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RESEARCH ARTICLE

Zhidanyuan sluice of Yuan-dynasty, Shanghai area of Yangtze delta: Discussion of its abandonment

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Abstract The present study examines the rise and fall of the sluice of the Yuan dynasty (1279–1368 AD) unearthed in Zhidanyuan, Shanghai, by means of radiocarbon-dated sediment profiles, sedimentary facies indices and the historical literatures. Magnetic fabric parameters of sediment profiles help reconstruct the tidal creek setting at the sluice site. Our records evidence a fluvially-dominated hydrodynamic setting before sluice construction, but a saltwater intruded setting in the later stage. Magnetic fabric shows a stable flow direction in the upstream of the sluice, implying the fluvial deposition, while scattering flow directions downstream, suggesting interactions between the river flow and tidal currents. It is concluded that the sluice construction was primarily aimed at preventing saltwater intrusion from the Yangtze River mouth, but its operation did not fully fit the high sediment siltation in the channel that occurred after the sluice construction. This weakens significantly the role of sluice operation, leading to its abandonment eventually.

Keywords geoarchaeology, Yuan-dynasty sluice of Zhidanyuan, Palaeo-Wusong River, sedimentary environment

1 Introduction

The Zhidanyuan sluice of the Yuan Dynasty (1279–1368 AD) is located at the western Shanghai city (Fig. 1–I). The sluice is buried 6.5 m below the present ground surface (Fig. 1–II). The sluice was unearthed in the May of 2001 and has been excavated in 2002 by Shanghai Museum. The sluice was defined as a hydraulic engineering on the Palaeo-Wusong River (the former Suzhou creek), 1 km just north of the Suzhou creek, with a history of ~700 years (Fu, 2005; The Archaeology Division of Shanghai Museum, 2007). The site was evaluated as one of the ten new findings of archaeology in China in 2006.

On the basis of AMS-radiocarbon dating, grain-size test, microfossil identification, magnetic susceptibility analysis and relevant literatures, this paper attempts to reconstruct the environment change before and after the sluice construction. This would help in a better understanding of the rise and fall of the sluice in dynastic history, especially considering many sluices constructed during that time period for agricultural purposes in the Yangtze delta plain. The study can further help reconstruct the historical change of local water networks, i.e., the Wusong River, the mainstream flowing eastward to connect the Huangpu Rive into the Yangtze estuary (Fig. 1).

2 Materials and methods

Geoarchaeological investigations and sampling were carried out in the sluice site of the Yuan Dynasty, 2005. Sediment trench profiles of A, B, C, F and G were obtained, with the burial depths of 4.3–5.1, 5.1–6.7, 4.5–7.05, 4.7–6.5 and 5.02–6.27 m, respectively (Fig. 1–III). Sediment logging was made for each profile to record macroscopic characteristics such as sediment color, sedimentary textures and structures, fossil content, plant debris and root traces. Two samples were collected from the profile G for AMS-^{14}C dating at the State Key Laboratory of Nuclear Physics and Technology, Peking University. $^{14}C/^{12}C$ ratios were measured for the age determination, and $\delta^{13}C$ was assumed to be −25 ‰ for the plant samples. The conventional dates were calibrated (cal. AD) by using the Calib Rev 5.1 (beta) program (Stuiver and Reimer, 1993).

Samples of the profiles A, B, F, and G were taken for grain size, magnetic susceptibility and foraminifera

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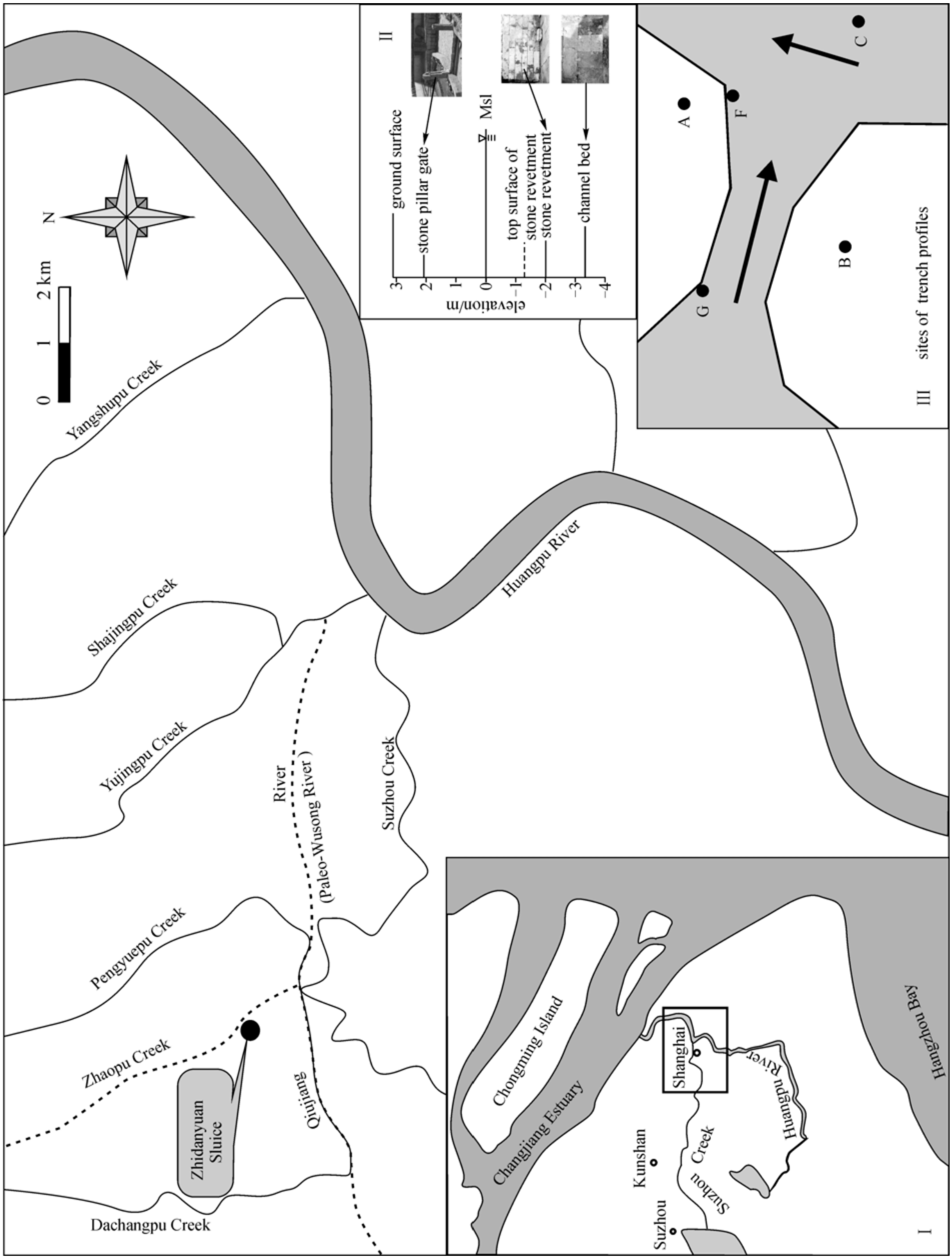

Fig. 1 Geographic site of the Zhidanyuan sluice (Dash line representing the Zhaopu creek and palaeo-Wusong river. Inset I–Yangtze delta plain; II–burial depth of sluice under mean sea level (elevation based on Wu-Song datum plane); III–sites of trench profiles (A, B, C, G, F). A–sediments after sluice abandonment; B–sediments before sluice construction. Note that the sediment depth of A and B can be laterally continuous; C and F–downstream sediments after sluice construction; G–upstream sediments after sluice construction)

analyses. Grain size and foraminera analyses were also applied to the profile C. Totally, 78 samples were taken for grain-size analysis, as well as foraminifera analysis, and 29 samples were tested for anisotropy of magnetic susceptibility. Grain-size samples were taken at 10-cm interval and were tested by Coulter LS13320 laser particle size analyzer, with a measurement range of 0.04–2000 μm. Samples for foraminifera analysis were taken with 10-cm interval for each profile. H_2O_2 solution (15%) was added into 50 g dried sample in order to make the sample fully dispersed. Then, the samples were sieved by using a 280-mesh sieve to keep the coarser materials ready for foraminifera identification. Selected samples were dried in the oven, placed into settling crucibles filled with carbon tetrachloride (CCl_4, density: 1.59) and remained stable after well stirred. Foraminifera were obtained by filtering CCl_4 through a filter paper fixed in a funnel. After drying, foraminifera were identified under binocular stereomicroscopy.

Samples for magnetic analysis were retrieved from each profile at 20-cm intervals using plastic boxes with a diameter of 25 mm. Samples were tested for anisotropy of magnetic susceptibility by a KappaBridge HKB-1 susceptibility meter in Nanjing Geology and Mineral Resources Institute.

3 Observation

3.1 AMS-^{14}C ages and sluice life

The AMS-^{14}C dates of the profile G are shown in Table 1. Plan debris buried at 5.6–5.9 m (0.6–0.9 m above the slab at the channel bed, Fig. 1) is dated about 1351–1390 Cal. AD. The bottom date of profile G is inferred to be around 1325 AD, considering the chronology of 1325 AD when the sluice was constructed (The Archaeology Division of Shanghai Museum, 2007). From above two dates, we can see a rapid siltation (about 0.9 m thick) occurring in the river channel in the upstream of the sluice. It is thus inferred that the sluice operated only for a short time period. This is further confirmed by the literature records in the Baoshan County Annals[1)], in which the sluice was operational only for ~20 years (Fu, 2005). As is also recorded in Sanwu Water Conservancy, the sluice had been already abandoned for a period by 1364 AD and a wide area of siltation appeared[2)]. In addition, an age (plant debris used for dating) at the profile depth of 5.52 m (0.98 m above the slab at the river-channel bottom) is 1638–1672 AD, about 300 years after the construction of the Zhidanyuan sluice.

3.2 Grain-size characteristics pre- and post-sluice construction

The profile B represents the river channel sediments of pre-sluice construction. Silt is a dominant component (~60%–80%) with the mean grain size of ~40–50 μm (Fig. 2–I), while the contents of clay and fine sand are of only about 15% and 10%–35%, respectively. Thin sandy layers occur at the profile depth of 5.1–6.2 m, occasionally.

The profiles G and F of post-sluice construction are sited at the upstream and downstream of the sluice. They are mainly composed of silt (~80%) (Fig. 2–II, III). Fine sand and clay share a content of ~10 %, respectively. The mean grain size (~30 μm through the profile) of the two profiles remains lower variability. But there is a coarsening sediment trend at the depth of 5.6–5.9 m of the profile G with mean grain size of 40 μm (Fig. 2). The silt sediment and grain-size nature of the profile C downstream of the sluice are similar to those of the profiles G and F (Fig. 1–III).

The profile A represents post-sluice deposition. The sediment is finer than the profiles B, F, and G, with the mean grain size of 18–25 μm (Fig. 2–I). The content of clay increases to about 20%–30%, while fine sand reduces below 5%.

3.3 Magnetic parameters pre- and post-sluice construction

The corrected anisotropy degree (P) which is able to reflect the preferred direction of unconsolidated sediment transport is primarily controlled by the intensity of depositional dynamics and the stability of sedimentary environment. Generally, a higher value of P suggests a stable depositional environment with relatively high flow energy where sediment particles are well arrayed, while a lower value of P indicates an unstable depositional environment (e.g.

Table 1 AMS-^{14}C dates of profile G

sample location	burial depth/m	materials	conventional ^{14}C age /(a BP)	calibrated age /(Cal. AD)	probability
profile G	5.52	plant debris	240±35	1638–1672	0.6025
				1778–1799	0.3249
profile G	5.6–5.9	branch with diameter of ~2 cm, length of ~30 cm	635±40	1292–1319	0.4
				1351–1390	0.6

1) *Baoshan County Annals*, vol 4, *Water Conservancy*, Guangxu version, index in Fu, 2005
2) (Yuan dynasty) Zhou Wenying, *Zhou Wenying Scripts*, 3, indexed in *San Wu Water Conservancy*, vol 3, edited by Gui Youguang (Ming dynasty)

turbulence) with lower flow energy where sediment particles are arrayed disorderly. The magnetic lineation (L) can reflect the degree of alignment of sediment particles with their long axis to be able to indicate the intensity of depositional dynamics. A higher value of L implies stable current, while a lower L means the opposite situation. The magnetic foliation (F) reflects the extent of the face-like distribution of sediment particles. Well-laminated sediments usually have a high value of F and vice versa (Hrouda, 1982). The magnetic ellipsoid shape (q) negatively correlated to the homogeneity of sediment and to aligned extent of sediment particles can be regarded as event deposition. In general, a q value of < 0.5 implies fluvial sedimentary setting (Liu et al., 1994; Chen et al., 1998).

P and F of the profile B of pre-sluice construction is relatively high in the upper sediment section (> 1.06, in general) and further increases downwards (Fig. 2), while L and q lower to 1.02 and 0.3, respectively. P and F of the profile F of post-sluice construction are correlated insignificantly, while F and L keep in an opposite direction, both fluctuating around 1.02 (Fig. 2). The value of q is about 0.5, with some greater than 0.7. The magnetic fabric parameters of the profile G differ obviously from other profiles (Fig. 2), showing changes of P, F and L with same trend, except the bottom section. P and F are mostly greater than 1.06, while L and q are relatively low, and especially q is lower than 0.4.

P and F of the profile A of post-sluice construction fluctuate around 1.04–1.06. L and q are low overall. L is below 1.02, and q is lower than 0.5 throughout. At the profile depth of 4.65 m, P and F decrease abruptly. In the meantime, L and q reach their highest values in the whole profile with the q value far greater than 0.7.

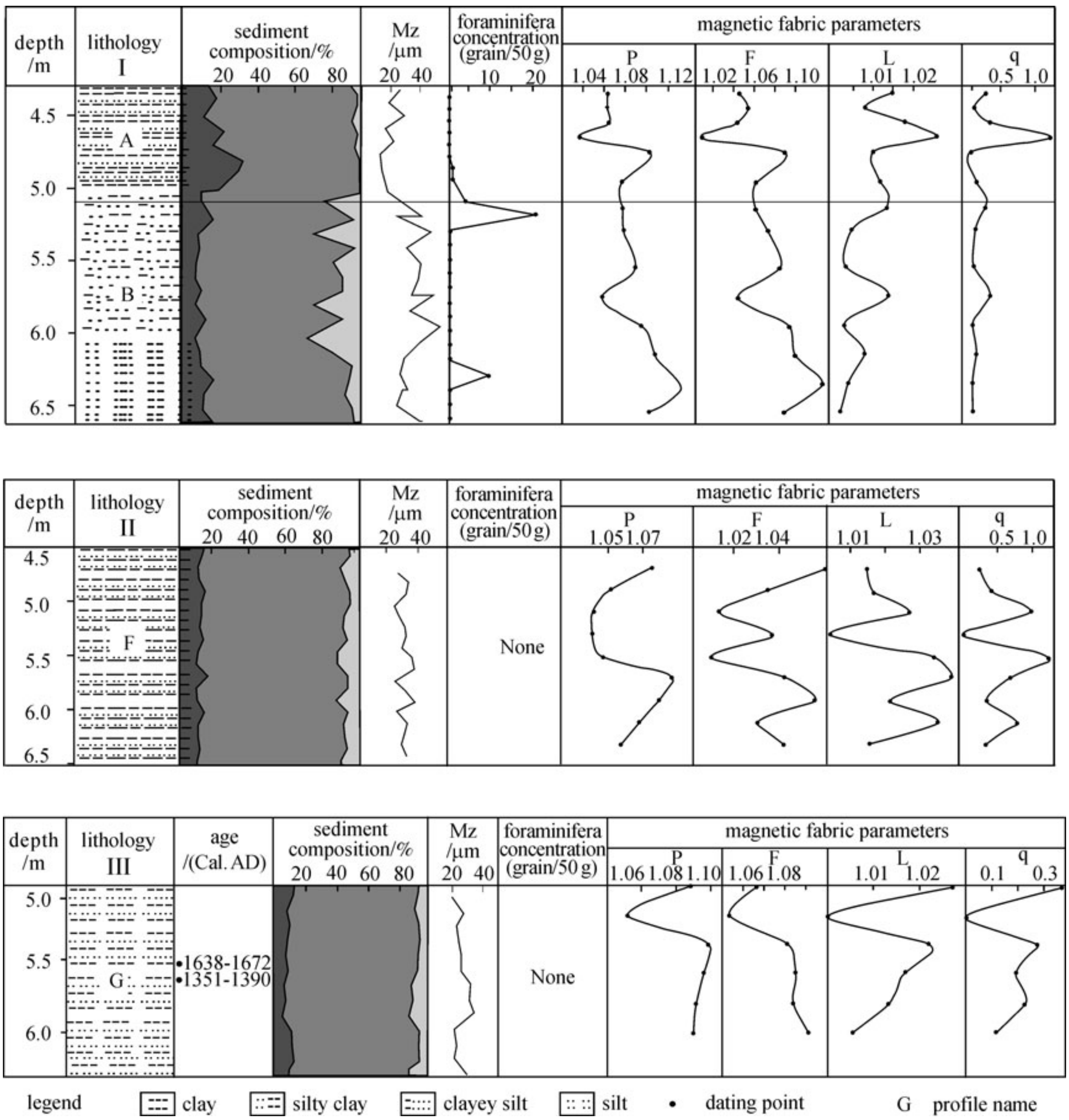

Fig. 2 Sediment profiles of A + B (I), F (II), and G (III) (Profile C was not measured for magnetic fabric, so it is not shown in the figure)

3.4 Reconstructed paleo-flow current directions

Paleo-flow current directions of each sediment profile were reconstructed on the basis of declination of the maximum susceptibility (Ellwood, 1978; Cong et al., 1990; Zhang et al., 1997) (Fig. 3). Results show that the paleo-flow current in the profile A is primarily heading west but, occasionally, southeast. The paleo-flow current in the profile B remains in bidirectional, i.e. NNW and SE. The paleo-flow current in the profile F seems to be scattering, but the one in the profile G is more east-, southeast- and southward.

3.5 Distributions of foraminifera

Foraminifera (about 10–20 in per 50 g) were found in the lower sediment sections (5.3 and 6.4 m) of the profile B (Fig. 2), and their species is too small to identify, and also due to abrasion. Sporadic foraminifera were also found at the bottom of the profile A. No foraminifera appear in the sediments of the profiles F and G, deposited after the sluice construction. A few foraminifera appear at the depth of 6.8 m of the profile C.

4 Hydrodynamics of river-channel and the cause of sluice construction and abandoning

Previous study on magnetic fabric suggests that P and F of riverine sediment from the Yangtze basin are larger than 1.02, while the values of L and q are relatively low (<1.01 and 0.5, respectively) (Zhang and Li, 2003; Zhang et al., 2008; Chen et al., 1998). P and F of a tidal flat setting are relatively high, and L (>1.02 in general) is usually higher than the value of fluvial setting. The value of q stays around 0.6.

P and F of the profile B are generally high (>1.02; Fig. 2) and decrease upwards. The value of L in the bottom sediment section of the profile B is below 1.01, while in the upper sediment section, L remains at 1.005–1.015. The value of q in the lower profile B is all smaller than 0.5, while keeping the increase upwards. All these suggest a riverine depositional environment, with relatively stable hydrodynamics in the early stage before sluice construction, but strong tidal influence happened in the later stage in this area as recorded by the paleo-flow current (Fig. 3). Taking into account the stratigraphic contact (Figs. 2 and 3), the sediments of the profile B are considered to be deposited before sluice construction, approximately in the Tang and Song dynasty. Wang et al. (2002) and Zhang and Lu (2007) have revealed that there were abundant rainfalls on the eastern China coast during the time period of the Tang and Song dynasty, which provided richer freshwater sources for the Paleo-Wusong River (Fig. 1). This is reflected by the strong river-channel hydrodynamics indicated by the coarsest grain size and magnetic fabric parameters in the profile B (Fig. 2). However, the Paleo-Wusong River gradually declined as the tidal intrusion increased with the time before sluice construction. This can be supported by the occurrence of foraminifera that appear only at the upper sediments of the profile B (Fig. 2).

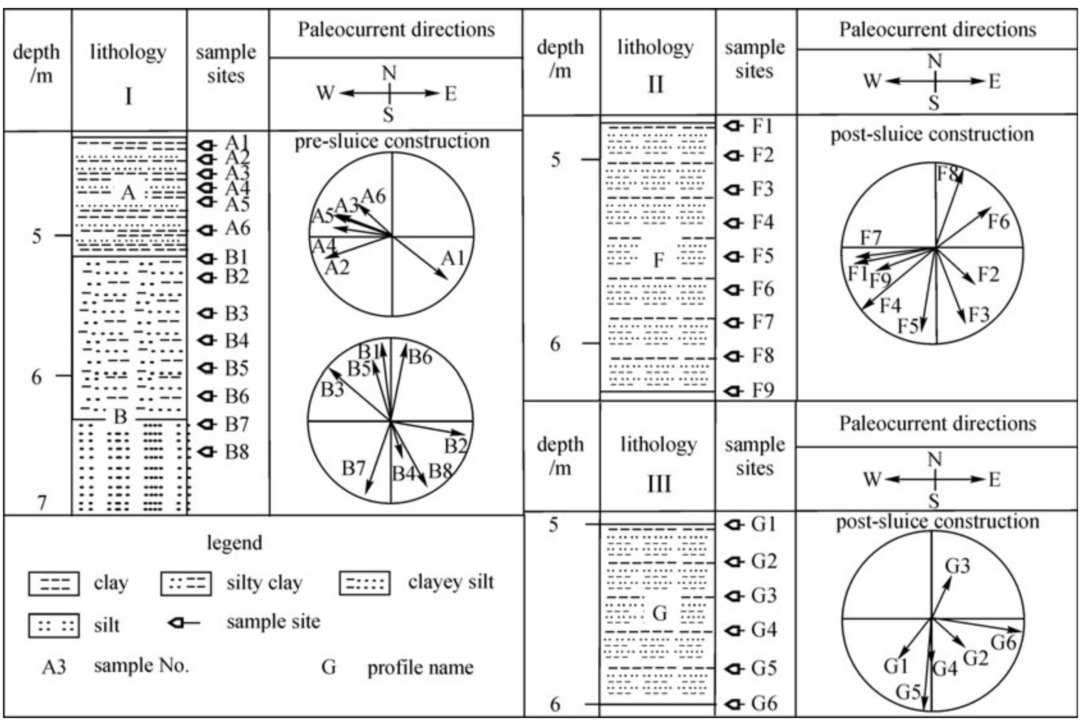

Fig. 3 Simulated paleo-flow current directions for sediment profiles A, B, F, and G

The evolution of Paleo-Wusong river was also affected by the Yangtze River sediments. Previous study shows that a large amount of the Yangtze sediments had been silted on the coast to build up the delta plain since the mid-Holocene (Xu et al., 1985; Chen et al., 1988). The Paleo-Wusong River was also silted from the Yangtze sediment loads since then. The siltation of the Paleo-Wusong River was associated with tidal intrusion. History literatures reveal that severe siltation had happened in the study area in the Song Dynasty (960–1127 a BC)[1)–3)] and became even worse in the Yuan Dynasty (1279–1368 a BC)[4)], causing difficulties for discharging freshwater into the estuary. This makes the rapid siltation in Wusong River, which needs to be dredged for navigation and farming purposes. Consequently, it became necessary for sluice construction to prevent from siltation through tidal intrusion. Actually, there were many sluices constructed during the Yuan Dynasty, and Zhidanyuan sluice (named as Zhaopu sluice) is one of the sluices by Mr. Renfa Ren, a famous hydrologist in the Yuan dynasty. As literature recorded, there were more than six sluices built in the study area for the purpose of minimizing siltation[5)].

As above-mentioned, there is no good consistency among P, F and L of the profile F in the downstream of the sluice (Fig. 2). Here, L and q (1.02 and >0.5) show an unstable depositional setting, most likely in association with tidal intrusion (Zhang et al., 2008). Sporadic foraminifera that appeared in the profile C also support this argument (Fig. 2). The relatively high value of P and F in the profile G, together with lower L and q, can indicate unidirectional fluvial flow above the sluice.

Reconstructed paleo-flow currents also revealed the dominant fluvial flow heading southeast above the sluice (Fig. 3) and the multi-directional flow currents below the sluice in association with tidal intrusion. This shows the success of the sluice construction. However, the radiocarbon-dated profile G and historical literature suggest that the sluice was operational only for about 20 years (Table 1). Heavy siltation in the river channel above the sluice was probably the major reason, e.g. the coarse sediment in the profile G (burial depth of 5.6–5.9 m, ~0.6–0.9 m above the bottom of the river bed) can be related to the river flooding event. In addition, the study area suffers from heavy storm (typhoon) rain and semi-diurnal tides. It is presumable that the sluice could be operational for a limited time a day. When storm rains and spring tides occur at the same time, abundant slack water in the Wushong River can not be effectively expelled into the estuary, causing tremendous siltation in the river channel, and thus weakening the role of sluice. This is also the reason that Paleo-Wusong River was abandoned to be replaced by the Suzhou creek that was channelized artificially in recent history[6), 7)].

Grain-size analysis of the profile C, F and G shows finer sediments (mean grain size, 30 μm) of the post-sluice river channel (Fig. 2–II, III) than that (~40–50 μm) of the profile B of pre-sluice river channel sediment. These illustrate the weakening trend of the hydrodynamics of the Paleo-Wusongjiang River after sluice construction. Furthermore, we argue that the morphology of the study area also contributed to the siltation of the river and associated abandoning of the sluice. Since there is an extremely flat topography in the lower Yangtze delta coast, this leads to the river channel silted easily in the delta plain (Xu et al., 1985; Chen and Stanley, 1998).

According to the radiocarbon dates, the sediment profile in the upstream of the sluice was mostly deposited in recent 300 years, while sediment accumulation during 1351–1390 Cal. AD and 1638–1672 Cal. AD was relative small (Table 1). So, we can infer that the sluice was closed all the time after its abandonment, and sandy sediment can not be brought in the upstream channel. Finer sediment of the profile A above the sluice can be attributed to the reduced discharge and sediment sources caused by artificial diversion projects of the Wusongjiang River in the late Ming Dynasty.

5 Summary

The sea level on the Yangtze coast is obviously rising, which is threatening the societal sustainable development and human habitation, especially taking into consideration the global temperature warming and human impact (Li et al., 1998). The rising sea level will intensify tidal intrusions and associated hazardous events both from land and open marine, which will force to re-plan and re-structure the human resources on the delta coast. The present study would provide an example from a geoarchaeological point of view to help our better understanding of homogeneity between nature and human in the future development.

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