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Fire and flood management of coastal swamp enabled first rice paddy cultivation in east China

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The adoption of cereal cultivation was one of the most important cultural processes in history, marking the transition from hunting and gathering by Mesolithic foragers to the food-producing economy of Neolithic farmers[1]. In the Lower Yangtze region of China, a centre of rice domestication[2], the timing and system of initial rice cultivation remain unclear. Here we report detailed evidence from Kuahuqiao that reveals the precise cultural and environmental context of rice cultivation at this earliest known Neolithic site in eastern China, 7,700 calibrated years before present (cal. yr BP). Pollen, algal, fungal spore and micro-charcoal data from sediments demonstrate that these Neolithic communities selected lowland swamps for their rice cultivation and settlement, using fire to clear alder-dominated wetland scrub and prepare the site for occupation, then to maintain wet grassland vegetation of paddy type. Regular flooding by slightly brackish water was probably controlled by 'bunding' to maintain crop yields. The site's exploitation ceased when it was overwhelmed by marine inundation 7,550 cal. yr BP. Our results establish that rice cultivation began in coastal wetlands of eastern China, an ecosystem vulnerable to coastal change but of high fertility and productivity, attractions maximized for about two centuries by sustained high levels of cultural management of the environment.

The major climate amelioration from the late Pleistocene to the Holocene epoch markedly altered global ecological systems, prompting changes in human environmental adaptations and, in favourable regions including China[3,4], enabling transitions from hunting and gathering to domestication. Mesolithic foragers gathered aquatic perennial wild rice (*Oryza rufipogon*) in the middle Yangtze basin[5] and the lower Yangtze region[6] from the beginning of the Holocene epoch, an adaptation resulting from its availability due to the favourable environmental conditions of a warm, humid, monsoonal climate[7]. Such exploitation of wild rice was a prelude to its cultivation and then domestication[8] in these two core areas[9]. Understanding the process leading to rice domestication is constrained by ignorance of the precise ecological conditions that accompanied its initial cultivation. Our research at the wetland site of Kuahuqiao in the lower Yangtze region (Fig. 1) has answered this fundamental question regarding the origin of wet rice cultivation systems.

Excavation of cultural layers in organic deposits at Kuahuqiao[10] recovered rich assemblages of biological remains and archaeological artefacts, including a dugout canoe[11] and both forager- and cultivator-type bone, bamboo and wooden tools, well preserved because of their waterlogged condition and dated between 7,700 and 7,550 cal. yr BP (Table 1). Rice-tempered ceramics were common. The settlement's wooden pile dwellings prove that it was situated within wet marshes, and its excellent preservation of biological remains allows reconstruction of its economy and environment. Oysters provide evidence of the exploitation of coastal resources. Common animal bones include domestic pig and dog but mainly comprise wild species, as do the abundant plant remains, which include many edible types, such as acorns. Hunting and gathering dominated the economy. Many grains and phytoliths of rice occur, mostly wild varieties but including large numbers of morphologically advanced (but not yet domesticated) forms[12]. The cultural sediments represent the *in situ* location of first rice cultivation by hunter–gatherers establishing sedentary villages and undergoing Neolithic economic transition. Cultural activities continued for almost two centuries before the site was abandoned after inundation by mid-Holocene sea-level rise[13] and sealed beneath marine clay.

Lakeside and coastal swamps are good candidates for the ecological zone where earliest rice cultivation occurred[14], and Kuahuqiao's waterlogged sediments and cultural soils are ideal for testing this proposal, as they contain evidence of wild and early cultivated rice

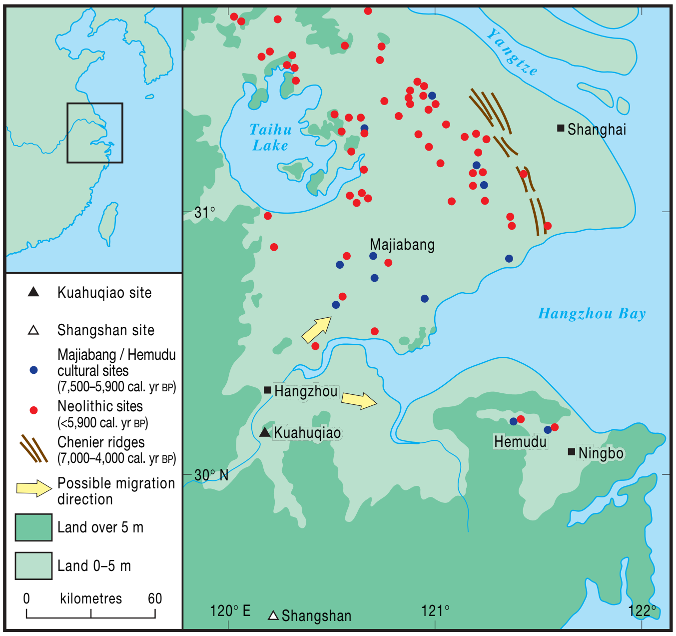

Figure 1 | Location of the Kuahuqiao site, and others, in the lower Yangtze region. The Kuahuqiao site lies at the gateway between sites in the upland valleys, south and west of Kuahuqiao, occupied by late Mesolithic and early Neolithic hunters and foragers including occupants at the Shangshan site[27], and sites on the coastal wetlands of Hangzhou Bay, east and north of Kuahuqiao, occupied by early Neolithic farmers such as those in Hemudu[25] and Majiabang[9] (blue dots). Red dots indicate locations of Songze and Liangzhu cultural sites[19]. The yellow arrows indicate the possible migration directions of the early Neolithic communities. Ages shown are in calibrated years BP.

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Table 1 | Chronology and the radiocarbon dates for the Kuahuqiao site

Depth (cm below sea level)	Laboratory code	Methods	^{14}C age (yr BP, ± 1σ)	Material	Calibrated age (yr BP, 1σ)	Central calibrated age (yr BP, ± 1σ)	Events
195.0	From ref. 10	Radiometric	6,330 ± 190	Bulk organic	7,144–7,428	7,286 ± 142	Brackish water conditions
200.0	BA05766	AMS	6,710 ± 40	Organic fragments	7,564–7,612	7,588 ± 24	End of human activities
208.0	BA05767	AMS	6,805 ± 35	Organic fragments	7,616–7,670	7,643 ± 27	Rise in cultural NPMs
210.5	GZ1311	AMS	6,743 ± 36	Organic fragments	7,574–7,622	7,598 ± 24	Decline in reed-swamp NPMs
213.5	GZ1312	AMS	6,710 ± 31	Organic fragments	7,566–7,608	7,587 ± 21	Rise in *Typha*
224.5	GZ1314	AMS	6,752 ± 33	Charcoal	7,579–7,622	7,601 ± 22	End of large-scale burning
229.5	GZ1315	AMS	6,783 ± 32	Leaf	7,607–7,662	7,635 ± 28	Increase in reed-swamp NPMs
238.0	GZ1316	AMS	6,851 ± 33	Organic fragments	7,653–7,709	7,681 ± 28	Start of human activities. Burning and end of alder carr
238.0	BA05768	AMS	6,870 ± 40	Organic fragments	7,663–7,746	7,705 ± 42	
242.5	GZ1317	AMS	6,996 ± 33	Organic fragments	7,792–7,863	7,828 ± 36	Rise of alder carr
282.0	From ref. 10	Radiometric	8,125 ± 250	Bulk organic	8,722–9,319	9,021 ± 299	Change to freshwater conditions

AMS, accelerator mass spectrometry.

in secure archaeological contexts, while wild rice occurred naturally in the area[15]. Whereas previous studies of the origins of rice cultivation in China have relied on rice phytoliths[8,16], and only rarely using pollen[17], we have used high-resolution pollen and several other types of non-pollen microfossil (NPM) analyses to provide detailed, diagnostic palaeoecological data from Kuahuqiao, summarized in Fig. 2. Eleven radiocarbon dates, concentrated in the cultural layers, provide a secure chronology for the sequence of environmental changes.

High frequencies of marine and brackish water diatoms and estuarine NPMs—mainly intertidal fungal spores and dinoflagellate cysts—in the clays of units A and G reflect marine sedimentation. Salt-marsh herb pollen occurs in these marine units, but much of the pollen assemblage comes from freshwater communities, indicating estuarine rather than open coast environments. The radiocarbon dates indicate about 1,500 yr of mainly organic freshwater sedimentation in phases B to F, when the rate of sea-level rise was greatly reduced[18], between two marine episodes. The combined pollen curve for deciduous (*Quercus*) and evergreen (*Cyclobalanopsis*) oaks represents the dominant upland vegetation (that is, sub-tropical woodland), indicating a warm, wet monsoonal climate[19].

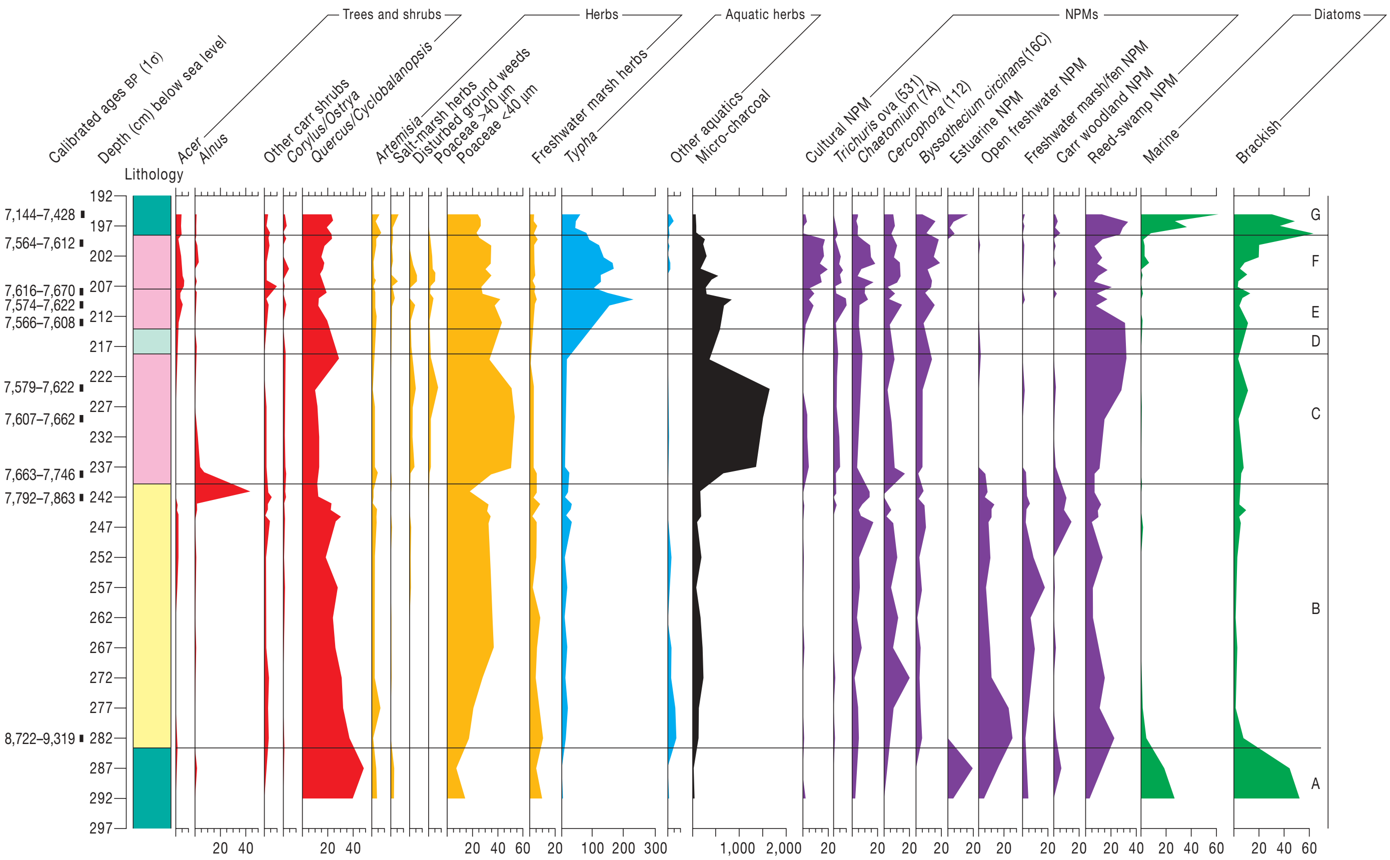

Figure 2 | Integrated palaeoecological data from Kuahuqiao. Generalized stratigraphical units and calibrated radiocarbon age ranges BP are shown. Microfossil data are subdivided into seven phases. Pollen and microscopic charcoal frequencies are calculated as percentages of a total land pollen sum including trees, shrubs and terrestrial herbs, but not aquatic herbs or pteridophyte and bryophyte spores. NPMs are shown as percentages of their own total counted sums. Numbers after NPM taxa names refer to the standard catalogue[21]. Some curves are aggregated percentages of several taxa of similar ecological affinities. Major increases in micro-charcoal, Poaceae/reed-swamp microfossils and cultural indicators occur in phases C, E and F.

The organic clay microfossil evidence in unit B indicates freshwater conditions, with no saltwater influence. Swamps with open-water pools are indicated by many aquatic fungi, macrophytes and algae, giving way to marsh, fen and reed-swamp wetland types. In the upper part of unit B, increases in grass (Poaceae $<40\,\mu m$) and freshwater marsh herb pollen indicate progressively shallower water as reed-swamp expanded. Abundant *Cercophora*, a fungal decomposer of herbaceous material, is further proof of the fen–marshland vegetation. By the end of phase B, successions culminated in the establishment of dense wetland scrub: first birch–willow (*Betula–Salix*) then alder (*Alnus*). Diatom evidence from here onwards shows a very slight rise in brackish water influence.

This scrub was cleared by fire at about 7,700 cal. yr BP at the start of the first cultural episode (phase C), as the curves for alder pollen, swamp woodland NPMs and aquatic/fen taxa collapse and micro-charcoal frequencies increase tenfold. Curves for cereal (*Oryza*)-type pollen (thick annulus Poaceae $>40\,\mu m$), disturbed ground weeds, 'cultural' NPMs and the ova of the parasitic worm *Trichuris*, hosted by pigs and people[20], begin at this time. After scrub clearance, human occupation and rice cultivation began on wet organic soils in grass–reed-swamp environments. This first intensive culture phase lasted over a century before interruption by a flooding episode and silt-clay deposition, with some woodland regeneration and reduced microfossil evidence of cultural activity (phase D). From the end of unit B throughout cultural phases C, E and F increased levels of salt-marsh herb pollen and salt-tolerant diatoms indicate regular flooding by slightly brackish water (freshwater diatoms still $>85\%$ of total). The cultural phases E and F saw intensive exploitation but reduced burning. 'Cultural' microfossil levels are very high during these two phases, including fungal spores indicative of soil disturbance and erosion, and some (*Chaetomium* and *Cercophora*) that are indicative of decomposing dung[21]. Seasonal high-tide flooding of coastal rice fields[22] combined with animal grazing[23] and low-intensity controlled burning of the reed-swamp promoted the growth of cattail (*Typha*). The micro-charcoal data in the cultural phases plus the dung-associated fungi and the site's abundant pig bones suggest human management, with burning and manuring to enhance rice cultivation yields. This encouraged abundant *Typha* growth around the cultivated area, which was perhaps deliberate as *Typha* is itself an important crop for food and materials[24]. This intensive human manipulation of the environment continued until 7,550 cal. yr BP, when marine inundation ended settlement and cultivation.

The cultural evidence shows that the forager/cultivator site at Kuahuqiao was the forerunner of a concentration of early Neolithic sites in the coastal lowlands around Taihu Lake and Hangzhou Bay (Fig. 1), including classical sites of the Chinese Neolithic, such as Hemudu[25,26]. This area was a major centre of rice exploitation from the very early Holocene, as shown by rice husks and phytoliths in pottery fabric before 9,000 cal. yr BP at Shangshan[27], with the establishment at 6,500 cal. yr BP of agricultural villages, as at Hemudu, and the intensive farming of fully domesticated rice varieties during the Songze and Liangzhu Neolithic cultures after 6,000 cal. yr BP[19]. There is strong debate over how agriculturally meaningful the earliest Holocene rice records are[27,28], but rice grain morphology suggests that records such as Shangshan are of exploited wild rice varieties, with dedicated cultivation (of evolving but still pre-domestication forms[12]) starting in the cultural occupation at Kuahuqiao and then at Hemudu[28]. The precise ecological data from Kuahuqiao are therefore critical to understanding the early stages of the forager–cultivator transition. A similar lengthy transitional period, with increasingly intensive cultivation of pre-domesticated rice varieties, also occurred in the central Yangtze valley around Lakes Poyang and Dongting at sites like Bashidang and Pengtoushan[29]. These sites have abundant rice grain and rice-tempered ceramic evidence comparable to Kuahuqiao, whereas similar sites in that area, like Diaotonghuan, may well be forager/cultivator correlatives of Kuahuqiao. Although their precise ecological history remains unknown, these sites provide a context for Kuahuqiao, and it is likely that the transition to dedicated rice cultivation was encouraged along the Yangtze valley by the major climate switch to benign, warm, wet conditions under the strengthening summer monsoon after 9,000 cal. yr BP[30], a critical environmental prompt to cultural change, permitting rice cultivation at this latitude.

The environmental evidence from Kuahuqiao not only establishes the presence of extremely early dedicated rice cultivation but allows an assessment of the earliest Neolithic rice cultivation system itself. Our detailed ecological analyses at Kuahuqiao establish that in eastern China the earliest significant rice cultivation system was located in slightly brackish coastal reed-swamps, and that, even at this early stage, rice cultivation involved very high-intensity clearance and management of the coastal marsh vegetation by fire. The abundant *Typha* stands that formed at the site, encouraged by human management activity, provided another highly productive crop, and rice cultivation may have been only one aspect of the exploitation of coastal resources that encouraged settlement, environmental manipulation and early cultivation in locations like Kuahuqiao. It is likely that floodwater input to the cultivated areas was also controlled by humans, as the proportion of tidal brackish water influence is maintained at a consistently low level throughout the later cultural phases. The earliest system of rice cultivation in China may well have been a form of 'receding-flood' water regulation, with artificial bunding used to retain some nutrient-rich seasonal floodwater, prevent major inundation and provide rice with the consistent water regime it requires. The eventual overwhelming of the site by marine inundation reflects the breakdown of this system of flood regulation and highlights the vulnerability of early rice cultivation in this productive but environmentally unstable coastal ecosystem. Our conclusion that incipient Neolithic groups in China used fire management to modify coastal wetlands for intensive early rice cultivation may pertain to other areas, such as around the lakes of the central Yangtze valley, and requires testing there.

METHODS SUMMARY

Field and laboratory methodology was designed to produce high-resolution palaeo-ecological data. Sediments for analysis were collected from an exposed section at the edge of the archaeological site, close enough to preserve evidence regarding on-site and near-site activities but far enough away from the main occupation area to avoid disturbance of the deposits' stratigraphy in antiquity. The altitude of the sampled profile was recorded relative to modern Yellow Sea Datum so that the site's relationship with past sea level could be established. Close interval sampling of the deposits was undertaken so that short timescale events could be recognised and studied. Multiple accelerator mass spectrometry (AMS) dates provide a robust and detailed chronology for the sedimentary sequence. Laboratory chemical preparations removed all mineral and organic material except for microfossils and microscopic charcoal fragments. Pollen grains were selected as the main source of evidence because they derive from a spatial variety of source areas, so that both on- and off-site vegetation can be reconstructed. Fungal spores, diatoms, other algae and invertebrate remains were also recorded, as these provide evidence sensitive to changes in local environmental conditions, including tidal brackish water influence. Micro-charcoal particles were recorded so that local fire history could be studied.

Full Methods and any associated references are available in the online version of the paper at www.nature.com/nature.

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Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Correspondence and requests for materials should be addressed to Y.Z. (y.q.zong@durham.ac.uk) or J.B.I. (j.b.innes@durham.ac.uk).

METHODS

Further details of the Kuahuqiao site. The site is located about 5 km south of Hangzhou City, between the hilly area to the south and west and the coastal lowland of Hangzhou Bay to the east and north, and is at the gateway between the catchment basin of the rivers and the coast. The archaeological site lies on the edge of a low-lying depression or a lake, with ground altitudes around 3.8 m above mean sea level, between two lines of hills.

The lacustrine sediments at the site were dug for brick making in the 1970s. As a result, part of the archaeological site was destroyed, and no cemetery was found during later excavations. The site was excavated for the first time in 1990, and excavated again in 2001 and 2002, by the Zhejiang Provincial Institute of Cultural Relics and Archaeology, an area of 1,080 m^2 in total[10]. At the centre of the site the cultural layer is about 3 m thick, covering the living quarter of the site from which at least four piled dwellings were found. The current research investigates the eastern edge of the site where the cultural layer is about 0.5 m thick and from which palaeoecological reconstruction is more reliable. The eastern profile (facing west) of trench T0512 was sampled in 2005, and this profile is about 8 m from the location where a dugout canoe was found and dated to approximately 8,000 cal. yr BP[11]. The sedimentary sequences at the profile are recorded against the Yellow Sea Datum: altitude −97 to −161 cm, grey, laminated fine sands, silt and clay, with abundant foraminifera, interpreted as tidal flat deposits; altitude −161 to −199 cm, brownish grey, uniform silt and clay, with abundant foraminifera, interpreted as tidal flat deposits; altitude −199 to −239 cm, dark brown silt and clay with abundant organic detritus and cultural remains, cultural layers C, E and F; altitude −239 to −283 cm, blue to grey, soft clay, turning brownish towards the top, with abundant plant fragments, interpreted as lacustrine deposits; altitude −283 to −297 cm, blue to grey, silt and clay, changing into yellowish sands and gravels at the base.

Geographically, the Kuahuqiao site lies at the gateway between the hilly areas and the coastal lowlands. Archaeologically, the Kuahuqiao site marks the beginning of the cultural transition between foraging Mesolithic hunter–gatherers and Neolithic food-producing farmers. In Kuahuqiao, over 1,000 rice grains were found, some of the grains show characteristics of domestic form, dated to 7,000 to 8,000 cal. yr BP[10]. Thus the Kuahuqiao site is considered important as it bridges the transition between sedentary foraging in Shangshan, approximately 90 km south of Kuahuqiao, where pottery pastes were found tempered with charred plants including rice husks and dated to about 10,000 to 8,000 cal. yr BP[27], and full domestication in Hemudu, about 140 km east of Kuahuqiao, where a large quantity of rice grains and husks were found and dated to approximately 7,000 to 6,000 cal. yr BP[9]. Recent examination of rice grains from the Lower Yangtze region suggests that there is an extended period, a millennium or more, of pre-domestication cultivation, which exists between a much longer period of wild rice use by foragers and the full domestication around 6,000 cal. yr BP[28]. The cultural activities found in Kuahuqiao fall right within this transitional pre-domestication cultivation period.

According to ref. 10, other archaeological findings from Kuahuqiao include piled dwelling and storage pits. There are a large number of ceramics, mostly tempered with charred plants and rice husks. There are also a large number of bones from a variety of animals, birds and fish, as well as oyster shells and a variety of nuts and fruit seeds, acorns in particular. These remains suggest a wide range of activities of the Kuahuqiao community, including hunting, fishing and gathering as well as cultivation.

Laboratory methods. Microfossils (that is, $<180\,\mu m$ in size) from the sampled section were counted using a Nikon stereomicroscope at magnifications of $\times400$, using $\times600$ oil immersion lenses for identification of critical features. Thirty-six sub-samples were taken for analysis at no more than 5 cm vertical increments, closing to 1 cm intervals through most of the cultural layers. Samples were prepared for pollen analysis using standard preparation techniques including alkali digestion, hydrofluoric acid digestion and acetolysis[31]. Microfossil concentration was good although preservation was variable, and a minimum of 200 pollen grains was counted at each sampled level, after which the rest of the microscope slide was scanned for rare or indicator types and to confirm the presence or absence of cultigen pollen. Non-pollen microfossils (NPMs), mainly comprising fungal spores and remains of algae and invertebrates, were also recorded with at least 100 identified at each level and usually many more. NPMs have been proven to be accurately represented on slides prepared for pollen analysis[32]. Microscopic charcoal fragments were counted, their numbers at each level calculated by their aggregated size relative to a unit of measurement equal to an average-sized pollen grain, providing a pollen/micro-charcoal ratio[33]. Diatom counts were also made, with taxa classified according to a halobian system based on salinity tolerances[34]. Frequency curves for selected types of these proxy data are shown in Fig. 2, correlated with radiocarbon assays and stratigraphical units. The calibration to calendar dates used the Calibration Program Calib 5.1 (ref. 35).

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