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Sediment provenance and paleoenvironmental changes in the northwestern shelf mud area of the South China Sea since the mid-Holocene

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ABSTRACT

The late Quaternary paleoceanography and paleoenvironment of the South China Sea (SCS) have been well reconstructed over the last decade. In contrast, the provenance of the terrigenous sediments that have accumulated in the northwestern continental shelf mud area remains enigmatic. This study investigated the provenance of these sediments and the paleoenvironmental changes archived in Core X2 via the analysis of geochemical elements, grain size, and accelerator mass spectrometry (AMS) ^{14}C ages. Based on the upper continental crust (UCC)-normalized REE patterns and REE fractionation parameters, southwestern and western Taiwanese rivers and the Pearl River were identified as the main sources of the fine-grained sediment deposited in the northwestern shelf mud area off Hainan Island. This finding further confirms the long-distance transport (> 1000 km) of fine-grained sediment from Taiwanese rivers to the northern SCS shelf and slope. Obvious changes in the grain size and Chemical Index of Alteration (CIA) record occurred at approximately 4.0 cal kyr BP and were likely caused by increased Hainan Island inputs due to sea level changes.

1. Introduction

The South China Sea (SCS) is one of the largest marginal seas along the Asian continent. Numerous rivers, including large rivers (e.g., the Mekong River, Pearl River, and Red River) and small mountain rivers (e.g., the rivers on Taiwan Island), supply as much as 570 Mt yr^{-1} (million tons per year) of suspended sediment to the SCS (Liu et al., 2008; Milliman and Syvitski, 1992). Most previous studies in the northern SCS have considered the Pearl River to be the main sediment source (e.g., Clift et al., 2002; Tamburini et al., 2003). However, recent investigations have emphasized significant contributions from Taiwanese rivers (e.g., Hu et al., 2012; Liu et al., 2010; Wan et al., 2010). Unfortunately, the scientific community has a limited understanding of the distances that Taiwanese materials can be transported and distributed along the coast of the northern SCS. Recently, clay mineral analysis has shown that Taiwanese materials can be transported to the continental shelf area off eastern Hainan Island (Tian et al., 2015), which suggests long-distance transport of fine-grained sediment from Taiwanese rivers to the northern SCS shelf. Furthermore, few studies have been conducted on the weathering products of Hainan Island (Hu et al., 2014; Liu et al., 2016), which is the second largest island in the northern SCS. Recently, Hu et al. (2014) suggested that Hainan Island, which remains poorly studied, likely represents the 'missing' end member. Therefore, further research regarding the provenance of sediment on the continental shelf of the SCS and the depositional mechanisms is required.

Holocene mud deposits are commonly found in estuaries and on continental shelves (Díaz et al., 1996; Ge et al., 2014; Liu et al., 2009, 2014b; Xu et al., 2009, 2011). Geological and geophysical studies have shown that mud deposits on continental shelves are ideal for provenance and paleoenvironment studies (Ge et al., 2012; Xiang et al., 2008; Xu et al., 2009). Numerous studies have also focused on the northern continental shelf of the SCS (Li et al., 2010b; Yang et al., 2011). However, few provenance and paleoenvironment studies have

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examined the northwestern continental shelf mud area of the SCS, which features the greatest water depths (50–100 m) off Hainan Island (Chang et al., 2011).

Geochemical approaches have been shown to be effective in identifying sediment provenances. Among the various methods, rare earth element (REE) compositions, which are largely resistant to the influence of water, are widely accepted as reliable provenance tracers because they behave conservatively during sediment formation (Dou et al., 2010; Prajith et al., 2015; Sahoo et al., 2014; Taylor and McLennan, 1985; Wang et al., 2014; Yang et al., 2002b). However, certain researchers have noted that REE compositions can be affected by intense weathering (Potter et al., 2005). Additionally, several studies have noted that bulk REE results can be used to reflect the distribution characteristics of sediment types but not to faithfully trace sediment sources due to grain size effects on the elemental concentrations (Li et al., 2013; Liu et al., 2013; Yang et al., 2002a). These studies have therefore suggested that the REE compositions of fine-grained sediments may be more appropriate in identifying sediment provenances. Recently, comprehensive studies have been conducted to determine the REE distribution patterns in sediments from the rivers adjacent to the continental shelf of the SCS, including the Pearl River in South China (Xu and Han, 2009) and small mountain rivers on Taiwan Island (Li et al., 2013), and in surface sediments from the northern shelf of the SCS (Liu et al., 2013; Wang et al., 2014). However, few REE studies have examined the northwestern continental shelf mud area of the SCS.

Specific intrinsic proxies of sediments, such as grain size and Chemical Index of Alteration (CIA) values, have been widely used as effective indicators of sediment provenances, oceanic current transport, sea level, and paleoclimatic evolution (Boulay et al., 2003; Nesbitt and Young, 1982). Our study focused on new records of the REE compositions and CIA values in fine-grained sediments and on the grain sizes in Core X2, which was collected from the northwestern continental shelf mud area off Hainan Island. The objectives of this study were to 1) explore the contributions of the small rivers on Taiwan Island, 2) highlight the long-distance transport of Taiwanese sediments by the coastal current, and 3) investigate changes in the sedimentary environment and the responsible forcing mechanisms.

2. Regional setting

The study area is the northwestern continental shelf mud area off Hainan Island (Fig. 1). Hainan Island, which is composed of continental crust, is approximately 200 km wide and 300 km long and is characterized by a central mountainous region (with a maximum elevation of 1876 m) that is surrounded by low hills and alluvial plains in the coastal areas (Shi et al., 2011; Zhang et al., 2013).

The climate of the SCS is typical of the East Asian monsoon (EAM) system (Liu and Xie, 1999). The SCS is dominated by a strong northeasterly monsoon during the winter, and the winds reverse direction to the southwest during the summer (Liu and Xie, 1999). Because of the seasonal reversal in the summer and winter monsoon winds, the annual average rainfall on Hainan Island ranges between 961 and 2439 mm yr^{-1}, with 80% falling between May and October when the southwesterly winds dominate (Zhang et al., 2013). Tropical storms and typhoons frequently pass through the study area in August and September, during which heavy rainfall events occur (Mao et al., 2006). Altogether, Hainan has approximately 100 rivers with drainage areas of over 100 km^2. Approximately 40 of these rivers discharge into the SCS, and their total discharge is approximately 31×10^9 m^3 yr^{-1}. In this region, 80–85% of the runoff occurs in the wet season (Zhang et al., 2013).

The northern coastal waters of the SCS are controlled by the Guangdong Coastal Current (GCC), cyclonic circulation, and the Qiongdong upwelling (Jing et al., 2009; Li et al., 2010a; Zhang et al., 2013). Because of the monsoon climate, the GCC flows southwestward in winter, when the northeasterly East Asian winter monsoon (EAWM) prevails, and it turns northeastward in summer, when the southwesterly East Asian summer monsoon (EASM) prevails. A longshore current that exists south of South China flows southwestward during all seasons of the year (Li et al., 2010a; Liu et al., 2010). The current flows northeastward along the eastern side of Guangzhou Bay because of the southwesterly monsoon, but it flows southwestward along the western side of Guangzhou Bay, thereby forming a cyclonic circulation pattern. During the summer, an upwelling driven by the strong southwesterly monsoon and the topography dominates the eastern side of Hainan Island (Jing et al., 2009). The SCS warm current (SCSWC) is a consistent northeastward current that straddles the shelf break region. This current spreads over most of the shelf during the summer monsoon but remains near the shelf break under the strong northeasterly winter monsoon (Yin et al., 2011). A deep-water current (2000–2500 m) enters the SCS through the Luzon Strait, turning northwestward and then southwestward along the continental margins off southeastern China and eastern Vietnam (Liu et al., 2010; Qu et al., 2006) (Fig. 1).

Both large and small mountain rivers are major sediment suppliers to ocean margins around the world (Milliman and Meade, 1983; Milliman and Syvitski, 1992). The sediments on the continental shelf of the northern SCS are mainly fluvially derived, whereas eolian material from North Asia (Liu et al., 2010) and volcanic material (Chen et al., 2005) are considered insignificant sedimentary inputs. Taiwanese rivers export 384 Mt yr^{-1} of suspended sediment into the coastal ocean, with approximately half directly entering the northern SCS (Liu et al., 2008). The Pearl River, the second largest river in China in terms of water discharge, delivers 54–80 Mt yr^{-1} of sediment into the SCS (Zhang et al., 2008, 2012). The discharge from these rivers far exceeds that of the local rivers on Hainan Island. Over the past several decades, the annual total riverine sediment load from Hainan only amounted to 4 Mt yr^{-1} (Zhang et al., 2013), most of which occurred during flood seasons (Yang et al., 2013). The Red River supplies 100–130 Mt yr^{-1} of sediment into the Gulf of Tonkin, but most of these sediments have been sequestered close to the deltaic coast during the Holocene (Liu et al., 2014a; Tanabe et al., 2006). Furthermore, our study area is separated from the Red River by the Hainan Block. Therefore, presumably only a negligible portion of Red River sediment is able to reach eastern Hainan Island (Clift et al., 2008). Likewise, small mountain rivers in the Annamite Chain in central Vietnam supply 40–100 Mt yr^{-1} of sediment to the SCS, and the majority of the sediment is deposited in the central part of the Vietnamese shelf (Liu et al., 2014a; Schimanski and Stattegger, 2005). Previous studies in the western Pacific have revealed that the westward branches of the North Pacific Deep Water and the Kuroshio Current, which crosses the Luzon Strait, might transport Luzon-derived sediments to the continental slope and even the shelf of the northern SCS (Liu et al., 2008). On the northern SCS shelf, however, the SCSWC flows northeastward from the offshore area to the east of Hainan Island. The SCSWC and the considerable width (> 1000 km) of the broad and deep SCS might prevent Luzon-sourced sediments from being transported and deposited in the study area (Liu et al., 2008, 2014a).

3. Materials and methods

Sediment Core X2 was collected in September 2012 from the northern continental shelf of the SCS (Fig. 1) using a gravity corer aboard the R/V Shiyan 3, South China Sea Institute of Oceanology, Chinese Academy of Sciences. Six riverine sediments were collected downstream of the estuary sites on eastern Hainan Island in November 2013 (Fig. 1). These samples were obtained from river channel or bed deposits to avoid contamination from bank sediments. Core X2 was 240 cm long and was extracted at 18°25.753′N, 110°17.079′E at a water depth of 77 m. After collection, the core was split, described, photographed and subsampled in the laboratory of the Institute of Oceanology, Chinese Academy of Sciences (IOCAS). Subsamples 2 cm