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Geochemistry and sedimentary environment

Clay minerals in the Pliocene−Quaternary sediments of the southern Yangtze coast, China: Sediment sources and palaeoclimate implications

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Abstract Clay mineralogy was used as an indicator of the sediment source and prevailing climate and five suites (I−V) were identified throughout the borehole. Smectite was dominant in the bottom suite of the borehole, indicating the sediment was mainly derived from the local basalt when the study area stood as uplands during the Pliocene. The sharp reduction of smectite in suites II and III (Early Pleistocene) reflects a broader sediment provenance due to neo-tectonic subsidence of the study area. Significant climate fluctuations are indicated by distinct variations in the ratios of illite versus smectite and kaolinite, and by the illite crystallinity in suites II and IV. Especially the suite IV, which forms mottled muddy sediments that underwent pedogenesis, possibly represents glacial/interglacial cycles during the Mid-Pleistocene climate transition (MPT). The rare presence of smectite in suite V which formed during the Late Quaternary suggests a significant contribution of fine-grained sediment derived from the upstream of the Yangtze catchment. Such changes in sediment sources are consistent with the evolution of regional sedimentary environments, which evolved towards an open coast/deltaic setting and imply that the study area became the depositional basin of the Yangtze fine-grained sediment due to the final submergence of the Wu-Nan-Sha and Fukien-Reinan Massifs since the Late Quaternary.

Key words smectite, neo-tectonic subsidence, Mid-Pleistocene climate transition, Yangtze depocenter, Pliocene−Quaternary, southern Yangtze coast

1 Introduction

The Late Cenozoic sediment sources and associated environmental evolution in the southern Yangtze coastal area of eastern China have been debated because of its close relationship with the uplift of the eastern Qinghai-Tibetan Plateau and the development of the east China marginal sea (Clark *et al.*, 2004; Wang, 2004; Yang *et al.*, 2006a; 2006b; Chen *et al.*, 2009). In the past decades, many studies have been carried out in this area regarding the neo-tectonic subsidence, sedimentary environment and stratigraphy, sediment provenance, palaeoclimatic change, marine transgression and regression (Lin *et al.*, 1989; Chen and Stanley, 1995; Chen *et al.*, 1997; Wang *et al.*, 2005, 2014; Yang *et al.*, 2006a; 2006b; Chen *et al.*, 2009). Recently, analyses focused on tracing the sediment sources by diagnostic indices including geochemical elements and heavy minerals from the upstream of the Yangtze catchment. For example, Yang *et al.* (2006b) used geochemical elements

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and monazite age patterns to identify the variation of sediment sources since the Late Cenozoic. Their results suggested that the palaeo-Yangtze River changed its drainage basin from a local small one to a large river originating on the eastern Qinghai-Tibetan Plateau during the Early Pleistocene. Meanwhile, Chen *et al.* (2009) linked suites of heavy minerals in the Late Cenozoic sediments of the southern Yangtze coast to different source rocks in the catchment and argued that the heavy minerals from the upper catchment did not appear until the Late Pleistocene. To examine these different opinions, more studies are needed considering the nature of the coastal sediments which reflect both the evolution of the sedimentary basin and changes in sediment sources.

Clay minerals and their distributions have been widely used for the reconstruction of palaeoenvironments and palaeoclimates (Vanderaveroet *et al.*, 1999; Pehlivanoglou *et al.*, 2000; Perederij, 2001; Madhavaraju *et al.*, 2002; Liu *et al.*, 2003, 2004). Kaolinite, smectite, chlorite and illite are the major four proxies of clay minerals to test palaeoenvironmental hypotheses. Kaolinite is a product of strong chemical weathering in a high-temperature and high-moisture climate setting (Chamley, 1989; Velde, 1992). Smectite indicates either an alkaline weathering environment, regardless of what the parent rock is, or basalt bedrock as the sediment provenance (Chamley, 1989; Aoki and Kohyama, 1991; Velde, 1992; Naidu *et al.*, 1995; Wahsner *et al.*, 1999; Viscosi-Shirley *et al.*, 2003). Chlorite and illite tend to be linked to a cold and/or temperate climate regime, where physical weathering predominates (Velde, 1992).

Previous study revealed that clay mineral assemblages differ clearly in the suspended sediments from different rivers of eastern China. Smectite decreases from the Yellow River of northern China to the Pearl River of southern China, in combination with an increase of kaolinite. The diagnostic clay mineral in the Yellow River is smectite; in the Yangtze River it is illite, and in the Min and Pearl River it is kaolinite (Yang, 1988; He and Liu, 1997; Ma *et al.*, 2010). Besides, the ratio of illite to smectite has been proposed as a provenance proxy for the Yellow and Yangtze Rivers (Fan *et al.*, 2001).

Therefore, the present study aims to examine the temporal distribution of four clay minerals in a Late Cenozoic borehole, coded PD from the coast of the southern Yangtze delta (Figure1), so that to discuss the changes of sediment sources through time and also to reveal possible relationship with climate change. This will help to better understand the evolution of the southern Yangtze coast and associated eastern China marginal sea.

2 Geological setting

The southern Yangtze delta plain is located on the Wu-Nan-Sha Massif that collided with the Fukien-Reinan Massif during the Late Mesozoic (Wageman *et al.*, 1970; Guo *et al.*, 1997; Figure 2A). The East China Sea (ECS) Shelf Depression initiated coincidently with the collision (Figure 2A). Several separate terrestrial basins were also formed in eastern China, including the Subei-Southern Yellow Sea (YS), Qingdong, Northern YS, and the Bohai Sea. The outer ECS was formed during the Himalayan movement of the Neogene, as the result of tensional spreading of the back-arc basin. The inner ECS shelf, however, was still dominated by the Fukien-Reinan Massif. The Cenozoic sediment is generally over 1500 m thick in these basins (Wageman *et al.*, 1970; Jin, 1992). In contrast, the total sediment thickness is generally less than 1000 m where it overlies the basement of the Wu-Nan-Sha and Fukien-Reinan Massifs. For the present southern Yangtze coast, the sediment thickness over the bedrock is mostly <200 m in the western and southern areas and 300−500 m in the east and north, with several deep and narrow valleys to the northeast (Zhang *et al.*, 2008; Figure 2B). Previous studies also show that most (200−450 m) unconsolidated sediments date from the Quaternary, with thinner (<50 m thick) Pliocene deposits underneath in local basins (Chen and Stanley, 1995; Chen *et al.*, 1997). The Wu-Nan-Sha and Fukien-Reinan Massifs started to subside in response to the strong uplift of the Qinghai-Tibetan Plateau, and as a result led to the coalescence of the ECS and the southern YS during the Quaternary (Guo *et al.*, 1997).

3 Materials and methods

Sediment borehole PD, 365 m long, was recovered from the southern Yangtze delta coast, ~5 km inland from the shoreline in 2001 (Figure 1). The borehole was obtained using a rotary rig and the bedrock (basalt) of Miocene age (Shanghai Geological Survey, 2001) was reached. On-site sediment description was made during the coring. Detailed sediment logging was carried out in the laboratory when splitting the core samples, including sediment lithology, bedding, fauna fossils, plant fragments/root traces, and nodule distribution.

The sediments of borehole PD were dated palaeomagnetically (Chen *et al.*, 2009). In the present study, we incorporate four quartz-rich samples for electron spin resonance (ESR) dating by using an ECS−106 ESR spec-