Continental Shelf Research 90 (2014) 33–40

Contents lists available at ScienceDirect

Continental Shelf Research

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

Research papers

Clay minerals in surface sediment of the north Yellow Sea and their implication to provenance and transportation

Yan Li [a,b], An-Chun Li [a,*], Peng Huang [a], Fang-Jian Xu [c], Xu-Feng Zheng [a]

[a] Key Laboratory of Marine Geology and Environment, Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, China
[b] Yantai Ocean Environmental Monitoring Central Station of State Oceanic Administration, Yantai 264006, China
[c] School of Geosciences, China University of Petroleum, Qingdao 266580, China

ARTICLE INFO

Article history:
Received 19 June 2013
Received in revised form
9 January 2014
Accepted 18 January 2014
Available online 31 January 2014

Keywords:
North Yellow Sea
Clay mineral
Provenance
Sedimentary environment

ABSTRACT

The clay minerals in surface sediments of the north Yellow Sea have been identified with X-ray diffraction analysis and scanning electron microscope and energy dispersive X-ray spectrometer analysis to constrain the provenance and sediment transportation system in the area. Illite, with an average abundance of 58%, is the dominant mineral, followed by smectite (20% on average), chlorite (16% on average) and kaolinite (6% on average). The result of the a K-mean clustering analysis for the clay minerals show a close relationship between sedimentary types and clay mineral assemblages: there is more kaolinite and smectite in the muddy area in the western part of the north Yellow Sea and more chlorite in the sandy area in the eastern part. The Huanghe (Yellow River) is considered to provide most of the clay minerals, and in particular, rich kaolinite and smectite to the muddy area, whereas the Yalujiang provides large amounts of illite and chlorite. The spatial distribution characteristics of the clay minerals are closely related with the local circulation system, including the Shandong Coastal Current and Yellow Sea Warm Current. The former transports the outflow of the Huanghe to the north Yellow Sea, whereas the intrusion of the latter in wintertime is responsible for the annular enrichment of smectite in central part, as well as poor classification near Dalian Bay.

1. Introduction

The north Yellow Sea is regarded as the important passage for materials and energy exchange between the Bohai Sea and the south Yellow Sea (Liu et al., 1998; Lv et al., 2005) (Fig. 1). Two significant features have recently been identified in the north Yellow Sea and are now attracting much research attention. The first is a mud wedges off the Shandong Peninsula, with maximum thickness of 40 m (Liu et al., 2004, 2007, 2009b) that indicative of the huge discharges from the Huanghe to the Yellow Sea during the Holocene (Liu et al., 2002, 2007; Martin et al., 1993; Saito et al., 2001). Fine materials from the Huanghe have been deposited on the mud wedge driven by the Shandong Coastal Current (SDCC) since mid-Holocene (Liu et al., 2002, 2004), and then spread northward (Yang and Liu, 2007), and finally redeposit as mud in the north Yellow Sea (Cheng et al., 2004; Wang et al., 2009). Another is the wintertime Yellow Sea Warm Current (YSWC), which is reported to play an important role in transporting matter and heat flux from the East China Sea to the Yellow Sea. The YSWC intrudes into the north Yellow Sea in wintertime, resulting in relatively high temperature and salinity (Beardsley et al., 1985; Naimie et al., 2001; Xu et al., 2009) and greatly influences the sedimentary environment through interaction with the coastal current (Ichikawa and Beardsley, 2002; Naimie et al., 2001; Zhang et al., 2008). Numerous investigations of the north Yellow Sea have been published, including indexes of clay minerals (Park and Khim, 1992), detrital minerals (Li et al., 2001, 2009; Liu et al., 2007), carbonate minerals (Ren and Shi, 1986; Qin et al., 1989) and geochemistry (Kim et al., 1999; Lim et al., 2006; Liu et al., 2009a). These studies were usually employed to characterize the provenance of the sediments, and close attention has been paid to local features, such as the Shandong subaqueous clinoforms and north Yellow Sea mud. The lack of large-scale and high-density sampling (e.g., an interval of 12–20 km is used in this paper) has led to poor constraints on interpretations in the north Yellow Sea (Yang et al., 2003).

Entrained in a specific water mass, fine-grained clay minerals can be transported over a considerable distance to finally settle in an area far from their original source (Gingele, 1996, 2001). The contents, assemblages and distribution of clay minerals provide a useful tool for interpreting a number of issues such as transportation and hydrodynamic environment (Hover and Ashley, 2003), as well as climate change and provenance identification (Park and Khim, 1992). Here, we intend to use a similar approach to constrain provenance and transportation in the north Yellow Sea.

* Corresponding author. Tel.: +86 532 82198521.
E-mail address: 153119689@qq.com (A.-C. Li).

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http://dx.doi.org/10.1016/j.csr.2014.01.020

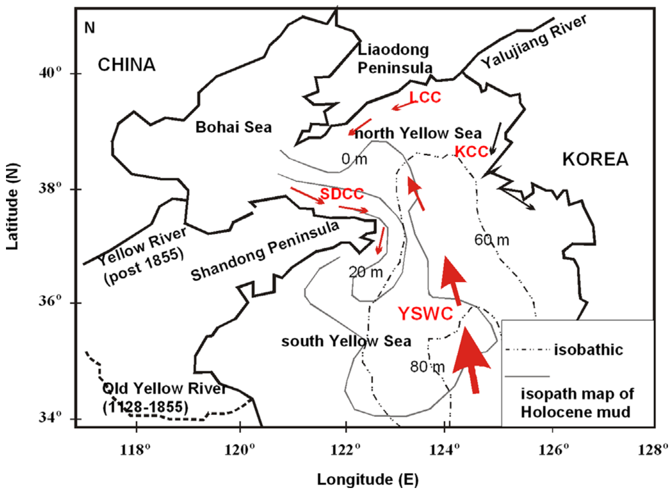

Fig. 1. Schematic map of the bathymetry and regional circulation pattern in the Yellow Sea and adjacent areas during wintertime (modified after Liu et al., 2004, 2007; Yang and Liu, 2007). Water depth is in meters. SDCC: Shandong Coastal Current; YSWC: Yellow Sea Warm Current; LCC: Liaodong Coastal Current; KCC: Korean Peninsula Coastal.

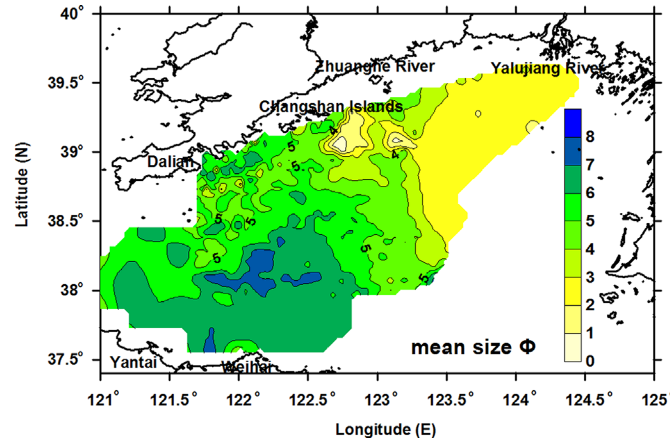

Fig. 2. The grain size (Φ) distribution (b) (modified after Wang et al., 2009) in the north Yellow Sea.

The prerequisites for this are the favorable determination of significantly different source rocks and climate conditions along the rivers in Shandong, Liaodong and Korean Peninsular (Lee et al., 1988; Ren and Shi, 1986; Yang and Li, 2000). Once the relationship of a specific clay mineral assemblage with certain source and circulation system is established, variations of this assemblage can be used to assess fluctuations in the propagation of the sedimentary environment (Gingele et al., 2001).

The objectives of this paper are to adequately constrain the clay mineral distribution characteristics and their relationships to provenance and sediment transportation in the north Yellow Sea.

2. Regional setting

The north Yellow Sea lies on a shallow, semi-enclosed, low-gradient continental shelf between the Chinese mainland and the Korean Peninsula, with a water depth generally less than 70 m (Fig. 1). It is separated from the Bohai Sea to the west by the Bohai Strait and from the south Yellow Sea to the south by the eastern tip of Shandong Peninsula and western tip of Korea Peninsula.

The north Yellow Sea has received an abundant supply of terrigenous material during Holocene, accompanied by a high accumulation rate (Alexander, 1990). A complex hydrodynamic environment was reported in there as a result of interaction in the Yellow Sea circulation system, mainly including the YSWC, SDCC, LCC and KCC. Tides are typically semidiurnal, ranging from 1.5 to 8 m (Chough et al., 2000) and generally considered to exert a great control on sediment resuspension, transportation, and deposition in the eastern Yellow Sea (Lee and Chu, 2001). A series of radial tidal sand ridges in the eastern part of the sea were deemed to be residual deposit originating before the onset of Holocene transgression due to the strong tidal currents (up to 100 cm/s according to Qin et al. (1989) and Xiu et al. (1989)).

The investigated area is situated in the northern part of the Yellow Sea with maximum water depths of 67 m and deepen progressively to the south and southeast (Fig. 1). According to the grain-size analysis of surface sediment retrieved from the north Yellow Sea, Wang et al. (2009) found that muddy deposits have an average grain size of Φ5–8 and that they are characterized by a higher clay fraction (exceeding 30%) in the west part (Fig. 2). The mud is considered to have derived primarily from the Huanghe (e.g. Alexander et al., 1991; Lee and Chough, 1989; Qin and Li, 1983), corresponding roughly with the Yellow Sea Cold Water in summertime (Weng et al., 1988; Zhang et al., 2008). However, sandy deposition (Φ1–4) located in the northeastern part of the investigated area are generally characterized by the enrichment of sand fraction (> 80% according to Wang et al. (2009)) and are reported to be affected primarily by tidal currents (Liu et al., 2004; Qin et al., 1989).

3. Materials and methods

Clay mineral content was assessed in a total of 330 box-samples from the north Yellow Sea (Fig. 3) and in 37 samples from river estuaries (including 20 from the Huanghe estuary, 7 from the Changjiang estuary and 10 from the Yalujiang estuaries) with X-ray diffraction (XRD) at the Key Laboratory of Marine Geology and Environment, Institute of Oceanology, Chinese Academy of Sciences. Most of the samples were suitable for XRD analysis with the exception of a few of the coarse-grained sediments from the northeastern area (Fig. 3), which contains too little clay to be measured.

To ensure the deflocculation of the clay minerals, the samples were treated by washing twice with distilled water after decarbonation with 10% HAC and the removal of organics with 10% H_2O_2. Particles smaller than 2 μm were separated based on Stoke's law. XRD curves (Fig. 4) are obtained using a D8 ADVANCE diffractometer with Cu*K*α radiation (40 kV, 40 mA) and Ni filter. Each sample was evaluated three times: (1) under dry air conditions (scanning from 3 to 30° $\Delta 2\theta$, with a step size of 0.02°); (2) after saturating with ethylene glycol (3–30° $\Delta 2\theta$, 0.02° steps), and (3) after saturating with ethylene glycol (24–26° $\Delta 2\theta$, 0.01° steps). The last test was used to distinguish kaolinite and chlorite at 3.53 Å/3.57 Å. In addition, some samples were randomly selected for measuring after heated to 550 °C for 2 h to further identify kaolinite and chlorite, and confirm the existence of smectite. Identification of clay minerals was based mainly on the position of the (0 0 1) series of basal reflections on the XRD diagrams. Semi-quantitative calculation of peak areas on the basal reflections for smectite (17 Å), illite (10 Å), and kaolinite + chlorite (7 Å) were undertaken on the glycolated curve with intensification factor of 1, 4 and 2, respectively.

The illite chemical-index, which can mirror the weathering regimes of sediment provenance (Ehrmann, 1998; Liu et al., 2003), refers to ratio of the 5 Å/10 Å peak area in the glycolated curve. Ratio above 0.5 indicates Al-rich illite altered by strong hydrolysis, whereas ratios below 0.5 represents Fe- and Mg-rich illite formed by physical erosion (Gingele et al., 1998; Liu et al., 2008). According to Petschick et al. (1996), the illite crystal-index denoted as “IB” is usually