**Widespread Paleoproterozoic basement in the eastern Cathaysia Block:
evidence from metasedimentary rocks of the Pingtan-Dongshan
metamorphic belt, in southeastern China**

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16 **Abstract**

17 The Cathaysia Block in South China Block (SCB) is famous for its polyphase granitic
18 magmatism and world-class mineralization, especially W, Sn and REE. Although isotopic
19 data suggest that widespread igneous rocks were derived from Precambrian basement,
20 outcrops of the basement rocks are rare in the Cathaysia Block. Therefore, the distribution of
21 the Archean-Paleoproterozoic basement beneath Cathaysia Block is still unclear.

22 The northeastern-striking Pingtan-Dongshan metamorphic belt (PDMB) is located along
23 the coastal region of southeastern China, and consists mainly of voluminous granites and
24 volcanic rocks with minor metasedimentary rocks. These metasedimentary rocks were
25 intruded or captured by 160-143 Ma granites. U-Pb dating of detrital and metamorphic
26 zircons from seven metasedimentary rocks indicates that their protoliths were deposited
27 between 183 Ma to 160 Ma, rather than pre-Devonian as previously proposed. Dating of
28 metamorphic zircons suggests that the most important metamorphism took place at ca 97 Ma,
29 consistent with emplacement of A-type granites and mafic magmatism in the coastal region,
30 and implying an extensional setting.

31 Age spectra of detrital zircons in samples from the middle and southern PDMB exhibit a
32 bimodal distribution with abundant Late Paleoproterozoic and Early Mesozoic zircons. In
33 contrast, age spectra of detrital zircons from the northern PDMB display pronounced
34 Neoproterozoic and Early Paleozoic age peaks as well as Late Paleoproterozoic and Early
35 Mesozoic ones, suggesting a different provenance. The comparisons of age and Hf-isotope
36 with the exposed rocks of the SCB suggest that the terrigenous material in these sediments
37 was sourced from the Wuyi terrane, in the eastern Cathaysia Block.

The age spectra of detrital zircons from Early Paleozoic to Late Mesozoic sedimentary rocks in the SE SCB show that late Paleoproterozoic (1.9-1.8 Ga) detritus increases markedly in Middle Permian to Early Cretaceous sedimentary rocks. Comparison with zircon U-Pb-Hf isotopic data from exposed Paleoproterozoic rocks suggests that a Paleoproterozoic basement existed extensively beneath the eastern Cathaysia Block. It has been uplifted and eroded since Middle Permian time, and then covered by Late Cretaceous volcanic rocks. The uplift of the Paleoproterozoic basement was probably caused by the Late Paleozoic orogeny in the eastern Cathaysia Block.

Keywords: Paleoproterozoic basement, Jurassic meta-sedimentary rocks, Pingtan-Dongshan Metamorphic Belt, Cathaysia Block

1. Introduction

The study of metamorphic basement rock series has become a major research focus in solid Earth Science, as it can provide fundamental information on the composition, formation and evolution of the deep continental crust and the amalgamation and breakup of Precambrian supercontinents. Unfortunately, the exposures of pre-Neoproterozoic crystalline basement rocks are scarce in the South China Block (SCB). The oldest rocks are locally preserved in the Kongling terrane, in the northern Yangtze Block, which is composed of Mesoarchean to Early Paleoproterozoic TTG and high-grade metamorphic rocks (Gao et al., 2011; Jiao et al., 2009; Li LM et al., 2014; Qiu et al., 2000; Yin et al., 2013). However, early Precambrian basement rocks are unknown in the Cathaysia Block of the SCB. The oldest rocks identified in the

60 Cathaysia Block are 1.91~2.5 Ga metamorphic rocks (i.e. the Badu complex and Mayuan
 61 Group) and the associated 1.85-1.91 Ga granites in SW Zhejiang and NW Fujian provinces in
 62 the eastern Cathaysia Block (Li LM et al., 2011a; Liu et al., 2009, 2014; Xia et al., 2012;
 63 Xiang et al., 2008; Yu et al., 2009, 2012; Zhao et al., 2014, 2015). A few meta-mafic rocks
 64 (1.77-1.78 Ga) outcrop in the Jianning area of northwestern Fujian Province and in the
 65 Chencai area of northern Zhejiang Province (Li XH, 1997; Li ZX et al., 2010). Some groups,
 66 such as the Wanquan, Taoxi, Mamianshan, Zhoutan and Longquan groups in the Wuyi terrane,
 67 which were originally defined as Paleoproterozoic to Mesoproterozoic metamorphic strata,
 68 actually formed mostly in the Neoproterozoic and were metamorphosed in early Paleozoic (Li
 69 LM et al., 2011b; Li WX et al., 2005; Li ZX et al., 2010; Wan et al., 2007; Xu et al., 2010;
 70 Yao et al., 2013; Yu et al., 2005, 2010). This re-evaluation of the chronological framework
 71 seems to vastly decrease the area of exposed Precambrian basement rocks, and implies that
 72 the early Paleozoic (Caledonian) orogeny played a crucial role in the tectonic and magmatic
 73 scenario of Cathaysia Block. However, an opposing model, emphasizing the significance of
 74 the “Cathaysia oldland” has been re-invoked on the basis of increasing amounts of evidence.
 75 Published Nd isotopic data from the Cathaysia Block indicate that the Precambrian basement
 76 rocks and their Phanerozoic derivatives predominantly originated from 1.7~2.2 Ga crust
 77 (Chen and Jahn, 1998; Chen et al., 1999; Hong et al., 1999; Shen et al., 1993). Moreover,
 78 more and more early Precambrian detrital/inherited zircons have been found in
 79 Neoproterozoic to Phanerozoic sedimentary and igneous rocks (e.g. Wang et al., 2007b, 2011,
 80 2012; Xing et al., 2014; Yu et al., 2005, 2007a, 2009), supporting the existence of the early
 81 Precambrian magmatism and tectonics in the Cathaysia Block. There may be three reasons for

82 the scarcity of early Precambrian rocks outside of NW Fujian and SW Zhejiang. First, the old
83 rocks are covered by extensive Phanerozoic sedimentary and volcanic rocks. Second, they
84 were strongly recycled and altered to form new successions. Third, the old detritus might
85 come from another continent, which once was contiguous with the Cathaysia Block (e.g. Li
86 XH., 2014; Yu et al., 2008).

87 As an effective probe of provenance characteristics, detrital zircons from sedimentary
88 rocks can be used to dissect each tectono-thermal event in their source area, and help to
89 evaluate crustal evolution history (Griffin et al., 2004; Iizuka et al., 2005; Kemp et al., 2006;
90 Rino et al., 2004). Recent studies on detrital zircons from late Neoproterozoic to early
91 Paleozoic sediments in the Cathaysia block (Wang et al., 2007b; Wan et al., 2007, 2010; Yao
92 et al., 2011, 2012; Yu et al., 2010) allow the Precambrian crust of the Cathaysia Block to be
93 subdivided into two distinct tectonic domains, the Wuyi terrane to the northeast and the
94 Nanling-Yunkai terrane to the southwest (Yu et al., 2010). However, whether there was an
95 Archean-Paleoproterozoic crust in the Cathaysia and its possible areal distribution, have been
96 unclear.

97 Along the coastline of Fujian Province there is a metamorphic belt with NE orientation,
98 termed the Pingtan-Dongshan metamorphic Belt (PDMB), which is separated from the inner
99 volcanic belt by the Changle-Nan'ao Fault (Fig. 1). The PDMB is characterized by polycyclic
100 magmatism and multiple episodes of metamorphism and deformation in Mesozoic time (Chen,
101 1997; Huang et al., 1993; Kong et al., 1996; Shi and Zhang, 2010; Shi, 2011; Tong and
102 Tobisch, 1996; Zhang et al., 2012). Some meta-sedimentary rocks are found locally along the
103 PDMB, and show amphibolite facies metamorphic mineral assemblage (Chen, 1997; Yu and

Shu, 2002; Yu et al., 2007a), much different from the inner late-Mesozoic volcanic belt. Due to the lack of accurate isotopic dating and ambiguous contact relationships with country rocks, the ages of the meta-sedimentary rocks have not been well constrained. Because of their high metamorphic grade, they were previously expected to have old formation ages (Huang et al., 1989; Zhuang et al., 2000).

In this study, we have carried out *in situ* U-Pb dating and Hf-isotope determinations on zircons separated from seven meta-sedimentary rocks in the PDMB, and obtained a total of 423 concordant U-Pb ages and 221 Hf-isotope data. The aim of this study is to constrain the formation and metamorphic ages of the meta-sedimentary rocks, and further to reveal the relationship of the PDMB with continent further inland. Integrating previously published geochronological data, we attempt to unravel the formation age, distribution area, exposure and denudation of the crystalline basement of the eastern Cathaysia block.

2. Geological background and sampling

The SCB is bounded by the Qingling-Dabie-Sulu orogen to the north, the Tibetan Plateau to the west and the Indochina block to the southwest. The SCB consists of the Yangtze Block to the northwest and the Cathaysia Block to the southeast (Fig. 1). Since its amalgamation with the Yangtze Block in early Neoproterozoic time, the Cathaysia Block has suffered intensive polyphase tectonic-magmatic events, including Early Paleozoic, Late Paleozoic, Early Mesozoic and Late Mesozoic ones. An Early Paleozoic tectonothermal event, the Kwangsian or Wuyi-Yunkai orogeny (Li ZX et al., 2010; Wang et al., 2011, 2012), is marked by an angular unconformity between strongly deformed pre-Silurian strata and the overlying

126 Middle to Upper Devonian coarse-clastic rocks (Huang et al., 1980; Ren, 1991), as well as
127 variable degrees of metamorphism and subsequent anatexis (granitic magmatism). A Late
128 Paleozoic orogeny, whose geodynamic setting and distribution are poorly known, probably
129 includes an early phase of compression (Middle-Late Carboniferous) and later extension
130 (since Early Permian) in the eastern Cathaysia Block (Yu et al., 2013). The Early Mesozoic
131 (Indosinian) orogeny is characterized by a regional angular unconformity between Late
132 Triassic and Early Jurassic strata, and voluminous S-type granites. The Late Mesozoic
133 (Yanshanian) tectono-magmatic event strongly affected the eastern margin of the SCB and
134 produced abundant igneous rocks with magmatic features typical of active continental
135 margins, and is ascribed to the westward subduction of the paleo-Pacific Plate (Li ZX and Li
136 XH, 2007; Zhou and Li, 2000; Zhou et al., 2006).

137 The Zhenghe-Dabu Fault and the Changle-Nan'ao Fault are the most significant
138 NE-trending faults in the southeastern SCB (Fig. 1); they divide the Cathaysia block into the
139 Early Paleozoic fold-thrust belt, the late Mesozoic volcanic belt, and the PDMB. The PDMB,
140 extending along the coastal region of Fujian Province, is up to 400 km long and 20 km to 40
141 km wide. The metamorphic belt includes both deformed and undeformed granites, and
142 volcanic rocks with minor meta-sedimentary rocks (BGMRFJ, 1985, 1997; Shu and Xu,
143 2002). These metamorphic rocks were termed the Aojiao Group, and have been subdivided
144 into the Yanya and Qinyingshan formations. The former consists mainly of migmatites and
145 granitic gneisses; the latter is composed of meta-sedimentary rocks. Recent studies show that
146 the granitic gneisses or “migmatites” in the Yanya formation probably are deformed granites
147 (Yu and Shu, 2002; Nie, 2007). Therefore, the redefined Aojiao “Group” only includes

meta-sedimentary rocks of the Qinyinshan Formation. The granitic intrusions are widely distributed in the PDMB, including dominant early Cretaceous I-type granites, late Cretaceous A-type granites and minor Jurassic granites (e.g. Cui et al., 2013; Feng et al., 2011, 2014b; Li WX et al., 2003; Liu et al., 2011, 2012; Shi and Zhang, 2010; Tong and Tobisch, 1996). It is generally believed that these granites are genetically associated with the subduction of the paleo-Pacific plate and late post-orogenic extension, respectively (Cui et al., 2013; Jahn et al., 1990; Lapierre et al., 1997; Liu et al., 2012; Zhou and Li, 2000; Zhou et al., 2006). Jurassic to Early Cretaceous granites generally show a foliation and lineation concordant with the country rocks, recording different extents of deformation and metamorphism (Chen, 1997; Shu et al., 2000; Yu and Shu, 2002).

Seven meta-sedimentary samples were collected from Pingtan Island (DS09-45-2), Longhai County (DS09-23-2) and Dongshan Island (DS09-3-1, DS09-11, DS09-13-3, -5, -7) (Fig. 1, 2). These metamorphic rocks are collectively intruded by Late Jurassic to Cretaceous granites (Cui et al., 2013; Feng et al., 2011; Li WX et al., 2003; Liu et al., 2012; Shi and Zhang, 2010; Tong and Tobisch, 1996) (Fig. 3). Sample DS09-45-2 from the Nanwuli village on Pingtan Island is a garnet-bearing two-mica schist with the mineral assemblage Grt + Mus + Bt + Qz + Pl (Fig. 4i), and sample DS09-23-2 from Gangwei in Longhai is a sillimanite-bearing garnet-muscovite gneiss with the mineral assemblage Grt + Mus + Sil + Qz + Pl (Fig. 4h). A sillimanite-bearing two-mica quartz schist (DS09-3-1) and a garnet-bearing two-mica schist (DS09-11) were sampled from the Sufengshan and Daroushan areas on Dongshan Island, respectively (Fig. 2d, 3a). Their mineral assemblages are Mus + Bt + Qz + Sil + Pl (DS09-3-1) and Grt + Mus + Bt + Qz + Pl (DS09-11) (Fig. 4a, b). Samples

DS09-13-3, DS09-13-5 and DS09-13-7 were collected from the Aojiao area of southern Dongshan Island (Fig. 2d, 3). Sample DS09-13-7 has the mineral assemblage Spl + Grt + Sil + Mus + Bt + Qz + Pl (Fig. 4f, g), suggestive of high-amphibolite facies to granulite-facies metamorphism. The other two samples have mineral associations of Grt + Pl + Mus + Bt + Qz + Kf (Fig. 4c-e). Fabrics are well developed in these meta-sedimentary rocks, with mostly NE-striking foliations, variable dip angles and subhorizontal lineations.

3. Analytical methods

The detrital zircons were separated from rock samples using conventional techniques, including heavy liquid and magnetic techniques. Zircons were handpicked from heavy-mineral concentrates under a binocular microscope, mounted on adhesive tape, and enclosed in epoxy resin. This was ground and polished to expose the zircon cores. Cathodoluminescence (CL) imaging was carried out at the GEMOC National Key Centre, Macquarie University, using a CAMECE-SX100 electron microprobe. These images characterize the internal structures and external morphology, to guide the LA-ICPMS analyses.

In situ zircon U-Pb dating was performed using an Agilent HP 7500 ICP-MS at the State Key Laboratory for Mineral Deposits Research, Nanjing University. The ablated material is transported in a He carrier gas through 3 mm PVC tubing and then combined with Ar to enter the ICP-MS for isotopic quantification. The working parameters of laser instrument are as follows: 213 nm wavelength, 5Hz repetition rate and energy of 10-20J/cm², 32 or 25 μm ablation diameter. Data acquisition for each analysis takes 100s (40s on background, 60s on

192 ablated signal). The raw ICP-MS data were acquired using GLITTER 4.0 (Griffin et al., 2008),
193 and common Pb was corrected using the method described by Andersen (2002). The age
194 calculations and plotting of Concordia diagrams were drawn by Isoplot (Ludwig, 2001). The
195 $^{206}\text{Pb}/^{238}\text{U}$ age is adopted for young (<1000Ma) zircons, whereas the $^{207}\text{Pb}/^{206}\text{Pb}$ age is used
196 for those >1000 Ma.

197 *In situ* Hf-isotope analyses were carried out at the GEMOC National Key Centre,
198 Macquarie University, using a Nu Plasma MC-ICPMS with a Merchantek/NWR 213 nm
199 laser-ablation microprobe. The ablation time is 60s with a repetition rate of 10 Hz and laser
200 beam energy of 4.40-5.27 J/cm², resulting in pits with 60 μm in diameter and 40μm deep.
201 Before analyzing unknown samples, the 91500 standard zircon was analyzed to check
202 instrument reliability and stability. The analytical conditions and procedures are those
203 described by Griffin et al. (2000). To calculate the Hf model ages and epsilon Hf, we adopted
204 the ^{176}Lu decay constant of 1.865×10^{-11} per year (Scherer et al., 2001), the depleted mantle
205 with $^{176}\text{Hf}/^{177}\text{Hf}=0.28325$ and $^{176}\text{Lu}/^{177}\text{Hf}=0.0384$ (Griffin et al., 2002) and chondrite with
206 $^{176}\text{Hf}/^{177}\text{Hf}=0.282772$ and $^{176}\text{Lu}/^{177}\text{Hf}=0.0332$ (Blichert-Toft and Albarede, 1997). Two-stage
207 “crustal” model ages (T_{CDM}) are calculated based on the assumption that the parental magma
208 of the zircon was derived from a source with an average continental crust $^{176}\text{Lu}/^{177}\text{Hf}$ of 0.015
209 (Griffin et al., 2002).

4. Analytical results

4.1 U-Pb ages of zircons

4.1.1 *Two-mica schist (DS09-45-2) from Pingtan, northern PDMB*

The zircons separated from this sample are mainly subhedral, with a few presenting rounded morphology. The grains mostly have 50 μ m to 160 μ m in length and 30 μ m to 80 μ m in width, yielding axial ratios of 1:1 to 3:1. CL images show that most grains have oscillatory compositional zoning (Fig. 5b-g), and some have narrow highly luminescent overgrowth rims. 101 detrital zircons were dated and yield ages ranging from 2542 Ma to 188 Ma (Appendix Table 1). Most of these zircons are concordant (concordance = 95~105%) or near-concordant (concordance = 80~95 and 105~120%), and define four major age peaks at 1741~1907 Ma (n=15), 627~938 Ma (n=21), 494~422 Ma (n=10), and 188~284 Ma (n=25), with a subordinate age peak at 2399~2542 Ma (n=6) (Fig. 6, 7). 72 analyses have Th/U ratios > 0.4, and only two grains have Th/U < 0.1, indicating that most are of magmatic origin. A loosely constrained discordia yields an upper intercept age of 1882 ± 31 Ma (Fig. 6). The youngest zircon gives an age of 188 ± 3 Ma.

4.1.2 *Sillimanite-bearing garnet-muscovite gneiss (DS09-23-2) in Gangwei, middle PDMB*

Compared with the Pingtan schist (DS09-45-2), the zircons in this sample mostly show clearly zoned internal structure and more idiomorphic shapes (Fig. 5j-q). They are relatively large, ranging from 120 μ m to 260 μ m in length and from 60 μ m to 100 μ m in width, with axial ratios varying from 1.5:1 to 3:1. 70 analyzed zircons give concordant and near-concordant

ages ranging from 183 Ma to 2604 Ma ([Appendix Table 1](#); [Fig. 6](#)), forming a major age peak at 1829~1901 Ma (n=33) and two subordinate peaks at 211~261 Ma (n=14) and 2397~2604 Ma (n=8) ([Fig. 7](#)). Most zircons have Th/U ratios > 0.4, indicative of magmatic origin. Twenty-eight concordant late Paleoproterozoic zircons yield a weighted mean age of 1863±9 Ma (MSWD=0.39), consistent with an upper intercept age of 1868±10 Ma ([Fig. 6](#)). The youngest zircon has an age of 183 Ma.

4.1.3 Samples DS09-3-1, DS09-11, DS09-13-3, DS09-13-5 and DS09-13-7 in the Dongshan Island, southern PDMB

The zircons separated from samples DS09-13-3, DS09-13-5 and DS09-13-7 on southern Dongshan Island mostly have stubby prismatic or ellipsoidal shapes, with a few having euhedral shapes ([Fig. 5r-ae](#)). Some zircons show clear oscillatory zoning, but the others show irregular variations in luminescence. The grains mostly range from 100µm to 180µm in length and from 40µm to 100µm in width, leading to axial ratios of 1.5:1 to 2:1, with the exception of a few grains ([e.g. Fig. 5w](#)). Zircons from samples DS09-3-1 and DS09-11 are analogous to those in the Gangwei gneiss DS09-23-2 in terms of morphology.

57 of 60 analyses from sample DS09-3-1 are concordant or near-concordant, and have ages ranging from 192 Ma to 2492 Ma ([Appendix Table 1](#)), forming two significant age peaks clustered at 1815~1940 Ma (n=31) and 192~261 Ma (n=14), along with a subordinate age population at 2350~2492 Ma (n=5) ([Fig. 6, 7](#)). 41 analyses have Th/U ratios greater than 0.4, and only two young zircons have Th/U < 0.1, indicating that most are of magmatic origin. The weighted mean age of the late Paleoproterozoic concordant zircons is 1870±11 Ma

(MSWD=1.00, n=21), in accord with an upper intercept age of 1880 ± 16 Ma (Fig. 6). The early Mesozoic group can be subdivided into two subgroups at 238~261 Ma and 192~220 Ma, roughly corresponding to two early Mesozoic magmatic stages known in the SCB (Wang et al., 2007a; Yu et al., 2007b). The two youngest detrital zircons have the same age of 192 ± 3 Ma, restricting the maximum depositional age of the sedimentary protolith.

53 zircons with concordance of >80% from sample DS09-11 exhibit ages ranging from 189 Ma to 3133 Ma (Fig. 6, 7; Appendix Table 1), and the vast majority (84%) of the analysed zircons are of Paleoproterozoic – Archean age, defining a major peak at ca 1860 Ma (n=23) and a subordinate age group at 2324~2493 Ma. The younger zircons cluster at 189~254 Ma. 18 concordant late-Paleoproterozoic zircons give a weighted mean age of 1851 ± 12 Ma, coincident with the upper intercept age of 1869 ± 20 Ma (Fig. 6). The youngest zircon in this sample gives an age of 189 ± 3 Ma, similar to those of the samples above.

Samples DS09-13-3, DS09-13-5 and DS09-13-7 present somewhat different zircon U-Pb age spectra from above samples (Fig. 6, 7), and have relatively more grains with young ages (Appendix Table 1; Fig. 6, 7), especially in sample DS09-13-7. The young zircon populations have ages spanning from 94 Ma to 258 Ma with several subordinate peaks (Fig. 9).

The older zircon groups in three samples are also mainly of late Paleoproterozoic to late Neoarchean age. 13 concordant late Paleoproterozoic zircons in sample DS09-13-3 yield a weighted mean age of 1865 ± 13 Ma (MSWD=0.76), consistent with an upper intercept age of 1861 ± 16 Ma for a discordia line (Fig. 6). The other old zircons have ages spanning from 2641 Ma to 2025 Ma. Concordant late Paleoproterozoic zircons of sample DS09-13-5 yield a weighted mean age of 1851 ± 19 Ma (MSWD=1.04, n=6), in accord with an upper intercept

age of 1861 ± 19 Ma (Fig. 6). Older zircons in this sample have ages of 2516~1979 Ma except for one grain (3110 Ma). Sample DS09-13-7 has fewer old zircons. Several late Paleoproterozoic zircons loosely define a discordia with an upper intercept of 1871 ± 39 (MSWD=2.4; Fig. 6). The ages of two concordant middle-Paleoproterozoic zircons are 2179 Ma and 2117 Ma.

4.2. Hf-isotope composition

4.2.1 Two-mica schist (DS09-45-2) from the Pingtan, northern PDMB

We selected 59 zircons from sample DS09-45-2 for Hf-isotope analysis (Fig. 8a). ~2.5 Ga zircons mostly have positive $\epsilon\text{Hf}(t)$ with similar model ages (2.99~2.71 Ga) except for grain c-11, which has a Hf model age identical to its crystallization age, suggesting its parental magma was derived from a late Neoproterozoic juvenile source (Appendix Table 2; Fig. 8a). The $\epsilon\text{Hf}(t)$ values of most late Paleoproterozoic zircons vary from -1.77 to +1.84 (except for a grain x-14 with $\epsilon\text{Hf}(t)$ of +4.47), corresponding to a late Neoproterozoic (~2.5 Ga) model age, similar to that of grain c-11. Thus, the Hf-isotope compositions of Neoproterozoic and Paleoproterozoic zircons indicate two significant episodes of juvenile crustal growth at *ca* 2.8 Ga and *ca* 2.5 Ga. The Neoproterozoic and Late Paleozoic to Early Mesozoic zircons have large ranges of $(^{176}\text{Hf}/^{177}\text{Hf})_i$ ratios, indicative of reworking of crustal materials with a subordinate contribution from mantle-derived magmas. Notably, the $(^{176}\text{Hf}/^{177}\text{Hf})_i$ values of the Neoproterozoic zircon grains display a trend to lower values with decreasing age (Fig. 8a), indicating that their host magmas contain a mix of ancient crustal components (Neoproterozoic)

and juvenile inputs from the depleted mantle; the late magmatism involved progressively more of the crustal components. The early Paleozoic zircons exhibit a tight distribution along or slightly below the CHUR reference line (Fig. 8a), with the $\epsilon_{\text{Hf}}(t)$ values ranging from -3.5 to -0.09. Except for the least radiogenic grain c-69, most Phanerozoic zircons give variable Mesoproterozoic model ages similar to those of the Neoproterozoic zircons. However, no Mesoproterozoic juvenile crust is known in the Cathaysia Block, suggesting that the host magmas of these zircons probably resulted from the mixing of reworked early Precambrian components with Neoproterozoic juvenile magmas (Li WX et al., 2005, 2010; Shu et al., 2011).

4.2.2 Sillimanite-bearing garnet-muscovite gneiss (DS09-23-2) in Gangwei, middle PDMB

The Hf-isotope compositions of 38 zircon grains from sample DS09-23-2 have been analyzed (Fig. 8b). Late Paleoproterozoic zircon grains from this sample lie tightly below the CHUR reference line. They have Hf model ages of 2.99-2.62 Ga, yielding a weighted mean age of ~2.8 Ga. Early Paleoproterozoic to late Neoproterozoic zircons also lie near the 2.8 Ga crustal-evolution line (Fig. 8b), suggesting that host magmas of these zircons originated from sources similar to that recorded by the Late Paleoproterozoic zircons.

The late Paleozoic to Early Mesozoic groups display large Hf-isotope variations, with $\epsilon_{\text{Hf}}(t)$ ranging from 11.93 to -20.41, suggesting that these episodes of magmatism involved both the reworking of ancient crust (Neoproterozoic) and growth of juvenile crust.

4.2.3 Samples DS09-3-1, DS09-11, DS09-13-3, DS09-13-5 and DS09-13-7 from Dongshan Island, southern PDMB

124 zircons in five samples from Dongshan Island were analyzed for their Hf-isotope compositions. The early Paleoproterozoic to late Neoproterozoic zircons have $\epsilon\text{Hf}(t)$ values ranging from -13.1 to +5.6, suggesting a variety of sources. Their Hf model ages mostly concentrate at 3.3-2.5 Ga (Appendix Table 2). However, two ~2.5 Ga zircon grains from samples DS09-11 and DS09-13-3 have old model ages (3.7 Ga and 3.9 Ga), similar to a Mesoproterozoic zircon in sample DS09-11 with a Hf model age of *ca* 4.0 Ga assuming a crustal $^{176}\text{Lu}/^{177}\text{Hf} = 0.018$ (Fig. 8b). Late Paleoproterozoic zircons cluster mostly below the CHUR reference line (Fig. 8b), with model ages ranging from 3.2 Ga to 2.5 Ga, similar to most early Paleoproterozoic to late Neoproterozoic zircons.

The late Paleozoic to Early Mesozoic (>170 Ma) zircons, like those in sample DS09-23-2, exhibit extremely large Hf isotope variations with model ages spanning from ~2.5 Ga to 0.65 Ga, suggesting that some of their host magmas originated from the reworking of ancient crustal material, and others from the mixing of old crustal components with varying proportions of mantle-derived material.

5 Discussion

5.1 Timing of deposition and subsequent metamorphism of the Aojiao “Group” sedimentary rocks

The time of formation and metamorphism of the Aojiao “Group” rocks is critical for

understanding the relationship of the PDMB and inner volcanic and Caledonian fold belt. Although many studies have been made on the Aojiao “Group” metamorphic rocks, their protolith ages have not been well constrained. The metamorphic rocks were once regarded as a suite of Early Mesozoic volcanic-sedimentary rocks (BGMRFJ, 1985; Li GK et al., 1983; Ren et al., 1984), as a part of the “Cathaysia oldland” with Precambrian ages (IGFJ, 1995; Zhuang et al., 2000), or as Early Paleozoic metamorphic rocks (Gao et al., 1991, 1993; Huang et al., 1988, 1989, 1993; Xie et al., 1986; Yang et al., 1985; Yu et al., 1988). However, due to the uncertainty of the previously-used isotopic dating methods (Sm-Nd and Rb-Sr isochrons) and microfossils for constraining the protolith age of these meta-sedimentary rocks, they sometimes have been roughly defined as pre-Devonian (Li JH et al., 1995; Song and Wu, 2002). However, Cui et al. (2013) and Nie (2007) recently carried out U-Pb dating of detrital zircons from quartz schists in the northern PDMB, and obtained youngest detrital zircon ages of ~200 Ma, suggesting a younger sedimentation age for their protoliths.

A consensus on the time of the metamorphism is that the PDMB was formed in the Mesozoic, so that it has been termed the Mesozoic Metamorphic Belt (Chen, 1997; Gao et al., 1991, 1993; Huang et al., 1989; Jahn et al., 1976; Li GK et al., 1983; Lin and Song, 1982). However, metamorphic periods and exact ages are ambiguous. Huang et al. (1993) thought that the peak metamorphism occurred at 170 Ma, whereas Kong et al. (1996) proposed that the PDMB suffered three periods of metamorphism at 165 Ma, 120 Ma and 90 Ma, respectively. Shi (2011) also argued for three periods of metamorphism, but thought that they took place at 149-145 Ma, 145-137 Ma and 100 Ma.

The detailed zircon U-Pb isotopic analyses of seven metamorphic rocks from the whole

PDMB were carried out in this study help to clarify these arguments on the depositional and metamorphic ages of Aojiao “Group”. The youngest detrital zircon groups in samples DS09-45-2, DS09-23-2, DS09-3-1 and DS09-11 have similar concordant $^{206}\text{Pb}/^{238}\text{U}$ ages of 192-183 Ma, constraining the sedimentation time to < 192~183 Ma. Field observations indicate that these meta-sedimentary rocks in the PDMB are intruded by gneissic granites (Fig. 3), which have formation ages of 160-121 Ma (e.g. Cui et al., 2013; Feng et al., 2011; Li WX et al., 2003; Liu et al., 2012; Shi and Zhang, 2010; Tong and Tobisch, 1996). Thus, these sedimentary rocks probably were deposited in late Early to Middle Jurassic time (183 ~ 160 Ma). However, samples DS09-13-3, -5 and -7 collected from the Aojiao seaside of Dongshan Island have numerous younger zircon grains (< 200 Ma), especially sample DS09-13-7. These young zircons (<200 Ma) can be approximately divided into four brackets (Fig. 9): 94~99 Ma (n=6), 105~131 Ma (n=11), 154~176 Ma (n=14) and 180~200 Ma (n=15). Because these metamorphic rocks on Dongshan Island are intruded or captured by 147~140 Ma gneissic granites (Fig. 3; Feng et al., 2011; Liu et al., 2012), their protoliths must have formed before 155~140 Ma, and the 94~99 Ma and 105~131 Ma zircons are not detrital zircons at all.

The 94~99 Ma zircon group is exclusively found in sample DS09-13-7, which has the characteristic assemblage of spl-sill-gt-pl-bt-qz (Fig. 4f, g) , suggesting low pressure and high temperature (LP-HT) metamorphism up to high amphibolite facies or even to granulite-facies (Yu and Shu, 2002). These zircons show stubby euhedral morphology and simple internal structure (Fig. 5ab, ac) with high Th/U. Therefore, we suggest that they are probably anatectic zircons crystallized from small-volume melts produced during high-grade metamorphism. Their weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age (97 ± 1 Ma, MSWD=0.71; Fig. 9) is interpreted to reflect

the time of high-grade metamorphism of sample DS09-13-7. This peak LP-HT metamorphism is also contemporaneous with the extensive late Cretaceous magmatic event in the SE SCB (Chen et al., 2008; Feng et al., 2014b; Li HM et al., 1995; Liu et al., 2012; Qiu et al., 2004; Yang et al., 2010; Yui et al., 1996), suggesting a late Cretaceous extensional tectonic environment in the SCB.

The second group of young zircons (105~131 Ma) is also mostly found in sample DS09-13-7 (Fig. 9), and have euhedral shape with little internal zoning (fig. 5aa) and high Th/U ratios. Available geochronological data show that during this period granitoids and their volcanic counterparts occurred widely in the SE SCB (Cui et al., 2013; Dong et al., 1997; Feng et al., 2014b; Li WX et al., 2003; Liu et al., 2012; Tong and Tobisch, 1996; Yui et al., 1996). Consequently, this group of young zircons may be related to the above magmatic event or result from different extent of Pb-loss of old zircons as evidenced by their Hf-isotope compositions (Fig. 8b; Appendix Table 2).

The 154~176 Ma zircons are mainly present in sample DS09-13-7 (Fig. 9) and typically exhibit weak compositional zoning (Fig. 5x) and high Th/U ratios. This period of magmatism is absent in the SE SCB, but relatively abundant in the Nanling Range region far from the PDMB (Li XH et al., 2003; Zhou et al., 2005; Zhu et al., 2010). Two possibilities can account for this zircon group. Firstly, they are detrital zircons derived from the Nanling Range or a similar source, thus suggesting that these meta-sedimentary rocks from Aojiao Village on Dongshan Island formed at 154~140 Ma, later than other meta-sedimentary rocks in the PDMB. However, these 176~154 Ma zircons selectively are found sample DS09-13-7, but a few in samples DS09-13-3 and DS09-13-5, which were collected in the same location. On the

other hand, 150-160 Ma magmatism is much more extensive in the Nanling Range than the 160-176 Ma magmatism (Guo et al., 2011; Zhang et al., 2015; Zhou et al., 2006; Zhu et al., 2009), but 150-160 Ma zircons are less common than 176~160 Ma ones (Fig. 9). An alternative, and more probable, interpretation is that the young ages reflect Pb-loss from Early Jurassic zircons caused by the later metamorphism, because this rock suffered the strongest metamorphism, as evidenced by its mineral assemblage. This inference is also in accord with the low proportion of old zircons in the sample (Fig. 7) and the similarity, in terms of Hf-isotope compositions, of these zircons with the 180~200 Ma ones (Fig. 8b; Appendix Table 2). Consequently, we infer that the Aojiao “Group” sedimentary rocks in the PDMB most likely were deposited in late Early Jurassic to Middle Jurassic time (*ca* 183 Ma to 160 Ma), and the main metamorphism occurred at *ca* 97 Ma. The depositional and metamorphic ages of these metasedimentary rocks are similar to those of meta-sedimentary rocks in the Tananao metamorphic Complex of northern Taiwan (Lan et al., 2008) and the Higo belt in southwest Japan (Sakashima et al., 2003). In addition, another period of metamorphism was identified in the PDMB and constrained to 140-144 Ma (Liu et al., 2012), simultaneous with intrusion of some granitoid rocks. Thus, the PDMB probably underwent two episodes of metamorphism at 140-144 Ma and 97 Ma, which is roughly consistent with the chronology proposed by Shi (2011).

5.2 Provenance of the meta-sedimentary rocks in the PDMB

U-Pb ages and Hf-isotope analyses of detrital zircons from seven samples indicate that the sedimentary rocks in the southern and middle PDMB display similar bimodal age spectra

and zircon Hf-isotope compositions (Fig. 7, 8), different from sample DS09-45-2 in the northern PDMB, which is characterized by abundant Early Paleozoic and Neoproterozoic ages, as well as late Paleoproterozoic and late Paleozoic to Mesozoic ages, more radiogenic Hf isotopic compositions in late Neoproterozoic to early Paleoproterozoic and late Paleoproterozoic zircons than those from the middle and southern PDMB (Fig. 8), suggesting a different provenance.

Minor late Neoproterozoic to early Paleoproterozoic (~2.5 Ga) detrital zircons are present in all samples in the PDMB. Although ~2.5 Ga rocks have not been found in the Cathaysia Block, ~2.5 Ga detrital zircons are widespread in sediments of various ages (e.g. Li XH et al., 2012, 2014; Wan et al., 2007; Xu et al., 2010; Yao et al., 2011, 2012; Yu et al., 2005, 2008, 2010, 2012). Therefore, this old detritus in the PDMB probably was derived from recycled sedimentary rocks, e.g. the Badu complex (Yu et al., 2012).

Late Paleoproterozoic (ca 1.9~1.85 Ga) clastics are one of the most important components in all samples except for DS09-13-7 (Fig. 7). The late Paleoproterozoic basement rocks are fragmentarily exposed in southwestern Zhejiang Province and northwestern Fujian Province of the eastern Cathaysia Block, including the Badu complex, Mayuan Group, deformed granitic intrusions and meta-mafic rocks (amphibolites) (Gan et al., 1995; Li LM et al., 2011a; Li XH, 1997; Li ZX et al., 2010; Liu et al., 2009, 2014; Xia et al., 2012; Xiang et al., 2008; Yu et al., 2009, 2012; Zhao et al., 2014, 2015). 1.9~1.85 Ga zircons in these Paleoproterozoic basement rocks have a range of Hf-isotope compositions (Li LM et al., 2011a; Liu et al., 2014; Xia et al., 2012; Yu et al., 2009, 2012). Those from the southwestern Zhejiang have relatively low and constant $\epsilon_{\text{Hf}}(t)$, ranging mostly from 0 to -7.5 with model

ages of 2.55~2.95 Ga, except for minor zircons with positive $\epsilon\text{Hf}(t)$ values from an I-type granite (Liu et al., 2014; Fig. 8). In contrast, those from northwestern Fujian exhibit larger variations in $\epsilon\text{Hf}(t)$ from 2 to -11 with a peak at -4.7 (Li LM et al., 2011a). Although Paleoproterozoic orogenic activity also has been identified in the northern Yangtze Block (Wu et al., 2008; Sun et al., 2008), it does not appear to have supplied clastic material for the sediments in the PDMB, because of the mismatch in chronological and Hf isotopic data (Xiong et al., 2009), and the long transport distance involved. Therefore, the early Precambrian outcrops in the Wuyi terrane of the eastern Cathaysia Block are the most probable source for these Neoproterozoic to Paleoproterozoic clastics in the meta-sedimentary rocks in the PDMB.

Neoproterozoic and Early Paleozoic zircons occur mainly in the metasedimentary rocks in the northern PDMB (Fig. 6, 7; Cui et al., 2013; Nie, 2007). Neoproterozoic rocks in the Cathaysia Block are sparsely and sporadically preserved in the middle-northern Wuyi terrane, and mostly dated to *ca* 0.86-0.80 Ga (Li WX et al., 2005; Li ZX et al., 2010; Shu et al., 2011; Wan et al., 2007; Yao et al., 2012). They have experienced regional metamorphism of lower greenschist to amphibolite facies (locally up to granulite-facies, Yu et al., 2005, 2014) during an Early Paleozoic orogeny which also produced voluminous granites, mostly with ages of 400-460 Ma, across the Cathaysia Block (Feng et al., 2014a; Li ZX et al., 2010; Wang et al., 2007b, 2010, 2011, 2012; Yu et al., 2005). The pre-Devonian chronological barcode and Hf-isotope compositions (Fig. 8, 10) of the detrital zircons from the northern PDMB generally match those of the magmatic rocks in the central Wuyi terrane of northwestern Fujian Province (Feng et al., 2014a; Wang et al., 2011; Shu et al., 2011; Xia et al., 2014; Yao et al.,

2012; Zhao et al., 2015), which is the most likely potential source. The 465~494 Ma zircons of sample DS09-45-2 are rarely reported in the SCB (Wang et al., 2010; Yu et al., 2005), and may reflect an unidentified thermal event.

Late Paleozoic (Hercynian) zircon grains are preserved in all samples in the PDMB, but do not define a clear age peak. Although a few Hercynian-aged granites and volcanics have been identified in the eastern Cathaysia Block (Yu et al., 2013; and references therein), the related detrital zircons are abundant in middle Permian to early Jurassic clastic sedimentary rocks (Hu et al., 2012; Li XH et al., 2012). These data suggest that a Late Paleozoic orogeny may have occurred in the eastern Cathaysia Block. Significantly, these rocks become the most probable source for the Jurassic sediments in the PDMB.

Early Mesozoic zircon grains are abundant and have a bimodal age distribution, clustering at *ca* 245 Ma and *ca* 205 Ma, roughly contemporaneous with known early Mesozoic magmatism and metamorphism in the SCB (Li WY et al., 2012; Qiu et al., 2014; Wang et al., 2007a; Sun et al., 2005; Yu et al., 2007b, 2012; Zhao et al., 2013). This magmatic episode in the SCB is characterized by predominantly S-type and minor I-type granites and alkaline rocks, whose zircons have with low and varied ϵ_{Hf} (e.g. Qi et al., 2007; Wang et al., 2007a; Zhao et al., 2013), in partial agreement with the compositions of early Mesozoic detrital zircons in our samples (Fig. 8). In addition, 187-200 Ma granites have recently been found in the coastal and inner regions (Feng et al., 2014b; Liu et al., 2011), and probably are the source of coeval detritus in our samples.

The above comparisons (Fig. 7, 8) suggest that the clastic materials in Early to Middle Jurassic sediments in the northern PDMB were probably sourced from the central Wuyi

terrane of northern Fujian in the eastern Cathaysia Block (Fig. 10).

Jurassic sedimentary rocks in the middle – southern PDMB contain little Neoproterozoic to Early Paleozoic detritus, which is inconsistent with the magmatic and metamorphic events in the central Wuyi terrane of northern Fujian. However, the northern Wuyi terrane in southwestern Zhejiang may be a potential provenance for the meta-sedimentary rocks in the southern and middle PDMB, because the geochronology and Hf-isotope compositions of the detrital zircons in these sedimentary rocks in the PDMB are comparable to those of igneous rocks in the northern Wuyi terrane.

However, contradictions are apparent. (1) As confirmed above, terrigenous grains in the sediments in the northern PDMB probably were transported from the central Wuyi terrane in NW Fujian. Thus, mutual drainage disturbance is inevitable if the synchronous sediments in the southern and middle PDMB were directly sourced from the northern Wuyi terrane in SW Zhejiang (Fig. 10). (2) The overwhelming majority of detrital zircons are idiomorphic (Fig. 5j-q), and early Precambrian zircons are abundant (up to 70%-80%) of in some samples in the middle and southern PDMB (except for DS09-13-3, -5 and -7). Therefore, the potential provenance for the meta-sedimentary rocks is probably somewhere close by, rather than far away in SW Zhejiang. Unfortunately, no Paleoproterozoic rocks have yet been recognized in the vicinity. To resolve this dilemma, we suggest that Paleoproterozoic rocks once outcropped in the vicinity, e.g. southwestern (SW) Fujian (Fig. 10) and now have been eroded, or covered by Late Mesozoic sedimentary and volcanic rocks. SW Fujian and SW Zhejiang both are characterized by a regional negative Bouguer gravity anomaly and a relatively shallow Moho discontinuity (Zeng et al., 1997). Furthermore, the isoline map of Nd isotopic model ages

(T_{DM}) shows that SW Fujian also is a high-T_{DM} region, similar to SW Zhejiang and northern Fujian (Yu et al., 2010; Zhou et al., 2006), suggesting the existence of ancient basement beneath the Late Mesozoic sedimentary and volcanic rocks in SW Fujian.

5.3 Widespread Paleoproterozoic basement in southeastern China

The Cathaysia Block was once defined as an “oldland” (Grabau, 1924; Gan et al., 1993, 1995; Hu et al., 1992; Li XH et al., 1992; Li XH, 1997; Shui et al., 1988). However, Precambrian basement, including the Late Paleoproterozoic igneous and metamorphic rocks, is only exposed locally in the central to northern Wuyi terrane in southwestern Zhejiang and northwestern Fujian Province (Fig. 1). Many groups which were previously mapped as Paleoproterozoic to Mesoproterozoic units, such as the Taoxi, Dikou, Mamianshan and Wanquan groups in the central and southern parts of the Wuyi terrane, have been redated to Neoproterozoic and even younger (Li WX et al., 2005; Li LM et al., 2011b; Wan et al., 2007; Yu et al., 2005, 2008, 2010; Xu et al., 2010). Therefore, the distribution of Precambrian basement, especially Paleoproterozoic rocks, in the Cathaysia Block has been a subject of debate. Does widespread Precambrian (Paleoproterozoic to Archean) basement underlie the Phanerozoic volcanic and sedimentary rocks?

Integration of U-Pb ages and Hf-isotope compositions of detrital zircons from clastic sediments is not only a powerful tool in tracing sedimentary provenance (e.g. Cawood et al., 2007; Fedo et al., 2003; Hu et al., 2012; Wang et al., 2009; Yu et al., 2008), but also is used to reveal crustal evolution processes on a continental scale (e.g. Griffin et al., 2004; Kemp et al., 2006; Condie et al., 2009; Yang et al., 2009; Yu et al., 2010). Geochronological studies of

detrital zircons in the Mississippi river sands shows that the age-population structure of the zircons is consistent with the age distribution of basement rocks in the hinterland, indicating that the river sands represent an averaged sample of the hinterland (Rino et al., 2004). This correlation is also shown by detrital zircons in other rivers, such as the Oujiang river (Xu et al., 2007), the Huanghe river (Yang et al., 2009), Minjiang river (Xu and Chen, 2010) and rivers in Africa (Iizuka et al., 2013). Zircon age frequencies acquired from the Minjiang River mouth (Fig. 1, 10), close to the northern PDMB, are marked by predominant Mesozoic (37.6%), essential early Paleozoic (27.4%) and late Paleoproterozoic (17.1%) populations, and minor early Paleoproterozoic to late Neoproterozoic constituents, approximately in agreement with the distribution of rocks in the drainage area (Xu and Chen, 2010; Fig. 10). The age spectrum of modern estuary sands of the Jiulong River, near the middle PDMB (Fig. 1, 10), is characterized by an abundant Mesozoic zircon population and lesser Neoproterozoic and Early Paleozoic ones, much different from those of the Minjiang River (Xu and Chen, 2010; Fig. 10), but analogous to the rocks now outcropping in southern Fujian. Thus, the age frequencies of detrital zircons in sedimentary rocks may suggest the real distribution of rocks with different ages in the drainage basin.

The above discussions on provenance have suggested that the PDMB sediments were derived from the eastern Cathaysia Block. A similar bimodal age spectrum was also obtained from Jurassic sedimentary rocks in the Fuding inlier, northeastern Fujian (Fig.10, 11; Hu et al., 2012), which is far from the PDMB but close to southern Zhejiang (Fig. 1). The observations suggest that the area of exposed Paleoproterozoic basement in the Wuyi terrane (eastern Cathaysia) was larger during Early to Middle Jurassic time than it is at present. The lower

proportion of Paleoproterozoic clastics in the modern river sands, compared to the Jurassic sediments, may be attributed to strong late Mesozoic volcanic activity across the eastern SCB after Early Jurassic time.

In fact, Paleoproterozoic basement was widely exposed in the eastern Cathaysia Block before Jurassic time. Detrital zircons from the Late Triassic Wenbinshan Formation in Kanchi County, southern Fujian (Fig. 10, 11), exhibit a prominent Paleoproterozoic (1.9-1.8 Ga) population (Wang et al., 2009). Moreover, most of Paleoproterozoic zircons are euhedral to subhedral, suggesting short transport from an autochthonic provenance. Notably, samples from the Wenbinshan Formation are spatially and temporally close to those from the southern and middle PDMB (Fig. 10). Similar age spectra (Fig. 11) imply that Late Triassic and Jurassic sediments in southern Fujian were sourced from a similar provenance with a large exposure of Paleoproterozoic basement. Triassic sandstones from Jian'ou County in northern Fujian (central Wuyi) (Fig. 10, 11; Yao et al., 2012) also exhibit a bimodal age spectrum similar to that of the Late Triassic Kanchi sandstone in the southern Fujian, except for some differences in the Phanerozoic zircon population; this again suggests extensive exposure of Paleoproterozoic basement during Triassic time. The lack of Neoproterozoic and Early Paleozoic zircons in the Jian'ou Triassic sandstones is not consistent with the abundant Neoproterozoic and Early Paleozoic igneous rocks in the central Wuyi terrane, and implies that the sediments were mainly derived from the northern Wuyi terrane in southern Zhejiang.

Li XH et al. (2012) collected five Permian sandstones from the SE SCB (Fig. 1, 11), which contain abundant Paleoproterozoic zircons with mostly euhedral to subhedral crystals. The Jiangxi Permian sandstone from central Wuyi terrane has mainly ~1870 Ma detrital

zircons with a few Early Paleoproterozoic to Neoproterozoic and Late Paleozoic grains (Fig. 11), strongly suggesting a Paleoproterozoic basement in the nearby region. Another Permian sandstone from Yongding, southern Fujian, has a relatively weak Paleoproterozoic age population (Fig. 10, 11), suggesting a different source from the Jiangxi Permian sandstone.

Three other Permian sandstones were sampled from the Nanling terrane (Fig. 1, 11), and have similar zircon age spectra with peaks at ~2.5 Ga, 1.85 Ga and ~1.0 Ga, besides abundant Phanerozoic grains (Fig. 11). Precambrian populations in these Permian sandstones are different from those of Late Neoproterozoic basement rocks and Early Paleozoic sedimentary rocks in the Nanling terrane (Fig. 11; Li XH et al., 2014; Wang et al. 2010b; Wu et al., 2010; Yao et al., 2011; Yu et al., 2008, 2010), suggesting a significant input of Paleoproterozoic fragments from the Wuyi terrane to the Nanling basin during Middle to Late Permian sedimentation.

Three Mid- to Late Cretaceous sedimentary rocks from the Yuli belt in eastern Taiwan also exhibit age spectra with high proportions of Paleoproterozoic detrital zircons and weak Neoproterozoic age peaks (Yui et al., 2012), similar to those of the Kashi Triassic and Pingtan Jurassic sedimentary rocks (Fig. 11). Phanerozoic zircons define four age populations at 456-370 Ma, 298-207 Ma, 203-181 Ma and 153-105 Ma, corresponding to the magmatic events in the SE SCB. Both Precambrian and Phanerozoic clastic components suggest the Cretaceous sedimentary rocks in the Yuli belt were derived from the Wuyi terrane, in the eastern Cathaysia Block.

In summary, the predominance of Paleoproterozoic zircons in these Permian to Cretaceous sediments in the SCB strongly suggests a broad exposure of the Paleoproterozoic

basement not only in southwestern Zhejiang and northern Fujian but also in the whole Wuyi terrane or even areas further afield, such as South Korea (Cheong et al., 2000; Jeon et al., 2007; Lee et al., 2000, 2005; Sagong et al., 2003), from Middle Permian to Late Cretaceous time.

The Paleoproterozoic basement of the Wuyi terrane contains some Neoarchean components (Li XH, 1997; Yu et al., 2012), and was overprinted by multi-phase tectono-thermal activity after the Paleoproterozoic orogeny, including Neoproterozoic, Early Paleozoic, Late Paleozoic, Early Mesozoic and Late Mesozoic events. However, the nature and extent of these events are different. Neoproterozoic magmatic activity mainly occurred in the central Wuyi terrane; Early Paleozoic magmatism and metamorphism strongly affect the central and southern area, and Early and Late Mesozoic magmatism extensively influenced the whole Wuyi terrane. Late Paleozoic magmatic activity is local, and probably limited to the eastern part of the central to southern Wuyi terrane (Yu et al., 2013). These spatial differences lead to discrepancies in the Neoproterozoic to Mesozoic clastic components among Permian to Late Cretaceous sedimentary rocks in different areas.

Systematic U-Pb dating of detrital zircons from the Paleozoic to Mesozoic sediments in southwestern Fujian Province has been carried out (Li RQ, 2011). The results show that Early Paleozoic sedimentary rocks consist mainly of >2400 Ma, 1700-1000 Ma and 1000-930 Ma detritus, characteristic of the Nanling-Yunkai terrane basement (Yu et al., 2010). In the Devonian to Early Permian sedimentary rocks, 850-750 Ma and 750-450 Ma components increase and >2400 Ma clastics persist in high proportions. From Late Permian to Triassic time, the proportion of 1900-1700 Ma detrital zircons in the sediments increases greatly.

Likewise, Cambrian to Devonian sedimentary rocks in the Nanling Range area exhibit age spectra similar to those of Precambrian basement rocks (Fig. 11). However, Middle-Late Permian sedimentary rocks in the Nanling Range area have significantly different clastic compositions from the Nanling terrane basement (Fig. 11), but show affinity with the Wuyi terrane. Combined with paleogeographic change from Devonian to Permian (Liu and Xu, 1994), it is suggested that the Paleoproterozoic basement of the Wuyi terrane has been strongly uplifted and eroded before Middle Permian, and provided abundant sediments to more extensive basins, including the Wuyi terrane and eastern Nanling area. The uplift of the Wuyi terrane in Late Paleozoic time probably resulted from the Late Paleozoic orogeny in eastern Cathaysia (Yu et al., 2013).

5.4 Widespread Archean deep crust?

While the zircon age spectra demonstrate the widespread occurrence of Paleoproterozoic crust across E. Cathaysia, the Hf-isotope data on these zircons carry even more important implications. Many of the igneous zircons from the Proterozoic and Phanerozoic populations described here have low ϵ_{Hf} values and give Archean T_{DM}^{C} model ages, implying that the Proterozoic to Mesozoic magmas were partly, or even largely, derived by remelting of Archean material, presumably residing in the lower crust. These data strongly suggest that the E. Cathaysia block represents a block of Archean continental crust, progressively reworked through Proterozoic and Phanerozoic time. As more Hf-isotope data on dated zircons accumulate, it should be possible to map out the distribution and evolution of this ancient crust.

Conclusions

1. Integration of field geological observations and detailed zircon U-Pb dating constrains the depositional age of Aojiao “Group” sedimentary rocks in the PDMB to late Early to Middle Jurassic. These metasedimentary rocks suffered at least two periods of metamorphism at 144~140 Ma and *ca* 97 Ma. The peak metamorphism was characterized by LP-HT conditions, consistent with an extensional tectonic regime in the SE SCB during late Cretaceous time.
2. The metasedimentary rocks from the southern and middle PDMB display similar detrital zircon age distributions marked by prominent Late Paleoproterozoic and Mesozoic populations. They differ from the sediments of the northern PDMB, which are marked by abundant Neoproterozoic and Early Paleozoic clastics in addition to Late Paleoproterozoic and Mesozoic components. Correlations with tectono-magmatic events in the SCB show that the terrigenous fragments in the Jurassic sedimentary rocks in the northern PDMB were sourced mainly from the central Wuyi terrane in northern Fujian, whereas the equivalents in the southern and middle PDMB most likely were derived from the southern Wuyi terrane in southern Fujian.
3. Comparisons of clastic components from the sedimentary rocks of different age in the SE SCB suggest that there was widespread Paleoproterozoic basement in the eastern Cathaysia Block. It has been strongly uplifted and eroded before Middle Permian, and provided abundant sediments for Middle Permian to Cretaceous basins in eastern Cathaysia.
4. The Hf-isotope data from Proterozoic to Mesozoic zircons suggest that their parental

magmas contain a large component of melts derived from Archean protoliths, which probably reside in the lower crust. Future work will allow mapping of the distribution and evolution of this Archean crust.

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Figure captions:

Fig. 1. Distribution of Precambrian rocks in the Cathaysia Block and sampling locations of Permian to Cretaceous sedimentary rocks in SE China. ① Jiangshan- Shaoxing- Yushan- Pingxiang Fault, ② Zhenghe-Dabu Fault, ③ Changle-Nan'ao Fault, ④ Jiulong River, ⑤ Minjiang River, ⑥ Oujiang River.

Fig. 2. a. Simplified geological map of the Pingtan-Dongshan Metamorphic Belt; b. geological map of Nanwuli, Pingtan Island; c. geological map of Gangwei County, Longhai; d. geological map of the Sufengshan-Aojiao area, Dongshan Island.

Fig. 3. Field photographs showing the relations between the metasedimentary rocks and granites on Dongshan Island. (a) pelitic gneiss intruded by ~146 Ma (Liu et al. 2012) gneissic granite, Yanya village; (b) schist intruded by coarse-grained granite, Aojiao; (c) gneiss and granite deformed together, Aojiao; (d) pelitic gneiss intruded by gneissic 147-153 Ma (Feng et al., 2011) granite, Aojiao.

Fig. 4. Photomicrographs of metasedimentary rocks from the PDMB. a. DS09-3-1; b. DS09-11; c, d. DS09-13-3; e. DS09-13-5; f, g. DS09-13-7; h. DS09-23-2; i. DS09-45-2. Mus-muscovite, spl-spinel, sill-sillimanite, gt-garnet, pl-plagioclase, bt-biotite, qz-quartz

Fig. 5. CL images of the representative zircons from the DS09-45-2 (a-i), DS09-23-2 (j-q), and DS09-13-7 (r-ae). The yellow circles show dating ablation spots with diameters of ~25μm, and the numbers near the circles are the ages (Ma).

Fig. 6. Concordia plots of zircons from samples DS09-45-2, DS09-23-2, DS09-3-1, DS09-11, DS09-13-3, DS09-13-5, and DS09-13-7.

Fig. 7. Zircon U-Pb age spectra of the metasedimentary rocks in the PDMB, SE SCB.

Fig. 8. Plot of initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios vs U-Pb ages of the zircons in sample from the northern PDMB (a) and those from the middle and southern PDMB (b). Other data sources: Paleoproterozoic granites in northern Fujian (Li LM et al., 2011a); Paleoproterozoic granites in southern Zhejiang (Yu et al., 2009; Liu et al., 2014); the Badu Complex (Yu et al., 2012).

Fig. 9. U-Pb age spectra of younger zircons from samples DS09-13-3, 5, 7.

Fig. 10. Schematic diagram of the Wuyi terrane displaying the transport routes of terrigenous fragments in the Aojiao “Group” sediments. Data sources: Minjiang and Jiulong rivers (Xu and Chen, 2010); Fuding Jurassic (Hu et al., 2012), Kashi Triassic (Wang et al., 2009), Yongding and Jiangle Permian (Li XH et al., 2012), Jian’ou Triassic (Yao et al., 2012), NW Neoproterozoic (Wan et al., 2007), SW Zhejiang Paleoproterozoic (Yu et al., 2012).

Fig. 11. U-Pb age spectra of zircons from Early Paleozoic to Early Cretaceous sediments in the SCB. Age data sources: Tailuko-Yuli Cretaceous (Yui et al., 2012); Ji'an and Leiyang Permian (Li XH et al., 2012); Shaoguang Permian (Li XH et al., 2012; Liang et al., 2013); Devonian (Xiang and Shu, 2010); Early Paleozoic (Wang et al., 2010; Wu et al., 2010; Xiang and Shu, 2010; Yao et al., 2011); Pingtan, Longhai and Dongshan Jurassic (this study). The others are the same as those in Fig. 10. Data for plots d-h are from the Nanling Range (central Cathaysia), and the others from the eastern Cathaysia.

Appendix Table 1 U-Pb ages of detrital and metamorphic zircons from metasedimentary rocks in the PDMB

Appendix Table 2 Hf-isotope compositions of zircons from the metasedimentary rocks in the PDMB

Figure1

Figure2

Figure 3

Figure 4

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Figure 11