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Resolved the Tectonic Setting of South China in the Late Paleozoic

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Abstract

The tectonic setting of South China during the late Paleozoic is essential to understanding the geodynamics of the eastern margin of Pangea supercontinent due to its unique paleo-position at the confluence of the Paleo-Tethys and Panthalassic oceans. Limited late Paleozoic magmatic and metamorphic records in South China have hampered resolution of this tectonic setting. Here, we present integrated biostratigraphic, geochronological, and isotopic geochemical data on the late Carboniferous siliciclastic rocks from southeast South China in order to decipher the tectonic evolution of the South China Block. The sandstones were predominantly sourced from the Wuyi Terrane via short-distance transportation. Rapid exhumation of ca. 318 Ma plutonic rocks in the source region, evolution of source of magmatism, and continuous crustal thinning demonstrate that southeast South China underwent episodic lithospheric delamination triggered by thermal perturbation as a result of subduction of the paleo-Pacific plate beneath the South China Block in the late Paleozoic.

Plain Language Summary

The South China Block, composed of the Yangtze and Cathaysia blocks, lay off the eastern edge of Pangea supercontinent during the late Paleozoic, drifting in isolation near the paleoequator until eventually amalgamated with the North China Block in the Permian-Triassic. Widespread carbonate platform sedimentation and the absence of significant contemporaneous magmatic, structural, and metamorphic records are collectively interpreted to indicate a stable passive continental margin setting. Recently, abundant late Paleozoic detrital zircons have been reported from Permian-Triassic siliciclastic rocks in southeast South China. Here we carried out an integrated biostratigraphic, detrital zircon geochronological and Hf isotope geochemical study on a late Carboniferous succession in South China. Our fusulinid biostratigraphy and ages of youngest detrital zircons suggest rapid exhumation of plutonic rocks of ca. 318.5 ± 6.8 Ma. Besides, the Cathaysia Block underwent a continuous thinning and two distinct tectono-thermal events at 370 and 335 Ma. Hf isotopic data suggests a trend of lesser contribution of melts from younger crust for middle-late Paleozoic magmatisms. We propose that the southeastern South China underwent episodic lithospheric delamination triggered by thermal perturbation as a result of subduction of the paleo-Pacific plate beneath the South China Block in the late Paleozoic.

1. Introduction

The late Paleozoic was a dynamic and crucial time in the evolution of the Earth system. It is characterized by the assembly of supercontinent Pangea (Metcalfe, 2013; Stampfli et al., 2013), superplume activities embodied by the Skagerrak-Centered large igneous province (LIP), Tarim LIP, and Panjal traps (Shellnutt, 2018; Torsvik et al., 2008; Xu et al., 2014), the longest-lived icehouse of the Phanerozoic (Isbell et al., 2003; Montañez & Poulsen, 2013; Rosa & Isbell, 2020), and significant perturbations in biodiversity and major extinctions (Chen et al., 2022; Erwin, 1994; Fan et al., 2020). During the late Paleozoic, the Alleghanian-Ouachita, Variscan, and Urals orogenic belts formed by collisions between Gondwana and Laurussia, and between East European craton and the Asian collage of terranes (Figure 1b) (Berzin et al., 1996; Cawood & Buchan, 2007; Stampfli et al., 2013). Meanwhile, the Panthalassa-Pacific ocean system encircled Pangea with subduction zones (Collins et al., 2011) linked to three accretory orogens: the Terra Australis Orogen (Cawood, 2005), Central Asian Orogenic Belt (Jahn et al., 2004), and Cordilleran accretionary orogens (Colpron et al., 2009; Domeier & Torsvik, 2014; Gutierrez-Alonso et al., 2008).
Subsequent to the opening of the Paleo-Tethys Ocean in the Early-Middle Devonian, the South China Block was drifting in isolation near the paleoequator until eventually amalgamated with the North China Block in the Permian-Triassic (Metcalfe, 2013; Shu et al., 2021). During the late Paleozoic, the South China Block lay off the eastern edge of Pangea supercontinent (Scotese, 2016) with widespread carbonate platform sedimentation, and the absence of significant contemporaneous magmatic, structural and metamorphic records was interpreted to indicate a stable passive continent margin setting (Feng et al., 1999; Liu and Xu, 1994; Shu et al., 2021). Notably, however, abundant late Paleozoic detrital zircons were reported from Permian-Triassic siliciclastic sedimentary rocks in southeastern South China (the lower Yangtze region) (Hu et al., 2012, 2015, 2017; Li et al., 2012, 2020).

Three tectonic models are invoked to account for this change in the rock record: (a) a tectonic shift from the passive continental margin in the Carboniferous to a convergent margin in the early Permian (Li et al., 2020; Shen et al., 2018); (b) an active convergent plate margin throughout the late Paleozoic (Hu et al., 2021); and (c) a rifting-related tectonic setting (Zhao et al., 1996). Although some Paleozoic continental fragments along the margin of East Asia (e.g., Japan and Khanka) are recently hypothesized to be linked with the South China Block, suggesting a prolonged subduction since the early Paleozoic (Aoki et al., 2015; Isozaki, 2019; Isozaki et al., 2014, 2015; Sakashima et al., 2003; Yamamoto et al., 2022), the tectonic setting and evolution of southeast South China during late Paleozoic still remain unresolved.
The controversial understanding of the tectonic setting in the southeastern South China in the late Paleozoic primarily centered around the interval of the late Carboniferous, which was a critical transition as to the shift of the tectonic regime. However, limited occurrences and studies of late Carboniferous siliciclastic rocks hamper further understanding of the tectonic setting and paleogeographic evolution of South China in the Late Paleozoic. In this paper, we carried out an integrated biostratigraphic, detrital zircon geochronological and Hf isotope geochemical study on the late Carboniferous Outangdi (OTD) succession in Zhejiang Province, South China (Figure 1a), aiming to disentangle the enigmatic tectonic setting of southeastern South China in the Late Paleozoic. Integration with previously published data supports a protracted convergent plate margin setting through the late Paleozoic.

2. Geological Background

The South China Block formed by amalgamation of the Yangtze Block to the northwest and the Cathaysia Block to the southeast along the Jiangnan Orogen during the early Neoproterozoic (Cawood et al., 2020; Zhao and Cawood, 2012). The Jiangnan-Shaoxing fault zone (Figure 1a) marks the western margin of the Cathaysia Block (Yao et al., 2019). Compositions of South China’s crystalline basement have been provided in Supporting Information S1.

During the Phanerozoic, the South China Craton underwent three main tectonothermal events, leading to regional angular unconformities in both Cathaysia Block and the adjacent regions of the Yangtze Block. The mid-Paleozoic Kwangsian orogeny is characterized by voluminous S-type granites peaking at 456–419 Ma (Shu et al., 2015). The early Mesozoic Indosinian orogeny is also associated with the emplacement of extensive S-type granites, dated at 250–200 Ma (Shu et al., 2015; Wang et al., 2007; Zhou et al., 2006). The late Mesozoic Yanshanian Movement predominantly affected southeastern South China Block, and generated widespread magmatic rocks (Charvet et al., 1994; Gilder et al., 1996). Late Paleozoic igneous rocks have so far only been documented in three areas (Figure 1a): Daixi-Wufenglou granites (317 ± 3 Ma) in northern Fujian Province (Shen et al., 2018), Wuzhishan orthogneiss (267–262 Ma) on the Hainan Island (Li et al., 2006), and Tieshan alkaline syenite (ca. 254 Ma) in western Fujian Province (Wang et al., 2005). After the early Paleozoic Kwangsian orogeny, eastern South China gradually translated from terrigenous/marine clastic lithofacies to carbonate platform deposits till the Early Permian (Feng et al., 1996; Zhou et al., 2017).

The Carboniferous-Permian strata in Jiangshan, Zhejiang Province (Figure 1a) consist of, in ascending order, the Yejiatang, OTD, and Chuanshan formations, and unconformably overlie the late Ordovician Changwu Formation (Guo, 1993). The early Carboniferous Yejiatang Formation is predominantly composed of sandy conglomerate, sandstone, muddy siltstone, and shale, which formed in fluvial environments. The late Carboniferous OTD Formation is a mixed carbonate-siliciclastic sedimentary succession, composed of dolostone, bioclastic limestones, sandy conglomerate, sandstone, and mudstone/shale, which formed in a coastal marine environment. The latest Carboniferous-Early Permian Chuanshan Formation consists mainly of thick-bedded lime mudstone and bioclastic wackestone, which was deposited on a shallow marine carbonate platform.

3. Material and Methods

We measured a 50 m-thick succession of the OTD Formation in the OTD section in Jiangshan, southwestern of Zhejiang Province (Figure 1a). The succession consists dominantly of medium-to thick-bedded dolostones, thin-to thick-bedded limestones and medium to very coarse sandstones, and several layers of paleosols (Figures 1c and 1d). A total number of 19 limestone samples were collected, and 133 slices of thin section were made for fusulinid biostratigraphy. We collected three siliciclastic samples from the section at stratigraphic heights of 0.6 m, and 26 m (Figure 1c). Sample OTD-0.6 is a light gray, medium, calcareous sandstone, containing 80% quartz, 15% limestone lithic fragments, and 5% feldspar. Sample OTD-16 is a light gray, coarse sandstone, containing 85% quartz, 10% feldspar, and 5% lithic fragments (Figure 1e). Sample OTD-26 is a gray, coarse sandstone, containing ~90% quartz, 5% feldspar, and 5% lithic fragments. Detailed methods and analytical procedures for zircon U-Pb geochronology and Hf isotope geochemistry are provided in Supporting Information S1.
4. Results

Sample OTD-0.6 yields 97 concordant U-Pb zircon ages ranging from 2,670 to 322 Ma, with over 90% of the grains younger than 1,000 Ma. The age spectrum mainly consists of four age clusters with age peaks at 340, 445, 700, and 855 Ma (Figure 2a).

Sample OTD-16 yields 114 concordant U-Pb zircon ages, ranging from 2,441 to 307 Ma, with over 94% grains younger than 1,000 Ma. The age spectrum consists of four age groups with peaks at 335, 460, 660, and 840 Ma (Figure 2b).

Sample OTD-26 yields 113 concordant U-Pb zircon ages ranging from 2,302 to 330 Ma, with over 95% of detrital zircons younger than 1,000 Ma. The age spectrum shows mainly three age populations with peaks at 450, 830, and 935 Ma, with a subordinate group of age ca. 374–330 Ma (Figure 2c).

Three sandstone samples yielded 187 $\varepsilon$Hf(t) values for detrital zircons with ages between 307 and 1,000 Ma. For zircons of Precambrian age, their $\varepsilon$Hf(t) values predominantly range between −21 and +4. The Paleozoic detrital zircons are characterized by $\varepsilon$Hf(t) values ranging between −16 and +5. Notably, there is a clear decline trend in the maximal $\varepsilon$Hf(t) values from ca. +5 in the early Paleozoic to ca. −10 in the late Carboniferous (Figure 2d).

A total of 28 fusulinid species are discovered in depth from −9.0 to 27.0 m in the OTD section. They are the common elements from the upper Kashirian to Myachkovian substages in the Eastern European Platform and the corresponding strata in South China (Ueno, 2021). The detailed distribution of fusulinid fossils are exhibited in Figure S3 of Supporting Information S1. This fauna mainly constrains a depositional time of middle to late Moscovian (late Kashirian to Myachkovian substages; ca. 310–307 Ma) for the OTD succession (Figure 1c).

5. Discussion

5.1. Provenance

The three samples from the OTD Formation have overall similar zircon U-Pb age spectrums. They comprise four major age clusters, peaked at ca. 850, 680, 445, and 340 Ma, with two subordinate clusters peaked at ca. 940 and 370 Ma. Sporadic pre-Neoproterozoic zircon grains are also present in the samples.

The cluster of zircon grains aged 460–430 Ma accounts for a proportion of detrital zircons up to 45% in the sample OTD-26. These grains are euhedral to subhedral in shape, suggesting a short-distance transport. Rocks with ages of ca. 460–430 Ma are widely exposed in the Wuyi and Nanling-Yunkai terranes that formed during the Kwangsian Orogenesis (Li et al., 2010; Xu et al., 2016). Therefore, these early Paleozoic zircon grains were most likely ultimately sourced from the Kwangsian granites to the southeast.

Detrital zircons with ages of ca. 370 Ma were found in all the samples. Most of these zircon grains are euhedral (see Figure S2 in Supporting Information S1), indicative of short-distance transport. Detrital zircons of this age have been widely reported in Permian-Triassic sedimentary strata in the eastern South China (Hu et al., 2012, 2015; Li et al., 2012, 2020). No magmatic rocks of similar age have been reported in the Cathaysia Block, however these detrital zircons were most likely derived from the southeast of the Cathaysia Block (Hu et al., 2015).
The youngest detrital zircon cluster of 340–310 Ma consists mostly of euhedral grains. Although widespread late Paleozoic detrital zircons were reported in the eastern South China Block (Hu et al., 2015, 2017; Li et al., 2012, 2020), large-scale magmatism or metamorphism has not been documented. The only Carboniferous magmatic record is the Daixi-Wufenglou granite on the eastern part of South China (Shen et al., 2018), having a crystallization age of about 317 ± 3 Ma. Hence, we suggest that the Daixi-Wufenglou granite and coeval igneous rocks in the eastern South China Block could have provided detritus for the late Carboniferous OTD succession.

See Supporting Information S1 for the provenance analysis of the Precambrian detrital zircon grains. In summary, the late Carboniferous siliciclastic rocks in the OTD section were sourced primarily from the Wuyi Terrane to the southeast via a short-distance transport.

5.2. Tectonic Evolution

Fusulinids biozones give a depositional time of middle to late Moscovian (ca. 310–307 Ma) for the OTD succession. Meanwhile, 10 grains of the youngest detrital zircon ages of all the analyses of OTD samples yield a weighted mean age of 318.5 ± 6.8 Ma (MSWD = 0.4, n = 10; Figure 3a). Consequently, the time difference of the youngest detrital zircons crystallization age and the depositional age of OTD succession is within ca. 15 Myr, and such a rapid exhumation of ca. 318 Ma plutonic rocks suggests an active tectonic setting during late Carboniferous (Spencer et al., 2019). The difference between the crystallization and depositional ages of the detrital zircons can reflect the tectonic setting of the basins in which sediments are deposited (Cawood et al., 2012). For the late Carboniferous detrital zircons, cumulative proportions of CA – DA < 100 Ma and CA – DA < 150 Ma are 15.8% and 29.2%, respectively, which are both plotted in the field of collisional basins (i.e., basins formed during and after continental collision) (Figure 3b; Cawood et al., 2012). Given that the detrital zircon age population of ca. 445 Ma makes a significant contribution to our data falling in the field of collisional basin (see B in Figure 3b), it most likely reflects a tectonic setting of collapse of the Kwangsian orogen.

The internal structures of these grains revealed by cathodoluminescence (CL) imaging have clear magmatic oscillatory zoning and inherited cores, suggesting a crustal reworking origin (Wang et al., 2012). Rare earth element and trace element concentrations of youngest zircons indicate an S-type granitoid origin and an arc-related/orogenic setting (Plots are provided in Figure S3 of Supporting Information S1), which is consistent with the tectonic model based on a geochemical study of the late Carboniferous (317 ± 3 Ma) Daixi-Wufenglou granite (Shen et al., 2018).

We compile U-Pb ages and εHf(t) values of detrital zircons from the Devonian to Triassic sediments of the eastern South China (Hu et al., 2012, 2015; Li et al., 2012, 2020) as well as the data from this study (Figures 3c and 3d) in order to reveal tectonothermal events and corresponding magma sources during the Paleozoic. The εHf(t) values of Paleozoic detrital zircons exhibit an overall decrease trend during the interval from 450 to ca. 310 Ma and a subsequent rapid increase trend (Figure 3d). The distinct decreasing trend of maximal εHf(t) value from the early Paleozoic to the Late Carboniferous (Figures 2 and 3d) suggest that a lesser contribution of melts from the younger crust for magmatisms during the middle to late Paleozoic. On the contrary, the minimal εHf(t) value disclosed an abrupt increase at around 335 Ma, which suggests a significant decrease of melts from ancient crust for magmatisms of ca. 335 Ma. Integrated with published detrital zircon ages and εHf(t) values, a more detailed process can be depicted as follow. Detrital zircons of ca. 445 Ma, with εHf(t) values between −20 and +14, derived from granites formed during the Wuyi-Yunkai Orogeny in southeastern China (Li et al., 2010). Two-stage Hf model ages (T∗DM) of zircons aged 445 Ma suggest that the host magma of these zircons was derived from late Neoproterozoic (close to depleted mantle) to late Paleoproterozoic crustal materials, which is supported by a detailed zircon Hf and O isotopic study of these zircons (Li et al., 2012). Zircons of ages peaked at 370 Ma have εHf(t) values of −23–+8.5, suggesting that crystals were derived from melts by reworking early Neoproterozoic to early Paleoproterozoic crustal rocks. Coincidentally, Li et al. (2012) suggested that these zircons were crystallized from melts by reworking supracrustal sediments (e.g., the Badu Complex and Mayuan Group Paleoproterozoic metasedimentary rocks) and preexisting mantle-derived igneous rocks (ca. 0.8 Ga crust; Figure 3d).

The zircon age group of 340–310 Ma (peaks at 335 Ma) also exhibits a minor peak in εHf(t) values (Figure 3d). Remarkably, these zircons (peaks at 335 Ma) have a narrow range of εHf(t) values (−13.5—−2.5), predominantly crystallized from melts by reworking the late Paleoproterozoic crust without contribution from preexisting
mantle-derived igneous and the early Paleoproterozoic supracrustal materials. A detailed geochemical study of the Daixi-Wufenglou granite (317 ± 3 Ma) suggests an origin of partial melting due to an input of mantle-derived heat (Shen et al., 2018). Given that the juvenile crust or preexisting mantle-derived igneous rocks situated at the bottom of continental crust (e.g., Chu et al., 2020), the evolution of magma source for magmatisms from the early

Figure 3. (a) Weighted mean age of 10 youngest detrital zircons and zircon CL imaging of six typical grains from the OTD section (this study). Yellow circles and red circles are zircon U-Pb age and Hf isotope analysis spots, respectively. The values in black brackets are εHf(t) values. (b) Discrimination diagram of tectonic settings (modified after Cawood et al., 2012). The two red stars represent cumulative proportions at CA-DA = 100 and CA-DA = 150 Ma from this study. (c) Compiled detrital zircon age spectrum and (d) detrital zircon εHf(t) values of Devonian to Triassic sediments in South China (black dots from this study; gray dots from Hu et al., 2012; Li et al., 2012; Li et al., 2017, 2020), showing three tectonothermal events (blue shades) and the evolution of their corresponding magma sources during the Paleozoic. Dotted green lines are crustal evolution lines of different ages. The two red lines with arrows demonstrate the evolution trend of magma source. (e) Reconstructed crustal thickness of southeastern South China from 500 Ma to 310 Ma based on a zircon Eu/Eu*-based proxy (Tang et al., 2020, 2021) of detrital zircons from this study, showing a largely thickening trend from 500 to 445 Ma (rising arrow) and a thinning trend from 445 to 310 Ma (declining arrow).
Paleozoic to the late Carboniferous depicted a prolonged process of crust delamination (Figure 4). Hence, we suggest that the magmatism peaked at 335 Ma was likely triggered by the thermal perturbation associated with delamination of the preexisting mantle-derived crustal material and the late Paleoproterozoic supracrustal rocks, which was a continuation of the earlier delamination at 370 Ma (Figure 3d). Besides, there are two facts that laid the foundation for the delamination processes: (a) the thickened crust of the Cathaysia Block during the early Paleozoic Kwangsian orogeny and (b) the thermo-mechanic erosion of lithospheric mantle caused by the persistent subduction of the paleo-Pacific oceanic plate underneath the southeastern margin of South China during the middle to late Paleozoic.

Zircons of ca. 290 Ma display a distinct rise in $\varepsilon$Hf($t$) values ($-21$ and $+15$), suggesting a binary mixing of melts extracted from continental crustal rocks and depleted mantle sources. In addition, detailed zircon Hf and O isotopes (Li et al., 2012) and grain framework composition of the lower Permian sandstone (Hu et al., 2012; Li et al., 2020) suggest the existence of a continental arc along the southeastern South China.

In order to further explore the evolution history of the Cathaysia Block from 500 to 310 Ma, crustal thickness was estimated using a zircon Eu/Eu*-based empirical equation (Tang et al., 2020, 2021). It is clearly shown that the maximal crustal thickness underwent a continuous thinning process from about 85 km at ca. 445 Ma to about 50 km at ca. 310 Ma (Figure 3e), consistent with the delamination processes revealed from the zircon $\varepsilon$Hf($t$) values (Figure 3d). Additionally, lithospheric delamination of the Kwangsian orogen in South China at ca. 435 Ma has been recognized (Yao et al., 2012), which probably marked the initiation of crustal thinning after the Kwangsian orogeny.

Proto-Japan arc was hypothesized to be attached to the South China margin, based on the comparable age peaks and $\varepsilon$Hf($t$) value ranges between Precambrian detrital zircons of Silurian to Cretaceous siliciclastic rocks in Tohoku, Japan, and the provenance from the South China Block (Cawood et al., 2018; Pastor-Galán et al., 2021). A long-lived subduction system in Japan has initiated at least since 500 Ma (Isozaki et al., 2010); and three significant tectonothermal events have been identified, taking place at 430 ± 20, 360 ± 10, and 270 ± 20 Ma during the Paleozoic (Pastor-Galán et al., 2021), which are coincident with the archive of the Paleozoic magmatic activities in South China (Figure 3c). Hence, our study further supports the hypothesis of “Greater South China” (Isozaki, 2019; Isozaki et al., 2014, 2017) from the perspective of southeast South China. Taken together, we suggest that the magmatisms that occurred at ca. 370 and 335 Ma in southeastern South China were originated from thermal perturbation associated with delamination, which was probably caused by slab roll-back (e.g., Pastor-Galán et al., 2021) during the subduction of the paleo-Pacific plate beneath the South China Block (Figure 4). Subsequent isostatic adjustment led to rapid exhumation of granites (e.g., Daixi-Wufenglou granite),
extensional tectonic regime, and a more gentle landscape, which paved the way for shedding continental arc detritus into inner basins on southeastern South China in the Early Permian (ca. 290 Ma).

6. Conclusions

We draw the following conclusions based on the biostratigraphic framework, geochronological and geochemical analyses of detrital zircons from the late Carboniferous sandstones in the southeastern South China.

The late Carboniferous siliciclastic rocks in the OTD section were sourced primarily from the Wuyi Terrane by a short-distance transport. The provenance comprises of the early Paleozoic granites (peaks at ca. 445 Ma) formed in the Kwangsian orogeny, the late Paleozoic magmatic rocks (peak at and 370 and 335 Ma) emplaced in the Wuyi Terrane, and the Precambrian strata in the Cathaysia Block, which contains zircons of ages peaking at ca. 940, 850, and 670 Ma.

Rapid exhumation of plutonic rocks of ca. 318.5 ± 6.8 Ma and relatively extensional tectonic setting in the southeastern South China in the late Paleozoic were attributed to lithospheric delamination. The ca. 370 and 335 Ma magmatisms in southeast South China were triggered by thermal perturbation associated with delamination during the subduction of the paleo-Pacific plate beneath the South China Block.

Crustal thickness of the Cathaysia Block underwent a continuous thinning process from about 85 at ca. 445 to about 50 km at ca. 310 Ma. Due to isostatic adjustment and erosional pediplanation, the Kwangsian orogenic highlands were denudate, which eliminated the barrier for shedding continental arc detritus into inner basins on southeastern South China in the Early Permian.

Data Availability Statement

Supporting figures and data tables are provided in Figure S1–S3 of Supporting Information which have been uploaded in the repository Dryad (https://doi.org/10.5061/dryad.5x69p8d66).

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