Deep–Sea Research I 118 (2016) 46–56

Contents lists available at ScienceDirect

Deep–Sea Research I

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

Sources and burial of organic carbon in the middle Okinawa Trough during late Quaternary paleoenvironmental change

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ARTICLE INFO

Keywords:
Organic carbon
Okinawa Trough
Sediment
Late Quaternary
Paleoenvironment

ABSTRACT

The sediments from a piston core ECS12A recovered from the middle Okinawa Trough in the East China Sea were measured for total organic carbon (TOC), total nitrogen (TN), and other biogenic elements to provide constraints on the sources and burial rates of depositional organic matter (OM) and on the changes in primary productivity since 19 ka. The last glacial sediments (ca. 17–19 ka) are characterized by low contents of biogenic elements and well-developed turbidite layers, suggesting low primary productivity but a high component of terrigenous sediment. With rising sea level and enhanced monsoons during the deglacial period, the proportion of marine OM gradually increased. The least negative $\delta^{13}C_{org}$ values and the smallest grain size of sediments deposited ca. 10–14.5 ka indicate high primary productivity and a sedimentary environment dominated by the marine component. The source and burial rates of OM in the Holocene sediments (ca. 5.4–10 ka) were largely controlled by the intensification of the Kuroshio Current, which caused a slight decrease in primary productivity, but strengthened the oceanic circulation in the East China Sea. Overall, the source-to-sink process of OM in the Okinawa Trough is governed by complex interactions between sea level, climate and ocean circulation.

1. Introduction

The carbon cycle, which is one of the most important global elemental cycles, exerts major controls on the composition of atmospheric CO_2, life processes, climate, and oceanic ecosystems (Walsh et al., 1981; Berner, 1982; Zachos et al., 2001; Jiao et al., 2014). Although the deep ocean plays a critical role in the global carbon cycle, the continental margin is more important in terms of carbon input and burial because of high production and preservation rates of particulate organic carbon (Jahnke et al., 1990; Goñi et al., 1997; Muller-Karger et al., 2005; Bauer et al., 2013). Rivers are major sources of fresh water, nutrients, organic matters and minerals (Bianchi et al., 2002; Gordon and Goñi, 2003; Zong et al., 2012), and shelves are suggested to be an important sink for organic matter (OM) (de Haas et al., 2002; Bianchi and Allison, 2009; Chen and Borges, 2009). However, the major part of terrestrial organic matter (TOM) buried on the continental shelf may be mineralized and/or transported over the shelf break and deposited on the continental slope, and even in the open ocean (Walsh and Nittrouer, 1999; Kao et al., 2003). In addition, the marine organic matter (MOM) produced by plankton usually dominates the OM deposited offshore along the continental margins (Lamb et al., 2006; Ramaswamy et al., 2008; Bauer et al., 2013).

The marginal seas account for only about 10% of the total ocean surface area, but contribute more than 20% of the global marine primary productivity (Wollast, 1991). The rate of marine primary production in the East China Sea (ECS) is mostly regulated by seawater temperature and the availability of a variety of nutrients, especially phosphate (Gong et al., 2003). Biogenic silica (Bio-Si) is produced in the euphotic zone by siliceous plankton, such as diatoms or radiolarians (Schlüter and Sauter, 2000). Generally, these siliceous planktons tend to bloom in high productivity areas with a preservation ratio of ~3% in sediments (Treguer et al., 1995). Therefore, the Bio-Si concentration can indicate the primary productivity in certain environments (Takahashi, 1989; Okazaki et al., 2003). In comparison, due to dissolution and decomposition in the deep marine environment, $CaCO_3$ produced by foraminifera and nannofossil, together with TOC and biogenic barium (Bio-Ba) (such as barite), generally have low preservation rates (Babu et al., 2002; Yang et al., 2011).

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http://dx.doi.org/10.1016/j.dsr.2016.10.005
Received 8 April 2016; Received in revised form 12 October 2016; Accepted 17 October 2016

Over the last decade, the sources and sinks of OM on the ECS shelf have been well documented. The changing contributions of TOM and MOM are influenced by many factors, including river input, climate, hydrodynamic forcing, primary productivity and depositional/post-depositional environments (Zong et al., 2006; Yao et al., 2015; Zhu et al., 2013; Deng et al., 2006). The sources of depositional OM in the Okinawa Trough (OT) have also been well studied using organic carbon isotopes and biomarkers (Kao et al., 2005, 2006, 2008; Dou, 2010). Records from several sediment cores exhibit variable sources and burial rates of OM during certain periods, but the general trend is that the proportions of TOM decreased from the last glacial maximum (LGM) to the Holocene.

Although many studies have investigated the sources of OM in the OT, few of them have associated source variations with changes in primary productivity, as well as the response to paleoclimate, river input and hydrodynamic forcing. In this study, we present the organic and inorganic carbon compositions and examine the primary productivity of a sedimentary core from the middle OT in order to identify the sources and burial rates of depositional OM in this unique marginal setting.

2. Regional setting

The ECS (Fig. 1) is a river-dominated marginal sea in the western Pacific Ocean with one of the widest (~650 km) continental shelves in the world. It has high primary productivity and also receives tremendous terrigenous input from the East Asian continent and the island of Taiwan (Gong et al., 2003; Yang et al., 2014).

The OT is located in the southeast of the ECS and is regarded as an incipient intra-continental basin formed behind the Ryukyu arc–trench system (Fig. 1). It has a length of about 1000 km and a width of 140–200 km and extends in a NE-SW direction paralleling the orientation of the ECS (Letouzey and Kimura, 1986; Qin, 1994; Bian et al., 2010). The water depth in the OT gradually increases from 600–900 m in the north to 1000–2000 m in the south (Sibuet et al., 1987).

The Changjiang (Yangtze River) is one of the largest rivers in the world and it, together with the small mountain rivers of Taiwan, governs the depositional and biogeochemical processes in both the ECS and OT (Yang et al., 2015). The sedimentary environments of the ECS shelf and OT hence consist of coastal, delta, littoral, neritic, and hemipelagic facies (Yang et al., 2014). Sediments are dominated by terrigenous siliciclastic sediment, but also include other terrigenous clastic sediment, biogenic sediment, and volcanic debris and hydrothermal sediments (particularly in the mid-OT) (Li, 2005; Shao et al., 2015). In addition, several mud wedges in the large estuarine and inner shelf areas were formed mostly in the mid-late Holocene, and relict sand ridges that were developed during the postglacial transgression occupy the open shelf (Yang, 1989; Liu et al., 2007).

The ocean circulation in the ECS is complex and includes several current systems. The Kuroshio Current (KC), which is generally weaker in winter and stronger in summer, flows through the eastern part of the ECS and enters the northwest Pacific Ocean at the northern extremity of the OT (Fig. 1; Yuan et al., 1991; Hu, 1994; Zhu and Chang, 2000; Yuan et al., 2008). The Taiwan Warm Current (TWC) flows NE, and forms anticlockwise gyres on the ECS shelf (Zhu and Chang, 2000). The Zhemin Coastal Current (ZMCC) and Yellow Sea Coastal Current (YSCC) flow southward along the coast of southeast and northeast China (Fig. 1).

Recent studies have summarized the evolution of the sedimentary system and sequence stratigraphy in the ECS since the LGM in response to the rise in sea level of about 120 m and the concomitant changes in oceanic circulation (Saito et al., 1998; Liu et al., 2004; Peltier and Fairbanks, 2006; Li et al., 2014; Yang et al., 2014, 2015). The last deglaciation interval witnessed rapid sea-level rise that reached its high stand in the middle Holocene at ~7 ka (Saito et al., 1998; Li et al., 2014). The sedimentation on the ECS shelf since the LGM can thus be divided into three tracts: low-stand, transgressive and high-stand (Li et al., 2014). Another factor that plays an important role in paleoenvironmental change in the ECS is the East Asia monsoon (Dykoski et al., 2005; Wang et al., 2005a, 2005b; Cheng et al., 2012). The East Asian Monsoon (EAM) may cause downwelling and upwelling cells on the ECS shelf and in the OT, and may result in the formation of seaward bottom flow during the winter northeast monsoon in winter (Hu, 1994; Iseki et al., 2003). However, the variability of winter and summer monsoon and its influence during the Holocene is still not well understood (Tian et al., 2010; Wang et al., 2012).

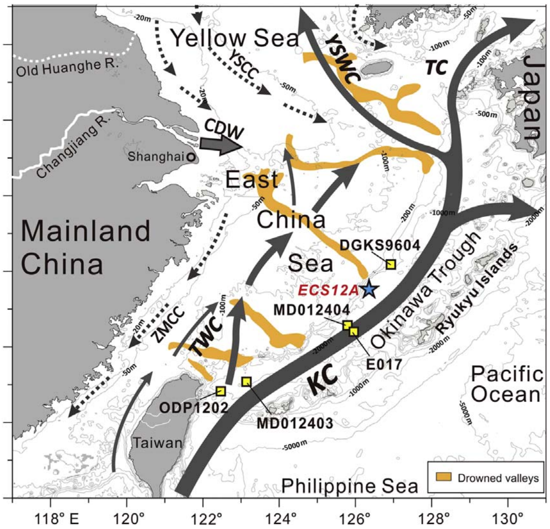

Fig. 1. Map showing the East China Sea and Okinawa Trough with the locations of Core ECS12A (blue star) and other reference cores (yellow boxes): Core E017 (Chang, 2004); Core DGKS9604 (Dou, 2010); Core MD012404 (Kao et al., 2006) and Core MD012403 (Kao et al., 2005); ODP Site 1202 (Zhang et al., 2014). The major oceanic currents (winter) are also shown by solid and dotted arrows (Yuan et al., 1991; Hu, 1994): KC: Kuroshio Current; TWC: Taiwan Warm Current; ZMCC: Zhemin Coastal Current; CDW: Changjiang Diluted Water; YSCC: Yellow Sea Coastal Current; YSWC: Yellow Sea Warm Current; TC: Tsushima Current. The locations of drowned river valleys formed during glacial periods (orange shaded areas) are modified from Ujiié et al. (2001).

3. Samples and methods

3.1. Samples and laboratory methods

The 4 m-long piston core ECS12A was recovered from the west slope of the OT (126. 41°N, 27.44°E; seawater depth: 1201 m) in 2012 (Fig. 1). About 1 m at the top of the core was lost before lifting the gravity sampler on the deck. A strong pungent smell emanated from the sediment core suggesting reducing conditions at shallow depths at this location. Mixed benthic foraminifera from nine samples were picked for accelerator mass spectrometry (AMS) ^{14}C dating at the Beta Analyses Company, USA. All radiocarbon dates were calibrated to calendar years before the present (cal. BP, 0 cal. BP=AD 1950) using Calib 6.0 software with the calibration curve Marine 09 (Reimer et al., 2009) and a constant average global reservoir age of 400 yr.

The core was then sliced into 4 cm-thick segments for the analyses of total organic carbon (TOC), total nitrogen (TN), biogenic silica (Bio-Si) and other elements. For TOC and TN measurements, the samples were acidified with 1N HCl to remove carbonates. After rinsing with deionized water several times and drying in an oven at 40 °C, the carbonate-free samples were measured for TOC and TN using a Vario Cube CN Elemental Analyzer (made by Elementar in Germany) at the State Key Laboratory of Marine Geology, Tongji University.

The Bio-Si concentration were determined using the wet alkaline method (Wang et al., 2014) using ultraviolet and visible spectrophotometry at the Key Laboratory of Submarine Geosciences and Prospecting Techniques, Ministry of Education, Ocean University of