Catastrophic Tidal Bores Associated with Sea Level Rise: A Lesson from the Collapse of Kuahuqiao Neolithic Culture, East Coastal China

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Key Points:

- Qiantangjiang tidal bores, east coastal China, initiated around 7,600 cal BP, when a funnel-shaped coastal embayment started to form.
- Kuahuqiao, being among the earliest Neolithic sites of rice domestication, was inundated by catastrophic Qiantangjiang tidal bores.
- The tidal bores manifest a non-linear response to the complexity of forces at the interface between sea level rise and coastal evolution.

Abstract

Extreme climatic/environmental events associated with sea level rise in the context of global warming are a prime concern in coastal management. Kuahuqiao, the type-site for the early Neolithic culture of the same name, is of critical importance to understanding the development of rice-based agriculture and settlements, as well as human-environment relations in east coastal China. Abandonment of Kuahuqiao at around 7,600 cal BP has been attributed to marine inundation, marking the onset of settlement hiatus that lasted until occupation, several hundred years later. New sedimentary dataset, combined with microfossil identification and AMS ^{14}C dating, reveal that Kuahuqiao settlements were destroyed by catastrophic overbank flooding associated with tidal bores. Such extreme events manifest a non-linear response to the complexity of forces at the interface between sea level rise and changes in coastal morphology, and provide an alarming example of the difficulties in anticipating future conditions in highly dynamic, coastal environments.

Plain Language Summary

Kuahuqiao, the type-site for the early Neolithic culture of the same name, is famous for unearthing the world's earliest canoe, as well as being one the earliest places of rice domestication. It serves as a sound analogue to understanding the development of early settlements, as well as human-environment relations in east coastal China. Sedimentary evidence suggests that the site was destroyed by catastrophic Qiantangjiang tidal bores at about 7,600 cal BP. Such extreme events manifest a non-linear response to the complexity of forces at the interface between sea level rise and changes in coastal morphology, and provide an alarming example of the difficulties in anticipating future conditions in highly dynamic, coastal environments in the context of global warming scenario.

1. Introduction

Deltas and estuaries have long attracted humans because of the rich variety of resources available, and the opportunities for transport and dispersal afforded (Pope & Terrell, 2008). However, opportunity-rich locations are often associated with high levels of risk. In the case of the east coast of China, sea level rise related hazards such as storm surge and flooding occur in different frequencies, causing damages with various magnitudes (Chen, 1997; Su et al., 2001; Wang et al., 2012).

The Qiantangjiang River is known for having one of the world's largest tidal bores, attributing mainly to the funnel-shaped geometry of the Hangzhou Bay (Fig.1). The tides propagate into the river mouth from the Hangzhou Bay, pilling up while moving upstream, reaching up to 9 meters at extremes, and have caused catastrophic overbank flooding in history (Su et al., 2001). However, it remains unknown when the Qiantangjiang bores initiated and what effects they might have had on Neolithic settlements. While great efforts are being made to better manage current and predict future hazards (Wu et al., 2003), historical archives can provide warning lessons for understanding the interplay between environmental changes and human activities at these vulnerable locations.

During the Last Glacial Maximum (LGM), the East China Sea shelf was entirely exposed. Sea level rose rapidly during the Last Deglaciation, and the shelf was almost merged at about 9.5 ka (Zheng et al., 2018). Formation of the deltas commenced around 8,000 years ago, when sea level rise decelerated and sediment discharge increased due to increased erosion associated with strengthened monsoon rains (Hori et al, 2002; Stanley & Warne, 1994; Wang et al., 2020). Human occupation of the delta occurred soon after, where the world’s earliest rice agriculture originated (Itzstein-Davey et al., 2007; Chen et al, 2008; Atahan et al., 2008; Innes et al., 2009; Qin et al., 2011) (Fig. 1 and Fig. S1).

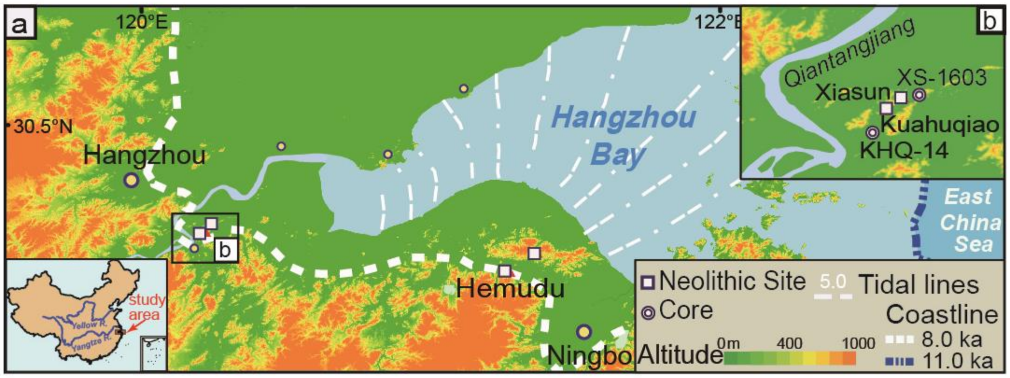

FIGURE 1. Location map. (a) Topography map of Qiantangjang River and Hangzhou Bay area, showing the location of major Neolithic sites (Kuahuaqiao, Xiasun, Hemudu and Tianluoshan). White dashed lines indicate tidal heights; (b) Topography map showing the location of Kuahuaqiao, Xiasun, and the sediment cores.

The Qiantangjiang flooding plain is home to a series of Neolithic cultures, with Kuahuqiao being the site of world's earliest canoe, as well as being among the earliest places of rice domestication (Jiang & Liu, 2005; Liu et al., 2007; Yuan et al., 2008; Pan, 2008; Fuller et al., 2008, 2009; Jiang, 2013) (Figs. 1 & 2). Early Neolithic people established their settlements close to surface bodies of freshwater (Zong et al., 2007). Archaeological excavations have yielded the remains of at least four wooden pile-dwellings, representing settlement at a location vulnerable to frequent flooding (Jiang, 2013). One of the most important finds is a pinewood canoe, dated by two Accelerator mass spectrometry (AMS) ^{14}C dates (Jiang & Liu, 2005) to around 7,850 cal BP. The excavations also yielded a rich variety of food remains, together with evidence of the incipient cultivation of rice (*Oryza sativa*) (Jiang & Liu, 2006; Liu et al., 2007;

Fuller et al., 2009; Pan, 2008). Archaeological and sedimentary evidence, including new data presented here, indicates abandonment of the site *ca.* 7,600 cal BP, and thus several hundred years before the establishment of Neolithic settlements farther to the east at Hemudu (Sun, 2013) (Fig. 1). The reason why Kuahuqiao was abandoned has been vigorously debated, with dominant view suggesting that it was inundated by direct marine transgression (Zong et al., 2007). Whether this is true remains a fundamental issue to our understanding of the regional sea level history. Occupation layers are indeed located 2–3 m below the current mean sea level (m.s.l.), or the present-day Ordnance Datum (OD) (Jiang, 2013). However, they were a few meters higher than the 7,600–7,500 cal BP sea level according to the latest global sea level reconstruction (Lambeck et al., 2014). What was then the cause of the collapse of Kuahuqiao culture, if not direction marine inundation?

In this study we took sedimentological approach to investigate the sedimentary facies, not only for the archaeological sites, but also for drilling cores and trenches in the vicinity. Analysis on grain size distribution, geochemistry and microfossils, together with high resolution ^{14}C AMS dating was performed to determine the sedimentary environments. Our new evidence revealed a sedimentary facies diagnostic of flooding nature, suggesting that Kuahuqiao was destroyed by catastrophic tidal bores, rather than direct marine inundation.

2 Materials and Methods

The archaeological site at Kuahuqiao (N30° 08’ 42”, E120° 13’ 02”) is located between two parallel, southwest-northeast trending low ridges, at about +3.8 m OD; a 2.4-meter long expose profile from Kuahuqiao Site (hereinafter referred to as KhqS) was sampled. The coring site for XS-1603 was located within the area excavated by archaeologists at Xiasun (N30°09'25", E120°13'56", +6.40 m OD) and is situated about 2 km to the northeast of KhqS, where a 14-

meter long core was retrieved. The coring site for KHQ-14 (N30°07'29", E120°11'33", +5.26m OD) is approximately 1.5 km to the southwest of KhqS (more details see SI) and a 33.2-meter long core was retrieved.

Sediment cores were divided longitudinally using a core Splitter (GEOTEK). The archive half of the cores was used for XRF analysis and stratigraphic description, while the working half was subsampled at 0.01 m intervals for laboratory analyses. Chronological control is provided by 17 AMS ^{14}C dated samples of plant macrofossils and fragments of charred material. AMS ^{14}C dates were calibrated using the OxCal online software (OxCal v4.4.2) and the INTCAL20 dataset (Reimer et al., 2020).

Analyses of sediment samples focused on several abiotic and biotic proxies of past environmental conditions. Evidence of variations in coastal environmental conditions can be inferred from the particle sizes of inorganic fractions of deposits (e.g. Machado et al., 2016), while variations in biogenic calcium (Ca) are a proxy of coastal inundation (e.g. Delaine et al., 2015). The remains (sub-fossils) of diatom, foraminifer, pollen and spores, charcoal and non-pollen palymorphs (freshwater algae and dinoflagellate cysts) are commonly used in the reconstruction of past environmental conditions (Smol et al., 2001; Zong et al., 2013).

3 Results and Discussion

3.1 Initiation of Qiantangjiang Tidal Bores

Four broad stratigraphic units (U1 to U4) are observed in the sediment stratigraphy across the three sample profiles (Fig. 2 and Fig. S3a, b & c). Of the four units, U1 corresponds with the paleosol of Last Glacial age. Previous study suggests that U1 is widely distributed in coastal east China (Li et al., 2002; Qin et al., 2008) at depths ranging from 25 to 5 m below present-day OD when the shelf was entirely exposed. Therefore, it represented the paleo-surface of the landscape. KHQ-14 and XS-1603 have recovered the full length of U2 unit, which starts with rhythmitic mud and fine sand, typical of tidal flat deposition, marking the onset of marine inundation during the early stage of the post-glacial transgression. The upper and dominant part of U2 is massive and sticky grey clay, typical of estuarine deposition (Fig. S3a). U3 is present at KhqS (-3.30 to -2.35 m OD) and XS-1603 (-2.50 to -2.25 m OD) and is representative of the "human-affected", or culture, phase (Jiang, 2013). The uppermost stratigraphic unit, U4, is represented at all three sites and has been further confirmed by extensive drilling and trenching over the Qiantangjiang flood plain. It is a yellow-brown, sandy silt, with relatively high (but varying) sand content and a comparatively high median grain size (Fig. 2). The most distinctive feature of U4 is its rhythmitic, but twisted, contorted and convoluted bedding structure (Fig. S3b & c), a feature typical of turbulent sedimentation, in distinct contrast to U2 which was deposited in a relatively still water typical of estuary environment (Fan et al., 2014, 2015). The contact of U4/U3 in KhqS and XS-1603, or U4/U2 in the case of KHQ-14, is sharp and erosional. In sum, all sedimentary facies points to a flooding origin for U4.

Apart from sedimentary facies, diatom and foraminifera data also provide diagnostic information about the environments. CONISS cluster analysis of diatoms identified three zones for KhqS (Fig. 2). KhqS-D1, corresponding to U2, is dominated by freshwater and marine taxa, accompanied by brackish species, indicating a tidal flat condition between ca. 9,300 and 8,240 cal BP. KhqS-D2, being closely associated with U3, is characterized by a reduction in freshwater species, and increases in those indicative of brackish and marine-brackish conditions, which present a stable shallow estuary. KhqS-D3, corresponding to U4, contains microfossil assemblages characterized by mixed marine and/or brackish and shallow fresh water species.

Further examination of diatom morphology revealed that most of the marine and/or brackish diatoms from U4 are broken (Fig. 2f), in contrast to the well-preserved appearance from U2 (Fig. 2g), which indicates that they were not living in-situ.

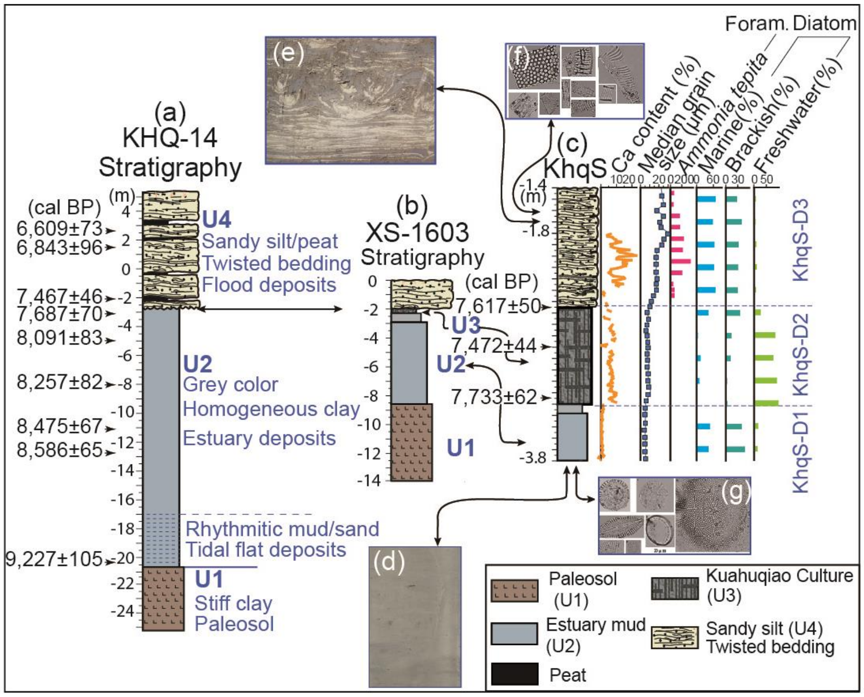

FIGURE 2. Lithosrtatigraphy and sedimentary facies of core KHQ-14, XS-1603 and KhqS profile. (a) Lithosrtatigraphy of core KHQ-14 with emphasis on sedimentary facies; (b) Lithosrtatigraphy of core XS-1603; (c) Lithosrtatigraphy of profile of Kuahuqiao site, with dataset of grain size, foraminifer and diatom; (d) Photo shows the grey colored homogeneous clay, typical of estuary deposits; (e) Photo shows the sandy silt with twisted bedding structure, indicating tidal bore deposit; (f) Photo shows diatom fragments from tidal bore deposit; (g) Photo shows well-preserved diatom from estuary deposits.

AMS ^{14}C dating of plant fragments and charred material are summarized in Table S1. Six dates were used in age-depth modelling (Fig. S4) for KHQ-14. The U2/U4 boundary was dated to be *ca.* 7,600 cal BP (Fig. 3). This is almost the same as that for the onset of U4 at KhqS (the transition is dated by two bracketing AMS ^{14}C dates, both of which yielded a calibrated age of 7,617±50 cal BP) (Fig. 2c). Based on sedimentological investigation, combined with AMS ^{14}C dating, we conclude that Qiantangjiang tidal bores started to take effect around 7,600 cal BP, when the geometry of local landscape started resembling to today.

3.2 Paleoecology and Food Production

Results from the analyses of sub-fossil pollen, spore and algae of KHQ-14 are summarized in Figure 3 (for more information refer to Fig. S6, S7 & S8). Pollen, spore, charcoal and non-pollen palymorphs (NPPs, freshwater algae and dinoflagellate cysts) counts were divided into four zones (KHQ-P1 to KHQ-P4), which correspond generally to stratigraphic units U1 to U4. The basal pollen zone KHQ-P1 corresponds with U1 of the Last Glacial age. Climatic conditions were generally cool and slightly wet during this period of time. Climate became warmer and wetter from *ca.* 9,300 cal BP according to a range of arboreal taxa. Freshwater fen conditions dominated the sedimentary environment between *ca.* 9,300 and 8,240 cal BP of KHQ-P2, roughly corresponding to U2. Increased salinity since *ca.* 8,240 cal BP is evident as indicated by the rise in the abundance of dinoflagellate cysts and foraminifera lining with less prominence of Typha. This hydrological condition continued up to *ca. 7,600 cal BP*, the entire KHQ-P3, which is closely associated with U3, overlapping the period of Kuahuqiao occupation. From around *ca.* 8,150 cal BP, abundant wild rice, inferred from the increase of smaller-sized (≤37 μm) Poaceae, probably attracted people to settle in this region, taking food security into account. During this period, the clearance of vegetation involving the use of fire by humans, may be indicated by relatively high charcoal flux values and reduction of arboreal pollen. However, saltmarshes expanded locally, immediately following occupation, at around *ca.* 7,600 cal BP, as indicated from the remains of *Spiniferites* and increased levels of Chenopodiaceae in KHQ-P4.

In summary, fossil pollen and spore data reveal a subtropical ecological environment, corresponding generally to the Holocene climatic optimum (Wang et al., 2005), which favored early Neolithic settlement and growth of rice.

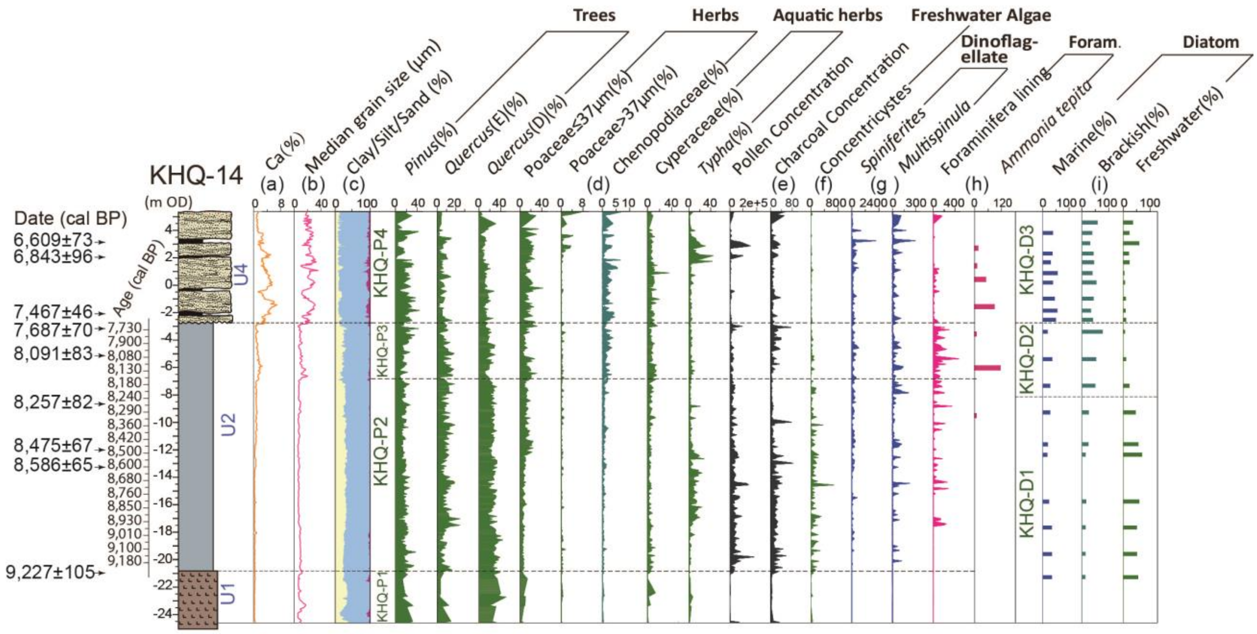

FIGURE 3. Paleoecological data from core KHQ-14. (a) Ca content obtained by XRF scanning; (b) Median grain size (μm); (c) Persentage of clay/silt/sand; (d) Pollen data; (e) Charcoal; (f) Freshwater algae; (g) Dinoflagellate; (h) Foraminifera data; (i) Diatom data.

3.3 Collapse of Kuahuqiao Culture

Had the abandonment of Kuahuqiao been attributed to direct inundation (Zong et al, 2007), it would lead to the long-standing argument: whether sea level was higher than present-day OD around 7,600 cal BP (Li et al., 2014; Zhu et al., 2003; Chen and Stanley, 1998; Zhao and Tang, 1994)? Re-construction of global sea level history suggests that sea level rose continuously since the early Holocene to current OD (Lambeck et al., 2014). Same is true for the east coast of China (Zheng et al., 2018).

A tidal bore is a series of waves that propagate upstream as an ebbing tide turns and begins to flow (Wells, 1995; Chanson, 2012). They are most pronounced during autumn tide conditions, when the tidal range is greater than 4–6 m and where the rising tide is restricted within, and resultant hydraulic jump amplified by, a narrow, relatively shallow, estuary mouth (Pan et al., 2007). The Qiantangjiang River drains into Hangzhou Bay, which today has a distinctive funnel-shape, about 100 km wide at its mouth and tapering over a distance of about 90 km to 20 km wide at the head of the bay (Fig. 1). This geometry has a major effect on incoming tidal flows, greatly increasing the tidal range between the mouth and head of the bay, leading to the generation of bores generally 2–3 m high, but at times attaining heights of well over 5 m (Zhang et al., 2014), powerful enough to cross the river bank and cause severe flooding.

A funnel-shaped coastal embayment favors the development of tide- over wave-dominated coastal processes, with the change between the two potentially being geologically instantaneous (Zhang et al., 2014). Quite possibly the initiation or increased magnitude of tidal bores associated with a proto-Hangzhou Bay around *ca.* 7,600 cal BP could have enhanced the effects of rising sea level, and at extremes the tidal bores caused devastating overbank flooding and ruined Kuahuqiao.

4 Conclusions

Kuahuqiao is important to our understanding of early settlement and food production in Asia, and serves as a perfect example of the interplay between human activities and environments in this vulnerable setting. New sedimentary data suggest that the settlement was destroyed by overbank flooding induced by catastrophic tidal bores of the Qiantangjiang River.

Initiation of Qiantangjiang tidal bores in the early Holocene resulted from the long-term morphological evolution, in response to the balance between rising sea level and sediment supply, leading to the formation of a proto- funnel-shaped Hangzhou Bay. Extreme events such as the ones that destroyed the Kuahuqiao settlement manifest a non-linear response to the complexity of forces at the interface between sea level rise and changes in coastal morphology, and provide an example of the difficulties in anticipating future conditions in highly dynamic, coastal environments in the context of global warming.

Acknowledgments

This work was jointly supported by the National Natural Science Foundation of China (U1902208, 41991323, 41672344, 41888101), the Strategic Priority Research Program of Chinese Academy of Sciences (XDB26020301), the National Basic Research Program of China (2015CB953804) and Yunnan Leading Talent Program (for H.Z.). Thanks go to Prof. Zhongli Ding and Prof. Sumin Wang from Chinese Academy of Sciences for initiating the projects.

Data Availability Statement

All the data presented in this paper are available via the Mendeley database (http://dx.doi.org/10.17632/5y68nd4jnv.1).

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