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China's Yangtze delta: Geochemical fingerprints reflecting river connection to the sea

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ABSTRACT

This study investigates sediment source to sink relating the connection of the Yangtze River to the sea. A sediment borehole (PD) on the river coast, penetrating thick Quaternary sediments and thin sediments of late Pliocene age down to the bedrock, recorded a change in sediment provenance through time. Geochemical elements and magneto-stratigraphy help identify five zones. *Zone I* (the late Pliocene–the Early Pleistocene), characterized by Pb, Th, U, Ba, La, Ce, Nd, Hf, Y, Zr, Nb and Mn, indicates a local sediment provenance. This means that the study area was a localized sub-basin. *Zone II* (the Early Pleistocene–the mid-stage of the Early Pleistocene), with remarkable high Fe, K, As and Rb implies a new sediment provenance joining the sub-basin from the middle Yangtze reach after the opening of the Zhenjiang Gorge. *Zone III* (the mid-stage of Early Pleistocene–the Middle Pleistocene), featured by Ti, V, Cr, Sr, Sc, Cu, Co, Ni, Mg, Ca, Na and P suggests a further extension of sediment provenance to the upper Yangtze basin, where a large block of the E'mei basalt and carbonate occurs. This suggests that the Three Gorges valley linking the upper and middle Yangtze reaches had developed by that time. *Zones IV* and *V* (the Middle Pleistocene–the Holocene) have shown their geochemical similarity to *Zone III*. Discrimination ratio f(Cr, Th), f(La) and f(K, La), a new approach developed for tracing sediment provenance, confirms a basin-wide sediment source through *Zones III–V*. These together witness a progressive extension of the sediment provenance towards the upper Yangtze basin, corresponding to the long-term tilting effect of the Cenozoic Topographic Reversal of the eastern China continent. The timing of the Yangtze River running through into the East China Sea appears at ca. 1.0–1.2 Ma (bottom of *Zone III*).

1. Introduction

The Yangtze River sourced from the eastern Tibetan Plateau occupies a huge drainage basin area of >1.8 million km^2 (Fig. 1; Chen et al., 2009). The river basin owns a complex geology, characterized by many tributaries (Fig. 1). In the upstream reaches, the river, also called Jinshajiang River, flows southeasterly, and then turns NE through an angle of 90° at Shigu (Fig. 1). The river traverses the Sichuan Basin and the Three Gorges valley, and further drains downstream into the Jianghan Basin and Dongting Basin — large subsidence basins in the middle Yangtze reaches. The river then continues its long journey to the eastern China coast, by flowing through the Zhenjiang Gorge, a little gorge at the delta apex (Fig. 1).

A source to sink approach has been followed by many researchers in recent years, providing insights into geological and geomorphological evolution of the river basins (Clift et al., 2006). Much attention has been drawn to the rivers draining the southeastern Tibetan Plateau in response to the uplift of the plateau (Clift et al., 2001; Clark et al., 2004; Meade, 2008; Chen et al., 2009). The evolution of the Yangtze River has been debated extensively since the last century (Li, 1924; Ye and Xie, 1925; Ren, 1957). Some hypotheses are given as: 1) the river originated due to the Cenozoic Topographic Reversal in the eastern China continent (Wang, 1990, 1998) (Fig. 1); 2) the paleo-Yangtze system consisted independently of the upper, middle and lower Yangtze reach basins (Wang, 1985); and 3) the former Yangtze once flowed southward along the Red River into the South China Sea (Zhao, 1996; Clark et al., 2004). The upper basin includes the Jinshajiang reach and the tributaries that developed to the western Three Gorges, so-called westward flowing streams before opening of the Three Gorges (Zhao, 1996). The middle Yangtze basin is dominated by inland rivers in the Jianghan Basin (Wang, 1985; Zhang et al., 2003). The lower Yangtze basin consists of several short-distance rivers, flowing eastward from the regional mountains aligned along the southeastern China coast (Fan et al., 2012).

There are three 'key gorges' for the river evolution. The 'First Bend' at Shigu of the upper Yangtze reach is linked with tributaries of the plateau and those to the western of the Three Gorges (Fig. 1). Three Gorges links the Sichan Basin and Jianghan Basin and the Zhenjiang Gorge of the lower reach is the last one that the river cuts through into the sea (Fig. 1). Hence, many previous researches have focused on how and when the river flowed through these gorges, integrating sub-basins

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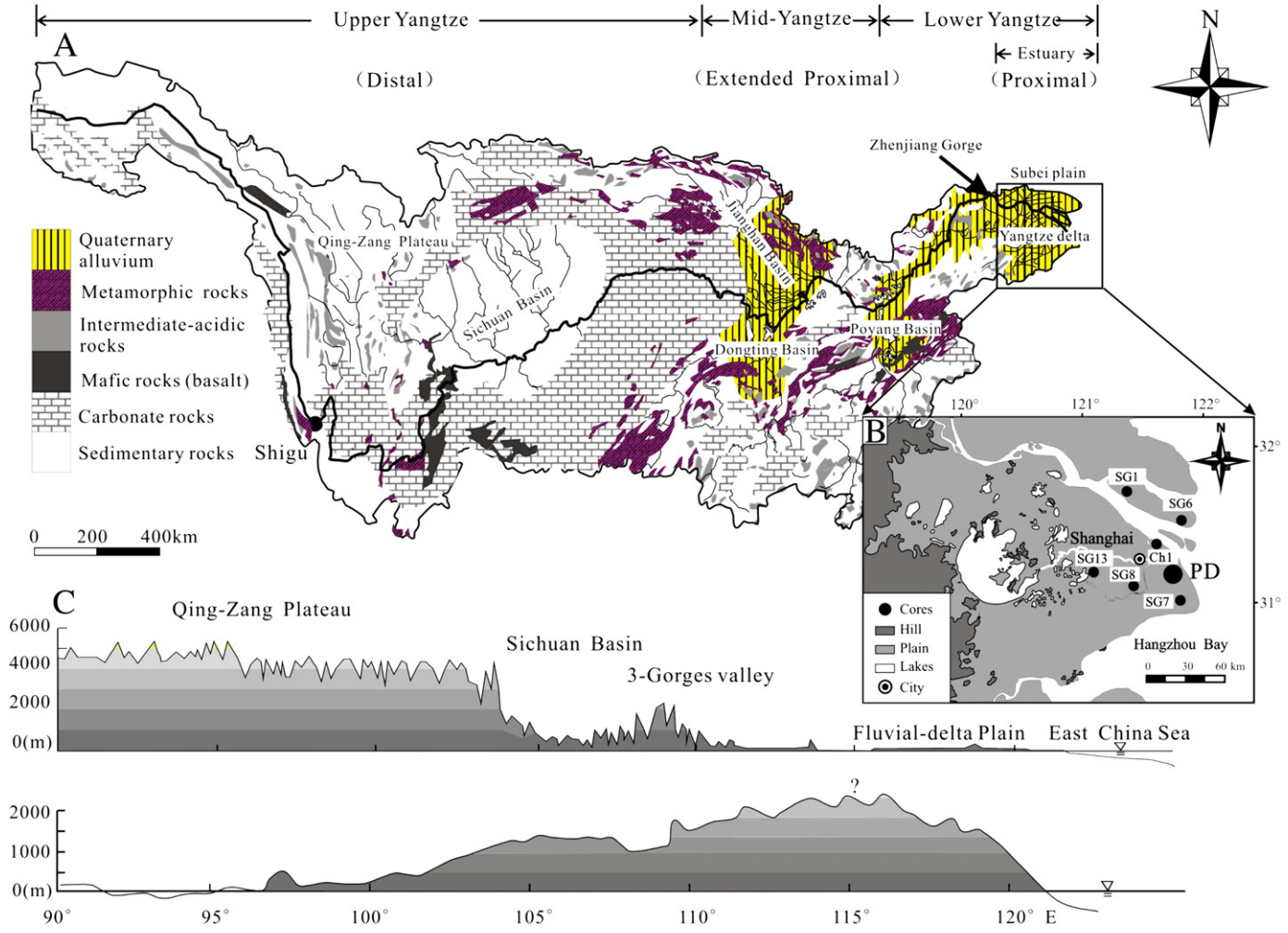

Fig. 1. Geological and geomorphological details of the Yangtze drainage basin, showing (A) source rocks in the Yangtze basin (after Changjiang River Water Resources Commission, 1999); (B) the Yangtze estuary, where indicated are the sediment borehole PD of the present study, and the others collected; C) Cenozoic topographic reversal, showing the present three steps of morphological elevation of the Yangtze basin, and the pre-Quaternary topographic features with a lower landform in the former Tibet area and a highland in the eastern China coast (Wang, 1990).

into an entity. However, most previous studies failed to take into account the stepwise cutting through the gorges. Especially, the opening of the Zhenjiang Gorge is seldom discussed.

Until now, there is no consensus on the formation of the Yangtze River, particularly the timing of incision of Three Gorges. Previous studies reported the timing of opening of the Three Gorges to range from pre-Miocene (>40 Ma) to Late Pleistocene (<0.12 Ma), but primarily lying between the Early and Middle Pleistocene (Fig. 2). Re-digesting the previous results is necessary, comprehensively considering tectonic geology, climatic forcing, fluvial geomorphology, magneto-chronostratigraphy, sedimentary facies, etc. (Yang et al., 2006; Zhang et al., 2008; Chen et al., 2009).

The present study aims at examining one continuous sediment borehole (PD, Fig. 1) located in the southern Yangtze delta plain, access for the Yangtze River flowing into the sea, penetrating the Quaternary–Pliocene strata until bedrock (354 m in depth). The main objectives of this paper are: 1) to examine downcore variations of geochemical compositions; 2) to identify the linkage of diagnostic elements in core sediments to the Yangtze basin sources; and 3) to reconstruct the Yangtze River development through time.

2. Source rocks, chrono-stratigraphy and sedimentary facies

2.1. Source rocks in the Yangtze River basin

Geologically, the Yangtze River basin is mostly situated on the Yangtze Craton, primarily formed by Mesozoic Yanshanian orogenesis and comprising metamorphics, sedimentary rocks and Quaternary clastic sediments (Wang and Shen, 2003; China Geological Survey, 2004; Yang et al., 2004). The upper Yangtze basin is dominated by limestone, E'mei basalt, sedimentary rocks and intermediate-acidic igneous rocks. Metamorphic rocks occur sporadically (Fig. 1). Limestone and E'mei basalt cover a large area of ~600 × 10^3 km^2, mainly in the upper Yangtze reach basin (Fig. 1). The E'mei basalt is a major source rock of V–Ti magnetite of the basin (Lei et al., 2009). The previous studies show that Ti–V–Cr concentrations in E'mei basalt are >6%, >0.3% and >0.05% respectively, much higher than those in other types of magnetites (<1%, <0.1 and <0.02%) (Lei et al., 2009). In addition, Sc is also high in E'mei basalt (Liu et al., 1984). High concentration of Mg and Ca is observed in the sediments of the upper Yangtze reach, sourced from limestone provenance (Ding et al., 2004; Zeng et al., 2012).

The middle-lower Yangtze reach basin is mostly dominated by sedimentary rocks, intermediate–acidic igneous and metamorphic rocks. Granitoids are widely distributed in the southeastern basin (Wang and Shen, 2003; China Geological Survey, 2004), in which abundant Th–U (radioactive elements) occurs (Yang et al., 2006). A previous study shows that Fe, K, and As are enriched in sediments of the Hanjiang River in the middle reach (Mei et al., 2007), being unique provenance proxies of the region. Intermediate–acidic igneous rocks are rich in rare earth elements (REE) including La, Ce, Nd, Zr, Hf, Y, and Nb (Liu et al., 1984). We summarize the above-mentioned diagnostic elements of the upper, middle and lower Yangtze reaches in Table 1.