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Widespread Neoarchean (~2.7–2.6 Ga) magmatism of the Yangtze craton, South China, as revealed by modern river detrital zircons

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ABSTRACT

The Kongling Terrane, which is the Archean nucleus of the Yangtze craton, preserves Paleoarchean-Proterozoic rocks as old as 3.45 Ga. However, the dominant stage of formation of this Archean terrane remains unclear. In this paper, U-Pb and Lu-Hf isotopes of detrital zircons from two rivers and one stream in the northern part of the Kongling Terrane were studied by LA-ICP-MS and LA-MC-ICP-MS, respectively. These zircons show complicated internal structures in cathodoluminescence images, but the majority of them have linear or oscillatory zoning patterns, indicating magmatic origins. In general, the detrital zircons from these three local rivers show similar U-Pb age distributions. Together, they yield age peaks at 3.3–3.1 Ga (5%), 3.0–2.8 Ga (18%), 2.7–2.6 Ga (30%), 2.6–2.2 Ga (15%), 2.0–1.9 Ga (27%), 1.9–1.7 Ga (1%), 1.7–1.5 Ga (2%), and 1.0–0.8 Ga (1%). This age distribution implies that the North Kongling Terrane formed primarily during the Meso- to Neoarchean (3.0–2.6 Ga). Lu-Hf isotopic data reveal predominant subchondritic to chondritic $\varepsilon_{Hf}(t)$ values (−11.3 to 0) for the Mesoarchean zircons, indicating the dominant role of crustal reworking during this period. In comparison, most Neoarchean zircons exhibit near chondritic to suprachondritic $\varepsilon_{Hf}(t)$ values (up to +7.4), suggesting juvenile crustal additions. The 2.0–1.9 Ga zircons have similar initial Hf isotopic compositions as those of the 2.7–2.6 Ga zircons, suggesting a metamorphic recrystallization origin. This observation further implies that the proportion of Neoarchean ages might be underestimated. Previous studies have reported several 2.7–2.6 Ga Archean outcrops, minor detrital zircons in Precambrian sedimentary rocks and xenocrystal zircons in volcanic rocks from the Yangtze craton. Combined with our data, we propose that the 2.7–2.6 Ga magmatism may have played an important role in forming the Kongling Terrane and have widely affected other parts of the Yangtze craton as well, similar to many other Archean cratons worldwide. The ~2.7–2.6 Ga may correspond to the initial stabilization of the Archean nucleus of the Yangtze craton. Thereafter, this craton shows comparable 2.5–2.2 Ga age records to the recently proposed Nunavutia supercraton, which could provide further clues to the early tectonic process of the Yangtze craton.

1. Introduction

The Neoarchean is one of the most important periods for studying the formation of the Earth's crust. Significant changes have been documented to approximately 2.7–2.6 Ga, including the possible initiation of subduction-collision plate tectonics on a global scale, the formation of voluminous continental crust, and the cratonization of many Archean cratons (e.g., Bradley, 2011; Eriksson et al., 2013; Laurent et al., 2014). Thus far, the corresponding records of the 2.7–2.6 Ga magmatism and metamorphism have been widely documented in many Archean cratons, e.g., the Superior craton in North America (Polat and Münker, 2004; Davis et al., 2005; Ketchum et al., 2008; Bedard and Harris, 2014), the Yilgarn craton in Australia (Ivanic et al., 2012; Wyche et al., 2012), the Dharwar craton in South Asia (Sunder Raju et al., 2013; Glorie et al., 2014; Khanna et al., 2014), and the North China and Tarim cratons in East Asia (Zhai and Santosh, 2011; Yang et al., 2013; Zong et al., 2013; Ge et al., 2014; Wan et al., 2014).

The Yangtze craton is one of the largest ancient cratons in eastern Asia. Recent studies on granitoid gneisses revealed the existence of Paleoarchean rocks as old as 3.4–3.3 Ga from the Kongling Terrane, which is the Archean nucleus located in the northern part of the Yangtze craton (Gao and Zhang, 1990; Jiao et al., 2009; Gao et al., 2011; Guo et al., 2014). However, the early evolutionary history of this craton is still poorly understood, due to the heavy vegetation and uncommon Archean outcrops. Detrital zircons from fine-grained sediments could retain their primary isotopic information during subsequent transportation and sedimentation. Thus, U-Pb and Lu-Hf isotopes of detrital zircons have been widely used in provenance studies and evaluation of regional tectono-thermal events, as well as to determine the crustal

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growth and reworking history (e.g., Hawkesworth and Kemp, 2006; Zhang et al., 2006c; Sun et al., 2008; Yang et al., 2009; Condie and Aster, 2010; Hawkesworth et al., 2010; Iizuka et al., 2010; Condie et al., 2011; Lancaster et al., 2011; Cawood et al., 2013; He et al., 2013).

In this study, we conducted 323 U-Pb and 190 Lu-Hf isotope analyses on detrital zircons from three modern rivers (Gongjia River, Wudu River, and Bianyuchi Stream) crossing the northern part of the Kongling Terrane. The new dataset suggests that the 2.7–2.6 Ga granitoid magmatism dominates the northern part of the Kongling Terrane. Together with previous studies of Neoarchean zircons and rocks in the Yangtze craton, the ~2.7–2.6 Ga magmatism appears to have widely affected the Yangtze craton.

2. Geological background and sample descriptions

The Yangtze craton is separated from the North China craton by the Qinling-Dabie-Sulu orogen to the north and from the Cathaysia block by the Jiangnan orogen to the southeast. It is also connected to the Tibetan Plateau in the west (Fig. 1A). The Yangtze craton is mainly covered by Proterozoic rocks with only sporadic outcrops of Archean rocks, such as the Kongling Terrane, Huangtuling granulite, Yudongzi group, Houhe complex, and Douling complex in the northern part of the Yangtze craton (Gao and Zhang, 1990; Qiu et al., 2000; Zhang et al., 2001, 2006a, 2006b; Sun et al., 2008; Wu et al., 2008; Jiao et al., 2009; Gao et al., 2011; Wu et al., 2012; Chen et al., 2013a; Guo et al., 2014; Wu et al., 2014). Moreover, minor Archean xenocrystal zircons in volcanic rocks and detrital zircons from sediments were found throughout the Yangtze craton, which may also imply a broad spatial extent of Archean rocks (Zheng et al., 2006; Zhao and Cawood, 2012; Zhang and Zheng, 2013).

The Kongling Terrane is the only well-documented Archean basement of the Yangtze craton. According to the lithology and geochronology, it can be divided into two segments: the South and North Kongling Terranes (Fig. 1B) (Qiu et al., 2000; Gao et al., 2011; Zhao and Cawood, 2012). The South Kongling Terrane is dominated by the Neoproterozoic Huangling batholith (Zhang et al., 2009a). In striking contrast, the North Kongling Terrane comprises Archean-Paleoproterozoic granitoid gneisses and metasedimentary rocks (metapelites, metasandstones and marbles), with minor amphibolites and mafic granulites that occur as lenses or boudin layers in the gneisses (Gao and Zhang, 1990; Gao et al., 1999). Previous studies revealed that the granitoid gneisses are primarily 3.3–2.9 Ga tonalite-trondhjemite-granodiorite (TTG) and 2.8–2.0 Ga granites. Both the TTG and granites were pervasively overprinted by a 2.0 Ga high-grade metamorphic event and intruded by the 1.85 Ga Quanyishang A-type granite (Fig. 1C) (Guo et al., 2015). The 2.0 Ga geological process resulted in (1) widespread amphibolite to high-pressure granulite facies metamorphism in the pre-existing granitoid and metasedimentary rocks (Zhang et al., 2006a, 2006c; Wu et al., 2009; Gao et al., 2011; Yin et al., 2013; Chen et al., 2013a; Guo et al., 2014) and (2) crustal anatexis that produced voluminous S-type granites (Yin et al., 2013; Li et al., 2014).

In this study, sand samples from three local rivers (Gongjia River, Wudu River, and Bianyuchi Stream) in the North Kongling Terrane were collected (Fig. 1C). In general, the watersheds of the Gongjia and

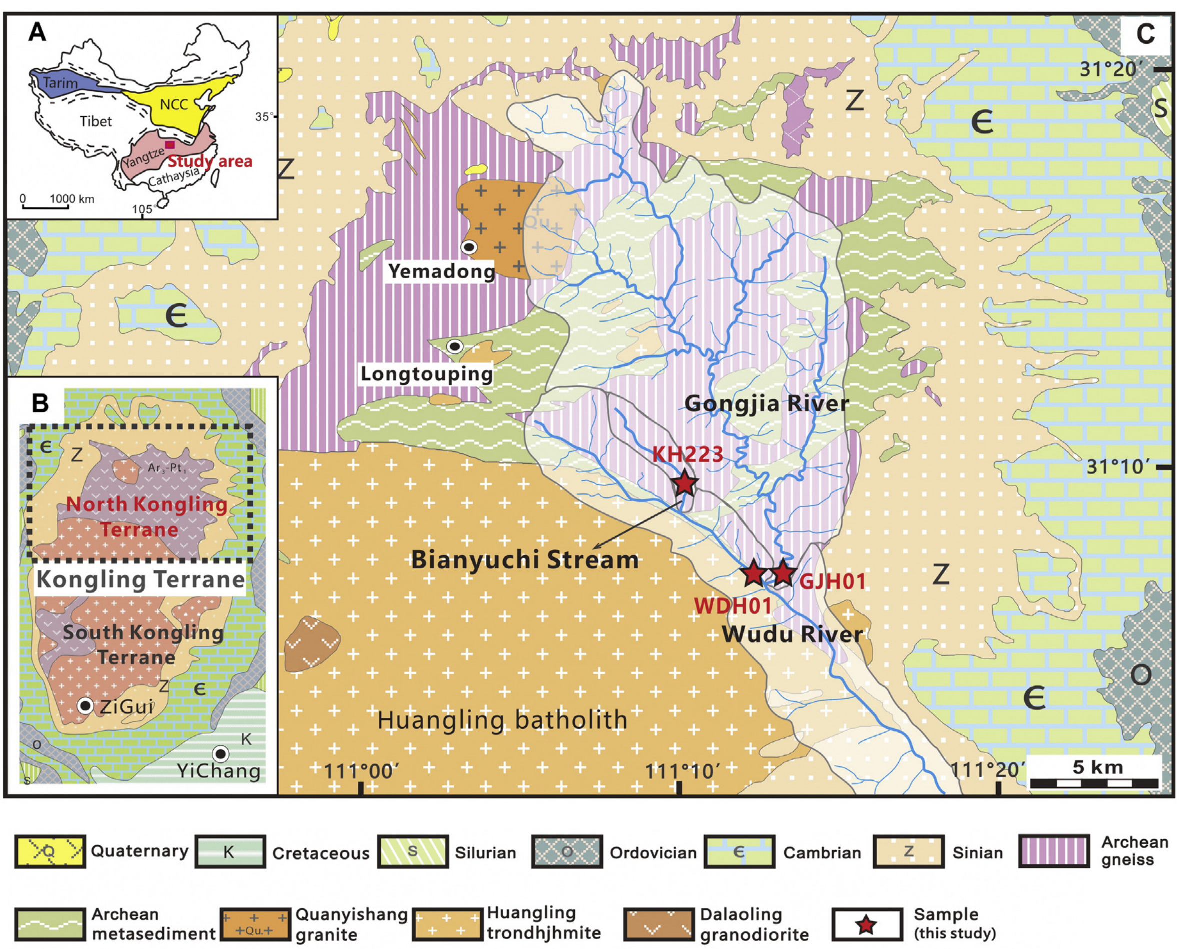

Fig. 1. (A) Simplified tectonic map of China, where the North China craton is abbreviated to 'NCC'. (B) Structure and division of the Kongling Terrane, modified from Liu et al. (2008). (C) Geological map of the North Kongling Terrane and the drainage areas (in gray) of the Gongjia River, Wudu River and the Bianyuchi Stream. The red stars represent the sample locations in this study.

Wudu Rivers and the Bianyuchi Stream are confined to the Archean-Paleoproterozoic North Kongling Terrane. The Wudu River (~50 km long and 10 m wide) is the largest river in the Kongling Terrane. It mainly flows along the Wudu fault. The Gongjia River is approximately 35 km long and 8–15 m wide, flowing across most of the North Kongling Terrane. The Bianyuchi Stream is only 3–8 m in width and flows a short distance of approximately 6 km across the southern part of the North Kongling Terrane. Both the Gongjia River and Bianyuchi Stream join together in the middle reach of the Wudu River (Fig. 1C). Samples GJH01 (31°06′35.5″N, 111°12′53.3″E) and KH223 (31°08′48.4″N, 111°10′15.1″E) were collected from the riverbanks of the Gongjia River and Bianyuchi Stream, respectively, before their intersections with the Wudu River. Sample WDH01 (31°06′34.6″N, 111°12′20.0″E) was collected from the midstream section of the Wudu River upstream of the confluence with the Gongjia River.

3. Analytical techniques

More than 10 mg zircons were separated for each sample by conventional magnetic and heavy-liquid methods. At least 300 grains were selected under a binocular microscope, according to their color and morphology. Then, they were mounted in epoxy resin and polished to expose their centers. Cathodoluminescence (CL) images and optical photomicrographs under both transmitted and reflected lights were documented to reveal the internal structures of zircons and to select spot locations for in-situ U-Pb and Lu-Hf analyses. The CL images were taken by a FEI Quanta 450 high resolution field emission gun (FEG) scanning electron microscope (SEM) coupled with Gatan Mono CL4+ system at the State Key Laboratory of Geological Process and Mineral Resources, China University of Geosciences, Wuhan.

3.1. Zircon U-Pb dating

Zircon U-Pb dating was conducted using a GeoLas2005 laser ablation system (Lambda Physik, Germany) coupled with an Agilent 7500a ICP-MS (Agilent, Japan) at the State Key Laboratory of Geological Process and Mineral Resources, China University of Geosciences, Wuhan. The laser beam was set to 32 μm in diameter with a frequency of 6 Hz, and helium was used as a carrier gas within the ablation cell. The energy density was about 4 J/cm^2. Zircon 91500 was used as an external standard to correct isotopic fractionation. U, Th, and Pb concentrations were calibrated against the NIST SRM 610 and using ^{29}Si as an internal standard. The raw data were processed using Excel-based software ICPMSDataCal (ver. 9.0) (Liu et al., 2010). Common Pb correction followed the method of Andersen (2002), but was negligible for most of the zircons in this study. All of the concordia diagrams and weighted averages were produced using the Isoplot software (ver. 3.76) (Ludwig, 2012). The measurements of zircon GJ-1 as an unknown yielded a weighted average ^{206}Pb/^{238}U age of 601.6 ± 7.3 Ma (1 SD, n = 83), consistent with its reference ^{206}Pb/^{238}U age of 599.8 ± 1.7 Ma (2σ) within analytical uncertainty (Jackson et al., 2004). Zircons with age concordance between 95% and 105% are defined as concordant zircons. Finally, ^{207}Pb/^{206}Pb and ^{206}Pb/^{238}U ages were adopted for zircons with ^{206}Pb/^{238}U ages > 1000 Ma and < 1000 Ma, respectively.

3.2. Hf isotopic analysis of zircon

Hafnium isotope analyses were performed on a Neptune Plus MC-ICP-MS (Thermo Fisher Scientific, Germany) coupled with a GeoLas 2005 laser ablation system (Lambda Physik, Germany) at the State Key Laboratory of Geological Process and Mineral Resources, China

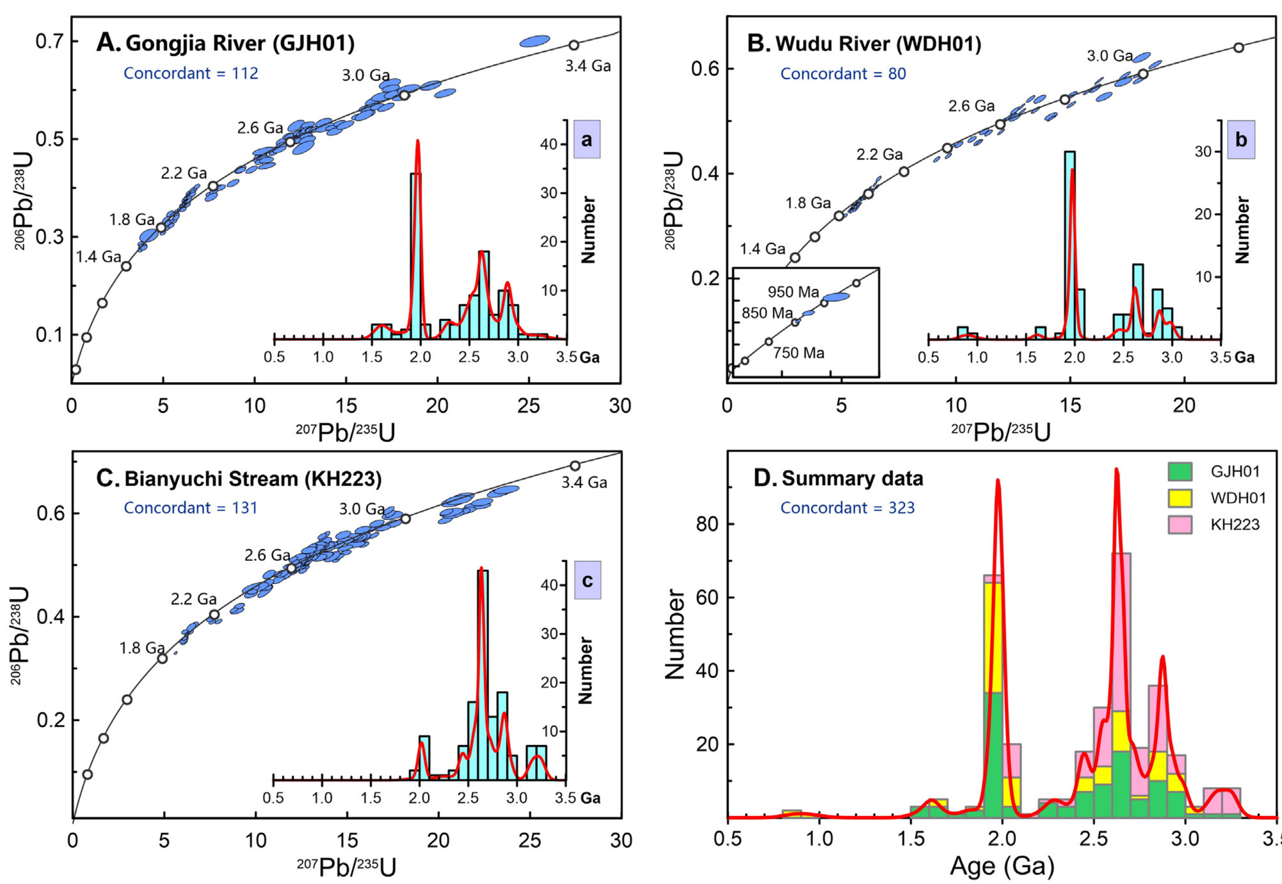

Fig. 2. U-Pb concordia plots of the concordant detrital zircons (solid ellipses) from samples (A) GJH01, (B) WDH01, and (C) KH223. Data-point error ellipses are 1σ. The U-Pb age distribution histograms of the concordant zircons are shown in the inset figures (a–c). The U-Pb results of this study are summarized in panel D. A bandwidth of 18 Ma was used for the probability density plot following the Kernel Density Estimation method of Vermeesch (2012).

University of Geosciences, Wuhan. The laser beam was set at 44 μm in diameter with a frequency of 8 Hz and an energy density of ~4 J/cm^2. The analyzed spots for the Lu-Hf isotopes were overlapping or as close as possible to the spots used in U-Pb dating. The analyzed isotopes included ^{171}Yb, ^{173}Yb, ^{174}(Hf, Yb), ^{175}Lu, ^{176}(Hf, Yb, Lu), ^{177}Hf, ^{179}Hf, ^{180}(Hf, W) and ^{182}W. The interference of ^{176}Yb on ^{176}Hf was corrected by measuring the interference-free ^{173}Yb isotope and using the recommended ^{176}Yb/^{173}Yb ratio of 0.78696 (Thirlwall and Anczkiewicz, 2004). Similarly, the relatively minor interference of ^{176}Lu on ^{176}Hf was corrected by measuring the interference-free ^{175}Lu isotope and using the recommended ^{176}Lu/^{175}Hf ratio of 0.02656 (Blichert-Toft and Albarède, 1997). Time-drift correction and external calibration were performed using the zircon standard 91500. More details on the technique were reported in Hu et al. (2012). Data reduction was performed using ICPMSDataCal (ver. 9.0) (Liu et al., 2010). The measured average ^{176}Hf/^{177}Hf values for zircons GJ-1 and Temora-2, as unknowns, were 0.282016 ± 0.000014 (1 SD, n = 13) and 0.282685 ± 0.000019 (1 SD, n = 30), consistent with their reference values of 0.282015 ± 0.000019 (2σ) (Elhlou et al., 2006) and 0.282686 ± 0.000008 (2σ) (Woodhead and Hergt, 2005), respectively.

The initial ^{176}Hf/^{177}Hf ratios of zircons were calculated with reference to the chondritic uniform reservoir (CHUR) at the time of zircon crystallization. The decay constant was 1.865×10^{-11} yr^{-1} for ^{176}Lu (Scherer et al., 2001). A present-day ^{176}Hf/^{177}Hf ratio of 0.282772 and a ^{176}Lu/^{177}Hf ratio of 0.0332 were used for the CHUR (Blichert-Toft and Albarède, 1997) to calculate the $\varepsilon_{Hf}(t)$ value. The single-stage model age (T_{DM1}) was calculated using the present-day ^{176}Hf/^{177}Hf ratio of 0.28325 and ^{176}Lu/^{177}Hf ratio of 0.0384 for the depleted mantle (Griffin et al., 2000), while the two-stage model age (T_{DM2}) was based on a ^{176}Lu/^{177}Hf ratio of 0.0093 for the upper continental crust (Vervoort and Jonathan Patchett, 1996).

4. Results

4.1. Zircon U-Pb geochronology

In this study, there were 112 concordant ages out of 158 (71% in proportion), 80 out of 125 (64%), and 131 out of 183 (72%) detrital zircons from samples GJH01, WDH01, and KH223, respectively (Fig. 2A–C, Supplementary Table S1). The majority of the zircons display oscillatory zoning (Fig. 3) and high Th/U ratios (>0.3) (Fig. 4), typical for magmatic zircons (Corfu et al., 2003; Wu and Zheng, 2004). However, the 2.0–1.9 Ga zircons have variable Th/U ratios (Fig. 4) and diverse zoning patterns, e.g., oscillatory zoning (Fig. 3-7), sector zoning (Fig. 3-8), or structureless (Fig. 3-17), indicating diverse origins (magmatic and metamorphic).

4.1.1. Gongjia River (GJH01)

Most zircon grains are subhedral or rounded, with lengths less than 100 μm. The ^{207}Pb/^{206}Pb ages of the concordant zircons range from 3250 Ma to 1533 Ma. The age distribution has four major peaks at 3.0–2.8 Ga (15% in proportion), 2.7–2.6 Ga (23%), 2.6–2.2 Ga (18%), and 2.0–1.9 Ga (33%), with minor peaks at 3.3–3.1 Ga (3%), 1.9–1.7 Ga (3%), and 1.7–1.5 Ga (5%) (Fig. 2A and a). Among these major age groups, the ages of the 2.6–2.2 Ga zircons are relatively scattered. The other three groups yield weighted average ages of 2911 ± 11 Ma

Fig. 3. Representative cathodoluminescence images of the concordant detrital zircons with U-Pb ages and $\varepsilon_{Hf}(t)$ values. Small dashed and large solid circles denote the ablated spots (32 and 44 μm in diameter) for the U-Pb and Lu-Hf isotope analyses, respectively. Age errors are given at 1σ level.

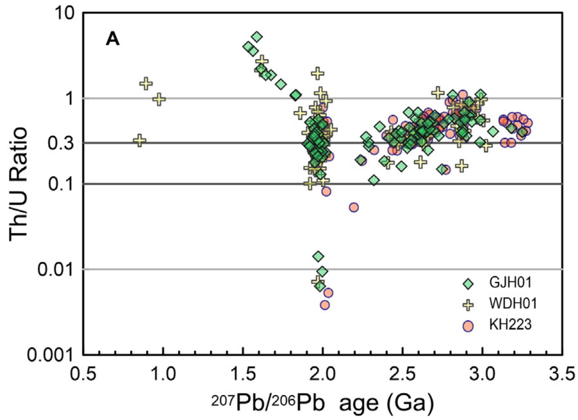

Fig. 4. Plots of the U-Pb ages versus the Th/U ratios for the concordant detrital zircons in this study.

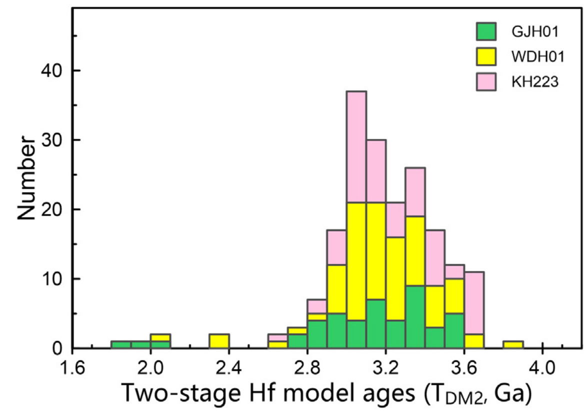

Fig. 6. Histograms of two-stage Hf model ages (i.e., crustal formation age) for the concordant detrital zircons in this study.

(2σ, MSWD = 6.8, n = 18), 2652 ± 10 Ma (2σ, MSWD = 4.0, n = 26), and 1969 ± 8 Ma (2σ, MSWD = 1.0, n = 37), respectively.

4.1.2. Wudu River (WDH01)

Most zircons in this sample are rounded, with only a few euhedral grains present. The oldest concordant zircon age is 3023 ± 21 Ma, while the youngest is 852 ± 6 Ma. All of the concordant ages yield three major age groups at 3.0–2.9 Ga (19%), 2.7–2.6 Ga (20%), and 2.0–1.9 Ga (48%), as well as a few minor age peaks at 2.5–2.4 Ga (6%), ~1.85 Ga (1%), ~1.60 Ga (3%), and 1.0–0.8 Ga (4%) (Fig. 2B and b). The three major age peaks yield weighted average ages of 2903 ± 4 Ma (2σ, MSWD = 61, n = 15), 2637 ± 3.9 Ma (2σ, MSWD = 20, n = 16), and 1976 ± 3 Ma (2σ, MSWD = 10, n = 38), respectively.

4.1.3. Bianyuchi Stream (KH223)

Most zircons are euhedral with lengths between approximately 80 and 150 μm. Their $^{207}Pb/^{206}Pb$ ages range from 3285 to 1929 Ma, exhibiting two major age peaks at 3.0–2.8 Ga (19%) and 2.7–2.5 Ga (52%), as well as three minor peaks at 3.3–3.1 Ga (11%), 2.5–2.2 (10%), and 2.0–1.9 Ga (8%) (Fig. 2C and c). The two major peaks yield weighted average ages of 2878 ± 7 Ma (2σ, MSWD = 4.8, n = 25) and 2639 ± 5 Ma (2σ, MSWD = 5.9, n = 6.8).

In summary, the detrital zircon grains from these three samples have similar age spectra (Fig. 2). Taken together, the age distribution can be defined by three major age peaks at 3.0–2.8 Ga (18%), 2.7–2.6 Ga (30%), and 2.0–1.9 Ga (27%), with a few minor peaks at 3.3–3.1 Ga (5%), 2.6–2.2 Ga (15%), 1.9–1.7 Ga (1%), 1.7–1.5 Ga (2%), and 1.0–0.8 Ga (1%) (Fig. 2D). However, it noteworthy that, as confined by the drainage areas of the studied rivers (Fig. 1C), the exact proportions of exposed rocks with different age records in the Kongling Terrane, need to be rechecked or updated until more related data is acquired in future.

4.2. Zircon Lu-Hf isotopic compositions

Hafnium isotope analyses were conducted on 46, 80, and 64 concordant zircons from samples GJH01, WDH01, and KH223 (Fig. 5A, Supplementary Table S2), respectively. As shown in Fig. 5B, the 3.3–3.1 Ga, 3.0–2.8 Ga, and 2.7–1.9 Ga zircons exhibit distinctly different Hf isotopic compositions. Their $^{176}Hf/^{177}Hf(t)$ ratios increase from 0.28061–0.28075, through 0.28075–0.28100, to 0.28095–0.28135

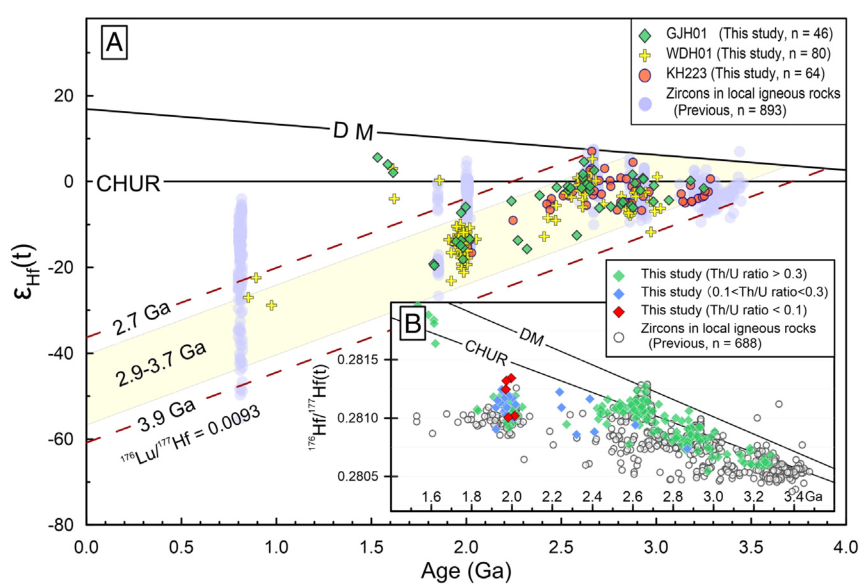

Fig. 5. (A) U-Pb ages versus $\varepsilon_{Hf}(t)$ values for the concordant zircons of modern river sand samples from this study (the green diamonds represent sample GJH01, yellow crosses represent WDH01, and orange circles represent KH223), and a few local magmatic rocks in the Kongling Terrane (pale purple circles) from Chen et al. (2013a), Gao et al. (2011), Guo et al. (2014), Jiao et al. (2009), Peng et al. (2009, 2012), Wei and Wang (2012), Wu et al. (2009), Xiong et al. (2009), Yin et al. (2013), Zhang et al. (2006a, 2009a, b) and Zheng et al. (2006). (B) U-Pb ages versus $^{176}Hf/^{177}Hf(t)$ ratios of the concordant detrital zircons from this study (filled squares) and magmatic zircons reported in previous studies (open symbols, Zheng et al., 2006; Gao et al., 2011; Wei and Wang, 2012; Chen et al., 2013a; Guo et al., 2014). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

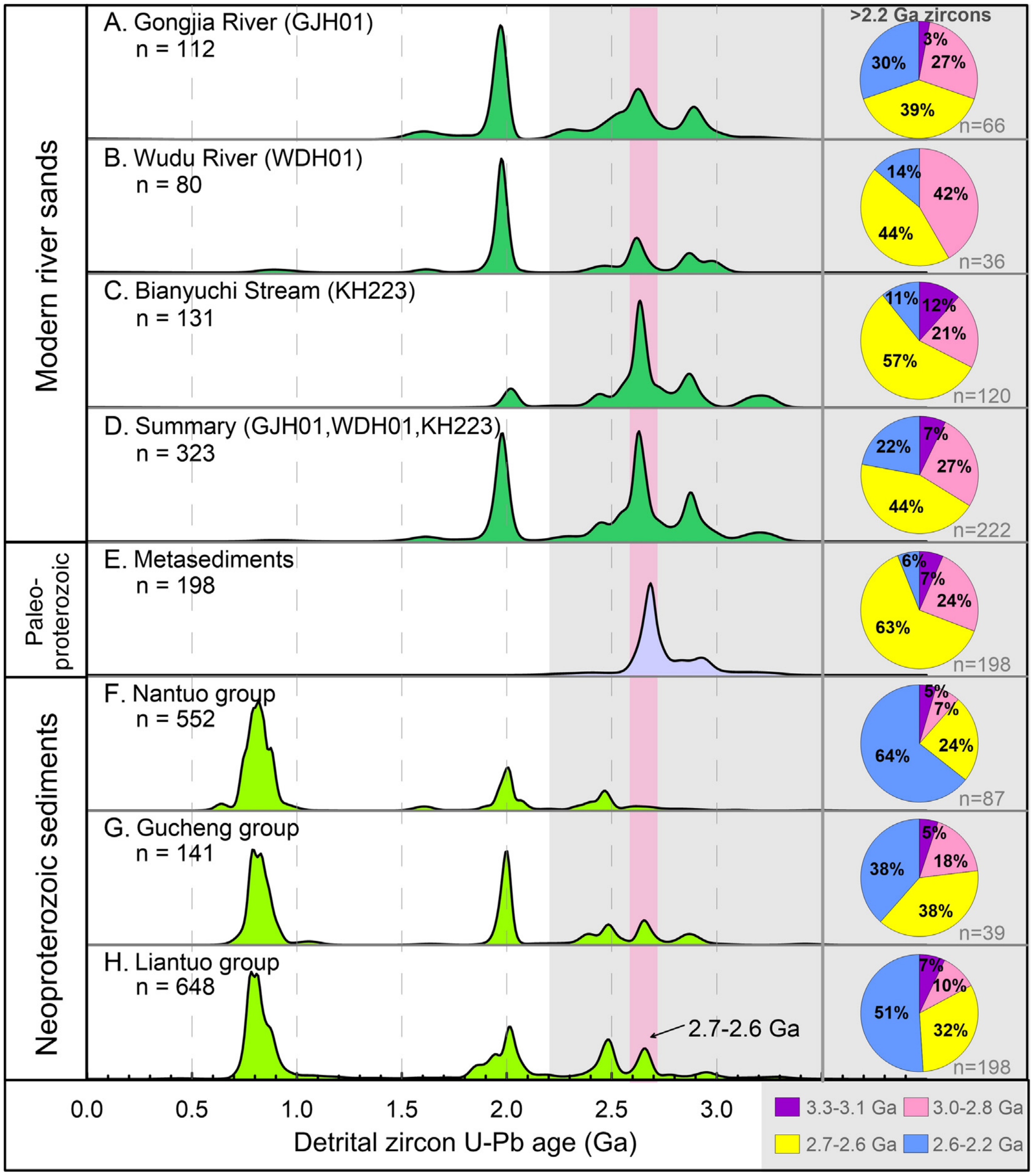

Fig. 7. Probability density plots of the concordant U-Pb ages of detrital zircons from the Kongling Terrane. (A–D) Detrital zircons from the modern river sands (this study); (E) Archean-Paleoproterozoic metasedimentary rocks (Qiu et al., 2000; Gao et al., 2011; Li et al., 2016); (F–H) Neoproterozoic sedimentary rocks from the periphery of the Kongling Terrane (Zhang et al., 2006c; Liu et al., 2008; Wang et al., 2013a; Cui et al., 2014). A bandwidth of 18 Ma was used for the probability density plot following the Kernel Density Estimation method of Vermeesch (2012). The inset pie charts show the relative proportions of 3.3–3.1 Ga, 3.0–2.8 Ga, 2.7–2.6 Ga, and 2.5–2.2 Ga zircons in all >2.2 Ga zircons, which illustrate the high proportions of 2.7–2.6 Ga age group.

for the 3.3–3.1 Ga, 3.0–2.8 Ga, and 2.7–1.9 Ga zircons, respectively (Fig. 5B). Interesting, the 2.0–1.9 Ga zircons have nearly identical $^{176}Hf/^{177}Hf(t)$ ratios to the 2.7–2.6 Ga zircons (Fig. 5B).

Among the Archean zircons, the 3.3–2.8 Ga grains have mostly subchondritic to chondritic $\varepsilon_{Hf}(t)$ values (−11.3 to 0). In contrast, the majority of the 2.7–2.6 Ga zircons have suprachondritic $\varepsilon_{Hf}(t)$ values (up to +7.4). Both the 2.6–2.2 Ga and 2.0–1.9 Ga zircons have subchondritic $\varepsilon_{Hf}(t)$ values (−15.3 to −0.8 and −22.8 to −5.5, respectively). Three 1.9–1.7 Ga zircons yield one chondritic value (+0.7) and two subchondritic $\varepsilon_{Hf}(t)$ values (−19.2 and −18.8). The 1.7–1.5 Ga zircon grains mainly have suprachondritic $\varepsilon_{Hf}(t)$ values, ranging from +2.4 to +6.0. The three 1.0–0.8 Ga zircon grains have extremely subchondritic $\varepsilon_{Hf}(t)$ values, from −28.4 to −22.0.

Fig. 6 shows the distributions of the two-stage Hf model ages for the concordant detrital zircons in this study. The crustal model ages show a prominent group at 3.7–2.6 Ga, with two peaks at 3.5–3.3 Ga and 3.2–3.0 Ga, for all three rivers. Uncommon T_{DM2} values also occur at ~3.8 Ga, ~2.4 Ga, and ~2.0 Ga for the Gongjia and Wudu Rivers.

5. Discussion

5.1. Provenance of detrital zircons in modern river sands from the Kongling Terrane

The detrital zircons in the river sand samples from the Gongjia and Wudu Rivers and the Bianyuchi Stream in the North Kongling Terrane show similar age spectra, namely, 3.3–3.1 Ga, 3.0–2.8 Ga, 2.7–2.6 Ga, 2.6–2.2 Ga, 2.0–1.9 Ga, 1.9–1.7 Ga, 1.7–1.5 Ga, and 1.0–0.8 Ga, as described above. These age groups are roughly consistent with local granitoid records. Therefore, we combine the results of all samples to explore the potential sources for each age group and their geological significance.

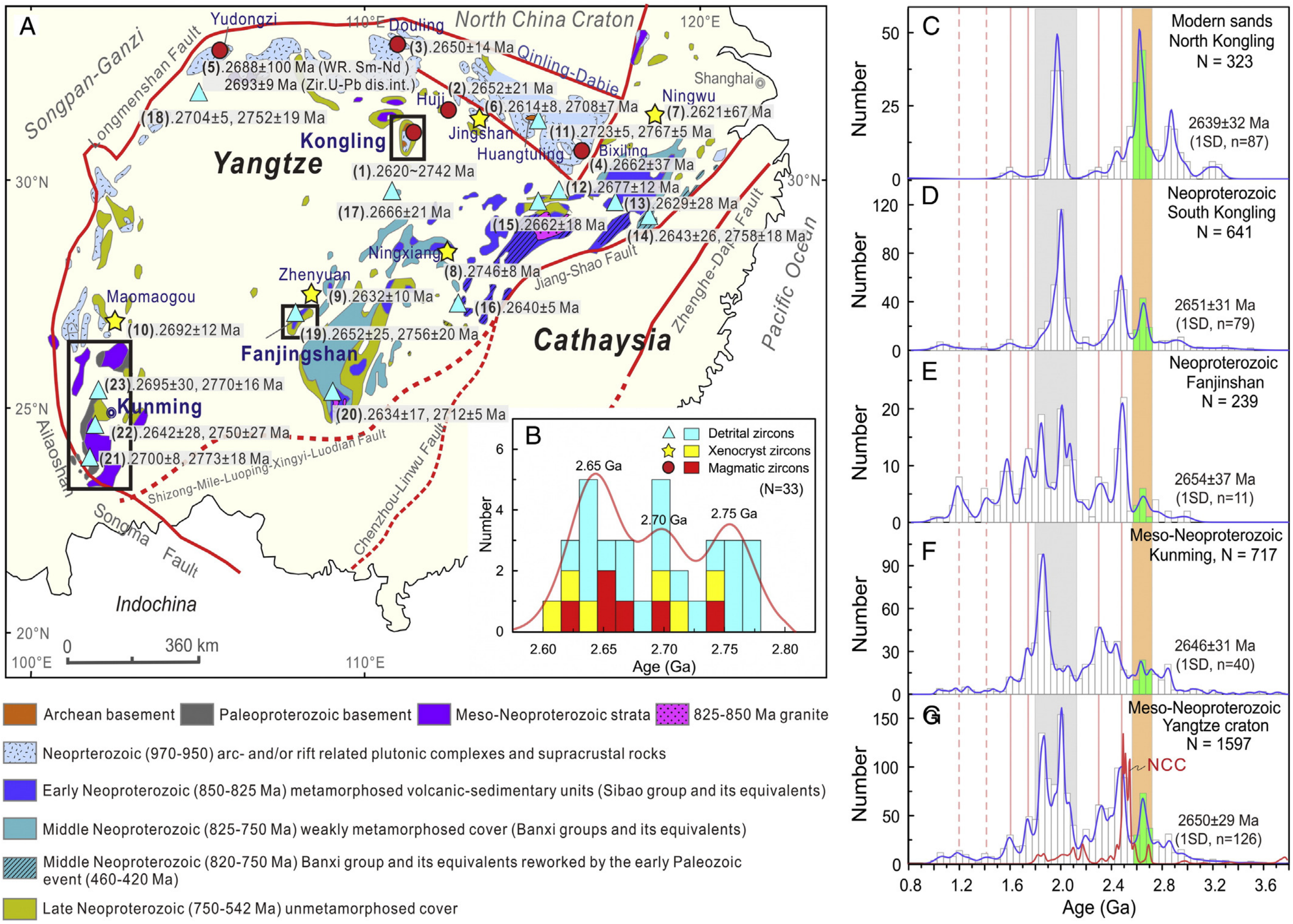

Fig. 8. (A) Distribution of the Archean-Proterozoic rocks in the Yangtze craton (modified from Zhao and Cawood (2012)). The locations of ~2.7–2.6 Ga rocks (circles), and ~2.7–2.6 Ga xenocrystal (stars) and detrital (triangles) zircons in the Yangtze craton from previous studies. The following numbers denote the localities: (1) Kongling (Gao et al., 1999; Chen et al., 2013a; Guo et al., 2014, 2015); (2) Huji (Hu et al., 2013; Zhou et al., 2015); (3) Douling (Zhang et al., 2004); (4) Bixiling (Cao and Zhu, 1995); (5) Yudongzi, the 2688 ± 100 Ma is a whole rock Sm-Nd isochron age and the 2693 ± 9 Ma is an upper intercept U-Pb age of few discordant zircons (Zhang et al., 2001); (6) Jingshan (Zheng et al., 2006); (7) Ningwu (Zhang et al., 2003); (8) Ningxiang (Zheng et al., 2006); (9) Zhenyuan (Zheng et al., 2006); (10) Maomaogou (Liu et al., 2004); (11) Huangtuling (Sun et al., 2008; Wu et al., 2002, 2008); (12) Huangshi basin (Yang et al., 2010); (13) Jingdezhen (Wang et al., 2008); (14) Jiangshan and Chun'an domains (Yao et al., 2012); (15) Wuning (Zhao et al., 2011); (16) Hengyang (Zhao et al., 2011); (17) Yangjiaping (Wang et al., 2012b); (18) Guixi (Duan et al., 2011); (19) Fanjingshan (Wang et al., 2010); (20) Sibao group (Wang et al., 2007, 2011, Wang et al., 2012c); (21) Dahongshan (Greentree and Li, 2008); (22) Kunming (Wang et al., 2012a); (23) Dongchuan (Zhao et al., 2010). Age errors are given at 1 SD level. (B) Cumulative histograms of the ~2.7–2.6 Ga age records for the magmatic, xenocrystal, and detrital zircons from the Yangtze craton (in panel A). (C) The U-Pb age distribution for >1.0 Ga concordant detrital zircons in modern river sands from the North Kongling Terrane in this study. (D–G) The U-Pb age distributions for >1.0 Ga concordant detrital zircons in Meso- and/or Neoproterozoic sedimentary rocks from the South Kongling Terrane (Zhang et al., 2006c; Liu et al., 2008; Wang et al., 2013a; Cui et al., 2014), Fanjingshan (Wang et al., 2010, 2014), Kunming (Greentree et al., 2006; Greentree and Li, 2008; Zhao et al., 2010; Wang et al., 2012a; Wang and Zhou, 2014) areas, and the summary for the whole Yangtze craton, respectively. The filled orange bars denote the ~2.7–2.6 Ga age groups. The red line represents the compiled crystallization ages of granitoid rocks in the North China craton (NCC), and these data were sourced from Condie et al. (2009a, b). The bandwidths of 12 and 18 Ma were used for the probability density plot of panel B and panels C–G, respectively, following the Kernel Density Estimation method of Vermeesch (2012).

5.1.1. 3.3–3.1 Ga

The 3.3–3.1 Ga zircons range from 3285 to 3066 Ma. Their $\varepsilon_{Hf}(t)$ values vary from −4.7 to +1.0. They have T_{DM2} ages of 3.7 to 3.4 Ga, which have a weighted age of 3614 ± 15 Ma (2σ, MSWD = 7.0, n = 14), suggesting reworking from pre-existing crust. These characteristics are consistent with the local 3.4–3.2 Ga TTG-granitic rocks from the North Kongling Terrane (Jiao et al., 2009; Gao et al., 2011; Guo et al., 2014). Specifically, the 3.3–3.1 Ga zircons are mainly from sample KH223. This sample was collected from the riverbank of the Bianyuchi Stream, where 3.4–3.2 Ga outcropped (Gao et al., 2011; Guo et al., 2014). Thus, the different amounts of the 3.3–3.1 Ga zircons in the three samples may result from the sporadic outcrops of Paleoarchean rocks in the North Kongling Terrane.

5.1.2. 3.0–2.8 Ga

The 3.0–2.8 Ga zircons have an age spectrum ranging from 3023 to 2788 Ma. They have $\varepsilon_{Hf}(t)$ values varying from −11.3 to +4.8, indicating diverse magma sources. At present, 3.0–2.8 Ga trondhjemitic and granitic gneisses have been widely reported from both the South and North Kongling Terranes (Qiu et al., 2000; Zheng et al., 2006; Zhang et al., 2006a; Gao et al., 2011; Chen et al., 2013a), which could be the source rocks for the 3.0–2.8 Ga detrital zircons. In this study, the similar proportions of the 3.0–2.8 Ga zircons in samples GJH01 (15%), WDH01 (19%), and KH223 (19%) imply that the 3.0–2.8 Ga magmatic rocks might be relatively evenly distributed across the North Kongling Terrane.

5.1.3. 2.7–2.6 Ga

The 2.7–2.6 Ga zircons exhibit the highest age peak in this study, ranging from 2771 to 2581 Ma. Their $\varepsilon_{Hf}(t)$ values have a large spread, ranging from −12.2 to +7.4, and the corresponding T_{DM2} ages vary from 3.5 to 2.7 Ga. Thus, the source rocks for the 2.7–2.6 Ga detrital zircons may be heterogeneous and include both juvenile and ancient crustal materials. This interpretation is consistent with the Lu-Hf isotopic features of the two types of granitic rocks in the North Kongling

Terrane. One type is the 2.67–2.62 Ga A-type (ferroan) granites in the eastern segment of the North Kongling Terrane (Chen et al., 2013a), which carry more radiogenic "depleted mantle" Hf signatures. The other type is the 2.7–2.6 Ga I/S-type (magnesian) granitic gneisses that hold more unradiogenic ancient crustal Hf features (Chen et al., 2013a; Guo et al., 2015).

This age is not uncommon in other parts of the Kongling Terrane. Ling et al. (1998) acquired three whole-rock Sm-Nd isochron ages of 2742 ± 83 Ma (MSWD = 1.60), 2728 ± 118 Ma (MSWD = 3.81), and 2684 ± 36 Ma (MSWD = 1.24) for amphibolites and TTG gneisses from the western segment of the North Kongling Terrane. Moreover, 2.7–2.6 Ga magmatic and/or metamorphic zircons are common in the TTG gneisses and metasedimentary rocks from both the South and North Kongling Terranes (Qiu et al., 2000; Zheng et al., 2006; Jiao et al., 2009; Gao et al., 2011). These lines of evidence suggest that the 2.7–2.6 Ga tectono-thermal event(s) could be widespread across the whole Kongling Terrane, which accounts for the high proportion of 2.7–2.6 Ga zircons in this study (23%, 20%, and 52% for sample GJH01, WDH01, and KH223, respectively).

5.1.4. 2.6–2.2 Ga

The 2.6–2.2 Ga detrital zircons exhibit scattered ages. Several subgroups could be recognized (e.g., 2.55 Ga, 2.45 Ga, and 2.30 Ga, Fig. 2D). The dominant subchondritic $\varepsilon_{Hf}(t)$ values (−15.3 to −0.8) in these zircons suggest that their source rocks may be reworked products of ancient crust. Until now, 2.6–2.2 Ga rocks are considered uncommon in the Kongling Terrane, with only sporadic ~2.4 Ga meta-granitoid rocks reported (Zheng et al., 1991; Ma et al., 1997; Wei et al., 2009). It is noteworthy that the 2.6–2.2 Ga rocks may be more widespread in other parts of the Yangtze craton. For example, ~2.5 Ga TTG gneisses were reported from the Douling complex on the northern edge of the Yangtze craton (Hu et al., 2013; Wu et al., 2014) and ~2.3–2.2 Ga granitic gneisses from the northern Vietnam in the southwestern Yangtze craton (Wang et al., 2016). Additional evidence comes from the detrital zircon records in the peripheral Paleo-Neoproterozoic sedimentary rocks around the Kongling Terrane (Zhang et al., 2006c; Liu et al., 2008; Wang et al., 2013a; Li et al., 2016) and other localities of the Yangtze craton (Greentree et al., 2006; Greentree and Li, 2008; Wang et al., 2010; Zhao et al., 2010; Wang et al., 2012a, 2014). Therefore, it is proposed that the 2.6–2.2 Ga age could also be an important tectono-thermal episode in the early evolution of the Yangtze craton (Wang et al., 2016).

5.1.5. 2.0–1.9 Ga

The 2.0–1.9 Ga detrital zircons have a narrow age range from 2051 to 1904 Ma. They have subchondritic $\varepsilon_{Hf}(t)$ values ranging from −22.7 to −5.5 and T_{DM2} ages from 3.5 to 2.7 Ga. These zircons have variable Th/U ratios (0.01–2.1) and diverse internal textures (Fig. 3-3, 3-8, and 3-17) that are indicative of various origins (metamorphic or magmatic). This interpretation is consistent with the widespread 2.0 to 1.9 Ga amphibolite- to granulite-facies metamorphic rocks and contemporaneous S-type granites in the Kongling Terrane (Qiu et al., 2000; Zhang et al., 2006b; Wu et al., 2009; Cen et al., 2012; Yin et al., 2013). Notably, most of the 2.0–1.9 Ga zircons exhibit $^{176}Hf/^{177}Hf(t)$ ratios that resemble those of the 2.7–2.6 Ga magmatic zircons (Fig. 5B). This agreement indicates that the majority of the 2.0–1.9 Ga zircons may have formed by metamorphic recrystallization of the 2.7–2.6 Ga zircons during crustal anatexis, which reset their U-Pb isotopic systems without changing their initial Hf isotopic compositions (Amelin et al., 2000; Gerdes and Zeh, 2009; Chen et al., 2010). This interpretation is supported by the occurrence of a 1.9 Ga metamorphic rim ($^{176}Hf/^{177}Hf(t)$ = 0.281163 ± 0.000016, 1σ) on a ~2.6 Ga zircon core ($^{176}Hf/^{177}Hf(t)$ = 0.281183 ± 0.000011, 1σ) (Fig. 3-8,9-1).

5.1.6. 1.9–1.8 Ga, 1.7–1.5 Ga and 1.0–0.8 Ga

Compared to the major age groups described above, the minor groups at 1.9–1.8 Ga, 1.7–1.5 Ga, and 1.0–0.8 Ga may suggest limited distributions of their source rocks. The 1.9–1.8 Ga zircons have scattered $\varepsilon_{Hf}(t)$ values (−19.2, −18.8, and +2.0), implying heterogeneous provenances that may be sourced from the 1.85 Ga Quanyishang granite ($\varepsilon_{Hf}(t)$ −26.3 to −16.7) and/or dolerite dikes ($\varepsilon_{Hf}(t)$ −0.6 to +0.5) in the Kongling Terrane (Peng et al., 2009; Xiong et al., 2009; Peng et al., 2012). The 1.7–1.5 Ga zircons have $^{207}Pb/^{206}Pb$ ages ranging from 1676 to 1533 Ma. They are mainly characterized by suprachondritic $\varepsilon_{Hf}(t)$ values (from +2.4 to +6.0), indicating the involvement of juvenile crustal or mantle-derived materials in the generation of their source rocks. However, coeval magmatic rocks have yet to be identified in the Kongling Terrane. The 1.0–0.8 Ga detrital zircons may be sourced from the Huangling batholith (Fig. 1C), as supported by their consistent subchondritic $\varepsilon_{Hf}(t)$ values (−28.4 to −22.0) (Zhang et al., 2009a).

It is noteworthy that these 1.7–1.5 Ga detrital zircons may reflect the breakup process of the Yangtze craton from the Columbia supercontinent. The initial fragmentation of this supercontinent began at ca. 1.6 Ga (Zhao et al., 2004) or 1.45–1.38 Ga (Pisarevsky et al., 2014) and was completed by 1.3–1.2 Ga (e.g., North China craton) (Zhao et al., 2004; Zhang et al., 2009b; Evans and Mitchell, 2011; Yang et al., 2011; Chen et al., 2013b; Pisarevsky et al., 2014; Wang et al., 2015). It was suggested that the final breakup of the Yangtze craton from the Columbia supercontinent may have accomplished before 1.5 Ga, as marked by the 1.7–1.5 Ga alkali mafic dykes (Chen et al., 2013c; Fan et al., 2013; Greentree and Li, 2008; Zhao et al., 2010) and rift-related sedimentary sequences in the western Yangtze (Wang and Zhou, 2014 and references therein). Zircons in these rocks often show similar suprachondritic $\varepsilon_{Hf}(t)$ values with the 1.7–1.5 Ga detrital zircons in this study.

5.2. Widespread 2.7–2.6 Ga magmatism in the Yangtze craton

In this study, 222 out of 323 zircon grains are older than 2.2 Ga (59%, 45%, and 91% for samples GJH01, WDH01, and KH223, respectively). For zircons older than 2.2 Ga, the 2.7–2.6 Ga zircons have the highest proportions, i.e., 39% for sample GJH01, 44% for WDH01, 57% for KH223, and 44% for all samples together (Fig. 7A–D). These proportions may be even underestimated, considering that most of the 2.0–1.9 Ga zircons were recrystallized from the 2.7–2.6 Ga zircons, given their consistent $^{176}Hf/^{177}Hf(t)$ ratios (Fig. 5B). Thus, the 2.7–2.6 Ga magmatism may have played a dominant role in forming the granitic crust in the Kongling Terrane. A similar scenario arises from the Paleoproterozoic metasedimentary rocks in the North Kongling Terrane (Fig. 7E), which have 63% 2.7–2.6 Ga zircons (Gao et al., 2011; Li et al., 2016; Qiu et al., 2000). This proportion is apparently higher than those in younger sediments (e.g., this study, Fig. 7A–D). The peripheral Neoproterozoic sediments of the Kongling Terrane also exhibit a major age peak at 2.7–2.6 Ga (Fig. 7F–H), and these sediments were usually assumed to be derived from the Kongling Terrane or similar sources (Cui et al., 2014; Liu et al., 2008; Wang et al., 2013a; Zhang et al., 2006c). Overall, these lines of evidence indicate that the 2.7–2.6 Ga rocks account for the largest proportion of the Archean Kongling Terrane.

In fact, increasing data suggest that the 2.7–2.6 Ga records are not just limited to the Kongling Terrane (Fig. 8A). Apart from the A-type granitic gneisses (2671–2622 Ma) in the eastern part of the Kongling Terrane (Chen et al., 2013a), coeval A-type granites (2656 ± 6 Ma, 2σ) were reported in Huji area, ~100 km northeast of the Kongling (Wang et al., 2013b, 2013c; Zhou et al., 2015). In the Dabie orogen, magmatic zircon cores were collected from Douling diopside leptynites (2650 ± 14 Ma) (Zhang et al., 2004) and Bixiling coesite-bearing eclogites (2662 ± 37 Ma) (Cao and Zhu, 1995). In the southeastern Qinling orogen, amphibolites from the Yudongzi group gave a Sm-Nd isochron age of 2688 ± 100 Ma (Zhang et al., 2001). Moreover, granites intruding into the Yudongzi amphibolites yielded a zircon U-Pb upper intercept age of 2693 ± 9 Ma (Zhang et al., 2001). It suggests that the

~2.7–2.6 Ga tectono-thermal event(s) could be widespread across at least the northern part of the Yangtze craton.

Xenocrystal and detrital zircon data further suggest that the ~2.7–2.6 Ga magmatism has also widely affected the whole Yangtze craton (Fig. 8A). First, ~2.7–2.6 Ga xenocrystal zircons were extracted from Mesozoic volcanic rocks in different parts of the Yangtze craton, e.g., its northern part (Ningwu, 2621 ± 67 Ma; Jingshan, 2614 ± 8 and 2708 ± 7 Ma), central part (Ningxiang, 2751 ± 8 and 2740 ± 9 Ma; Zhenyuan, 2632 ± 10 Ma), and southwestern part (Maomaogou, 2692 ± 12 Ma) (Zhang et al., 2003; Liu et al., 2004; Zheng et al., 2006). As shown in Fig. 8A, ~2.7–2.6 Ga detrital zircons are common in sediments from the Yangtze craton as well, e.g., the modern riversands (this study, Fig. 8C) and the Meso-Neoproterozoic sedimentary strata from the South Kongling (Fig. 8D), Fanjingshan (Fig. 8E) and Kunming (Fig. 8F) areas, which are located in the northern, central and southwestern parts of the Yangtze craton, respectively.

In summary, 2.7–2.6 Ga magmatism has played an important role in forming the Kongling Terrane, and it probably has also affected other parts of the Yangtze craton.

5.3. Implication for the Neoarchean evolution of the Yangtze craton

The 2.7–2.6 Ga was perhaps the most voluminous period of crust formation and recycling in Earth's history, accompanied by assembly of one or more supercontinents (e.g., Kenorland and Superia/Sclavia; Aspler and Chiarenzelli, 1998; Bleeker, 2003; Condie et al., 2009; Kranendonk and Kirkland, 2016). The 2.7–2.6 Ga magmatism has been widely recognized in most Archean cratons worldwide, and it is not a single event, but instead involves multiple peaks between 2760 and 2650 Ma (Condie et al., 2009). The 2.7–2.6 Ga in the Yangtze craton may also consist of multiple stages, as illustrated by the three age peaks in Fig. 8B: ~2.75, ~2.70, and ~2.65 Ga. These 2.7–2.6 Ga magmatic events in the Yangtze craton caused both juvenile crustal growth and ancient crustal reworking (Fig. 5). For instance, the 2.7–2.6 Ga A-type granites from the Kongling Terrane gave suprachondritic zircon ε_{Hf} (t) values (close to the depleted-mantle value), which suggest additions of mantle-derived materials during this period, while the coeval I/S-type granites exhibit subchondritic $\varepsilon_{Hf}(t)$ values (down to < -10), indicating the involvement of abundant pre-existing crustal materials (Chen et al., 2013a; Guo et al., 2015).

The 2.7–2.6 Ga may have indicated the initiation of the stabilization process of the Yangtze craton (Chen et al., 2013a; Zhou et al., 2015). The intracrustal differentiation, stabilization and growth of this craton during the Neoarchean were suggested by previous studies on the chemical compositions of Archean-Paleoproterozoic metasediments and granitoid gneisses in the Kongling (Gao et al., 1999; Guo et al., 2015). These studies reflect the change of granitoid magmatism, from local Na-rich TTG rocks (with weak or no Eu anomalies) to widespread K-rich granites (with negative Eu anomalies) during the Late Archean. The 2.7–2.6 Ga A-type granites are highly potassic and fertile with significant negative Eu anomalies (Chen et al., 2013a; Zhou et al., 2015), which probably marked the initial stabilization of the Yangtze craton.

Meanwhile, the Neoarchean evolution of the Yangtze craton was also characterized by ~2.5 Ga age peaks as shown by the detrital zircons (Fig. 8C–G), which could be confirmed by sporadic ~2.5 Ga xenocrystal zircons (Zhang et al., 2004; Chen et al., 2005, Zheng et al., 2006), and even the coeval Douling complex (Wu et al., 2014). Besides, 2.36–2.19 Ga metamorphism was identified in North Vietnam, southern Yangtze craton (Lan et al., 2001; Nam et al., 2003; Wang et al., 2016). These lines of evidence suggest that there exist a close link between the Yangtze craton and the constituent blocks of the supercraton Nunavutia (including Rae, Gawler-Mawson, peninsular India, West Africa, Amazonia, North China, and Sask crustal blocks), which was characterized by the 2.55–2.50 Ga MacQuoid and 2.50–2.28 Ga Arrowsmith orogenic events but also commonly recording major 2.7–2.6 Ga crustal additions (Pehrsson et al., 2013). This possible paleogeographic link could help decipher the tectonic process of the Yangtze craton during Neoarchean. However, this hypothesis remains speculative until more detailed studies are carried out to better understand the evolution patterns of the Yangtze craton from Neoarchean to early Paleoproterozoic.

6. Conclusions

Zircon U-Pb and Lu-Hf isotopic compositions of three river sand samples from modern rivers in the Kongling Terrane, Yangtze craton, were analyzed in this study. Integrating the new results with existing age data from the literatures leads to the following conclusions:

1. The Kongling Terrane experienced multiple magmatic episodes at 3.3–3.1 Ga, 3.0–2.8 Ga, 2.7–2.6 Ga, 2.6–2.2 Ga, 2.0–1.9 Ga, 1.9–1.7 Ga, 1.7–1.5 Ga, and 1.0–0.8 Ga. The zircon Hf isotopes show that significant additions of juvenile mantle materials occurred 2.7–2.6 Ga and 1.7–1.5 Ga, whereas the remaining Precambrian tectono-thermal events contained more reworked materials from ancient crust. As suggested by the nearly identical $^{176}Hf/^{177}Hf(t)$ ratios between the 2.0–1.9 Ga and 2.7–2.6 Ga zircons, the 2.0–1.9 Ga zircons could be metamorphic recrystallizations of the 2.7–2.6 Ga zircons.
2. The age groups of 2.1–1.9, 1.9–1.7, and 1.7–1.5 Ga may reflect the assembly and breakup of the Yangtze craton during the formation and fragmentation of the Columbia supercontinent.
3. The magmatism at 2.7–2.6 Ga may have played a dominant role in the formation of the Archean Kongling Terrane. The sporadic presence of ~2.7–2.6 rocks and the ~2.7–2.6 Ga xenocrystal and detrital zircons suggest that the ~2.7–2.6 Ga tectono-thermal events were probably widespread across the Yangtze craton and represent an important time period of crustal growth and reworking, similar to many other Archean cratons worldwide.
4. The ~2.7–2.6 Ga may correspond to the initial stabilization process of the Yangtze craton. Meanwhile, similar Neoarchean-Paleoproterozoic age records in the Yangtze craton are comparable to the recently proposed Nunavutia supercraton, which could provide clues for the early tectonic process of the Yangtze craton.

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