Provenances of Cenozoic sediments in the Jianghan Basin and implications for the formation of the Three Gorges

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1. Introduction

The continental collision between India and Eurasia resulted in large-scale changes in East Asian palaeogeomorphology which had profound impacts on East Asian drainage systems (Clark et al. 2004; Clift et al. 2006, 2008a). The Yangtze River, stretching ~6300 km from the Tibetan Plateau to the East China Sea, is Asia’s longest river. It features a complex drainage-system evolution with multiple river capture events that occurred in response to the uplift of the Tibetan Plateau and topographic adjustment in East Asia (Figure 1). In the process of river evolution, the Three Gorges (TG) is proposed to constitute the youngest capture site, and its formation established the modern east-flowing Yangtze River system. However, the evolution of the modern Yangtze River system, especially the formation of the TG, the most debated capture point, has been in dispute since the last century (Willis et al. 1913; Lee 1934; Chen et al. 2001; Clark et al. 2004; Fan et al. 2005; Clift et al. 2008a; Richardson et al. 2010; Zheng et al. 2013a; Fan et al. 2005; Chen et al. 2007; Fan and Li 2008; Zhang et al. 2008; Kang et al. 2009; Jia et al. 2010; Wang et al. 2010; Shao et al. 2012, 2015; Chen et al., 2016; Yue et al. 2016).

Based on low-temperature thermochronology data, Richardson et al. (2008, 2010) related a widespread cooling event in the Sichuan Basin and Huangling massif at ~45-40 Ma to the formation of the TG and modern Yangtze River. However, Yang et al. (1995) and Zheng et al. (2011), Zheng et al. (2013a) argued that the widespread evaporitic rocks in the Jianghan Basin before 36.5 Ma indicate the lack of a large drainage system and that, of consequence, the TG and the modern Yangtze River had not been formed (Dai et al. 1991; Zheng et al. 2011, 2013a).

In another view, Zheng et al. (2013a) related the widespread Yangtze Gravels along the Middle and Lower Yangtze River to TG formation. The gravels on such a large scale reflect a strong supply of water, and this can be related to hydrodynamic condition when the Yangtze River cut through TG. Although the depositional age of the Yangtze Gravels is still dispute, with estimates ranging from Miocene to Pleistocene (Li et al.,...
1979; Yang et al. 1995; Zhang et al. 2004; Zheng et al. 2011; Wang et al. 2014a), the basalt interbedded with Yangtze Gravels suggested that the earliest Yangtze Gravels formed before 22.9 Ma (Zheng et al. 2013a).

Based on undistinguishable zircon U-Pb age distributions from modern sediments in the Yangtze delta, Zheng et al. (2013a) proposed an Oligocene-Miocene age (~36.5–23 Ma) of TG formation. Most authors proposed an age ranging from Pliocene to Pleistocene (from 3.2 Ma to 7500 Ka), as indicated by the analysis of heavy minerals, monazite U-Pb, zircon U-Pb, detrital magnetite geochemistry, and magnetostratigraphy on sediments from Jianghan Basin and the Yangtze delta (Li et al. 2001; Xiang et al. 2007; Fan et al. 2005; Chen et al. 2007; Fan and Li 2008; Zhang et al. 2008; Kang et al. 2009; Jia et al. 2010, 2010; Wang et al. 2010; Shao et al. 2012, 2015; Cheng et al. 2016; Yue et al. 2016). These conclusions may be related to frequent channel migration or climatic variation in the Middle and Lower Yangtze River regions.

The Jianghan Basin is located just downstream of the TG (Figure 2). Once TG was incised by the Yangtze River, the detritus from Sichuan Basin and upper reaches would infill the Jianghan Basin. The sediments of the Jianghan Basin are sensitive to record critical information about source changes and the incision of the TG. Most likely, the incision of TG resulted from regional tectonic and drainage adjustment (Zheng et al. 2011), and unconformity can be used to reflect enhancement of hydrodynamic conditions or occurrence of regional tectonic activity. The timing of three unconformities detected in Jianghan Basin at ~43, 24.6, and 1.17 Ma (Figure 3; Xu et al. 1995; Wang et al. 2006; Zhang et al. 2008) roughly corresponds to the above mentioned three hypotheses on time of formation of TG, and these unconformities may be related to the formation of TG. In this article, we will provide new input into the debate by the analysis of the sediments of the Jianghan Basin across the three unconformities using detrital U-Pb zircon geochronology and heavy mineral analysis. The obtained dataset gives not only a clear picture of the erosion from the surrounding mountain belts but provides also a unique signature that identifies the provenance from the Tibetan Plateau.

2. Geological setting

2.1. River setting

The Yangtze River has its source in the Qiangtang Block of Tibetan Plateau; drains the Songpan-Ganzi subduction-accretion system of eastern Tibetan Plateau, the Yangtze Block, the Qinling-Dabie and Jiangnan orogens, the Cathaysia Block; and empties into the East China Sea (Figure 1; Chen et al. 2001; Zhang et al. 2016). Together with its major tributaries (Yalong, Dadu, Min, Jialing, Wu, Han, Yuan, Xiang, and Gan Rivers) the Yangtze River system...
drains approximately one-fifth of China (Chen et al. 2001). It is traditionally divided into Upper, Middle, and Lower reaches at the TG (Yichang region) and Hukou (Figure 1).

The TG is famous for the TG dam—one of the largest dams as well as hydroelectric power stations in the world. In this article, the TG is defined, therefore, as the dam area in the Yichang region. The TG lies in the Huangling massif which separates the Sichuan and Jianghan Basins. The >1500 m high Huangling massif consists of the Archaean Kongling complex, the Palaeoproterozoic Quanyitang granitoids (~1.8 Ga; Xiong et al. 2008), and the Neoproterozoic Huangling granitoids (750–850 Ma; Ma et al. 2002; Ling et al. 2006; Li et al. 2007a; Richardson et al. 2010; Wang et al. 2014a). Erosion-resistant rocks and an antiformal structural geometry constitute a physical boundary between the Upper and the Middle Yangtze River. Before TG formed, the Yangtze River is named as palaeo Yangtze River, and Huangling separates palaeo Upper and Middle Yangtze River. Palaeo Upper Yangtze as tributaries of palaeo Red River drainage system flowed south-westward from Huangling into South China Sea which is different flow direction from the present situation (Clark et al. 2004; Clift et al. 2006; Clift et al. 2008a). However, regional tectonic activity caused uplift of Tibetan Plateau, and palaeo Upper Yangtze River shifted from palaeo Red River drainage system during late Eocene-Oligocene (~37–~24 Ma; Clift et al. 2008a; Clift et al. 2006). After the Upper Yangtze cut through TG and merged in Middle Yangtze River into the Jianghan Basin, the Yangtze River evolved close to its present state (Clark et al. 2004; Clift et al. 2006, 2008a; Richardson et al. 2010; Zheng et al. 2013a; Lan et al. 2014, 2016; Lei et al. 2015; Deng et al. 2017; Yang et al. 2017).

2.2. The Jianghan Basin

The Jianghan Basin is part of the Yangtze Block and is located just downstream of the TG where the Yangtze River cuts through the Huangling massif (HL, Figure 2). The Jianghan Basin formed as a foreland basin with respect to the Qinling-Dabie orogens during the Late Triassic–Early Cretaceous, but then evolved into a rift basin with fluvial and lacustrine deposits during the Late Cretaceous—Cenozoic (Zheng et al. 2011; Zheng 2015). The Cenozoic strata comprise the Shashi, Xingouzui, Jingsha, Qianjiang, Jinghezhen, Guanghuasi, and Pingyuan formations (Figure 3). Covering the Palaeocene to late Eocene time span, the

Figure 2. Simplified geological map of the Jianghan Basin and sample locations.
130−1900 m thick Shashi (E1s), the 670−1070 m thick Xingouzui (E2x), and the 600−1300 m thick Jingsha (E2j) formations yield grossly similar lithologies of red-grey mudstone, siltstone, sandstone, gypsum, and halite. The oil-bearing late Eocene−early Oligocene Qianjiang Formation (E2−3q), unconformably covering the Jingsha Formation above the ~43 Ma unconformity, is made up of 650−4000 m thick dark-grey mudstone, black shale, mudstone, siltstone, sandstone, halite, gypsum, and basalt. The Oligocene, 0−1160 m thick Jinghezhen Formation (E3jh), tapers out locally and contains grey-blue gypsum-bearing mudstone, siltstone, and shale (Wang et al. 2018). Above the ~24.6 Ma unconformity, the Miocene-Pliocene Guanghuasi Formation is 300−900 m thick with conglomerate, sandstone, and siltstone; the conglomerate of the Lower Guanghuasi Formation—the 'Yangtze gravels'—are

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**Figure 3.** Stratigraphic column of the Jianghan Basin and sample positions. Basalt ages from Xu et al. (1995) and Wang et al. (2006), palaeomagnetism ages from Zhang et al. (2008) and Wang et al. (2006), samples Gsh-6 from Wang et al. (2010), samples W1 and W2 from Wang et al. (2014a).
widespread along the whole Middle and Lower Yangtze River from the TG to the Yangtze delta (Yang et al. 1995; Zheng et al. 2013a; Wang et al. 2014a). The 50–150 m thick quaternary Pingyuan (Qp) Formation consists of gravel, sand, and mud (Figure 3).

Basalts and palaeo-magnetism age are used to constrain the stratigraphy. Before ~36.5 Ma, sediments are interbedded with basaltic lavas dated by the $^{40}$Ar/$^{39}$Ar method (Xu et al. 1995). The Shashi, Xingouzui, and Jingsha Formations range from ~65 Ma to 56 Ma, 56 Ma to 47 Ma, and 47 Ma to 43 Ma, respectively. After ~36.5 Ma, basalt is not recorded in the Jianghan basin and magnetostratigraphic ages are used (Xu et al. 1995; Wang et al. 2006; Zhang et al. 2008). The Qianjiang, Jinghezhen, Guanghuasi, and Pingyuan Formations are from ~43 Ma to 32 Ma, 32 Ma to 24.6 Ma, 24.6 Ma to 1.17 Ma, and 1.17 Ma to present, respectively.

There are several unconformities detected in the Jianghan Basin during the Cenozoic (Figure 3, Wang et al. 2006; Liu et al. 2009). These unconformities may mark periods of tectonic activity and could be related to provenance changes. The unconformity T1 (~24.6 Ma) separates the Guanghuasi and Jinghezhen formations, whereas unconformity T10 (~65 Ma) lies between the Shashi and Yuyang formations. Both unconformities are on a regional scale and are visible as high-angle unconformities in seismic profiles (Figure 4). The unconformities are covered by thick conglomerates or coarse sandstones, suggesting an abrupt transition to a fluvial environment.

In some seismic profiles, the Qianjiang Formation truncates the top of the Jingsha Formation along the low-angle T7 (~43 Ma) unconformity, visible in restricted areas of the basin (Wang et al. 2006; Liu et al. 2009). The last unconformity (~1.17 Ma) lies between the Guanghuasi Formation and the Qp Formation, and is visible in outcrops. Between unconformities T10 and T1 (Palaeocene-Oligocene), the main sedimentary facies are lacustrine deposits, then evolved to fluvial deposits after T1 at ~24.6 Ma (Figure 3).

### 2.3. Potential source areas

The Jianghan Basin is surrounded by the Qinling-Dabie orogens to the north, the Jiangnan Orogen to the south-east, the Huangling massif to the northwest, and the Xiang’ei fold-thrust belt to the southwest (Figure 2). The Qinling-Dabie orogens resulted from Triassic collision between the Yangtze and North China Blocks; the orogen consists mainly of Neoproterozoic, Palaeozoic, and Mesozoic metasedimentary and magmatic and sedimentary rocks (Webb et al. 1999; Hacker et al. 2006; Ratschbacher et al. 2003; Liu 2003a; Liu et al. 2005; Wang et al. 2009; She et al. 2012; Xu and Zhang 2018). The Jiangnan Orogen was formed by the collision of the Yangtze and Cathaysia blocks; its zircon U-Pb age spectra, derived from foreland-basin studies, show clusters at 2.5–2.4, 1.8–1.6, and 1.0–0.86 Ga (Wang et al. 2007a; Su et al. 2014; Yan et al. 2015). The Xiang’ei fold-thrust belt is
mainly composed of the Palaeozoic-Middle Mesozoic limestone sediments (Wu et al. 2017). Songpan-Ganzi orogen and Qiangtang Block which are located in Upper Yangtze River region are also potential source areas of Jianghan Basin. Songpan-Ganzi is characterized by Triassic flysch complex (Weislogel et al. 2010; He et al. 2013) and intruded by many Triassic and Cenozoic magmatic rocks (Sun et al. 2018). Qiangtang Block was located in the west of the Yangtze River, most are covered by Triassic sedimentary rocks and intruded by Cenozoic magmatic rocks (van Hoang et al. 2009; Wang et al. 2013).

Detrital U-Pb zircon ages from the Cretaceous deposits of the Jianghan Basin show major peaks at 168, 253, 799, 1820, and 2512 Ma (Figure 5(a); Shen et al. 2012a), matching the ages of Qinling-Dabie orogens and the Huangling massif (Webb et al. 1999; Hacker et al. 1998; Ma et al. 2002; Ratschbacher et al. 2003; Liu et al. 2005; Ling et al. 2006; Li et al. 2007b; Xiong et al. 2008; Wang et al. 2014a). The Cretaceous sediments of the Sichuan Basin, part of the Upper Yangtze River drainage, show major zircon U-Pb age peaks are at 154, 229, 792, 1869, and 2494 Ma, implying again the erosion of Qinling Orogen, Yangtze Block, and, likely, the Songpan-Ganzi system (Figure 5(b); Li et al. 2016).

Zircon U-Pb ages from modern stream sediments of Han River and the Xiang River reveal major peaks at 145, 219, 447, 786, 1871, and 2543 Ma. This implies a provenance from the Qinling-Dabie orogens, Jiangnan Orogen, and Yangtze Block basement (Figure 5(c); Yang et al. 2007; He et al. 2013).

The sediment sources of the Upper Yangtze River drainages are mostly in the Qinling Orogen and the Yangtze Block. In addition, the Tibetan Qiangtang Block and the Songpan-Ganzi system rocks contribute to their supply. However, age spectra from modern river sands of the Upper Yangtze River differ from the Cretaceous deposits of the Jianghan and Sichuan basins. Besides the age peaks at ~200–270, ~800, ~1860, and ~2500 Ma, Cenozoic ages (18–55 Ma) are frequently found in the modern river sands (Figure 5(d–f); He et al. 2013), suggesting the erosion of Cenozoic igneous rocks. In fact, the Cenozoic magmatic events

| Location            | Samples                                                                 | Zircon U-Pb age distribution (Ma) | Source area                                                                 | Reference                        |
|---------------------|-------------------------------------------------------------------------|-----------------------------------|----------------------------------------------------------------------------|----------------------------------|
| Jianghan Basin      | Cretaceous sediments                                                    |                                   | Qinling-Dabie Orogen+Jiangnan Orogen+Yangtze Block                          | Shen et al.,2012                 |
| Sichuan Basin       | Cretaceous sediments                                                    |                                   | Qinling Orogen+Yangtze Block                                                | Li et al.,2016                   |
| Han River and Xiang Rivers | Modern rivers sands from Han River and Xiang River in First Bend      |                                   | Qinling-Dabie Orogen+Jiangnan Orogen+Yangtze Block                          | He et al.,2013                   |
| Upper Yangtze River | Modern rivers sands from Tuo River and Upper Yangtze River in First Bend |                                   | Qiangtang Block +Songpan-Ganzi Orogen+Yangtze Block                         | Yang et al.,2007                 |
| Upper Yangtze River | Modern Upper Yangtze River sands from First Bend to Three Gorges        |                                   | Qiangtang Block +Songpan-Ganzi Orogen+Yangtze Block                         | He et al.,2013                   |
| Yangtze River       | Modern rivers sands from tributaries of Upper Yangtze River, including Yangtze River, Dadu River, Min River, Jialing River, Wu River |                                   | Qinqling orogen+Songpan-Ganzi Orogen+Yangtze Block                          | He et al.,2013                   |

Figure 5. Zircon U-Pb age distribution, sample location shown in Figure 1.
(44–17 Ma) are widely recorded in the Tibetan Plateau (e.g. Qiangtang Block and Songpan-Ganzi orogen; Arnaud et al. 1992; Turner et al. 1993; Chung et al. 1998; Chi et al. 1999; van Hoang et al. 2009), but are rare in Middle and Lower Yangtze River regions. Wang and Fan (2013) proposed that Cenozoic zircons can be derived exclusively from the Qiangtang Block and Songpan-Ganzi Orogen, both are located in Upper Yangtze River region. These Cenozoic grains could, therefore, be considered a fingerprint to trace the Upper Yangtze River in the Jianghan Basin.

In summary, the zircon age distributions yield generally peaks at 145–168, 220–270, ~800, ~1800, and ~2500 Ma, but the Cenozoic age peaks only appear in the sediments of Upper Yangtze River sands (Fan et al. 2005; Fan and Li 2008; Wang et al. 2010, 2013, 2014a). Had the TG incised, these Cenozoic zircons from Upper Yangtze River would be detected in the Jianghan Basin immediately.

3. Samples and methods

3.1. Sample description

This study is based on 18 sandstone samples from commercial boreholes drilled through the Cenozoic strata of the Jianghan Basin (Figure 2). Sample information is listed in Table 1, and relative positions in the stratigraphy are shown in Figure 3. We tried to arrange three Miocene samples according to their depth and the youngest zircon age (shown in Results). From bottom to top, rough vertical locations show W2 (outcrop sample, youngest zircon age at 39 Ma), C51-1 (depth at 676 m, youngest zircon age at 32 Ma), and M9-1 (depth at 650 m, youngest zircon age at 18 Ma). All samples were analysed by heavy minerals, and five samples (M9-1, M9-2, M9-3, M2-1, and C51-1) were analysed by detrital U-Pb zircon geochronology. In addition, we integrated our data with those from Wang et al. (2010) and Wang et al. (2014a), and Kang et al. (2009).

3.2. Analytical methods

Samples were processed with standard techniques including a steel jaw crusher, a shaking table, heavy liquid techniques, and magnetic methods. Zircon, tourmaline, rutile, epidote, garnet, anatase, apatite, amphibole, and pyroxene grains were counted for heavy mineral provenance analysis (on average ~250 crystals each sample). Zircon grains were separated from other heavy minerals by handpicking under a binocular microscope, and ~200 grains from every sample were randomly selected, mounted in epoxy disks, and then polished to expose grain surfaces. The detrital U-Pb zircon dating was done at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan, using an Agilent 7500a ICP-MS coupled with a Geolas 2005 laser-ablation system with a spot size of 32 µm and a laser frequency of 8 Hz. We used zircon 91500 (1065.4 ± 0.3 Ma, Wiedenbeck et al. 1995) as an external standard. Concentrations of U, Th, Pb, and trace elements were calibrated using 29Si as an internal standard and NIST SRM610 as an external reference standard. Detailed procedures are referred by Liu et al. (2010).

Except for M9-3, which had small grains, we analysed 90–118 randomly selected grains per sample. The 207Pb/206Pb, 206Pb/238U, 207Pb/235U, and 206Pb/232Th isotopic ratios were calculated using ICPMSDataCal (Liu et al.

| Sample | Well | Longitude (E) | Latitude (N) | Stratigraphic age | Reference |
|--------|------|--------------|--------------|------------------|-----------|
| Gsh-6  | Zhoulao | 112°59′ | 30°02′ | ~1.17 | Wang et al. 2010 |
| M9-1  | M9  | 113°04′58″ | 30°24′49″ | ~24.6–18 | This study |
| C51-1  | C51  | 112°20′33″ | 30°23′38″ | 24.6–18 | This study |
| W2-1  | Outcrop | 112°05′ | 30°23′38″ | 24.6–18 | This study |
| M9-2  | M9  | 113°04′58″ | 30°24′49″ | ~32–24.6 | This study |
| M9-3  | M9  | 113°04′58″ | 30°24′49″ | ~32–24.6 | This study |
| M9-4  | M9  | 113°04′58″ | 30°24′49″ | ~32–24.6 | This study |
| M2-1  | M2  | 111°58′20″ | 30°09′19″ | ~32–24.6 | This study |
| M2-2  | M2  | 111°58′20″ | 30°09′19″ | ~32–24.6 | This study |
| M2-3  | M2  | 111°58′20″ | 30°09′19″ | ~32–24.6 | This study |
| M2-4  | M2  | 111°58′20″ | 30°09′19″ | ~32–24.6 | This study |
| M2-5  | M2  | 111°58′20″ | 30°09′19″ | ~32–24.6 | This study |
| M2-6  | M2  | 111°58′20″ | 30°09′19″ | ~32–24.6 | This study |
| M2-7  | M2  | 111°58′20″ | 30°09′19″ | ~32–24.6 | This study |
| M2-8  | M2  | 111°58′20″ | 30°09′19″ | ~32–24.6 | This study |
| H1-1  | H1   | 112°10′13″ | 30°11′32″ | ~32–24.6 | This study |
| W1    | Outcrop | ~47–43 | ~47–43 | ~47–43 & 47–43 | This study |
| L2-1  | L2   | 112°05′37″ | 30°22′12″ | ~56–47 | This study |
| L3-1  | L3   | 112°05′54″ | 30°21′41″ | ~56–47 | This study |
| F2-2  | F2   | 112°09′25″ | 30°17′22″ | ~56–47 | This study |
| F2-1  | F2   | 112°09′25″ | 30°17′22″ | ~56–47 | This study |

Table 1. Sample information.
2010). We used \(^{206}\text{Pb}/^{238}\text{U}\) ages for zircons <1 Ga and \(^{207}\text{Pb}/^{206}\text{Pb}\) ages for zircons >1 Ga and excluded all spot ages with <85% \(^{206}\text{Pb}/^{238}\text{U}\) and \(^{207}\text{Pb}/^{235}\text{U}\) concordance for zircons <2 Ga and <90% for zircons >2 Ga. For the Cenozoic zircons, we did not apply a discordance filter due to the low content of \(^{207}\text{Pb}\) (Gehrels 2011). Concordia and age probability-density diagrams were made using ISOPLOT v. 4.12 (Ludwig 2003). The internal zircon structure was revealed by cathodoluminescence (CL) imaging, using a Quanta 400FEG environmental scanning electron microscope equipped with an Oxford spectrometer and a Gatan CL3+ detector at the State Key Laboratory of Continental Dynamics, Northwest University, Xi’an. Its operating conditions were at 15 kV and 20 nA.

4. Results

4.1. Zircon morphology

Zircons are 30 to 250 µm long with length/width ratios mostly between 1.5:1 and 3:1. The euhedral shape of some zircons (e.g. grains C51-1–61, M9-1–77, Figure 6) may imply a short transport distance or simple sedimentary recycling, sub-rounded to rounded zircons (e.g. grains C51-1–14, C51-1–75, Figure 6), and suggest long transport distances or complex sedimentary recycling. Zircons derived from volcanic ash can also show euhedral shapes. However, the depositional ages of samples M2-1, M9-3, M9-2, C51-1, and M9-1 range from early Oligocene to Miocene (after ~36.5 Ma, shown in Figure 3), and it is documented that there is no volcanic activity after ~36.5 Ma in the Jianghan Basin (Xu et al. 1995; Wu et al. 2018). Therefore, a provenance from volcanic ash in the Jianghan Basin is unlikely. Most zircons show magmatic oscillatory zoning (Figure 6). A few zircons are black (e.g. grains C51-1–14, M9-2–82), probably due to their high Pb contents (Corfu et al. 2003; Li et al. 2014).

4.2. Zircon U-Pb data

Supplementary data tables S1–S5 list the analytical data, and Figure 7 shows the concordant ages in Wetherill diagrams. Th/U ratios, mostly >0.3, imply magmatic origin for the vast majority of zircons (Maas et al. 1992); ratios <0.1, which likely indicate metamorphic origin (Kinny et al. 1990), do not correlate with a specific age group (Supplementary Figure 1). The 470 zircon U-Pb ages from the Cenozoic sediments of the Jianghan Basin vary between 17 and 4120 Ma and include multiple clusters, especially in the Guanghuasi Formation (Figures 7, 8). The oldest grain is >4.0 Ga (C51-1, Guanghuasi Formation); the youngest grains are 17–32 Ma (M9-1 and C51-1; Guanghuasi Formation).

The 90 grains forming the Miocene Guanghuasi Formation sample M9-1 show ages from 17 to 2767 Ma; one youngest age peak is at ~18 Ma, and other peaks are at ~117, 440, and 797 Ma. The 118 discordant ages of Guanghuasi Formation sample C51-1 range from 32 to 4120 Ma; peaks are at ~32, 241, 646, 819, 1826, and 2511 Ma. The 96 ages of Oligocene Jinghezhen Formation sample M9-2 are between 149 and 2958 Ma; peaks occur at 157, 228, 450, 801, 1873, and 2486 Ma. The 74 discordant ages of the Eocene-Oligocene Qianjiang Formation sample M9-3 span 126 to 2817 Ma; peaks occur at 137, 227, 435, 781, 1844, and 2458 Ma. However, the statistical reliability of these peaks is questionable due to the fine grain size of this sample and the necessity to select the largest grains for analysis. Sample M2-1, also from the Qianjiang Formation, yielded 92 discordant zircon U–Pb ages ranging from 201 to 3156 Ma; peaks are at 264, 774, 1822, and 2459 Ma.

The data published by Wang et al. (2010) and Wang et al. (2014a) show different features. The quaternary sample Gsh-6 contains major peaks at 16, 227, 770, 1860, and 2484 Ma. The sample W2 is from the Miocene Guanghuasi Formation, and peaks occur at 39, 168, 228, 444, 798, 1874, and 2408 Ma. The Eocene Jingshan Formation sample W1 contains major peaks at 165, 240, 437, 780, 1892, and 2560 Ma. We grouped the ages of all samples into eight clusters with the following age ranges: <39, 65–199, 200–299, 300–599, 600–999, 1000–1599, 1600–2100, and >2100 Ma (Figure 8).

4.3 Heavy mineral data

Heavy mineral analysis (analytical details in supplementary Table S6), including the percentage of each mineral, ZTR index, and the basic heavy mineral assemblage, has been used to constrain the sources. The ZTR index is the percentage of zircon, tourmaline, and rutile among the transparent heavy minerals, omitting micas and authigenic minerals (Hubert 1962), which is thought to represent the stable detrital heavy mineral assemblage and mainly occurs in mature siliciclastic sediment (Morton et al. 2011). The garnet and epidote are mainly from metamorphic source rocks, and amphibole and pyroxene are mainly derived from magmatic or magmatic derived metamorphic basic rocks. Heavy mineral assemblages are given in Figure 9, where the ZTR index curve, the content of garnet+epidote, amphibole+pyroxene, and rutile are shown.

The samples under the unconformity T7 (~43 Ma) show high ZTR (>30), high content of rutile (>10%) but low content of garnet+epidote (<30%). Those characteristics are
similar to those from the Zhang River, which originates from Palaeozoic-Mesozoic sedimentary rocks exposed to the north of the Jianghan Basin (Figure 9, Xu et al. 2005; Kang et al. 2009). This suggests that major sources of the basin before ~43 Ma may be northern Palaeozoic and Mesozoic sedimentary rocks exposed in the Dangyang area.

Between the unconformities T7 (~43 Ma) and T1 (24.6 Ma), all samples reveal a low rutile content (<10%). Most samples have a low ZTR content (<30) but high garnet + epidote (>30%). These characters are similar to sediments of the Ju, Manao and Han Rivers that originate from old crystalline basement or metamorphic rocks such

Figure 6. Zircon cathodoluminescence images of samples from the Jianghan Basin.
as the Huangling and Dabie orogens (Kang et al. 2009). In addition, some samples (H1-1, M2-3, and M2-2) contain a high ZTR content and a relatively low content of garnet + epidote and rutile and share similar characters with Qing River sediments, which are derived from western Palaeozoic sedimentary rocks (Xiang et al.'exi fold-thrust belt). This suggests that the major sources probably are western sedimentary rocks, the Yangtze basement (Huangling massif), or Qinling-Dabie metamorphic rocks.

Above unconformity T1 (24.6 Ma), two samples (C51-1 and M9-1) reflect a relatively low content of ZTR and rutile but a high content of garnet + epidote, similar to the modern Yangtze River. In general, several samples (F2-1, M2-8, C51-1) contain a high content of amphibole + pyroxene (>30%), which probably reflects a basalt or high grade metamorphic source.

5. Discussion

5.1. Provenance of detrital zircons

Most zircons have a magmatic origin, and thus their ages are related to the time of their crystallization. Different age groups therefore result from different magmatic events.

The first cluster ranges from 2.1 Ga to 4.12 Ga with a peak at ~2.5 Ga. The oldest zircon age is 4120 Ma and has been found in the Guanghuasi Formation (sample C51-1). Zircon ages older than 4.0 Ga have only been found in the Tibetan Plateau and Upper Yangtze region (Duo et al. 2006, 2007; Wang et al. 2007b; He et al. 2011; Xu et al. 2012), ca. 2000 km from the Jianghan Basin. These zircons are even older than the previously reported oldest zircon in the Middle Yangtze crustal basement (3802 ± 8 Ma) (Zhang

Figure 7. Wetherill Concordia diagrams of LA-ICP-MS zircon U–Pb analytical results for the Cenozoic samples of the Jianghan basin. Ng, Guanghuasi Formation; E3j, Jinghezhen Formation; E2-3q, Qianjiang Formation.
et al. 2006a, 2006b), suggesting that the crystalline base-
ment of the Middle Yangtze Block cannot be the primary
source of our oldest zircons. Furthermore, the features of
rounded shape and dark in CL image suggest either long-
distance transport or multi-cycle transportation (Figure 6).
Therefore, we infer that the oldest zircons detected here

Figure 8. Relative probability–density plots of the detrital zircon U-Pb ages of samples from the Jianghan Basin. All samples comprise ~800, 1800, and 2500 Ma peaks, but Cenozoic ages only appear in the samples above unconformity T1 (~24.6 Ma). Peaks were obtained by weighted average of every cluster. Samples W1 and W2 from Wang et al. (2014a), Gsh-6 from Wang et al. (2010). Qp: quaternary Pingyuan Formation, Ng: Guanghuasi Formation, E3jh: Jinghezhen Formation, E3q: Qiangjiang Formation, E2j: Jingsha Formation.
could derive from the crystalline rocks of the Tibetan Plateau or Upper Yangtze Block.

Our second cluster is dated at 1.6−2.1 Ga with a mean peak at ~1.8 Ga, and it is present in all samples. Based on similar age clusters found in the Kongling Group, the Quanyitang granitoids, and the Nanhua system clastic sediments from the Huangling massif (Ma et al. 2002; Ling et al. 2006; Li et al. 2007b; Xiong et al. 2008; Wang et al. 2014a), our zircons could come from the Yangtze basement or recycled sedimentary materials (Wang et al. 2007b).

The third cluster is at 1000−1599 Ma. Although this group is weakly defined (Yang et al. 2007; Shen et al. 2012a), a similar age cluster can be found in the Qinling and Jiangnan orogens (Zhang et al. 2001; Wang et al. 2007a; Dong et al. 2008; Diwu et al. 2010; Su et al. 2014; Yan et al. 2015).

Around 30% of all zircon ages belong to the fourth cluster, dated at 600−999 Ma, with a peak at 760−800 Ma. These zircons could derive from Huangling granitoids (Ma et al. 2002; Ling et al. 2006; Li et al. 2007b; Wang et al. 2014a), matching the Neoproterozoic Jinningian orogeny and associated with the breakup of the Rodinia supercontinent (Chi et al. 1999; He et al. 2013). These events resulted in widespread igneous rocks in Yangtze Block during 820−750 Ma.

The fifth cluster is at 300−599 Ma, with a peak at ~430−450 Ma. These early Palaeozoic ages are observed in the South Qinling and Jiangnan Orogen (Zhang et al. 2003, 2007; Yang et al. 2007).

Zircon dated at 200−299 Ma represent the sixth cluster, with two major peaks at ~220 Ma and ~260 Ma. They correlate with the Indosinian Orogeny and are probably derived from the Qinling-Dabie orogens, which are associated with the collision between the North China Block and the Yangtze Block (Xue et al. 1996; Zhang et al. 1996; Hacker et al. 1998; Webb et al. 1999; Li et al. 2007a; Dong et al. 2012), whereas the age peak at ~260 Ma may be related to Permian basalts or arc-derived magmatism along the eastern margin of

**Figure 9.** Heavy mineral assemblages of the Cenozoic sediments from the Jianghan Basin, including the ZTR index curve, the content of garnet + epidote, and rutile and amphibole + pyroxene. Modern river data are from Kang et al. (2009), sample locations are shown in Figure 2.
Cathaysia, such as Emei Basalts (He et al. 2007; Xu et al. 2008).

The seventh cluster is at 65–199 Ma and has been found in most of the samples. Widespread late Mesozoic magmatic rocks can be found in the Qinling-Dabie orogens and in the eastern and southern Jianghan Basin, e.g. Huaron granitoids, and Mufushan massif (Figure 2, Wang et al. 2003; Shen et al. 2012b; Wang et al. 2014b). These zircons may be related to Yanshanian (Jurassic-Cretaceous) tectonothermal events associated with widespread granitoids of Jiangnan and adjacent Cathaysia Block (Wang et al. 2003, 2014b; Shen et al. 2012b).

The last cluster features Cenozoic ages, with peak ages at 15−39 Ma. These grains have been found only in the Guanghuasi Formation and Quaternary sediments. Our youngest zircons (~18 Ma from M9-1) may indicate the maximum deposition age of sample M9-1 (Dickinson and Gehrels 2009; Gehrels 2011; Ke et al. 2018). The occurrence of these zircons suggests a Cenozoic igneous rock provenance, which is recorded frequently in the Tibetan Plateau, but no Cenozoic intrusive rock has been found in the Middle Yangtze River region (Arnaud et al. 1992; Turner et al. 1993; Chung et al. 1998; Fan et al. 2005; Wang et al. 2010, 2014a). Although some Cenozoic basalts occur in the Jianghan Basin, they cannot be the source of these Cenozoic zircon grains for the following reasons: (1) active basalts only appeared before 36.5 Ma, and no Oligocene-Miocene basalts (32−15 Ma) are recorded in the Jianghan Basin (Xu et al. 1995; Wu et al. 2018); (2) zircon is inferred to source mainly from granite, pegmatite, and gneiss instead of basalts (Fan and Li 2008); (3) the youngest ages occur in sample M9-1, but low contents of amphibole + pyroxene do not reflect a basalt provenance. In other studies on Yangtze River sediments, Fan et al. (2005), Wang et al. (2010), Yang et al. (2010), Wang et al. (2013), He et al. (2013), and Wang et al. (2014a) proposed that the Cenozoic zircons (65−17 Ma) could be used as an indicator to trace Upper Yangtze detritus. Considering the location of samples, the Han and Xiang rivers could have also transported such grains. However, recent studies suggest that the modern Han River formed at ~1.8 Ma (Zhang et al. 2014, 2016) and that no Cenozoic ages have been detected in the modern river sands (Figure 4(b); Yang et al. 2007; Yang et al. 2010; He et al. 2013). These zircons must derive from Late Cenozoic acidic intrusions exposed only in the Qiangtang Block and the Songpan-Ganzi Orogen (Fan et al. 2005; Wang et al. 2010, 2013, 2014a). Therefore, we suggest that the source region of the Jianghan Basin had reached the Upper Yangtze River regions at the Guanghuasi stage (Miocene).

However, due to euhedral shapes of these <32 Ma zircons, wind transport should be excluded first, as it is very difficult to distinguish from sediments. Aeolian depositions are dominant in drought climate, especially in desert and the Loess Plateau. During Miocene (the depositional age of these <32 Ma zircon), Asian monsoon has been established and the climate of Jianghan Basin is characterized by high moisture levels and heavy summer rainfall (Guo et al. 2008; Molnar et al. 2010). This implies that sediments transport in Jianghan Basin is dominated by fluvial transport, and wind transport is of minor importance.

5.2. Palaeogeomorphological evolution of the Jianghan Basin

Although the hydraulic sorting and mineral fertility bias should be taken into account (Malusà et al. 2015), as a first approximation, big changes in the proportion of age populations and heavy minerals assemblages correspond to the importance of the source rock. Based on the geochronological and mineralogical fingerprints, the palaeogeography and the source-sink systems across the three unconformities are summarized and illustrated in Figure 10.

Generally, there are three age peaks at ~800, 1800, and 2500 Ma in all samples (Figure 8), and this suggests that most zircon grains derived from pre-Cambrian basement or recycling materials from the Yangtze Block. However, the occurrence of Cenozoic zircon grains only in the samples above unconformity T1 (24.6 Ma) tests a dramatic change in the source-sink systems between the late Oligocene and early Miocene.

Under the unconformity T7 at ~43 Ma, the heavy minerals suggest that the main sources are sedimentary rocks cropping out in the north (Dangyang areas). Detrital zircon age distributions show distinct age peaks similar to what have been detected in Cretaceous sediments (Figure 4(a); Shen et al. 2012a). This suggests a relatively stable source-sink system during the Cretaceous to Eocene Jingsha stage. In addition, we also agree with Liu et al. (2003b), Yi (2011), and Wu et al. (2017) who propose that the Dabie Orogen and Huangling massif supplied detritus to the basin.

Between the unconformities at ~43 Ma and ~24.6 Ma, the heavy mineral assemblage reflects a source from western sedimentary rocks (Xiang'exi fold-thrust belt), and from Huangling crystalline basement or Dabie pre-Cambrian metamorphic rocks (Figure 10). Our model is supported by low-temperature thermochronology data that show that the Huangling massif was affected by a rapid uplift phase at ~40−30 Ma (Li et al. 2008; Ge et al. 2013; Yang et al. 2017).
Above unconformity T1 at 24.6 Ma, the zircon distributions show a major change with respect to older samples. Cenozoic zircon grains (18–39 Ma) and the oldest zircon (4210 Ma) occurring in Guanghuasi Formation suggest that the source of the Jianghan Basin may have reached the Tibetan Plateau (Wang et al. 2014a). As unique drainage linkage between Tibetan Plateau (Qiangtang Block and Songpan-Ganzi) and Jianghan Basin (as shown in Figure 10).

Figure 10. Inferred sediment route and sedimentary facies of the Jianghan Basin during Palaeocene-Miocene time. After ~24.6 Ma, the palaeo-geomorphology of the Jianghan Basin evolved close to its present state. Sedimentary facies are modified from Dai et al. (1991), Liu et al. (2003), Yi (2011) and Wu et al. (2017).
The Yangtze River is most likely to transport these <32 Ma zircons to Jianghan Basin. High elevation of Eastern Sichuan Fold Belt and Qingling Orogen prevents other rivers from flowing from Tibetan Plateau, through Sichuan Basin and into Jianghan Basin (Wang et al. 2013). In other words, the Upper Yangtze River had started to flow through the unique path—TG—into the Jianghan Basin; this indicates that TG had been formed and the Modern Yangtze River has been established (Zheng et al. 2013a; Wang et al. 2014a; Zheng 2015; Deng et al. 2017). Besides, Neogene cooling events in the Sichuan basin suggest a rapid uplift or exhumation event (Shi et al. 2016; Yang et al. 2017) which contributes to the connection between the Upper Yangtze and Middle Yangtze River. It is interesting to note that there is very peculiar peak at ~100 Ma only appearing in sample W2 (Figure 8). The Yanshanian granites (Jurassic-Cretaceous) are widespread in Jianghan Basin (Wang et al. 2003, 2014b; Shen et al. 2012b), and they may provide detritus for this sample. W2 is an outcrop sample located in margin of basin, while the other samples (C5-1, M9-1, and Gsh-06) are sampled from boreholes in the interior of the basins. This may be the main reason why the peculiar peak only appears in W2.

### 5.3. Implications for formation of the TG

The Cenozoic sedimentary records in the Jianghan Basin provide a compelling constraint for the formation of the TG. The differences between pre-Miocene and Miocene-Quaternary sediments indicate that source area changed between the late Oligocene and the early Miocene. In Miocene-Quaternary samples, Cenozoic zircon age signals indicate a provenance of Cenozoic igneous rocks which are only widespread in Tibetan Plateau. This supports the idea that the TG may have formed between the late Oligocene and the early Miocene. Furthermore, the appearance of the Guanghuasi Fm at 24.6 Ma marks the transition from lacustrine to fluvial facies, and this indicates a large drainage system may have been formed.

To some extents, our proposed drainage evolution supports the model of Clift et al. (2006), Clift et al. (2008a), Zheng et al. (2013a), and Yang et al. (2017) with a shifting of the Upper Yangtze River from the palaeo-Red River system (Clift et al. 2006, 2008a). During Eocene, palaeo Upper Yangtze River as a tributary of palaeo Red River system flowed southwest into South China Sea (Clark et al. 2004; Clift et al. 2006, 2008a). Subsequently, the Upper Yangtze River shifted from palaeo Red River system during ~37-24 Ma (Clift et al. 2006, 2008a). Ultimately, the Upper Yangtze River terminated its shifting and cut through TG, and then established modern Yangtze River system (Zheng et al. 2013a; Lan et al. 2016; Deng et al. 2017).

The formation of TG and the modern Yangtze River probably are related to the general evolution of topography in East Asia during the Cenozoic (Wang 2004). China region was affected by a general west-wilting topography during Cretaceous-Eocene time (Wang 2004), and the India-Eurasia continental collision caused the surface uplift of Tibetan Plateau (Clark et al. 2004; Wang 2004; Clift et al. 2006, 2008a, 2008b; Wang et al. 2008; Zheng et al. 2013a; Deng et al. 2017). Low-temperature thermochronology data in Sichuan Basin revealed a phase of eastward growth and rise of the Tibetan Plateau at ~25–15 Ma (Shi et al. 2016; Yang et al. 2017). The T1 unconformity between the Oligocene and Miocene in the Jianghan Basin is in agreement with this uplift event. The deformation in the Sichuan Basin may have cut off the connection between the palaeo-Red River and the Yangtze River and established an east-flowing Yangtze River system (Wang 2004; Clift et al. 2008b; Yang et al. 2017). Of course, we also cannot ignore the possible contribution of climatic changes as the onset of the East Asian monsoon at the beginning of the Miocene could have caused enhanced erosion in the TG (Wang 2004; Clift et al. 2008b; Guo et al. 2008; van Hoang et al. 2009; Zheng et al. 2013a; Zheng 2015; Shen et al. 2018).

### 6. Conclusions

In this study, we used detrital zircon U-Pb dating and heavy mineral analysis to constrain the multiple source system in the Jianghan Basin. The dominant provenance was from the surrounding regions such as the Huangling massif, the Qinling-Dabie orogens, and the Jiangnan orogen during Palaeocene-Oligocene time, whereas the Upper Yangtze River supplied sediments to the Jianghan Basin since the Miocene. The Cenozoic sedimentary records in the Jianghan Basin also provide evidence for the formation of the TG, which is well-expressed by the unconformity at ~24.6 Ma.

### Acknowledgments

We are very grateful to Professor Lothar Ratschbacher for polishing the English; Dr. Zhao Yang for their kind help with CL analysis; and Dr. Lulu Wu for their sample collections. This work was supported by the National Natural Science Foundation of China (No. 41672140, 41372140), the Outstanding Youth Funding of Natural Science Foundation of Hubei Province (No. 2016CFA055), the Program of Introducing Talents of Discipline to Universities (No. B14031), the Wuhan Science and Technology Project (No. 2016070204010145), Fundamental Research Fund for the Central Universities, China University of Geosciences (Wuhan) (CUGCJ1820), and the China scholarship Council (201806410013).
Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the National Natural Science Foundation of China [41372140,41672140]; Outstanding Youth Funding of Natural Science Foundation of Hubei Province [2016CFA055]; the Fundamental Research Fund for the Central Universities, China University of Geosciences (Wuhan); [CUGC1820]; Wuhan Science and Technology Project [2016070204010145]; the China Scholarship Council [201806410013]; and Program of Introducing Talents of Discipline to Universities [B14031].

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