

# Appalachian-style multi-terrane Wilson cycle model for the assembly of South China

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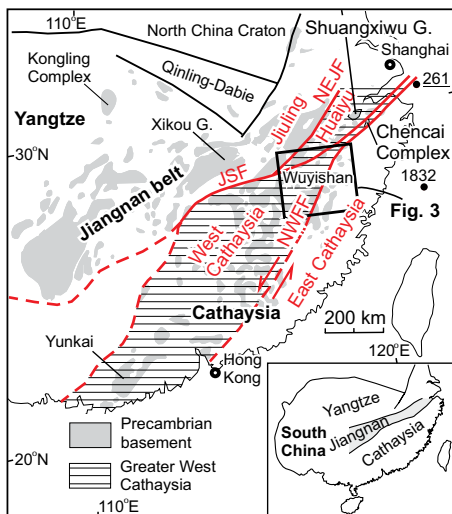
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## ABSTRACT

The evolution of South China involved accretion-collision of multiple terranes from the Proterozoic to the Mesozoic. Zircon U-Pb ages, Hf data, and structural data indicate that the Cathaysia block consists of two terranes, West Cathaysia and East Cathaysia, separated by a newly recognized major strike-slip fault. We propose that West Cathaysia was part of a microcontinent that originated from a Grenvillian-aged orogen in the Rodinia supercontinent, East Cathaysia originated from an Indosinian-aged orogen in the Paleo-Tethyan regime to the south and was translated to the east of West Cathaysia through strike-slip motion, and the early Paleozoic Wuyi-Yunkai orogeny was a result of direct collision of West Cathaysia with a yet-unidentified terrane that rifted away after the collision. We conclude that a multi-terrane Wilson cycle (multi-terrane accretion-collision, large-scale strike-slip motion, and separation of two terranes by post-collisional rifting along the suture zone) characterizes the history of South China and may be a common feature of orogens.

## INTRODUCTION

Wilson (1966) proposed a basic model for the tectonic history of eastern North America (Grenville and Appalachian orogens), involving



**Figure 1. Tectonic framework of eastern South China (modified from Cawood et al., 2013). NEJF—Northeast Jiangxi fault; JSF—Jiangshan-Shaoxing fault; NWFF—Northwest Fujian fault; G.—Group. Black numbers 261 and 1832 are U-Pb zircon ages (in Ma) (metamorphic and magmatic, respectively; see Data Repository [see footnote 1] for sources).**

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northeastern Jiangnan belt consists of two terranes (*sensu lato*), Jiuling and Huaiyu, separated by the Northeast Jiangxi fault (Fig. 1).

## Jiuling Terrane

The Jiuling terrane is characterized by a thick sequence of middle Neoproterozoic (ca. 850–825 Ma) turbidites and minor volcanic rocks (e.g., the Xikou Group) and includes the ca. 833 Ma Fuchuan ophiolite (e.g., Yin et al., 2013). These rocks are generally interpreted to have formed in an arc-back-arc system.

## Huaiyu Terrane

The Huaiyu terrane is characterized by a series of late Mesoproterozoic to early Neoproterozoic supracrustal rocks that are distinctly older than those in the Jiuling terrane (Fig. 2). Major units include (1) the Tieshajie Formation (Fig. 3), a ca. 1160 Ma continental rift sequence (Li et al., 2013); (2) the Tianli schist (Fig. 3), a Mesoproterozoic metasedimentary succession that was deformed and metamorphosed at ca. 1.0 Ga (Li et al., 2007); and (3) the Shuangxiwu Group (Fig. 1), a ca. 970–890 Ma juvenile arc sequence that was deformed and metamorphosed before ca. 850 Ma (Li et al., 2009). The terrane also contains ophiolite slivers, including the ca. 970 Ma Zhangshudun (Xiwan) ophiolite (Fig. 3) that was obducted at ca. 880 Ma (Li et al., 2008).

The Huaiyu terrane has been interpreted as part of a composite terrane that formed by the amalgamation of multiple terranes at ca. 1.0–0.88 Ga (Yin et al., 2013).

## Timing of Amalgamation of the Jiuling and Huaiyu Terranes

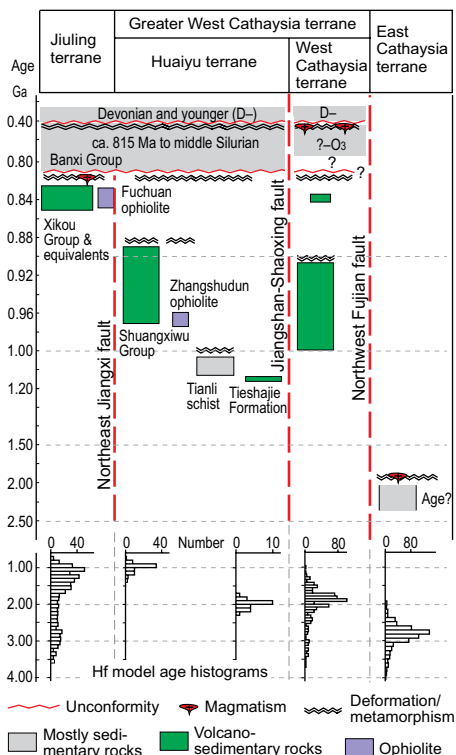
The pre-820 Ma units in both terranes are metamorphosed to greenschist facies and unconformably overlain by middle Neoproterozoic (815–750 Ma) (e.g., the Banxi Group) to middle Silurian cover (Fig. 2). This unconformity corresponds to the Jinning or Sibao orogeny, which was related to the amalgamation of the two terranes and the closure of the Jiuling back-arc basin (e.g., Yin et al., 2013).

progressive closing and reopening of oceans, that became known as the Wilson cycle. This model has since been refined using detailed evidence for multi-terrane accretion-collision and strike-slip faulting (e.g., van Staal et al., 2009; Lin et al., 2013).

South China is interpreted to have formed by the amalgamation of two blocks, Yangtze and Cathaysia (Fig. 1), but the proposed timing of amalgamation varies wildly, corresponding to various known tectono-thermal events, from Paleoproterozoic (Dong et al., 2015) to early Neoproterozoic (ca. 1.0–0.9 Ga, Grenvillian age; e.g., Li et al., 2007) to middle Neoproterozoic (ca. 820 Ma, Jinning or Sibao age; e.g., Zhao et al., 2011; Yin et al., 2013) to early Paleozoic (ca. 460–420 Ma; Caledonian age) to Mesozoic (ca. 250–230 Ma; Indosinian age). In this paper, we propose an alternative interpretation that is closer to the Wilson cycle. That is, South China formed by accretion-collision of multiple terranes, where each of the above tectono-thermal events corresponds to an accretional-collisional event and was modified by later rifting and large-scale strike-slip motion.

## YANGTZE BLOCK AND JIANGNAN BELT

The Yangtze block contains an Archean–Paleoproterozoic crystalline basement. Along its southeastern margin is a Neoproterozoic fold belt called the Jiangnan belt (or orogen) that is generally considered as the collision zone between the Yangtze and Cathaysia blocks. The



**Figure 2.** Summary of main characteristics of terranes of study area, South China. ?—O<sub>3</sub>—late Ordovician and older, base undefined. See Data Repository (see footnote 1) for sources for Hf data.

## CATHAYSIA BLOCK

The Cathaysia block is divided into two terranes, East Cathaysia and West Cathaysia, with contrasting geological histories (Figs. 2–4; see also Xu et al., 2007).

### West Cathaysia

The Precambrian basement in West Cathaysia consists of metavolcanic rocks of arc affinity (Cawood et al., 2013; Wang et al., 2014) and metasedimentary rocks, with dominantly

Neoproterozoic ages. They are intruded by early Paleozoic mostly felsic intrusions.

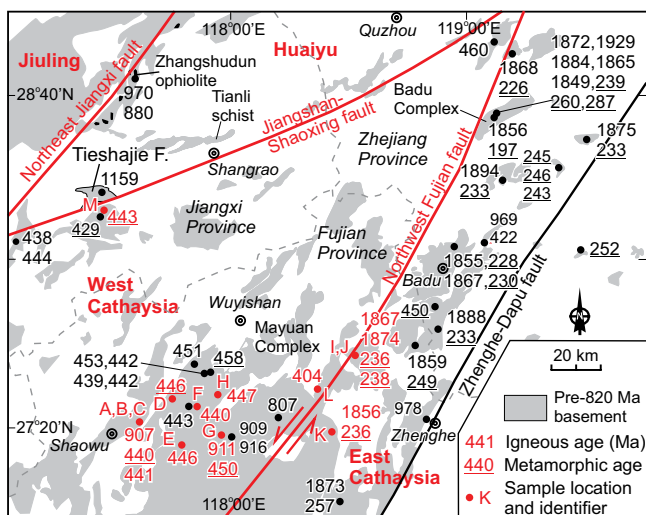
Ten new samples were collected from West Cathaysia for zircon sensitive high-resolution ion microprobe (SHRIMP) U-Pb geochronology and Hf isotope analysis. The results are summarized below and in Figures 3 and 4. More details are given in the GSA Data Repository<sup>1</sup>.

A pegmatite dike, a biotite gabbro, a two-mica granite, and a quartz diorite (samples C, E, F, and H, respectively) yield magmatic ages of  $441 \pm 3$  Ma,  $446 \pm 4$  Ma,  $440 \pm 2$  Ma, and  $447 \pm 4$  Ma, respectively. These magmatic ages are coeval with metamorphic ages of  $440 \pm 4$  Ma,  $446 \pm 6$  Ma,  $450 \pm 10$  Ma, and  $443 \pm 7$  Ma from two biotite gneisses, a felsic metavolcanic rock, and an amphibolite (samples A, D, G and M, respectively). A porphyritic granite (sample L) yields a younger age of  $404 \pm 2$  Ma. Gneissic melanosome and a felsic metavolcanic rock (samples B and G) yield magmatic ages of  $907 \pm 10$  Ma and  $911 \pm 7$  Ma, respectively, with evidence for a slightly younger metamorphic event present in some samples (e.g., sample B; see the Data Repository).

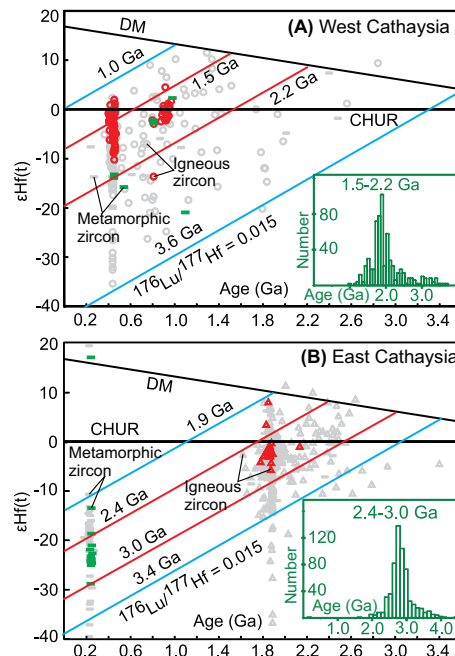
The new data, supplemented by previous results, indicate the following characteristics for West Cathaysia: (1) the Precambrian basement rocks were affected by a major magmatic and metamorphic event in the early Paleozoic (ca. 460–420 Ma), called the Wuyi-Yunkai or “Caledonian” orogeny (Li et al., 2010; Wang et al., 2013); (2) their protoliths mostly have ages between ca. 1.00 and ca. 0.91 Ga (Figs. 3 and 4; see also Wang et al., 2014); and (3) two-stage zircon Hf model ages ( $T_{MD2}$ ) cluster between 1.5 and 2.2 Ga (Fig. 4A).

The early Paleozoic metamorphism is characterized by clockwise pressure-temperature

<sup>1</sup>GSA Data Repository item 2018090, zircon U-Pb and Hf data from South China, is available online at <http://www.geosociety.org/datarepository/2018/> or on request from [editing@geosociety.org](mailto:editing@geosociety.org).



**Figure 3.** Simplified geological map of northeastern Cathaysia block, South China, showing terrane boundaries and new (red) and previous (black) U-Pb ages. See Data Repository (see footnote 1) for more information on ages.



**Figure 4.** Compilation of new (colored) and previous results of Lu-Hf analyses for zircons from West Cathaysia (A) and East Cathaysia (B), South China. Insets are histograms of two-stage Hf model ages of magmatic zircons. CHUR—chondritic uniform reservoir; DM—depleted mantle. See Data Repository (see footnote 1) for more information.

paths. Peak metamorphism reached upper amphibolite to granulite/eclogite facies (>1 GPa in metapelite; e.g., Zhao and Cawood, 1999), with associated partial melting.

### East Cathaysia

East Cathaysia consists of a series of meta-sedimentary and metaplutonic rocks. The former are likely a metamorphosed continental shelf sequence (Zhao et al., 2015a).

Zircon from three samples of monzonite gneiss, migmatite, and felsic metavolcanic rocks (samples I, J, and K, respectively) was dated during this study (Fig. 3), yielding similar upper and lower intercept ages at  $1867 \pm 7$  Ma and  $230 \pm 12$  Ma,  $1874 \pm 9$  Ma and  $243 \pm 3$  Ma, and  $1856 \pm 10$  Ma and  $236 \pm 8$  Ma, respectively. The lower intercept ages coincide with ages of  $236 \pm 3$  Ma,  $238 \pm 3$  Ma, and  $236 \pm 7$  Ma, respectively, of metamorphic zircon from the same samples. There is also evidence for a Paleoproterozoic metamorphic event, slightly younger than the magmatic zircon (e.g., samples I and K; see the Data Repository).

These results indicate two major tectono-thermal events: Paleoproterozoic (1.9–1.8 Ga) magmatism and metamorphism, and Mesozoic (ca. 250–230 Ma) metamorphism (see also Yu et al., 2009; Zhao et al., 2015a). Two-stage zircon Hf model ages ( $T_{MD2}$ ) cluster between 2.4 and 3.0 Ga (Fig. 4B). Detrital zircon records magmatic and metamorphic ages as old as ca. 4.1 Ga (Xing et al., 2015).

Mesozoic metamorphism ranges from amphibolite to granulite facies, with clockwise pressure-temperature paths and burial up to ~1 GPa (e.g., Yu et al., 2009; Wang et al., 2013).

### Boundary between West and East Cathaysia

Our data show that the boundary between West and East Cathaysia is not the Zhenghe-Dapu fault, as was generally believed (e.g., Xu et al., 2007). Our proposed boundary lies farther to the west and is marked by a major shear zone recognized during this study, here named the Northwest Fujian fault (Fig. 3).

The Northwest Fujian fault contains well-developed mylonite and abundant quartz and carbonate veins, with steep foliation and sub-horizontal lineations (Fig. 5). Deformation took place under greenschist-facies conditions, post-dating garnet growth (Fig. 5C) and the early Mesozoic peak metamorphism in East Cathaysia. Shear-sense indicators indicate sinistral followed by dextral strike-slip motion (Figs. 5A–5D).

## DISCUSSION

### Multi-Terrane Accretion-Collision Model for the Assembly of South China

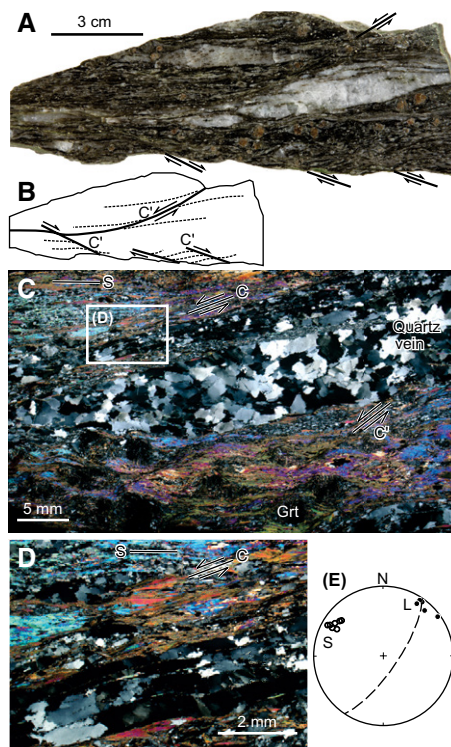
#### Neoproterozoic: “Grenvillian” and Jinning Orogenies

We propose that West Cathaysia and Huaiyu were part of a composite terrane (here named Greater West Cathaysia) that formed by the amalgamation of multiple terranes at ca. 1.0–0.88 Ga (the “Grenvillian” orogeny). Arc magmatism in the Shuangxiwu, Wuyishan, and Yunkai areas (Fig. 1), ca. 1.0–0.88 Ga metamorphism in the Tianli schist and the Wuyishan area, and emplacement of the Zhangshudun ophiolite (Fig. 3) were all related to the orogeny. It is likely that Greater West Cathaysia was a microcontinent that originated from a Grenvillian-aged orogen in the Rodinia supercontinent.

A collision between Greater West Cathaysia and the Yangtze block occurred along the Northeast Jiangxi fault/suture zone at ca. 820 Ma (the Jinning orogeny), following west-directed subduction that generated a ca. 850–825 Ma arc–back-arc system preserved in the Jiuling terrane (Figs. 6A and 6B).

#### Paleozoic: Wuyi-Yunkai Orogeny and Post-Collisional Rifting

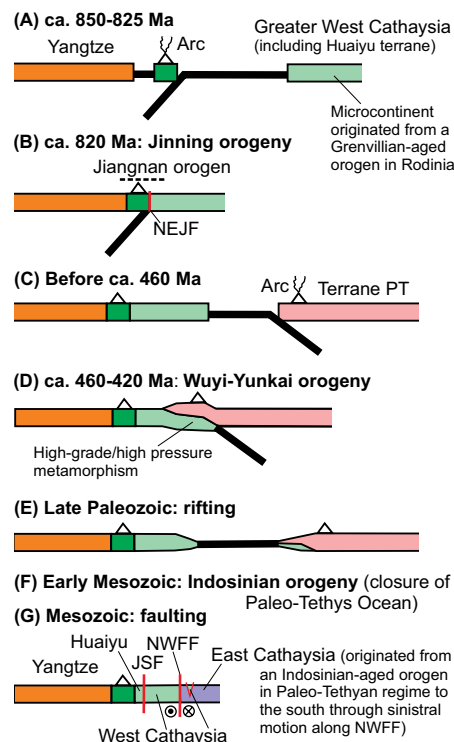
The early Paleozoic Wuyi-Yunkai orogeny was previously interpreted as an intraplate orogenic event (e.g., Li et al., 2010; Wang et al., 2013), presumably as a far-field reaction to a collision farther to the east (current coordinate). This interpretation was proposed mostly due to the lack of evidence for an early Paleozoic suture zone or magmatic arc in South China. However, it cannot readily explain the high-pressure metamorphism (>1 GPa, or burial to



**Figure 5.** Mylonites from Northwest Fujian fault, South China. A,B: Sample and sketch. See Figure DR4 in Data Repository (see footnote 1) for a field photo and enlargement of A. C,D: Photomicrographs. Note that a dextral shear band (C') overprints a sinistral one in A and B, and sinistral shear bands post-date garnet (Grt) growth in C. Also note the S-C structures in C and D. All surfaces are sub-horizontal. E: Projections of lineations (L) and poles to foliations (S).

>35 km depth) documented in West Cathaysia. Here we propose an alternative interpretation.

Considering the contrasting geological histories between West and East Cathaysia (Fig. 2), including evidence for the Wuyi-Yunkai orogeny in West Cathaysia and the lack of it in East Cathaysia (except in what is interpreted as fault slivers; see below), our data suggest that the two terranes were not amalgamated until the Mesozoic. This implies that (1) during the Wuyi-Yunkai orogeny, another geological terrane, referred to here as “terrane PT” (proposed terrane), was present to the east of what is now West Cathaysia, and (2) this terrane moved away after the orogeny and before and/or when East Cathaysia was amalgamated to the east of West Cathaysia. We suggest that the Wuyi-Yunkai orogeny was a result of West Cathaysia colliding directly with terrane PT. In this model, West Cathaysia was part of the downgoing plate (Figs. 6C and 6D), to explain its high-grade–high-pressure metamorphism, with associated syn-collisional magmatism. This interpretation is supported by the recent discovery of remnants of an early Paleozoic accretionary-collisional complex, including fault remnant arcs, within the Chencai Complex along the eastern margin of West Cathaysia (Fig. 1; e.g.,



**Figure 6.** Schematic diagrams showing proposed model for tectonic evolution of South China. Terrane PT—proposed terrane; NEJF—Northeast Jiangxi fault; JSF—Jiangshan-Shaoxing fault; NWFF—Northwest Fujian fault.

Zhao et al., 2015b). It should be noted that this interpretation was not a viable option until we concluded that East Cathaysia was not present to the east of West Cathaysia during the Wuyi-Yunkai orogeny (cf., Zhao and Cawood, 2012).

The eastern part of the Wuyi-Yunkai orogen, including the arc magmatic rocks and any potential ophiolite, and terrane PT are interpreted to have largely separated from West Cathaysia (and are thus not preserved in southern China) through rifting along the suture zone after the collision (Fig. 6E), most likely when South China rifted away from Gondwana in the late Paleozoic (Cawood et al., 2013, and references therein).

#### Mesozoic: Indosinian Orogeny and Strike-Slip Motion

In the early Mesozoic, closure of the Paleo-Tethys Ocean led to collisions to both northern and southern South China. East Cathaysia, characterized by a ca. 1.9–1.8 Ga and older basement and a major ca. 250–230 Ma high-grade metamorphism, may have originated from a resulting Indosinian-aged orogen situated to the south. It was translated into its present position with respect to West Cathaysia as a result of large-scale sinistral strike-slip motion along the Northwest Fujian fault (Fig. 1), and fault slivers of West Cathaysia occur in the area of East Cathaysia (Fig. 6G). The strike-slip motion along the fault may also have played a (potentially

significant) role in removing the eastern part of the Wuyi-Yunkai orogen (and evidence for the post-collisional rifting) from southern China.

Movement along the Jiangshan-Shaoxing fault divided Greater West Cathaysia into the lower-grade Huaiyu terrane and the higher-grade rocks of West Cathaysia (Fig. 6G).

### Similarity with Evolution of the Appalachian Orogen

The proposed model is similar in many ways to the evolution of the Paleozoic Appalachian orogen in North America. Here, multiple terranes accreted to the eastern margin of Laurentia from the Ordovician to Devonian (e.g., van Staal et al., 2009), preceding the Carboniferous Alleghenian continent-continent collision between Laurentia and Africa. Strike-slip motion along terrane-bounding shear zones also played a significant role (e.g., Lin et al., 2013). Both the Amazonian and African continents that collided with North America during the ca. 1.0 Ga Grenvillian and the Carboniferous Alleghenian orogenies, respectively, largely rifted away from Laurentia after each collision, leading to the opening of the Iapetus and Atlantic Oceans, respectively (Fig. DR5).

### CONCLUDING REMARKS

We conclude that a multi-terrane accretion-collision-separation model can readily explain the tectonic evolution of South China. In particular, we suggest the following:

(1) Greater West Cathaysia was a microcontinent that originated from a Grenvillian-aged orogen in the Rodinia supercontinent, and the ca. 1.0–0.9 Ga “Grenvillian” tectono-thermal event recorded in the terrane was related to the assembly of Rodinia, not to the assembly of South China.

(2) East Cathaysia originated from an Indosinian-aged orogen in the Paleo-Tethyan regime to the south and was translated to the east of West Cathaysia through large-scale strike-slip motion along the Northwest Fujian fault.

(3) The early Paleozoic Wuyi-Yunkai orogeny was a result of collision between Greater West Cathaysia and a terrane to the east (terrane PT) that moved away in the late Paleozoic (and Mesozoic?). Hence, the location of South China in, and thus the configuration of, Gondwana can be better constrained by locating the part of the early Paleozoic orogen (and terrane PT) that moved away from South China after the collision.

It should be noted that the recent discovery of evidence for a Pan-African orogeny in South China (Li et al., 2017) indicates the possibility for more terranes and more accretional-collisional events than presented in the current model.

Multi-terrane accretion-collision, large-scale strike-slip motion, and post-collisional separation of two terranes by rifting along the suture zone (a zone of inherent weakness due to post-collisional thermal weakening) appear to characterize the development of many, if not most, major orogens.

### ACKNOWLEDGMENTS

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