Geology of the Fuding inlier in southeastern China: Implication for late Paleozoic Cathaysian paleogeography

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ABSTRACT

The age and composition of the basement rocks underlying the Mesozoic volcanic rocks in southeastern China have been long debated. New field investigation, stratigraphical and sedimentological studies of the Fuding inlier in eastern Cathaysian block have identified the presence of three stratigraphic units. The Upper Carboniferous carbonate unit, composed of silicified limestone, deposited on carbonate platform in a continental shelf environment. The Lower Permian siliciclastic unit, consisting of slate and phyllite with minor arenites, deposited on shallow semi-restricted shelf. The third unit is a suite of Jurassic conglomerates and sandstones deposited in alluvial fan environment. Provenance data indicate that the Fuding inlier was part of the Wuyishan terrane in the eastern Cathaysian block. The U–Pb age and Hf isotope of detrital zircons indicate that extensive magmatic activity happened during 280–360 Ma in the source area. The εHf values of detrital zircons point to magmatic mixing of juvenile material and Precambrian crust. The similarities in rock compositions and detrital zircon ages among the Yeongnam massif in the Korean Peninsula, the Tananao complex in Taiwan and the Fuding inlier have led to the conclusion that these three regions most likely belonged to the Wuyishan terrane, eastern Cathaysia during the late Paleozoic.

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1. Introduction

More than 90% of the surface area of the eastern Cathaysian block (Zhejiang and Fujian provinces, southeastern China) (Fig. 1) is covered by late Mesozoic volcanic rocks (Gilder et al., 1996; Wang and Zhou, 2002; Zhou, 2007). The age and composition of the basement rocks underlying these Mesozoic volcanic rocks are poorly known. A few Upper Paleozoic sedimentary rocks are exposed in the eastern Cathaysian block, such as strata in the Fuding inlier in Fujian province (Shi and Liu, 1980; Wu and Li, 1990; Ying et al., 1994) and in the Qingtian inlier in Zhejiang province (Zhu et al., 1994). Paleozoic strata in the Fuding inlier were first reported as a suite of low-grade metamorphic rocks by the Zhejiang Regional Geological Survey Team (1975). The presence of the fusulinid Pseudostaffella sphaeroidea in the silicified limestone indicates the Late Carboniferous age (Zhejiang Regional Geological Survey Team, 1975), while conodonts from the microcrystalline limestones indicate the Early Carboniferous–Early Permian (Ying et al., 1994). Shi and Liu (1980) suggested that the clastic sedimentary rocks in the Fuding inlier are flysch type and were deposited in a deep-water environment. Consequently, this area was interpreted to present the late Paleozoic “Fu-Shan Trough” by Wang (1986) and this viewpoint was widely accepted. Although the Upper Paleozoic sedimentary rocks are exposed in the Fuding inlier, their stratigraphy, sedimentology and sedimentary sources for the strata remain uncertain.

We investigated the stratigraphy and sedimentology of the Fuding inlier (Fig. 2) and carried out provenance analysis of the clastic rocks based on detrital modes of the sandstones, Nd isotopes of the fine-grained clastic sediments and U–Pb age and Hf isotopes of the detrital zircons. The new data allow us to examine and comment on the late Paleozoic palaeogeography of the eastern Cathaysian block.

2. Geological setting

The South China block (SCB) consists of the Yangtze block to the northwest and the Cathaysian block to the southeast (Fig. 1). The present boundary between these two blocks is the northeasterly trending Jiang-Shao fault in the east, but the southwestern extension of this boundary is unclear (e.g. Charvet et al., 1994; Fig. 1). The timing of the amalgamation between the Yangtze and Cathaysian blocks remains controversial. The predominant view was an early Neoproterozoic age for the amalgamation, ca. 900 to 880 Ma (Li et al., 2007, 2009) to ca. 800 Ma (Zhao and Cawood, 1999; Wang et al., 2007, 2010a). The
Proterozoic crust of the Cathaysian block can be separated into two distinct tectonic domains, the Wuyishan terrane to the northeast and the Nanling-Yunkai terrane to the southwest (e.g. Yu et al., 2010). The Wuyishan terrane is characterized by dominant Paleoproterozoic (approximately 1.86 Ga) and lesser Neoarchean basement, which suffered strong Neoproterozoic and early Paleozoic tectono-thermal reworking. By contrast, the Nanling-Yunkai terrane contains abundant Neoarchean and Grenvillian-aged magmatism (approximately 1.0 Ga).

During the Phanerozoic time, the Cathaysian block experienced four main tectonic events. 1) The Kwangsian orogeny (Ting, 1929), which is traditionally called the Chinese Caledonian orogeny (Huang et al., 1980; Ren, 1991; Shu, 2006), is characterized by the angular unconformity that separates the Devonian-Permian cover from strongly deformed pre-Devonian strata (Huang et al., 1980) as well as syn-deformational metamorphism and subsequent anatexis (e.g. Li et al., 2010). It is generally considered to be an early Paleozoic intracontinental orogen (Shu, 2006; Faure et al., 2009; Charvet et al., 2010; Li et al., 2010); 2) Late Paleozoic extensional rifting, which probably started in the Devonian (Zeng et al., 1993; Zhao et al., 1996; Wang et al., 2010b); 3) The Indosinian orogeny, which extended from the Late Permian to the Middle Triassic, was a result of the collision between the Indochina block and South China (Carter et al., 2001; Cai and Zhang, 2009); 4) Late Mesozoic magmatism along the southeastern coast of South China (Charvet et al., 1994; Wang et al., 1995; Gilder et al., 1996; Zhou and Li, 2000; Griffin et al., 2002), which represents an active continental margin.

The Fuding inlier is located at approximately 20 km northwest of Fuding town in Fujian province. The Fuding inlier is about 20 km² in size, and is in fault contact with the surrounding Cretaceous volcanioclastic rocks comprised mainly by volcanioclastic sandstones and tuffs (Fig. 2).

3. Stratigraphy and sedimentology

Due to extensive faulting, it was not possible to find a continuous sedimentary succession in the study area (Fig. 4a). However, we could define three stratigraphic units in the field based on our geological mapping (Fig. 3).
3.1. Upper Carboniferous carbonate unit

The Upper Carboniferous carbonate unit in the study area is more than 35 m thick and is comprised of three different types of limestones (Fig. 3):

1) Partially or completely silicified gray thin-bedded micritic limestone (Fig. 4b), enclosing silicified sponge spicule (up to 10% in weight) and crinoidal debris (Fig. 5a). The limestone was most likely deposited in a deep carbonate shelf environment.

2) Partially or completely silicified grayish-yellow thin-bedded bioclastic limestone. The bioclastic debris includes echinoderm, fusulinid, algae and brachiopod. The bioclasts indicate deposition in an open carbonate platform environment.

3) Gray thick-bedded silicified oolitic limestone (Fig. 4c), replaced by silica with some residual oolitic structure preserved (Fig. 5b). The ooids are approximately 0.3 to 0.8 mm in diameter and have a radial fabric. A minor amount of crinoid debris and few bioclastic shells are also present. The sparry calcite cement filling the intergranular pores was replaced by silica. This rock may have been deposited in a high energy, very shallow-water environment, probably as oolitic shoal on a carbonate platform.

Fossils reported from these limestones include fusulinids (*Pseudostaffella sphaeroidea*, *Beedeina* sp. and *Profusulinella*), brachiopods (*Neospirifer* sp.) and conodonts (*Idiognathodus delicatus*) (Wu and Li, 1990; Ying et al., 1994), which indicates the Bashkirian–Moscovian (Late Carboniferous) age of the strata.

3.2. Lower Permian siliciclastic unit

The Lower Permian unit is comprised by black carbonaceous slate, silty slate and phyllite, occasionally interbedded with lithic arenites and micritic limestones (Fig. 3).

1) The black slate, silty slate and phyllite (Fig. 4d) are partially silicified and enclose plant debris. The total organic carbon (TOC) in the slates varies from 0.34 to 2.5% in weight (Zhejiang Petroleum Exploration Department, 1991). Shi and Liu (1980) suggested that these sediments in the Fuding inlier have flysch-type characteristics. However, we did not find any turbiditic structures during the field survey, such as the Bouma sequence, flute cast and normal graded beds, etc. The black color of slates and the increased organic carbon content indicate at least a dysoxic depositional environment and increased surface productivity at that time. The depositional environment of this unit was most probably semi-restricted continental shelf.

2) Thin-bedded sandstone layers occur sporadically within the slate-dominated strata (Figs. 4e and 5c). Sandstones are mainly fine-grained lithic arenites (Fig. 6). Grains are angular to subangular in shape and are poorly sorted with a diameter of 0.06 to 0.2 mm (Fig. 5c). The matrix is formed by illite. One bed of lithic arenite, located near a quartz vein (Fig. 4e), contained epidote and plagioclase (up to 10% in weight), resulting from local thermal metamorphism (Fig. 5e). The siltstone is dominated by lithic grains (60%) and quartz (40%), which are poorly sorted and poorly rounded. The matrix comprises up to 25% of the siltstones. We suggest that these sandstones and siltstones were probably deposited in a prodelta setting.
3) Microcrystalline limestones, intercalated within the slate succession, are thin-bedded and contain crinoid debris replaced with silica. We interpret them as being deposited on a deep carbonate shelf.

3.3 Jurassic coarse grained siliciclastic unit

A suite of siliciclastic rocks over 100 m thick is exposed in the central part of the Fuding inlier (Fig. 2). The lithology of the unit consists of conglomerates, sandy conglomerates and coarse sandstones, which unconformably overlie the late Paleozoic sedimentary successions. Conglomerates have sandy matrix (Fig. 4g) and are comprised by a variety of gravels and pebbles, including slate, phyllites, gneiss, volcanic rocks, granites, sandstones and silicified limestones (Fig. 5f). The pebbles are several to over 10 cm in diameter and are angular to well-rounded in shape. Clasts of dark-colored slate and phyllite lithoclasts in the conglomerate are considered to have been derived from the erosion of the underlying Lower Permian. The sandstones include lithic arenites, subarkoses and arkosic arenites. Lithic grains within the sandstones are dominated by volcanic grains, phyllites, minor schists and slates. The feldspars are mainly K-feldspars with minor plagioclases. Large-scale cross-stratification and normal grading were observed in the strata. We interpret this lithologic suite as being deposited in alluvial fan environment. The age of this unit is poorly constrained, but it is most likely of the Jurassic age based on regional geologic considerations (Fujian Bureau of Geology and Mineral Resources, 1997).

4. Sampling and methods

Over 50 samples were collected in the Fuding inlier (Fig. 2, Appendix A). More than 30 polished thin sections were prepared from sandstones and fine-grained conglomerates for the petrographic analysis. Four sandstone samples were selected for modal analysis with approximately 400 framework grains counted per thin section. To minimize the effect of grain-size variations, the rock fragments were counted using the Gazzi–Dickinson method (Dickinson and Suczek, 1979; Ingersoll et al., 1984).

Four slate samples from the Lower Permian were collected for the Sm–Nd isotopic analysis. Approximately 100 mg of powder for each sample was dissolved in a mixture of HF and HNO₃ in Teflon beakers. Sm and Nd were then separated and purified by conventional cation-exchange techniques. The isotopic measurements of the purified Sm and Nd solutions were performed on a Finnigan Triton TI thermal ionization mass spectrometer (TIMS) at the State Key Laboratory of Mineral Deposits Research, Nanjing University. The mass fractionation correction for the Nd isotopic ratios was based on 146Nd/144Nd = 0.7219. The blanks for Sm and Nd were 5 × 10⁻¹¹ g. A two-stage model age calculation is used because the Nd model age results are correlated with the Sm/Nd ratio (Miller and Harris, 1989).

Two Lower Permian litharenite samples (08M1–1 and 08NX12) and two Jurassic pebbly sandstone samples (08M1–17 and 08NX23) were selected for the detrital zircon U–Pb geochronology analysis. The zircons were randomly selected from heavy mineral concentrates. The selected zircons were then encased in epoxy mounts and polished.
The U–Pb dating of the detrital zircon was performed by laser ablation–inductively coupled plasma–mass spectrometry (LA–ICP–MS) at the State Key Laboratory for Mineral Deposits Research, Nanjing University, China, and at the State Key Laboratory of Lithosphere Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, following a previously described method (Jackson et al., 2004). The results and isotopic rates were calculated using the program GLITTER 4.4 (Van Achterbergh et al., 2001). Common Pb corrections were carried out using method described by Andersen (2002). The age calculations and plotting of concordia diagrams were performed using ISOPLOT v.2.49 (Ludwig, 2001). Detrital zircon age interpretations are complicated by Pb loss, which produces discordance for the zircons in the approximately 1.8–2.5 Ga age range from the Fuding inlier. Fortunately, the patterns of discordance by Pb loss are recognizable on U–Pb concordia diagrams as an array that projects from a greater than 1.8 Ga upper intercept to a very young lower intercept (Fig. 8). In this study, we use $^{207}\text{Pb}^{206}\text{Pb}$ ages for zircons that display discordance greater than 10%. For zircon ages that are concordant or slightly discordant (discordance < 10%), we use $^{206}\text{Pb}^{238}\text{U}$ ages for grains younger than 1 Ga and $^{207}\text{Pb}^{206}\text{Pb}$ ages for grains older than 1 Ga.

The Hf isotope analyses of detrital zircons were performed using a Neptune multiple collector inductively coupled plasma mass spectrometry (MC–ICP–MS) that was equipped with a 193 nm laser and housed at the State Key Laboratory of Lithosphere Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences. The details about the instrumental conditions and data acquisition can be found in Wu et al. (2006). In this study, the $^{176}\text{Hf}^{177}\text{Hf}$ ratio of standard zircon (91500) was $0.282265 \pm 0.00001$ (2 SD; n=18). To enable comparison among the laboratories, all of the Hf isotopic data were corrected by adjusting the $^{176}\text{Hf}^{177}\text{Hf}$ ratio of 91,500 to 0.282305. During the calculation, we adopted a depleted mantle model with $^{176}\text{Hf}^{177}\text{Hf}_{\text{DM}} = 0.28325$ and $^{176}\text{Lu}^{177}\text{Hf}_{\text{DM}} = 0.0384$ (Griffin et al., 2000), chondrite with $^{176}\text{Hf}^{177}\text{Hf}_{\text{CHUR}} = 0.282772$ and $^{176}\text{Lu}^{177}\text{Hf}_{\text{CHUR}} = 0.0332$ (BlichertToft and Albarede, 1997) and an average continental crust.
with $^{176}\text{Lu}^{177}\text{Hf}_\text{c} = 0.015$ (Griffin et al., 2002). We used a decay constant of $1.867 \times 10^{-11}$ for $^{176}\text{Lu}$ (Soederlund et al., 2004).

All the analytical results are given in Appendices B to F.

5. Provenance analysis

5.1. Nd isotopes of slate

As shown in Appendix C, the Lower Permian slate in the Fuding inlier have old Nd model ages, ranging from 2.05 to 2.23 Ga (averaging 2.14 Ga), which is approximately 1.7 Ga older than its depositional age. This result indicates that the Lower Permian slates were mainly derived from the erosion of the ancient Paleoproterozoic crust. The $\varepsilon_{\text{Nd}}(t)$ values of those Early Permian slate (calculation refers to Appendix B) are $-14.7$ to $-12.4$ (averaging $-13.5$). On the $\varepsilon_{\text{Nd}}(t)$–$t$ (strata) diagram (Fig. 7), these samples plot within the evolution zone of the Paleoproterozoic crust of South China (Shen et al., 2003, 2009). Furthermore, the Nd model ages of these slates are all older than 2.0 Ga, most probably derived from the basement rocks of the Cathaysian block rather than those of the southern Yangtze block (Shen et al., 2009).

5.2. Detrital modes of sandstones

Lower Permian sandstones in the Fuding inlier are classified as lithic arenites with averaged Q–F–L ratios of 43:0:57 (Appendix B and Fig. 6). Monocrystalline quartz grains dominate the grain framework with the quartz content being 34 to 53%. Lithic grains (47–66%) are dominated by felsic volcanic grains (Fig. 5d), and subordinate are lithoclast of shale and siltstones. No feldspar grains were observed.
5.3. Detrital zircon U–Pb ages

Totally 72 zircons (sample 08NX12) and 138 zircons (sample 08M1–1) were analyzed for U–Pb ages from the Lower Permian lithic arenites. Some zircons show discordance due to Pb losses (Fig. 8). The zircon ages from sample 08NX12 form three age populations clustered at 285 to 482 Ma (27%), 1.45–1.91 Ga (35%) and 2.07 to 2.63 Ga (38%) with peak ages at 311 Ma, 1.76, 1.78, 2.35 and 2.47 Ga. Sample 08M1–1 exhibits a similar age distribution with three age groups of 279 to 447 Ma (58%), 1.46 to 1.89 Ga (24%) and 2.18 to 2.59 Ga (17%) and major peaks at 315 Ma, 1.77, 1.85, 2.4 and 2.49 Ga (Table 1 and Fig. 9). Carboniferous–Permian zircons (ca 360–280 Ma) from these samples are abundant and comprise 22% to 52% of the total grains. The youngest zircon ages of 279±4, 283±4, 285±4 and 285±3 Ma, provide the maximum age constraint for the deposition.

Samples 08M1–17 and 08NX23 are Jurassic pebbly sandstones. A total of 118 zircon ages were obtained for the provenance analysis. The zircon ages have two predominant populations at 281 to 404 Ma (39%) and 1.31 to 2.05 Ga (52%) as well as a subordinate cluster at 2.24 to 2.52 Ga (8%) (Table 1 and Fig. 9). The broad similarity in the detrital zircon age spectrum between the Lower Permian and Jurassic clastic rocks suggests that they have the same source or that the Jurassic sediments were sourced from the late Paleozoic strata. The youngest ages from the Jurassic sample are 281±4, 287±3, 301±5 and 307±5 Ma. A lack of Late Permian–Jurassic zircons might indicate a magmatic quiescence period in the source area.

We also analyzed zircons from the Cretaceous volcaniclastic rocks that surround the Paleozoic strata in the Fuding inlier. Sample 08NX18 gave a weighted average age of 139.3±1.2 Ma (n=14, MSWD=0.31) (Fig. 10), confirming an Early Cretaceous age.

5.4. Detrital zircon Hf isotopes

Zircons (n = 131) from two Lower Permian sandstones (08NX12 and 08M1–1) were submitted to Hf isotopic analysis. On the εHf(t) vs. U–Pb age diagram, the zircons are distributed into three distinct groups (Fig. 11). Zircons of ca. 2.2 to 2.6 Ga have εHf(t) values of −8.7 to +6.6 with two-stage Hf model ages (TDM) between 2.7 Ga and 3.5 Ga, which indicate that the host magma of these zircons was derived from Meso- to Neoarchean crustal materials. Zircons of ca. 1.6 to 1.9 Ga have εHf(t) values of −15.5 to +0.4 with Hf model ages of 2.5 to 3.4 Ga similar to 2.2–2.6 Ga zircons. This suggests that...
Table 1
Detrital zircon U–Pb age distribution in the Fuding inlier.

<table>
<thead>
<tr>
<th>Age</th>
<th>Sample</th>
<th>Zircon numbers</th>
<th>Major age ranges (Ma)</th>
<th>Major age peaks (Ma)</th>
<th>Percentage of Paleozoic zircons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jurassic</td>
<td>08M1–17 and 08NX23</td>
<td>118</td>
<td>281–373 (n=45), 1732–1897 (n=54), 2240–2521 (n=9)</td>
<td>306 (n=3), 333 (n=25), 368 (n=6), 1760 (n=5), 1860 (n=46), 2335 (n=3), 2485 (n=3)</td>
<td>39% (48 grains)</td>
</tr>
<tr>
<td>Permain</td>
<td>08M1–1</td>
<td>138</td>
<td>279–366 (n=74), 1709–1894 (n=28), 2274–2592 (n=21)</td>
<td>292 (n=18), 315 (n=31), 337 (n=9), 351 (n=7), 362 (n=4), 1738 (n=6), 1775 (n=7), 1855 (n=10), 2318 (n=4), 2399 (n=4), 2428 (n=4), 2488 (n=5), 2571 (n=3)</td>
<td>58% (80 grains)</td>
</tr>
<tr>
<td>Permain</td>
<td>08NX12</td>
<td>72</td>
<td>285–360 (n=16), 1611–1911 (n=24), 2291–2494 (n=21)</td>
<td>300 (n=5), 311 (n=6), 319 (n=5), 340 (n=3), 1629 (n=5), 1685 (n=3), 1723 (n=4), 1757 (n=5), 1778 (n=5), 2295 (n=3), 2355 (n=6), 2394 (n=4), 2467 (n=4)</td>
<td>28% (20 grains)</td>
</tr>
</tbody>
</table>

6. Discussion

6.1. Constraining on the depositional age of the siliciclastic unit

The age of the siliciclastic unit in the Fuding inlier is poorly constrained because of the general lack of fossils. In the siliciclastic unit, their host magma was derived from the same sources. Zircons of ca. 280 to 400 Ma are characterized by negative εHf(t) values that vary from −34.3 to −3.1 and TDM between 1.5 Ga and 3.5 Ga. A wide range of εHf(t) values indicates that the host melt of these zircons probably originated from the mixed sources of an old continental crust, similar to the source of Neoarchean to Paleoproterozoic zircons, probably originated from the mixed sources of an old continental crust, similar to the source of Neoarchean to Paleoproterozoic zircons, and juvenile magma or young crust (ca. 1.5 Ga) to different extent.

Ying et al. (1994) found the conodonts Streptograptus fuchenensis, S. elongates and Gondolella sp. from interbedded limestones within the slates, which gave an age of the Middle Carboniferous to Early Permian for this unit. It is generally accepted that the youngest concordant detrital zircon age can be used to constrain the maximum depositional age. In this study, the youngest detrital zircons (Appendix D) from thin-bedded sandstones (samples 08NX12 and 08M1–1) in the Fuding inlier are approximately 280–285 Ma (Fig. 9), indicating that their depositional ages could not be older than the Artinskian stage (Early Permian, according to the time scale of Gradstein et al., 2004). Therefore, we suggested that the siliciclastic unit would be most probably Early Permian in age.

6.2. Fuding inlier was part of the northern Wuyishan terrane

Geologically, the Fuding inlier locates on the northeast of the Cathaysian block and belongs to the northern part of the Wuyishan terrane (Fig. 1). Moreover, the Nd isotopes and detrital zircon geochronology from the Permian clastic sediments suggests that the Fuding inlier is tectonically part of the Wuyishan terrane (Fig. 9). The Early Permian slates have Nd model age of 2.05–2.23 Ga, indicating existence of ancient Paleoproterozoic crust in the source area. In fact, the Paleoproterozoic basement rocks have been widely documented in the Wuyishan terrane (e.g., the Badu Group, Li, 1997; Wan et al., 2007; Yu et al., 2009, 2011). In this study, the detrital zircon U–Pb ages from the Lower Permian sandstones shows two age peaks of Paleoproterozoic–Neoarchean magmatism at 1.6–1.9 Ga and 2.2–2.6 Ga, respectively. The late Paleoproterozoic (1.6–1.9 Ga) magmatism was widely developed in the northern Wuyishan subterrane (Gan et al., 1995; Li, 1997; Wan et al., 2007; Xu et al., 2007; Yu et al., 2009), including...
the Paleoproterozoic granites and metamorphic rocks of the Badu and Tianjinping groups in southern Zhejiang and northern Fujian (Fig. 12). The early Paleoproterozoic–Neorarchean (2.2–2.6 Ga) zircons were observed in the northern and central Wuyishan subterranes (Fig. 12) as inherit zircons and considered to represent possibly Archean basement rocks (Yu et al., 2011). Detrital zircon Hf isotopes also support their sources from the northern Wuyishan terrane. On the εHf(t) vs. U–Pb age diagram (Fig. 11), zircons from the basement rocks in the northern Wuyishan terrane (Yu et al., 2010) overlap significantly with those Paleoproterozoic–Neorarchean detrital zircons in the Fuding inlier, which may indicate that the clastics of these sedimentary rocks are mainly from the northern Wuyishan terrane itself.

The widespread Neoproterozoic (0.72 to 0.82 Ga) magmatic activity in the central and southern parts of the Wuyishan terrane (Wanquan Group, Miamianshan Group, Mayuan Group, Taoxi Group) (Li et al., 2005; Yu et al., 2006; Wan et al., 2007; Yu et al., 2010) (Fig. 12). In the Nanling–Yunkai terrane, the Grenvillian period (ca 1.0 Ga) and the mid-Proterozoic magmatism are widely distributed (Wang et al., 2008; Yu et al., 2009, 2010; Wang et al., 2010b; Xiang and Shu, 2010; Yao et al., 2011) (Fig. 9). Those magmatic ages both in the southern and central Wuyishan and the Nanling–Yunkai terranes are not recorded in the detrital zircons from the Fuding inlier (Fig. 9). Also, the detrital zircons from Early Permian sandstones in Fuding inlier show different age patterns with those from eastern Yangtze terrane (Fig. 9), while the latter has abundant detrital zircons of ~1.1 Ga and ~0.86–0.78 Ga (Wang et al., 2010b). Therefore, we suggested that the detrital zircons in the Fuding inlier were most probably sourced from the northern part of the Wuyishan terrane.

6.3. Source rocks and tectonic setting induced from clastic sediments

Detrital modes of the Lower Permian sandstones in the Fuding inlier are dominated by lithic grains (mainly felsic volcanic, shales and siltstones) and monocrystalline quartz grains. On the QFL ternary diagram (Fig. 6; Dickinson, 1985), these sandstones are located in the ‘recycled orogen’ provenance field. However, there is no geological evidence for a late Paleozoic orogenic event in the Cathaysian block. Alternatively, occurrence of volcanic grains and abundant Carboniferous to Early Permian detrital zircons points to a volcanic provenance. Felsic volcanic grains in the sandstones could have been derived from the volcanic rocks, while lithoclasts of clay and siltstones and some of quartzes may be recycled from the basement or sedimentary covers. Detrital zircons from the sandstones indicate that the volcanism in the source area was active with peaks at ca 330 Ma and ca 310 Ma. However, regional correlation shows that late Paleozoic magmatism was rarely reported from the Cathaysian block (Wang and Liu, 1986; Charvet et al., 1994; Zhou et al., 2006), with only a small amount of granites from Hainan (267–262 Ma, Li et al., 2006) and rare basalts from southwestern Fujian (Early Carboniferous, Huang, 1982). This result leads us to question where the magmatism has occurred. The Early Permian paleogeographic maps of South China (Chen et al., 1994; Liu and Xu, 1994; Wang and Jin, 2000) show that the land was situated in the eastern and northern parts of the Cathaysian block during this period, and the west Cathaysian block was covered by a widespread sea (Grabau, 1924; Chen et al., 1994; Liu and Xu, 1994; Wang and Jin, 2000). Therefore, we speculate that the Carboniferous–Early Permian magmatism as well as the source area of sandstones located either northern or eastern side of the depositional area.

The εHf(t) values of the Carboniferous–Early Permian zircons varies greatly from ~34.3 to ~3.1, indicating mixed sources of old Precambrian basement and juvenile crust material (Fig. 11). Thus, the tectonic setting in the source area should account for continuous magmatism and magmatic mixing. Two possibilities may be considered: rifting-related magmatism or subduction-related magmatism. Geologically, the South China block experienced extensional rifting during late Paleozoic (Zeng et al., 1993; Zhao et al., 1996). Those volcanic clastics can come from rifting-related volcanic rocks near the Fuding inlier. Meanwhile, the possibility of subduction-related magmatism cannot be ruled out. Mesozoic igneous activity in east Cathaysia was suggested to be related to the initiation and activation of subduction of the Pacific Ocean lithosphere (Gilder et al., 1996; Wang and Zhou, 2002). Unfortunately, little is known about when Pacific Ocean lithosphere began to be subducted under the Asian continent. As a lack of geochemical and isotopic data from these volcanic grains in the sandstones, we cannot confirm the tectonic setting in the source area.

6.4. Relationships with the Yeongnam massif in the Korean Peninsula and the Tananao metamorphic complex in the Taiwan

The Korean Peninsula can be subdivided into five tectonic units or terranes (Fig. 1). From the south to the north, these are: Yeongnam massif, Ochcheon (Ogcheon) Belt, Gyeonggi (Kyonggi) massif, Imjingang Belt and Namgrim massif/Pyeongnam basin (Chough et al., 2000). The Qinling–Dabei–Sulu Belt, which represents the suture between South China and North China (Yin and Nie, 1993), extends into Korea either along the Imjingang Belt (Ree et al., 1996) or the Hongseong–Odesan
belt within the Gyeonggi massif (Oh et al., 2005; Kim et al., 2011a, b). The southernmost terrane, the Yeongnam massif, is mostly correlated with the Cathaysian block (Metcalfe, 2006). Recently, Yu et al. (2009, 2011) found that the Yeongnam massif shares similar geological features with the Wuyishan terrane, such as: 1) Paleoproterozoic magmatism at 1.91 to 1.83 Ga, which appears in the Wuyishan terrane as well as in the Yeongnam massif (Chough et al., 2000; Lee et al., 2000; Sagong et al., 2003); 2) basement rocks in both areas have similar Nd model ages of 2.75 to 2.84 Ga (Lee et al., 2000; Sagong et al., 2003); and 3) Triassic medium- to high-grade metamorphism and granitic magmatism are widely distributed in both terranes (Wang et al., 1995). All of these observations suggest that the crustal evolution of the Yeongnam massif is comparable with the Wuyishan terrane of the Cathaysian block from the Paleoproterozoic up to the Triassic.

Interestingly, the Early Permian clastic rocks in the Fuding inlier show similar geological features to the Early Permian strata in the Taebaeksan basin, located between the Gyeonggi and Yeongnam massifs in South Korea. Detrital zircon ages from the Manhang Formation (Carboniferous–Early Permian) show two main age clusters at 288–358 Ma and 1.78–1.81 Ga, respectively, with major peaks at 305 Ma and 1.87 Ga (Li et al., 2009). The detrital zircon age distribution is very similar to that we have found in the Fuding inlier (Fig. 9), but different to the detrital zircons from the western Gyeonggi massif where have four major age components of ~2.5–2.4 Ga, 1.0–0.9 Ga, ~820–750 Ma, ~430 Ma (Cho et al., 2010) (Fig. 9). In addition, the detrital modes of the Lower Permian Jangseong Formation in the Taebaeksan basin (Lee and Sheen, 1998; Ko et al., 1999) are also similar to those in the Fuding inlier (Fig. 6a). Sandstones from both places comprises poorly sorted, angular to sub-rounded quartz and lithic fragments, without feldspar grains. The much greater proportion of lithic grains in the Early Permian sandstones in Fuding may be ascribed to different criteria in grain-counting. We count the microcrystalline felsic detritus as lithic grains whereas other researchers (e.g., Lee and Sheen, 1998) count as polycrystalline quartzes (Fig. 6b). Together, our data further support that Yeongnam massif was part of the Wuyishan terrane of the Cathaysian block and suggests that the Early Permian Taebaeksan basin of the Yeongnam massif and the Fuding inlier might be connected and share the same sources (Fig. 13).

The pre-Cenozoic Tananao metamorphic complex in the Central Range of Taiwan consists of voluminous schist and marble as well as of scattered bodies of granitic rocks and amphibolite. A few fusulinids and corals, possibly of the Late Permian age (Yen, 1953), and Jurassic–Early Cretaceous dinoflagellates (Chen, 1989) were discovered from the Tananao Complex. U–Pb zircon dating of meta-granites and gneisses show two stages of magmatism at 190 to 200 Ma and 85 to 90 Ma (Jahn et al., 1986; Yui et al., 2009). The Tananao complex was considered to represent an exposed portion of the Asian continental crust (Ho, 1986), with rocks originating from the Permian to Cretaceous periods, and exhumed during late Cenozoic arc-continent collision (Beyssac et al., 2007). Recently, Lan et al. (2009) reported detrital zircons older than 2.3 Ga from the Tananao complex and Eocene rocks of the Central Range of Taiwan and documented a major age group of 2.3 to 2.6 Ga (Fig. 11). Both the age population and Hf isotopic compositions of those detrital zircons are very similar to the Paleoproterozoic to late Neoarchean zircons from the Wuyishan terrane (Figs. 9 and 11). Considering that Permian fusulinids and corals and similar 2.3–2.6 Ga detrital zircons were found in the Tananao complex, we speculate that at least the Late Paleozoic part of the Tananao complex may have been the eastern part of the Cathaysian block during the Permian period (Fig. 13).

7. Conclusion

Field investigation, petrological, sedimentological and geochronological studies identified three lithostratigraphic units in the Fuding inlier, which is located in the northern Fujian province of China. The Upper Carboniferous carbonate rocks are composed of silicified
micocrystalline limestone, bioclastic limestone and oolitic limestone, which were deposited on shallow carbonate shelf and in carbonate shoal environments. The Lower Permian siliciclastic unit is comprised of black organic-carbon-enriched slate, slaty slate and phylite, which are occasionally interbedded with lithic arenites and micocrystalline limestones. This sequence was deposited on moderately deep, semi-restricted shelf and in prodelta environments, with high surface bioproductivity. Jurassic coarse clastic rocks, represented by a suite of conglomerates and coarse-grained sandstones, were deposited in fluvial or alluvial fan environments.

The Nd isotopes and detrital zircon U–Pb–Hf isotopes indicate that the late Paleozoic Fuding inlier was part of the Wuyishan terrane of the Cathaysia continental block. A group of detrital zircons from sandstones shows that the main age peak extends from approximately 280 to 360 Ma, indicating prolonged magmatic activity in the source area through the Carboniferous to Early Permian. The εHf(t) values of these zircons vary from −34.3 to −3.1, suggesting mixing of the magma sourced from juvenile material and melted Precambrian basement rocks.

The similarities in the rock compositions and the detrital zircon ages among the Yeongnam massif in the Korean Peninsula, the Tananao complex in Taiwan and the Fuding inlier have led us to conclude that all three regions were likely part of the Wuyishan terrane, Cathaysia block during the late Paleozoic.

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Appendix A. Supplementary data

Appendix A GPS points in the Fuding inlier.
Appendix B The detrital modes of the Lower Permian sandstones from the Fuding inlier.
Appendix C Sm-Nd isotopic compositions of the Lower Permian slates from the Fuding inlier.
Appendix D Detrital zircon U–Pb isotope data measured by LA-ICPMS from the Fuding inlier.
Appendix E Detrital zircon Hf-isotope data measured by MC-LA-ICPMS from the Fuding inlier.

Supplementary data to this article can be found online at doi:10.1016/j.gr.2011.09.016.

References
