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High-resolution $\delta^{18}O$ and $\delta^{13}C$ records during the past 65 ka from Fengyu Cave in Guilin: Variation of monsoonal climates in south China

Hong-Chun Li [a, b, *], Miryam Bar-Matthews [c], Yuan-Ping Chang [d], Avner Ayalon [c], Dao-Xian Yuan [e], Mei-Liang Zhang [e], Mahjoor A. Lone [a]

[a] Department of Geosciences, National Taiwan University, Taipei 106, Taiwan, ROC
[b] School of Geographical Sciences, Northeast Normal University, Changchun 130024, China
[c] The Geological Survey of Israel, Jerusalem 95501, Israel
[d] Institute of Marine Geology and Chemistry, National Sun Yat-sen University, Kaohsiung 804, Taiwan, ROC
[e] Key Laboratory of Karst Dynamics, MLR and Guangxi, Guilin 541004, China

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The $\delta^{18}O$ and $\delta^{13}C$ records of a $^{230}Th/U$ dated, 2.2-m long stalagmite from Fengyu Cave in south China provide a continuous decadal-resolution (with 3698 measurements) proxy for regional climatic and environmental conditions during 4–65 ka. This single stalagmite reveals all Heinrich cold events, most Dansgaard-Oeschger warm events, deglaciation and Holocene Optimum, generally supporting the Hulu and Dongge records. On 5000–10000 year time-scales, the $\delta^{18}O$ and $\delta^{13}C$ variations show strongly positive correlations ($R = 0.7$), reflecting that a common climatic factor controls both $\delta^{18}O$ and $\delta^{13}C$ of F-1. The comparison of the speleothem, ice core, insolation and marine records reveals strong linkages between N. Atlantic temperature and the Asian summer monsoon over most of the study period. However, there are some regional discrepancies between the stalagmite $\delta^{18}O$ records following the deglaciation. Although the NH summer insolation provides the major forcing on Asian monsoon variability over orbital time-scales, the weakest summer monsoon intensity during the last glacial occurred ca. 16 ka corresponding to the Heinrich event 1; a 5–6 ky lag from the minimum insolation during the Last Glacial Maximum. Variations in the monsoonal climate of the study area over the past 700 years have been reconstructed from the $\delta^{18}O$ and $\delta^{13}C$ records of a 14.6-cm long stalagmite F4 in Fengyu cave, showing wet conditions between AD 1550 and AD 1850 (the Little Ice Age) and relatively dry conditions before and after this interval. Human impacts on local vegetation since AD 1700 were recorded by the $\delta^{13}C$ record of stalagmite F4.

1. Introduction

Previous studies have shown that speleothem records in eastern China reveal changes in the East Asian Summer Monsoon (EASM) intensity following variations of solar irradiation (i.e., insolation) with 23-ky cycles (Wang et al., 2001, 2008; Yuan et al., 2004; Wan et al., 2011a; Cheng et al., 2012; Li et al., 2014). The effect of solar irradiation on EASM variability also shows on the decadal-to-millennium scales (Wang et al., 2005; Zhang et al., 2008; Ma et al., 2012; Yin et al., 2014; Zhao et al., 2015). As the EASM plays an important role in affecting precipitation and temperature over the vast and densely populated region of eastern China, it is important to understand all possible causes for monsoonal variations on different time scales. In their study, Wan et al. (2011a) discussed discrepancies of Chinese stalagmite $\delta^{18}O$ records with variations of the NH summer insolation on sub-orbital scales, as well as miscorrelation of these records with the obliquity and eccentricity cycles. On the other hand, instrumental and historical climate records as well as high-resolution stalagmite $\delta^{18}O$ records, showed strong spatial variations of summer rainfall on annual-to-decadal scales over eastern China and highlighted that the relationship between rainfall and EASM intensity exhibits regional

* Corresponding author. Department of Geosciences, National Taiwan University, Taipei 106, Taiwan, ROC.
E-mail address: hcli1960@ntu.edu.tw (H.-C. Li).

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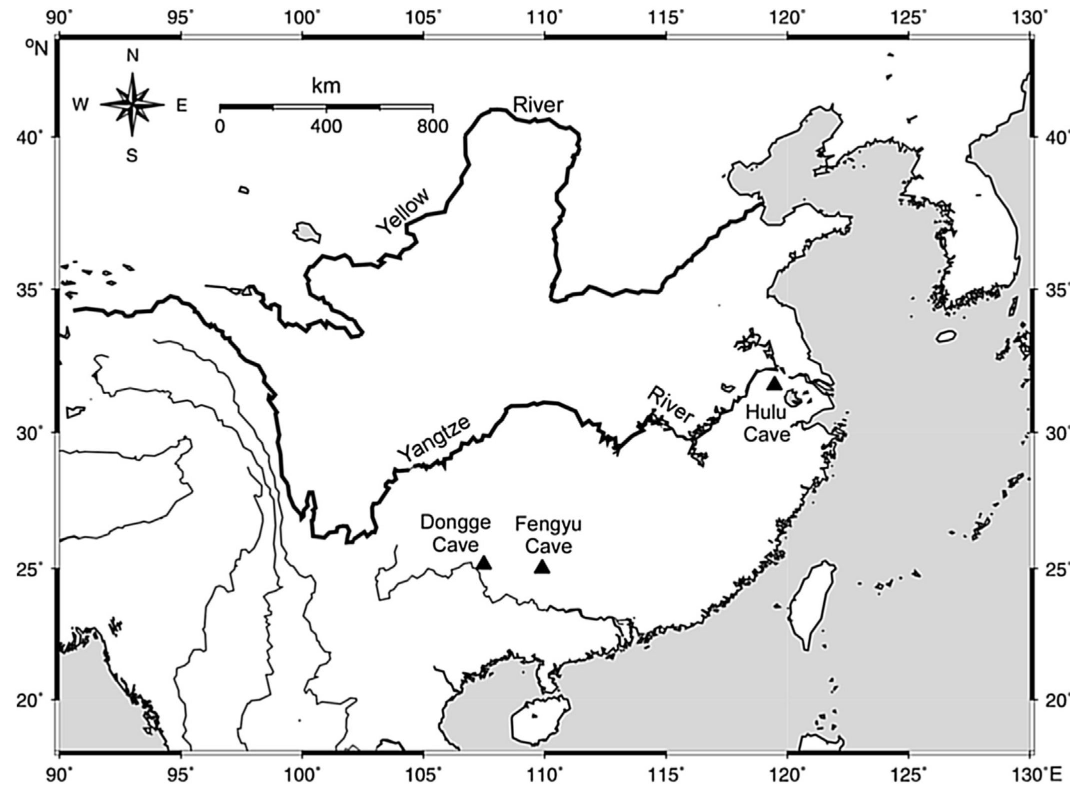

Fig. 1. Location map of the study area. Triangles denote the locations of Dongge Cave in Guizhou (Yuan et al., 2004), Fengyu Cave in Guilin (this study), and Hulu Cave in Nanjing (Wang et al., 2001) in eastern China.

disparities (Qian and Lin, 2005; Tan et al., 2009; Zhang et al., 2010; Wan et al., 2011b; Chu et al., 2012; Yin et al., 2014; Li et al., 2015; Zhao et al., 2015, in this issue). Thus, understanding the controlling factors of monsoonal variability and their influence on regional climates requires more high-resolution, well-dated, climate proxy records from multiple areas.

The published Hulu Cave $\delta^{18}O$ records between 10 and 75 ka revealed climatic episodes of Younger Dryas (YD) cooling, Bølling-Ållerød (BA) warming, Heinrich (H) cold events and Dansgaard-Oeschger (D-O) warming events (Wang et al., 2001). This detailed record compiled by several stalagmite records from the same cave provides almost every important climatic event between 10 ka and 75 ka. However, few other speleothem records from eastern China duplicate those events in a continuous manner. For instance, the Dongge Cave records lack a record between 15 ka and 41 ka (Yuan et al., 2004; Dykoski et al., 2005; Wang et al., 2005); and the Sanbao Cave records have a gap between 20 ka and 56 ka (Wang et al., 2008). Although some of the YD, H and D-O events can be found in other Chinese stalagmite records (i.e., Ma et al., 2012; Li et al., 2014; Han et al., 2016), none of the records involve the major features of the Hulu Cave record. Wang et al. (2008) compiled a 220-ky $\delta^{18}O$ record from Sanbao, Hulu and Dongge Cave based on similar trends in the overlapping periods to reflect EASM variations on orbital scales. While the 220-ky $\delta^{18}O$ record represents variations of the EASM intensity on orbital scales, whether the $\delta^{18}O$ record registers changes in rainfall amount or moisture source has been debated (e.g., Pausata et al., 2011; Liu et al., 2014). In order to understand whether speleothem $\delta^{18}O$ record reflects changes in wetness, an additional climate proxy is needed. $\delta^{13}C$ coupled with the $\delta^{18}O$ record in a stalagmite is a common proxy to be used (e.g., Dorale et al., 1992, 1998; Bar-Matthews et al., 1996, 1999; Ku and Li, 1998; Genty et al., 2003, 2006, 2010; Paulsen et al., 2003; Zhang et al., 2004, 2009; Zhu et al., 2006; Cosford et al., 2009; Fleitmann et al., 2009; Kuo et al., 2011; Li et al., 2011a,b; Kotlia et al., 2012; Oster et al., 2012; Denniston et al., 2013; Zhao et al., 2015). Because the characteristics of stalagmite $\delta^{13}C$ is site dependent, compiling $\delta^{13}C$ records from different stalagmites is rather difficult, especially when the records are from different caves. Thus, it would be valuable if a stalagmite with both $\delta^{18}O$ and $\delta^{13}C$ records can verify most climate events in the Hulu Cave record.

In this study, we present a 2.2-m long stalagmite (F-1) from Fengyu Cave, south Guilin, which reveals high-resolution (3698 measurements) $\delta^{18}O$ and $\delta^{13}C$ records spanning 4 ka to 65 ka. By comparison with existing climate proxy records from ice and marine sediment cores, the insolation as well as the Hulu and Dongge records, this study aims to understand the physical mechanism for variations in stalagmite $\delta^{18}O$ and $\delta^{13}C$, changes in monsoonal climates on millennium scales and their forcing factors. Spectral analyses have been performed on the $\delta^{18}O$ and $\delta^{13}C$ records to detect periodicities and correlations of the records. In addition, a 14.6-cm long stalagmite, F4, from Fengyu Cave is also presented in this paper. The $\delta^{18}O$ and $\delta^{13}C$ records of F4 not only provide depositional condition of modern calcite, but also reveal changes in monsoonal climate of the study area during the past 700 years.

2. Background of study area and sampling

2.1. Fengyu Cave

Fengyu Cave (24°25′N, 110°17′E, 150 m a.s.l) is located in Lipu County, ~120 km south of Guilin City, China (Fig. 1). This 7.1 km long cave through which an underground river flows for 3.1 km, was

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