Major sinks of the Changjiang (Yangtze River)-derived sediments in the East China Sea during the late Quaternary

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Abstract: The East China Sea (ECS) is a typical marginal sea located between the Eurasian continent and west Pacific Ocean. In this study, we review state-of-the-art research progress on the possible sinks of the Changjiang-derived sediments in the ECS during the late Quaternary. The major sinks of these sediments in the ECS are on the outer shelf and the Okinawa Trough during the last glacial maximum corresponding to a lowstand of sea level. During the deglacial marine transgression, the gently dipping shelf was rapidly inundated and strong tides prevented fine sediment from deposition on the open shelf, resulting in the development of a unique tidal sand ridge system. With sea level reaching the present situation and the modern marine environment being completed in the early Holocene, the Changjiang sediments mostly accumulated in the river’s estuary to build a large delta, with only a fraction reaching the inner shelf and coastal embayments. The late-Quaternary changes in monsoon-climate-induced river flux, sea level and oceanic circulation primarily controlled the source-to-sink transport of the Changjiang sediments in the ECS, and further determined the stratigraphic framework and sedimentary facies on the shelf.

The collision between the Indian and Eurasian Plates and the opening of the west Pacific marginal seas in the Cenozoic led to events and processes that have become some of the key scientific issues for the Earth sciences and global change studies, in particular these include the Tibet uplift, monsoon evolution, continental weathering and sediment transport from land to ocean (Raymo & Ruddiman 1992). Flux and fate of terrestrial sediment in marginal seas have been the major scientific objectives of international research programmes, such as Land Ocean Interaction in the Coastal Zone (LOICZ) and MARGINS Program (Svobodová et al. 2003).

The East China Sea (ECS) is located in the East Asian continental margin, linking the largest continent, Eurasia, with the largest ocean, the Pacific. It is characterized by a broad continental shelf, huge terrigenous sediment input from surrounding rivers, striking land–sea interaction and palaeoenvironmental changes during the late Quaternary (Milliman & Farnsworth 2011; Li et al. 2014; Yang et al. 2014). Basically, two types of river systems and sediment source-to-sink processes dominate the sedimentation on the ECS shelf (Fig. 1). One is represented by the Changjiang (Yangtze River), one of the largest rivers in the world, and another by the small mountainous rivers on Taiwan. Both river systems deliver very large volumes of sediment directly into the ECS, despite their striking differences in drainage basin areas, weathering regimes, and sediment erosion and transport processes. The Changjiang has developed a complicated tributary system and one of the largest deltas in the world and thus the sediment transfer from the large catchment to the sea depends on many factors. In comparison, the strong land erosion and fast sediment transfer especially during extreme weather events characterize the small mountainous rivers in Taiwan (Kao & Milliman 2008; Liu et al. 2013). Over the geological past, another large river, the Huanghe (Yellow River), might have also emptied a large volume of sediment into the ECS (Yang et al. 2002, 2003; Liu et al. 2010; Li et al. 2014). In this sense, the ECS can be regarded as a typical river-dominated pericontinental sea, which makes it an ideal natural laboratory for the study of land–sea interaction during the late Quaternary.

The ECS links the west Pacific by the Okinawa Trough in the east which has a large section >1000 m deep and with a maximum depth of 2716 m at its southeastern extent near Taiwan. The Okinawa Trough is regarded as an incipient intracontinental basin formed behind the Ryukyu arc–trench system where the Philippine Sea Plate is subducting under the Eurasia Plate (Clift et al. 2003; Fig. 1). It has continuously received terrigenous sediments from the surrounding rivers and thus became a major depocenter of the ECS during the late Quaternary.
The oceanic current system in the ECS is dominated by the northward intrusion of the Kuroshio Current and its branch, the Taiwan Warm Current, and the southward Zhe-Min (Zhejiang and Fujian) Coastal Current (Fig. 2; Guan 1994; Lee & Chao 2003). In summer, the Changjiang Diluted Water plays an important role in the shelf circulation in the northern ECS (Hu & Li 1993). The complicated oceanic circulation and tidal currents, as well as sea-level variability, primarily determine the distribution and dispersal patterns of terrigenous sediments in the ECS, forming unique muddy and sandy sedimentary systems (Gao 2013).

Fig. 1. A schematic model showing two types of river systems (Changjiang v. Taiwan mountainous rivers) and sediment transport processes in the ECS. (a) Possible sinks of the Changjiang sediments in the river basin and the ECS are indicated by numbers (1)–8). Mud areas ((5)–(8)) in the ECS are indicated in light grey. (1) Sichuan Basin; (2) Dongting Lake and Jianghan Basin; (3) Poyang Lake; (4) delta plain; (5) the mud off the Changjiang Estuary; (6) the inner shelf mud; (7) the mud in the SW of Cheju Island (SWCIM); (8) mud deposition in the Okinawa Trough; (9) Hupijiao Rise; (10) Zhedong and Xihu depressions (modified after Li (2008)); TGD refers to Three Gorges Dam. (b) Cross section showing the contrasting topography and relief between the Changjiang basin, ECS shelf and Taiwan.
Over the last decade, the provenances of these sediments and related depositional processes and palaeoenvironmental changes have been extensively investigated, but the sediment origins require further clarification, even though oceanographic, sedimentological, mineralogical and geochemical methods have been applied in the numerous studies mentioned above. In addition, appropriate interpretation of the late-Quaternary sedimentary record greatly depends on an improved understanding of the formation of these sedimentary systems and the reliable reconstruction of river–sea interaction at variable temporal and spatial scales (Gao 2013; Gao & Collins 2014; Li et al. 2014; Yang et al. 2014). In view of this, a fundamental scientific question for marine geological study of the river-dominated ECS is the transport and dispersal patterns of the fine-grained fluvial sediments from the surrounding Eurasian continent and Taiwan to the broad shelf.

In this study, we review state-of-the-art research progress on the possible sinks of the Changjiang-derived sediments in the ECS during the late Quaternary. In particular, the existing mineralological and geochemical approaches for provenance discrimination of the fluvial sediments in the ECS were compiled with the major aim of providing more robust constraints on sediment source-to-sink transport.

The river setting and key questions on river–sea interaction during the late Quaternary

The Changjiang originates from the Tibetan Plateau and its catchment is primarily situated on the Yangtze Craton, with a basin area of \(1.8 \times 10^6\) km\(^2\), more than a fifth of the land area of China. Geologically, the Changjiang basin comprises complex rock types, including Palaeozoic carbonate rocks, Jurassic red sandstone, Mesozoic igneous rocks, Palaeozoic marine and Quaternary fluvio-lacustrine sedimentary rocks (Yang et al. 2004). Geographically, the Changjiang catchment...
covers variable topography and tectonic relief, with mountainous terrains dominant in the upper valley and lake basins and a delta plain in the middle and lower valley (Fig. 1), which may considerably influence the source-to-sink transport of river sediment.

The monsoon climate characterizes the catchment, resulting in uneven rainfall over the basin at seasonal scale, with a mean annual precipitation and temperature of 1100 mm and 15°C respectively (Yang et al. 2004). Based upon long-term hydrologic observation, the water and sediment discharges of the Changjiang average at 8964 × 10^8 km^3 a^-1 and 390 × 10^6 t a^-1 respectively, which makes the Changjiang the largest terrigenous source contributing to the ECS. Nevertheless, the sediment flux of the Changjiang has been rapidly decreasing since the impoundment of the Three Gorges Reservoir in 2003, averaging at only c. 155 × 10^6 t a^-1 over the last ten years (2003–2013) (Changjiang Water Resources Commission 2013).

In the present day, a major part of the Changjiang sediment accumulates in the river’s estuary to sustain a large delta, while some fine-grained sediment escapes from being trapped in the estuary and is transported south-eastwards by the coastal current, finally developing into a unique mud belt on the inner shelf along the coasts of Zhejiang and Fujian Provinces (Yang & Milliman 1983; Nittouer et al. 1984; DeMaster et al. 1985; Milliman et al. 1989; J.P. Liu et al. 2006, 2007; Xu et al. 2009, 2012; Gao 2013; Gao & Collins 2014; Li et al. 2014; Yang et al. 2014). Nevertheless, the influence of the Changjiang on the sedimentation of the ECS has not been resolved yet, and some fundamental questions to be answered include: (1) whether the palaeo-Changjiang once reached the outer shelf of the ECS by incising the broad shelf during the LGM; (2) if so, how to recognize the pathways and sediment distribution of the palaeo-Changjiang on the shelf; (3) how to differentiate the Changjiang sediment in the ECS from the terrigenous sediments from other rivers and aeolian input; (4) how to quantitatively estimate the sediment influx from the Changjiang to the shelf and to relate the river discharges to natural processes and anthropogenic activities in the catchment. Therefore, the gap in the estimation of the sediment budgets and dispersal pattern on the ECS shelf is mainly due to poor recognition of the river-flow pathways, and uncertainty on past sediment fluxes from the ancient Changjiang (Yang et al. 2003; J. P. Liu et al. 2007; Xu et al. 2012).

It is obvious that provenance identification of marine sediment is the prerequisite for the reliable reconstruction of the sediment source-to-sink transport from land to sea and of the palaeoenvironmental changes. Mineralogical and geochemical compositions of detrital sediments in fluvial and marine environments are basically determined by source rock type (petrographic composition in drainage basin), physical and chemical weathering, hydrodynamic sorting, depositional and post-depositional alterations, and human activities as well (Yang et al. 2003). As introduced above, although various approaches have been applied to the provenance study of the marine sediments in the ECS and Yellow Sea, the source-to-sink transport pathways of the Changjiang sediment in East China’s marginal seas during the late Quaternary remain controversial. One major difficulty of the sediment provenance study lies in the poor characterization of the Changjiang-derived sediment that is discharged into the sea and the lack of reliable discrimination of the Changjiang sediment from the other river sediments in dynamic marine depositional environments.

For instance, a major challenge in reconstructing the source-to-sink transport of the Changjiang sediment in the ECS is the differentiation between the Changjiang- and Huanghe-derived sediments on the shelf and in the Okinawa Trough. As one of the largest rivers in the world, the Huanghe has high sediment load, reaching 10^9 t a^-1 before the 1980s, and it once flowed into the southern Yellow Sea during the period AD 1128–1855, which resulted in the formation of a large delta. Due to the shift of the course of the Huanghe northwards to North China, the abandoned Huanghe Delta in the southwestern Yellow Sea has been experiencing strong erosion, resulting in a large supply of the Huanghe-derived sediment into the northern ECS (Milliman et al. 1985a; Saito 1998; Yang et al. 2003; Liu et al. 2010; Gao & Collins 2014; Zhou et al. 2014).

In short, the river (Changjiang) and sea interaction on the wide continental shelf of the ECS was complicated by the changes in river flux, sea level and oceanic circulation during the last glacial period. Undoubtedly, more systematic seismic investigations combined with studies on high-resolution sediment cores are needed in order to better constrain the source-to-sink process of the fluvial sediments on the epicontinental shelf.

Discussion

Whether the palaeo-Changjiang entered the ECS during the LGM

As introduced above, there still exist different opinions on the localities and shifts of the palaeo-Changjiang river course and its mouth on the ECS shelf during the LGM. Two hypotheses have been proposed for the pathway of the palaeo-Changjiang...
during the last glaciation (Xiao et al. 2004). Some studies suggest that the palaeo-Changjiang entered a palaeolake north of Jiangsu Province and thus did not enter the sea during the LGM because the extremely arid climate caused low-water and sediment discharge at that time (Zhao 1984). Furthermore, the strong winter monsoon during the LGM might have introduced desertification of the open ECS shelf and thus prevented fluvial deposition (Zhao 1984).

A second possibility is that the palaeo-Changjiang incised the continental shelf, formed complicated incised river networks (Fig. 3), and delivered its sediment into the ECS shelf, Okinawa Trough or the Yellow Sea, during the lowest stand of sea level at the LGM (Qin et al. 1987; F. Li et al. 1993; C. X. Li et al. 2002; G. X. Li et al. 2005a, b, 2014; Li & Zhang 1995; Xia & Liu 2001; Warren & Bartek 2002; Wellner & Bartek 2003; K. Liu et al. 2009; Xu & Oda 2009; Dou et al. 2010a, b, 2012; Wang et al. 2013, 2014). The large sheet sand distributed on the mid to outer ECS shelf occupies an area >10 000 km², and is primarily composed of medium and fine sands with abundant fragments of microfossils. Early in 1968, Emery defined this sheet sand as ‘relict sediment’ formed under low sea level or the deglacial transgression (Niino & Emery 1961; Emery 1968). Radiocarbon dating results confirmed the deposition of the sheet sand during the last glaciation, yielding the ages of 20–15 ka (Qin et al. 1987). This sheet sand was also called the ‘Yangtze Shoal’ apparently suggesting a genetic relationship with the Changjiang (Yangtze River) sediment. It was regarded as as a palaeodeltaic or estuarine deposit while the palaeo-Changjiang river mouth was regarded as a palaeodeltaic or estuarine facies of a low-stand systems tract (Wang et al. 2013, 2014). Inter-pretive evidence by Wang et al. (2013, 2014) has revealed that the palaeo-Changjiang channels might have incised the ECS shelf during the LGM and directly supplied fluvial sediments to the outer shelf under the depositional environment of strong tidal reworking. This 3 m-thick tidally influenced palaeofluvial sediment can be clearly recognized on high-resolution seismic reflections and from the combined evidence from lithological character, microfossil assemblages, element geochemistry and chronology of borehole SFK-1 on the outer shelf (Fig. 4). This palaeofluvial sandy deposit, formed during the LGM, is thicker than that previously reported (c. 1 m) by Tang (1996), showing a fining-upward succession with an erosional surface at the bottom. The fine–medium sandy bedding with muddy flaser bedding and mud clasts all suggest typical river-channel deposition. Based on the high-resolution seismic profile, the LGM deposition is characterized by chaotic and irregular reflections, cutting across the underlying strata and locally pinching out on the outer shelf, which is interpreted as fluvial–estuarine facies of a low-stand systems tract (Wang et al. 2013, 2014). Interestingly, small fragments of marine microfossils often occur in this facies, showing an overall upward-increasing trend in its abundance. Most of them are heavily worn, and mixed with a small amount of larger and intact bodies of some benthic
Fig. 3. Map showing the ECS with the possible pathways of the palaeo-Changjiang and palaeo-Huanghe channels (Zhu et al. 1979; Zhao 1984; Qin et al. 1987; Zhu & An 1993; Wellner & Bartek 2003; Li et al. 2005b) and the palaeocoastal line at the LGM (yellow) (Saito et al. 1998). The locations of seismic profile A–B and borehole SFK-1 are indicated.
foraminifera. Based on the microfossil assemblage, and sedimentary structures and composition, this facies was interpreted to be tide-influenced fluvial facies; the fluvial discharge and process might have been weak compared to the present situation because of the cold and arid environment through the LGM (Saito et al. 1998; Wellner & Bartek 2003).

Geochronology of detrital zircon provides a more powerful and reliable tool for the provenance identification of sandy sediments than traditional heavy mineralogy, because the former is less influenced by hydrodynamic sorting in fluvial and marine environments. Three sandy samples taken from the early–middle Holocene and LGM deposits of borehole SFK-1 have very similar U–Pb age patterns of detrital zircons to the modern Changjiang sediment (Yang et al. 2009). Therefore, we suggest that the sandy palaeochannel sediments deposited on the ECS outer shelf during the LGM were probably derived from the palaeo-Changjiang. The Okinawa Trough has been regarded as a major depocenter of the ECS and might have continuously received terrigenous sediment from the East Asian continent and Taiwan during the late Quaternary. Sedimentological and geochemical studies of several cores (e.g. DGKS 9603, 9604, MD012404, ODP Site 1202) suggest that during the last glaciation (c. 30–10 ka) the sediment that accumulated in the middle Okinawa Trough was predominantly sourced from the palaeo-Changjiang (Diekmann et al. 2008; Dou et al. 2010a, b, 2012; Chen et al. 2011), or partly from eastern Taiwan (Chen et al. 2011). All of these studies imply that even during the LGM with a severe monsoon...
climate, the palaeo-Changjiang river mouth might have extended to the present-day outer shelf, supplying terrigenous sediment both to the shelf itself and even the Okinawa Trough. Therefore, we infer that during the last glaciation with a sea-level lowstand, the outer shelf and the Okinawa Trough could have been the major sink of palaeo-Changjiang sediment into the ECS. In comparison, the inner and middle ECS shelf were exposed during the last glaciation and thus could not be the major depocenters of the palaeo-Changjiang river sediment because of insufficient accommodation space.

**The shifts of the palaeo-Changjiang river course during the deglacial transgression**

With the onset of last deglacial transgression, the gentle ECS shelf was rapidly flooded by rising...
seawater, which caused the retreat of the coastline as well as the palaeo-Changjiang river mouth. Correspondingly, the delivery and dispersal patterns of the Changjiang-derived sediment on the ECS shelf were also altered with changing sea level and oceanic circulation. Previous studies suggest that the tidal currents were indeed strong during the post-glacial transgression and early periods of the Holocene when sea level was lower than present day (Uehara et al. 2002; Uehara & Saito 2003). The palaeo-Changjiang sediment accumulated on the mid–outer shelf during sea-level lowstands might have been reworked and winnowed by strong tidal currents, resulting in the formation of a tidal sand ridge system on the ECS shelf (Z. X. Liu et al. 2000, 2007; Berné et al. 2002; Yoo et al. 2002; Gao & Collins 2014; Li et al. 2014).

In the present day and under the present oceanic environment, the tidal sand ridges on the shelf are still in motion because of the strong tidal current (Z. X. Liu et al. 2007), unlike the so-called ‘mori-bund’ ridges described by Yang (1989). Nevertheless, the present-day sandy sediments from the modern Changjiang can hardly escape the estuary and inner shelf and replenish the sand ridges on the mid–outer shelf. Similar to the tidal sand ridges on the mid–outer ECS shelf, the Yangtze Shoal off the Changjiang river mouth is recognized as a tidal sheet sand (Liu 1997) with sandy sediments derived from the underlying pre-Holocene relic deposit, but with the tidal reworking here being much weaker than in the tidal sand ridges (Gao & Collins 2014).

In addition, during the deglacial sea-level rise, the fine-grained sediment winnowed from the open shelf by strong tide or wave currents might have been transported to the outer shelf and Okinawa Trough by shelf currents (Diekmann et al. 2008; Dou et al. 2010a, b, 2012), or to the inner shelf and coastal bays like the Hangzhou Bay mostly by tidal transport (Lin et al. 2005; Gao 2013; Zhang et al. 2014). Mineralogical and geochemical evidence of the core sediments confirm the accumulation of Changjiang-derived clay in the middle Okinawa Trough during the last deglacial period (Dou et al. 2010a, b, 2012; Chen et al. 2011).

The establishment of modern sediment source-to-sink transport of the Changjiang during the mid–late Holocene

With sea level rising to its present position in the early–mid Holocene at c. 7 ka, a normal marine environment characterized the ECS (Milliman et al. 1985b, 1989; Li et al. 2014), and modern sedimentary systems started to develop in the Changjiang river mouth and on the shelf. In response to the deceleration of global sea level in the early Holocene, the Changjiang Delta initiated by retaining more than half of the river sediment load in the large estuary, as with other large deltas (Stanley & Warne 1994; Hori et al. 2002; Li et al. 2002). In the present day, the Changjiang Delta consists of the sub-aerial and subaqueous parts with areas of c. $25 \times 10^3$ km$^2$ and $10 \times 10^3$ km$^2$ respectively, and the main body reaching a thickness of 30–50 m.

Over the last 6–7 kyr, the Changjiang fine-grained sediment that escaped the estuarine trapping was mostly transported southeastward and firstly accumulated in the Hangzhou Bay (Lin et al. 2005; Zhang et al. 2014), with the remainder being delivered further southwards and deposited on the inner shelf near the Zhejiang and Fujian coasts (Yang & Milliman 1983; Nittouer et al. 1984; DeMaster et al. 1985), forming a unique c. 800 km-long mud wedge during the last 7 kyr (Figs 1 & 2). Meanwhile, only a small amount of the Changjiang-derived sediment was dispersed eastwards to the open shelf, and hardly reached the shelf beyond 124°E or over a distance of 250–300 km eastwards (Beardsley et al. 1985; Milliman et al. 1985b, 1989; Zhang 1999). This means that the mid–outer shelf was a ‘starved shelf’ in the sense of Gao & Collins (2014), only the relict sandy deposits occupying the present-day seafloor. It is noteworthy that the construction of the Three Gorges Dam in 2003 has exerted a significant impact on marine deposition in the Changjiang subaqueous delta, causing coarsening and erosion of the pro-delta mud in response to the decline of sediment flux from the Changjiang to the ECS (Yang et al. 2007, 2011; Luo et al. 2012).

During the postglacial period, the fate of the Changjiang-derived sediment (and Huanghe sediments too) to the ECS varied with changing sea level and estuarine–shelf circulation (Li et al. 2014). In consequence, the sediment retention index, defined as the ratio between sediment retention in the estuary and sediment that has escaped to the open sea, also changed with depositional environment and sediment-dynamic conditions (Gao 2013). The modern Changjiang Delta started to form at 7–6 ka and since then >50% of discharged sediment has been retained in its estuary (Li et al. 2002). Nevertheless, the sediment retention index in the Changjiang estuary has gradually decreased as the delta front has advanced into deeper waters (Gao & Collins 2014), and/or the Changjiang sediment discharge has declined considerably in recent years, and will in the future (Yang et al. 2007, 2011).

Physical oceanographic observation suggests that fine-grained sediment can be transported towards the mid–outer ECS shelf, or even across the entire shelf, to the continental slope (e.g. Okinawa Trough) by shelf currents (Hoshika et al. 2003;
Katayama & Watanabe 2003). Recent study further suggests that the bottom turbid layers or sediment gravity flows may be a dominant process for the cross-shelf transport of fine-grained sediment, especially during typhoon events (Li et al. 2012). During the early stages of the Changjiang Delta development, fluvial sediments flowing into the estuary were largely dispersed and the delta front slope did not develop, which suggest that sediment gravity flow might not have exist at that time (Gao & Collins 2014). However, the present-day Changjiang river subaqueous delta becomes an ideal area for observational and theoretical studies of sediment gravity-flow-induced transport (Wright & Friedrichs 2006).

**Formation and sediment origins of muddy sedimentary systems in the ECS during the Holocene**

As unique sedimentary systems on the ECS shelf, several mud zones formed in the Holocene have received considerable attention in terms of their depositional history, sediment provenances and palaeoenvironmental records (Figs 1 & 2). The source-to-sink transport of muddy sediments in the ECS is closely related to the current system driven by the interaction of the East Asian Monsoon and Kuroshio Current (Li et al. 2014). The mud patch off the Changjiang estuary, as the pro-delta deposition of the Changjiang subaqueous delta, had its sediment sources dominated by the Changjiang during the late Holocene. Whether and to what extent the palaeo-Huanghe sediments originating from the southwestern Yellow Sea contributed to the deposition of this mud patch are still open questions (Sun et al. 2000; Liu et al. 2010; Zhou et al. 2014).

Another mud patch in the SW of Cheju Island (SWCIM, Yang et al. 2003), at the northern margin of the ECS, has also been widely documented; this sediment was suggested to be predominantly derived from the palaeo-Huanghe delta in the southwestern Yellow Sea (Yang & Milliman 1983; DeMaster et al. 1985; Lee & Chough 1989; Milliman et al. 1989; Alexander et al. 1991; Saito 1998; Lim et al. 2007; Youn et al. 2007; Youn & Kim 2011). This mud patch was first found in 1960s and has an area >10,000 km². The SWCIM has been regarded as the distal end of the Huanghe dispersal system in the ECS (DeMaster et al. 1985; Alexander et al. 1991), and was formed in a counterclockwise cyclonic eddy during the late Holocene (Hu 1984; Hu & Li 1993; Qu & Hu 1993). Interestingly, recent study by Kim et al. (2013) on magnetic properties of the surface sediments in and around this mud patch suggests mixing sources from the Changjiang palaeo-Huanghe Taiwanese rivers, or the NW Pacific and Korean rivers. Nevertheless, the boundaries between different sediment provenances are not always distinct.

The inner-shelf mud wedge of the ECS has been regarded as a good archive for palaeoenvironmental study, given its relatively continuous deposition and dominant sediment source from the Changjiang during the mid–late Holocene. The relatively continuous nature of the mud deposition with uniform sediment grain size and reliable constraints on radiocarbon dates imply that this elongated inner-shelf mud probably formed during the last 7–8 kyr (Xiao et al. 2006; Zheng et al. 2010). This suggests that the export of Changjiang sediment from its river mouth towards the open shelf probably occurred at an earlier stage, and not just within the last 2 kyr (Liu et al. 2006; Gao 2013; Gao & Collins 2014). The completion of the modern shelf-circulation system and favorable monsoon climate since the middle Holocene might account for the dispersal of the Changjiang-derived fine sediment to the open shelf, resulting in the formation of shelf mud.

Nevertheless, whether a part of the fine sediment in the inner-shelf mud belt was derived from the ‘older material’ previously accumulated on the mid–outer shelf during the sea-level lowstand (Gao & Collins 2014), or from the abandoned Huanghe Delta in the southern Yellow Sea, and local rivers in SE China and Taiwan remains to be clarified. Recently, Gao & Collins (2014) suggested that during the Holocene sea-level rise, intense tidal currents and tidally induced landward transport of fine-grained sediment might have played an important role in the formation of the shelf and coastal mud deposits. In addition, Shao (2012) investigated the sediment geochemistry of Core MD06-3040 (27° 43.37′ N, 121° 46.88′ E, 46 m seawater depth) retrieved from the inner-shelf mud area, and suggested that over the last 7 kyr, mud deposition was dominated by the Changjiang-borne sediment, while the sudden change in geochemical proxies (e.g. Al/Ti, Li/Sc, Co/Sc and Nb/Sc) at c. 1.5 cal. ka BP is related to the increasing sediment contribution from small local rivers in Zhejiang and Fujian Provinces (Fig. 6). In addition, deeper investigation is needed into the question of whether these abrupt changes in geochemical composition as well as magnetic property (hard isothermal remanent magnetization, HIRM) at c. 1.5 ka were caused by the evolution of the Asian summer monsoon, as suggested by Zheng et al. (2010), and/or by anthropogenic activities.

Although the inner-shelf mud of the ECS has been widely used for the palaeoenvironmental study of its relatively continuous deposition, resuspension under extreme conditions such as storm...
and typhoon events may result in a hiatus in the strata because the water depth (c. 20–60 m deep) of the mud belt lies within the range of wave action (Gao & Collins 2014). Therefore, the sampling resolution at an annual scale may be unrealistic, although results of both $^{210}$Pb and $^{137}$Cs dating of the muddy sediment indicate a general depositional rate of $10^{0.0}$ cm a$^{-1}$. Under circumstances of

![Fig. 6. Depth profiles of mean grain size (Mz), and ratios of major and trace elements in the sediments of Core MD06-3040 retrieved from the inner-shelf mud zone of the ECS (modified after Shao 2012). Data source of HIRM is from Zheng et al. (2010). The samples for geochemical measurement refer to the residual fraction after the leaching by 1N HCl. The core position is shown in Figure 2. The dashed lines indicate abrupt changes in geochemical compositions. Note the relatively uniform geochemical compositions between 7 and 1.5 ka suggesting the dominant sediment provenance is from the Changjiang. The significant shifts in geochemical proxies at 1.5–0 ka and at c. 10–7 ka suggest potential changes in sediment provenances. The change in HIRM is probably related to the variability of the Asian summer monsoon.](image)

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![Fig. 7. A model showing the changes in major sinks and depocenters of the Changjiang sediment in the ECS since the LGM (modified after Dou et al. 2010b). The blue arrows indicate the possible transport pathways of the Changjiang sediment, while the yellow arrows indicate the possible dispersals of the modern and palaeo-Huanghe sediments. See the text for detailed explanation. In (a) dash lines indicate possible pathways of the palaeo-Changjiang and palaeo-Huanghe channels; (b) dot dash lines indicate palaeo-coastal line; (c) dash lines indicate Holocene depocentres of the Changjiang sediment in the ECS.](image)
an ideal depositional environment, the resolution at decennial scale, or a ‘high-resolution slice’ in the sense of Gao & Collins (2014), can be expected for time-series palaeoenvironmental study in the mid-late Holocene.

Although modelling work suggests that the limit of delta growth has probably been reached already (Gao 2007), the distribution and dispersal patterns, as well as the budgets of the palaeo- and modern-Changjiang-borne sediment in the estuarine, coastal, shelf and continental slope regions of the ECS require further clarification. Apart from high-resolution core study with the development of new proxies for sediment provenance and palaeoenvironmental reconstruction, we urgently need more in-depth, in situ hydrodynamic observations in combination with geophysical investigations such as using a sub-bottom profiler for the better understanding of depositional processes and strata formation.

Concluding remarks

The ECS is characterized by a broad continental shelf, unique sedimentary systems, very large terrigenous sediment input and complex river–sea interactions during the late Quaternary. In terms of sediment source-to-sink studies, the ECS can thus be regarded as one of the best research sites for the investigation of sediment transfer from land to sea and for the study of land–sea interaction at various temporal and spatial scales.

In this contribution, we review state-of-the-art research progress in the sediment source-to-sink transport of the Changjiang in the ECS during the late Quaternary (Fig. 7). Various lines of evidence suggest that the palaeo-Changjiang incised the open shelf of the ECS and debouched its sediments to the shelf edge during the LGM with the lowest stand of sea level and a severe monsoon climate. With the onset of the last deglacial transgression, the major sinks and depocenters of the Changjiang sediment in the ECS changed in response to rising sea level. Due to the rapid sea-level rise and fast inundation of the gently dipping shelf, as well as strong tidal reworking during the late deglacial period to early Holocene, the Changjiang sediment was mostly dispersed or reworked and was hardly retained on the open shelf. The dispersed fluvial sediment was transported landwards (estuarine and coastal areas) and/or down slope (finally to the Okinawa Trough) by complicated marine processes, while the tidal sand ridges and sheets have dominated the mid–outer shelf up to the present day. Since the early–mid Holocene at c. 7 ka, with the gradual establishment of the modern marine environment and shelf circulation, the Changjiang sediment has been predominantly trapped in the estuary and has built a large delta, and the remainder of the sediment has been transported southeastwards by coastal currents and then deposited in the coastal bays and inner shelf. The overall geometry of major sedimentary systems in the ECS was reached in the late Holocene.

The establishment of Holocene shelf–coastal sedimentary systems associated with the Changjiang is strongly related to active sediment transport processes induced by tides and waves, shelf circulation and sediment gravity flow. For the river-dominated marginal sea, geochemical proxies and sedimentological and seismic profile observations may provide more robust constraints on the provenance and transport processes of these muddy and sandy sedimentary systems in the ECS at high-resolution spatial and temporal scales. In particular, the combination of in situ observation, experimental analysis and modelling work will significantly advance our understanding of the sediment source-to-sink process and river–sea interaction in this unique continental margin.

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References


sources, and the impact of high-energy storms on sediment transport and accumulation.

Recent studies have shown that the sediments in the Bohai Sea are primarily terrigenous, with terrigenous particulate load to the Okinawa Trough. However, the sources and mechanisms of sedimentation in this region are still not well understood. Further research is needed to better understand the sedimentation processes and their implications for coastal management and environmental protection.


supplier to continental shelves: example from the abandoned Old Huanghe (Yellow River) delta. Continental Shelf Research, 82, 43–59.
