Quaternary International xxx (2016) 1–11

Contents lists available at ScienceDirect

Quaternary International

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

Geochemical evidence of the indirect pathway of terrestrial particulate material transport to the Okinawa Trough

Chen-Tung Arthur Chen [a, b, *], Selvaraj Kandasamy [c, **], Yuan-Pin Chang [a], Yan Bai [b], Xianqiang He [b, d], Jung-Tai Lu [a], Xuelu Gao [e]

[a] Department of Oceanography, National Sun Yat-sen University, Kaohsiung, Taiwan, ROC
[b] State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography, State Oceanic Administration, Hangzhou, China
[c] State Key Laboratory of Marine Environmental Science and Department of Geological Oceanography, Xiamen University, Xiamen, China
[d] Institute of Oceanology, Chinese Academy of Science, Qingdao, China
[e] Key Laboratory of Coastal Environmental Processes and Ecological Remediation, Yantai Institute of Coastal Zone Research, Chinese Academy of Sciences, Yantai, Shandong, China

ARTICLE INFO

Article history:
Available online xxx

Keywords:
Marine sediments
East China Sea
Okinawa Trough
Typhoons
Biomarkers

ABSTRACT

The major source of particulate matter in the East China Sea (ECS) is the Changjiang (Yangtze) River. Sediment types, the geochemical indices of terrigenous and biogenic inputs (TOC, $CaCO_3$ and Sc), and biomarker indices such as the carbon preference index (CPI) of long-chain n-alkanes and the cinnamyl/vanillyl ratio (C/V) in surface sediments, all reveal that the influence of terrestrial material initially declines away from the mouth of the Changjiang River across the ECS continental shelf. However, the influence then strengthens from the middle ECS shelf toward the continental slope and the Okinawa Trough, because when the northeast winds prevail from September to April, the Changjiang River plume flows southwestward along the coast of China. Part of this flow turns eastward in the northern Taiwan Strait, and then joins the northeastwardly flowing Kuroshio to reach the Okinawa Trough. As the central ECS is bypassed, the sediments accumulated there are geologically older, carbonate-rich and organic-poor than those found off the coast of China and in the Okinawa Trough.

Between June and August, when southwest winds prevail, the Changjiang plume generally flows northeastward. Yet, strong cyclonic currents that are generated by typhoons that pass through the ECS move the suspended particulates and the resuspended sediments southwestward from the coast of China. The turbid water then turns toward Taiwan in the northern Taiwan Strait and joins the Kuroshio, before reaching the Okinawa Trough. Again, young sediments are transported to the Okinawa Trough without passing through the central ECS.

1. Introduction

Rivers offer the major route for the transport of land-derived dissolved and particulate materials to estuaries, and subsequently to continental shelves, slopes, and deep ocean basins (Milliman and Meade, 1983; Chen, 2004; Liu et al., 2008). Such transport provides an important link in the global biogeochemical cycles of carbon and nutrients (Chen, 2004; Bauer et al., 2013) both on shorter and longer timescales.

One of the world's largest rivers, the Changjiang (Yangtze) River empties into the East China Sea (ECS). The Changjiang is the longest and largest river in China (6380 km long, and third longest in the world after the Nile and Amazon Rivers). It has a discharge of 960×10^9 m^3 yr^{-1}, ranked fourth globally after the Amazon, Zaire and the Orinoco Rivers (Sun et al., 2002).

Approximately 70–80% of Changjiang-derived suspended particles are deposited close to the estuary and the inner shelf of the ECS (Milliman et al., 1989), while the rest is transported farther into the ECS (Fig. 1), which has an area of 7.7×10^5 km^2, and is the 11th largest marginal sea globally (Chen et al., 2010). A large fraction of the discharge of sediment from Changjiang must be exported out of

* Corresponding author. Department of Oceanography, National Sun Yat-sen University, Kaohsiung, Taiwan, ROC.
** Corresponding author.
E-mail addresses: ctchen@mail.nsysu.edu.tw (C.-T.A. Chen), selvaraj@xmu.edu.cn (S. Kandasamy).

http://dx.doi.org/10.1016/j.quaint.2016.08.006
1040-6182/

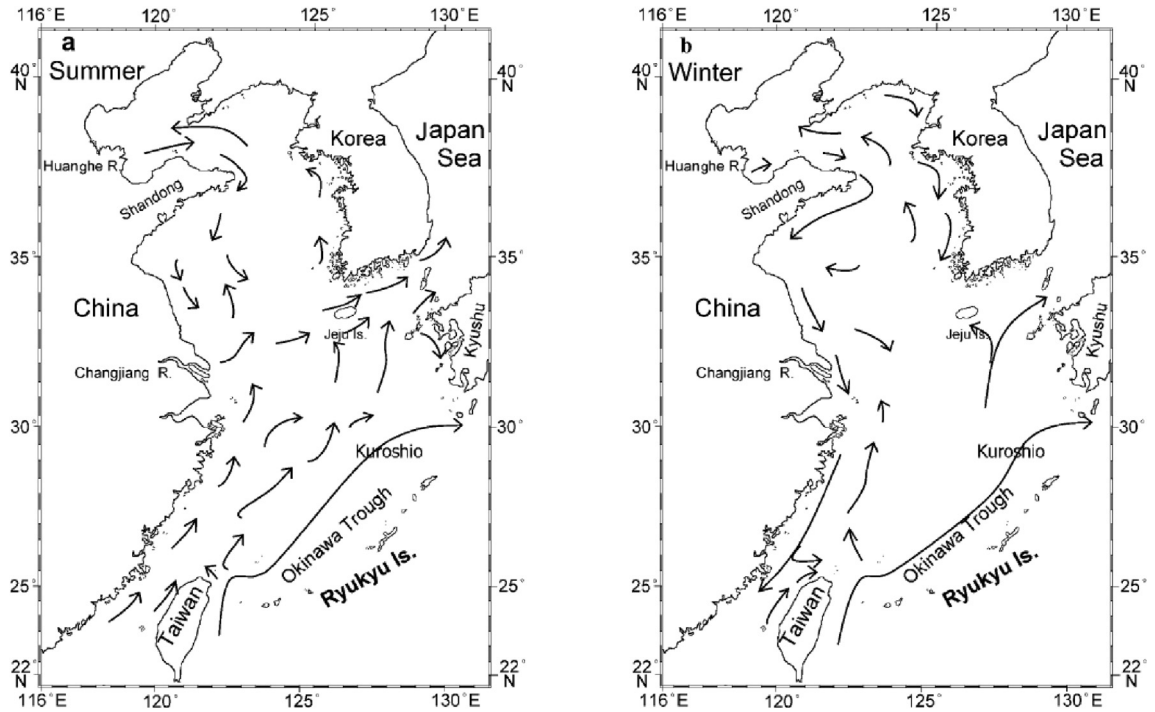

Fig. 1. Study area, showing major currents in (a) summer and (b) winter in East China Sea (taken from Chen, 2008).

the ECS continental shelf, and the exported particulate matter from the ECS shelf is most likely to be deposited in the Okinawa Trough (Iseki et al., 2003; Kao et al., 2003; Katayama and Watanabe, 2003; Bian et al., 2010; Wang et al., 2015). Most of the sediments accumulated since the Last Glacial Maximum in the western slope of the Okinawa Trough are generally agreed to be terrigenous, and the provenance of these sediments have been established through clay mineralogical, geochemical and isotopic studies (Dou et al., 2010a, 2010b, 2012). Although these studies suggested the predominant accumulation of Taiwan-derived sediments since the mid-Holocene, the modern source and transport pathway of the mud in the Okinawa Trough are unclear, and several pertinent theories have been offered.

Studies have established that transport of the terrigenous material to the Okinawa Trough from the ECS occurs mainly in the winter via strong wind-driven bottom flows (Hu, 1994; Yanagi et al., 1996; Iseki et al., 2003). Three explanations of these pathways have been suggested. The first theory is that most terrestrial sediments in the Okinawa Trough come from the Changjiang, and are delivered mostly by wind-driven transverse circulation in winter (Milliman et al., 1989; Yanagi et al., 1996; Hoshika et al., 2003; Iseki et al., 2003; Liu et al., 2003; Wang et al., 2015). The second theory is that most terrestrial sediments in the Okinawa Trough come from the Old Huanghe River submarine delta. Sediments are resuspended by strong winds in winter and carried to the ECS continental shelf and the Okinawa Trough via the Yellow Sea Warm Current (Milliman et al., 1985; Wang and Jiang, 2008; Yuan et al., 2008). The third theory presents a more indirect pathway: suspended particles that are discharged by the Changjiang River firstly extend southward; then, carried by bottom currents in the northeast monsoon period in winter, they veer offshore toward the southern Okinawa Trough (Liu et al., 2000; Kao et al., 2003; Zhu et al., 2008).

Apart from these three known theories of transport pathways, recent studies have highlighted the importance of gravity flows and tidal currents in driving the longshore and cross-shelf transport of fluvial sediment from the Changjiang estuary to the ECS shelf (e.g., Wu, 2015; Wu et al., 2015). For instance, through field observations, Wu et al. (2015) demonstrated that Changjiang-derived sediments was originally brought downslope by sediment gravity currents and then redistributed by benthic contour currents on the inner shelf. Wu (2015) suggested that the cross-shelf penetrating fronts along-isobath undulation of the pycnocline in fixed locations in the ECS shelf can trigger cross-shelf mass transport of water, which in turn, facilitating the dispersal of fine sediments across the shelf.

Further, typhoons can alter sediment transport flux and depositional regime. Using satellite-derived water transparency images, He et al. (2014) found that a strong typhoon in summer transported a significant quantity of terrestrial material to the Okinawa Trough via this indirect pathway. Continuous measurement of in-situ hydrographic data recorded before and after the passage of Typhoon Morakot in August 2009 along the mud deposition center off the Zhejiang-Fujian coast indicated several fold increase of bottom water turbidity after the typhoon passage owing to strong cyclone-induced mixing. Based on this observation, Li et al. (2012) suggested that the summer typhoon could play a role in re-suspending winter-transported distal mud and moving them across the shelf.

This work demonstrates that the indirect pathway is the major route for the transport of sediment from Changjiang to the Okinawa Trough. It will firstly show the current flow pattern and then will elucidate the properties of the sediments. Finally, sedimentary geochemical and biomarker indices will be presented as evidence.

2. Winds and flow patterns

The ECS is located in a monsoonal region with southwesterly winds in summer (June till August) and northeasterly winds in the

Please cite this article in press as: Chen, C.-T.A., et al., Geochemical evidence of the indirect pathway of terrestrial particulate material transport to the Okinawa Trough, Quaternary International (2016), http://dx.doi.org/10.1016/j.quaint.2016.08.006