Changes in detrital sediment supply to the central Yellow Sea since the last deglaciation

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Abstract. The sediment supply to the central Yellow Sea since the last deglaciation was uncovered through clay mineralogy and geochemical analysis of core 11YS-PCL14 in the Central Yellow Sea Mud (CYSM). The core can be divided into four units based on the various proxies such as grain size, clay mineralogy, geochemistry, and Sr–Nd isotopes: Unit 4 (700–520 cm; 15.5–14.8 ka), Unit 3 (520–310 cm; 14.8–12.8 ka), Unit 2 (310–130 cm; 12.8–8.8 ka), and Unit 1 (130–0 cm; < 8.8 ka). Unit 2 is subdivided into two subunits Unit 2-2 (310–210 cm; 12.8–10.5 ka), Unit 2-1 (210–130 cm; 10.5–8.8 ka) according to smectite content. Comparison of the clay mineral compositions, rare earth elements, and εNd indicate distinct provenance shifts in core 11YS-PCL14. Moreover, the integration of clay mineralogical and geochemical indices show different origins according to particle size. During the late last deglaciation (Units 3 and 4, 15.5–12.8 ka), Unit 4 sediments originated from all potential provenance rivers such as the Huanghe, Changjiang, and western Korean rivers, while the source of coarse sediments changed to Huanghe when beginning the Unit 3. Fine-grained sediment still supplied from all rivers during the deposition of Unit 3. Early Holocene (Unit 2) sediments were characterized by oscillating grain size, clay minerals, and moderate εNd values. In this period, the dominant fine sediment provenance changed from the Huanghe to the Changjiang, whereas coarse sediments most likely originated from western Korean rivers. The Unit 1 CYSM sediments were sourced primarily from the Changjiang, along with minor contributions from the western Korean rivers. Possible transport mechanisms concerning such changes in the sediment provenance include paleo-river pathways, tidal stress evolution, and the development of the Yellow Sea Warm Current and coastal circulation systems, depending on the sea-level fluctuations.

Keywords: Central Yellow Sea Mud (CYSM), clay mineralogy, sediment provenance, Sr–Nd isotopes, Rare earth elements

1 Introduction

The Yellow Sea, located between the China and Korean Peninsula, is a semi-enclosed epicontinental shelf with a complex oceanic circulation system (Fig. 1). It is notable for its large amount of runoff and terrigenous sediment supplied from several adjacent rivers, including two of the world's largest rivers, the Changjiang and Huanghe, as well as from several smaller Korean rivers, including the Han, Keum, and Yeongsan River. Although most riverine sediments are trapped in estuaries and along coastal areas, some are deposited on adjacent shelves (Milliman *et al*., 1985; Milliman *et al*., 1987), forming several shelf mud patch depositions such as Central Yellow Sea Mud (CYSM), Southeastern Yellow Sea Mud and Southwestern Cheju Island Mud (Fig 1). These deposits provide abundant information on paleo-environmental changes as well as sediment supply, marine hydrodynamics, and climate variation (*e.g.* Wang *et al*., 1999; Kim and Kucera, 2000; Li *et al*., 2014a; Cho *et al*., 2015; Kwak *et al*., 2016; Hu *et al*., 2018).

The provenance of CYSM sediments have attracted many researchers over the last three decades. Many studies have indicated that CYSM sediments originated mostly from the Huanghe considering the large amount of sediment load carried by that river (Milliman *et al*., 1987; Lee and Chough, 1989; Liu *et al*., 2002; Yang and Liu, 2007; Shinn *et al*., 2007; Xiang *et al*., 2008). On the other hand, other studies have used mineralogical, geochemical, and magnetic observations and determined that the CYSM was formed from a complex mixture of sediments from the Huanghe as well as the Changjiang and several Korean rivers (Zhao *et al*., 1990; Wei *et al*., 2003; Zhang *et al*., 2008; Li *et al*., 2014a; Wang *et al*., 2014; Koo *et al*., 2018). In addition, recent studies using core sediments suggested that the provenance of CYSM changed mainly from Huanghe to Changjiang with minor contribution from the Korean rivers during the Holocene (Lim *et al*., 2015; Hu *et al*., 2018). However, the timing of the CYSM formation and the deposition environment prior to the Holocene are remains unclear.

Discrimination of sediment source and reconstruction of paleo-environmental changes can be undertaken based on grain size, clay mineralogy, and elemental signals. In particular, clay mineralogy and geochemistry have been utilized as a powerful tool to trace provenance of the terrigenous fraction of marine sediments in the Yellow sea (Yang *et al*., 2002; Yang and Youn, 2007; Liu *et al*., 2007, 2010b; Dou *et al*., 2010; Hu *et al*., 2012; Wang and Yang, 2013; Li *et al*., 2014a; Koo *et al*., 2018). Several additional factors can also control sedimentary characteristics, including terrigenous inputs, sea level and climate conditions (Wang et al., 1999; Duck et al., 2001; Hwang et al., 2014; Li et al., 2014a; Lim et al., 2015; Badejo et al., 2016; Hu et al., 2018). In addition, paleo-river pathways, recently reconstructed by high-resolution seismic researches in the Yellow Sea, can account for sedimentation and sediment provenance since the last deglaciation because they are an important route of sediment transport during the low stand period (KIGAM, 1993; Xu *et al*., 1997; Yoo *et al*., 2015, 2016).

In this study, we aim to determine the sediment provenance and transport mechanism of CYSM using clay mineralogy and geochemistry multi-proxy. The purposes are to provide a broad insight into the supply of CYSM sediments and to reconstruct the paleo-environment since the last glacial maximum.

2. Oceanography

The hydrodynamic system in the Yellow Sea is characterized by two major circulation patterns (Fig. 1). One is a counterclockwise gyre in the western part consisting of the Yellow Sea Warm Current (YSWC) and Yellow Sea Coastal Current (YSCC) (Beardsley *et al*., 1985; Yang *et al*., 2003). The other is a clockwise gyre in the eastern part made up of the YSWC and the Korea Coastal Current (KCC) (Beardsley *et al*., 1985; Yang *et al*., 2003). The YSWC is one of the most important dynamic phenomena in the East China Sea and Yellow Sea. It is a branch of the Kuroshio Current that carries warm, salty water into the Yellow Sea roughly along the Yellow Sea Trough (Xu *et al*., 2009; Liu *et al*., 2010a; Wang *et al*., 2011, 2012). The YSCC and KCC flow south along the coasts of the China and the Korean Peninsula, respectively. Besides, the Transversal Current (TC), identified in recent studies, separates from the KCC southwest of the Korean Peninsula, and some of its water flows northward along the YSWC (Lie *et al*., 2013, 2016; Hwang *et al*., 2014) (Fig. 1). On the other hand,

freshwater input from the Changjiang to the Yellow Sea forms the plume of low-salinity water, called as the Changjiang Diluted Water (CDW) (Sukigara et al., 2017). A part of the CDW spreads eastward, reaching as far as Jeju Island and Korea Strait (Hwang *et al*., 2014; Li *et al*., 2014a). The oceanic fronts include the Shandong Front (SDF), Jiangsu Coastal Front (JSCF) and Western Korean Coastal Front (WKCF) located in the western and eastern boundaries of the Yellow Sea. These fronts play an important role in shaping Yellow Sea currents as well as in understanding sediment transport, as they separate different water masses in the centre and coast of the Yellow Sea and appear a barrier effect for sediment (Huang *et al*., 2010; Li *et al*., 2014a; Koo et al., 2018) (Fig. 1).

3. Materials and methods

Core 11YS-PCL14 (35°785' N, 124°115' E), which was 702 cm in length, was collected from CYSM at a water depth of approximately 80 m for multi-proxy paleo-environmental reconstruction. The core was subsampled at 10 cm intervals for grain size, clay mineralogy and geochemical analyses. The core 11YS-PCL14 is 702 cm recovered deeper than other studied cores around here (YSC-1; 437 cm, EZ06-1; 370 cm, EZ06-2; 360 cm) (Li et al., 2014; Lim et al., 2015).

The grain size and Accelerator Mass Spectrometer based ^{14}C dates were reported in Badejo *et al*. (2016). Radiocarbon ages for five selected depths (99 cm, 300 cm, 540 cm, 580 cm, and 698 cm) and the age-depth model was constructed based on the linear interpolation between the calibrated calendar ages (Badejo *et al*., 2016) (Table 1). The bottom of the core 11YS-PCL14 dated approximately 15.5 ka, that 11YS-PCL14 provides a continuous record of the late last deglaciation to Holocene in the CYSM.

The clay mineral analysis was conducted using X-ray diffraction (XRD) on preferred-orientation specimens of fine-grained sediment (< 2 μm) following the method in Cho et al. (2015). Semi-quantitative estimation of clay mineral abundances was completed using the Eva 3.0 program with the empirical factors from Biscaye (1965).

The composition of major and trace elements in 13 bulk samples was determined by Actlabs, Ontario, Canada, following the '4 LithoRes' methodology. The samples were fused using a lithium metaborate-tetraborate mixture. The melt produced by this process was completely dissolved with 5% HNO_3. Major elements were analysed in the resulting solution by inductively coupled plasma-optical emission spectrometry (ICP-OES), with an analytical accuracy of < 6%. Trace element analyses were done by inductively coupled plasma-mass spectrometry (ICP-MS). The analytical reproducibility ranged between 5 and 12%.

A total 18 samples of core 11YS-PCL14 and riverine sediments (Huanghe, Changjiang and Keum River) were selected for Sr–Nd isotopic analysis and were processed on the <63 μm fraction of each sample (Table 3). The inorganic silicate fraction was extracted from 18 samples following the method described by Rea and Janecek (1981). The samples were treated with acetic acid buffered to pH 5 with sodium acetate to remove calcium carbonate. They were subsequently treated with a hot sodium citrate-sodium dithionite solution buffered with sodium bicarbonate to remove coarse biogenic components and finally treated with Na_2CO_3 solution to remove biogenic silica. $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ analyses, including chemical separation and multicollector thermal ionization mass spectrometry (VG54-30, Isoprobe-T) analyses were performed at the Korea Basic Science Institute following Cheong *et al*. (2013). Sr and Nd isotope ratios were normalized to $^{86}Sr/^{88}Sr = 0.1194$ and $^{146}Nd/^{144}Nd = 0.7219$, respectively. Analysis of the Sr standard NBS 987 and the Nd standard JNdi-1 resulted in $^{87}Sr/^{86}Sr = 0.710246 \pm 3$ (2SD, n = 10) and $^{143}Nd/^{144}Nd = 0.512115 \pm 6$ (2SD, n = 10). For convenience, the εNd parameter was calculated using a $^{143}Nd/^{144}Nd$ value of 0.512638 for the Chondritic Uniform Reservoir ($\varepsilon Nd = [(^{143}Nd/^{144}Nd)/0.512638-1] \times 10^4$) (Hamilton *et al*., 1983).

4. Results

Core 11YS-PCL14 could be divided mainly into four units considering downcore patterns especially mean grain size and clay mineral compositions (Figs. 2 and 3): Unit 4 (700–520 cm; 15.5–14.8 ka), Unit 3 (520–310 cm; 14.8–12.8 ka), Unit 2 (310–

130 cm; 12.8–8.8 ka), and Unit 1 (130–0 cm; < 8.8 ka). In addition, Unit 2 could be subdivided into Unit 2-2 (310–210 cm; 12.8–10.5 ka), Unit 2-1 (210–130 cm; 10.5–8.8 ka) based on the variation trends of clay mineral compositions, especially smectite content. The content of smectite increases slightly during the deposition of Unit 2-2 but tends to decrease in Unit 2-1 (Fig. 3). Wang *et al*. (2014) reported that the CYSM mud blanket becomes thicker going westward based on a seismic profile. The mud layers in core sediments are thinner than expected from the seismic profile, but the trend is consistent (Fig. 2). Core EZ06-2, located east of 11YS-PCL14, contains a 100-cm-thick mud layer, while YSC-1, to the west, has a 375-cm-thick layer (Fig. 2). The lower part of the mud layer is known as the transgressive deposit and contains many sands (Fig. 2). This coarse layer appears in all cores in the CYSM, with a boundary of ~10 ka (Li *et al*., 2014a; Lim *et al*., 2015). However, core 11YS-PCL14 has additional mud layers with a high proportion of silt underneath the transgressive deposit and a coarse layer at the bottom. Therefore, core 11YS-PCL14 provides more records of the CYSM since the LGM which could not be reconstructed in previous cores (Li et al., 2014a; Lim et al., 2015), because the core 11YS-PCL14 not only recovered deeper than other studied cores.

The vertical granularity, clay mineralogical, and geochemical characteristics of core 11YS-PCL14 are plotted against the calibrated age on the *y*-axis in Fig. 3. The four clay minerals were dominated by illite (60.1–74.7%), followed by chlorite (12.0–22.6%), kaolinite (9.6–14.8%), and smectite (1.2–6.8%). The $^{87}Sr/^{86}Sr$ ratios ranged from 0.719 to 0.724 (mean 0.721) and the εNd values from −16.2 to −12.3 (mean −14.0).

Tables 2 and 3 list the detailed characteristics of the clay minerals and geochemistry in each unit and their main potential provenances (the Huanghe, Changjiang, and western Korean rivers). Each unit had distinct dissimilarities in clay mineral content and mean grain size, especially the sand content (Fig. 2). The Unit 2 sediments were 1.8–44.2% (mean 17.6%) sand with a mean grain size of 6.6 ϕ (10.3 μm) and Unit 4 sediments had a high sand content (8–58.7%, mean 26.3%) with a mean grain size of 6.0 Φ (15.6 μm). In comparison, Unit 1 contained only fine sediment with a mean grain size of 8.8 Φ (2.2 μm) and Unit 3 sediments were clayey silt with a mean grain size of 7.3 Φ (6.3 μm). The downcore variation in the clay mineral composition showed that the illite content decreased gradually from Unit 2 to 3 and was constant in the other parts of the core. Overall, the variations in the smectite and kaolinite+chlorite contents were opposite that of illite (Fig. 3). Units 3 and 4 had relatively constant compositions in terms of clay minerals, although their granularity was heterogeneous. The $^{87}Sr/^{86}Sr$ ratio was constant at the bottom and tended to increase in the upper part. The εNd value was low in Units 2 and 4. ΣLREE/ΣHREE was low only in Unit 3, and was mostly constant.

5. Discussion

5.1. Provenance discrimination based on clay mineralogy

Relative clay mineral contents and ratios can be used as powerful proxies for determining fine-grained marine sediment provenance, especially in terms of the rivers from China and Korea that may contribute to CYSM (Yang *et al*., 2003; Choi *et al*., 2010; Li *et al*., 2014a; Xu *et al*., 2014; Lim *et al*., 2015; Kwak *et al*., 2016). Generally, Huanghe sediments are characterized by high smectite, and Changjiang sediments contain a lot of illite contents. Western Korean rivers (e.g. the Han, Keum, and Yeongsan) contain more kaolinite and chlorite than do Chinese rivers (Table 2).

A ternary diagram of smectite–(kaolinite+chlorite)–illite is utilized to determine the provenance of fine sediments in core 11YS-PCL14 (Fig. 4). Although Unit 4 and 3 sediments differed in granularity, they had similar clay mineral compositions and plotted near the center of the three possible provenance end-members, indicating that fine-grained sediments were supplied with constant amounts from all potential rivers to the study area during these periods (Fig. 4a). Unit 2 sediments overall were characterized by an increasing illite content (Figs. 3 and 4b). It means that the influence of Changjiang-derived materials began to increase during this period. However, Unit 2-2 sediments displayed an increase in smectite content with illite, and then clay mineral compositions except illite decrease in Unit 2-1 (Fig. 4b). Variation of smectite content in Unit 2 appears to be closely

related to the change in coarse sediments (Figs. 3 and 4b). The relationship between smectite and coarse grains was also observed in the early Holocene sedimentary unit of core YSC-1 (Li *et al*., 2014a) and nearby core EZ06-2 between ~14.1 and ~9.0 ka (Lim *et al*., 2015). Unit 1 sediments had clay mineral compositions quite similar to those of Changjiang sediments, indicating that they might be originate mainly from the Changjiang (Fig. 4b). Consequently, clay mineralogical results suggest that the provenance of fine-grained sediments are changed according to each unit as follow; fine-grained sediments during the depositions of Unit 3 and 4 were supplied from all potential provenances, the influence of the Changjiang increased gradually during the deposition of Unit 2, Unit 1 sediments were mainly originated from the Changjiang.

5.2. Provenance discrimination based on geochemistry

Geochemical proxies for provenance discrimination in the Yellow Sea have been investigated actively and verified by several studies (*e.g.* Yang *et al*., 2002; Xu *et al*., 2009; Song and Choi, 2009; Jung *et al*., 2012; Ha *et al*., 2013; Lim *et al*., 2015; Hu *et al*., 2018; Koo *et al*., 2018). The chemical compositions of Korean and Chinese rivers differ, especially in their rare earth elements (REE) and Sr–Nd contents (Xu *et al*., 2009; Jung *et al*., 2012; Lim *et al*., 2014; Hu *et al*., 2018). The trace elements and isotopes are essentially unaltered during weathering, transport, and sedimentation, and can be a powerful tool for tracing the provenance of the terrigenous fraction of marine sediments (McLennan, 1989; Blum and Erel, 2003; Xu *et al*., 2009; Chaudhuri *et al*., 2020).

Recent studies have emphasized caution for misinterpretation of sediment provenance due to other factors which influence the geochemical composition of riverine and marine sediments such as grain size and biogenic component (Yang *et al*., 2002; Song and Choi, 2009; Lim *et al*., 2015; Hu *et al*., 2018). For example, major elements Fe and Mg as well as some trace elements have been proposed to be useful elements as provenance indicator in the Yellow Sea (Song and Choi, 2009; Koo et al., 2018), but they are closely correlated with particle size, which can lead to misinterpretation of sediment provenance (Fig. 5a). In addition, Ca has a problem based on biogenic carbonate despite the poor correlation with grain size (Fig. 5a). To complement the grain size effect, recent studies have suggested ratios of the binding of abundant elements at comparable grain sizes (*e.g.*, the La/Sc and Zr/Th ratios) (Yang *et al*., 2002; Lim *et al*., 2014). However, we observed that these ratios and mean grain size were strongly negatively correlated in our dataset (Fig. 5b), implying that these ratios are also unsuitable for studying provenance. Normalization of REE values to upper continental crust (UCC) is a widely accepted method for discriminating the sediment provenances of various geological materials (Taylor and McLennan, 1985; Song and Choi, 2009; Xu et al., 2009; Lim *et al*., 2015). This method can better offset differences caused by grain size, and could be a useful geochemical proxy (Fig. 5c). In addition, the Nd isotope ratio of silicate particles is essentially unaltered during weathering, transport, and sedimentation and can be a powerful tool for tracing the provenance of the terrigenous fraction of marine sediments (Blum and Erel, 2003; Hu *et al*., 2018). However, recent studies indicated that the Sr isotope composition in both Chinese and Korean riverine sediments was a function of grain size, with a higher $^{87}Sr/^{86}Sr$ in clay-dominated fractions than in silt-dominated fractions (Fig. 5d) (Hu *et al*., 2018). For these reasons, we used only the UCC-normalized REE and Nd isotope, independent of grain size effect, to distinguish sediment provenance.

Korean rivers are characterized by a high LREE and low εNd, while Chinese rivers have abundant MREE (middle REE) and high εNd (Table 3, Fig. 6). Figs. 6 are discrimination plots using the REE and εNd values that clearly separate the Chinese and Korean rivers. The REE and εNd values in these plots could represent the source of all sediments including coarse and fine sediments because the REE analysis performed using the bulk powder samples. Unit 1 sediments are generally close to the Changjiang, which is consistent with results in clay mineralogy (Figs. 4 and 6). Unit 4 sediments are plotted between China and Korean river end-members in all discrimination plots (Fig. 6), consistent with the results for clay minerals, which suggests that the coarse sediments included in Unit 4 were from contributions from all potential rivers.

Interestingly, the fine-grained sediments of Unit 2 were a composite of the Huanghe and Changjiang in Fig. 4, but the geochemical data were similar to Unit 4 (Fig. 6). This probably means that a significant amount of coarse sediments in Unit 2 was supplied from Korean rivers with a high LREE (Fig. 6a). The results of the isotope analysis in the core YSC-1 also showed an increased impact of Korean rivers and coarse sediments before ~8 ka, which is consistent with our results (Hu *et al*., 2018). Thus, the supply of smectite in fine-grained sediments and sand grains is synchronic, but possibly has different sources. In addition, Unit 3 sediments, identified as the homogenous origin as Unit 4 in clay mineralogy (Fig. 4), are biased towards Chinese rivers (Fig. 6), especially close to the Huanghe. A scatter plot of clay mineral ratio *vs*. εNd distinguished three possible provenances for particles smaller than 63 μm (Fig. 6c). Unit 3 sediments in this plot are certainly plotted close to the Huanghe, which is different distribution than previous plots.

This result is likely to be due to the influence of silt-sized particles that is not considered in clay mineralogy, because Unit 3 sediments contain much of silt content (Fig. 2). Therefore, fine-grained sediments were supplied from all rivers to the study area, but coarse-grained sediments appear to have been mainly sourced from the Huanghe during the deposition of Unit 3 (Figs. 4 and 6). Consequently, the estimated sediment provenances in each unit based on the clay mineralogical and geochemical indices were as follows. During the deposition of Unit 4, both coarse and fine sediments were influenced by all of these provenances. However, in Unit 3, silt-sized fractions were predominantly affected by the Huanghe. Unit 2 represented a period of great change in the sediment sources. The fine grains in the Unit 2-2 sediments were derived primarily from Chinese rivers, especially the Huanghe, while the Unit 2-1 samples were supplied mainly from the Changjiang, with minor contributions from the Huanghe and western Korean rivers. However, coarse sediments source in Unit 2 were identified as western Korean rivers based on geochemical indices. The source of CYSM sediments in Unit 1 was primarily the Changjiang.

5.3. Paleo-environmental implications for sediment provenance changes

The four units could be distinguished based on the characterization of the major sediment source changes in the CYSM over the last 15.5 kyr (Figs. 4–6). Identification of sediment sources is a useful method for understanding paleo-environmental dynamics and sediment transport mechanisms in the Yellow Sea since the late last deglaciation. The main factors that potentially influenced provenance changes in the Yellow Sea include pronounced sea-level fluctuations that regulate the positions of shorelines, paleo-river pathways, tidal stress amplitude, and the formation of modern ocean currents (Liu *et al*., 2004; Lim *et al*, 2007, 2015; Choi *et al*., 2010; Wang *et al*., 2014; Yoo *et al*., 2015, 2016). Here, we discuss how these complex processes have affected sedimentation in the CYSM during the last 15.5 kyr.

The sea level during the depositions of Units 3 and 4, which corresponds to the late last deglaciation (15.5–12.8 ka), was approximately 60–100 m lower than the present sea level (Li *et al*., 2014b). The high signatures of C/N values in Unit 4 indicated a significant influx of terrigenous materials (Badejo *et al*., 2016). Mixed deposits of fine and coarse sediments with high influx and sedimentation rates (Figs. 2 and 3) allows us to infer Unit 4 as a delta or prodelta environment. The paleo-river pathways of potential provenances, recently reconstructed based on seismic profiles, merged around the study area and were connected to the East China Sea (Yoo *et al*., 2015, 2016). During sedimentation of Unit 4, sediments in the study area would have been affected most strongly by direct inflow from paleo-rivers, because the low sea level led to the exposure of shelves in and near the Yellow Sea (Li *et al*., 2014b).

Sediment fining during the deposition of Unit 3 reflects an increase in distance between the river mouths and study area due to transgression, and the study area probably formed a mud flat during sedimentation of Unit 3. During this period, fine-grain sediments were supplied from all rivers (Fig. 4), while silt-sized particles were supplied mainly from the Huanghe (Figs. 4 and 6). The record for the same period in core EZ06-1 shows significant coarse sediments with a high sand content (Lim *et al*., 2015), indicating that the Huanghe was relatively close to the west side of the study area (Fig. 2). In addition, the substantial flux from the Huanghe would have supported the distant movement of coarse grains.

In Unit 2 (12.8~~1~~–8.8 ka), corresponding to the early Holocene, the sea level was approximately 20−60 m lower than at present (Li *et al*., 2014b). The Unit 2 period was thought to be cold and dry (Badejo *et al*., 2016) and was characterized by oscillating grain sizes and clay mineral and geochemical compositions (Fig. 3). In addition, increasing and decreasing trends of grain size with sand content, S/I ratio divided into two subsections (Fig. 3). This variation is also reported in the surrounding YSC-1 (Li *et al*., 2014a) EZ06-1, and EZ06-2 cores. In this period, the low sea level led to the seaward progradation of the shoreline and formation of a thin sand layer (generally < 3 m) called the transgressive deposit throughout the Yellow Sea (Cummings *et al*., 2016). The change in the coastline configuration caused shifts of the tidal fields therein, with tidal currents being more energetic than at present (Uehara and Saito, 2003; Lim *et al*., 2015), which supplied coarse grains to the central Yellow Sea. In addition, the bottom stress in the Unit 2 period was stronger around the Korean Peninsula (Uehara and Saito, 2003), which caused most of the coarse sediment to be of western Korean river origin (Fig. 6). The supply of fine sediments from the Huanghe was temporarily strengthened during sedimentation of Unit 2-2, but weakened in Unit 2-1 (Fig. 4). This could be due to a change in distance between the Huanghe and the study area as the sea level rose. In addition, the paleo-Changjiang Shoal moved northeastward into the Yellow Sea at ~12 ka (Li *et al*., 2000) and may have contributed some materials to the study area (Lim *et al*., 2015). The reduction in Huanghe-derived materials due to the increased distance could be strengthen the influence of the Changjiang in Unit 2-1.

Since sedimentation of Unit 1 (< 8.8 ka), the sea level rose slowly from −20 m to the present level (Li *et al*., 2014b). The tidal field of the Yellow Sea became similar to that of the present (Uehara and Saito, 2003), leading to obviously decreasing contributions from sea bed erosion. A modern-type circulation in the Yellow Sea may have developed between 8.47 and 6.63 ka, characterized by an increase in bottom-water salinity (Kim and Kucera, 2000). The clay minerals and geochemical composition generally point to the Changjiang, with minor influence from the western Korean rivers (Figs. 4 and 6), which is consistent with the reported 'multiple origin' concept (Wei *et al*., 2003; Li *et al*., 2014a; Lim *et al*., 2015; Koo *et al*., 2018). Therefore, the formation of the CYSM and modern ocean circulation could have been synchronic around ~8 ka. The timing of mud patch formation in the central Yellow Sea was inferred to be 9~8 ka with low tidal bottom stress (< 0.35 N/m^2) (Uehara and Saito, 2003), which is consistent with our results.

The YSWC played a major role in the unique passage of sediment into the study area since the Unit 1 (Li *et al*., 2014a; Lim *et al*., 2015; Koo *et al*., 2018). The Changjiang Diluted Water can spread some finer sediments to Cheju and nearby areas (Hwang *et al*., 2014; Li *et al*., 2014a; Lim *et al*., 2015; Kwak *et al*., 2016; Koo *et al*., 2018). And then, fine-grained materials could be carried northward along the YSWC path to the CYSM, where the weak tidal-current system and cyclonic eddies provided favorable environment for the formation and maintenance of muddy sediment (Shi *et al*., 2003; Lim *et al*., 2015). Meanwhile, barrier effect of oceanic fronts and strong coastal currents restricts to enter the sediments from the Huanghe and western Korean rivers into the CYSM (Li *et al*., 2014a; Koo *et al*., 2018). However, some fine-grained particles from western Korean rivers may influence the CYSM through the Transversal Current (Hwang *et al*., 2014; Koo *et al*., 2018).

6. Conclusions

The purpose of this study was to better understand the CYSM in terms of provenance changes and transport mechanisms and to reconstruct the paleo-environment of the Yellow Sea since late last deglaciation using clay mineralogy and geochemical indices from core 11YS-PCL14. The major conclusions are as follows.

Core 11YS-PCL14 provides a continuous record of the late last deglaciation to Holocene in the CYSM. The core could be divided mainly into four units: Unit 4 (700–520 cm; 15.5–14.8 ka), Unit 3 (520–310 cm; 14.8–12.8 ka), Unit 2 (310–130 cm; 12.8–8.8 ka), and Unit 1 (130–0 cm; < 8.8 ka). Unit 2 is divided into two subunits Unit 2-2 (310–210 cm; 12.8–10.5 ka), Unit 2-1 (210–130 cm; 10.5–8.8 ka) according to smectite content.

The integration of clay mineralogical and geochemical data distinguished the CYSM sediments into different provenances by grain size. During the deposition of Unit 4, fine and coarse sediments were supplied from all possible rivers in the Korea and China by direct inflow from paleo-rivers with the exposure of shelves. Sediment fining in the Unit 3 reflects an increase in distance between the river mouths and study area. In this period, Fine-grain sediments were still supplied from all rivers, while silt-sized particles were supplied mainly from the Huanghe. During the deposition of Unit 2, the bottom stress was stronger around the Korean Peninsula, which caused most of the coarse sediment to be of western Korean river origin. However, the supply of fine sediments from the Huanghe temporarily strengthened in the Unit 2-2, but weakened in Unit 2-1, due to a change in distance between the Huanghe and the study area as the sea level rose. Unit 1 sediments were composed mainly of the Changjiang. After the oceanic circulation was formed, the YSWC played a major role in the unique passage of sediment into the study area. In addition, barrier effect of oceanic fronts and strong coastal currents restricts to enter the sediments from the Huanghe and western Korean rivers into the study area.

Author contribution

H.G.Cho designed the experiment, and H.J. Koo carried them out and wrote the paper. Both the authors contributed to interpreting and discussing the results and reviewing the paper.

Competing interests

The authors declare that they have no conflict of interest

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Table 1. Representative accelerator mass spectrometer radiocarbon age data for core PCL14 from Badejo et al. (2016). OM = organic matter, Cali. Age = calibrated age.

Core	Depth (cm)	Sample type	^{14}C age (yr BP)	Cali. age (cal.yr.BP) ± 95% probability
11 YS PCL 14	90	OM	7,160 ± 40	8,040 ± 90
	300	Shell	10,360 ±40	12,630 ± 190
	540	Shell	12,400 ±50	15,030 ± 290
	580	Shell	12,530 ±50	15,160 ± 210
	698	Shell	12,720 ±50	15,430 ± 250

465

Table 2. Average compositions of clay minerals in core PCL14 sediments and their potential provenance rivers.

Samples	*n*	Illite (%)	Chlorite (%)	Kaolinite (%)	Smectite (%)	Reference
PCL14_Unit 1	9	69.0 ± 1.6	18.2 ± 1.3	10.9 ± 0.6	1.8 ± 0.4	This study
PCL14_Unit 2	16	67.0 ± 3.0	16.5 ± 2.3	12.1 ± 1.2	4.5 ± 1.1	
PCL14_Unit 3	24	63.0 ± 1.1	19.7 ± 1.0	13.7 ± 0.6	3.6 ± 0.5	
PCL14_Unit 4	18	63.2 ± 1.4	20.0 ± 1.3	13.0 ± 0.7	3.8 ± 0.7	
Changjiang	9	68.1	17.0	13.3	1.6	Koo et al. (2018)
	8	66	12	16	6	Yang et al. (2003)
	-	61.7	24.5	9.8	3.9	Choi et al. (2010)
Huanghe	13	62.2	15.8	13.1	8.9	Koo et al. (2018)
	4	56.7	17.7	14.1	11.5	Cho et al. (2015)
	8	62	16	10	12	Yang et al. (2003)
Western Korean rivers (Han / Keum / Yeongsan)	14/9/3	59.5	21.3	17.4	1.8	Cho et al. (2015)
	45	52	44		4	Lim et al. (2015)

Table 3. Isotopic and geochemical data of core PCL14 and riverine samples.

Samples	$^{87}Sr/^{86}Sr$ ($\pm 2\sigma \times 10^{6}$)	$^{143}Nd/^{144}Nd$ ($\pm 2\sigma \times 10^{6}$)	εNd	(La/Yb)ucc	(La/Lu)ucc	ΣLREE/ΣHREE	ΣLREE/Yb
PCL14-2 (47 cm)	0.722591 (14)	0.511999 (4)	-12.5	1.09	1.08	4.07	63.1
PCL14-4 (67 cm)	0.723603 (11)	0.511988 (5)	-12.7	1.18	1.11	4.09	68.1
PCL14-8 (107 cm)	0.720661 (11)	0.511971 (4)	-13.0	1.18	1.14	4.2	68.1
PCL14-11 (137 cm)	0.723536 (17)	0.511880 (3)	-14.8	1.2	1.15	4.18	70.5
PCL14-17 (197 cm)	0.719741 (11)	0.511860 (3)	-15.2	1.2	1.09	4.21	69.5
PCL14-25 (277 cm)	0.719819 (14)	0.511908 (3)	-14.2	1.15	1.07	4.06	65.8
PCL14-30 (327 cm)	0.718528 (27)	0.512010 (3)	-12.3	1.01	0.99	3.64	58.5
PCL14-37 (397 cm)	0.720141 (7)	0.511980 (4)	-12.8	1.12	1.04	3.75	64.8
PCL14-42 (447 cm)	0.720495 (50)	0.511965 (7)	-13.1	1.07	1.01	3.77	62.7
PCL14-54 (567 cm)	0.720030 (8)	0.511883 (6)	-14.7	1.17	1.10	4.09	67.5
PCL14-60 (627 cm)	0.720886 (8)	0.511808 (10)	-16.2	1.12	1.04	3.96	65.1
PCL14-67 (697 cm)	0.719559 (8)	0.511817 (5)	-16.0	1.19	1.18	4.09	67.4
Huanghe	0.717596 (9)	0.512073 (5)	-11.0				
	0.717260 (10)	0.512063 (4)	-11.2				
Changjiang	0.722954 (8)	0.511999 (6)	-12.5				
	0.726349 (7)	0.512018 (5)	-12.1				
Keum River	0.724526 (6)	0.511609 (4)	-20.1				
	0.724881 (5)	0.511700 (3)	-18.3				

Figure captions

Figure 1. Schematic map showing the location of core 11YS-PCL14 as well as the surface circulation in the Yellow Sea (modified from Li et al., 2014a; Wang et al., 2014). The gray dotted line indicate the paleo-river pathways (Yoo et al., 2016). ① Central Yellow Sea Mud (CYSM); ② Southeastern Yellow Sea Mud (SEYSM); ③ Southwestern Cheju Island Mud (SWCIM); KC = Kuroshio Current; YSWC = Yellow Sea Warm Current; SDCC = Shandong Coastal Current; YSCC = Yellow Sea Coastal Current; KCC = Korean Coastal Current; SDF = Shandong Front; JSCF = Jiangsu Coastal Front; WKCF = Western Korean Coastal Front.

Figure 2. (a) Isolines in thickness (m) of mud deposit CYSM (after Wang et al., 2014), (b) vertical lithology profile of core 11YS-PCL14 and other reference cores (YSC-1, Li et al., 2014a; EZ06-1 and EZ06-2, Lim et al., 2015).

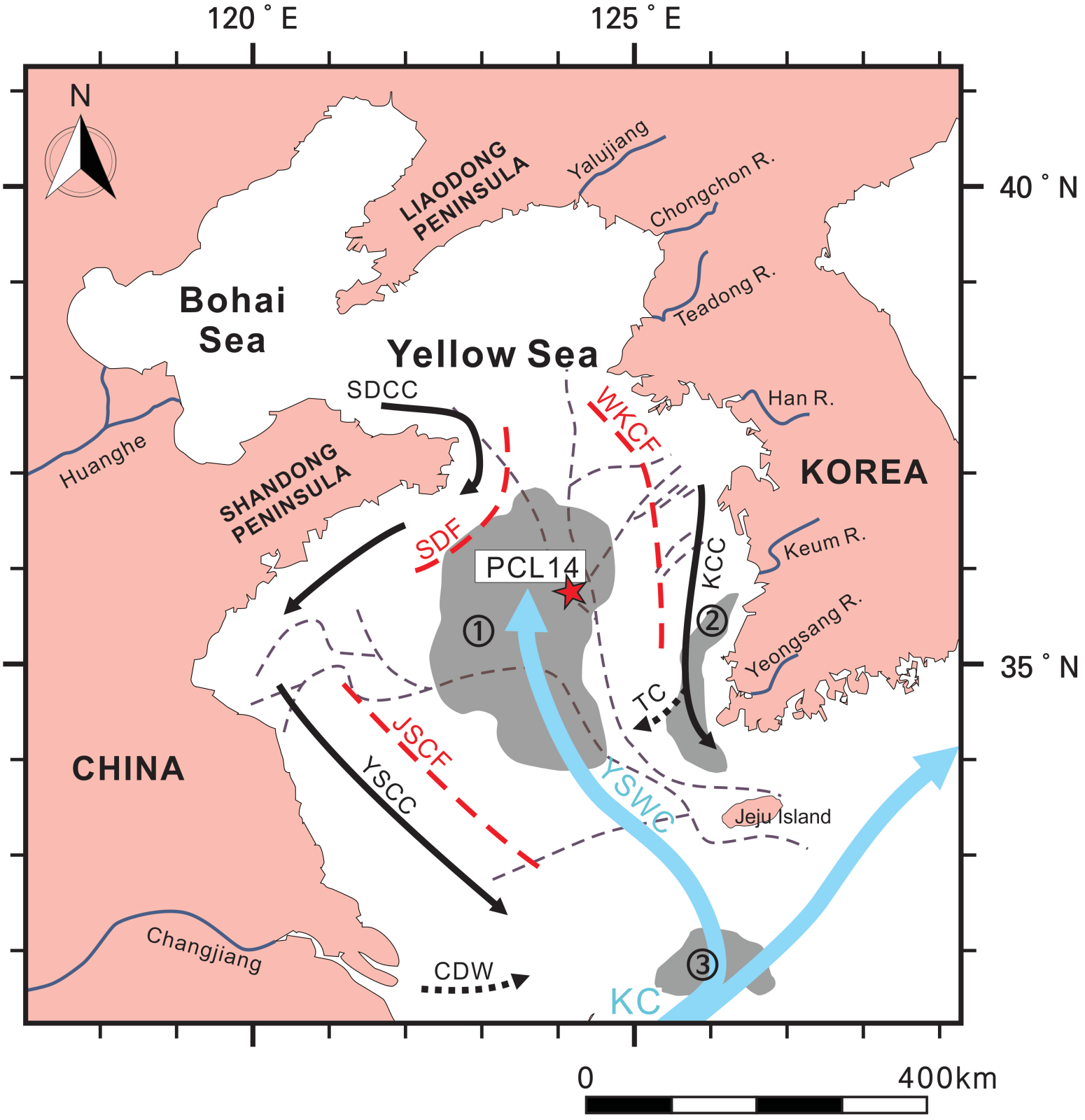
Figure 3. Downcore variations of mean grain size, clay mineralogical and geochemical data in core 11YS-PCL14 with sea level changes (Li et al., 2014b). Note the overall distribution into four units.

Figure 4. Ternary diagrams showing variations in clay mineral compositions of core 11YS-PCL14. Published data of potential source sediments including the Changjiang, Huanghe, and western Korean rivers (the Han, Keum, and Yeongsan Rivers) (Cho et al., 2015; Koo et al., 2018), which are plotted for comparison.

Figure 5. Correlation plots of grain size or clay/silt ratio with (a) major elements, (b) Zr/Th and La/Sc, (c) Upper Continental Crust (UCC)-normalized REEs (Taylor and McLennan, 1985), and (d) $^{87}Sr/^{86}Sr$ and εNd for core 11YS-PCL14.

Figure 6. Discrimination plots showing variations in (a) ∑LREE/Yb *vs*. $(La/Lu)_{UCC}$, (b) $(La/Yb)_{UCC}$ *vs*. εNd, and (c) (smectite+kaolinite+chlorite)/illte *vs*. εNd. Clay mineral (Cho et al., 2015; Koo et al., 2018), rare earth element (Xu et al., 2009), and isotope data of potential sources are also shown for comparison.

Fig. 7. Schematic diagram showing the influence of shoreline changes, and paleo-river pathways on riverine sediment supplied to the study area during (a) Unit 4 and 3 (15.5–12.8 ka), (b) Unit 2 (12.8–8.8 ka), and (c) Unit 1 (8.8 ka–present) (modified Lim et al., 2015).


120 ° E
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LIAODONG PENINSULA
Yalujiang
Chongchon R.
Teadong R.
Bohai Sea
Yellow Sea
SDCC
WKCF
Han R.
KOREA
Huanghe
SHANDONG PENINSULA
SDF
PCL14
KCC
Keum R.
Yeongsang R.
①
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TC
JSCF
YSCC
YSWC
Jeju Island
CHINA
Changjiang
CDW
③
KC
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400km

Figure 1.jpg

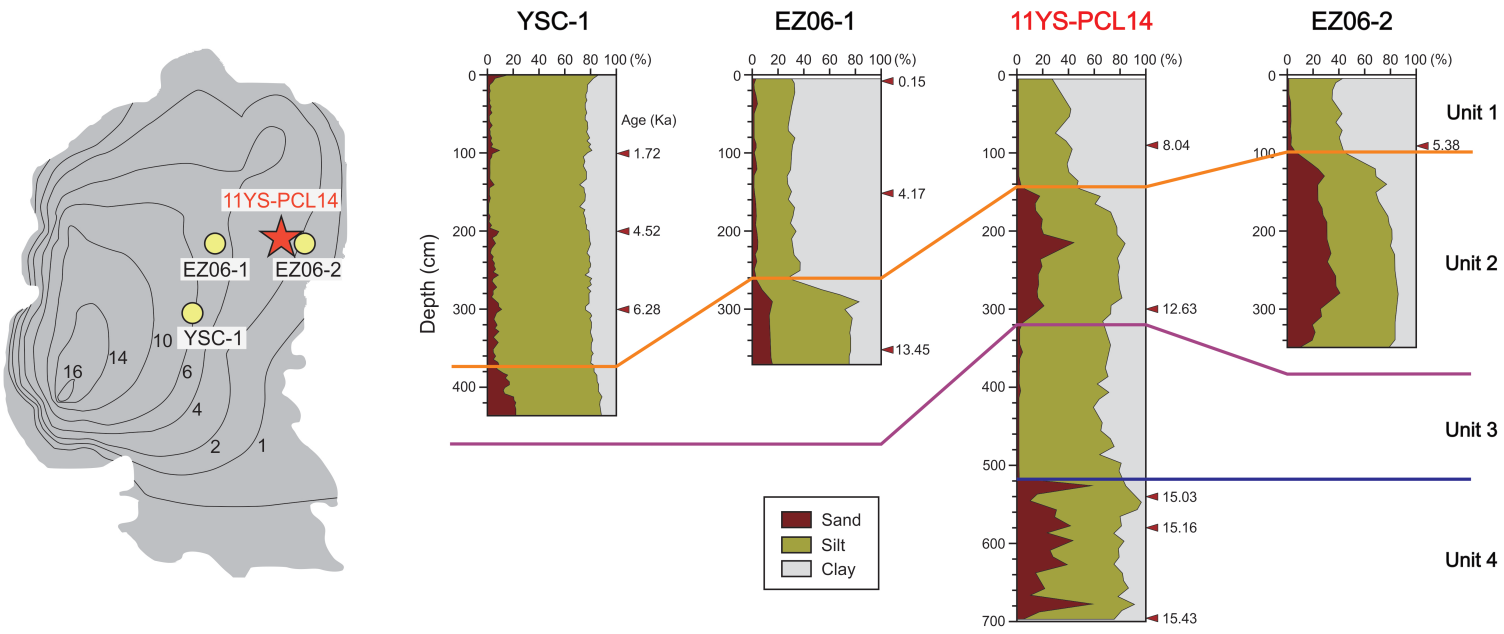
11YS-PCL14
EZ06-1
EZ06-2
YSC-1
16
14
10
6
4
2
1
YSC-1
EZ06-1
11YS-PCL14
EZ06-2
Depth (cm)
Age (Ka)
1.72
4.52
6.28
0.15
4.17
13.45
8.04
12.63
15.03
15.16
15.43
5.38
Unit 1
Unit 2
Unit 3
Unit 4
Sand
Silt
Clay

Figure 2.jpg

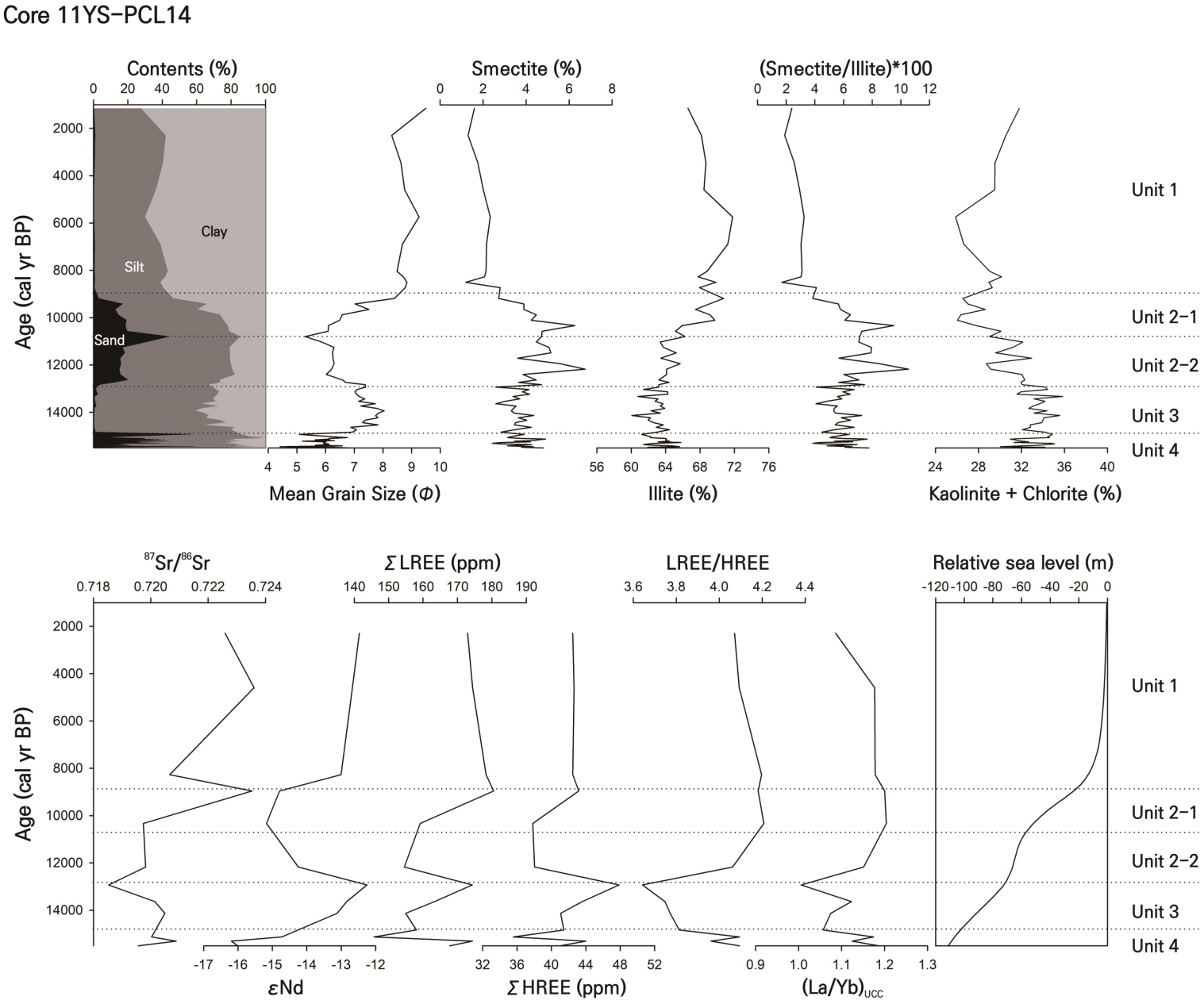
Core 11YS-PCL14
Contents (%)
Clay
Silt
Sand
Age (cal yr BP)
Mean Grain Size (Φ)
Smectite (%)
Illite (%)
(Smectite/Illite)*100
Kaolinite + Chlorite (%)
Unit 1
Unit 2-1
Unit 2-2
Unit 3
Unit 4
87Sr/86Sr
εNd
Σ LREE (ppm)
Σ HREE (ppm)
LREE/HREE
(La/Yb)UCC
Relative sea level (m)

Figure 3.jpg

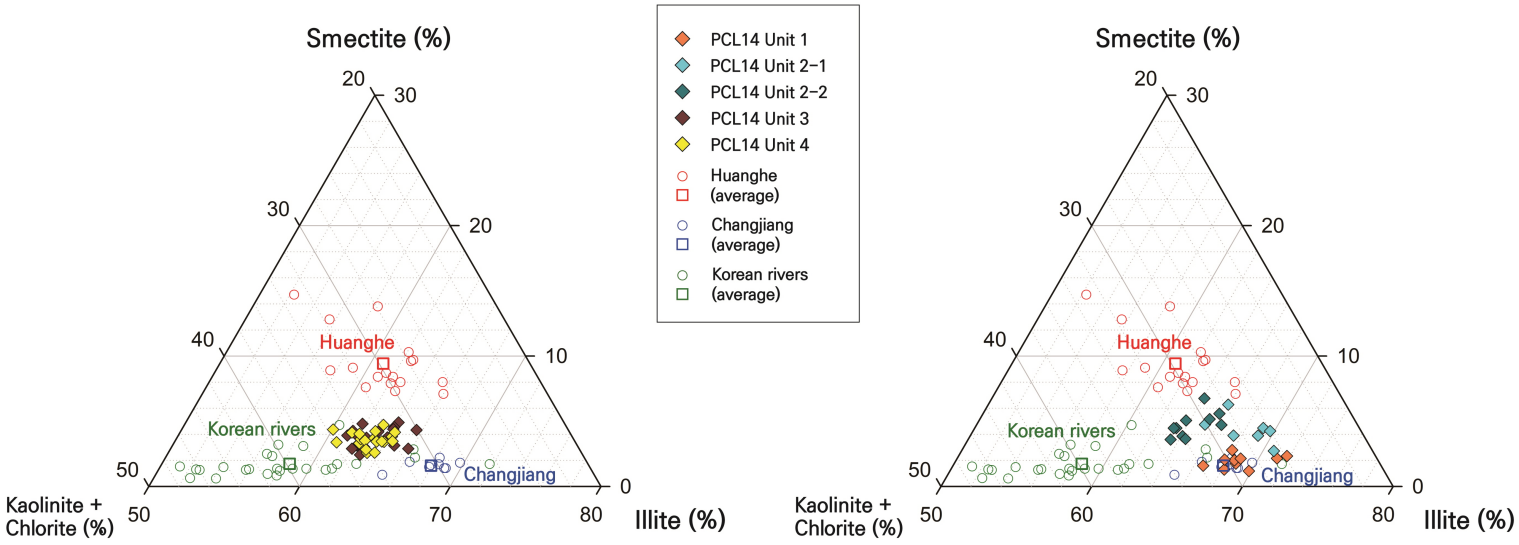
Smectite (%)
20
30
30
20
40
10
50
0
50
60
70
80
Kaolinite +
Chlorite (%)
Illite (%)
Huanghe
Korean rivers
Changjiang
PCL14 Unit 1
PCL14 Unit 2–1
PCL14 Unit 2–2
PCL14 Unit 3
PCL14 Unit 4
Huanghe
(average)
Changjiang
(average)
Korean rivers
(average)
Smectite (%)
20
30
30
20
40
10
50
0
50
60
70
80
Kaolinite +
Chlorite (%)
Illite (%)
Huanghe
Korean rivers
Changjiang

Figure 4.jpg

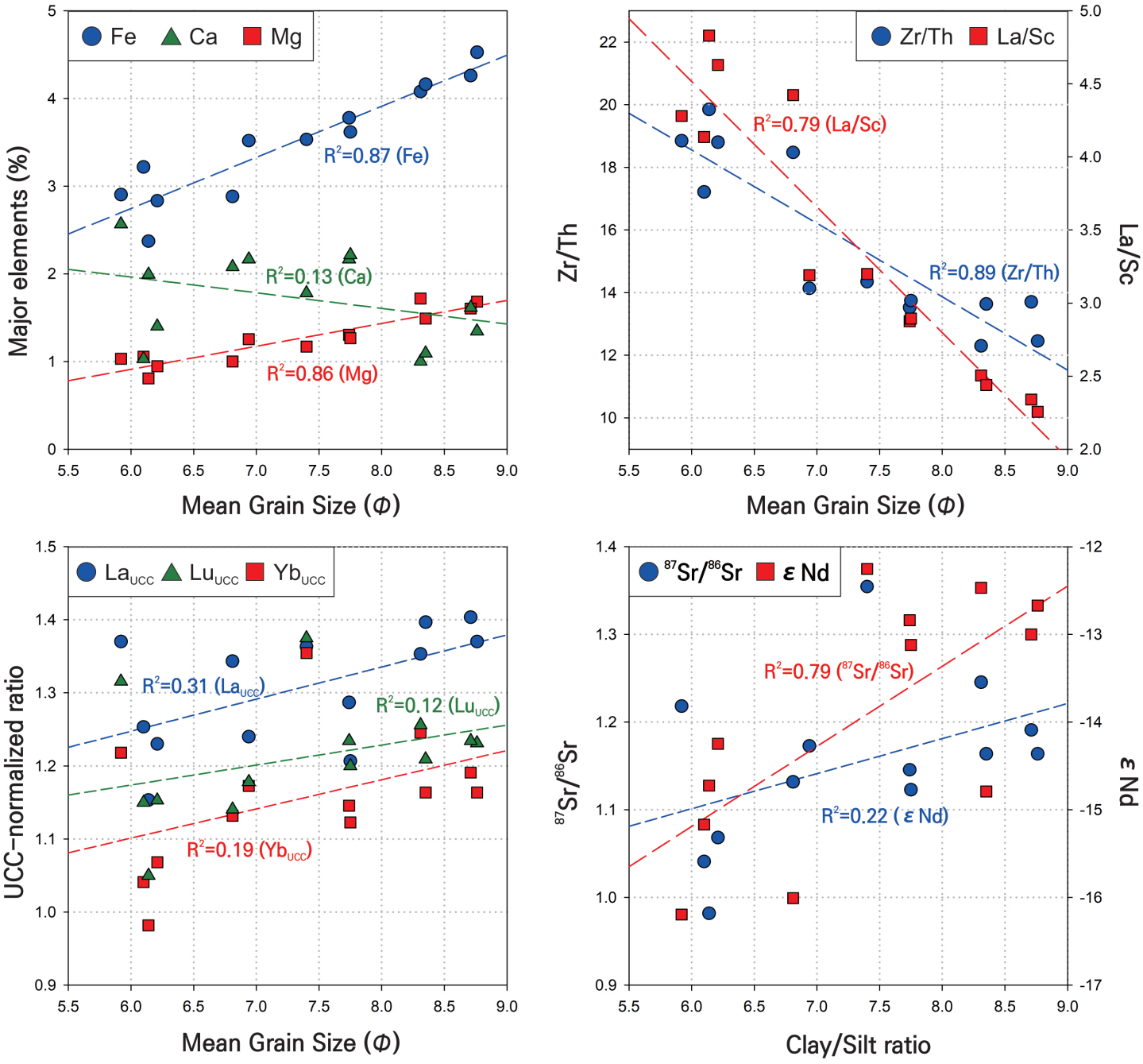
Fe
Ca
Mg
Major elements (%)
R²=0.87 (Fe)
R²=0.13 (Ca)
R²=0.86 (Mg)
Mean Grain Size (Φ)
Zr/Th
La/Sc
R²=0.79 (La/Sc)
R²=0.89 (Zr/Th)
Mean Grain Size (Φ)
La_UCC
Lu_UCC
Yb_UCC
UCC-normalized ratio
R²=0.31 (La_UCC)
R²=0.12 (Lu_UCC)
R²=0.19 (Yb_UCC)
Mean Grain Size (Φ)
87Sr/86Sr
ε Nd
R²=0.79 (87Sr/86Sr)
R²=0.22 (ε Nd)
Clay/Silt ratio

Figure 5.jpg

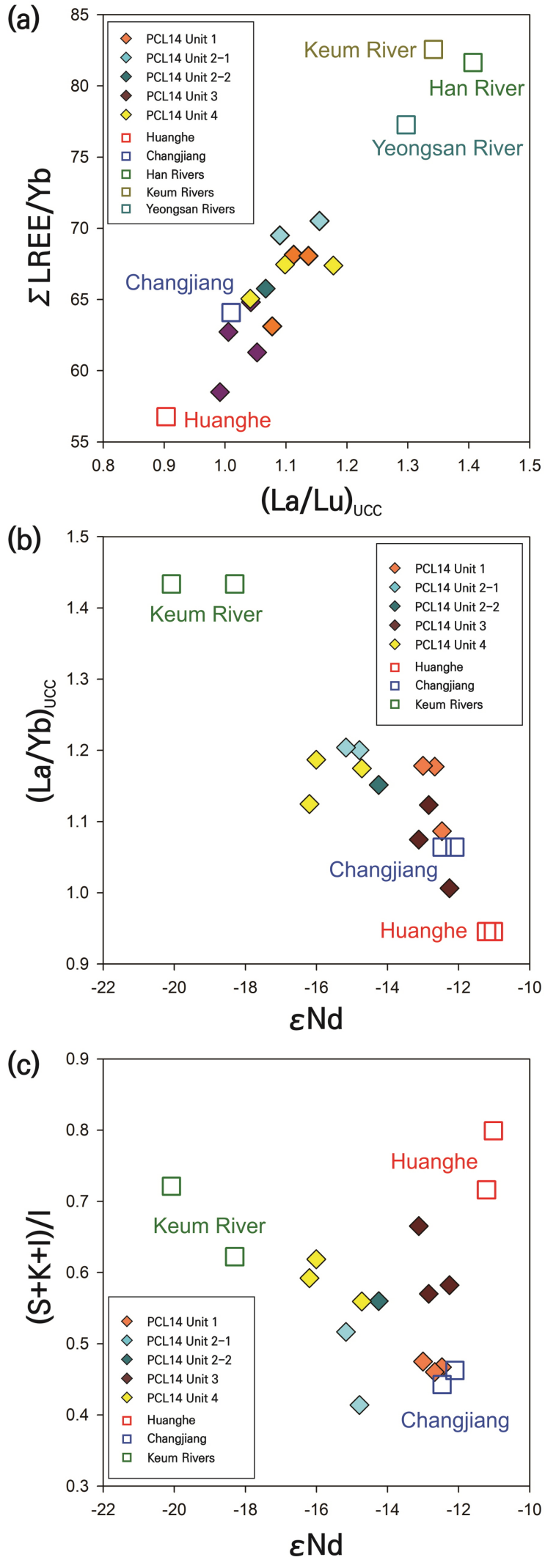
(a)
PCL14 Unit 1
PCL14 Unit 2-1
PCL14 Unit 2-2
PCL14 Unit 3
PCL14 Unit 4
Huanghe
Changjiang
Han Rivers
Keum Rivers
Yeongsan Rivers
Keum River
Han River
Yeongsan River
Changjiang
Huanghe
ΣLREE/Yb
(La/Lu)UCC
(b)
Keum River
Changjiang
Huanghe
(La/Yb)UCC
εNd
(c)
Huanghe
Keum River
Changjiang
(S+K+I)/I
εNd

Figure 6.jpg

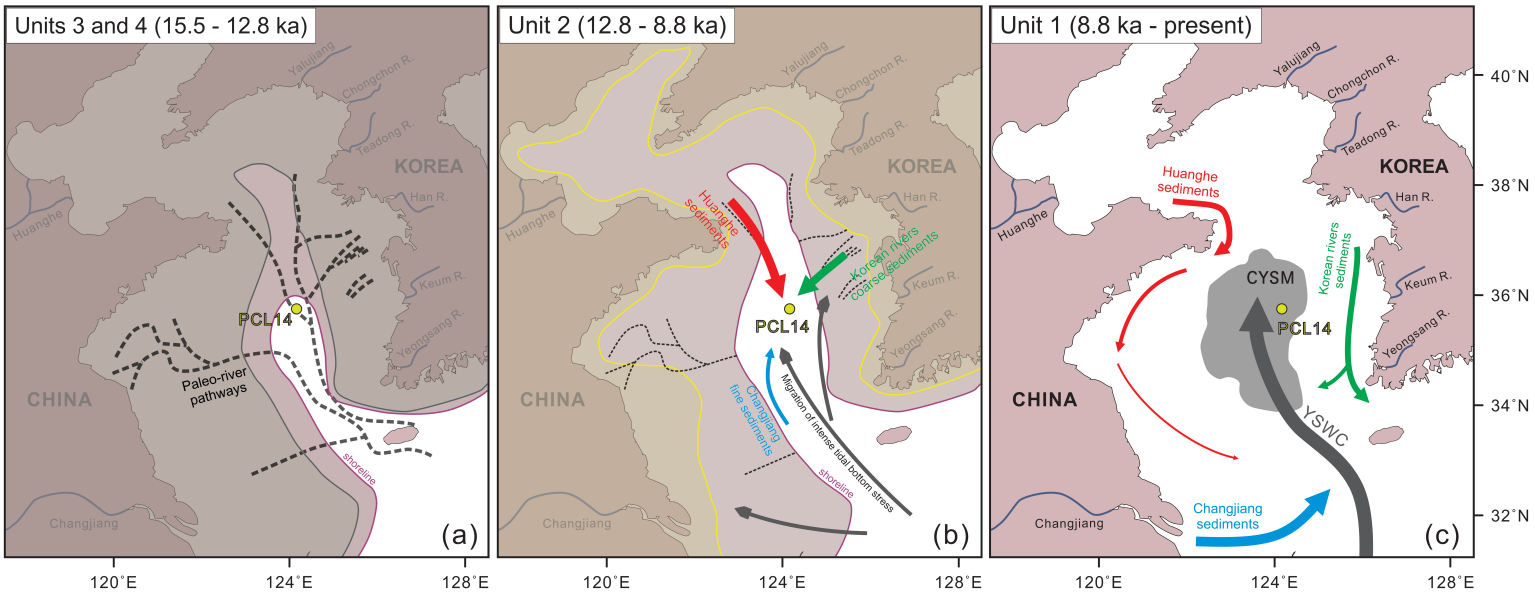
Units 3 and 4 (15.5 - 12.8 ka)
Unit 2 (12.8 - 8.8 ka)
Unit 1 (8.8 ka - present)
Yalujiang
Chongchon R.
Teadong R.
KOREA
Han R.
Huanghe
Keum R.
Yeongsang R.
PCL14
CHINA
Paleo-river pathways
shoreline
Changjiang
(a)
Huanghe sediments
Korean rivers coarse sediments
Changjiang fine sediments
Migration of intense tidal bottom stress
(b)
CYSM
Korean rivers sediments
YSWC
Changjiang sediments
(c)
40°N
38°N
36°N
34°N
32°N
120°E
124°E
128°E

Figure 7.jpg