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Stable isotope record in paleosol carbonates from the Chinese Loess Plateau: Implications for late Neogene paleoclimate and paleovegetation

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Abstract

Stable carbon and oxygen isotope analyses were conducted on pedogenic carbonates collected from a continuous, late Neogene terrestrial sequence located in Lantian, in the Chinese Loess Plateau. The sequence consists of 300 m of fluvial deposits (Bahe Formation) with a basal age of ca. 11 Ma overlain by ca. 50 m thick sequence of aeolian 'Red Clay' (Lantian Formation) deposited between 6.8 and 2.6 Ma.

Pedogenic carbonates from the fluvial part of the sequence (i.e., the Bahe Formation) show only slight variation in $\delta^{13}C$ and $\delta^{18}O$ values suggesting that no marked change in plant photosynthetic pathway or climate took place during ca. 10 – 6.8 Ma. The carbon isotope compositions imply a pure C_3 vegetation. However, most data are in the upper C_3 plant range suggesting that water stress conditions prevailed in the area.

A shift in both carbon and oxygen stable isotope curves occur at the boundary of the two formations where the sedimentation regime changed from fluvial to mainly aeolian. The $\delta^{13}C$ record shows more depleted values in the Lantian Formation with no indications of C_4 plant contribution in the soil carbonate except for the youngest sample at ca. 2.7 Ma. The formation boundary marks a general rise in $\delta^{18}O$ values. Moreover, the $\delta^{13}C$ and $\delta^{18}O$ values scatter more in the Lantian Formation compared to those measured from the Bahe Formation. As the shift in $\delta^{13}C$ and $\delta^{18}O$ values at the formation boundary is concurrent, we hypothesize that the reason for the changes in both values are mostly interrelated. The changes probably reflect increased summer precipitation related to the onset and/or intensification of the Asian monsoon system.

Sedimentological and fossil vertebrate analyses suggest that stable environments with relatively dry conditions prevailed during the time when the Bahe Formation was laid down. Slightly below the formation boundary there is a faunal turnover event implying a marked change into more humid and closed habitats. The paleoenvironmental patterns deduced from carbon and oxygen isotopes are in good agreement with the palaeoenvironments inferred from sedimentological and paleontological studies from the Lantian area.

Keywords: Neogene; China; Lantian; Pedogenic carbonate; Carbon and oxygen isotopes; Asian monsoon; Paleoenvironment

1. Introduction

The stable isotopic composition of oxygen and carbon in pedogenic carbonates has been used as a tool for

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obtaining information of terrestrial paleoenvironments. Oxygen isotope values of pedogenic carbonates reflect climatic factors such as temperature and precipitation, whereas carbon isotope values can be used to reconstruct the relative proportions of plants using C_3 and C_4 metabolic pathways (e.g. Cerling, 1984, 1991; Quade et al., 1989). The majority of the present-day plants are of C_3 type, comprising trees, temperate shrubs, and cool-season and high altitude grasses. C_4 plants include mainly warm season grasses that are adapted to light, warm, varying moisture conditions, as well as conditions of low atmospheric CO_2.

Isotope studies on soil carbonates and fossil tooth enamel show evidence of major expansion of C_4 grassland ecosystems in the late Neogene (8–4 Ma) in the Siwalik sequences (Quade and Cerling, 1995; Quade et al., 1995; Cerling et al., 1997), North America (Cerling et al., 1997), South America (MacFadden et al., 1994; Latorre et al., 1997), and Kenya (Kingston et al., 1994; Morgan et al., 1994). In most regions, the vegetation change has been linked to changes in precipitation (monsoonal climates) (Quade et al., 1989, 1995; Pagani et al., 1999) or alternatively to the global lowering of the atmospheric CO_2 partial pressure during the late Miocene (Cerling et al., 1997), or the compound effect of regional climatic factors and lowering of pCO_2 in the atmosphere (e.g. Fox and Koch, 2004; Sanyal et al., 2004).

Many studies have shown that the aeolian 'Red Clay' and the superimposed loess sequence in northern China constitute an important record for the evolution of East Asian paleoenvironments and atmospheric system. A significant amount of research has focused on the use of e.g. grain size, pedology, geochemistry, and magnetic properties (e.g. Sun et al., 1997, 1998; Ding et al., 1998, 2001; Guo et al., 2001; Lu et al., 2001; Liu et al., 2003) as proxies for the evolution of the Asian monsoon system, as well as for paleoclimatic and paleoecologic conditions through the late Neogene. Systematic carbon and oxygen isotope studies have been very limited and have almost entirely concentrated on the Pleistocene loess sequences (e.g. Wang and Zheng, 1989; Wang et al., 1997; Wang and Follmer, 1998; Liu et al., 2005). However, Ding and Yang (2000) investigated a 'Red Clay' and loess sequence in Lingtai covering the past 7.0 Ma and showed that the major expansion of C_4 plants occurred at around 4.0 Ma ago.

A long, terrestrial sequence in Lantian in the southeastern loess plateau offers a unique opportunity to trace the evolution of late Neogene environments in China. The sequence studied here consists of the fluvial Bahe Formation and the overlying aeolian 'Red Clay' deposits, named as the Lantian Formation. The sequence is well dated and covers a time span between ca. 11 and 2.6 Ma (Kaakinen, 2005).

Paleoenvironmental data in the study area have been previously generated from mammal fossils (e.g. Zhang et al., 2002; Qiu et al., 2003), sedimentology (Kaakinen and Lunkka, 2003), and taphonomy (Andersson and Kaakinen, 2004). The stratigraphic sequence includes abundant paleosols that commonly contain pedogenic carbonates. The purpose of this study is to report stable carbon and oxygen isotope values in pedogenic carbonates occurring across the late Neogene sequence in Lantian, and interpret these data in terms of environmental variables. Our aim is also to understand the nature of environmental change that is mirrored in the change of depositional regime from the Bahe Formation to the Lantian Formation. Additionally, our goal has been to examine whether there is a significant vegetation change from C_3- to C_4-dominated floras in the Lantian study area as demonstrated in several other late Neogene sequences (e.g. Quade et al., 1995; Cerling et al., 1997; Latorre et al., 1997).

2. Study area

The study area in Lantian is situated on the southeastern margin of the Chinese Loess Plateau in the northern foothills of the Qinling Mountains (Fig. 1). The east–west striking Qinling Mountain range makes up the southern boundary of the Loess Plateau and is the traditional dividing line between temperate and subtropical zones in China. The southern Qinling slopes maintain subtropical, evergreen forest habitat, while a warm–temperate, deciduous, broad-leaved forest occurs north of the mountains (Zhao et al., 1990).

The present climate in the Lantian region is influenced in the summer season by both Indian and East Asian monsoons that bring warm, moist air to the area fed from the tropical oceans while the Siberian – Mongolian monsoon is dominant during the winter season (Domrös and Peng, 1988). Currently, the mean annual precipitation is about 575 mm at Xian (World Climatological Normals). Nearly 60% of the annual precipitation occurs between July and October. The average annual temperature is 13.4 °C, while the mean air temperature is −0.5 °C in January and 26.3 °C in July.

The present study in Lantian is concerned with the late Neogene stratigraphic sequence that is exposed along the north-east facing slope of the Bailuyuan Plateau. The basal unit in the sequence, the Bahe Formation, consists of about 300 m of principally

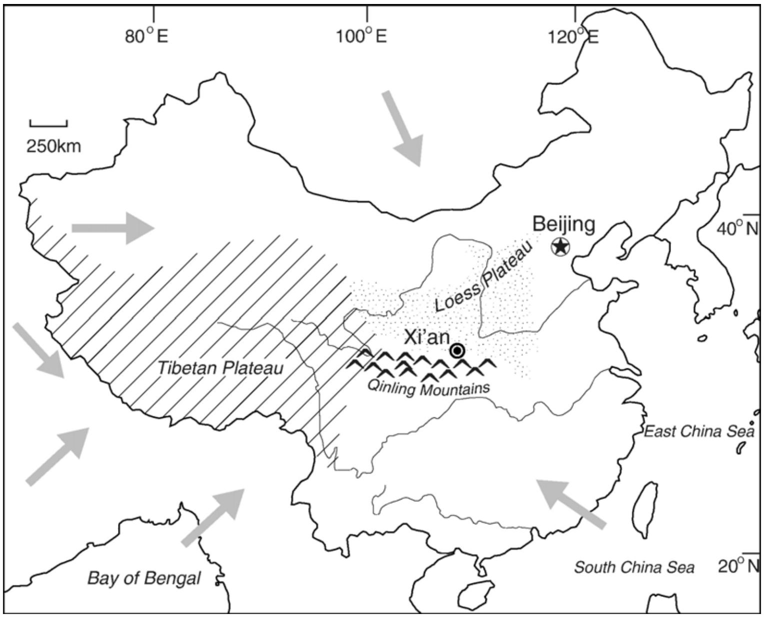

Fig. 1. A map showing location of the study area (near Xian) in the southernmost Chinese Loess Plateau relative to Qinling Mountains and the Tibetan Plateau. The prevailing atmospheric circulations are shown as arrows.

fine-grained fluviatile sediments with predominant lithologies consisting of reddish and greenish mudstones with subordinate sandstones and conglomerates. The varicoloured, mottled overbank mudstones with localized crevasse splay sheets form thick and laterally extensive units throughout the formation. Channel deposits typically exhibit fining-up cycles from conglomerates via sandstones to mudstones. Together the facies associations suggest a relatively quiet braided to anastomosing river depositional regime favourable to soil formation and preservation. The detailed description of facies assemblages and depositional environments within the Bahe Formation are described by Kaakinen and Lunkka (2003).

The overbank sediments in the Bahe Formation are fossiliferous with vertebrate fossil remains (Liu et al., 1960; Jia et al., 1966; Zhang et al., 1978, 2002; Li et al., 1984; Qiu et al., 2003, 2004a,b; Zhang, 2003; Andersson and Kaakinen, 2004; Chen and Zhang, 2004). The large faunal remains include a variety of ungulates as well as remains of carnivores (Zhang et al., 2002). The fossil record points to a rich animal life in open and relatively arid environments (Mikael Fortelius, personal communication) on the large floodplain areas between the fluvial channels. The base of the Bahe Formation has been dated as ca. 11 Ma (Kaakinen, 2005).

The Bahe Formation is overlain by the Lantian Formation, or what is commonly known as the 'Red Clay'. The origin of the 'Red Clay' deposits in China was originally postulated to be fluvio-lacustrine (Andersson, 1923) and has since been debated. However, during the last decade the weight of evidence is firmly in favour of the aeolian origin of the 'Red Clay' (Ding et al., 1998; Sun et al., 1998; Guo et al., 2001; Lu et al., 2001). The Lantian Formation is about 50 m thick in the study area, spanning from 6.8 Ma to ca. 2.6 Ma (Kaakinen, 2005). It consists of dark red silts and clays interbedded with carbonate nodule horizons, typical features for the 'Red Clay' deposits in northern China. Based on abundant pedogenic features (e.g., the aforementioned red coloration, high clay content, carbonate nodules and Fe–Mn coatings) the 'Red Clay' deposits have been regarded as an extremely thick soil complex (Ding et al., 1998, 1999, 2001; Han et al., 2002). Although the 'Red Clay' in the Lantian area is composed almost entirely of silt and clay, sand constitutes a variable fraction in the lower part of the formation indicating fluvial activity. In the study area there was no apparent depositional hiatus between the fluvial Bahe Formation and the overlying 'Red Clay' (i.e. Lantian Formation) (Kaakinen and Lunkka, 2003).

Vertebrate fossils in the Lantian Formation are very rare, apart from the basal, partly fluvial portion of the formation. This basal unit has yielded several fossil accumulations, including both large and small mammals (e.g. Zhang et al., 2002; Qiu et al., 2003). Mammalian fauna discovered from the lowermost part of the Lantian Formation displays a shift from more dry and open habitats to more humid and closed adaptations (Zhang et al., 2002).

3. Material and methods

Pedogenic carbonate nodules are a common feature in the fine-grained overbank units of the Bahe Formation. The calcic nodules that are few centimetres in diameter are typically concentrated as laterally pervasive nodule-bearing horizons developed in the upper parts of fluvial fining-upward units. These nodular calcic horizons occur at irregular intervals within the formation. There seems to be no stratigraphic trend in the distribution or maturity of these units. The host material in nodule-bearing fines typically displays a reddish brown colour and is thoroughly bioturbated. Other soil features like mottling and rhizoliths are often encountered in the context of carbonate nodules in the Bahe Formation.

Nodular carbonate is almost ubiquitous in the Lantian Formation. Nodules are concentrated as distinctive horizons, but they also occur dispersed individually throughout the profile (Fig. 2). The nodules in the Lantian Formation are mainly subspherical to elongate with mostly sharp external boundaries to the surrounding red clay groundmass. Generally, the nodules increase in size and abundance towards the upper part of the sequence. In the basal portion of the sequence, the nodules are mainly one to a few centimetre-size while the upper horizons consist of elongate nodules up to 15 cm in length. Internally, these larger forms are often composed of smaller nodules that are coalesced together.

The pedogenic carbonates were analysed for mineralogical composition. Random X-ray diffractometer (XRD) checks ($n = 20$) at various levels of the sequence indicate that calcite is the dominant component of the nodules. Other minerals such as quartz, feldspar, plagioclase, chlorite, and in few cases, dolomite, also occur. Thin section studies of the nodules ($n = 10$) revealed the dominance of homogenous micrite (generally <5 μm), indicating that these carbonates have undergone minimal recrystallization. The abundant presence of sparite would indicate recrystallization after the precipitation of original carbonate (Cerling, 1984).

Pedogenic carbonate was collected for isotope analyses from both formations. One sample per level was collected from the Bahe Formation, while in the Lantian Formation sampling was mainly done for several nodules in single horizons. The total amount of samples is 102 of which 77 are from the 'Red Clay' sequence. In the laboratory, the outermost surface of the carbonate nodules was removed with hydrochloric acid (10%) etching. The samples were dried and crushed. Samples for isotope analysis were reacted with phosphoric acid (1.91 g/cm^3) in vacuum over night at 25 °C to release carbon dioxide, which was measured for carbon and oxygen isotopic composition on a mass spectrometer (Delta E, Finnigan MAT). Ratios of carbon and oxygen isotopes are given as part per thousand relative to the V-PDB standard, and expressed as δ values

$$\delta = \left(R_{sa}/R_{st} - 1\right)*10^3$$

where R is the isotope ratio $^{13}C/^{12}C$ or $^{18}O/^{16}O$ of sample (R_{sa}) or standard (R_{st}), respectively. The stan-

Fig. 2. A distinctive carbonate nodule horizon in the upper part of the Lantian Formation.

dard deviation ($n = 41$) for repeated measurements of a laboratory reference calcite was 0.02‰ for carbon and 0.06‰ for oxygen.

4. Stable carbon and oxygen isotopes of pedogenic carbonates

Pedogenic carbonate forms in isotopic equilibrium with soil CO_2, which in turn is determined by the relative proportions of C_3 and C_4 plants where soil respiration rates are high enough to exclude isotopic inputs from atmospheric CO_2 (Cerling, 1984, 1991; Cerling and Hay, 1986; Cerling et al., 1989; Quade et al., 1989; Cerling and Quade, 1993). Terrestrial plants employ three distinct photosynthetic pathways reflecting different carbon isotopic fractionation. The bulk of continental plants (i.e., basically all trees, most shrubs and herbs, and cool-season and montane grasses) follow C_3 photosynthetic pathway (Calvin cycle). These display a range in $\delta^{13}C$ values between −33‰ and −21‰ and averaging about −27‰ (Cerling and Quade, 1993). The higher values are associated with higher water-use efficiency in water stress (Ehleringer, 1989). The C_4 (Hatch-Slack) photosynthetic pathway is less discriminating against $^{13}CO_2$ and therefore, C_4 plants are more enriched in $\delta^{13}C$ than are C_3 plants. They have $\delta^{13}C$ values between −6‰ and −19‰ (Deines, 1980) with an average of −13‰. C_4 plants include warm season grasses, sedges, and a few halophytic shrubs and are better adapted to moisture and heath stress than C_3 plants. C_4-dominated ecosystems are commonly associated with monsoonal precipitation patterns. The plants having a Crassulacaean Acid Metabolic (CAM) cycle use a combination of the C_3 and C_4 photosynthetic pathways and have $\delta^{13}C$ values intermediate between C_3 and C_4 plants (Ehleringer, 1989). These plants comprise succulent cacti and they can be neglected for ecosystems outside of deserts.

The carbon isotope values in soil carbonates are shown to possess higher $\delta^{13}C$ values than the coexisting local biomass due to gas diffusion processes and isotopic fractionation between the soil CO_2 and precipitating carbonate (Cerling, 1984; Cerling et al., 1991; Quade et al., 1995). The soil carbonates formed in the presence of pure C_3 vegetation are between −14‰ and −8‰, whereas values above −8‰ are indicative of a mixture of C_3 and C_4 plants.

The oxygen isotopic composition of pedogenic calcite has been shown to be principally controlled by the isotopic composition of soil water, which, in turn, is controlled by the local rainfall (Cerling, 1984; Quade et al., 1989). The $\delta^{18}O$ value of precipitation is primarily determined by temperature (Rozanski et al., 1993), but other parameters, such as continentality, altitude, seasonality, and amount of precipitation also play an important role. Additionally, soil carbonate in arid regions may become isotopically enriched relative to the precipitation due to evaporation (Quade et al., 1989).

5. Stable isotope record

The isotope record in Lantian extends from ca. 10 Ma to 2.7 Ma. The results of isotopic analysis are given in Fig. 3. The time scale for the samples was obtained by linear interpolation between each paleomagnetic reversal boundaries from C5n.2n to C2An.1n of Cande and Kent (1995). Every polarity zone except C3Br.1r was recorded (Kaakinen, 2005).

The $\delta^{13}C$ values of the pedogenic carbonates in the Bahe Formation representing a time interval ca. 10 – 6.8 Ma remain relatively constant and average −8.7 ± 0.2‰. The values are more scattered in the Lantian Formation (ca. 6.8 – 2.6 Ma), where the carbonate isotopic composition (76 out of the 77) ranges from −10.8‰ to −8.3‰ across the formation and the $\delta^{13}C$ compositions within a single nodule horizon may vary by 0.9‰. However, the values are clustered between −9‰ and −10‰, with an average value −9.4 ± 0.5‰. The fluctuation curve shows a weak trend of increasing $\delta^{13}C$ values for the youngest samples from ca. 4.5 Ma that culminates at ca. 2.7 Ma with the first appearance of $\delta^{13}C$ value greater than −8‰.

The carbon isotope compositions of the soil carbonates imply a pure C_3 vegetation throughout the sequence. Only the youngest data point in the Lantian Formation (−7.3‰) at around 2.7 Ma, suggests a mixed C_3/C_4 plant community. However, most data within the Bahe Formation are in the upper C_3 plant range, implying that plants were exposed to prolonged water stress. Therefore, the shift to more depleted $\delta^{13}C$ values in the Lantian Formation may have been triggered by either increased precipitation or cooler summer temperatures.

The $\delta^{18}O$ record shows little variation throughout the Bahe Formation. Values fall between −10.3‰ and −11.4‰ and the average value for the formation is −11.1 ± 0.3‰. Values of $\delta^{18}O$ in the Lantian Formation show a much more complex record. The $\delta^{18}O$ values range between −8.0‰ and −11.4‰, although compositions of carbonates within a nodule horizon display a smaller range in values (maximum ca. 2‰). The formation boundary marks a general rise in $\delta^{18}O$ values. The average value in the Lantian Formation

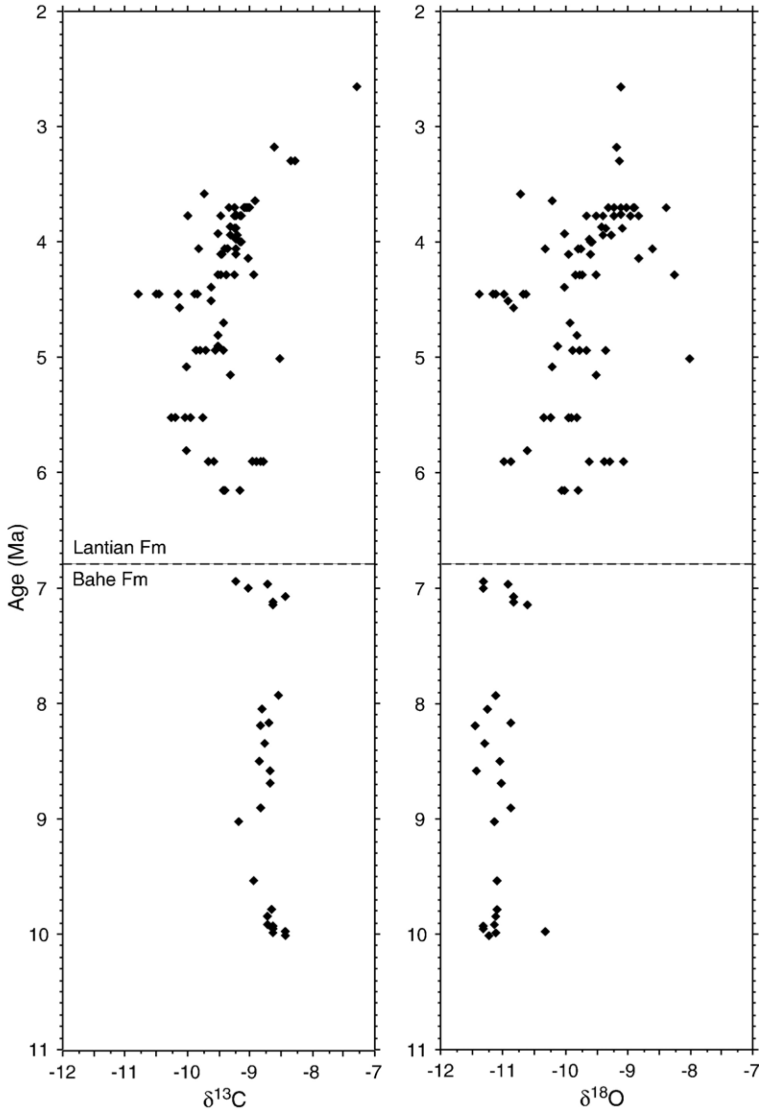

Fig. 3. Age plot of $\delta^{13}C$ and $\delta^{18}O$ in carbonate nodules from the Lantian study area. Note the relatively constant $\delta^{13}C$ and $\delta^{18}O$ values in the Bahe Formation values and the parallel variations of isotope values in the Lantian Formation.

increases by 1.4‰ to -9.7 ± 0.7‰ with respect to the Bahe Formation samples.

The more enriched oxygen isotope values in the Lantian Formation attest to warmer temperatures and/or a greater proportion of summer (monsoonal) precipitation than in the Bahe Formation. The $\delta^{18}O$ values may also reflect drier conditions and therefore, increased soil–water evaporation rates in the Lantian Formation that leads to enrichment in $\delta^{18}O$ of residual soil water. However, considering that the simultaneous decrease in $\delta^{13}C$ values could have been related to increased moisture, an increase in summer rains is expected. This is corroborated by the fact that the accumulation of 'Red Clay' is related to the onset and/or intensification of the Asian monsoon system (Sun et al., 1997, 1998; An et al., 2001).

6. Discussion and conclusions

The isotope values are relatively invariant throughout the Bahe Formation, suggesting moderately stable environments while the formation was being deposited. Additionally, the high $\delta^{13}C$ values in a C_3 context point to water stress (and open) conditions in the Bahe Formation. These deductions are in accordance with sedimentological and fossil vertebrate analyses. The calcic paleosols indicate good drainage and possibly a semi-arid climatic regime throughout the Bahe Formation with no marked change in paleosol character within the formation (Kaakinen and Lunkka, 2003). In turn, the vertebrate record of the Bahe Formation consists of faunas adapted to relatively arid and open environments. Moreover, paleontological studies have revealed a striking lack of faunal change within the Bahe Formation (Zhang et al., 2002), further suggesting its stable environment of deposition.

A shift in isotope values occurs at the upper formation boundary where the sedimentation regime changes from fluvial to mainly aeolian. This change coincides with the faunal turnover at the formation boundary. The fossil localities in the lowermost Lantian Formation have yielded species of, for example, proboscideans, hipparions, suids, giraffids, cervids, and bovids. The paleoecologic context of these localities has been interpreted to represent closed habitats implying more humid environments (Zhang et al., 2002). These observations are consistent with our inferences from carbon and oxygen isotopes. The more depleted $\delta^{13}C$ values in the Lantian Formation may have been triggered by an increased water supply, whereas slightly enriched $\delta^{18}O$ values may signify increased summer precipitation. A comparable shift in the $\delta^{18}O$ was also detected in pedogenic carbonates in the Pakistan and Nepal Siwaliks in late Miocene (Quade and Cerling, 1995; Quade et al., 1995). A shift to more humid conditions in the Lantian Formation is recognized by Fortelius et al. (2002). They used mean ordinated molar hypsodonty (i.e. tooth height) as a semi-quantitative paleoprecipitation proxy for reconstructing of rainfall patterns during the Neogene. Their data set for Lantian fossil localities yields lower precipitation values for the Bahe Formation compared to those in the Lantian Formation. Furthermore, a rough comparison of the precipitation values inferred from the hypsodonty proxy to the modern rainfall values in Xian suggests that precipitation during the deposition of the Bahe Formation was slightly less than the present day, whereas the model yields a somewhat more humid setting for the Lantian Formation compared to the present conditions in the area (Fortelius et al., 2002; Mikael Fortelius, personal communication).

The shifts in the carbon and oxygen isotope records at the formation boundary at 6.8 Ma are concurrent and suggest that the changes are most probably interrelated (Fig. 3). The relationship between $\delta^{18}O$ and $\delta^{13}C$ values was examined with rank correlation analysis (Fig. 4). The correlation for the entire data set is insignificant ($r_S=0.019$; $p=0.8447$). However, when splitting the data to two different groups representing Bahe and Lantian Formation samples, it was found that the carbon and oxygen isotope record from the Lantian Formation has a strong positive correlation and statistically

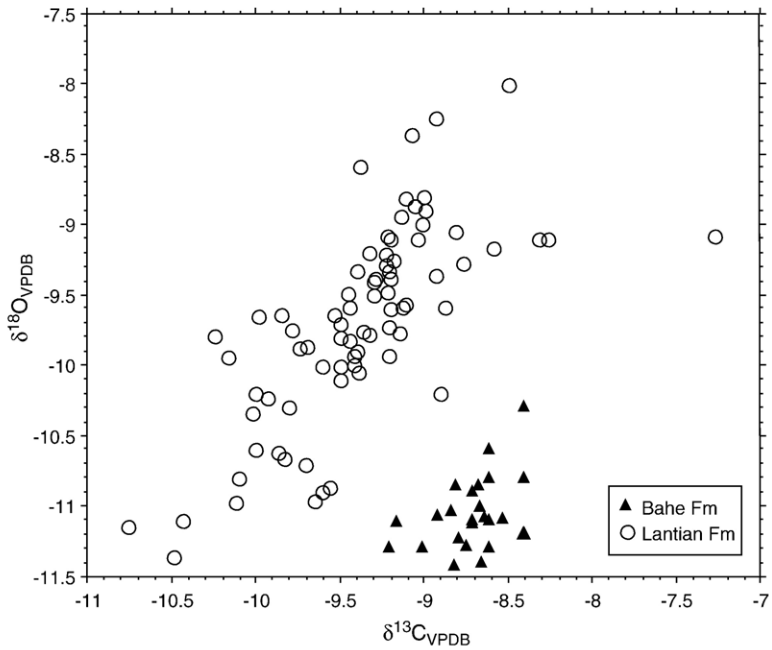

Fig. 4. Cross-plot to show correlation between stable carbon and oxygen isotopes. Bahe Formation samples are shown as solid triangles and Lantian Formation samples as open circles.

significant ($r_S=0.792$; $p \leq 0.0001$), whereas the correlation in the Bahe Formation is weaker ($r_S=0.351$; $p=0.0852$). This points out to a major difference between the units. It can be suggested that during the deposition of the Bahe Formation, local environmental factors, like vegetation cover and sedimentation, controlled isotopic compositions. During the deposition of the 'Red Clay' a strong common environmental control developed, leading to a marked positive correlation between the analysed isotope values. This enforced environmental control most probably relates to changes in seasonal precipitation patterns, which developed at the formation boundary. The strong correlation between the carbon and oxygen isotopes also suggests that climate was the primary factor controlling the vegetation during the deposition of the Lantian Formation.

The large spread of isotope values for oxygen, even at the same stratigraphic levels in the Lantian Formation, may be derived from several factors. The complexity of the oxygen isotope changes in soil carbonates is documented in many studies (e.g. Quade and Cerling, 1995; Quade et al., 1989, 1995; Stern et al., 1997) and any inferences and conclusions must be done with caution. The 'Red Clay' sequences typically yield low accumulation rates of about 2 – 4 cm/ka (e.g. Han et al., 2002), in southern areas within the Loess Plateau even less (Evans et al., 1991; Kaakinen, 2005), and the overlapping of pedogenic zonation is common in the 'Red Clay' (Han et al., 2002). It is therefore possible that the variation in $\delta^{18}O$ is attributable to pedogenic overprinting due to the low sedimentation rates (Cerling, 1984). Diagenetic effects are not considered plausible as sparry calcite was not found in any thin sections done for this investigation. One possible source of data scatter is the discrepancies between the $\delta^{18}O$ of soil water compared to the average composition of local meteoric water. This may result from differences in the soil permeability (Sanyal et al., 2004). Another possibility for the high variability in oxygen isotope ratio is that oxygen isotope values in the Lantian Formation reflect precipitation from multiple sources. The oxygen isotopic composition for the modern summer monsoon rainfall in the Lantian area is associated with both East Asian and Indian monsoons that have distinct isotopic compositions (Wang et al., 1997; Wang and Follmer, 1998), or the figures might derive from fluctuations between the oxygen isotopic compositions of summer and winter monsoons. Weighted mean monthly $\delta^{18}O$ values of modern precipitation in Xian are between 10.84‰ and -3.92‰ (1985–1992 average values; see recent site information GNIP stations, IAEA/WMO, 2004). It can also be speculated that the largely variant oxygen isotope values in the Lantian Formation could mirror oscillations in monsoon intensity, similar to those observed throughout the Pleistocene and Holocene (e.g. Kukla, 1987). In fact, the existence of discernible warm–cool (humid–dry) alterations during the late Miocene and Pliocene has been demonstrated in a recent study of grain size characteristics of the 'Red Clay' (Vandenberghe et al., 2004).

C_4 grasslands became widespread in the late Miocene. Although many records indicate that the shift in carbon isotope values occurred at around 7–8 Ma, the timing of the grassland expansion is not consistent. For example, in the North American records, there is evidence of C_4 vegetation in equid diets by 6.8 Ma (Latorre et al., 1997; Passey et al., 2002), whereas in some regions of Europe, northern North America, North Africa and Afghanistan C_4 plants have never been demonstrated (Cerling et al., 1997; Bocherens and Sen, 1998; Zazzo et al., 2002).

The Lingtai region in the Chinese Loess Plateau witnessed a rise in C_4 vegetation at ca. 4 Ma (Ding and Yang, 2000). Although Lantian is located less than 200 km southeast and ca. 1° of latitude lower from Lingtai, the carbon isotopic record from the Lantian sequence does not demonstrate signs of C_4 vegetation in the area during the time interval studied for this investigation, except for the youngest data point. Yet it is known that C_4 vegetation spread later to the Lantian area: modern grass samples confirm that the region is currently vegetated by a mixture of C_3 and C_4 flora (Linda Ayliffe, personal communication) and carbon isotopic results from the late Pleistocene loess deposits and two middle Pleistocene hominid sites in Lantian indicate that C_4 biomass was present in the area at least during the last glacial–interglacial cycle (Wang and Follmer, 1998), and 1.15 Ma and 650 ka ago (Wang et al., 1997).

The striking lack of evidence of C_4 vegetation before 2.7 Ma in Lantian and the temporal difference in C_4 expansion between the two adjacent areas Lantian and Lingtai is not fully understood and remains speculative. According to the model of Cerling et al. (1997), this delay could indicate anomalously low temperatures in Lantian. An alternative explanation is offered by Wang (2004) who proposed a weak East Asian summer monsoon to be the cause for the absence of C_4 plants prior 2.5 Ma in the Linxia basin at the north-eastern margin of the Tibetan Plateau. Taking into account other evidence from carbon isotopes, mammal fossils, and hypsodonty, all indicative of a shift towards more humid habitats, we hypothesize that the observed lack of C_4 vegetation in the

Lantian area can be explained by a high rainfall or, rather, a cool rainy season favouring the growth of C_3 plants over C_4 plants. Presently, the Indian monsoon produces rains to the southernmost Chinese Loess Plateau in September. Possibly a net effect of strong Indian summer monsoon and weak East Asian summer monsoon could be, at least partly, responsible for the delayed increase of C_4 vegetation in this area. Given the precipitation pattern and the vicinity to the Qinling Mountains, also the modern environments in Lantian differ from those in the interior Loess Plateau sites, including Lingtai. In conclusion, this study further supports the view that the expansion of C_4 grasslands in different regions was largely controlled by regional climatic factors and that low pCO_2 alone was an insufficient trigger resulting in the expansion of C_4 plants (e.g. Quade et al., 1995; Pagani et al., 1999). The study also demonstrates that more work is needed to determine the timing of the extent of C_4 grasslands to the Chinese Loess Plateau and before any general conclusions can be drawn about the relationship between vegetation change and development of the Asian monsoon system.

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