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Abstract: Together with the companion article dedicated to sedimentary geochemistry and clay mineralogy, this study investigates the interplaying controls on the generation and composition of river sediments across South China. In the Pearl River and southern Yangtze catchments, dominantly sedimentary and basaltic rocks of the Yangtze block shed quartzo-lithic sedimentary sand, whereas mostly granitic and sedimentary rocks of the Cathaysia block generate feldspatho-quartzose sand. Rivers of the Fujian and Zhejiang Provinces draining the SE Coast Magmatic Belt carry feldspatho-litho-quartzose volcaniclastic sand containing epidote with minor clinopyroxene and olivine locally. Within the Pearl River catchment, 35-40% of the sand is derived from the Yangtze block, and 60-65% from the Cathaysia block. Erosion rates are fairly evenly distributed across the basin, reaching higher values in the Hongshui headwaters where topographic relief is greater. South China hosts one of the largest and most spectacular karst areas on Earth, where two landscape types are characterized by different intensity of chemical dissolution. In fengcong (cone) karst, carbonate detritus attacked by carbonic and sulfuric acids is partly preserved, whereas carbonate grains are completely dissolved in fenglin (tower) karst developed in wetter regions to the east. The strong climatic gradient from the dry Tibetan plateau in the west to monsoon-drenched coastal areas is faithfully reflected in illite-rich vs. kaolinite-rich clay-mineral assemblages, but in sand the weathering effect is much harder to isolate from the dominant effects of source-rock lithology and recycling. The different durability of tectosilicates (quartz > microcline > orthoclase > plagioclase) or the degree of surficial corrosion displayed by heavy minerals offer complementary information but cannot represent robust proxies for weathering intensity. The sand generation index SGI reveals whether lithologies are under- or over-represented in detrital assemblages and proved to be most useful to trace different weathering regimes across South China.

Direct comparison between sand generated today in the Chinese mainland and Taiwan sandstones is prevented because of the diagenetically depleted mineralogical suite of the latter. The relative proportions of durable minerals, complemented by zircon-geochronology data, indicates that Neogene sandstones exposed in western Taiwan were principally fed by a paleo-Yangtze River.

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#### Research Data Related to this Submission

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There are no linked research data sets for this submission. The following reason is given:  
Data will be made available on request



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*To the Editors*

Dear Sirs,

we would like to submit the enclosed manuscript, entitled *Provenance versus weathering control on sediment composition in monsoonal subtropical climate (South China) - 2. Sand petrography and heavy minerals*” for publication in Chemical Geology. This manuscript is companion to the article entitled “*Provenance versus weathering control on sediment composition in monsoonal subtropical climate (South China) - 1. Geochemistry and clay mineralogy*”, submitted in March and currently under revision.

The two combined papers characterize quantitatively the petrography, mineralogy and geochemistry of sediments generated across southern China, from the Pearl River catchment and coastal rivers of the Fujian and Zhejiang Provinces to the southern tributaries of the Yangtze River. Our principal aim is to investigate the compositional modifications induced by superposed factors principally including source-rock lithology, chemical weathering, and recycling.

This second article dedicated to sand touches on critical aspects of sedimentary petrology, including the selective dissolution of carbonate grains in different types of karst terranes, the relative durability of detrital feldspars, as well as the controversial topic of complex dispersal pathways of detritus generated in mainland China and now incorporated in the Taiwan accretionary prism.

We will deeply appreciate critical comments from the Reviewers to improve on our manuscript, which is original and not being considered for publication elsewhere.

Sincerely yours,

Eduardo Garzanti (on behalf of all coauthors)

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Milano, 2<sup>nd</sup> June 2020

1 **Provenance versus weathering control on sediment composition in monsoonal**  
2 **subtropical climate (South China) - 2. Sand petrology and heavy minerals**  
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54 **Key Words:** Pearl River; southern Yangtze tributaries; Rivers of Fujian and Zhejiang Provinces;  
55 Provenance of Taiwan sandstones; Sediment budgets and erosion rates; Fengcong and fenglin karst;  
56 Dissolution of carbonate grains; Durability of detrital minerals; Cathaysia and Yangtze blocks.  
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3 mineralogy, this study investigates the interplaying controls on the generation and composition of  
4 river sediments across South China. In the Pearl River and southern Yangtze catchments,  
5 dominantly sedimentary and basaltic rocks of the Yangtze block shed quartzo-lithic  
6 sedimenta- clastic sand, whereas mostly granitic and sedimentary rocks of the Cathaysia block  
7 generate feldspatho-quartzose sand. Rivers of the Fujian and Zhejiang Provinces draining the SE  
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9 minor clinopyroxene and olivine locally. Within the Pearl River catchment, 35-40% of the sand is  
10 derived from the Yangtze block, and 60-65% from the Cathaysia block. Erosion rates are fairly  
11 evenly distributed across the basin, reaching higher values in the Hongshui headwaters where  
12 topographic relief is greater.  
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18 grains are completely dissolved in *fenglin* (tower) *karst* developed in wetter regions to the east. The  
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24 but cannot represent robust proxies for weathering intensity. The *sand generation index* SGI reveals  
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31 proportions of durable minerals, complemented by zircon-geochronology data, indicates that  
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1           ”It’s said that there was nothing there until a jewel merchant from across the sea dropped  
 2 the best of his pearls in the river ... It lay at the bottom, glowing like a lantern and slowly  
 3 growing larger until it grew into an island. And from then on that waterway became  
 4 famous as the Choo Kiang, or “Pearl River”.           *Amitav Gosh, River of smoke, ch. 13*  
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## 10 1 11 1 12 2 **1. Introduction** 13

14 3  
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 16 4 The compositional signatures of sand and sandstone are controlled primarily by the mineralogy of  
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 18 5 parent rocks and secondarily by a range of physical and chemical processes ([Johnsson, 1993](#); [Weltje](#)  
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 20 [and von Eynatten, 2004](#)). Because of nature’s complexity, there is little chance of finding simple  
 21 6  
 22 straightforward answers to geological problems if sand detrital modes are used without taking the  
 23 7  
 24 necessary care to detangle such an intricate system of interplaying factors ([Garzanti, 2016](#); [Basu,](#)  
 25 8  
 26 [2017](#)). Conversely, once we succeed in isolating and understanding the different mark of each, we  
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 28 9 find in sediment composition a key that unlocks a bounty of information, helping us to investigate a  
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 30 wide range of phenomena. These include tectonic processes in diverse geodynamic environments  
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 33 11 ([Dickinson, 1985](#); [Ingersoll, 2012](#)), the characteristics of weathering in different climatic and  
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 35 12 geomorphological settings ([Nesbitt et al., 1997](#); [von Eynatten et al., 2016](#)), and hydraulic  
 36  
 37 parameters during erosion, transport, or deposition ([Garzanti et al., 2008, 2009](#)). To complete this  
 38 13  
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 40 14 hard passage we need first to gain thorough experience on modern sedimentary systems and next  
 41  
 42 use it as a conceptual guide during our cautious exploration of past conditions.  
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 47 17 South China is characterized by a strong climatic gradient from the dry Tibetan plateau in the west  
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 49 to monsoon-drenched coastal areas in the east, with an additional latitudinal rainfall gradient. A  
 50 18  
 51 most interesting peculiarity of this vast continental region is the extensive exposure of carbonate  
 52 19  
 53 rocks, which makes its western part one of the world’s largest karst terrains. Because of sharp  
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 55 20 climatic gradients and varied geological and geomorphological conditions, South China is  
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 57 21 excellently suited to appraise the relative effect of source-rock lithology and chemical weathering,  
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as well as other interplaying factors affecting sediment generation and composition. This study focuses on sand produced in the catchments of the Pearl River, of major southern tributaries of the Yangtze River, and of smaller rivers draining the Fujian and Zhejiang Provinces between the Pearl and Yangtze river mouths (Fig. 1).

Our aims are diverse. The characterization of the petrographic and mineralogical signatures in each river catchment allows us to: a) calculate a provenance budget, assess sediment yields, and trace erosion patterns in the Pearl River basin; b) evaluate the extent to which detrital modes are modified by chemical weathering in different climatic conditions; c) investigate the processes that control the dissolution of soluble carbonate grains in different types of karst terrains; d) determine the relative durability of detrital tectosilicates; e) verify whether corrosion features on heavy minerals can be used as a proxy of weathering conditions. Additionally, we touch on the highly controversial topic of provenance and dispersal pathway of Cenozoic Taiwan sandstones fed from the Chinese mainland. To reach these multiple goals, original petrographic and heavy-mineral data are integrated with clay-mineral and geochemical data from the companion paper (He et al., companion), petrographic and heavy-mineral data on Yangtze sand and Neogene to modern sediments of western Taiwan (Nagel et al., 2014; Vezzoli et al., 2016; Resentini et al., 2017), and zircon-geochronology data from river sand in mainland China and Taiwan (Xu et al., 2007; He et al., 2013; Xu et al., 2014, 2016; Zhao et al., 2015; Deng et al., 2017; Liu et al., 2017; Zhong et al., 2017; He et al., 2019). Previous heavy-mineral studies on sand carried by the Pearl River and smaller rivers of coastal SE China include those of Xu and Li (2003), Xiang et al. (2011), Chen et al. (2018), and Ma et al. (2018).

## 2. Geology and geomorphology

The South China block consists of the Yangtze block to the north and the Cathaysia block to the south, welded by the early Neoproterozoic Jiangnan orogen (Fig. 2; Shu et al., 2011; Yao et al.,

149 2016). The timing and location of the suture zone are however disputed, as in general the complex  
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 4 pre-Devonian geological evolution of southern China (Wang et al., 2007; Li et al., 2009; Zhao and  
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 6 Cawood, 2012; Li et al., 2014).

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 9 Basement rocks of the Yangtze block are as old as Mesoarchean to Paleoproterozoic (Qiu et al.,  
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 11 2000; Wang et al., 2012) but are rarely exposed, whereas widely distributed are upper Paleozoic  
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 13 carbonates overlain by the Permian Emeishan Traps, representing the largest igneous province in  
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 15 China. The thickness of basaltic flows increases from 200 m in the Guizhou Province to as much as  
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 17 5 km in the west, being ~700 m on average (Shellnutt, 2014). Carbonate sedimentation continued  
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 19 into the Triassic, replaced by siliciclastic strata during the Late Triassic to Jurassic (Liu and Xu,  
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 21 1994).

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 24 The Paleoproterozoic basement core of the Cathaysia block, as old as ~2 Ga and consisting of  
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 26 granitoid gneiss and schist presently exposed in SW Zhejiang and NW Fujian (Li, 1997; Wan et al.,  
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 28 2007; Yu et al., 2009; Xia et al., 2012), collided with the Yangtze block between 800 and 900 Ma  
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 30 during the Jiangnan orogeny and was subsequently fragmented in diverse terranes and sedimentary  
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 32 basins hosting thick successions of clastic rocks (Shu, 2006). A major tectonic boundary  
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 34 corresponds to the Zhenghe-Dapu Fault, which separates a SE domain (eastern Cathaysia block)  
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 36 dominated by upper Mesozoic igneous rocks (Xu et al., 2007) from a NW domain (western  
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 38 Cathaysia block) characterized by a fold-thrust belt formed during the late Ordovician-Silurian  
 39  
 40 Wuyi-Yunkai (Kwanghsian) orogeny and unconformably overlain by upper Paleozoic clastic and  
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 42 subordinately carbonate rocks (Li et al., 2010). Western Cathaysia is further subdivided into the  
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 44 Wuyi terrane in the north, drained by the studied rivers of coastal SE China, and the Nanling-  
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 46 Yunkai terrane in the south, drained by lower-course tributaries of the Pearl River (Fig. 2; Yu et al.,  
 47  
 48 2010).

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2.1. Pearl River catchment

175 The Pearl River (Chinese name Zhujiang, from *zhu*, pearl, and *jiang*, river; length 2320 km,  
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 476 catchment area 450,000 km<sup>2</sup>) is the third longest river in China, and changes names downstream of  
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 677 each major confluence (Fig. 1). The Nanpan and Beipan headwater branches are sourced in the  
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 878 Yunnan-Guizhou Plateau of southeastern Tibet at an elevation of ~2800 m a.s.l., and flow eastward  
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 1179 across the Yangtze block where elevation is >1800 m to join and form the Hongshui River (Table  
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 1480 1). Downstream, the Hongshui (from *hong*, red, and *shui*, water) enters the Cathaysia block, where  
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 1681 it takes the name of Qian after the confluence with the Liu River and of Xun after the confluence  
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 1882 with the Yu River. In the lower course, it takes the name of Xi (*west* in Chinese) downstream of the  
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 2183 confluence with the Gui (Li) and He Rivers, and is eventually joined by the Bei (*north* in Chinese)  
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 2384 and Dong (*east* in Chinese) Rivers in the Guangzhou area to form both a delta in the south and an  
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 2685 estuary in the north (the Humen, known by Europeans as *Bocca Tigris*).

286 The Pearl River basin straddles the Tropic of Cancer. The average annual temperature in the  
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 3187 catchment ranges between 14°C and 22°C, reaching as low as -10°C and as high as 42°C. Climate  
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 3388 is strongly influenced by the East Asia summer monsoon with annual precipitation, concentrated  
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 3689 between April and September, increasing steadily from 0.7 m in the west to 2.4 m along the coast  
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 3890 (Fig. 3; Zhang et al., 2012; Liu et al., 2016). The estimated mean annual water and sediment fluxes  
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 4091 range between 280 and 330 km<sup>3</sup> and between 65 and 86 million tons, respectively (Pearl River  
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 4392 Water Resources Commission, 2006).

4593 The Pearl River catchment encompasses diverse geological domains (Fig. 2): a) the upper Middle  
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 4894 Permian Emeishan Large Igneous Province in the northwest consists of basalt and minor basaltic  
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 5095 andesite, picrite, trachyte, and rhyolite (Song et al., 2001; Shellnutt, 2014); b) the Chuandian  
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 5396 fragment in the far west comprises a suite of igneous rocks from small ultramafic bodies and gabbro  
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 5597 to granodiorite and granite (Li et al., 2003); c) the Youjiang Structural Belt in the west includes  
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 5798 deformed Cambro-Ordovician carbonates unconformably overlain by Devonian to Middle Triassic  
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 6099 carbonates and siliciclastic rocks (Yang et al., 2012; Li et al., 2017); d) the North Vietnam terrane

100 in the southwestern corner of the catchment comprises Neoproterozoic metasedimentary and  
 101 igneous basement intruded by Silurian granitoids, and Paleozoic–Mesozoic sedimentary and  
 102 volcano-sedimentary cover strata (Yang et al, 2012); e) the Jiangnan orogen in the north consists of  
 103 Neoproterozoic schist and minor granite (Li, 1999; Wang et al., 2014); f) the Shiwandashan  
 104 Structural Belt in the south contains Paleozoic-Mesozoic siliciclastic strata with Triassic granitoid  
 105 intrusions (Hu et al., 2015; Li et al., 2017); g) the Yunkai Massif, also in the south, includes  
 106 amphibolite-facies to granulite-facies metamorphic rocks deformed during the Early Paleozoic  
 107 Wuyi-Yunkai orogeny (Wang et al., 2013); h) the SE Coast Magmatic Belt contains widespread  
 108 Jurassic to Cretaceous Yanshanian granitoids with high-K calc-alkaline affinity (Chen et al., 2008).  
 109 The Hongshui and Yu headwater branches of the Pearl River drain the Yangtze block in the western  
 110 part of the catchment, where upper Paleozoic carbonates, Emeishan basalts, and Triassic dolomites  
 111 and continental redbeds are widely exposed (Fig. 4; Chen and Pei, 1993). The Rong tributary of the  
 112 Liu River is sourced in the Jiangnan orogen in the north. All Pearl River tributaries in the eastern  
 113 catchment drain entirely within the Cathaysia block, characterized by Paleozoic limestones and  
 114 subordinate siliciclastic strata in the west (Gui and He catchments) and by Yanshanian granites in  
 115 the east with Paleozoic carbonates (Bei catchment) or Jurassic sandstones and mudrocks (Dong  
 116 catchment) (Jahn et al., 1990).

## 2.2. Coastal SE China

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 120 The Fujian and Zhejiang Provinces of SE China at latitudes between 24°N and 30°N have  
 121 subtropical climate dominated by the East Asia monsoon, with average annual temperatures of 17-  
 122 21°C. Annual precipitation increases southward from 1.6 to 2.2 m (Fig. 3). Several rivers drain  
 123 eastward across this hilly region characterized by elevations between 500 and 1000 m. The largest  
 124 is the Min River, which annually delivers ~56 km<sup>3</sup> of water and ~8 Mt of suspended sediment to the  
 125 Taiwan Strait (Table 1).

126 All coastal rivers drain entirely within the Cathaysia block, the SE part of which largely consists of  
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 427 granite and volcanic rocks with ages younging eastward from Jurassic to Cretaceous (Fig. 4; Zhou  
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 628 et al., 2006; Li and Li, 2007). The rhyolite-dominated bimodal volcanic suite including minor basalt  
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 829 and mafic dykes is distributed over 800 km in the so-called SE Coast Magmatic Belt, and  
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 10 documents the late stages of westward subduction of the paleo-Pacific plate beneath the South  
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 1431 China block with subsequent crustal thinning and incipient back-arc extension in the South China  
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 1632 Sea (Chen et al., 2008). Jurassic-Paleogene siliciclastic rocks intercalated with rhyolitic ignimbrites  
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 1833 and deposited during this subduction-related, Basin-and-Range-type upper-plate extension widely  
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 2134 occur in coastal areas (Wang and Shu, 2012).  
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2335 In the northwestern Wuyi terrane, deformed Cambrian feldspatho-quartzose metasandstones and  
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 2636 slates are overlain with angular unconformity by a ~3.5 km-thick upper Paleozoic succession  
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 2837 dominated by quartz-rich sandstone and conglomerate intercalated with mudrock and bioclastic  
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 3138 limestone (Fujian Institute of Geological Survey, 2015). The occurrence of granitoid intrusions and  
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 3339 volcanic detritus in the Lower Permian has suggested a continental-arc setting related to the initial  
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 3640 westward subduction of the paleo-Pacific plate (Li et al., 2020).  
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### 3841 2.3. Southern Yangtze catchment

3942 The Yangtze (Chinese name Changjiang, from *chang*, long and *jiang*, river) is the largest river in  
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 4244 China. The southern part of its huge catchment, with mean annual temperature 16-18°C, is situated  
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 4545 in the humid subtropical zone influenced by the East Asia monsoon. Annual precipitation,  
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 4846 concentrated from May to October, increases from 0.6-1.2 m in the Wu catchment, where elevation  
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 5147 is 500-2000 m a.s.l., to 1.2-2.5 m in the Yuan, Xiang and Gan catchments lying mostly below 500  
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 5448 m a.s.l. (Fig. 3).  
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5649 The Wu River drains entirely within the Yangtze block, including mostly upper Paleozoic to  
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 5951 Triassic carbonates with coal-bearing strata and basalt in the upper reaches and mudrocks with  
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 6252 sporadic Neoproterozoic greenschist-facies volcano-sedimentary rocks in the lower reaches. The  
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153 other three tributaries to the east drain Neoproterozoic schist and granite of the Jiangnan orogen  
 154 (from *jiang* = river, and *nan* = south; i.e., “located south of the river”), overlain by middle-upper  
 155 Neoproterozoic (Sinian) siliciclastic cover locally including stromatolitic dolostone (Wang et al.,  
 156 2007; Zhao, 2015). The Yuan River drains both sedimentary rocks of the Yangtze block and middle  
 157 Neoproterozoic schist of the Jiangnan orogen. The Xiang and Gan tributaries (Table 1) are sourced  
 158 in the northern part of the Cathaysia block and cut across the Jiangnan orogen including granite,  
 159 schist, and mostly siliciclastic sedimentary cover (Fig. 4).

#### 2.4. Western Taiwan

162 Taiwan Island, located between ~22°N and ~25°N, has mild tropical climate through the year, with  
 163 average annual temperature from 22°C to 24°C; summer temperatures reach 38°C, whereas frost or  
 164 snow may cover the high mountains during winter. Annual rainfall, concentrated between May and  
 165 October, increases from 1-1.5 m along the western coast to the northern foothills and central high-  
 166 mountain area, which receive up to 5-6 m of annual precipitation. Typhoons may bring more than 2  
 167 m of torrential rain in two days, triggering multiple landslides (Hovius et al., 2000; Montgomery et  
 168 al., 2014). Because of such harsh climatic conditions coupled with rapid tectonic deformation,  
 169 extreme relief, and frequency of high-magnitude earthquakes, erosion rates are among the highest  
 170 on Earth, averaging 3–7 mm/a and reaching several cm/a locally (Dadson et al., 2003; Fuller et al.,  
 171 2006; Resentini et al., 2017). Sediment geochemistry and clay-mineral assemblages dominated by  
 172 illite and chlorite testify to the prevalence of physical erosion with limited weathering effects (Liu  
 173 et al., 2008; Nagel et al., 2014; Garzanti and Resentini, 2016).

174 The Tsengwen, Bazhang, and Houlong rivers (Table 1) carry detritus entirely recycled from  
 175 Neogene strata along the western front of the Taiwan orogen. Exposed in the western foothills are  
 176 sandstones and mudrocks originally accumulated offshore of the SE China coast during opening of  
 177 the South China Sea and derived from the Chinese mainland in the west, overlain by Plio-  
 178 Quaternary foreland-basin deposits fed from the growing Taiwan orogen in the east (Lin et al.,  
 179

2003; Nagel et al., 2013). The basal unconformity of the foreland basin corresponds to a sharp change in sandstone composition from quartzose in the Miocene to litho-feldspatho-quartzose metasedimentaclastic in the Pliocene, and finally feldspatho-litho-quartzose sedimentaclastic in the Pleistocene, documenting the progressive frontal accretion of unmetamorphosed thrust sheets during the outward growth of the orogen (Nagel et al., 2014).

### 3. Sampling and analytical methods

For this study, we have selected 40 samples overall (Fig. 1), including 22 very fine to medium sands collected between summers 2018 and 2019 from various tracts and tributaries of the Pearl River, 10 very fine to coarse sands collected mainly in March to November 2011 from five coastal rivers in SE China (Ou, Min, Mulanxi, Jiulong, Han) and their main tributaries, sample #23 collected at 105 b.s.l. offshore of the Pearl River mouth, and one sample each from the four major southern tributaries of the Yangtze River (Wu, Yuan, Xiang, and Gan) and from three selected rivers in western Taiwan (Tsengwen, Bazhang, and Houlong). Full information on sampling sites (numbered from 1 to 40 in Figs. 2 and 3) is given in Appendix Table A1 and in the Google Earth™ file PearlProv.kmz.

#### 3.1. Petrography

A quartered fraction of each sand sample was impregnated with araldite epoxy and cut into a standard thin section stained with alizarine red to distinguish dolomite and calcite. Petrographic analysis was carried out by counting between 400 and 500 points under the microscope according to the Gazzi-Dickinson method (Ingersoll et al., 1984). Sand classification was based on the relative abundance of the three main framework components quartz (Q), feldspars (F) and lithic fragments (L), considered if exceeding 10%QFL. According to standard use, the less abundant component goes first, the more abundant last (e.g., a sand is named feldspatho-litho-quartzose if  $Q > L > F >$

10%QFL or quartzo-lithic if  $L > Q > 10\%QFL > F$ ; classification scheme after [Garzanti, 2019](#)).  
 Quartz-rich feldspatho-quartzose ( $4 < Q/F < 9$ ) and quartz-rich litho-quartzose subfields ( $4 < Q/L < 9$ ) are also distinguished. Metamorphic grains were classified according to their protolith composition and metamorphic rank ([Garzanti and Vezzoli, 2003](#)). Petrographic parameters used in this article include the Q/F, P/F, and Mic\*/F ratios (P = plagioclase; Mic\* = microcline with cross-hatch twinning, called for brevity microcline\* through the text). Median grain size was determined in thin section by ranking and visual comparison.

### 3.2. Heavy minerals

From a split aliquot of the 15-500  $\mu\text{m}$  size window (32-355  $\mu\text{m}$  for Yangtze tributaries and 32-500  $\mu\text{m}$  or bulk sample for Taiwan rivers) obtained by wet sieving, heavy minerals were separated by centrifuging in Na-polytungstate ( $2.90 \text{ g/cm}^3$ ) and recovered by partial freezing with liquid nitrogen. For each sample, ~200 transparent heavy minerals (or all of those present in the grain mount) were either point-counted at appropriate regular spacing to obtain correct volume percentages or grain-counted by the area method ([Galehouse, 1971](#)). Transparent heavy-mineral assemblages, called for brevity “tHM suites” throughout the text, are defined as the spectrum of detrital extrabasinal minerals with density  $>2.90 \text{ g/cm}^3$  identifiable under a transmitted-light microscope. According to the transparent-heavy-mineral concentration in the sample (tHMC), tHM suites are defined as very poor ( $\text{tHMC} < 0.5$ ), poor ( $0.5 \leq \text{tHMC} < 1$ ), moderately poor ( $1 \leq \text{tHMC} < 2$ ), or moderately rich ( $2 \leq \text{tHMC} < 5$ ) ([Garzanti and Andò, 2019](#)). The sum of zircon, tourmaline, and rutile over total transparent heavy minerals (ZTR index of [Hubert, 1962](#)) measures the relative proportion of durable minerals in the tHM suite and can thus be used as an index of recycling ([Garzanti, 2017](#)).

In all analysed samples, corrosion features were systematically evaluated on ~ 5300 transparent heavy-mineral grains, following the classification of surface textures in [Andò et al. \(2012\)](#). The

Corrosion Index  $CI = [(\text{etched grains} + 50\% \text{ corroded grains}) / \text{total grains} \times 100]$  could thus be defined for each mineral (Garzanti et al., 2018). The Raman spectra of 38 garnet grains separated by hand-picking from Ou, Min, Jiulong, and Han sand samples were obtained with a Renishaw inVia™, and their chemical composition was recalculated from Raman peak wavenumbers elaborated by the Matlab® routine MIRAGEM (Bersani et al., 2009). Significant detrital components are listed in order of abundance (high to low) throughout the text. Key compositional parameters are summarized in Table 2. The complete petrographic and heavy-mineral datasets are provided in Appendix Tables A2, A3, and A4.

### 3.3. Statistical/graphical displays and chemical indices

The compositional biplot (Gabriel, 1971), drawn using CoDaPack software by Comas-Cufí and Thió-Henestrosa (2011) and used to illustrate integrated petrographic, heavy-mineral, and geochemical data, allows discrimination among multivariate observations (points) while shedding light on the mutual relationships among multiple variables (rays). The length of each ray is proportional to the variance of the corresponding variable in the dataset. If the angle between two rays is close to 0°, 90° or 180°, then the corresponding variables are directly correlated, uncorrelated, or inversely correlated, respectively.

Literature data on zircon ages are visualized as kernel density estimates (KDE) and as multidimensional-scaling (MDS) maps, plotted using the *provenance* package of Vermeesch et al. (2016). In a MDS map, the distance among samples is approximately proportional to the Kolmogorov-Smirnov dissimilarity of their compositional or chronological signatures (Vermeesch, 2013; Vermeesch and Garzanti, 2015). Closest and second-closest neighbours are linked by solid and dashed lines, respectively, and the goodness of fit is evaluated using the “stress” value of the configuration (0.2 = poor; 0.1 = fair; 0.05 = good; Vermeesch, 2018).

Used in this article are the Chemical Index of Alteration [ $CIA = 100 \cdot A1_2O_3 / (A1_2O_3 + (CaO - 3.33 P_2O_5) + Na_2O + K_2O)$ ] (Nesbitt and Young, 1982) and the Weathering Index [ $WIP = 100 \cdot ((CaO -$

$3.33 \text{ P}_2\text{O}_5) / 0.7 + 2 \text{ Na}_2\text{O} / 0.35 + 2 \text{ K}_2\text{O} / 0.25 + \text{MgO} / 0.9]$  (Parker, 1970), calculated using  
 molecular proportions of mobile alkali and alkaline earth metals corrected for CaO in apatite.  
 Weathering intensities are calculated separately for each single mobile element  $E$  by comparing its  
 concentration to that of non-mobile Al in our samples and in the Upper Continental Crust [ $\alpha^{\text{Al}}E =$   
 $(\text{Al} / E)_{\text{sample}} / (\text{Al} / E)_{\text{UCC}}$ ] (Garzanti et al., 2013; UCC standard after Taylor and McLennan, 1995;  
 Rudnick and Gao, 2003). None of these indices can be confidently used as a proxy of weathering  
 conditions, because they depend primarily on the lithology of source rocks and on other factors as  
 well, including grain size and hydraulic sorting (Garzanti and Resentini, 2016; Dinis et al., 2020).  
 Because the addition of quartz grains *via* recycling of parent sandstones directly affects the WIP,  
 but not the CIA, the CIA/WIP ratio can be considered as an index of recycling (Garzanti et al.,  
 2014).

#### 4. PETROGRAPHY AND HEAVY MINERALS

In this section we first illustrate the petrographic and heavy-mineral signatures of modern sand  
 generated in the Pearl River catchment and in coastal SE China. Next, we summarize data  
 previously collected with the same methods and following the same criteria on modern river sand  
 from southern Yangtze tributaries (Vezzoli et al., 2016) and western Taiwan (Garzanti and  
 Resentini, 2016; Resentini et al., 2017), and on Miocene-Pleistocene sandstones of the outer  
 western Taiwan foothills (Nagel et al., 2014).

##### 4.1. Headwater Pearl River tributaries

Sand carried by Pearl River tributaries draining the Yangtze block ranges from quartzo-lithic  
 (Hongshui catchment) to litho-quartzose (Yu catchment) and from feldspatho-litho-quartzose to  
 quartz-rich litho-quartzose (Liu catchment) (Fig. 5A). The P/F ratio is varied, with subequal  
 amounts of K-feldspar and plagioclase overall. Feldspars, including common microcline\*, are most

frequent in Rong sand, partly derived from basement rocks of the Jiangnan orogen. In the Hongshui catchment, mafic and subordinately felsic volcanic grains are mostly derived from the Emeishan Traps, limestone grains from extensive Upper Paleozoic to Triassic carbonates, and siltstone/metasiltstone to shale/slate grains from siliciclastic rocks. Felsic and mafic volcanic rock fragments occur in You River sand but are diluted in Yu sand downstream, whereas only felsic volcanic grains derived from the Jiangnan orogen occur in Liu sand. Limestone rock fragments associated with some dolostone and chert are common in Yu sand, whereas Rong sand contains significant metamorphic rock fragments and muscovite shed by schists of the Jiangnan basement. Mica is otherwise negligible. Siltstone/metasiltstone to shale/slate grains are subordinate but widespread.

The mostly very poor tHM suites reflect provenance dominantly from carbonate and terrigenous sedimentary rocks. Clinopyroxene (largely brown augite) derived from the Emeishan Traps dominates the tHM suite in Beipan and You sand, and is diluted but still abundant in Hongshui and Yu sand downstream. Amphibole (actinolite with subordinate hornblende) shed from Jiangnan schists is most abundant in Long and Rong sand and is diluted but still common in Liu sand downstream. ZTR minerals are widespread. Tourmaline is most common in Rong and Liu sand, and zircon in Zuo sand, whereas rutile is invariably rare. Epidote is also widespread, and most common in Liu sand. Apatite is abundant in the Nanpan tributary sample but otherwise minor to rare. Minor garnet occurs in Zuo sand. Olivine was detected in You sand, Cr-spinel in Zuo sand, and topaz in Rong, Long, and Liu sand. Other minerals include titanite, anatase, brookite, and pumpellyite. Corrosion indices are higher for amphibole than for pyroxene – but only pyroxene grains may be deeply etched – and low for epidote and other minerals (Table 2).

#### 4.2. Lower-course Pearl River tributaries

Sand carried by Pearl River tributaries draining the Cathaysia block is feldspatho-quartzose or locally litho-feldspatho-quartzose (Gui and upper Bei sand) (Fig. 5A). K-feldspar, including

<sup>1</sup><sub>2</sub> common microcline\*, is twice as abundant as plagioclase. Rock fragments derived from granitoid  
<sup>3</sup><sub>4</sub> and mostly metasedimentary rocks occur in all samples. Felsitic volcanic rock fragments occur in  
<sup>5</sup><sub>6</sub> Gui, Dong, lower Bei, and He sand. Sedimentary rock fragments are most common in Gui sand  
<sup>7</sup><sub>8</sub> (siltstone, shale, limestone, chert) and frequent in upper Bei sand (siltstone), but otherwise  
<sup>9</sup><sub>10</sub> negligible. Mica (muscovite  $\approx$  biotite) is common.

<sup>11</sup><sub>12</sub> The very poor tHM suites include mainly amphibole (green brown to subordinately blue/green  
<sup>13</sup><sub>14</sub> hornblende) with epidote, tourmaline, and zircon. The ZTR index ranges from 8 (He sand) to 47  
<sup>15</sup><sub>16</sub> (Xinxing sand). Andalusite mostly showing unoriented carbonaceous inclusions is abundant in  
<sup>17</sup><sub>18</sub> Dong sand, where it is associated with fibrolitic sillimanite, and minor in He and Bei sand. Some  
<sup>19</sup><sub>20</sub> garnet, associated with staurolite and kyanite in Xinxing sand, and pyroxene (mainly brown augite)  
<sup>21</sup><sub>22</sub> invariably occur. Other minerals include titanite, anatase, apatite, rutile, topaz, and monazite.  
<sup>23</sup><sub>24</sub> Corrosion indices are only slightly higher than in headwater branches ([Table 2](#)), but deeply etched  
<sup>25</sup><sub>26</sub> to skeletal amphibole or locally apatite occur.

#### <sup>27</sup><sub>28</sub> 4.3. The Pearl River mainstem

<sup>29</sup><sub>30</sub> Xi river sand is litho-feldspatho-quartzose ([Fig. 5A](#)) with K-feldspar  $\approx$  plagioclase. Rock fragments  
<sup>31</sup><sub>32</sub> are mainly sedimentary to very low-rank metasedimentary (siltstone/metasilstone, shale/slate,  
<sup>33</sup><sub>34</sub> limestone and rare dolostone and chert) and subordinately metamorphic (mainly low-rank  
<sup>35</sup><sub>36</sub> metasedimentary) and granitoid types, with minor lathwork and felsitic volcanic grains. Mica  
<sup>37</sup><sub>38</sub> (muscovite  $\approx$  biotite) is common. The very poor tHM suite consists of epidote, amphibole  
<sup>39</sup><sub>40</sub> (blue/green to green/brown hornblende and actinolite), tourmaline, zircon, and clinopyroxene  
<sup>41</sup><sub>42</sub> (mainly brown augite). Other minerals include anatase, apatite, titanite, and locally barite, rutile,  
<sup>43</sup><sub>44</sub> monazite, garnet, and prehnite. From the Qian River to the Xi River downstream, quartz,  
<sup>45</sup><sub>46</sub> metamorphic rock fragments, mica, and amphibole progressively increase at the expense of  
<sup>47</sup><sub>48</sub> sedimentary and especially mafic volcanic rock fragments.

1 In the Pearl River delta, estuary, and shelf, composition ranges from litho-feldspatho-quartzose for  
 2  
 3  
 4 very fine sand to feldspatho-quartzose for fine sand (Fig. 5A). K-feldspar is  $\geq$  plagioclase;  
 5  
 6 microcline\* is minor. Metamorphic and sedimentary rock fragments (mostly siltstone/metasiltstone,  
 7  
 8  
 9 shale/slate, schist, and very-low-rank to low-rank metavolcanic grains) prevail over granitoid and  
 10  
 11 minor volcanic (mainly felsitic), limestone or chert grains. Mica (biotite > muscovite) is most  
 12  
 13 common in estuary sand. The very poor tHM suite consists of tourmaline, zircon, clinopyroxene  
 14  
 15 (mainly brown augite), amphibole (mostly blue/green hornblende with green/brown hornblende and  
 16  
 17 actinolite), epidote, and locally frequent apatite and garnet. Other minerals include anatase or  
 18  
 19 andalusite; one grain of olivine was identified. Shelf sand is richer in epidote and amphibole, and  
 20  
 21 poorer in clinopyroxene. Corrosion indices, relatively low in the Qian tract (CI 60 for amphibole, 7  
 22  
 23 for pyroxene, and 6 for epidote), tend to irregularly increase downstream reaching higher values in  
 24  
 25 estuary and shelf sand (up to CI 74 for amphibole, 23 for pyroxene, and 39 for epidote).  
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 27  
 28  
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#### 352 4.4. Coastal rivers of SE China

353  
 354  
 355 Coastal rivers in SE China drain the Cathaysia block. Sand ranges from feldspatho-litho-quartzose  
 36  
 37 to feldspatho-quartzo-lithic in the Ou and Min catchments in the north, is litho-feldspatho-quartzose  
 38  
 39 in the Mulanxi catchment, and ranges from feldspatho-quartzose to quartzose in the Jiulong and  
 40  
 41 Han catchments in the south (Fig. 5A). Plagioclase prevails over K-feldspar in Ou, Min and  
 42  
 43 Mulanxi sand, where microcline\* is scarce, whereas K-feldspar prevails over plagioclase in sand of  
 44  
 45 Jiulong and Han tributaries where microcline\* is more common. Mostly felsitic volcanic rock  
 46  
 47 fragments are abundant in the Ou catchment, common in the Min and Mulanxi catchments, and  
 48  
 49 minor in the Jiulong and Han catchments. Granitoid rock fragments are common especially in  
 50  
 51 Mulanxi and Jiulong sand. Other rock fragments include schist (Mulanxi sand) and mainly low-rank  
 52  
 53 metasedimentary and felsic to mafic metavolcanic types, as well as shale/siltstone grains. Carbonate  
 54  
 55 rock fragments are lacking. Biotite and muscovite are common in Ou, Min, and Mulanxi sand.  
 56  
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1  
 2 366 Very poor to moderately rich tHM suites are epidote-dominated with amphibole, zircon and minor  
 3  
 4 367 garnet in Ou, Min, and Mulanxi sand, very poor to moderately poor and dominated by epidote and  
 5  
 6 368 amphibole with locally common zircon and garnet in the Jiulong catchment, and very poor with  
 7  
 8 369 zircon, amphibole, epidote, tourmaline, and garnet in Han sand. Blue/green hornblende is the most  
 9  
 10  
 11 370 common amphibole. Garnet grains are mainly spessartine associated with andradite and uvarovite in  
 12  
 13  
 14 371 Jiulong sand, almandine and spessartine in Ou sand, and andradite in Han sand. Other heavy  
 15  
 16 372 minerals include brown augite in Min sand, andalusite (mainly grains free of carbonaceous  
 17  
 18 373 inclusions in Min sand), titanite, apatite, rutile, olivine, hypersthene, sillimanite, and topaz.  
 19  
 20  
 21 374 Corrosion indices tend to be slightly higher than in the Pearl River catchment (Table 2).  
 22

#### 23 375 24 25 376 4.5. Southern Yangtze tributaries

26  
 27 377 Sand of the Wu River, chiefly draining sedimentary rocks of the Yangtze block are quartzo-lithic  
 28  
 29  
 30 378 sedimenta-  
 31 379 clastic with few feldspars (plagioclase  $\approx$  K-feldspar) and common sandstone/siltstone,  
 32  
 33 380 shale, limestone, chert, dolostone, and felsic to mafic volcanic rock fragments. Mica is negligible.  
 34  
 35 381 The very poor tHM suite consists of amphibole (actinolite and hornblende), epidote, augitic  
 36  
 37 382 clinopyroxene, zircon, garnet, and barite.  
 38

39  
 40 383 Sand of the Yuan River, largely draining the Jiangnan orogen and its mainly siliciclastic cover  
 41  
 42 384 strata, is litho-quartzose with minor feldspars (plagioclase  $\geq$  K-feldspar, including rare microcline\*)  
 43  
 44 385 and mainly sandstone/siltstone and shale rock fragments associated with felsic volcanic and mostly  
 45  
 46 386 very-low-rank to medium-rank metasedimentary grains. Limestone grains are rare. Biotite occurs.  
 47  
 48  
 49 387 The very poor tHM suite chiefly consists of zircon, epidote, amphibole (hornblende, actinolite), and  
 50  
 51  
 52 388 tourmaline.  
 53

54  
 55 389 Coarse-grained sand of the Xiang and Gan rivers draining both the Cathaysia block and the  
 56  
 57 390 Jiangnan orogen are, respectively, quartz-rich feldspatho-quartzose and feldspatho-quartzose. K-  
 58  
 59 391 feldspar including microcline\* predominates over plagioclase (Table 2) Granitoid and  
 60  
 61 392 siltstone/sandstone rock fragments are associated with a few volcanic, shale, chert, and medium-  
 62  
 63  
 64  
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rank metamorphic grains. Biotite occurs. Very poor tHM suites include tourmaline and zircon, with subordinate epidote, amphibole (mostly hornblende), locally common topaz, minor garnet, and rare clinopyroxene, rutile, and andalusite. Corrosion indices for sand of Yangtze tributaries are markedly higher than in the Pearl River catchment and coastal rivers of SE China (Table 2), which is however chiefly ascribed to inter-operator bias.

#### 4.6. Taiwan river sands and Neogene sandstones

Sand carried by the Tsengwen, Bazhang, and Houlong rivers, selected because they exclusively drain Neogene strata exposed in the outer western Taiwan foothills, are litho-quartzose to feldspatho-litho-quartzose. Plagioclase prevails over K-feldspar, which may include significant microcline\*. Rock fragments are dominantly sedimentary (siltstone and shale, with subordinate limestone and marl) but felsitic volcanic, slate, metasiltstone, and a few granitoid grains frequently occur. The very poor tHM suite include zircon, garnet, epidote, tourmaline, apatite, rutile, minor amphibole, and sporadic augite.

Mid-Miocene to Pleistocene sandstones of the outer western Taiwan foothills are mainly litho-feldspatho-quartzose with subequal K-feldspar and plagioclase. Rock fragments are dominantly sedimentary to low-rank metasedimentary (shale/slate, siltstone/metasiltstone) with minor volcanic grains. Bioclasts are locally abundant. Very poor tHM suites include zircon, tourmaline, garnet, epidote, apatite, and rutile.

### 5. Provenance control on sand composition

The area investigated in this study covers the whole of southern China south of the Yangtze River. The geology of this large region is complex, comprising the Archean Yangtze (Wang et al., 2012) and Paleoproterozoic Cathaysia (Li, 1997) crustal blocks, the early Neoproterozoic Jiangnan orogen that welded them (Yao et al., 2016), as well as the late Ordovician-Silurian Wuyi-Yunkai thrust belt

(Li et al., 2010), the Triassic Indosinian orogen (Hu et al., 2015), and the SE coastal belt characterized by Basin-and-Range-style Jurassic-Cretaceous tectonics and magmatism (Li and Li, 2007; Wang and Shu, 2012). Despite the variety of source rocks, sediments produced in this vast area display two main compositional signatures: quartzo-lithic sand generated by erosion of sedimentary and basaltic cover rocks of the Yangtze block, and feldspatho-quartzose sand generated by erosion of igneous and sedimentary rocks of the Cathaysia block. Virtually all studied sands have poor, and mainly very poor tHM suites with common durable minerals (ZTR mainly  $\geq 30$ ), reflecting the dominance of sedimentary and granitic rocks with only sporadic exposure of denser – and consequently dense-mineral-rich (Garzanti et al., 2001, 2006) – mid-crustal crystalline basement. Not only sand generated in western Taiwan, but also sediments produced across southern China are thus largely polycyclic.

### 5.1. The Yangtze block as a source of sand

In the Guizhou and Guangxi Provinces of SW China, basement rocks of the Yangtze block are extensively covered by upper Paleozoic to lower Mesozoic carbonate, basaltic, and siliciclastic rocks. Consequently, the Wu, Hongshui, and Yu Rivers carry lithic-rich sand with subordinate quartz and low feldspar. Quartz grains frequently display abraded overgrowths as direct witnesses of sandstone recycling. Despite the thickness and extent of carbonate rocks, sedimentary rock fragments are mainly siltstone and shale rather than limestone, an issue discussed specifically in section 6. Volcanic detritus from the Emeishan Traps is documented by mainly mafic lathwork grains and common to dominant augitic clinopyroxene in sand of the Beipan River and of the Hongshui River downstream. Composition is similar but richer in quartz in sand of the Yu River and of its You branch upstream, draining the Youjiang Basin where siliciclastic rocks are more common and granite occurs. Basaltic rock fragments are minor, and yet augite derived from the Emeishan Traps may dominate the very poor tHM suite. Quartz and feldspar increase further in

146 sand of the Zuo River, partly draining the Vietnam terrane in the southwestern corner of the Pearl  
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 3  
 447 River catchment, and of the Rong River, draining Neoproterozoic schists of the the Jiangnan orogen  
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 448 at the northern edge of the catchment. Quartz is most abundant in the Long River and in the Liu  
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 8  
 449 River downstream, where quartz grains with abraded overgrowths are particularly common,  
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 1450 documenting extensive recycling of quartz-rich sandstones. Conversely, carbonate grains are  
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 13  
 1451 negligible despite widespread exposure of carbonate rocks, as discussed in [section 6](#)  
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 15  
 1452 The Wu River, draining cover strata of the Yangtze block north of the Hongshui catchment, carries  
 17  
 18  
 1453 quartzo-lithic sedimentaelastic sand relative rich in carbonate grains. Instead, the Yuan River,  
 19  
 20  
 21454 draining both cover strata of the Yangtze block and schists and siliclastic cover strata of the  
 22  
 23  
 2455 Jiangnan orogen north of the Liu catchment, carries litho-quartzose sand rich in siltstone and shale  
 24  
 25  
 2456 grains.

## 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65

5.2. *The Cathaysia block as a source of sand*

3459 The Cathaysia block comprises diverse geological domains characterized by partly different  
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 3451 lithological assemblages and thus shedding detritus with partly different compositional signatures:  
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 37  
 3762 a) the Yunkai and Nanling terranes in the south; b) the Wuyi terrane in the north, bounded by the  
 38  
 39  
 4063 Jiangnan orogen farther north; and, c) the SE Coast Magmatic Belt in the east ([Fig. 2](#)).

4064 The Xinxing River draining the Yunkai terrane south of the Pearl River, and the He, Bei, and Dong  
 43  
 44  
 4455 Rivers draining the Nanling terrane north of the Pearl River, all carry feldspatho-quartzose sand  
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 46  
 4466 with K-feldspar largely prevailing over plagioclase, some metamorphic detritus (low-rank to  
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 49  
 4967 medium-rank metasedimentary grains and mica), and very poor tHM suites with common  
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 5068 hornblende or locally andalusite and other minerals contained in medium-grade metasedimentary  
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 5469 rocks (garnet, sillimanite, staurolite, or kyanite). Sand of the Gui and upper Bei Rivers contain a  
 55  
 56  
 5470 little more carbonate and very-low-rank metasedimentary grains, respectively. Amphibole decreases  
 58  
 59  
 5971 steadily from west to east. Common andalusite with unoriented carbonaceous inclusions associated

with sillimanite in Dong sand may be derived from graphitic metapelites in the contact aureole of Jurassic-Cretaceous granites (Tong and Tobish, 1996).

Sand shed by the Wuyi terrane and carried by the Han and Jiulong Rivers shares a similar signature. Differences include some more quartz and volcanic rock fragments, and less sedimentary rock fragments. Han sand contains more zircon, and Jiulong sand more epidote. Instead, sand generated in the Mulanxi, Min and Ou catchments farther north is compositionally distinct. Volcanic detritus from the SE Coast Magmatic Belt is testified by felsic volcanic grains, most common in the Ou catchment where volcanic rocks are most abundant (Fig. 4), and by poor, epidote-dominated tHM suites only locally including some clinopyroxene, minor olivine, and rare Cr-spinel.

Although the Xiang and Gan Rivers drain also the Jiangnan orogen in their lowermost course, their sand has detrital modes similar to Jiulong sand and nearly identical to Han sand, indicating that sediment is dominantly generated in the Cathaysia block. Topaz grains, quite common in Xiang sand and frequently detected in sediment generated all across the Cathaysia block from the Liu catchment in the west to the Han catchment in the east, are presumably derived from topaz-bearing peraluminous granites and felsic subvolcanic rocks of both Late Triassic (Indosinian) and Jurassic-Cretaceous (Yanshanian) ages, peculiar of SE China and typically associated with tungsten and tin ore deposits (Ottens and Cook, 2005; Yu et al., 2007).

### 5.3. Sediment budget and erosion rates in the Pearl River catchment

Within a drainage basin, the relative sediment contribution from different geological units or different tributaries (i.e., provenance budget) can be assessed by forward mixing calculations based on a complete set of petrographic and mineralogical data (method and pitfalls illustrated and discussed in Garzanti et al., 2007, 2012). If information on gauged sediment loads is available, then sediment yields from different geological units or different tributaries (i.e., sediment budget) and an average erosion rate in each catchment can be estimated. The procedure, largely empirical and based on a series of untested assumptions, suffers from several

199 sources of uncertainty. The major source of error stems from chronically incomplete and  
200 inaccurate data on sediment loads, and especially on bedload that is generally roughly  
201 considered to represent ~5-10% of suspended load on average ([Milliman and Farnsworth, 2013](#)  
202 p.24).

203 In theory, the proportional supply from diverse sediment sources can be robustly constrained  
204 whenever the signature of each source is sufficiently well differentiated by a wide set of  
205 compositional parameters. In practice, the accuracy of results is limited by a variety of factors.  
206 These include grain-size-dependent or seasonal variability of sediment composition in each  
207 river, selective loss of mechanically (e.g., shale) or chemically (e.g., carbonate) labile grains  
208 during sediment generation and transport, hydraulic-sorting effects during erosion, transport and  
209 deposition, irregular distribution in time and space of easily eroded recent deposits (e.g.,  
210 landslides, terraces, moraines), imperfect sediment mixing and homogenization along the river,  
211 field sampling or laboratory procedures failing to satisfying in full requirements of  
212 reproducibility and representativeness, and errors during analysis. Only a few of these undesired  
213 effects can be tested. Moreover, data on sand can be extrapolated to the entire sediment flux only  
214 under the fragile assumption that mud is supplied in the same proportion as sand in each  
215 catchment.

216 Uncertainties can be minimized by collecting replicate samples especially in the deltaic region,  
217 and by performing multiple series of calculations according to a range of plausible criteria which  
218 simultaneously satisfy best-fit conditions for diverse successive tracts of the river system (e.g.,  
219 [Vezzoli et al., 2020](#)). In the Pearl River, we analysed four samples along the Qian, Xun, and Xi  
220 tracts, and four samples with different grain size in the delta and estuary. Nevertheless, because  
221 of the marked compositional variability observed in the coastal region, characterized by a very  
222 complex network of distributaries, the mineralogical signature of sediment delivered to the  
223 South China Sea could not be assessed precisely.

1 24 With these limitations, we calculated that 35-40% of Pearl River sand is generated from mostly  
 2  
 3  
 4 25 sedimentary and mafic volcanic rocks of the Yangtze block in the western upstream reaches, and  
 5  
 6 26 60-65% from mostly felsic igneous and sedimentary rocks of the Cathaysia block in the eastern  
 7  
 8 27 reaches. Sand is contributed in similar amount from each major tributary (~15% from the  
 9  
 10  
 11 28 Hongshui, and 10-15% each from the Yu, Liu, Gui, He, Bei, Dong). Based on gauged  
 12  
 13 29 suspended-load data (Table 1), and on the assumptions that grain density is 2.67 g/cm<sup>3</sup> as  
 14  
 15  
 16 30 indicated by mineralogical data (SRD index of Garzanti and Andò, 2007) and that bedload  
 17  
 18 31 represents 10% of suspended load, the annual sediment yield and erosion rate averaged across  
 19  
 20  
 21 32 the catchment are assessed as 160-210 t/km<sup>2</sup> and 0.06-0.08 mm, respectively. Forward mixing  
 22  
 23 33 calculations and suspended-load data converge to indicate that erosion rates are distributed rather  
 24  
 25  
 26 34 evenly, ranging mostly between 0.05 and 0.1 mm/a and reaching slightly higher values in the  
 27  
 28 35 headwaters where topographic relief is greater (up to ~0.2 mm/a in the Beipan catchment) (Table  
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 30  
 31 36 1). Extensive chemical erosion in carbonate-dominated areas, as discussed in section 6,  
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 33 37 contributes to reduce solid sediment supply to the South China Sea.

#### 34 35 38 36 37 39 *5.4. Evaluating polycyclic*

38 40 Although it has long been known that a large percentage of sand is generated by recycling of parent  
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 42 41 sandstones, estimating the relative amount of polycyclic detritus proves to be exceedingly difficult  
 43  
 44 42 even in modern settings (Blatt, 1967; Garzanti et al., 2019). Direct petrographic evidence of  
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 47 43 polycyclic origin is limited to abraded overgrowths and sandstone, siltstone, or shale rock fragments  
 48  
 49 44 (Johnsson et al., 1988 p.275; Basu, 2017). Only unrobust semiquantitative inferences can thus be  
 50  
 51  
 52 45 drawn. Considering that quartz and ZTR minerals are the most durable detrital components, and  
 53  
 54 46 therefore the most likely to survive multiple sedimentary cycles, quartz abundance and ZTR-rich  
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 56  
 57 47 depleted tHM suites may be used as indicators of the extent of recycling. It must be kept in mind,  
 58  
 59 48 however, that even labile grains are recycled in abundance in weathering-limited regime, and that  
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the effect of selective chemical breakdown attained during diagenesis and inherited during recycling is hardly discriminated from that of intense weathering (Garzanti, 2017).

In South China, quartz abundance is largely controlled by provenance, being markedly more abundant in sand derived from the Cathaysia block than from largely carbonates and basalts of the Yangtze block. Quartz grains with abraded overgrowths are ubiquitous and locally quite common (e.g., Liu catchment), terrigenous rock fragments widespread, and tHM suites invariably poor and mostly very poor, testifying to extensive recycling. Poor tHM suites, however, are also characteristic of detritus shed by low-density – and consequently dense-mineral-poor (Garzanti et al., 2006) – granitic rocks, which are widespread in the Cathaysia block.

As a gross mineralogical indicator of recycling, we may use the Q/F ratio to empirically subdivide the studied samples as follows: A)  $Q/F \leq 2$ , largely first cycle; B)  $Q/F$  2.5-3, partly recycled; C)  $Q/F$  3-4, significantly recycled; D)  $Q/F$  4.5-5.5 extensively recycled ; E) 7-10 mostly recycled; F) 15-20, dominantly recycled. No studied sand displays  $Q/F < 1.5$  or  $> 20$ . Group A only includes Nanxi (northern tributary of the Ou River) and Mulanxi sand dominantly derived from granites and felsic volcanic rocks of the SE Coast Magmatic Belt (eastern Cathaysia). Group B includes He, Bei and Xinxing sand derived from the Nanling and Yunkai terranes (western Cathaysia). Group C includes Rong, Gui, Dong, Jiulong, Gan, and mixed Pearl River sand. Group D includes Han and Min sand mainly derived from the Wuyi terrane, as well as Xiang sand to the north and Bazhang sand in Taiwan. Group E includes Hongshui, Yu, and Long sand derived from cover rocks of the Yangtze block as well as Yuan sand to the north and Houlong and Tsengwen sand in Taiwan. Finally, group F includes Beipan, Liu, and Wu sand draining cover rocks of the Yangtze block in the northwestern part of the study area.

### 5.6. Assessing provenance of Taiwan sandstones

One goal of this study is to establish which specific river system and region of the Chinese mainland originally fed siliciclastic detritus now incorporated in sandstones accreted to the western Taiwan foothills and recycled in modern sand of western Taiwan rivers. Three main possible sources are confronted here: 1) a paleo-Pearl River feeding the South China Sea in the southwest (e.g., figure 9b in Yokoyama et al., 2007); 2) coastal rivers feeding the Taiwan Strait in the west (e.g., Chen et al., 2006; Xu et al., 2014); 3) a paleo-Yangtze River feeding the East China Sea in the north (e.g., figure 9a in Yokoyama et al., 2007; Deng et al., 2017).

A direct comparison with detrital modes of modern sand could have provided a straightforward answer but is precluded because the original mineralogical signature of Taiwan sandstones has undergone significant diagenetic modifications. As a consequence of post-depositional dissolution of unstable minerals, Neogene sandstones of the western Taiwan foothills are notably enriched in durable zircon, tourmaline, rutile, garnet, and apatite (Fig. 5D). This is most clearly shown by sandstones from the TSW core (diagenetic minerofacies 4 of Garzanti et al., 2018, indicating moderate-deep burial). Such a relative enrichment in durable minerals is inherited in modern sands, which display a higher Q/F ratio and more sedimentary rock fragments than their parent sandstones as an effect of progressively increasing detritus recycled from sedimentary rocks of the outer western foothills through time (figure 5 in Nagel et al., 2014). Additional supply of shale and/or carbonate rock fragments from mudrocks and/or carbonates interbedded in source rocks is a common result of physical recycling (Garzanti, 2017).

Because of these reasons, a comparison between Taiwan sandstones and modern sand of the Chinese mainland can be based on the relative proportions of durable minerals only (Fig. 6). Such an approach, similar to what currently done in the correlation of hydrocarbon reservoir sandstones (Morton and Hallsworth, 1994; Morton and McGill, 2018), has large uncertainties but allows us to rule out coastal rivers draining the Wuyi terrane and the SE Coast Magmatic Belt as the dominant source, suggesting that Neogene Taiwan sandstones were fed by a major river system, either a

1 paleo-Pearl in the south or a paleo-Yangtze in the north. These two potential sources may be  
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 4 601 discriminated by zircon-age data, although even this method has significant limitations. Age-spectra  
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 6 602 may be strongly distorted by fertility effects and heavily biased in favour of felsic igneous and  
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 8 603 metaigneous sources. Moreover, zircon grains recycled even several times from siliciclastic rocks  
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 11 604 cannot be distinguished from first-cycle grains derived directly from basement rocks.

12  
 13 605 The comparison of zircon-age data from modern sand of the Zhuoshui and Lanyang Rivers –  
 14  
 15  
 16 606 respectively the largest in western Taiwan and the largest in eastern Taiwan draining exclusively  
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 19 607 Eocene-Miocene strata of the Hsuehshan and central ranges (Deng et al., 2017) – with datasets from  
 20  
 21 608 various parts of mainland China, including the Pearl River (He et al., 2019), rivers of SE China (Xu  
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 23 609 et al., 2007; Xu et al. 2014, 2016), and the Yangtze River (He et al., 2013) provide crucial help. Age  
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 25  
 26 610 spectra in Figure 7 show much greater affinity of Zhuoshui zircons with Yangtze rather than Pearl  
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 28  
 29 611 River zircons, as highlighted further by MDS analysis (Fig. 8). Neogene sandstones of the western  
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 31 612 Taiwan foothills were thus originally supplied principally by a paleo-Yangtze River.

32  
 33 613 Yangtze sediments entrained for ~ 1000 km by prevailing southward marine currents (figure 11 in  
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 36 614 Deng et al., 2017) were deposited on the Chinese passive margin offshore of the present Fujian  
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 39 615 Province and eventually uplifted and tectonically incorporated in the Taiwan accretionary prism  
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 41 616 since ~6 Ma (Byrne et al., 2011). As noted by Deng et al. (2017), the zircon signature of Lanyang  
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 44 617 sand is distinct, reflecting dominant ultimate provenance from the Cathaysia block in pre-Neogene  
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 46 618 times, thus constraining the timing of the early development of the Yangtze river system (Zheng et  
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 48 619 al., 2013; Zheng, 2015).

## 50 620 51 52 621 **6. Weathering control on sand composition**

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 56 622 Tropical to subtropical South China is characterized by a strong climatic gradient, with intensity of  
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 59 623 annual rainfall that increases steadily from the dry edge of the Tibetan plateau to the humid coastal  
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 61 624 region heavily hit by the East Asia monsoon (Fig. 3). The different climatic and geomorphologic  
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conditions in the west and in the east, coupled with notably different source-rock lithologies, account for different weathering regimes, reflected in the distinct mineralogy and geochemistry of sediments generated in the Yangtze and Cathaysia blocks.

### 6.1. Weathering in the Yangtze block: carbonate grains as weathering tracers

Carbonate strata are widely exposed in western South China and represent a third to more than half of the Wu, Hongshui, Yu, Liu, and Gui catchments (Table 3). None of these rivers, however, carry a corresponding amount of carbonate detritus. Limestone grains, associated with rare dolostone grains in Yu and Beipan sand, represent 15-16% of Hongshui and Yu sand but only 3% of Gui sand,  $\leq 1\%$  of Zuo, Long, and Bei sand, and are undetected in Liu and He sand. Downstream, limestone and rare dolostone grains represent only 2-3% of Qian, Xun, and Xi sand and are undetected in Pearl River delta and estuary sand. XRD data on fine silt ( $<15 \mu\text{m}$  fraction) reveals the presence of carbonate particles (3-5%) in Beipan, Yu, and Long mud, and geochemical data confirms that carbonate detritus is common in Yu mud and Beipan and You sand, and significant in Beipan and Long mud and in Zuo, Long and Nanpan tributary sand (He et al., companion). In all these catchments, the areal exposure of carbonate rocks far exceeds the percentage of carbonate grains (as quantitatively discussed in subsection 6.4) but two regions are distinguished: 1) a western region drained by the Wu and Hongshui Rivers, where annual rainfall is  $\sim 1 \text{ m}$  and carbonate grains are preserved although strongly reduced in amount; and, 2) an eastern region drained by the Liu and Gui Rivers, where annual rainfall is  $\sim 1.5 \text{ m}$  and carbonate grains are rare to negligible. The sharp contrast in the effectiveness of carbonate dissolution in these two regions calls for an explanation that takes into account the peculiarity of geomorphic processes in this wide carbonate domain.

### 6.2. Karst processes in South China

Thousands of m-thick Devonian to Triassic carbonates exposed in South China are part of one of the world's largest and most spectacular karst terrain (Tang, 2002; Han and Liu, 2004). Two types

of karstic landscapes are identified. *Fengcong* (cone) *karst* (in Chinese *feng*, hill, and *cong*, clustered), dominant in the Yunnan, western Guangxi, and Guizhou Provinces, is characterized by deep dolines and residual conical hills standing on a common base of carbonate bedrock and by mostly underground drainage through a long and deep system of caves. *Fenglin* (tower) *karst* (in Chinese *feng*, hill, and *lin*, isolated), dominant in the eastern Guangxi Province, is an even more advanced form of karst characterized by isolated rock towers rising for 100 m or more from an alluvial plain typically covered by rice paddies. In hot-wet climate with abundant biogenic carbon dioxide and presence of sulfuric acid, bedrock limestone is undercut by dissolution at the water table, promoting gravitational collapse and consequent retreat of vertical cliffs. Fluvial drainage is associated with significant groundwater flow but great caves or large springs do not occur.

In an ideal temporal sequence, tropical karst originating from a peneplaned limestone surface progresses from an initial stage of doline karst, to *fengcong karst* when dolines enlarge and coalesce to the point of leaving residual conical hills, and next continues to evolve until the doline floor reaches base level. At this point the process changes from surface lowering to lateral planation, thus developing *fenglin karst* (Waltham, 2010).

### 6.3. Chemical breakdown of carbonate grains in different karst terrains

Karst coverage is estimated to represent 64% of the Hongshui catchment, 42% and 39% of the Yu and Liu catchments, respectively, and as much as 44% of the entire Pearl River basin upstream of the Bei confluence (Li et al., 2016). If in each catchment we compare the percentage of carbonate grains in sand with the extent of karst coverage, then we find ratios between 23% (Hongshui) and 42% (Yu) in terrains characterized by *fengcong karst*. Ratios drop drastically in terrains characterized by *fenglin karst*, where they approach (Gui, Zuo, Long and Bei catchments) or even reach 0% (Liu and He catchments). The same ratios calculated for mud (data from He et al., companion) are consistently lower than for sand, and range 10-15% for the Yu, Beipan and Long Rivers and 0% for the He tributary and Pearl River delta. Carbonate grains are thus reduced to

between less than half and a fifth in sand and to between one sixth and one tenth in mud in terrains characterized by *fengcong karst*, where residual conic hills still share a common base of carbonate bedrock. Instead, they are completely or quasi-completely dissolved in terrains characterized by *fenglin karst*, where tower-like residual rock outcrops are separated by an alluvial plain underlain by a water table containing abundant dissolved carbon dioxide.

In the monsoon-drenched lower reaches of the Pearl River, carbonate sand grains survive in minor amount as far as downstream of the Bei confluence (ratios to carbonate exposures range 5-9% in the Xun to Xi tracts) but were not detected in Pearl River estuary and delta sand and mud, testifying to virtually complete chemical dissolution of carbonate detritus before reaching the South China Sea.

In the upper reaches of the Yangtze River, carbonate grains are quite common in all tributaries and in the trunk river as far as the Three Gorges, tend to decrease downstream but are still common at Wuhan, and are preserved as far as the mouth (Vezzoli et al., 2016).

#### 6.4. Sand generation indices as weathering tracers

The sand generation index SGI is defined as the capacity of a given rock unit A to generate sand relative to other rock units (Palomares and Arribas, 1993). Under the assumption of uniform erosion rate across the considered source area, the SGI of rock unit A is dependent only on its mineralogical and textural characteristics and can be calculated as the ratio between its proportional sand contribution  $S_A/S$  and its proportional outcrop area  $A_A/A$  ( $SGI = \frac{S_A}{S} \frac{A}{A_A}$ ; Vezzoli et al., 2004, 2020).

Patterns of variations in SGI indices can be used to investigate how sand-production rates vary for diverse rock types in different climatic and geomorphological settings across southern China. The proportional sand contributions  $S_A/S$  for each major rock type in each subcatchment were calculated by reapportioning petrographic and mineralogical data (Table 1) as follows: **carbonate** -> carbonate grains; **basalt** -> mafic volcanic grains and pyroxene; **granite** -> the part of quartz and feldspar grains in proportion 1:2 (considered typical of granitoid rocks) that leaves excess quartz and

feldspar in proportion ~10:1 (considered typical of sandstone); **schist** -> metamorphic grains and metamorphic heavy minerals; **clastics** -> terrigenous rocks fragments, ZTR minerals, excess quartz and feldspar. Felsic volcanic rock fragments were assigned to “basalt” in the Yangtze block and to “granite” in the Cathaysia block. Proportional outcrop areas  $A_A/A$  for each subcatchment are from [Table 3](#). Results are displayed in [Fig. 10](#), where the “granite” category comprises schist, and the “clastic” category includes sandstone and mudrock.

Although SGI calculations are approximate, the SGI readily reveals which lithologies are under-represented in detrital assemblages relative to their outcrop area, and which are consequently over-represented. The carbonate SGI highlights the stark contrast between *fengcong karst*, where half of carbonate detritus may survive dissolution, and *fenglin karst*, where carbonate dissolution is virtually complete. The basalt SGI suggests that basaltic detritus survives in drier climate but is prone to be weathered out in humid climate. The granite SGI indicates that feldspar grains persist in drier climate but especially plagioclase starts to be weathered and destroyed as climate becomes wetter and wetter eastwards in the Pearl River catchment or southward along coastal SE China. The SGI, therefore, turned out to be a most useful parameter to highlight the link between climatic gradients and different regimes of sand generation across South China ([Fig. 10](#)).

### 6.5. Weathering in the Cathaysia block: tectosilicates as weathering tracers

Diverse mineralogical and geochemical parameters indicate that weathering conditions become progressively more intense from west to east across South China, associated with higher rainfall fuelled by the East Asia monsoon ([Fig. 3](#)). Kaolinite represents an increasing percentage of clay minerals from the headwater to lower course tributaries of the Pearl River, reaching maximum in Dong mud, decreasing progressively with increasing latitude along the coast, and decreasing further away from the coast in southern tributaries of the Yangtze ([He et al., companion](#)). Geochemical proxies follow a similar pattern, but are affected far more than clay mineralogy by multiple controls. This is particularly true for sand, where the influence of parent-rock lithology may be

overwhelming (Garzanti and Resentini, 2016). Extracting weathering information from sand composition is therefore challenging (Fig. 11).

Sand carried by rivers of coastal SE China displays clear mineralogical trends. From north to south, quartz increases ( $r = 0.85$ ) at the expense especially of volcanic and other lithic fragments ( $r = -0.82$ ).

The Mic\*/F ratio and ZTR minerals also tend to increase ( $r = 0.69$  in both cases), whereas the P/F ratio and epidote decrease ( $r = -0.71$  and  $-0.76$ ). The probability that correlation coefficients  $r > 0.63$ ,  $> 0.72$ , and  $> 0.77$  are obtained by chance with 10 data points are less than 5%, 2%, and 1%, respectively (Lee and Lee, 1982), which gives us confidence that these trends are real.

The most durable tectosilicates (i.e., quartz and microcline\*) and ZTR minerals tend to increase southward, which suggests that these trends are at least partly controlled by southward increase of rainfall intensity and weathering conditions (Fig. 3). Comparable mineralogical trends from drier western catchments to wetter eastern catchments in the Pearl and Yangtze river basins are, however, less clear. The Q/F ratio does increase but the relative proportions among feldspars are virtually unchanged from He sand in the west to Dong sand in the more humid east. All mineralogical parameters are very similar in sand of the Xiang and Gan tributaries of the Yangtze and in Han sand in the wetter south, which is most readily explained by similar provenance, all three rivers draining the Wuyi terrane of western Cathaysia (Fig. 2).

Mineralogical signatures of sand generated in the Cathaysia block are primarily controlled by different lithologies in different terranes (Fig. 11), namely dominant Yanshanian plutonic and volcanic rocks in eastern Cathaysia and older granitoid rocks in western Cathaysia (Fig. 8). Detrital modes are also strongly influenced by widespread recycling of siliciclastic strata, and discriminating the effect of weathering (chemical dissolution in the present sedimentary cycle) from that of recycling (chemical dissolution during previous cycles of weathering and diagenesis) remains elusive.

## 6.6. Chemical indices as weathering tracers

760  
 761 The interplaying effects of source-rock lithology, recycling, and weathering may be detangled by  
 762 integrating mineralogical and geochemical data. In strong weathering conditions, mobile alkali and  
 763 alkaline-earth metals are expected to behave coherently (i.e., to be all depleted, although to different  
 764 degrees depending on the durability of hosting minerals), implying positively correlated  $\alpha^{\text{Al}}$  values  
 765 all > 1. Inspection of Fig. 12, instead, shows a sharp anticorrelation between two groups of mobile  
 766 elements. K, Rb and Ba, hosted principally in K-feldspar and muscovite, are undepleted or even  
 767 enriched relative to the UCC standard in sand largely derived from granites and schists of the  
 768 Cathaysia block and Jiangnan orogen. Conversely, Ca, Mg, and Sr are undepleted or only scarcely  
 769 depleted in detritus derived from carbonates and basaltic rocks of the Yangtze block (He et al.,  
 770 companion). This behaviour matches what observed along the pro-side and retro-side of the Taiwan  
 771 orogen (e.g., figure 10 in Garzanti and Resentini, 2016), indicating that the weathering effect is  
 772 overwhelmed by the effect of source-rock lithology in sand generated in both southern China and  
 773 Taiwan. The extent of recycling may be qualitatively evaluated by mineralogical and geochemical  
 774 proxies (i.e., ZTR index and CIA/WIP ratio; Garzanti et al., 2019) but no mineralogical or  
 775 geochemical parameter can be considered as a faithful indicator of weathering,

#### 6.7. Heavy minerals as weathering tracers

778  
 779 The degree of corrosion and the percentage of etched grains for each detrital mineral provides direct  
 780 textural evidence of chemical attack (Andò et al., 2012). Surficial features, however, tell us the state  
 781 of what is preserved but nothing about how much was destroyed. Downstream of the Pearl River,  
 782 from the western Hongshui branch to the South China Sea, corrosion indices tend to increase for all  
 783 minerals (r 0.83, sign. lev. 2%), more clearly for epidote (r 0.89) but erratically for pyroxene and  
 784 only imperceptibly for amphibole and garnet. Corroded tourmaline grains first appear in the Xi  
 785 tract and represent one tenth and a third of total tourmaline grains in deltaic and shelf sand,  
 786 respectively. A few corroded zircon grains first appear in deltaic sand and represent one fifth of

total zircon grains offshore. In river sand of the SE China coast, corrosion indices are somewhat higher, but do not show any apparent trend from north to south. Similarly, no trend is displayed in sand of southern Yangtze tributaries from west to east.

Pyroxene, one of the least chemically durable minerals at the Earth's surface, is preserved along the course of the Pearl River, where it is progressively diluted downstream by pyroxene-poor sand derived from the western Cathaysia block. The same trend chiefly ascribed to progressive dilution is observed along the Yangtze River, where augite, shed in abundance by the Emeishan Traps in the upper course, persists downstream and represents 5-10% of the tHM suite as far as the mouth. Instead, pyroxene is mostly lacking in rivers of coastal SE China. The only exceptions are the Min River, which carries some corroded to uncorroded augite and minor olivine, and the Beixi tributary of the Jiulong River, which carries mostly uncorroded hypersthene. Although richest in volcanic detritus from the SE Coast Magmatic Belt widely exposed in the Zhejiang province (Fig. 4), Ou sand lacks pyroxene, which suggests complete chemical dissolution. The relative abundance of heavy minerals and their degree of surficial corrosion do provide complementary, but largely qualitative to semiquantitative hints on the intensity of weathering in South China.

## 7. Conclusion

We have combined petrographic and mineralogical data on sand with the geochemical and clay-mineral data presented in the companion paper (He et al., companion) to study processes of sediment production and dispersal in the wide region of southern China including the Pearl River, the southern tributaries of the Yangtze, and coastal rivers draining the Fujian and Zhejiang Provinces between the two big rivers' mouths. Southern China can be subdivided into two major geological domains, the Yangtze and Cathaysia blocks. Quartzo-lithic sedimentary sand with augite is shed by the extensive sedimentary and basaltic covers of the Yangtze block, whereas mainly granitic and sedimentary rocks of western

~~813~~<sub>1</sub> Cathaysia generate feldspatho-quartzose sand including amphibole, epidote, zircon, and tourmaline.  
~~814~~<sub>2</sub> Mesozoic magmatic rocks of eastern Cathaysia shed feldspatho-litho-quartzose sand with epidote.  
~~815~~<sub>3</sub> The dominance of sedimentary and granitic rocks throughout this vast region is reflected in  
~~816~~<sub>4</sub> invariably poor heavy-mineral suites which, together with the occurrence of common terrigenous  
~~817~~<sub>5</sub> rock fragments and quartz grains with abraded overgrowths, indicates that sediment generated in  
~~818~~<sub>6</sub> southern China is largely polycyclic. An accurate assessment of the amount of first-cycle *versus*  
~~819~~<sub>7</sub> recycled detritus, however, remains prohibitive.  
~~820~~<sub>8</sub> Mineralogical signatures in different parts of the Pearl River catchment are sufficiently distinctive  
~~821~~<sub>9</sub> to estimate that 35-40% of Pearl River sand is generated from mostly sedimentary and mafic  
~~822~~<sub>10</sub> volcanic rocks of the Yangtze block in the western upstream reaches, and 60-65% from mostly  
~~823~~<sub>11</sub> felsic igneous and sedimentary rocks of the Cathaysia block in the eastern reaches. Major tributaries  
~~824~~<sub>12</sub> supply detritus in subequal proportions, and erosion rates are distributed rather evenly across the  
~~825~~<sub>13</sub> drainage basin, reaching ~0.2 mm/a in the Hongshui catchment where topographic relief is greater.  
~~826~~<sub>14</sub> As an attempt to envisage how the present dispersal system operated in the past, we compared  
~~827~~<sub>15</sub> petrographic and heavy-mineral data on modern sand and Neogene sandstones, complemented by  
~~828~~<sub>16</sub> zircon-geochronology data from the literature, to identify the ultimate sources of siliciclastic  
~~829~~<sub>17</sub> detritus originally generated in mainland China and now incorporated in, and recycled from, the  
~~830~~<sub>18</sub> Taiwan accretionary prism. It is suggested that sediment supplied by a paleo-Yangtze River was  
~~831~~<sub>19</sub> entrained for ~1000 km southward by marine currents and deposited on the Chinese passive margin  
~~832~~<sub>20</sub> before being accreted at the front of the Taiwan orogen since ~6 Ma.  
~~833~~<sub>21</sub> A most interesting peculiarity of the western part of the studied region is the extensive exposure of  
~~834~~<sub>22</sub> upper Paleozoic to Triassic carbonate rocks, which makes it one of the best known karst areas on  
~~835~~<sub>23</sub> Earth. Two types of karstic landscapes are distinguished by the sharply different effectiveness of  
~~836~~<sub>24</sub> chemical dissolution. Carbonate grains are attacked by carbonic and sulfuric acids but partly  
~~837~~<sub>25</sub> preserved in *fengcong* (cone) *karst*, developed in the Yunnan, Guizhou, and western Guangxi

838 Provinces, whereas they are completely dissolved in *fenglin* (tower) *karst*, a more advanced form  
 839 of karst developed in the wetter central-eastern Guangxi Province.

840 Other factors that can be exploited to trace weathering processes include the different durability of  
 841 tectosilicates or the degree of surficial corrosion displayed by heavy minerals. These variables do  
 842 offer useful but largely qualitative to semi-quantitative complementary information, and fail to  
 843 provide robust proxies for weathering intensity. Although calculations are rough, the sand  
 844 generation index SGI readily reveals which lithologies are under-represented in detrital assemblages  
 845 relative to their outcrop area, and which are consequently over-represented. The SGI thus resulted  
 846 to be a most useful parameter to trace the different regimes of sand generation as closely linked to  
 847 the strong climatic gradients characterizing South China.

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## 862 **Supplementary Materials**

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Supplementary data associated with this article, to be found in the online version at <http://dx.doi>  
\_\_\_\_\_, include information on sampling sites (Table A1), petrographic data (Table A2), and  
heavy-mineral data with frequency of corrosion features (Tables A3 and A4). The Google-Earth™  
map of sampling sites [PearlProv.kmz](#) is also provided.

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869 FIGURE AND TABLE CAPTIONS

870

871 **Figure 1.** Topography and drainage in tropical and subtropical southern China with sampling sites.

872 PRD: Pearl River Delta.

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874 **Figure 2.** Tectonic sketch map of southern China (redrawn after the 1:12 000 000 tectonic map of

875 China) with numbered sampling sites. Two blue dashed lines indicate hypothetical boundaries

876 between the Yangtze and Cathaysia blocks (Zhao and Cawood, 2012). **Geological domains:** CF:

877 Chuandian Fragment; ELIP: Emeishan Large Igneous Province; JO: Jiangnan Orogen; QDO:

878 Qinling-Dabie Orogen; SG: Songpan-Ganzi; SWSB: Shiwandashan Structural Belt; YB: Youjiang

879 Basin. **Main faults:** ALF: Anhua-Luocheng, JSF: Jiangshan-Shaoxi; LMF: Longmenshan; RRF:

880 Red River; TLF: Tan-Lu; ZDF: Zhenghe-Dapu. **Taiwan:** CP: Coastal Plain; CR: Central Range;

881 HR: Hsuehshan Range; OR: Coastal Range; WF: Western Foothills.

882

883 **Figure 3.** Rainfall map of SE China (after <http://www.chinawater.com.cn>) with numbered sampling

884 sites.

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886 **Figure 4.** Geological map of SE China with sampling sites (after [China Geological Map](#)).

887

888 **Figure 5.** Petrography and mineralogy of river sand in southern China and Taiwan. **A)** Array of

889 detrital modes from quartzo-lithic in the Hongshui catchment to feldspatho-quartzose in several

890 coastal rivers of SE China. **B)** Felsic volcanic lithics are dominant in rivers draining the SE Coast

891 Magmatic Belt, whereas sedimentary and mafic volcanic lithics characterize headwater Pearl River

892 tributaries draining the Yangtze block. Metamorphic lithics prevail in sand of Pearl River tributaries

893 draining the Cathaysia block. **C)** The biplot (explanation in [subsection 3.3](#)) discriminates three main

894 provenances: a high-ZTR suite recycled from siliciclastic cover strata, a high-clinopyroxene suite

shed from the Emeishan Traps, and a richer amphibole-epidote suite shed from the Cathaysia block.

**D)** Array of heavy-mineral modes indicating dominant durable minerals in Miocene to modern Taiwan sediments (data from Ta'an and Tsw cores after Nagel et al., 2014). Q = quartz; F = feldspars; L = lithics (Lm = metamorphic; Lv = volcanic; Ls = sedimentary); tHMC = transparent heavy-mineral concentration: ZTR = zircon + tourmaline + rutile; Grt = garnet; Ap = apatite; Amp = amphibole; Ep = epidote; Px = pyroxene.

**Figure 6.** Investigating the ultimate provenance of Neogene Taiwan sandstones (biplot explained in subsection 3.3). An excess of recycled sedimentary rock fragments and depleted tHM suites relatively enriched in durable minerals precludes direct comparison with modern sand generated in the Chinese mainland. The comparison of the relative proportions of quartz (Q), K-feldspar (KF), plagioclase (Pl), volcanic lithics (Lv) and durable transparent heavy minerals allows us to discard coastal rivers of SE China and the Cathaysia block as the unique original source. Taiwan sandstones were derived from a larger fluvial system, either the Yangtze in the north or the Pearl River in the south.

**Figure 7.** U-Pb age spectra of detrital zircon as a complementary means to constrain provenance of Neogene Taiwan sandstones. Early to late Yanshanian (IYe) zircons are dominant in rivers of coastal SE China draining eastern Cathaysia, whereas the three Yanshanian, Indosinian (I) and Wuyi-Yunkai (WY) peaks are the fingerprint of Pearl River sand. Yangtze zircons have much more abundant Jiangnan (J) ages and significant Lüliangian (L) and Wutai-Fuping (WF) clusters reflecting ultimate provenance from the older Yangtze block. Zhuoshui River zircons display all six modes (Yanshanian to Wutai-Fuping) indicating affinity with Yangtze zircons. Lanyang River zircons, instead, display prominent Yanshanian and Wuyi-Yunkai peaks, indicating major contribution from the Cathaysia block in pre-Neogene time (figure 9 in Deng et al., 2017). Sources

of zircon ages: Zhuoshui River and compilations for eastern Cathaysia, western Cathaysia, and Yangtze blocks after [Deng et al. \(2017\)](#); Yangtze River and tributaries after [He et al. \(2013\)](#); Pearl River and tributaries after [Xu et al. \(2007\)](#), [Zhao et al. \(2015\)](#), [Liu et al. \(2017\)](#), [Zhong et al. \(2017\)](#), and [He et al. \(2019\)](#).

**Figure 8.** MDS map based on U-Pb age spectra of detrital zircon in modern sand (MDS explained in [subsection 3.3](#)). The ultimate provenance of multicyclic detritus in western Taiwan is constrained by comparison with data from Pearl River (rhombs for mainstem, triangles for tributaries, names in brown; from [Xu et al., 2007](#), [Zhao et al., 2015](#), [Liu et al., 2017](#), [Zhong et al., 2017](#), and [He et al., 2019](#)), rivers in coastal SE China (circles, names in orange; from [Xu et al., 2007](#) and [Xu et al., 2014](#)), and Yangtze (stars for mainstem, squares for tributaries, names in blue; from [He et al., 2013](#)). Detrital zircons in the Zhuoshui River draining western Taiwan (data from [Deng et al., 2017](#)) indicate affinity with Yangtze rather than Pearl River zircons, and minimal affinity with zircons in rivers of coastal SE China.

**Figure 9.** Areal distribution of *fengcong* and *fenglin karst* (after [Waltham, 2010](#)) versus carbonate detritus in sand and mud (geochemical and XRD data after [He et al., companion](#)). Carbonate grains are drastically depleted but survive in Wu, Hongshui and Yu catchments characterized by *fengcong karst* but are almost completely dissolved in catchments characterized by *fenglin karst*.

**Figure 10.** Sediment generation indices for carbonate (yellow), basaltic (purple), clastic (grey), and granitic rocks (light blue). In the Yangtze block, the SGI is  $\geq 1$  for clastics, basalt, and granite (**A**). The carbonate SGI is  $\sim 0.5$  in *fengcong karst* but goes to 0 in the wetter eastern Guangxi Province characterized by *fenglin karst*, where the clastics SGI consequently increases sharply (**B**). The SGI for basalt, carbonate and granite decreases steadily towards the Pearl River mouth, and the SGI for

clastics consequently increases (C). In the Cathaysia block, the granite SGI decreases eastward in the Pearl River catchment (D) and increases instead northward in costal rivers (E), reflecting trends in weathering intensity controlled by rainfall gradients; the clastics SGI follows a specular path. The SGI remains <0.1 for carbonate, <1 for granite, and >1 for clastics in eastern Yangtze tributaries (F).

**Figure 11.** Modern sand generated in the Cathaysia block (biplot explained in subsection 3.3).

Anticorrelation between quartz (Q) and microcline (Mic\*), which is the most durable detrital feldspar, and lack of correlation with plagioclase (P) indicate that relative tectosilicate abundance is primarily controlled by provenance (to which the 1<sup>st</sup> principal component is broadly associated) rather than by weathering and/or recycling (to which the 2<sup>nd</sup> principal component is broadly associated). Or\*: untwinned K-feldspar. ZTR (Hubert, 1962) is a crude indicator of recycling.

**Figure 12.** Dominant provenance control on detrital modes, tHM suites, and chemical indices (mineralogical parameters as in Fig. 11; biplot and chemical indices explained in subsection 3.3).

The  $\alpha^{Al}$  values of K, Rb, Ba hosted in K-feldspar and muscovite anticorrelate with  $\alpha^{Al}$  values of Ca, Mg, Sr hosted in carbonates, indicating that weathering effects (higher in humid coastal regions of the Cathaysia block) are obscured by the effect of source-rock lithology. Rough mineralogical (ZTR; Hubert, 1962) and chemical (CIA/WIP; Garzanti et al., 2013) indices of recycling are highest in modern sand of western Taiwan.

**Table 1.** Characteristics of the studied river catchments (data from <http://www.chinawater.com.cn>, Changjiang Water Resources Commission, 2005; Pearl River Water Resources Commission, 2006; Kao and Milliman, 2008). Sediment yields and erosion rates calculated assuming that bedload is 10% of suspended load and average source-rock density is 2.67 g/cm<sup>3</sup>.

170 **Table 2.** Key petrographic and heavy-mineral signatures of river sand. Q = quartz; F = feldspars (P =  
 171 plagioclase; Mic\* = cross-hatched microcline); L = lithic grains (Lvm = volcanic to low-rank  
 172 metavolcanic; Lc = carbonate; Lsm = sedimentary to low-rank metasedimentary; Lm = higher-rank  
 173 metamorphic); tHMC = transparent heavy-mineral concentration; ZTR = zircon + tourmaline +  
 174 rutile; Ep = epidote; Grt = garnet; CSKA= chloritoid + staurolite + andalusite + kyanite +  
 175 sillimanite; Amp = amphibole; Px = pyroxene; &tHM = other transparent heavy minerals. CI =  
 176 corrosion indices; n.d. = not determined.

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 178 **Table 3.** Distribution of main rock types exposed in different subcatchments of the Pearl and  
 179 southern Yangtze catchments (areal percentages calculated by the *Getarea.gms* plugin after [China](#)  
 180 [Geological Map](#)).

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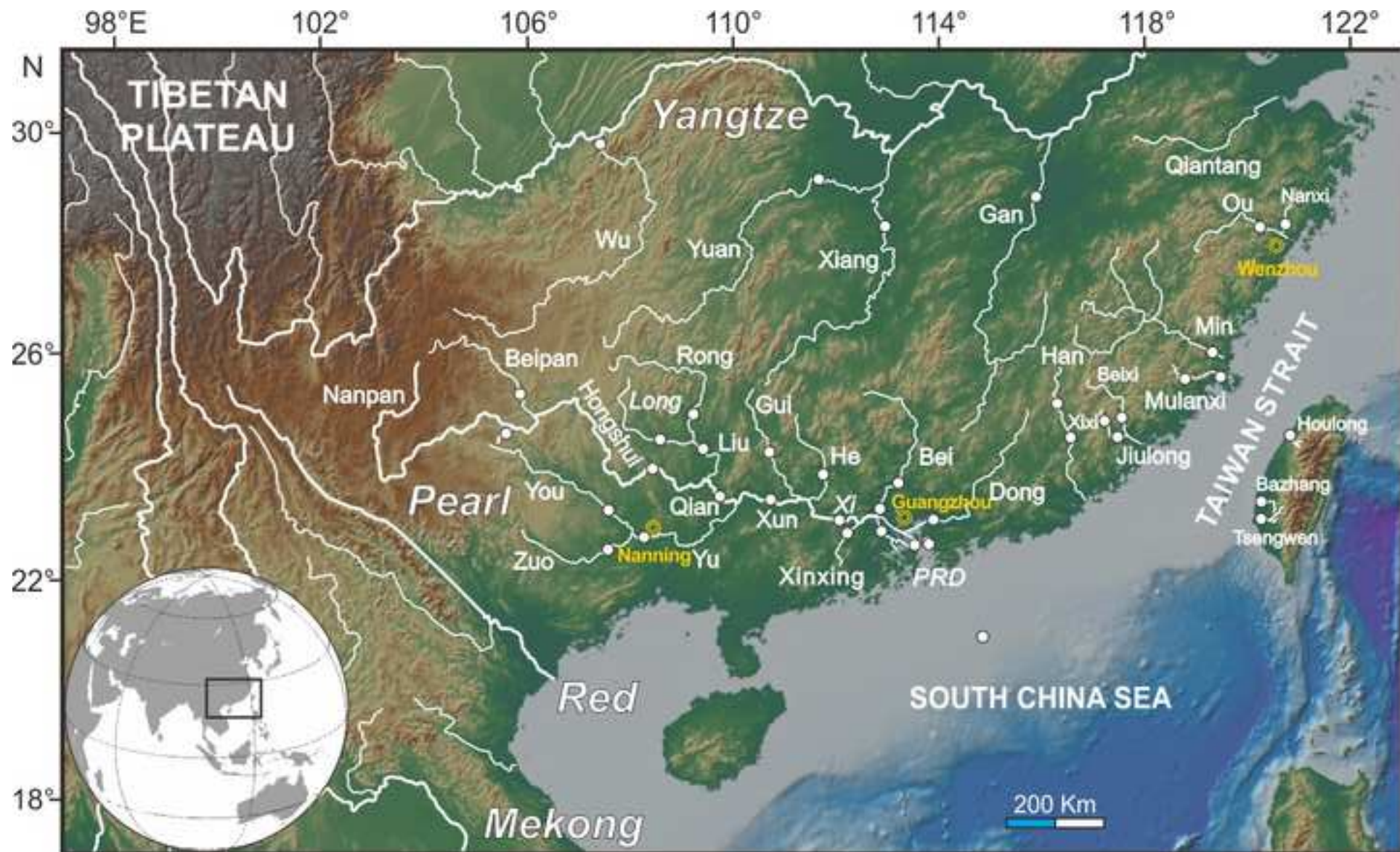


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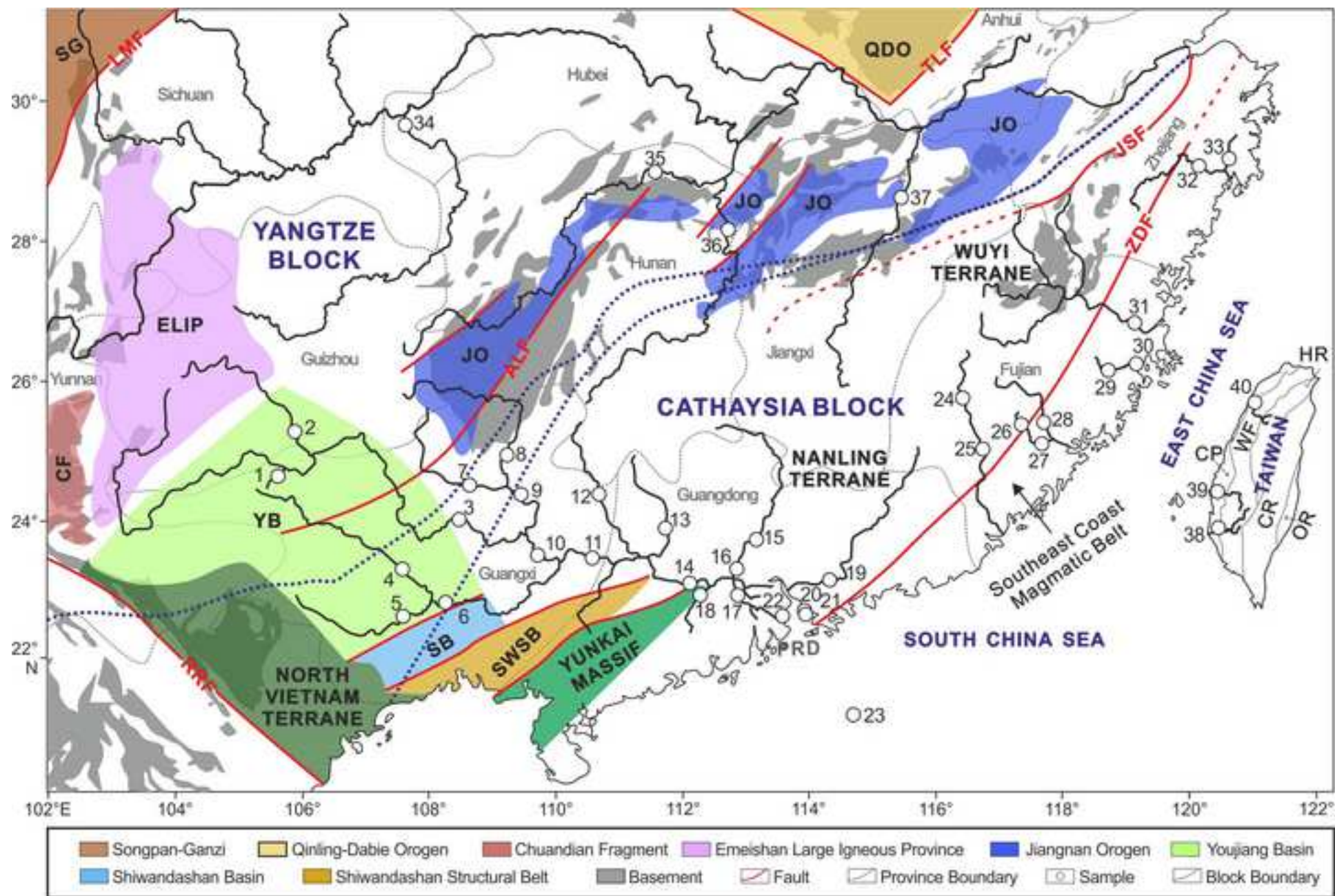


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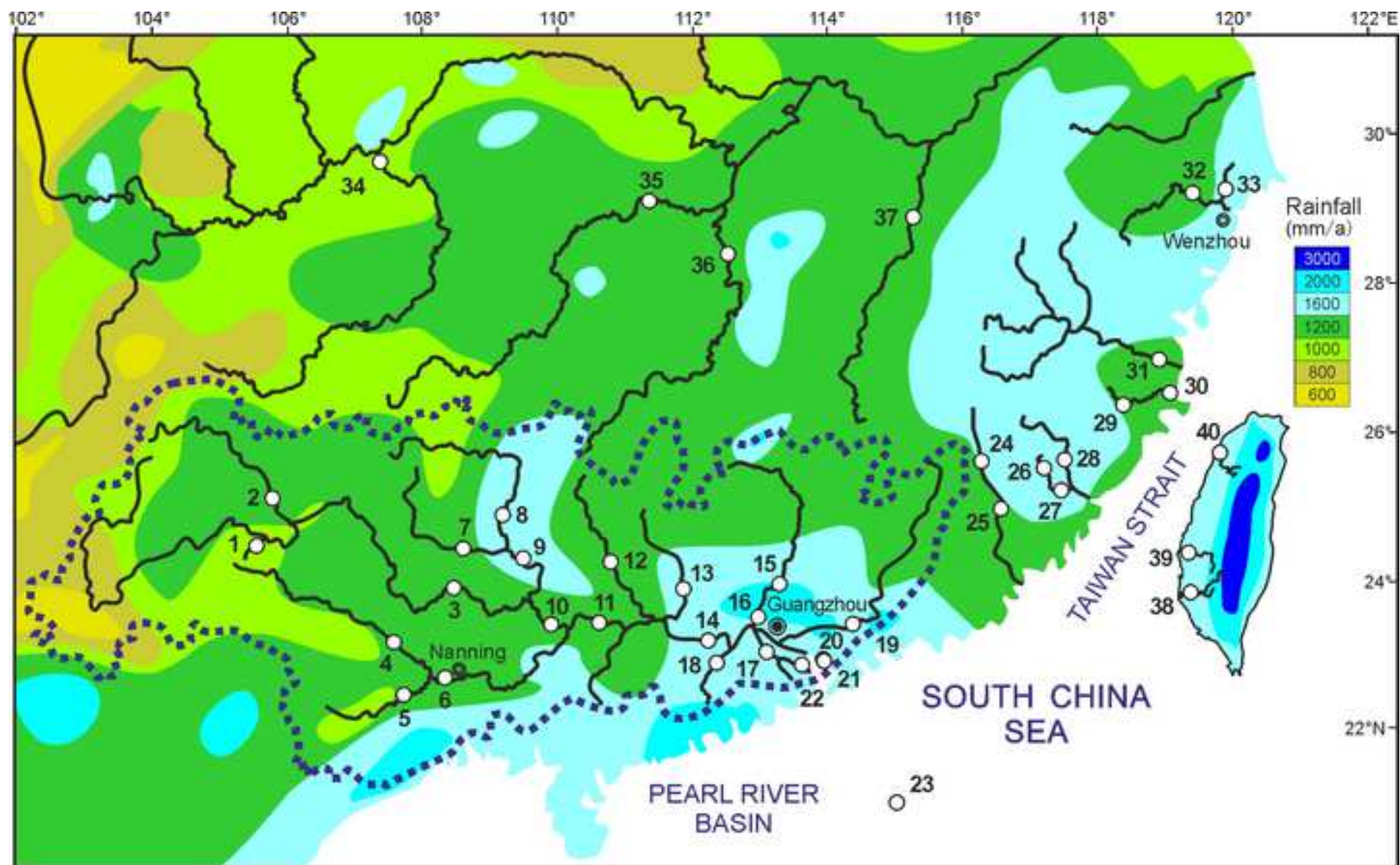


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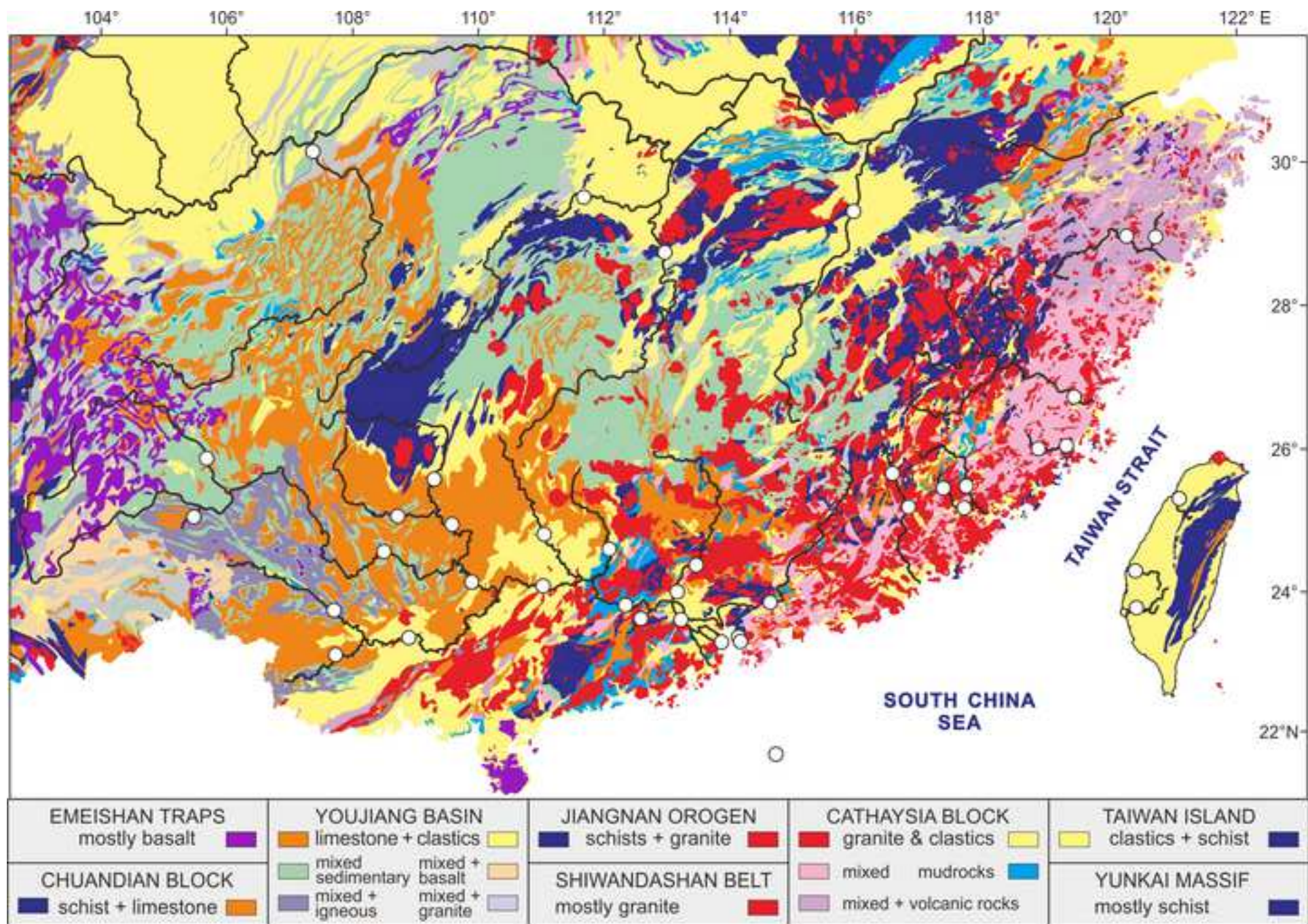


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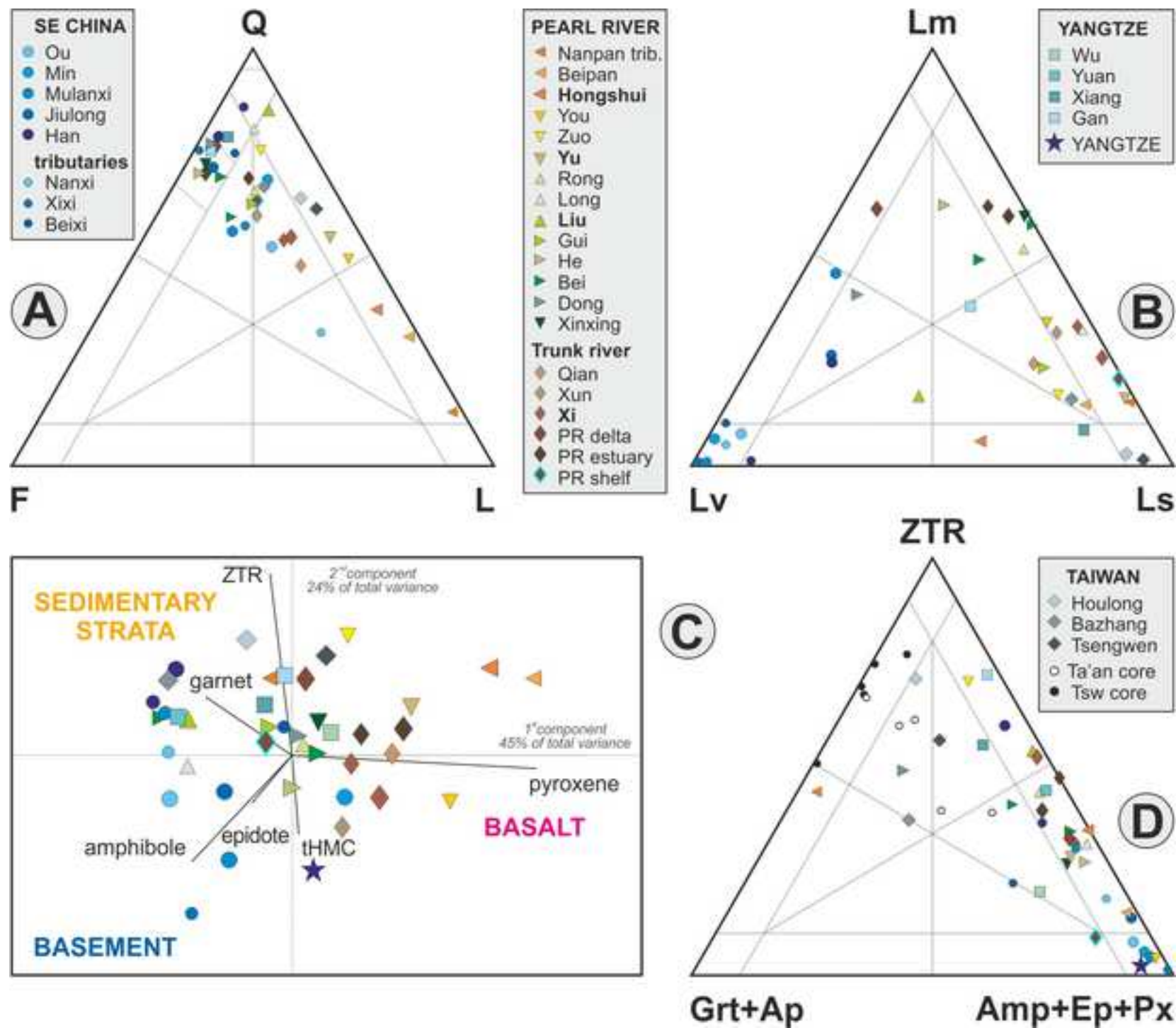


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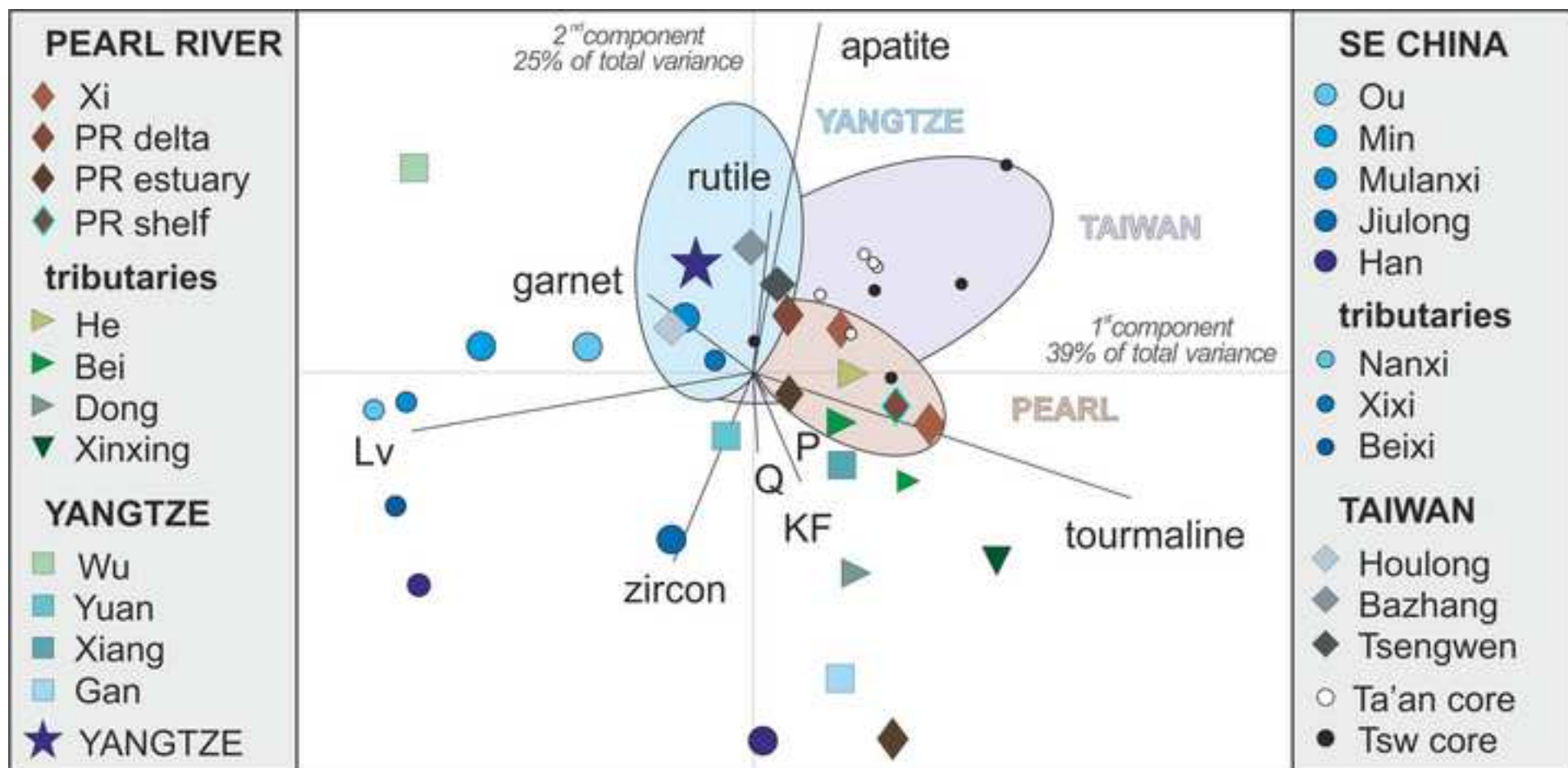


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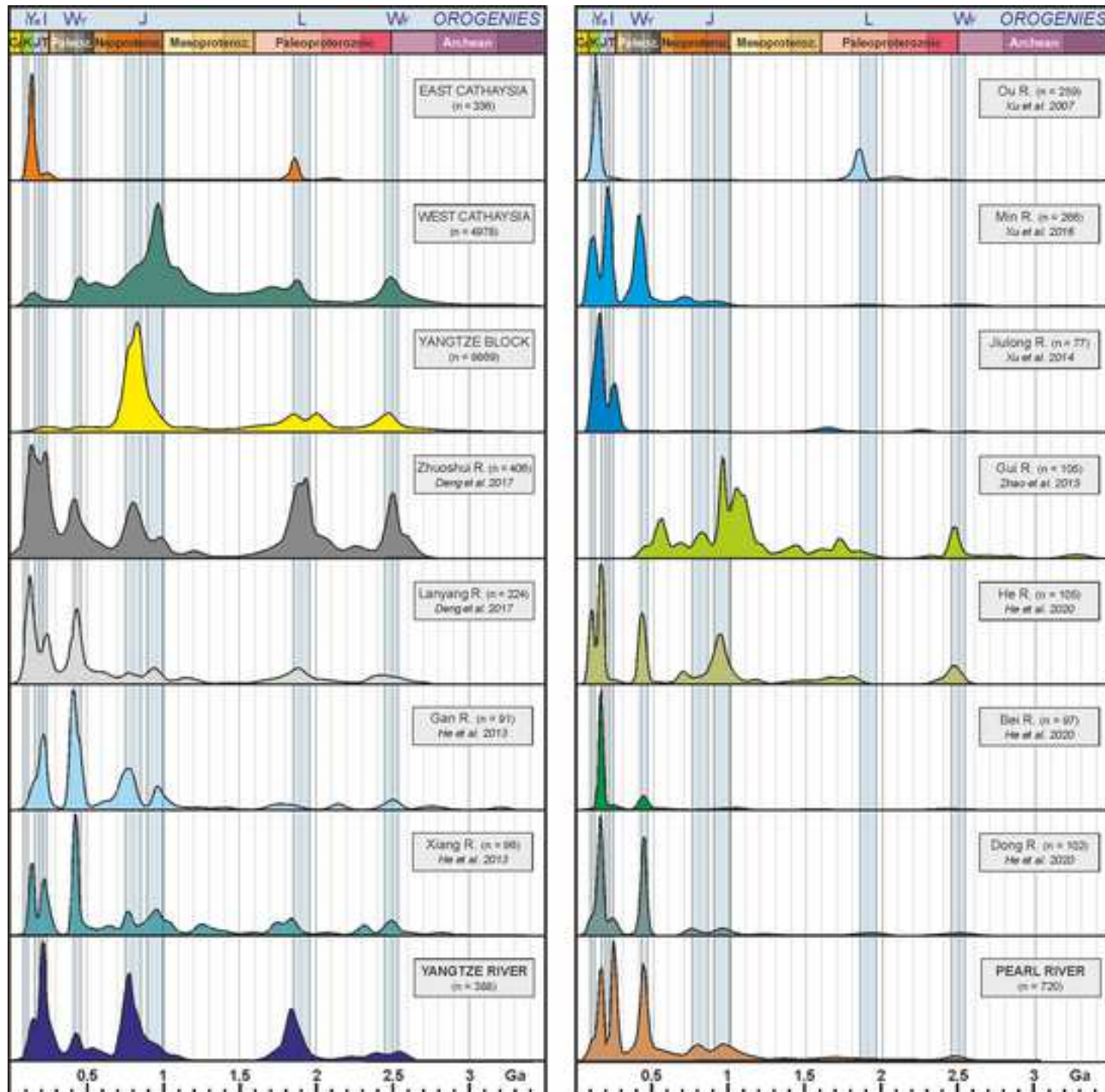


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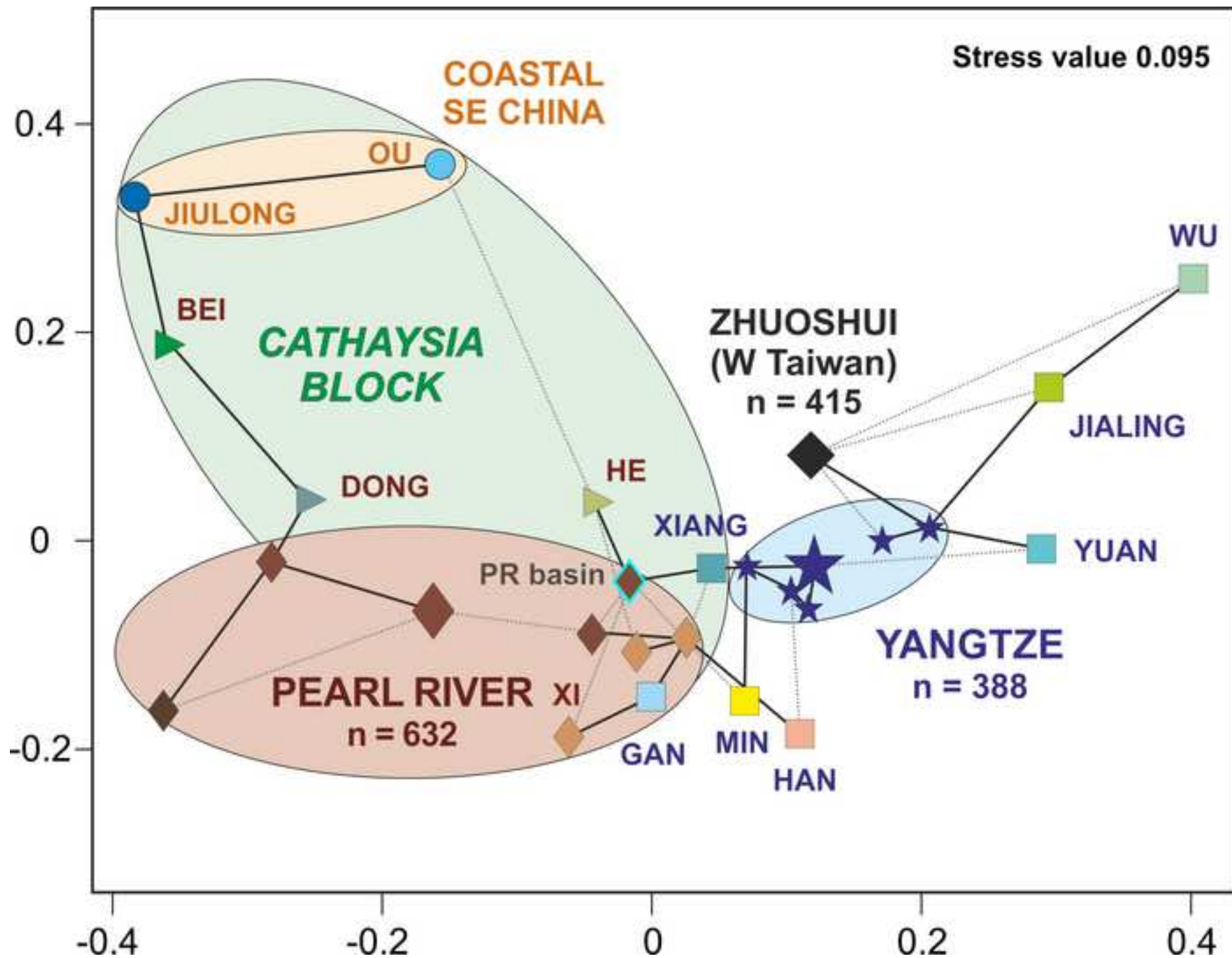


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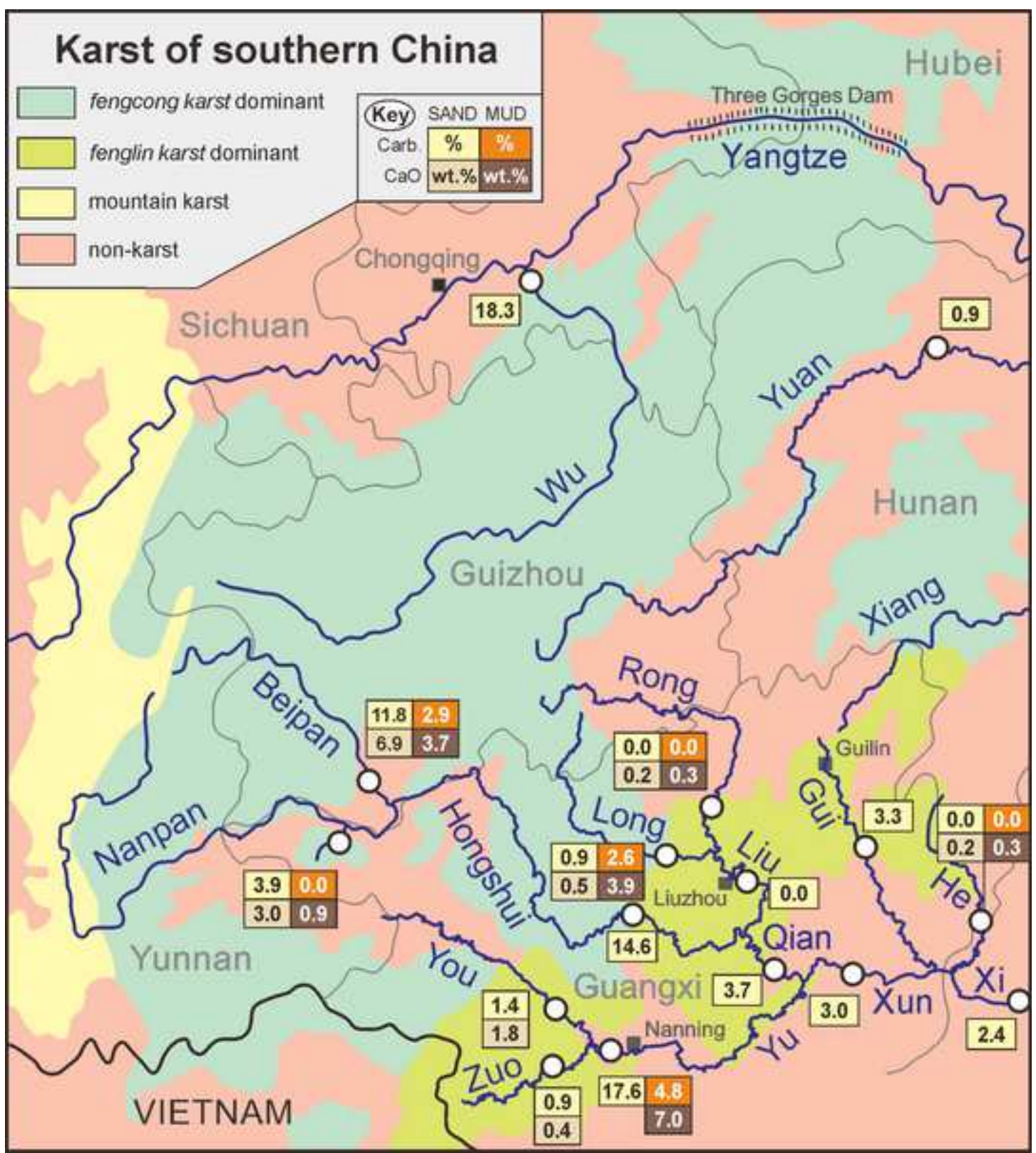


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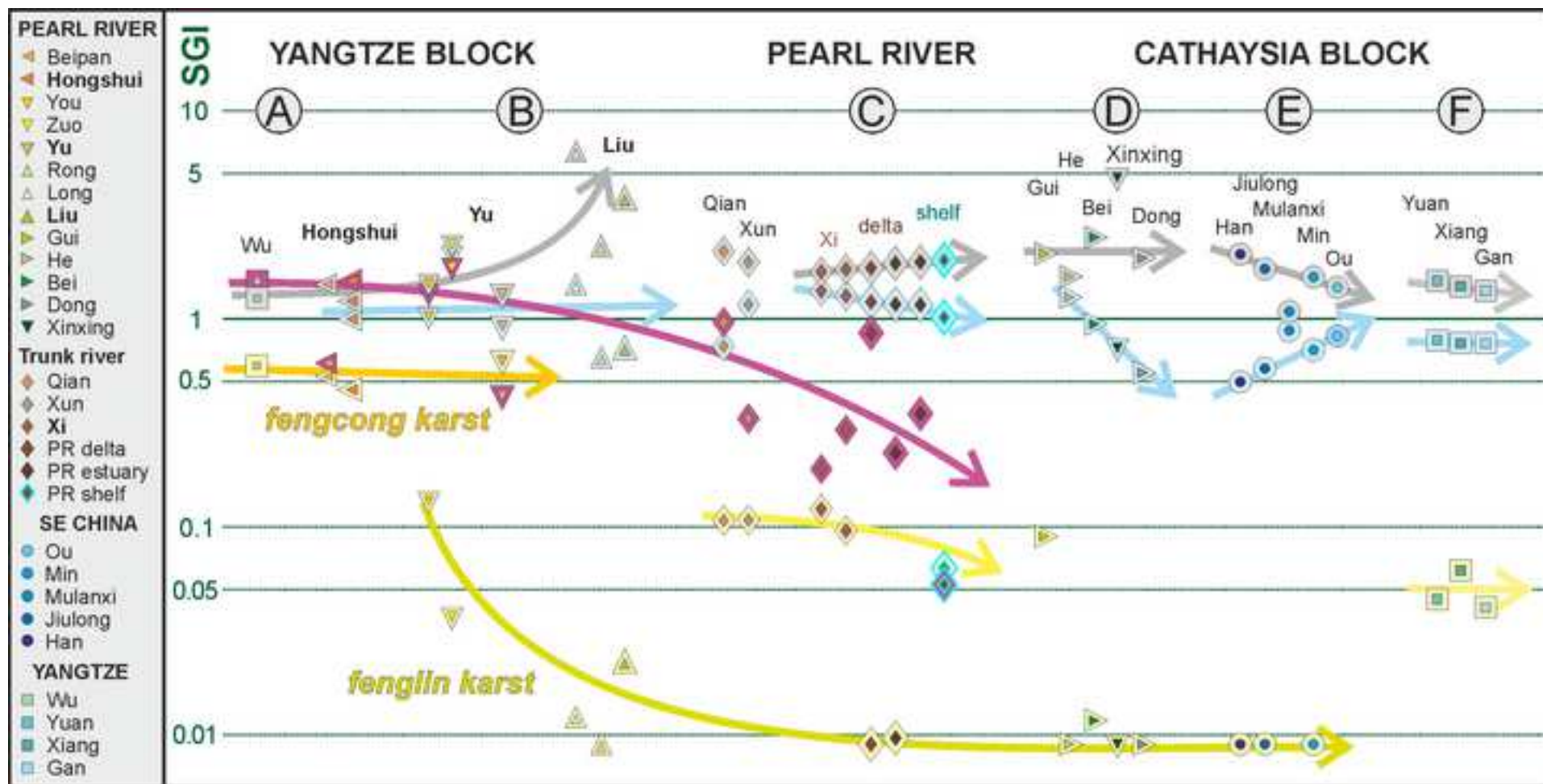


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2<sup>nd</sup> principal component: 34% of total variance

1<sup>st</sup> principal component: 55% of total variance

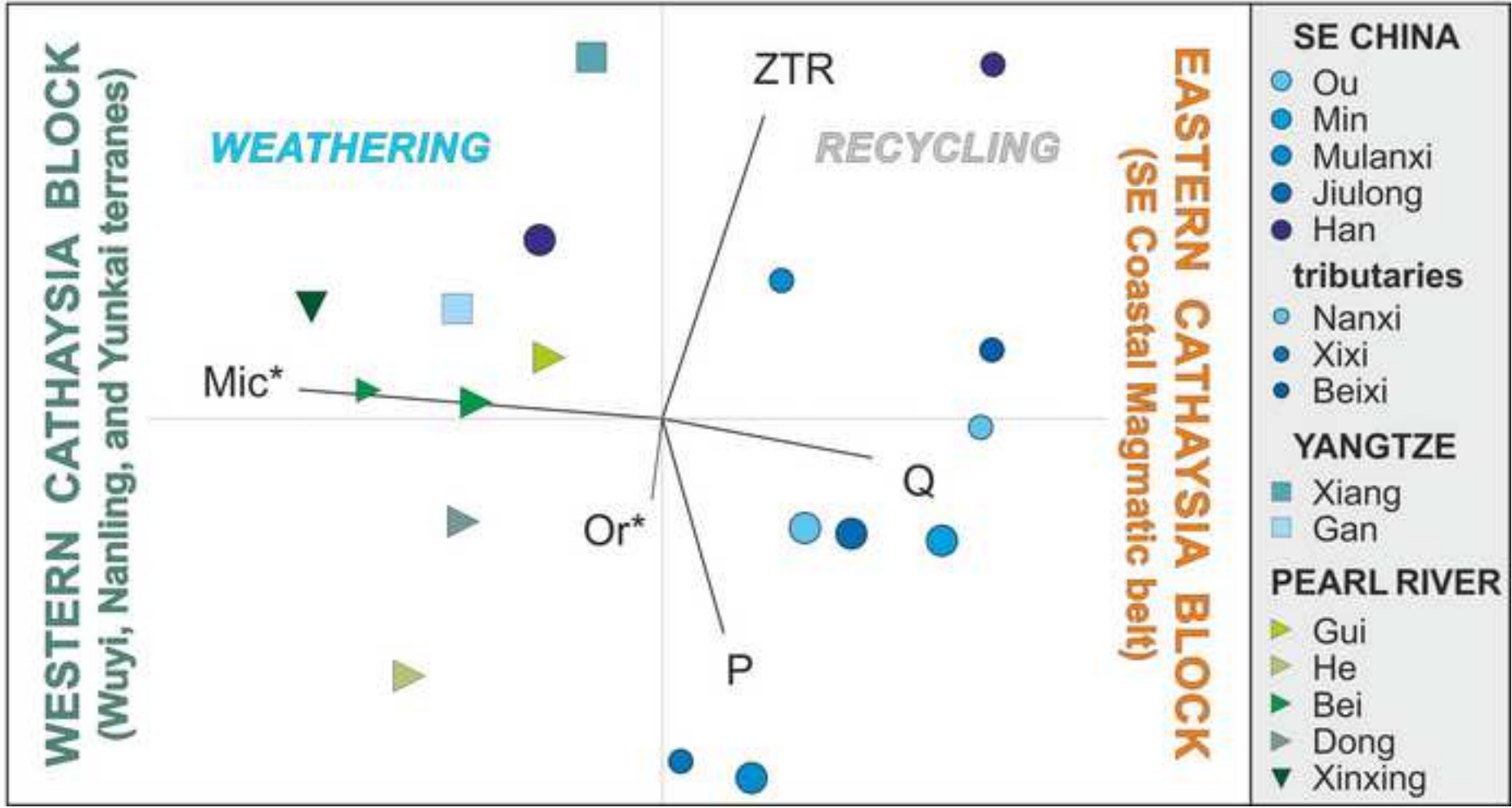


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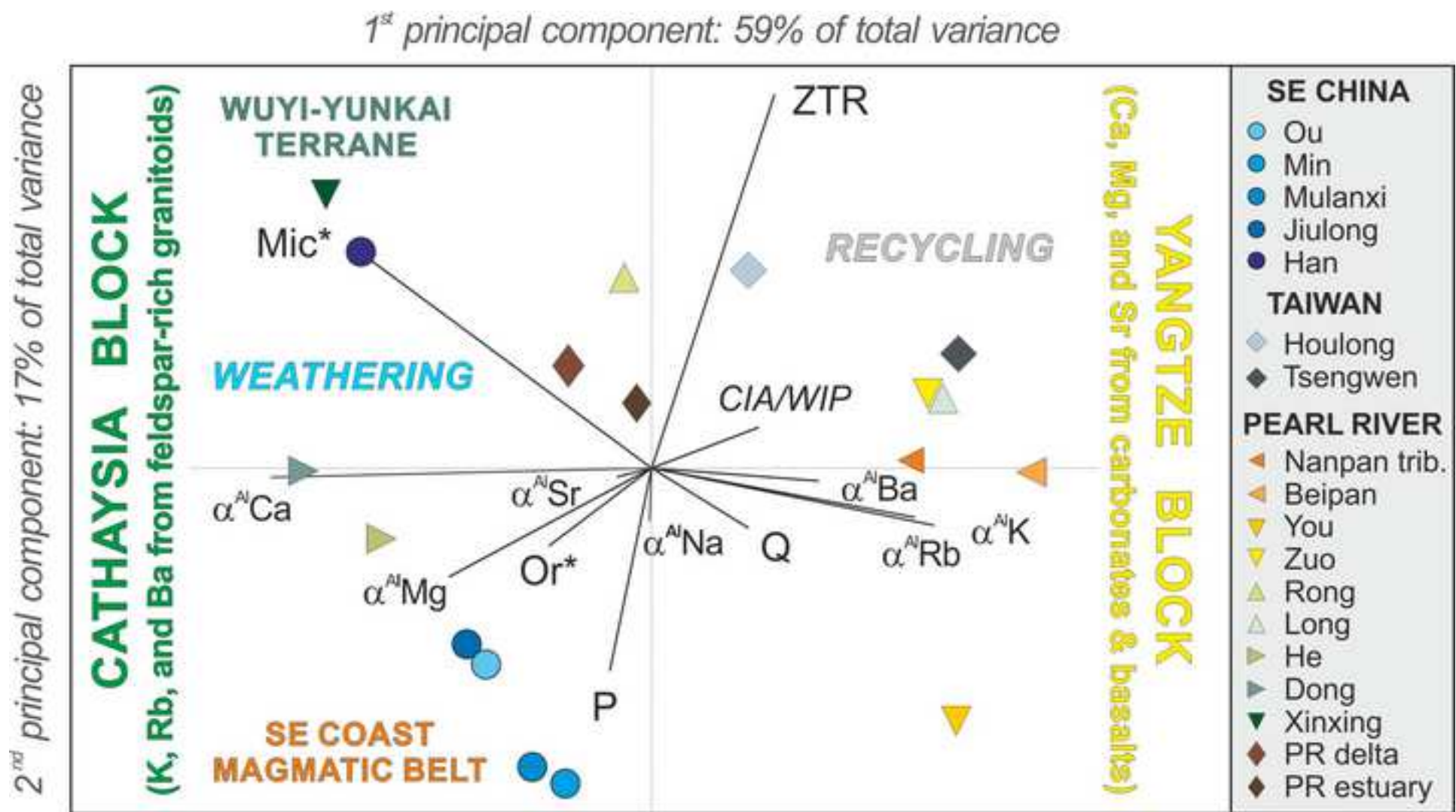


Table 1

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Rivers	Drainage area (10 <sup>3</sup> km <sup>2</sup> )	Length (km)	Water discharge (km <sup>3</sup> /yr)	Suspended load (10 <sup>6</sup> t/yr)	Sediment yield (t / km <sup>2</sup> / yr)	Erosion rate (mm/yr)
<b>PEARL RIVER</b>						
Nanpan	56.8	914	21.7	7.0	135	0.05
Beipan	26.6	449	12.3	12.3	509	0.19
Hongshui	52.6	659				
<b>TOTAL HONSHUI</b>	<b>136.0</b>	<b>1573</b>	<b>69.6</b>	<b>45.6</b>	<b>369</b>	<b>0.14</b>
Rong	21.6	218	25.6	2.8	145	0.05
Long	16.4	367	12.7	1.5	97	0.04
<b>TOTAL LIU</b>	<b>57.2</b>	<b>773</b>	<b>58.8</b>	<b>6.5</b>	<b>124</b>	<b>0.05</b>
<b>Qian</b>	<b>198.0</b>	<b>1694</b>	<b>135</b>	<b>52.1</b>	<b>289</b>	<b>0.11</b>
You	38.6	707	17.2	5.5	157	0.06
Zuo	32.1	539	17.4	3.2	110	0.04
<b>TOTAL YU</b>	<b>90.7</b>	<b>1179</b>	<b>47.9</b>	<b>16.3</b>	<b>198</b>	<b>0.07</b>
<b>Xun</b>	<b>308.2</b>	<b>1866</b>	<b>229.3</b>	<b>33.5</b>	<b>119</b>	<b>0.04</b>
Gui	19.3	426	17.5	2.8	158	0.06
He	11.5	352	6.4	1.5	147	0.06
<b>Xi</b>	<b>329.7</b>	<b>2074</b>	<b>202.5</b>	<b>45.7</b>	<b>152</b>	<b>0.06</b>
Xinxing	2.4	145	1.2	n.d.	n.d.	n.d.
Bei	46.7	468	51.0	12.7	299	0.11
Dong	35.3	562	25.7	6.9	216	0.08
<b>TOTAL PEARL</b>	<b>450</b>	<b>2320</b>	<b>280</b>	<b>65</b>	<b>160</b>	<b>0.06</b>
<b>COASTAL SE CHINA</b>						
Han	30.1	470	24.5	6.9	253	0.09
Jiulong	14.7	258	14.1	2.5	184	0.07
Mulanxi	1.7	168	1	0.5	304	0.11
Min	61.0	577	56.1	8.2	149	0.06
Ou	18.0	390	20.2	2.7	165	0.06
<b>YANGTZE BASIN</b>						
Wu	115.7	1037	52.0	17.0	162	0.06
Yuan	89.2	1022	68.4	17.6	217	0.08
Xiang	94.7	948	72.2	11.4	132	0.05
Gan	83.5	766	68.7	9.9	130	0.05
<b>TAIWAN ISLAND</b>						
Houlong	0.5	58	1.4	3.3	7260	2.72
Bazhang	0.5	81	0.7	2.6	5720	2.14
Tsengwen	1.2	138	1.1	23.0	21083	7.90

Table 2

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	n°	Q	F	Lvm	Lc	Lsm	Lm	P/F	Mic <sup>2</sup> /F	tHMC	ZTR	Ep	Grt	CSKA	
PEARL RIVER															
Hongshui	3	31	3	18	12	36	0	47%	5%	0.1	25	7	0	0	
Yu	3	60	7	5	7	20	1	55%	2%	0.5	30	11	3	0	
Liu	3	77	10	2	0	8	2	50%	6%	0.2	41	18	1	0	
Gui + He	2	66	23	2	2	6	2	34%	11%	0.1	18	11	6	1	
Bei + Dong + Xinxing	4	69	23	1	0	5	2	29%	18%	0.3	32	16	5	17	
Xi River	2	54	16	1	3	23	2	56%	13%	0.3	27	17	1	1	
Pearl River mouth	4	70	20	2	0	7	1	44%	8%	0.3	37	18	5	2	
SE CHINA															
Jiulong + Han	5	77	18	4	0	1	0	41%	6%	0.6	26	33	8	1	
Ou + Min + Mulanxi	5	53	20	23	0	1	2	59%	2%	0.9	13	61	3	2	
YANGTZE BASIN															
Wu	1	34	2	7	18	40	0	50%	0%	0.1	17	17	12	0	
Yuan	1	48	6	7	1	36	1	58%	6%	0.1	44	27	1	0	
Xiang+Gan	2	77	18	1	0	3	1	26%	18%	0.3	55	13	5	1	
WEST TAIWAN	3	64	9	2	3	21	0	68%	5%	0.2	52	13	15	2	

Table 3

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Rivers	Area (10 <sup>3</sup> km <sup>2</sup> )	Granite	Schist	Basalt	Carbonat	Sandstone
<b>Pearl River tributaries</b>						
Nanpan	56.8	4%	4%	26%	16%	26%
Beipan	26.6	0%	0%	26%	24%	27%
HONGSHUI	136.0	3%	2%	18%	33%	24%
You	38.6	6%	0%	10%	28%	26%
Zuo	32.1	2%	0%	2%	56%	33%
YU	90.7	7%	0%	6%	32%	37%
Rong	21.6	5%	38%	0%	23%	32%
Long	16.4	0%	8%	0%	77%	10%
LIU	57.2	2%	19%	0%	55%	21%
Gui	19.3	3%	0%	0%	54%	43%
He	11.5	27%	3%	0%	29%	19%
Xinxing	2.4	44%	12%	0%	32%	3%
Bei	46.7	32%	3%	0%	38%	13%
Dong	35.3	44%	10%	0%	9%	26%
<b>Pearl River</b>						
Qian	198	3%	7%	12%	40%	23%
Xun	308.2	5%	5%	10%	36%	28%
Xi	329.7	13%	5%	7%	33%	27%
<b>Coastal SE China</b>						
Han	30.1	45%	14%	0%	6%	23%
Jiulong	14.7	53%	4%	0%	4%	27%
Mulanxi	1.7	44%	3%	0%	0%	28%
Min	61	37%	29%	0%	1%	19%
Ou	18	40%	32%	0%	0%	19%
<b>Yangtze tributaries</b>						
Wu	115.7	0%	1%	5%	45%	24%
Yuan	89.2	1%	22%	1%	22%	40%
Xiang	94.7	13%	12%	1%	19%	34%
Gan	83.5	15%	25%	1%	7%	38%

## Appendix Tables

[Click here to download Background dataset for online publication only: Appendix A PearlProv.xlsx](#)

**Interactive Map file (.kml or .kmz)**

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## **Conflict of Interest Statement**

The authors declared that they have no conflicts of interest to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.