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Radiocarbon anomalies suggest late onset of agricultural intensification in the catchment of the southern part of the Yangtze Delta, China

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Highlights

- Erosion history for the catchment of the southern part of the Yangtze Delta
- Radiocarbon anomalies provide evidence for erosion of older soils and sediments
- An Early Holocene cluster of radiocarbon anomalies reflects marine transgression
- A later anomaly cluster suggests erosion from a late expansion of food production

Abstract

Previously underused information from radiocarbon dates in well-characterised sedimentary sequences in the southern Yangtze Delta, China, is here utilised in reconstruction of patterns of ancient erosion. The southern Yangtze Delta was an important focus of food production in the early Neolithic. Anomalous radiocarbon dates in Holocene sediments from the southern part of the delta are unevenly distributed through time. Two clusters of dates -- in sediments ca. 9,000-7,000 cal. BP and ca. 3,000-1,000 cal. BP -- most likely indicate two periods of intensive erosion and redeposition of organic materials. The older of the two clusters may have been associated with a marked episode of marine transgression, whereas the younger cluster could reflect increasing levels of human disruption of soils and sediments in the catchment. A relatively late increase in anthropogenic soil erosion supports recent archaeological evidence that, following its early Neolithic origins, agricultural expansion and intensification occurred later on the southern Yangtze Delta than previously thought.

Keywords: radiocarbon; alluvial; Holocene; archaeology; $\delta^{13}C$; rice

1 Introduction

Alluvial deposits in the lower reaches of large rivers were foci of early agriculture in many parts of the world (Bellwood, 2005). Soil that was tillable and that had its fertility frequently replenished during periods of inundation, additional nutritional security provided by aquatic and wetland resources, and ease of travel and trade proved attractive to early human settlers (Stanley and Warne, 1997). Understanding the history of human settlement and activity and the interactions between early farmers and their environment in these locations is, however, often hampered by the dynamism of the sedimentary environment. This dynamism not only impacts the length and continuity of sediment records, but can also severely affect the quality and reliability of chronological control (Brown, 1997). Radiocarbon, as a principal method for establishing the age of material dating to the last ca. 50,000 years (Walker, 2005), often produces high percentages of dating anomalies -- i.e. radiocarbon measurements that disagree with other dated evidence or that are associated with irregularities in age-depth profiles (Stanley and Chen, 2000; Hunt et al., 2015).

Anomalous radiocarbon dates in alluvium, through erosion and redeposition of old carbon, are common, including in the lower part of the Yangtze River (Stanley, 2001). Organic carbon in surface soil and sediments in a drainage basin often experiences temporary storage and remobilisation, the latter resulting from increased fluvial activity (Hoffmann et al., 2009) or soil erosion. The time between the initial fixing and burial of carbon and its subsequent re-exposure and re-mobilisation varies, and can be as long as several millennia (Galy and Eglinton, 2011). Organic carbon in sediments deposited along the lower reaches of a river with an extensive catchment may thus come from a diversity of sources and incorporate a range of different ages (Stanley, 2001). Dating anomalies are likely in this situation, which is a major reason why radiocarbon dates in alluvial environments often show systematically older ages than expected (Stanley and Hait, 2000).

The southern part of the Yangtze Delta, China (Fig. 1), is a prime example of an alluvial plain that became a focus of early agriculture. Human populations, their settlements and level of technological achievement and changes in the development of food production, are manifested in a series of cultural phases that left their mark on the archaeology of the region (Zong et al., 2012b). Rice (*Oryza sativa*) is a crop that is now consumed by more than half of the world's population (Khush, 2005). The Lower Yangtze valley is thought to have been a centre of origin of rice-based agriculture (Bellwood, 2005; Fuller et al., 2009; Fuller and Qin, 2010). The palaeoenvironmental context, early history and trajectory of rice-based food production on the southern Yangtze Delta is still poorly understood, however, in part owing to difficulties in establishing reliable chronologies. According to Stanley and Chen (2000), about 75% of radiocarbon dates from the Yangtze Delta appear 'erroneous', with the vast majority of these thought to be anomalously old.

Previous studies on the Yangtze Delta (e.g. Tao et al., 2006; Long et al., 2014) have circumvented the potential problem of using 'erroneous' dates by filtering out those that appear to be anomalous, and instead utilising only those over which there is a reasonable level of confidence that they represent the time of sediment deposition. For example, ages that do not fit into an *a priori* chronological framework for a particular set of cultural remains (such as pottery from an archaeological site) in the same layer with these dates are often considered not reliable and were discarded when establishing site-based chronologies (e.g. Archaeology Institute of Zhejiang Province, 2005). Unfortunately, such filtering may also remove potentially useful information, while leaving too few dates that are deemed acceptable to establish a robust and reliable chronology. The approach to dating adopted in previous studies on the Yangtze Delta, though reliant on highly constrained sources of data, is thus sub-optimal.

Fundamental improvements in chronological control will largely involve future developments in absolute dating methods that already offer some promise, including further improvements in techniques, such as luminescence dating. This paper adopts a different approach, however, in the form of a more effective use of previously underused radiocarbon dating information to better understand the early histories of occupation and food production on the southern part of the Yangtze Delta. In particular, information associated with radiocarbon dating anomalies, which was overlooked in previous studies, is utilised. Results presented here suggest that an Early Holocene (ca. 9,000-7,000 cal. BP) marine transgression may have been responsible for a cluster of radiocarbon dating anomalies, and support a relatively late date (after ca. 3,000 cal. BP) for a widespread intensification of human activity in the catchment for and on the southern part of the Yangtze Delta.

2 Research region

The early development of agriculture and associated human populations in the Lower Yangtze Valley is commonly viewed as a cultural sequence that is sub-divided into several, supposedly distinct phases, the dating of which remains somewhat contentious (see Long and Taylor, 2015). These cultural phases comprise the Shangshan (ca. 13,620-7,960 cal. BP), Kuahuqiao (ca. 7,920-7,300 cal. BP), Hemudu (ca. 7,230-5,070 cal. BP) / Majiabang (ca. 7,320-5,030 cal. BP), Songze (ca. 5,880-5,070 cal. BP), Liangzhu (ca. 5,590-3,870 cal. BP) and Maqiao (ca. 3,810-3,010 cal. BP).

Shangshan and Kuahuqiao-aged sites, equating to the earliest period of the Neolithic, are located south of Hangzhou Bay (Zong et al., 2007). The centre of Neolithic activity in the Lower Yangtze region appears to have moved to the north of Hangzhou Bay after ca. 7,000 cal. BP (Zheng and Chen, 2005). After ca. 4,200 cal. BP, the Liangzhu cultural phase appears to have declined and, after an archaeological hiatus, was replaced by the Chalcolithic Maqiao (ca. 3,810-3,010 cal. BP) (Stanley et al., 1999; Long and Taylor, 2015). Compared with the earlier Liangzhu and the contemporary Shang Dynasty civilisation (ca. 3,600-3,000 cal. BP) along the middle reaches of the Yellow River (Zong et al., 2012a; Wagner et al., 2013), the Maqiao in the Lower Yangtze was thought to represent something of a cultural backwater.

The southern plain of the Yangtze Delta, especially the area to the north of Hangzhou Bay and west of a series of shelly chenier ridges (Wang et al., 2012) (Fig. 1), provided a setting for the development of food production during the Neolithic (Zong et al., 2011). Sediments in this part of the delta are largely sourced locally, from the delta plain itself and from relatively raised areas of land to the west and south, such as the Tianmu Mountains (Wu et al., 2005; Chen et al., 2009). The region east of the chenier ridges, by comparison, was only above sea level during the Late Holocene (Li et al., 2000), and was therefore unavailable for occupation throughout much of the Neolithic period. Sediments in this part of the delta potentially originate from the full extent of the Yangtze River catchment (Wu et al., 2005; Chen et al., 2009) and their source is therefore potentially difficult to define precisely. As a consequence of the relatively short history of occupation of the area to the east, we focus in this paper on the southern plain of the Yangtze Delta on the landward (western) side of the chenier ridges.

3 Data and methods

3.1 radiocarbon dates as a source of palaeoenvironmental information

Radiocarbon dates from the southern Yangtze Delta have at least two types of associated information that can be used to ensure more effective palaeoenvironmental reconstruction and age control than would otherwise be the case.

The frequency of occurrence of radiocarbon dates, and in particular radiocarbon dating anomalies, can be considered a potential indicator of intensity of erosion. According to Hoffmann et al. (2013), burial of organic carbon in the lower reaches of a drainage basin is often linked to erosion intensity: generally, the higher intensity of that erosion, then the more organic carbon (including a large amount of radiocarbon-depleted carbon from upstream (Raymond and Bauer, 2001)) is buried on the continental margin contemporaneously. Statistically, because non-systematically collecting/discovering multiple radiocarbon samples (from different locations) is similar to a quasi-random sample of an organic carbon reservoir (Williams, 2012), more radiocarbon samples will be sampled from locations with more abundant organic carbon (these locations have a higher probability of being sampled than in a fully randomised sampling strategy). Also, it is more likely that radiocarbon dating anomalies would occur in these layers, where a considerable amount of radiocarbon-depleted carbon, exposed by increased erosion, was redeposited. Variations in frequency of occurrence of radiocarbon dates on material from the southern Yangtze Delta can therefore potentially act as a proxy of erosion history. Moreover, because human activity (e.g. deforestation and other alterations of the land surface associated with agriculture) are linked to increased erosion rates during the Holocene (McNeill and Winiwarter, 2004; Koppes and Montgomery, 2009), changes in the intensity and extent of food production on the southern Yangtze Delta are also likely to have affected the remobilisation and redeposition of organic carbon locally.

An increased occurrence of radiocarbon dates, notably radiocarbon dating anomalies, can be considered as a relative dating tool. Because carbon is often extensively buried in the lower reaches of a catchment (Dong et al., 2012), an increase in burial rates of carbon because of disturbance elsewhere in the watershed is likely to be recorded at a number of different locations; therefore peaks in occurrence of radiocarbon dates -- indicating increases in organic carbon burial -- can be considered as marker horizons in different sediment sequences. One potential application of such marker horizons in the current study is to identify periods of increased erosion caused by intensification of human activity on the southern Yangtze Delta in relatively poorly dated sediment sequences.

3.2 Data sources

Only dates from sediment sequences that were reported with clearly described litho-stratigraphy -- notably the litho-stratigraphic division between Holocene and Pleistocene -- were selected from internationally published sources to form the radiocarbon database used in the current research, as the stratigraphical information was critical for assessing whether a radiocarbon measurement is unusual (i.e. anomalous) when compared with the expected value. The division between Holocene and Pleistocene on the Yangtze Delta is associated with a characteristic stratum widespread in the region, the so-called 'First Layer of Stiff Clay', which is identifiable through its colour, hardness, and microfossil content (Qin et al., 2008). Given the focus of the current study, we only considered dates from sediment samples that were assumed, based on their stratigraphical position, to be Holocene in age. Thus radiocarbon dates (expressed as the median of the 2σ calibrated range) that suggest an age older than Holocene were classed as radiocarbon dating anomalies.

Many of the published radiocarbon dates (e.g. the majority of more than 250 archaeological dates compiled in the database in Long and Taylor (2015)) for the Yangtze Delta are absent of clearly described stratigraphical context, and thus not included in the current study. The resulting radiocarbon database (Supporting Information 1) comprised a total of 90 radiocarbon dates from the southern Yangtze Delta. Of this total, 27 were previously published in Stanley and Chen (2000). The remaining 63 radiocarbon dates were from more recently published sources (these are provided in Supporting Information 1). These dates are from a total of 17 sediment sequences: CD (Long et al., 2014), D2 (Stanley and Chen, 2000), DGY (Zhao et al., 2007), E2 (Wang et al., 2001), GFL core (Wang et al., 2012), JLQ (Stanley and Chen, 2000), MJB (Long et al., 2014), Pingwang (Zong et al., 2011), Siqian (Zong et al., 2011), SL (Stanley and Chen, 2000), T1 (Stanley and Chen, 2000), T4 (Stanley and Chen, 2000), W1 (Wang et al., 2001), WC1 (Stanley and Chen, 2000), WJB (Qin et al., 2011), Z4 (Stanley and Chen, 2000), and ZX1 (Stanley and Chen, 2000) (Fig. 1).

Five Holocene-aged sections are dated by seven or more radiocarbon dates. These have been labelled *relatively* high-resolution dated sequences. By comparison, twelve Holocene-aged sequences are dated by fewer than seven radiocarbon ages and were classed as *relatively* low-resolution dated sequences. We define the occurrence of a group of dates where one or more pre-Holocene date is immediately adjacent to another such date in the same sediment sequence as a set of pre-Holocene dates (PDS). A set of pre-Holocene dates can, however, also refer to a single pre-Holocene date that has no other pre-Holocene dates immediately adjacent to its position (PDS in Supporting Information 1).

Supporting Information 1 also includes available palaeoenvironmental information associated with the radiocarbon dates considered here. Signals of hydrological change (primarily based on indicative microfossils) are of particular interest. Previous studies (e.g. Qin et al., 2011) have indicated the important role that may have been played by variations in hydrological conditions during the Holocene in shaping environments and early agriculture on the southern Yangtze Delta. Radiocarbon samples associated with marine-influenced sediment layers are labelled as M, samples associated with non-marine-influenced sediment layers are labelled as NM, and samples without palaeoenvironmental information reported are labelled NA.

Some of the newly available dates were also reported along with $\delta^{13}C$ values, which provide a guide to the biological origins of organic carbon, and in particular the photosynthetic pathway adopted by the original source plants. These $\delta^{13}C$ values are also listed in Supporting Information 1. In general, organic material from marine sources accumulating in coastal/deltaic locations has a systematically higher $\delta^{13}C$ value than material that is of terrestrial origin. High $\delta^{13}C$ (less negative) values may thus represent marine inundation (e.g. Yu et al., 2011), with $\delta^{13}C$ data thus providing an independent line of evidence to support marine signals identified through microfossil evidence. The difference between marine-influenced and non-marine-influenced $\delta^{13}C$ values is primarily due to different photosynthesic pathways of both macro- and micro- plants in marine and terrestrial environments (Lamb et al., 2006). For example, terrestrial/freshwater-sourced organic material from the Pearl River Delta of China has an average $\delta^{13}C$ value of -25‰, whereas organic material of marine origin has a higher (less negative) value of -21‰ (Yu et al., 2011). Comparison between $\delta^{13}C$ values of terrestrial and marine-sourced organic material are, however, likely to be complicated by – notably -- changes in carbon isotope composition in the atmosphere on glacial-interglacial time scales and variations in contributions from C_4 plants (generally tropical and sub-tropical grasses and herbs). Where C_4 plants contribute to organic material in sediments, then samples are likely to be enriched in ^{13}C (i.e. generate $\delta^{13}C$ values that are less negative when compared with material from C_3 taxa). Also, changes in carbon dioxide in the atmosphere (pCO_2) -- in addition to isotopic fractionation -- are likely to result in notable changes in sedimentary organic carbon deposited at the time (Flores et al., 2009). Therefore, $\delta^{13}C$ values as an indication of sources of organic materials must be interpreted with caution.

3.3 Methods

3.3.1 Age-depth diagram

First, we plotted each radiocarbon date in a coordinate system of calibrated age (X) and sample depth (Y). This method was proposed by Stanley and Chen (2000) to estimate difference between the radiocarbon determined age for a sample and its expected age. The sample depth here is a standardised depth determined by transforming the depth of each sample into a proportion of the total thickness of the entire Holocene section in the sequence from which the sample is collected. Standardisation of sample depth was necessary here in order to facilitate comparison between different sequences, in which the thickness of the Holocene section varies between sites. For clarity in the diagrams, the median of the 2σ calibrated range of a radiocarbon sample was used as a representative of the sample's calibrated age. Although we used a previously published method, we are also aware that the method is weakened through not accommodating the effects of sedimentary hiatuses, of uneven sedimentary rates and the errors associated with using the median as a measure of an uneven probability distribution with calibrated radiocarbon dates.

Second, a straight line simulating an idealised sequence that had a continuous and constant sedimentation rate throughout the Holocene was used as a baseline for assessing the difference between the determined age of a sample and its expected age. The straight line is diagonal in the coordinate system, because ideally upper sections of a sediment sequence are younger than its lower sections. If the measured age of a sample drifted substantially away from this straight line (i.e. the sample's expected age), then the measured age can be considered as either younger or older than expected.

The baseline adopted in the current study was a straight line starting from the beginning of the Holocene epoch (i.e. ca. 11,600 cal. BP: (Barrows et al., 2007)), because we aim to assess dates from all types of Holocene-aged sections, rather than exclusively the deltaic sections. A summary of sedimentary facies of 265 sediment cores from the Yangtze Delta (Li et al., 2003) revealed that the total volume of Holocene-aged sediments of marine facies underlying deltaic sediments is larger than the volume of the deltaic sediments in the region. Therefore dates from sections lower than deltaic sections were retained in the analysis.

3.3.2 Age-transgression-$\delta^{13}C$ diagrams and Analysis of Variance

The set of age-transgression-$\delta^{13}C$ diagrams was designed to investigate the relationships between temporal distribution of radiocarbon dates, $\delta^{13}C$ values of these dates, and related marine transgression signals according to microfossil evidence. The main diagram plotted each radiocarbon date in a coordinate system of $\delta^{13}C$ (X) and calibrated age (Y), and projected the third line of information of marine influence in the coordinate system. In order to resolve the relationship between the $\delta^{13}C$ value and the marine influence signal of a dated sample in more detail, a second diagram was designed to calculate the difference in $\delta^{13}C$ values between marine-influenced and non-marine-influenced samples.

Given the fact that random errors (e.g. $\delta^{13}C$ measurement errors) might have significant influence to the dataset with such a limited number of data, the standard Analysis of Variance (ANOVA) method was adopted to test the difference. This statistical method examines the potential influence of factor(s) on a response through ruling out effects from random errors (Mullins, 2003). In the current case, we were examining whether the marine influence (identified through microfossil evidence) was associated with a statistically significant change in the $\delta^{13}C$ value of marine-influenced samples, the single factor under investigation being the marine influence (with only two categorical levels: M (marine influenced) and NM (non-marine-influenced)) and the response being the $\delta^{13}C$ value.

The $\delta^{13}C$ measurements of radiocarbon samples were considered as two groups of quasi-random samples (see Williams, 2012) from two different organic carbon reservoirs, one influenced by marine transgression and the other not. These measurements were statistically independent both within and between the two groups. Standard procedures such as an Anderson-Darling Normality Test and an equal variances test (plus visualisation of equal variances on a residual vs. the fitted value plot) were carried out to confirm, respectively, normality of the entire $\delta^{13}C$ dataset and equal variances of the two sets of $\delta^{13}C$ measurements, before the ANOVA model was applied (cf. Lawal, 2014). The null hypothesis in the current context was that the means of the two populations where the two groups of samples were collected were equal to each other (i.e. there was no difference in $\delta^{13}C$ values between marine-influenced and non-marine-influenced samples), whereas the alternative hypothesis was that the two means were not equal (i.e. $\delta^{13}C$ values of the two groups of samples were significantly different). A critical value of $p_c=0.05$ (i.e. with a 95% confidence level to reject a null hypothesis) is often considered sufficiently robust (Mullins, 2003) and was therefore adopted in all the above-mentioned statistical tests. The ANOVA was carried out using the statistical package MINITAB v.14.

Only those data points that were reported with $\delta^{13}C$ values in the source literature were included in the above analyses. In addition, a further selection was carried out, as radiocarbon dates in the current dataset were made from various sample types, including organic-rich mud, pollen residues, single pieces of charcoal, oyster shell, and plant fragments (Supporting Information 1), which vary in $\delta^{13}C$ values in nature regardless of their environmental contexts (Lamb et al., 2006). In order to compare like with like (Mackay et al., 2012), only determinations that were based on carbon in bulk sediments were selected in this analysis. This treatment is the most practical choice because bulk sediment dates, including dates based on undifferentiated organic material, peat, and pollen residues retrieved from bulk sediment samples, comprise the majority of the dataset. In contrast, dates based on material such as oyster shells, individual plant fragments, and charcoal, which are in the minority in the dataset, were excluded from further analysis. Focusing on bulk samples to compare like with like also allowed us to carry out a One-factor ANOVA (Mullins, 2003), because the influence of different types of sample materials (which otherwise can be considered as an additional factor with a series of levels that are complex to ascertain in ANOVA) on $\delta^{13}C$ values was then eliminated.

Of note is that a correlation rather than a causal relationship between the variables is evident. Even if a statistically significant difference in a $\delta^{13}C$ value between the two groups of samples (i.e. with or without a marine influence) exists, there is no basis for assuming that marine influence (a categorical variable) is the reason for the difference (another categorical variable). Other possibilities cannot be ruled out, such as that a third variable correlated to both original variables is a determinant variable that resulted in a superficial inter-correlation of the two.

4 Results and analysis

4.1 Age-depth diagram

A series of observations can be made from the age-depth diagram (Fig. 2). First, a considerable number of dates (23 data points or 26% of all dates in the dataset) have their median calibrated ages earlier than the initiation of the Holocene (i.e. ca. 11,600 cal. BP). The large percentage of pre-Holocene dates found in Holocene-aged sequences (according to stratigraphical information) exemplifies the frequent occurrence of dating anomalies in alluvial environments. Second, Holocene-age radiocarbon dates cluster in two time periods: the first period from ca. 9,000 to ca. 7,000 cal. BP (with 23 data points in 2,000 years), and the second period from ca. 3,000 to ca. 1,000 cal. BP (with 18 data points in 2,000 years). The two periods are in evident contrast with other periods, in terms of the size of cluster: ca. 11,600-9,000 cal. BP (with 12 data points in 2,600 years), ca. 7,000-5,000 cal. BP (with 9 data points in 2,000 years), ca. 5,000-3,000 cal. BP (with 4 data points in 2,000 years), and ca. 1,000-0 cal. BP (with 1 data point in 1,000 years). Third, most pre-Holocene dates (20 data points; i.e. 87% of all 23 pre-Holocene dates) occur in the high-resolution dated sequences. The likely reason why the low-resolution dated sequences seem to be associated with fewer dating anomalies, however, could be because the relatively few age determinations resulted in dating anomalies going undetected. Finally, there are eight PDSs in the dataset. Four of them (PDS3, PDS4, PDS7, and PDS8) are stratigraphically close to radiocarbon dates associated with ca. 9,000-7,000 cal. BP (Fig. 2 and Supporting Information 1). Two other PDSs (PDS2 and PDS5) are stratigraphically close to radiocarbon dates of ca. 9,069 cal. BP and ca. 9,640 cal. BP, respectively, and just beyond the range of ca. 9,000-7,000 cal. BP. The other two PDSs (PDS1 and PDS6) are close to radiocarbon dates of ca. 5,768 cal. BP and ca. 3,370 cal. BP, respectively.

4.2 Age-transgression-δ^{13}C diagrams and Analysis of Variance

A division between samples from marine- and non-marine-influenced layers is evident (Fig. 3(a)); the two categories of sediment layers were distinguished based on microfossil evidence described in the source literature where these radiocarbon dates were reported. Most of the samples from marine-influenced layers are placed in the upper part of the diagram (representing the pre-Holocene), whereas most of the samples from non-marine-influenced horizons are located in the lower part of the diagram (representing the Holocene), except a small group of samples that appear to be unusual. One notably unusual sample (a date for organic-rich mud (Wang et al., 2012)), with its δ^{13}C determination lower than -47‰ (different from δ^{13}C values of all types of organic inputs typical in alluvial and coastal environments (cf. Lamb et al., 2006)), is marked on the diagram and is considered an erroneous measurement and was thus excluded from further analysis. The distribution pattern implied that marine-influenced samples were closely related to pre-Holocene dating anomalies.

In addition, δ^{13}C values associated with the radiocarbon dates appear to support the separation into marine-influenced and non-marine-influenced sediment samples. Thus, in accordance with the principle that marine-influenced samples should generally have higher (less negative) δ^{13}C values (Section 3.1), higher δ^{13}C values (average = -23‰, with a standard deviation (SD) = 2.0‰) are associated with samples from the layers that were labelled as marine-influenced layers, compared with the values (average = -25‰, with a SD = 2.3‰) in samples from non-marine-influenced layers (Fig. 3(b)). An important caveat here is the possible and previously mentioned confounding influence on measurements of $\delta^{13}C$ of material from C_4 taxa and/or reduced pCO_2 on C_3 taxa. The caveat can perhaps reasonably be discounted in this case, because of the accompanying microfossil evidence.

Further confirmation of the difference in $\delta^{13}C$ values between the two groups of samples came from the ANOVA. The dataset was eligible for ANOVA, because it passed through the Anderson-Darling Normality Test ($p=0.30>p_c=0.05$) (Fig. 4(a)) and the equal variances visualisation/test ($p=0.71>p_c=0.05$ in the F-test and $p=0.56>p_c=0.05$ in the Levene's test (Brown and Forsythe, 1974)) (Fig. 4(b) and Fig. 4(c)), in addition to the fact that the dataset can be viewed as a series of quasi-random, independent data (Section 3.3). The null hypothesis that $\delta^{13}C$ values of the two groups were indistinguishable was rejected at a confidence level of 95% ($p=0.02<p_c=0.05$) (Fig. 4(d)): although $\delta^{13}C$ values for the two groups of samples overlap (Fig. 3(b) and Fig. 4(d)). The alternative hypothesis that the two groups of samples are from two distinct populations was thus confidently accepted, despite the limited number of available data for the ANOVA.

Results highlight the correspondence between marine-influenced samples and occurrence of pre-Holocene dating anomalies, the latter of which, in turn, were stratigraphically close to radiocarbon dates associated with ca. 9,000-7,000 cal. BP (Section 4.1).

5 Discussion

The two peaks of occurrence of radiocarbon records – ca. 9,000-7,000 cal. BP and ca. 3,000-1,000 cal. BP -- possibly correspond to two periods of increased catchment erosion that enhanced rates of organic carbon burial on the southern Yangtze Delta, raising probabilities of a particular stratigraphic horizon yielding datable carbon. Given the significance of humans as drivers of landscape modification in the Lower Yangtze, where vegetation is currently largely anthropogenic (Yi et al., 2003), the history of intensification of human activity, in particular expansion of rice-based agriculture, is of relevance.

Expansion of rice-based agriculture in the Lower Yangtze region may explain the earlier cluster of radiocarbon dates (ca. 9,000-7,000 cal. BP), given that the earliest evidence of the human exploitation of rice (e.g. rice husks in the matrix of pottery sherds) in the region have been dated to the Shangshan cultural period (Jiang and Liu, 2006). This is unlikely, however, since a wide body of archaeological evidence suggests that the earliest human activity on the southern part of the Yangtze Delta occurred only after ca. 7,500 cal. BP. Early Holocene human settlements in the Lower Yangtze region are all distributed, although sparsely, south of Hangzhou Bay, whereas no archaeological sites north of Hangzhou Bay have been dated to prior to ca. 7,500 cal. BP (Zong et al., 2012b).

In addition, domestication of rice in the Lower Yangtze was barely underway by ca. 9,000-7,000 cal. BP (Fuller et al., 2009). Rice exploited during the Shangshan is now thought to have been from wild varieties and was consumed along with material from other wild-growing plants e.g. acorns (*Quercus* spp.), Job's tears (*Coix lacryma-jobi*), and water caltrop (*Trapa natans*) (Liu et al., 2010). Gradual fixation of key domestication-related traits in rice -- closely associated with selection and thus with intensification of use by humans (Crawford, 2012) -- did not appear until ca. 7,000 cal. BP or perhaps later (Callaway, 2014). Land cover and other disturbances associated with farming were therefore unlikely to have been a cause of increased erosion at this time.

The fact that most of the pre-Holocene dating anomalies are stratigraphically close to the sediment layers associated with the period of ca. 9,000-7,000 cal. BP indicates a possibility that most were a result of contamination by old carbon exposed by intensive erosion in the sediment source areas. Marine signals associated with these pre-Holocene dating anomalies, based on microfossil and isotopic evidence, provide a useful clue for understanding the nature of this episode of erosion. In normal conditions, it is the upper and middle reaches of a catchment that act as the major source areas of sediments (including buried carbon) that are deposited in the lower reaches of the same catchment

(Stanley, 2001). The source areas could, however, differ significantly during a marine transgression. With a similar mechanism to drainage basin erosion, a marine transgression should also be able to introduce old carbon stripped from elsewhere (soils eroded by the incoming sea and sediments eroded by tidal currents on adjacent continental shelves, for example) into sediment sequences formed by the transgression, along with autochthonous carbon contemporary with the time of deposition, as reported, for example, by Oguri et al. (2000).

In this regard, occurrence of the pre-Holocene radiocarbon dates is not, therefore, an indicator of the timing of deposition, but an indicator of the ability of processes associated with the marine transgression to expose, erode and redeposit old carbon. The suggested high intensity of marine erosion also correlates well with a wider body of palaeoenvironmental evidence (e.g. Song et al., 2013) that points to an episode of rapid and extensive transgression between ca. 9,000 and ca. 7,000 cal. BP that impacted the entire proto-Yangtze Delta.

The second peak (ca. 3,000-1,000 cal. BP) of burial of organic carbon as a result of increased erosion can be linked to intensification in human activity in the Lower Yangtze. Given the absence of both microfossil and isotopic evidence for marine influence, another marine transgression as the erosive force that led to increased carbon burial is unlikely. Increased agricultural activity associated with population growth, including migration from northern China, is a more likely cause of increased erosion. Historical records suggest that increased population pressure, late-Holocene environmental deterioration and frequent warfare with nomads led to a series of waves of southward migration, beginning around the end of the Shang Dynasty (ca. 3,550-3,000 cal. BP) (Qian, 1998) and continuing throughout much of subsequent history (Duan et al., 1998). Population growth was associated with deforestation and expansion of agriculture by the migrants, who possessed more advanced technologies than earlier settlers (Liu and Wang, 2013). The Lower Yangtze region finally established its position as an important population and economic centre at the end of the Song Dynasty (ca. 820-670 cal. BP) (Duan et al., 1998). The erosion record on the southern Yangtze Delta also corresponds with an increase in the progradation rate of the main Yangtze Delta (Fig. 1) and of the region east of the chenier ridges on the southern Yangtze Delta, which was caused by intensified human activity (Hori et al., 2001). Sediment transfer in the Lower Yangtze River after ca. 2,000 cal. BP is estimated to have been almost double that prior to ca. 2,000 cal. BP (Hori et al., 2001).

In comparison, the period between ca. 7,000 and ca. 3,000 cal. BP has little radiocarbon evidence for intensification of erosion in the catchment of the southern part of the Yangtze Delta. This seems to support a relatively late expansion of agriculture in the area. Rice might have become a staple since the Liangzhu cultural period (Fuller and Qin, 2010), but it seems that only after ca. 3,000 cal. BP did human activity on and around the southern part of the Yangtze Delta increase to a level that produced a detectable mark in the erosion records. Existing site-level sedimentary data (e.g. Poaceae pollen and phytoliths from domesticated forms of rice) also suggest that rice-based agriculture did not became widespread until ca. 3,000 cal. BP (e.g. Itzstein-Davey et al., 2007). Thus the expansion of human activity on the delta seems a surprisingly long process, given the societal complexity demonstrated by palatial buildings, sophisticated ritual objects, and hierarchical burial system that characterised the late Neolithic Liangzhu period (Lawler, 2009). This could be because of the limited capability of radiocarbon records to reflect the intensity of erosion. The existence of this long process is exemplified by the contrast in archaeological remains between the Liangzhu and the Maqiao culture that followed the Liangzhu. The Maqiao was a less developed culture than the Liangzhu, with less advanced crafts, higher reliance on hunting and gathering as a subsistence strategy, and fewer settlement remains (Stanley et al., 1999), indicating that development of civilisation (and agriculture) in the Lower Yangtze was not a linear process and was perhaps characterised by at least one episode of progress followed by setback.

Relatively few studies have focused on the organic carbon content of sediment sequences from the southern Yangtze Delta. A peak in total organic carbon (TOC) is detected between ca. 9,000 and 7,000 cal. BP in the The GFL core sequence (Wang et al., 2012). This TOC peak also correlates with a marked increase in foraminifera remains, which is interpreted as evidence of marine transgression, supporting the possible marine origin of organic carbon in the section studied. In addition, a collection of information about TOC in lakes in China (Wang et al., 2015) suggests increased rates of carbon burial over the last ca. 4000 years, closely linked to heightened organic carbon input as a result of anthropogenically induced, intensification of land use. However, in today's Yangtze estuary, which is adjacent to the research area but might have been more exposed to transgression during the mid-Holocene owing to its more seaward location, Yang et al. (2011) finds little evidence of changes in organic carbon content of sediments throughout the entire Holocene. This discrepancy between different sediment sequences may reveal the complexity of TOC as a mixed assemblage of carbon from different sources, such as deposition of particulate organic carbon in various sizes and of once dissolved organic carbon (Raymond and Bauer, 2001). Thus, equating TOC to radiocarbon datable material in sediments may not always be appropriate. Nevertheless, using radiocarbon data as a proxy for reconstructing basin-scale erosion in this paper represents a methodological exploration. Just as Wang et al. (2014) equated the intensity of radiocarbon dated sediments from archaeological sites to prehistoric human population levels, this methodological exploration is based on a simplified, idealised model, the further testing of which will require more high-resolution chronological and palaeoenvironmental data, especially results from other dating methods (e.g. luminescence dating) independent of radiocarbon.

Finally, a seeming decline in the amount of available dates linked to the last 1,000 years might be more a reflection of methodological practice used in previous studies, and not linked to a most recent phase of erosion. The uppermost sections of sediment cores were often discarded or over-looked because signs of modern human contamination in those sections excluded their suitability for palaeoenvironmental studies (see Wang et al., 2012). It was likely that many of these discarded upper core sections included sediments associated with the last 1,000 years but containing recycled carbon.

6 Conclusion

Occurrence of radiocarbon dates, notably radiocarbon dating anomalies, can be used as an indirect measurement of basin-level erosion and a relative dating tool for understanding palaeoenvironmental and human history, if the underused information in these radiocarbon records can be considered in a holistic way, along with other available palaeoscientific and archaeological data. For the southern part of the Yangtze Delta, two peaks (ca. 9,000-7,000 cal. BP and ca. 3,000-1,000 cal. BP) in occurrence of anomalous radiocarbon dates likely relate to two periods of intensive erosion in the catchment. The first period was possibly associated with an episode of intensive marine transgression, whereas the second with an extension of intensified human activity (e.g. deforestation and expansion of rice-based agriculture). The latter may have been linked to a major increase in human population levels, associated with a phase of migration from other parts of China. In particular, the first period of erosion was responsible for the prevalence of pre-Holocene radiocarbon anomalies recovered from the southern part of the Yangtze Delta. Evidence for a late intensification of human activity in the Lower Yangtze region also accords with recent discoveries that the occurrence and expansion of intensified rice-based agriculture occurred relatively late on the delta (Balter, 2009), and with the idea that the development of food production in the region was a protracted process (Fuller, 2010).

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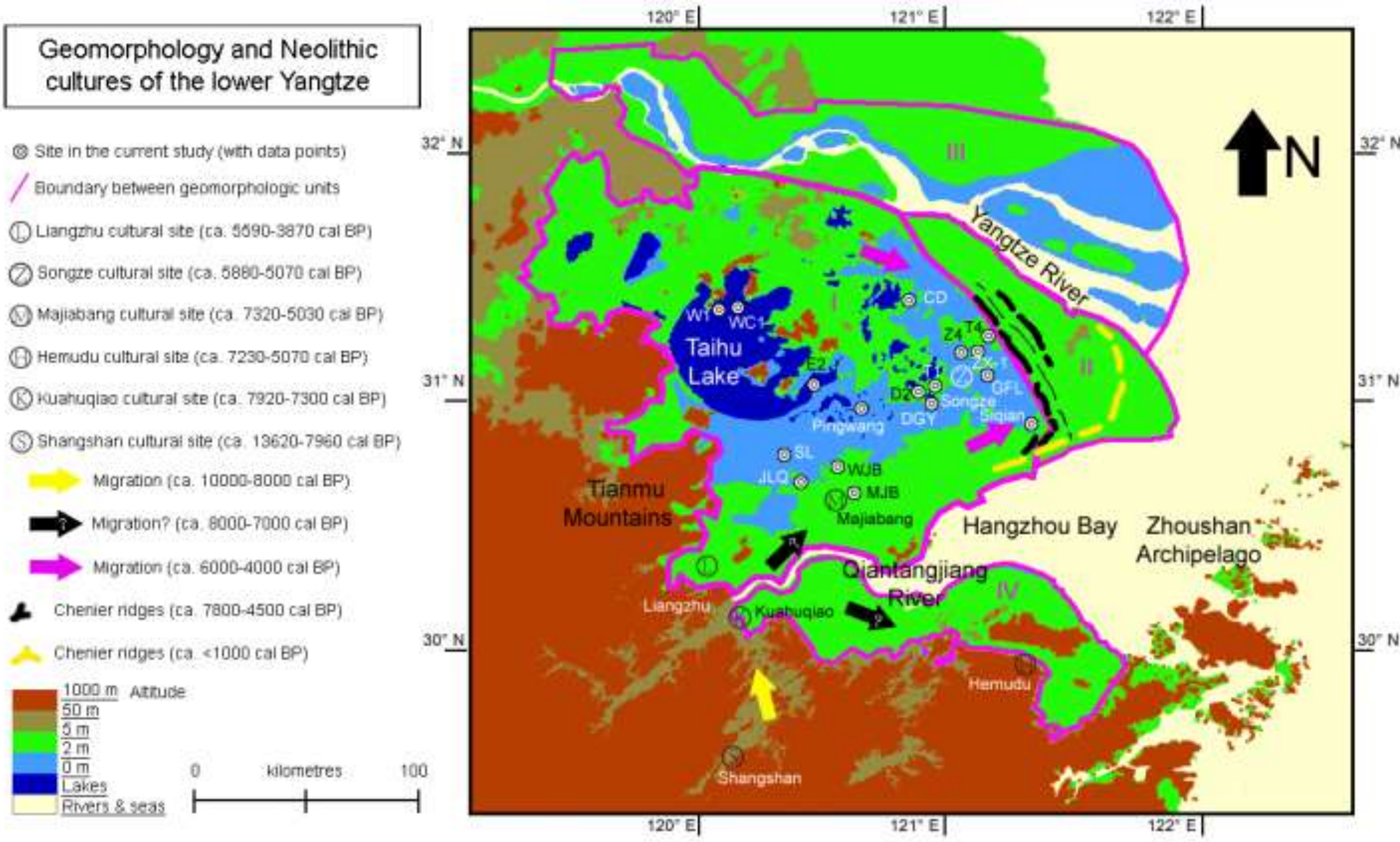

Fig. 1: A map of geomorphology and archaeology in the Lower Yangtze. Region I=region west of the chenier ridges on the southern Yangtze Delta; region II=region east of the chenier ridges on the southern Yangtze Delta; region III=the main Yangtze Delta; and region IV=the Ningshao Plain. Typical Neolithic sites are shown on the map. The locations of the 17 sediment sequences examined in the current study are labelled on the map: CD (Long et al., 2014), D2 (Stanley and Chen, 2000), DGY (Zhao et al., 2007), E2 (Wang et al., 2001), GFL core (Wang et al., 2012), JLQ (Stanley and Chen, 2000), MJB (Long et al., 2014), Pingwang (Zong et al., 2011), Siqian (Zong et al., 2011), SL (Stanley and Chen, 2000), T1 (Stanley and Chen, 2000), T4 (Stanley and Chen, 2000), W1 (Wang et al., 2001), WC1 (Stanley and Chen, 2000), WJB (Qin et al., 2011), Z4 (Stanley and Chen, 2000), and ZX1 (Stanley and Chen, 2000).

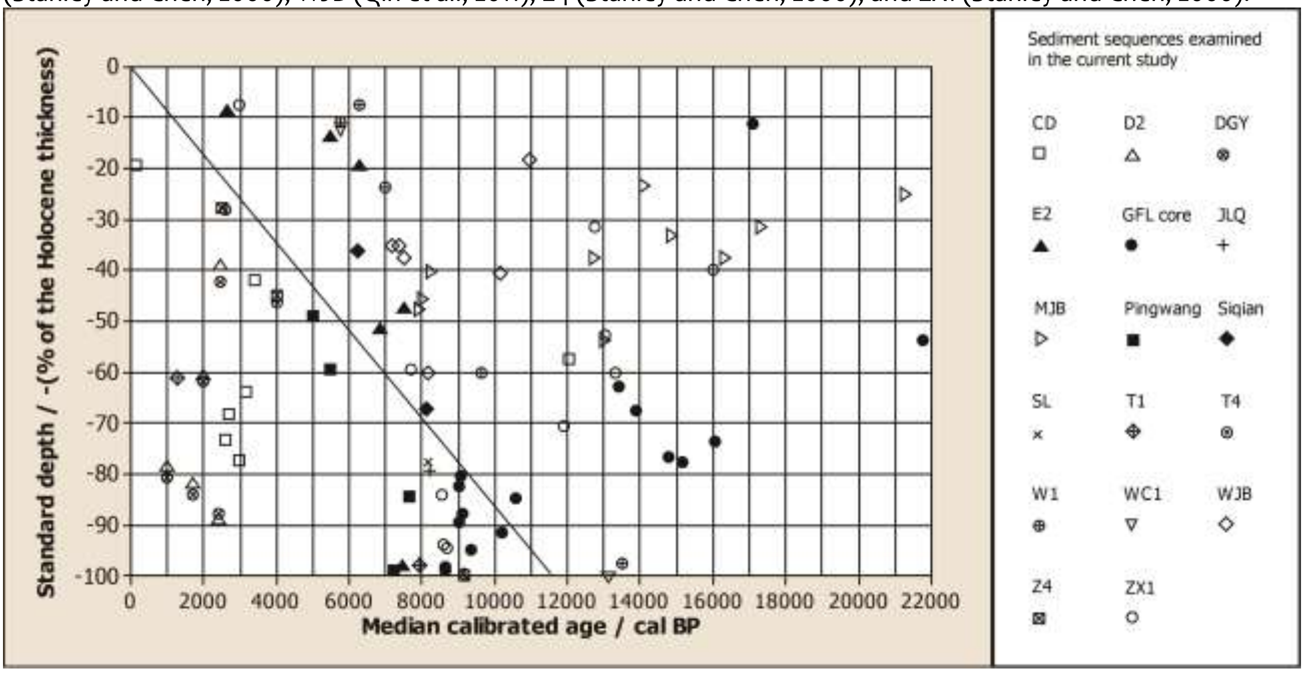

Fig. 2: Median calibrated age plotted versus standardized depth of ^{14}C data in 17 Holocene-aged sediment sequences recovered from the southern Yangtze Delta, China. The figure primarily shows temporal differences in occurrence of ^{14}C dates. Data from a same sequence use a same symbol; therefore 17 different symbols are used to represent the 17 sequences: CD (Long et al., 2014), D2 (Stanley and Chen, 2000), DGY (Zhao et al., 2007), E2 (Wang et al., 2001), GFL core (Wang et al., 2012), JLQ (Stanley and Chen, 2000), MJB (Long et al., 2014), Pingwang (Zong et al., 2011), Siqian (Zong et al., 2011), SL (Stanley and Chen, 2000), T1 (Stanley and Chen, 2000), T4 (Stanley and Chen, 2000), W1 (Wang et al., 2001), WC1 (Stanley and Chen, 2000), WJB (Qin et al., 2011), Z4 (Stanley and Chen, 2000), and ZX1 (Stanley and Chen, 2000). The diagonal line on the plot represents a baseline of a constant sedimentation rate. The standardized depth of a ^{14}C sample is calculated as a proportion of the actual depth of that sample to the total thickness of the Holocene in the sequence which the sample is collected from.

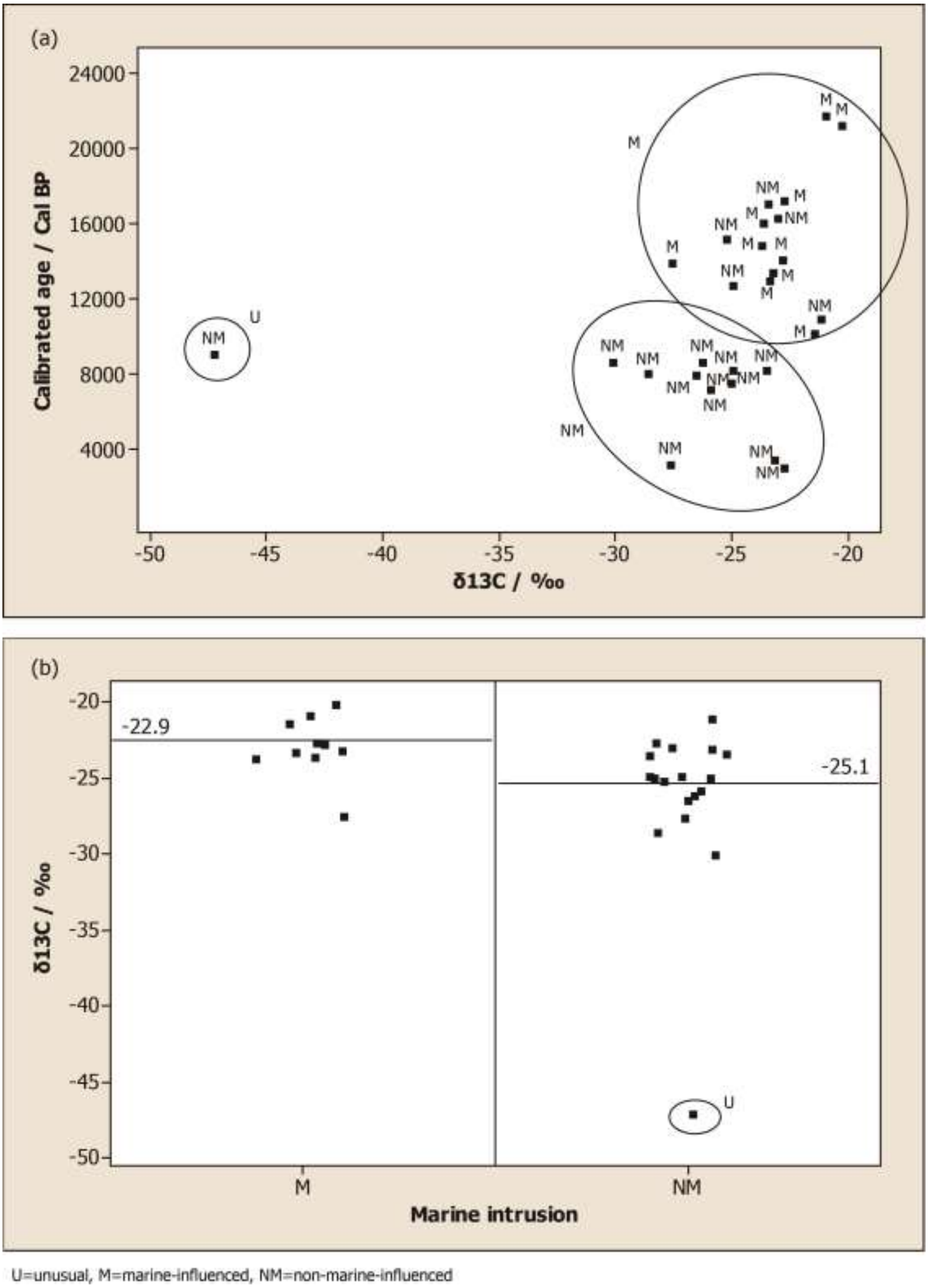

Fig. 3: The $\delta^{13}C$ values of ^{14}C samples in sediment sequences from the southern Yangtze Delta: (a) $\delta^{13}C$ values versus measured age, where pre-Holocene dating anomalies are found in association with marine influences -- except a minor proportion of unusual samples. The circle marked with M indicates where marine-influenced samples cluster, whereas the circle marked with NM indicates where non-marine-influenced samples cluster. An unusual sample (dated on organic-rich mud) is identified given its unusual $\delta^{13}C$ value. (b) $\delta^{13}C$ values of marine-influenced samples and non-marine-influenced samples, where marine-influenced samples (labelled according to microfossil evidence) are found with systemically higher $\delta^{13}C$ values than non-marine-influenced samples. The two lines, -25‰ and -23‰ in value, represent an average of $\delta^{13}C$ values of all samples in, respectively, the non-marine-influenced and marine-influenced assemblage. Therefore $\delta^{13}C$ values actually provide an independent line of evidence to confirm results from microfossil evidence.

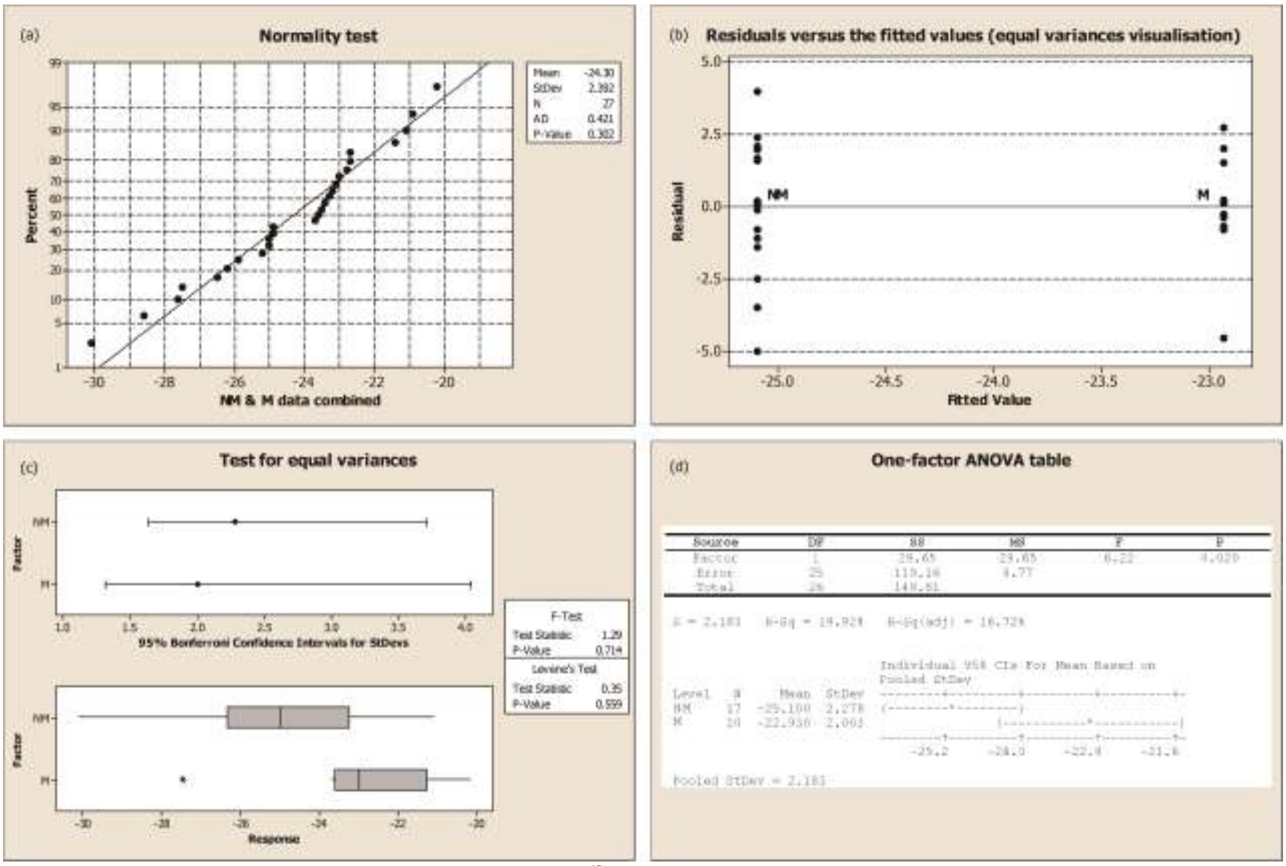

Fig. 4: One-factor Analysis of Variance (ANOVA) on $\delta^{13}C$ data from marine-influenced and non-marine-influenced samples: (a) $\delta^{13}C$ data are normally distributed, passing through the Anderson-Darling Normality Test. (b) $\delta^{13}C$ values of the two types of samples have no distinctly different variances. (c) $\delta^{13}C$ values of the two types of samples pass through the statistical tests of equal variances. (d) This One-factor ANOVA table shows that the two types of samples have statistically significant difference in $\delta^{13}C$ value. M=marine-influenced; NM=non-marine-influenced.