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Increased seasonality and aridity drove the C4 plant expansion in Central Asia since the Miocene–Pliocene boundary

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ABSTRACT

Continuous and high-resolution records of the content, mass accumulation rate (MAR) and $\delta^{13}C$ values of black carbon obtained from Integrated Ocean Drilling Program (IODP) Site U1430 in the southwestern Japan Sea have been established and combined with previous results obtained from Central Asia. The main objective of this work is to reconstruct the historical changes in vegetation types (C3–C4), and to constrain the driving force of C4 plant expansion over the last 13 Ma. The stable carbon isotope value of black carbon ($\delta^{13}C_{BC}$) shows a major shift since the Miocene–Pliocene boundary (∼5.3 Ma), suggesting significant expansion of C4 plants in broad areas of Central Asia, including the inland basins of northwestern China and the Loess Plateau. However, a decline in the content and MAR of black carbon reveals the absence of any link between fire and C4 plant expansion in Central Asia, due to the dramatic decrease in biomass under a drying regime. On a global scale, asynchronous expansion of C4 plants suggests that regional hydroclimatic change, rather than decline in CO_2 concentration, was the most important factor to influence C4 expansion. We propose that the increased seasonality and the enhanced long-term aridity driven by the concurrent decline in winter westerly vapor, and increase in East Asian summer monsoon precipitation, were the main driving forces of C4 plant expansion in broad areas of Central Asia. Variations in winter westerly moisture have played a significant role in changes of regional climate and vegetation in Central Asia since the late Miocene.

1. Introduction

With the highest mountain range (Tibetan–Himalayan) and the second largest desert (Taklimakan), Central Asia is a key climate system for studying the relationships of tectonic evolution, the Asian monsoon and teleconnections between high- and low-latitude climate changes (Caves et al., 2016; Guo et al., 2002; Molnar et al., 2010; Shen et al., 2017; Tada et al., 2016). The climate of East Asia is currently dominated by the East Asian monsoon system and shows significant seasonality, with warm and wet climate occurring in summer and cold and dry conditions occurring in winter (Molnar et al., 2010; Sun et al., 2010). In addition to the East Asian monsoon, the westerlies are another important moisture source that can transport humid air masses from the West Atlantic Ocean and Mediterranean Sea to Central Asia in winter (Caves et al., 2015; Vandenberghe et al., 2006). On tectonic time-scales, the Central Asian climate has been influenced by Cenozoic global cooling and tectonic deformation, such as the India–Asia collision, followed by the Himalayan–Tibetan Plateau uplift and westward retreat of Paratethys (Molnar et al., 2010; Tada et al., 2016; Zachos et al., 2001). Although past changes in rainfall intensity over Central Asia have been widely investigated, the links among the humidity conditions in Central Asia, plant evolution (C3–C4 plant transition), global climate changes and tectonic evolution throughout the Miocene remain unclear, which is mainly because high-resolution and long-term plant records since

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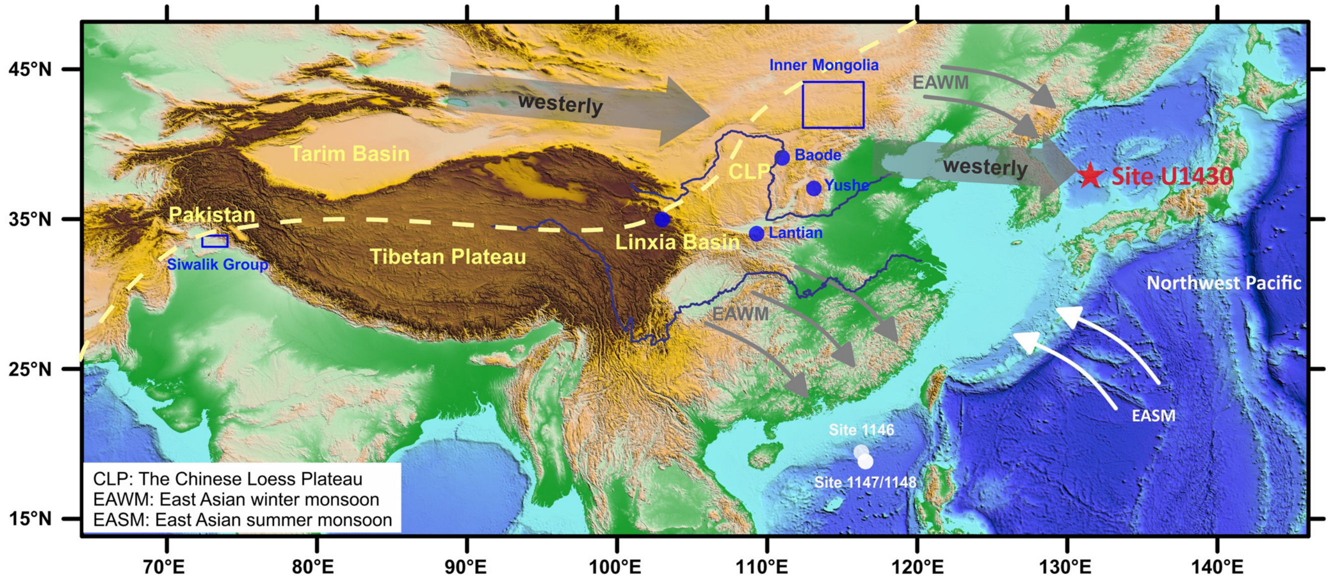

Fig. 1. Location of related Asian terrestrial and marine records. The locations of the terrestrial carbon isotope records are marked by blue solid circles and blue solid boxes. The investigated IODP Site U1430, and the mentioned ODP Sites 1146 and 1147/1148, are shown as a red star and white circles, respectively. In addition, the westerlies (westerly jet) (gray shaded arrows), the major rivers (blue lines), the East Asian summer monsoon directions (white arrows), winter monsoon directions (gray arrows) and the inland extent of the summer monsoonal moisture (light yellow dashed line) are shown. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

the middle Miocene are very scarce, and the driving forces involved are complex (Passey et al., 2009; Wang and Deng, 2005; Zhang et al., 2009; Zhang et al., 2007; Zhou et al., 2014).

Three types of plants are found on Earth and are distinguished based on their photosynthesis pathways: C3, C4 and CAM (crassulacean acid metabolism). C3 plants tend to be distributed in high-latitude areas and regions in which rainfall is mainly concentrated in the cold season, whereas C4 plants generally grow in conditions with a wetter summer followed by a drier winter (Edwards et al., 2010; Strömberg, 2011). CAM plants are relatively less important in most ecosystems because they are limited to deserts; thus, their influence on ecosystem changes is usually neglected (Cerling et al., 1997; Zhang et al., 2009). The evolutionary history of plants on Earth has mainly been controlled by changes in climate and environment, such as variations in precipitation, temperature and seasonality, among of which sufficient water availability and seasonality are extraordinarily important during the growing season (Bond, 2014; Osborne, 2008; Tipple and Pagani, 2007).

C4 plants are widely acknowledged to have expanded during the mid-late Miocene, and most studies have focused on climatic drivers, such as aridity, seasonality, strengthened summer monsoon circulation, decreased atmospheric CO_2 levels, and fire frequency (Bond, 2014; Cerling et al., 1997; Keeley and Rundel, 2005; An et al., 2005). Prevailing opinions have attributed humidity variability in Central Asia to variations in the strength of monsoon precipitation (Guo et al., 2002; Zhang et al., 2007), despite the precipitation brought by the westerlies, which has recently been proposed to be another important moisture source for arid areas in Central Asia (Caves et al., 2015).

Fire is another predominant influencing factor in C4 expansion and promotes the expansion of C4 grasslands, which replaced C3 woodlands during the late Miocene (Keeley and Rundel, 2005; Retallack, 2013; Tipple and Pagani, 2007). However, as mentioned above, most studies have attributed the shift in C3 to C4 plants to overall increased aridity during the latest Miocene (Strömberg, 2011). Furthermore, the role of fire in sustaining C4 grasslands remains obscure at present (Osborne, 2008). Therefore, the relationship between C4 plant expansion and the fire regime since the Miocene must be determined.

More than 5 Tg (1 Tg = 10^{12} g) of black carbon is transported by the atmosphere from the source regions to distal lands and oceans annually, and that black carbon has a significant impact on global climate (Bird et al., 2015). In addition, black carbon has been used as an effective proxy to determine fire intensity and frequency, both of which are strongly modulated by past climate aridity/humidity conditions over geologic time (Zhou et al., 2014), and to estimate the relative contribution of C3 and C4 vegetation (Jia et al., 2003; Zhou et al., 2014). Until now, the long-term fire history in Central Asia since the middle Miocene is not well known (Zhou et al., 2014).

Based on the clay mineral and Sr–Nd–Pb isotopes, most of the fine-grained silicate sediment at IODP Site U1430 in the southwestern Japan Sea was determined to be eolian dust, derived from broad areas of dry land in Central Asia (Shen et al., 2017). The considerable amount of fine black carbon particulates accompanying the eolian dust from Central Asia could have been transported to the Japan Sea over long distances by atmospheric circulation and can provide a comprehensive record of changes in the vegetation types (C3–C4) over a large dry land region in Central Asia. In this study, the content, mass accumulation rate (MAR) and $\delta^{13}C$ values of black carbon in the sediments of the Japan Sea were investigated. Combined with other published carbon isotope records of Central Asian C4 expansion, we attempt to constrain the primary cause of the temporal and spatial variations in C4 plants since the middle Miocene.

2. Materials and methods

IODP Site U1430 (37°54.16′N, 131°32.25′E, water depth 1072 m) is located on the northern margin of the Ulleung Basin of the southwestern Japan Sea (Fig. 1). The lithology of this site is mainly composed of silty clay, clayey silt, diatom ooze, nanofossil ooze, claystone and sandstone (Tada et al., 2015). The age model of the study site was established based on magnetostratigraphy and biostratigraphy (Kamikuri et al., 2017; Shen et al., 2017; Tada et al., 2015). For this study, we investigated composite depth samples of the upper 264 m, which span the last 13 Ma. The average sedimentation rate of this site is 2.1 cm/k.y.