# Rice domestication and climatic change: phytolith evidence from East China

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Fossil rice phytoliths have been identified from a lateglacial to Holocene sequence of epicontinental sediments in the East China Sea that were probably transported by the Yangtze River from its middle and/or lower reaches. The rice phytoliths occurred first in the sequence at about 13 900 cal. yr BP and disappeared during the period of 13 000–10 000 cal. yr BP, implying the earliest domesticated cereal crops of the world ever reported. Based on the records of phytoliths, pollen, diatoms and foraminifera from the sequence, the climate between 13 000 and 10 000 cal. yr BP was notably colder (Younger Dryas). The coincidence of disappearance of domesticated rice phytoliths with cold climate conditions may suggest a great climatic influence on human activities during that time. Warmer and wetter conditions during the period 13 900 to 13 000 cal. yr BP and after 10 000 cal. yr BP have probably favoured rice domestication in the area.

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Rice, one of the most important crops in the world, has long been thought cultivated 6500 years ago in southern Asia, where the climate at the time was warm enough to support luxuriant stands of wild rice (Pringle 1998). However, recent archaeological discovery indicates earlier rice remains in the middle-lower Yangtze River and upper Huaihe River regions in China (Pei 1989; Yan 1991; You 1995; Chen *et al.* 1995; Wang & Sun 1996; Normile 1997; Zhao 1998). These remains were radiocarbon-dated to 8000–9000 years ago (Hedges *et al.* 1992; Chen & Hedges 1994; Wang & Sun 1996; Zhao 1998). By counting the proportions of wild and domesticated rice phytolith fossils (double-peaked glume cell phytolith) from the Diaotonghuan cave in the northern Jiangxi Province along the middle Yangtze River, Zhao (1998) identified a rice horizon dated to 13 000 yr BP, based on a relative chronology of ceramic and stone artifacts of known styles. With this age constraint, the rice would be the earliest domesticated cereal crop in the world. It can also be inferred that hunter-gatherers along the banks of the middle Yangtze River had begun to domesticate wild rice before the Younger Dryas (YD). In light of possible synchronous origins of agriculture in several different areas of the world shortly after the termination of the last glaciation, the environmental changes that marked the transition from the last glaciation to the Holocene may be crucial in understanding the causes of plant domestication in the Yangtze River valley and elsewhere (Zhao & Piperno 2000). However, detailed knowledge of the relationship between rice cultivation and climate is still limited owing to the lack of a continuous sedimentary sequence for both records. Here we present a new phytolith record of the sediment core from the palaeo-Yangtze River estuary in East China Sea to illustrate the relationship between rice fossil and climate change over the past 20 000 years.

## Study area

The East China Sea (ECS), with one of the widest shelves in the world, is a marginal sea over an area of about 770 000 km$^2$ between the Ryukyu Islands and the Asian continent (Wang 1985). The oceanic current system in this area consists mainly of the Kuroshio and the Coastal Currents. The East China Sea receives huge amounts of riverine water (about $1 \times 10^{12}$ m$^3$/year), mainly from the Yangtze River, and sediments (about 2 billion tonnes annually) from the Yellow River and the Yangtze River (Hu *et al.* 1998). During the Last Glacial Maximum (LGM), the sea level was 150–130 m lower than the present in the ECS, and most of the present shelf was exposed (Wang 1995; Saito *et al.* 1998) (Fig. 1). The palaeo-estuary of the Yangtze River was located on the shelf edge, facing the central part of the Okinawa Trough (Wu *et al.* 1996), and provided a large amount of fresh water and terrigenous material to the Okinawa Trough area at the LGM.

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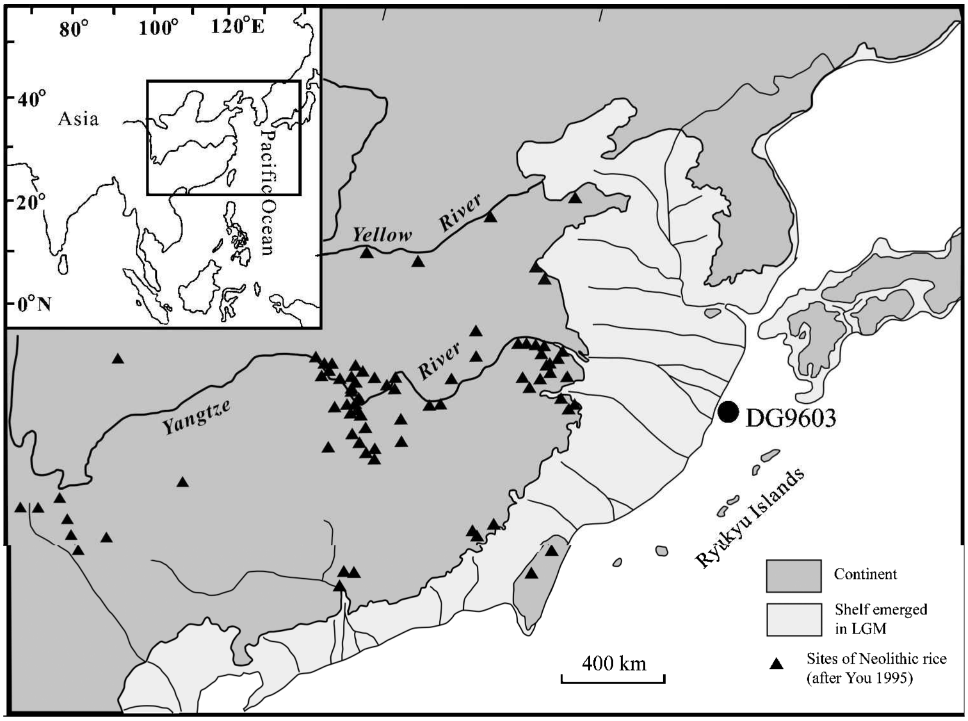

*Fig. 1.* Map of East Asian epicontinental seas showing the location of the coring site (core DG9603, 28°08.869′N, 127°16.238′E, water depth 1 100 m).

## Materials and methods

In 1996, a 592 cm core was collected in the palaeo-estuary of the Yangtze River at the mid-west margin of the Okinawa Trough (Fig. 1). The core (DG9603, 28°08.869′N; 127°16.238′E, water depth 1 100 m) recorded a continuous accumulation of semi-pelagic abyssal ooze containing abundant microfossils.

The age model for the DG9603 was constructed using accelerator mass spectrometry (AMS) $^{14}$C ages. Samples for AMS $^{14}$C dating were obtained from monospecific specimens of planktonic foraminifer *Globorotalia menardii* and *Globigerinoides sacculifer*. The dating was conducted by Beta Analytic, Inc., USA. Calendar age was calculated using CALIB 4.1.2 (Stuiver *et al.* 1998) (Table 1). The analyses of diatoms (Lu *et al.* 2000), foraminifera (Li *et al.* 2000), pollen (Lu *et al.* 2002) and phytoliths were conducted at about 2-cm intervals for the upper 176 cm of the DG9603 core. All phytolith samples were treated with 10% HCl to remove calcareous matter, washed with distilled water, and further treated with 30% $H_2O_2$ (0.5–1 h in a water bath at 60°C) to destroy organic material, and then treated with heavy liquid ($CdI_2 + KI + H_2O$). An average number of phytolith grains was 320 per sample. Age estimates for each sample were determined by assuming constant sedimentation rates between the dated age controls. Time resolution between samples was about 370 years for the Holocene and about 190 years for the period 10–20 ka BP.

*Table 1.* Radiocarbon dating of core DG9603 (Beta Analyses Co. USA). The measured age is based on $^{12}$C/$^{14}$C. The conventional ages are $\delta^{13}$C revised ages. Dates were calibrated using CALIB 4.1.2. (Stuiver *et al.* 1998). The ages are reported as intercept midpoint with $1\sigma$ in parentheses. CALIB 4.1.2 uses special reservoir age automatically. A standard marine reservoir correction was selected as we consider that the Okinawa Trough is still connected to the open ocean by passageways between the islands. *G.m* = *Globorotalia menardii*; *G.s* = *Globigerinoides sacculifer*.

| Depth (cm) | Species | Measured age (yr BP) | $\delta^{13}$C ‰ | Conventional age (yr BP) | Calendar age (yr BP) | Sedimentation rate (cm/kyr) |
|---|---|---|---|---|---|---|
| 11–13 | *G. m* | 2710 ± 50 | 1.1 | 3140 ± 50 | 2914 (2969–2846) | 4.2 |
| 26–31 | *G. m* | 4470 ± 50 | 1.1 | 4900 ± 50 | 5259 (5291–5200) | 6.7 |
| 47–49 | *G. s* | 8070 ± 60 | −0.3 | 8480 ± 60 | 8950 (9001–8898) | 5.3 |
| 63–65 | *G. s* | 9660 ± 40 | 1.0 | 10 090 ± 40 | 11 090 (11 156–10 828) | 7.5 |
| 89–94 | *G. s* | 11 190 ± 50 | 1.6 | 11 630 ± 50 | 13 141 (13 732–13 009) | 13.4 |
| 128–130 | *G. s* | 12 940 ± 50 | 1.6 | 13 380 ± 50 | 15 514 (15 715–15 301) | 16.0 |
| 174–179 | *G. s* | 16 760 ± 60 | −11.5 | 16 980 ± 60 | 19 643 (19 965–19 335) | 11.4 |

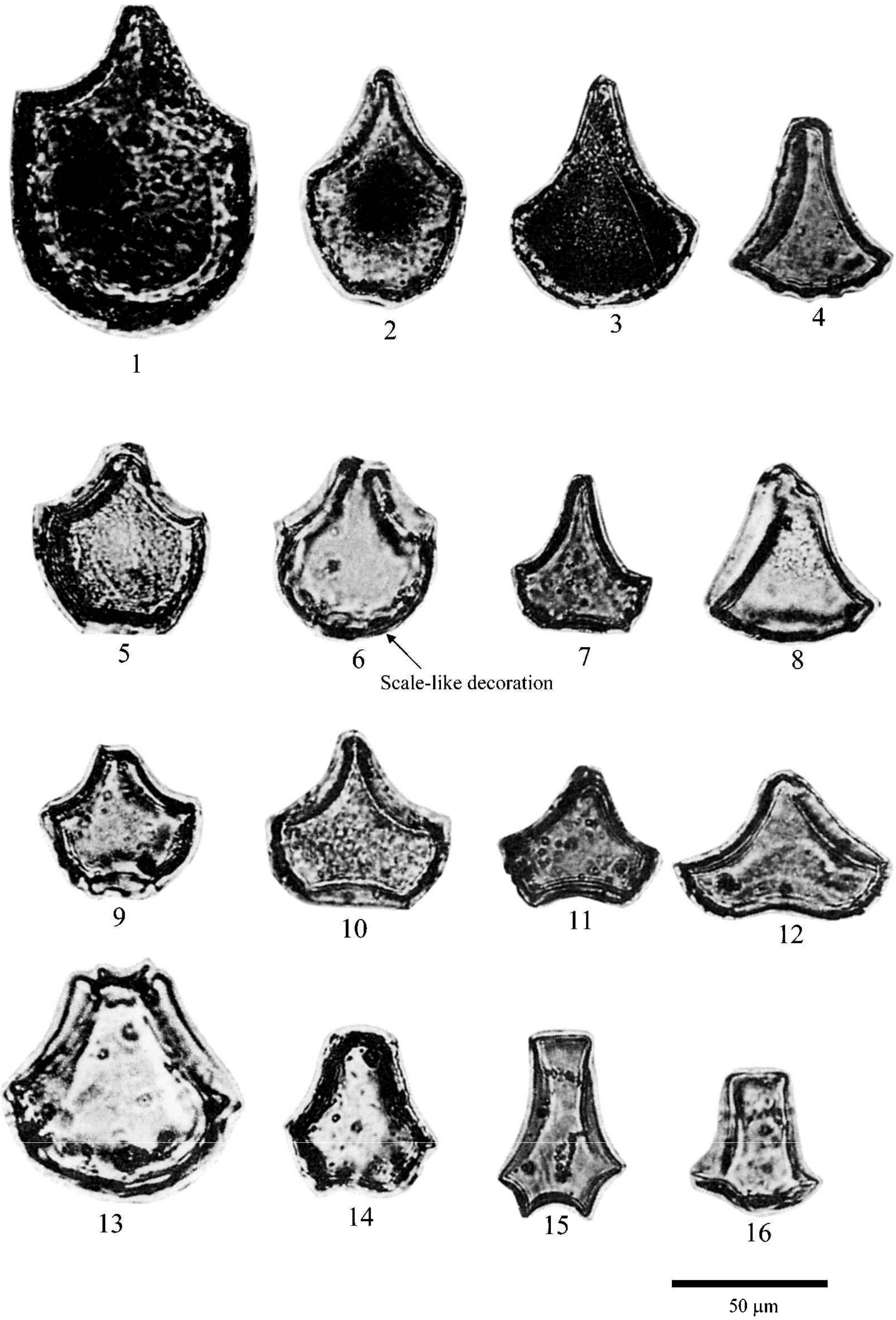

*Fig. 2.* Characteristics of bulliform phytoliths from 16 grasses showing rice phytoliths with scale-like decoration. 1, 2. *Phragmites australis*; 3. *Paspalum* sp.; 4. *Miscanthus floridulus*; 5, 10. *Cynodon dactylon*; 6. *Oryza sativa*; 7. *Bathriochloa ischaemum*; 8. *Coix lacryma-jobi* var. *ma-yuen*; 9. *Chimonobambusa quagrangularis*; 11, 12. *Buchloe dactyloides*; 13. *Indocalamus tessellates*; 14. *Msicanthus sinensis*; 15. *Oplismenus undulatifolius*; 16. *O. compositus*.

## Rice phytoliths

Phytoliths are a type of microscopic silica body that precipitates in or between cells of living plant tissues. They occur in many plant families (Piperno 1988), but are especially abundant, diverse and distinctive in the Gramineae (Prat 1936; Blackman 1971; Piperno & Pearsall 1998). Many taxa in Gramineae produce phytoliths with characteristic morphology and taxonomic significance.

Phytoliths from rice plants can be identified into genus or species on the basis of morphological characteristics (Fujiwara 1993; Pearsall *et al.* 1995; Zhang 1996; Lu *et al.* 1996; Zhao 1998; Piperno *et al.* 1999). For example, rice glumes produce large and solidly silicified hair cell phytoliths characterized by single or double 'peaks'. Discriminant function analysis of the double-peaked glume phytoliths can be used to separate domestic rice from its wild relatives (Zhao *et al.* 1998). However, the double 'peaks' phytoliths have not been distinguished in this study, because they are difficult to distinguish from the fragments of radiolarian. Dumbbell with scooped ends, paralleled arrangement in leaf tissue, is typical of the Oryzoideae subfamily, in contrast to the characteristic features of *Oryza* plants (Wang & Lu 1993).

Keystone bulliform cells are also common in the genus *Oryza*. There are two opinions concerning whether bulliform measurements could be used to separate cultivated *Oryza* species from wild ones. Previous studies suggested the validity of bulliform measurements and even for the two subspecies of *Oryza sativa*, spp. *japonica* and *indica* in terms of the different discriminant functions obtained by Fujiwara (1976, 1993), Fujiwara & Sasaki (1978), Sato *et al.* (1986, 1990), Wang & Lu (1993) and Lu *et al.* (1996) based on examined cultivars and wild strains from southeast and east Asian countries. Pearsall *et al.* (1995), however, measured bulliforms from five species of Oryzeae and Bambusina tribes, suggesting that the bulliform measurements (vertical length, horizontal length, lateral length, ratio of the base length and length of the non-base portion) alone could not separate the wild *Oryza* species from the cultivated ones in areas where species overlapped.

Generally, the bulliform phytolith (fan-shaped) in *Oryza* is characterized by numerous small shallow scale-like decorations on the half round side (lateral side) (Fujiwara 1976; Fujiwara & Sasaki 1978). Other similar grass phytoliths have no such specific decoration (Fujiwara & Sasaki 1978; Wang & Lu 1993; Lu *et al.* 1996). Fig. 2 shows the characteristics of bulliform phytoliths from 16 grass plants. It can be seen that only the rice phytolith has the scale-like decoration. It should be emphasized that a few fan-shaped phytoliths from wild rice have similar decoration, but these decorations are different from those of *O. sativa* (Fujiwara 1976; Wang & Lu 1993) (Fig. 3).

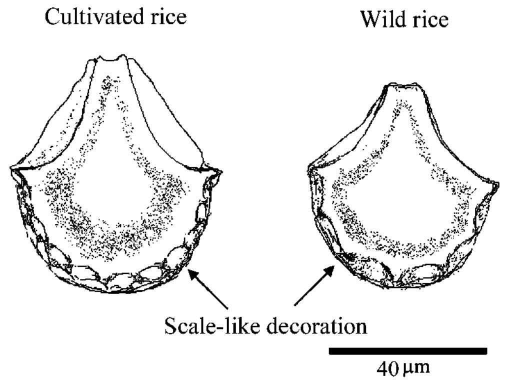

*Fig. 3.* Difference in decorations between wild rice and cultivated rice (after Fujiwara 1976).

In this study, we compared the characteristics of scale-like decoration from seven wild and six cultivated rice species and found that the cultivated rice has a larger number of scale-like decorations than the wild rice (Table 2). The bulliform phytoliths of *O. sativa* show generally 8 to 14 scale-like decorations, while those belonging to varieties of wild rice have commonly less than 9. Moreover, the decoration of wild rice is irregular and highly variable. Although these features are not sufficient to distinguish cultivated rice (*O. sativa*) from wild species (*O. perennis*) partly because of the overlap in the number of scale decorations between species, they can still be used to separate the *O. sativa* from wild rice statistically. From the data in Table 2, it seems that a number of decorations equal to 9 or higher would be a useful reference by which to identify the cultivated species.

## Results and discussion

### *Record of rice phytoliths*

In this study, the typical rice bulliform phytoliths (more

*Table 2.* Numbers of scale-like decorations in wild and cultivated rice species.

| Oryzoideae | No. of scale-like decorations along the bulliform phytoliths (mean ± SD) | Bulliform phytolith count |
|---|---|---|
| *Oryza sativa* | 9.7 ± 2.3 | 37 |
| *O. perennis* | 5.9 ± 1.5 | 39 |
| *O. punctaia* | 4.4 ± 1.0 | 40 |
| *O. minuta* | 5.6 ± 0.7 | 40 |
| *Leersia oryzoides* | 5.2 ± 1.3 | 40 |
| *L. hexandra* | 2.8 ± 2.1 | 39 |
| *Zizania caduciflora* | 4.2 ± 0.9 | 37 |
| *Z. miliacea* | 4.0 ± 0.8 | 38 |

SD = standard deviation.

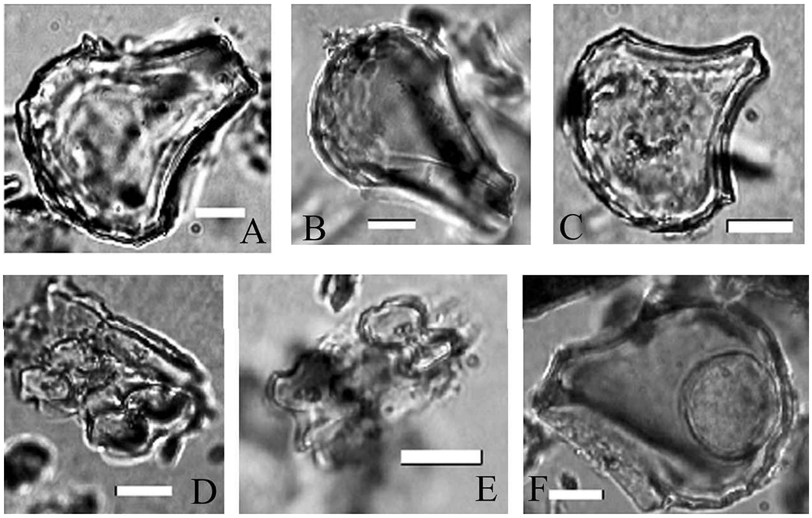

*Fig. 4.* Optical micrographs of fossil rice phytoliths from the DG9603 core. A, B, C, F. Bulliform phytolith (fan-shaped) with more than nine small shallow scale-like decorations on the half round side. D, E. Dumbbell-shaped with scooped ends, paralleled arrangement. Scale bar = 10 μm.

than nine scale-like decorations around the edge of fan-shaped phytoliths) were first found in sample 46 (depth 105–103 cm, 13 950–13 800 cal. yr BP) of the DG9603 core (Fig. 4A). Subsequently, all the samples were re-examined. As a result, seven grains of typical fan-shaped rice phytoliths and three grains of paralleled dumbbell phytoliths were found among a total of about 2 800 phytolith grains from samples 46 and 45 (Fig. 4B). Fifteen grains of typical fan-shaped rice phytoliths were identified in samples 43 (depth 97 cm, 13 470 cal. yr BP) to 40 (depth 90.5 cm, 13 050 cal. yr BP). Moreover, 32 grains of typical fan-shaped rice and paralleled dumbbell phytoliths occurred discontinuously from sample 23 (depth 53 cm, 9470 cal. yr BP) upwards (Fig. 4C–F). No such typical rice phytoliths were found between 90.5 and 53 cm (13 050–9470 cal. yr BP) and below 105 cm (>13 950 cal. yr BP) in the DG9603 core.

The phytolith record of the DG9603 core reveals a sudden appearance of fossil rice phytoliths at about 13 900 cal. yr BP, corresponding in time to the first emergence of domesticated rice strain (Zhao 1998), and an abrupt disappearance between 13 000 and 10 000 cal. yr BP. It is clear that a distinct difference in decorations occurs through the DG9603 core. However, it is still difficult to classify the phytoliths into cultivated rice or early-domesticated rice, because of the lack of reference data both on early-domesticated rice phytoliths and cultivated rice fossils before 10 000 years. Nevertheless, we suggest that the phytoliths with more than 9 scale-like decorations in core DG 9603 between *c.* 13 900 and 13 000 cal. yr BP are possibly an indicator of an early-domesticated rice strain.

According to the data above, the rice plant firstly emerged before, but disappeared during, the YD. What led to this change? The records of phytoliths, pollen, diatoms and foraminifera from the DG9603 core provide a detailed environmental history of the past 20 000 years (Lu *et al.* 2000, 2001; Li *et al.* 2000), thus provide insight into such a change.

## Environmental reconstruction of the last 20 000 years

The fossil assemblages of both diatoms and foraminifera were used to reconstruct the oceanographic changes of the ECS (Wang 1985; Jiang 1987). Changes in abundance of the typical Kuroshio diatom species in the DG9603 core (*Coscinodiscus nodulifer, Cos. africanus, Nitzschia marina, Rhizosolenia bergonii* and *Hemidiscus cuneiformis*), and sea-surface temperature (SST) were used to infer changes in oceanographic processes (Wang *et al.* 1997; Li *et al.* 2000; Liu *et al.* 2001; Lu *et al.* 2002) (Fig. 5).

Distributions of pollen and phytoliths in modern marine sediments of the ECS are mainly related to the epicontinental vegetation in adjacent East China and Japan. The major part of pollen and phytoliths was transported by wind and the longshore current system (Wang *et al.* 1997; Wang 1997). The most abundant types of phytoliths in the sediments of the DG9603 originate from grasses. The different subfamilies of grasses produce different phytolith shapes. For example, the Panicoideae subfamily, generally representing warm moist conditions, produces dumbbell (bilobate) and cross-shaped phytoliths, whereas the Festucoideae subfamily, a representative of cold xerophytes from steppes of North China (Wang & Lu 1993), produces trapezoid and rondel phytoliths. The Chloridoideae subfamily, indicative of a warm dry habitat, produces a short-saddle type, whereas the Bambusoideae subfamily, a good indicator of tropical and subtropical humid areas, produces a long-saddle type (Twiss *et al.* 1969; Piperno & Pearsall 1998). The ratio of cold–dry (trapezoid and rondel) to warm–moist (bilobate, cross, and saddle) phytolith types can therefore provide

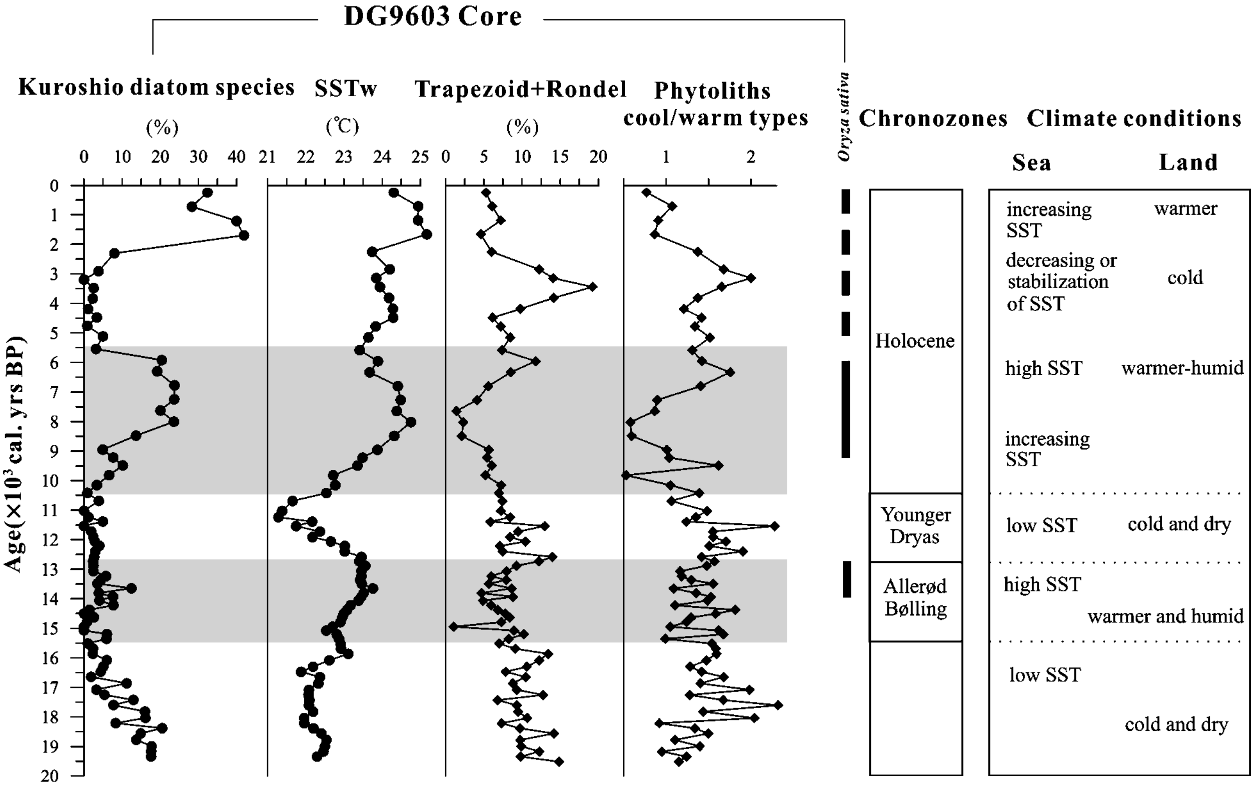

*Fig. 5.* Correlation of climatic proxy records of the Kuroshio Current diatom species (including *Coscinodiscus nodulifer, Cos. africanus, Nitzschia marina, Rhizosolenia bergonii* and *Hemidiscus cuneiformis*), SSTw, (Lu *et al.* 2000; Li *et al.* 2000), fossil phytoliths of Gramineae and rice from the DG9603 core. SSTw = winter sea surface temperature.

information on terrestrial climatic conditions and the vegetation community of the source area. Higher values are indicative of relatively cold and dry conditions, while the lower refer to warm and humid conditions (Wang & Lu 1993).

Diatom, foraminifera, pollen and phytolith records of core DG9603 show a series of cold/warm fluctuations in the oceanographic conditions, and a remarkable consistence in the number, duration and timing with the climate events in the last 20000 years (Fig. 5). During 20000–16000 cal. yr BP, and particularly between 18500 and 16500 cal. yr BP, the winter sea-surface temperatures (SSTw) were relatively low (Fig. 5). The high ratios of cold/warm phytolith types suggest relative cold and dry terrestrial climate. The annual average temperature in Shaanxi province, North China, might have been 7–8°C lower than it is now, and annual precipitation about 120–200 mm less than at present during this period (Wu *et al.* 1995).

Significant changes in oceanographic and terrestrial conditions occurred at about 16000–13000 cal. yr BP, approximately corresponding to the Bølling-Allerød period. The SSTw began to increase at 16000 cal. yr BP, and a distinct warmer stage (about 2°C higher than LGM) was reached between 14000 and 13000 cal. yr BP. The low ratios of cold/warm phytolith types also indicate relatively warm and humid conditions, comparable to the climate of early Holocene.

The YD climatic oscillation is well documented in northwestern Europe and in the West Pacific marginal seas (Alley *et al.* 1993; Wang *et al.* 1996). In the GISP2 record, the YD began at 12940 ± 50 and ended at 11640 ± 50 cal. yr BP (Stuiver *et al.* 1995; Grootes & Stuiver 1997). Our study shows that a rapid cooling of the ECS, and a cold and dry event in the epicontinental climate characterize the time period 13000–11000 cal. yr BP, approximately corresponding to the YD event. The SSTs decreased by 2.4–3.5°C in winter. The continental shelf of eastern China was sparsely forested, and was characterized by more herbaceous components (Meng *et al.* 1998; Sun *et al.* 2000).

After 10500 cal. yr BP, the SSTw abruptly increased in the Okinawa Trough. This change was accompanied by a remarkable increase of the Kuroshio Current diatom species between 9000 and 8000 cal. yr BP. Phytolith data generally show warmer and more humid conditions than previously. In the early Holocene, both the SSTw and the epicontinental temperature were higher (Fig. 5). In the mid-Holocene (5500–3000 cal. yr BP), climate cooled down and warmed again from 3000 cal. yr BP.

Palaeoclimate data from Maar lake in southern China

(Liu *et al.* 2000), pollen records from East China (Liu *et al.* 1992; Wang *et al.* 1997; Meng *et al.* 1998) and archaeological information (You 1995) show that the epicontinental climate was warmer and wetter from early to mid-Holocene (9000–6000 cal. yr BP) in response to intensification of the Asian summer monsoon.

Archaeological evidence from many sites in the middle and lower reaches of the Yangtze River reveals that cultivated rice was present around 10 000–9 000 cal. yr BP shortly after termination of the last glaciation (You 1995; Wang & Sun 1996). Domesticated rice began to develop at about 13 000 cal. yr BP (Zhao 1998). Our evidence of rice phytoliths from the DG9603 core in the palaeo-Yangtze estuary indicates that the earliest domesticated rice occurred at 13 900 cal. yr BP, on the basis of direct radiocarbon dating (Fig. 5). During late Pleistocene to early Holocene, the rising sea level probably included standstill (or minor falls), at *c.* −150 to −130 m (*c.* 15 000 yr BP), −110 m (*c.* 12 000 yr BP), −60 m (*c.* 10 000 yr BP) and 2 m (*c.* 5 500 yr BP) (Wang 1985; Wang *et al.* 1997; Saito *et al.* 1998). Thus, before 13 900 cal. yr BP, most of the continental shelf of the East China Sea was still exposed, which means that the Yangtze River delta was near the Okinawa Trough, about 600 km east of the present Yangtze River estuary (Wu *et al.* 1996) (Fig. 1). During the Bølling-Allerød period, the climate became warm enough for cultivation of rice on the middle and/or lower reaches, even on the continental shelf along the palaeo-Yangtze River, suggesting the possibility of the occurrence of rice phytolith in ECS.

The YD is a short-term climatic reversal to glacial-like conditions that might have had great influence on feral rice growth and human activities, including rice domestication. This might explain the lack of rice phytolith findings in the sediments deposited between 13 000 and 10 000 cal. yr BP.

Based on our phytolith record from the DG9603 core and archaeological evidence in China (Wang & Sun 1996; You 1995), we propose that many of the early rice domesticators did become true farmers around 10 000 years ago, when climate conditions became humid and warm during the lateglacial/early Holocene transition period. The rice phytoliths may have been transported to the East China Sea by the palaeo-Yangtze River from its middle or lower reaches.

## Conclusions

Phytolith data from the palaeo-estuary of Yangtze River at the mid-west margin of the Okinawa Trough indicate that significant natural and human-induced vegetation changes have occurred in the middle and/or lower reaches of the Yangtze River during the late Pleistocene and Holocene periods. The rice phytoliths occurred first in this area at about 13 900 cal. yr BP or during the time span 13 900–13 000 cal. yr BP; warmer and more humid conditions probably favoured rice domestication and cultivation in the area. This rice would be the earliest domesticated cereal crop in the world. During the period 13 000–10 000 cal. yr BP (YD), the climate was cooler and drier than today, which might have had a great influence on human activities, including rice domestication, and explain the disappearance of the rice phytoliths at this time. After *c.* 10 000 cal. yr BP the climate conditions became humid and warm, and the early rice domesticators became true farmers.

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