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Detrital zircon record of Neoproterozoic active-margin sedimentation in the eastern Jiangnan Orogen, South China

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ABSTRACT

Precambrian sedimentary sequences in the eastern Jiangnan Orogen, South China, include the Neoproterozoic Shuangqiaoshan and Xikou Groups and the overlying Nanhua Sequence. U–Pb ages of detrital zircons provide tight constraints on the deposition of the Shuangqiaoshan and Xikou Groups at 831–815 Ma and 833–817 Ma, respectively. Rocks from the lower parts of these strata contain dominantly Neoproterozoic detritus with a pronounced age peak at 830–850 Ma, interpreted to be derived from a magmatic arc that has been mostly eroded. This magmatic arc was associated with sedimentation characterized by compositionally immature sediments with dominant early-Neoproterozoic (~860–810 Ma) zircons that have variable $\varepsilon_{Hf(t)}$ values of −21.5 to 14.8. The upper parts of these strata, uncomfortably underlain by the low units, are molasse-type assemblages with additional input of pre-Neoproterozoic detritus, representing sediments accumulated in a retro-arc foreland basin associated with the Jiangnan Orogen.

Combining four samples from the Nanhua Sequence, three major magmatic activities at 2.50–2.35 Ga, 2.10–1.90 Ga and 980–810 Ma in the source areas are identified. The older two events are characterized by reworking of pre-existing continental crust. Grenville magmatism and juvenile crust were insignificant in the eastern Jiangnan Orogen. Neoproterozoic zircons reflect generation of juvenile crust at 980–860 Ma, involvement of both juvenile and recycled materials at 860–810 Ma and reworking of pre-existing crust at 805–750 Ma, corresponding to island arc, continental magmatic arc and post-collisional rifting stages in the eastern Jiangnan Orogen.

1. Introduction

The Jiangnan Orogen in South China witnessed the amalgamation of the Yangtze and Cathaysia Blocks. Recent studies of sedimentary and igneous rocks have demonstrated that the Jiangnan Orogen is a Neoproterozoic rather than Mesoproterozoic tectonic unit, but the timing and evolution of this orogen are still matters of debate (Wang et al., 2006, 2007, 2012b; Zheng et al., 2008; Li et al., 2009; Zhao et al., 2011). The Jiangnan Orogen was thought to be part of the worldwide Grenville Orogen, formed by the collision between the Yangtze and Cathaysia Blocks (Li et al., 2007, 2009), followed by extensive rift-related magmatism at ca. 820 Ma (Wu et al., 2006; Li et al., 2008c, 2009, 2010a; Zheng et al., 2008). On the other hand, this orogeny is thought to have lasted until ca. 830 Ma or even later, followed by post-extensional magmatism beginning at ca. 800 Ma (Li, 1999; Zhao and Cawood, 1999; Wang et al., 2006, 2011b, 2012b; Zhao et al., 2011; Zhang et al., 2012b).

The eastern segment of the Jiangnan Orogen is crucial for the understanding of the orogenic cycle because it contains widespread sedimentary sequences, igneous plutons and two major ophiolite belts, that witness the final amalgamation between the Yangtze and Cathaysia Blocks (Li et al., 2009) (Fig. 1). In past decades, numerous studies examined the petrogenesis and tectonic affinity of igneous rocks (Wu et al., 2006; Li et al., 2007, 2008b, 2009; Zheng et al., 2008; Zhang et al., 2012a), but associated sedimentary sequences in the eastern Jiangnan Orogen are poorly understood, due in part to unresolved stratigraphy, incomplete biostratigraphic data, poor exposure and strong overprint by later deformation. These sedimentary sequences in the eastern Jiangnan Orogen include the Shuangqiaoshan Group in northern Jiangxi Province and the Xikou Group in southern Anhui Province (Fig. 1), which were interpreted to have formed in a back-arc basin associated with Mesoproterozoic NW-dipping (current coordinates) oceanic subduction beneath the Yangtze Block (Cheng and Wang, 2000; Huang et al., 2003). However, dating results of the Shuangqiaoshan

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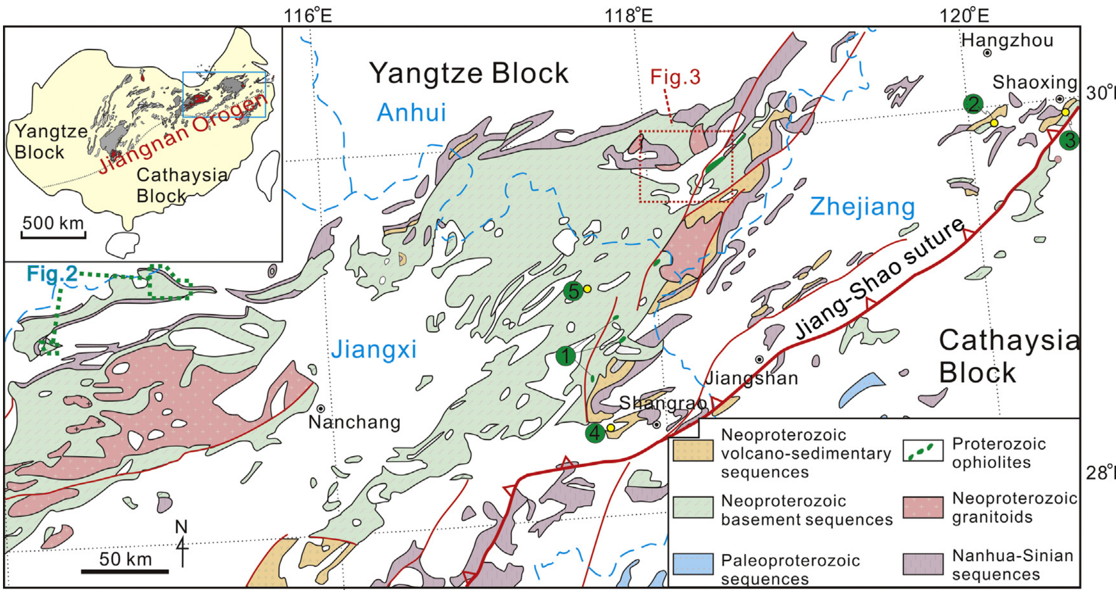

Fig. 1. Distribution of Precambrian units in the eastern segment of the Jiangnan Orogen (modified after Ma et al., 2002; Wang et al., 2011b). Inserted map on the top left showing location of the Jiangnan Orogen in the South China Craton. Blue dash line shows the boundary between provinces. (1) ca. 970–880 Ma northern Jiangxi ophiolitic complex (Li and Li, 2003; Li et al., 2008a); (2) ca. 930–890 Ma Shuangxiwu volcanic rocks (Li et al., 2009); (3) ca. 910–900 Ma Pingshui plagiogranite (Ye et al., 2007; Chen et al., 2009b); (4) ca. 848 Ma Gangbian alkaline complex (Li et al., 2010b); (5) ca. 850 Ma Zhenzhushan volcanic rocks (Li et al., 2010a). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Group do not support this model and it has been proposed that these sequences were deposited in a retroarc foreland basin, synchronous with the amalgamation of the Yangtze and Cathaysia Blocks (Wang et al., 2008). More recent studies suggest the Shuangqiaoshan Group likely formed at ca. 830 Ma (Gao et al., 2008; Zhao et al., 2011), which is taken as the timing for the Jiangnan Orogeny (Zhao et al., 2011). These sequences are also suggested to have formed in an early-phase of rifting that post-dated the Jiangnan Orogen (Li et al., 2009) based on ca. 850 Ma dolerite dykes (Li et al., 2008b) and bimodal volcanic rocks (Li et al., 2010a).

Due to the strong later deformation of these sedimentary strata and intensive reworking and erosion of the pre-existing igneous provenance (Wu et al., 2006; Zheng et al., 2008), one possible way to examine the timing and evolution of orogenic cycles is to unearth the information contained by detrital zircons (Cawood and Nemchin, 2001; Liu et al., 2011; Wang et al., 2011c). Detrital zircon age spectra may contain information about various sources linked to eustatic, depositional and tectonic change (Wang et al., 2010b, 2012a), and thus can provide insight into the basin-orogen coupling (Horton et al., 2010; Myrow et al., 2010). Hf isotopes of zircons can be used for understanding juvenile or reworked zircon-hosting magma (Griffin et al., 2004; Xia et al., 2006; Zheng et al., 2006b, 2007; Zhu et al., 2011; Liu et al., 2012; Wang et al., 2012a), thought to be one of the most discriminating features among plume, rift and arc-related magmatism (Zheng et al., 2008).

In this paper, we present the first integrated study of U–Pb ages and Hf isotopic compositions of detrital zircons from the major Neoproterozoic sedimentary strata in the eastern Jiangnan Orogen. This new dataset allows us to refine the depositional age of the hosting strata and to track provenance changes. The provenance characteristics can help define the relationship between sedimentation and tectonism and potential link to the configuration of the supercontinent Rodinia.

2. Geological background

The South China Craton comprises the Yangtze and Cathaysia Blocks, with the Jiangnan Orogen being the southeastern part of the Yangtze Block. The Cathaysia Block has voluminous Phanerozoic igneous rocks with rarely exposed Precambrian rocks (Yu et al., 2010). Metamorphic complexes in the eastern Cathaysia Block were traditionally thought to be Paleo-Mesoproterozoic to Neoarchean basement (Li, 1997), but recent studies suggest that these complexes formed in the Neoproterozoic or even younger (Wan et al., 2007; Li et al., 2010c). A Paleoproterozoic orogen is inferred on the basis of abundant Paleoproterozoic granites and metamorphic rocks in the eastern Cathaysia Block (Yu et al., 2009). Precambrian rocks in the Yangtze Block are sporadically exposed and include Archean Tonalite–Trondhjemite–Granodiorite (TTG) in the north (Qiu et al., 2000; Gao et al., 2011) and Paleoproterozoic strata in the west (Sun et al., 2009; Zhao et al., 2010b), whereas Neoproterozoic sedimentary sequences and igneous plutons are widespread (Zhou et al., 2002b; Li et al., 2003a,b; Wang et al., 2006, 2010b; Zhao and Zhou, 2007a; Zheng et al., 2008; Zhao et al., 2011). The sedimentary cover of the Yangtze Block consists mainly of folded Paleozoic and Lower Mesozoic strata formed in a shallow marine environment (Yan et al., 2003; Chu et al., 2012).

Precambrian rocks in the eastern Jiangnan Orogen include the Mesoproterozoic Tianli schist (Li et al., 2007), early-Neoproterozoic Shuangxiwu volcanic-clastic sequences (Ye et al., 2007; Li et al., 2009), mid-Neoproterozoic sedimentary strata (Gao et al., 2008; Zhao et al., 2011), igneous plutons (Zhong et al., 2005; Wu et al., 2006; Li et al., 2008b, 2009, 2010b; Zheng et al., 2008), and ophiolitic complexes (Bai et al., 1986; Zhou, 1989; Zhang et al., 2012a). Mid-Neoproterozoic sedimentary strata including the Shuangqiaoshan and Xikou Groups in the eastern Jiangnan Orogen are overlain unconformably by a post-orogenic extensional basin deposits as the Nanhua Sequence. Granitoid plutons intruding the sedimentary sequences are represented by the Jiuling pluton in NW Jiangxi (Li et al., 2003a; Zhong et al., 2005) and the Xucun, Shexian and Xiuning plutons in southern Anhui (Li et al., 2003a; Wu et al., 2006). The NE-SW trending ophiolite complexes are in tectonic contact with the Shuangqiaoshan and Xikou Groups (Bai et al., 1986).

A stratigraphic framework of the sedimentary succession in northwestern Jiangxi and southern Anhui Provinces is outlined in Figs. 2 and 3.

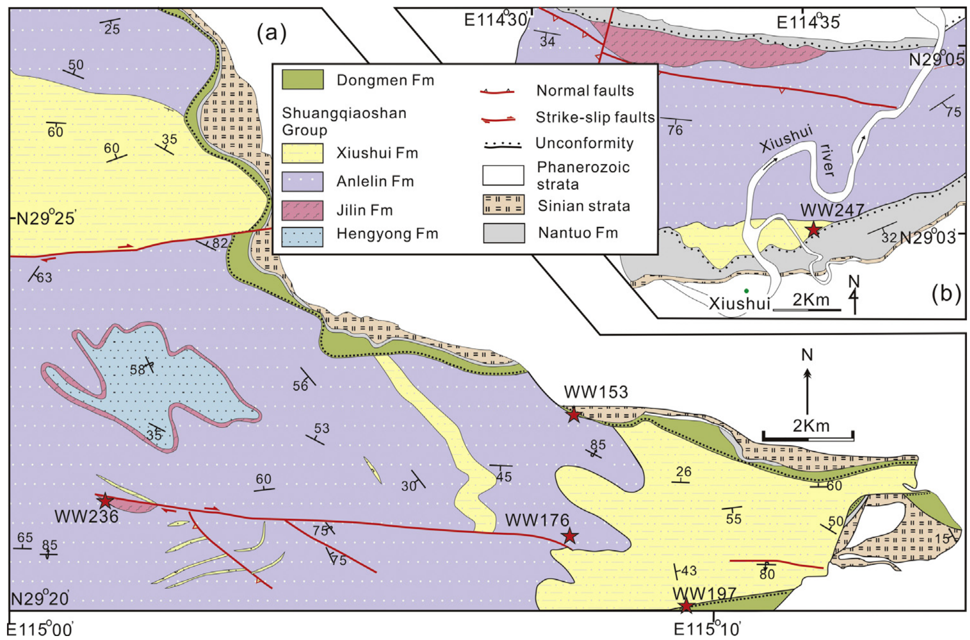

Fig. 2. Sketch map showing the distribution of the Shuangqiaoshan Group and Nanhua sequence in the northwestern Jiangxi Province.

2.1. Shuangqiaoshan Group

The Shuangqiaoshan Group consists of silty, volcanic clastic detritus that gradually coarsens upwards, and has partially preserved primary sedimentary structures. Based on primary sedimentary structure and lithology, this strata is divided into the Hengyong, Jilin, Anlelin and Xiushui Formations (Fms) from the base upward (Fig. 4) (BGMRJX, 1996).

The Hengyong Fm comprises of gray to reddish, feldspar-lithic sandstone, feldspar-quartz sandstone and siltstone. The sandstone consists dominantly of subangular to subrounded, lithic fragments, with lesser amounts of quartz and feldspar. Graded bedding, banded bedding, and scour and slump marks are well developed.

The Jilin Fm is conformable with both its underlying and overlying strata and contains mostly purplish-red, silty slate, usually referred to as a red bed sequence. Within the silty slate are interbeds of siltstone and sandstone (Fig. 5a). Cross-bedding, graded bedding and partial Bouma sequences are common.

The Anlelin Fm is widespread in northern Jiangxi province and is composed of thick gray to charcoal gray flysch with some tuffaceous siltstone and slate. In addition to greywacke, there are fine-grained, tuffaceous beds, feldspar-, quartz-rich sandstone and tuffaceous lithic-quartz sandstone. Lithic components include andesite, siliceous rocks, granite, basalt and silty mudstone (Wu, 2007). Cross-bedding, parallel bedding, scour and slump marks, and partial Bouma sequences are well developed (Fig. 5b and c).

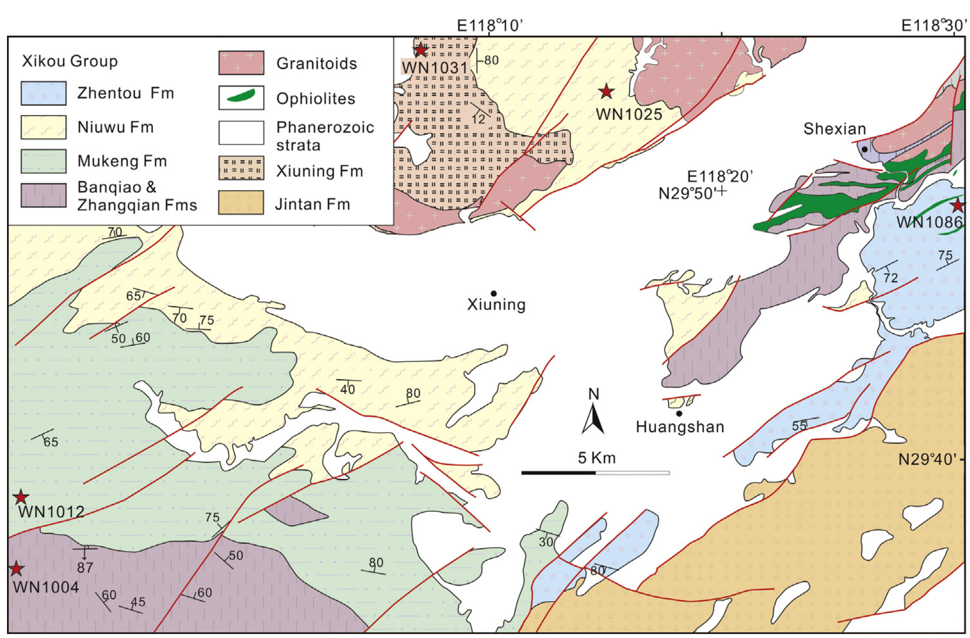

Fig. 3. Sketch map showing the distribution of the Xikou Group as well as other Neoproterozoic units in the southern Anhui Province. Faults in this figure refers to legend in Fig. 2.

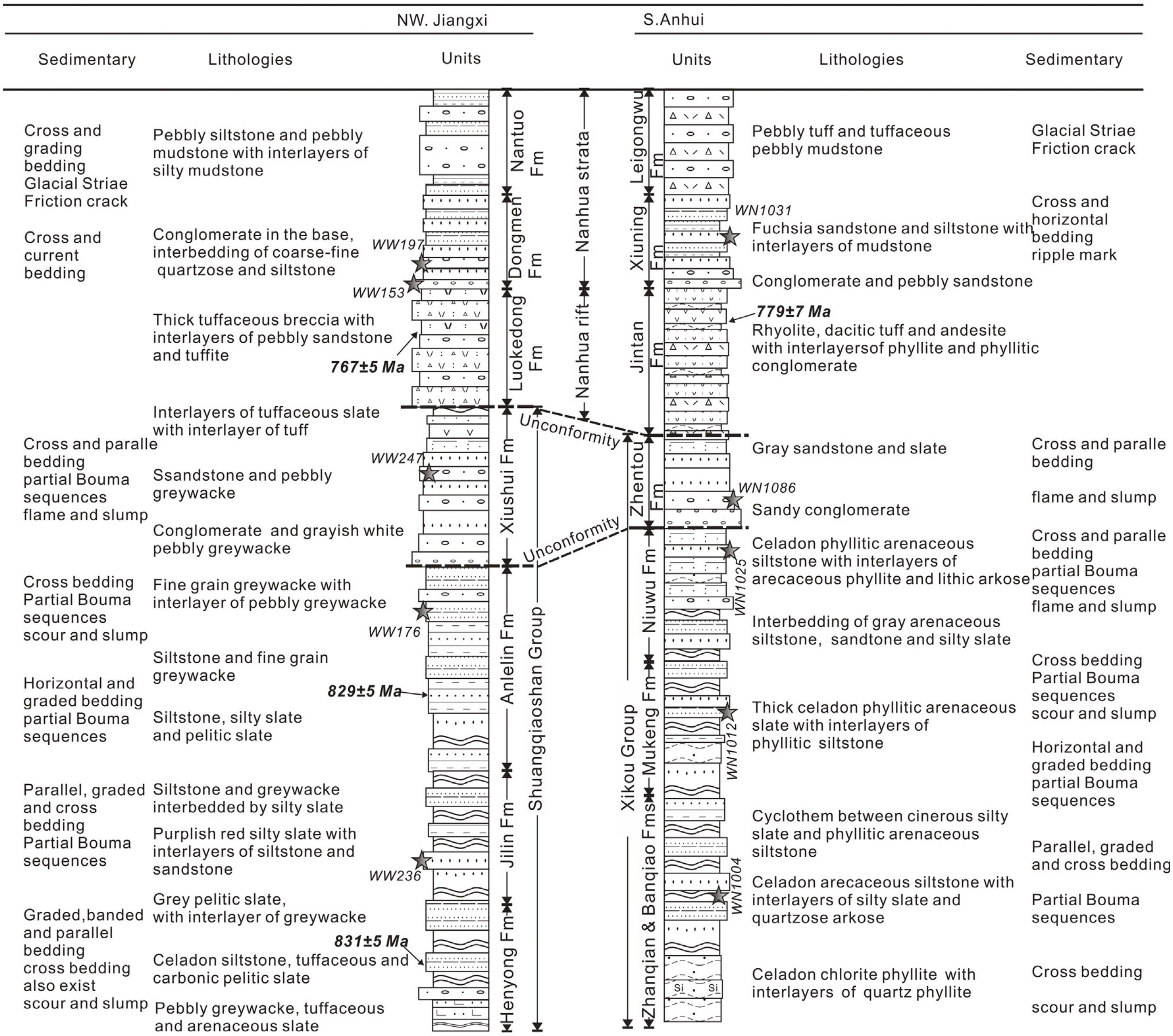

Fig. 4. Stratigraphy of the major Neoproterozoic sedimentary units in the eastern Yangtze Block. The Zhentou Fm is tentatively considered as the upper part of the Xikou Group, considering its similarity with the Xiushui Fm in the upper part of the Shuangqiaoshan Group. The columns are not strictly to scale. Stars and italic numbers represent sample location relative to stratigraphic column and sample numbers. Bold italic numbers represent the reported ages of volcanic tuffs; see text for details and discussion.

The Xiushui Fm, overlying the Anlelin Fm, has a basal ca. 2.5 m thick layer of conglomerate (Fig. 5d). Conglomerate contains gravels of variable sizes that are parallel to the orientation of the sedimentary layer. In some cases, this conglomerate layer is absent and the bottom of the Xiushui Fm is marked by a 40-m-thick layer of grayish-white, pebbly sandstone or quartz conglomerate. The upper part of the Xiushui Fm consists mainly of grayish-white, gray or green yellow, tuffaceous slate interbedded with tuff. Cross-bedding, parallel-bedding and partial Bouma sequences are also common in this unit.

2.2. Xikou Group

Widely distributed in southern Anhui Province, the Xikou Group has experienced weak to strong deformation and low-greenschist facies metamorphism, whereas graded and crossing bedding are perfectly preserved (BGMRAH, 1984). The Xikou Group is divided into the Zhangqian, Banqiao, Mukeng and Niuwu Fms upwards (Fig. 4) (BGMRAH, 1984). The Zhentou Fm unconformably overlies the Niuwu Fm and is tentatively interpreted as the upper part of the Xikou Group in this study, because of its similarity with the Xiushui Fm of the Shuangqiaoshan Group.

The Zhangqian Fm comprises green sericite-quartz schist, arenaceous to silty phyllite and sericite-chlorite-quartz schist. Original pelitic rocks have been metamorphosed to phyllite during regional metamorphism, resulting in well developed phyllitic structure. Spotted or banded magnetite is common and interlayers of basic volcanic rocks are also sporadically present.

Dark to gray phyllite, phyllitic slate and feldspar quartz sandstone are the dominant rocks of the Banqiao Fm that overlies the Zhangqian Fm conformably. Rhythmic layering between sandstone and slate are commonly observed and lenticular sandstone is developed probably due to current lamination (Fig. 5e). Feldspar and quartz with a few lithic detritus are the dominant clastic fragments, which is hosted by cemented fine-grained sericite and clay minerals.

The Mukeng Fm is composed of thick gray to grayish-green silt- to arenaceous-siliciclastic rocks dominated by fine-grained siltstone and sericite-chlorite slate, whereas fine-grained sandstone occurs as interlayers in the slate. Graded and parallel bedding, are

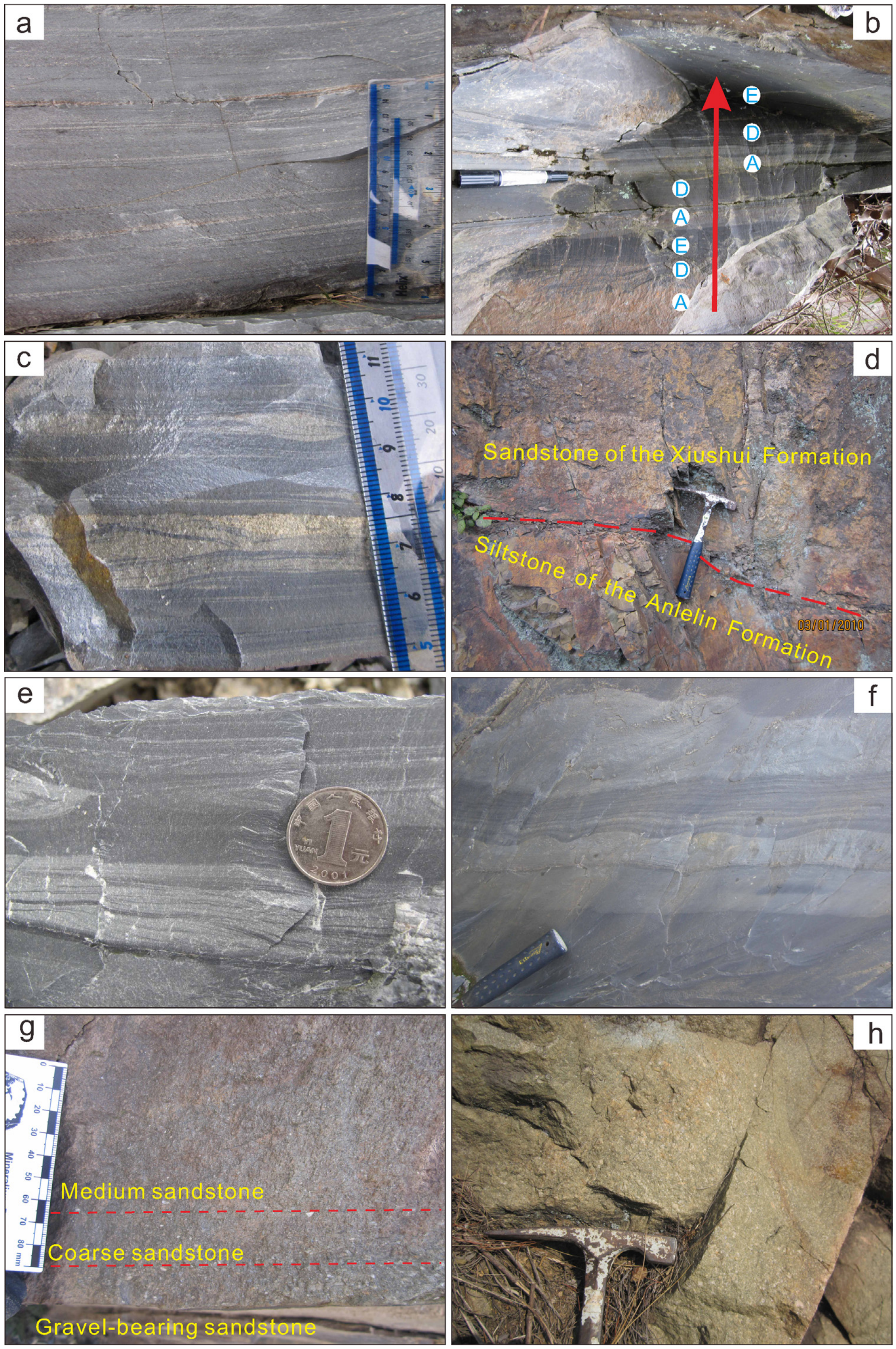

Fig. 5. Structures of sedimentary rock investigated during this study: (a) parallel bedding and rhythmic layers between reddish siltstone and sandstone in the Jilin Formation; (b) partial Bouma sequences in the Anlelin Fm; (c) Graded and cross bedding in the Anlelin Fm; (d) boundary between the Anlelin and Xiushui Fms. The sandstone interlayers in the silty slate are lenticular which may be result of wave current in the Banqiao Formation; (e) lenticular and cross bedding developed between gray siltstone and slate; (f) wavy contoured bed with different wavelength and slump structure in the Mukeng Fm; (g) grading bedding developed in the Niuwu Fm; (h) coarse quartz sandstone from the Xiuning Fm.

well preserved (Fig. 5f). Contorted bed with varying wavelength formed by wave current and slump structure are observed (Fig. 5f), suggesting fast sedimentation in a turbulent environment.

The Niuwu Fm is typical of turbiditic deposition, consisting of thick layer of grayish-green to grayish-purple litharenite and thin layer of medium-grained sandstone. Gravel-bearing sandstone and coarse- to medium-grained sandstone form well developed graded bedding (Fig. 5g), typical of turbidite. Features of shallow water and storm flow deposits are observed in the upper part of the Niuwu Fm, where ashy black slate is interbedded with thick layers of sandstones.

Unconformably underlain by the Niuwu Fm, the Zhentou Fm contains conglomerate, gravel-bearing sandstone and gravel-bearing silty slate from the base to the top. Angular to subangular gravels of the stratigraphically basal conglomerate are poorly-sorted with diameters ranging between 1 and 8 cm and are dominated by fragments of slate, silicolite, granite and quartz. Gravel-bearing sandstone and slate from the upper Zhentou Fm contain gravels smaller and less than the conglomerate and quartzite, volcanic rocks and siltstone are the dominant rock fragments.

2.3. Nanhua Sequence

The Nanhua Sequence is a set of glacial sedimentary rocks corresponding to the Cryogenian System defined by the International Commission on Stratigraphy (Plumb, 1991). The Nanhua Sequence includes the lower Dongmen and Xiuning Fms and the upper Nantuo and Leigongwu Fms. The Dongmen and Xiuning Fms, correlated with the pre-glacial Liantuo Fm in the central Yangtze Block, are composed largely of a clastic succession unconformably underlain by the Shuangqiaoshan and Xikou Groups, respectively. The basal parts of these units consist of conglomerate and coarse quartzose sandstone, formed in an alluvial fan or fluvial environment. The Nantuo and Leigongwu Fms, are widespread in the entire Yangtze Block, are composed of diamictite typical of tillite formed during the Neoproterozoic "snowball Earth" event (Zheng, 2003).

3. Sampling and analytical methods

Ten samples were selected across major stratigraphic units for zircon dating in order to constrain depositional ages, provenance and tectonic setting of the sedimentary basin. Zircon was separated using standard heavy-liquid and magnetic separation from ca. 5 kg samples. Zircon separates were mounted in epoxy and polished.

U–Pb isotope analysis of zircon was performed by LA-ICP-MS at the State Key Laboratory of Ore Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang. A GeoLasPro laser-ablation system (Lamda Physik, Gottingen, Germany) and Agilent 7700x ICP-MS (Agilent Technologies, Tokyo, Japan) were combined for the experiments. The 193 nm ArF excimer laser, homogenized by a set of beam delivery systems, was focused on the zircon surface with the fluence of 10 J/cm^2. The ablation protocol employed a spot diameter of 32 μm at 5 Hz repetition rate for 45 s (equating to 225 pulses). Helium was applied as a carrier gas to allow efficient transportation of aerosol to the ICP-MS. Zircon 91500 was used as the primary standard to correct elemental fractionation. Meanwhile, zircon GJ-1 (Jackson et al., 2004) and Plešovice (PL, Sláma et al., 2008) were analyzed as unknown samples for quality control. Trace element compositions of zircon were external calibrated against NIST SRM 610 with ^{91}Zr as the secondary standard. Raw data reduction was performed off-line by *ICPMSDataCal* (Liu et al., 2010) and the results were reported with 2σ errors. Reported uncertainties (2σ) of the ^{206}Pb/^{238}U ratio were propagated by quadratic addition of the external reproducibility (2 SD%) of standard zircon 91500 during the analytical session and the within-run precision of each analysis (2 SE%; standard error) (cf. Gerdes and Zeh, 2006, 2009). Common Pb correction was corrected using the MS Excel program "ComPbcorr# 3.15"(Andersen, 2002). Data were processed using the ISOPLOT program (Luding, 2003). The analytical results of standard and reference materials are presented in Supplementary Table 1. The concordant ages of analyzed GJ-1 (601 ± 17 Ma, 2σ, MSWD = 1.3) and PL (334.2 ± 7.5 Ma, 2σ, MSWD = 2.9) are consistent with the reported or recommended values (GJ-1: 599.8 ± 1.7 Ma, 2σ, Jackson et al., 2004; PL: 337.13 ± 0.37 Ma, 2σ, Sláma et al., 2008).

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.precamres.2013.05.013.

Hf isotopic analysis of zircons were conducted using a Resonetics Resolution M-50 193 nm excimer laser ablation system, attached to a Nu Plasma HR multi-collector inductively coupled plasma mass spectrometer (MC-ICPMS) at the University of Hong Kong. Hf isotopes were obtained with a beam diameter of 55 μm, pulse rate of 10 Hz and energy density of 15 J/cm^2. Atomic masses 172 to 179 were simultaneously measured in a static-collection mode. Isobaric interference of ^{176}Yb with ^{176}Hf was corrected against the ^{176}Yb/^{172}Yb ratio of 0.5886 (Chu et al., 2002). Instrumental mass bias correction of Yb isotope ratios were normalized to ^{172}Yb/^{173}Yb of 1.35274 (Chu et al., 2002) and Hf isotope ratios to ^{179}Hf/^{177}Hf of 0.7325 (Patchett et al., 1981) using an exponential law. A relationship between Yb and Hf of $\beta_{Yb} = 0.872\beta_{Hf}$ are obtained and used for the mass bias offset (cf. Xu et al., 2004). Interference of ^{176}Lu with ^{176}Hf was corrected by measuring the intensity of the interference-free ^{175}Lu isotope and using a recommended ^{176}Lu/^{175}Lu ratio of 0.02655 (Machado and Simonetti, 2001). Due to insignificant contribution of signal intensity of ^{176}Lu on ^{176}Hf (generally <1%), the mass bias of Lu isotopes (β_{Lu}) can be assumed to be identical to β_{Hf} (cf. Iizuka and Hirata, 2005). Quality control was made by measuring zircon standard 91500 and GJ-1 for the unknown samples during the analyses to evaluate the reliability of the analytical data (Supplementary Table 2).

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.precamres.2013.05.013.

4. Analytical results

Results of U–Pb dating are present in Supplementary Table 3 and concordant diagrams (Figs. 6 and 7). Detrital zircons with concordant U–Pb ages (with concordance between 90 and 110%) were selected for in situ Hf isotopic analyses and the results are given in Supplementary Table 4.

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.precamres.2013.05.013.

4.1. The Shuangqiaoshan Group

4.1.1. The Jilin Fm

Sample WW236, a reddish medium-grain sandstone from the Jilin Fm, contains a predominant population of Neoproterozoic zircon grains with two major age peaks at ca. 826 and ca. 850 Ma and three sub-peaks at ca. 870, 895 and 950 Ma (Fig. 8). Pre-Neoproterozoic zircon grains are rare, with ages grouping at 1.15–1.26 Ga, 1.76–1.76 Ga and 1.87–2.22 Ga. One Archean zircon grain has a ^{207}Pb/^{206}Pb age of 2.59 Ga. Generally, all zircon grains have oscillatory zoning but are variably rounded (Fig. 6a).

Neoproterozoic zircon grains have highly variable $\varepsilon_{Hf(t)}$ values (−16.8 to 14.8) and two stage hafnium model age (T_{DM2}) (781–2758 Ma) (Fig. 9). Two Mesoproterozoic zircon grains have identical ages but different $\varepsilon_{Hf(t)}$ values (3.3 and 10.8) and T_{DM2} ages (1.84 and 1.38 Ga). Five Paleoproterozoic zircon grains have variable $\varepsilon_{Hf(t)}$ values (−8.1 to 7.2) and T_{DM2} ages (2.19–2.95 Ga).

4.1.2. The Anlelin Fm

Sample WW176 is a combination of chips from a series of thick layers of fine-medium grained siltstones in the middle Anlelin Fm. Neoproterozoic (795–978 Ma) euhedral and oscillatory-zoned (Fig. 6b) grains are the dominant population and have two major age peaks at ca. 818 Ma and ca. 843 Ma (Fig. 8). Nine Pre-Neoproterozoic zircons have ^{207}Pb/^{206}Pb ages scattering from 1.14 Ga to 2.46 Ga. These zircon grains are generally subhedral to rounded with partly preserved oscillatory zoning (Fig. 6b).

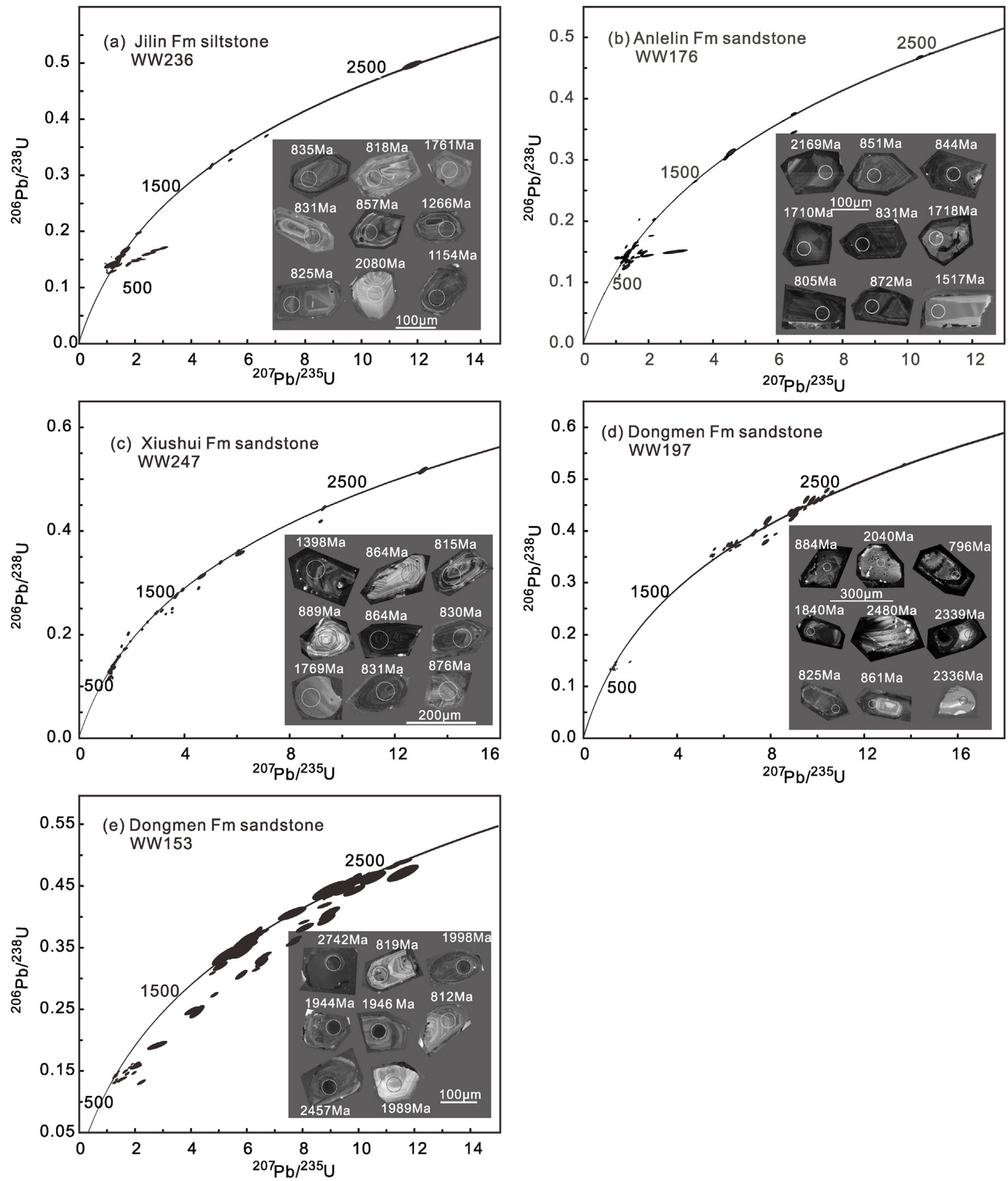

Fig. 6. Concordia diagrams showing results of U–Pb dating of detrital zircon grains from the Shuangqiaoshan Group and Dongmen Fm. Inserted diagrams show representative CL images and concordant ages (for ages < 1.0 Ga, $^{206}Pb/^{238}U$ ages are presented and for ages > 1.0 Ga, $^{207}Pb/^{206}Pb$ ages are presented) of individual analyzed grains.

Mid-Neoproterozoic (795–850 Ma) zircon grains have positive $\varepsilon_{Hf(t)}$ values (1.2 to 15.1) and T_{DM2} ages ranging continuously from 739 to 1653 Ma (Fig. 9). In contrast, Early-Neoproterozoic (851–978 Ma) zircon grains have highly variable $\varepsilon_{Hf(t)}$ values (−17.7 to 14.7) and T_{DM2} ages (742–2836 Ma). Two Mesoproterozoic (1.14 and 1.35 Ga) zircon grains have identical $^{176}Hf/^{177}Hf$ ratios (0.282232 and 0.282216), whereas the other Mesoproterozoic grain (1.52 Ga) has a low $^{176}Hf/^{177}Hf$ ratio of 0.281980.

4.1.3. The Xiushui Fm

Sample WW247, a coarse sandstone from the Xiushui Fm, contains predominant Neoproterozoic grains, with five age peaks at ca. 815, 825–835, ca. 869, ca. 900 and ca. 930 Ma (Fig. 8). All Neoproterozoic grains are euhedral and have well preserved oscillatory zoning. Pre-Neoproterozoic zircon grains have ages scattering from 1.01 to 2.68 Ga. All these zircon grains are subhedral to rounded and show partially oscillatory zoning or uniform internal structure (Fig. 6c).

Neoproterozoic (811–935 Ma) zircon grains have variable $\varepsilon_{Hf(t)}$ values (−16.0 to 13.7) and T_{DM2} (742–2727 Ma) (Fig. 9). Eight Mesoproterozoic (1.01–1.49 Ga) zircon grains have a wide range of $\varepsilon_{Hf(t)}$ values (−9.7 to 6.9) and T_{DM2} (1.42–2.47 Ga). Zircon grains with ages between 1.57 and 1.63 Ga have a wide range of $\varepsilon_{Hf(t)}$ values (1.0–13.8) and T_{DM2} (1.43–2.26 Ga). Paleoproterozoic to later

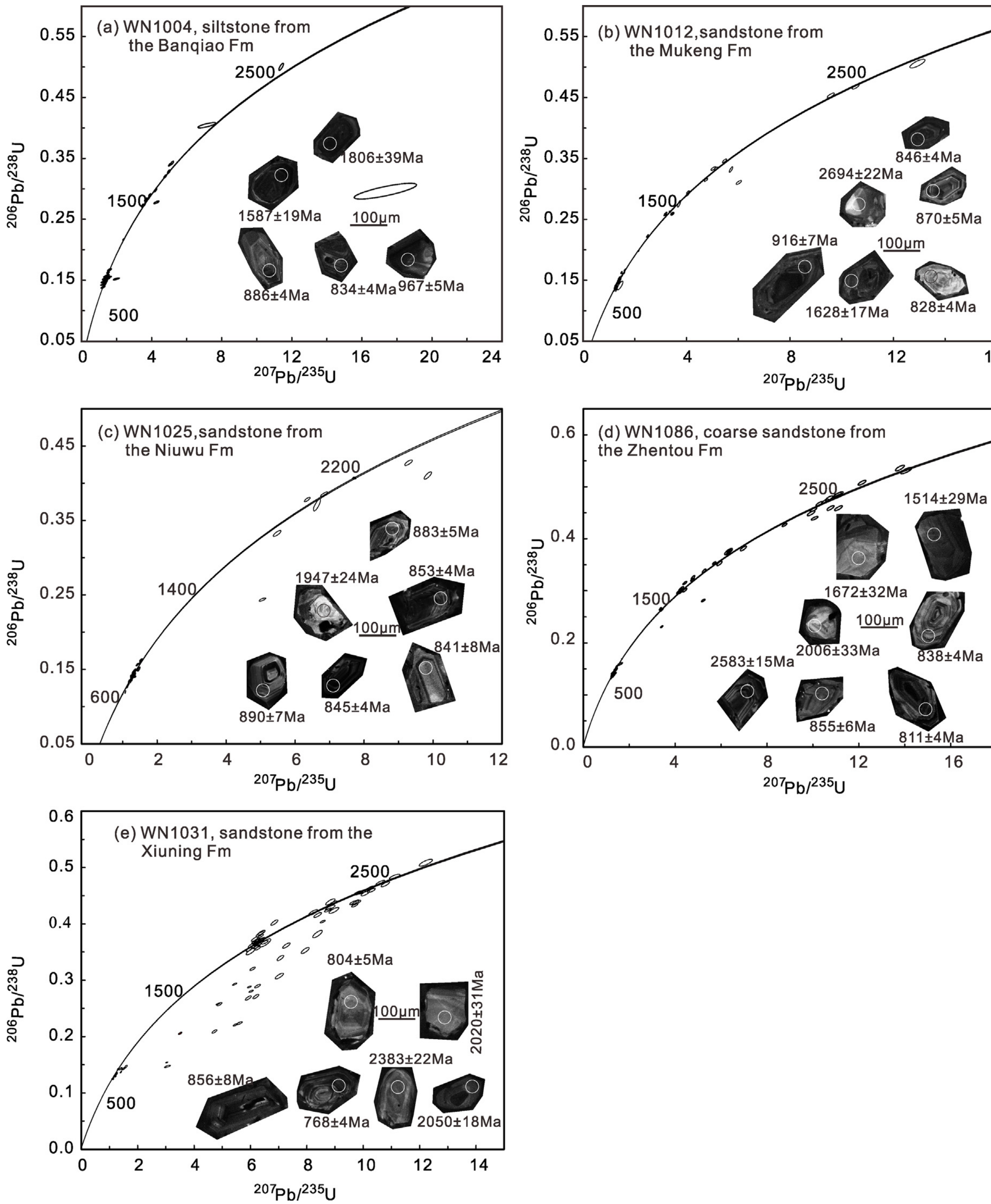

Fig. 7. Concordia diagrams showing results of U–Pb dating of detrital zircon grains from the Xikou Group and Xiuning Formation. Inserted diagrams show representative CL images and concordant ages (for ages < 1.0 Ga, $^{206}Pb/^{238}U$ ages are presented and for ages > 1.0 Ga, $^{207}Pb/^{206}Pb$ ages are presented) of individual analyzed grains.

Archean zircon grains have negative $\varepsilon_{Hf(t)}$ values (−16.1 to −2.7) and old T_{DM2} (2.77–3.53 Ga).

4.2. The Xikou Group

4.2.1. The Banqiao Fm

Zircon grains from a gray phyllitic siltstone WN1004 are fairly small (<100 μm), mostly euhedral and show oscillatory zoning with rare preexisting cores and overgrowth rims (Fig. 7a). These detrital zircon grains are predominantly Neoproterozoic and have ages ranging from 831 to 990 Ma with four age peaks at ca. 833, 860, 884 and 932 Ma (Fig. 8). There are also a few Meso- to Paleoproterozoic zircon grains with ages scattering from 1.21 to 2.46 Ga.

Nearly all Neoproterozoic zircon grains have positive $\varepsilon_{Hf(t)}$ values (1.2–14.0), except for two zircon grains with negative $\varepsilon_{Hf(t)}$ values (−4.1 and −6.3) (Fig. 10). Three Mesoproterozoic (1.21 to 1.53 Ga) zircon grainshave similar $\varepsilon_{Hf(t)}$ values (−5.0 to −2.3) and T_{DM2} (2.32–2.45 Ga). All Paleoproterozoic zircon grains, except for the 1.81 Ga zircon grain ($\varepsilon_{Hf(t)}$ = 7.9), have negative $\varepsilon_{Hf(t)}$ values (−8.6 to −1.9) and T_{DM2} (2.59–3.16 Ga).

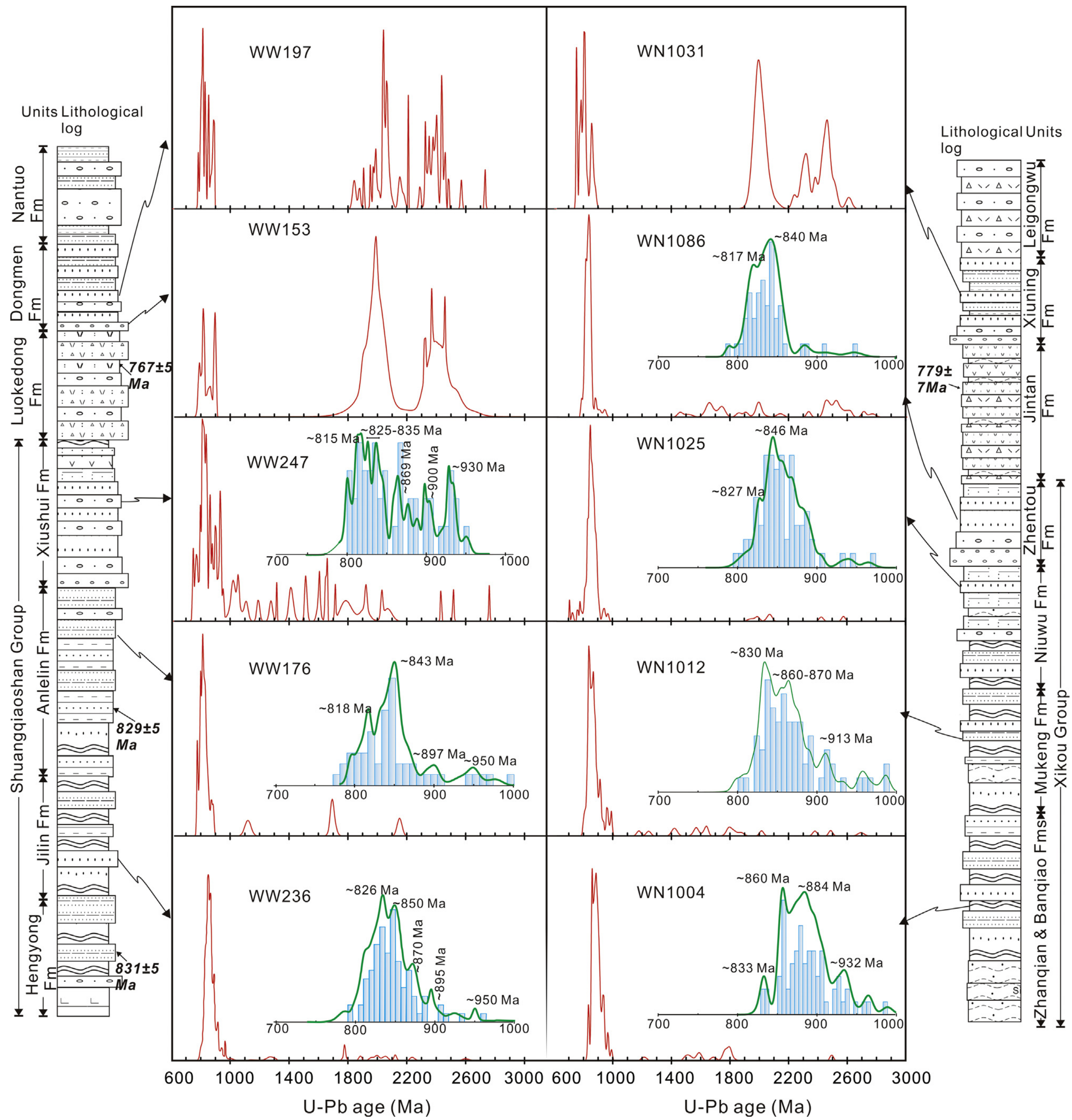

Fig. 8. Relative probability versus age diagrams. The reds curves show the frequency of individual zircon populations (for details see text). Some samples are plotted at two scales to highlight the distribution of Neoproterozoic ages. Samples are presented in stratigraphic order. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

4.2.2. *The Mukeng Fm*

Sample WN1012, a grayish-green phyllitic tuffaceous sandstone from the Mukeng Fm, contains dominantly Neoproterozoic (798–988 Ma) zircon grains, with three peaks at ca. 830, 860–870 and 913 Ma (Fig. 8). Pre-Neoproterozoic grains have a wide range of ages between 1.18 and 2.70 Ga. Neoproterozoic grains are generally euhedral with well developed concentric oscillatory zoning (Fig. 7b).

Neoproterozoic zircon grains from sample WN1012 have variable $\varepsilon_{Hf(t)}$ values (−9.0 to 14.0) and T_{DM2} (862–2401 Ma). Pre-Neoproterozoic zircon grains have evolved and scattered Hf isotopic compositions, with $\varepsilon_{Hf(t)}$ values from −3.8 to 7.5 and T_{DM2} from 1.82 to 3.10 Ga (Fig. 10).

4.2.3. *The Niuwu Fm*

Sample WN1025, a gray tuffaceous sandstone from the Niuwu Fm, contains zircon grains mostly with Neoproterozoic ages (805 to 965 Ma). Four of the six Pre-Neoproterozoic grains cluster between 1.95 and 2.08 Ga and the other two have ages of 2.42 and 2.58 Ga. Neoproterozoic grains have uniform internal structure with typical concentric oscillatory zoning (Fig. 7c).

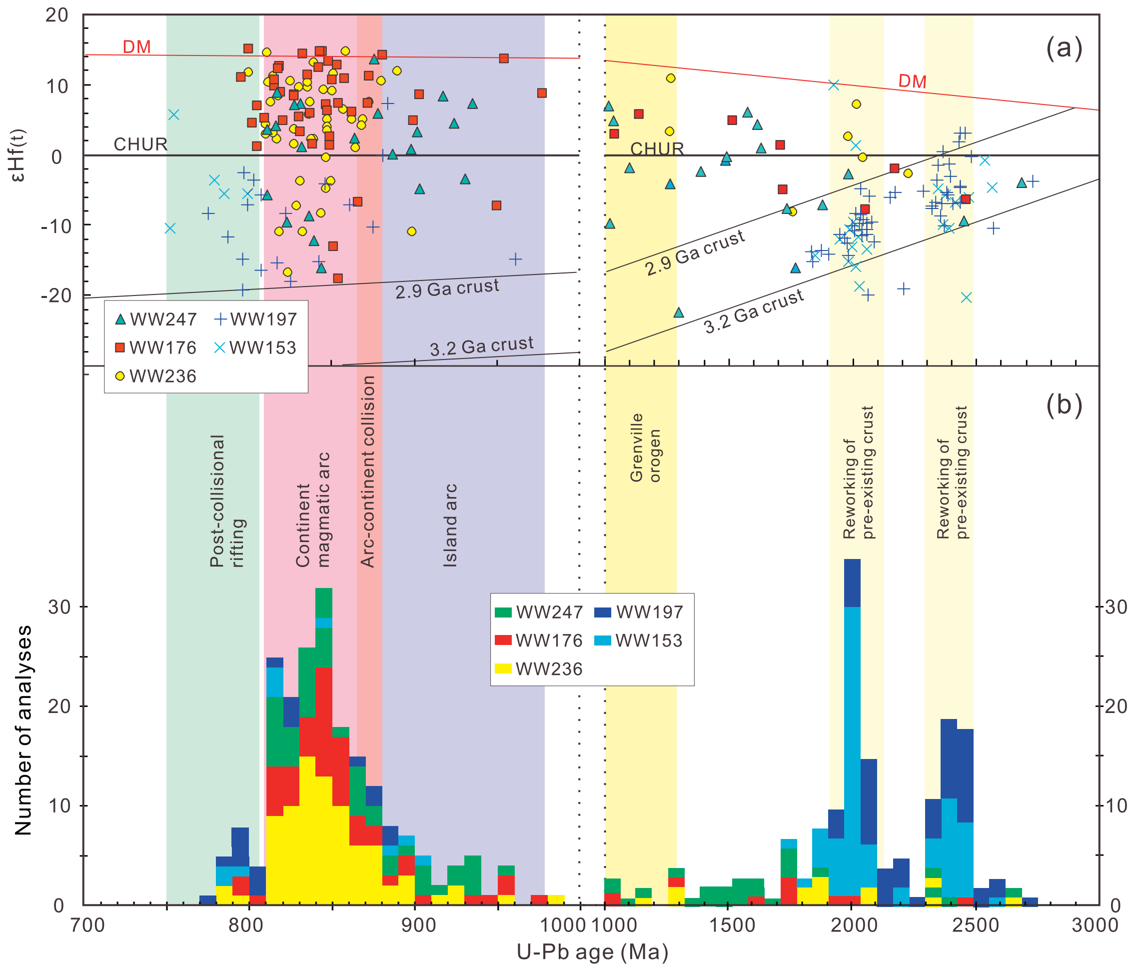

Fig. 9. Hf isotopic compositions of detrital zircons from Shuangqiaoshan Group and Dongmen Fm. (a) $\varepsilon_{Hf(t)}$ values versus U–Pb ages; (b) histograms of U–Pb ages. DM: delepted mantle; CHUR: chondritic uniform reservoir; 3.2 Ga crust means materials were derived from delepted mantle at 3.2 Ga and evolved with average continental crust $^{176}Lu/^{177}Hf$ of 0.015.

The Neoproterozoic zircon grains have variable $\varepsilon_{Hf(t)}$ values (−17.2 to 14.2) and T_{DM2} (842–2809 Ma) (Fig. 10). The Paleoproterozoic to late Archean zircon grains have relatively constant $\varepsilon_{Hf(t)}$ values from −9.2 to −0.6 and T_{DM2} from 2.71 to 3.30 Ga.

4.2.4. The Zhentou Fm

Sample WN1086 from the Zhentou Fm contains nearly half (48%) of Neoproterozoic (mostly between 801 and 860 Ma) zircon grains. Pre-Neoproterozoic zircon grains cluster at groups of 1.64–1.75 Ga, 1.98–2.01 Ga and 2.44–2.58 Ga (Fig. 8).

Neoproterozoic (798–965 Ma) zircon grains have a wide range of $\varepsilon_{Hf(t)}$ values from −21.5 to 10.6 and T_{DM2} from 1.06 to 3.04 Ga (Fig. 10). Six late to mid-Paleoproterozoic zircon grains (1.64–2.14 Ga) have $\varepsilon_{Hf(t)}$ values (−12.8 to −5.1) and T_{DM2} (2.85–3.27 Ga). Zircon grains with ages between 2.33 and 2.76 Ga have a wide range of $\varepsilon_{Hf(t)}$ values of-7.6 to 10.7 and T_{DM2} of 2.43–3.47 Ga.

4.3. The Nanhua Sequence

4.3.1. The Dongmen Fm

Two coarse-grained sandstones (WW153 and WW197) from the Dongmen Fm contain zircons with similar detrital age distribution dominated by two major age groups at 1.80 to 2.10 Ga and 2.30 to 2.50 Ga and one sub-group of 800 to 900 Ma (Fig. 8). Neoproterozoic grains are oscillatory-zoned and euhedral. Paleoproterozoic zircon grains are euhedral to rounded and partly oscillatory-zoned (Fig. 6d and e).

Most Neoproterozoic zircon grains have sub-chondritic $\varepsilon_{Hf(t)}$ values scattered between −19.2 and 7.4 (Fig. 9). Nearly all Pre-Neoproterozoic zircon grains have $\varepsilon_{Hf(t)}$ values falling between the evolved Hf isotopic composition defined by the Hf evolution trend of juvenile material derived from a depleted mantle reservoir at ca. 2.90 and 3.60 Ga (Fig. 9).

4.3.2. The Xiuning Fm

Detrital zircon grains of sample WN1031 from the upper part of the Xiuning Fm are mostly later Archean to mid-Paleoproterozoic in age, including 2.38–2.52 Ga and 1.95–2.07 Ga populations, with a small number of grains clustering at 2.24–2.33 Ga (Fig. 8). Neoproterozoic zircon grains range in age from 750 to 874 Ma with no early-Neoproterozoic detritus (900–1000 Ma).

Neoproterozoic zircon grains have highly scattered Hf isotopic compositions (Fig. 10) with a wide range of $\varepsilon_{Hf(t)}$ values (−21.9 to 6.3) and T_{DM2} (1.31–3.05 Ga). Late- to mid-Paleoproterozoic (∼1.9–2.1 Ga) zircon grains have $\varepsilon_{Hf(t)}$ values between −13.1 and −6.3 and T_{DM2} between 2.99 Ga and 3.42 Ga. 2.24–2.61 Ga zircon grains have scattered $\varepsilon_{Hf(t)}$ values (−18.0 to 5.1) and T_{DM2} (2.65–3.89 Ga).

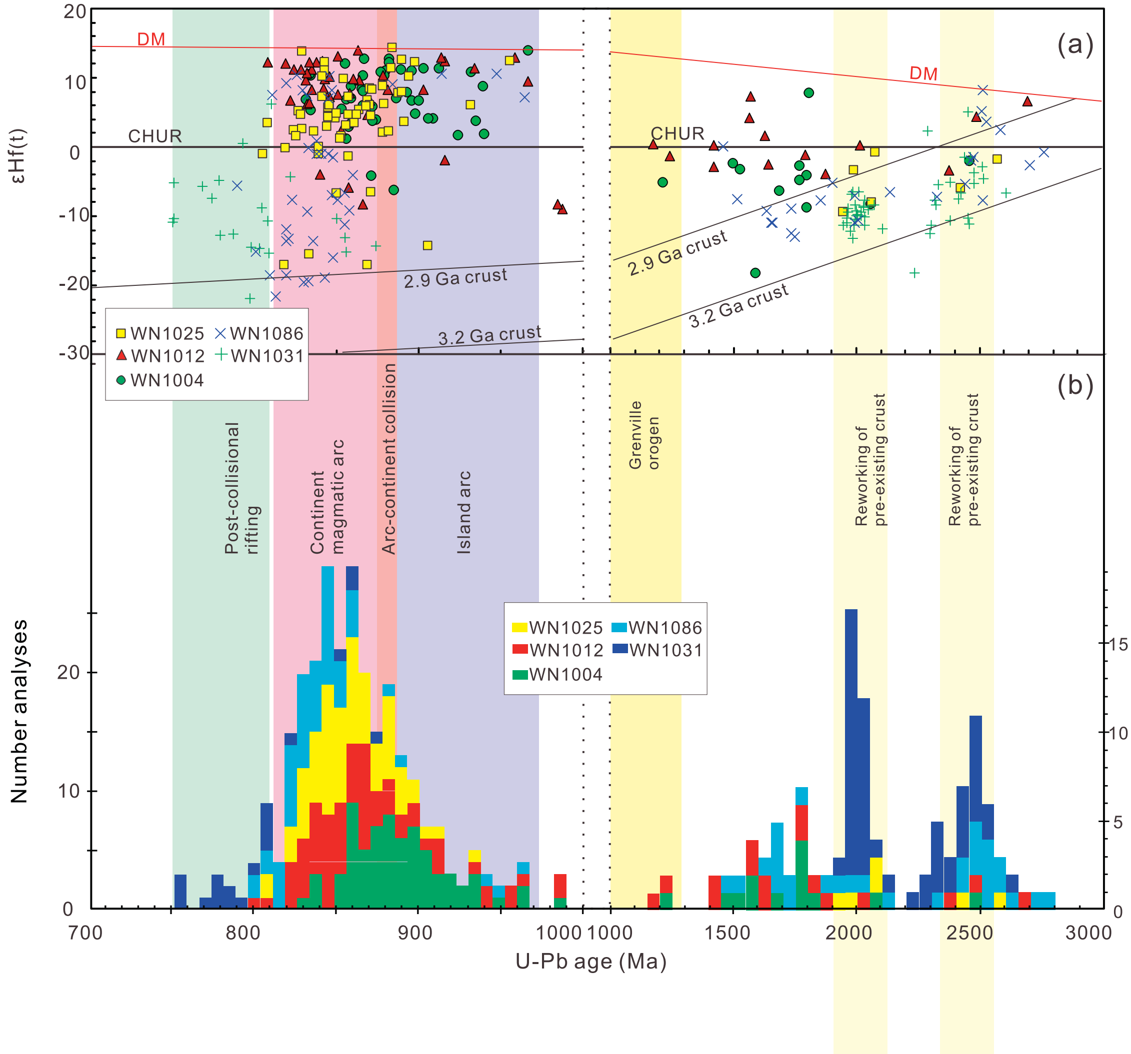

Fig. 10. Hf isotopic compositions of detrital zircons from Xikou Group and Xiuning Fm. (a) $\varepsilon_{Hf(t)}$ values versus U–Pb ages; (b) histograms of U–Pb ages. The meaning of DM, CHUR and 3.2 Ga crust is explained in caption of Fig. 9.

5. Discussion

5.1. Constraints on the timing of deposition

5.1.1. The Shuangqiaoshan Group

The Shuangqiaoshan Group was traditionally thought to be Mesoproterozoic in age (1400–1000 Ma) (Huang et al., 2003; Wu, 2007), whereas a Neoproterozoic depositional age has been widely inferred recently (870–820 Ma) (Gao et al., 2008; Wang et al., 2008; Zhao et al., 2011). Combined with previously published data, new age data in this study can provide tighter constraints on the age of the Shuangqiaoshan Group. All Neoproterozoic zircons have oscillatory-zoning and euhedral shape without metamorphic rim and fractures (Fig. 6). The Shuangqiaoshan Group underwent only low greenschist-facies metamorphism and all Neoproterozoic zircons have high Th/U ratios (generally >0.5), indicating detrital zircons are pristine and can constrain the maximum depositional age of the sediments as they represent the ages of source rocks (Fedo et al., 2003). The initial deposition of the Shuangqiaoshan Group is constrained by a SHRIMP zircon U–Pb age of 831 ± 5 Ma for a thin-bedded bentonite in the middle part of the Henyong Fm, lowermost Shuangqiaoshan Group (Gao et al., 2008). The youngest detrital zircons from the Jilin Fm have a weighted mean age of 826 ± 3 Ma (2σ, MSWD = 1.18), placing the maximum deposition age for the Jilin Fm at ca. 828 Ma. A maximum age of 829 ± 5 Ma, bracketed by an inter-bedded bentonite in the Anlelin Fm (Gao et al., 2008), indicates immediate deposition of the Anlelin Fm after the Jilin Fm. One sample from the upper part of the Anlelin Fm contains the youngest zircons with a weighted mean age of 818 ± 3 Ma (2σ, MSWD = 1.12), indicating a depositional age of ca. 818 Ma or younger. The Xiushui Fm contains detrital zircons as young as 800 Ma and the youngest zircons yield a weighted mean age of 815 ± 5 Ma (2σ, MSWD = 0.32), consistent with the minimum depositional age of 819 ± 9 Ma bracketed by the Jiuling granitic intrusion (Li et al., 2003a).

5.1.2. The Xikou Group

The Xikou Group is intruded by ca. 824 Ma granitic plutons (Li et al., 2003a; Wu et al., 2006). The youngest zircons of sample WN1004 from the Banqiao Fm have a weighted mean age of 833 ± 8 Ma (2σ, MSWD = 0.04), bracketing the initial depositional age to the mid-Neoproterozoic. The youngest zircon group of sample WN1012 give a weighted mean age of 830 ± 4 Ma (2σ, MSWD = 0.45), constraining the maximum deposition age of the Mukeng Fm at ca. 830 Ma. Sample WN1025 from the uppermost Niuwu Fm have the youngest zircons with a weighted mean age of 827 ± 5 Ma (2σ, MSWD = 0.58), indicating the Niuwu Fm formed at ca. 827 Ma or younger. There are only two single-grains with younger ages of 805 and 808 Ma, but these are inconsistent with inferred ages from field relationship. Because of the similar lithological assemblage and sedimentary environment, as well as being separated from underlying strata by a similar regional unconformity (Ma et al., 1999; Zhang et al., 1999), the Zhentou Fm can be correlated with the Xiushui Fm and is regarded as the upper part of the Xikou Group. Apart from two exceptionally young (789 and 801 Ma) zircons, the youngest zircons have a weighted mean age of 817 ± 4 Ma (2σ, MSWD = 0.33), providing a maximum constraint on the deposition of the Zhentou Fm. Therefore, the Xikou Group likely formed at 833–817 Ma.

5.2. Age groups and source terrains

Among 888 zircon grains analyzed, 692 analyses are considered to be significant in terms of concordance and have meaningful U–Pb ages. There are four principal age groups (Fig. 11 and Table 1): (1) Neoproterozoic zircons with ages between 750 and 980 Ma; (2) Early-Mesoproterozoic to Late-Paleoproterozoic zircons (1.50–1.80 Ga); (3) Mid-Paleoproterozoic zircons defining a maximum frequency group at 1.80–2.10 Ga; and (4) Early-Paleoproterozoic to Late-Archean zircons (2.35–2.75 Ga).

5.2.1. Neoproterozoic (750–980 Ma) zircons

All Shuangqiaoshan and Xikou samples have dominantly Neoproterozoic zircons in spite of slightly diverse maximum age frequency. The early-Neoproterozoic (980–860 Ma) detritus may be sourced from the ca. 970 Ma adakitic granite within the northeastern Jiangxi ophiolite (Li and Li, 2003; Gao et al., 2009), the 930–890 Ma volcanic rocks of the Shuangxiwu Group (Chen et al., 2009a; Li et al., 2009), ca. 910 Ma granitoid plutons intruding the Shuangxiwu Group (Ye et al., 2007) or ca. 880 Ma obduction-type granite within the NE Jiangxi ophiolite (Li et al., 2008a). 860–820 Ma detritus makes up one of the most important age populations. These zircons have morphology and internal structure of igneous origin and the age spectrum is similar to that recorded by a series of igneous events in the eastern Jiangnan Orogen. Sporadically exposed igneous rocks, the ca. 848 Ma Gangbian alkaline complex (Li et al., 2010b), ca. 849 Ma Shenwu dolerite (Li et al., 2008b) and ca. 850 Ma Zhenzhushan volcanic rocks (Li et al., 2010a) may have provided the relevant detritus. However, the abundance of detrital zircons in this study and inherited zircons within this age range observed from younger granites and volcanic rocks (Wu et al., 2006; Zheng et al., 2008), demonstrate the wider spread of sources that were largely reworked by later processes (Wu et al., 2006; Zheng et al., 2008) or eroded into associated basins.

5.2.2. Early-Mesoproterozoic to Late-Paleoproterozoic (1.50–1.80 Ga) zircons

Early-Mesoproterozoic to Late-Paleoproterozoic (1.50–1.80 Ga) material is an important part of the Pre-Neoproterozoic detritus in the analyzed samples but does not match any proximal source in the eastern Jiangnan Orogen (Fig. 11). The 1.5–1.7 Ga Dahongshan Group (Greentree and Li, 2008) and the Dongchuan Group (Zhao et al., 2010b; Wang et al., 2011a) in the western Yangtze Block may be the distal source of the 1.50–1.80 Ga detritus. Nevertheless, the cumulative age histogram constructed from these published data shows that the dominant ages from the western Yangtze Block are ca. 150 million younger than those of the detrital zircons in this study (Fig. 11).

5.2.3. Mid-Paleoproterozoic (1.80–2.10 Ga) zircons

There are only a few zircon grains with ages of 1.82–1.90 Ga. This age spectrum is similar to the ages of the 1.86–1.89 Ga granitic and metamorphic rocks in the eastern Cathaysia Block (Yu et al., 2009, 2011), but the Cathaysia Block is questionable as the source because of the paucity of such detritus. The mid-Paleoproterozoic age spectrum (1.95–2.08 Ga) is similar to the ages of major metamorphic events recorded by ca. 1.97 Ga metapelite in the Kongling terrane (Zhang et al., 2006a) and ca. 2.00 Ga granulite in the Dabie orogenic belt (Sun et al., 2008; Wu et al., 2008). However, typical core-rim internal structure and low Th/U ratios of most of the metamorphic zircons in both terranes are entirely different from the igneous characteristics of the detrital zircons in this study. In addition, the granulites contain abundant 2.70–2.90 Ga inherited igneous zircons (Sun et al., 2008; Wu et al., 2008), which are absent in the Neoproterozoic sediments, demonstrating the poor connection between these sources and the basin. The ultimate sources for these grains can be the Tianli schist and/or nowadays unexposed crustal fragments, because both sources contain a prominent mid-Paleoproterozoic age population (Fig. 11) (Zheng et al., 2006a; Li et al., 2007).

5.2.4. Early-Paleoproterozoic to Late-Archean (2.35–2.75 Ga) zircons

A significant early-Paleoproterozoic (2.37–2.50 Ga) age peak is present, whereas tectonothermal activities at 2.30–2.50 Ga are not known in the Yangtze Block. Similar to Archean detritus, the ultimate sources for the early-Paleoproterozoic materials were likely the Tianli schist and unexposed basement (Fig. 11).

The Archean (2.51–2.76 Ga) zircons are significantly younger than the 2.9–3.3 Ga Kongling TTG of the Yangtze Block but similar to the age-frequency peak at 2.51–2.70 Ga of the Mesoproterozoic Tianli schist of the eastern Yangtze Block (Li et al., 2007) (Fig. 11). Thus the Tianli schist may have likely provided the recycled Archean material to the Neoproterozoic sediments. In addition, abundant 2.50–2.60 Ga xenocrystic zircons in lamproite are used to suggest a widespread Archean basement of the Yangtze Block (Zheng et al., 2006a), reflecting this nowadays unexposed Archean basement was available to supply detritus to the Neoproterozoic sedimentary basin in the eastern Jiangnan Orogen during Neoproterozoic.

5.2.5. Temporal and spatial variations in provenance

To examine the statistical relationship between the zircon age populations of various samples, the Kolmogorov–Smirnov (K–S) test (Massey Jr, 1951) was applied using the Excel macro developed by the Arizona LaserChron Center. The K–S test suggests a strong correlation among samples WW176, WW236, WN1012 and WN1015 (Fig. 12 and Table 2), all of which have a relatively uniform zircon provenance dominated by Neoproterozoic detritus with ages ranging from 810 to 860 Ma. Sample WN1004 seems to be less correlated with other samples (Table 2), which is mainly due to the variable amounts of relative contribution of similarly old detritus (Fig. 12). Apart from the prominent 810–860 Ma zircons, samples from the Xikou Group also contain significant addition of 860–980 Ma materials, roughly consistent with the present geographic framework of the eastern Jiangnan Orogen considering that the 860–980 Ma materials were largely derived from volcanic rocks of the Shuangxiwu Group. Sample WW247 from the Xiushui Fm has a detrital zircon pattern similar to sample WN1086 from the Zhentou Fm (Fig. 12), both of which have dominant Neoproterozoic detritus with several equal age peaks between ca. 800 and 900 Ma (Fig. 8) accompanied by significantly increased Pre-Neoproterozoic zircons, indicating that the Xiushui and Zhentou Fms formed in a more open setting with a broad source region than other formations of the Shuangqiaoshan and Xikou Groups.

The Nanhua Sequence is inferred to have accumulated in a passive margin setting where the sedimentary detritus was mainly sourced from the interior part of the Yangtze Block (Jiang et al., 2003), as reflected by the significant contribution from cratonic

Table 1
Age groups for analyzed detrital zircons from the eastern Jiangnan Orogen.

Age groups	Northwestern Jiangxi					Southern Anhui				
	The Shuangqiaoshan Group			The Nanhua Sequence		The Xikou Group				The Nanhua Sequence
	WW236	WW176	WW247	WW153	WW197	WN1004	WN1012	WN1025	WN1086	WN1031
~750–1000 Ma				753 ± 8(2,0.06)						751 ± 8(3,0.007)
										777 ± 7(6,0.99)
				792 ± 9(5,0.53)	801 ± 5(7,0.54)					804 ± 6(7,0.49)
		818 ± 6(6,0.06)	815 ± 5(9,0.32)	817 ± 9(3,0.17)	823 ± 8(4,0.08)				817 ± 4(12,0.33)	
	826 ± 3(34,1.18)		830 ± 5(8,0.42)			833 ± 8(4,0.04)	830 ± 4(26,0.45)	827 ± 5(10,0.28)		
	850 ± 4(23,0.32)	843 ± 3(24,1.12)			844 ± 8(3,0.07)			846 ± 3(28,0.75)	840 ± 3(22,0.61)	854 ± 11(3,0.1)
		865 ± 7(7,0.41)				860 ± 4(17,0.35)	860 ± 4(19,0.67)	862 ± 6(6,0.06)		
	872 ± 5(13,0.27)		869 ± 6(6,0.83)					870 ± 5(9,0.03)		
					879 ± 7(4,0.45)	884 ± 3(27,1.12)	884 ± (12,1.13)	884 ± 8(12,0.11)	886 ± 14(2,0.06)	
	895 ± 10(3,0.23)	897 ± 9(3,0.62)	898 ± 6(6,1.04)	895 ± 9(3,0.47)		906 ± 6(9,0.19)	913 ± 8(5,0.06)	906 ± 16(1)		
	946 ± 22(5,2.3)	950 ± 21(5,2.3)	931 ± 6(6,0.32)			932 ± 6(8,0.59)	960 ± 11(3,0.34)	932–965(3)		
~1000–1600 Ma	1253 ± 38(3,1.8)	1139–1517(3)	1021 ± 31(3,0.16)							
			1392 ± 32(2,0.11)			1551 ± 72(4,3.4)	1419 ± 35(2,0.004)		1457–1514 Ma(2)	
							1567 ± 33(2,0.007)			
		1720 ± 26(3,0.24)	1620 ± 26(3,0.04)						1658 ± 23(5,0.36)	
~1600–2500 Ma	1764 ± 28(2,0.014)					1785 ± 22(5,0.56)	1803 ± 28(3,0.62)		1741 ± 29(3,0.11)	
	2083 ± 87(5,31)		1945 ± 110(4,8.2)	1993 ± 12(33,0.8)	2027 ± 19(21,3.5)	2058 ± 156(1)	2015 ± 42(1)	2040 ± 76(4,3.7)	1991 ± 27(4,0.07)	1999 ± 12(25,1.4)
			2369–2449(2)	2397 ± 22(23,3.1)	2366 ± 17(13,2.1)		2379 ± 44(1)			2319 ± 34(9,4.1)
		2461 ± 38(1)			2445 ± 13(8,0.31)	2495 ± 40(1)	2487 ± 42(1)	2424 ± 42(1)	2479 ± 26(9,2.1)	2462 ± 19(12,1.8)
> 2500 Ma	2594 ± 50(1)			2545 ± 35(4,0.83)	2566 ± 38(1)			2576 ± 38(1)	2582 ± 33(3,0.51)	
			2683 ± 34(1)		2727 ± 36(1)		2694 ± 48(1)		2702–2759(2)	2611 ± 46(1)

Note: Weighted mean ages of each group of ages according to the age peaks shown in Fig. 8. Only concordant ages (90% < concordance < 110%) are used. For ages older than 1000 Ma, $^{206}Pb/^{238}U$ ages are used and for ages younger than 1000 Ma, $^{206}Pb/^{238}U$ ages are used. Data in parentheses refer to number of analyses used to calculate each group and the MSWD value of the group. Mean ages for all groups are quoted with 95% confidence limits. Some groups show scatter of individual analyses.

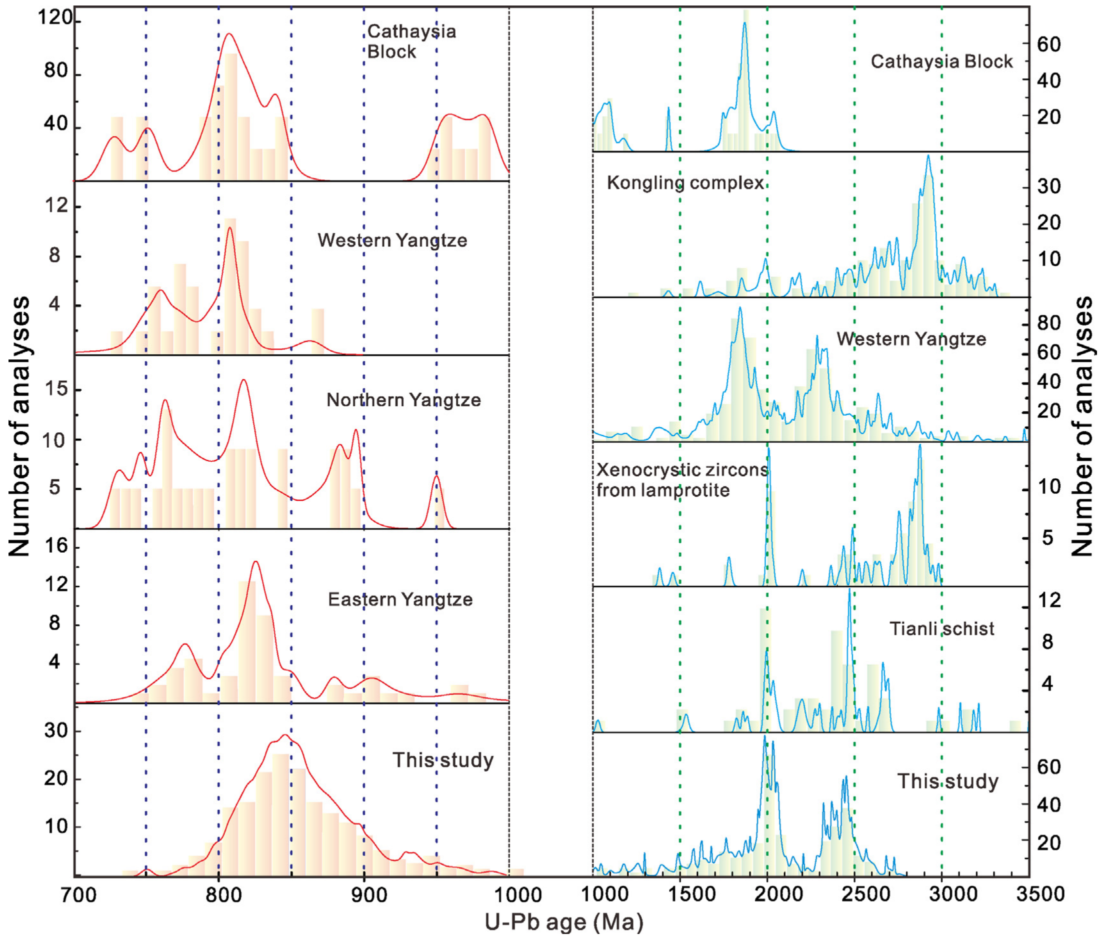

Fig. 11. Probability plots of detrital zircons from Neoproterozoic sedimentary units in the eastern Yangtze Block and their potential sources. The number of *y*-axis represents the number of analyses. Data sources for Pre-Neoproterozoic units: the Kongling complex (Qiu et al., 2000; Zhang et al., 2006a,b; Gao et al., 2011); the Tianli schist, (Li et al., 2007); Xenocrystic zircons from lamproite, (Zheng et al., 2006a); the western Yangtze Block, (Greentree et al., 2006; Greentree and Li, 2008; Zhao et al., 2010b; Wang et al., 2011a); the Cathaysia Block, (Li, 1997; Wan et al., 2007; Li et al., 2010c; Yu et al., 2011). Data sources for Neoproterozoic unit: the southeastern Yangtze Block, (Li and Li, 2003; Li et al., 2003b, 2008b, 2009, 2010b; Wang et al., 2006; Wu et al., 2006; Zheng et al., 2008); the western Yangtze Block, (Zhou et al., 2002b, 2006a; Li et al., 2003b; Zhao and Zhou, 2007a,b); the northern Yangtze Block, (Zhou et al., 2002a, 2006b; Zhao and Zhou, 2008; Zhao et al., 2010a), the Cathaysia Block (Wan et al., 2007; Li et al., 2010c; Shu et al., 2011).

components with Paleoproterozoic ages clustering at 1.90–2.10 Ga and 2.40–2.50 Ga.

5.3. Magmatic and crustal evolution

U–Pb ages of detrital zircons reveal three major episodes of magmatic activity at 2.50–2.35 Ga, 2.10–1.90 Ga and 980–810 Ma with some minor magmatic events at 2.70–2.50 Ga, 1.90–1.50 Ga and 800–750 Ma.

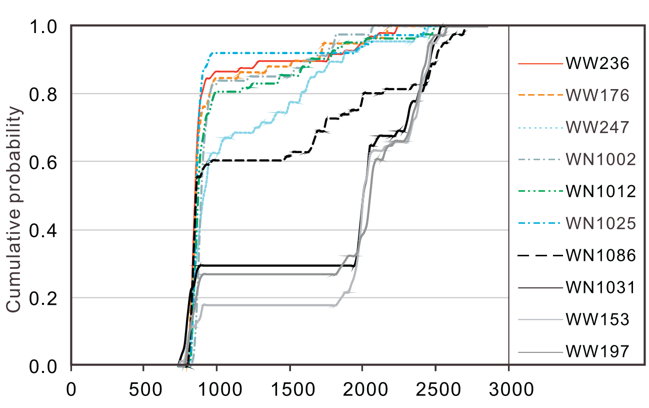

Fig. 12. Cumulative probability plots of the zircon age data for Neoproterozoicsiliciclastic sequences of the eastern Yangtze Block.

5.3.1. Reworking of pre-existing crust in the late Archean to Mesoproterozoic

Most late Archean to early Paleoproterozoic (∼2.70–2.30 Ga) zircons have sub-chondritic $\varepsilon_{Hf(t)}$ values (−20.4 to −0.2) and old T_{DM2} (2.97–4.20 Ga), suggesting this period of magmatism was characterized by reworking of a common pre-existing continental crust. One 2.46 Ga zircon from WW153 has the oldest T_{DM2} age of 4.20 Ga, indicating the generation of continental crust as old as 4.20 Ga in the source terrain. Six zircons with ages between 2.49 Ga and 2.61 Ga have $\varepsilon_{Hf(t)}$ values of (4.6 to 10.7) near to the depleted mantle (DM) reservoir, reflecting minor addition of juvenile continental crust at this period.

Most Mid-Paleoproterozoic (1.90–2.10 Ga) zircons have T_{DM2} ages (2.80–3.30 Ga) similar to the 2.70–2.30 Ga zircons discussed above (Figs. 9 and 10), suggesting that both periods of magmatism involved reworking of comparably evolved but age-restricted source regions. One zircon grain has a T_{DM2} age of 1.94 Ga identical to its U–Pb age of 1.92 Ga, and high $\varepsilon_{Hf(t)}$ value (9.9), indicating minor addition of juvenile crust at this period.

The majority of late Paleoproterozoic zircons with negative $\varepsilon_{Hf(t)}$ values (−16.1 to −1.0) and old T_{DM2} ages (2.51–3.42 Ga) suggest recycling origin of the zircon-saturated magma. Two zircons with

Table 2
K–S *P*-values using error in the CDF.

	WW236	WW176	WW247	WN10-02	WN10-12	WN10-25	WN10-86	WN10-31	WW153	WW197
WW236		**0.998**	0.000	0.000	0.026	**0.157**	0.001	0.000	0.000	0.000
WW176	**0.998**		0.011	0.000	**0.118**	**0.633**	0.011	0.000	0.000	0.000
WW247	0.000	0.011		0.032	**0.095**	0.000	**0.079**	0.000	0.000	0.000
WN10-02	0.000	0.000	0.032		0.006	0.000	0.000	0.000	0.000	0.000
WN10-12	0.026	**0.118**	**0.095**	0.006		**0.097**	0.012	0.000	0.000	0.000
WN10-25	**0.157**	**0.633**	0.000	0.000	**0.097**		0.001	0.000	0.000	0.000
WN10-86	0.001	0.011	**0.079**	0.000	0.012	0.001		0.000	0.000	0.000
WN10-31	0.000	0.000	0.000	0.000	0.000	0.000	0.000		**0.312**	**0.299**
WW153	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.312**		**0.597**
WW197	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.299**	**0.597**	

K–S: Kolmogorov–Smirnov test (Massey Jr, 1951); *P* values: the probability, if the test statistic really were distributed as it would be under the null hypothesis, of observing a test statistic the one actually observed; CDF: Cumulative Distribution Function.

ages of 1.62 and 1.81 Ga have positive $\varepsilon_{Hf(t)}$ values (4.3 and 7.9) and T_{DM2} ages (1.98 and 2.05 Ga), again supporting the possibility of minor addition of juvenile materials between 1.90 and 2.10 Ga.

Early Mesoproterozoic zircons (1.40–1.60 Ga) with scattered $\varepsilon_{Hf(t)}$ values (−18.1 to 13.8) and T_{DM2} ages (1.43–3.41 Ga), with the majority at (2.15–2.37 Ga) suggest recycling of variable amounts of pre-existing continental crust. Nearly all late Mesoproterozoic (1.00–1.30 Ga) zircons have $\varepsilon_{Hf(t)}$ values (−9.7 to 6.9) significantly lower than the depleted mantle reservoir (Figs. 9 and 10), implying reworking of older crust with insignificant addition of juvenile crust during this period.

5.3.2. *Early-Neoproterozoic addition of juvenile crust*

The dominantly early Neoproterozoic (750–980 Ma) zircon detritus has significant implications. Chondritic to near DM Hf isotopic compositions ($\varepsilon_{Hf(t)}$ values mostly from 0 to 16.4) (Figs. 9 and 10) reveal formation of juvenile material at 860–980 Ma. A few 860–980 Ma zircons with negative $\varepsilon_{Hf(t)}$ values (−17.0 to −2.0) and old T_{DM2} ages (1.91–2.81 Ga) suggest involvement of reworked older crust. The most predominant detrital zircons between 810–860 Ma have a wide range of $\varepsilon_{Hf(t)}$ values (−21.5 to 15.8) and T_{DM2} ages (739–3041 Ma) (Figs. 9 and 10), demonstrating derivation of magmas from both depleted mantle reservoir and older continental curst. Variable $\varepsilon_{Hf(t)}$ values and T_{DM2} ages imply variable degrees of mixing between juvenile magmas and ancient crust, possibly due to the assimilation during magma ascent. Addition of juvenile crustal materials likely became insignificant after ca. 805 Ma (Figs. 9 and 10) as most 750–805 Ma detrital zircons have sub-chondritic Hf isotopic compositions, e.g. low $\varepsilon_{Hf(t)}$ values (−21.9 to −2.5) and old T_{DM2} ages (1.85–3.05 Ga).

5.4. *Implications for the tectonic evolution of the eastern Jiangnan Orogen*

5.4.1. *Tectonic setting of the basin*

The obtained age spectra with predominant Neoproterozoic zircons and statistically insignificant older continental-derived zircons in all Shuangqiaoshan (except WW247 from the Xiushui Fm) and Xikou samples (except WN1086 from the Zhentou Fm) are typical of sediments accumulated in basins associated with a magmatic arc (DeGraaff-Surpless et al., 2002; Goodge et al., 2004) but are inconsistent with continental rift or passive margin sedimentation, which would be expected to have the majority of detritus derived from exhumed older continental crust (Goodge et al., 2002, 2004). The nearly syn-magmatic sedimentation and euhedral igneous zircons suggest a nearby source within the eastern Jiangnan Orogen for the Neoproterozoic detritus and reflect fast erosion and deposition of newly formed igneous rocks. The Cathaysia Block could be a possible source if it was connected with the Yangtze Block during the sedimentation of the Shuangqiaoshan and Xikou Groups. However, detritus derived from the Cathaysia Block would be expected to contain Grenville (extending from 1300 to 950 Ma) materials (Wang et al., 2010a and reference therein), which are scarce in the studied samples (Fig. 11), suggesting the Cathaysia Block was separated from the Yangtze Block and could not provide detritus to the Shuangqiaoshan and Xikou Groups. Additionally, Hf isotopic compositions of the early Neoproterozoic (~810–860 Ma) zircons reveal variable degrees of assimilation of pre-existing older crust to the juvenile magma, the mixing process of which is typical of granitoid rocks in modern-day magmatic arc settings (Tatsumi and Kogiso, 2003). Chemical compositions of the siliciclastic rocks from the Shuangqiaoshan and Xikou Groups have features similar to sedimentary rocks accumulated at active continental margins (Huang et al., 2003; Zhang et al., 2010), consistent with the magmatic arc setting suggested by the detrital zircons. Sandstone from both the Shuangqiaoshan and Xikou Groups are compositionally immature with dominantly poorly-sorted volcanic lithic and feldspar detritus and minor detrital quartz (Ma et al., 2001; Huang et al., 2003), suggesting sedimentary detritus derived exclusively from volcanic sources in a magmatic arc setting (Dickinson, 1970). The Xiushui Fm in northwestern Jiangxi and the Zhentou Fm in southern Anhui contain thick layers of conglomerate, pebbly sandstone and coarse sandstone at their bases (Fig. 5), representing syn-orogenic molasse formed in a retro-arc foreland basin at 817–815 Ma. Samples WW247 from the Xiushui Fm and WN1086 from the Zhentou Fm have additional input of Pre-Neoproterozoic detritus (Fig. 8), likely derived from the uplifted older basement complexes.

5.4.2. *An integrated tectonic model*

Our new dataset together with published data allow us to propose a modified model for the tectonic evolution of the eastern Jiangnan Orogen (Fig. 13). A NW-dipping oceanic subduction zone along what is the present-day eastern margin of the Yangtze Block is possible on the basis of the 930–890 Ma arc volcanic rocks in the Shuangxiwu Group (Li et al., 2009) and the presence of 930–890 Ma detrital zircons with chondritic to DM-like Hf isotopic compositions (Figs. 9 and 10). Arc-continent collision probably took place at 880–860 Ma as bracketed by the emplacement of 880 ± 19 Ma obduction-type granites (Li et al., 2008a) and the 858 ± 11 Ma Huaiyu ophiolite (Shu et al., 2006). A back-arc basin was initialed above the continental crust as marked by the 848–824 Ma supra-subduction zone ophiolite in southern Anhui (Li et al., 1997; Ding et al., 2008; Zhang et al., 2012a). Volcanic rocks in this period were largely eroded and transported to the back-arc and retroarc foreland basins due to subsequent orogenic uplift. Abundant 860–810 detrital zircons have Hf isotopic compositions, indicating mixture between juvenile crust and continental basement (Figs. 9 and 10) and providing support for the existence of an extensive magmatic arc during this period. The basin began to form at ca. 830 Ma and was filled with a set of volcanic-terrigenous arenopelitic flysch sequence with some well-preserved primary sedimentary

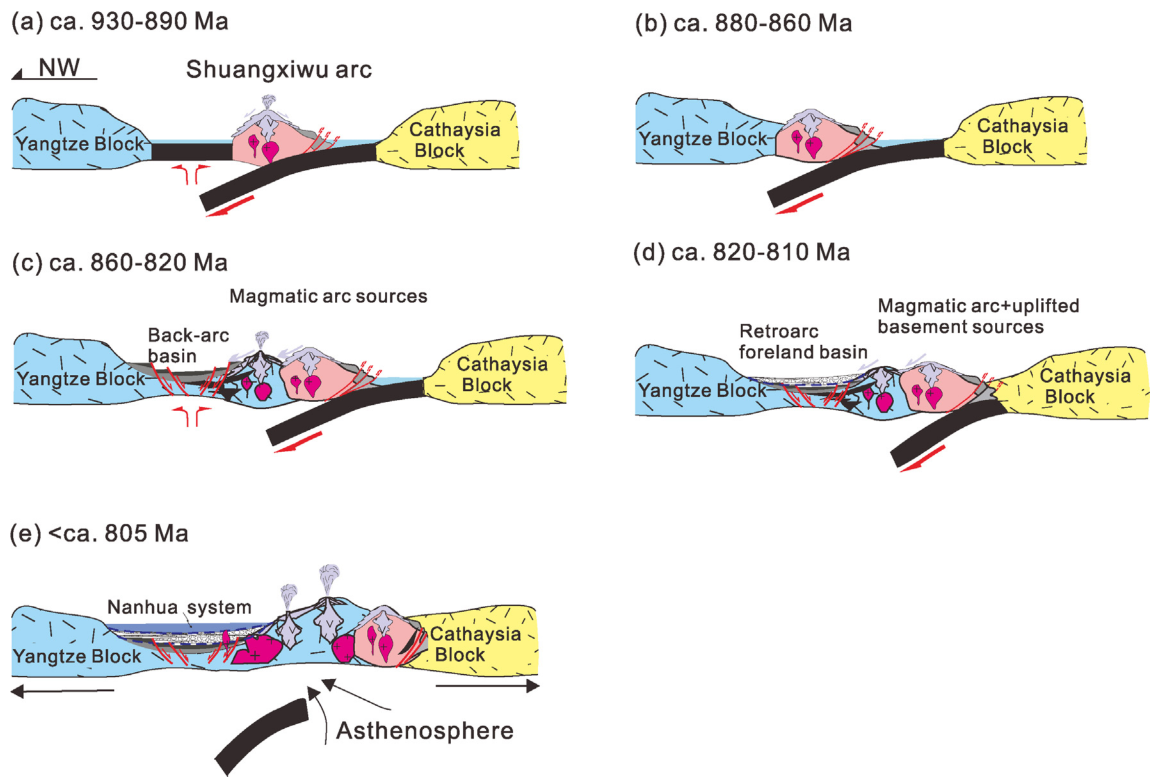

Fig. 13. Sequential tectonic evolution of the eastern Jiangnan Orogen. See text for discussion.

structures, such as cross- and graded-bedding and scoured based sequences (Fig. 5) (Wu, 2007; Zhang et al., 2010). Greywacke of the flysch sequence contains poorly-sorted and subangular fractions of lithic fragments and less feldspar and quartz (Wu, 2007). Along with basin evolution, the sedimentary strata contained additional interlayered calc-alkaline felsic-intermediate volcanic lava of arc-affinity that strongly supports a magmatic arc setting (Zhang et al., 2010). The Niuwu and Anlelin Fms are characterized by repeated sedimentary cycles of pebbly sandstone and shale (Fig. 5), typical of flysch formed in a back-arc basin. Basin closure was marked by the 828–819 Ma syn-collisional cordierite-bearing peraluminous granitoids (CPG) (Li et al., 2003a; Zhong et al., 2005; Wang et al., 2006) and subsequent syn-orogenic uplift which led to basin restriction and the formation of a regional unconformity. As a result, a retro-arc foreland basin was formed, in which the Xiushui and Zhentou Fms were deposited with detritus from both remnant magmatic arc and uplifted basement. Subsequently, the emplacement of extensive 805–760 Ma bimodal volcanic sequences (Wang et al., 2011b) and 780–770 Ma K-rich calc-alkaline granitoids (KCG) (Zheng et al., 2008; Xue et al., 2010) in the eastern Jiangnan Orogen record post-collisional orogenic rifting, which is marked by remelting of pre-existing rocks as recorded by the sub-chondritic Hf isotopic compositions of most 805–750 Ma detrital zircons (Figs. 9 and 10).

5.4.3. *Possible reconstruction of the Yangtze Block in Rodinia*

It has long been debated if the Yangtze Block was in the central Rodinia, likewise whether or not the Jiangnan Orogen is part of a Grenville Orogen (Li et al., 1995, 2008d; Zhou et al., 2002a,b, 2008; Yan et al., 2002; Zheng, 2004; Yu et al., 2008; Wang and Zhou, 2012). However, the back-arc to retro-arc foreland setting for the 830–815 Ma Shuangqiaoshan and Xikou Groups does not support an intra-cratonic setting. Neither coeval mantle plume rift system nor a Grenville Orogen recorded in southeastern Australia and western Laurentia (Li et al., 2008d) exist in the eastern Jiangnan Orogen. In addition, the facts that the Jiangnan Orogen is somewhat younger than the Grenville Orogen and that there is insignificant Grenville magmatism and no Grenville juvenile crust recorded by detrital zircons from the strata in the Jiangnan Orogen suggest that this orogen cannot be correlated with the worldwide Grenville Orogen and that the Yangtze Block was unlikely located between Australia–East Antarctica and Laurentia as proposed by Li et al. (1995). However, source analysis suggests interior rather than extraneous detritus supplied to the widespread 830–815 Ma sedimentary sequences of the Jiangnan Orogen (Wang et al., 2010a and this study), suggesting that the Yangtze Block was likely located along the margin of Rodinia as an individual continental block rather than in the center of the supercontinent.

6. Conclusions

(1) The previously thought Mesoproterozoic sedimentary sequences in the eastern Yangtze Block was deposited between 833 and 815 Ma.
(2) The 833–815 Ma sedimentary sequence represents a sedimentary cycle from a back-arc to retro-arc foreland basin.
(3) The juxtaposition of the Yangtze and Cathaysia Blocks likely lasted to ca. 815 Ma or even later.
(4) Three major episodes of magmatic activities at 2.50–2.35 Ga, 2.10–1.90 Ga and 980–800 Ma are recognized in the source areas of the Neoproterozoic sedimentary basin, whereas the Grenville (1.30–1.00 Ga) magmatism was insignificant.
(5) No Grenville juvenile crust in the eastern Yangtze Block is identified. The most important generation of juvenile crust occurred at early Neoproterozoic (~980–810 Ma) in combination with reworked older crust at 860–810 Ma.

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