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Hydrodynamic processes and their impacts on the mud deposit in the Southern Yellow Sea

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ABSTRACT

The sedimentation processes of mud deposits on the continental shelves of the Yellow Sea (YS) are investigated using a combined data analysis and hydrodynamic modeling approach in order to identify the dominant factors that contribute significantly to the formation of these deposits. The data analysis makes extensive use of existing data, especially recently collected deep core data while the hydrodynamic and sediment transport processes are studied using a 3D hydrodynamics model that incorporates the effects of tides, waves and wind. The average deposit rate of the Central Yellow Sea Mud (CS) is estimated to be 3.6×10^7 t a^{-1} based on high-resolution Chirp sonar profiles combined with core data. Available sedimentological, mineralogical, geochemical and fluid flow data all indicate that the fine sediments discharged from Huanghe River and Changjiang River as well as the resuspended sediments from the Old Huanghe Delta are the main sources for the mud deposits in the Southern Yellow Sea (SYS). This study confirms that tidal current flow is indeed the main agent for transporting the fine sediment to the mud patch in the central SYS but wave effect is also significant as it is responsible for maintaining suspension concentration and causing sediment resuspension. The wave influence is particularly notable around the Old Huanghe Delta in winter storms as during these storm periods current circulation, mainly caused by the Asian Monsoon, can transport a large quantity of fine sediments from the Old Huanghe Delta to the central SYS. Under the present hydrodynamic conditions, the modeling results showed that approximately 16% (1.33×10^8 t a^{-1}) of the Huanghe River-derived sediment is transported out of Bohai Strait, of which around 44% (5.72×10^7 t a^{-1}) will finally be transported to the South Yellow Sea. The corresponding values without accounting for the wave effects are 9.8% and 2.6%, respectively. It is noted that the deposition rate in the CS mud area over the past 12 kyr is virtually constant despite the significant rise in sea-level and associated changes in the tidal current fields and wave distributions in the Yellow Sea. The reason for this is believed to be that the weaker currents and waves during a lower water period is compensated by the shorter distance the suspended sediments have to travel from the paleo-Huanghe River to the CS mud area, thus maintaining a nearly constant deposition rate in the CS mud area.

1. Introduction

Large fine-grained sedimentary deposits are widely found on the continental shelves around the world, mostly associated with rivers that discharge a large quantity of fine sediments to the coasts. These include muddy deposits on the Southern Yellow Sea shelf, in the Gulf of Maine shelf off the northeastern U.S. (Piotrowicz et al., 1981; Barnhardt et al., 1997; Ward et al., 2008), in the northern Irish Sea shelf (Belderson, 1964; Kershaw et al., 1988; McCabe, 1997; Merino et al., 2000; Macken et al., 2009), the North Sea shelf (De Haas et al., 1997; Graham et al., 2010), and off Amazon River (Kineke and Sternberg, 1995; Kineke et al., 1996). As fine sediments can carry pollutants from a near shore area to deeper water and the thick stable mud deposits can also contain rich information about late Holocene sea-level rise, temperature change and large historical flood events the formation genesis of these deposits has attracted much research attention (Walsh and Nittrouer, 2009).

Among the well known mud deposits in the world, those in the Yellow Sea are particularly notable for their large size and stability. As with other basin settings, the first-order controls on the formation of the mud deposits in the Yellow Sea are sediment supply and sea level changes over geological time scale. Once sediments are carried beyond the near shore region, they have the potential of being moved farther seaward in any of the three modes: (1) surface-plume transport, (2) dilute-suspension bottom-boundary layer dispersal, and (3) sediment gravity flows (Walsh and Nittrouer, 2009). All of these modes of

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transport have been known to occur in different parts of the Yellow Sea at different times but it is less clear which, if any, is the dominant transport mode that determines dispersal patterns of the Yellow Sea sediments (Shi et al., 2002; Lim et al., 2007; Guo et al., 2010).

Part of the difficulties in understanding the sediment transport in the Yellow Sea is the complexity of the hydrodynamics and strong seasonal variability of wind and waves. Considerable progress has been made in recent decades. Bao et al. (2001) calculated the M2, S2, K1, and O1 tides and tidal currents in the Bohai, Yellow and East China Sea (ECS) using a three dimensional model. Lee et al. (2002) simulated the seasonal oceanic current in the YS and ECS with an M2 tide force. Xia et al. (2004) applied a wave–tide-circulation coupled numerical model to simulate the temperature structure in the Yellow Sea and obtained good comparison with the observations. Park and Chu (2006) examined seasonal variability of surface and subsurface thermal/saline fronts in the Yellow Sea based on three-dimensional monthly-mean temperature and salinity data from U.S. Navy's Generalized Digital Environmental Model. Yang et al. (2004) calculated the wave-induced mixing effect and showed that it is strongest in the winter due to winter monsoon and weakest in spring. It can affect temperature distribution even to 40–50 m below the sea surface in summer. The wave in a shallow water area is shown to have a significant impact on the bottom shear stress and the net sediment transport process (Holmedal and Myrhaug, 2006; Xing et al., 2011). Three-dimensional circulation has been computed to show the two distinct circulation modes for winter and summer based on seasonal hydrography, mean winds, mean discharge from the Changjiang River, and invariant oceanic tides without consideration of the waves (Naimie et al., 2001). This seasonal dependency was confirmed by Yuan and Hsueh (2010) in their general ocean circulation model results which show that the shelf circulation of the Yellow Sea and East Sea in winter is induced primarily by the northerly monsoonal winds.

In parallel with these hydrodynamic modeling researches, a large number of field studies have also been carried out to determine the origin of sediments on the mud deposits in the Yellow Sea using various methods ranging from sedimentological, radiochemical and geochemical analyses, to geological methods such as stratigraphy, sediment cores, and sedimentary facies analysis. Many of these studies were designed to identify proximal parameters pertaining to geology, hydrodynamics or geochemistry that can be used to determine the geo-environmental condition, provenance and accumulation rate of the mud deposits (Alexander et al., 1991; Kim et al., 1999; Wei et al., 2003; Hu et al., 2013). For example, smectite, one of the clay minerals, whose contents are reported to be much higher in Huanghe sediments (>10%) and in Changjiang sediments (>5%) than those in Korean river sediments (< 5%) (Park and Khim, 1992; Lee and Chu, 2001), was used for provenance discrimination in the Yellow Sea. The smectite content distribution shows a higher value in the western Yellow Sea than in the eastern part. The North Yellow Sea Mud has relatively higher smectite contents than that in the Central Southern Yellow Sea (denoted by CS) and southeast Yellow Sea Mud, suggesting the obvious influence of the Huanghe sediment there (Cheng et al., 2003). It was also suggested that the provenance of the CS may be closely related to the old and present-day Huanghe River system based on clay mineral (especially smectite) concentration analysis of 52 sediment samples from the Yellow Sea continental shelf (Park and Khim, 1992). However, new data and analysis show that clay mineral assemblages in Chinese or Korean river sediments can actually vary significantly (Yang et al., 2003), depending on sampling processes, analytical conditions, and calculation methods (Park and Khim, 1992; Zhao et al., 2001), which could be the reason for the higher smectite contents in Korean river sediments than that in the previous reports and casts doubt on the suitability of using smectite content to distinguish Chinese and Korean river sediments. Furthermore, clay mineralogy, especially smectite, may undergo changes in the sea due to submarine weathering and diagenesis of clay minerals (Chamley, 1997), which will lead to further uncertainties in the use of smectite contents as a proxy indicator to discriminate the sediment sources in the sea.

Heavy minerals, which are detrital grains of minerals with a high density (>2.9) such as magnetite, garnets, zircon, rutile and so on, were also adopted to discriminate the sediment source of CS (Lee and Chough, 1989; Zhao et al., 1990; Li et al., 2001), but suggestions from heavy minerals are not always consistent with the results from the mineralogical characters. The strong hydrodynamic regime in the Yellow Sea, especially in the eastern part, may restrict the application of heavy minerals as the indicators of sediment source because distribution patterns of heavy minerals can be easily changed by the reworking and redistribution of bottom sediments (Morton, 1991).

Alkaline earth element (Ca, Sr, Ba, Mg) concentrations vary a lot between Chinese and Korean river sediments, resulting from remarkably different provenance compositions and weathering processes in their drainage basins. The distribution of alkaline earth elements of surface samples of the Yellow Sea also suggested that the sediment of CYSM mainly originated from Huanghe River (Kim et al., 1999). However, the application of alkaline earth elements to trace the Huanghe sediments in the Yellow Sea has been confined to limited areas because of the instability of these elements in sedimentary environments and because of the strong disturbance of biogenic components (Martin et al., 1993; Cho et al., 1999).

Despite the clear usefulness of these proximal methods, the incompleteness of the stratigraphic record has made the interpretation of strata and quantifying deposit difficult, which is further compounded by the lack of consistency in many of these data (Yang et al., 2003).

Due to the large size of the flow system and the complexity of sediment transport processes, direct simulation of the mud deposit formation over geological time scales is not possible. The formation mechanism of the mud patch has often been inferred indirectly from the relevant short term hydrodynamic processes. The earliest and also perhaps most widely cited explanation is the flow upwelling mechanism proposed by Hu (1984) and Pang and Hu (2002). Using a simple ocean circulation model, Hu (1984) has shown that the flow upwelling can occur in the central part of a cyclonic cold eddy which coincides with the location of the mud deposits. This explanation based on water eddy is however not universally accepted. Zhu and Chang (2000) demonstrated that the muddy patches can form in areas with weak tidal currents without the requirement of the presence of cold eddies based on a numerical simulation, implying that the existence of cold eddies is not a necessary condition for the formation of mud patches. Recently, it was shown by Wang et al. (2014) that the confusing situation described above is partly due to the complexity of the problem but also caused by over reliance on a single or a few limited processes/parameters. In order to resolve some of the existing controversies and improve the understanding of the genesis of the mud deposit in the Yellow Sea, an integrated approach based on a combination of numerical simulations of isolated processes and a pure data-based study, is needed which will draw on information from all relevant sources and provide a consistent interpretation of sediment origin, sediment pathways, budget and deposition rate.

The work reported in this paper is intended to examine critically the existing data, investigate the fine sediment deposition processes in the central Southern Yellow Sea and identify the key factors contributing to its formation. To this end a combined geological (based on the core analysis) and hydrodynamic (3D modeling) approach has been adopted in order to quantify the relative contributions of different processes to the formation of the deposits by considering the effects of waves, currents and winds on the flow field, and to establish the linkages between sediment supply, accumulation, and dynamics for the deposits and determine the dominant processes responsible for the formation of the deposits.

This paper is organized as follows. We first present the study site including a description of the currents, waves and sediments in Section 2. Section 3 outlines the methodology adopted including the