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Late-Miocene palaeoecological evolution of the Tianshui Basin, NE Tibetan Plateau: Evidence from stable organic carbon isotope record

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ABSTRACT

The spatial and temporal variations and the driving mechanisms of C_3/C_4 vegetation evolution throughout the Miocene have been a matter of long-standing debate. A continuous lacustrine–fluvial sediment sequence widely exposed in the Tianshui Basin, NE Tibetan Plateau provides great potential for deciphering the C_3/C_4 vegetation dynamics during the Miocene. Based on the measurements of $\delta^{13}C_{org}$, C, N, and C/N ratios of organic matter of this sediment sequence, here we present a new perspective on vegetation history in inland Asia during the period from 17.1 to 6.1 Ma. The organic matter preserved in the Tianshui Basin is most likely a mixture of terrestrial and aquatic origins. The lack of correlation between organic $\delta^{13}C_{org}$ and carbonate $\delta^{13}C_{carb}$ indicates that terrestrial plants made a dominant contribution to the organic matter. The $\delta^{13}C_{org}$ of organic matter shows negative values (between −24.1‰ and −28.3‰) along the sequence from 17.1 to 6.1 Ma, indicating a predominance of C_3 plants. More specifically, our results indicate that the $\delta^{13}C_{org}$ values of organic matter show a significant increase by ca. 1.4‰ from −26.6‰ to −25.2‰ from 7.1 Ma onwards (equivalent to ca. 10% increase in C_4 plants), reflecting the initial occurrence of C_4 plants. The occurrence and expansion of the C_4 component in the study area is supposed to be a result of increasing summer precipitation due to the enhanced Asian Summer Monsoon since that time.

1. Introduction

Although significant ecosystem changes characterized by a progressive expansion of the C_4 plant biomass during the late Miocene have been widely documented around the world (Quade et al., 1989; Cerling et al., 1993, 1997; Quade and Cerling, 1995; Wang and Cerling, 1994; Macfadden et al., 1996; Latorre et al., 1997; Wang et al., 2006; Passey et al., 2009; Zhang et al., 2009, 2012), the precise timing of expansion of C_4 plants is still a matter of debate. It was thought that the C_4 pants have occurred in Pakistan, Kenya, North America, and Asia's interior much earlier than 8 Ma (Morgan et al., 1994; Fox and Koch, 2003, 2004; Jia et al., 2012). However, stable carbon isotope measurements on carbonate and organic matter in the Chinese Loess Plateau (CLP), NW China suggest that C_4 plants began to expand at about 4 Ma (Ding and Yang, 2000). A much later timing (i.e. 2.9–2.7 Ma) was also proposed (An et al., 2005), which was supported by stable carbon isotope data of tooth enamel, soil carbonates, and organic matter (Wang and Deng, 2005). However, Passey et al. (2009) argued that the expansion of C_4 plants in China was not significantly delayed compared to elsewhere of the world.

Plants can be divided into three categories regarding the photosynthetic pathways to fix atmospheric CO_2 (Osmond, 1978): C_3 plants (including virtually all trees, most shrubs, herbs and forbs, and cool-season grasses), C_4 plants (mainly including warm-season grasses), and crassulacean acid metabolism (CAM) plants (including succulents such as cacti and some yuccas). In contrast to the widespread presence of C_3 and C_4 plants, CAM plants only represent a minor component of desert vegetation (Quade et al., 1989; Cerling et al., 1997; Wang et al., 2008). C_3 plants typically have $\delta^{13}C$ values ranging from −22‰ to −34‰, averaging at −27‰ (Deines, 1980; O'Leary, 1988; Farquhar et al., 1989). Under closed canopy conditions, the $\delta^{13}C$ values of C_3 plants may be much lower than the average values as a result of the influence of soil respiration (Schleser and Jayasekera, 1985; Sternberg et al., 1989); whereas the $\delta^{13}C$ values of C_3 plants may be higher

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than the average values under the water-stressed conditions and/or low pCO_2 (Schleser and Jayasekera, 1985; Farquhar et al., 1988; Sternberg et al., 1989). C_4 plants have $\delta^{13}C$ values ranging from −10‰ to −14‰, averaging at −13‰ (Deines, 1980; O'Leary, 1988; Farquhar et al., 1989). These isotopic fingerprints can be preserved in soil organic matter with little or no alteration (Melillo et al., 1989; Cerling et al., 1997). Therefore, the variation of C_3/C_4 vegetation composition may be inferred from the $\delta^{13}C$ values of organic matter in sediments (Rao et al., 2006; Fan et al., 2007; Yang et al., 2012).

The driving mechanism of the expansion of C_4 plants in the late Miocene is also a matter of debate. The abrupt and widespread increase in C_4 biomass has been widely believed as a result of the lowing pCO_2 and rising temperature (Cerling et al., 1997; Ding and Yang, 2000). However, this hypothesis has been challenged by three lines of evidence: first, the low pCO_2 alone is insufficient to drive the expansion of C_4 plants unless other factors were involved (Osmond, 1987; Field et al., 1992; Henderson et al., 1995; Huang et al., 2001; An et al., 2005); second, there was no evidence for a significant drawndown of the atmospheric CO_2 concentrations in the late Miocene (Pagani et al., 1999); finally, temperature was actually declining rather than rising in the late Miocene (Zachos et al., 2001). Recent studies suggested that regional climate may have exerted more impact than pCO_2 and temperature on the expansion of C_4 vegetation (Huang et al., 2001, 2007; An et al., 2005; Wang and Deng, 2005; Yang and Ding, 2006; Passey et al., 2009; Zhang et al., 2009, 2012; Yang et al., 2012).

The widely and continuously distributed sediments of Miocene age in the Tianshui Basin, NE Tibetan Plateau provide great potential for deciphering the Miocene C_3/C_4 biomass evolution and its linkage to regional climatic change. Here, we present new records of $\delta^{13}C_{org}$ and C/N ratios of organic matter from the Tianshui Basin, NE Tibetan Plateau. We aimed at reconstructing palaeoecological changes during the Miocene by comparing the $\delta^{13}C_{org}$ values of organic matter with those of carbonate from the same section and other records around the world to pinpoint the precise timing of expansion of C_4 plants in this area.

2. Geological and geographical settings

The Tianshui Basin (34.1–35.2°N, 104.4–106.4°E) is located on the northeastern margin of the Tibetan Plateau. It is a low relief basin with an elevation ranging from 1200 to 1800 m a.s.l. (Fig. 1A). The basin is bordered to the north by the left-lateral strike-slip Haiyuan fault, to the east and northeast by the Liupan Shan Mountains, and to the south by the western Qinling Mountains, respectively (Fig. 1B) (Hui et al., 2011). This area is characterized by temperate climate with annual mean temperature of 10.4 °C. Average monthly maximum temperature is 22.8 °C that occurs in July, and monthly minimum temperature is −2 °C that occurs in January. Average annual precipitation is 504 mm, which decreases from southeast to northeast. Regulated by the East Asian Summer Monsoon, most of the precipitation occurs in the summer, while the cold and dry Asian winter monsoon dominates the winter climate. The present-day ecosystems in this area are classified as warm-temperature forest-grasslands and warm grasslands (Huang, 1997). Continuous mudflat/distal fan and Neogene shallow lacustrine deposits are widely exposed and distributed in the basin, which provide an ideal setting for studying the palaeoclimate history in inland China (Li et al., 2006; Alonso-Zarza et al., 2009; Peng et al., 2012; Zhang et al., 2013; Hou et al., 2014).

The Yanwan (YW) section (34°58′N, 105°34′E) lies about 14 km northwest of Qin'an County, Gansu Province (Fig. 1C). Unconformably overlying the metamorphic rocks of the Sinian Formation, the Neogene fluvial-lacustrine sediment unit is ca. 288 m thick, and capped by ca. 60 m thick Quaternary loess. The age assignment of this section was based on both fossil mammal assemblages and palaeomagnetic studies (Zhang et al., 2013). Based on lithologic texture, the Neogene strata can be divided into three units from bottom to top. Unit I (17.1–11.7 Ma), Unit II (11.7–7.1 Ma), and Unit III (7.1–6.1 Ma). The lithology and chronology of these units have been described in detail by Zhang et al. (2013).

3. Field and laboratory work

At the YW section, a total of 108 samples were collected at average intervals of 2.6 m (equivalent to a temporal resolution of ca. 100 ka) for $\delta^{13}C_{org}$, C, N, and C/N ratio analyses. All of the samples were reacted with 30 ml of 10% hydrochloric acid for 24 h to remove carbonate, then washed repeatedly with distilled water to neutral pH, and dried overnight at room temperature. The dried samples were combusted in evacuated and sealed quartz tubes along with 0.6 g Cu and 0.2 g Ag foil at 890 °C for at least 3 h, then purified and isolated by cryogenic distillation for stable isotopic analysis. The stable isotopic composition of CO_2 was measured using a Finnigan Delta Plus XL mass spectrometer that is connected via a Finnigan MAT Conflo III split interface. The stable carbon isotopic composition was expressed using the delta notation against the Vienna PDB standard. The relative abundance (percentage) of C and N and their ratios were analyzed following the procedures described in detail in Fan et al. (2007). Dried and homogenized subsamples of ca. 10 μg were wrapped in tin capsules, and then combusted at 1030 °C in a Costech Elemental Analyzer. Repeated measurements ($n = 5$) of a homogenized sample show that this procedure may yield a standard deviation of ±0.1‰ for stable carbon isotopic composition and ±0.2% for C and N content.

4. Results

The $\delta^{13}C_{org}$, C, N, and C/N ratios of bulk organic matter covering the period of 17.1–6.1 Ma from the YW section are shown in Fig. 2. The $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ of carbonate (Hou et al., 2014) in the same section are also plotted for comparison (Fig. 2). From 17.1 to 7.1 Ma, all of the samples display $\delta^{13}C_{org}$ values ranging from −24.8‰ to −28.3‰ with an average of −26.62‰. Between 7.1 and 6.1 Ma, the $\delta^{13}C_{org}$ values show a significant increase by ca. 1.4‰ from −26.6‰ to −25.2‰, and all samples lie within a range between −24.1‰ and −26.1‰, averaging at −25.24‰. Student's *t*-test provides strong evidence (p-value <0.00001) against the null hypotheses of equal mean of the $\delta^{13}C_{org}$ values prior to and after 7.1 Ma. Furthermore, the one-sample *t*-test indicates that the mean of $\delta^{13}C_{org}$ values after 7.1 Ma is significantly different from −27‰ (p-value <0.00001), the end-member value of C_3 plants. The C/N ratios of most samples range from 1 to 4 along the entire section with a few exceptions. It is noteworthy that inorganic nitrogen was not removed from the bulk sediment samples before combustion for measuring C and N, due to the extremely low content of both organic matter and nitrogen (<0.2%). Our results are comparable with that obtained from the Linxia Basin adjacent to our study area (Fan et al., 2007). Therefore, the presence of inorganic nitrogen may play an important role in measured C/N ratio (Meyers, 1997, 2003; Fan et al., 2007).

5. Discussion

5.1. Source of organic matter in lacustrine sediments

Organic matter in lacustrine sediments is mainly derived from terrestrial and aquatic primary production (Meyers, 1994, 2003). To better interpret the stable carbon isotope record of lacustrine