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Foraminiferal evidence for Holocene environmental transitions in the Yaojiang Valley, south Hangzhou Bay, eastern China, and its significance for Neolithic occupations

Bin Dai, Yan Liu, Qianli Sun*, Fuwei Ma, Jing Chen, Zhongyuan Chen

State Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai 200062, China

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ABSTRACT

The transition from a marine-influenced environment to a coastal plain setting during the Early to Middle Holocene was crucial for early human occupation along the eastern China coast. Here, detailed foraminiferal analyses were completed for two sediment cores (YJ1505 and YJ1508) retrieved from the Yaojiang Valley (YJV) along the southern Hangzhou Bay coast of eastern China. Brief environmental changes in the YJV during the Early-Middle Holocene were recovered on the basis of radiocarbon chronology. The assemblages and Detrended Correspondence Analysis (DCA) results of the foraminifera of both cores indicated that the YJV was evidently under a marine influence from 9200 to 7900 cal yr BP; prior to that, it was a fluvial incised valley. The increasing trends in shallow marine foraminifera and the planktonic/benthic foraminifera (P/B) ratio showed that a transgressive period possibly occurred in the valley *ca.* 9200–7900 cal yr BP, and their following decreases suggested that a rapid regression process occurred thereafter. The disappearance of foraminifera and formation of a peaty layer in core YJ1505 *ca.* 7600–6500 cal yr BP implied a brief environmental transition to a limnetic wetland setting in the valley centre, which would have been attractive to early human settlers. The disappearance of foraminifera in core YJ1508 at the valley's eastern entrance suggested that most areas of the valley were located far from marine influence after *ca.* 6250 cal yr BP. Then, the limnetic wetland setting transitioned into a coastal plain environment, attracting more people to the valley. Such a transition in the YJV would have provided more opportunities for ancient people and possibly catalysed the development of the Hemudu culture (HC) for approximately two millennia.

1. Introduction

Coastal sediments are valuable archives for the reconstruction of sea-level changes and land-sea interactions and the evaluation of their impacts on human occupations during the Holocene (Stanley and Warne, 1993; Lambeck et al., 2004; Kemp et al., 2011; Reynolds and Simms, 2015). As sea level rise decelerated ~8000–7000 years ago, it gradually created coastal environments that were attractive to human settlers (Chen and Stanley, 1998; Sandweiss, 2003; Zong, 2004; Innes et al., 2009; Song et al., 2013; Zong et al., 2013; Anthony et al., 2014). In eastern China, two relatively independent trajectories of Neolithic cultures occurred on both flanks of Hangzhou Bay during the Holocene. One is that of the Majiabang (~7000–6000 cal yr BP)—Songze (~6000–5200 cal yr BP)—Liangzhu (~5200–4000 cal yr BP) and the Maqiao (~3900–3200 cal yr BP) cultural sequence in the Taihu Lake basin of the northern Hangzhou Bay, and the other is the Shangshan (~11,000–8600 cal yr BP)—Kuahuqiao (~8000–7200 cal yr BP) and the Hemudu (~7000–5000 cal yr BP) cultures on the southern Hangzhou Bay, respectively (ZPICRA, 2003; Liu, 2005) (Fig. 1A and B).

The Yaojiang Valley (YJV) of the southern Hangzhou Bay is well known for its fostering of the long-lasting Neolithic Hemudu culture of the eastern China coast. Over the past decades, Holocene sea-level changes, landscape processes and Neolithic human adaptations in the YJV have been intensively studied by scholars of various disciplines. For example, some researchers reconstructed the Holocene vegetation and geomorphological changes of the Yaojiang Valley *via* pollen and algal analyses and geochemical proxies (Li et al., 2009; Qin et al., 2011; Liu et al., 2014). Geo-archaeological investigations have also reported the subsistence of the Hemudu population and the associated rice farming at the representative sites of Hemudu (HMD), Tianluoshan (TLS), Zishan (ZS) and Fujiashan (FJS) on the hilly margins of the valley. Further, the linkage between human occupation and sea-level

* Corresponding author.
E-mail address: qlsun@sklec.ecnu.edu.cn (Q. Sun).

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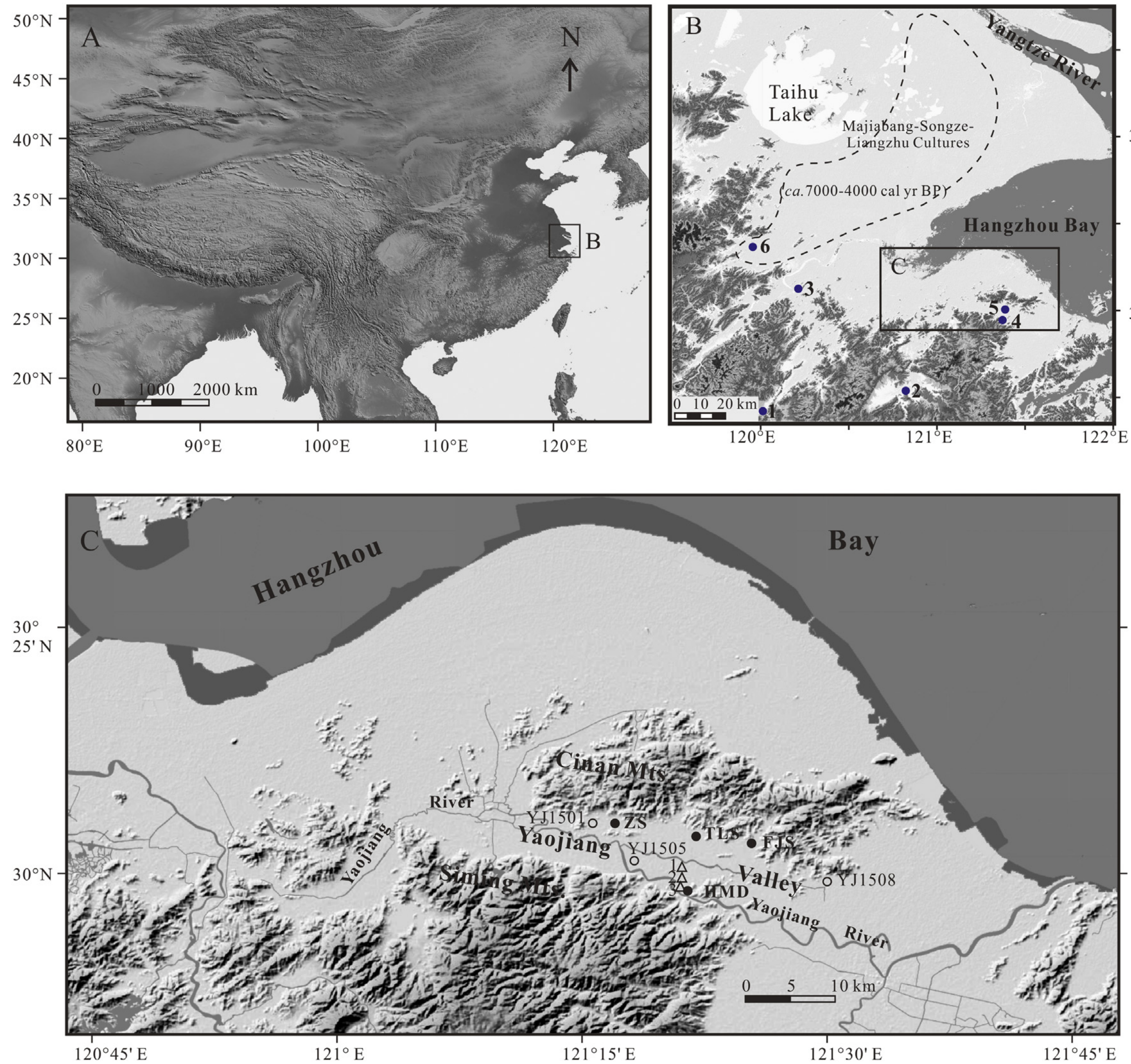

Fig. 1. A) Map of East Asia showing the study area. B) Map of the Yangtze Delta and the Hangzhou Bay showing the YJV and several representative Neolithic sites. 1-Shangshan site, 2-Xiaohuangshan site, 3-Kuahuqiao site, 4-Hemudu (HMD) site, 5-Tianluoshan (TLS) site, and 6-Liangzhu sites. C) Map of the YJV; the circles are sediment core sites in the present study, the black dots are Neolithic sites, and the triangles are the collection sites of sediment cores 1) HMD-1, 2) HMD1501, and 3) HMD1502.

and landscape changes has been outlined (Tang and Yu, 1996; Jiao, 2007; Fuller et al., 2009; Zheng, 2009; Li et al., 2010; Zheng et al., 2012; Liu et al., 2016). Although these previous studies have established a preliminary framework of Holocene landscape changes in the YJV, some key issues still remain. For example, the timings of marine transgressions and regressions are still not clear, and whether land processes or marine factors, or both, influenced the evolution of the Hemudu culture in the Yaojiang Valley remains debatable.

The present study focused on two sediment cores retrieved from the centre and the east entrance of the YJV (Fig. 1C). Foraminiferal analysis was completed to decipher the marine transgression and regression processes on the basis of radiocarbon chronology. With references to other sediment cores of previous studies in the region, brief environmental transitions in the Yaojiang Valley during the Early to Middle Holocene are shown. Furthermore, the possible impacts of both marine and land processes on the occupations of the Hemudu culture were re-evaluated from a geo-archaeological perspective.

2. Physical setting

The YJV is located in the central part of the Ningshao Plain along the southern Hangzhou Bay of eastern China. The valley connects the Shaoxing Plain from the west and the Ningfeng Plain from the east, extending in a NW-W–SE-E direction. The valley is *ca.* 40 km in length and *ca.* 6 km in width, with an average altitude of *ca.* 3 m above mean sea level (a.m.s.l.). Mountains and hills ranging between *ca.* 100–500 m in elevation lie on the south and north sides of the valley. The Yaojiang River runs through the valley from the west and flows eastward before it drains into Hangzhou Bay (Fig. 1C).

In this study area, which is located in the subtropical region of south-eastern China, the average temperature is ~4 °C in January and ~28 °C in July, and the mean annual precipitation is *ca.* 1100 mm (NCCC, 1995). At present, the study area often is subject to severe floods caused by typhoons and poor drainage during the monsoon season. The highlands of the study area are vegetated with evergreen and deciduous broadleaved forests, while the lowland area features wetlands vegetated by freshwater herbs (Fang, 2006).

3. Material and methods

The sediment cores, YJ1505 (121°17.78′ E, 29°59.58′ N, 1.90 m in elevation) and YJ1508 (121°28.64′ E, 29°58.50′ N, 1.95 m in elevation), were retrieved with a > 95% recovery rate during the winter of 2015. YJ1505 was collected at the centre of the YJV, and the YJ1508 core was collected at the east entrance of the valley (Fig. 1C). The YJ1505 and YJ1508 cores were sampled at 20- and 10-cm intervals for grain size, and 20–30-cm intervals for foraminiferal analysis with a sample thickness of 1 cm. Additionally, the lithology of core YJ1501 (121°15.75′E, 30°2.32′ N, 2.01 m in elevation) was used as a reference.

Grain-size measurements were conducted using a Beckman Coulter Laser Diffraction Particle Size Analyzer (Model: LS13320, measurement range 0.04–2000 μm) at the State Key Laboratory of Estuarine and Coastal Research, East China Normal University (SKLEC, ECNU). Samples were dried at 40 °C for 24 h; then, 10% HCl was added to eliminate carbonates, 10% H_2O_2 was added to remove organic matter, and $Na(PO_3)_6$ was finally added to disperse the samples prior to testing.

The foraminiferal assemblages of the YJ1505 and YJ1508 cores were assessed at the SKLEC, ECNU. For core YJ1505, the sampling interval was 30 cm at depths of 0–11.2 m and 20 cm at depths of 11.2–19.0 m, yielding 71 samples in total. For core YJ1508, the sampling interval was 30 cm at depths of 3.6–23.0 m, and another 5 samples were obtained at an interval of 20 cm in the uppermost 3.6–2.6 m, yielding 65 samples in total. The thickness of each sample was 1 cm. The samples were dried in the oven at 40 °C to obtain 25 g of dried sample, which was fully dispersed in distilled water for two days. Then, these samples were washed using distilled water *via* a 63-μm mesh-size sieve. The coarse residue obtained was transferred to filter paper, dried at 50 °C and weighed (Wang et al., 1985). Foraminifera were identified using a Nikon stereo binocular microscope under 40× magnification. Counts of > 250 specimens were conducted for most of the samples, except some samples in which few foraminifera were found. Detrended Correspondence Analysis (DCA) was performed using the program CANOCO 4.5 to detect the species-assemblage response to environmental variations (ter Braak and Smilauer, 2002). For statistical analysis, samples with low counts of < 50 specimens were excluded. Foraminiferal percentages were transformed to square roots to maximize the "signal to noise" ratio. In this study, 31 and 34 taxa that had a relative abundance of > 3% in at least one sample were included in the multivariate analysis for the YJ1505 and YJ1508 cores, respectively. The classifications of euryhaline and shallow marine foraminifera were based on previous studies in the east China coastal area (Wang et al., 1988: Zheng, 1988; Gu et al., 2017).

Radiocarbon dating was completed for 13 samples using Accelerator Mass Spectrometry (AMS) performed at the AMS facility at the Institute of Earth Environment, Chinese Academy of Sciences (IEECAS). Material for these date evaluations comprised organic matter (OM), plant fragments (PFs), charred woods (CWs) and shells (Table 1). Dates were provided as calibrated at 95.4% confidence intervals (2σ) in the present study in years Before Present (cal yr BP). These dates were calibrated using the Calib 7.0.1 program with INTCAL13 datasets for OM, PFs and CWs. Marine 13 datasets were used for shells to minimize the carbon reservoir effect (Reimer et al., 2013). The dates from the shells were calibrated using a reservoir factor (ΔR59 ± 66) based on the average of the five nearest sites of the East China Sea (Yoneda et al., 2007).

The information about human occupation in the Yaojiang Valley were collected from archaeological literature, excavation reports and published documents (*e.g.*, ZPICRA and XU, 2001; ZPICRA, 2003; SACH, 2009; CSCA and ZPICRA, 2011; NMICRA, 2013). These data comprised the temporal and spatial distributions of cultural sites and relics, human subsistence and local environmental changes.

4. Results

4.1. Sediment lithology

Core YJ1501 consisted of brownish stiff mud at the bottom, with Fe-Mn nodules (5.2–3.9 m) overlain by brownish clayey silt with Fe-Mn nodules (3.9–3.0 m). Upwardly, greyish mud with organic matter (3.0–0.7 m) and taxitic mud with plant fragments at the top (above 0.7 m) were noted (Fig. 2).

The basal unit (19.7–18.8 m) of core YJ1505 was gravel and sand with freshwater shells. It was then overlain by a section of silty clay with abundant plant rootlets, freshwater shells and gastropods at 18.8–17.15 m, as well as a coarse sandy sediment unit rich in marine shell fragments, gastropods and bioturbations at 17.15–13.4 m. A fine sediment unit with marine shell fragments was seen at 13.4–10.6 m, which was overlain by a coarse sediment sequence with abundant organic matter (a thin peaty layer at 5.6 m) and a few shell fragments at 10.6–5.0 m. A yellowish clayey silt with a few pieces of organic matter and Fe-Mn nodules occurred at the top of the core, *i.e.*, above 5.0 m (Fig. 2).

Upwardly, core YJ1508 consisted of a thick layer of dark greyish clay with occurrences of plant fragments and organic matter at the bottom (23.3–20.0 m) and dark silty clay with lamina and abundant shell and plant fragments at 20.0–17.3 m. Coarser greyish silt with shell fragments appeared at 17.3–16.2 m, followed by a section of greyish clayey silt and silt with bedding and shell fragments at 16.2–10.6 m. A layer of dark silt and sand with few shell fragments was observed at 10.6–9.0 m, overlain by dark silty clay with lamina at 9.0–3.9 m. The upper section of the core was dark greyish clay with abundant organic matter and charred plants at 3.9–1.0 m and taxitic fine clay with abundant Fe-Mn nodules and a thin peaty layer at 0.9–0.8 m (Fig. 2).

4.2. Chronology

A total of 13 AMS ^{14}C dates were obtained from the three sediment cores. Except for the dates in core YJ1501 that were dated back to the Late Pleistocene, the other dates from cores YJ1505 and YJ1508 were

Table 1
the radiocarbon dates of the sediment cores.

Lab. code	Cores	Depth (m)	Material	$\delta^{13}C$ (‰)	Conventional ^{14}C Age (yr BP)	Calibrated age (cal yr BP)	Probability (2δ)
XA17041	YJ1501	0.91	OM	−28.49	9970 ± 60	11,243–11,646	95.4%
XA17042		2.30	OM	−22.98	13,990 ± 50	16,726–17,201	95.4%
XA17043		5.18	OM	−24.36	18,250 ± 80	21,875–22,349	95.4%
XA15946	YJ1505	5.64	PFs	−28.84	5715 ± 30	6413–6604	95.4%
XA17147		7.60	OM	−28.49	6770 ± 40	7574–7675	95.4%
XA15928		11.40	SHELL	−4.92	7830 ± 40	8066–8404	95.4%
XA15929		14.55	SHELL	−5.41	8290 ± 40	8565–8989	95.4%
XA16020		16.85	CWs	−32.29	7666 ± 35	8402–8539	95.4%
XA16021		17.35	OM	−26.21	8000 ± 40	8717–9009	95.4%
XA17135	YJ1508	1.30	OM	−27.09	5460 ± 30	6209–6303	95.4%
XA15930		9.45	SHELL	−6.04	7510 ± 30	7772–8114	95.4%
XA16026		20.10	PFs	−26.26	8050 ± 40	8772–9032	95.4%
XA16027		21.55	PFs	−29.83	8240 ± 40	9081–9400	95.4%

OM = organic matter; PFs = plant fragments; CWs = charred woods.

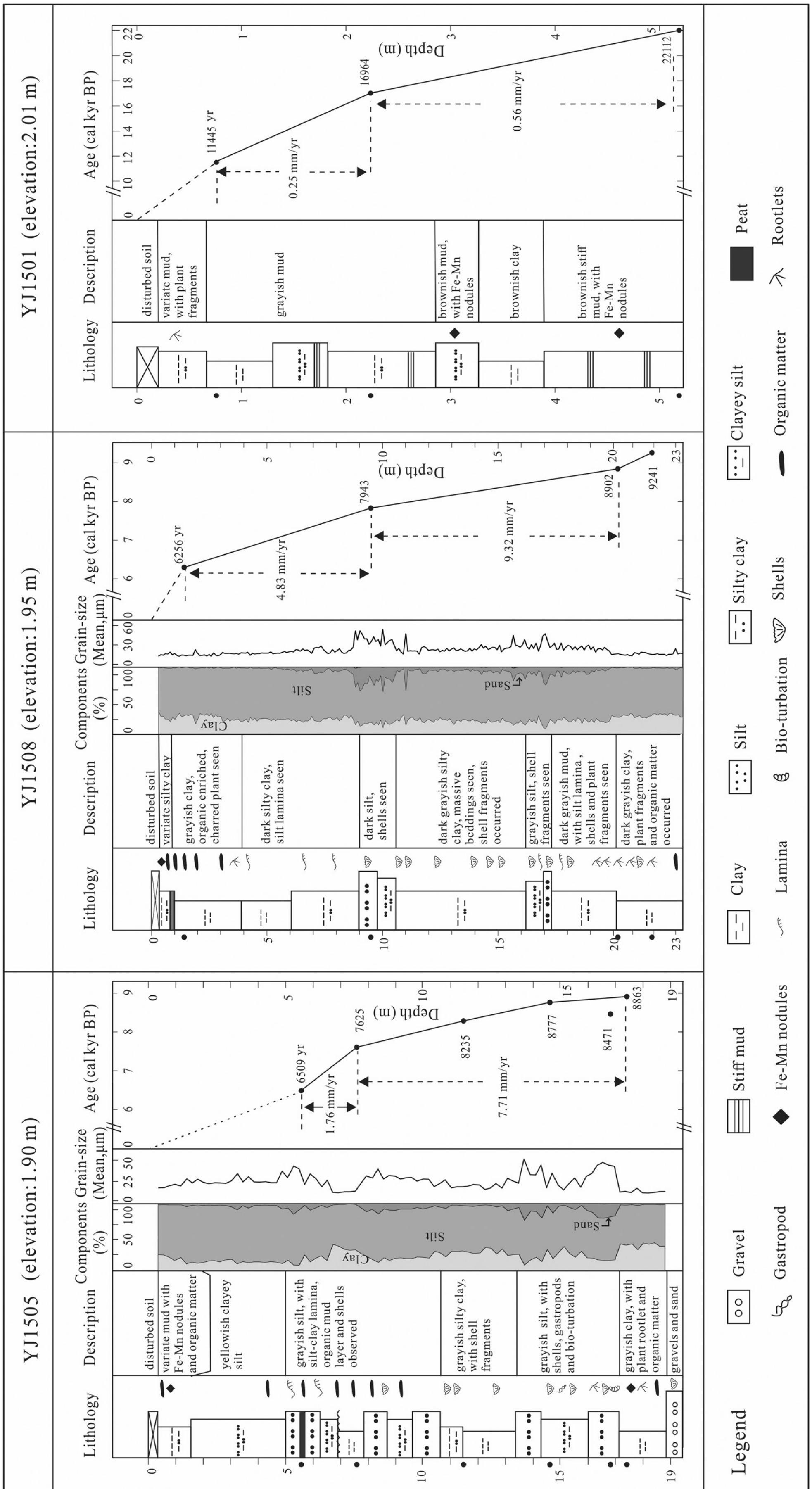

Fig. 2. Lithology and chronology of cores YJ1501, YJ1505, and YJ1508.

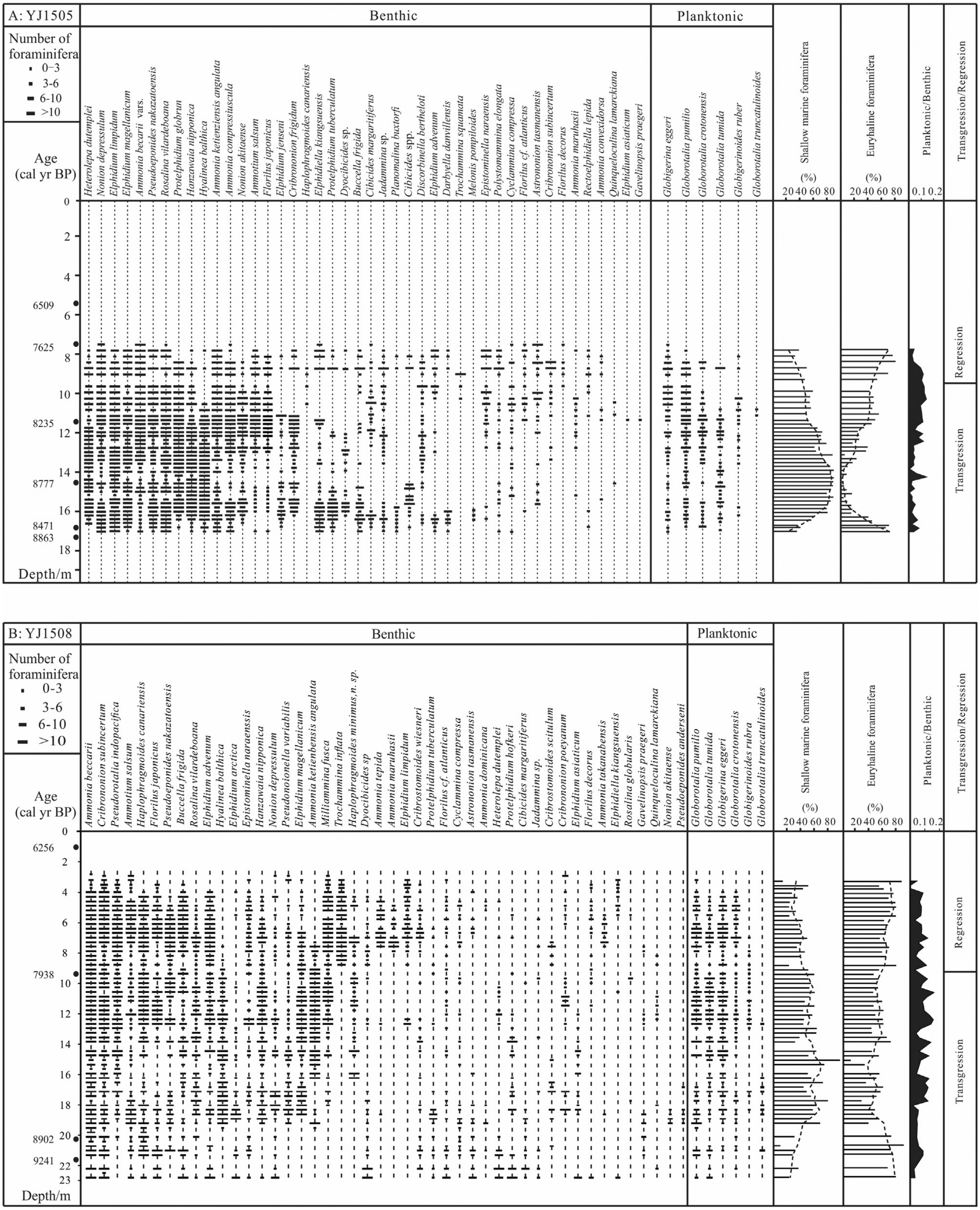

Fig. 3. Occurrences and vertical variations in major foraminifera species in the sediment cores. A) YJ1505 core and B) YJ1508 core. The dash-lines were plotted after smoothed by 10-points of window to show the general trend of foraminiferal distributions.

from the Holocene (Table 1). Both the radiocarbon dates of the YJ1505 and YJ1508 cores showed a rapid sedimentation rate from *ca.* 8900–7600 cal yr BP (7.71–9.32 mm/yr, average of 8.51 mm/yr), while the sedimentation rates significantly decreased thereafter (0.17–4.8 mm/yr) with much lower sedimentation rates at the core tops (Fig. 2).

4.3. Foraminiferal assemblages

In total, 53 species of 33 genus of foraminifera in core YJ1505 and

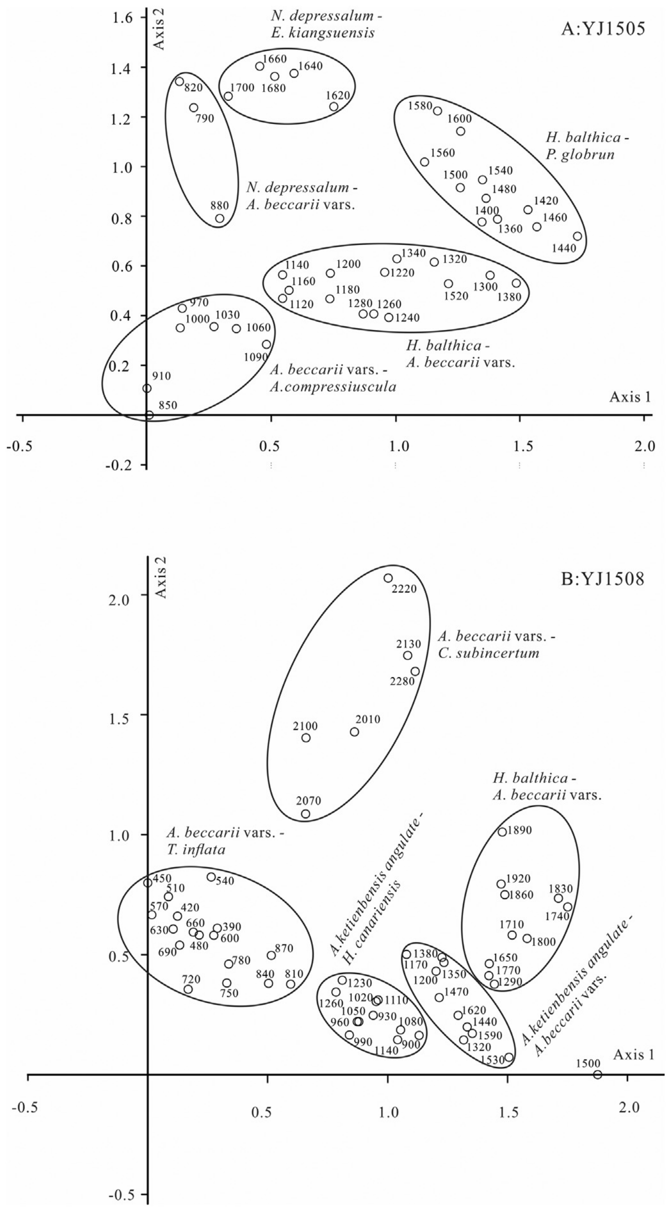

Fig. 4. Detrended Correspondence Analysis (DCA) of the benthic foraminiferal assemblages of the A) YJ1505 core and B) YJ1508 core. Also labelled are the major species of each assemblage.

64 species of 35 genus in core YJ1508 were identified (Fig. 3 A and B). Among these foraminifera, most were benthic types, and the planktonic types were generally < 15%. Foraminifera were not found at the lowermost core section of 19.30–17.20 m and the uppermost section of 7.60–0 m in the YJ1505 core, and foraminifera were found upwardly from the bottom to a depth of 2.80 m in the YJ1508 core.

Detrended Correspondence Analysis (DCA) of the benthic foraminiferal data shows five major assemblages for both cores (Fig. 4A and B). For the YJ1505 core, assemblage A from the bottom of the core (1700–1620 cm) was dominated by *Nonion depressalum* and *Elphidiella kiangsuensis*. Assemblage B (1600–1360 cm) featured *Hyalinea balthica* and *Protelphidium globrun*. Assemblage C (1340–1120 cm) was characterized by an abundance of *Hyalinea balthica* and *Ammonia beccarii* vars. Assemblage D (1090–850 cm) showed a dominance of *Ammonia beccarii* vars. and *Ammonia compressiuscula*. Assemblage E was represented by *Nonion depressalum* and *Ammonia beccarii* vars.

On the DCA plot, the YJ1508 core was marked by five assemblages. Assemblage A was dominated by *Ammonia beccarii* vars. and *Cribrononion subincertum* at a depth of 2280–2010 cm. Assemblage B (1980–1650 cm) was represented by an abundance of *Hyalinea balthica* and *Ammonia beccarii* vars. Assemblage C (1620–1170 cm) featured the occurrence of *Ammonia ketienbensis angulate* and *Ammonia beccarii vars*. Assemblage D (1140–900 cm) was characterized by *Ammonia ketienbensis angulate* and *Haplophragmoides canariensis*. Assemblage E (970–390 cm) was dominated by *Ammonia beccarii* vars. and *Trochammina inflata*.

4.4. Neolithic human occupation in the Yaojiang Valley

Intensive archaeological excavations and field investigations have been conducted in the YJV since the 1970s. The results have shown that the history of human occupation in the YJV began during the Middle Holocene, when shelters at the Hemudu and Tianluoshan sites were first built as early as *ca.* 7000 cal yr BP. The temporal and spatial distributions of Neolithic sites have shown that the Hemudu cultural sites during the early stage were mainly distributed on foothills, while the latter sites spread to the valley centre (Fig. 5). The number of Neolithic sites significantly decreased after *ca.* 5000 cal yr BP, with only a few sites distributed on the foothills of the valley.

5. Discussion

5.1. Holocene transgressive and regression in the Yaojiang Valley

In the YJV, foraminifera were first witnessed along with marine shell fragments at the bottom of the YJ1508 core collected from the east entrance of the valley (Figs. 2 and 3). This indicated that the east entrance of the YJV was subject to marine invasion no later than *ca.* 9240 cal yr BP. However, in the centre of the valley, the bottom of the YJ1505 core consisted of sandy deposits with gravels topped by a section of fine silty clay with abundant plant rootlets but without foraminifera before *ca.* 8900 cal yr BP. This would suggest that a river channel-floodplain setting existed prior to the transgression (Fig. 2). The successive appearances of foraminifera in cores YJ1508 and YJ1505 suggested a westward transgression process in the valley, with a rapid relative sea level (RSL) rise from *ca.* −19.6 m to *ca.* −15.4 m from *ca.* 9240–8900 cal yr BP. Then, the percentage of shallow marine foraminifera in both cores increased upwardly from *ca.* 8900–7900 cal yr BP, which was in agreement with the relatively high P/B ratios of the two cores during this period (Fig. 3). Both proxies indicated enhanced marine influences because of sea level rise. After *ca.* 7900 cal yr BP, increasing contents of euryhaline foraminifera and decreasing P/B ratios with lower foraminiferal abundances in both cores suggest that declining seawater intrusion in the valley occurred thereafter (Fig. 3). The vanishing foraminifera in core YJ1505 after *ca.* 7600 cal yr BP suggest that the centre of the Yaojiang Valley was the first to change from a marine influence. For the YJ1508 core, the marine influence ceased no earlier than *ca.* 6200 cal yr BP when the foraminifera disappeared.

The DCA of the foraminiferal data of both the YJ1505 and YJ1508 cores show that axis 1 is the most significant axis because it captures 29.2% and 22.3% of the total variance, respectively. In addition to Axis 1, Axis 2 is also an evident contributor to the total variance (17.3% and 15.0%, respectively) (Table 2). The DCA results reflect the variations in salinity and other associated variables (water depth and diluted water) linked to seawater penetration into the YJV, as salinity gradients and water depth have major influences on species composition. From the DCA plot, the bottoms of both cores showed a shallow water setting with low salinity, suggesting a tidal flat environment during the early stage of marine transgression (Figs. 3 and 4). Then, the YJV underwent a higher-salinity period with increasing water depths from *ca.* 9200–7900 cal yr BP. This was indicative of a continuous marine transgressive influence in the YJV. After *ca.* 7900 cal yr BP, both the water salinity and water depth significantly decreased in the upper

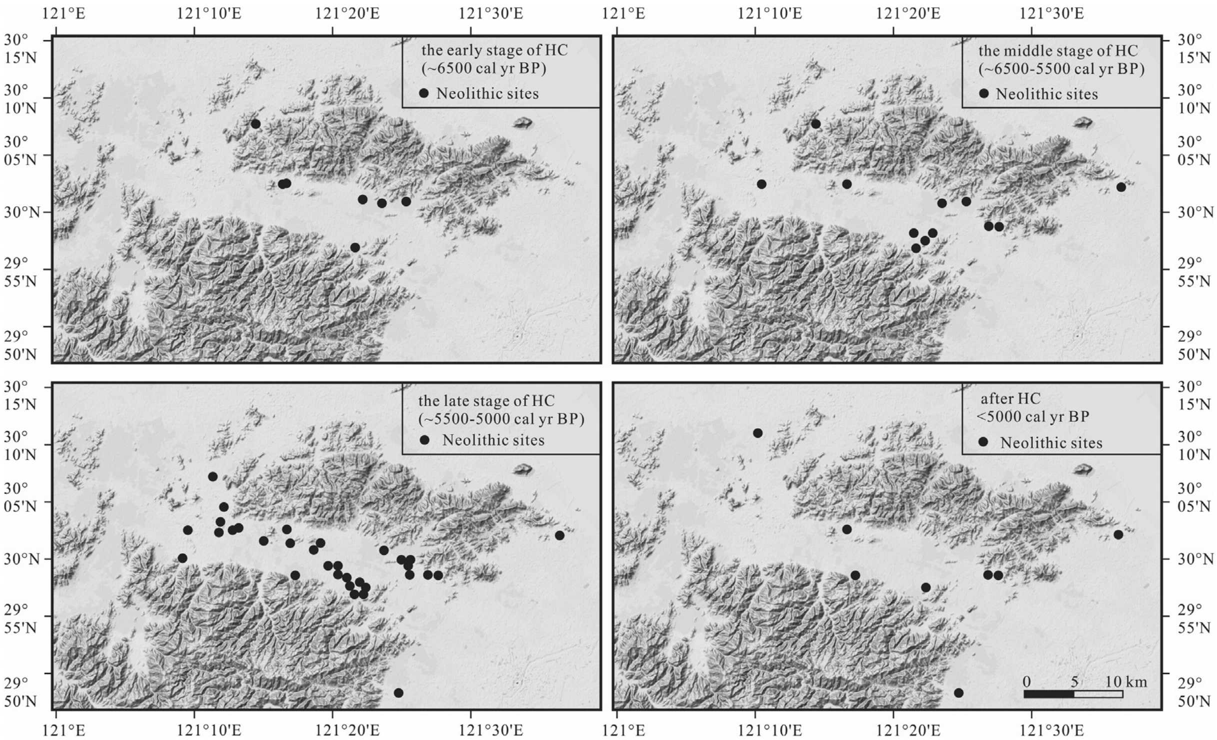

Fig. 5. Distribution of Neolithic sites in the YJV during different stages of the Hemudu culture and thereafter.

Table 2
Summary statistics of detrended correspondence (DCA) of benthic foraminiferal data from YJ 1505 and YJ 1508 cores.

Sediment cores	Axes	1	2	3	4
YJ 1505	Eigenvalues	0.197	0.116	0.033	0.016
	Lengths of gradient	1.732	1.4.4	1.023	0.741
	Cumulative % variance of species data	29.2	46.5	51.3	53.6
YJ 1508	Eigenvalues	0.229	0.155	0.046	0.028
	Lengths of gradient	1.875	2.070	1.294	1.090
	Cumulative % variance of species data	22.3	37.3	41.8	44.5

parts of the two cores, implying a desalinized setting in the valley centre and a lagoonal environment at the valley's east entrance (Figs. 2, 3 and 4).

Briefly, the YJV underwent marine transgression processes from *ca.* 9200–7900 cal yr BP; then, regression processes occurred after *ca.* 7900 cal yr BP. The diminished foraminifera suggest that the YJV started to transition from a marine-influenced setting to a limnetic environment *ca.* 7600 cal yr BP in the valley centre and after *ca.* 6200 cal yr BP at the east valley entrance.

5.2. Neolithic humans and environment

The history of Neolithic occupation along the southern Hangzhou Bay could extend back in time to the mountainous Shangshan culture (~11,000–8600 cal yr BP). Then, the appearance of the Kuahuqiao culture from *ca.* 8000–7200 cal yr BP marked the earliest human occupation that engaged in rice farming on the coastal lands of the southern Hangzhou Bay. In the YJV, previous archaeological evidence shows that the innovative Hemudu cultural pioneers entered the valley no later than *ca.* 7000 cal yr BP, just several hundred years after the Kuahuqiao culture. The Hemudu culture (*ca.* 7000–5000 cal yr BP) then developed and thrived in the valley for approximately two millennia. The distribution of Neolithic sites in the valley shows that the early arrivals dwelled at the Hemudu (HMD), Tianluoshan (TLS), Fujiashan (FJS) and Zishan (ZS) sites near the foothills (Fig. 5). Then, people moved to the valley centre and the eastern hilly margins of the valley after *ca.* 6500 cal yr BP. The migration of Neolithic sites during the early to middle stages of the Hemudu culture coincided with the rapid landscape transition from a marine-influenced setting to a limnetic environment after *ca.*7600 cal yr BP, which was a result of marine regression and coastal propagation. Consequently, the formation of peat layers and wetland habitat in the valley after *ca.* 7600–6500 cal yr BP would have provided more opportunities for humans to engage in rice farming in addition to fishing and gathering (Zong et al., 2013). Such an environmental transition has also been revealed by previous pollen studies from the HMD-1, HMD1501 and HMD 1502 cores, which indicated a limnetic setting in the valley centre after *ca.* 7.8, 7.2 and 6.8 cal kyr BP, respectively (Li et al., 2009; Zheng et al., 2016) (Fig. 6). Human subsistence revealed by archaeological excavations of representative sites (HMD, ZS, FJS and TLS) suggested that rice farming supplemented by hunting, fishing and gathering became the major food sources of the Hemudu people. The stilt house, an architectural design built on an elevated wooden underframe, was popular during the early stage of the Hemudu culture (ZPICRA, 2003). This also implied a positive human adaptation to the limnetic and wetland environment, which was suitable for rice farming and gathering but also vulnerable to water level fluctuations during the Early to Middle stages of the Hemudu culture.

Sediment cores showed that above the limnetic deposits (*ca.* 6500–5000 cal yr BP) was yellowish silty clay, taxitic silty clay or cultivated soil with Fe-Mn nodules (Fig. 2) (Zheng et al., 2016). Other cores have indicated that rice farming became popular in the valley during the late stage of the Hemudu culture (Li et al., 2009; Liu et al., 2016). Archaeological findings have also revealed that the sites of the late stage nearly expanded to the whole Yaojiang Valley with rice farming and that stilt houses were no longer necessary for the Hemudu people. The Hemudu people dug wells for freshwater further confirmed a decreased water level from shoreline advancement (ZPICRA, 2003). This represented a much more favourable environment for living,

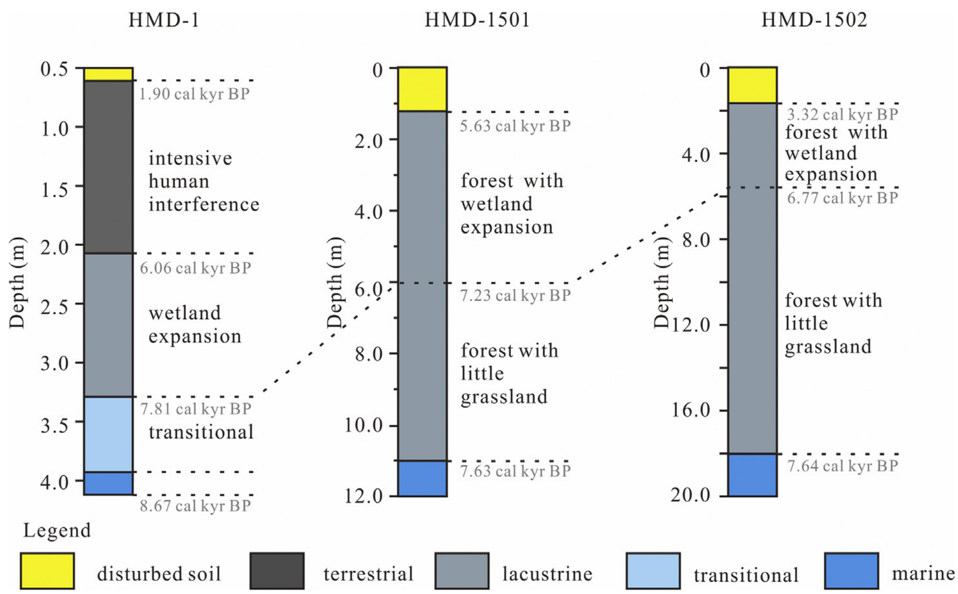

Fig. 6. Core-recorded environmental changes in the YJV (referenced from Li et al., 2009 and Zheng et al., 2016).

which may have been associated with the formation of a fluvial plain, although a few peaty layers were still distributed in places in the valley.

5.3. Significance for early human occupation and the decline of Hemudu culture

The present study shows that coastal progradation began after *ca.* 7900 cal yr BP in the YJV, which was nearly coeval with the formation of the Kuahuqiao site at the head of the southern Hangzhou Bay. Additionally, no marine influence is apparent in the core sediment of YJ1501 over the last 22,000 years (Fig. 2). These data imply that the hilly margins of the YJV, which have a relatively higher paleotopography, would not have been affected by marine invasion since the Last Glacial Maximum (LGM). Compared to the Kuahuqiao and Xiasun sites of the Kuahuqiao culture, which were occupied nearly immediately after marine regression *ca.* 8000 cal yr BP but still suffered from marine influence (*via* tidal fluctuation) during their existence (Zong et al., 2007; Innes et al., 2009; Shu et al., 2010), the hilly marginal areas of the YJV would be safer places for early arrivals to choose. These results could provide some implications for archaeologists to explore if there were counterparts of the Kuahuqiao culture or even earlier human presence in the valley and to understand how early humans responded to changes in the landscape due to marine transgression and regression processes.

The exodus of the Hemudu population was unexpected in the YJV. There were only a few successive sites distributed on the hilly margins of the valley after *ca.* 5000 cal yr BP (Fig. 5). Simultaneously, along the northern Hangzhou Bay, the Liangzhu culture (*ca.* 5200–4000 cal yr BP) began to thrive (Liu et al., 2015). Although some new archaeological findings have shown signs of the Liangzhu culture in the YJV thereafter, the reason for the Hemudu people leaving remains unclear. From a geological perspective, as the marine influence waned from the YJV, it was accompanied by the formation of a fluvial plain (Liu et al., 2018). This suggests that terrestrial processes have played a key role in the environment of the valley since that time, which would have made the YJV less attractive to people. Furthermore, with coastal propagation on both flanks of Hangzhou Bay and adjacent regions, more choices were available to people for migration.

6. Conclusions

Foraminiferal results from sediment cores clearly show the Holocene marine transgression and regression processes in the YJV. A relatively rapid sea level rise was indicated from *ca.* 9200–7900 cal yr BP from marine transgression, and a regression process happened afterwards. The YJV transitioned from a marine-influenced setting to a limnetic habitat and wetland environment after *ca.* 7600–6500 cal yr BP to the east, which would have attracted early human occupation in the valley. The formation of a fluvial plain after *ca.* 6500–5000 cal yr BP would have facilitated the development of the Hemudu culture and rice farming. The hilly margins of the Yaojiang valley might have provided safer shelter for the innovative pioneers, and this provides new clues for the exploration of earlier human occupation comparable to the Kuahuqiao culture at the head of the southern Hangzhou Bay coast. The decline of the Hemudu culture in the YJV is still an open topic, and an integrated geological, geomorphological and archaeological study is needed to combine both natural and social factors. This would provide some insights into this key issue.

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