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Lake geochemistry reveals marked environmental change in Southwest China during the Mid Miocene Climatic Optimum

Julie Lebreton-Anberrée · Shihu Li · Shu-Feng Li · Robert A. Spicer · Shi-Tao Zhang · Tao Su · Chenglong Deng · Zhe-Kun Zhou

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Abstract The Mid-Miocene Climatic Optimum (MMCO; ~15–17 Ma) was one of the short-term climatic warm events that punctuated the Cenozoic long-term cooling trend. Because there are very few terrestrial records of this event, most of our understanding comes from marine cores. In this report, we first present new palaeomagnetic data that revises the dating of our 400 m-thick lacustrine section in Wenshan (Yunnan), previously thought to be Late Miocene. These new data suggest an older age, ca. 15.2–16.5 Ma, coinciding with the MMCO. We measured $\delta^{13}C$ on bulk organic matter ($\delta^{13}C_{org}$), total organic carbon (TOC), total nitrogen (TN) and C/N ratios at a high sample resolution to: (1) reconstruct the palaeoenvironmental changes in the lake catchment area, and (2) infer mechanisms responsible for these changes. Our results show that all four geochemical parameters demonstrate that a strong environmental change occurred around the middle of the section, shortly after the C5Cn/C5Br geomagnetic reversal and the Early/Middle Miocene boundary at 15.97 Ma. We propose that the environmental shift may be due to a combination of a change in climate, which became cooler, together with a change in organic matter cycling within the lake. This study provides a new insight into the MMCO and demonstrates that although the MMCO was generally a warm event, it was also a time of climatic instability and abrupt environmental changes.

Keywords Yunnan · Mid-Miocene Climatic Optimum · Bulk organic carbon isotopes ($\delta^{13}C_{org}$) · C/N ratio · TOC

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J. Lebreton-Anberrée · S.-F. Li · T. Su · Z.-K. Zhou (✉)
Key Laboratory of Tropical Forest Ecology, Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Mengla 666303, China
e-mail: zhouzk@xtbg.ac.cn

J. Lebreton-Anberrée
University of Chinese Academy of Sciences, Beijing 100049, China

S. Li (✉) · C. Deng
State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
e-mail: lsh917@mail.iggcas.ac.cn

S.-F. Li
State Key Laboratory of Paleobiology and Stratigraphy, Nanjing Institute of Geology and Paleontology, Chinese Academy of Sciences, Nanjing 210008, China

R. A. Spicer
Environment, Earth and Ecosystems, The Open University, Milton Keynes MK7 6AA, UK

S.-T. Zhang
Faculty of Land Resource Engineering, Kunming University of Science and Technology, Kunming 650093, China

Z.-K. Zhou
Key Laboratory of Biogeography and Biodiversity, Kunming Institute of Botany, Chinese Academy of Sciences, Kunming 650204, China

1 Introduction

Marine isotopic data have revealed that the long-term cooling trend of the Cenozoic was punctuated by short-term climatic events [1]. The Miocene climate exhibited marked changes including the Mid-Miocene Climatic Optimum (MMCO, ~15–17.0 Ma [2]) during which temperatures were inferred to be ~3–8 °C higher than pre-industrial level [3, 4]. The mechanisms leading to the MMCO are still debated [2], but evidence points to an increase in the concentration of atmospheric CO_2 [4].

Until now, the MMCO has been mainly investigated using marine isotopic data [1, 2, 5, 6], since terrestrial outcrops are relatively scarce. In Antarctica, a palynological study and leaf wax geochemistry revealed a warmer and wetter climate than today, and demonstrated that Antarctica could support a tundra vegetation [7, 8]. In China, a lithological study conducted in the northeast Tibetan Plateau and a palynological investigation in Tian Shan (northwest China) show evidence of a warm and wet period during the MMCO [9, 10], demonstrating that the lower latitude continental areas were also affected by the MMCO. However, it is still unclear how subtropical environments responded to the MMCO due to the scarcity of suitably dated outcrops.

In Yunnan (southwest China), the evolution of the Miocene climate has been extensively investigated using different floral proxies, such as pollen [11, 12] and plant mega-fossils [13–17], indicating that Yunnan was already under a monsoonal climate in the Miocene [11, 14]. We have previously reported palynological results from a 400 m-thick sedimentary succession in Wenshan, southeast Yunnan, to reveal how the vegetation dynamics responded to a monsoonal climate [11]. Lakes are environmentally sensitive and so are ideal to study past climatic fluctuations [18]. For example, lake sediment geochemistry has been widely used to explore environmental changes on the Tibetan Plateau during the Miocene [19, 20] and in Yunnan during the Quaternary [21–23]. However, there is very limited research using terrestrial geochemistry to investigate environmental changes in Yunnan during the Miocene, and the MMCO in particular.

In the present study, we present new magnetostratigraphic data to date the sedimentary succession. Then, we employ lake sediment organic geochemistry with high sampling density to: (1) further investigate palaeoenvironmental changes in the lake catchment area in Wenshan using geochemical proxies ($\delta^{13}C$ on bulk organic matter, total organic carbon, total nitrogen, and C/N ratio); and (2) discuss the factors responsible for these palaeoenvironmental changes.

2 Materials and methods

2.1 Geological setting

Our study section of the Wenshan palaeo-lake is located on the South China Block, close to the Ailao Shan-Red River Fault, which underwent a mid-Tertiary (~35–17 Ma ago) sinistral shear displacement before being reactivated as a right lateral system during the Pliocene [24]. The time when this fault was active is still debated, but evidence shows that there was movement during the Miocene and this may have influenced the topography of Wenshan at the time of sediment accumulation [25, 26]. A recent study showed that Xiaolongtan Basin, located about 110 km east of the Wenshan Basin, had already attained its near modern elevation by ~13 Ma [27].

Today, Wenshan experiences a monsoonal climate with a mean annual temperature (MAT) of 18.2 °C and a mean annual precipitation (MAP) of 1059 mm, with most precipitation occurring during the summer [28]. On limestone, the vegetation is composed of a semi-humid broadleaved evergreen forest, while on acidic soil the vegetation is mainly classified as subtropical monsoon broadleaved evergreen forest [29].

The sampling site (23°24′ N; 104°12′E, 1270 m a.s.l.) of the Wenshan palaeo-lake is situated near Dayigu village in the Wenshan Basin, southeast Yunnan, China (Fig. 1). The site is surrounded by mountains that are mainly composed of limestone and mudstone, with ages ranging from the Cambrian to the Triassic [30] (Fig. 1). The palaeo-lake sediments are about 400 m thick and unconformably overlie Paleogene breccia. In the lower third of the succession, Quaternary conglomerates cover approximately 100 m of the section, dividing the succession into two parts: the lower part (~90 m thick) and the upper part (~300 m thick) (Fig. 2a). There is, however, no obvious sedimentological difference between the two parts. The Miocene sediments are composed of thin to medium (<30 cm) cycles of sandstone, siltstone, and calcareous mudstone. The transition between each cycle is always gradual, suggesting nearly continuous deposition. The sediments are often unconsolidated, ranging in colour from dark grey to creamy yellow, and contain numerous fragments of organic matter (Fig. 2c). The sediments were deposited in thin to very thin parallel beds and thick laminae (Fig. 2b, e). The depositional environment is interpreted to be lacustrine [31] and the presence of a thick succession of laminae suggests that the lake was relatively deep, while the absence of bioturbation reveals that the bottom of the lake might have been suboxic to anoxic, promoting organic matter preservation (Fig. 2c). We