Introduction to the river-dominated shelf sediments of the East Asian Seas

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Asian shelves as environmental recorders

The marginal seas of eastern Asia are supplied by some of the largest, and most sediment-rich, rivers on Earth. Many of these rivers have their original sources on the Tibetan Plateau and are fed by the rains of the summer monsoon that are especially intense around the edge of the plateau (Fig. 1). In turn, the climate and tectonically generated topography account for the high sediment loads of the rivers that subsequently construct a number of giant deltas across the region and result in the construction of some of the widest continental shelves seen anywhere globally. Understanding the marine sedimentary records of the East Asian marginal seas has been a focus for geologists for many years. This is because the sediments can be used to constrain the origin of the sedimentary basins themselves, via subsidence analysis, and because the sediments can be used to reconstruct sedimentary conditions onshore in the terrestrial basins at the time of their deposition. Theoretically, the weathering conditions, floral assemblages, and both erosion rates and patterns within the drainage basin might be reconstructed from the sediment deposited within the deltas and under the shelves.

Although, sediment storage and recycling may result in the loss of erosional signals in many larger river floodplains (Castelltort & Van Den Driessche 2003; Jerolmack & Paola 2010), at least over timescales of less than 1 myr, it has also been recognized that there is a response to climate change in the supply of sediment to the ocean both in terms of volumes and composition over millennial timescales in several east and south Asian river systems (Goodbred & Kuehl 2000; Clift et al. 2008; Hu et al. 2013). There is a climatic response in most river systems to even seasonal discharge cycles, where floods linked to the wet season (summer monsoon in East Asia) will tend to dominate the clastic flux to the ocean over discharge during drier times and to overwhelm the effects of sediment transport by tidal currents (Gugliotta et al. 2016; Hoitink & Jay 2016).

The resultant chronological archive of terrestrial environmental conditions could be used to address outstanding questions in Asian marine and geosciences, such as the history of the Asian monsoon, and the timing and patterns of topographical uplift in the Tibetan Plateau and surrounding areas, as well as the environmental responses to climatic and tectonic forcing factors. Shelf sediments might be used to test models for drainage evolution onshore in the global type area for tectonically induced headwater capture (Brookfield 1998; Clark et al. 2004), since large-scale transfer of drainage between neighbouring river basins must have an impact on the rate of sediment delivery and on the provenance of the clastic materials reaching the coastal ocean.

Transport on the shelf

Any interpretation of sediment preserved on the continental shelf requires us to understand how sediment is transported after its arrival in the marine environment (Fig. 2). The same would be true concerning deciphering the records of sediments accumulating on the continental slope and abyssal
plain, because such sediments must necessarily pass through the shelf zone on their way to deep-water depocentres. High-energy conditions are common on continental shelves, which facilitates the dispersal of sediment from river mouths, as well as the reworking and mixing of new sediment with material already on the shelf. Such currents also control the form and location of shelf depocentres (Xu et al. 2012). Furthermore, longshore currents can transport sediment great distances parallel to the coastline, resulting in additional signal scrambling (Liu et al. 2009). Continental shelves are swept by powerful bottom currents, which may redistribute material across and along the shelf.

The northern shelf of the South China Sea provides a typical example of the complex nature of forces distributing sediments delivered by different riverine sources (Harff et al. 2013). A permanent longshore current transports the load delivered by the Pearl River to the west of the estuary. Particulate matter enters the Beibu Gulf through the bottleneck of the Qiongzhou Strait, where it mixes with the sediment load of the Nanliu and the Red rivers before it settles out and is preserved in the depocentre of the Gulf of Tonkin. The year-long east to west transport is superposed on by seasonal fluctuating transports induced by the Asian summer and winter monsoons. The switch in transport direction has induced the formation of a ‘Butterfly Delta’ east and west of the Qiongzhou Strait (Ni et al. 2014). In eastern Asia, the Kuroshio Current is especially noteworthy for its role on the East China Shelf (Andres et al. 2008) (Fig. 1). Reworking, recycling and mixing of fluvial sediment with older shelf deposits may cause the preserved stratigraphy of any continental margin to be at least partly homogenized over millennial time-scales. Understanding the processes responsible for building clastic shelves can be applied to the oil and gas industry because high-energy, well-sorted shelf sediments are important hydrocarbon reservoirs whose nature needs to be well defined if exploitation of the preserved hydrocarbons is to be maximized. A particular consideration is the origin of shelf-edge deltas, whose origin is usually not linked to sea-level highstands, but, instead, tend to be formed during periods of forced regression (Muto & Steel 2002; Limmer et al. 2012), where sediment supply is better able to keep up with accommodation space. This is especially true in East Asia where the shelves are mostly wide.

**Climatic feedbacks**

Continental shelves may play a part in controlling global climate by providing a feedback via the
processes of chemical weathering. When sea level falls as glaciers expand, wide areas of sediment are exposed and potentially made available for chemical weathering by direct interaction with the atmosphere, as well as via groundwater flow under the exposed shelf. Although work in high latitudes suggests no net change in weathering flux because of the reduced rates of weathering (Foster & Vance 2006), it is unclear whether the low latitude shelves of East Asia operate in a similar fashion. This is because of their great expanse compared to most Atlantic Ocean examples and because the temperature variations during glacial times at low latitudes may not be as great at high latitudes (deMenocal et al. 2000; Lea et al. 2003), so that the reductions in chemical weathering rates are not so great.

**Eustacy and stratigraphy**

The wide continental shelves of East Asia are also ideal natural laboratories for the study of how sea-level rises have influenced shelf stratigraphy. Traditional sequence stratigraphy is based on data derived from basins and continental margins surrounding the North Atlantic and Gulf of Mexico (Vail et al. 1977), but it is open to question as to whether such models are generally applicable. Deltas feeding the wide shelves around East Asia have far greater volumes of accommodation to fill before they would be able to regain a connection with their deep-water depositional systems following a transgressive period (Liu et al. 2004). This consideration must be balanced by the accelerated

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**Fig. 2.** Schematic block model showing the different processes that can affect fluvial sediment on its way from source to sink in East Asia. Modified from Fagel et al. (1994).
sediment delivery during highstands that typifies those drainages fed by regions influenced by an intensified summer monsoon. The summer monsoon tends to intensify as the global climate warms and sea levels rise because this is primarily controlled by solar insolation (Clemens et al. 2010).

This collection has been brought together to highlight recent developments in our understanding of how fluvial sediment has been delivered to the marginal seas of eastern Asia and to show what these deposits can tell us about the various processes mentioned above. The collection represents the final product of a special session on this topic convened at the 2012 International Geological Congress (IGC) in Brisbane, Australia, and an international follow-up workshop held at Sun Yat-Sen University, Guangzhou, China, in 2013.

Provenance

Provenance reconstructions are a major driver in the study of East Asian shelf sediments. This problem is now addressed by integration of geochemical and mineral proxies, and by thermochronological methods, especially the increasing popular U–Pb dating of detrital zircons. Clift (2015) reviewed the general application of such methods to the tracing of sediments in the South China Sea where material may be delivered from a series of diverse tectonic blocks. This study highlights the issue that anthropogenic disruption of the landscape since the establishment of agriculture means that modern river compositions may make poor fingerprints for tracing the effects of a given river in the geological past because sediment tends to be more altered in the modern day compared to the recent past. The popular provenance-related Nd and Sr isotope systems work best at identifying sediment flux from younger volcanic islands, especially Luzon, but are problematic when attempting to separate the flux from other continental blocks around the basin. Instead, differential exhumation rates, traced by low-temperature thermochronometers, in different possible source terrains proved more effective as discriminants. Apatite fission track, in particular, was highlighted as being more effective than either U–Pb zircon or Ar/Ar muscovite dating.

Shao et al. (2015) applied some of these provenance methods when they analysed sedimentary rocks from Pearl River Mouth Basin, offshore southern China, as well as from various parts of the Pearl River Basin. This study considered the bulk sediment geochemistry, and also looked at the heavy mineral suites in both the depocentres and source rivers. They were able to show that the Pearl River Basin can be divided into three regions – east, central and west – and that each region generated sediment with a distinctive fingerprint. Comparison with offshore deposits indicates that in the Early Oligocene sediment sources were close to, or within, the basin, but had expanded to the coastal granites of southern China by the end of the Oligocene. After the regional 23 Ma unconformity, the river appears to have widened through time. Although the palaeo-Pearl River continued to supply sediments to most parts of the northern South China Sea during the Early Miocene, the southern part of the Baiyun Sag, a particularly deep continental margin sub-basin, was affected by basic volcanic sources close to this depression.

Chemical weathering

Geochemical proxies are also used to reconstruct the intensity of chemical weathering, but it is not always clear which proxies are the most effective and whether any of these have universal applicability. This issue was addressed by Hu et al. (2015), who compared bulk sediment geochemical ratios and clay mineral proxies from the Pearl River delta, as well as from Ocean Drilling Program sites 1144 and 1146 (Fig. 1). Comparison with speleothem rainfall records since the Younger Dryas (c. 12 ka) indicates that K/Al tracks variations in precipitation most closely and out-performs the widely used Chemical Index of Alteration (CIA). Correlation of K/Al and kaolinite/illite indicates that this clay ratio is also an effective proxy of weathering intensity across all sites and timescales. In contrast, while kaolinite/smectite, and smectite/(illite + chlorite), are also indicative of weathering intensity, they show more scatter between sites that may be linked to provenance effects.

Geochemical proxies were also applied by Cui et al. (2015) to investigate Holocene environmental conditions in the Tonkin Gulf, in the NW South China Sea. Changing values of Al/Ti, K/Al and Mg/Al were used to reconstruct the intensity of chemical weathering in the source regions. Zr/Ti and SiO2/Al2O3 are believed to reflect the sand content of the sediment, and thus, potentially, record the history of current velocity. La/Co and La/Sr values coupled with rare earth element characteristics were used to argue that Hainan Island was the main source of the sediment to the basin during the Holocene. Based on these results, the authors divided the Holocene into four phases of climatic development. At 10.1–6.5 ka, sea level rose as the climate warmed. From 6.5 to 4.3 ka, the depositional environment was stable, but the local climate became colder and drier. From 4.3 to 3.5 ka, the currents changed following the opening of the Qiongzhou Strait between Hainan and the Leizhou Peninsula, thus also affecting sediment provenance.
Since 3.5 ka, the depositional environment appears to have been relatively stable.

**Sea-level rise and sediment storage**

Closer to the Qiongzhou Strait, Ni et al. (2016) for the first time report on a shelf mud accumulation within the Beibu Gulf known as the Southern Beibu Gulf Mud Depocentre (SBGMD). Identification was based on high-resolution sub-bottom profiles. The SBGMD lies in water depths of 50–80 m, and covers an area of more than 11 000 km². The SBGMD is imaged as a homogenous seismic unit surrounded by an erosive area of gullies and sand/mud waves. The SBGMD unconformably overlies a parallel-bedded seismic unit. Lithological and geochemical analysis of a core within the high sedimentation rate area of the SBGMD shows that before 17.0 ka this area was exposed and had a terrestrial, fluvial environment. From 17.0 to 11.6 ka BP, conditions appear to have been brackish and lacustrine. Subsequently (11.6–8.4 ka), the area experienced marine transgression, followed by continuous shallow-marine conditions to the present day.

Further to the south, Chen et al. (2015) investigated the relationship between sea-level changes during the Last Glacial Cycle and stratigraphic sequences offshore western Hainan using a combination of coring and high-resolution seismic reflection data. An age model was developed from AMS 14C, optically stimulated luminescence (OSL) and δ18O dates, spanning 110 ka in a 88.3 m-long core. Correlation with a sediment core in the adjacent basin allows identification of Marine Isotope Stages (MIS) 1–5e. They identify unconformities that separate seven sea-level cycles preserved within the study area, and which correlate with regional and global sea-level change models. Seismic imaging indicates a primary control by sea-level change on the shelf stratigraphy, modified by sediment flux and tectonic uplift. High sediment discharge, as well as tectonically driven uplift of Hainan, may have resulted in the development of prograding lowstand delta wedges on the shelf margin that took place during MIS 5–2.

Recent sediments on the northern margin of the South China Sea were considered by Zong et al. (2015). This review paper identified two marine successions offshore of the Song Hong (Red) River, Han River and Pearl River deltas. These two are dated as younger than the Last Glacial Maximum (c. 20 ka) and spanning the period 120–126 ka. The authors proposed that all these marine basins are bounded by active faults and because the older marine succession is recorded at a minimum of ~15 m below present sea level, this requires active tectonic subsidence to account for the marine conditions after accounting for the difference in sea level at 120–126 ka and the present day. Zong et al. (2015) linked these vertical motions to the long-term thermal subsidence of the northern South China Sea continental shelf, but noted that active faulting has enhanced local subsidence, resulting in marine inundation during interglacial high sea levels.

The fate of late Quaternary sediment delivered by the Yangtze to the East China Sea was considered by Yang et al. (2015). Most Yangtze sediment has been preserved on the outer shelf and in the Okinawa Trough during the last glacial maximum, which is not surprising given the lowstand of sea level. During the deglacial marine transgression, the gently dipping shelf was rapidly inundated and strong tides prevented fine-grained sedimentation on the open shelf, resulting in the development of a unique tidal sandridge system. As sea level stabilized close to the modern level, most Yangtze sediment accumulated in its estuary where it then built a large delta, with only a fraction reaching the inner shelf and coastal embayments. Source to sink transport of sediment in the East China Sea is heavily controlled by sea level, although monsoon-modulated sediment flux and bottom-current activity also plays a role in controlling the fate of Yangtze sediment reaching the ocean.

**Sediment transport**

Sediment dispersal in the Yangtze offshore regions was investigated by Wu et al. (2015), who focused on the large-scale mud belt on the inner shelf developed south of the river mouth. The processes responsible for sediment transport in this area were investigated by field observations during the 2013 monsoon season, with special attention paid to shelf circulation currents and their interaction with the Yangtze river outflow, as well as small- and meso-scale processes, including bottom boundary-layer flows, stratification, mixing and upwelling. The role of river-borne sediment-gravity and contour currents were also considered. Turbidity maxima within the estuary trap sediment suspensions near the seafloor and move these downslope to form sediment-gravity currents that are strengthened by tidal currents. In contrast, the buoyant coastal current is not a controlling factor in the formation of the mud belt. Long-distance dispersal of material to the mud belt is made possible by near-bed sediment transport along the shelf, together with a potentially significant contour-parallel sediment channel.

**Anthropogenic impacts**

The more recent and future evolution of the Pearl River delta were considered by Jia et al. (2016).
These workers compared two marine geophysical surveys from 2003 to 2012 across Lingdingyang Bay, the estuary in front of the Pearl River delta front. Within this area, they mapped three shoals and two channels that appear to be heavily impacted by anthropogenic activities. In the four river mouths that empty into Lingdingyang Bay, the sediment dispersal is controlled by tides, discharge strength and the presence of islands. The surveys show that, in the recent past, these outlets have become narrower, so that the water area of the bay is diminishing. Sediment flux into the bay is reducing and becoming finer grained because shoals and islands are blocking marine currents, so that sediments are easier to deposit as the energy in the water reduces. At the same time, water exchange between the inner bay and the open South China Sea is decreasing because of unrestricted anthropogenic activities. Without better management the bay will eventually sediment up and infill, resulting in potential hazards in the form of flooding and tides.

Further north, the Yellow River currently has the highest sediment load of any single river on Earth. The offshore growth of the Yellow Delta was constrained by Wang et al. (2015), who used cores within the Diaokou lobe of the Yellow Delta to date the construction of this feature. This lobe was especially active during the period 1964–76, after the river changed its course to the present location. This study used grain-size data, magnetic property data and AMS 14C dating of cores across the Diaokou lobe to define the Holocene stratigraphy. They identified a clear upwards succession from shallow-marine, to river and lake, to salt-marsh and, finally, to delta facies. This area started to receive deltaic deposits in 1855, and has experienced prodelta, delta-front and delta-plain environments. During the formation of the Diaokou lobe sediment transport was first by dispersed-flow deposition, then by single-channel deposition, followed by diversion deposition, and then culminated in abandonment and erosion.

Environmental impacts

Monsoon conditions since 290 ka were reconstructed by Zhou et al. (2015) using a benthic foraminiferal record from the northern continental slope of the South China Sea. Changes in oxygenation and types of organic matter reflect the palaeoproductivity linked to monsoon variability. Four assemblages, characterizing different palaeoenvironmental changes, were recognized. These show that interglacial periods MIS 7, MIS 5 and MIS 3 were associated with well-oxygenated bottom-water environments linked to a weak East Asian Winter Monsoon (EAWM). Foraminifera that depend on seasonal supplies of more altered organic matter are mainly found in interglacial periods (MIS 5, MIS 3 and MIS 1), suggesting highly seasonal palaeoproductivity associated with the intensification of the EAWM. Times of increased river run-off and increased primary productivity correlate with an enhanced EAWM, and have lead to severe bottom-water oxygen depletion. In contrast, during MIS 4, MIS 5, MIS 7 and MIS 8, there is evidence of an enhanced EAWM with low seasonality of palaeoproductivity. Changes in bottom-water environments of the northern South China Sea since 290 ka are proposed to have been driven by the fluctuating palaeoproductivity linked to the variability of the EAWM.

Paleo-environmental reconstructions can also be achieved using other types of microfossil, such as diatoms. Zhang et al. (2015) employed Paralia sulcata for this task because it is often well preserved in siliciclastic sediments. These workers synthesized the distribution of P. sulcata in sediment cores across the Asian marginal seas. They also noted that P. sulcata is strongly variable in abundance through time over glacial cycles, with lower abundances during the last glacial maximum and higher values during deglaciation within the South China Sea. This diatom is very common at 8–11 ka, a phenomenon linked to the opening of the Taiwan Strait to more flow, as well as to the general coastal water circulation pattern associated with the deglaciation process. In contrast, P. sulcata is less abundant in the East China Sea during the Holocene, but more common during the Last Glacial Maximum and especially during 11–15 ka.

Gao et al. (2015) considered the wider region of the Bohai, Yellow and East China seas as a single wide continental shelf environment. Holocene sediment distribution, composition and deposition rates are related to active sediment transport processes including tides, waves and shelf currents, as well as sediment gravity flows. Theoretically, the sediments in any one place should contain a record of high temporal resolution, but each site would only have limited duration. Gao et al. (2015) argue that if these records are connected, then they may form a complete archive for environmental change studies. Mid-Holocene coastal deposits on the Jiangsu coast and early–middle Holocene sequences in Hangzhou Bay, as well as the Holocene mud deposits off the Zhejiang–Fujian coasts, are of importance in process–product relationship studies. Sediment may be supplied to the shelf both from seabed reworking during times of sea-level rise and from enhanced river discharges.

This collection highlights some of the complexities of fluvial sediment transport on continental shelves, demonstrating what can and cannot be deduced from such deposits in the geological record.
INTRODUCTION

The scale of sediment flux in East Asia, reflecting the size of the rivers and the intensity of the summer monsoon, makes this region an ideal place to work on sediment transport issues. While these studies have advanced the science by a significant degree, they also show how much we still have to learn and so provide a stimulus for further studies.

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