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U-Pb and Hf Isotopic Analyses for Detrital Zircon of the Danzhou Group in the Western Jiangnan Orogenic Belt and Tectonic Implications

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Abstract: In order to better constrain the specific depositional age and provenance of the Danzhou Group and understand the geological evolution of the Jiangnan Orogenic Belt, we conducted a combined U-Pb and Hf-isotope analysis of detrital zircons from the Gongdong and Hetong formations of the Danzhou Group in the Longsheng area of the Western Jiangnan Orogenic Belt. Detrital zircons from the Gongdong Formation yield three age populations of 2658–2517 Ma, 2427–1678 Ma and 891–781 Ma, and the youngest ages suggest that the sedimentation began after ca. 783 Ma. U-Pb ages of detrital zircons from the Hetong Formation yield major populations at 2769–2502 Ma, 2492–2100 Ma, and 991–731 Ma, and the youngest ages redefine the maximum depositional age of this unit is 760 Ma, much younger than previously considered. Thus, the upper part of the Hetong Formation in the Longsheng area is newly subdivided into the Sanmenjie Formation, which is characterized by a large amount of 765–761 Ma volcanic rocks. The dominant 991–731 Ma detrital zircons for all samples were likely sourced from the Neoproterozoic igneous rocks of the southeast margin of the Yangtze Block. The subordinate 2494–1678 Ma detrital zircons were probably sourced from the Cathaysia Block. Minor amounts of 2769–2502 Ma detrital zircons may have been sourced from the Yangtze Block. Detrital zircons from the Gongdong Formation have mainly negative εHf (t) values (−1.1 to 21.8, 90%), suggesting that the detritus of the Gongdong Formation is dominated by the recycling of old crustal materials. The εHf (t) values of detrital zircons from the Hetong Formation have a large spread of −22.2 to +9.7, indicating that the source material of the Hetong Formation includes both the juvenile crustal materials and the recycled ancient crustal materials. The above age populations and Hf isotopic characteristics are consistent with the magmatic rocks in the Jiangnan Orogenic Belt and the Southeast Yangtze Block. Taking into account the lithostratigraphic features, provenances, and depositional ages, the Danzhou Group in the Western Jiangnan Orogenic Belt was deposited in a back-arc basin.

Keywords: detrital zircon; U-Pb dating; Hf isotope; Danzhou Group; Western Jiangnan Orogenic Belt

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1. Introduction

The Jiangnan Orogenic Belt (JOB), located on the southeastern margin of the Yangtze Block, was formed by the collision of the Yangtze and Cathaysia Blocks in the Neoproterozoic (Figure 1a) [1–5]. Due to the multiple stages of orogenic and magmatic events, the formation and tectonic evolution of the JOB has always been a hot issue, and it is also a key area to discuss the tectonic framework of the South China Block (SCB), which is associated with the assembly and breakup of the Rodinia supercontinent [1–12]. However, the specific timing of the amalgamation between the Yangtze and Cathaysia Blocks, and the tectonic evolution of the JOB remain controversial. In the past decades, three tectonic models have been proposed. The first model is the "plume-rifting" model. Some researchers propose that the timing of the amalgamation between the Yangtze and Cathaysia Blocks at ca. 880 Ma, and the JOB is a part of the Grenvillian orogeny, which is associated with the assembly of the Rodinia supercontinent. The 850–750 Ma magmatism in the SCB is the product of the upwelling of the superplume during the breakup of the Rodinia supercontinent [13–16]. However, some researchers proposed the "slab-arc" model. The Neoproterozoic magmas (830–820 Ma) were island arc magmas caused by the subduction of the Paleo South China Ocean under the Yangtze Block, later than the Grenvillian orogeny [17–19]. In contrast, the "plate-rift" model is proposed. The island arc magmatism around the Yangtze Block occurred at 1.3–1.1 Ga, and the collision occurred at 960–860 Ma. The early Neoproterozoic magmatic events are believed to be caused by the intra-continental rifts that extended and stretched after the early arc-continental collision, and the late Neoproterozoic magmatic events are believed to be caused by intra-plate rifts [20,21].

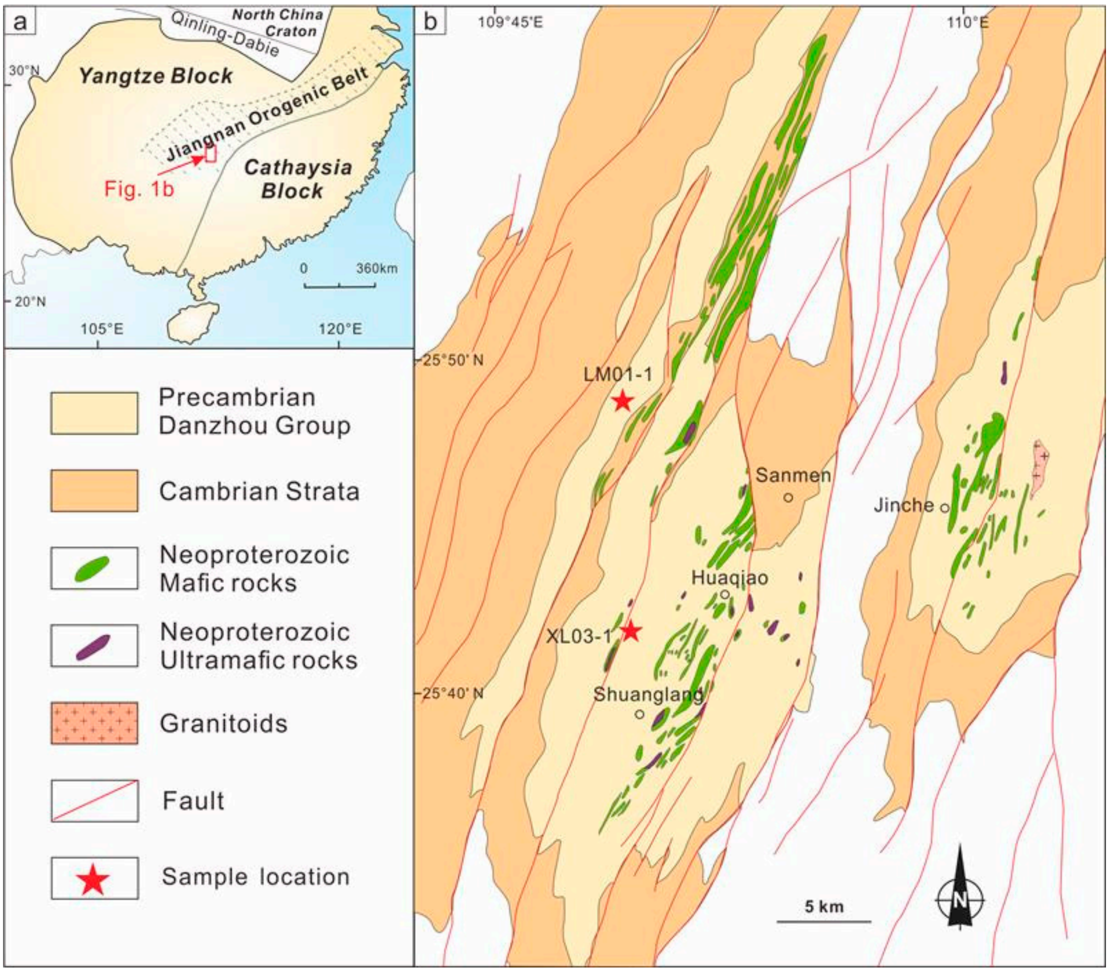

Figure 1. (**a**) Geological sketch map of the Jiangnan Orogenic Belt in the South China Block (modified after Yao et al. [9]); (**b**) Sketch geological map of the Longsheng area (Guilin, Guangxi) with sampling location (modified after GXRGST [22,23]). The yellow part of (**a**) is South China Block.

The Precambrian crystalline basement rocks of the Western JOB are exposed in the Fanjingshan, Lengjiaxi, and Sibao Groups with unconformably overlying strata of the Xiajiang, Banxi, and Danzhou Groups. Previous studies on a large number of sedimentary rocks, tuff, and medium-acid intrusive rocks in the Sibao Group limit their sedimentary age to 860–820 Ma [24–26], and 820 Ma is also the lower depositional limit of the Danzhou Group. The Danzhou Group is composed of, in ascending order, the Baizhu, Hetong, and Gongdong formations (Figure 2) [23]. Previous studies on the geochronology of the metasedimentary rocks and syn-sedimentary volcanic rocks of the Danzhou Group suggest that the depositional age is 820–725 Ma [2,24,25,27–29]. However, some researchers recognized 765–761 Ma volcanic rocks in the upper part of the Hetong Formation and newly subdivided these strata into the Sanmenjie Formation [22,30,31]. Due to the lack of reliable isotope age data, the deposition age of each formation of the Danzhou Group and the material source are still controversial, which hinders the discussion on the formation and evolution of the JOB.

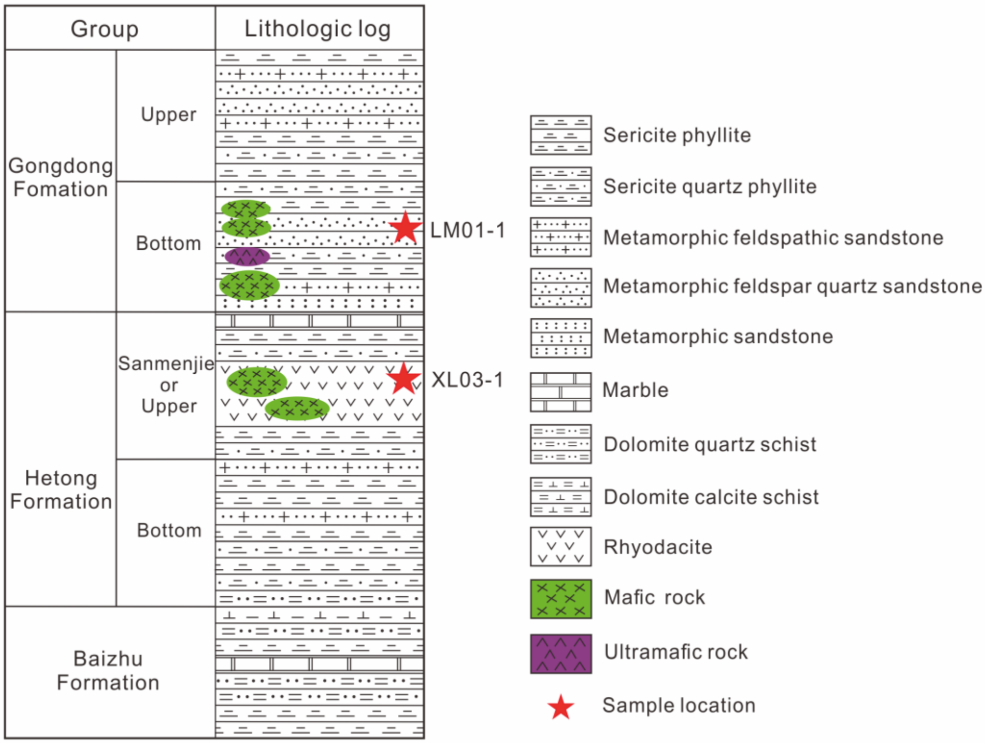

Figure 2. Stratigraphic column of the Neoproterozoic Danzhou Group in the Longsheng area (modified after GXRGST [23]).

In this study, we report new detrital U-Pb zircon geochronological and Hf isotopic data for the Gongdong and Hetong formations of the Danzhou Group from the Longsheng area in Western JOB. Few detailed geochronological data have been reported in the Longsheng area because it is heavily weathered and has few outcrops. Our new data, integrated with previously available data, aim to revise the deposition age of each formation of the Danzhou Group, constrain the main sedimentary provenance, and further provide new constraints for the Neoproterozoic tectonic evolution of the Western JOB in the SCB.

2. Geological Background and Sample Descriptions

2.1. Regional Geology

The SCB is composed of the Yangtze Block in the north and the Cathaysia Block in the south, forming the JOB, which is about 1500 km long and 200 km wide, with a NE-SW direction (Figure 1a) [4,5,22,23,32,33]. The Yangtze Block is considered to have an

Archean–Paleoproterozoic crystalline basement, such as the Kongling complex, which is mainly composed of Mesoarchean TTG basement rocks and the Palaeoproterozoic Kongling Group, while the Cathaysian Block has not reported Archean crystalline basement, only Paleoproterozoic crystalline basement [5,34]. Based on the comparison of crustal composition and buried faults, the JOB is divided into the east and west parts. In the Eastern JOB, the basement includes the Shuangxiwu, Xikou, and Shuangqiaoshan groups, which correspond to the unconformably overlying early Neoproterozoic metamorphic volcano–sedimentary strata, including Heshangzhen, Likou and Dengshan groups, respectively. The basement in the Western JOB is mainly composed of the early to middle Neoproterozoic volcano–sedimentary sequences, sporadically exposed in the Lengjiaxi Group in west Hunan, the Sibao Group in North Guangxi and the Fanjingshan Group in Northeast Guizhou [4,32]. The Sibao Group and its equivalents are mainly composed of a set of greenschist facies metamorphosed mudstone, siltstone, and pyroclastic rock, mafic–ultramafic intrusive rocks, and S-type granite, which are considered to have been deposited before ca. 820 Ma [3,4,26,29,34–40]. The Sibao Group and its equivalents are covered by a series of angular unconformable sedimentary rocks, including the Xiajiang, Banxi, and Danzhou groups, which are composed of weakly metamorphic marine sandy shales, tuff and a small amount of carbonate rocks deposited in ca. 820–725 Ma (e.g., [41]).

The Longsheng area is located in the Western JOB, mainly exposed to the early Neoproterozoic Sibao Group and overlying the Neoproterozoic Danzhou Group, the Nanhua, Sinian, and Phanerozoic strata. The regional magmatic activity is strong, and there are intermediate–acidic extrusive rocks and mafic–ultramafic intrusive rocks (Figure 1) [31]. The Danzhou Group in the Longsheng consists of, in ascending order, the Baizhu, Hetong, and Gongdong formations (Figure 2) [23]. The main lithologic sequences of the Baizhu Formation consist of dolomite quartz schists, dolomite calcite schists, marble, and phyllites. The overlying Hetong Formation changes from lower dolomite quartz schists, sericite quartz phyllites, and metamorphic feldspathic sandstones to upper sericite phyllites, sericite quartz phyllites, and marbles. The Gongdong Formation is composed of sericite phyllites, sericite quartz phyllites, metamorphic sandstones, metamorphic feldspathic sandstones, metamorphic feldspar quartz sandstones, and a few mafic–ultramafic intrusions. The geochronology of detrital zircon and tuff in the Danzhou Group shows that the depositional age is 820–725 Ma, and the deposition age of the Baizhu Formation is 820–805 Ma [2,27], the bottom part of Hetong Formation is 805–800 Ma, the upper part is 800–780 Ma [24,28], and the Gongdong Formation is 780–725 Ma [25,29].

However, some researchers proposed that the upper part of the Hetong Formation was deposited at 765–761 Ma [30,31] and newly subdivided these strata into the Sanmenjie Formation [22]. The Sanmenjie Formation, which is in integrated contact with the Gongdong Formation in the Longsheng area, is characterized by a large amount of marine volcanic rocks and a small amount of terrigenous clastic rocks. The volcanic rocks of the Sanmenjie Formation are mainly composed of pillow basalts and basaltic andesite (more than 200 m thick) with minor rhyodacite (less than 30 m). Zircon U-Pb ages of 765 $\pm$ 14 Ma [31] and 761 $\pm$ 8 Ma [30] are reported from rhyodacite and gabbro diabase intrusions and limit the depositional age of the Sanmenjie Formation to 765–761 Ma. Therefore, some researchers proposed that the marine volcanic rock series in Sanmenjie could be separated and reformed into the Sanmenjie Formation [36]. The deposition age of each formation of the Danzhou Group needs to be clarified.

2.2. Sample Descriptions

Two meta-sedimentary rock samples were collected from the Gongdong and Hetong Formations. Their locations are shown in Figures 1 and 2. Sample LM01-1 (GPS:

25°48′1.03″ N, 109°49′0.63″ E), collected from the Gongdong Formation, is a dark gray quartz sandstone. The outcrop is dark gray, medium-thick layered, showing thick quartz arkose beds (Figure 3a). Sample LM01-1 is composed of 50%–55% quartz, 25%–30% feldspar, and ~20% rock fragments, which are mainly igneous type (Figure 3b). Sample XL03-1 (GPS: 25°41′25.15″ N, 109°48′46.89″ E) is a dark gray meta-siltstone collected from the Hetong Formation, 4 km southwest of the Sanmenjie Town. The outcrop is a dark grey outcrop with well-defined bedding (Figure 3c). The sample contains quartz, plagioclase, sericite, and a few lithic clasts (Figure 3d).

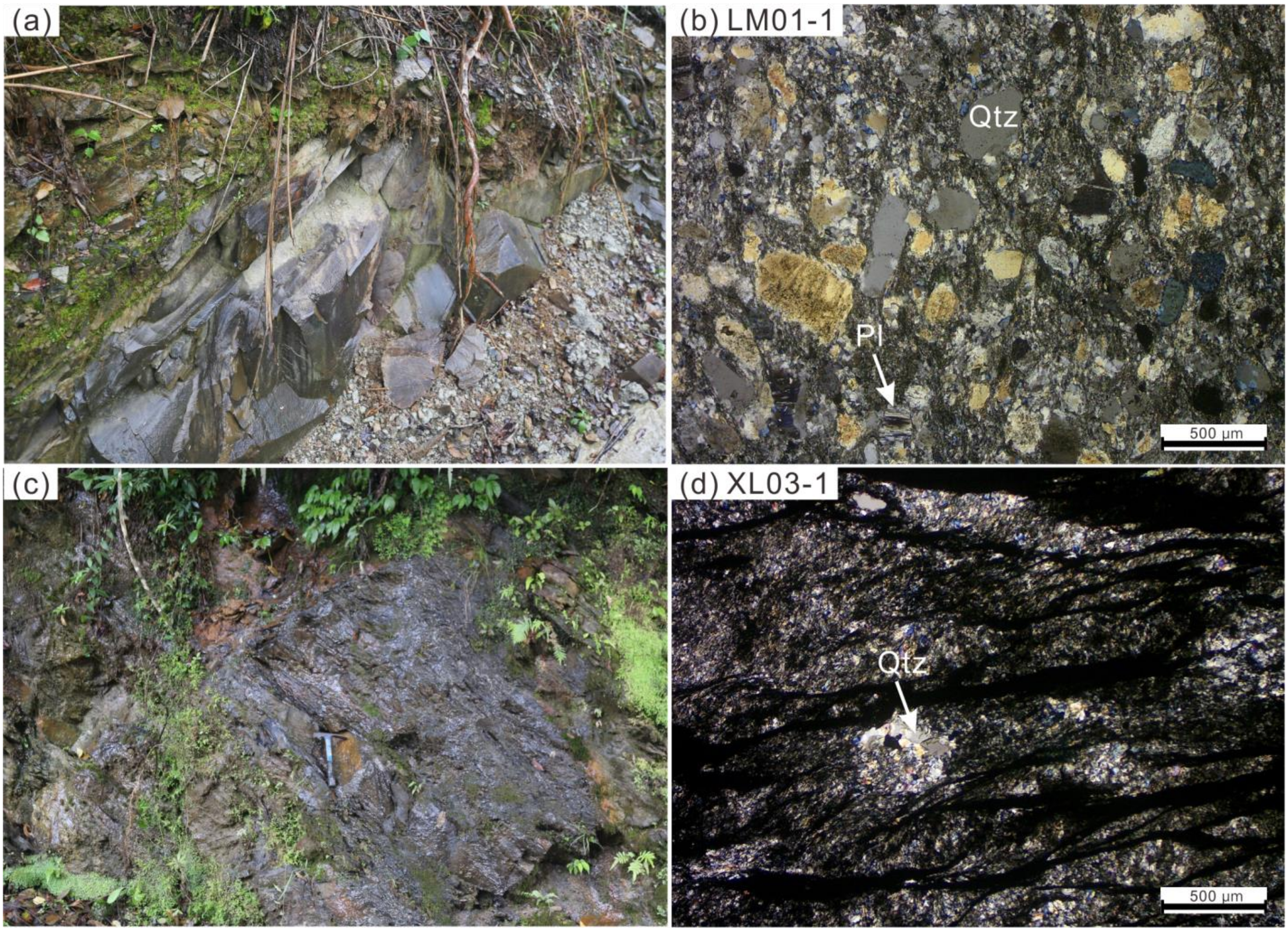

Figure 3. Field photographs and photomicrographs of the meta-sedimentary rock of the Danzhou Group from the Longsheng area. (**a**,**b**) Quartz sandstone (Sample LM01-1) from the Gongdong Formation. (**c**,**d**) Metamorphic siltstone (Sample XL03-1) from the Hetong Formation. Qtz—quartz, Pl—plagioclase.

3. Analytical Methods

Zircons were picked by conventional heavy liquid and magnetic techniques after rock crushing at the Guangzhou Tuoyan Analytical Technology Co., Ltd., Guangzhou, China. Cathodoluminescence (CL) imaging was carried out to identify internal structures of zircon and select potential sites for U-Pb dating and in situ Hf isotope analysis.

Detrital zircon U-Pb isotopic compositions and trace element concentrations were analyzed at the Wuhan SampleSolution Analytical Technology Co., Ltd., Wuhan, China, using a Plasma Quant MS elite ICP-MS instrument coupled with an excimer 193 nm laser ablation system. The spot size of 24 μm with frequency of the laser of 8 Hz in this study. Zircon 91,500 was used as the external standard for correcting mass discrimination and isotope fractionation, and zircon GJ-1 was analyzed as an unknown. Two 91,500 samples were inserted into every five zircon spots for correction [42], and the accuracy was controlled by one GJ-1 sample [43]. The analytical methods and operation conditions are described by Liu et al. [44]. Concordia diagrams and weighted mean calculations of zircon U-Pb data were undertaken with the ISOPLOT 4.15 program [45].

Zircon in situ Hf isotopic measurements were determined following U-Pb analyses by using a Nu Plasma II MC-ICP-MS coupled to 193 nm ArF excimer laser at the Nanjing FocuMS Technology Co. Ltd., Nanjing, China. The Hf isotopic analysis spots were made at the same or nearly the same zircon spots. The laser parameters were set as follows: beam diameter, 40 μm; repetition rate, 10 Hz; energy density, 6 J/cm^2. For every ten zircon spots, the Lu-Hf fractionation was corrected by one Plesovice sample ($^{176}Hf/^{177}Hf = 0.282482 \pm 0.000013$) [46] and two Penglai samples ($^{176}Hf/^{177}Hf = 0.282906 \pm 0.000010$) [47]. Zircon initial $^{176}Hf/^{177}Hf$ ratios were calculated with measured $^{176}Lu/^{177}Hf$ and $^{176}Hf/^{177}Hf$ ratios and ^{176}Lu decay constant of 1.865×10^{-11} [48]. The present-day chondritic $^{176}Hf/^{177}Hf$ ratio of 0.282772 and $^{176}Lu/^{177}Hf$ ratio of 0.0332 were used to calculate εHf values [49]. To calculate depleted mantle model ages (T_{DM1}), we used a depleted mantle reservoir having present-day $^{176}Lu/^{177}Hf$ ratio of 0.0384 and $^{176}Hf/^{177}Hf$ ratio of 0.283251 [50]. Crustal model ages ($T_{DM}{}^{C}$) were calculated by assuming that the zircon parental magma originated from an average continental crust ($^{176}Lu/^{177}Hf = 0.015$, [50]), which was derived from the depleted mantle.

4. Results

4.1. Zircon U-Pb Ages

In order to avoid unreliable ages, only analyses with less than 10% discordance were evaluated, other ages were excluded in the following discussion. $^{207}Pb/^{206}Pb$ ages were used for zircons older than 1000 Ma, and $^{206}Pb/^{238}U$ ages for zircons younger than 1000 Ma. Th, U content and Th/U ratio are used to distinguish different types of zircons [51], and it is generally considered that magmatic zircons have higher Th and U content, Th/U ratio (>0.4), while metamorphic zircons and hydrothermal zircons have lower Th and U content, and Th/U ratio (<0.1) [52,53]. Cathodoluminescence (CL) images of representative zircons from samples of the Gongdong and Hetong formations are shown in Figure 4, and zircon U-Pb dating results are shown in Figure 5 and listed in Supplementary Table S1.

4.1.1. Gongdong Formation

Sample LM01-1 was collected from the Gongdong Formation of the Danzhou group. Most zircon grains are euhedral to subhedral, with poor roundness, ranging from 50 to 200 μm in length, and exhibit aspect ratios of 1:1–2:1. Most zircon grains from sample LM01-1 (>95%) have oscillatory zoning internal structures, and a few zircon grains show concentric oscillatory zoned cores with narrow structureless rims (Figure 4). Detrital zircon grains contain variable concentrations of Th and U and have high Th/U ratios ranging from 0.29 to 2.85 (generally >0.4, Figure 5). These characteristics of detrital zircon grains suggest a magmatic origin.

A total of seventy zircon grains were randomly selected for analysis, and sixty-four reliable U-Pb ages were obtained, ranging from 2658 Ma to 781 Ma (Figure 6). The probability density plots are dominated by Neoproterozoic ages (70%) ranging from 891 Ma to 781 Ma, with a prominent peak at 805 Ma. Paleoproterozoic ages (27%) ranged from 2427 Ma to 1678 Ma, with a peak at 2021 Ma. Two Neoarchean ages (3%) are 2658 ± 32 Ma and 2517 ± 34 Ma.

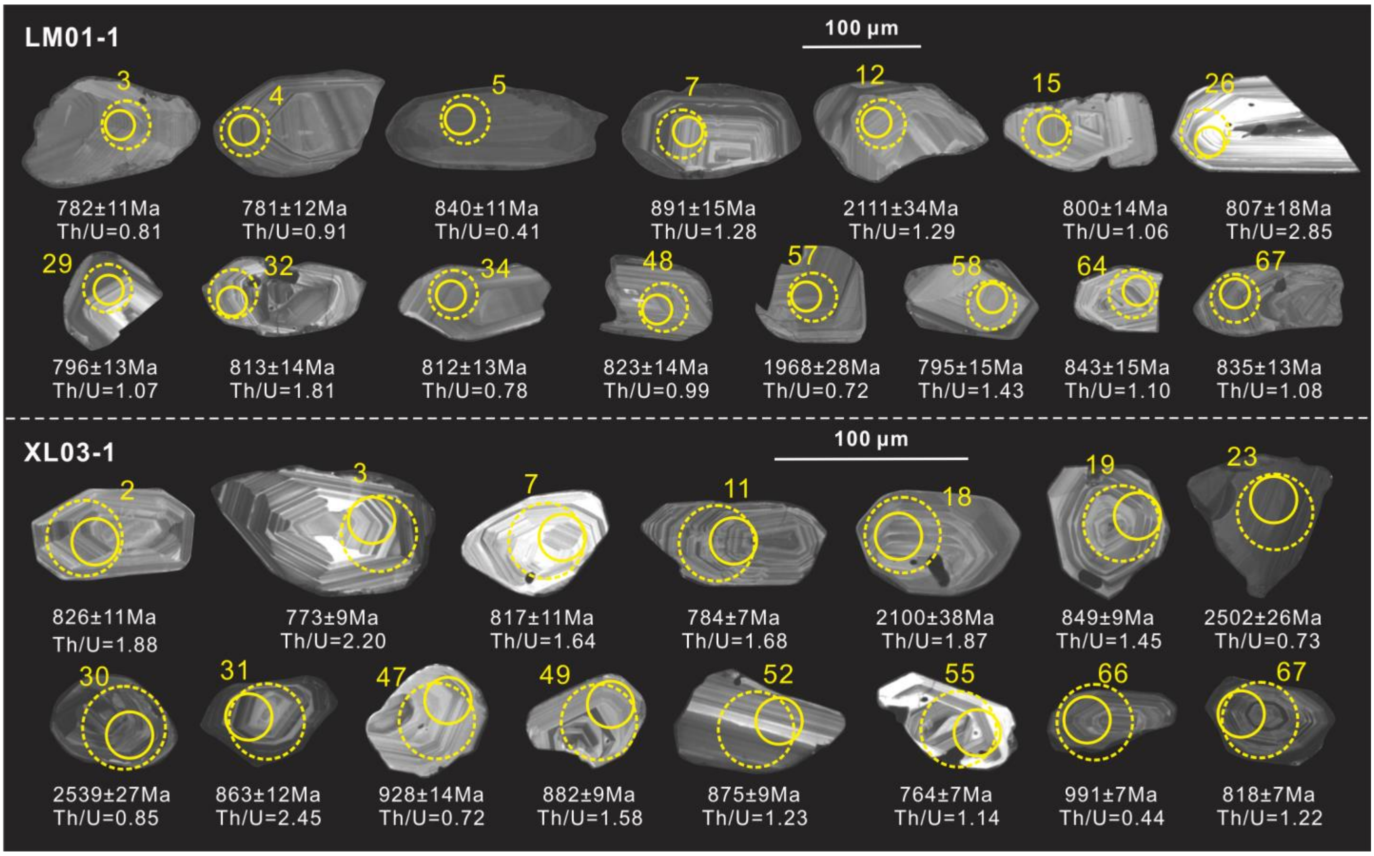

Figure 4. Representative cathodoluminescence (CL) of dated zircons from samples of the Gongdong and Hetong formations. The small solid circles denote the sites of U-Pb age analyses, and the large, dashed circles denote the sites of Hf isotope analyses.

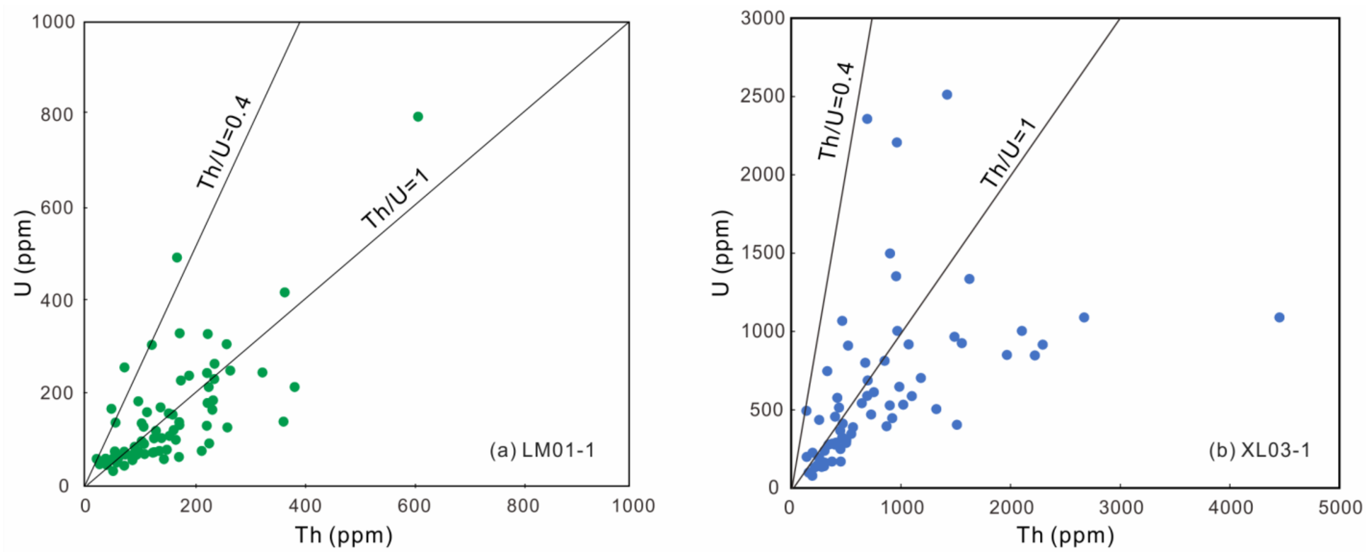

Figure 5. Th/U ratios of zircon grains from sample LM01-1 and XL03-1 (modified after Rubatto et al. [52]).

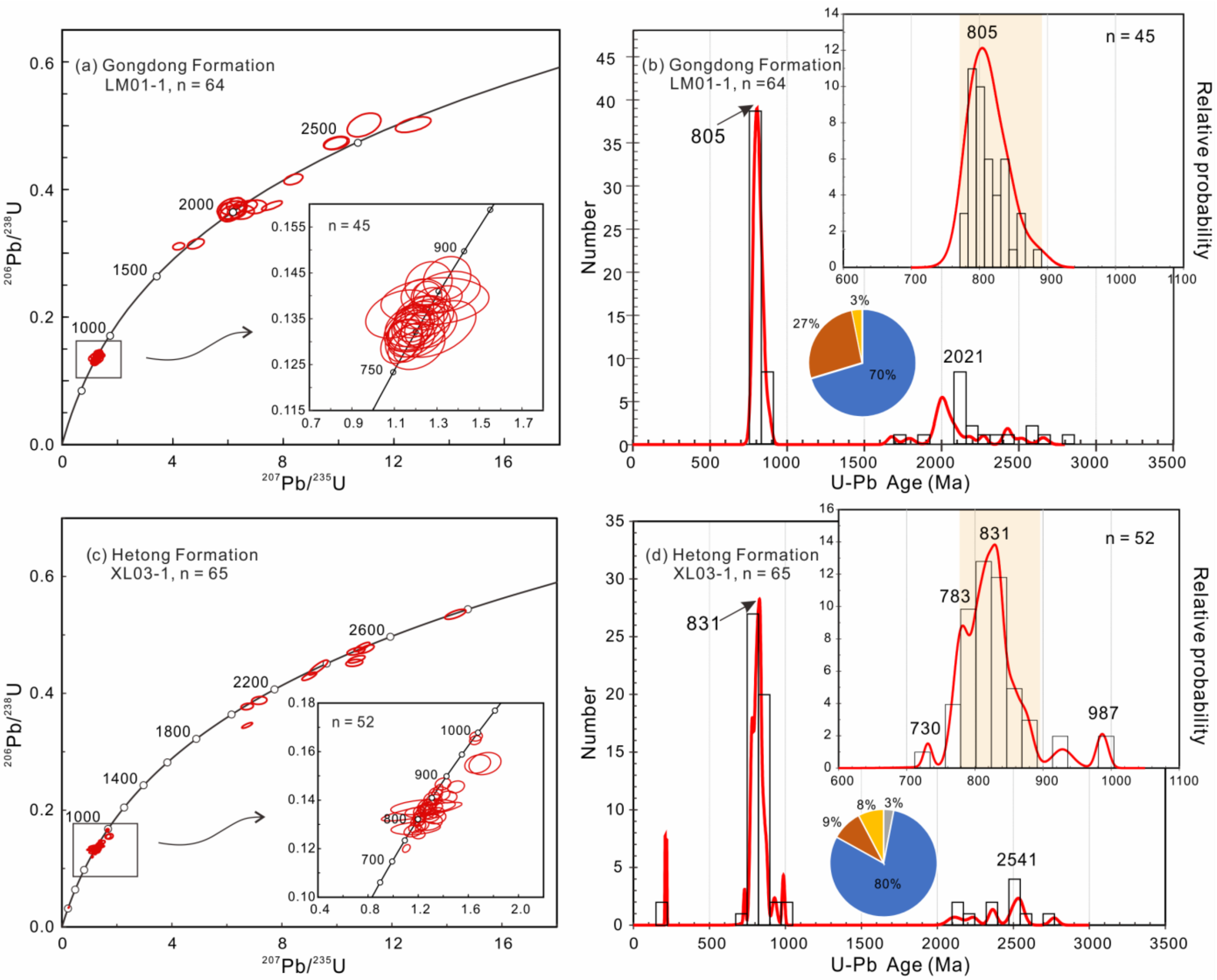

Figure 6. U-Pb Concordia age and probability density plots (PDPs) and proportions of detrital zircons of the Gongdong and Hetong formations in the Danzhou Group. Blue PDPs fills: Neoproterozoic zircon ages; Orogen PDPs fills: Paleoproterozoic zircon ages; Yellow PDPs fills: Archean zircon ages; Gray PDPs fills: Triassic zircon ages.

Maximum depositional age (MDA) is calculated from the weighted average of the youngest ages of at least three grains, each with an error <10% [54], rather than the youngest single grain that could be affected by Pb loss. The youngest suite of five grains has a weighted average age of 783 ± 13 Ma (MSWD = 0.025), so U-Pb detrital zircons MDA for sample LM01-1 is 783 ± 13 Ma.

4.1.2. Hetong Formation

Sample XL03-1 was collected from the Hetong Formation. Most zircon grains are euhedral to subhedral, with a length of ~50–150 μm and aspect ratio of 1:1 to 3:1. Detrital zircon grains show clear concentric oscillatory zoning and have high Th/U ratios ranging from 0.29 to 4.09 (generally >0.4), indicating that they have a magmatic origin (Figure 5).

A total of seventy zircon grains were randomly analyzed, of which sixty-three spots yielded concordant ages from 2769 Ma to 731 Ma, except two Triassic ages (218 ± 2 Ma, 209 ± 2 Ma) (Figure 6). The composite age distribution is mainly composed of Neoproterozoic ages (80%), ranging from 991 Ma to 731 Ma, of which 831 Ma is a prominent peak, 987 Ma and 783 Ma are two subordinate peaks. The Paleoproterozoic age (9%) is scattered, ranging from 2494 Ma to 2100 Ma, and the sparse Neoarchean age (8%) is between 2769 Ma and 2502 Ma (peak at 2541 Ma). The youngest five zircon grains have a weighted average age of 760 ± 26 Ma (MSWD = 8.3), so U-Pb detrital zircons MDA for sample XL03-1 is 760 ± 26 Ma.

4.2. Zircon In Situ Hf Isotopes

In situ Hf isotope analysis was performed on zircons with concordant ages from two samples (LM01-1 and XL03-1) of the Gongdong and Hetong formations. The results are listed in Supplementary Table S2.

4.2.1. Gongdong Formation

Sixty-three dated zircons from sample LM01-1 were selected for Hf isotope analysis. These zircons show variable εHf (t) values ranging from −21.8 to +10.3, and most of them are negative (Figure 7a). Their initial $^{176}Hf/^{177}Hf$ ratios range from 0.280957 to 0.282542. Two-stage Hf model ages (T_{DM}^{C}) range from 3830 Ma to 1093 Ma, with a major peak of 2590 Ma and three peaks of 3210 Ma, 2250 Ma, and 1160 Ma (Figure 7b).

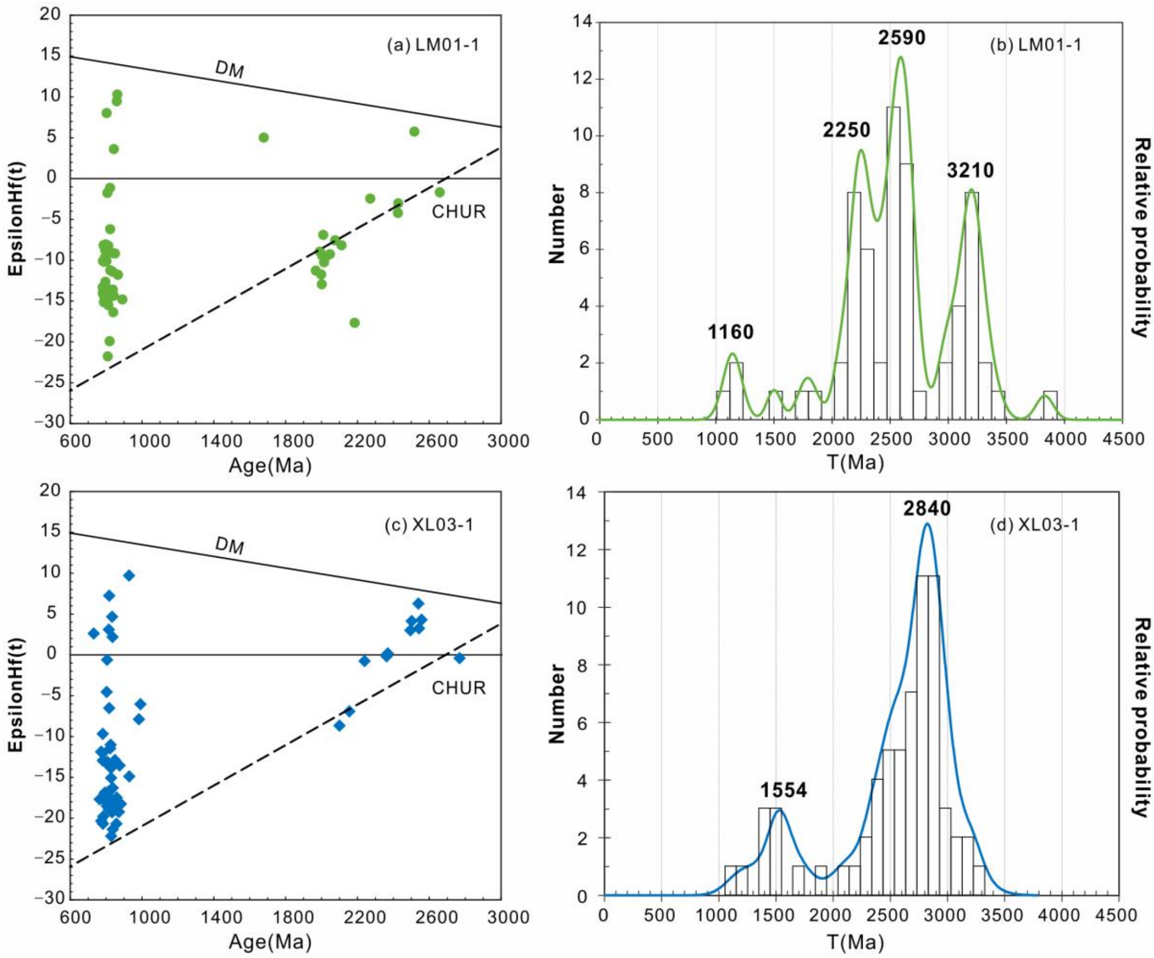

Figure 7. Hf isotopic features for detrital zircon through stratigraphy in the Danzhou Group. (**a**) εHf (t) versus age for detrital zircon from the Gongdong Formation. (**b**) Probability density plots of T_{DM}^{C} age of the detrital zircon from the Gongdong Formation. (**c**) εHf (t) versus age for detrital zircon from the Hetong Formation. (**d**) Probability density plots of T_{DM}^{C} age of the detrital zircon from the Hetong Formation. DM—depleted mantle; CHUR—chondritic uniform reservoir.

Almost all Neoproterozoic zircons show negative εHf (t) values of −21.8 to −1.1 except for four spots that have positive values (+3.6, +8.0, +9.5 and +10.3) (Figure 7a), corresponding T_{DM}^{C} ages of 3097–1782 Ma. This means that they possibly derived from ancient crustal material recycling. The Paleoproterozoic zircons mainly show negative εHf (t) values of −17.7 to −2.5 (except one spot of +5.0), and T_{DM}^{C} ages of 3830–2973 Ma, suggesting that they were produced by ancient crustal material recycling. The εHf (t) values of two Archean zircons are −1.7 and +5.8, corresponding T_{DM}^{C} ages of 3223 Ma and 2661 Ma, respectively, which indicated that they were derived from the mixing of Paleoarchean crustal material with Neoarchean juvenile crustal additions.

4.2.2. Hetong Formation

A total of sixty-five zircons from samples XL03-1 were selected for Hf isotopic analysis, covering the whole crystallization age determined by zircon U-Pb geochronology. Their initial $^{176}Hf/^{177}Hf$ ratios range from 0.281073 to 0.2825215, corresponding to εHf (t) values of −22.2 to +9.7 and T_{DM}^{C} ages (Hf model ages) of 3234–1183 Ma (Figure 7c,d).

Among them, the two early Triassic zircons show negative εHf (t) values of −5.7 to −4.4, and the corresponding T_{DM}^{C} ages are 1609 Ma and 1523 Ma, implying that they come from the recycling of Mesoproterozoic crust material. Almost all Neoproterozoic zircons show negative εHf (t) values of −22.2 to −0.6 except for six spots that have positive values of +0.1 to +9.7 and T_{DM}^{C} ages of 3097–1737 Ma (peaks of 2840 Ma and 1554 Ma, Figure 7d), suggesting that they were derived from the recycling of Mesoarchean to Paleoproterozoic crustal material, similar with sample LM01-1. Six Paleoproterozoic zircons show four negative εHf (t) values of −8.7 to −0.2 and two positive values of +0.1 to +3.0, corresponding T_{DM}^{C} ages of 3224–2848 Ma and 2890–2815 Ma. This means that they were produced by the mixing of Neoarchean crustal material with juvenile crustal additions. The Neoarchean zircons show positive εHf (t) values of +3.2 to +6.2 (except one spot of −0.5) and T_{DM}^{C} ages of 2838–2650 Ma, suggesting their origin from the Neoarchean juvenile crust.

5. Discussion

5.1. Constraints on the Depositional Ages

The Danzhou Group consists of, in ascending order, the Baizhu, Hetong and Gongdong formations [23]. The Gongdong Formation is the uppermost formation of the Danzhou Group, and the overlying formation is the Chang'an Formation of the Nanhua system. Due to the limitations of early dating techniques and the lack of precise age constraints, the depositional age of the Gongdong Formation still controversial, which is hinders the interpretation of the tectonic evolution of the JOB. Some researchers suggested that the sedimentation of the Gongdong Formation probably took place at ca. 730 Ma [16,55]. However, Cui et al. [41] suggested that the maximum depositional age of the Gongdong Formation is ca. 780 Ma, constrained by the age of the tuff intercalations. Recently, Kou et al. [56] suggested that the Gongdong Formation was deposited in ca. 706 Ma based on detrital zircons of siltstone. Our new dating results reveal that the youngest five detrital zircons from the Gongdong Formation, give a weighted mean age of 783 ± 13 Ma (MSWD = 0.025), indicating that the MDA is ca. 783 Ma. The Gongdong Formation was deposited after ca. 783 Ma, which is consistent with previous age data by Cui et al. [41].

The Hetong Formation was previously divided into the upper and lower formations [23], and the depositional age of the upper and lower part of the Hetong Formation is 800–780 Ma and 805–800 Ma, respectively [25,28,41]. However, the upper part of the Hetong Formation was newly subdivided into the Sanmenjie Formation, based on the geochronological data of volcanic rocks concentrated in the Sanmenjie Twon, Longsheng area [36]. Previous studies on the Sanmenjie Formation suggest that its deposition age is later than 765 Ma [30,31] and that the Sanmenjie Formation is a part of the Gongdong Formation [41]. The depositional age of the upper part of the Hetong Formation and the structural relations of major lithological units remain controversial. In this study, our new age data for the upper part of the Hetong Formation ranged from 2769 Ma to 731 Ma. The weighted mean age of the youngest five zircons from the upper part of the Hetong Formation is ca. 760 Ma, implying that the MDA is ca. 760 Ma. The upper part of the Hetong Formation belongs to the Sanmenjie Formation.

In conclusion, combined with our new geochronological data and previous data reported, we consider that the depositional age of the Gongdong Formation is ca. 783 Ma. The deposition age of the upper part of the Hetong Formation is ca. 760 Ma, and the upper part of the Hetong Formation belongs to the Sanmenjie Formation.

5.2. Provenance

Detrital zircon can preserve sedimentary rock composition information, and its U-Pb age is an effective method to trace sediment provenance [57]. The U-Pb ages of detrital zircons of the Gongdong Formation are distributed between 2658 and 781 Ma, which are divided into three parts, mainly in Neoproterozoic (>70%, 891–781 Ma, peak at 805 Ma), Paleoproterozoic (27%, 2427–1678 Ma, peak at 2021 Ma), and a small amount of scattered Archaean zircon ages (3%, 2658–2517 Ma) (Figure 6). Detrital zircons of the Hetong Formation scattered in the period of 2769–209 Ma, including 80% Neoproterozoic ages (991–731 Ma, peak at 831 Ma), 9% Paleoproterozoic age (2494–2100 Ma), 8% Neoarchean age (2769–2502 Ma), and two Triassic ages (218 $\pm$ 2 Ma and 209 $\pm$ 2 Ma). Two Triassic ages correspond to late hydrothermal or magmatic intrusions in this area and may be derived from these events. Detrital zircon age distribution and their peaks of the Gongdong and Hetong formations have similar characteristics, which indicates that the sedimentary protoliths of the Gongdong and Hetong formations could come from similar provenance and have similar growth and evolution history.

In addition, most of the zircon grains show magmatic crystallization characteristics, euhedral to subhedral, and poor roundness (Figure 4), indicating that most of them come from near-source magmatic regions. Therefore, taking into account all the data, detrital zircon U-Pb ages of the Gongdong and Hetong formations can be generally divided into three populations: 2769–2502 Ma, 2494–1678 Ma, and 991–731 Ma.

Detrital zircons from 991–731 Ma are the most abundant of all the dated samples, corresponding to two peak ages of 831 Ma and 805 Ma (Figures 6 and 7). Most of these zircons show highly negative εHf (t) values, suggesting that the parent magma is primarily from the recycling of ancient crustal material. Furthermore, the zircon age spectrum of detrital zircons from the Hetong Formation is wider than that of the Gongdong Formation and contains more Neoproterozoic zircons. Combined with the previous studies in the adjacent regions, the Neoproterozoic magmatic rocks were widely exposed at the margin of the Yangtze Block, but relatively scarce in the Cathaysia Block [9,13,17,18,26,55]. Neoproterozoic magmatic events (900–760 Ma) have been widely reported in the Sanfang granitic pluton, Yuanbaoshan granitic pluton, and the mafic–ultramafic intrusion in the southeast margin of the Yangtze Block. For example, S-type granites which dated at ca. 850–820 Ma, and mafic–ultramafic rocks which dated at 820–780 Ma ([6,7,58–61] and references therein). Furthermore, early Neoproterozoic igneous rocks (825–800 Ma) found in the adjacent regions are considered to be related to the breakup of the Rodinia supercontinent [4,25,62–64]. In addition, the Neoproterozoic (870–820 Ma) sedimentary sequence is also widely distributed in the Yangtze Block, while the Cathaysia Block is mostly composed of 900–1300 Ma detrital zircons and is considered to be related to the Greenville orogeny [8,25,65,66]. In summary, considering the proximity of the study area, we infer that the Neoproterozoic detrital zircons may have originated from the southeastern margin of the Yangtze Block, not the Cathaysia Block.

The secondary age group consists of Paleoproterozoic detrital zircons from all dated zircons with an age range of 2494–1678 Ma (peak at 2021 Ma, Figure 6). The majority of Paleoproterozoic detrital zircons show negative εHf (t) values, corresponding to T_{DM}^{C} ages of 3830–2848 Ma (Figure 7), suggesting that they may have been derived from ancient crustal material recycling. Previously, studies have reported Palaeoproterozoic magmatic and metamorphic rocks in the Cathaysia Block ([67,68] and references therein), and 2.1–1.5 Ga is considered to be an important period for the assembly and breakup of the Columbia supercontinent [69–71]. Thus, the age of the Paleoproterozoic detrital zircons in this study suggests that they may have come primarily from the Cathaysia Block and associated with the assembly and breakup of the Columbia supercontinent.

A small number of Archean detrital zircons (2769–2517 Ma, peak at 2541 Ma, Figure 6) have variable Hf isotopes (−1.7 to +6.2), indicating that they were derived from both ancient crustal material recycling and mantle material (Figure 7). The Kongling complex is an Archean basement in the northwest margin of the Yangtze Block, with a main age of 3200–2650 Ma [72,73]. These lines of evidence supported the idea that the Yangtze Block was probably the predominant provenance of the Archean detrital zircons in this study.

5.3. Tectonic Implications

The tectonic evolution of the JOB, which has undergone multiple subduction and collisions, has been controversial for a long time, and the "plume-rifting" [2,16], "slab-arc" [17–19], and "plate-rift" models have been proposed in the past decades [20,21].

Cawood et al. [74] proposed that the cumulative probability curve of the difference between the crystallization age (CA) and the deposition age (DA) of detrital zircon could be used to identify the possible tectonic setting of the basin, which can be divided into three main tectonic settings: convergent, collisional and extensional settings. Convergent plate margins (e.g., a fore-arc or back-arc basin) are typically characterized by intense magmatic activity, so the CA of the youngest 30% detrital zircons, which were deposited in a convergent setting, is close to the DA, and a back-arc basin would have some older detrital detritus input from adjacent craton. As shown in Figure 8, the CA-DA of the youngest 5% of detrital zircons from the Gongdong and Hetong formations is <150 Ma, while the CA-DA of the youngest 30% is <100 Ma, indicating that all samples from the Gongdong and Hetong formations can be deposited in a convergent setting.

Our detrital zircon provenance analyses indicate that the Neoproterozoic detrital zircons (991–731 Ma) were possibly derived from Neoproterozoic igneous rocks in the southeast margin of the Yangtze Block. Previous studies proposed that ca. 860–810 Ma mafic–ultramafic rocks of the Danzhou Group show arc-like geochemical affinities, implying that a continental arc derived from an arc mantle metasomatized and formed in an extensional setting (e.g., [26,37,75,76]). Li et al. [58] considered that bimodal volcanism within the Danzhou Group in the Longsheng area could have occurred in a back-arc extensional setting based on the geochemical signatures. Combined with the previous results and this study, we conclude that the Danzhou Group could be deposited in a back-arc basin, consistent with the episodic magmatism and metamorphism of the Danzhou Group and further supported by the conclusion that volcanic–sedimentary rocks of the JOB were formed in the back-arc basin [3,4,38,77].

The ca. 1000–866 Ma mafic rocks, arc-related volcanic rocks ([63,68] and references therein), ophiolitic gabbro [10] and blueschist [78] were reported in the JOB, indicating that subduction occurred between the Yangtze and Cathaysia Blocks during ca. 1000–860 Ma [5,59]. The early Neoproterozoic (860–810 Ma) mafic–ultramafic and volcanic rocks in the Western JOB show that they are continental arc rocks derived from an arc mantle (e.g., [75,76]), and 770–750 Ma mafic–ultramafic rocks show OIB-like geochemical features, which suggested that they could have originated from magmatism arising in the extension setting (e.g., [75,76]). Although the final formation of the JOB is still controversial, it is generally believed that the assembly of the Yangtze and Cathaysia Blocks occurred after 860 Ma and probably between ca. 820 and 800 Ma (e.g., [7,27,66]).

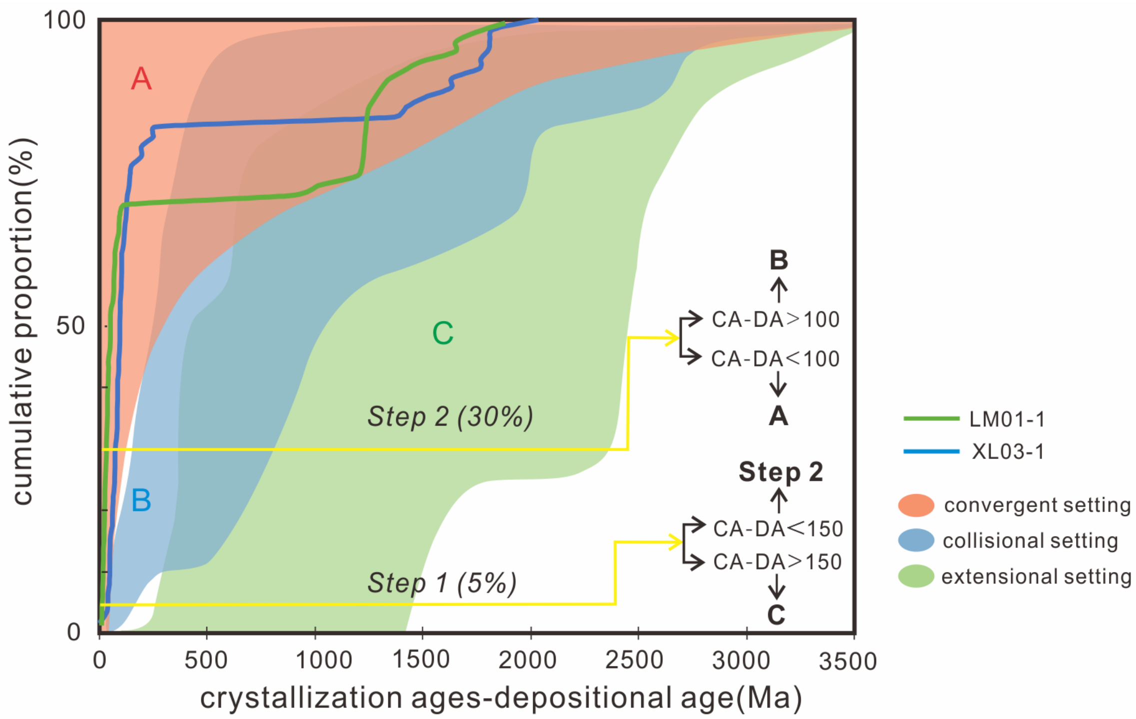

Figure 8. Cumulative probability curves diagram of detrital zircons age from the Gongdong and Hetong formations in the Longsheng area (modified after Cawood et al. [70]). Orange—A: convergent basin, Blue—B: collisional basin, Green—C: extensional basin.

In conclusion, through our new geochronological data, together with previous studies, we propose a preliminary scenario for the tectonic evolution of the JOB. At ca. 1000–860 Ma, the Paleo South China Ocean existed between the Yangtze and Cathaysia Blocks and was subducted beneath the Yangtze Block. The Cathaysia and Yangtze Blocks collided after ca. 860 Ma and finally formed the JOB at ca. 820–800 Ma. After ca. 800 Ma, the JOB entered the stage of intracontinental extension; the Danzhou Group unconformably covered the Sibao Group.

6. Conclusions

The U-Pb geochronology and Hf isotopic analyses of detrital zircons were conducted on the Gongdong and Hetong formations of the Danzhou Group in the Western JOB. Integrating our new data and previous published data in adjacent regions, we can conclude the following results:

1. Detrital zircons from the Gongdong Formation yield U-Pb ages ranging from 2658 to 781 Ma, and the youngest ages redefine the depositional age of ca. 783 Ma. Detrital zircons from the Hetong Formation show an age population of 2769–731 Ma and deposited at ca. 760 Ma. The upper part of the Hetong Formation belongs to the Sanmenjie Formation.
2. The detrital zircon age spectra of the Gongdong and Hetong Formation indicate that Neoproterozoic igneous rocks in the Southeastern Yangtze Block were the main source rocks and a small amount of Archean–Paleoproterozoic detritus-derived from the Yangtze and Cathaysia Blocks.

3. The Gongdong and Hetong formations were deposited in a convergent setting and possibly a back-arc basin.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/min15010070/s1, Table S1: LA-ICP-MS zircons U-Pb data of meta-sedimentary rocks from Danzhou Group in the Longsheng area; Table S2: Zircon Hf isotopic data of meta-sedimentary rocks from Danzhou Group in the Longsheng area.

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