Geomorphology 268 (2016) 14–20

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

# Magnetite with anomalously high $Cr_2O_3$ as a fingerprint to trace upper Yangtze sediments to the sea

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ARTICLE INFO

*Article history:*
Received 13 October 2015
Received in revised form 26 May 2016
Accepted 30 May 2016
Available online 31 May 2016

*Keywords:*
Magnetite
E'mei Basalt
Tectono-geomorphology
Yangtze River

ABSTRACT

This paper examines geochemical properties of detrital magnetite, in order to link sediments in a Plio-Quaternary core taken in the delta area to their sources in the Yangtze River basin. A total of 40 sediment samples were collected from both the main river channel/tributaries and a sediment core from the Yangtze delta. The geochemical compositions of detrital magnetite in these sediments were analyzed by electron microprobe, including FeO, $TiO_2$, CoO, MgO, $Cr_2O_3$, MnO, ZnO, $Al_2O_3$ and $V_2O_3$. The results revealed that the detrital magnetite grains with anomalously high $Cr_2O_3$ occurred exclusively in the upper reaches of the Yangtze (upstream of the Three Gorges Dam), where the E'mei Basalt block is located. This type of magnetite could therefore be considered a unique sediment proxy of the upper river basin to help identify sediment source in the delta area. Our analysis found such magnetite grains with high $Cr_2O_3$ occurring throughout the core depth above 186.5 m, in contrast to the extremely low $Cr_2O_3$ below this depth. The boundary between high and low $Cr_2O_3$ in magnetite grains of the core sediments was dated by paleomagnetism at ca. ~1.2–1.0 Ma, signifying that the linkage between the Yangtze River course and the sea was before ~1.2–1.0 Ma. This demonstrates that the sediment provenance of the Yangtze delta has experienced a change from local to distal Yangtze River, which took place with the uplift of the Tibetan plateau and coastal subsidence during the Plio-Quaternary.

## 1. Introduction

The Yangtze River originates from the Tibetan Plateau at an elevation of above 5000 m. The river is >6300 km long with a drainage basin of 1.80 million $km^2$ (Chen et al., 2001). It discharged ca. 900 × $10^9$ $m^3$ of freshwater and 4.5 × $10^8$ t of sediments each year during the period of 1951–2001 before construction of the Three Gorges Dam (1.5 × $10^8$ t per year thereafter) into the East China Sea (Changjiang Water Resources Commission, 2014). The large amount of riverine sediments accumulates on the coast to build the extensive delta-coast system. This process progresses as the result of the coupling between tectonic movement and climate change (Clark et al., 2004). Inevitably, the sediment fingerprints of the upper Yangtze basin can be identified in the Plio-Quaternary sediment at the river mouth (Yang et al., 2006). Sediment fingerprinting provides us a unique approach to explore not only the timing of the upper Yangtze sediment contribution to the depositional evolution of the delta but also the evolution of the Yangtze fluvial system.

Since the early 20th century, the geomorphological evolution of the Yangtze River has become an academic focus. Much was related to tectono-geomorphological processes in the upper part of the river (Willis et al., 1907; Lee, 1933; Barbour, 1936; Shen, 1965; Yang, 1985; Li et al., 2001; Kong et al., 2012). There are several key arguments ongoing among geomorphologists. Firstly, it has been hypothesized that the Yangtze River once flowed into the South China Sea via the Red River before the river was captured at Shigu of the upper Yangtze basin (Fig. 1; Zhao, 1996; Clark et al., 2004), although the timing of the capture is unclear. Secondly, the timing of the opening of the Three Gorges valley (Fig. 1) vs. the river capture has been highly questionable. The Yangtze River would not flow into the East China Sea had the Three Gorges valley not been channelized. This had taken place through uplift of the Tibetan plateau and subsidence of the eastern China coast, the so-called Cenozoic Topographic Reversal (Wang, 2005). Thirdly, the connection of inter-mountainous basins, represented by the Sichuan basin of the upper Yangtze, Jianghan basin of the middle Yangtze and the coastal basin is ambiguous in terms of the surficial processes accompanying substantial subsidence of eastern China continent (Schneiderman et al., 2003; Gu et al., 2014).

Apart from these debates, more attention has recently been paid to the Yangtze coast with regard to the river connection to the sea by means of a sediment source-to-sink approach. Previous studies used detrital minerals (such as monazite and zircon) in a chronostratigraphic investigation of sediments of the lower Yangtze basin to trace the

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http://dx.doi.org/10.1016/j.geomorph.2016.05.032
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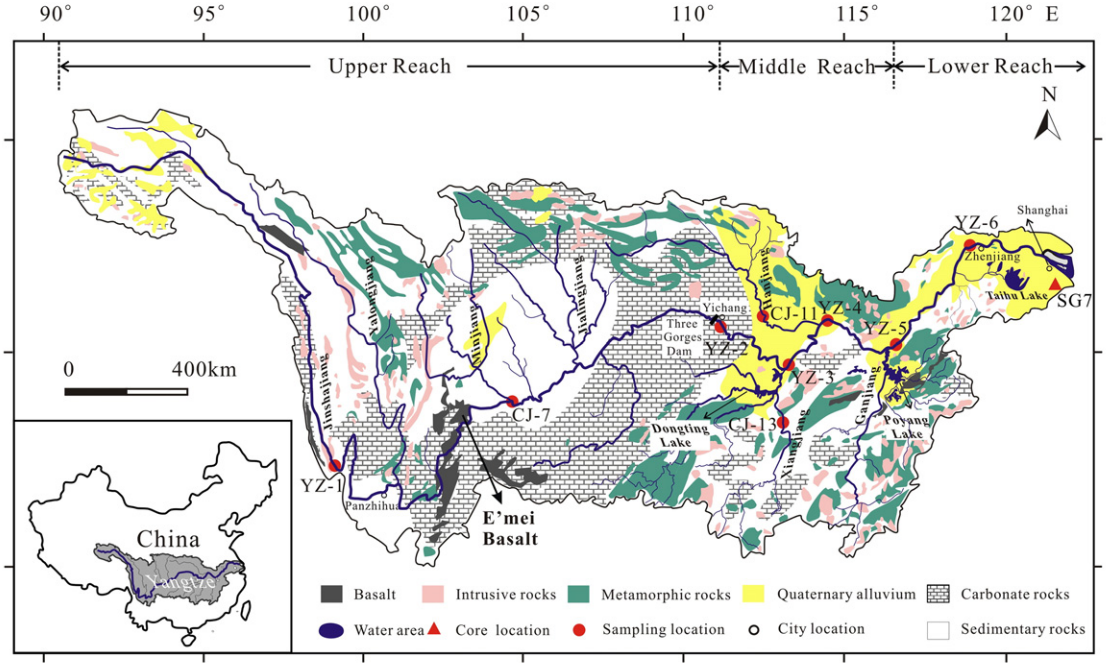

**Fig. 1.** Sampling locations and main rock types in the Yangtze drainage basin (modified from Changjiang Water Resources Commission, 1999).

sediment sources, especially the diagnostic sediment proxies derived from the upper Yangtze (Yang et al., 2006; Chen et al., 2009; Jia et al., 2010; Zheng et al., 2013). This approach is effective for sediment source identification of the lower Yangtze basin sediments. However, results showed various diagnostic detrital minerals with a wider range of timings of the Yangtze River connection to the sea (Fan et al., 2005; Yang et al., 2006; Huang et al., 2009; Chen et al., 2009; Gu et al., 2014). The key point was the reliability of provenance interpretation from the proxies used, and that these may be influenced by climatic factors and tectonic cycles in the source region (Suttner et al., 1981; Dickinson et al., 2009), hydrodynamic sorting during transport or reformation during deposition (Garzanti et al., 2009; Lawrence et al., 2011). However, the unclear spatial distribution of the provenance proxies in the source regions of Yangtze coastal sediment pool has been a limitation of provenance interpretations. The question then is how to link diagnostic sediments with regional outcrops of the Yangtze basin and improve the reliability of provenance proxies?

Detrital magnetite is often considered as a sediment source tracer due to its stable properties and widespread distribution, easy separation and differential geochemical composition (Pettijohn et al., 1987; Grigsby, 1990). The present study specifically focused on the linkage of magnetite geochemistry of detrital minerals in the modern river sediment to the large block of E'mei basalt rock that exclusively occurs in the upper Yangtze (upstream of the Three Gorges Dam) (Fig. 1; Bureau of Geology and Mineral Resources of Sichuan Province, 1987; Xu et al., 2001; Xiao et al., 2004). By establishing their intercorrelation, we applied this linkage to a Plio-Quaternary core sediment from the delta area, which enabled us to define the occurrence and timing of such minerals in well-dated core strata. This interpretation would then provide a better understanding of the connection of the Yangtze River to the sea in association with long-term tectono-geomorpholgical evolution of the river basin.

## 2. Materials and methods

Six sediment samples were collected from the mainstream of the upper, middle and lower Yangtze River (YZ-1, YZ-2, YZ-3 YZ-4, YZ-5 and YZ-6; Fig. 1). One long and continuous sediment core (SG7, 320.9 m long) was taken from the Yangtze delta, penetrating the Holocene, Pleistocene, and Late Pliocene until bedrock (basalt) (Fig. 1). A total of 267 fine sediment samples were taken at an interval of 1.0–1.5 m for paleomagnetic dating at Nanjing Institute of Geology and Mineral Resources, China. Thirty-seven samples, including 6 from the modern river, were taken for geochemical analysis on detrital magnetite grains. To better understand the geochemical differences of detrital magnetite in relation to regional bedrock outcrops, 3 samples were also collected from the upper mainstream and the mid-lower Yangtze tributaries, including the Hanjiang River and Dongting Lake (CJ-7, CJ-11and CJ-13; Fig. 1; Wang et al., 2007).

Detrital magnetite grains were separated from the bulk sediments using a bar magnet wrapped by vinyon repeatedly. More than 150 magnetite grains were mounted on copper tubes full of resin glue for each sample, polished and then coated with carbon. More than 10 magnetite grains with a size range of 63–125 μm were randomly selected for geochemical determination, i.e. Fe, Ti, Mg, Al, Co, Mn, V, Cr and Zn by electron microprobe analyzer (JXR-8900 M) in the Department of Materials and Optoelectronic Science, the National Sun Yat-sen University, Taiwan. The working time of the microprobe was 30s for Fe, Mg, Al, Co, Mn, V, Cr and Zn and 60 s for Ti. The content of Fe was synthesized by the percent of $Fe_2O_3$ and FeO according to Carmicheal's method (1967). The test was repeated on three points and on one plane for each grain under a 15 kV accelerating voltage and a 20 nA current. The averaged value of the three points and one plane was regarded as representative of each magnetite grain in this study. Elemental oxide concentrations of magnetite were calculated from the values of above elements according to Bence and Albee correction methods (1968). Coefficient of Variability was calculated for each oxide according to the formula of CV = standard deviation/average value, which demonstrated compositional variability in the magnetite. The texture of magnetite grains were also imaged for analysis during geochemical determination.

## 3. Results

### 3.1. Geochemical characteristics of detrital magnetite in the Yangtze River

The average values of FeO, $TiO_2$, MgO, $Al_2O_3$, CoO, MnO, $V_2O_3$, $Cr_2O_3$ and ZnO in detrital magnetite of the river surficial sediment are listed in