Provenance discrimination of last deglacial and Holocene sediments in the southwest of Cheju Island, East China Sea

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A B S T R A C T

The ultimate provenance of muddy sediment in the southwest of Cheju Island, East China Sea, remains enigmatic thus far. In this study, rare earth elements (REEs) were used to investigate sediment provenances of cores E03-6, E03-10 and E03-11 taken from the mud patch. Discrimination plots based on REE fractionation parameters and trace elements suggest that the sediments deposited during the last deglacial period (>15 ka) were derived predominantly from the paleo-Huanghe (Yellow River) which might have delivered sediments directly into the northeastern East China Sea during the lowstand of sea level. The coarse-grained sediments deposited at transgressive stage (15–6 ka) were primarily sourced from the Changjiang (Yangtze River) and partly from the Korean Peninsula, probably transported by tidal currents. In comparison, the clayey sediments deposited at highstand stage (<6 ka) were mostly derived from the modern and old Huanghe. In particular, the fine-grained sediments eroded from the old Huanghe Delta in the southwestern Yellow Sea can be transported to the northeast of the East China Sea by the coastal current and the Changjiang Freshwater Plume as well, and finally trapped within a cyclonic upwelling gyre. The dispersal and deposition of terrigenous sediments in the northeast of the East China Sea are remarkably controlled by the oceanic circulation related to sea level variability. The variable depositional rates and drastic river–sea interaction during the late Quaternary make it difficult to reliably reconstruct a high-resolution paleoenvironmental change in the river-dominated shelf sea. Nevertheless, geochemical approach can provide important constraints on sediment source–to–sink transport patterns in this typical pericontinental sea.

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1. Introduction

The East China Sea, as a typical marginal sea in the West Pacific, has increasingly received research attention over the past two decades. It is characterized by complicated oceanic circulation and sediment dispersal patterns, remarkable sea level change, huge input of terrigenous sediment and strong land–sea interactions during the late Quaternary. The provenances of terrigenous sediments on the East China Sea shelf thus become the foci of Asian marine geological study, and especially, the influence of large rivers including the Changjiang (Yangtze River) and Huanghe (Yellow River) on the shelf sedimentation has been widely investigated (Xu and Oda, 1999; Liu et al., 2003; Yang et al., 2003a; Jung et al., 2006; Lim et al., 2007; Xu et al., 2011; Youn and Kim, 2011; Xu et al., 2012; Kim et al., 2013; Um et al., 2013).

The mud patch in the southwest of Cheju Island (SWCIM, Yang et al., 2003a), the northern margin of the East China Sea, attracted many research attempts in terms of its sediment provenance and depositional mechanism. It was once regarded as the distal end of the dispersal system of the modern Huanghe in the East China Sea (DeMaster et al., 1985; Alexander et al., 1991), and was formed in a counterclockwise cyclonic eddy (Hu and Li, 1993). The muddy surface deposits of the SWCIM were considered to be derived primarily from the modern Huanghe based on clay mineral and detrital calcite compositions (Milliman et al., 1985; Lee and Chough, 1989), or jointly from the old Huanghe and modern Changjiang sediments based on remote sensing observation, sediment budget calculation, and sediment geochemical and environmental magnetic studies (Saito, 1998; Sun et al., 2000; Liu et al., 2003; Yang et al., 2003a; Xiang et al., 2006; Yang et al., 2009).

The suspended sediments from Korean rivers are transported southward and may also contribute to the sedimentation of the southeastern Yellow Sea and northern margin of the East China Sea (Park and Khim, 1992; Lee and Chu, 2001; Lim et al., 2007). Despite these previous research attempts, the ultimate sediment provenance and depositional mechanism of the SWCIM are still open questions mainly because of the lack of high quality data from bore holes.

Recent finding of large ore deposit of rare earth elements (REEs) around Japan Islands in the West Pacific has received global attentions.

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Three gravity cores E03-6, E03-10 and E03-11 were taken from the northeastern East China Sea in 2003, with seawater depth from 65 to 80 m, among which E03-6 and E03-10 were drilled directly from the SWCIM, and core E03-11 was located in the south of the SWCIM (Fig. 1). Core E03-6 is 305 cm long and the upper unit (Unit 1) is mainly composed of silt clay, while the lower unit (Unit 2) is predominately sand. Core E03-10 is 370 cm long and composed of silt clay without apparent sand layers. Core E03-11 is also 370 cm long and consists of mixture of sand, silt and clay. The detailed locations of these cores and AMS14C ages of selected benthic foraminifera and peaty sediment samples were given in Table 1. The AMS14C dates reveal different basal ages of the three cores, albeit with similar core lengths. Core E03-11 sediments were deposited during the last deglacial to middle Holocene period, while the other two cores have the depositional ages of the mid–late Holocene. The linear sedimentation rate is of the lowest value in core E03-11 whereas it reaches the highest in core E03-10.

A total of 106 bulk samples were selected from the cores for elemental analysis. For removing the mobile, authigenic and biogenic fractions from the bulk sediments, 65 bulk samples were pretreated by acid to get the residual fractions, i.e. about 0.2 g bulk sediment samples being leached with 20 ml 1 N hydrochloric acid (HCl) for 24 h at 50 °C. In this study, we followed the 1 N HCl-leaching method by Choi et al. (2007). Yang et al. (2004) and Song and Choi (2009) also used this method to leach the river sediments for separating leachable and residual phases. All the samples were combusted in the muffle furnace for 2 h at 600 °C before the acid digestion. About 50 mg powdered samples were digested with 4 ml HNO3 and 1 ml HClO4 for 24 h in a tightly closed Teflon vessel on a hot plate at less than 150 °C, heated to dryness, and then digested with a mixture of 4 ml HF and 1 ml HClO4. Afterwards, the solution was evaporated to dryness, and extracted with 10 ml 1% HNO3. Concentrations of rare earth elements and other trace elements in the bulk samples were measured by an Inductively Coupled Plasma Mass Spectrometer (ICP-MS) at the University of London, while the REE concentrations of the residues were measured at the State Key Laboratory of Marine Geology at Tongji University, China. The analytic errors monitored by the international geostandard MAG-1 and Chinese Geostandard GSD-9 are below 5%. The sediment grain size compositions were measured by laser grain-size analyzer (Coulter LS 230) with the analytic precision of about 1%.

3. Results and discussions

3.1. Sediment grain size and REE compositions of the core sediments

The mean grain size (Mz) and REE concentrations as well as the REE fractionation parameters including (La/Yb)UCC, (Sm/Nd)UCC, and cerium (iCe) and europium (iEu) anomalies in the bulk samples are given in Fig. 2 and Table 2. (La/Yb)UCC indicates the degree of fractionation between light (La to Eu) and heavy (Gd to Lu) REEs while (Sm/Nd)UCC indicates the fractionation degree of middle (Sm to Dy) REE relative to light REE. In this study, the average composition of the Upper Continental Crust (UCC, Taylor and McLennan, 1985) was used to normalize the REE concentrations in the core sediments.

The compositions of Mz and REE in the three cores exhibit different downcore variations, with larger variations occurring in cores E03-06
Fig. 2. Grain size and REE compositions of core E03-6, E03-10 and E03-11 sediments from the northern East China Sea. REE parameters including \((\text{La}/\text{Yb})_{\text{UCC}}\), \((\text{Sm}/\text{Nd})_{\text{UCC}}\), and cerium (\(\delta\text{Ce}\)) and europium (\(\delta\text{Eu}\)) anomalies are used to indicate the REE fractionation. UCC means the normalization of REE concentrations in the core sediments by the average composition of the upper continental crust (Taylor and McLennan, 1985). See the text for more detailed description.
and E03-11. In comparison, core E03-06 has uniform compositions of grain size and REE in the upper 150 cm (Unit 1) and large variations in the lower 150 cm (Unit 2, Fig. 2). The homogeneous silty clay dominates Unit 1 whereas the sandy sediments characterize Unit 2. Core E03-10 is dominated by silty clay and has small compositional variations of REEs, and Mz and REE concentrations are close to those in Unit 1 of core E03-6. Large variations of sediment grain size, REE concentrations and fractionation parameters as well, however, are observed in the upper part of core E03-11 (Unit 1), and relatively uniform variations occur in the lower part below 75 cm (Unit 2, Fig. 2). It is noteworthy that the REE concentrations in Unit 2 of core E03-11 are close to those of core E03-10 and Unit 1 in core E03-6.

REE distribution pattern and fractionation parameters can be good indicators for sediment provenances (Yang et al., 2003b; Song and Choi, 2009). Despite remarkably different REE concentrations among the core sediments in this study, the REE patterns of the bulk samples normalized by UCC (Taylor and McLennan, 1985) yield overall similar fractionations, showing as “W-type” convex distributions with relative enrichments of the middle REE in most of the samples (Fig. 3a-e). The uniform and small variations of UCC-normalized REE patterns are also present in the core E03-10 (Fig. 3e).

However, the REE patterns of the residues in cores E03-6 and E03-10 are much different from those of the bulk samples, exhibiting different fractionations in the cores, as shown in Fig. 3f-h. The core E03-6 sediments are characterized by an apparent enrichment of light rare earth element in Unit 2 and “W-type” convex patterns in Unit 1 (Fig. 3g, h). The residual sediments of core E03-10 overall have similar UCC-normalized patterns with that of Unit 1 of core E03-6, showing weak REE fractionations (Fig. 3f, g).

Table 2

<table>
<thead>
<tr>
<th>Samples</th>
<th>Core depth (cm)</th>
<th>Mz (µm)</th>
<th>REE (ppm)</th>
<th>δEu</th>
<th>δCe</th>
<th>(La/Yb)UCC</th>
<th>(La/Sm)UCC</th>
<th>(Sm/Nd)UCC</th>
<th>(Gd/Yb)UCC</th>
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<tr>
<td>E03-6-Unit 1 (16)</td>
<td>0–150</td>
<td>128.2</td>
<td>162.2</td>
<td>1.08</td>
<td>0.96</td>
<td>1.08</td>
<td>0.90</td>
<td>1.11</td>
<td>1.10</td>
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<tr>
<td>E03-6-Unit 2 (14)</td>
<td>150–290</td>
<td>145.7</td>
<td>1.10</td>
<td>0.95</td>
<td>1.20</td>
<td>0.92</td>
<td>1.08</td>
<td>1.18</td>
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<tr>
<td>E03-10 (39)</td>
<td>0–370</td>
<td>160.5</td>
<td>1.06</td>
<td>0.96</td>
<td>1.09</td>
<td>0.88</td>
<td>1.12</td>
<td>1.12</td>
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<tr>
<td>E03-11-Unit 1 (8)</td>
<td>0–70</td>
<td>174.0</td>
<td>1.05</td>
<td>0.94</td>
<td>1.30</td>
<td>0.96</td>
<td>1.07</td>
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<td>E03-11-Unit 2 (29)</td>
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<td>172.8</td>
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<td>1.14</td>
<td>0.91</td>
<td>1.09</td>
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<td>0.96</td>
<td>1.17</td>
<td>0.96</td>
<td>1.10</td>
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<td>0.95</td>
<td>1.05</td>
<td>0.92</td>
<td>1.08</td>
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<td>128.8</td>
<td>1.06</td>
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<td>1.02</td>
<td>1.17</td>
<td>0.96</td>
<td>1.04</td>
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<tr>
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<td>127.8</td>
<td>1.12</td>
<td>0.98</td>
<td>1.21</td>
<td>1.08</td>
<td>1.00</td>
<td>1.33</td>
<td></td>
</tr>
<tr>
<td>E03-10 (39)</td>
<td>0–370</td>
<td>145.0</td>
<td>1.05</td>
<td>0.97</td>
<td>0.98</td>
<td>1.16</td>
<td>0.96</td>
<td>1.02</td>
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<tr>
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<td>0.95</td>
<td>1.15</td>
<td>1.13</td>
<td>1.01</td>
<td>1.09</td>
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<tr>
<td>Huanghe (20)</td>
<td></td>
<td>119.4</td>
<td>0.90</td>
<td>0.96</td>
<td>0.99</td>
<td>1.01</td>
<td>1.03</td>
<td>1.13</td>
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<tr>
<td>Cheju (1)</td>
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<td>2.48</td>
<td>0.50</td>
<td>1.03</td>
<td>0.76</td>
<td>1.31</td>
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<tr>
<td>Cheju-fine (1)</td>
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<td>49.14</td>
<td>1.55</td>
<td>0.92</td>
<td>1.12</td>
<td>0.98</td>
<td>1.13</td>
<td>1.26</td>
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</table>

The figures in the bracket mean the number of studied samples.

Table 2

Comparisons of mean grain size (Mz) and total REE (ΣREE) compositions in the sediments between cores E03-6, E03-10 and E03-11 and the potential end-members including the Changjiang and Huanghe (Yang et al., 2002a), Keum River (Yang et al., 2004), and Cheju Island coastal sediments (unpublished data).

REE compositions in sediments are basically controlled by source rock types in the provenance area, sediment grain size, mineral partitioning, intensity of chemical weathering, post-depositional diagenesis and anthropogenic activity as well. Among these competing processes, sediment provenance is regarded as the first and most important constraint on REE compositions (Taylor and McLennan, 1985; McLennan, 1989; Condie, 1991; Yang et al., 2002a, 2004; Song and Choi, 2009). REEs are generally enriched in clay and silt fractions, but depleted in sand fraction, because of the dilution by quartz, carbonate and other rock-forming minerals (Vital et al., 1999). Nevertheless, heavy minerals such as zircon, apatite, monazite, garnet, allanite and sphene, despite their low contents in most sandy sediments, may contribute a considerable proportion of the bulk REE concentrations because of high REE abundances in these minerals (Gromet and Silver, 1983; Taylor and McLennan, 1985; McLennan, 1989; Hannigan and Sholkovitz, 2001; Yang et al., 2002a).

The poor correlation between mean grain size (Mz) and concentrations of total REE in the core sediments (Fig. 5a) suggests that the grain size is not a dominant control of REE compositions in these samples. Similarly, no clear correlation was observed between the proxy (La/Yb)UCC and Mz (Fig. 5b), and La and Fe (Fig. 5d) indicating the weak influence of grain size and iron oxide minerals on REE compositions.

Element Zr is primarily enriched in zircon and thus, often used as an indicator of zircon abundance in sediments. The fine samples from core E03-10 and part of core E03-6 have the lowest concentrations of Zr and higher concentrations of La, while the silty samples of core E03-11 have the highest Zr concentrations and variable La concentrations. The irregular variation between the concentrations of La and Zr (Fig. 5c) for core E03-6 and core E03-10 seemingly implies that zircon may not play a significant role in constraining REE concentrations in these two sediments.

However, an apparent positive correlation is observed between concentrations of La, Zr, and Th for the samples of core E03-11 (Fig. 5e, f). This implies that REE-rich monazite and apatite may contribute to the REE compositions of the core samples, but overall, the poor and weak correlations between concentrations of La and Fe, and Zr and Th for other cores (core E03-6 and core E03-11) in this study suggest that the mineral partitioning by Fe–Mn oxide minerals, zircon, apatite and other minerals may not be a predominant constraint of REE compositions (Gromet and Silver, 1983; McLennan, 1989; Condie, 1991; Yang et al., 2002a).

The sandy sediments of Unit 2 in core E03-6 have lower Zr and La concentrations, suggesting that zircon is not always rich in the coarse-grained sediments.

3.2. Constraints of REE compositions in the core sediments
3.3. Sediment provenance discrimination of the cores

As introduced above, there exist different opinions on the sediment sources in the northern East China Sea, and Chinese rivers, especially the Changjiang and Huanghe, are suggested to be the primary sediment suppliers (DeMaster et al., 1985; Milliman et al., 1985; Lee and Chough, 1989; Zhao et al., 1995; Liu et al., 2003; Shi et al., 2003; Yang et al., 2003a; Li et al., 2005; Xiang et al., 2006; Lim et al., 2007; Youn and Kim, 2011; Kim et al., 2013). Korean rivers such as the Keum River and local rivers from Cheju Island might also provide part of the suspended sediments, given that the north East China Sea is closer to the Korean Peninsula and Cheju Island, and the coastal current may transport the river-borne sediments southward (Fig. 1; Park and Khim, 1992; Lee and Chu, 2001; Yang et al., 2004; Jung et al., 2006; Lim et al., 2007). The island weathering in Asia may be a quantitatively important source of rare earth elements to the Western Pacific Ocean (Sholkovitz et al., 1999). However, how island-derived terrigenous materials can influence the sedimentation in the West Pacific marginal seas has not been resolved yet.

The distinct enrichment of light REE in the Korean river sediments relative to the Chinese river sediments makes REE a good sediment provenance tracer for discriminating the Chinese and Korean river sediments in East Asian marginal seas (Yang et al., 2004; Jung et al., 2006; Song and Choi, 2009). The UCC-normalized REE patterns of the Cheju

![Fig. 3. UCC-normalized REE fractionation patterns of the bulk samples and residual fractions for the core sediments. Note the uniform and similar REE patterns between the cores. Diagrams a to e indicate the bulk samples and f to h indicate the residual fraction.](image-url)
coastal sediments exhibit significant enrichments of middle REE (unpublished data), while the REE compositions of the East China Sea shelf sediments are similar with the average of Chinese river sediments (Zhao et al., 1990, 1995; Zhao and Yan, 1994).

Most of the bulk samples from the studied cores show “W-type” convex distributions with the relative enrichments of the middle REE (Fig. 3a–h), apparently suggesting that they have similar sediment provenances. In this study, we compare the REE compositions of the core samples with the potential provenance end-members including the Changjiang, Huanghe, Keum River, Cheju coastal sediments and modern shelf of the East China Sea. The results suggest that most of the core sediments have REE patterns close to the Huanghe river sediments, and some samples are similar with the Changjiang and Keum River (Figs. 3 and 4). This implies that Chinese and Korean river sediments may dominate the sediment sources of the studied cores. There exist no REE patterns in all of the core samples similar with Cheju coastal sediments, indicating that the local sediment sources from Cheju Island contribute little to the study area, although the studied cores are close to the island. Furthermore, different REE compositions between Unit 1 and Unit 2 in core E03-6 occur not only in the bulk samples but also in the residues, indicating different sediment provenances of these two depositional units. Similarly, REE compositions of the two units in core E03-11 also imply their different sediment sources, with Unit 1 sediments of core E03-11 showing significant enrichments of light REE relative to heavy REE (Fig. 3).

The discrimination plots of (La/Yb)UCC vs. (Sm/Nd)UCC for the bulk samples and residues were applied for distinguishing provenances of the core sediments (Fig. 6a, b). Obviously, the Unit 1 sediments of core E03-06, Unit 2 sediments of core E03-11 and sediments of core E03-10 plot together with the Huanghe sediments with lower value of (La/Yb)UCC (ratios < 1.1), whereas the Unit 2 sediments of core E03-06 and Unit 1 sediments of core E03-11 plot in another group that is close to the sediments from Changjiang and/or Keum River with higher value of (La/Yb)UCC (ratios > 1.1). Accordingly, we infer that the last deglacial sediments (Unit 2 of core E03-11) in the study area were derived predominantly from the paleo-Huanghe, while the coarse-grained sediments deposited at transgressive stage (Unit 2 of core E03-6 and Unit 1 of core E03-11) were primarily sourced from the Changjiang and partly from Korean rivers. Jung et al. (2006) also proposed the mixed sediment provenances between Chinese and Korean rivers, based on REE geochemistry of the surface sediments in the northern East China Sea. The clayey sediments deposited at highstand stage (Unit 1 of core E03-6 and core E03-10) originated mainly from modern Huanghe and/or old Huanghe delta.

Due to the limited AMS14C dates and hiatuses of the core sediments, we cannot quantitatively estimate the sediment accumulation flux of specific provenances. Nevertheless, the geochemical discrimination results provide important constraints of provenances of the postglacial sediments in the three cores. The clayey sediments of core E03-10 and Unit 1 in core E03-6 were predominantly derived from the Huanghe during the mid–late Holocene. Furthermore, the fine-grained sediments accumulated around the muddy patch during the pre-Holocene and deglacial period (Unit 2 of core E03-11) were also primarily derived from paleo-Huanghe. It is noteworthy that the REE parameters cannot distinguish the composition between the modern and paleo-Huanghe sediments. In comparison, the coarse-grained sediments deposited in
the northern East China Sea (Unit 2 in core E03-6 and Unit 1 in core E03-11) might jointly originate from the Changjiang and Korean peninsula during the transgressive stage.

3.4. Sediment transport patterns since the last deglacial period

The sediment transport pathways in the East China Sea and the Yellow Sea during the last glacial and postglacial periods are tightly related to the changes of influx of river sediments, sea-level changes and oceanic circulation as well (Yang et al., 2014). The lowest sea level of East Asian marginal seas was estimated to be at −120 ± 5 m during the Last Glacial Maximum (Saito, 1998; Hanebuth et al., 2000), and the continental shelf of the East China Sea was thus largely exposed. Correspondingly, the river mouths of the paleo-Changjiang and paleo-Huanghe might have been positioned significantly closer to the present day’s outer shelf. As a result, the terrigenous fine-grained sediments from the paleo-Changjiang and Huanghe might have deposited directly in the northeastern East China Sea. The REE compositions of the Unit 2 sediment in core E03-11 verified this possibility, suggesting the dominant sediment source from the paleo-Huanghe during the last deglacial period (>15 ka) (Fig. 7a).

With the onset of rapid postglacial transgression at ca. 15 ka, sedimentation on the shelves of the East China Sea and Yellow Sea was dominated by tidal process in response to the rapid sea-level rise (Liu et al., 1998; Saito, 1998; Yoo et al., 2002; Uehara and Saito, 2003). The tidal sand ridges on the East China Sea shelf might have formed at sea levels from −75 to −60 m at ca. 13.5–12 ka (Uehara and Saito, 2003), under the circumstance of very strong bottom stress (over 2.0 N/m²). Strong bottom stress (exceeding 1.0 N/m²) caused by tidal force also occurred on the outer shelf, which accounts for the continuous development of large tidal sand ridges. The coarse-grained sediments of Unit 2 in core E03-6 and Unit 1 in core E03-11 deposited no older than 15.7 ka and no younger than 5.26 ka (Fig. 2), corresponding with the formation time of tidal sand ridges on the shelf. REE discrimination

![Fig. 5. Correlation plots of La with mean grain size ($M_z$) and other elements (Fe, Zr, Th) in the bulk samples.](image-url)
results suggest that these sandy sediments are remarkably different from the Huanghe sediments, but very similar with those of the Changjiang, partly with Korean-derived sediments. This implies that these deglacial and early Holocene sandy sediments were primarily sourced from the Changjiang, the shelf of the East China Sea, and/or the Korean Peninsula, probably transported by residual tide currents, after their initial deposition at the shelf edge during the transgressive stage (Fig. 7b). Provenance study by Yang and Youn (2007) also suggests that part of Korean river sediments could escape the estuarine trapping and be delivered to the southeast of the Yellow Sea shelf.

With the postglacial sea level rising to the highest stage and close to its present position at about 6–7 ka, the Changjiang river mouth gradually retreated, and the depositional regime in the Yellow Sea and the East China Sea significantly changed (Yang et al., 2014). A counterclockwise cyclonic eddy was formed in the southwest of Cheju Island, with northward inflow of the Yellow Sea Warm Current along the eastern margin, and a southward inflow of the Yellow Sea Coastal Current along the west coast (Fig. 7c, Beardsley et al., 1985; Yuan et al., 1987; Hu and Li, 1993). In contrast, the tidal bottom stress became sufficiently weak accompanied by the postglacial sea-level rise (Saito, 1998). Since then, the shelf sedimentation in the southwest of Cheju Island was dominated by the competing processes of modern oceanic circulations in the Yellow Sea and the East and China Sea. The REE results in this study imply that the clayey sediments (core E03-10 and Unit 1 in core E03-6) deposited during the mid–late Holocene were predominantly derived from the Huanghe sediments. In other words, the fine-grained Huanghe/old-Huanghe delta sediments might have been transported to the study area since the hightstand stage, which is consistent with previous studies (Milliman et al., 1985; Alexander et al., 1991; Lin et al., 2002; Yoo et al., 2002; Liu et al., 2003; Lim et al., 2006).

The modern Huanghe-derived sediment mostly deposits near the river mouth and around the Shandong Peninsula, and the fine-grained particles are transported southward along the coast, forming the central Yellow Sea mud (Fig. 7c; Milliman et al., 1989; Park and Khim, 1992). In this study, we cannot conclude whether the modern Huanghe-derived muddy sediment can reach the study area (SWCIM) although some previous studies proposed this long-distance transport (Lee and Chough, 1989; Milliman et al., 1985; Alexander et al., 1991; Lin et al., 2002; Yoo et al., 2002; Li et al., 2009). The modern and old Huanghe sediments have very close REE compositions because of their similar provenance, which makes it difficult, if not impossible, to discriminate them in the shelf environment.

Benthic foraminifera and stable isotopic evidences in the southern Yellow Sea (Core YE-2, Fig. 1) suggest that the Huanghe might shift its river course northward at about 7 ka (Xiang et al., 2008), which implies that since then the Huanghe in the north may not considerably influence the sedimentation in the southern Yellow Sea and northern East China Sea. Accordingly, the old Huanghe Delta in the west coast of the southern Yellow Sea may be the more important sediment supplier to the SWCIM than the modern Huanghe in the north, considering the strong erosion in the old Huanghe Delta (Milliman et al., 1985; Saito, 1998; Yang et al., 2003a; Lim et al., 2007; Kim et al., 2013). Anyhow, the fine-grained sediments from the old and/or modern Huanghe dominate the formation of the SWCIM since 5–6 ka, and the development of a cyclonic upwelling gyre in the northeast of the East China Sea accounted for the mud deposition (Fig. 7c; Milliman et al., 1985; Hu and Li, 1993; Yoo et al., 2002; Gao and Jia, 2003; Shi et al., 2003; Lim et al., 2007). Although some studies suggest that the distal mud sediment in the SWCIM may partly originate from the Changjiang and the East China Sea shelf (Milliman et al., 1985), carried by the Yellow Sea Warm Current (Gao et al., 1996; Yang et al., 2003a), this study based on REE geochemistry suggests that their contributions are minor.

In this study, the exact formation time of the SWCIM cannot be determined because of inadequate AMS14C ages. Previous studies reveal that the base of muddy sediments in the central part of the mud patch (around 32°N, 126°E) was younger than 8 ka (Yang et al., 1995), or ca. 6–6.5 ka (Liu et al., 1999; Xiang et al., 2008; Li et al., 2009) and older than the formation of modern oceanic circulation in the Yellow Sea (Yoo et al., 2002). Data from stable isotope of foraminifera and grain size of core YE-02 from the central southern Yellow Sea reveals that the modern oceanic circulation in the Yellow Sea was established no earlier than 6–5 ka (Xiang et al., 2008). The study by Kong et al. (2006), however, suggested that the inflow of Yellow Sea Warm Current (YSWC) began at 4.3 ka and was fully developed at 3.5 ka. In this study, a radiocarbon age of the top of Unit 1 (just above the sand ridge, Fig. 2) in core E03-11 was about 5.3 ka, apparently confirming the formation time of the mud patch no earlier than 6 ka. This age is consistent with the YSWC formation time of 5.7 ka proposed by Wang et al. (2014).

4. Conclusions

REE geochemical method has been applied to decipher the sediment provenance of cores E03-6, E03-10 and E03-11 taken from the northeastern East China Sea and to discuss the changes of sediment sources in response to the variability of sea level and oceanic circulation since the last deglacial period.

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![Figure 6](image_url)  
**Fig. 6.** Discrimination plot of (La/Yb)UCC vs. (Sm/Nd)UCC of the sediments from the SWCIM and the potential end-members, including the Changjiang and Huanghe (Yang et al., 2002a), Keum River (Yang et al., 2004), and Cheju Island coastal sediments (unpublished data).
Fig. 7. Schematic map summarizing the sediment transport patterns in the study area since the last deglacial period. During the last deglacial period (> 15 ka), the paleo-Huanghe delivered the sediments directly to the study area with the sea level staying at a low stand. During the transgressive stage (15–6 ka) with rapid rising of sea level, the paleo-Huanghe river mouth retreated northward and the paleo-Changjiang and Korean rivers might dominate the sedimentation in the northern East China Sea. The sandy sediments deposited in the study area were tightly related to the winnowing of the tidal sand ridges in the mid-outer shelves of the Yellow Sea and East China Sea. During the highstand stage (< 6 ka) with the completion of modern oceanic environment, the study area has received the fine-grained sediments mostly from the old-Huanghe Delta in the southwestern Yellow Sea. The Chinese and Korean coastal currents as well as the Yellow Sea Warm Current exert an important role in the formation of the mud patch.
The compositions of sediment grain size and REE in the three cores exhibit different downcore variations. Core E03-06 has uniform compositions of grain size and REE in the upper 150 cm and large variations below 150 cm. Clear downcore variations in grain size and REE also occur in core E03-11, with the upper 75 cm sediments much different from the lower part. Core E03-10 is dominated by silty clay and has smaller variations of REE compositions. The bulk samples of the cores have overall similar REE fractionations, showing the enrichment of middle-REE relative to the upper continental crust, while the REE patterns of residual fractions leached by 1 N HCl exhibit significant fractionations within the cores.

The silty sediment deposited during the deglaciation period (>15 ka) was derived predominantly from the paleo-Huanghe, and the lowstand of sea level accounted for the direct delivery of the paleo-Huanghe sediment into the northeastern East China Sea. With the rapid postglacial transgression and gradual retreat of the river mouths, the sandy sediment deposited at transgressive stage was primarily sourced from the paleo-Changjiang and partly from the Korean rivers, and probably winnowed by residual tide currents, after their initial deposition at the shelf edge during the lowstand stage. In comparison, the clayey sediments deposited at highstand stage (<6 ka) were predominantly derived from the modern or old Huanghe via the transport by the Yellow Sea Coastal Current.

The change of sea level basically controlled the formation of oceanic circulation in the East China Sea and Yellow Sea, which consequently determined the depositional environment and formation of typical sedimentary systems in these seas. Our study suggests that proper geochemical proxies can reliably identify the sediment origin in the river–dominated shelf sea. However, the variable depositional rates and drastic river–sea interacting during the late Quaternary make it difficult to reliably reconstruct a high-resolution paleoenvironmental change.

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