

Response of rice cultivation to fluctuating sea level during the Mid-Holocene

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Archaeological analysis of a section of ancient rice fields at Tianluoshan for diatoms, seeds and phytoliths has shown that the highest local sea level in eastern China during the Holocene appeared before 7.0 ka BP. Entering the Mid-Holocene, as seawater regressed, a vast wetland plain appeared in the coastal area, where farmers of the Neolithic Hemudu culture cultivated rice. However, there were still several sea-level fluctuations in the Mid-Holocene, of which the biggest were from 6.4 to 6.3 ka BP and from 4.6 to 2.1 ka BP. In addition, in the period dominated by wetland grass vegetation, 6.3 to 4.6 ka BP, smaller fluctuations apparently pushed the coastline back on to the land. Even though the sea-level rises associated with these shoreline transgressions did not have the intensity of the highest sea level period, there still would have been profound impacts on the lives and production activities of people living in the region. Archaeological evidence from ancient rice fields at Tianluoshan shows that larger sea-level rise events pushed seawater onto the land and inundated large areas of rice fields, whereas weaker sea-level rise events resulted in the intrusion of seawater along rivers, causing an increase in soil salinity and a decrease in rice yields. The impact of sea-level rise on rice cultivation caused changes in local diet. In regions where rice production fell, the prevalence of gathering and hunting rose. High sea levels in the early Holocene imply that the origin of rice cultivation in the eastern coastal plain is likely to have been in small nearby mountain basins.

eastern China, Mid-Holocene, Hemudu culture, Tianluoshan site, rice cultivation, sea-level rise

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At the end of the last glacial period (dated from 18 to 15 ka BP), as continental ice sheets quickly ablated and global sea levels rose, the gradual transition to the Holocene (post glacial) epoch occurred with a series of climatic fluctuations. Significant sea-level rise happened in the early Holocene, although there are many opinions on the magnitude, process, and rate of sea-level rise [1]. Relatively rapid sea-level rise continued until 7.5 ka BP, after which there was a general falling trend in the rate of sea-level change; however, fluctuations continued [2].

Most coastal areas in China have records of transgressions caused by sea-level rise in the Holocene. However, there are some local differences in the recognition of peak transgressions and the process of regressions because of

regional differences in geological structures, paleotopography and depositional patterns from rivers and ocean currents [3]. For example, in the lower regions of the Yangtze River, the peak of transgression appeared between 7.5 and 7.0 ka BP, during which time the vertices of the estuary advanced to the areas between Zhenjiang and Yangzhou. Since then, the rate of sea-level rise has decreased and the rate of river deposition has increased resulting in the infilling of the huge estuary with a great deal of sediments, and the development of a delta [4,5]. The improved ecology of the delta provided suitable environments for lush vegetation and a rich faunal community. As a result, a series of Neolithic cultures prospered there. In succession, these were the Hemudu, the Majiabang, the Songze, and the Liangzhu cultures (from 7.0 to 4.0 ka BP). Most of the coastal archaeological sites in this part of China have generally low eleva-

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tions, with some even lower than present-day sea level.

The Yangtze Delta has developed since the Mid-Holocene providing a suitable environment for the establishment of Neolithic cultures. Geographic features and their evolution also affected the survival of communities and the development of living environments. After the Mid-Holocene, intermittent transgressions resulting from fluctuations of sea level led to environmental changes that might be one of the most important factors affecting the prosperity or decline of specific Neolithic cultures [6,7]. The patterns of settlements and migrations in the Neolithic age are closely related to sea-level rise between 7.0 and 4.0 ka BP. For example, settlements waned considerably, possibly due to further marine inundation combined with cold climate [8]. In contrast, there are some examples where significant cultural developments were not in response to sea-level rise. This is particularly the case during the period between 7.0 and 5.0 ka BP when high sea levels did not occur in the Yangtze Delta [9].

Rice cultivation is one of the most important identifiable characteristics of the Neolithic cultures in eastern China. However, the understanding of the prehistoric rice cultivation is limited by the lack of palaeoenvironmental research. Therefore, multidisciplinary studies of the palaeoecology of archaeological sites are very important for studying the origin and development of rice cultivation, and its relationship to the diet of early societies [10]. The early and later rice fields of the Hemudu culture found in the Tianluoshan site, date from 7.0 to 6.4 ka BP and 6.3 to 4.6 ka BP, respectively [11]. The stratigraphic section, showing interbedded aqueous sediments and rice fields, reflects the environmental changes since the Mid-Holocene that have affected rice cultivation in the coastal areas. Such sediments are important for studying the response of prehistoric cultures to changes of sea level during the Holocene.

1 Materials and methods

(i) Occupation site. The Tianluoshan site is located in Xiangao, Yuyao, Zhejiang, China, in the Yao River valley. It is located 30–40 km inland from the coast of the East China Sea, and is surrounded to the north by offshoots of the Siming Mountains (Figure 1). The archaeological site is found at Tianluoshan, a small hill that is approximately 5 m above sea level. Presently, rice fields in the region around the hill are located at 2 m above sea level. The occupation site was excavated by the Zhejiang Provincial Institute of Relics and Archaeology, and divided into early and later cultural periods dating from 7.0 to 6.5 ka BP and from 6.5 to 5.0 ka BP, respectively. Many artifacts have been recovered from this site, including pottery and tools made of stone, wood and bone. A large number of upright wooden piles indicate that dwellings were adapted to a wetland environment. Due to the good preservation of anaerobic conditions, large amounts of organic remains have been found.

Evidence of predominantly wild fauna includes bones from such animals as buffalo, deer, pig, and fish. Seed and fruit remains include: rice, acorns, hog plum, peach, mume apricot, water caltrop, and foxnut. These provide evidence of a mixed economy comprised of hunting and gathering and rice cultivation. The sediment cores indicate that the occupied site was approximately 30000 m² in area [12].

(ii) Trenching the rice field. While excavating at the Tianluoshan archaeological site, the rice fields associated with the occupation site were investigated in a region extending over an area of 14.4 ha. The analysis of stratigraphy, phytoliths, and seeds for coring samples from the region showed that two rice field strata were distributed in the vast area around the occupation. The area of rice fields could have covered 6.3 ha for the early period and 7.4 ha for the later period. These rice fields were confirmed by a recent 350 m² excavation. The excavation locations were about 400 m southwest, and about 70 m west, respectively, of the occupation site. These were the first rice fields discovered in association with the Hemudu Culture. Many seeds were recovered from the rice field strata, including rice and field weeds. In addition, wooden artifacts, pottery shards, and a path were found, giving some indication of the farmers' rice cultivation activities [11].

(iii) Materials. Sixty-one soil samples for analysis of seeds, phytoliths, and diatoms were taken from the southern section of trench T705 from the rice fields, which was about 70 m west of the Tianluoshan occupation site. At this location, the early and the later rice fields lie buried at depths between 95 and 180 cm, and between 255 and 295 cm respectively. Samples were taken at regular 5 cm intervals between depths of 45 and 355 cm. Each sample was about 2000 mL in volume.

(iv) Analysis of phytoliths. Soil samples (50 mL) were dried in a convection oven at 100°C, and after calculating their volume weights, were mechanically crushed. A 1 g sample of soil and 300000 glass beads (40 μm) were moved to a 12 mL sample bottle. 10 mL of water and 1 mL of 5% sodium silicate were added, then the sample was vibrated in an ultrasonic cleaner (38 kHz, 250 W) for about 20 min to separate the particles. Using Stokes' Law, the sample was filtered in water to remove particles less than 20 μm in diameter, then dried again. Using the EUKITT® mounting medium, the filtered sample was distributed uniformly on a microscope slide to facilitate the investigation of phytoliths densities. After being magnified 200 times under a microscope (Nikon E600), the phytoliths and glass beads were counted in the same field of vision (300 glass beads at least), and the densities of phytoliths were calculated in comparison to the weight of soil samples, the number of added glass beads, and the number of observed phytoliths and glass beads.

(v) Analysis of diatoms. For each sample, 3 mL of soil were moved to a 100 mL beaker. Six mL of 35% H₂O₂ was added, and after the reaction had finished, the sample was moved to a 15 mL polypropylene boiling tube. The sample

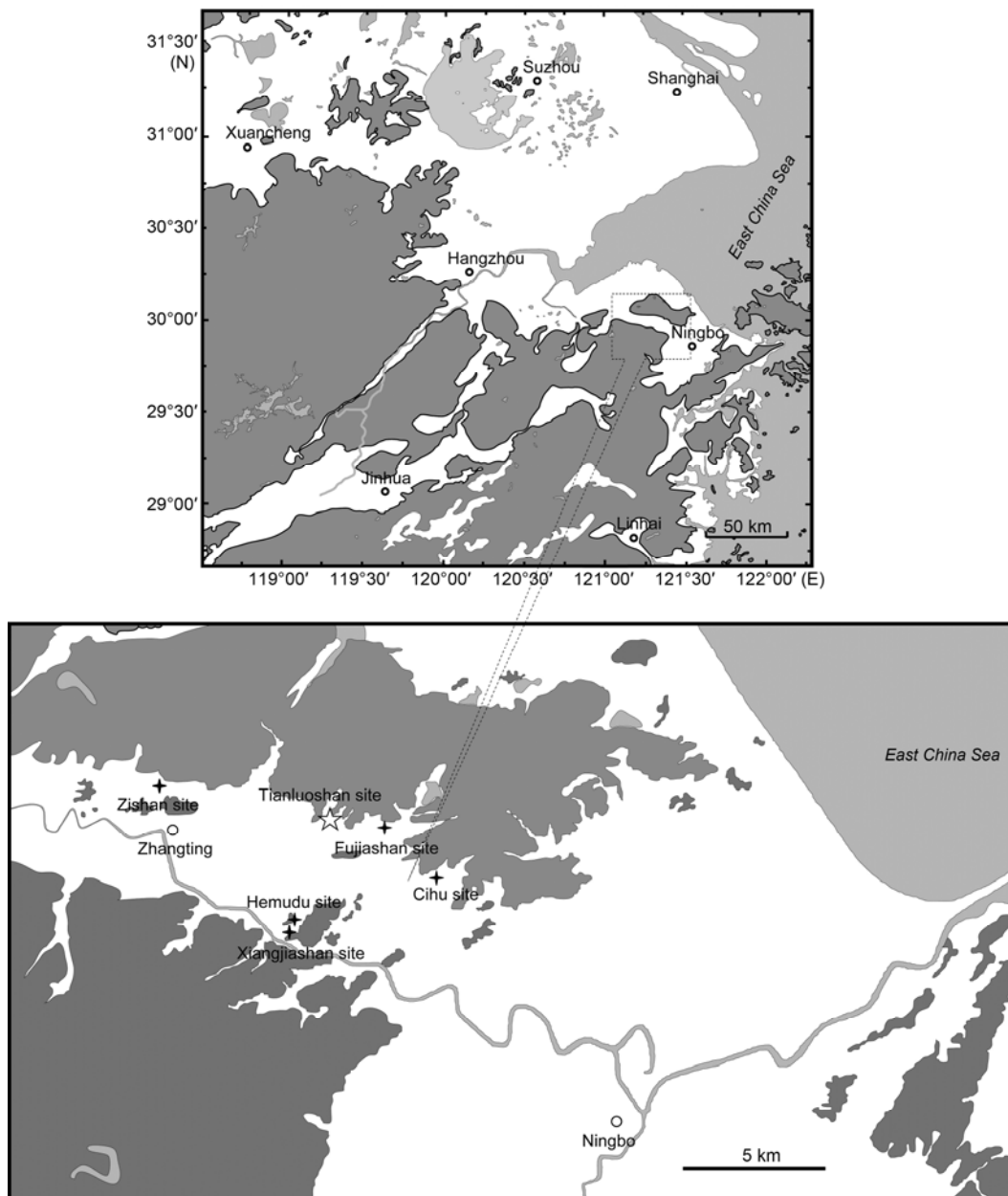


Figure 1 Geographic location of Tianluoshan site.

was washed, centrifuged (2000 revolutions per minute for 2 min) and decanted until the liquid was clear. Using a mounting medium[®], the filtered sample was distributed uniformly on a cover glass and dried to facilitate the investigation of diatoms and their densities. After being magnified 600 times under a microscope (Nikon E600), the diatoms were identified and counted (400 diatoms at least), and the densities and percentages of each diatom species were calculated.

(vi) Analysis of seeds. A 100 mL sample of soil was moved to a 1000 mL beaker, and 500 mL of 5% NaHCO₃ were added. The sample was placed in a 70–80°C water bath for 3 h, during which time the sample was stirred well to separate soil particles. The sample was then washed through a sieve (Φ340 μm) until the water was clear. The

remaining sample was investigated for plant seeds with a stereo microscope (Nikon SMZ1000).

(vii) Radiocarbon dating. Selected plant seeds or remains, by immersion of the soil samples, were sent to the Peking University AMS Laboratory to determine radiocarbon age, using the accelerator mass spectrometry (AMS) method. Dates were calibrated with the Oxcal 3.10 and INTCAL 104 curve.

2 Results

2.1 Stratigraphy of trench T705

The southern section of trench T705 was divided into 13

stratigraphic layers numbered sequentially from top to bottom (Figure 2). Layer 1 corresponds to the modern paddy field which is about 20 cm thick and consists of gray silty clay. Layer 2 is about 25 cm of gray-yellow silty clay, containing impressive pottery shards. Layer 3 is about 35 cm of grayish yellow silt. Layer 4 is about 15 cm of dark brown clay and peat, containing abundant plant remains such as reed stems and leaves. Layer 5 is about 25 cm of brown clay loam, containing plant remains and a small number of pottery shards of the later Hemudu culture. Layer 6 is about 15 cm of gray clay, containing many plant stems, leaves and other organic material. Layer 7 is about 45 cm of grayish brown clay, containing plant remains, a small number of the pottery shards of the late Hemudu culture, and the handle of a farm tool. In the same layer in both trenches T703 and T803, a convex arc uplift resembling a rice field ridge 20–30 cm high and about 50 cm wide, was found. Layer 8 is about 75 cm of gray clay containing an aqueous sedimentary layer. Layer 9 is about 10 cm thick and, similar to Layer 6, contains a large number of plant stems, leaves and other organic material. Layer 10 is about 15 cm thick and, similar to Layer 9, contains a small amount of early Hemudu culture pottery; specifically, two wooden dibbles and one wooden knife were unearthed. Layer 11 is about 15 cm of gray-brown peat-like deposits with rich plants remains. Layer 12 is about 25 cm of gray clay with abundant reed stems, leaves and other organic material. Finally, Layer 13 lies below 320 cm, and consists of an aqueous deposit of gray silt. According to soil properties like color and the presence of plant remains, the strata at depths below 45 cm can be roughly divided into five characteristic zones. Zone I lies below 295 cm, containing Layers 12 and 13, and is dated from before 7.0 ka BP. Zone II lies between 255 and 295 cm, containing Layers 9, 10 and 11, and is dated from 7.0 to

6.4 ka BP. Zone III lies between 180 and 255 cm, containing Layer 8, and is dated from 6.4 to 6.3 ka BP. Zone IV lies between 80 and 180 cm, containing Layers 4 to 7, and is dated from 6.3 to 4.6 ka BP. Finally, zone V lies between 45 and 80 cm, containing Layer 3, and is dated from 4.6 to 2.1 ka BP. The results of radiocarbon dating are summarized in Table 1.

2.2 Phytolith stratigraphy

As shown in Figure 3, the phytolith composition in the five soil zones was distinctive. The composition of zones I, III and V was roughly the same, with a very small number of phytoliths of *Miscanthus* and *Phragmites*, and showing obvious features of aqueous sedimentary layers. Zones II and IV were roughly the same, with many phytoliths of *Phragmites* and *Miscanthus*, indicating undulating wetland ecosystems and vegetation. Wet or aquatic plants, like *Phragmites*, were found in the lowlands, whereas plants tolerant of drought conditions, like *Miscanthus*, were found in higher places. In addition, dense phytoliths, derived from the motor cells of rice (*Oryza*) leaves, were also detected in zones II and IV. Their average densities were 9764 and 16429 grains per gram of soil, significantly higher than the 5000 grains per gram of soil indicative of rice fields. The results support the burial of rice fields in these zones.

2.3 Diatom stratigraphy

As shown in Figure 3, diatom analysis showed that the distributions of diatoms in the five zones have distinctive features.

In zone I offshore, coastal, and intertidal diatoms account for 86.2% of the total. *Conscinodiscus*, *Cyclotella stylorum*,

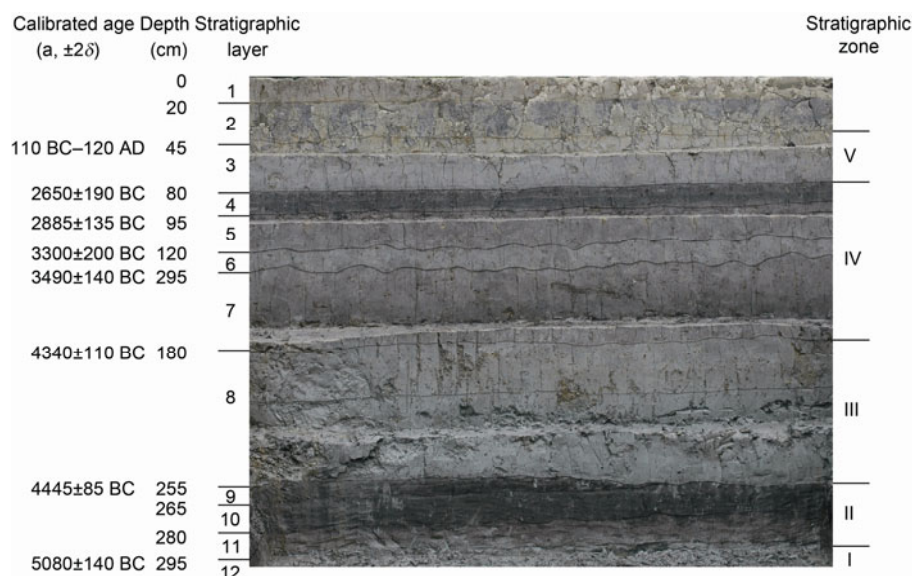


Figure 2 Southern section of trench T705.

Table 1 Chronology and the radiocarbon dates for T705 at the Tianluoshan site with AMS^{a)}

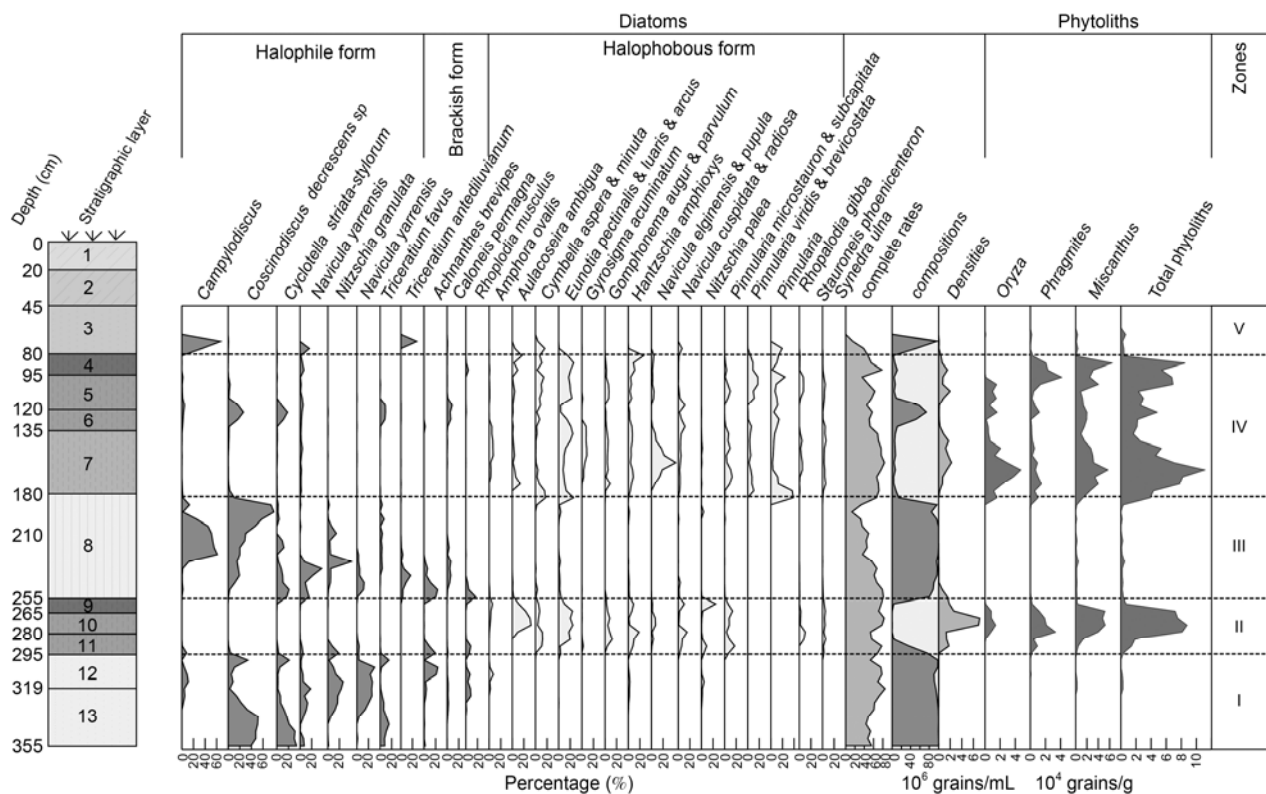
Depth (cm, below surface)	Number in the lab	Material	¹⁴ C age (a BP, ±1δ)	Calibrated age (BC, ±2δ)
45–50	BA091044	remains of plants	1990±40	110 BC–120 AD
80–85	BA091045	seeds	4020±40	2650±190 BC
90–95	BA091046	seeds	4275±40	2885±135 BC
115–120	BA091047	seeds	4585±35	3300±200 BC
130–135	BA091048	seeds	4660±40	3490±140 BC
175–180	BA091049	seeds	5465±45	4340±110 BC
250–255	BA091050	seeds	5620±35	4445±85 BC
290–295	BA091051	seeds	6120±45	5080±140 BC

a) AMS, Accelerator mass spectrometry, Peking University AMS Laboratory, calibrated by Oxcal 3.10 and INTCAL 104.

Nitzschia granulata and *Navicula yarrensii* make up more than 10% each, and collectively account for 63.0%. *Diploneis smithii*, *Triceratium favus*, *Campylodiscus biangulatus*, *Melosira sulcata* and *Nitzschia cocconeiformis* are more than 1% each, and collectively account for 19.4%. In addition, *Actinocyclus normanii*, *Actinoptychus vulgaris*, *Bidulphia tridens*, *Diploneis weissflosii*, *Grammatophora oceanica*, *Navicula marina*, *Roperia tessellata*, *Tryblioptychus cocconeiformis*, *Thalassionema nitzschioides*, and other species have been identified. Estuary diatoms account for 8.6% of the total, including *Achnanthes brevipes* and *Rhoplodia musculus*. Fresh water diatoms account for less than 5% of the total.

Zone II is dominated by freshwater diatoms, accounting for 87.8% of the total. *Aulacoseira ambigua* and *Eunotia pectinalis* are more than 10% each, and collectively account for 32.1%. *Pinnularia microstauron* and *Hantzschia amphioxys* are more than 5% each, and collectively account for 13.5%. *Nitzschia palea*, *Navicula radiosa*, *Synedra ulna*, *Navicula pupula*, *Gomphonema parvulum*, *Cymbella minuta*, *Cymbella aspera*, *Gomphonema augur*, *Amphora ovalis*, *Eunotia luaris*, *Rhoplodia gibba*, *Navicula mutica* and *Pinnularia subcapitata* are more than 1% each. Offshore, coastal, and intertidal diatoms account for only 12.2% of the total.

Zone III is dominated by offshore, coastal and intertidal diatoms, which account for 80.6% of the total. *Conscindiscus*

**Figure 3** Diatoms and phytolith data from the south section of trench T705 at the Tianluoshan site.

and *Campylodiscus biangulatus* are more than 10% each, totally accounting for 43.0%. *Diploneis smithii*, *Navicula yarrensii*, *Cyclotella stolorum*, *Triceratium antediluvianum*, *Nitzschia granulate* and *Triceratium favus* are more than 1% each, totally accounting for 34.7%. In addition, *Actinocyclus normanii*, *Nitzschia cocconeiformis*, *Melosira sulcata*, *Navicula marina*, *Grammatophora oceanica*, *Roperia tessellata*, *Actinoptychus vulgaris*, *Bacillaria paradoxa*, *Diploneis weissflosii* and *Thalassionema nitzschioides* were noticed. Estuarine diatoms, mainly *Achnanthes brevipes* and *Rhoplodia musculus*, account for 8.4%. Freshwater diatoms account for only 11.0%.

Zone IV is dominated by freshwater diatoms that account for 86.0% of the total. *Pinnularia* is the most abundant, accounting for 22.3%, including *Pinnularia viridis*, *Pinnularia microstauron*, *Pinnularia brevicostata* and *Pinnularia gibba*. *Eunotia* is the next most abundant, accounting for 16.7% and mainly including *Eunotia pectinalis*, *Eunotia luaris*, *Eunotia arcus*, and *Eunotia robusta*. *Navicula* includes mainly *Navicula elginensis*, *Navicula cuspidata* and *Navicula pupil*, accounting for 9.9% in total. In addition, *Gomphonema augur*, *Gomphonema parvulum*, *Gyrosigma acuminatum*, *Aulacoseira ambigua*, *Amphora ovalis*, *Anomoeomeis sphaerophora*, *Synedra ulna*, *Stauroneis phoenicenteron* and *Aulacoseira ambigua* were noticed to make up more than 1% of the total each. Offshore, coastal, and intertidal diatoms are few, totally accounting for only 14.0%.

Zone V contains only a small quantity of a limited number of diatom species, which were only detected in the two samples near zone IV. Offshore, coastal, and intertidal diatoms include *Campylodiscus biangulatus*, *Conscinodiscus decrescens*, *Grammatophora oceanica* and *Triceratium antediluvianum*, totally accounting for 71.6%. The only estuarine diatoms identified were *Caloneis permagna*, totaling less than 1%. Freshwater diatoms accounted for 27.7%, including *Navicula cuspidate*, *Hantzschia amphioxys* and *Pinnularia viridis*.

The occurrence patterns of diatoms in the five stratigraphic zones reflect environmental alternations between intertidal and freshwater wetlands at the Tianluoshan site. Zones I, III and V are dominated by offshore, coastal, and intertidal diatoms, indicating seawater environments, and zones II and IV are dominated by freshwater diatoms, indicating freshwater wetland environments. The interbedding of aqueous sedimentary layers and rice fields might therefore be considered as environmental alternations between tidal flats and wetlands caused by the fluctuation of sea level in the coastal areas during the Mid-Holocene.

2.4 Plant seed stratigraphy

As shown in Figure 4, seed analysis shows that the compositions of plant seeds found in the five zones also had distinctive features.

Zone I, with low concentrations and only a few species

present, was dominated by salt-tolerant plants that account for 68.8% of the seeds found, including *Typha* and *Scirpus mariqueter*, whereas salt-intolerant plants, including more than ten species, like *Scirpus planiculmis*, *Potamogeton*, *Najas* and *Ischaemum* account for 33.2%.

Zone II has abundant numbers of seeds and plant species. Salt-tolerant and salt-intolerant plants accounted for 59.4% and 40.6%, respectively. Salt-tolerant plants included three species, *Scirpus mariqueter*, *Atriplex fera* and *Typha*, and salt-intolerant plants included more than 30 species, including *Scirpus juncooides*, *Scirpus triangulates*, *Cyperus compressus*, *Cyperus iria* and *Potamogeton*. The remains of rice, e.g. husk chips and short rachillae, account for 2.2%.

Zone III, contains abundant seeds but only a few species. It is dominated by the salt-tolerant plants, *Scirpus mariqueter* and *Typha*, that account for 94.0%. Salt-intolerant plants include more than 10 species, like *Scirpus planiculmis* and *Scirpus juncooides*, which in total account for 6%. Rice remains were only found in a 10 cm stratum near Zone II, accounting for 0.25%.

Zone IV, with a great number of seeds and species, is dominated by salt-intolerant plants that account for 70.9% of the total and include more than 40 species, like Gramineae, *Cyperus compressus*, *Scirpus triangulates*, *Scirpus juncooides*, *Eleocharis dulcis*, *Ceratophyllum*, *Najas*, *Potamogeton*, *Rumex* and *Polygonum hydropiper*. The remains of rice account for 30.8%. *Scirpus mariqueter* is the main salt-tolerant plant found. In addition, *Typha*, *Scirpus triqueter*, *Atriplex fera* and others were noticed.

Zone V had low numbers of seeds and species. Plant seeds are only found in a 25 cm stratum near zone IV, and consist mainly of intertidal populations, including *Scirpus mariqueter* and *Scirpus triqueter* that account for 98.6%. Some *Scirpus juncooides* was also identified.

Because of varied elevations and soaking time from place to place, the coastal mudflats of southeastern China show the characteristics of a few plant communities. The lowest, the outermost mudflats, are dominated by communities of salt algae, *Scirpus triqueter* and *Phragmites*. High tide mudflats are dominated by *Phragmites*, *Carex scabrifolia* and *Spartina alterniflora* (an alien plant). Low tide mudflats are dominated by *Scirpus triqueter* and *Scirpus mariqueter*. The seed compositions in the five zones also reflect environmental alternations between intertidal and freshwater wetlands at the Tianluoshan site.

According to the plant compositions, zones I, III and V are characterized by low tide coastal mudflats, whereas zones II and IV are characterized by wetlands or marshes. Abundant rice remains and communities of wetland plants suggest that rice fields were buried in zones II and IV. Morphological analysis of the short rachillae of rice from the rice field strata show that wild and domesticated types co-existed in both the early and later rice fields, indicating that the cultivated rice was primitive. The results are almost the same as those found from trench T1041 for the excavation

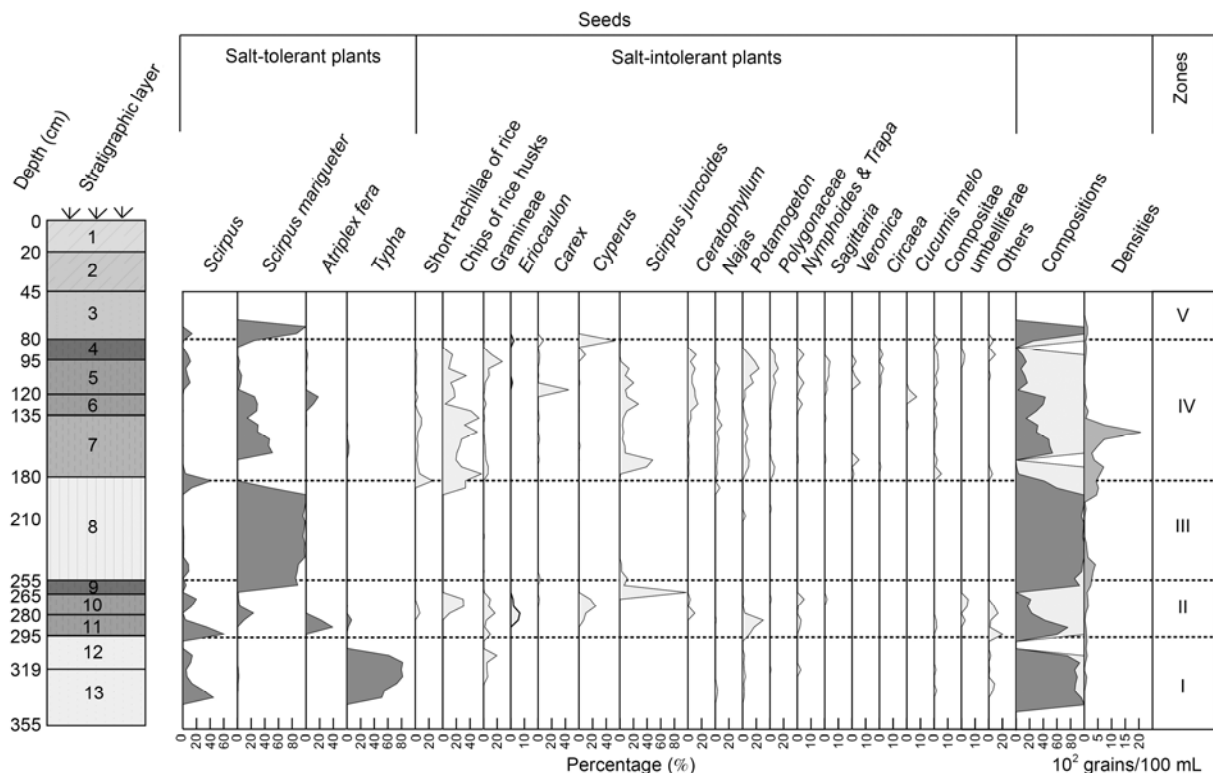


Figure 4 Plant seed data from the southern section of trench T705 at the Tianluoshan site.

of rice fields and the occupation site [11,13,14].

3 Discussion

3.1 Changes of sea level during the Mid-Holocene

There are many points of view concerning high sea levels since the Mid-Holocene in the Yangtze Delta. Yang et al. [15] considered 10 sea level fluctuations that occurred in eastern China in the last 20000 years, five of which occurred in the Holocene. The peak of the transgression appeared between 7.0 and 6.5 ka BP, when sea level was close to that of the present day. Zhao et al [16]. proposed that seven clear fluctuations of sea level occurred between 7.5 and 4.0 ka BP, with the highest of these being 2 to 3 m higher than the present level. This view has been supported by evidence from the Hangzhou Bay area [17]. Shao [18] considered that the greatest transgression in the Yangtze Delta occurred about 6.9 ka BP. The different opinions of past high sea levels in the Mid-Holocene are likely related to the geological stability and nature of observed sediments, as evidence of past high sea levels generally requires stable geological structures to be preserved in coastal areas [19].

The studies of the Tianluoshan site provide explanations for the changes in sea level in the Yangtze Delta during the Holocene. The aqueous sedimentary layers observed in trench T705 are widely distributed around the Tianluoshan occupation site [11], and there is little difference in the thickness of deposits or their burial depth. These sedimen-

tary layers were also noticed in the second excavation of the Hemudu site between 1977 and 1978 [20]. The deposits, characterized by gray mud or silt, are dominated by offshore, coastal and intertidal diatoms and salt-tolerant plant species, reflecting an intertidal mudflat environment. The analysis of diatoms and plant seeds from trench T705 suggests that there had been at least two huge transgressions in Ning-shao Plain since the regression between 7.5 and 7.0 ka BP. They were dated from 6.4 to 6.3 ka BP and from 4.6 to 2.1 ka BP. In addition, a small transgression might have occurred between 6.3 and 4.6 ka BP, as evidenced in zone IV by a thin gray layer from 120 to 135 cm, in which there were abundant halophile diatoms. The studies of the Tianluoshan site suggest that there was a fluctuating sea level, even though the process of regression began after the Mid-Holocene. As accelerating sea-level rise advanced the shoreline onto the land, parts of the coastal plain would become bays or mudflats again. Such sea-level fluctuations in the Mid-Holocene affect evaluations of the times of highest sea levels and greatest transgressions. The impacts of sea-level rise during a period of overall regression must be less than during the period of the high sea level. However, it is certain that such fluctuations in sea level would have had profound impacts on the lives and activities of people living along the coast.

3.2 Changes in rice cultivation in response to sea-level rise

During the Mid-Holocene, as regression began, the coastal region had a large number of lakes and waterways and veg-

etation was dominated by the wetland species *Phragmites* and *Miscanthus*. The improved ecological environment provided a good habitat for herbivorous animals and birds. As a result, people migrated to the region to gather wild plant resources, to hunt for mammals, fish and birds, and to reclaim wetland for rice production, thereby establishing the prosperous Hemudu Culture. As mentioned previously, the coring investigations, and particularly the analysis of phytoliths and seeds from the cores, showed large areas of early (6.3 ha in extent) and later (7.4 ha) Hemudu-period rice fields buried at depths of 95–180 cm and 255–295 cm, respectively [11].

However, the regional ecology in this area was fragile because of the influence of frequent intrusions of seawater from the nearby East China Sea. As sea level rose between 6.4 and 6.3 ka, and again between 4.6 and 2.1 ka BP, seawater advanced into the Tianluoshan area. Large areas of rice fields were submerged and became intertidal mudflats, which were flooded at high tide and uncovered in low tide, and therefore were incapable of supporting rice production. Reduction in the extent of rice fields is therefore the characteristic response of rice cultivation to large-scale sea-level rises. In addition, later rice fields at the Tianluoshan site also provide evidences for response of rice cultivation to weak sea-level rise. Abundant halophile diatoms and the thin aqueous deposit in the strata between 6.3 and 4.6 ka BP show that the intrusion of seawater along the rivers had increased the salinities of irrigation water and soil. As shown in Figure 3, the densities of rice phytoliths were 8271 grains/g between 95 and 135 cm, and 20582 grains/g between 140 and 180 cm, showing a changing trend from high to low, and a negative correlation to the concentration of halophile diatoms, indicating that the intrusion of seawater had affected rice yields.

3.3 Impacts of sea-level rise on human diet

As the ecology in the Yangtze Delta in the Mid-Holocene improved, rice cultivation became greatly developed [13,14,21]. However, the studies of the Tianluoshan site have also confirmed that rice cultivation was affected by sea level fluctuations. Because of decreases in rice field coverage or yield caused by the intrusion of seawater, there would tend to be a corresponding decrease in rice consumption of rice paired with an increase in the consumption of the foods from gathering or hunting activities, in the diet of local people.

At the Tianluoshan occupation site, plant remains other than rice, such as acorns, water caltrop, and bones from mammals and fish, were abundant, indicating that gathering and hunting were still of dietary importance. As shown in Figure 5, the relative quantities of rice, acorn and water caltrop were different from one stratigraphic layer to the next. Large fluctuations in rice were accompanied by a decreasing trend in water caltrop and increasing trends in acorn and animal bones. This result implies that increases or decreases

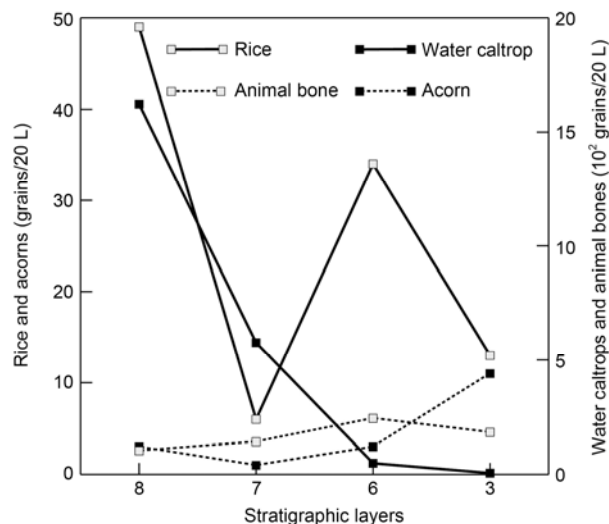


Figure 5 Quantitative changes of seeds and animal bones with stratigraphic layers of the occupation site.

in gathering and hunting activities for dietary purposes might be linked to fluctuations in rice cultivation.

In the early period of settlement in the region, there were not only large areas of wetland, but also many ponds and lakes. People reclaimed the wetland for rice cultivation, and also gathered the fruits of aquatic plants for food. As population was expanding in the area, the nearby area available for gathering decreased in extent. Therefore, any decrease in the output of rice cultivation caused by fluctuations of sea level necessitated the strengthening of gathering tree fruits in the mountains, fishing in the lakes and rivers, and hunting large animals for food. Several accumulations of gathered acorns found in later cultural periods of the Tianluoshan occupation site might be evidence of a human response to rice shortages [12].

3.4 Geographic characteristics of rice cultivation affected by fluctuating sea level

In the early Holocene, most of the lower areas of the Ningshao region were located in intertidal zones or gulfs, and often covered by seawater, so there were neither habitable lands nor large area of wetlands for rice cultivation in the area. Therefore, people living in the Ningshao Plain in the Mid-Holocene, as evidenced by rice cultivation, likely migrated there from higher topographic areas that were not be affected by seawater.

Recently, early Neolithic sites, like Shangshan and Xiaohuangshan, dating back to between 10.0 and 9.0 ka BP, have been found in the small basins of nearby hilly regions. At these sites, earthenware fragments containing abundant rice husks and dense phytoliths of rice have been unearthed. This indicates that the origin of rice cultivation in the lower regions of the Yangtze River was much earlier than the Hemudu Culture, and might be traced back to 10000 years

ago [13,22,23]. These early archaeological sites are located in hilly areas between 40 and 100 m above sea level, so it is likely that the environments of that time would be suitable for human settlement and food production. Although there was not a vast wetland available to extensively cultivate rice, the flat lands in these basins with rivers and ponds could still provide satisfactory conditions for more moderately sized cultivation efforts. In addition, morphological analysis of rice phytoliths showed that the rice from these early Neolithic sites had some of the biological characteristics of dry rice, similar to tropical varieties, indicating that the rice might be cultivated not only in wetlands, but also in higher and drier land with poor water conditions [22].

The discoveries of the early Neolithic sites in the hilly basins of central Zhejiang provide a key to the origin of rice cultivation in the lower regions of the Yangtze River, and imply that the middle Neolithic cultures located in the plains, like the Hemudu Culture, could be traced back to higher topographic areas.

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