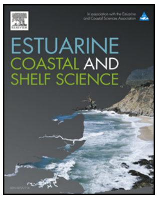
Estuarine, Coastal and Shelf Science 212 (2018) 353–364

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

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



Distribution of biogenic silica in seafloor sediments on the East China Sea inner shelf: Seasonal variations and typhoon impact

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ARTICLE INFO

Keywords:
Biogenic silica
Seafloor sediment
Seasonal variation
Typhoon Morakot

ABSTRACT

The content and distribution of biogenic silica (BSi) in sediments, as effective proxies for marine paleo-productivity and sedimentary environment evolution studies, has significant seasonal and event-based differences. Based on measurements of BSi content in the seafloor sediments acquired during three surveys in winter and before and after typhoons in summer in the Fujian-Zhejiang coastal mud deposition center (MDC-ZFC), respectively, the seasonal and event-based (typhoon process) differences of BSi in seafloor sediments are discussed by combining with data of the sediments grain sizes and the abundances of dominant diatom species. Conceptual models of the modern sedimentary environment (including BSi) are summarized. The study results show that the BSi in the seafloor sediments in the study region is relatively low, generally less than 1%. Generally, the BSi in the winter seafloor sediments is lower than that under normal summer sea conditions and the BSi in the sediments after the summer typhoons is higher than that under normal summer sea conditions. The differences in the origin of biogenic siliceous materials (seasonal growth of siliceous organisms) and the marine hydrodynamic environment (such as seafloor sediment resuspension and elutriation caused by strong marine hydrodynamic processes) are the major factors for different relative BSi content. The seasonal and event-based variations of BSi have important significance in paleo-oceanography and event sedimentology studies.

1. Introduction

Biogenic silica (BSi) in seafloor sediments primarily originates from the deposition of siliceous organisms from the overlying water (mainly diatoms, radiolarians, silicon flagellates, and sponge spicules) (DeMaster, 1981; Brzezinski et al., 1998; Schlüter, M. and E. Sauter, 2000; Tréguer and De La Rocha, 2013). The generation, deposition, transport, burial, and preservation of BSi in sediments is closely related to the primary productivity of the overlying water and the marine sedimentary (dynamic) environment (including the properties of seafloor sediments), which show seasonal and event variations (DeMaster, 1981; Nelson et al., 1991; Colman et al., 1995; Liu et al., 2005; Gallinari et al., 2008; Sánchez et al., 2008; Cheng et al., 2009; Fan et al., 2011; Wang et al., 2014; Zhang et al., 2015). A comprehensive and systematic understanding of these variations is necessary for using BSi as an important proxy for past productivity.

Due to low nutrients supply (due to the relatively low river runoff), low water temperature and strong mixing, the growth of siliceous organisms in water is limited in winter but with increasing nutrients supply, temperature and stratification, siliceous organisms start to grow explosively in spring, often leading to a spring/summer bloom (Furuya et al., 2003; Zhou et al., 2013; Carstensen et al., 2015; Gallegos and Neale, 2015; Haraguchi et al., 2015; Koshikawa et al., 2015). Consequently, the BSi in sediments deposited in winter is lower than that in spring and summer. In addition, different marine dynamics in winter and summer also have significantly different effects on seafloor sediments, thereby affecting the component proportions in the seafloor sediments (Gallinari et al., 2008; Sánchez et al., 2008; Carstensen et al., 2015; Zhang et al., 2015). In the estuaries and near-shore mud sedimentary areas, with sufficient sediment supply and high deposition rate, this type of seasonal sedimentary layer could be preserved effectively and can thus be used to study the seasonal sedimentary characteristics of BSi and the high-resolution seasonal sedimentary records (Fan et al., 2011).

Typhoons, as one of the largest ocean-atmosphere interactions, greatly increase the sea-atmosphere energy and material exchange on a short meteorological scale, significantly changing the water column structure (Price, 1981; Emanuel, 2001; Zamudio et al., 2010; Li et al.,

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https://doi.org/10.1016/j.ecss.2018.07.023
Received 24 September 2017; Received in revised form 11 July 2018; Accepted 29 July 2018
Available online 31 July 2018
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2012; Meyers et al., 2016), seafloor morphology (Allison et al., 2005; Milliman et al., 2007; Goff et al., 2010; Li et al., 2015a), biogeochemical processes (including phytoplankton population) (Lin et al., 2003; Walker et al., 2005; Shi and Wang, 2007; Wetz and Paerl, 2008; Zhou et al., 2011; Li et al., 2013a; Wang et al., 2016), and sediment transport and deposition in the affected regions (Wren and Leonard, 2005; Milliman et al., 2007; Li et al., 2015a). These processes all affect marine cycles. Typhoon processes form storm deposition sequences that are significantly different from the sequences under normal sea conditions (Allison et al., 2005; Li et al., 2015a). Most storm deposition sequences are transformed by later deposition processes and mix with the underlying and overlying sedimentary layers, and their sequences and sedimentary characteristics are difficult to preserve (Shinn et al., 1993; Keen et al., 2006). However, in some regions with a high sediment accumulation rate and a stable sedimentary environment, the sedimentary layers can be preserved and gradually evolve into paleo-storm deposition sequences (Shinn et al., 1993; Keen et al., 2006).

The East China Sea, with a broad continental shelf, an abundant particle material supply, and a complex dynamic water environment, is one of the major marginal seas in the Northwest Pacific (Hu and Yang, 2001), which also is a sink for BSi deposition (Liu et al., 2005; Fan et al., 2011; Wang et al., 2014). The Fujian-Zhejiang coastal mud deposition center (MDC-ZFC), is one area where fine-grained materials are deposited (Liu et al., 2006, 2008; Xu et al., 2009, 2012). Affected by the dynamic marine environment and sediment supply and transport, the modern marine deposition environment and processes in the MDC-ZFC have significant seasonal variations (Li et al., 2013b). In summer, the mud deposition center is frequently affected by strong typhoon processes (Li et al., 2012, 2015b). These processes all affect the generation, deposition, preservation, and distribution of BSi. Over the years, researchers have conducted numerous studies in the East China Sea and surrounding waters using BSi to infer the marine paleo-productivity (Liu et al., 2005, 2013). Meanwhile, some researchers have also tried to study seasonal geological records (Fan et al., 2011). However, comprehensive studies on seasonal and event-based BSi deposition are rare.

Based on the relative content and distribution variations of BSi in the seafloor sediments in the MDC-ZFC acquired during three surveys, this study examines the seasonal variations and typhoon impacts on BSi by comparing it with sediment grain size and distributions of the dominant diatom species' abundances. Conceptual models of the seasonal evolution and typhoon impact on the modern sedimentary environment (including the BSi) in the coastal area are summarized based on these results. Combined with hydrographic data for the water column, this study offers insight on the mechanisms controlling BSi distribution that should be considered when using BSi in sediments as a proxy for paleo-productivity.

2. Background

A detailed description of the study area, surveys and the evolution of Typhoon Morakot can be found in Li et al. (2012; 2013b). However, a brief description of the study background is provided here.

2.1. Study area and surveys

The study area was located in the MDC-ZFC, which acts as a sink for sediments from Yangtze River and accounts for one of the main mud deposits on the ECS shelf (Fig. 1a) (Liu et al., 2006). The seasonal sedimentary processes, controlled by Asian Monsoon and unique sediment supply and marine hydrodynamics, significantly vary in the ECS shelf (including MDC-ZFC) (Hu and Yang, 2001; Lie and Cho, 2016). The circulation system in the MDC-ZFC and its adjacent area includes the Zhejiag-Fujian coastal current (ZFCC) with relatively low temperature, low salinity and high turbidity, which flows northward in summer and southward in winter due to Asian Monsoon and the Taiwan Warm Current (TWC) with high temperature, high salinity and low turbidity, which perennially flows northward (relatively strong in summer and weak in winter) (Hu and Yang, 2001; Lie and Cho, 2016). The sediments discharged from the Yangtze River are generally rapidly deposited in the Yangtze estuary area in summer and formed the mud deposition center of the Yangtze delta (MDC-YD). The deposited sediments can be resuspended by extreme storms and transported southward again along the coast by ZFCC in winter and formed the thickened MDC-ZFC (Liu et al., 2006; Li et al., 2013b). At the same time, the ECS shelf was located in a typhoon-active area in the Northwest Pacific Ocean, and according to long-term records, on average, 4 typhoons pass over the ECS shelf annually, which significantly impact the marine sedimentary environment and sedimentary process (Li et al., 2015c).

Three surveys were conducted on the MDC-ZFC (Fig. 1b). The first survey (as winter survey) was conducted from Dec. 5th to 7th, 2008, with 25 seafloor sediment samples were collected. Due to the winter storm, the weather was unfavorable, with wave heights of 2.3–3.5 m and the wind speed higher than 13.0 m/s, during the survey (www.zjhy.net.cn). The second (as summer/pre-typhoon) and the third (as summer/post-typhoon) surveys were conducted on Aug. 1st and Aug. 12th, 2009, respectively. Both surveys lasted about 3 days. The post-typhoon survey started about 2.5 days after typhoon Morakot making landfall in Fujian, China. 29 and 24 seafloor sediment samples were collected in the two surveys, respectively. The weather was calm, with south wind speed less than 10.7 m/s and wave height less than 1.6 m, during the second survey (www.zjhy.net.cn). The weather was unfavorable due to the typhoon, with wave height of 2.0–2.5 m and wind speed higher than 13.0 m/s, during the third survey (www.zjhy.net.cn). As our cruise moved northward, the sea conditions deteriorated so much that we were forced to abandon the survey for the northernmost 5 stations (Fig. 1) in the third survey.

2.2. Typhoon Morakot

Typhoon Morakot was the deadliest typhoon impacting Taiwan in recorded history. The Morakot, as a severe tropical storm, was making second landfall in mainland China on August 9th, 2009, after first landing in central Taiwan and then crossing the Taiwan Strait. The wind speed was approximately 33.0 m/s at its second landfall, which is approximately 100 km from the center of the study area. Subsequently, Morakot migrated along the Eastern China Coast and its influence gradually decreased to August 12th, when it entered the southern Yellow Sea and weakened into a tropical depression. During approximately four days of lingering near the study area, Morakot produced up to 1240 mm of rain in Zhejiang province, which was the highest in nearly 60 years, raising several rivers above their flood stages (NMCCMA, 2009). According to previous study results, water structure, biogenic process and suspended particles distributions in water column were greatly affected by typhoon Morakot in the study area (Li et al., 2012, 2013a, 2015b).

2.3. Observed water structure and it's differences in three surveys

According to previous study results, water temperature, salinity, turbidity and Chl-*a* distributions in the water column were greatly different between winter and summer and significantly affected by Typhoon Morakot (Li et al., 2013b, 2015b) (Fig. 2). In winter, the water column was completely mixed with relatively low temperature and salinity and high turbidity due to the coastal current (Fig. 2, a1, a2 and a3). In the whole water column, the content of Chl-*a* was relatively low due to the cold water temperature and high turbidity (Fig. 2, a4). After the passage of the typhoon, the water column was mixed and the stratification and thermocline were interrupted (Fig. 2, b1 and c1). Due to the abundance of fresh water supply, low-salinity water spreading in the upper water produced a halocline near the coast (Fig. 2, b2 and c2). The water turbidity in the bottom water increased several times to more than ten-fold after the typhoon (Fig. 2, b3 and c3). The content of Chl-*a*

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