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RAPID COMMUNICATION

Was there a Cambrian ocean in South China? – Insight from detrital provenance analyses

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Abstract

We use detrital provenance data from Cambrian sandstones to examine whether the Yangtze and Cathaysia blocks in South China were separated by an ocean during the Cambrian period. Zircons from the Cambrian sandstones exhibit a dominant ~ 800 Ma age peak in the central Yangtze Block, being sourced from the western Yangtze Block, whereas a ~ 980 Ma peak dominates in the northwestern Cathaysia Block, being sourced from an exotic continent once connected to Cathaysia. A mixed provenance with both age peaks is found in Cambrian sandstones from the southeastern Yangtze Block, indicating that detritus can travel from the Cathaysia Block to the Yangtze Block, and therefore arguing against the existence of a broad Cambrian ocean.

Keywords: South China, Cambrian ocean, detrital provenance, U–Pb geochronology.

1. Introduction

The South China Block comprises the Yangtze Block in the northwest and the Cathaysia Block in the southeast (Fig. 1a). The Ordovician–Silurian Wuyi–Yunkai orogeny caused deformation and metamorphism over much of southeastern South China, and the development of a foreland basin in the northwestern Cathaysia Block and southern Yangtze Block (Li *et al.* 2010). However, the pre-Wuyi–Yunkai configuration of South China and the nature of the orogeny remain controversial. Some have suggested that an ocean existed between the Yangtze and Cathaysia blocks for at least the latest Neoproterozoic to Cambrian period (Shui, 1988; Liu & Xu, 1994) or even until the Jurassic (Hsü *et al.* 1988, 1990) before the two blocks joined together. The Mesozoic ocean model did not receive much support because the key evidence for the so-called 'Mesozoic Banxi mélange' was later proved to be Neoproterozoic in age and with different tectonic affinities (e.g. Zhou, 1989; Li *et al.* 1994; Li, Z. X. *et al.* 2003). The Cambrian ocean model (Shui, 1988; Liu & Xu, 1994) suggests that the Yangtze and Cathaysia blocks first docked at their eastern ends during the early to middle Neoproterozoic period, with a V-shaped ocean widening to the west (as wide as ~ 2000 km) until the Cambrian period. This residual ocean closed during the Ordovician–Silurian period, leading to the formation of a coherent South China Block.

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Such a collision was taken as the cause of the Ordovician–Silurian 'Caledonian orogeny' in South China (Huang *et al.* 1980; Yang, Cheng & Wang, 1986; Ren, 1991), which was recently renamed the Wuyi–Yunkai orogeny with a redefined age range of > 460– 415 Ma (Li *et al.* 2010). The boundary between the two blocks was consequently considered a suture zone due to the closure of the Cambrian ocean (e.g. Xu & Qiao, 1989; Liu & Xu, 1994; Xu, Xu & Pan, 1996; Chen *et al.* 2006).

Alternatively, it has been argued that the complete amalgamation between the Yangtze and Cathaysia blocks had already finished by the Neoproterozoic period (e.g. Li, Zhang & Powell, 1995; Charvet *et al.* 1996; Zhao & Cawood, 1999; Zhou *et al.* 2002; Li *et al.* 2008, 2009), and that the Wuyi–Yunkai orogeny was an intraplate orogeny related to South China's collision with Gondwanaland, which closed a Neoproterozoic failed continental rift (Li, 1998; Li & Powell, 2001). In such a model, no ocean floor is required for the basin (the Nanhua Basin) between the Yangtze and Cathaysia blocks. The intraplate model was also supported by other researchers, based on magmatic and metamorphic analyses of lower Palaeozoic rocks (Li *et al.* 2010), provenance analyses of Cambrian–Silurian sandstones (Wang *et al.* 2010) and structural analyses of lower Palaeozoic strata in the region (e.g. Faure *et al.* 2009; Charvet *et al.* 2010; Shu *et al.* 2014). However, the provenance analyses by Wang *et al.* (2010) combined data from Cambrian–Silurian sandstones together, thus mixing the Cambrian provenance data with that of the Ordovician–Silurian sandstones formed during the Yangtze-ward propagation of the intraplate Wuyi–Yunkai orogeny from the Cathaysia Block. As syn-orogenic foreland basin sedimentary rocks on the Yangtze Block would naturally contain detritus shed from the growing orogen on the Cathaysia Block, we do not regard Wang *et al.*'s (2010) provenance analysis as a vigorous enough test for the Cambrian ocean model.

Here we use a provenance analysis of Cambrian sedimentary rocks to test whether or not a Cambrian ocean was present. If the ocean existed, the provenance of Cambrian sandstones from the Yangtze and Cathaysia sides of the Nanhua Basin will likely be different. Otherwise, detrital exchanges between the two blocks are expected. We report new detrital zircon U–Pb geochronological data for four Cambrian sandstone samples from the Yangtze Block side (two from central Yangtze and two from southeastern Yangtze) of the Nanhua Basin, and compare them with published U–Pb results from both northwestern Cathaysia and southeastern

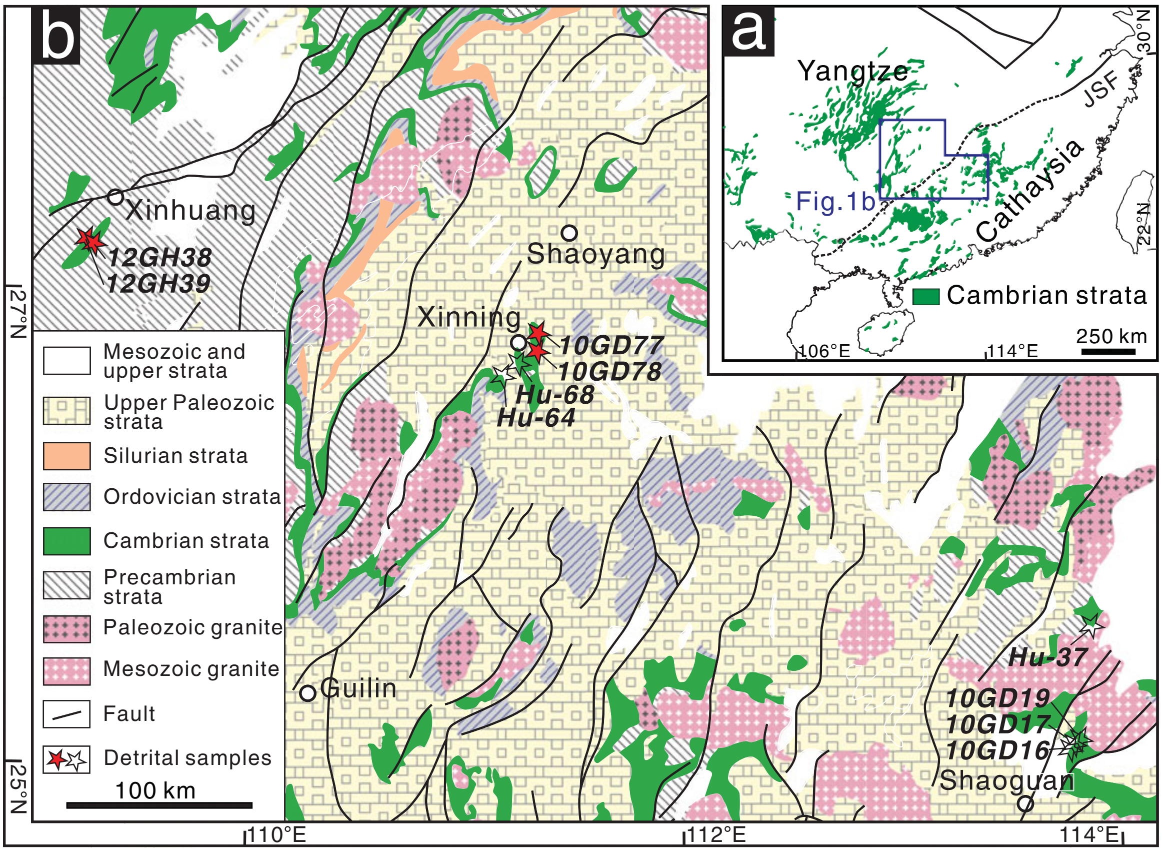

Figure 1. (Colour online) (a) Distribution of Cambrian strata in the South China Block, highlighting the inferred boundary between the Yangtze and Cathaysia blocks. JSF – Jiangshan–Shaoxing Fault. (b) Geological map of central South China, highlighting three Cambrian sampling regions from central Yangtze, southeastern Yangtze and northern Cathaysia. Red stars are samples from this study, and white stars are samples reported in previous studies.

Yangtze to argue against the Cambrian ocean model in South China.

2. Geological setting and sampling

The boundary between the Yangtze and Cathaysia blocks lies approximately along the Jiangshan–Shaoxing Fault in the NE South China Block (Fig. 1a). The southwestern extension of the boundary is unclear due to poor exposure and tectonic modifications (Ren, 1991; Li *et al.* 2010), but has been defined using the mostly disconnected Cambrian lithofacies boundaries between Cathaysian clastic sedimentary facies and Yangtze clastic–carbonate facies (Fig. 2a, b) (Liu & Xu, 1994). This boundary was also taken as a suture zone of the Cambrian ocean by Liu & Xu (1994) and Chen *et al.* (2006). During the Cambrian period, sedimentation over the Yangtze Block was dominated by carbonate, muddy carbonate and sandy carbonate, with some clastic–carbonate intercalations in the lower Cambrian (Fig. 2a) (e.g. BGMRHN, 1988; RGMRHN-a, 1975; RGMRHN-b, 1972; Liu & Xu, 1994). In contrast, the Cathaysia Block received massive clastic sedimentation, consisting of shale, siltstone, arkosic sandstone, quartz sandstone and pebbly sandstone (Fig. 2a, b) (e.g. BGMRJX, 1984; BGMRGD, 1988; Zhang & He, 1993; Liu & Xu, 1994; Yao *et al.* 2014).

Three sampling localities across the Yangtze–Cathaysia boundary were selected, including central Yangtze (Xinhuang), southeastern Yangtze (Xinning) and northwestern Cathaysia (Shaoguan) (Fig. 1b). The Xinhuang section consists of ~ 1400 m of Cambrian strata, with massive carbonate–shale units and minor fine-grained sandstone layers in the lower Cambrian strata (Fig. 2c) (RGMRHN-b, 1972). The Xinning section consists of ~ 1800 m of Cambrian strata, including 680 m of clastic strata. It consists of shale, siliceous shale and minor carbonate in the lower Cambrian strata, shale and sandstone intercalations in the middle Cambrian strata, and carbonate with minor shale in the upper Cambrian strata (Fig. 2d) (RGMRHN-a, 1975). The Shaoguan section consists of ~ 3800 m of Cambrian strata, with thick siltstone, feldspathic quartz sandstone, pebbly sandstone and thin grey-purple mudstone beds (Fig. 2e) (Zhang & He, 1993).

A grey medium-grained quartz sandstone sample (12GH38) and a grey-white fine-grained sandstone sample (12GH39) were collected from the lower Cambrian strata at the Xinhuang section (Fig. 2c), whereas a dark green medium-grained sandstone sample (10GD77) and a grey fine-grained sandstone sample (10GD78) were collected from the middle Cambrian strata at the Xinning section (Fig. 2d). Results of two sandstone samples (Hu-64, Hu-68) from the middle to upper Cambrian strata of the Xinning region (Fig. 2d), three sandstone samples (10GD16, 10GD17, 10GD19) from the middle to upper Cambrian strata, and one sandstone sample (Hu-37) from the lower Cambrian strata of the Shaoguan region (Fig. 2e) were reported in previous studies (Wang *et al.* 2010; Yao *et al.* 2014) and used here for comparison.

3. Analytical methods

Mineral separation of sandstone samples was conducted at the Institute of Hebei Regional Geology and Mineral Survey

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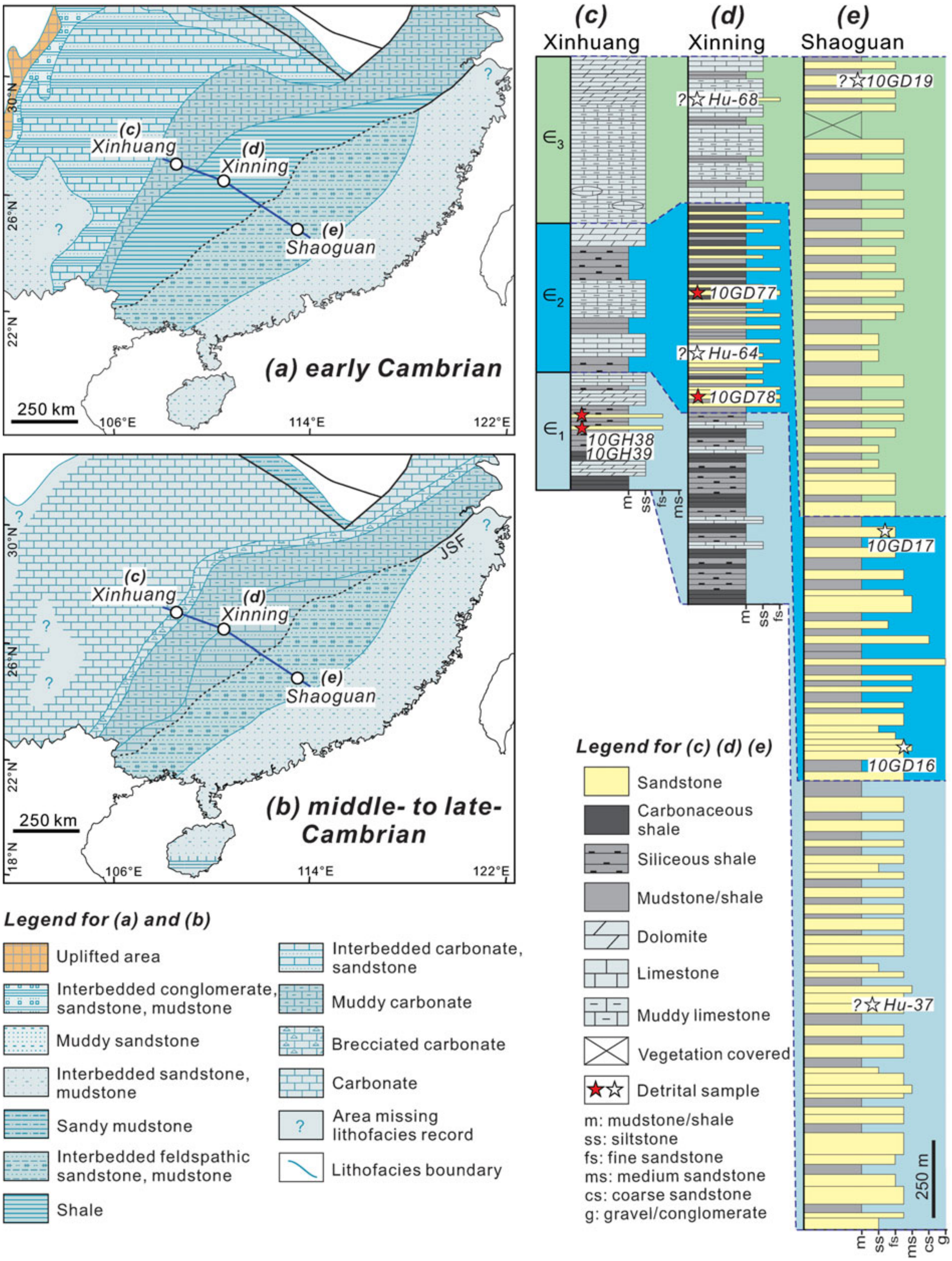

Figure 2. (Colour online) (a, b) Palaeogeographic maps of the South China Block (revised after Liu & Xu, 1994): (a) early Cambrian, (b) middle to late Cambrian. (c–e) Stratigraphic columns of Cambrian strata and sandstone samples from (c) the Xinhuang section of central Yangtze (RGMRHN-b, 1972), (d) the Xinning section of southeastern Yangtze (RGMRHN-a, 1975), and (e) the Shaoguan section of northern Cathaysia (Yao *et al.* 2014; W. H. Yao & Z. X. Li, unpub. data, 2014). Red stars are samples from this study, and white stars are samples reported in previous studies.

in Langfang, China. Conventional magnetic and density techniques were adopted to concentrate non-magnetic and heavy fractions. Zircon grains, together with zircon standards, were cast in epoxy mounts and polished to reveal half sections for analysis. All zircons were documented with transmitted and reflected light microphotographs as well as cathodoluminescence (CL) images to reveal their internal structures. Zircon U–Pb analyses were carried out in the John de Laeter Centre at Curtin University, Australia, using the Sensitive High Resolution Ion MicroProbe (SHRIMP) facility. Standard operating conditions of 2 nA O_2^- primary beam and a spot size of ~ 25 μm in diameter and ~ 2 μm in depth were followed, and each U–Th–Pb measurement consisted of six cycles. U abundance was calibrated using zircon standard BR266 (Stern, 2001), and $^{206}Pb/^{238}U$ ratio was constrained by zircon standard Plešovice (Sláma *et al.* 2008). The detailed analytical procedure follows that of Williams (1998). Data reduction was carried out using the SQUID v2.50 (Ludwig, 2001*a*) and Isoplot/Ex v2.49 (Ludwig, 2001*b*) packages. Zircon U–Pb data and Concordia plots are shown in Figures S1, S2 and Table S1 in the online Supplementary Material available at http://journals.cambridge.org/geo.

4. Analytical results

Samples 12GH38 and 12GH39 from central Yangtze (the Xinhuang section) are similar in U–Pb age patterns. Of the total 161 analyses, 145 are concordant (in the 90–110 % range), with ages ranging from 3050 ± 12 to 480 ± 10 Ma. Both samples show a prominent age peak at 850–750 Ma and a moderate age peak at 530–500 Ma, with a few scattered Proterozoic ages (Fig. 3a). Samples 10GD77 and 10GD78 from southeastern Yangtze (the Xinning section) are quite consistent in their U–Pb age patterns. Of the total 133 analyses, 132 are concordant, ranging from 3576 ± 11 to 509 ± 6 Ma. Both samples show prominent age peaks at 1100–900 Ma and 530–500 Ma, a moderate age peak at 2500 Ma, plus a few scattered Proterozoic ages (Fig. 3b). The detrital zircons of all four samples exhibit large compositional variations in Th and U contents, and most zircons (84 %) have Th/U > 0.3; only eight grains (3 %) have Th/U < 0.1 (Table S1 in online Supplementary Material available at http://journals.cambridge.org/geo). Th/U ratios and zoning structures of zircons indicate that most detrital zircons are probably of magmatic origin.

5. Discussion

5.a. Cambrian sediment dispersal across South China

Geochronological results show that lower Cambrian sandstones from central Yangtze (Xinhuang) have a prominent age peak at ~ 790 Ma and a subordinate peak at ~ 530 Ma (Fig. 3a), whereas Cambrian sandstones from northwestern Cathaysia (Shaoguan) have a different prominent peak at ~ 960–910 Ma and a subordinate peak at ~ 530 Ma, with minor peaks at ~ 800 Ma and ~ 2500 Ma (Fig. 3d, e) (Wang *et al.* 2010; Yao *et al.* 2014). This indicates that the Yangtze and Cathaysia blocks likely had different provenances during the Cambrian period. Statistical analysis (K–S test) (Kolmogorov, 1933; Smirnov, 1944) was conducted on samples from central Yangtze and northwestern Cathaysia, and the results (Table S2 in online Supplementary Material available at http://journals.cambridge.org/geo) also indicate that these two groups of samples had different provenances.

The palaeogeography of South China shows that, during the early Cambrian period, the Yangtze Block was dominantly a marine carbonate platform, receiving intercalated clastic and carbonate sediments with water deepening to the southeast; around an isolated land area, conglomeratic facies were deposited (Fig. 2a). During the middle to late Cambrian period, it received carbonate and muddy carbonate deposition (Fig. 2b) (Liu & Xu, 1994). Since Cryogenian volcanic, volcaniclastic and intrusive rocks (860–750 Ma) are widespread in western Yangtze Neoproterozoic rift basins (e.g. Zhou *et al.* 2002, 2006; Li, X. H. *et al.* 2003; Li, Z. X. *et al.* 2003; Li, X. *et al.* 2003; Wang & Li, 2003), we speculate that these *c.* 860–750 Ma rocks in western Yangtze were probably uplifted during the early Cambrian period and provided detritus to the Cambrian sandstones of central Yangtze (Fig. 4a, b). The Cathaysia Block, on the other hand, received deposits of intercalated marine sandstones and

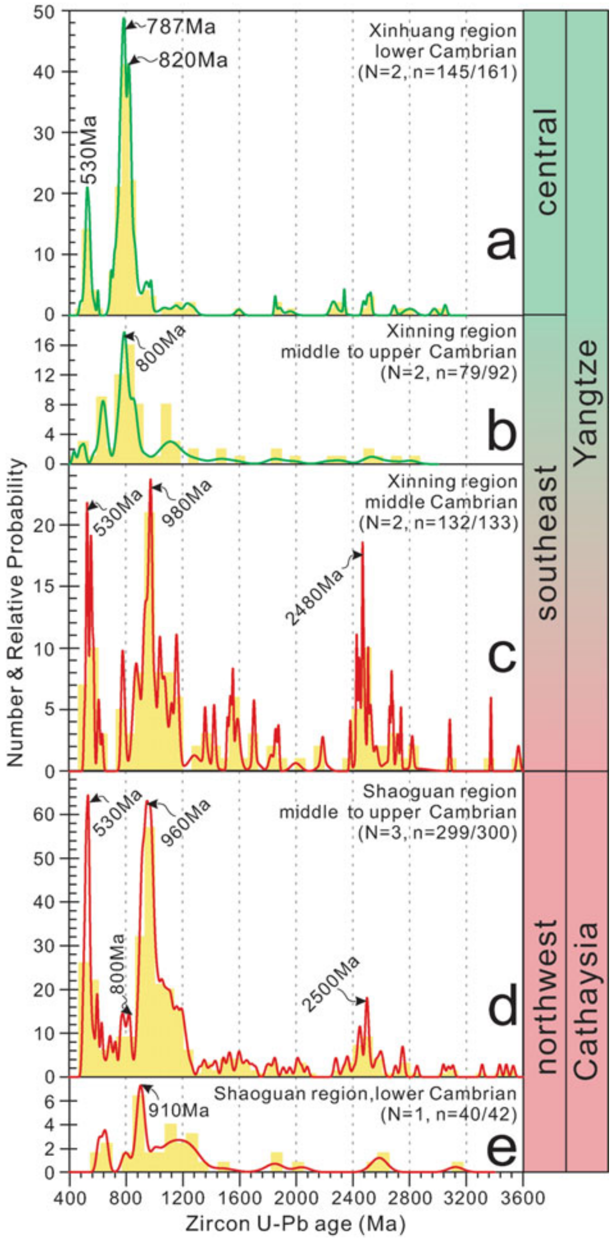

Figure 3. (Colour online) Plots of zircon U–Pb age histograms and relative probability of Cambrian sandstone samples from (a) Xinhuang (this study), (b) Xinning (this study), (c) Xinning (Wang *et al.* 2010), (d) Shaoguan (Yao *et al.* 2014), and (e) Shaoguan (Wang *et al.* 2010). Plotted ages are within concordance of 90–110 % for analysed zircons. N – number of samples, n – number of concordant analyses/total number of analyses.

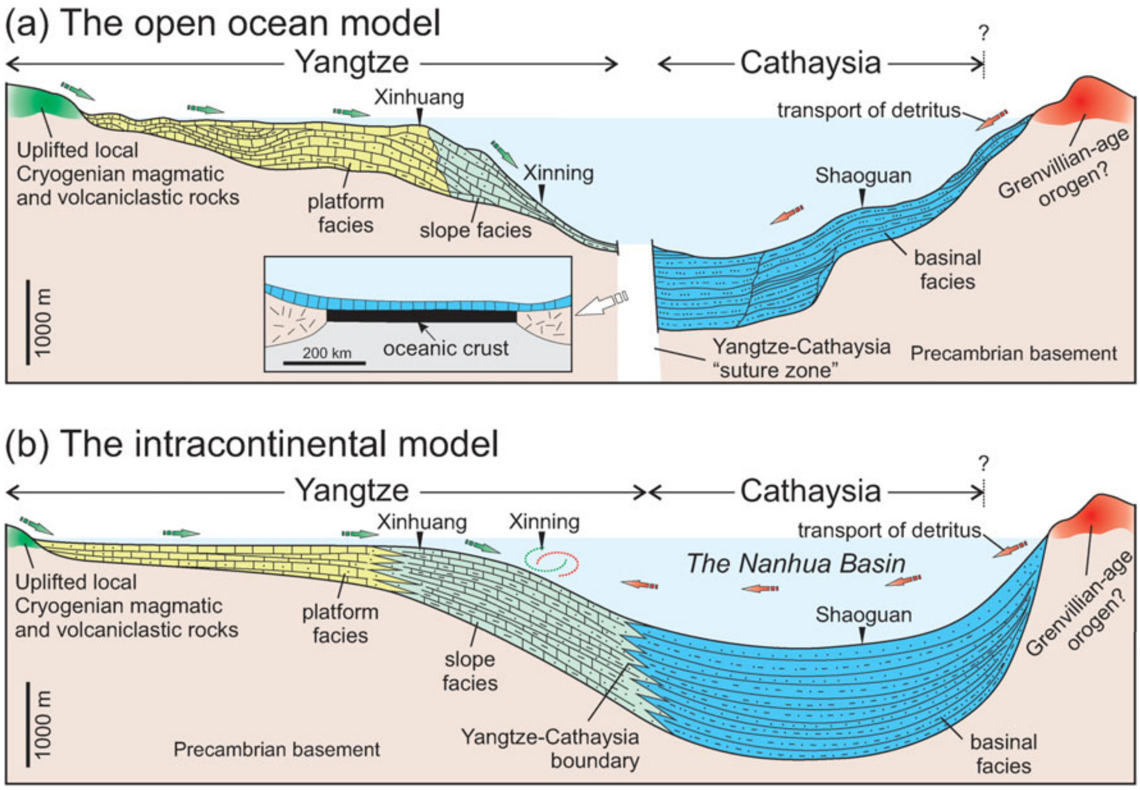

Figure 4. (Colour online) Cartoons illustrating possible paths of sediment transport during the Cambrian period for (a) the open ocean model and (b) the intracontinental model (revised after Liu & Xu, 1994). Detrital provenance analyses of Cambrian sandstones support the intracontinental model.

mudstones, possibly with no exposed land in the region during the Cambrian period (Fig. 2a, b). Both the NW-directed palaeocurrents and northwestward-fining sediments in the Cambrian strata of Cathaysia and southeastern Yangtze indicate an external provenance outboard to southeastern Cathaysia (Wang *et al.* 2010; W. H. Yao & Z. X. Li, unpub. data, 2014). Yao *et al.* (2014) proposed that South China was probably once connected to the northern Indian part of Gondwanaland, along the southeastern margin of Cathaysia. The Grenvillian magmatic rocks (1100–950 Ma) (e.g. Liu *et al.* 2007; Cottle *et al.* 2009), minor *c.* 880–820 Ma magmatic rocks and recycled 2500 Ma zircons in sedimentary rocks (e.g. Myrow *et al.* 2010) of northern India and adjacent orogens probably provided detritus to Cathaysia during the Cambrian period (Figs 4b, 5).

The common age peak at ~ 530 Ma in both central Yangtze and northwestern Cathaysia (Fig. 3a, d, e) suggests that both source areas (western Yangtze and northern India?) were affected by an early Palaeozoic orogeny and produced ~ 530 Ma magmatic rocks in the source regions. The 530 Ma magmatic detritus was recorded in Cambrian sandstones not only from central Yangtze and northwestern Cathaysia, but also from southeastern Yangtze (Xinning) (Fig. 3c). However, Cambrian sandstones in southeastern Yangtze exhibit mixed age patterns, with a major ~ 800 Ma peak in the middle to upper Cambrian sandstones (Fig. 3b) and a major ~ 980 Ma peak in the middle Cambrian sandstones (Fig. 3c). The ~ 800 Ma age peak is probably of the same origin as those in the lower Cambrian sandstones from central Yangtze (Fig. 3a), i.e. from western Yangtze. However, the ~ 980 Ma peak in southeastern Yangtze (Fig. 3c) indicates that detritus was probably sourced from northern India, and transported across Cathaysia to southeastern Yangtze (Figs 4b, 5). This interpretation is supported by the NW-directed palaeocurrents in the Xinning Cambrian strata (Wang *et al.* 2010).

Sediment dispersal in South China can thus be summarized as the following. During the early Cambrian period, Cryogenian magmatic rocks in western Yangtze provided detritus to central Yangtze (Xinhuang). Northwestern Cathaysia (Shaoguan) received detritus from the southeast – an external source, possibly northern India, which likely hosted a Grenvillian-aged orogen (Fig. 4b). In southeastern Yangtze (Xinning), on the lower slope of the Yangtze platform compared to the Xinhuang region, mainly deep-water shales and siliceous shales were deposited during the early Cambrian period. During the middle to late Cambrian period, southeastern Yangtze probably received a major flux of detritus from a Grenvillian-aged orogen to the southeast, with a smaller portion of detritus from local western Yangtze sources (Fig. 4b).

5.b. Was there a Cambrian ocean in South China?

In the Cambrian ocean model as proposed by Shui (1988) and Liu & Xu (1994), the Yangtze Block (central and southeastern Yangtze) should only have recorded detrital grains from western Yangtze (e.g. with a ~ 800 Ma age peak) (Fig. 3a, b) rather than showing a ~ 980 Ma age peak (Fig. 3c). The fact that the southeastern Yangtze recorded a dominantly Cathaysia-like provenance argues against the Cambrian ocean model. There are additional lines of evidence arguing against the ocean model, including: (1) the absence of early Palaeozoic ophiolites or arc-like magmatic rocks related to ocean closure in the region (Chen *et al.* 1995; Li, 1998); (2) early Palaeozoic granites in South China that are largely sourced from remelting of old basement rocks with little input of juvenile mantle (e.g. Chen & Jahn, 1998; Zhou, 2003; Zeng *et al.* 2008; Li *et al.* 2010; Wang *et al.* 2011); (3) lower Palaeozoic sedimentary rocks in South China exhibit strongly negative $\varepsilon_{Nd}(t)$ values (e.g. Li & McCulloch,

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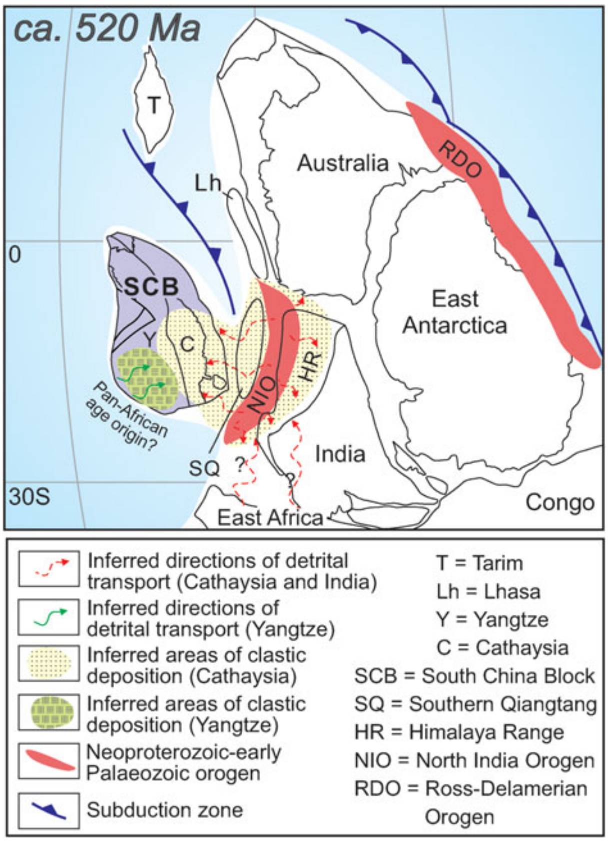

Figure 5. (Colour online) A palaeogeographic reconstruction of South China on the margin of eastern Gondwanaland at *c*. 520 Ma (revised after Yao *et al.* 2014), showing mixing of two different detrital provenances at the Yangtze–Cathaysia boundary.

1996; Chen & Jahn, 1998), which is inconsistent with being originated from a juvenile crust generated during an ocean closure in the early Palaeozoic period; and (4) sedimentary facies across the Cambrian Nanhua Basin are laterally coherent and vertically continuous and conformable (e.g. Liu & Xu, 1994), with no sign of convergent tectonics.

Based on the palaeogeography of South China and mixed provenance of Cambrian sandstones in southeastern Yangtze, we therefore favour the intracontinental model (e.g. Li, 1998; Faure *et al.* 2009; Charvet *et al.* 2010; Li *et al.* 2010; Wang *et al.* 2010; Shu *et al.* 2014). In this model, the Yangtze and Cathaysia blocks had become a coherent block before the Cambrian period. Detritus from the uplifted western Yangtze was transported along the Yangtze platform and deposited in central Yangtze (Xinhuang) (Fig. 3a) as well as southeastern Yangtze (Xinning) (Fig. 3b). Detritus shed from northern India or even eastern Africa (a Grenvillian-age orogen? see Yao *et al.* 2014 for detailed discussion) travelled to northern Cathaysia (Shaoguan) (Fig. 3d, e) and all the way to southeastern Yangtze (Xinning) (Fig. 3c). Since central Yangtze (Xinhuang) is located on the upper opposite slope of the Nanhua Basin, it would have been difficult for Indian detritus to reach that region.

Provenance analyses of Cambrian sandstones across the Yangtze–Cathaysia boundary therefore provide evidence that argues against the existence of a broad Cambrian ocean, but is consistent with the intracontinental model, which is also supported by sedimentary facies analyses across South China (Chen *et al.* 1995; Shu *et al.* 2014; W. H. Yao & Z. X. Li, unpub. data, 2014). Since southeastern Yangtze received shale and siliceous shale without clastic deposits in the lower Cambrian strata, it failed to record provenance mixing from the Cathaysia side. This may lead to the speculation that an ocean could still have existed during the early Cambrian period. However, as mentioned before, such a speculation can be ruled out because there is neither any record of an arc system nor any sign of convergent tectonics within the Nanhua Basin during the entire Cambrian period.

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Declaration of interest

None.

Supplementary material

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