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Freshwater supply by Korean rivers to the East Sea during the last glacial maximum: a review and new evidence from the Korea Strait region

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Abstract This study presents a review of extensive literature and reports new findings extracted from previously collected cores. Globally lowered sea level during the last glacial maximum (LGM) reduced the cross-sectional area in the Korea Strait, minimizing volume transport of the paleo-Tsushima Current and increasing freshwater input to the East Sea. The higher supply of freshwater played an important role in compositional changes of surface water in the sea, indicated by low sea surface salinity (down to about 20‰) and light δ^{18}O of planktonic Foraminifera (lighter than 1‰) recorded in core sediments. The Korean fluvial systems (Nakdong and Seomjin rivers) emptying into the southeastern sea of Korea may have contributed substantially to freshwater supply to the surface layer of the LGM East Sea, although Chinese paleo-river (Huanghe and Yangtze rivers) waters, together with the paleo-Tsushima Current, also seem to have supplied some freshwater to the sea. The higher supply of river waters to the East Sea is strongly evidenced by the high amount of terrigenous material (quartz, feldspar and rock fragments) in core sediments. In addition, high magnetic susceptibility, high grain density, and high C/N ratios were documented in cores MB98PC-11 and 95PC-1. In contrast with earlier studies, we propose that Korean rivers played a more substantial role in supplying freshwater to the East Sea during the LGM than previously thought.

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Introduction

The East Sea is a typically marginal sea which geomorphologically consists of a narrow shelf, steep slope and deep basin with a maximum depth of about 3,700 m. The sea is surrounded by the Asian continent and Japanese islands, and it is linked with the South Sea of Korea through the Korea (Tsushima) Strait, to the Pacific Ocean through the Tsugaru and Soya straits, and to the Sea of Okhotsk through the Tartarsky Strait (Fig. 1). The sill depths of all the straits in the sea are less than 140 m, which is shallower than that in, for example, the Strait of Gibraltar (about 300 m). The sea is also characterized by three topographic highs (the Korea Plateau, the Oki Bank, and the Yamato Rise) and lows (the Japan, Yamato and Ulleung basins).

Modern surface water circulation in the East Sea is dominated by the Tsushima Current, a branch of the warm Kuroshio western boundary current. The former surface current enters the East Sea through the Korea Strait which has a sill depth of about 140 m, carrying warm (26 °C in summer and 14 °C in winter) water at a rate of about $1{\sim}2{\times}10^6$ m^3 s^{-1} (Toba et al. 1982; Lim and An 1985). It exits the sea mostly through the Tsugaru and Soya straits into the Pacific Ocean. By and large, the incoming Tsushima Current counterbalances the outgoing surface currents (Toba et al. 1982; Lim and An 1985). It has been suggested that, together with the Tsushima Current, a small portion of the East China Sea coastal water intrudes into the East Sea along the southern margin of the Korea Peninsula (Suk et al. 1996).

Circulation patterns of the surface current in the late Quaternary differed from the present-day patterns due mainly to changing sea levels. In particular during the last glacial maximum (LGM) when sea level was about 130 m lower than today (e.g., Fairbanks 1989; Pirazzoli 1996), oceanographic conditions in the East Sea were presumably very different. The Tsugaru (about 130-m sill depth), Soya (55 m) and Tartarsky (15 m) straits

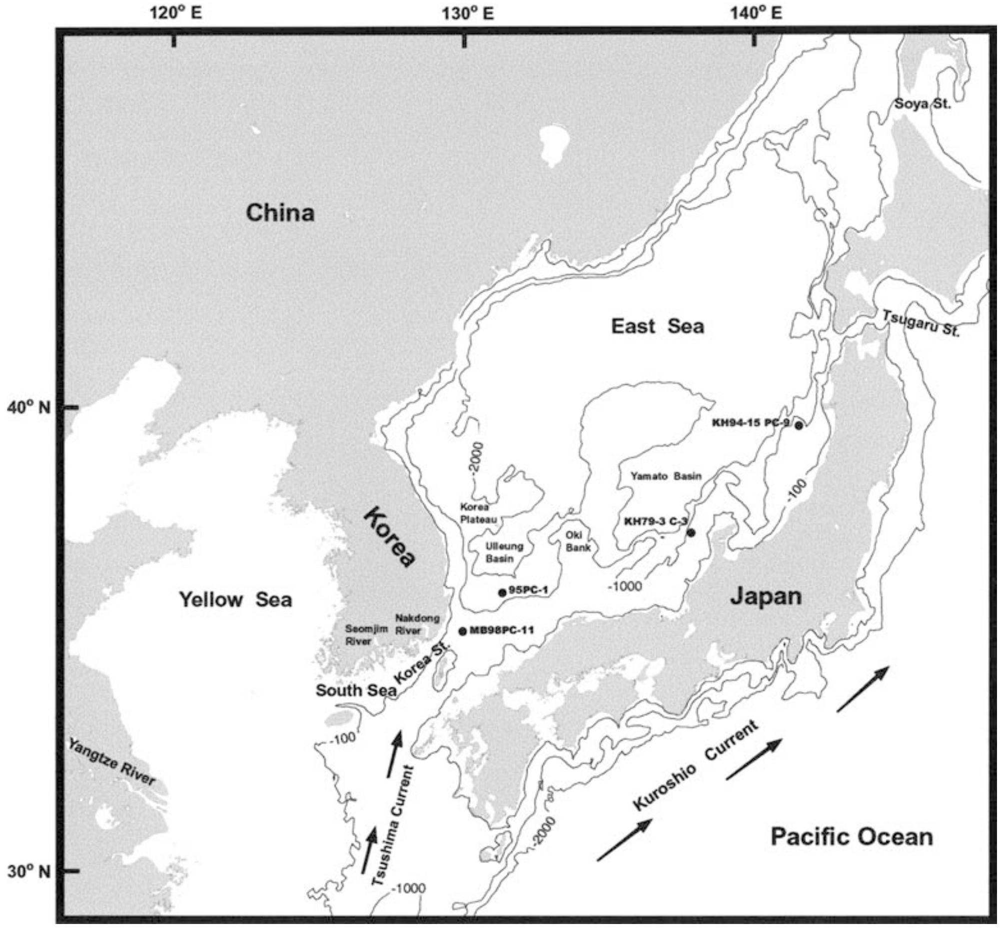


Fig. 1 Map of the study area and surrounding landmass. The Tsushima Current enters the East Sea through the Korea Strait. Water exits the sea mostly through the Tsugaru and Soya straits into the Pacific. Water depths are in meters. *Closed circles* indicate core sites

would have been closed due to the globally lowered sea level, meaning that there would have been essentially no outflow through these straits to the Pacific Ocean. In the Korea Strait region, decreased sea level would have reduced the cross-sectional area, creating a much narrower width and shallower depth in the strait, and thereby substantially diminishing volume transport. Indeed, several authors have suggested that during the LGM the East Sea was nearly isolated or even entirely closed, reflecting no Tsushima current influx to the region (Oba et al. 1991; Keigwin and Gorbarenko 1992). On the other hand, more recent studies (Morley et al. 1986; Matsui et al. 1998; Tada 1999; Park et al. 2000) proposed that the Korea Strait was open at the time. Despite the lowering of sea level, these authors suggested that the paleo-Tsushima Current continued to flow, albeit at a reduced level. Additionally, freshwater supply via the paleo-Korea Strait was raised, further affecting water properties of the East Sea. In particular, it is still not clear what the major sources for freshwater are in the region, and which rivers contribute more to freshwater supply to the East Sea—the Korean or Chinese river systems.

The main aim of the present study is to assess the relative importance of freshwater influx via major Koran river systems into the East Sea during the LGM. For this purpose, we carried out an extensive literature survey of existing information on the major freshwater sources in the region. Additionally, we present new evidence derived from published reports and monographs, based on two cores collected in 1995 and 1998 by the Korea Ocean Research and Development Institute (KORDI) in the vicinity of the Korea Strait in the southwestern sector of the East Sea.

Paleo-Tsushima water influx and precipitation

Changing sea levels have greatly regulated oceanographic conditions in the East Sea. Freshwater input to the region has been inferred during sea-level lowstands (Koizumi 1989; Oba et al. 1991; Gorbarenko 1993; Matsui et al. 1998; Tada 1999; Tada and Irino 1999). There are two possible sources of freshwater – river water and/or precipitation.

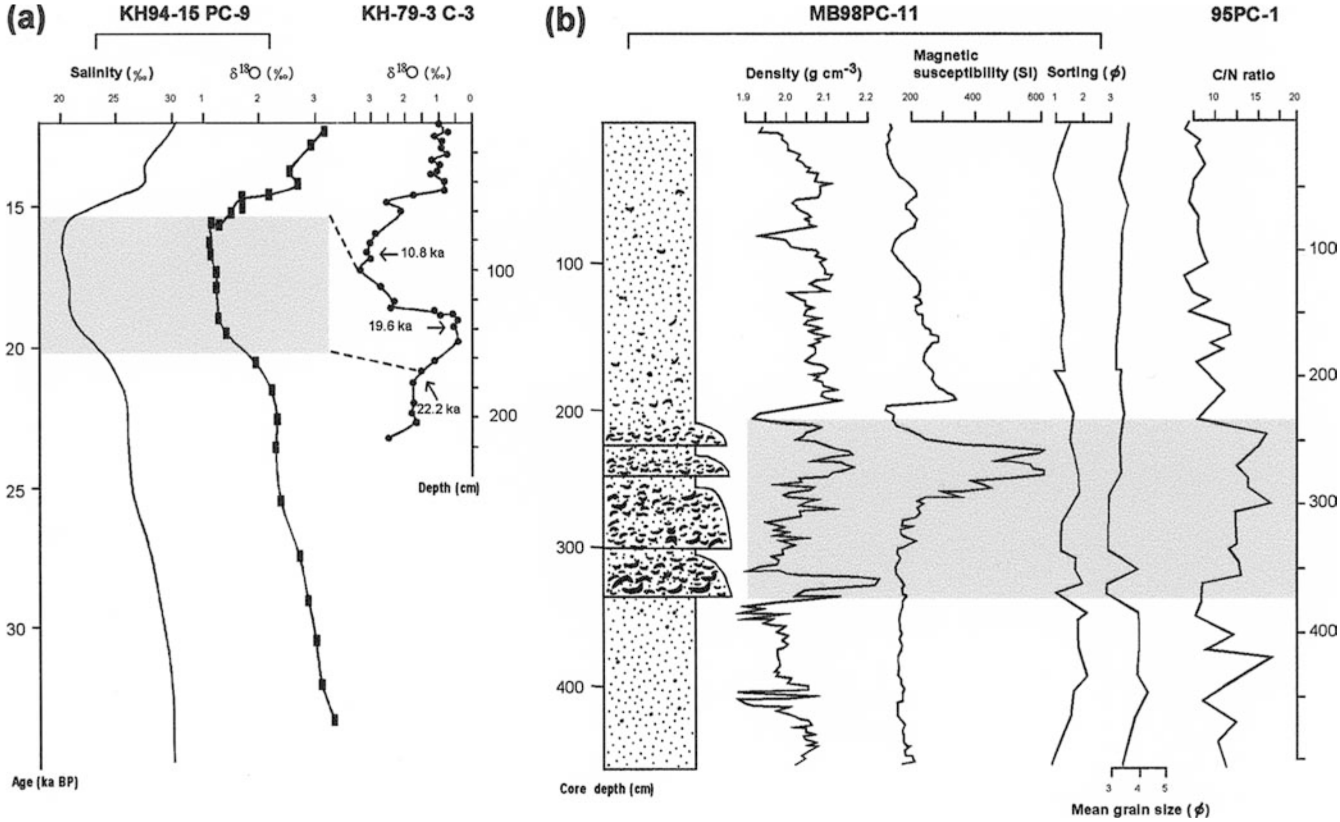
Oba et al. (1991) suggested that Huanghe (Yellow) River waters may have been introduced to the East Sea from 27 to 20 ka B.P. During the sea-level lowstand the Huanghe River mouth migrated seawards (see below), releasing freshwater in the Korea Strait region (Oba et al. 1991). On the basis of $\delta^{18}O$ signatures of planktonic Foraminifera in two cores (KH94-15-PC-9 and

KH79-3-C-3), Oba et al. (1991, 1995) inferred a lowering of surface salinity and consequent stratification of the water column, with the establishment of anoxic conditions in the deep-water areas. About 3‰ lower $\delta^{18}O_{\mathrm{p.f.}}$ values may have been triggered by the incoming water which may have been a mixture of paleo-Tsushima saline current and freshwater (Kim et al. 2000). Low salinity during the LGM, as noted in Fig. 2a, is well-correlated with the light $\delta^{18}O$ patterns of planktonic Foraminifera in the East Sea (Oba et al. 1991; Tada 1999; Gorbranko and Southon 2000). This contrasts strongly with the heavy $\delta^{18}O_{\mathrm{p.f.}}$ signal recorded generally in deep-sea cores (Shackleton 1982; Chappell and Shackleton 1986). The negative $\delta^{18}O_{\mathrm{p.f.}}$ value was interpreted as resulting from the complete isolation of the sea induced by the glacioeustatic sea-level fall (Oba et al. 1991), implying that the paleo-Tsushima Current flow would have been blocked, or more precipitation would have occurred during the LGM. Therefore, the light $\delta^{18}O_{\mathrm{p.f.}}$ record associated with lower salinity would reflect increased freshwater input through river runoff from the surrounding landmass as well as via precipitation, as proposed by Gorbarenko (1987), and Keigwin and Gorbarenko (1992).

Sea-surface temperatures were estimated to have been essentially identical in the southern and northern parts of the East Sea between 19 and 15.5 ka B.P. when global sea level was lowest (Oba et al.1991; Okumura et al. 1996). This means that surface waters may have been horizontally well-mixed during this time period, and that ocean temperature was probably not a major factor controlling planktonic oxygen isotopic composition in this case.

In contrast with the views that the East Sea was essentially closed off during the LGM, the opening of the East Sea during the last glacial lowstand of sea level was proposed by Morley et al. (1986) on the basis of the occurrence of open-sea radiolarians, that is, the sea remained open at the time. Furthermore, the warm-water diatoms and the low-salinity diatom *Paralia sulcata* were identified in core sediments (Morley et al. 1986; Park et al. 2000) from the southern East Sea, indicating inflow of both Tsushima Current and East China Sea coastal waters through the paleo-Korea Strait (Koizumi 1989; Tada 1999; Tada and Irino 1999). Presumably, freshwater discharged from the Huanghe and Yangtze rivers may have flowed through the strait into the East Sea. The lowered salinity, reflected in the $\delta^{18}O_{\mathrm{p.f.}}$ records, was interpreted to have been caused by the glacioeustatic drop in sea level and a relative reduction of Tsushima water influx (Matsui et al. 1998). Matsui

Fig. 2 a Correlation between sea surface salinity and $\delta^{18}O_{\mathrm{p.f.}}$ records, based on cores KH94-15-PC-9 and KH79-3-C-3 (Oba et al. 1991, 1995). The *shaded section* marks a period of lowered surface salinity when sea level was the lowest, further indicating an enhanced influx of freshwater to the East Sea. **b** Association between the coarse-grained layer, higher grain density (g cm^{-3}) and higher magnetic susceptibility (SI) in core MB98PC-11 (adapted from KORDI 1999), and higher C/N ratios in core 95PC-1 (Hyun et al. 2001). This reflects an increased supply of terrigenous material during the LGM in the East Sea



et al. (1998) emphasized the relatively high supply of freshwater to the East Sea, compared with the smaller contribution of seawater to the region. These authors suggested that the paleo-Tsushima connection remained uninterrupted, occurring through a channel-like strait which was estimated to have a sill depth of only 20 ± 10 m during the LGM (Tada 1995; Matsui et al. 1998).

Precipitation is another source for freshwater, and it was suggested to explain low salinity in the East Sea during the LGM (Tada 1999; Keigwin and Gorbarenko 1992; Gorbarenko and Southon 2000). In general, evaporation exceeds precipitation in the world's oceans, although there are considerable variations from one region to another (Berner and Berner 1987; Pickard and Emery 1988). Presumably, this pattern is maintained in both the glacial and interglacial times. According to simulated modeling results, evaporation in the East Sea region during the LGM may have exceeded precipitation (Rind and Peteet 1985; Crowley and North 1991). This argues against precipitation having been a critical factor directly controlling sea-surface salinity in the LGM East Sea, although there was no single source for freshwater supply to the sea (Keigwin and Gorbarenko 1992). All in all, therefore, the evidence strongly suggests that the paleo-water passing through the Korea Strait was a mixture of warm, saline Tsushima Current water and freshwater derived from Chinese rivers (Huanghe and Yangtze).

Relative contribution of Korean and Chinese river systems

Assuming that the East Sea was cut off during the last glacial maximum, no seawater nor fresh water could have flowed into the sea via the Yellow and East China seas. Seeing that precipitation is unlikely to have been a major, direct source of freshwater during the LGM (as discussed above), the only other source would have been riverine waters. Actually, riverine freshwater input both from the east coast of Korea and the west coast of Japan seems to have been extremely limited. It is hard to conceive that precipitation was high enough to affect oxygen isotopic composition of surface water in the LGM East Sea (as mentioned above). The only major rivers which discharge directly into the East Sea are the Nakdong and Seomjin rivers, the largest fluvial systems in Korea (Fig. 1). Thus, we propose that, if the East Sea was essentially cut off from other freshwater sources, then influx via these two rivers could largely account for signs of decreased salinity in the region.

If the East Sea was linked to the open sea during the LGM (see above), freshwater could have originated from both the Korean as well as the Chinese river systems. In this study we emphasize that the main Korean river systems (Nakdong and Seomjin rivers) made a major contribution to freshwater supply to the East Sea during the LGM, regardless of whether the sea was opened or closed. Presently, total freshwater discharges from the Nakdong and Seomjin rivers are about 6.3×10^{10} and 7.2×10^{8} m^3 $year^{-1}$, respectively (Korea Ministry of Construction 1980; Park and Chu 1991). Despite the generally drier climate during the LGM (Crowley and North 1991), it is likely that these two rivers carried substantial amounts of freshwater into the East Sea at the time.

Paleo-channels developed off the two river systems when most of the shelf was exposed during the lowstand of sea level, as evidenced by seismic refection profiles (Yoo and Park 1997, 2000; Fig. 3). The interpretation of seismic profiles collected from the strait shelf reveals that a lowstand deltaic wedge (LDW) was formed with siliciclastic sediments derived mainly from the Nakdong and Seomjin rivers when sea level was about 130 m lower than today. The LDW thins and is elongated to the northeast (Yoo and Park 1997, 2000; Park et al. 2000). Radiocarbon dates documented in the shelf sediments range from about 15 to 21 ka B.P., corresponding well with the period of lowest sea level. The channels

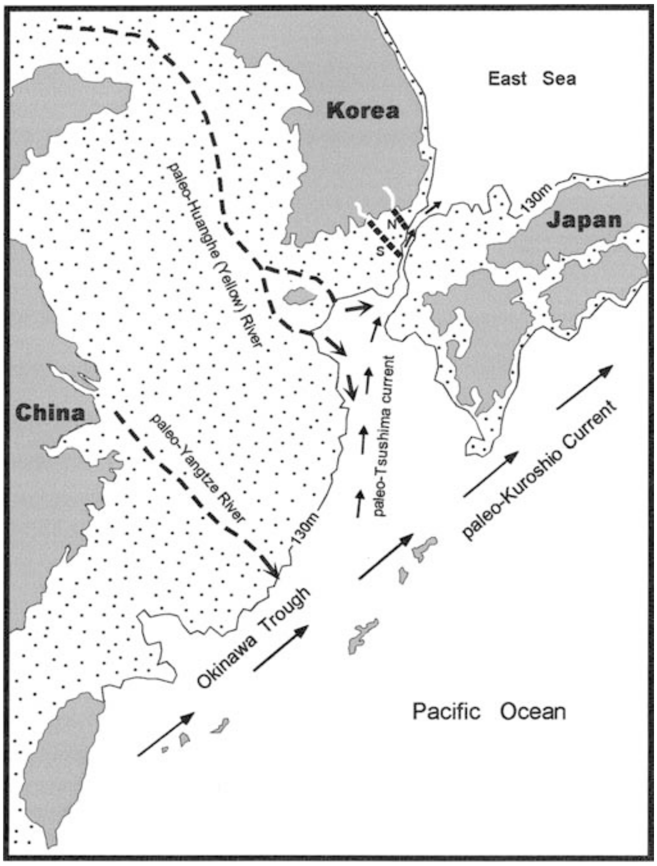


Fig. 3 The Nakdong River (*N*) and the Seomjin River (*S*), shown as thick *dotted lines*, were major sources of freshwater to the East Sea. The paleo-Tsushima water flowed at reduced volume through the narrow, shallow Korea Strait into the sea. The Huanghe and Yangtze rivers drained directly into the Okinawa Trough region, indicating a limited northeastward migration (data extracted from Xu and Oda 1999). The *dotted area* denotes the exposed shelf during the LGM

were important conduits for sediment transport to the East Sea. Coarse-grained sediments in the Korea Strait shelf region were transported via adjacent, local river systems, including the Nakdong and Seomjin rivers (Yoo and Park 1997, 2000). The sediments are composed of quartz (55–67%), feldspar (25–35%), and rock fragments (3–11%) of terrigenous origin. Therefore, there is abundant evidence that freshwater as well as various sediment types was transported through paleo-channels during the LGM, subsequently reaching the paleo-Korea Strait, and eventually entering the East Sea.

Cores MB98PC-11 and 95PC-1

A piston core (MB98PC-11 shown in Fig. 1) was collected from the southernmost East Sea (at water depth of about 145 m), a passage of the paleo-water flow (KORDI 1999). The core sediments are characterized by poorly sorted sands. Coarser material with gravel and shell fragments occurs from about 220 to 320-cm core depths (Fig. 2b). The coarser layer also shows high magnetic susceptibility associated with relatively high grain density. These coarser sediments are interpreted to have been deposited under high-energy conditions and/or harsh climate, when sea level was the lowest due to maximal expansion of global continental ice volume. Moreover, the C/N ratios measured in core 95PC-1 (1,630-m water depth) from the southern Ulleung Basin are higher than 10 during the LGM, and indicate the relative dominance of terrigenous organic matter derived from the nearby land (Hyun et al. 2001). This high C/N ratio layer is well-correlated with the coarse sediment section of core MB98PC-11 in Fig. 2b. Sources for the terrigenous organic carbon could be the adjacent Korea rivers (e.g., the Nakdong and Seomjin), supporting freshwater influx primarily through the paleo-channels.

Discussion

Xu and Oda (1999) suggested that, during the lowstand of sea level, freshwater from the Chinese Huanghe and Yangtze rivers intruded mainly into the East China Sea. At that time period, Huanghe river water flowed in paleo-channels across the emerged Yellow Sea and reached the Okinawa Trough region (Fig. 3). This may denote the extreme restriction of the old Huanghe water to the South Sea, and further to the East Sea during the LGM. Although Chinese freshwater input to the sea can not be completely excluded, it seems unlikely that large amounts of Huanghe-derived water could move to the East Sea during the time of the lowest LGM sea level. Since then, increasing sea level began to flood the exposed shelf and then triggered the expansion of the Huanghe water to the East Sea (Gorbarenko and Southon 2000). Moreover, paleo-Tsushima water inflow to the East Sea may have been extremely restricted during the LGM, because the Kuroshio Current intrusion to the Okinawa Trough region was minimized due to the establishment of the Ryukyu-Taiwan land bridge, caused by the globally lowered sea level (Ujiie and Ujiie 1999).

Consequently, compared to Chinese rivers and the paleo-Tsushima Current, Korean river systems, such as the Nakdong and Seomjin rivers, seem to have contributed substantially to freshwater supply to the East Sea (Fig. 3). Nevertheless, two aspects deserve further investigation: (1) the exact timing of the lowest sea level during the LGM, and (2) the potential role of the Amur River discharge at that time. Gorbarenko and Southon (2000) documented that the lightest value of $\delta^{18}O_{p.f.}$, well-correlated with low surface salinity, was in a core layer deposited at about 15 ka B.P. (ranging from 17 to 14 ka B.P.). However, it is not clear whether the timing of the lowest sea level during the LGM corresponds to about 15 ka B.P. when the $\delta^{18}O_{p.f.}$ value was minimal. Moreover, recent paleo-climate modeling indicates that, compared to the present-day situation, river discharge to the Amur Basin was roughly twice as high during the LGM (Kim et al. 2003), further implying freshwater influx to the northern part of the East Sea. To verify our suggestions, detailed investigations are required with well-preserved core acquisition and accurate chronological analyses.

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