Geol. Mag. **149** (*6*), *2012, pp. 1124–1131.* © *Cambridge University Press 2012*
doi:10.1017/S0016756812000404

RAPID COMMUNICATION

Detrital zircon evidence for the linkage of the South China block with Gondwanaland in early Palaeozoic time

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(*Received* 22 November 2011; *accepted* 11 May 2012; *first published online* 5 July 2012)

Abstract

LA-ICP-MS U–Pb dating of Lower Devonian detrital zircon samples from three representative sections in the South China block yields dominant Grenvillian and Pan-African populations, similar to the age distribution of early Palaeozoic samples from Gondwana, the Tethyan Himalaya and West Australia, in particular. Hf isotopic compositions indicate the contributions of juvenile crust at 1.6 Ga and 2.5 Ga, and bear a resemblance to their counterparts from SE Australia and West Antarctica, revealing the mixed origin of the Pan-African and Grenvillian grains from juvenile magmas and melting of pre-existing crustal rocks. These results suggest that the South China block should be considered an integral part of East Gondwana in early Palaeozoic time, rather than a discrete continental block in the Palaeo-Pacific or a fragment of Laurentia.

Keywords: South China block, Lower Devonian, U–Pb age, Hf isotopes, detrital zircons, Gondwana

1. Introduction

After semicentennial quiescence, the stimulating area of supercontinent construction trail-blazed by Alfred Wegener in 1912 became, in a modified form, acknowledged. From then on, reconstructing the configuration of supercontinents has long been one of the focuses of geological investigations, especially in the last two decades (e.g. Hoffman, 1991; Dalziel, 1997; Meert, 2001; Cocks & Torsvik, 2002; Meert & Torsvik, 2003; Zhao *et al*. 2004; Li *et al*. 2008; Evans & Mitchell, 2011). Many palaeogeographic models were advanced, but the position of the South China block (SCB) during the period from the Neoproterozoic to early Palaeozoic has been a matter of debate (e.g. Li, Zhang & Powell, 1995; Evans *et al*. 2000; Li & Powell, 2001; Yang *et al*. 2004; Li *et al*. 2008; Yu *et al*. 2008; Wu *et al*. 2010; Duan *et al*. 2011). Palaeomagnetic studies showed that the SCB was adjacent to the western Antarctic–Australia region of Gondwana (Huang, Opdyke & Zhu, 2000; Yang *et al*. 2004), and quite probably located close to West Australia. Li & Powell (2001) and Li *et al*. (2008), however, argued that the SCB was a discrete plate in the Palaeo-Pacific, far away from the northeastern margin of East Gondwana. The SCB was also regarded as an isolated continental block close to peri-Gondwana according to Fortey & Cocks's (2003) early Palaeozoic biogeographic models. Recent detrital zircon studies revealed that the Cathaysia block might have been a fragment on the northern margin of East Gondwana (Wang *et al*. 2010). By comparing Neoproterozoic histories of the Lesser Himalaya in northern India and the Yangtze platform in the SCB on the basis of zircon geochronological data, Hofmann *et al*. (2011) postulated that the Indian continent and the SCB were close to each other in late Neoproterozoic time when Rodinia was fragmented from and located at the same passive margin. In contrast, Wu *et al*. (2010) contended that the SCB had an obvious affinity with Laurentia rather than with Gondwana. In addition, the SCB was unfortunately omitted in many palaeogeographic reconstructions of Gondwanaland (Dalziel, 1997; Boger, Wilson & Fanning, 2001; Powell & Pisarevsky, 2002; Cocks & Torsvik, 2002; Collins & Pisarevsky, 2005; Collins, 2006; Boger, 2011).

To decipher the controversial tectonic affinity of the SCB in the early Palaeozoic, we collected three samples for detrital zircon U–Pb dating and Hf isotope analysis from Lower Devonian successions on the northwestern and southwestern margins of the Yangtze platform. Although the relationship between sedimentary maturity and detrital zircon ages is still uncertain (Fedo, Sircombe & Rainbird, 2005), we insist that highly mature clastic rocks are suitable for researching information for large regions, and the results can be used to testify to the tectonic relationships among different continents. Lower Devonian quartz arenites widely deposited along the western margin of the Yangtze platform archived a detrital record of the unroofing of an early Palaeozoic sedimentary edifice that was folded and uplifted by intracontinental tectonics in around Silurian time, thus provide natural samples of the re-sedimentation of lower Palaeozoic strata in the SCB. The results of both U–Pb geochronology and Hf isotope geochemistry provide some crucial information to constrain the provenances and the tectonic affinity of the SCB.

2. Regional geology

The SCB is a composite terrane resulting from the assembly of the Yangtze platform and Cathaysia terrane during the so-called Jiangnan orogeny around 830 Ma (Zhao *et al*. 2011) (Fig. 1). The Yangtze platform comprises a crystalline basement and overlying Neoproterozoic to Middle Triassic marine sedimentary sequences. Magmatism was widespread in the SCB from 850–740 Ma (Zhao *et al*. 2011), especially

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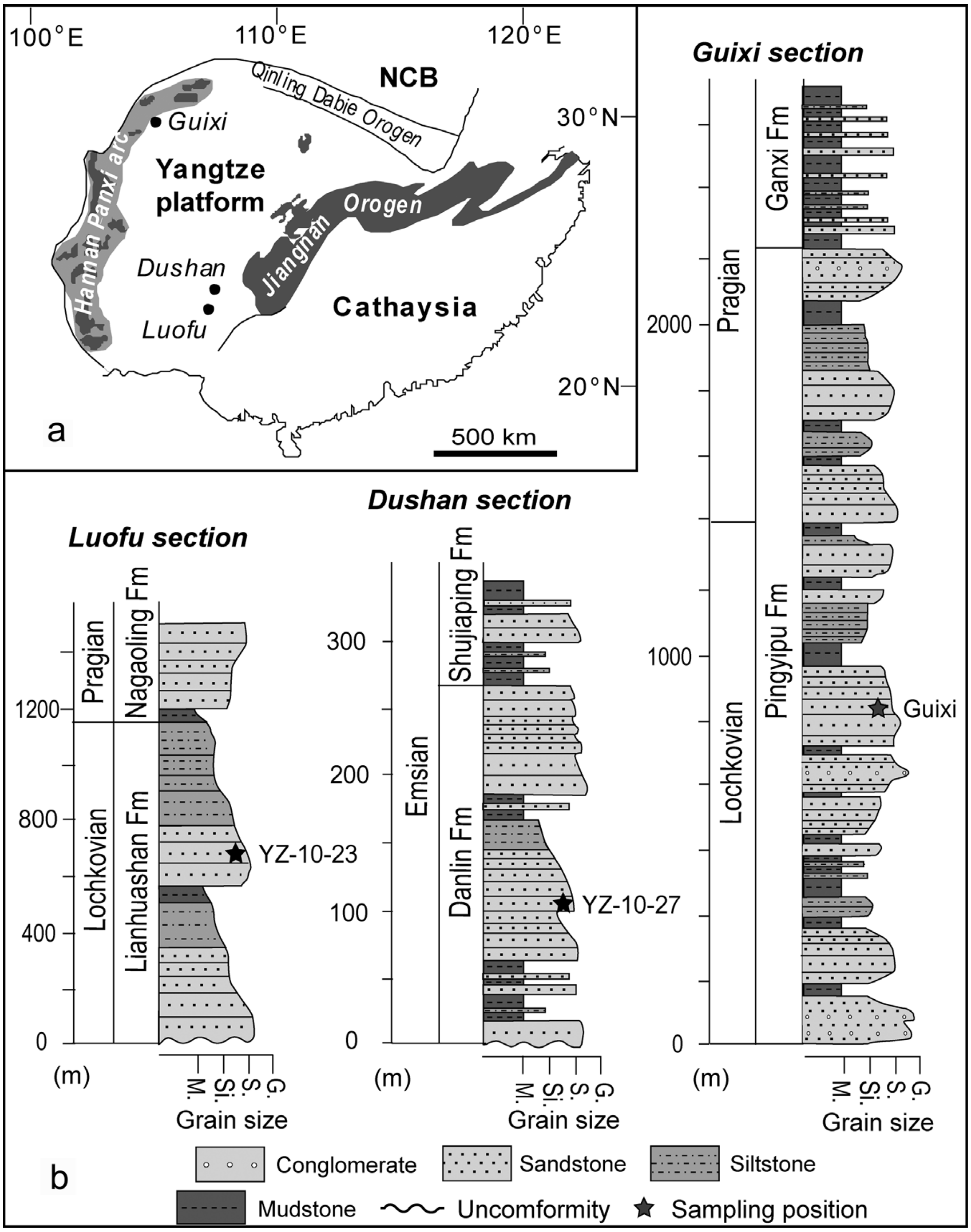

Figure 1. Simplified tectonic map of the South China block (a), showing the SCB as a composite terrane formed by the assembly of the Yangtze and Cathaysian blocks, and simplified stratigraphic columns of three representative Lower Devonian sections, showing the stratigraphic position of the collected samples (b). The dark grey regions, Jiangnan orogen and Hannan–Panxi arc, are the main areas of Neoproterozoic magmatism from 850 to 740 Ma. Detrital zircon sample localities of three representative sections (Luofu: 24° 57′ 4.8″ N, 107° 23′ 40.6″ E; Dushan: 25° 57′ 45.2″ N, 107° 38′ 19.6″ E; Guixi: 31° 58′ 39.3″ N, 104° 38′ 34.1″ E) are indicated by black dots. NCB – North China block.

in the Jiangnan orogen and along the western edge of the Yangtze platform, also called the Hannan–Panxi arc in the literature (Zhou *et al*. 2002) (Fig. 1). The Cathaysia terrane is made up largely of Palaeoproterozoic gneisses, amphibolites and migmatites, which are overlain by Upper Triassic to Lower Cretaceous continental sediments, and magmatism took place in different stages (Wang *et al*. 2010), such as the Jingningian (850–770 Ma), Kwangsian (∼430–400 Ma), Indosinian (245–200 Ma) and Yanshanian (170–120 Ma).

The Lower Devonian is well preserved in the southwestern and northwestern areas of the Yangtze platform. Three quartz arenite samples were collected from the Luofu, Dushan and Guixi sections, respectively (Fig. 1), and the ages of the stratigraphic units are well constrained by marine fossils. An angular unconformity exists between the Lower Devonian and the underlying strata, and the quartz arenites were deposited along the margin of the Yangtze platform as a result of a marine transgression. Given the difference between the specific gravity of zircon (4.65) and quartz (2.65), hydraulically equivalent zircon is expected to be approximately one sand grade finer than associated quartz grains (Komar, 2007). Accordingly, samples of medium-grained quartz arenites were collected from the Guixi, Luofu and Dushan sections, and labelled as Guixi, YZ-10-23 and

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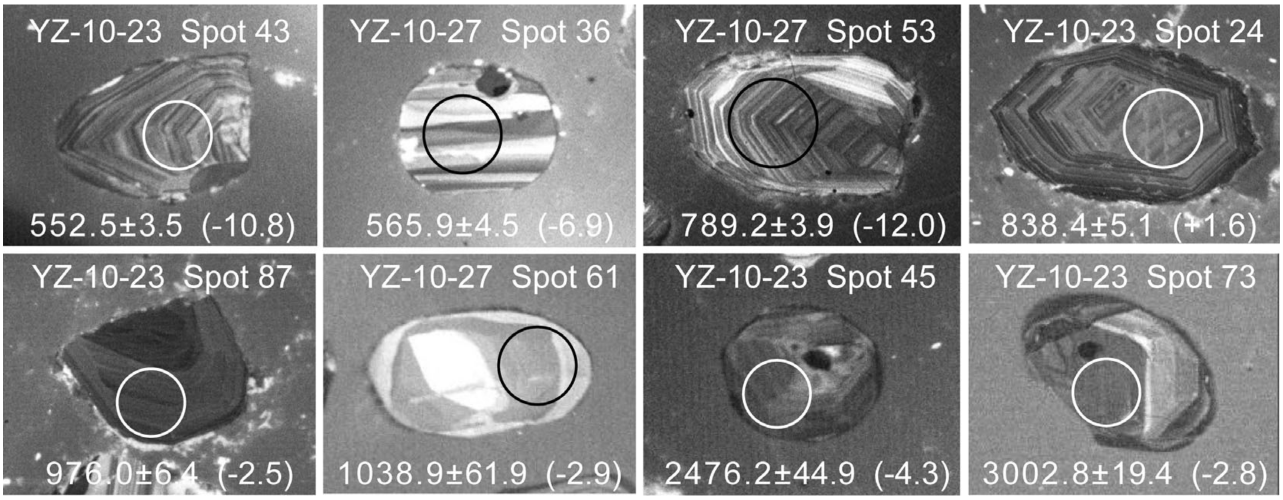

Figure 2. CL images of representative detrital zircon grains in distinct age populations. The results of U–Pb ages and $\varepsilon_{Hf(t)}$ values (within parentheses) are marked with circles representing the analytical spots. The diameter of all analytical spots is 44 μm.

YZ-10-27, respectively. Among them, YZ-10-23 and YZ-10-27 are reported for the first time, whereas the Guixi sample was previously reported by Duan *et al*. (2011).

3. Methodology

Zircon crystals were extracted from samples by standard density and magnetic separation techniques. All analysed zircon grains were documented using cathodoluminescence (CL) images for morphology prior to analyses. Here, we follow the methods of Yuan *et al*. (2008), where U–Pb and Lu–Hf isotopic ratios were collected simultaneously from the same spot (diameter of 44 μm) on the zircon, using laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) for detrital zircon U–Pb geochronology and a Nu Plasma HR multicollector ICP-MS for *in situ* zircon Hf isotopic analyses at the State Key Laboratory of Continental Dynamics, Northwest University, Xi'an (see Yuan *et al*. 2008 for details). Analyses that are > 10 % discordant (by comparison of $^{206}Pb–^{238}U$ and $^{206}Pb–^{207}Pb$ ages) are not considered or discussed further. We use $^{207}Pb–^{206}Pb$ ages of > 1.0 Ga zircons and $^{206}Pb–^{238}U$ ages of < 1.0 Ga zircons.

4. Results

Most detrital zircons are transparent to light yellow, with grain sizes varying from 50 to 160 μm. Many zircon grains are rounded and have medium to high sphericity. There are also some euhedral grains with low sphericity (Fig. 2). A variety of internal zonation exists, ranging from strong oscillatory zoning, with some xenocrysts occurring as cores mantled by newly grown zircon, to weak zonation (Fig. 2). Variations both in shape and internal structures suggest that the well-rounded zircons might have experienced long-distance transport and multistage reworking, and the euhedral grains were likely to have been deposited relatively close to source areas.

The three samples share many similarities. Most zircons are clustered in age ranges of *c*. 500–650 Ma and *c*. 900–1200 Ma, and some grains are of middle Mesoproterozoic age (Fig. 3). Although widely distributed, zircons with ages > 1.0 Ga are relatively sparse (Fig. 3). The $\varepsilon_{Hf(t)}$ values vary considerably from negative to positive (−42.7 to 15.3), with $^{176}Hf/^{177}Hf$ ratios being from 0.281237 to 0.282705. Although both Pan-African and Grenvillian grains were derived from juvenile magmas and melting of pre-existing crustal rocks, the more depleted nature of Grenvillian populations is evident (Fig. 4). Juvenile continental crust growth around 1.6 Ga and 2.5 Ga is also revealed. A complete list of the U–Pb ages and Hf isotopic data is presented in the online Supplementary Material table at http://journals.cambridge.org/geo.

5. Provenance interpretation

Rodinia and Gondwanaland, two great supercontinents in the deep geological past, were produced by assembly of various-scale plates in the intervals of 1250–900 Ma and 680–530 Ma through the Grenvillian and Pan-African orogenies, respectively. The two tectonic events were well recorded in East Gondwana. However, the influence of Pan-African orogenesis on the SCB was poorly known, and whether the Grenvillian event exerted any impact on the SCB has been debated as well. The Jiangnan orogen was thought to be a typical Grenvillian orogenic belt (Li, Zhang & Powell, 1995; Li *et al*. 1997, 2002, 2009), but it is characterized by widespread occurrence of Neoproterozoic granites from 850 to 730 Ma (e.g. Zhao *et al*. 2011). Neither granitoids nor high-grade metamorphic rocks of Grenvillian ages have been discovered. Based on reappraisal of the ages of Neoproterozoic strata of the SCB, Zhao *et al*. (2011) claimed that the Jiangnan orogen was not created during the Grenvillian event. Grenvillian volcanic suites exist in the Shennongjia region at the northwestern edge of the SCB (Qiu *et al*. 2011), but their limited distribution precludes them from serving as a major source. In contrast to the Grenvillian and Pan-African orogenesis, the middle Neoproterozoic tectonism was obvious in the SCB, as recorded by widespread large-volume magmatism, especially along the Jiangnan orogen and Hannan–Panxi arc. Liu *et al*. (2008) reported U–Pb ages and Hf isotopic compositions of detrital zircons from the Neoproterozoic, suggesting that the crustal growth of the Yangtze platform resulted from crustal addition between 720 and 910 Ma, with a peak at 830 Ma. Consequently, we propose that the Jiangnan orogen and Hannan–Panxi arc could be the potential provenances for detrital zircon grains of middle Neoproterozoic age in the Lower Devonian samples of the SCB.

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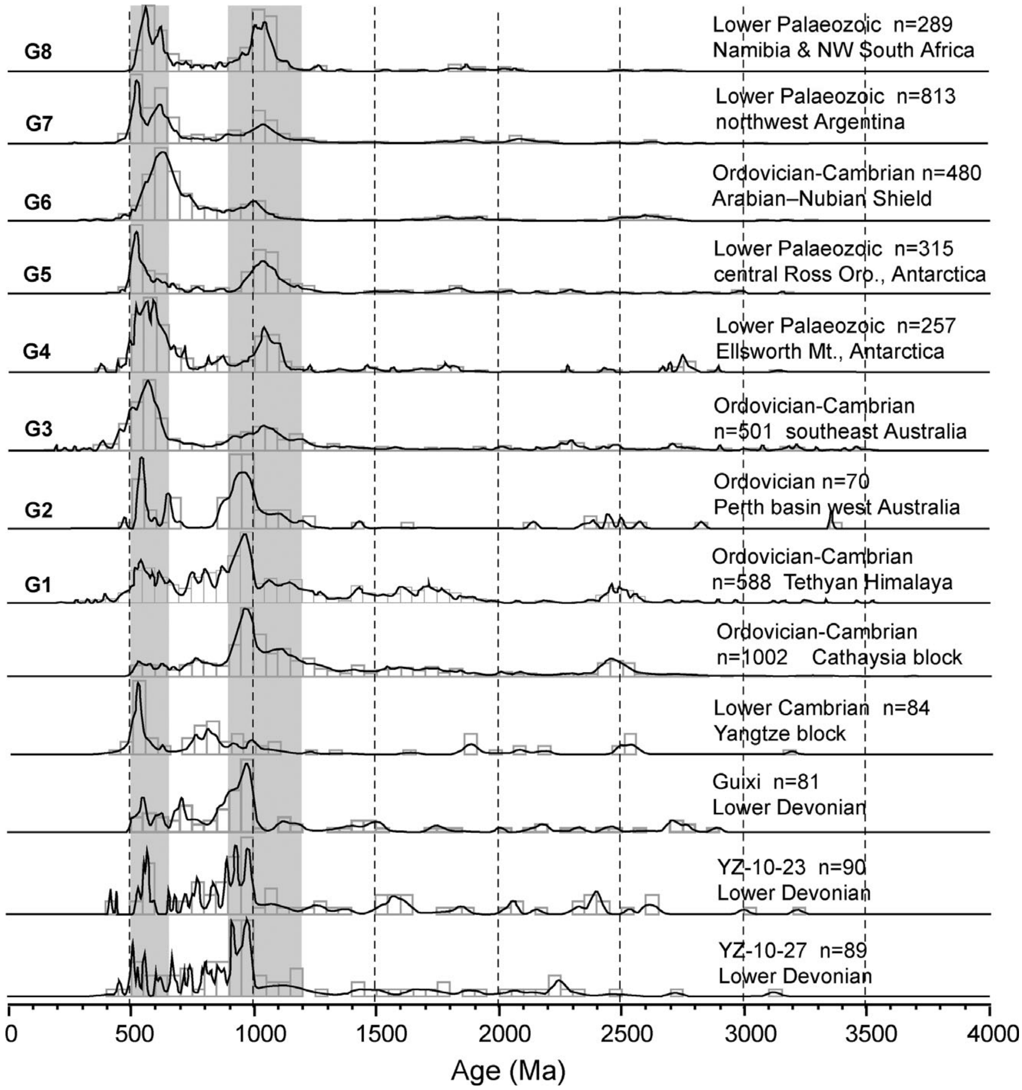

Figure 3. Detrital zircon age relative probability (based on 1-sigma errors) and histogram distribution plots for Lower Devonian quartz arenite samples from the Yangtze block and other samples for comparison. Highlighted areas show the common trends of Pan-African and Grenvillian populations. U–Pb age spectra of this study show similarity with the age distribution of early Palaeozoic samples both in East Gondwana and West Gondwana, the Tethyan Himalaya and West Australia, in particular, suggesting that the SCB had been amalgamated into East Gondwana before fragmentation and dispersal and should have been involved in most of the weighty tectonic episodes in the early history of the Earth, thus challenging the prevailing view that envisaged the SCB as a separate continental block in the Palaeo-Pacific and far away from Gondwanaland in early Palaeozoic time. Locations of samples for comparison from Gondwana are shown in Figure 5. Data sources of U–Pb ages of detrital zircons compiled for comparison include: Weislogel *et al*. (2011) for Cambrian zircons from the Yangtze block; Wu *et al*. (2010) and Yao, Shu & Santosh (2011) for Ordovician and Cambrian zircons from the Cathaysia block; Myrow *et al*. (2010) for Ordovician and Cambrian zircons from the Himalaya; Cawood & Nemchin (2000) for Ordovician zircons from the Perth Basin in West Australia; Ireland *et al*. (1998) and Kemp *et al*. (2006) for Ordovician and Cambrian zircons from SE Australia; Flowerdew *et al*. (2007) for lower Palaeozoic zircons from Ellsworth–Whitmore Mountains in West Antarctica; Goodge, Williams & Myrow (2004) for lower Palaeozoic zircons from the central Ross orogen, Antarctica; Kolodner *et al*. (2006) and Avigad *et al*. (2007) for Ordovician and Cambrian zircons from the northern and southern Arabian–Nubian Shield; DeCelles, Carrapa & Gehrels (2007), Collo *et al*. (2009) and Adams *et al*. (2011) for lower Palaeozoic zircons from northwestern Argentina; and Blanco *et al*. (2011) for lower Palaeozoic zircons from Namibia and northwestern South Africa.

Provenance for the Grenvillian and Pan-African zircons has not been identified within the SCB itself, but some parts of East Gondwana might be the possible sources, such as the East African and Kuunga orogens. The two orogens formed during the amalgamation of Gondwana, and contain abundant rocks of 900–1200 Ma and 650–500 Ma age. They were interpreted as sources of the Grenvillian and Pan-African grains of the Tethyan Himalaya (DeCelles *et al*. 2000; Myrow *et al*. 2010) and of the Palaeo-Pacific margin of East Antarctica (Goodge, Williams & Myrow, 2004). We make a qualitative comparison of age spectra for early Palaeozoic samples from the following places: the SCB, Tethyan margin of the Himalaya, Perth Basin in West Australia, Delamerian orogen and Lachlan Fold Belt in SE Australia, Ellsworth Mountains succession and central Ross orogen in Antarctica, northern and southern Arabian–Nubian Shield, northwestern Argentina, southern Namibia and northwestern South Africa. The results show that there are two age clusters that are clearly indicative of Grenvillian and Pan-African orogenic episodes (Fig. 3). This fact suggests that the dispersal of Grenvillian and Pan-African grains is widespread in the lower Palaeozoic of Gondwanaland, and that the SCB should

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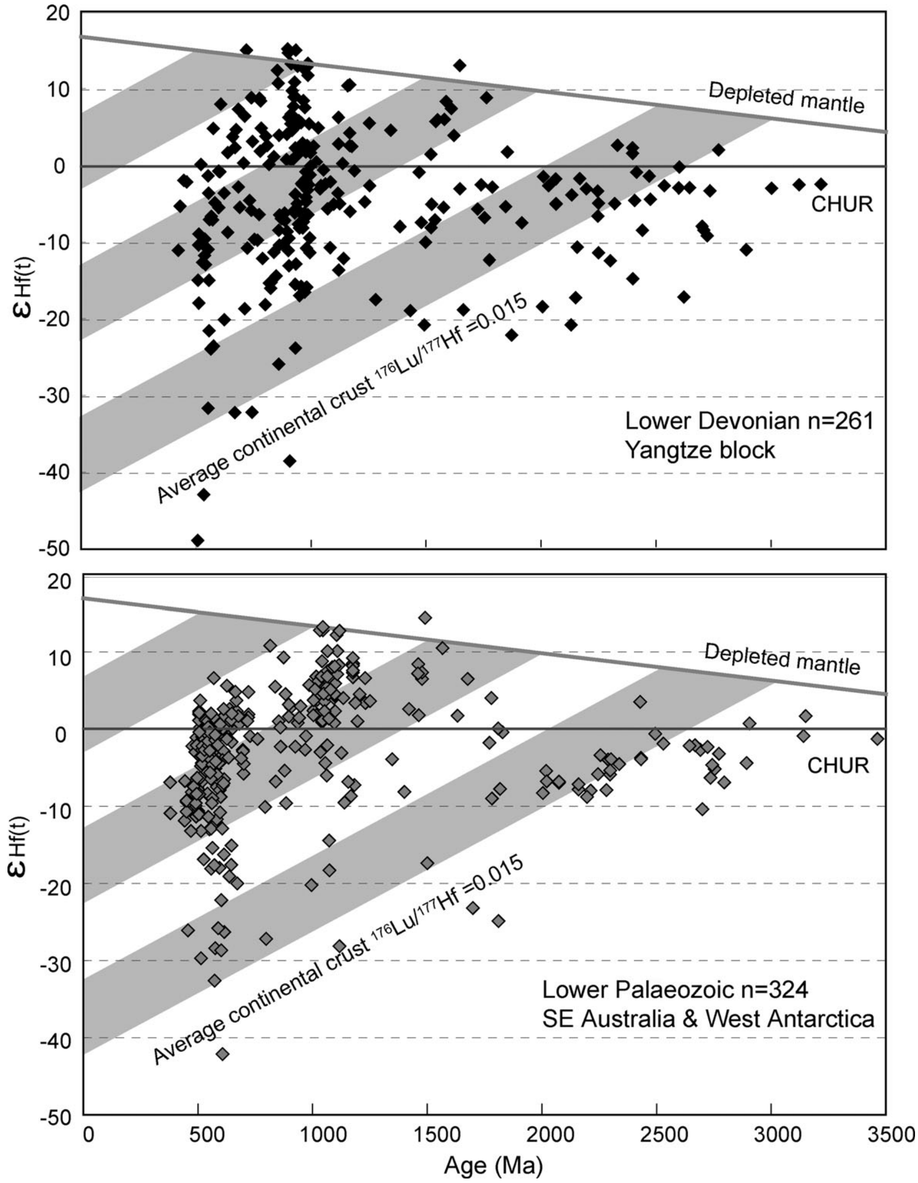

Figure 4. Plots of $\varepsilon_{Hf(t)}$ value versus U–Pb age for detrital zircons from Lower Devonian samples from the Yangtze block (upper panel) and lower Palaeozoic samples from SE Australia and West Antarctica (lower panel) (Kemp *et al*. 2006; Flowerdew *et al*. 2007), both indicating the mixed origin of the Pan-African and Grenvillian grains from juvenile magmas and melting of pre-existing crustal rocks, and the contribution of juvenile continental crust at around 1.6 Ga and 2.5 Ga. Grey fields show evolution of typical zircons (with a $^{176}Lu/^{177}Hf$ ratio of 0.0015) with depleted mantle model ages between 500 and 1000 Ma, 1500 and 2000 Ma, and 2500 and 3000 Ma.

also be of Gondwanan affinity. Another piece of convincing evidence for the Gondwanan affinity of the SCB comes from comparisons of crustal growth histories of the source areas where these zircons were produced. Hf isotopic compositions of detrital zircons from the samples of this study and from lower Palaeozoic samples from SE Australia (Kemp *et al*. 2006) and West Antarctica (Flowerdew *et al*. 2007) indicate the origin of the Pan-African and Grenvillian grains from juvenile magmas and melting of pre-existing crustal rocks and the reworked character of most pre-Grenvillian grains (Fig. 4). In addition, the Grenvillian grains are more depleted (compared with Pan-African grains), and the contribution of juvenile continental crust around 1.6 Ga and 2.5 Ga is also obvious (Fig. 4). These features show the similarities in crustal growth histories of the source areas of the Grenvillian and Pan-African grains recorded in the SCB, Australia and West Antarctica. Consequently, in addition to the middle Neoproterozoic grains within the SCB, the abundant Grenvillian and Pan-African grains in the Lower Devonian of the SCB were likely derived from the East African Orogen and Kuunga Orogen, sharing the same provenances as their counterparts in East Gondwana.

6. New configuration model of Gondwana

Given the resemblance in U–Pb age distributions of detrital zircons from lower Palaeozoic sandstone samples from the SCB, Himalaya and West Australia, and the similarity in Hf isotopic compositions of detrital zircons from the SCB, SE Australia and West Antarctica, the SCB is likely to have once been linked with the Himalaya and West Australia, and thus been an integral part of East Gondwana during the assembly of Gondwanaland (Fig. 5). This result apparently conflicts with the prevailing palaeogeographic reconstructions of Gondwanaland, which treated the SCB as a discrete continent in the Palaeo-Pacific.

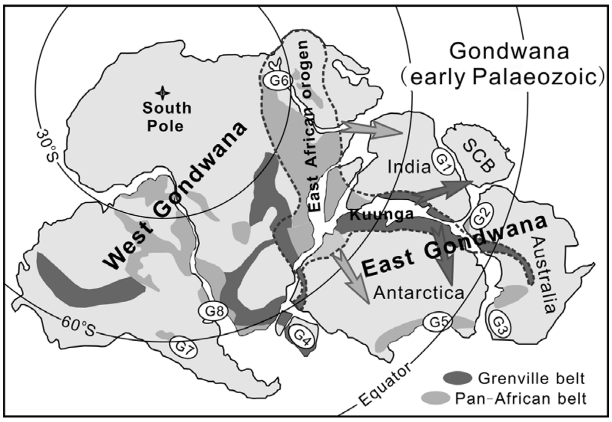

Figure 5. New configuration model of Gondwanaland with restored position of the SCB. Arrow denotes transport direction of detritus from the East African Orogen, where Pan-African ages dominate, and the Kuunga Orogen, where Grenvillian and Pan-African ages dominate. Numbers following capital G's within circles are positions of samples for comparison shown in Figure 3. Modified after Duan *et al*. (2011). See text for details.

Palaeomagnetic studies for determining the position of the SCB during the Neoproterozoic–early Palaeozoic periods are at odds, partially due to the scarcity of good palaeomagnetic data (Wu *et al*. 2010). However, the close relationship between the SCB and West Australia is supported by three high-quality palaeomagnetic poles for the middle Neoproterozoic, Middle Cambrian and Middle Silurian obtained from the SCB, which implicitly indicate a long-term connection (750–380 Ma) between the SCB and Australia (Evans *et al*. 2000; Yang *et al*. 2004). Furthermore, our inferred position of the SCB in Gondwana (Fig. 5) can account well for the similar Neoproterozoic stratigraphy of the Lesser Himalaya and Yangtze platform (Jiang, Sohl & Christie-Blick, 2003) and correlatable marine fauna between the SCB and East Gondwana (Nie, 1991; Metcalfe, 1996*a,b*, 2006), Australia (Burrett, Long & Stait, 1990; Jiang, Sohl & Christie-Blick, 2003) and the Himalaya (Nie, 1991; Metcalfe, 1996). In addition, the crustal growth history of both the SCB and other continents concerned (Fig. 4) is comparable with the episodic growth model of global crust (Condie *et al*. 2011), thereby suggesting that these continents were involved in most of the weighty tectonic episodes in early Earth history and amalgamated into East Gondwana before the onset of continental fragmentation and dispersal. As a result, the SCB was likely connected with North India and West Australia, and was a component of East Gondwana during the assembly of Gondwanaland, rather than a discrete continent in the Palaeo-Pacific or a fragment of Laurentia (Fig. 5).

The restored orientation and geometry of the SCB in our previous reconstruction (fig. 6 in Duan *et al*. 2011) is modified based on the recent recognition of a Grenvillian volcanic suite in the northwestern SCB and evaluation of the identical latest Neoproterozoic facies assemblages between the Lesser Himalaya of northwestern India and the Yangtze platform (Jiang, Sohl & Christie-Blick, 2003). The modification is consistent with palaeomagnetic studies, which show that the SCB rotated 77° clockwise in the period from the Late Silurian to Early Permian after it rifted away from the South Qinling belt (Zhu *et al*. 1998) and continued rotating approximately 70° clockwise in the Permian–Triassic period when it collided diachronously with the North China block from east to west (Zhao & Coe, 1987). Clockwise rotation of the SCB may have persisted after its amalgamation with the North China block in late Mesozoic time (Meng, Wang & Hu, 2005). Geometric changes in our modified model take into account the inevitable variations of original plate boundaries due to late-stage interactions among adjacent continental plates, such as continuous convergence between the North and South China blocks and large-scale intracontinental transcurrent faulting along the Tan-Lu fault from the Jurassic to Cenozoic.

In conclusion, our integrated study of detrital zircon U–Pb geochronology and Hf isotopes of Lower Devonian quartz arenites from the Yangtze platform provides a fingerprint of the Gondwanan affinity of the SCB and its adjacency to the Indian–Australian margin of East Gondwana in early Palaeozoic time. It is suggested that the deposition of immense amounts of sand at the margins of the SCB, similar to their equivalents in North India, West Australia, Antarctica, Africa and South American, archived a detrital record of the unroofing of the tectonic edifice caused by the amalgamation of Gondwanaland through long-distance sediment transport.

Acknowledgements. This work was supported by grants from the National Nature Science Foundation of China (40830314) and from the Chinese Academy of Sciences (KZCX2-YW-Q05-02). Liang Liu, Meng-Ning Dai, Kai-Yun Chen and Lei Kang are thanked for their lab support. We are grateful to Mandy Hofmann and an anonymous reviewer for their constructive and helpful comments that led to significant improvement of the paper.

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