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Clay mineralogy and source-to-sink transport processes of Changjiang River sediments in the estuarine and inner shelf areas of the East China Sea

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ABSTRACT

We examined the source-to-sink sediment transport processes from the Changjiang River to the estuarine coastal shelf area by analyzing the clay mineral assemblages in suspended sediment samples from the Changjiang River catchment and surface samples from the estuarine coastal shelf area following the impoundment of the Three Gorges Dam (TGD) in 2003. The results indicate that the clay mineral compositions throughout the study area are dominated by illite, with less abundant kaolinite and chlorite and scarce smectite. The clay minerals display distinct differences in the tributaries and exhibit obvious changes in the trunk stream compared with the periods before 2003, and the source of sediment has largely shifted to the mid- to lower reaches of the river after 2003. Spatially, the clay mineral assemblages in the estuarine area define two compositionally distinct provinces. Province I covers the mud area of the Changjiang River estuary and the Zhe-Min coastal region, where sediment is primarily supplied by the Changjiang River. Province II includes part of the Changjiang River estuary and the southeastern portion of the study area, where the sediment is composed of terrestrial material from the Changjiang River and re-suspended material from the Huanghe River carried by the Jiangsu coastal current. Moreover, the other smaller rivers in China (including the Oujiang and Minjiang rivers of mainland China and the rivers of West Taiwan) also contribute sediments to the estuarine and inner shelf areas. In general, the clay mineral assemblages in the Changjiang River estuarine area are have mainly been controlled by sediment supplied from upstream of the Changjiang River tributaries. However, since the completion of the TGD in 2003, the mid- to downstream tributaries have become the main source of sediments from the Changjiang catchment into the East China Sea. These analyses further demonstrate that the coastal currents and the decrease in the sediment load of the river have the greatest impacts on the distribution and transport of clay minerals assemblages in the sediments.

1. Introduction

Rivers are the major pathways linking continents and oceans, and they deliver large amounts of terrestrially derived sediment, freshwater, and natural elements to the global ocean (Milliman and Meade, 1983; Walling and Fang, 2003). Rivers transport approximately 15×10^9 metric tons of sediment to the ocean annually, and more than half of this global fluvial sediment is delivered by Asian rivers (Milliman and Meade, 1983; Milliman and Syvitski, 1992; Meade, 1996). However, most of these sediments are deposited in estuaries and along adjacent continental shelves, with only much smaller quantities of fluvial sediments eventually reaching the deep sea (Meade, 1996). The estuarine inner shelf area of the East China Sea (ECS) is one of the widest of the shelves and most river-dominated ocean margins in the world (Guo et al., 2003; Gao et al., 2015). It receives a large amount of fluvial terrigenous materials every year, approximately 70% of which comes from the Changjiang River, and sediment contributions from other small rivers in the coastal areas of the Zhejiang and Fujian provinces amount to only approximately 4% of the annual sediment load of the Changjiang River (Liu et al., 2007; Deng et al., 2006). However, in

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recent years, the terrestrial input from the Changjiang River to the oceans has decreased due to the concurrent construction of more than 50,000 dams in the Changjiang River basin, the most significant of which is the Three Gorges Dam (TGD), which represents the world's largest hydropower project (Lu and Higgitt, 2001; Nilsson et al., 2005). This dam construction has changed the sediment deposition and the transport patterns of Changjiang River sediments from "source to sink", and has exerted a significant direct impact on local depositional environments and ecological systems in the estuarine subaqueous deltas and adjacent sedimentary systems (Syvitski and Saito, 2007; Gao, 2013).

In recent decades, the regional geological conditions and the sources of the terrigenous sediments in the inner shelf areas of the ECS have been extensively investigated (Fan et al., 2001a,b; Ding et al., 2004; Fang et al., 2007). Additionally, recent work has investigated the magnetic properties (Wang et al., 2007; Liu et al., 2010a,b), heavy mineral compositions (Yang et al., 2009), and Sr-Nd isotopic compositions (Yang et al., 2007) of sediments to elucidate their sources in the Changjiang River. Despite these advances, the "source-to-sink" transport pattern from the Changjiang River to the estuarine inner shelf areas of the East China Sea remains poorly understood, especially with regard to the influence of the TGD on the variation in provenance over time.

Clay minerals are the main constituents of fine-grained sediments, which can be transported long distances to locations far from their sources, especially when transported in the nepheloid layer (Jones, 1984; Gingele et al., 2001; Sionneau et al., 2008). Clay mineral composition is also used as a good indicator of the source area, weathering intensity and maturity of both sedimentary rocks and modern marine and fluvial sediments (Guyot et al., 2007). Therefore, clay mineral composition has long been regarded as an important tool for tracing the "source-to-sink" pathways of suspended matter, for tracking transportation routes and for identifying provenance (Franz et al., 2001; Chen et al., 2003; Kessarkar et al., 2003; Liu et al., 2003a,b; Dou et al., 2010; Li et al., 2014; Shi et al., 2015; Liu et al., 2016; Guyot et al., 2007).

In this study, we use clay minerals to trace the "source to sink" pathway from the Changjiang River to the inner shelf of the East China Sea. We set the following three goals: (1) to investigate changes in the clay mineral compositions of suspended sediment samples from the Changjiang basin to the East China Sea following the construction of the TGD in 2003; (2) to analyze the distribution of clay minerals and identify sediment provenance along the inner shelf of the East China Sea; and (3) to explore the impact of changes in the Changjiang River catchment on the sedimentary environment along the inner shelf of the East China Sea.

2. Study area setting

The Changjiang River is the largest and most important river in Southeast Asia. This river is 6300 km long, has a drainage basin of $180 \times 10^4\,km^2$ and produces an annual sediment discharge of 478×10^6 t (Milliman and Farnsworth, 2011). The Changjiang River ranks 5th globally in water discharge and 4th in sediment flux, and its basin is home to more than 400×10^6 human inhabitants (Milliman and Farnsworth, 2011; Zhao et al., 2000; Yang et al., 2005) as it flows through eleven provinces. In the past 50 years, more recent data have shown that the water discharge and sediment load of the Yangtze River have been significantly altered by the influences of human activities and climate variations. The average annual sediment load transported to the sea by the Changjiang River was 320 Mt/year between 1986 and 2004, equivalent to only 65% of the sediment load of 480 Mt/year from 1951 to 1968. Furthermore, the sediment load observed at the Datong Hydrological Station decreased to 134 Mt/year between 2003 and 2010, representing only 30% of the 1951–1968 level (Yang et al., 2006). The basin is divided into three reaches: the upper reach, which extends from the uplands to the Yichang gauging station; the middle reach, which extends from Yichang to the Hukou gauging station; and the lower reach, which extends from the section from the Hukou gauging station to river estuary area (Chen et al., 2001; Gao et al., 2015). The Changjiang River catchment includes seven major tributary basins: the Jinsha, Min, Jialing, Wu, and Han rivers and the Dongting and Poyang lakes. Geologically, the Changjiang drainage basin is characterized by a series of complex rock compositions that include Archean metamorphic rocks, Paleozoic carbonate and sedimentary rocks, Mesozoic–Cenozoic igneous and clastic rocks, and Quaternary detrital sediments. Different drainage basins along the mainstream and its major tributaries consist of distinct rock types and tectonics environments (Yang et al., 2004; Wu et al., 2005; He et al., 2013).

As a typical continental margin in the western Pacific, the estuarine and inner shelf regions of the ECS receive amounts of terrestrial sediments from Eurasian continent runoff (especially from the Changjiang River) and are also greatly influenced by the Changjiang River, which is one of the largest fluvial systems on the western Pacific coast (Liu et al., 2006; Yang et al., 2006; Bianchi and Allison, 2009). Additionally, this region features several coastal mud areas such as the Changjiang estuary mud area in the north and the Zhejiang-Fujian coastal mud area in the south (DeMaster et al., 1985; Hu et al., 2001). The various currents in this region such as the Yellow Sea Coastal Current (YSCC), the Taiwan Warm Current (TWC), the Changjiang Diluted Water (CDW), and the East China Sea Coastal Current (ECSCC), actively interact with the nearby Changjiang plume (Beardsley et al., 1985; Lee and Chao, 2003; Liu et al., 2007). These strong tidal currents and large circulation systems impact the hydrodynamics of the ECS and affect the mobility of its benthic sediments (DeMaster et al., 1985; Guo et al., 2003).

3. Data and methods

3.1. Sample collection

Twenty-one suspended sediment samples were collected from the main branch and major tributaries of the Changjiang River basin in June-July 2015 and were filtered in situ using membranes with a pore size of 0.45 μm. The sampling sites extended throughout the entire river system. A total of 50 surface sediment samples were collected in 2013 using grab buckets in the estuarine inner shelf areas of the East China Sea (Fig. 1).

3.2. Analytical methods

The grain size composition of the sediment samples was measured using a Mastersizer 2000 laser particle analyzer at the Key Laboratory of Coast and Island Development, Nanjing University, China. This instrument has a measurement range of 0.02–2000 μm, a size resolution of 0.01 φ and a measurement error of less than 3%. Before undergoing grain size analysis, all air-dried samples were successively pretreated with 30% hydrogen peroxide solution to remove organic matter and 10% HCl to remove carbonates. The particle size parameter was calculated using the moment method (McManus, 1988).

The clay mineral analyses were performed by X-ray diffraction (XRD) using a D8 ADVANCE diffractometer with a CuKα radiation source (40 kV voltages, 25 mA intensity), mainly at the State Oceanic Administration (SOA) in China. Prior to these analyses, the samples were pretreated with solutions of 10% hydrogen peroxide and 0.5% HCl for 24 h to remove organic matter and carbonates, respectively. Then, minerals in the clay size fraction (< 2 μm) were separated from the bulk sediment samples using conventional Stoke's Law and were concentrated by centrifuging (Wan et al., 2006). XRD analyses were then performed three times following the detailed procedure described by Huang et al. (2011) and Wan et al. (2010). Identification and interpretation of the main clay minerals, i.e., smectite (17 Å), illite (10 Å) and kaolinite + chlorite (7 Å), were performed on the glycolated curve established by the XRD diagram (Fig. 2), with respective intensification