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SHORT COMMUNICATION

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Ancient paddy soils from the Neolithic age in China's Yangtze River Delta

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Abstract Identifying prehistoric irrigated rice fields and characterizing the beginning of paddy soil development are important for a better understanding of human development and agricultural history. In 2003, paddy soils and irrigated rice fields buried at a depth of 100–130 cm were excavated at Chuo-dun-shan in the Yangtze River Delta, close to Suzhou, China. The fields of sizes between 1.4 and 16 m^2 were surrounded with ridges that were connected to ditches/ponds via outlets to control the water level within the fields. Many carbonized and partly carbonized rice grains with an age of 3,903 B.C.(measured ^{14}C age 5,129± 45 a BP) were recovered. The surface layers of these buried paddy fields showed a high content of soil organic matter and a considerable high density of rice opals. The latter were identified to derive from *Oryza* spp. Solid-state ^{13}C nuclear magnetic resonance spectroscopy revealed aromatic carbon (C) as the predominant organic C form in the fossil surface layer. This is expected, if the major source represents burnt rice and straw. In summary, our data are in agreement with new evidences indicating that in China, paddy soils and irrigated rice cultivation were initiated and developed more than 6,000 years ago.

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Introduction

Worldwide, scientists of various disciplines are interested in the origin and spread of rice farming (Chang 1976; Greenland 1998; Higham 1984; Shao 1998). From the soil science point of view, wetland rice cultivation is directly related to the origin, formation, and development of paddy soils which are also classified as a man-made type of soil (De Datta 1981; FAO/UNESCO 1994; Gong 1994; Greenland 1998; Li 1992). During the end of the 1970s to the early 1980s at a site near Hemudu on the lower reaches of the Yangtze River, Yuyao, China, large quantities of carbonized rice grains were recovered and dated to 5,500 BC by ^{14}C-dating (Tang 1994; Yan 1991). This site was previously thought to represent the earliest place of true rice domestication (Chang 1976; De Datta 1981; Greenland 1998; Higham 1984; Shao 1998). Within the same soil layer, rice husks, stalks, and leaves were disclosed together with 76 pieces of spades made from animal bones with attached wooden handles (Chang 1976; Shao 1998). This discovery provided conclusive evidence for early cultivation of *Oryza sativa* (rice) at this location (Chang 1976; Greenland 1998; Shao 1998). However, a clear assignment to irrigated rice fields has not been obtained yet. In fact, up to now, it was not possible to determine whether rain-fed or irrigated rice was cultivated at the Hemudu site or any other place where carbonized rice grains were found (Higham 1984; Yan 1991). On the other hand, identification of prehistoric irrigated rice fields allowing for characterizing paddy soil formation from its beginning is important for a better understanding of the origin(s) and development of paddy soils, and also for obtaining insights into the long-term impact of human agricultural activity on soil properties.

From 1992 to 1995, at a site near Cao-xie-shan, the first excavation of ancient irrigated rice fields was conducted jointly by Chinese and Japanese archaeologists (Fujiwara and Ding 1996). Unfortunately, soil scientists were not involved in that excavation, and the site was refilled by a highway construction in 2000. To fill this gap, a further excavation site approximately 7 km northeast of that at

Cao-xie-shan was examined by combining archaeological approaches and analytical tools applied in modern soil science. It was hoped that this approach would supply new evidence for the existence of prehistoric paddy soils and irrigated rice culture in China.

Materials and methods

In November 2003, the sixth excavation of the Chuo-dun-shan site (31°24′07″ N, 120°50′41″ E) in the Yangtze River Delta was performed by archaeologists from the Suzhou Museum according to the standard procedures of the Archaeology Society of China.

Chuo-dun-shan is located in the east of the Taihu Lake alluvial plain at 3 to 4 m above sea level. Its distance from the Yangchen Lake is approximately 200 m, which is about 150 km from the present coastline of the Eastern China Sea and about 60 km south from the bank of the Yangtze River. According to (Xu et al. 1996), at 10,000 until 5,000 a BP, the climate at this location belonged to a warmer period of the Holocene, with humid subtropical vegetation and an average temperature of 1 to 2°C higher than at present. Remains of broad-leaved plants, aquatic plants, large animals such as deer, pigs, buffaloes, elephants, etc., were identified here and at surrounding sites. The favorable conditions with plenty of fresh water, a forest vegetation, wild life and hillside plain represented an excellent place for ancient humans to settle. It allowed for hunting, fishing, and gathering as well as for initiating agriculture (Jiaxing Cultural Bureau 2004).

Soil scientists from the Chinese Academy of Sciences involved in this excavation, described the examined soil profile according to the Soil Survey Manual (USDA 1993). Together with the archaeologists, they identified irrigated rice fields with methods provided by (Fujiwara and Ding 1996). The rice opal density (method 1) was analyzed microscopically using the method of (Zheng et al. 2003). The ^{14}C age (method 2) was determined with a liquid scintillation counter and calculated by comparing the radioactive intensity of a ^{14}C standard, the background and the sample (Skripkin and Kovaliukh 1998). The ^{14}C half-

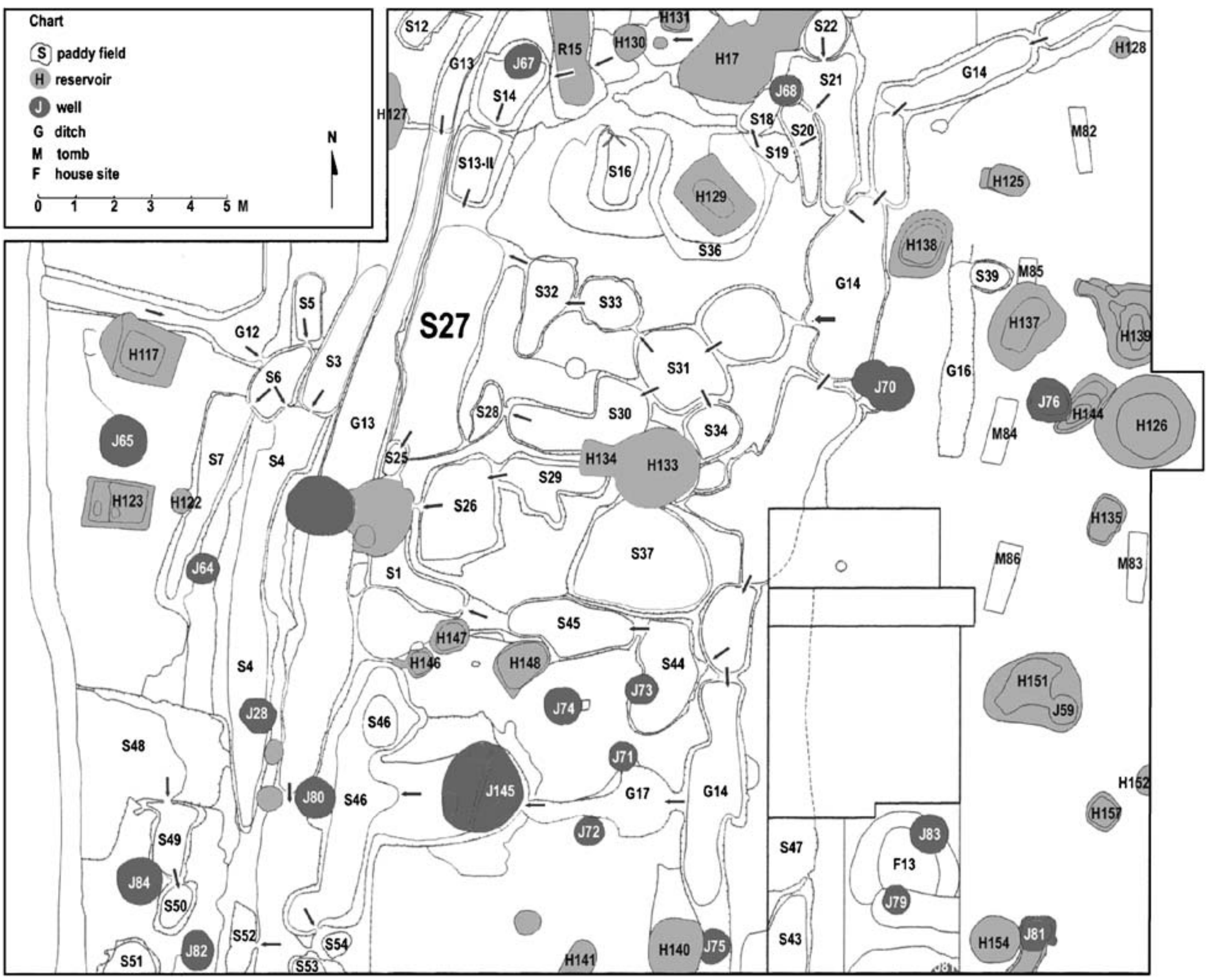

Fig. 1 Archaeological map of prehistoric irrigated paddy fields in Chuo-dun-shan site

Table 1 Description of a buried prehistoric paddy soil profile and some properties analyzed

Buried layer (cm)	Color	pH (KCl)	Texture	Corg (g kg^{-1})	Rice opal (no. g^{-1} soil)	Fe and Mn mottle	Bio-materials and others
100–116	10YR2/1	5.85	Heavy loam	22.31	105,159	++ Grey silt coatings	Rice grains and pot pieces
116–130	10YR4/1	5.90	Heavy loam	18.26	64,007	+ Grey silt coating	Humus and root residues
130–150	7.5YR4/1	5.86	Light clay	19.68	17,327	++ Many mottle	Root residues
150–160	10YR5/1	5.75	Light loam	17.20	19,678	+ Some mottle	
160–174	10YR5/1	5.71	Light clay	10.70	0	+ Mottle	
174–200	10YR4/6	5.35	Light clay	4.00	0		

life was taken as 5,730 years. Soil sampling and analysis were conducted according to the Methods of Soil and Agrochemistry Analysis (Lu 2000). Solid-state ^{13}C nuclear magnetic resonance (NMR) spectroscopy (method 3) of carbonized rice grains and demineralized soil (10% m/m hydrofluoric acid) from one of these prehistoric irrigated rice fields was performed on a Bruker DSX 200. The cross polarization magic-angle spinning technique with a ramped ^{1}H-pulse during a contact time of 1 ms was used. A spinning speed of 6.8 kHz and a pulse delay of 350 ms were applied.

Results

At a depth of 100 to 120 cm, in a layer assigned to the Majiabang culture (4,000 BC), a settlement was discovered with house remains, wall foundations, post hole, and door ways. The kitchen included a fire place, drinking wells, and cooking utilities such as a rice cooker, backing pots, and earthenware pots. Additionally, animal bones and ash pile as well as 29 tombs with five skeletons were excavated (Jiaxing Culture Bureau 2004). Approximately 1 to 20 m away from the settlement, a total of 46 prehistoric rice fields containing fossil rice grains were revealed within an area of 500 m^2 (Fig. 1). The approximate size of the fields ranged from 1.4 to 16 m^2 with almost round, round-rectangular, or irregular shapes. The surface layer was marshy meadows with a soft dark grayish color. Each rice field was surrounded with ridges (consisting of parent material) in yellowish and white color. Outlets of the ridges, most tentatively constructed to control the water levels, connected the paddies and ditches and/or small ponds for water diversion and/or drainage from the fields.

Rice opals were frequently detected in this prehistoric rice fields. In most of them, the densities were >5,000 and some even excited >10,000. In addition to rice, opal of reeds, *Cyperaceae spp* millet, caltrop, etc. were also detected in various quantities.

A large amount of carbonized rice grains was sieved out from the surface soils of these prehistoric rice fields. For instance, more than 200 fossil rice grains were found in 0.04 m^3 soil sample taken from the field S27 (Fig. 1). Their measured ^{14}C age is 5,123±45 a BP, which corresponds to an calibrated age of 5,907 a BP. Morphologically, the fossil rice grains were larger than that of wild rice. Double breast peaks, the shallow valley in the surface as well as the round shape of the grain showed that the recovered fossil rice grains differed from wild rice (Gu 1998; Thompson 1996) and belonged to the type of "Japonica" rice. This is in agreement with the results from the first excavation at Cao-xie-shan (Fujiwara and Ding 1996; Gu 1998) and the rice opal analysis above. Depending on the duration of irrigated rice domestication/cultivation, the paddy soils of these prehistoric irrigated rice fields had developed to a cultivated horizon of a height between 20 and 50 cm above the parent material.

Table 1 gives a description and some analytical data of a buried prehistoric paddy soil profile in the field S27 at the depth of 100 to 200 cm. Because no marine fish bones and shells were observed throughout the whole profile, it was concluded that this area was far enough from the coast to have not been affected by ocean deposition at that period.

Soil organic matter (SOM) concentration in the uppermost horizon (100–116 cm) of the prehistoric rice field at S27 is comparable to the average SOM content of present-day rice soils in this region (Zhang et al. 2003), but is about five times higher than in the parent material layer (160–

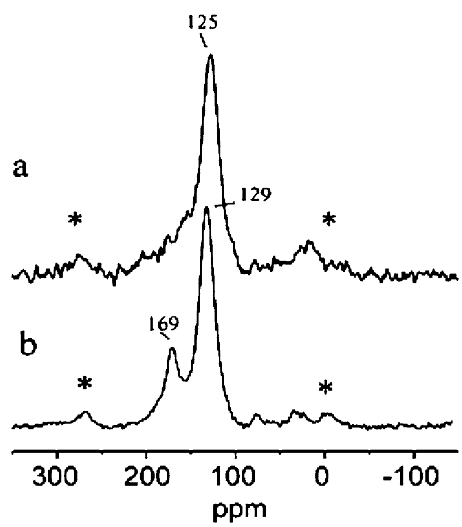

Fig. 2 Solid-state ^{13}C NMR spectra of fossil rice grain (**a**) and soil organic matter (**b**) derived from the layer 100–116 cm of the prehistoric irrigated rice field S27. The asterisks indicate the spinning side bands

200 cm). ^{14}C-dating of SOM from the uppermost horizon portrayed a measured ^{14}C age of 5,450±147 a BP, corresponding to a calibrated age of 6,280 a BP, which is about 300 years older than the measured ^{14}C age of 5,123±45 a BP determined for the charred rice grains (calibrated age 5,907 a BP) found in the same layer.

Figure 2 depicts the solid-state ^{13}C NMR spectrum of milled fossil rice grains screened out of the ancient rice field S27. It shows a strong signal at 125 ppm in the chemical shift region assignable to olefins or aromatic C compounds. As aromatic C is the predominant C form formed during biomass burning (Almendros et al. 1992; Knicker et al. 1996), the spectrum implies that the fossil rice grains were charred. This confirms their blackish color and supports the assumption that these fossil rice grains were part of the ash remains that ancient farmers returned to the field or the ash pile where straw burned in the field.

The dominance of the aromatic signal is also visible in the solid-state ^{13}C NMR spectrum of the SOM from the 100- to 116-cm soil layer of the respective prehistoric paddy field, unveiling charred material as the most important organic matter constituent. The lack of higher amounts of other C groups allows the conclusion that those char-derived constituents persisted more efficiently than the unburnt natural SOM. The resonance at 169 ppm in the spectrum is typical for carboxyl C in benzoic acids and indicates oxidation of the charred residues during the prolonged time of burial.

Discussion

The morphology and shape of the excavated rice soils indicated that a distinct irrigation system existed. This is supported by its close resemblance to the irrigation system disclosed at the Cao-xie-shan site, although the latter was classified to belong to the Majabang culture (Fujiwara and Ding 1996). Supposedly, these two sites had some relationship with respect to farming techniques applied during the Neolithic period. Many broken earth pot pieces dating back to the Neolithic age of 6,000 BP were recovered from the newly excavated fields and neighboring ponds. Considering that no other artifacts or sophisticated devices were found for carrying water, they were most tentatively used also for irrigation during drought periods when ditches had no water. With an average volume of these pots of 4 l, it may have taken 0.7 h to irrigate the largest rice field (16 m^2) by hand. Although not very efficient, this practice could have been, without doubt, helpful for securing food supply. Except a stone axe and a stone knife, no other tools for rice cultivation were found. Thus, at this time, irrigated rice cultivation was at an initial stage. Most probably, the ancient farmers used their hands and feet or wooden sticks for leveling and plowing these small pieces of rice fields. Their wooden tools, on the other hand, would have been disintegrated over the years without leaving any traces.

According to (Zheng et al. 2003), a soil with rice opal density greater than 5,000 per gram soil indicates rice-growing over a long period. This amount was largely extended in the entire horizon of the excavated prehistoric paddy soil, demonstrating that here rice grew for an extended time period. Considering further the age difference between the SOM and the fossilized rice grains of the prehistoric horizon, it may be concluded that here rice was cultivated already for more than 300 years before a large-scale lake flooding, possibly caused by the rise of the sea level in this region, resulted in new deposition, burying this site (Xu and Shen 1990).

In addition to rice, the occurrence of opals of other plants reveal that the weed control techniques were still on a low level. Indeed, for the ancient rice farmers the only available method to control the weed invasion was to use saturated or irrigated soil condition that favored for rice and aquatic weeds but were unfavorable to the majority of upland weeds.

Conclusion

Close to a formerly discovered prehistoric settlement, at Chuo-dun-shan in the Yangtze River Delta, Suzhou, China, 46 buried prehistoric paddy fields, connected with ditches and ponds or wells were revealed. Artifacts and grain remains found therein support their origin from irrigated rice cultivation. The lack of higher amounts of evolved farm tools implies that here the irrigated rice culture and paddy soil development was at an initial state. The solid-state ^{13}C NMR spectra of the fossil rice grains and the SOM in the uppermost layer of the prehistoric irrigated rice field assigns most of their C as derived from charred rice residues having remained in the ash after post-harvest burning. Together with the presence of opals of weeds, this supports the hypothesis stating that "to plow with fire and to weed with water" represents an important aspect of early irrigated rice cultivation in China (Gu 1998). According to this theory, the fields were plowed by post-harvest burning of the rice straw residues in fall. During spring, to kill the upland weeds, water was diverted from the ponds via ditches into the fields where the rice seeds were directly sown.

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