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Sedimentary laminae in muddy inner continental shelf sediments of the East China Sea: Formation and implications for geochronology

Xilin Zhang [b, c, d], Dejiang Fan [a, c, *], Jingping Xu [a, c], Ming Liu [a, c], Yuan Tian [a, c], Bin Chen [b, c], Zhilei Sun [b], Weiliang Liu [d], Zuosheng Yang [a]

[a] Key Laboratory of Submarine Geosciences and Technology of Ministry of Education, Ocean University of China, Qingdao 266100, China
[b] Key Laboratory of Marine Hydrocarbon Resources and Environment Geology, China Geological Survey, Ministry of Land and Resources, Qingdao Institute of Marine Geology, Qingdao 266071, China
[c] Laboratory for Marine Geology, Qingdao National Laboratory for Marine Science and Technology, Qingdao 266061, China
[d] Guangdong Provincial Key Laboratory of Marine Resources and Coastal Engineering /Guangdong University Key Laboratory of Offshore Oil Exploration and Development, School of Marine Sciences, Sun Yat-sen University, Guangzhou 510275, China

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ABSTRACT

The sedimentary rhythm is well developed in the environment which is controlled by strong seasonal climate changing condition. This rhythm is important for sediment core dating purpose. In this study, we examine muddy sediments on the inner continental shelf of the East China Sea that are influenced under seasonal change of the East Asian monsoon. We use Ensemble Empirical Mode Decomposition (EEMD) method to process sediment grain size and X-radiograph negatives grayscale value data in three sediment cores from this area and use the results to analyze the patterns of sedimentary variability and the causes of cyclic variability of the sedimentary process. The variability in the grain size and grayscale values of the core sediments has three components: the high-frequency variability, low-frequency variability and a secular trend. Among these components, the high-frequency component reflects variability on annual time scale can be well recognized, we suggest that the annual variability is derived from seasonal variation in the sediment flux from the Yangtze River to the sea, as well as the East Asian monsoon's impact on the sedimentary dynamics of the East China Sea's inner continental shelf. However, the other variability is hard to identify which cycles there are. This variability may reflect decadal winter monsoon oscillation and human activity of dam construction in the Yangtze River. Each annual variability presents a varve in the sediment sequence, which can be used to determine the sediment deposition rate and accurately date the core sediment. We found that the average deposition rates of the three cores from north to south on the inner shelf were 3.1 cm/yr, 1.0 cm/yr, 0.9 cm/yr, indicating that the Yangtze-derived sediment decreased with the increasing distance from the Yangtze estuary to the shelf. The deposition rate of each core varies over time, and the maximum deposition rate can be 3–5 times greater than the minimum rate. The sediment ages obtained from varve chronology and radiometric dating are fairly consistent on a centennial scale, differing only by 2–5 years. Thus, varve counting is a useful supplementary approach to radiometric age dating for constructing chronologies for core sediment in shelf seas influenced by monsoons.

1. Introduction

Sediment core can serve as important archive of paleoclimatic and paleoenvironmental records. To explore the proxies of paleoclimate and paleoenvironment in this archive can elucidate the evolution of regional climate and environmental factors (Bianchi and Allison, 2009; Ojala et al., 2012). Previous studies showed that geochronology in core sediment is crucial to the successful reconstruction of paleoclimatic and paleoenvironmental changes. Various relative and absolute dating methods have been used to determine the ages of the core sediment, including paleomagnetic stratigraphy approach, high resolution oxygen isotope stratigraphy approach, and radiometric dating methods (Aksu and

* Corresponding author. College of Marine Geosciences, Ocean University of China, 238 Songling Road, Qingdao 266100, China.
E-mail address: djfan@ouc.edu.cn (D. Fan).

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Mudie, 1985; Klein et al., 1996; Kirchner, 2011), which have been successfully applied to paleoenvironmental reconstruction. However, these methods have various limitations. First, the resolution of relative dating methods is rather low. Second, radiometric dating can only be applied to some specific sediment layers, and when the deposition rate is variable, it could be difficult to assign ages accurately throughout entire sediment core. Finally, there is a dating gap for sediment with ages between 100 and 400 years old by using these methods. These weaknesses in core age dating methods impede the analysis of high-resolution sediment records, requiring developing new dating methods to solve the problems. Previous studies illustrated that well-defined sediment varves are formed in certain sedimentary environments (Zolitschka et al., 2015); the good examples are the lacustrine varves (Nederbragt and Thurow, 2001; Migowski et al., 2004; Bendle et al., 2015), the varves in delta-front influenced by monsoons (Allison et al., 2000; Palinkas et al., 2005), and the varves in some bays and on open continental shelves (Dallimore et al., 2005; Larsen et al., 2011). These varves result from a combination of climatic, hydrodynamic, and biological processes (Ojala et al., 2012). Varve identification can help determine chronology of sediment in core profile, providing time scale for studying interannual and interdecadal variations of paleoclimate or environment in the sedimentary records.

The sedimentary environment on the inner continental shelf of the East China Sea is unique. A large amount of terrigenous material delivered by the Yangtze River deposits along the Zhejiang-Fujian coast due to the interaction of coastal currents, the warm Taiwan current, and the influence of waves and tides (Liu et al., 2006). At the same time, a small amount of biogenic deposits adds to this total sediments (Liu et al., 2011). This material would form thick and continuous muddy sediments throughout the region, providing a high-resolution sedimentary record (Wang et al., 1999; Qiao et al., 2011; Zhou et al., 2014). The East Asian monsoon strongly affects the Yangtze River-derived sediment input, the marine biogenic matter supply, and the strength and direction of coastal currents. During the summer, input from the Yangtze River is high and there is abundant biogenic material, but coastal currents are weak. In contrast, during the winter, input from the Yangtze River is low and there is little biogenic material, but coastal currents are strong (Liu et al., 2007; Hu et al., 2011). This seasonal variability in sedimentary process is a prerequisite for the formation of sedimentary laminae. Previous *in-situ* studies found that the concentration and distribution of total suspended matter in this region showed significant seasonal variations (Yang et al., 1992; Li et al., 2013). Recently, Fan et al. (2011) noted well-developed 'annual sedimentary lamination' in the muddy sediments at the mouth of the Yangtze River, with a varve thickness on the scale of several centimeters. Unlike traditional varves, these are difficult to recognize at the macro scale and can only be identified through component analysis. Such hidden varves can be used to date sediments. In theory, they could exist throughout the mid-latitude continental shelves that are influenced by the East Asian monsoon. Due to the complexity of the continental shelf environment and the elusiveness of varve signals, there is still debate over how varves form and how to identify them (Hori et al., 2002; Fan et al., 2011).

This study uses Ensemble Empirical Mode Decomposition (EEMD) method to analyze high-resolution X-radiograph negatives grayscale values in the three sediment cores from inner continental shelf of the East China Sea. We explore methods of identifying sedimentary laminae in this area and analyze their formation mechanisms by comparing grain sizes in the sediment cores with regional monsoon activity. We also compare our varve counting results with radiometric dating and assess the applicability of varve counting for constructing sediment core chronologies.

2. Samples and methods

2.1. Study area and sample collection

The East China Sea is a typical open epicontinental sea. It is connected to the Pacific Ocean via the Okinawa Trough to the east and mainland China to the west (Liu et al., 2000). Because of the influence of the Kuroshio Current, the Taiwan warm current, and the East China Sea coastal current, the East China Sea has a complex and dynamic sedimentary environment (Huh and Su, 1999). The East China Sea receives terrigenous inputs of approximately $0.9–1.0 \times 10^9$ t/yr, mainly from the Yangtze River and the Yellow River (Deng et al., 2006). Terrigenous inputs delivered by the Yangtze River account for 34–50% of the total inputs (Yang et al., 2002), and terrigenous inputs from the Yellow River account for 2–16% (Su and Huh, 2002). Because of the abundant sediment supply to the East China Sea, there are active sedimentary processes in the area, and these have formed muddy sediments at the mouth of the Yangtze River, along the Zhejiang-Fujian coast, and southwest of Jeju Island (Fig. 1). These muds have been developed as global sea level rose since the last glaciation (Yang and Liu, 2007). Their high deposition rates and continuous stratification record climatic and environmental changes well. Thus, the East China Sea is an ideal place in which to investigate the regional response of the western Pacific epicontinental seas to global change.

The three sediment cores used in this study (18, C0702, and DH6-1) are from the regions of muddy sediments at the mouth of the Yangtze River and along the Zhejiang-Fujian coast (Fig. 1). They are gravity cores collected from the *Dong Fang Hong II* research vessel during three scientific expeditions in 2006, 2009, and 2011. Their lengths are 225 cm, 176 cm, and 171 cm, respectively, and they were taken from water depths of 20.4 m, 40 m, and 53.8 m. In this study, we analyze the sections from 0 to 225 cm of core 18 and from 0 to 120 cm of cores C0702 and DH6-1.

2.2. Methods

Following core collection, we produced the X-radiograph negatives for the three cores and examined their sedimentary characteristics.

First, we inserted special square PVC tubes (200 cm × 5.5 cm × 2 cm) into the cores to retrieve samples of equal thickness. Then, we used a SIEMENS-FX X-ray imaging system (the working conditions were set to a 16 mA current and 70 keV voltage) to obtain X-radiograph negatives of the cores. The X-radiograph negatives grayscale values of the cores were determined at a 1 mm resolution after digitization of the negatives.

Next, we collected sub-samples of approximately 1 g at 0.25 cm intervals of the imaged cores for grain size analysis. We measured the grain size of the sediments using a Mastersizer 2000 laser diffractometer, with the applicable range in 0.02–2000 μm, the resolution of 0.01 Φ, and the analytical error at ± 2%.

The relict sediments in the cores were used to measure the radioactive intensity and water content. We took samples at irregular intervals of 3–5 cm for radioactivity analysis. The activity of ^{210}Pb and ^{137}Cs in the sediments was measured using a EG&G Ortec γ spectrum analysis system. Standards for ^{137}Cs and ^{226}Ra were provided by the China Institute of Atomic Energy. The standard for ^{210}Pb was provided by the University of Liverpool, UK. We used a 3 cm-diameter stainless steel circular knife with a fixed volume to collect samples at 10 cm intervals for water content analysis. The water content and dry density of the sediments were measured by weighing the wet and dry sediments, respectively.

Spectral analysis methods have been used to reveal periodic variations preserved in sediment sequences in order to help us