Jurassic to Early cretaceous sedimentary record: indications of Paleo-Pacific Plate subduction in Southeast China

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ABSTRACT
Plate subduction plays a decisive role in continental tectonics, and subduction history is closely connected to deformation and sedimentation in the overriding plate. When and how the Paleo-Pacific Plate subducted beneath Southeast China in the Mesozoic is debated. Here, we show that provenance data, including detrital composition point counts, palaeocurrent data, and detrital zircon U-Pb geochronology from basins in Southeast China, record the timing and process of Paleo-Pacific Plate subduction during the Jurassic and Earliest Cretaceous. The U-Pb dating of detrital zircons from Jurassic samples indicates that the sediments were transported from multiple sources, including inacratonic mountains, tectonic belts and the inferred active continental margin arc that resulted from Paleopacific Plate subduction. The clastic composition and U-Pb dating of Early Cretaceous tuffs suggest that they were sourced from nearby magmatic rocks and the eastern inferred magmatic arc. Based on detrital zircon U-Pb dating, igneous rock isotope, sedimentary, and structural data, we infer that an active continental magmatic arc developed along the coast of Southeast China in the Early Jurassic to Early Cretaceous (~200 Ma-135 Ma). The westward subduction of the Paleo-Pacific Plate initiated in the Early Jurassic (~200 Ma) and continued to the Early Cretaceous (~135 Ma). Paleo-Pacific Plate subduction resulted in the uplift of the northern Wuyi Mountain region and eastern South China and controlled the provenance characteristics of the sedimentary basins in Southeast China during the Jurassic to Early Cretaceous.

1 Introduction
The tectonics of the East Asian continental margin changed dramatically in the Mesozoic, and an intracontinental orogenic belt with a width of 1300 km formed in South China, which exposed large areas of igneous rocks (Zhao et al., 1994; Liu et al., 2003, 2005; Li and Li, 2007; Dong et al., 2007; Zhang et al., 2009), involved complicated deformation, and produced residual sedimentary basins. South China experienced Triassic and Middle Jurassic-Late Cretaceous tectonic movements (Xu et al., 2009; Zhang et al., 2009; Li et al., 2014a). The geotectonic processes and their dynamics in South China during the Mesozoic have always been key research topics, and many scholars have conducted much research on tectonics, magmatism, and sedimentation, which are closely related to the subduction of the Paleo-Pacific Plate (Zhou and Li, 2000; Li and Li, 2007; Zhang et al., 2009; Liu et al., 2014, 2016; Xu et al., 2017; Suo et al., 2020; Zhang et al., 2020).

Previously, some scholars even proposed an Alpine collisional orogeny model in the Triassic for South China (Hsu et al., 1987, 1988, 1990), while later comprehensive geological data showed the intracontinental character of deformation in South China during the early Mesozoic (Rodgers et al., 1989; Rowley et al., 1989; Yu et al., 2005; Shu et al., 2007). Some researchers concluded that the ages of the Late Mesozoic magmatic rocks tended to become younger from inland to the coast of Southeast China and proposed that the angle of subduction of the Paleo-Pacific Plate beneath South China from the Middle Jurassic varied, accompanied by the underplating of basaltic magma from 180–80 Ma (Zhou and Li, 2000; Zhou et al., 2006; Shu et al., 2009a; Liu et al., 2012; Liu et al., 2014). Zhang et al. (2009) suggested that the formation and development of the NNE-trending folded tectonic system in South China well recorded the beginning of Paleo-Pacific Plate subduction beneath South China in the Middle Jurassic.
Li and Li (2007) proposed a flat-slab subduction, founding and retreating arc model (late Permain-Middle Jurassic), which well explained the origin of the 1300–km-wide Mesozoic magmatic belt in the South China Plate and the magmatic activity of the Early-Middle Jurassic in the Nanling area. Subsequently, this model has been improved by a series of recent studies (Li et al., 2012a; Meng et al., 2012; Li et al., 2013; Li et al., 2014). Li et al. (2012a) provided a more comprehensive summary and commentary on the Mesozoic evolution of the East Asian continental margin and the paleo-Pacific subduction process and concluded that paleo-Pacific subduction started ca. 280 Ma, flat subduction occurred from 250–190 Ma, and normal subduction occurred between 190 Ma and 90 Ma. Zhu et al. (2014) considered that normal subduction of the Paleo-Pacific Plate started ca. 280 Ma and became flat-slab subducted at 230–215 Ma, and then founding of the eclogitic flat slab caused water-fluxed melting of the oxidized and hydrous continental crust between 170 Ma and 150 Ma. Zhang et al. (2020) suggested that the Paleo-Pacific Plate began to subduct northward beneath Asia in the Guadalupian Epoch, which brought the Palaeozoic passive-margin evolution of SE Asia to an abrupt end.

Given different research perspectives and methods, differences or debates regarding the timing and process of plate subduction are unavoidable; therefore, more investigations of this tectonic process are of great value for understanding the Mesozoic transformation from Tethys tectonics to Pacific tectonics in South China. The investigation of sedimentary records in sedimentary basins may lead to an improved understanding of the connection between plate subduction history and basin sedimentation on the overriding plate. The breakthrough of detrital zircon U-Pb geochronology (especially LA-ICP-MS U-Pb dating technology) has greatly promoted the development of provenance analyses of sedimentary basins. This technique is an effective method to trace the source area by analysing the clastic sediments in basins and then to discuss the regional tectonic evolution. Zircons in the sediments of basins are widely distributed and highly stable, so they can preserve considerable source information, and the analysis of zircon morphology, composition and age has become an important probe for tracing the source area of sediments in basins. Southeast China is located between the Yangtze Block and the Paleo-Pacific Plate and developed Early Jurassic to Early Cretaceous sedimentary strata, such as the Lishan, Jinji, Lantang, Yutian, Zhangping, Malong, and Maxingping groups, with abundant sandstones and tuff, which preserve important plate subduction information. In this study, petrographic data, modal sandstone grain compositions, detrital zircon U-Pb geochronology, and field palaeocurrent data were obtained for the Early Jurassic to Early Cretaceous sedimentary sequences in Southeast China to study their sedimentary provenances and tectonic setting, which can be used to constrain the timing of subduction and deduce the dynamic processes of the Paleo-Pacific Plate.

2 Geological setting

South China is located at the southeastern margin of the Eurasian Plate adjacent to the Pacific subduction zone and was formed by the combination of the northwest Yangtze Block and the southeast Cathaysian Block in the Neoproterozoic (Charvet et al., 1996; Li et al., 2002a; Wang et al., 2013). To the north, the South China Block and the North China Block collided along the Qinling-Dabie-Sulu orogenic belt in the Triassic, and to the southwest, the South China Block collided with the Indosinian Plate along the Aliashan-Songma belt (Liu et al., 2003; 2005; 2015a; Faure et al., 2014, 2016). In the early Palaeozoic, intracontinental orogeny occurred in the South China Block, which resulted in strong fold belts in the Cathaysian Block and on the southern margin of the Yangtze Block and extensive development of Caledonian granites (early Palaeozoic) (Wang et al., 2007a, 2011). In the Mesozoic, an angular unconformity formed in South China between the Upper Triassic or Upper Triassic-Middle Jurassic strata and the underlying older strata as a result of Indosinian (Triassic) tectonic movement (Shu et al., 2009b). Moreover, an intracontinental orogenic belt with a width of approximately 1300 km and a large area of exposed igneous rocks was formed by Yanshanian (Middle Jurassic-Late Cretaceous) tectonic movement (Zhou and Li, 2000; Zhou et al., 2006; Li and Li, 2007).

A series of main faults, such as the Zhenghe-Dapu fault and Shaoxing-Jiangshan fault, developed in the South China Block. The Precambrian basement is mainly distributed along the Jiangnan orogenic belt, and Palaeozoic to Mesozoic (Devonian-Triassic) strata, such as those of the Jiangnan Orogen, Youjiang Basin, Yunkai Massif, and Shiwandashan Basin, are widely distributed in southwestern South China and the Cathaysian Block, while Jurassic strata are developed in the Sichuan Basin, Jianghan Basin, and Southeast China (Figure 1a). Magmatic rocks of various ages are widely distributed in southeast China, including the Paleoproterozoic (2500–1600 Ma), the Neoproterozoic (1000–541 Ma), the Early Palaeozoic (541–359 Ma), the Late Palaeozoic (359–252 Ma), the Early Mesozoic (252–200 Ma), the Middle-Late Jurassic (200–145 Ma), and the Earliest Cretaceous (145–135 Ma) (Davis et al., 1997; Sun, 2006; Xing et al.,
Figure 1. (A) Simplified geological map of South China showing the major faults, Palaeozoic to Mesozoic (Devonian-Triassic) strata, and Jurassic strata, including the Northern Wuyi Region, Nanling Belt, Yong’an Basin, Yunkai Region, Penglaitan Region, Youjiang Basin and Shiwandashan Basin (modified after Xu et al., 2016). (B) The spatial distribution of granites in the South China Block, showing Paleoproterozoic (2500–1600 Ma), Neoproterozoic (1000–541 Ma), Early Palaeozoic (541–359 Ma), Late Palaeozoic (359–252 Ma), Early Mesozoic (252–200 Ma), Middle-Late Jurassic (200–145 Ma), and Earliest Cretaceous (145–135 Ma) magmatic rocks (revised from Sun, 2006; Xu et al., 2009; Xia et al., 2012; Zhang et al., 2013; and Li et al., 2014). (The early Palaeozoic and early Mesozoic data are summarized in Wang et al., 2013a, and Song et al., 2015. Data from 145 Ma-135 Ma are from Davis et al., 1997; Xing et al., 2008; Liu et al., 2012; Cui et al., 2013. The data are shown in Appendix E).
In most areas of eastern China, the ages of rhyolite and granite, originally designated as of Late Jurassic origin, have been redefined as Early Cretaceous by high-quality dating data in recent years, and the previously determined Late Jurassic strata have also been redefined as Early Cretaceous strata by palaeontological data (Wang and Zhou, 2002; Zhou, 2007; Shu, 2009c). Therefore, the distribution and records of the Late Jurassic volcanic rocks in Southeast China are limited and found mostly in the west.

3. Methods

3.1. Sample collection

Twelve samples were collected from Southeast China for detrital zircon U-Pb dating, eleven of which are from five sections, namely, Banmian in Youxi, Gongqiao in Zhangping, Dama in Dapu, Meinan in Meixian, and Haifeng areas from northeast to southwest (Figure 2), while the remaining sample is from Huizhai in the Jixi region. Six sandstone samples consist of three Early Jurassic samples (BM201901, HF201902, and HF201903) and three Middle Jurassic samples (BM201903, ZP201903, and DB201910), while six tuff samples include BM201907, ZP201908, DB201905, MN201912, HZ201901, and HF201904. Moreover, another 19 published Jurassic sedimentary clastic rock samples from Southeast China were collected, and the specific GPS position information for the twelve samples is provided in Table 1.

Thirty-four samples (including BM201901, BM201903, ZP201903, DB201910, HF201902, and HF201903) from Southeast China were selected for sandstone composition counting (Table 1). Sandstone compositions were based on the Gazzi-Dickinson point counting method, including at least 300 framework grains per thin section (Dickinson et al., 1983; Ingersoll et al., 1984; Dickinson, 1985). According to the classification scheme of Dickinson and Suczek (1979), the counted grains were divided into five components, which contain monocrystalline quartz (Qm), polycrystalline quartz (Qp), plagioclase feldspar (P), potassium feldspar (K), sedimentary and metamorphic lithic fragments (Ls), and volcanic lithic fragments (Lv), where Q = Qm + Qp, L = Ls + Lv, F = P + K, and Lt (total lithic fragments) = L + Qp. Sandstone composition counting results were plotted on Q-F-L, Qm-F-Lt and Qp-Lv-Ls ternary diagrams used to reveal the tectonic setting of provenances. Detailed counting results are listed in Appendix A.
Figure 2. Geological map and measured field sections in Southeast China. (a) Geological map of Southeast China based on the 1:200,000 geologic maps of Fujian, Jiangxi, and Guangdong showing the section sites. (b) Measured field sections of the Early Jurassic to Early Cretaceous strata in Southeast China at Youxi, Zhangping, Dapu, Meixian, and Haifeng, with red stars indicating the stratigraphic locations of samples BM201901, BM201903, BM201907, ZP201903, ZP201908, DB201910, DB201905, MN201912, HF201902, HF201903, and HF201904. Abbreviations: T3w, Early Triassic Wenbinshan Formation; T3xp, Early Triassic Xiaoping Formation; J1ls, Early Jurassic Lishan group; J1jn, Early Jurassic Jinji group; J2zh, Middle Jurassic Zhangping group.
Figure 3. Field photographs from Southeast China: (a) Lower Jurassic sandstone and siltstone with horizontal bedding; (b) Middle Jurassic yellow sandstone; (c) Lower Jurassic quartz sandstone; (d) Middle Jurassic variegated sandstone; (e) Upper Triassic interbedded quartz sandstone and siltstone; (f) Fault contact between Upper Triassic siltstone and Lower Jurassic quartz sandstone; (g) Fault in Lower Jurassic strata; (h) Fold in Lower Jurassic sandstone; (i) Middle Jurassic purple-red sandstone; (j) Middle Jurassic interbedded sandstone and mudstone; (k) (coordinate position: 23°26′23″N, 115°57′37″e) and (l) (coordinate position: 22°59′23″N, 115°19′29″e) Interbedded sandstone and carbonaceous mudstone; and (m) Thick-bedded siltstone (coordinate position: 23°14′32″N, 115°13′41″e). T_{xp}, Upper Triassic Xiaoping Formation; J_{ls}, Lower Jurassic Lishan Group; J_{jn}, Lower Jurassic Jinji Group; J_{zh}, Middle Jurassic Zhangping group.
3.2. Zircon U-Pb geochronology

Reflected and transmitted light photomicrographs and cathodoluminescence (CL) images of twelve samples (BM201901, BM201903, BM201907, ZP201903, ZP201908, DB201910, DB201905, MN201912, HF201902, HF201903, HZ201901, and HF201904) were taken of the zircon targets embedded in epoxy resin at Beijing Zirconia Navigation Technology Co., Ltd., Beijing, China. Zircon U-Pb isotope dating was conducted using an Elan 6100 inductively coupled plasma mass spectrometry (ICP-MS) instrument or an Agilent 7500a ICP-MS instrument equipped with a 193-nm (wavelength) ArF excimer laser (MicroLas™ Beam Delivery Systems, Lambda Physik AG, Germany) at the State Key Laboratory of Continental Dynamics (SKLCD), Northwest University, Xi’an, China. Throughout the data acquisition, the focus of the laser beam was fixed at the sample surface, with a beam diameter of 30 μm, repetition rate of 6 Hz and energy density of 20 J/cm², and helium was used as the carrier gas (0.9 L/min) to enhance the transport efficiency of the ablated material. The 207Pb/206Pb, 206Pb/238U, 207Pb/235U, and 208Pb/232Th ratios were calculated using the GLITTER 4.0 programme (Macquarie University), with the Harvard zircon 91,500 used as the primary reference to correct for both instrumental mass bias and isotopic fractionation (Wiedenbeck et al., 1995). The secondary reference zircon GJ-1 (Jackson et al., 2004) was used to validate the 91,500 normalization. The detailed analytical procedure followed Yuan et al. (2004), and the data for the primary and secondary standards, including the data table and figure, with average values and uncertainty with the MSWD, are presented in Appendix B. When calculating the age concordance, the formula 100 * (207Pb/206Pb/238U) was used for the zircon ages greater than 1000 Ma, while the formula 100 * (207Pb/235U/206Pb/238U) for zircon ages younger than 1000 Ma; finally, those calculated values between 90 and 110 are harmonic. When selecting zircon ages, 206Pb/238U ages and 1σ values were used for zircon grains with ages younger than 1000 Ma, and 207Pb/206Pb ages and 1σ values were selected for zircon grain ages older than 1000 Ma (Compston et al., 1992). Moreover, the element content was calculated using the GLITTER 4.0 program (Macquarie University), and the NIST 610 or NIST 612 values were used to calibrate the U-Th-Pb ratios and absolute U abundances. Then, the radiogenic Pb* content and Th/U or U/Th values were calculated. When analysing rare earth elements (REEs), we need to standardize the values of rare earth elements, and the CI chondrite data are from Sun and McDonough (1989).

4. Results

4.1. Petrography and sandstone modal composition

Lower-Middle Jurassic sandstone samples are mainly composed of sand-grade clasts, which mostly consist of subangular and minor subrounded feldspar, quartz, and
Table 1. Locations and lithologies of samples from Southeast China

| Sample No. | Lithopetologv | Sample site | Stratigraphic unit/Age (Ma) |
|------------|---------------|-------------|-----------------------------|
| BM201901   | Quartz sandstone | 26°02' 12.7" N, 117°59' 18" E | Lower Jurassic |
| BM201903   | Sandstone     | 26°01' 52.0" N, 118°02' 31" E | Middle Jurassic |
| ZP201903   | Sandstone     | 25°16' 25" N, 117°25' 15" E | Middle Jurassic |
| DB201910   | Siltstone     | 24°22' 18" N, 116°33' 22" E | Middle Jurassic |
| HF201902   | Quartz sandstone | 23°14' 20" N, 115°13' 41" E | Lower Jurassic |
| HF201903   | Quartz sandstone | 22°54' 50" N, 115°05' 16" E | Lower Jurassic |
| Another 28 samples | | | |
| BM201902   | Lithic Sandstone | 26°02' 44" N, 118°02' 25" E | Lower Jurassic |
| BM201904   | Lithic Sandstone | 26°01' 45" N, 118°03' 25" E | Lower Jurassic |
| BM201905   | Quartz sandstone | 26°00' 30" N, 118°04' 18" E | Lower Jurassic |
| BM201906   | Quartz sandstone | 26°02' 55" N, 118°05' 18" E | Lower Jurassic |
| ZP201902   | Quartz sandstone | 25°15' 57" N, 117°23' 50" E | Lower Jurassic |
| ZP201904   | Lithic Sandstone | 25°16' 42" N, 117°21' 39" E | Lower Jurassic |
| ZP201905   | Lithic Sandstone | 25°16' 35" N, 117°21' 35" E | Lower Jurassic |
| ZP201907   | Quartz sandstone | 25°15' 16" N, 117°20' 36" E | Lower Jurassic |
| DB201901   | Sandstone     | 24°19' 09" N, 116°44' 02" E | Lower Jurassic |
| DB201903   | Sandstone     | 24°20' 16" N, 116°47' 59" E | Lower Jurassic |
| DB201904   | Quartz sandstone | 24°17' 48" N, 116°52' 31" E | Lower Jurassic |
| DB201907   | Sandstone     | 24°27' 18" N, 116°33' 11" E | Lower Jurassic |
| DB201908   | Quartz sandstone | 24°26' 29" N, 116°39' 56" E | Lower Jurassic |
| DB201909   | Siltstone     | 24°25' 12" N, 116°35' 28" E | Lower Jurassic |
| DB20111    | Sandstone     | 24°21' 46" N, 116°32' 57" E | Lower Jurassic |
| MN201901   | Lithic Sandstone | 24°02' 25" N, 116°12' 59" E | Lower Jurassic |
| MN201902   | Quartz sandstone | 24°02' 04" N, 116°13' 50" E | Lower Jurassic |
| MN201903   | Quartz sandstone | 24°02' 50" N, 116°13' 27" E | Lower Jurassic |
| MN201904   | Quartz sandstone | 24°03' 17" N, 116°13' 32" E | Lower Jurassic |
| MN201905   | Quartz sandstone | 24°03' 37" N, 116°13' 36" E | Lower Jurassic |
| MN201906   | Quartz sandstone | 24°03' 51" N, 116°13' 41" E | Lower Jurassic |
| MN201907   | Quartz sandstone | 24°04' 53" N, 116°12' 47" E | Lower Jurassic |
| MN201908   | Quartz sandstone | 24°06' 26" N, 116°11' 20" E | Middle Jurassic |
| MN201909   | Sandstone     | 24°06' 46" N, 116°10' 46" E | Middle Jurassic |
| MN201910   | Quartz sandstone | 24°07' 44" N, 116°09' 02" E | Middle Jurassic |
| MN201911   | Quartz sandstone | 24°07' 45" N, 116°08' 26" E | Lower Jurassic |
| MN201913   | Quartz sandstone | 24°07' 41" N, 116°08' 22" E | Middle Jurassic |
| HF201901   | Siltstone     | 23°13' 17" N, 115°16' 09" E | Lower Jurassic |
| Tuff samples | | | |
| BM201907   | Tuff          | 26°05' 56" N, 118°08' 58" E | 140.90 ± 1.30 (n = 27) |
| ZP201908   | Tuff          | 25°15' 39" N, 117°29' 37" E | 139.07 ± 0.64 (n = 27) |
| DB201905   | Tuff          | 24°14' 24" N, 116°54' 23" E | 138.02 ± 0.75 (n = 29) |
| MN201912   | Tuff          | 24°00' 43" N, 116°15' 42" E | 140.26 ± 0.96 (n = 29) |
| HZ201901   | Tuff          | 23°37' 02" N, 115°54' 14" E | 140.11 ± 0.75 (n = 27) |
| HF201904   | Tuff          | 22°54' 50" N, 115°05' 16" E | 139.53 ± 0.79 (n = 26) |
| Published data | | | |
| GMC12      | Sandstone     | 25°15' 53.3" N, 117°23' 52.3" E | Lower Jurassic |
| GMC22      | Sandstone     | 25°15' 53.3" N, 117°23' 52.3" E | Lower Jurassic |
| ZP201902   | Sandstone     | 25°15' 57.0" N, 117°23' 50.0" E | Lower Jurassic |
| YAB-01     | Sandstone     | 24°07' 41" N, 116°08' 26" E | Middle Jurassic |
| YAB-03     | Sandstone     | 24°20' 33" N, 116°48' 34" E | Lower Jurassic |
| YAB-04     | Sandstone     | 24°25' 40" N, 116°02' 24" E | Lower Jurassic |
| EGB-02     | Sandstone     | 23°29' 59" N, 116°00' 53" E | Lower Jurassic |
| EGB-03     | Sandstone     | 24°00' 43" N, 116°15' 43" E | Lower Jurassic |
| EGB-04     | Sandstone     | 24°06' 51" N, 114°28' 26" E | Middle Jurassic |
| EGB-05     | Sandstone     | 24°07' 20" N, 114°28' 54" E | Lower Jurassic |
| EGB-06     | Sandstone     | 24°07' 05" N, 114°26' 38" E | Middle Jurassic |
| HZ-2R      | Sandstone     | 23°27' 38" N, 115°58' 56" E | Lower Jurassic |
| HZ-9R      | Sandstone     | 23°27' 38" N, 115°58' 56" E | Lower Jurassic |
| HZ-9R      | Sandstone     | 23°27' 38" N, 115°58' 56" E | Lower Jurassic |
| SY-04      | Sandstone     | 22°47' 22.5" N, 113°55' 11.9" E | Lower Jurassic |
| SY-05      | Sandstone     | 22°47' 22.5" N, 113°55' 11.9" E | Lower Jurassic |
| SY-06      | Sandstone     | 22°47' 22.5" N, 113°55' 11.9" E | Lower Jurassic |
| SY-01      | Sandstone     | 22°47' 22.5" N, 113°55' 11.9" E | Lower Jurassic |
| SY-02      | Sandstone     | 22°47' 22.5" N, 113°55' 11.9" E | Lower Jurassic |

Lithic fragments (generally sedimentary or volcanic). The rocks have heterogeneous clay and siliceous cements (Figure 4). The five sandstone samples of the Lower Jurassic Lishan Group from the northeastern part of Southeast China are mainly composed of quartz grains (30–
92%), feldspar grains (0.4–6%) and lithic fragments (8–64%), and partial filler (mainly clay matrix) (1–5%). In the Q-F-L and Qm-F-Lt ternary diagrams, four of the samples plot in the recycled orogenic domain, while one plots in the transitional arc domain (Figure 5(a,b)). In the Qp-Lv-Ls ternary diagram, all five samples plot in the collision suture, fold-thrust belt and mixed orogenic sand fields (Figure 5(c)).

Thirteen sandstone samples of the Lower Jurassic Jinji Group from the Dapu and Meixian regions in the Yong’an Basin and the Haifeng region in the East Guangdong Basin contain quartz grains (63–92%), feldspar grains (0.2–16.4%), and lithic fragments (3.6–36.7%) that are metamorphic and sedimentary in origin. In the Q-F-L and Qm-F-Lt ternary diagrams, all the samples plot in the craton interior, transitional continental, and recycled orogenic domains (Figure 5(a,b)), while they plot in the collision suture, fold-thrust belt and mixed orogenic sand fields in the Qp-Lv-Ls ternary plot (Figure 5(c)).

In the sixteen Middle Jurassic Zhangping Group sandstone samples, the proportions of quartz and feldspar grains range from 15.9% to 88.3% and from 0.3% to 27.6%, respectively. The lithic fragments increased to the range between 5.3% and 83.4% compared with the Early Jurassic samples. In the Q-F-L and Qm-F-Lt ternary diagrams, all the samples plot in the transitional continental, recycled orogenic, and transitional arc domains (Figure 5(a,b)), whereas

![Figure 4](image-url)  
**Figure 4.** Photomicrographs of the lower-middle Jurassic succession in Southeast China showing the main compositional features of sandstone samples. (a) Medium- to fine-grained lithic quartz sandstone, Lower Jurassic Lishan Group, Banmian section, Youxi region; (b) Fine-grained lithic sandstone, Middle Jurassic Zhangping Group, Banmian section, Youxi region; (c) Lithic quartz sandstone, Lower Jurassic Lishan Group, Zhangping region; (d) Fine-grained lithic sandstone, Middle Jurassic Zhangping Group, Zhangping region; (e) Siltstone, Middle Jurassic Zhangping Group, Dapu region; (f) Medium- to fine-grained feldspathic quartz sandstone, Lower Jurassic Jinji Group, Haifeng region. Abbreviations: Qz, quartz; L, lithic fragment; P, plagioclase.

![Figure 5](image-url)  
**Figure 5.** Ternary diagrams of modal sandstone grain compositions for Jurassic samples from Southeast China (the ages of the Jinji Group and Lishan group were between 201.3 Ma and 174.1 Ma, and the age of Zhangping group was from 174.1 Ma to 163.5 Ma) (modified after Dickinson and Suczek, 1979; Dickinson, 1985). Abbreviations: Qm, monocrystalline quartz; Qp, polycrystalline quartz; Q, total quartz; P, plagioclase feldspar; K, potassium feldspar; F, total feldspar; Ls, sedimentary and metamorphic lithic fragments; L, volcanic lithic fragments; Q = Qm + Qp, L = Ls + Lv, F = P + K, and Lt (total lithic fragments) = L + Qp.
in the Qp-Lv-Ls diagram, they plot in the collision suture, fold-thrust belt and mixed orogenic sand fields (Figure 5(c)).

In the Q-F-L ternary diagram, the compositions of the Early and Middle Jurassic sandstone samples contain more quartz and lithic fragments and relatively fewer feldspar grains, which indicates that the particles have been transported a certain distance. In the Qm-F-Lt ternary diagram, most plotted points of the Middle Jurassic samples move down and to the right compared with the Early Jurassic samples, which indicates that the content of polycrystalline quartz of the Middle Jurassic samples is not high and that there are relatively more lithic fragments, which is consistent with the observation results under the microscope. In the Qp-Lv-Ls ternary diagram, the Early and Middle Jurassic sandstone samples plot in the collision suture, fold-thrust belt and mixed orogenic sand fields, which shows that there are more polycrystalline quartz and sedimentary lithic rocks. Therefore, according to the comprehensive analysis of the locations of the plotted points of the samples, the provenance of the sediments comes from the source areas of the recycled orogenic belt and the volcanic arc orogenic belt.

4.2. CL images, Th/U ratios, and ages of sandstone detrital zircons

Cathodoluminescence (CL) images of representative detrital zircon grains in the Jurassic samples from Southeast China show that they have euhedral, subhedral, subrounded, and rounded shapes and are 40–200 µm long and 30–150 µm wide. Most zircon grains have clear oscillatory zoning, whereas a few have metamorphic overgrowth rims (Figure 6).

Zircons of different origins have different U and Th contents and Th/U ratios, and the Th/U ratios of zircons are often used as markers of their origin, such as Th/U > 0.40 and Th/U ratios < 0.10, which are often taken to indicate the difference between magmatic zircons (Th/U > 0.4) and metamorphic zircons (Th/U ratios < 0.10) (Wu and Zheng, 2004; Kirkland et al., 2015). The Th/U ratios of most zircon grains are greater than 0.4, and the ratios of 27 grains (4.5% of the total grains) are less than 0.1 (Figure 7(a)) (Appendix C). These features of CL images and Th/U ratios of detrital zircons indicate that most zircon grains are of magmatic origin.

A total of 304 zircon grains from the three Lower Jurassic samples BM201901, HF201902, and HF201903 were used for zircon U-Pb dating, and 289 concordia

![Figure 6](image_url). Cathodoluminescence (CL) images of representative detrital zircon grains in the Jurassic samples from Southeast China (please see the supporting documents).
Sample BM201901 is a medium- to fine-grained debris quartz sandstone from the bottom of the Early Jurassic Lishan Group in the Banmian section of the Youxi region (Figure 2), whose detrital zircon grains are mainly euhedral and subhedral, and most of them have oscillatory zoning (Figure 6). The 84 concordant age groups of BM201901 were 2700–2000 Ma, 2000–1600 Ma, 1600–1000 Ma, 1000–540 Ma, 540–360 Ma, 360–300 Ma, 300–250 Ma, and 200–175 Ma (Figure 8, Appendix C). Sandstone samples HF201902 and HF201903 were collected from the bottom and top of the Early Jurassic Jinji
Group in the Haifeng region, respectively. The age range of HF201902 is between 2700 and 180 Ma, with age groups at 2700–2000 Ma, 2000–1600 Ma, 1000–540 Ma, 540–360 Ma, 360–300 Ma, 300–250 Ma, 250–200 Ma, and 200–175 Ma, while HF201903 shows nine age clusters at 2600–2000 Ma, 2000–1600 Ma, 1600–1000 Ma (Chen et al., 1000–540 Ma, 540–360 Ma, 360–300 Ma, 300–250 Ma (Dickinson and Suczek), 250–200 Ma, and 200–175 Ma. These samples thus show five main age clusters at 2500–2000 Ma, 2000–1800 Ma, 900–700 Ma, 520–400 Ma, and 310–250 Ma, and two minor clusters are present at 250–200 Ma and 200–175 Ma. The youngest detrital zircon $^{206}$Pb/$^{238}$U ages of samples BM201901, HF201902, and HF201903 are 195 ± 3 Ma, 193 ± 2 Ma, and 178 ± 2 Ma, respectively (Figure 8, Appendix C).

A total of 252 zircon grains from the three Middle Jurassic samples BM201903, ZP201903, and DB201910 were used for zircon U-Pb dating, and 248 concordia ages were obtained. Samples BM201903, ZP201903, and DB201910 were from the bottom of the Middle Jurassic Zhangping Group in the Banmian section of the Youxi region, Gongqiao section of the Zhangping region, and Dama section of the Dapu region and have the youngest detrital zircon $^{206}$Pb/$^{238}$U ages of 171 ± 3 Ma, 169 ± 2 Ma, and 170 ± 3 Ma, respectively (Figure 8, Appendix C). The age groups of BM201903 are from 3000–2000 Ma, 2000–1600 Ma (He et al.), 1600–1000 Ma, 1000–540 Ma (Chen), 540–360 Ma, 360–250 Ma, 250–200 Ma, and 175–160 Ma. Sample ZP201903 has eight age clusters at 2600–2000 Ma, 2000–1600 Ma, 1600–1000 Ma, 540–360 Ma, 360–250 Ma, 250–200 Ma, 200–175 Ma, and 175–160 Ma (Dickinson and Valloni), and sample DB201910 shows five main age groups at 2600–2000 Ma (Davis et al.), 2000–1800 Ma, 360–250 Ma, 250–200 Ma, and 200–175 Ma (Figure 8, Appendix C).

4.3. CL images, trace elements, and ages of tuff detrital zircons

Six tuff samples were collected from the Youxi, Zhangping, Dapu, Meixian, Jiexi, and Haifeng regions from northeast to southwest in Southeast China (Table 1). The zircon grains of the six tuff samples are mostly euhedral and form long columns with clear oscillating ring structures (Figure 9). Most of the Th/U ratios of the tuff zircon grains are greater than 0.4, and the ratios of a few grains are less than 0.4 but greater than 0.3 (Figure 7(b)). These features of CL images and Th/U ratios of detrital zircons indicate that all the zircon grains are of magmatic origin.

Ratios of the elements Nb, Hf, Th, U, and Yb can be used to reflect the possible types of tectonic settings, including within-plate/anorogenic, arc-related/orogenic, continental arc, ocean-island, and mid-ocean ridge (Yang et al., 2012; Grimes et al., 2015), and the diagram of trace

![Figure 9](image_url)

Figure 9. Cathodoluminescence (CL) images of representative detrital zircon grains in tuff samples from Southeast China. The $^{206}$Pb/$^{238}$U weighted mean ages of the six tuff samples BM201907, ZP201908, DB201905, MN201912, HZ201901, and HF201904 are 140.2 ± 0.8 (n = 27, MSWD = 0.62), 138.3 ± 0.6 (n = 27, MSWD = 0.58), 138.1 ± 0.8 (n = 29, MSWD = 0.48), 139.9 ± 0.7 (n = 29, MSWD = 0.67), 140.2 ± 0.8 (n = 27, MSWD = 1.68), and 138.9 ± 0.8 (n = 28, MSWD = 2.2), respectively.
elements U, Yb, Hf, and Y can be used to show the crystallization environment of zircon. In the Th/U vs. Nb/Hf diagram, most analysed detrital zircon grains in tuff from Southeast China lie in arc-related/orogenic fields, and a few grains plot in within-plate/anorogenic fields (Figure 10(a)). Moreover, all trace elements analysed for detrital zircons plot in the continental arc field in the Nb/Yb vs. U/Yb diagram (Figure 10(b)) (Appendix D), which suggests that these detrital zircon grains originated from a continental arc in a convergent environment. In the U/Yb vs. Hf and U/Yb vs. Y diagrams, all the analysed detrital zircon grains in tuff from Southeast China plot in the continental environment (Figure 10(c,d)).

The $^{206}\text{Pb}^{238}\text{U}$ weighted mean ages of the six samples BM201907, ZP201908, DB201905, MN201912, HZ201901, and HF201904 are 140.2 ± 0.8 (n = 27, MSWD = 0.62), 138.3 ± 0.6 (n = 27, MSWD = 0.56), 138.1 ± 0.8 (n = 29, MSWD = 0.48), 139.9 ± 0.7 (n = 29, MSWD = 0.67), 140.2 ± 0.8 (n = 27, MSWD = 1.68), and 138.9 ± 0.8 (n = 28, MSWD = 2.2), respectively (Figure 11) (Appendix D).

5. Discussion

5.1. Provenance of the Jurassic sediments

Field palaeocurrent data are important tools for provenance analysis. For the Early Jurassic, the 42 measurements from the Early sandstones and siltstones of the Haifeng region (coordinate positions: 22°59′28″N, 115°19′29″E, and 23°26′23″N, 115°57′37″E) show that the Early Jurassic palaeocurrents were in a northward direction, and the 31 measurements from the Early sandstones of the Meixian and Dapu regions (coordinate positions: 24°08′47″N, 116°07′25″E, and 24°17′48″N, 116°52′32″E) show that the Early Jurassic palaeocurrents were in a southward direction. We thus conclude that the Early Jurassic detritus may have been derived from the Yunkai Mountain region, the Nanling tectonic belt, and the Wuyi Mountain region. The 30 measurements obtained from the Middle Jurassic sandstones of the Meixian region (coordinate positions: 23°21′03″N, 116°03′27″E, and 24°14′17″N, 116°13′17″E) show that the palaeocurrents were in a westward direction, reflecting that their source areas were situated to the east. Moreover, Shu et al. (2009c) measured the palaeocurrent direction in the Early Jurassic strata from the Yanshan Basin in eastern Jiangxi, the Yongding Basin in western Fujian, and northern Wuyi Mountain, corresponding to maximum points of 208° ± 36° and 215° ± 28°, respectively, indicating sources situated to the north. Meanwhile, the palaeocurrent directions in the Middle Jurassic sequences from the Longnan Basin in western Wuyi Mountain, the Yongding Basin, and the northern Wuyi Mountains correspond to predominant directions of 267° ± 25°, 276° ± 18°, and 328° ± 36°, respectively, reflecting source areas situated to the east and the north. Pang et al. (2014, 2016) obtained a series of palaeocurrent directions in the Early Jurassic sequences from the Xinfeng-Lianping Basin and the Meixian Basin in eastern

![Figure 10](image-url)

Figure 10. Zircon trace elements of the Earliest Cretaceous tuff samples BM201907, ZP201908, DB201905, MN201912, HZ201901, and HF201904 show tectonic setting and crystallization environment according to (a) Th/U vs. Nb/Hf ratios (based on Yang et al., 2012); (b) log10(Nb/Yb) vs. log10(U/Yb) ratios (based on Grimes et al., 2015); (c) and (d) U/Yb vs. Hf and U/Yb vs. Y (based on Grimes et al., 2007) (please see the supporting documents).
Guangdong, suggesting that these basins have multiple provenances, mainly including northern and eastern source areas.

Synthesizing detrital composition point counts of sandstone (Figure 5) and the palaeocurrent data, the Jurassic sedimentary debris in Southeast China clearly had multiple provenances, including near-source supply from the craton interior, such as the Yunkai, southern Wuyi Mountain, Nanling, and northern Wuyi Mountain regions, and an inferred Jurassic continental margin arc to the east.

The six Jurassic sandstone samples BM201901, BM201903, ZP201903, DB201910, HF201902, and HF201903 and another 19 published Jurassic sedimentary clastic rock samples from Southeast China contain zircon grains with age groups of 2700–2000 Ma and age peaks of ~2500 Ma that have mainly subrounded and rounded shapes (Figures 6, 12), indicating that they underwent long-distance transport and abrasion or multiple cycles of deposition in old strata. Meanwhile, no magmatic rocks with ages of ~2500 Ma have been reported in the Cathaysian Block to date, while zircon
grains with ages of ~2500 Ma are widely distributed in the South China Plate (Figure 13), so the clastic zircons of this period originated from the recycling of old strata.

D detrital zircons with age groups from 2000–1600 Ma are the main component of these Jurassic samples (Figure 12). Paleoproterozoic (ca. 2000–1600 Ma) detrital zircons are abundant in the Early to Middle Jurassic samples, with an age peak at ~1860 Ma (Figure 12), and mainly display euhedral to subhedral crystal forms (Figure 6), indicating near-source deposits. Paleoproterozoic magmatic and metamorphic rocks are located in the northern Wuyi Mountain region in the Cathaysia Block, where gneissic granites of the Badu Group crop out, with an age peak between 1830 Ma and 1890 Ma (Li and Li, 2007; Yu et al., 2009; Xia et al., 2012), while there have been no reports of Paleoproterozoic magmatic and metamorphic rocks in other regions of the Cathaysia Block (Figure 1(b)), and they are enriched in the ancient strata on the South China Plate (Figure 13). These Paleoproterozoic detrital zircons show Th/U ratios > 0.1, and CL images also indicate that most zircons are magmatic in origin. Moreover, Paleoproterozoic magmatism also existed in the northern and southwestern margins of the Yangtze Plate (Zhang et al., 2006a; Chen et al., 2006; Yang et al., 2016; Hieu et al., 2012; Guo et al., 2014; Wang et al., 2016), so these regions may provide material for Southeast China. Provenance analysis shows that the Paleoproterozoic detrital zircons feature both the recycling of ancient strata, the northern and southwestern margins of the Yangtze Plate, and the near-source input from the northern Wuyi Mountain region.

Mesoproterozoic (ca. 1600–1100 Ma) detrital zircons are found in samples BM201901 (1331 ± 17 Ma), BM201903 (1127 ± 36 Ma), DB201910 (1178 ± 29 Ma), and HF201903 (1254 ± 48 Ma, and 1135 ± 27 Ma), and the zircon grains are subhedral (Figure 8, Appendix C). There have been no reports of Mesoproterozoic magmatic rocks in Southeast China, but only in sedimentary rocks of various periods, and the Mesoproterozoic basement is mainly composed of the Shilu Group, Baoban Group, and Shihuiding Formation on Hainan Island, which formed between 1440 and 1000 Ma (Zhou, 2015). Li et al. (2002a) obtained zircon accretionary ages of 1300–1000 Ma and granite ages of 1200–1000 Ma in the Baoban Group of Hainan Island. Moreover, there are both extrusive and intrusive rocks, which are a set of intermediate acid rocks with an age of 1300–1000 Ma in the western margin of the Yangtze Plate, such as Xide County and Xide-Huili County (Mabi et al., 2018). Therefore, provenance analysis shows that

Figure 12. Kernel density plots (KDEs) for the Jurassic sandstone samples BM201901, BM201903, ZP201903, DB201910, HF201902, and HF201903 and another 19 published Jurassic sedimentary clastic rock samples from Southeast China (Yang and He, 2013; Xu et al., 2018; Liu et al., 2018; Xu et al., 2019; Li et al., 2020).
the Mesoproterozoic detrital zircons in Southeast China may come from these sedimentary strata, Hainan Island, and the western margin of the Yangtze Plate.

Neoproterozoic (ca. 1100–700 Ma) detrital zircons occur as a minor component in all Early Jurassic samples, while they have few Neoproterozoic (ca. 1100–700 Ma) detrital zircons in the Middle Jurassic samples except in the Shenzhen region (Figure 8 and 12). A great number of detrital zircons with age groups at 1100–700 Ma before the early Mesozoic are also found in different regions of South China, such as the northern Wuyi, Nanling Belt and Jiangxi, Yong’an Basin, Yunkai region, Youjiang and Shiwandashan Basin, and Penglaitan region (Figures 8, 12, and 13) (Li et al., 2012aa; Hu et al., 2015a, 2015b; Meng et al., 2015; Yu et al., 2010, 2012; Yao et al., 2011, 2014; Wu et al., 2010; Wan et al., 2007, 2011; Yang and He, 2012; Zhou et al., 2009; Wang et al., 2007, 2010, 2011; Zhong et al., 2013).
(Figure 13); thus, these regions, which were uplifted and where the magmatic and metamorphic rocks were widely distributed during the 1000 Ma to 700 Ma (Zhang et al., 2013; Wang et al., 2013a), may be potential provenances for the study area. Early Palaeozoic to early Late Palaeozoic (ca. 540–370 Ma) detrital zircons account for approximately 10 to 15% of each sample, and Triassic (ca. 250–200 Ma) detrital zircons account for a certain proportion (Figure 8). Magmatic and metamorphic rocks from these two periods are mainly distributed in the Wuyi, Nanling, and Yunkai domains in the Cathaysian Block, with age peaks between 423 Ma and 443 Ma, between 240 Ma and 228 Ma, and between 220 Ma and 210 Ma (Figure 1b), respectively (Sun, 2006; Wang et al., 2013b; Song et al., 2015. The data are shown in Appendix E), which are the most likely source areas.

Carboniferous-Permian (ca. 350–250 Ma) detrital zircons are important components of the six samples from Southeast China (Figure 8, Appendix C), and the zircon grains are mainly euhedral to subhedral, indicating close provenance. Geological data show that Carboniferous-Permian magmatic activity was rare in the interior of the Cathaysian Block, except for 313 Ma gneissic granite in Wufengliu village, Zhouning County, northeastern Fujian Province (Yu et al., 2013). Meanwhile, Carboniferous-Permian magmatic and metamorphic rocks are widely distributed on Hainan Island, belonging to the South China Plate during the period, such as in the Chenxing, Qiongzhong, Wuzhishan, and Tunchang regions (Chen et al., 2011, 2013; Wen et al., 2013, Liang et al., 2013). Furthermore, southwestern Japan was located in the northeastern part of the South China Plate during the Jurassic (Maruyama et al., 1997) and contains rocks such as 334–350 Ma metamorphic rocks in the Kitakami zone, 300–330 Ma granite in the Hida zone, and 264–327 Ma metamorphic rocks in the Nagato-Renge zone (Uchino et al., 2008; Wakita, 2013). The Carboniferous-Permian (ca. 350–
250 Ma) detrital zircons are inferred to have originated mainly from Hainan Island and southwestern Japan.

The Early Jurassic (200–175 Ma) detrital zircons are all euhedral (Figure 6). The Early Jurassic magmatic rocks are mainly distributed in the western Nanling belt and Dongshanshan-Talun-Yandang igneous zone of the southeastern coast, and there is also a small area of distribution in the northern Wuyi Mountain and Jiangnan orogenic belt (Figure 14). The magmatic rocks in the Nanling belt are mainly bimodal volcanic rocks, A-type granites and alkaline syenites (Zhang et al., 2009; Zhu et al., 2010), such as A-type granite in Keshubei, Pitou, Hanhu, Wengong, and Xialan and gabbro in Hanhu and Chenglong (Chen et al., 2005; Li and Li, 2007; He et al., 2010; Zhu et al., 2010; Yu et al., 2010; Huang et al., 2014; Jiang et al., 2015; Gan et al., 2016) (Figure 14). The Dongshanshan-Talun-Yandang igneous zone of the southeast coast mainly includes Jincheng granite with ages of 200 ± 2 Ma, 193 ± 2 Ma, and 187 ± 1 Ma (Liu et al., 2012); Talun granite in Taiwan with ages of 200 ± 2 Ma and 191 ± 10 Ma (Yu et al., 2009; Yui et al., 2016); granite in ESC611 with ages of 187 ± 1 Ma (Xu et al., 2016a); and granite in LF3511 of Dongsha with ages of 198 ± 1 Ma and 195 ± 2 Ma (Xu et al., 2017) (Figure 14). Therefore, these areas are possible source areas of Early Jurassic detrital zircons.

The Middle Jurassic (175–163 Ma) detrital zircons are all euhedral and have clear oscillatory zoning (Figure 6). The Middle-Late Jurassic magmatic rocks in Southeast China are mainly granite and are mainly distributed on both sides of the Zhenghe-Dapu fault zone and Ganjiang fault zone, with an age peak at ~164 Ma (Figure 1(b) and 14, Appendix E). Moreover, the Middle-Late Jurassic magmatic rocks are also distributed in the southeastern China Sea, such as granite with ages of 167 Ma and 174 Ma in the Mingyuefeng 1 well (Yuan et al., 2018; Zhang et al., 2019) and granite in some wells of the East China Sea shelf with ages of 167 Ma and 172 Ma (Li X L et al., 2020) (Figure 14); therefore, these locations are possible source areas of Middle Jurassic detrital zircons.

5.2 Provenance of the earliest cretaceous sediments

The six tuff zircon U-Pb ages are between 145 Ma and 134 Ma and belong to the Early Cretaceous. The Late Jurassic strata in most areas of Southeast China, such as the Laocun, Huangjian, Shouchang, Nanyuan, and Douling Formations, have been confirmed as Early Cretaceous strata by high-quality isotopic data and palaeontological studies (Zhou et al., 2000, 2007; Shu et al., 2009a, 2009b, 2009c). However, there are still a small number of Late Jurassic strata in Southeast China; for example, some volcanic rocks are exposed in a small part of Guangdong, western Fujian, and southern Jiangxi, and the continental strata are hardly exposed (Zhou et al., 2000, 2007; Shu et al., 2009a, 2009b, 2009c; Pang et al., 2014). Previous studies have shown that Earliest Cretaceous (145–135 Ma) magmatic rocks are widely distributed in the middle and lower reaches of the Yangtze River, Jiangxi Province, southeastern coast, and Hong Kong regions. The rock types are mainly amphibole diorite, granodiorite, monzogranite, gneissic granite and migmatite, and their isotopic ages are between 145 Ma and 135 Ma (Davis et al., 1997; Xing et al., 2008; Liu Q et al., 2012; Cui et al., 2013; Li et al., 2014) (Figure 1(b)).

The geochemical characteristics of these magmatic rocks in the middle and lower reaches of the Yangtze River show high Al2O3, MgO, TiO2, Ba, and Sr contents; low Y and Yb contents; and high Sr/Y ratios that are similar to those of adakite in the circum-Pacific tectonic belt, while the magmatic rocks on the southeastern coast may be related to the partial melting of the ancient Neoproterozoic crust and the contamination of oceanic crust materials, and it is believed that they formed in a compressional tectonic environment (Cui et al., 2013; Li et al., 2014). Therefore, the exposure of these adakitic rocks and gneissic granites together reflects the tectonic setting in which the eastern part of South China was still in compression in the Earliest Cretaceous (145–135 Ma) (Li et al., 2014). Moreover, the Hf isotopic composition of zircons in volcanic rocks is characterized by relative depletion in the Late Jurassic to the Earliest Cretaceous and an obvious tendency of gradual enrichment since the Earliest Cretaceous, indicating that the subducted plates and sediments released fluids to metasomatize the lithospheric mantle with the gradual enhancement of subduction. This process enriches the mantle wedge source area and induces more continental crust melting and further indicates the existence of crust mantle coupling, and the crust-mantle interaction gradually strengthened from 150 Ma to 90 Ma (Figure 15) (Xu et al., 2007; Guo et al., 2012; Liu et al., 2012, 2014, 2016; Zhou et al., 2015; Duan et al., 2015; Yan et al., 2016, 2017; Fan et al., 2017, 2018; Zhang et al., 2018; Jia et al., 2019; Cao et al., 2020). Meanwhile, in the Th/U vs. Nb/Hf, Nb/Yb vs. U/Yb, U/Yb vs. Hf, and U/Yb vs. Y diagrams, most analysed detrital zircon grains in tuff from Southeast China show a continental arc environment (Figure 10). Therefore, the Earliest
Cretaceous (145–135 Ma) tuff clastic material may be mainly from nearby magmatic rocks and the eastern inferred magmatic arc.

5.3. Subduction of the Paleo-Pacific Plate

Studies have shown that Jurassic to Cretaceous subduction accretion complexes, the product of subduction of the Paleo-Pacific Plate to South China in the Mesozoic, remained along southwestern Japan through Taiwan, Palawan and Kalimantan (Isozaki, 1997; Wakita et al., 1998; Zamoras and Matsuoka, 2001; Yu et al., 2012; Zhang et al., 2019). These subduction accretion complexes record geological information on the subduction zone of the Paleo-Pacific Plate, indicating that there was a subduction zone of southwestern Japan east of Taiwan-Palawan-Kalimantan Island to the east of Southeast China. Moreover, Jurassic-Early Cretaceous (200–135 Ma) magmatic rocks are also widely distributed on the southeastern coast and near the trench area, such as granite at 167 Ma and 174 Ma in Mingyuefeng well 1, granite at 187 Ma in well ESC611, granite with ages between 198 Ma and 195 Ma in well LF3511, Talun granite at 200–190 Ma in Taiwan, and Dongshan granite with ages between 139 Ma and 144 Ma. These magmatic rocks were mainly the product of mantle melt evolution in the subduction background and had the characteristics of a rich water oxidation source area in the subduction zone (Maruyama et al., 1997; Liu et al., 2012; Yui et al., 2016; Xu et al., 2017; Yuan et al., 2018; Zhang et al., 2019); thus, there was a Jurassic-Cretaceous continental magmatic zone near the Changle-Nan’ao fault from the China Sea to South China Sea.

Recent studies show that the magmatic activity along the continental margin arc in the Early Jurassic (200–175 Ma) mainly occurred in the eastern sea area and offshore trench areas, producing rocks such as the magmatic rocks (zircon U-Pb ages of 198–195 Ma) from well LF3511 and the Talun granite (zircon U-Pb ages of 200–190 Ma) in the southern Taiwan region (Figure 14); these rocks are mainly the products of mantle-derived melt evolution against a subduction background and have water-rich and oxidized source characteristics from the subduction zone (Yui et al., 2016; Xu et al., 2017); meanwhile, the inland region of Southeast China widely developed A-type granites, bimodal volcanic rocks, basalts and other rock assemblages with ages between 188 Ma and 180 Ma (Figure 16) (Li et al., 2007; Huang et al., 2011; Ye et al., 2013). These changes indicate that the tectonic setting of the continental margin zone in Southeast China may have been different from the inland tectonic setting in the Early Jurassic. This evolution indicated that the effect of Paleo-Pacific Plate subduction may have weakened from the Southeast China Sea to the

Figure 15. U-Pb zircon ages of Jurassic and early cretaceous magmatic rocks and εHf(t) value diagrams in Southeast China (Xu et al., 2007; Guo et al., 2012; Liu et al., 2012, 2014, 2016; Zhou et al., 2015; Duan et al., 2015; Yan et al., 2016; Fan et al., 2017, 2018; Zhang et al., 2018; Jia et al., 2019; Cao et al., 2020).
continental margin and indicated that Paleo-Pacific Plate subduction changed from the trench (to the east of the subduction zone of the Paleo-Pacific Plate to the South China Plate) to the continental margin of Southeast China in the Early Jurassic.

The Middle-Late Triassic tectonic movement resulted in structural traces, which are primarily represented by the nearly east-west fold, thrust nappe and NE-NNE sinistral strike-slip shear zone (Dong et al., 2007; Zhang et al., 2009; Xu et al., 2009; Liu et al., 2015a, 2015b), and it also resulted in magmatic rocks that are widely distributed in Fujian, Hunan, Guangdong, Jiangxi, Guangxi and other locations to the west of the Zhenghe Dapu fault zone. Moreover, the magmatic rocks in this period only included granitic intrusive rocks, with age peaks at ~236 Ma, ~220 Ma, and ~210 Ma (Zhou, 2007) (Figure 16). The fold structural line strikes produced by the tectonic event beginning in the early Middle Jurassic (~170 Ma) were mainly NE-NNE trending, and their distribution is characterized by east-west zoning (Dong et al., 2007; Zhang et al., 2009, 2013; Xu et al., 2009). The tectonic movement resulted in intense magmatic activity, which was widely distributed in the inland areas of Southeast China, and an important crustal melting event occurred in the early Middle-Late Jurassic with an age peak at ~164 Ma (Figure 16, Appendix E). In addition, the Pingtan-Dongshan high-temperature and low-pressure metamorphic belt along the southeastern coast developed gneissic granite or mixed granite, and isotope measurements show that these granites formed between the Middle and Late Jurassic and may represent the products of crustal anatexis under compression (Zhang et al., 2009). Moreover, almost no tectonic activity occurred in the Early Jurassic, while the tectonic movement between the Middle Jurassic and Early Cretaceous resulted in extensive nappe structures and fold deformation with mainly NE-NNE trends (Liu et al., 2015a, 2015b), such as strong metamorphism and deformation in the Changle-Nan’ao metamorphic belt (Cui et al., 2013; Li et al., 2014; Feng et al., 2014; Dong et al., 2015). Different tectonic styles and different magmatic activities may show two different tectonic settings in South China; that is, geological information may record the timing of the subduction of the Paleo-Pacific Plate in Southeast China.

Faure et al. (2015) suggested that Triassic geodynamics of the southern part of the South China Block (SCB) are the consequence of intracontinental subduction in Xuefengshan and collision of the SCB with a continental block equivalent to Indochina presently hidden below the South China Sea by the lithosphere-scale interpretative cross-section from Xuefengshan to the southeastern coast of the SCB. Xu et al. (2017) believed that the subduction of the Paleo-Pacific Plate was initiated during the Early Jurassic by combining residual Dongsha-Talun-
Yandang magmatic arc records, regional subduction complexes, and magmatic rocks of the same period in South China. Suo et al. (2020) proposed that the Paleo-Pacific Plate began to subduct in Southeast China during the Early Jurassic, resulting in a NNE-striking Jurassic magmatic arc along the East China Sea, by using multiple disciplinary data comprising seismic profiles, field observations and numerical paleotopographies. The above studies indicate that the Paleo-Pacific Plate began to subduct beneath Southeast China in the Early Jurassic.

In this study, lithofacies palaeogeography and the sedimentary environment showed that the Southeast China region was shallow sea and delta facies in the Late Triassic, and the southeastern coast was almost a shallow sea facies (Ma et al., 2009), indicating that the Paleo-Pacific Plate may not have begun to subduct beneath Southeast China. The scope of the shallow sea facies narrowed in the Early Jurassic and was lacustrine, fan delta, delta, and fluvial facies in the Middle Jurassic, and it was a volcanic basin in the Late Jurassic to the Earliest Cretaceous (Ma et al., 2009) (Figure 17). The change in basin sedimentary facies was the response to the transgression and regression of Southeast China and the response to basin expansion to contraction, and it was also influenced by the subduction of the Paleo-Pacific Plate (Figure 17).

The above evidence indicates that subduction of the Paleo-Pacific Plate beneath Southeast China occurred in the Early Jurassic and continued into the Early Cretaceous and that an active continental magmatic arc developed in the Southeast China Sea during the Early Jurassic to Early Cretaceous (200–135 Ma), which resulted in the uplift of the northern Wuyi Mountain region (Figure 18). In the Early Jurassic Period (200–175 Ma), continental margin arcs were located in the Southeast China Sea and

Figure 17. Lithofacies palaeogeography from the Late Triassic to the early cretaceous (~135 Ma) (modified after Ma et al., 2009).
Taiwan offshore trench area, and the inland area of Southeast China may have been less affected by subduction, with a limited range of magmatic activity. In the Middle Jurassic to Early Cretaceous (175–135 Ma), Southeast China was affected by a wider range of subduction fluids and developed larger-scale magmatic activity, with the further expansion of Paleo-Pacific Plate subduction. The rollback of the Paleo-Pacific Plate occurred from the Early Cretaceous (~135 Ma) and formed pronounced NE-striking extensional basins and magmatic zones (Li et al., 2014). The model of westward subduction of the Paleo-Pacific Plate beneath Southeast China controlled the provenance characteristics of the sedimentary basins and the tectonic framework of Southeast China, and this model may provide a reference for understanding the Mesozoic tectonic evolution of the South China Block (Figure 18).

6. Conclusions

In this paper, we discuss the westward subduction of the Paleo-Pacific Plate beneath Southeast China by analysing provenance data, including detrital composition point counts and detrital zircon U-Pb geochronology, tectonic deformation, isotopic ages of granite and volcanic rocks from basins. The following conclusions are reached:

(1) The zircon ages of the Jurassic samples from Southeast China form three major age clusters at 2000–1800, 540–360, and 350–200 Ma as well as two minor clusters at 2500–2100 and 200–160 Ma. The sediments were transported from multiple sources, including intracratonic mountains and tectonic belts and the inferred active continental margin arc that resulted from Paleo-Pacific Plate subduction. The zircon ages of six Early Cretaceous tuff samples are mainly between 145
and 134 Ma, and the tuff clastic material may be mainly from nearby magmatic rocks and the eastern inferred magmatic arc.

(2) An active continental magmatic arc developed along the coast of Southeast China during the Early Jurassic to Early Cretaceous (200 Ma–135 Ma). The westward subduction of the Paleo-Pacific Plate initiated in the Early Jurassic (~200 Ma) and continued to the Early Cretaceous (~135 Ma). Paleo-Pacific Plate subduction resulted in uplift of the northern Wuyi Mountain region and eastern South China and controlled the provenance characteristics of the sedimentary basins during the Jurassic to Early Cretaceous in Southeast China.

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Disclosure statement

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Appendices

Appendix A. Detrital composition point count information of all the samples.
Appendix B. Zircon U-Pb dating results for primary and secondary standards.

Appendix C. Zircon U-Pb dating results and rare earth elements for sandstone samples BM201901, BM201903, ZP201903, DB201910, HF201902, and HF201903.

Appendix D. Zircon U-Pb dating results and related rare earth elements for the six tuff samples BM201907, ZP201908, DB201905, MN201912, HZ201901, and HF201904.

Appendix E. Summary of the crystallization and metamorphic ages of the Triassic rocks (Table 1), the Early Palaeozoic rocks (Table 2), the Early to Middle Jurassic rocks (Table 3), and the Middle to Late Jurassic rocks (Table 4) from Southeast China.

The supporting information for this paper can be downloaded from the Mendeley Data repository (https://data.mendeley.com/datasets/x6hsv688mx/6).