High-resolution absolute-dated Indian Monsoon record between 53 and 36 ka from Xiaobailong Cave, southwestern China

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ABSTRACT

The oxygen isotopic record of stalagmite XBL-1 from southwestern China reveals millennial-scale variability of the Indian Monsoon between 53 and 36 ka, synchronous with changes in the East Asian Monsoon recorded at Hulu Cave and similar to Dansgaard-Oeschger cycles recorded in Greenland ice. Our record, in general, confirms the chronology of Hulu Cave. If our correlations between Greenland and the Xiaobailong Cave record are correct, both the Greenland Ice Sheet Project 2 and Greenland Ice Core Project (ss09sea) chronologies are accurate within quoted errors. A dry interval that we correlate with Heinrich Event 5 (H5) and the Greenland stadial preceding Greenland Interstadial 12 (GIS 12) is centered ca. 48.0 ka and a shift to drier conditions, correlated to the end of GIS 12, is ca. 43.5 ka. Overall, the variability of the Indian Monsoon, from XBL-1 data, on millennial scales is similar to and correlated with high-latitude ice core records from the Northern Hemisphere. However, some Indian Monsoon characteristics more closely resemble, but are anticorrelated with, features in the Antarctic record, suggesting some link to climate of the high southern latitudes, in addition to the clear link to the climate of the high northern latitudes.

Keywords: southwest China, stalagmite, U-series dating, $\delta^{18}O$, paleoclimate, absolute chronology, Indian summer monsoon, Chinese Interstadials.

INTRODUCTION

Ice core records from Greenland clearly show multiple climate events during the last glaciation, called Dansgaard-Oeschger (D/O) events. These millennial-scale events were characterized by abrupt temperature shifts in Greenland. Evidence for similar millennial-scale climate events is found in numerous records from other Northern Hemisphere locations and some Southern Hemisphere records, including records from the Southern Ocean. Various hypotheses have been proposed to explain the forcing behind such variations (Clark et al., 1999, and references therein; Braun et al., 2005). Precise and accurate chronology is the basis of correlating climate events in records from different geographic regions and is thus important for understanding the mechanisms behind the variability.

Cave calcite is an ideal archive for determining accurate correlations; U-series dating techniques can be applied to assess the absolute age of climatic events during the last glacial period with high precision (e.g., Wang et al., 2001). A recent study of an Austrian stalagmite (Spötl and Mangini, 2002) indicates that Greenland Interstadials (GIS) 14 and 15 began 54.2 and 55.6 ka, respectively, supporting previous results from Hulu Cave, eastern China (54.1 and 55.6 ka; Wang et al., 2001). Another stalagmite from Moomi Cave, Socotra Island, Indian Ocean (Burns et al., 2003, 2004), also gives a chronology for GIS 8–13 that is identical to the Hulu record (Wang et al., 2001). Given accurate correlations, these stalagmite chronologies are consistent within dating errors with the recently proposed Greenland summit ice core chronology (Greenland Ice Core Project [GRIP] [ss09sea]) (Johnsen et al., 2001).

However, the end of GIS 12 (midpoint between maximum and minimum), as obtained from a western European stalagmite, is dated as ca. 42.5 ka (Genty et al., 2003), 1500–1800 yr younger than that in the GRIP (ss09sea) record and the other stalagmite records mentioned here. In addition, it has been proposed that oscillations of the East Asian and the Indian Monsoons have an inverse phase relationship during the Holocene (Hong et al., 2005). It has previously been documented that $\delta^{18}O$ variations of stalagmites from Hulu and Dongge Caves in China record the history of Asian Monsoon precipitation, and millennial-scale strong Asian Monsoon events. A nomenclature has been established for these Chinese Interstadials (CIS), with those of the last glacial-interglacial cycle denoted with an "A" and numbered from youngest to oldest, CIS A.1–A.24 (Cheng et al., 2006). CIS A.1–A.24 have been correlated to GIS 1–24 (Wang et al., 2001; Cheng et al., 2006; Kelly et al., 2006). Here we present a precisely dated stalagmite $\delta^{18}O$ record from Xiaobailong Cave, Yunnan, China, to characterize Indian Monsoon history from 53 to 36 ka (CIS A.8–A.13). Given an accurate correlation, the record provides a better constraint on the timing of CIS A.12 and directly tests the phase relationships between the Indian Monsoon and the East Asian Monsoon, as documented at Hulu Cave (Wang et al., 2001).

SAMPLE AND METHODS

Stalagmite XBL-1 was collected from Xiaobailong Cave, 20 km south of Mile, Yunnan, China (N24°12′, E103°21′) (Fig. 1), located in the region affected by the Indian Monsoon. The entrance is ~1500 m above sea level. Cave air temperature is 17.2 °C, close to local mean annual temperature (17.3 °C). Mean annual precipitation is ~940 mm in Mile. Stalagmite XBL-1, 58 cm in height and ~19 cm in diameter, is composed of dense low-Mg calcite (GSA Data Repository Fig. DR1[1]).

Subsamples ($n = 22$) were drilled along the growth axis for ^{230}Th dating using inductively coupled plasma–mass spectroscopic (ICP-MS) techniques (Shen et al., 2002). Chemical procedures were similar to those described by Edwards et al. (1987), and details of instrumental approaches were explained by Cheng et al. (2000) and Shen et al. (2002). A $^{230}Th/^{232}Th$ atomic ratio of $4.4 \pm 2.2 \times 10^{-6}$ was used to correct for initial ^{230}Th (Table DR1; see footnote 1). For most dates,

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[1] GSA Data Repository item 2006128, supplementary information on ^{230}Th dating results (Table DR1), cave and sample descriptions, sample image (Figure DR1), subsampling method and isotope measurement (Figures DR2 and DR3), and Hendy Test (Figures DR4 and DR5), is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Geology; August 2006; v. 34; no. 8; p. 621–624; doi: 10.1130/G22567.1; 2 figures; Data Repository item 2006128.

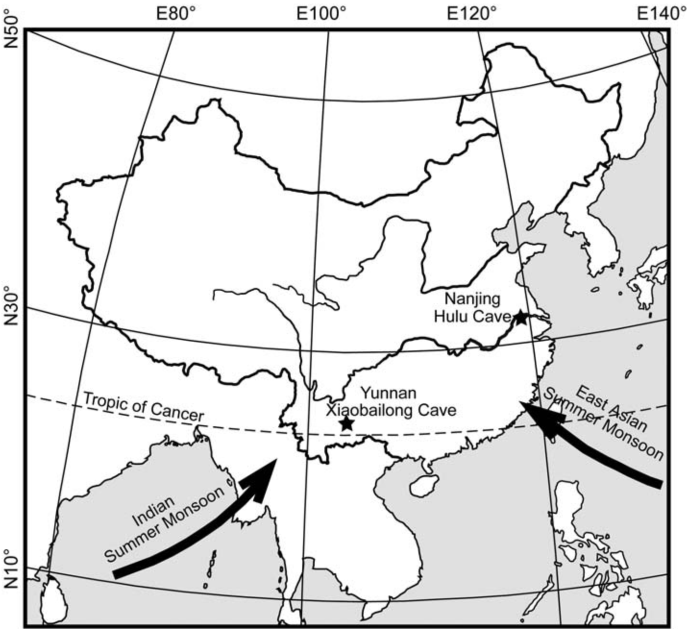

Figure 1. Location of Xiaobailong Cave (Yunnan) and Hulu Cave (Jiangsu), China.

initial corrections are trivial (≤10 yr) due to high ^{230}Th/^{232}Th atomic ratios in the subsamples. Linear interpolation was used to establish the chronology (age vs. depth is shown in Fig. DR2; see footnote 1). We obtained 747 oxygen and carbon isotope analyses (sampling and isotope analysis are described in detail in the Data Repository; see footnote 1), yielding a resolution between ~2 and 93 yr.

RESULTS AND DISCUSSION

Interpretation of Oxygen Isotope Records

A critical requirement for the use of speleothem δ^{18}O as a climate proxy is that the calcite was deposited under isotopic equilibrium conditions. Xiaobailong Cave has one small entrance with a narrow and long passageway, so the XBL-1 site, 360 m from the entrance, has weak ventilation. The cave relative humidity is ≥95% even during the dry season from November to April. Such conditions favor growth at isotopic equilibrium. Hendy Test (Hendy, 1971) results show that the δ^{18}O values are essentially the same along a single band. In addition, δ^{18}O and δ^{13}C have no statistically significant correlations along the single layers or for the entire data set (Figs. DR4, DR5; see footnote 1), another feature consistent with isotopic equilibrium precipitation of calcite.

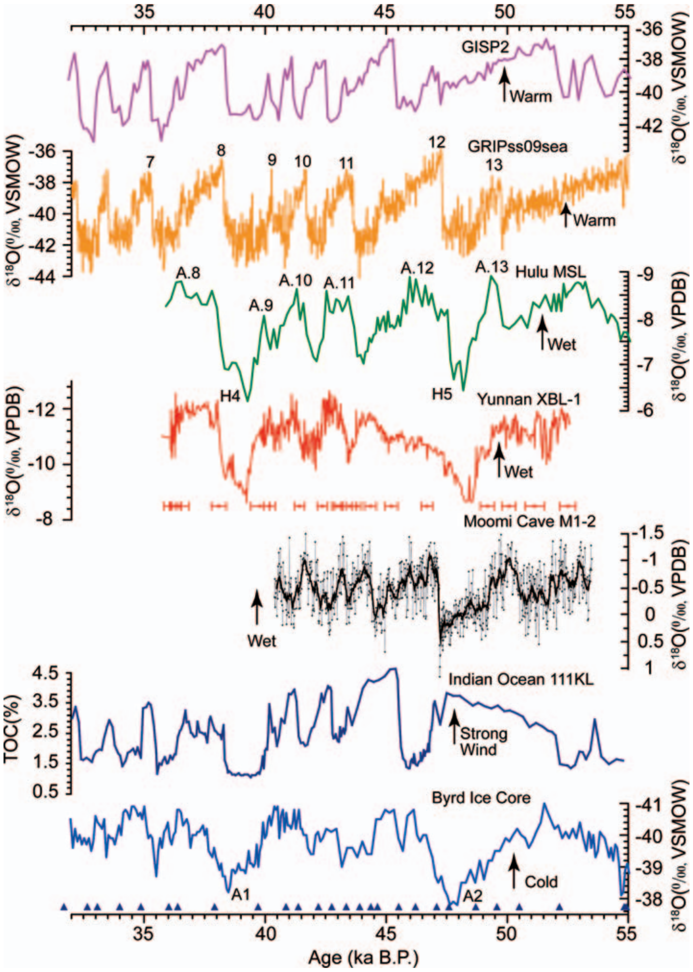

Figure 2. Comparison of δ^{18}O records of XBL-1 (red), Hulu (green, MSL, Wang et al., 2001), Moomi (black, Burns et al., 2004), Greenland Ice Core Project (GRIP) (ss09sea) (dark yellow, Johnsen et al., 2001), Greenland Ice Sheet Project 2 (GISP2) (pink, Grootes and Stuiver, 1997), Byrd (blue, Blunier and Brook, 2001; 28 tie points are indicated with triangles at bottom) and total organic carbon (TOC) record (dark blue, Schulz et al., 1998) of Indian Ocean core 111KL. Error bars indicate ^{230}Th ages and 2σ errors. Numbers 8–13 and A.8–A.13 indicate Greenland Interstadials (GIS) and Chinese Interstadials (CIS), respectively. δ^{18}O scales are reversed for XBL-1, Hulu, and Byrd ice core (increasing down) as compared to Greenland ice cores (increasing up). VSMOW—Vienna standard mean ocean water; VPDB—Vienna Peedee belemnite.

Under equilibrium deposition, the δ^{18}O of stalagmite calcite is controlled simultaneously by the isotopic composition of drip water and temperature inside the cave (Hendy, 1971). Although temperature is important, the large amplitude of the data set (3‰–3.5‰, Fig. 2) suggests that the primary control on calcite δ^{18}O is change in the δ^{18}O of meteoric precipitation. Temperature-dependent changes are likely small because the slope of the calcite/water fractionation–temperature curve is small (−0.23‰/°C, O'Neil et al., 1969), and evidence suggests that there is only ~5 °C temperature difference between the present and the Last Glacial Maximum in this area (Yu et al., 2003). Two patterns affect the δ^{18}O of precipitation in this region. First, in low-latitude areas, δ^{18}O of meteoric precipitation is negatively correlated with precipitation, i.e., the "amount effect" (Dansgaard, 1964; Rozanski et al., 1993). Nearby meteorological records also show that the δ^{18}O of precipitation is negatively correlated with rainfall amount (Johnson and Ingram, 2004). Second, ~85% of annual precipitation in the Yunnan province falls during the rainy season, from May to October, when the Indian summer monsoon (ISM) prevails. In general, temperature increase in the Northern Hemisphere enhances the ISM and results in a northward shift of the intertropical convergence zone (ITCZ), producing more convective precipitation in this region, characterized by a lighter oxygen isotope composition. Conversely, temperature decrease in the Northern Hemisphere weakens the ISM and shifts the ITCZ southward. As a result, it increases the proportion of dynamic precipitation, characterized by a heavier oxygen isotope composition (Cheng et al., 2005, 2006). This is consistent with the observation of the positive correlation between rainfall and temperature in southwestern China (Qin et al., 1997). Therefore, the δ^{18}O of Xiaobailong Cave stalagmites can serve as a proxy for summer monsoon precipitation, i.e., more precipitation leads to lower δ^{18}O values of the stalagmite, and less precipitation results in higher δ^{18}O values.

A similar relationship exists for the Moomi Cave record, where more negative stalagmite δ^{18}O values are indicative of higher rainfall and increased temperature (Burns et al., 2003). Another proxy of the monsoon comes from the total organic carbon record of core SO90-111KL, Indian Ocean (Schulz et al., 1998; Fig. 2), a record with a chronology mainly based on that of the Greenland Ice Sheet Project 2 (GISP2) ice core. The Moomi Cave record, our XBL-1 record, and the Hulu Cave record all resemble the ISM changes recorded in core SO90-111KL (Fig. 2). These additional lines of evidence further support the idea that the $\delta^{18}O$ changes in our stalagmite reflect variations in precipitation.

Correlation with the East Asian Monsoon and High Northern Latitude Records

The Indian Monsoon and East Asian Monsoon systems are both components of the larger Asian Monsoon system. The Asian Monsoon is driven by seasonal temperature differences and the resulting pressure gradient between Asia and the surrounding oceans (Pacific and Indian). Nevertheless, different sensitivities to internal feedback mechanisms may exist between the Indian Monsoon and East Asian Monsoon because of the different land-ocean configurations and respective geographic locations (Webster et al., 1998; Wang et al., 2003). Hong et al. (2005) proposed that the Indian Monsoon and the East Asian Monsoon have an inverse phase relationship on both orbital and millennial time scales in the Holocene. However, records of monsoon variations over D/O cycle time scales reported from both ocean sediments and continental deposits have generally been interpreted as being in phase with each other and with northern high-latitude climate during the last glaciation, i.e., an enhanced summer monsoon during Greenland interstadials and a stronger winter monsoon during Greenland stadials, although the chronologies of these archives are not always sufficiently precise to determine their phase relationships (Wang et al., 2005, and references therein).

The broad extent of East Asian Monsoon variations documented by the $\delta^{18}O$ of the Hulu Cave stalagmites has been well established (Cheng et al., 2005, 2006). The $\delta^{18}O$ time series of stalagmite XBL-1 between 53 and 36 ka shows a similarity to the $\delta^{18}O$ record from Hulu Cave (Wang et al., 2001), including CIS A.8–A.12, and those correlated to H4 and H5 (Fig. 2). This resemblance suggests that, within U-series dating errors (~300 yr), the variability of these two monsoon systems was in phase on millennial time scales over this period. The millennial-scale variability of XBL-1 $\delta^{18}O$ also approximately matches the $\delta^{18}O$ record of the Greenland ice cores (GRIP [ss09sea]; Fig. 2), further supporting the general correlation between low-latitude monsoonal climate variability and temperature fluctuations over Greenland (Schulz et al., 1998; Leuschner and Sirocko, 2000; Altabet et al., 2002). The covariation of the monsoon systems and their ties to high northern latitude climate are likely due to the fact that the monsoons are driven by the Asian continent-ocean temperature difference (Webster et al., 1998).

The absolute ages of the CIS A.8–A.12 in the XBL-1 record are consistent with those in the Hulu Cave record (Wang et al., 2001) and GRIP (ss09sea) (Johnsen et al., 2001) records, supporting the Hulu Cave and GRIP (ss09sea) chronologies over this time period (Fig. 2). The XBL-1 H5 event coincides with one of two possible correlations to H5 in Hulu Cave record, the older one at 48.0 ± 0.4 ka (Wang et al., 2001). Furthermore, the XBL-1 H4 event is centered at 38.5 ± 0.35 ka, supporting the chronology of this event in the GISP2 record (Meese et al., 1997). The XBL-1 record confirms that, within the U-series dating error of the stalagmite and the layer-counting uncertainty of the ice core, millennial climate oscillations in the low-latitude Asian summer monsoon system, including both the East Asian and Indian summer monsoons, are in phase with northern high-latitude climate fluctuations recorded by Greenland ice cores. The link between D/O events and Asian Monsoon variations suggests a positive correlation and/or feedback between high northern latitude temperature and moisture transmission from low to high northern latitudes. Therefore, it is plausible that the millennial-scale variability of the Asian Monsoon during the last glacial period may result from interactions between high northern latitude cold air advection and summer moisture transported across the tropical ocean (Zhou et al., 2001), and that a coupling mechanism may exist among high-latitude temperature, tropical moisture transport, Asian Monsoon circulation, and the migration of the mean position of the ITCZ (Wang et al., 2004), resulting in synchronous millennial climate changes in the Northern Hemisphere.

Although there are broad similarities, there are some differences between the Asian Monsoon and Greenland ice-core records. During GIS 12, $\delta^{18}O$ values increased abruptly and then decreased slowly in Greenland, in a sawtooth pattern. CIS A.12 in the Hulu Cave record began with a rapid drop in $\delta^{18}O$ values, followed by $\delta^{18}O$ oscillations of $\sim -8‰$, and finally ended with a rapid increase in $\delta^{18}O$ values, making an approximate trapezoidal pattern (Fig. 2). In the XBL-1 record, however, the $\delta^{18}O$ values decreased gradually to a minimum during CIS A.12, and then rose quickly at the end of the event. This feature may indicate an influence of climatic changes in the Southern Hemisphere as discussed in the following.

TELECONNECTION WITH THE SOUTHERN HEMISPHERE

The chronology of the Byrd ice core has been correlated to GRIP and GISP2 by matching methane fluctuations (Blunier and Brook, 2001). An updated time scale for Byrd based on the GRIP (ss09sea) chronology can be obtained by using the same methane matching procedure. Here we attained a new chronology between 55 and 32 ka for the Byrd ice core based on 28 tie points located at midpoints in shifts in the GRIP $\delta^{18}O$ record and by linear interpolation between the tie points (Fig. 2). The uncertainty in this revised Byrd time scale should be approximately the same as the previous one (~500 yr during the glacial period; Blunier and Brook, 2001). As shown by Blunier and Brook (2001), the cold event correlated with H5 thus corresponds to the warm event A2 in the Byrd ice core record. The decreasing trend of XBL-1 $\delta^{18}O$ values at the beginning of CIS A.12, which indicates increasing precipitation in China, thus correlates to a similar feature in the Byrd ice core, which records decreasing temperature in Antarctica (Fig. 2). In agreement with previous results (Leuschner and Sirocko, 2000; Altabet et al., 2002), the XBL-1 $\delta^{18}O$ variation seems to be analogous to Greenland ice cores in terms of in-phase millennial-scale variability, but around the time of CIS A.12, more similar to (but anticorrelated with) Antarctic ice in terms of the gradual nature of these changes.

Meteorological studies (Clemens et al., 1996) show that the ISM mainly originates from the subtropical high-pressure cell in the Southern Hemisphere, and travels through the strong low-level Somali jet from the East African coast. The Southeast Trade Winds over the southern Indian Ocean then turn into the ISM of the Northern Hemisphere after crossing the equator. Positive (negative) anomalies of the Darwin pressure in the southern Indian Ocean prior to the monsoon season correlate with a weak (strong) ISM (Shukla and Paolino, 1983). Li et al. (2003) showed that persistent storms during the Asian summer monsoon are closely linked to transequatorial air flow, which is strengthened by cold air originating in the southern high latitudes that is in turn influenced by sea-ice extent in the Southern Ocean. An (2000) proposed that the strengthened East Asian summer monsoon during late MIS 3 is related to strengthening of the transequatorial flow tied to cold temperatures in Australia. All of these lines of evidence suggest that ISM variability is closely tied to temperature change in the southern high latitudes, and that transequatorial flow may be an important link between Southern and Northern Hemisphere climate. Considering that more than 80% of ISM precipitation comes from the southern Indian Ocean (Clemens et al., 1996), it is likely that changes in moisture supply and temperature in the Southern Hemisphere may play an important role in driving the ISM or even the entire Asian summer monsoon system. Our record implies that during Greenland Interstadials, the Asian summer monsoon, including both Indian and East Asian summer monsoons, is strengthened due to low pressure above the Tibetan Plateau and the Asian continent. Meanwhile, southern high-latitude cooling leads to a higher temperature gradient in the Southern Hemisphere, which induces a stronger transequatorial flow and further contributes to an intensified ISM.

ACKNOWLEDGMENTS

This work was supported by Chinese Academy of Sciences grants KZCX2-SW-118 and KZCX3-SW-120; the National Basic Research Program of China grant 2004CB720206; National Science Foundation of China grants 40403001 and 40328005; U.S. National Science Foundation grants 0116395, 0214041, and 0502535; and Gary Comer Science and Education Foundation grant CC8. We thank Christoph Spötl and other two anonymous reviewers for their constructive suggestions.

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Manuscript received 10 January 2006
Revised manuscript received 8 March 2006
Manuscript accepted 12 March 2006

Printed in USA