21 | 0.67 | 1.22 | 0.17 | 1.11 | 0.16 | 20.81 | 18.31 | 1.24 | 17.07 | 0.07 | 0.61 | 24.06 |
| 8.1 | 0.003 | 0.070 | 0.003 | 0.016 | 0.259 | 0.391 | 4.70 | 1.42 | 7.53 | 0.88 | 1.26 | 0.17 | 1.37 | 0.17 | 24.53 | 18.24 | 0.74 | 17.50 | 0.04 | 0.55 | 6.11 |
| 9.1 | 0.000 | 0.110 | 0.003 | 0.023 | 0.265 | 0.371 | 4.54 | 1.23 | 6.59 | 0.84 | 1.48 | 0.23 | 1.53 | 0.20 | 23.72 | 17.41 | 0.77 | 16.64 | 0.05 | 0.54 | 13.62 |
| Sample 160602 |
| 1.1 | 0.000 | 0.542 | 0.000 | 0.123 | 0.361 | 0.219 | 3.55 | 1.50 | 20.68 | 8.95 | 43.97 | 10.33 | 113.19 | 20.43 | 248.97 | 223.84 | 1.25 | 222.60 | 0.01 | 0.38 | 3.66 |
| 2.1 | 0.000 | 1.110 | 0.005 | 0.081 | 0.987 | 1.187 | 11.46 | 3.28 | 21.75 | 4.03 | 9.68 | 1.40 | 10.02 | 1.36 | 117.34 | 66.34 | 3.37 | 62.97 | 0.05 | 0.66 | 65.89 |
| 3.1 | 0.011 | 0.157 | 0.000 | 0.040 | 0.085 | 0.115 | 0.95 | 0.54 | 7.79 | 3.29 | 14.35 | 2.88 | 25.76 | 4.67 | 111.01 | 60.63 | 0.41 | 60.22 | 0.01 | 0.77 | 2.65 |
| 4.1 | 0.005 | 0.709 | 0.005 | 0.107 | 0.564 | 0.704 | 8.74 | 3.07 | 20.86 | 3.36 | 6.84 | 0.95 | 6.60 | 0.99 | 87.20 | 53.51 | 2.09 | 51.41 | 0.04 | 0.53 | 29.44 |
| 5.1 | 0.043 | 0.619 | 0.015 | 0.107 | 0.406 | 0.582 | 6.88 | 2.82 | 23.57 | 5.60 | 10.48 | 1.41 | 10.22 | 1.43 | 122.36 | 63.17 | 1.78 | 61.39 | 0.03 | 0.56 | 6.01 |
| 6.1 | 0.010 | 0.652 | 0.004 | 0.048 | 0.615 | 1.091 | 14.75 | 5.45 | 34.85 | 5.02 | 9.00 | 1.10 | 7.56 | 1.08 | 130.40 | 81.22 | 2.42 | 78.80 | 0.03 | 0.50 | 23.52 |
| 7.1 | 0.085 | 0.745 | 0.008 | 0.057 | 0.573 | 0.571 | 5.94 | 2.32 | 18.24 | 3.68 | 11.29 | 1.89 | 18.53 | 3.02 | 97.20 | 66.94 | 2.04 | 64.90 | 0.03 | 0.60 | 5.44 |
| 8.1 | 0.006 | 0.462 | 0.004 | 0.058 | 0.479 | 0.436 | 5.66 | 2.41 | 20.07 | 3.64 | 8.47 | 1.41 | 9.04 | 1.21 | 109.72 | 53.10 | 1.44 | 51.65 | 0.03 | 0.49 | 23.57 |
| 9.1 | 0.043 | 1.384 | 0.012 | 0.262 | 0.830 | 1.104 | 10.69 | 3.87 | 29.21 | 5.22 | 11.55 | 1.69 | 12.14 | 1.74 | 154.76 | 79.75 | 3.63 | 76.11 | 0.05 | 0.66 | 14.63 |
| 10.1 | 0.077 | 0.552 | 0.010 | 0.101 | 0.411 | 0.479 | 7.22 | 2.07 | 26.75 | 5.50 | 13.42 | 1.93 | 15.02 | 2.12 | 162.40 | 76.66 | 1.63 | 75.03 | 0.02 | 0.44 | 4.24 |
| 11.1 | 0.005 | 0.534 | 0.000 | 0.000 | 0.428 | 0.554 | 7.07 | 2.04 | 24.19 | 4.90 | 11.59 | 1.72 | 12.61 | 1.87 | 137.70 | 68.51 | 1.52 | 66.99 | 0.02 | 0.51 | 80.78 |
Figure 3: Concordia plot (Figures (a)–(c)) showing the zircon analysis from the retrograded eclogite. Chondrite-normalized REE plot (Figures (d)–(f)) of the retrograded eclogite from the Chicheng area. The values for chondrite are from [21].
the metamorphic event of 348.5–325 Ma from the Chicheng eclogite is in accordance with the Phanerozoic metamorphic event of the Hongqiyinzi Complex. The metamorphism (granulite facies or amphibolite facies) of the eclogite country rock (garnet biotite plagioclase gneiss) occurred from 351 Ma to 343 Ma (our unpublished data). Combined with the fact that the retrograded eclogite occurs as separate tectonic lenses or lumps in the garnet biotite plagioclase gneiss and its major axes direction is in line with regional gneissosity, we come to the conclusion that the tectonic subduction and exhumation of the eclogite may lead to the regional Mesozoic metamorphism of Hongqiyinzi Complex.

### Table 3: Isotopic features of zircon Lu-Hf from the retrograded eclogite (sample 160601 and 160602).

| Spot | 206Pb/238U age (Ma) | 176Yb/177Hf | ±(2δ) | 176Lu/177Hf | ±(2δ) | 176Hf/177Hf | ±(2δ) | 178Hf/177Hf | ±(2δ) | εHf (t) | TDM (Ma) |
|------|---------------------|-------------|-------|-------------|-------|-------------|-------|-------------|-------|---------|-----------|
| 1.1  | 348.6 Ma            | 0.000269    | 0.000007 | 0.000009 | 0.000000 | 0.282893 | 0.000014 | 1.467956 | 0.000052 | 12.0    | 495.8     |
| 2.1  | 363.7               | 0.000164    | 0.000004 | 0.000004 | 0.000000 | 0.283015 | 0.000008 | 1.467831 | 0.000033 | 16.3    | 326.7     |
| 4.1  | 350.7               | 0.000625    | 0.000011 | 0.000013 | 0.000000 | 0.282726 | 0.000009 | 1.468006 | 0.000031 | 6.0     | 725.8     |
| 5.1  | 356.4               | 0.000306    | 0.000004 | 0.000005 | 0.000000 | 0.282868 | 0.000009 | 1.467985 | 0.000028 | 11.1    | 529.0     |
| 6.1  | 342.1               | 0.000195    | 0.000004 | 0.000004 | 0.000000 | 0.282892 | 0.000007 | 1.468000 | 0.000026 | 11.9    | 497.8     |
| 7.1  | 352.0               | 0.000378    | 0.000006 | 0.000006 | 0.000000 | 0.282869 | 0.000008 | 1.468050 | 0.000027 | 11.1    | 529.0     |
| 8.1  | 345.0               | 0.000678    | 0.000011 | 0.000013 | 0.000000 | 0.282726 | 0.000009 | 1.468006 | 0.000031 | 6.0     | 725.8     |
| 9.1  | 346.2               | 0.000192    | 0.000004 | 0.000004 | 0.000000 | 0.282892 | 0.000007 | 1.468000 | 0.000026 | 11.1    | 529.0     |
| 10.1 | 356.5               | 0.000163    | 0.000003 | 0.000002 | 0.000000 | 0.283025 | 0.000008 | 1.468040 | 0.000028 | 16.6    | 312.7     |
| 11.1 | 339.4               | 0.000437    | 0.000008 | 0.000008 | 0.000000 | 0.282961 | 0.000007 | 1.468070 | 0.000030 | 14.4    | 402.0     |
| 13.1 | 341.2               | 0.000632    | 0.000004 | 0.000004 | 0.000000 | 0.282997 | 0.000008 | 1.467967 | 0.000026 | 15.6    | 351.7     |
| 14.1 | 354.4               | 0.000129    | 0.000003 | 0.000003 | 0.000000 | 0.282904 | 0.000006 | 1.467954 | 0.000028 | 12.3    | 480.8     |
| 15.1 | 362.6               | 0.000326    | 0.000003 | 0.000003 | 0.000000 | 0.282962 | 0.000008 | 1.467977 | 0.000029 | 14.4    | 399.7     |
| 16.1 | 348.9               | 0.000199    | 0.000003 | 0.000003 | 0.000000 | 0.282952 | 0.000008 | 1.468013 | 0.000024 | 14.0    | 414.0     |
| 17.1 | 345.1               | 0.000173    | 0.000003 | 0.000003 | 0.000000 | 0.282986 | 0.000008 | 1.468018 | 0.000024 | 15.2    | 367.3     |
| 2.1  | 340.6 Ma            | 0.007992    | 0.000018 | 0.000279 | 0.000001 | 0.283099 | 0.000013 | 1.468003 | 0.000038 | 15.9    | 337.3     |
| 3.1  | 325.1               | 0.015066    | 0.000064 | 0.000059 | 0.000012 | 0.283069 | 0.000012 | 1.468001 | 0.000045 | 18.0    | 255.4     |
| 6.1  | 352.0               | 0.000378    | 0.000004 | 0.000004 | 0.000000 | 0.282892 | 0.000007 | 1.467954 | 0.000028 | 12.3    | 480.8     |
| 7.1  | 358.3               | 0.000262    | 0.000004 | 0.000005 | 0.000000 | 0.282921 | 0.000008 | 1.468039 | 0.000025 | 15.8    | 340.0     |
| 8.1  | 350.9               | 0.001480    | 0.000055 | 0.000043 | 0.000001 | 0.282948 | 0.000009 | 1.468046 | 0.000033 | 13.8    | 420.6     |
| 9.1  | 338.4               | 0.001213    | 0.000023 | 0.000027 | 0.000000 | 0.282974 | 0.000010 | 1.467941 | 0.000034 | 14.7    | 383.7     |
| 10.1 | 333.9               | 0.001200    | 0.000008 | 0.000024 | 0.000000 | 0.282972 | 0.000010 | 1.468016 | 0.000030 | 14.6    | 387.0     |

**Figure 4:** Cathodoluminescence (CL) images of analyzed zircons from the retrograded eclogite. The red circles represent the sites of analyzed points with diameter of 32 μm. The ages depicted in the pictures are 206Pb/238U ages. (a) 160601. (b) 160602.
7. Conclusions

(1) Two groups of the metamorphic zircons from the Chicheng retrograded eclogite were identified. Group one shows characteristics of depletion in LREE and flat in HREE curves and exhibit no significant Eu anomaly, and this may imply that they may form under eclogite facies metamorphic condition. Group two is rich in HREE and shows slight negative Eu anomaly and indicate that they may form under amphibolite facies metamorphic condition.

(2) Zircon Lu-Hf isotopic of $\varepsilon_{Hf}$ from the Chicheng eclogite has larger span range from 6.0 to 18.0, which suggests that the magma of the eclogite protolith may mix with partial crustal components.

(3) The peak eclogite facies metamorphism of Chicheng eclogite may occur at 348.5–344.2 Ma and its retrograde metamorphism of amphibolite facies may occur at ca. 325.0 Ma.

(4) The Hongqiyingzi Complex may experience multi-stage metamorphic events mainly including Late Archean (2494–2448 Ma), Late Paleoproterozoic (1900–1734 Ma, peak age = 1824.6 Ma), and Phanerozoic (495–234 Ma, peak age = 323.7 Ma). The metamorphic event (348.5–325 Ma) of the Chicheng eclogite is in accordance with the Phanerozoic metamorphic event of the Hongqiyingzi Complex.

(5) The eclogite facies metamorphic age of the eclogite is in accordance with the metamorphism (granulite facies or amphibolite facies) of its surrounding rocks.
and implies that the tectonic subduction and exhumation of the eclogite may lead to the regional metamorphism of garnet biotite plagioclase gneiss.

**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.

**Authors’ Contributions**

Xueyuan Qi & Xu Kong equally contributed to the work, they are joint first authors.

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