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Millennial-scale Asian summer monsoon variations in South China since the last deglaciation

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A B S T R A C T

Characterizing spatiotemporal variability of the Asian summer monsoon (ASM) is critical for full understanding of its behavior, dynamics, and future impacts. The present knowledge about ASM variations since the last glaciation in South China largely relies on several precisely-dated speleothem stable oxygen isotope ($\delta^{18}O$) records. Although these speleothem $\delta^{18}O$ signals provide useful evidence for regional past environmental changes, their validity for denoting ASM intensity remains a great controversy. The Huguangyan Maar Lake (HML) provides one of the most complete archives of environmental and climatic changes in the tropical–subtropical South and East Asia since the last glaciation. Here we document a continuous centennial- to millennial-scale ASM record over the past 16 ky BP from the high-sedimentation-rate HML sediments. In contrast with the low-amplitude variations of Chinese speleothem-derived $\delta^{18}O$ signals and the Chinese loess-based monsoon precipitation proxy indexes, our multi-proxy records reveal a pattern of high-amplitude regional climatic fluctuations, including fine-scale oscillations during the Bølling–Allerød warming, the 8.2 ka cooling event, and an abrupt climate shift from 6.5–5.9 ka. The existence of Bond-like cold/dry events indicates a distinct influence of the North Atlantic circulation on low-latitude monsoon changes. The broad comparability between the HML paleo-proxies, Chinese speleothem $\delta^{18}O$ records, and the northern hemisphere summer insolation throughout the Holocene, suggests that solar insolation exerts a profound influence on ASM changes. These findings reinforce a model of combined insolation and glacial forcing of the ASM.

1. Introduction

The Asian monsoon, a key component of the global climate system, influences more than half of the World's population and the associated ecosystems. Investigation of Asian monsoon variability is crucial for improving our knowledge of its dynamics and monsoon-related hydrological processes (An, 2000; Wang et al., 2000, 2005; Lu et al., 2013; Sun et al., 2015; Liu et al., 2015a). In South China, the paucity of reliable paleoclimatic records, except for several speleothem sequences found in certain localities (e.g., Dykoski et al., 2005; Wang et al., 2005), hampers our full understanding of the Asian monsoon behavior and dynamics. Although a few precisely-dated speleothem records are among the best-dated records capable of documenting annual-scale variations in hydrologic processes and atmospheric circulation regime over a large part of the Indo-Asian region (Caley et al., 2014), interpreting the stable oxygen isotope ($\delta^{18}O$) signal archived in speleothems as a proxy for the Asian summer monsoon (ASM) strength is complex and highly controversial (Dykoski et al., 2005; Wang et al., 2000, 2005) since it may integrate many processes across space and time (Konecky, 2015; Liu et al., 2015a).

The sediments of Huguangyan Maar Lake (HML) constitute one of the most complete archives of environmental and climatic changes in tropical–subtropical South and East Asia since the last glaciation (Chu et al., 2002; Mingram et al., 2004; Yancheva et al., 2007; Wang et al., 2012a, 2012b). The high-sedimentation-rate records from this unique crater lake not only complement the $\delta^{18}O$ signal of speleothems from South China but also provide an excel-

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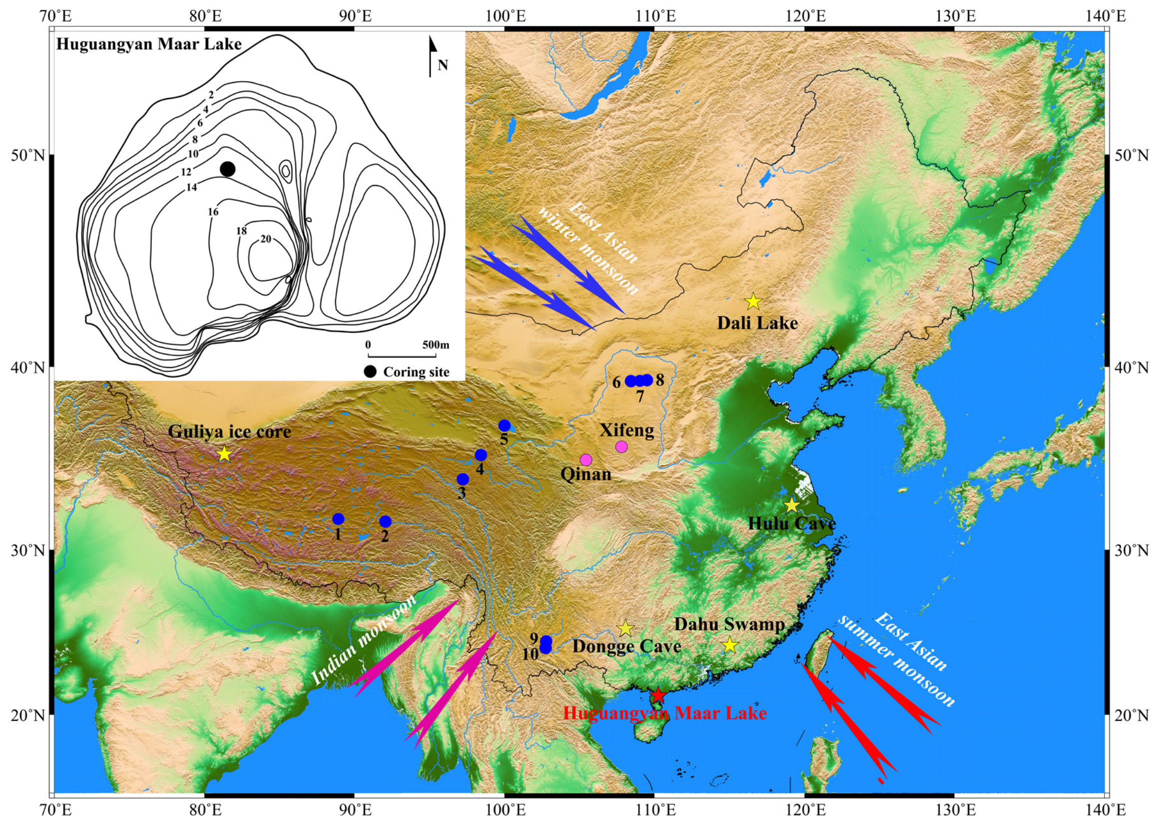

Fig. 1. Topography and atmospheric circulation systems of China. Arrows indicate the wind directions of the East Asian summer monsoon (red), the East Asian winter monsoon (blue), and the Indian monsoon (Magenta). Stars mark the locations of HML (red), Hulu Cave (Wang et al., 2000), Dongge Cave (Dykoski et al., 2005; Wang et al., 2005), Guliya ice core (Thompson et al., 1997), Dahu Swamp (Zhou et al., 2004), and Dali Lake (Liu et al., 2015b) (yellow). Blue circles denote the locations of ten lakes, from which carbonate oxygen-isotope records ($\delta^{18}O_{carb}$) are synthesized by Zhang et al. (2011): 1 Selin Co; 2 Ahung Co; 3 Lake Koucha; 4 Donggi Cona; 5 Lake Qinghai; 6 Lake Hamaertai; 7 Hetongchahan Nur; 8 Bahan Nur; 9 Lake Xingyun; 10 Lake Qilu. The locations of Xifeng and Qinan loess sections (Liang et al., 2009) are marked with pink. The inset shows the bathymetry of the Huguangyan Maar Lake and the location of the coring site (solid circle). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

lent opportunity for disentangling the inter-related environmental processes controlled by lithology, vegetation, hydrology and possible diagenesis, as well as human activities (Mingram et al., 2004; Zhou et al., 2009; Wang et al., 2012a, 2012b; Shen et al., 2013), and for testing the potential for recording geomagnetic field behavior (Yang et al., 2012). Despite the fact that the HML sediments contain a wealth of paleoclimatic information, uncertainties remain regarding both the provenance of the sediments and whether or not the various climate proxies (e.g., magnetic susceptibility, *S*-ratio, and Ti content) mainly reflect the strength of the East Asian winter monsoon (EAWM) (Yancheva et al., 2007), the East Asian summer monsoon (EASM) (Wu et al., 2012; Shen et al., 2013), or the Indian summer monsoon (ISM) (Duan et al., 2014). In addition, chronological discrepancies between different studies, as well as possible ambiguities in the interpretation of climate proxies, severely impede detailed comparisons of spatio-temporal climatic variability (Jia et al., 2015). Therefore a well-dated multi-disciplinary investigation is essential for fully understanding the nature of the Asian monsoon variability recorded by the HML sediments and the possible forcing mechanisms.

Here we present the results of integrated mineral magnetic, pollen, and total organic matter (TOM) analyses, supplemented by geochemical and X-ray diffraction (XRD) analyses of the HML sediments from a new suite of overlapping piston cores with well-constrained AMS ^{14}C and ^{137}Cs age determinations. Our multi-proxy records reveal a continuous Asian monsoon evolution history for tropical–subtropical South China over the past 16 ky BP. We propose that the variations of these proxy indexes are closely linked to ASM precipitation which was jointly controlled by Northern Hemisphere summer insolation and perturbations in North Atlantic circulation.

2. Coring, analytical methods, and chronology

HML (21°9′N, 110°17′E, Fig. 1), situated on the Leizhou Peninsula in the southernmost part of mainland China, is the deepest recent crater lake among the identified volcanic structures in the Leiqiong Volcanic Field. The bi-lobate lake, with a diameter of ∼1.7 km and a depth of ∼20 m, is surrounded by a high tephra wall and is underlain by a basalt sheet. K/Ar-dated basalts from the volcanoclastic breccia of the crater rim have yielded an age of ca. 127 ka, indicating its formation at roughly that time (Ho et al., 2000).

In September 2011 four parallel long cores (A, B, C, and D) were recovered from a water depth of 13.5 m with a high-precession rod-operated corer (Usinger-corer). Cores B and C, with lengths of 9.6 m and 10.6 m, respectively, were used for this study. The cores were split in half longitudinally; one half was used for continuous measurements of total organic matter (TOM) and magnetic parameters at a resolution of 1 cm, while the other half was sub-sampled for pollen analyses. Additionally, ten pyroclastic rock samples were collected from eight localities surrounding the lake for determinations magnetic susceptibility and rare earth element (REE) content.

The mass-specific magnetic susceptibility (χ) was performed on 809 dried samples, using an AGICO MFK1-FA Kappabridge magnetic susceptibility meter at the frequency of 976 Hz, with sensitivities of 2×10^{-8} in a peak magnetic field of 200 A/m. Saturation