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Potential influence of temperature changes in the Southern Hemisphere on the evolution of the Asian summer monsoon during the last glacial period

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A B S T R A C T

A precisely ^{230}Th-dated $\delta^{18}O$ record of a stalagmite from Yangkou Cave, Chongqing, southwest China, is proposed to reconstruct the evolution of the East Asian summer monsoon (EASM) during the last glacial period (LGP) from 37.8 to 48.7 ka BP. The $\delta^{18}O$ record reveals Dansgaard/Oeschger (D/O) 8–12 and Heinrich (H4, H5) climatic events. The inferred D/O events at EASM territory do not exhibit the asymmetrical feature of "rapid warming, slow cooling" recorded in Greenland ice cores. The Yangkou record is consistent with other records of Hulu and Xiaobailong Caves in the Chinese monsoon realm. Changes in the period from D/O 12 to D/O 9 and H4 events in the stalagmites is similar to the temperature changes recorded in the European Project for Ice Coring in Antarctica (EPICA) Dronning Maud Land Ice core (EDML). This similarity implies that Southern Hemisphere thermal condition could affect the EASM, the location of the Intertropical Convergence Zone (ITCZ), and also the Hadley circulation. Changes in D/O 12 and the end of the H5 in Chinese records are different from those in Socotra Island, located in the Indian summer monsoon (ISM) region, which are concurrent with NGRIP records. During the H5 period, in the Southern Hemisphere, temperature increased gradually to a maximum and the Hadley circulation intensity in the Southern Hemisphere decreased. Simultaneously, the southeast trade winds in the Southern Hemisphere gradually weakened, resulting in the weakening of the ISM and eventually the weakest ISM at ~47.2 ka BP. Our records support that the evolution of the summer monsoon in the low-latitude Asian zones was not only affected by summer insolation and climatic changes in the high latitudes of the Northern Hemisphere but also by temperature changes in the Southern Hemisphere.

1. Introduction

The climate of the last glacial period (LGP) was not always cold (Genty et al., 2003). Paleoclimatic records from ice cores and deep marine sediments in the polar, mid-latitude, low-latitude and tropical regions indicated that the most typical characteristic of climate change during the LGP was a series of century-to millennial-scale rapid climate fluctuations, such as the Dansgaard/Oeschger (D/O) cycle and Heinrich (H) events (Bond et al., 1993; Thompson et al., 1995, 1997; Blunier et al., 1998; Colin et al., 1998; Schulz et al., 1998; Voelker et al., 1998). The D/O and H events were first recognized in Greenland ice cores (Dansgaard et al., 1993; Lang et al., 1999) and north Atlantic oceanic sediments (Heinrich, 1988; Bond et al., 1992, 1993). These climatic events were then tracked around the world, including in Europe

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(Reille and De Beaulieu, 1990), Asia (Porter and An, 1995; Chen et al., 1997), the northeast Pacific Ocean (Behl and Kennett, 1996), the Bay of Bengal (Colin et al., 1998), the Arabian Sea (Schulz et al., 1998), South America (Kanner et al., 2012) and other locations. Interstadial events recorded in the Greenland ice cores were also recorded in Antarctic ice cores (Bender et al., 1994). Leuschner and Sirocko (2000) have summarized the geographical distribution of the D/O and H events on a global scale, as recorded in different geological records. The authors found that the D/O and H events were distributed worldwide, particularly in the Northern Hemisphere (Leuschner and Sirocko, 2000). The global footprints of the D/O and H events suggest the interactions among the constituent elements of the earth's climate system, especially the coupling of the ocean–atmosphere–cryosphere systems (Bond et al., 1993). Multiple studies have confirmed that there are close links between the global-scale systems at high and low latitudes (Cheng et al., 2013b). Series of climatic events recorded in both polar regions and in both the Northern and Southern Hemisphere exhibit an antiphase relationship (Stocker, 1998; Blunier and Brook, 2001; Stocker and Johnsen, 2003; Wang et al., 2006; Cheng et al., 2013b). The mechanisms of climate coupling between the Northern and Southern Hemispheres have been a key issue for understanding the dynamics of the earth's climate systems. Therefore, the D/O and H events are an important subject of research regarding the characteristics and linkages of climate change in different regions. Further study of the timing, duration and internal features of the D/O and H events on a global scale will contribute to the understanding of the features of climate change; the interaction among the oceans, atmosphere, and continents at both high and low latitudes and in the Northern and Southern Hemispheres and the impact of these interactions on specific climate events, such as the Asian monsoons. Therefore, better understanding climate change during the LGP requires additional climate records with highly precise absolute age data from mid-to low latitude regions. These climate records can be compared with those in mid-to high latitudes in both hemispheres to understand the relationship between climate change in the mid-to high latitudes of the Northern and Southern Hemispheres and that related to the Asian summer monsoon (ASM).

In this paper, we reconstructed the evolution of the EASM during the period of 37.8–48.7 ka BP using the stalagmite records from Yangkou Cave in Chongqing, southwest China. By comparing the JFYK7 records with other records of Chinese monsoon regions and ice cores from polar regions, we investigated the response of the EASM to D/O warming events 8–12 and the H4–H5 cooling events during this period. Finally, we assessed the possible effect of the temperature changes in the Southern Hemisphere on the evolution of the ASM.

2. Geological setting and sample collection

2.1. Geological setting

Stalagmite JFYK7 was collected from Yangkou Cave (29°02′N, 107°11′E; altitude: 2140 m; length: 2245 m), located on Jinfo Mountain (Fig. 1) (Li et al., 2014). The climate is a subtropical, humid monsoon climate, which is mild and rainy, with an average annual relative humidity of >90%. The average annual temperature is 14.5 °C, and the average annual precipitation is 1435 mm. From April to October, the monthly average precipitation is above 100 mm, which accounts for more than 80% of the annual precipitation (Wang et al., 2005a,b).

Yangkou Cave developed in Permian limestone stratum (Zhang et al., 1998), when shaft-like skylights developed along the northeast fissures. The flat-shaped portion of the cave has a single corridor. There is also a branch cave parallel development along the northeast–southwest direction and a connected channel (Fig. 1c). The fissures developed in the overlying host rock, and there are numerous dripping sites on the roof of the cave. The residence time of precipitation is shorter in the epikarst, and large amounts of rainwater can quickly enter the cave during the rainy season (April to October). Although some dripping occurs during the dry season (November to next March), the discharge is considerably less (Zhang et al., 1998).

2.2. Sample collection

Stalagmite JFYK7 is 555 mm in length, with bottom and top diameters of approximately 125 mm and 40 mm, respectively, forming a cylindrical shape (Fig. 2a). Halved along the stalagmite's growth axis, the color of the vertical section is dark and the growth banding is clear. There are numerous offshoots from the central growth axis that formed during the deposition of the stalagmite. The top section, from 0 to 185 mm, was studied in this paper. There are three offshoots along the depositional axis in this section, which are at ~60 mm, 120 mm and 181 mm. However, there is no visible growth hiatus in this section. Furthermore, the continual deposition of JFYK7 was validated via high-precision dating methods (Fig. 2a, Table 1).

3. Analytical methods

3.1. ^{230}Th dating

A total of 21 subsamples were drilled from the polished profile of JFYK7 using carbide dental burrs with a diameter of 1 mm (Fig. 2a). The 21 dating subsamples were ^{230}Th dated by multi-collector inductively coupled plasma mass spectrometry (ICP-MS) (Thermo, Neptune), in the Isotope Laboratory of the University of Minnesota and Xi'an Jiaotong University, errors are given with two standard deviation (2σ) (Edwards, 1988; Shen et al., 2012; Cheng et al., 2013a). The decay constants of ^{230}Th, ^{234}U, and ^{238}U are 9.1705×10^{-6} yr^{-1} (Cheng et al., 2013a), 2.82206×10^{-6} yr^{-1} (Cheng et al., 2013a), and 1.55125×10^{-10} yr^{-1} (Jaffey et al., 1971), respectively. The age correction for the initial ^{230}Th was performed using the crust ^{230}Th/^{232}Th average ratio of $4.4 \pm 2.2 \times 10^{-6}$ (Taylor and McLennan, 1995), and the results are shown in Table 1. The concentration of ^{238}U is very high in the stalagmites in Yangkou Cave (Li et al., 2014). For JFYK7, the concentration of ^{238}U changed from 5.3 ppm to 13.2 ppm, with an average value of 9.0 ppm (Table 1). Because of the high ^{238}U content, the dating precision for JFYK7 is very high, and all of the age errors were less than 0.4% (Table 1). A linear interpolation method was used to construct the chronology for the JFYK7 records.

3.2. Carbon and oxygen isotopes

δ^{18}O and δ^{13}C analyses were completed at the Geochemistry and Isotope Laboratory of the Southwest University. A total of 364 subsamples were drilled for isotope testing along the growth axis of the stalagmite using a 0.5 mm diameter drill bit and with a sampling interval of 0.5 mm. Analyses were performed using a Delta-V-Plus Mass Spectrometer, combined with a Kiel IV Carbonate Device. Every seven samples were bracketed with one standard, NBS 19. Isotopic results are given with respect to Vienna Pee Dee Belemnite (VPDB) standard (Fig. 3) with one-sigma external error $<\pm 0.1$‰ for δ^{18}O and $<\pm 0.06$‰ for δ^{13}C (Li et al., 2011).

3.3. The Hendy test

The oxygen isotope equilibrium fractionation during the deposition of the stalagmite is the precondition that determined