

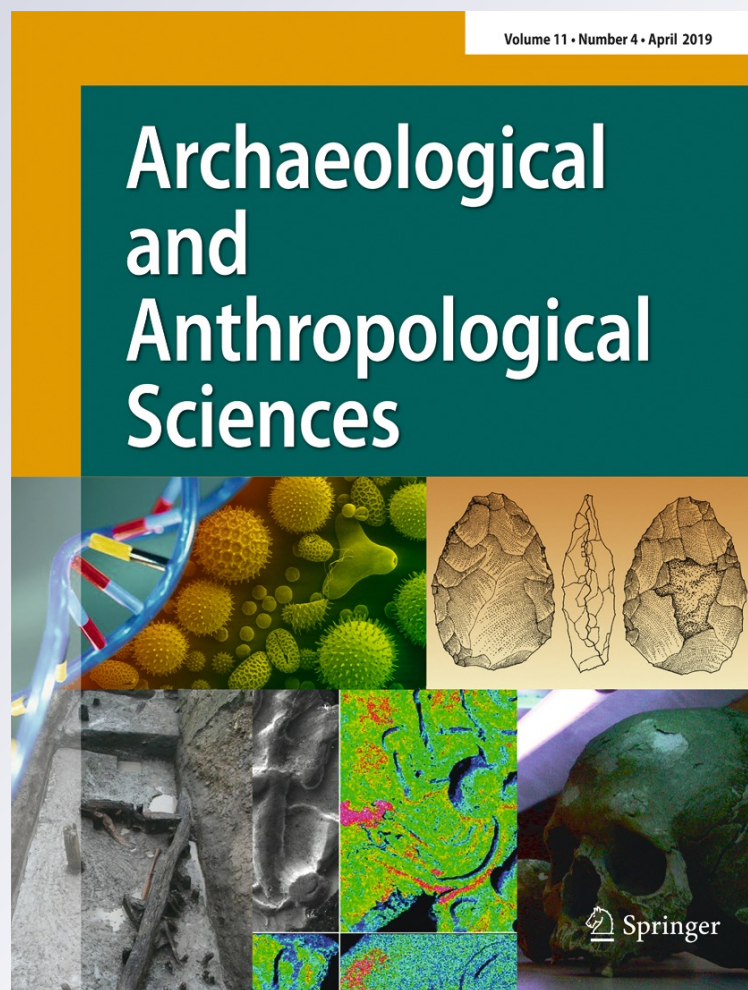
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# New evidence for rice cultivation from the Early Neolithic Hehuashan site

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## Abstract

Phytolith analysis was conducted on soil samples from an archeological profile at the Hehuashan site, located in the upper Qiantang River region, China. This paper focuses on: (1) changes on the morphometric features of *Oryza*-type bulliform phytoliths from the rice leaves of the Early Neolithic Hehuashan site, (2) human adaptations during the Early Holocene, and (3) the cultivation of rice by Early Neolithic occupants in the upper Qiantang River region. The phytolith assemblage before and during the Early Neolithic Shangshan Culture occupation of the Hehuashan site indicates a landscape composed of reeds (*Phragmites australis*), rice (*Oryza* sp.), Bambusoideae, and some woody plants. The amount of *Oryza*-type bulliform phytoliths and the number of scale-like decorations present along their margins increased from the lowest to the uppermost deposits at the site. The change in the amount and morphology of bulliform phytoliths indicates the presence of wild rice around the site at the time of human occupation, which provides evidence of a shift from the collection and possible manipulation of wild rice to cultivation during the Shangshan Culture period (11400–8600 BP).

**Keywords** *Oryza*-type bulliform phytolith · Scale-like decorations · Wild rice · Rice cultivation · Early Neolithic

## Introduction

The timing and location of the origin of rice cultivation and agriculture have not been well established. Collection and/or management of wild plants have long been an important focus of archaeological research in China (Wang et al. 2010; Zhao 2010; Zong et al. 2007). Zhao (2010) holds the view that rice cultivation began during 11,000 to 9000 BP with a full

domestication of rice at around 10,000 BP. His work is based on (a) the study of macrobotanical rice remains in conjunction with rice phytoliths, (b) the phytoliths extracted from the Xianrendong and Diaotonghuan sites, (c) the analysis of rice grains and rice husks in burnt clay blocks, and (d) the rice phytoliths unearthed from the Shangshan site. Meanwhile, Jiang and Liu (2006) put forward that the Shangshan rice was probably in an early stage of domestication based on the morphologic changes observed in the rice husks. The beginning of rice agriculture is considered to have occurred between 9000 and 7500 BP (Zhao 2010). However, Fuller et al. (2007, 2016) suggested that rice domestication took place around the seventh millennium BP, and there were at least two distinct processes around the Middle Yangtze region before 8000 BP, and subsequently in the Lower Yangtze region from 8000 to 6000 BP. In order to reach domestication, a period of prior cultivation and genetic isolation from wild varieties of *Oryza* would have taken place at an earlier time. To date, there are at least two different rice domestication areas in China, and both probably provided independent rice domestication processes along with different characteristics of archeological remains (Liu et al. 2007b). In combination with recent archeological and archeobotanical studies from the Shangshan, Kuahuqiao, Hemudu, and the Tianluoshan sites

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(Wu et al. 2014; Zong et al. 2007), it indicates the progression of the rice domestication was non-linear and lasted through much of the Early Holocene. To date, nearly no macrobotanical rice remains such as spikelet bases and rice grains, both of which were viewed as effective measure of rice domestication have been recovered dating before 10,000 BP, except for charred rice risk tempered in sintering soil and/or pottery (Jiang and Liu 2006) and a latest work on Shangshan site by Zhao and Jiang (2016) who floated and obtained two charred rice grains attributed to the Shangshan Culture. Thus, rice phytoliths could be treated as an important source of evidence to identify early rice cultivation and domestication. Regardless of the timing of the origin for rice agriculture, the area where rice agriculture in China began is considered to be in the middle and lower reaches of the Yangtze River. Based on the presence of ancient paddy fields unearthed at the Tianluoshan (Zheng et al. 2009), Chuodun (AISC 2011), Caoxieshan (Zou et al. 2000), and the Jiangli sites (Qiu et al. 2014), organized paddy field rice farming was practiced in the lower Yangtze River during the time of the Hemudu or Majiabang Cultures (7000–5800 BP) (Ding 2004). The emergence of advanced irrigation systems and field management techniques such as weeding occurred during the Songze Culture (5800–5300 BP). Large paddy fields were present in and beyond the lower Yangtze River valley during the Liangzhu Culture (5300–4300 BP) (Zheng et al. 2009).

In cases that no other types of plant macrofossils are recovered during excavation, phytoliths are considered as the most reliable indicator of plants that were present in the past. Phytoliths can resist many natural chemical and biological processes due to their silica-rich composition. As phytoliths usually represent local plants, their presence is likely to reflect the vegetation (Piperno 1988). Phytolith analysis has demonstrated its usefulness in reconstructing the use of ancient plants, including rice domestication, and reconstruction of ancient landscapes.

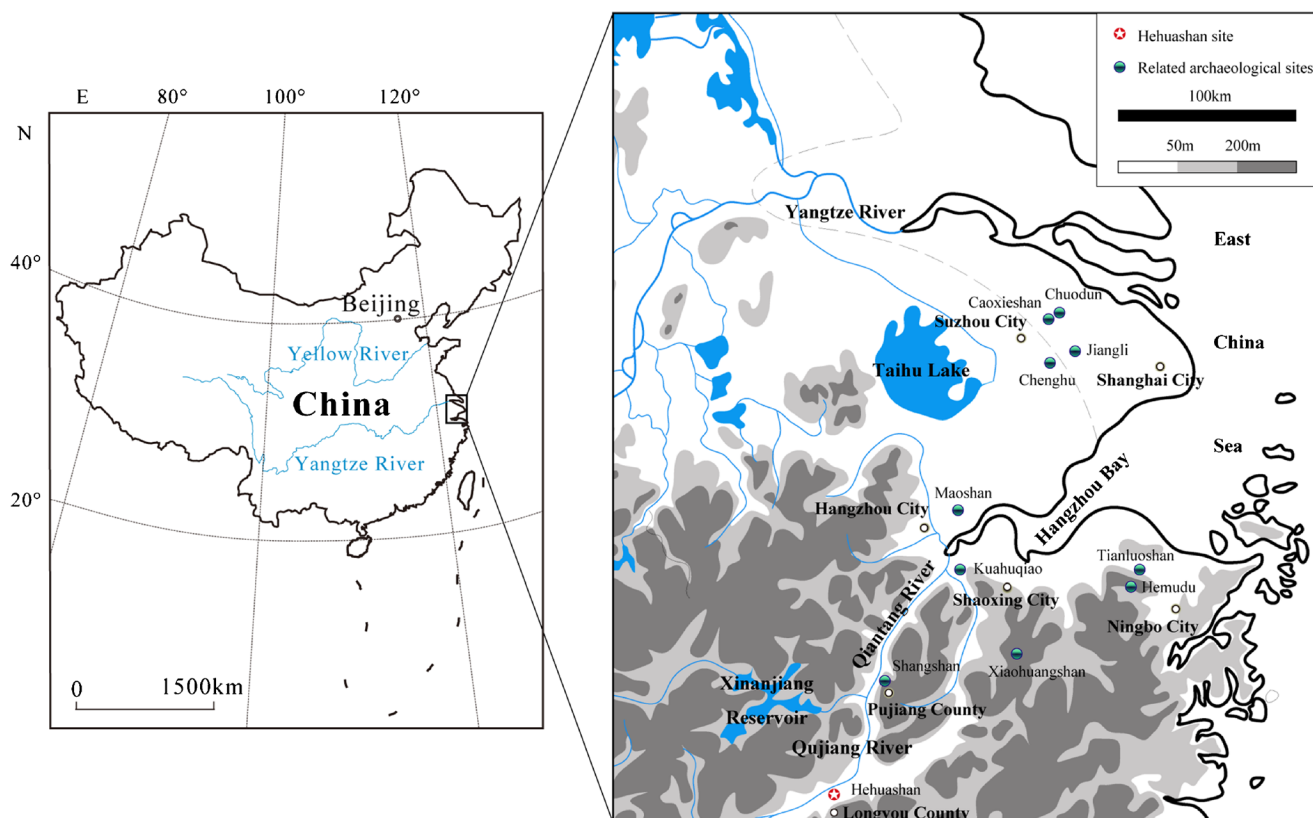
Changes in the morphology of phytoliths derived from rice husks and leaves, rice grains, and spikelet bases are regarded as indicative of rice domestication and evidence of cultivation (Fuller 2007; Fuller et al. 2007, 2008, 2009; Zheng et al. 2007). Wild rice is supposed to be a necessary element when discussing the origin of rice cultivation and domestication (Zheng et al. 2007). There are three major genetic populations of wild rice in China, *Oryza rufipogon* Griff., *Oryza officinalis* Wall. ex Watt., and *Oryza meyeriana* Baill. subsp. *granulata* Nees et Arn. ex Watt. (Fan et al. 2000; Gao et al. 1996). Common wild rice (*Oryza rufipogon*) is generally considered as the progenitor of modern Asian cultivated rice (*Oryza sativa*) (Chang 1984; Khush 1997). Based on the examination of evidence of the selection in the genomes of different types of cultivated rice (*japonica*, *indica*, and *aus*), recent work involving rice DNA indicates that there were likely three independently domesticated populations of rice in different parts

of Asia (Civán et al. 2015). Different geographical origins were inferred for the three varieties of rice including the *japonica* variety in southern China and the Yangtze valley, the *indica* variety in Indochina and the Brahmaputra valley, and the *aus* variety in central India or Bangladesh (Civán et al. 2015). However, these geographical inferences are inconsistent with the rice history sketched by genetics results together with the archeobotanical study by Fuller et al. (2010). Moreover, the latest research points out a different situation that multiple origins of cultivation may have shared a single domestication in terms of key genetic changes (Choi et al. 2017). This model (Choi et al. 2017) presents several key points: (1) different rice subspecies had separate origins, but de novo domestication occurred only once in *Oryza sativa* spp. *japonica*, (2) the first domesticated *Oryza sativa* spp. *japonica* population diverged from modern wild rices at ~ 13.1–24.1 kya, which is consistent with the expansion of *Oryza rufipogon* populations after the Last Glacial Maximum and archeobotanical evidence in China, (3) introgressive hybridization from early *japonica* to proto-*indica* and proto-*aus* led to domesticated *indica* and *aus* rice. Taking this into consideration, the birthplace of cultivated rice need not share a common range of distribution with modern wild rice. Previous studies of common wild rice revealed it as perennial and widely distributed in the tropics and subtropics of monsoonal south Asia (Vaughan 1994). Common wild rice is widely distributed in eight provinces or regions in southern China, including Guangxi, Guangdong, Hainan, Yunnan, Hunan, Jiangxi, Fujian, and Taiwan (Fan et al. 2000; Gao and Hong 2000; Zhou et al. 2003), but cultivation may have begun to the north of this modern range (Fuller et al. 2010).

In this paper, phytoliths from rice husks and leaves recovered from archeological deposits are used as indicators of whether common wild or early cultivated rice was presented during the Early Neolithic occupations at the Hehuashan site. Furthermore, we attempt to present evidence of rice management or cultivation in the Early Holocene.

## Physical settings and archeological background

The Hehuashan site is located in the upper reaches of the Qiantang River, on a small hill named Hehuashan, in Longyou County, Zhejiang Province. The site is 56–65 m above the sea level. The Hehuashan site is situated southwest of the Shangshan site and the Xiaohuangshan site, in the lower Yangtze area (Fig. 1). Today, this area has four distinct seasons, moderate and moist climate with an annual temperature of 15–17 °C and an annual precipitation of 1000–1400 mm. Regional natural vegetation is subtropical mixed with evergreen-deciduous broadleaved secondary or successional forests. Today,



**Fig. 1** Location of the Hehuashan site and related archaeological sites [prepared by Z. Qiu using Adobe Illustrator CC 2015 (<https://creative.adobe.com/products/download/illustrator>)]. This map was modified from Qiu et al. (2016)

rice is the major cereal crop and cultivated plant in the study area (Wu 1993).

Previous pollen studies (Yi et al. 2003, 2006) of sediments from the lower Yangtze area have revealed regional vegetation history and climate change since the latest Pleistocene. In the transition from the latest Pleistocene to the Early Holocene (about 12,900–10,300 BP), regional vegetation consisted of coniferous forest and grasslands. During the Early Holocene (about 10,300–9000 BP), coniferous forest and grasslands changed to a mixed broadleaved evergreen-deciduous forest. In general, this area was in a warm and wet condition among which the climate was warm (temperatures 1–2 °C higher than present) and wet from 10,300 to 9000 BP while cool and dry from 9000 BP to 7600 BP (Yi et al. 2003, 2006).

The Hehuashan site was investigated by the Zhejiang Provincial Institute of Cultural Relics and Archaeology from 2011 to 2013, led by Prof. Leping Jiang. The Hehuashan site covers an area of about 50,000 m<sup>2</sup>, of which 900 m<sup>2</sup> were excavated. Seven successive cultural layers were identified in the deepest part of the site. Pits, postholes, and rubble mounds together with pottery, stone artifacts, and other cultural remains were recovered during the excavation. Ceramics with characteristic shapes including wide basins, flat plates,

ring foot plates, amphora together with stone tools including milling stones, stone clubs, and ground slate blades (similar to the findings from the Shangshan Culture) were also recovered. The similarity of the ceramics (Fig. 2) and lithic tools from the Hehuashan site to those previously identified occupations of the Shangshan Culture (11400–8600 BP) suggests strong correlation between the two entities. Rice husks were used to temper some of the pottery, which is a common technological ceramic practice of the Shangshan Culture as well. The Hehuashan site also produced cultural deposits from the later Kuahuqiao Culture (8500–7500 BP) overlying that of the Shangshan Culture, indicating continuity between these two Neolithic Cultures. Artifacts associated with the later Kuahuqiao Culture, such as Jomon-like pottery *Fu*, round-bottomed bowls, adze-shaped stone hammers, and stone adzes of limestone, appeared in the late occupation of the western portion of the Hehuashan site. Discontinuous cultural deposits are separated into the East and West Districts of the site (Fig. 3), which should also be one of the Shangshan Cultural features as observed from the Shangshan and Xiaohuangshan sites. In addition, cultural deposit of the West District is thinner and relatively later than that of the East District at the Hehuashan site. Previous archeological study (Jiang 2013) revealed a Shangshan-Kuahuqiao-Hemudu Cultural System (~11,000–7000 BP) in the Qiantang River region and a later



**Fig. 2** Ceramic wide basin from the Hehuashan site

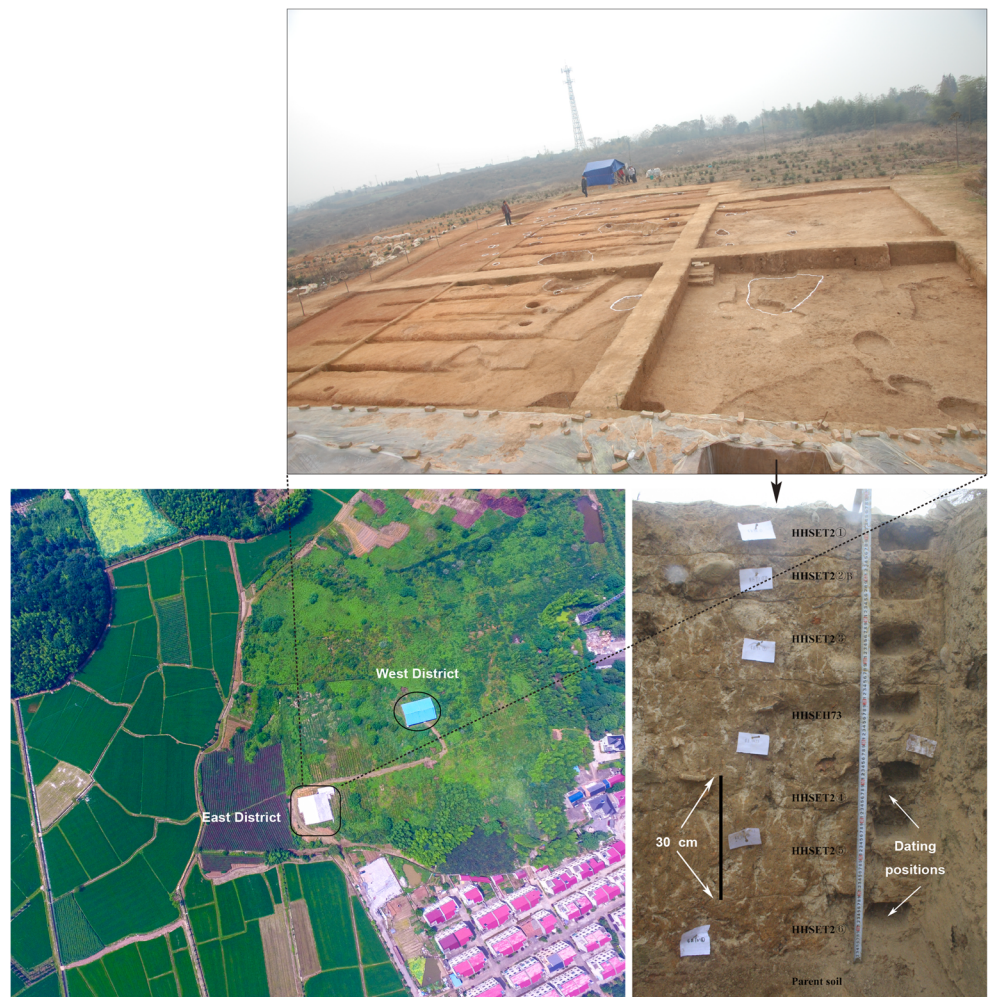
Majiabang-Songze-Liangzhu Cultural System (7000–4300 BP) mainly distributed in the Taihu Lake Basin, both of which are generally consistent with the evolution of rice in the Lower Yangtze River valley. As a result, the Hehuashan site is just situated within the former Cultural System and probably can shed light on the linkage among local archeological cultures as well as the evolution of rice, especially the origin and cultivation of rice.

## Material and methods

### Material

The archeological excavation of the Hehuashan site was divided into the East and West Districts. We choose the deepest depositional profile (no.1) at the southeast corner of trench of HHSET2 in the East District, which was attributed to the Shangshan Culture, to collect samples (Table 1) from stratified deposits for phytolith analysis (Fig. 3). Among these, pit H73 deposited between the cultural layers of ③ and ④. It presents an irregular rectangular plane and a pot-shape profile, in 240 cm long by 152 cm wide by 36 cm deep. Potsherds of wide basin and jar together with milling stones with characteristics of the Shangshan Culture was unearthed from the pit. Considering pit H73 is located in the north side of the house ruins indicated by the remains of two rows of pillars, it is likely to be a conventional storage pit, or the storage pit was discarded as a garbage one.

**Fig. 3** Map of the site excavation with depositing profile 1 location and sampling positions at the trench of HHSET2



**Table 1** Morphological description of sedimentary samples from the trench of HHSET2 in the East District of the Hehuashan site

Deposits	Depth (cm)	Description of samples				
		Sampling position (cm)	Color	Structure	Texture	Inclusions
①	0–11	4–8	Gray-brown	Soft-porous	Clay	Pottery sherd, burned soil
②B	11–20	12–16	Gray-white	Soft-porous	Clay	Pottery sherd, burned soil
③	20–42	27–31	Gray-white	Hard-compact	Clay	Pottery sherd, burned soil
H73	42–68	43–47	Yellow-brown	Soft-porous	Clay	Pottery sherd, stone artifacts, burned soil
④	52–68	61–65	Gray-brown	Hard-compact	Clay	Pottery sherd, burned soil
⑤	68–97	74–78	Red-brown	Hard-compact	Clay	Pottery sherd, burned soil
⑥	97–111	101–105	Yellow-brown	Hard-compact	Clay	Pottery sherd
Archeologically sterile soil	> 111	113–117	Red-brown	Hard-compact	Clay	Fe and Mn concretion

**Methods**

**Dating**

Potsherds containing organic material, such as rice husks or straws, were dated by accelerator mass spectroscopy (AMS) <sup>14</sup>C by the Beta Analytic Radiocarbon Dating Laboratory. The dates were then calibrated using IntCal 09 and OxCal v3.10.

**Phytolith analysis**

The samples were processed using a procedure slightly modified from Piperno (1988) and Lu et al. (2007). The soil samples consist of compacted clay and were dried and ground into powder prior to phytolith analysis. The dry powder samples were first treated with 30% H<sub>2</sub>O<sub>2</sub> and heated, followed by 10% HCl, then, washed by distilled water for three times. A tablet of *Lycopodium* maker (ca. 18,583 spores per tablet) was added to each sample in order to estimate the concentration of grains per gram of dry sample before mineral separation with a dense solution ZnBr<sub>2</sub> (d = 2.4 g/ml). Identification and counting of the phytoliths were conducted under a Nikon Eclipse LV100POL microscope using the published keys (Piperno 1988; Piperno and Pearsall 1998) and modern reference collections located in the Key Laboratory of Vertebrate Evolution and Human Origins of Chinese Academy of Sciences, Institute of Vertebrate Paleontology and Paleoanthropology (IVPP), Chinese Academy of Sciences (CAS). The samples were mounted in glycerin to rotate them if necessary so as to obtain accurate measurements, which was carried out using *NIS-Elements D* software. Canada balsam acted as the medium to get better identification and take photos. The percentage of phytoliths in each sample is based on the sum of at least 500 grains of phytoliths (individual cells and multi-cell panels) were counted per slide. The results of the percentages and concentrations are present in Figs. 4 and 5, which were created using the TILIA and

TILIA-GRAPH programs. Phytolith nomenclature follows Madella et al. (2005).

It is worth noting that there are potential weaknesses and strength of the morphological method of using rice bulliform phytolith to discuss wild and domesticated rice. First of all, bulliform measurement alone is unable to differentiate wild from domesticated rice species in regions where species overlap (Gu et al. 2013; Pearsall et al. 1995). However, Lu et al. (2002) reported that generally, the scale-like decorations of wild rice are irregular, highly variable, and usually have less than nine decorations present on the bulliform phytoliths, while that of cultivated ones display eight to 14 decorations qualitatively. Nevertheless, due to overlap in the number of scale-like decorations between cultivated rice and wild species, this characteristic is not by itself sufficient to distinguish the wild from the domestic rice. As a result, more clear specification that the proportion of featured bulliform phytoliths with nine decorations serving as a reliable criterion to distinguish wild rice species from domesticated ones was improved by Huan et al. (2015). Considering that the *Oryza*-type double-peaked phytolith, which was promising for separating domesticated from wild rice (Gu et al. 2013; Pearsall et al. 1995; Zhao et al. 1998), was few, the morphology of bulliform phytoliths is used to discuss rice cultivation, which is considered the most efficient way in this case because nearly no macro-plant remains were obtained.

**Results**

**Dating**

The organic tempered potsherds unearthed from cultural layers HHSET2 ⑥ and HHSET2 ④ (Fig. 3) were determined to be 10,490–10,240 cal. BP and 9010–8780 cal. BP, respectively (Table 2), which is in coherence with relative ages determined by corresponding archeological remains and in good agreement with the chronological placement of the Shangshan Culture (11400–8600 BP) (Jiang and Sheng 2007). It is

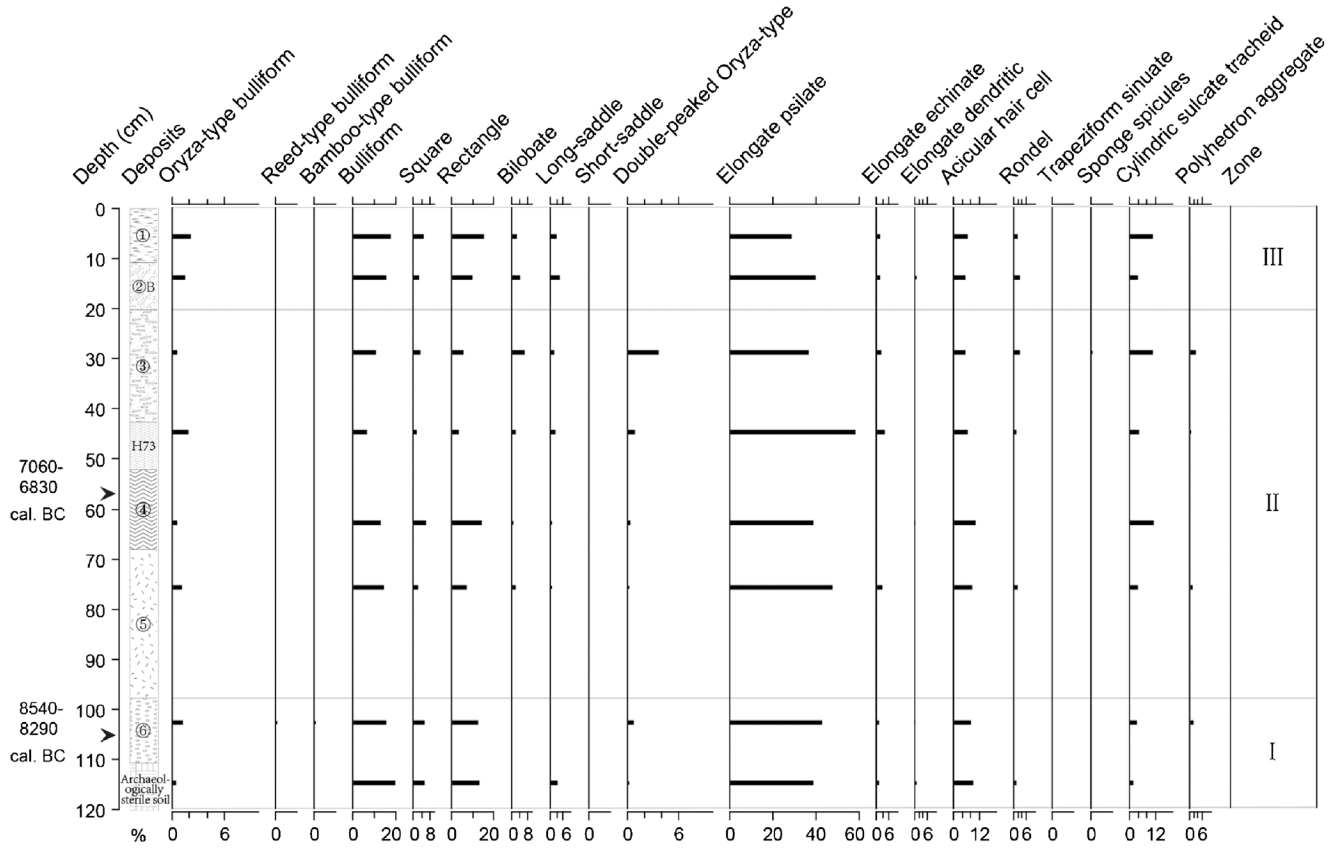


Fig. 4 Percentages of phytolith extracted from the Hehuashan site

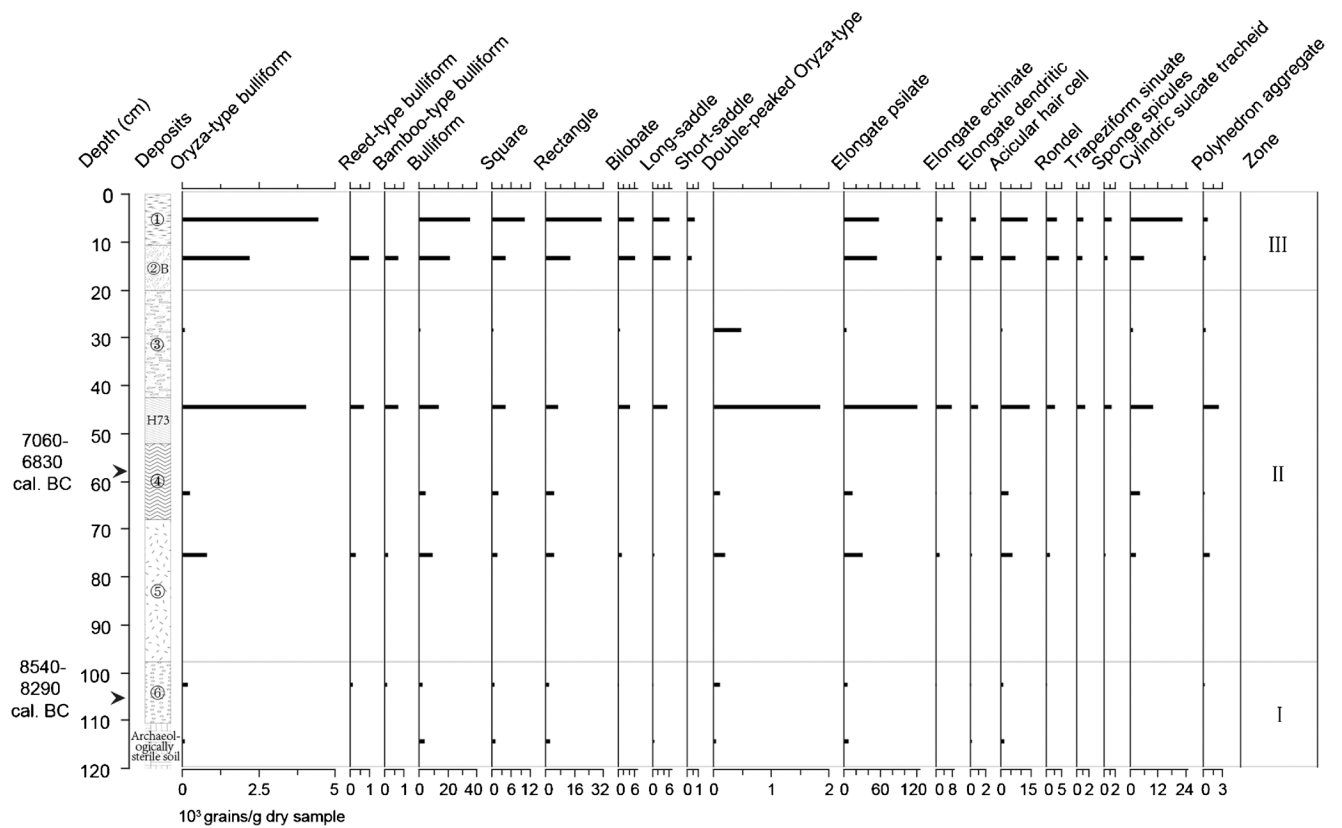


Fig. 5 Concentrations of phytolith extracted from the Hehuashan site



**Table 2** Results of radiocarbon dating: age of the organic tempered potsherds from the Hehuashan site

Sample no.	Sample	Deposition unit	<sup>14</sup> C years (T <sub>1/2</sub> = 5568)	Dendrocalibrated age ranges (± 1δ, 68%)	Dendrocalibrated age ranges (± 2δ, 95%)
Beta-392752	Organic tempered potsherds	HHSET2④	8030 ± 30 BP	Cal BP 9010 to 8975 Cal BP 8920 to 8900 Cal BP 8880 to 8870 Cal BP 8830 to 8790	Cal BP 9010 to 8970 Cal BP 8960 to 8955 Cal BP 8920 to 8865 Cal BP 8830 to 8780
Beta-347055	Organic tempered potsherds	HHSET2⑥	9180 ± 40 BP	Cal BP 10,400 to 10,310 Cal BP 10,310 to 10,250	Cal BP 10,490 to 10,460 Cal BP 10,440 to 10,240

planned that further dates will be obtained by direct dating plant macrofossil remains in the near future.

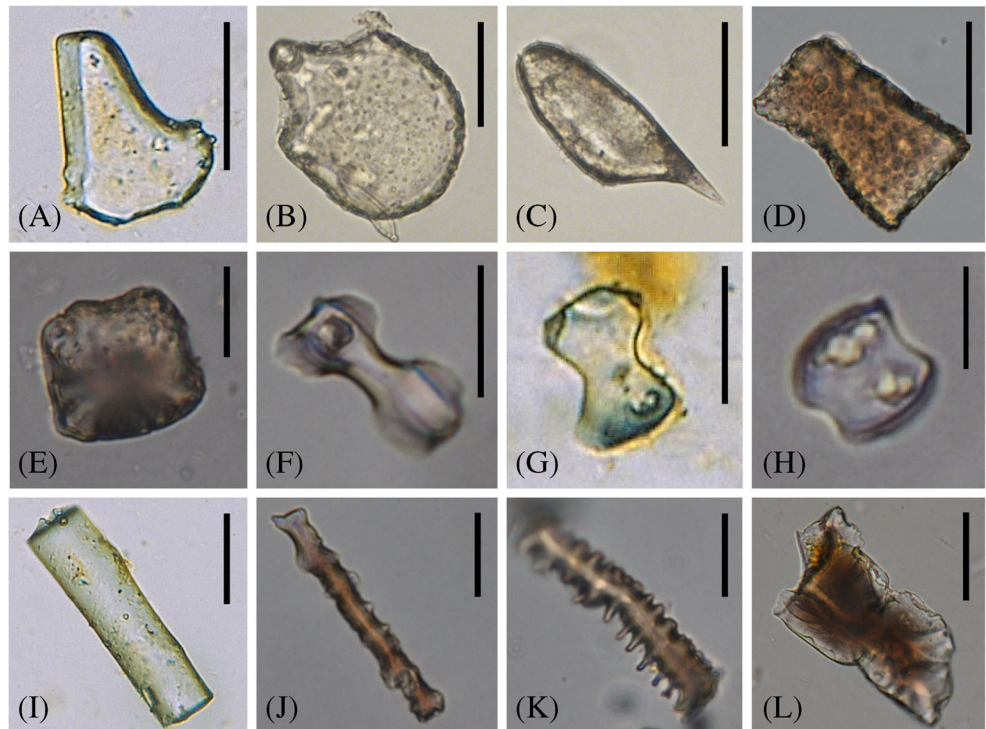
**Phytoliths record**

The soil samples contain common grass phytolith morphotypes, including elongate psilate, elongate echinate and elongate dendritic long cells, cuneiform bulliform cells, rondel, bilobate, square and rectangular, acicular hair cell, long-saddle (collapsed saddle), short-saddle, as well as double-peaked *Oryza*-type, trapeziform sinuate, cylindrical sulcate tracheid, and polyhedron aggregate (Fig. 6). Besides, some sponge spicules were also extracted. Among these, rice (*Oryza* sp.), reed (*Phragmites australis*), Bambusoideae, and woody plants were identified (Table 3).

**Percentages and concentrations of phytoliths**

Elongate psilate and bulliform phytoliths represent the predominant morphotypes in the assemblage with the average percentages occurring in the soil samples between 41.6 and 14.5%. These two types of phytoliths are quite prevalent varying from 7003 to 121,161 grains per g of dry sample and from 1454 to 36,051 grains per g of dry sample, respectively. The phytolith assemblage from H73 depicts a different record from the other samples with the total concentration of phytoliths in H73 having 206,643 grains per g of dry sample. *Oryza*-type bulliform, elongate psilate, and elongate dendritic long cells reach the highest value of the excavated soil samples except for those from the uppermost cultural layer ①. The percentages of bulliform, rectangular, and square short cells from the deposit in H73 have the lowest value. The concentration of

**Fig. 6** Common phytolith types extracted from the Hehuashan site. **a** Cuneiform bulliform, **b** Reed-type bulliform, **c** Acicular hair cell, **d** Rectangular, **e** Square, **f** Bilobate, **g** Long-saddle, **h** Short-saddle, **i** Elongate psilate, **j** Elongate echinate, **k** Elongate dendritic, **l** Polyhedron aggregate. Scale bars: **a–d, e–g, i, l**, 40 μm; **j, k**, 20 μm; **h**, 10 μm



**Table 3** Source plant taxa and corresponding organs of phytoliths extracted from the Hehuashan site

Phytolith morphotypes	Source plant taxa	Plant organs or parts
Bulliform	Poaceae	Leaf
Reed-type bulliform	<i>Phragmites australis</i>	Leaf
<i>Oryza</i> -type bulliform	Oryzoideae	Leaf
Square	Poaceae	Leaf
Rectangle	Poaceae	Leaf
Long-saddle	Bambusoideae	Leaf
Elongate psilate	Poaceae	Leaf
Elongate echinate	Poaceae	Leaf
Elongate dendritic	Poaceae	Leaf
Acicular hair cell	Poaceae	Leaf
Trapeziform sinuate	Pooideae	Leaf
Rondel	Pooideae	Leaf
Short-saddle	Arundinoideae, Eragrostidoideae	Leaf
Bilobate	Panicoideae, Arundinoideae, Eragrostidoideae	Leaf, stem
Double-peaked <i>Oryza</i> -type	Oryzoideae	Husk
Polyhedron aggregate	Woody plants	Leaf, bark

*Oryza*-type bulliform, in particular, from H73 is relatively high with 4088 grains per g of dry sample. Except for the anomalous phytolith sample from H73, the phytolith percentages and concentrations of major taxa provide a basis for dividing the diagram into three phytolith zones (Figs. 4 and 5).

Zone I (before 10,240 BP, including deposits of HHSET2 ⑥ and the archeologically sterile soil, below 97 cm).

The concentration of phytoliths in this zone is the lowest with 18,500 grains per g of dry sample. The phytolith sample is dominated by elongate psilate (41%) and bulliform (19%). Other ingredients include *Oryza*-type bulliform (0.9%) with 160 grains per g of dry sample on average; Reed-type bulliform, bamboo-type bulliform, and double-peaked *Oryza*-type (0.5%) with 85 grains per g of dry sample; long-saddle phytoliths are present in a lesser amount. Scarce sponge spicules, cylindrical sulcate tracheid, and polyhedron aggregate make up the rest of the phytolith assemble from this zone.

Zone II (the Shangshan Culture period, about 10,240–8600 BP, including deposits of HHSET2 ⑤, ④, ③, 97–20 cm).

The total concentration of phytoliths is greater in this zone with 48,333 grains per g of dry sample. The phytolith assemblage is dominated by elongate psilate (41%) and bulliform (13%). Other ingredients include *Oryza*-type bulliform (0.9%) with 370 grains per g of dry sample, double-peaked *Oryza*-type (1.4%) with 270 grains per g of dry sample. The amount of bilobate, long-saddle, cylindrical sulcate tracheid, and polyhedron aggregate phytoliths increased while bamboo-type bulliform, square, and rectangular decreased.

Zone III (post ~ 8700 BP, including deposits of HHSET2 ②B, ①, above 20 cm).

Excluding H73, the amount of phytoliths in this zone is the highest among the cultural layers with 169,601 grains per g of

dry sample. The phytolith assemblage is still dominated by elongate psilate (34%) and bulliform (17%). Other ingredients include bulliform, *Oryza*-type bulliform (1.9%) with 3340 grains per g of dry sample on average. The amount of square, rectangular, bilobate, long-saddle, and trapeziform sinuate was increased, while the amount of elongate psilate, acicular hair cell, and polyhedron aggregate decreased. Double-peaked *Oryza* type disappeared, while short-saddle appeared. It is noted that the concentration of *Oryza*-type bulliform in the layer ① reached 4460 grains per g in the dry sample.

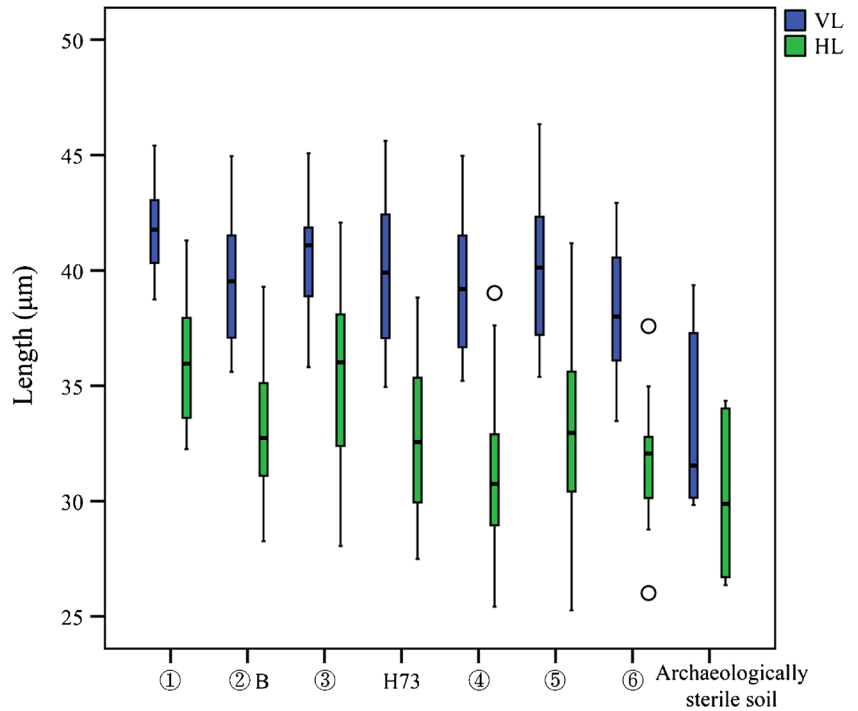
**Morphometric measurement of *Oryza*-type bulliform phytolith**

As illustrated in Fig. 7, the vertical and horizontal lengths of the *Oryza*-type bulliform phytoliths (selected randomly) were measured and graphed. The corresponding average values are present in Table 4. It seems that the vertical and horizontal lengths show an increase in length. However, some variations in the mean photoliths size from the bottom to the top of the slide were observed. This is probably due to an irregular distribution of *Oryza*-type bulliform phytoliths on slides that affected the measurements. Nevertheless, *Oryza*-type bulliform phytoliths from the archeologically sterile soil are smaller than those from the upper deposits, especially the uppermost cultural layer.

**Characteristics of scale-like decorations on *Oryza*-type bulliform phytoliths**

The number of scale-like decorations of *Oryza*-type bulliform phytoliths (selected randomly) retrieved from deposits from

**Fig. 7** Morphometric measurements of *Oryza*-type bulliform phytoliths extracted from the Hehuashan site. VL vertical length, HL horizontal length



the Hehuashan site can be separated into six different categories (varying from five to ten) as presented in Figs. 8 and 9 ( $n \geq 30$ , per depositing unit). The number of phytoliths with scale-like decorations increased in number from the archeologically sterile soil to cultural layer ①. Eight pieces of scale-like decorations appeared in layer ⑤ of the second phase (the Shangshan Culture), while nine and ten scale-like decorations were present on phytoliths from layer ④ of the second phase and layer ②B of the third phase (post ~8700 BP).

**Discussion**

Generally, phytoliths extracted from the Hehuashan site suggest that at least wild rice, reed, Bambusoideae, and other Poaceae were present at or near the site at the time of initial occupation. In spite of the effects of possible human

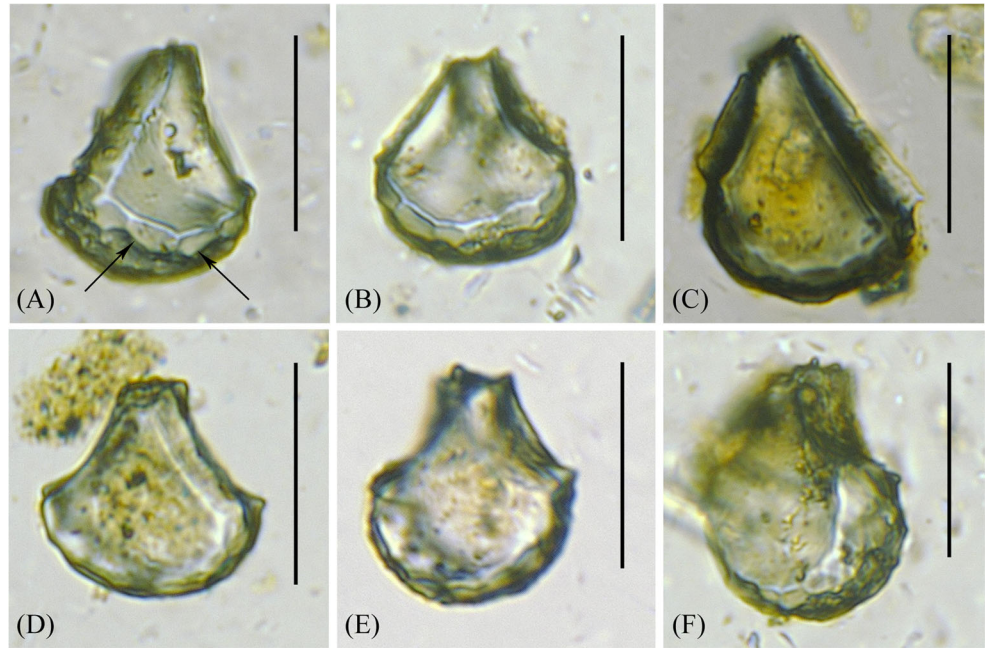
intervention in the local plant communities, it is possible to reconstruct the local vegetation to some extent.

Unconscious (non-intentional) selection for a larger non-shattering seed has been suggested to be one trait of crop domestication under cultivation (Fuller and Allaby 2009). According to Huan et al. (2015), wild rice generally grows in environments with abundant water, while domesticated rice grows away from water, and wild rice is overall more scattered and easier to prostrate on the surface of the water than the domesticated rice plant. As a result, domesticated rice has leaves that need to curl repeatedly to hold water. The adaptation of *Oryza* to dryer conditions resulted in the changing size and morphological features. This is exhibited by bulliform phytoliths that represent the “motor cells” of the leaves (Dong et al. 2006). Bulliform cells increase in size to store more water in the upper epidermis of leaf blades (Jane and Chiang 1991; Qu et al. 2010; Vecchia et al. 1998). Increased leaf curling in order to resist water stress resulted in the

**Table 4** Average values of vertical and horizontal lengths of *Oryza*-type bulliform phytoliths extracted from the Hehuashan site

Cultural deposits	Vertical length (µm)	Horizontal length (µm)	<i>n</i>
①	41.86	36.16	43
②B	39.53	33.15	50
③	40.56	35.24	41
H73	39.87	32.83	50
④	39.24	31.10	40
⑤	39.98	32.93	54
⑥	38.22	31.70	49
Archeologically sterile soil	33.28	30.20	46

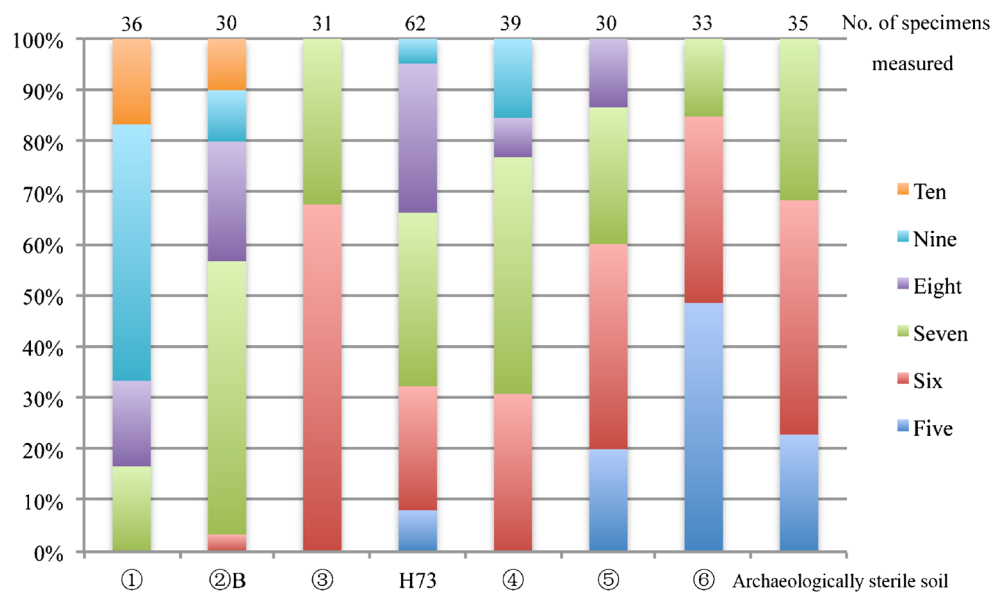
**Fig. 8** Scale-like decorations on *Oryza*-type bulliform phytoliths extracted from the Hehuashan site. **a–f** *Oryza*-type bulliform phytoliths showing five to ten scale-like decorations, respectively (arrows indicating scale-like decorations). Scale bars = 40 μm



presence of an increase in scale-like decorations on *Oryza*-type bulliforms (Huan et al. 2015; Parry and Smithson 1958; Wang 2005). Environmental factors include how much water is going through the plant together with interaction of physiological factors such as where the phytolith is located on the leaf. For example, phytoliths in cells above the vein are generally larger than cells within the vein. Other factors that affect phytolith morphology include the ratio of the number of leaf midribs. The vein index, the number of rows of silica cells in the vein, and various genetic mechanisms also affect phytolith size (Piperno 1988, 2006). The size of phytoliths will also depend on a plant's metabolic function and stage of plant growth (Piperno 1988). The sizes of *Oryza*-type bulliform

phytoliths from cultivated rice are commonly larger than those of the modern wild species (Ma and Fang 2007; Zhang and Wang 1998). *Oryza*-type bulliform phytoliths recovered from the Hehuashan site display an increase in size from the lowest to the more recent levels in trench HHSET2. This result is in accord with research on the change in the size of phytoliths of rice from the Majiabang Culture (7000–5800 BP) to the Liangzhu Culture (5300–4300 BP) (Fuller 2007; Fuller et al. 2007; Zheng et al. 2002). However, some fluctuations of phytolith size occurred during the deposition of the phytolith record, especially at the middle phase of the Hehuashan site's occupation, which is likely to relate to the types of sampling deposits or to the specific taphonomy of these depositions, or

**Fig. 9** Numbers of scale-like decorations increased from the bottom to the top at the Hehuashan site



may reflect the retention of some primitive traits of *Oryza*-type bulliform phytoliths from rice leaves at the initial stages of domestication.

The proportions of scale-like decorations of *Oryza*-type bulliform phytolith increase with time from the Shangshan Culture (11400–8600 BP) to the Hemudu Culture (7000–5800 BP). This change indicates that the morphology of rice phytoliths changed under the selective pressure of domestication (Wu et al. 2014). In the present study, the numbers of scale-like decorations of *Oryza*-type bulliform phytoliths retrieved from the Hehuashan site demonstrates similar morphological characteristics to bulliform phytoliths from the Shangshan H244 period (Fig. 10). The presence of similar *Oryza*-type bulliform phytoliths indicates that the rice from the Hehuashan period was the same stage of development in the domestication process as the Shangshan Culture.

The number of scale-like decorations on bulliform phytoliths increased, varying from five to ten, from the lowest to uppermost stratigraphic zones, suggesting that changes of morphometric characteristics of rice phytoliths (*Oryza*-type bulliform) including an increase in the size and number of scale-like decorations developed during the Early Holocene. However, it is to be noted that there is no bulliform phytoliths with eight or more scale-like decorations in layer ③ of the Hehuashan site (East District) as shown in Fig. 9, which might be due to an unusual localized concentration of wild rice.

The percentage and amount of *Oryza*-type bulliform phytoliths increased sharply during the second phase (about 10,240–8700 BP). The concentration of double-peaked *Oryza*-type phytoliths from the deposit H73 is above 1858 grains per g of dry sample while that of *Oryza*-type bulliform reached 4088 grains per g of dry sample, which is close to that of the identification standard of 5000 grains per g of dry sample, characteristic of phytolith assemblages from an ancient rice paddy field (Fujiwara 1979; Zheng et al. 2009). Combined with the in situ context, H73 served as a pit that may have been used to store rice or have been lined with rice

stems and leaves, or just an ash pit that is closely related to inhabitants of the Hehuashan site then. These multiple proxies indicate a more intensive human activity related to rice, such as rice collection and storage practices possibly related to cultivation. Moreover, if H73 was excluded, both the percentage and concentration 4460 grains per g of dry sample of *Oryza*-type bulliform phytoliths reached their highest values in the profile during the final Hehuashan occupation (post ~ 8700 BP). The disappearance of double-peaked *Oryza*-type phytoliths derived from rice husks during the most recent occupation of the Hehuashan site (Zone III) is probably due to the intentional use of rice husks, which resulted in a decrease of their presence in the archeological record. Based on the increase in the size of *Oryza*-type phytoliths, the number of scale-like decorations and the amount of *Oryza*-type bulliforms from the base to the top of the stratigraphic profile from trench of HHSET2 wild rice was utilized and most likely cultivated by the occupants of the Hehuashan site during the Shangshan Culture period (~ 11,400–8600 BP).

Though uncommon, phytoliths of *Oryza*-type bulliform and double-peaked *Oryza*-type are present in the archeologically sterile soil before ~ 10,490–10,240 BP. Previously, early rice remains including seeds, husks, and phytoliths, have been recovered from the Shangshan (Liu et al. 2007a; Zhao and Jiang 2016) and Xiaohuangshan sites (Innes et al. 2009) in this area. The presence of wild rice is one of the essential elements for identifying the origins of rice cultivation and domestication (Zheng et al. 2007). It can be concluded that wild rice was present in the Qiantang River region. This is in concordance with the view that wild rice was present in the lower and middle of the Yangtze River Valley based on the presence of carbonized rice and phytoliths from the Hemudu and Diaotonghuan sites during the Early Holocene (Crawford and Shen 1998; Tang et al. 1994). Besides, the high concentration of rice leaf phytoliths and the absence of rice husk phytoliths might be the results of the location of rice processing such as removal of the spike or dehusking.

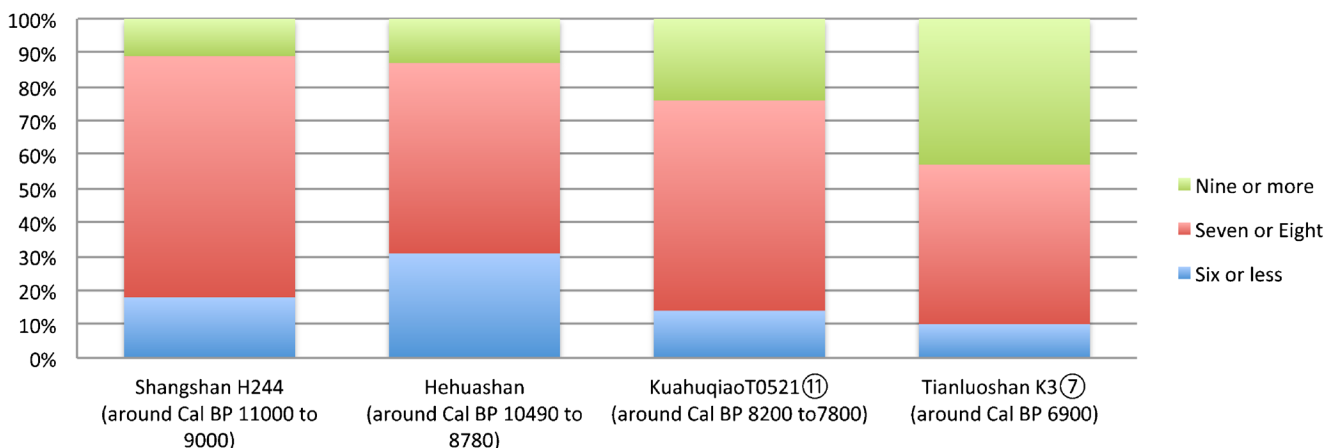


Fig. 10 Predictions of scale-like decorations on *Oryza*-type bulliform phytolith from Shangshan Period to Hemudu period

Archeological excavations indicate that the Hehuashan site is one of the earliest Neolithic sites in the upper Qiantang River in Zhejiang province (Jiang 2013). In comparison with other sites belonging to the Shangshan Culture, distinctive material culture and AMS  $^{14}\text{C}$  dating results indicate that the Qiantang River basin is not only the birthplace of Neolithic civilization in Zhejiang province, but also plausibly served as one of the cradles of rice agriculture in China (Jiang and Sheng 2007; Liu et al. 2010; Mao et al. 2008). Later, rice farming using systematic paddy fields began later in association with the Hemudu and Majiabang Cultures (7000–5800 BP) (Ding 2004) in the lower reaches of the Yangtze River 200–300 km northeast of the Hehuashan site.

## Conclusions

The phytoliths study at the Hehuashan site presented above suggests a shift of *Oryza*-type bulliform phytoliths features during the Early Holocene.

The amount of *Oryza*-type bulliform phytoliths increased from the lowest to the uppermost layers of occupation of the site. Rice phytoliths presented in the archeologically sterile soil indicate that wild rice existed in the upper Qiantang River region. The presence of *Oryza*-type bulliform phytoliths with an increased number of scale-like decorations from earlier to later deposits likely represents the local shift from the collection and possible manipulation of wild *Oryza* to cultivated rice during the Shangshan Culture occupation (11400–8600 BP).

During the Early and Middle Holocene, about 8500–7500 BP, Neolithic groups migrated to better dwelling places with reliable food sources compared with food collection by foraging (Zong et al. 2012). With the knowledge of wild rice utilization and possibly cultivation, the carriers of the Shangshan Culture migrated to the lower Qiantang River. These people later became the Hemudu Culture. During the middle Holocene (about 7000 BP), possibly related peoples migrated to the north to the Taihu Lake region and became acculturated to the local Majiabang Culture. In the later Majiabang-Songze-Liangzhu Cultural System (7000–4300 BP), the intensification of rice cultivation played an increasingly important role in the local subsistence strategy.

Archeological sites attributed to the Early Holocene in the lower Yangtze River are rarely documented, and our sample of sites is relatively small. Hence, it is necessary to scrutinize whether the features observed in our study are typical of early rice cultivators during the Early Holocene. Studies such as this one will contribute to our growing knowledge of the origins of rice agriculture in China.

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