1 **U-Pb dating of zircons from tuff layer, sandstone and tillite**
2 **samples in the uppermost Liantuo Formation and the**
3 **lowermost Nantuo Formation in Three Gorges area, South**
4 **China**

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16 **Abstract:** Uranium-lead (U-Pb) dating was conducted on zircons in tuff layers and
17 sandstone samples from the uppermost Liantuo Formation and in a tillite sample from
18 the lowermost Nantuo Formation in Three Gorges area, South China, using SHRIMP
19 and LA-ICP-MS techniques. Zircons from these samples yielded age spectrum
20 (within 1000 Ma) of ~890, ~830, ~780, ~730, and 646 Ma. Zircons from the Liantuo
21 tuffs have a weighted mean ²⁰⁶Pb/²³⁸U age of 734.1±8.1 Ma (2σ, n=7, MSWD=0.48),
22 which was regarded as the best estimation of the upper boundary age of the Liantuo

Formation. Combining with previous geochronologic data, the Liantuo Formation was proposed to be a pre-Chang'an glaciation unit, and it is comparable to the middle-upper Banxi/Danzhou Group in South China.

Key words: U-Pb dating, zircon, Liantuo Formation, Three Gorges, South China.

1. Introduction

During the last decades, great efforts have been made on the Neoproterozoic history of South China, and a stratigraphic framework of this time interval was proposed as following: The Neoproterozoic strata of South China included the Qingbaikouan, Nanhua, and Sinian Systems in ascending order, and the Nanhua System was comprised of three glacial intervals, i.e. Chang'an Formation, Gucheng Member and Nantuo Formation in ascending order, and two inter-glacial intervals, i.e. Liangjiehe Member and Datangpo Formation in ascending order (see Fig. 1 in Zhu *et al.* 2007). In Three Gorges area, the Nantuo tillite directly covers the Liantuo Formation sandstone. This leads to two controversial speculations: the Liantuo Formation is an interglacial unit between Nantuo and Gucheng or Chang'an glaciation (Xue *et al.* 2001, Peng *et al.* 2004), or the Liantuo Formation is a unit before Chang'an glaciation (Wang and Li 2003, Zhang and Chu 2006, Zhang *et al.* 2008a).

This controversy is partly caused by the lack of precise age of the Liantuo Formation. Up to now, only few ages are obtained for the upper boundary age of Liantuo Formation (Compston 1982, Ma *et al.* 1984, Zheng 2003, Gao and Zhang

2009, Du *et al.* 2013, Lan *et al.* 2015). Gao and Zhang (2009) firstly set the upper boundary age of Liantuo Formation at 724 ± 12 Ma according to two zircon U-Pb dating data (Suppl. Table 1), and then Du *et al.* (2013) suggested the upper boundary age of Liantuo Formation was 736 ± 5.8 Ma based on an zircon U-Pb dating age group (722-747Ma). Recently, Lan *et al.* (2015) constrained the upper boundary age of Liantuo Formation at 714 ± 8 Ma. The variation casts great uncertainty on the upper boundary age of the Liantuo Formation.

In this study, we conducted U-Pb dating of zircons from the uppermost tuff beds to constrain the upper boundary age of the Liantuo Formation. In order to confirming our results, we also dated detrital zircons from sandstone and tillite collected from the Liantuo/Nantuo Formation boundary.

2. Geological setting and sampling

The Liantuo Formation was once considered as the lower boundary of the former Sinian System (consisting of Liantuo, Nantuo, Doushantuo and Dengying Formations in ascending order, Liu *et al.* 1991), but at present it is moved out from the modified Sinian System (consisting of Doushantuo and Dengying Formations only). The Liantuo Formation is widely exposed in Three Gorges area, Hubei Province, and occurs with varying thickness, between 50~260 m, covering on the Huangling granite (locally referred to the Jinning orogeny) and underlying unconformably the Nantuo Formation tillite (Liu *et al.* 1991). The Liantuo Formation is mainly composed of aubergine-coloured medium/coarse-grained sandstones, demonstrating a variation

from “coarse at the bottom to fine at the top” (Liu *et al.* 1991). The lower part is mainly composed of aubergine-coloured quartz sandstone and quartzose arkose, and the upper part is mainly composed of laminated tuff and tuffaceous sandstones.

Tuff samples in this study were taken from the Tianjiayuanzi section, near Sandouping Town, Yiling district, Yichang (T-11 and T-12; N 30°50'05.3", E 111°07'01.6"), and the Wuhe-Gaojiayi section (WG-16; N 30°46'59.3", E 111°02'00.6") in the uppermost Liantuo Formation (Fig. 1). They are green in color, thin in thickness (< 1 cm), and loose in texture, containing major clays and minor sands and/or gravels (their photomicrograph petrography can be referred to Fig. 5 of Lan *et al.*, 2015). One sample each was also collected from the sandstone in the uppermost Liantuo Formation at the Tianjiayuanzi section (T-13) and from the tillite in the lowermost Nantuo Formation at the Jiulongwan section (JL-1; N 30°48'23.9", E 111°03'15.0"). Sandstone is red in color, compact in texture, and thick in thickness, containing major sands. Tillite is colorful, loose to compact in texture, and thick, containing gravels, sands and clays in variable percent.

3. Analytical method

Zircon grains were separated using the standard heavy mineral dressing process. First, tuff samples (~10 kg) were crushed and ground to <60 mesh. This was conducted with primary washing by hydraulic force to remove clay minerals with lighter specific gravity. The samples were then dressed with heavy liquid to remove minerals with medium specific gravity. Finally, residual heavy minerals were

collected and zircon grains were further picked up under an optical binocular.

3.1. SHRIMP U-Pb dating of zircon

The zircon grains were mounted in epoxy, together with standard zircons SL13 (used for correcting the content of U, Th, and Pb) and TEM (used for correcting the age; the recommended value is 417 Ma), and then polished to section the crystals in half for analysis. Zircon samples were documented with transmitted and reflected light micrographs as well as cathodoluminescence (CL) images to reveal their internal structures (Fig. 2). Zircons from samples T-11 and T-12 were analyzed in Beijing SHRIMP Center, Institute of Geology, Chinese Academy of Geological Sciences using the standard experiment procedure on a SHRIMP II instrument (Compston *et al.* 1992). To ensure the analytical quality, zircon samples and the TEM standard were cross-tested at a frequency of 3:1. The beam spot diameter was about 25 μm during the analysis. The analytical result was calculated using a standard Pb correction program using the actual measurement of ^{204}Pb for common Pb correction. Data were processed using SQUID (1.02 version; Ludwig 2001a) and ISOPLOT (3.23 version; Ludwig 2001b).

3.2. LA-ICP-MS U-Pb dating of zircon

Zircons from samples T-13, WG-16, and JL-1 were analyzed in the State Key Laboratory for Mineral Deposits Research, Nanjing University, using an Agilent 7500a LA-ICP-MS instrument combined with a New Wave UP213 solid laser ablation system. He gas was used as the carrier gas of ablated substance, which was transported to the ICP-MS through 3 mm diameter PVC pipe, and mixed with Ar gas

before entering the instrument. Mass fractionation correction was carried out using standard zircon GJ-1 (608 Ma). About 15 points were analyzed in each round of analysis in the following order: two for standard zircon GJ-1, one for a zircon sample with known age (Mud Tank: 735 Ma), 10 to 12 for unknown zircon samples, and two for standard zircon GJ-1. For detailed analytical procedures please refer to [Jackson *et al.* \(2004\)](#). Common lead correction was carried out using the method developed by [Andersen \(2002\)](#). Data were processed using ISOPLOT (3.23 Version; [Ludwig 2001b](#)).

4. Results

As shown in [Fig. 2](#), the zircon crystals display various forms, from relatively idiomorphic to round shape. Relatively idiomorphic crystals have a smooth surface and flat, straight crystal edges, indicating that they were not reworked from old sedimentary or volcanic rocks. The zircons show a typical size of 70~200 μm , with a length/width ratio of 2:1 to 4:1. As shown by the CL images, most zircons have an apparent zonal structure ([Fig. 2](#)).

All of the U-Pb dating results are listed in [Suppl. Table 1](#).

4.1. Sample T-11 tuff

A total of 25 zircon grains were analyzed. Their U contents vary from 34.2 to 426 ppm, and Th contents vary from 35.2 to 520 ppm, with Th/U ratios of 0.45 to 2.72. Their individual $^{206}\text{Pb}/^{238}\text{U}$ ages vary from 640 to 2,523 Ma ([Suppl. Table 1](#)). One grain (T-11-1.1) plots to the right of concordia line ([Fig. 3a](#)). One grain (T-11-21.1)

gives a Late Archean $^{206}\text{Pb}/^{238}\text{U}$ age. Five grains (T-11-6.1, T-11-10.1, T-11-12.1, T-11-22.1 and T-11-23.1) have increasingly discordant ages, and give an upper intercept age of 779 ± 30 Ma (2σ , $n=5$, $\text{MSWD}=0.74$), if forcing the regression through 0 Ma, suggesting that they are ca. 780 Ma in age, and may have suffered recent Pb loss. The remaining 18 grains are concordant, and give a weighted mean age of 782.2 ± 6.6 Ma (2σ , $n=18$, $\text{MSWD}=0.77$).

4.2. Sample T-12 tuff

A total of 13 zircon grains were analyzed. Their U contents vary from 41.4 to 483 ppm, and Th contents vary from 41.4 to 287 ppm, with Th/U ratios of 0.55 to 1.29. Their individual $^{206}\text{Pb}/^{238}\text{U}$ ages vary from 730 to 2,008 Ma (Suppl. Table 1). One grain (T-12-6.1) has the youngest $^{206}\text{Pb}/^{238}\text{U}$ age of 730 Ma. Two grains (T-12-12.1 and T-12-13.1) give Early Proterozoic $^{206}\text{Pb}/^{238}\text{U}$ ages. The left 10 grains give a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 802 ± 19 Ma (2σ , $n=10$, $\text{MSWD}=3.5$, Fig. 3b). The high MSWD value suggests that this group may not be a simple single population. Of them, six grains give a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 782 ± 12 Ma (2σ , $n=6$, $\text{MSWD}=0.68$, Fig. 3b), identical to the age of the main group in sample T-11; four grains (T-12-1.1, T-12-2.1, T-12-8.1 and T-12-11.1) appear to be significantly older, with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 830 ± 14 Ma (2σ , $n=4$, $\text{MSWD}=0.56$, Fig. 3b), consistent with the age of underlying Huangling granite (837 ± 7 Ma; Gao and Zhang 2009).

4.3. Sample WG-16 tuff

A total of 92 zircon grains were analyzed, and 89 grains yield concordant ages.

Their U contents vary from 13 to 500 ppm, and Th contents vary from 21 to 811 ppm, with Th/U ratios of 0.16 to 3.35. Their individual $^{206}\text{Pb}/^{238}\text{U}$ ages vary from 726 to 3,225 Ma (Suppl. Table 1). Of the 89 concordant grains, 41 grains have $^{206}\text{Pb}/^{238}\text{U}$ ages older than 1,800 Ma. The remaining 48 grains can be divided into four groups (Fig. 3 c): Group I (10 grains) shows a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 900 ± 11 Ma (2σ , $n=10$, MSWD=1.8), Group II (20 grains) has a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 822.3 ± 6.3 Ma (2σ , $n=20$, MSWD=1.3), Group III (12 grains) has a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 785.6 ± 7.9 Ma (2σ , $n=12$, MSWD=1.18), and Group IV (6 grains) has a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 734.4 ± 8.4 Ma (2σ , $n=6$, MSWD=0.55). The ages of Groups II to IV match well with the age spectrum in sample T-12.

4.4. Sample T-13 sandstone

A total of 91 zircon grains were analyzed, and 35 grains yield concordant ages. Their U contents vary from 31 to 521 ppm, and Th contents vary from 55 to 623 ppm, with Th/U ratios of 0.67 to 3.03. Their individual $^{206}\text{Pb}/^{238}\text{U}$ ages vary from 752 to 3,384 Ma (Suppl. Table 1). Of the 35 concordant grains, eight grains have $^{206}\text{Pb}/^{238}\text{U}$ ages older than 2,000 Ma. The remaining 27 grains can be divided into three groups (Fig. 3d): Group I (2 grains) shows a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 889 ± 21 Ma (2σ , $n=2$, MSWD=0.23), Group II (7 grains) has a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 827.8 ± 9.4 Ma (2σ , $n=7$, MSWD=0.60), and Group III (18 grains) has a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 778.9 ± 6.9 Ma (2σ , $n=18$, MSWD=1.4). The ages of Groups I to III in this sample compare well with those in sample WG-16.

4.5. Sample JL-1 tillite

A total of 94 zircon grains were analyzed, and 87 grains yield concordant ages. Their U contents vary from 19 to 602 ppm, and Th contents vary from 24 to 1,081 ppm, with Th/U ratios of 0.17 to 4.71. Their individual $^{206}\text{Pb}/^{238}\text{U}$ ages vary from 645 to 2,833 Ma (Suppl. Table 1). Of the 87 concordant grains, two grains have great error, and 17 grains have $^{206}\text{Pb}/^{238}\text{U}$ ages older than 1,000 Ma. The remaining 68 grains can be divided into five groups (Fig. 3e): Group I (6 grains) shows a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 889 ± 29 Ma (2σ , $n=6$, MSWD=5.4), Group II (34 grains) has a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 820.9 ± 4.9 Ma (2σ , $n=34$, MSWD=1.6), Group III (23 grains) has a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 779.6 ± 7.8 Ma (2σ , $n=23$, MSWD=2.5), Group IV (3 grains) has a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 734 ± 16 Ma (2σ , $n=3$, MSWD=0.08), and Group V (2 grains) has a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 646 ± 12 Ma (2σ , $n=2$, MSWD=0.01).

5. Discussion

5.1 The upper boundary age of Liantuo Formation

T-13 is a sandstone sample taken from the uppermost Liantuo Formation and located just below the tuff sample T-12. Thus, zircons from the sandstone sample T-13 are of detrital origin, and its age distribution can help us to better identify the detrital zircons in the tuff samples T-11, T-12 and WG-16.

In sample T-13, the youngest weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age is 778.9 ± 6.9 Ma, which has also been reported in other lower to upper Liantuo sandstones (Liu *et al.* 2008; Hofmann *et al.* 2011; Wang *et al.* 2013), indicating that zircon grains with age

199 older than 779 Ma (including 779 Ma) of detrital origin. Hence, we consider zircons
200 with the youngest weighted mean age of 782.2 ± 6.6 Ma in the tuff sample T-11 are of
201 detrital origin. Again, we regarded most of zircons in the tuff sample T-12 are of
202 detrital origin, since their ages are greater than 780 Ma; except one grain (T-12-6.1),
203 which has a youngest concordant $^{206}\text{Pb}/^{238}\text{U}$ age of 730 ± 14 Ma (Fig. 3b), and may be
204 of tuffaceous origin. Similarly, we suggest zircons with ages greater than 780 Ma in
205 the tuff sample WG-16 are of detrital origin, while the youngest group zircons, which
206 yield a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 734.4 ± 8.4 Ma (Fig. 3c), are of tuffaceous
207 origin. The ca. 730 Ma age is in good agreement with the youngest weighted mean
208 age (728 ± 5 Ma, $n=8$) in Liantuo sandstones reported by Hofmann *et al.* (2011), but is
209 older than the youngest age (704 ± 6 Ma) in Liantuo sandstones reported by Liu *et al.*
210 (2008). However, if with a deep insight into the data from Liu *et al.* (2008), we find
211 that, there were another two ages of 731 Ma and 737 Ma in sample LT07 taken from
212 the upper part of the Liantuo Formation. This leads us to reckon that sample LT07 in
213 Liu *et al.* (2008) and sample CH-2 in Hofmann *et al.* (2011) could be tuffaceous
214 sandstone, which may have preserved some zircon grains from synchronous
215 volcanism.

216 JL-1 is a tillite sample taken from the Nantuo Formation, zircons of which are
217 generally reworking materials. Hence, its zircon age distribution can also give a
218 constraint on the detrital zircons in the tuff samples T-11, T-12 and WG-16.

219 The age spectra in sample JL-1 are comparable to previous results on Nantuo
220 tillite (Liu *et al.* 2008; Hofmann *et al.* 2011; Wang *et al.* 2013) and on other

Neoproterozoic sedimentary rocks (Duan *et al.* 2012; Shi *et al.* 2013). The youngest age of 646 ± 12 Ma (Fig. 3e) is well consistent with the youngest age (643 ± 7 Ma) reported by Hofmann *et al.* (2011), but is older than the youngest age (600 ± 7 Ma) reported by Liu *et al.* (2008), and also younger than the youngest age (745 ± 8 Ma) reported by Wang *et al.* (2013). The variation in the youngest ages could be due to the lower or upper sampling position, and/or that magmatism of ca. 640 Ma are too weak to be widely recorded in sedimentary rocks in South China. The second youngest age of 734 ± 16 Ma is slightly younger than the second youngest weighted mean age (745 ± 3 Ma, $n=15$) from Hofmann *et al.* (2011) and the youngest age (745 Ma) from Wang *et al.* (2013), but is consistent with the age of 733 Ma in Liu *et al.* (2008), and our age measured for the tuffs from the uppermost Liantuo Formation (T-12: 730 Ma and WG-16: 734 Ma), indicating that these zircon grains were probably derived from weathering of magmatic rocks with ca. 730 Ma age. The other three age spectra of 779 ± 7.8 Ma, 820 ± 4.9 Ma and 889 ± 29 Ma are well matched with the time of the known Neoproterozoic magmatism in the northern Yangtze Block (Zheng 2003; Zhang *et al.* 2008b), indicating the Neoproterozoic magmatic rocks could be a potential provenance providing zircons for the Nantuo tillite (Wang *et al.* 2013).

To summarize, we suggest that the age of tuff from the uppermost Liantuo Formation should be around 730 Ma. Taking together all the seven tuff zircon grains in sample T-12 (T-12-6.1) and sample WG-16 (WG-16-12, WG-16-52, WG-16-70, WG-16-72, WG-16-84, and WG-16-90), we calculate a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 734.1 ± 8.1 Ma (2σ , $n=7$, $\text{MSWD}=0.48$, Fig. 3f), and regard it as the best age

estimation of the tuff, hence constraining the upper boundary age of the Liantuo Formation at ca. 734 Ma.

This age is identical with the result presented by [Du *et al.* \(2013\)](#), who gained 736 ± 5.8 Ma for the upper boundary age of Liantuo Formation, but is older than the ages obtained by [Gao and Zhang \(2009\)](#) and [Lan *et al.* \(2015\)](#), who suggested the upper boundary age of Liantuo Formation was 724 ± 12 Ma and 714 ± 8 Ma respectively. The older age in this study could be related to our sampling position. According to the work of [Lan *et al.* \(2015\)](#), tuffs of 733-735 Ma age existed widely below the top Liantuo Formation by 2.6-22 m. This means that the tuff we sampled may equal to them, and tuff layer of 714 ± 8 Ma age may be eroded in our sampling section. However, we also note that the tuff sample with age of 714 ± 8 Ma have four zircons with ages of 730-740 Ma ([Lan *et al.* 2015](#)). The present of such ages challenges the age of 714 ± 8 Ma to an alternative explanation that it may be a result from suffering loss of radioactive Pb in these zircons. In this case, the upper boundary age of Liantuo Formation was more reasonably estimated to be ca. 734 Ma.

5.2 Stratigraphic correlation

The dispute on the correlation of the Liantuo Formation has continued for several decades. Four different opinions have been hold by various researchers: (1) the Liantuo Formation was correlated with deep-water facies sedimentation during the Chang'an glaciation ([Lu *et al.*, 1985](#)), (2) the Liantuo Formation was correlated with the middle/lower part of Fulu Formation ([Lin 1995](#), [Xue *et al.* 2001](#), [Peng *et al.* 2004](#)), (3) the Liantuo Formation was correlated with the interglacial sedimentary deposition

between the Nantuo and Chang'an glaciations (Ma *et al.* 1984, Yin *et al.* 2003, Wang *et al.* 2006), and (4) the Liantuo Formation belongs to the sedimentation before the Chang'an glaciation, and is comparable to the middle-upper part of Banxi Group/Danzhou Group (Liu *et al.* 1991, Wang and Li 2003, Zhang *et al.* 2008a).

Zircon U-Pb dating of a tuff layer at the uppermost Banxi Group, which underlied directly the Chang'an Formation in Zhijiang and Hunan province, gives an age of 725 ± 10 Ma (Zhang *et al.* 2008a). The youngest age population in the Gongdong Formation at the top of the Danzhou Group, which also underlied directly the Chang'an Formation, gives a mean $^{206}\text{Pb}/^{238}\text{U}$ age of 731.3 ± 4.4 Ma (2σ , $n=8$, MSWD= 1.3) (Wang *et al.*, 2011). Both ages constrain the onset age of Chang'an glaciation at ca. 725 Ma. The age (734.1 ± 8.1 Ma) we obtained in this study from the uppermost Liantuo Formation is approximately consistent with them. Hence, we conclude that the Liantuo Formation is a pre-Chang'an glaciation unit.

Compston (1982) dated a tuff in the upper Liantuo Formation at 740 ± 16 Ma. Ma *et al.* (1984) reported a tuff from the medium-upper Liantuo Formation at 748 ± 12 Ma (2σ , $n=23$), and this age was corrected to 766 ± 18 Ma (2σ , $n=10$, MSWD=2.6) after re-calculation by Zheng (2003). Du *et al.* (2013) constrained the lower boundary age of Liantuo Formation to be ca. 790 Ma. On the other hand, the deposition ages of Banxi/Danzhou Group are inferred to be ca. 814-716 Ma (Lan *et al.* 2015). Combined with these ages, we suggest that the Liantuo Formation is equivalent to the middle-upper part of the Banxi/Danzhou Group.

5.3 Implications for the Neoproterozoic glaciation

The Neoproterozoic glaciations were widely developed in many continents in the world (Arnaud *et al.* 2011), and four episodes were identified, namely Kaigas, Sturtian, Marinoan and Gaskiers glaciation in turn. The Sturtian and Marinoan glaciations were considered to occur globally, while the Kaigas and Gaskiers glaciations were thought to develop locally (Kennedy *et al.* 1998; Condon *et al.* 2005). In South China, the Chang'an and Gucheng glaciations were supposed to correlate to the Sturtian glaciation, and the Nantuo glaciation to the Marinoan glaciation.

Bowring *et al.* (2007) obtained an ID-TIMS U–Pb zircon age of 711.5 ± 0.2 Ma from the Gubrah Formation, and interpreted it to represent the most approximate onset age of the Sturtian glaciation in Oman, while Macdonald *et al.* (2010) reported an ID-TIMS U–Pb zircon age of 716.5 ± 0.2 Ma from a tuff bed within the diamictite of the Upper Mount Harper Group, and regarded it as the onset age of the Sturtian glaciation in northwestern Canada. The age we obtained in this study constrained the onset of Chang'an glaciation to be later than 734.1 ± 8.1 Ma, but earlier than 646 Ma (the youngest detrital zircon age in the basal Nantuo tillite). Therefore, the Chang'an glaciation is in general corresponded to the Sturtian glaciation. Whether they are synchronous or not is still unclear and needs a further study.

The oldest glaciation in South Namibia regarded as the Kaigas diamictite was dated at ca. 741–780 Ma, the Jequitai diamictite in Brazil was dated at ca. 740 Ma (Zheng *et al.* 2007), and the Bayixi glaciation in the Tianshan Mountains was dated at 740–725 Ma (Zhu *et al.* 2011). From these ages, a possible age of the Kaigas glaciation at about 760 to 720 Ma can be inferred. The age of 734.1 ± 8.1 Ma we

obtained in this study is roughly consistent with the inferred Kaigas ice age. Thus, it is possible that this age has dated the continental glaciation of this episode in South China, lending support to the previous inference by Zheng *et al.* (2007) for the presence of the Kaigas iceage in South China.

6. Conclusion

The tuff from the uppermost Liantuo Formation gives a U-Pb age of 734.1 ± 8.1 Ma, which constrains the upper boundary age to ca. <734 Ma. The Liantuo Formation is a pre-Chang'an glaciation unit, and is equivalent to the middle-upper part of the Banxi/Danzhou Group.

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App. Suppl. Table 1 U-Pb dating results of zircons from the uppermost Liantuo and lowermost Nantuo Formation in Three Gorges area, South China

Figure captions:

Fig. 1 Geological setting and sampling locations in Three Gorges area, South China (revised from [Zhu *et al.* 2007](#)).

Fig. 2 Cathodoluminescence images of representative zircons from the uppermost Liantuo Formation and the lowermost Nantuo Formation in Three Gorges area, South China (scale bars are 100 μm).

Fig. 3 Concordia diagram of zircon U-Pb dating for sample: a) T-11, b) T-12, c) WG-16, d) T-13, e) JL-1 and f) seven tuffaceous zircons from the uppermost Liantuo Formation in Three Gorges area, South China. WMA: weighted mean age

Figure 1

Figure 2

Figure 3