Timing, Duration, and Transitions of the Last Interglacial Asian Monsoon

Daxian Yuan,1 Hai Cheng,2 R. Lawrence Edwards,2* Carolyn A. Dykoski,2 Megan J. Kelly,2 Meiliang Zhang,1 Jiamiing Qing,1 Yushi Lin,1 Yongjin Wang,3 Jiangyin Wu,3 Jeffery A. Dorale,4 Zhisheng An,5 Yanjun Cai5

Thorium-230 ages and oxygen isotope ratios of stalagmites from Dongge Cave, China, characterize the Asian Monsoon and low-latitude precipitation over the past 160,000 years. Numerous abrupt changes in 18O/16O values result from changes in tropical and subtropical precipitation driven by insolation and millennial-scale circulation shifts. The Last Interglacial Monsoon lasted 9.7 ± 1.1 thousand years, beginning with an abrupt (less than 200 years) drop in 18O/16O values 129.3 ± 0.9 thousand years ago and ending with an abrupt (less than 300 years) rise in 18O/16O values 119.6 ± 0.6 thousand years ago. The start coincides with insolation rise and measures of full interglacial conditions, indicating that insolation triggered the final rise to full interglacial conditions.

The characterization of past climate is often limited by the temporal resolution, geographic coverage, age precision and accuracy, and length and continuity of available records. Among the most robust are ice core records (1–2), which characterize, among other measures of climate, the oxygen isotopic composition of precipitation.

1To whom correspondence should be addressed. E-mail: edwar001@umn.edu

2Department of Geology, University of Minnesota, Twin Cities, MN 55455, USA. 3College of Geography Science, Nanjing Normal University, Nanjing 210097, China. 4Department of Geoscience, University of Iowa, Iowa City, IA 52242, USA. 5State Key Lab of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi’an 710075, China.

Although many such records are benchmarks, they are limited to high-latitude or high-elevation sites, which record the oxygen isotopic composition of the last fraction of atmospheric moisture remaining after transit from moisture source regions. Cave calcite also contains information about the isotopic composition of meteoric precipitation, is widespread, and can be dated with 230Th methods. Thus, caves may yield well-dated, low-latitude, low-elevation records that characterize atmospheric moisture earlier in its transit from source regions. We report here on such a record of Asian Monsoon precipitation, which covers most times since the penultimate glacial period, about 160 thousand years ago (ka). We have previously reported a cave oxygen isotope record of the East Asian Monsoon (3) from Hulu Cave, China [32°30’N, 119°10’E; elevation 100 m; cave temperature 15.7°C; mean annual precipitation δ18O_MSMW = −8.4 per mil (‰) (Vienna standard mean ocean water); and mean annual precipitation 1036 mm (table S1), covering the last glacial period (75 ka to 10 thousand years (ky) before the present). We now report similar data from Dongge Cave, China, 1200 km WSW of Hulu Cave, a site affected by the Asian Monsoon. The Dongge record more than doubles the time range covered in the Hulu record and overlaps the Hulu record for ∼35 ky, allowing comparison between sites. Highlights include the timing and rapidity of the onset (4) and end of the Last Interglacial Asian Monsoon and the degree of Last Interglacial Monsoon variability.

Dongge Cave is 18 km SE of Libo, Guizhou Province (25°17’N, 108°5’E), at an elevation of 680 m. The cave temperature (15.6°C), mean annual δ18O of precipitation (−8.3‰), and seasonal changes in precipitation and δ18O of precipitation are similar to those at Hulu, with mean annual precipitation being higher (1753 mm) (table S1). Stalagmites D3 and D4 were collected ∼100 m below the surface, 300 and 500 m from the entrance, in the 1100-m-long main passageway. D3 is 210 cm and D4 is 304 cm long, with the diameters of each varying between 12 and 20 cm. Stalagmites were halved vertically and drilled along growth axes to produce subsamples for oxygen isotope analysis (5) and 230Th dating by thermal ionization (6, 7) and inductively coupled plasma mass spectrometry (8). Sixty-six 230Th dates from D3 and D4 (table S2) and 10 dates from Hulu Cave stalagmite H82 (table S3), all in stratigraphic order, have 2σ analytical errors of ±80 years at 10 ky and ±1 ky at 120 ky. Six hundred and forty δ18O measurements have spatial resolution corresponding to 20 years to 2 ky for different portions of D3 and D4.
(Dongge Cave, table S4), and 830 δ¹⁸O measurements on H82 have average spatial resolution corresponding to 7 years (Hulu Cave, table S5).

A key issue is whether stalagmite δ¹⁸O values (Figs. 1 and 2) can be interpreted solely in terms of the δ¹⁸O of precipitation and cave temperature. The general replication (3) of δ¹⁸O values for 35 ky of contemporaneous growth, for D3 and D4 (Fig. 2), argues that the δ¹⁸O values are not strongly affected by water/rock interactions or kinetic fractionation (9, 10). Although we have not yet identified young calcite from Hulu, D4’s youngest calcite (Fig. 2) was deposited in isotopic equilibrium, because its δ¹⁸O value, the mean annual δ¹⁸O of modern meteoric precipitation, and mean annual temperature (table S1) satisfy the equilibrium calcite/water fractionation equation (11). For times of contemporaneous deposition of D4 and the Hulu Cave stalagmites (~35 ky), the caves’ records replicate remarkably well (Figs. 1 and 2), indicating not only that the calcite δ¹⁸O can largely be interpreted in terms of the δ¹⁸O of meteoric precipitation and cave temperature, but also that the two sites have a similar history of meteoric δ¹⁸O and cave temperature. Because Dongge is 1200 km from Hulu, this generalizes the Hulu results to areas well to the southwest. Indeed, the broad trends in the Dongge/Hulu data have similarities with Northern Hemisphere tropical and subtropical records at least as far west as the Middle East (12, 13) and probably as far away as northern South America (14).

An important characteristic of the Hulu/Dongge record (Fig. 2) is the large amplitude of the oxygen isotope ratio: 4.7‰. Because the change in the calcite/water fractionation of oxygen isotopes with temperature is small [−0.23‰ per °C (11)], the amplitude must result largely from changes in the δ¹⁸O of meteoric precipitation. A second important observation is the general anticorrelation between δ¹⁸O values at Hulu Cave and in Greenland ice during the last glacial period and the last deglaciation (Figs. 1 and 2) (3), a relation that has now been observed at a number of northern low-latitude sites [Israel (12) and Venezuela (14), in addition to Hulu (3) and Dongge Caves].

Interpretations of changes in precipitation δ¹⁸O have focused on (i) the correlation between mean annual temperature and δ¹⁸O of modern meteoric precipitation [for temperatures <10°C (15)] and (ii) the anticorrelation between rainfall amount and precipitation δ¹⁸O [the “amount effect” (15)]. However, modern precipitation δ¹⁸O trends basically result from the progressive removal of water vapor from air masses as they move from moisture source regions, resulting in decreasing water vapor and precipitation δ¹⁸O, which explains the first-order observation of lower precipitation δ¹⁸O values at higher latitudes. Precipitation δ¹⁸O at Hulu/Dongge is therefore largely a measure of the fraction of water vapor removed from air masses between the tropical Indo-Pacific and southeastern China. To first order, this process can be modeled assuming Rayleigh fractionation (15). Although more sophisticated models may ultimately be useful, any model for which meteoric δ¹⁸O decreases with the removal of water vapor will lead us, at least qualitatively, to the conclusions below. Using the standard Rayleigh equation (16), the percentage of water vapor lost before reaching Hulu/Dongge is 63% (16) during the mid-Holocene and Last Interglacial Period, 59% (16) today, and 52% (16) during glacial periods [about 16 ka (Heinrich Event 1) and immediately before and after the Last Interglacial Period], indicating that rainfall...
integrated between tropical sources and southeast China was lower during glacial than interglacial times, perhaps related to lower relative humidity.

To estimate absolute amounts of rainfall integrated from sources to southeast China, we must make assumptions about absolute humidity in tropical source regions. Even assuming a glacial relative humidity as high as today’s and only a modest tropical temperature depression (2.5°C), we calculate an absolute tropical glacial vapor pressure that is 85% of today’s and 79% of mid-Holocene/Last Interglacial values (at a mid-Holocene temperature 1°C greater than today and constant relative humidity). Coupled with the Rayleigh calculations, the amount of precipitation integrated between tropical sources and southeast China is today ~87% of mid-Holocene/Last Interglacial values and was ~65% of mid-Holocene/Last Interglacial values at glacial times corresponding to the heaviest Hulu/Dongge calcite δ18O values, indicating that this region was significantly drier during glacial times. This phenomenon may be applicable to broad areas of the northern tropics and subtropics, because precipitation δ18O records from Israel (12) and Venezuela (14) have the same general character as the Hulu/Dongge record (high δ18O during glacial times), and Amazon discharge has been estimated to have been diminished by 40% or more during the Younger Dryas (17).

Thus, the Hulu/Dongge record indicates major and abrupt changes in tropical and subtropical precipitation, which correlate with temperature in the North Atlantic region as recorded in Greenland ice.

Whatever the ultimate causes of the observed changes, the inferred moisture differences may play an important role in amplifying climatic change through feedbacks tied to water vapor’s greenhouse properties. Because atmospheric general circulation modeling of glacial precipitation does not recover low-latitude δ18O values as high (18, 19) as those observed here and elsewhere (12), it is plausible that this feedback is not fully captured in these models.

The timing of the Last Interglacial Period’s onset [Termination II; see (4) and references therein], duration (6, 20–23), and ending have been the source of extensive research and controversy. The low δ18O excursion associated with the Last Interglacial Asian Monsoon (Figs. 2 and 3) is characterized by (i) a large abrupt decrease in δ18O of about 3‰ (Monsoon Termination II), which took place 129.3 ± 0.9 ka; (ii) δ18O values varying within a range of ~1‰ for the ensuing 9.7 ± 1.1 ky; and (iii) a large and abrupt increase in δ18O of about 3.0‰ 119.6 ± 0.6 ka. Based on constant growth rates, the transitions took place extremely rapidly: most of Monsoon Termination II in <200 years and most of the transition at the end of the Last Interglacial in <300 years. Monsoon Termination II is similar in rapidity, magnitude, and relation to insolation to the transition into the Bolling-Allerød during Termination I (Fig. 1) (3). Thus, the rapidity of changes that characterizes the last glacial period also pertains to the glacial/interglacial transitions.

The Last Interglacial “square wave” is centered under the 25°N summer insolation peak (24). Monsoon Termination II takes place after a significant insolation rise, and the transition at the end of the Last Interglacial takes place after a significant insolation decrease, indicating that the low Last Interglacial Monsoon δ18O values result from Northern Hemisphere insolation changes (25). Indeed, the low-frequency component of the whole Hulu/Dongge record (Fig. 3) correlates with insolation, indicating that insolation is important in controlling monsoon intensity as predicted (25). At higher frequency, the correlation between millennial-scale events in Greenland and southeast China indicates that Asian Monsoon changes are an integral part of millennial-scale reorganization of ocean/atmosphere circulation patterns (3). Although the timing of the Last Interglacial Monsoon is consistent with insolation forcing, the abruptness of the transitions indicates that the detailed mechanism likely includes threshold effects. Although smaller in range than that of the last glacial period, the δ18O range of the Last Interglacial Period (~1‰) is still significant, amounting to about half the amplitude of typical last glacial period monsoon interstadial events (Fig. 2) (3). This supports indications of Last Interglacial Monsoon variability from loess deposits (26) and the idea that, in addition to well-documented examples of glacial climate instability, interglacial climate is also characterized by substantial variability.

Monsoon Termination I (the transition into the Bolling-Allerød) and Monsoon Termination II are each characterized by an abrupt lowering of δ18O in less than 200 years (Fig. 2). Both shifts occur after significant rises in summer insolation but before insolation peaks. The clearest difference is Termination I’s prominent high δ18O excursion during the Younger Dryas, a feature not observed in Monsoon Termination II, indicating that Younger Dryas-type events are not a general feature of terminations. Another difference is the fact that δ18O trends toward lower values for several millennia after Termination I, whereas δ18O values in the millennia immediately after Termination II do not follow a clear trend. Both differences could be related to ice volume, because sea level during and after Monsoon Termination II (27–29) may have been higher than during Termination I (30). If so, the cause of the Younger Dryas is likely to be ice sheet-related, and the intensity of the monsoon is affected by ice sheet volume.

**Fig. 3. (Bottom)*** An enlargement of the portion of the Dongge δ18O record around the Last Interglacial Period versus time. The gray curve is the summer (June, July, and August) insolation curve at 25°N (24). (Top) Portions of the direct sea level record [after (34)] and other directly dated measures of climate change. Error bars depict the ages of the half-height (1/2) of Devils Hole Termination II (20), the half-height of the marine oxygen isotope Termination II (29), and the first full interglacial δ18O values at Crevice Cave, MO (36). The three black horizontal bars centered at ~125 ky indicate the duration of the Last Interglacial sea level high stand from Bahamian corals [upper bar (1)], Australian corals [middle bar (22)], and direct dating of the marine oxygen isotope record [lower bar (35)]. The timing of Monsoon Termination II coincides within error with insolation rise, the final rise of sea level (34), the final rise of Crevice Cave δ18O (35), and the final rise of Soreq Cave δ18O [not depicted (12)] to full interglacial values. Thus, Monsoon Termination II appears to mark the final insolation-forced rise to full Last Interglacial conditions. However, a number of events not directly caused by insolation change preceded Monsoon Termination II by thousands of years [Devils Hole Termination II (20), marine oxygen isotope Termination II (29), a significant fraction of the sea level rise toward interglacial values (27, 28), Antarctic temperature rise (not depicted) (32, 33), and atmospheric CO2 rise (not depicted) (4, 32, 33)]. Thus, Monsoon Termination II appears to be an event forced by Northern Hemisphere insolation.
Although the timing of Monsoon Termination II is consistent with Northern Hemisphere insolation forcing, not all evidence of climate change at about this time is consistent with such a mechanism (Fig. 3). Sea level apparently rose to levels as high as —21 m as early as 135 ky before the present (27, 28), preceding most of the insolation rise. The half-height of marine oxygen isotope Termination II has been dated at 135 ± 2.5 ky (29). Speleothem evidence from the Alps indicates temperature near present values at 135 ± 1.2 ky (31). The half-height of the δ18O rise at Devils Hole (142 ± 3 ky) also precedes most of the insolation rise (20). Increases in Antarctic temperature and atmospheric CO2 (32) at the time of Termination II appear to have started at times ranging from a few to several millennia before most of the insolation rise (4, 32, 33). On the other hand, Monsoon Termination II coincides within error with the final rise in sea level to full Last Interglacial values (6, 21–23, 28, 34, 35) and the last rise to full Last Interglacial δ18O at Soreq Cave (12) and Crevice Cave (36). Thus, Monsoon Termination II appears to be an event forced by Northern Hemisphere insolation change, coincident with other such events but after a number of events not directly caused by Northern Hemisphere orbital forcing. As such, it may mark the inception of full interglacial conditions worldwide.

References and Notes
5. Oxygen isotope analyses were performed at the Isotope Laboratory, Institute of Karst Geology, Guilin, China, using a VG MM-903 gas mass spectrometer (for Dongge Cave D3 and D4 analyses, except for D4 between 15.81 ky and 9.98 ky); at the State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Xi’an, China, using a Finnigan MAT 252 Kiel Device III (Dongge Cave D4 between 15.81 ky and 9.98 ky); and on a Finnigan MAT 251 at the Nanjing Institute of Geology and Paleontology, Chinese Academy of Sciences (Hulu Cave H82 between 15.34 and 16.30 ky before present). Other HBZ analyses were reported earlier in (3).
8. C.-C. Shen et al., Chem. Geol. 185, 165 (2002).
10. In detail, D4 did not replicate perfectly, with some times characterized by differences in δ18O that are large as compared to analytical error but small compared to the amplitude of the record (Fig. 2). These discrepancies are likely due to kinetic effects, water/rock interactions, and/or differential evaporation of water at the land surface. There is little evidence for kinetic fractionation on the basis of C and O isotope correlations. C and O isotope ratios do not correlate strongly for any of the three stalagmites in this study or even for portions of these stalagmites. The highest R2 value for any of the three stalagmites is 0.27 (table S6). Because the top of D4 was deposited in isotopic equilibrium and because a portion of D4 replicates the Hulu record, D4 is less likely to have been affected by kinetic effects or water/rock interactions than D3.
16. We used the following form of the Rayleigh equation, modified from (37): [1000 + δ18Owater] [1000 + δ18Oair] = f18Oair. Where δ18Oof meteoric precipitation, δ18Oof seawater, f is the fraction of the original water vapor remaining, and α is the water vapor fractionation factor. We assumed a constant water/rock interaction ratio of 1.0094. We used the following values in our calculations: (i) Mid-Holocene/Last Interglacial values: calcite δ18Oofrock = −9.2‰, temperature 1°C today, and seawater δ18Oofseawater = 0.0‰. (ii) Today: calcite δ18Oofrock = −8.1‰ and seawater δ18Oofseawater = 0.0‰. (iii) Glacial times: calcite δ18Oofrock = −4.5‰ and temperature 4°C (VPDB, Vienna Pee Dee belemnite standard).
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**Early Life Recorded in Archean Pillow Lavas**

Harald Furnes,1* Neil R. Banerjee,1,2* Karlis Muehlenbachs,2 Hubert Staudigel,3 Maarten de Wit4

Pillow lava rims from the Mesoarchean Barberton Greenstone Belt in South Africa contain micrometer-scale mineralized tubes that provide evidence of submarine microbial activity during the early history of Earth. The tubes formed during microbial etching of glass along fractures, as seen in pillow lavas from recent oceanic crust. The margins of the tubes contain organic carbon, and many of the pillow rims exhibit isotopically light bulk-rock carbonate δ13C values, supporting their biogenic origin. Overlapping metamorphic and magmatic dates from the pillow lavas suggest that microbial life colonized these subaqueous volcanic rocks soon after their eruption almost 3.5 billion years ago.

Biologically mediated corrosion of synthetic glass is a well-known phenomenon (1). Early studies of natural volcanic glass suggested that colonizing microbes can actively dissolve glass substrates to extract nutrients, thereby producing channel-like tubular structures (2, 3). This mechanism has been verified experimentally (4–7). Over the past decade, numerous studies have documented micrometer-sized corrosion structures produced by microbial activity in natural basaltic glasses throughout the upper few hundreds of meters of the oceanic crust (8–13). These structures have textural characteristics (such as size range, morphology, and organization) that are consistent with a biogenic origin. The presence of carbon and nitrogen (10, 12, 13) as well as nucleic acids associated with the corrosion textures (10, 13) and characteristically depleted δ13C values of disseminated carbonate within microbially altered basaltic glass (10, 13, 14) further support the biogenic origin of these structures. In this paper, we document evidence of ancient microbial activity within exceptionally well-preserved pillow lavas of the ~3.5 billion-year-old Bar-