The record of paleoclimatic change from stalagmites and the determination of termination II in the south of Guizhou Province, China

ZHANG Meiliang[1], YUAN Daoxian[1], LIN Yushi[1], CHENG Hai[2], QIN Jiaming[1] & ZHANG Huiling[1]

1. Karst Dynamics Laboratory, Institute of Karst Geology, Chinese Academy of Geological Sciences, Guilin 541004, China;
2. Geography Department, Minnesota University, MN 55455, USA

Correspondence should be addressed to Zhang Meiliang (email: mlzh@karst.edu.cn)

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Abstract A high-resolution climate record from 163.00 kaBP to 113.80 kaBP has been obtained through TIMS-U series dating and carbon and oxygen isotope analysis of the three large stalagmites from two caves in the south of Guizhou Province, China. The record of the oxygen isotopes from the stalagmites reveals that the undulation characteristics between the cooling event of the glacial period and the warming event of the interglacial period in the research area can compare well to those of ice cores, lake sediments, loess and deep sea sediments on the scale of ten-thousand years or millennium time scale. The climate undulation provided by the record of the stalagmites has a coherence with the global changes and a tele-connection to the paleoclimate changes in the north polar region. Our results suggest that the direct dynamics of paleo-monsoon circulation changes reflected in the record of the stalagmites might be caused by changes of the global ice volume, and in turn related to various factors, including the solar radiation strength at the mid-latitudes in the Northern Hemisphere, the southern extension of the ice-rafted event in the North Atlantic, and changes of the equatorial Pacific sea surface temperature at the low-latitudes. Using δ^{18}O values, we have calculated the temperatures and the results show that the temperature difference between the penultimate glacial period (with an average temperature of 8.1℃, and a minimum temperature range from 0.65℃ to –1.43℃ at stage 6) and the last interglacial period (with an average temperature of 18.24℃ at sub-stage 5e) was about 10℃. This temperature difference from the record of the stalagmites corresponds in general to the record temperature variation (about 10℃) of measured ice cores. The climate records from the three stalagmites in the two caves have shown that the circulation strength of the Asian summer monsoon and the winter monsoon in the penultimate glacial period and the last interglacial period had a clear change.

With the TIMS-U series method, termination II of the penultimate glacial period has been precisely dated at an age of (129.28±1.10) kaBP for the three stalagmites in the south of Guizhou Province, China. This borderline age represents the beginning of the last interglacial period or the boundary between the Middle Pleistocene and the Late Pleistocene, and corresponds to the beginning age of the last interglacial period shown by the ice cores and in the

SPECMAP curve of the marine oxygen isotopes. The chronology determination of termination II is not only of stratigraphic and chronological significance, but also lays an important foundation for discussing the short time scales of climate oscillation and rapidly changing events of paleoclimate in the circulation region of the East Asian monsoon.

Keywords: stalagmite, paleoclimatic change, termination II, south of Guizhou.

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The key characteristics of Quaternary climate are alternations of the glacial and interglacial periods. The Quaternary period contained the multiple cycles of the glacial and the interglacial periods, reflected in good records from the deep sea sediments, lake sediments, ice cores, loess section and speleothem-stalagmites in caves.

On the basis of the record of the oxygen isotopes from the V28-238 drill hole and its comparison with records from the V28-238, V28-239, RC11-12, DSDP502, V30-40 and V22-174 drill holes, Imbrie and Martinson[1,2] have established a synthetic (SPECMAP) curve of the marine oxygen isotopes, by which 19 stages and 9 climate cycles[3—5] are divided.

China has the most important and extensive karst areas in the world. The karst in China is well developed and karst caves and speleothems are widely distributed all over the country; especially, stalagmites in caves are well developed. It is possible to establish a reliable climatic time-series from stalagmites and to reconstruct paleoclimate environments owing to the wide distribution of stalagmites in caves which contain rich information of environment and the length of record time, and especially, due to the introduction of high resolution dating age techniques of precise TIMS-U series and AMS-^{14}C. Here we present a climate record from the three stalagmites collected from two caves on the south margin of Guizhou Province, South China, and then discuss the cycles of climate fluctuation between the penultimate glacial period and the last interglacial period according to the dating ages of TIMS-U series and the analysis of the oxygen isotopes. We find that our stalagmites-based climate record is similar to those of the marine oxygen isotope (SPECMAP) curves on the scale of ten-thousand years or millennium time. Our record shows that a dominant cycle of the East Asian monsoon change is controlled by the forcing dynamics of the 100 ka periods of the global ice volume changes and in turn might be controlled by various factors, including the solar radiation strength at the mid-latitude in the Northern Hemisphere, the southern extension of the ice-rafting event in the North Atlantic and changes of the equatorial Pacific sea surface temperatures[6—9].

Meanwhile, the boundary age of termination II between the penultimate glacial period and the last interglacial period has been clearly determined. The age determination of termination II has both stratigraphic and chronological significances.

1 Collection and analysis of samples

For this study, we collected samples from the three stalagmites together from the Qixing cave and the Dongge cave in the south of Guizhou, China. Qixing cave is situated about 1.5 km southwest of Kaiyou, about 100 km from the southwest of Duyun City in the south of Guizhou. Qixing cave is over 250 m long. The annual average air temperature in this area is about 15.8℃. The Q2 stalagmite from the Qixing cave is about 200 m from the cave entrance on the calcareous tufa. The Q2 stalagmite is 219 cm high, and has a diameter of 13.5 cm. The interval we studied here covers a distance from 183 cm to 219 cm from the bottom of the stalagmite. The lower part of the interval stalagmite (from185 cm to 219 cm) shows continuous deposition and constitutes a whole sediment cycle and has a conformable contact with the middle-upper part of the stalagmite from 185 cm upward. The calcite crystals of the stalagmite are very fine, grey and grayish white in color, and consists of 0.1 mm or 1.5 mm thick calcite laminae. The sediment laminae are clear, without obvious recrystallization phenomenon. Fortyfive samples for analyses of carbon and oxygen isotopes were taken along the central growth axis of the stalagmite, with a resolution of one sample in every 1 cm interval, of which 4 samples are duplicated. We collected 5 samples for dating ages by TIMS-U series.

Dongge cave is situated about 3 km southeast of Laochangcun in the Dongtan township of Libo County in the south part of Guizhou Province. Dongge cave is about 1107.70 m long and consists of both an upper layer cave and a middle layer cave. The annual average air temperature in this area is about 18.3℃. The D3 and D4 stalagmites were collected from depths of 300 m and 500 m, respectively, in the middle layer of the cave.

The D3 stalagmite is 210.20 cm high, with diameter varying from 17 cm to 20 cm. The samples were collected by truncating from 102.50 cm to 210.20 cm in the middle and lower parts of the stalagmite. The lower part of the stalagmite, which ranges from 185.75 cm to 210.2 cm, shows continuous deposition, constituting a whole sediment cycle and conformable contact with the middle-upper part of the stalagmite over 185.75 cm. The calcite crystals of the stalagmite are very fine, grey and grayish white in color, and consist of 0.1 mm or 1.5 mm thick calcite laminae. The sediment laminae are quite clear, without the obvious recrystallization phenomenon. Seventy-nine samples for carbon and oxygen isotope analyses were taken with each sample in every 0.50 cm interval along the central growth axis of the stalagmite, of which 4 samples are overlapped. We also collected 12 samples for dating ages by TIMS-U series.

The D4 stalagmite is 304 cm high, with diameter varying from 12 cm to 20 cm. The samples were collected by truncating from 236 cm to 304 cm in the middle and lower parts of the stalagmite. The lower part of stalagmite, which ranges from 260.75 cm to 304 cm, has continuous sedimentation and constitutes a whole sediment cycle. It is in conformable contact with the middle-upper part (over 260.75 cm) of the stalagmite. The calcite crystals of the stalagmite are very fine, grey and grayish white in color, and consist of 0.1 mm or 1.5 mm thick calcite laminae. The sediment laminae are quite clear, without obvious recrystallization phenomenon. Seventy-eight samples for carbon and oxygen isotope analyses were taken with each sample in every 0.50 cm interval along the central growth axis of the stalagmite, of which 4 samples are paralleled. We also collected 11 samples for dating ages by the TIMS-U series method.

The samples from the three stalagmites were dated by using the TIMS-U series method (thermal ionization mass spectrometric instrument of Finnigan MAT262-RPQ). The chemistry procedure was modified from Edwards et al. The age dating was performed by Dr. Cheng Hai in the Geography Department of the University of Minnesota, USA. The ^{229}Th-^{233}U-^{236}U is used in the diluent material. The error of dating ages is within 1% or less (2σ).

The analyses of the carbon and oxygen isotopes were performed at the Isotope Laboratory, the Institute of Karst Geology, Guilin, China, using a VG MM-903 gas mass spectrometer. Samples obtained by reacting with phosphoric acid at 72℃ were converted to CO_2. The values of the carbon and oxygen isotopes are reported in per mil; that is to say, the δ value standard of water sample is related to SMOW and the δ value standard of the calcium carbonate is related to PDB with analytical precision within 0.1 per mil.

2 Dated ages by TIMS-U series method

The dated ages of TIMS-U series from the middle-lower parts of the three stalagmites from the two caves are shown in tables 1 and 2. The ages range from 162.30 kaBP to 113.90 kaBP for the D3 stalagmite and from 147.60 kaBP to 113.80 kaBP for the D4 stalagmite and from 151.30 kaBP to 121.70 kaBP for the Q2 stalagmite from the south of Guizhou Province. It can be seen that the lower part cycle of the three stalagmites ended all deposits of the penultimate glacial period before 129.28 kaBP according to chronology and the characteristics of the sediment cycle of the stalagmites and the sudden changes in the stable isotopes of the stalagmites. This age can be taken as the interface of the middle and lower sediment cycles of the stalagmites and the boundary age between the penultimate glacial period and the last interglacial period.

Table 1 ^{230}Th ages of D3 and D4 stalagmites from Dongge cave of Libo, Guizhou Province

Sample No.	Distance to the top/cm	^{238}U×10^{-9}/g • g^{-1}	^{232}Th×10^{-12}/g • g^{-1}	δ^{234}U* (measured)	^{230}Th age/ka (corrected)
D3u-20	102.5	1181±1	383±5	−193.4±0.8	113.9±0.6
D3u-19	116.9	1334±2	514±3	−203.5±0.9	118.4±0.7
D3u-18	161.5	1367±1	1137±5	−195.3±0.8	121.9±0.6
D3u-17	181.5	1115±1	16671±151	−187.9±0.8	124.1±0.6
D3u-16	185.1	714±1	21024±156	−191.8±0.9	127.8±1.0
D3u-15	185.9	1021±2	66580±480	−189.5±1.8	129.5±1.8
D3u-14	187.3	833±1	9523±39	−179.5±1.5	132.7±1.0
D3u-13	191.4	953±2	7055±51	−183.1±1.6	136.6±1.1
D3u-6(1)	195.9	915±1	3986±28	− 177.5±0.9	145.2±1.0
D3u-12	204.3	1231±1	2310±11	−177.8±0.7	149.8±0.9
D3u-11	205.8	1383±6	27464±211	−177.6±6.6	158.9±5.1
D3u-10	209.3	936±4	12827±106	−162.7±6.4	162.3±4.5
Annotation	The interface of two sediment cycles between D3u-16 and D3u-15.				
D4u-5	236	685.1±1.7	61±9	−94.9±2.1	113.8±1.1
D4u-6	240	503.9±0.5	387±11	−116.0±1.2	114.3±0.7
D4u-7	244	522.3±0.4	1639±27	−63.7±0.8	124.7±0.7
D4u-8	254	565.3±0.9	67±10	−52.1±2.1	126.9±0.9
D4u-9	259	514.5±0.6	379±9	− 41.0±1.7	128.5±0.8
D4u-10	261	558.0±0.8	186±9	−37.5±1.8	129.34±0.9
D4u-11	268	312.9±0.3	375±10	−18.7±1.7	131.9±0.9
D4u-12	276	450.0±0.6	176±9	−36.5±2.0	136.5±1.0
D4u-13	290	433.2±0.9	2561±10	−49.2±1.5	138.1±1.2
D4u-14	293	395.2±0.6	3966±39	−41.9±2.3	146.2±1.3
D4u-15	299	534.4±1.0	1517±11	−45.5±1.4	147.6±1.3
Annotation	The interface of two sediment cycles between D4u-9 and D4u-10				

Table 2 ^{230}Th ages of the Q2 stalagmite from Qixing cave of Duyuan, Guizhou Province

Sample No.	Distance to the top/cm	^{238}U×10^{-9}/g • g^{-1}	^{232}Th×10^{-12}/g • g^{-1}	δ^{234}U (measured)	^{230}Th age/ka (corrected)
Q2u-11	179	275.2±0.8	795±21	515.2±3.7	74.1±0.7
Q2u-13	183	2445±5	496±19	552.2±2.4	121.7±0.8
Q2u-14	187	1534±3	2357±19	288.0±2.7	130.6±1.2
Q2u-15	202	1062±2	7333±21	412.2±1.9	140.8±1.0
Q2u-16	218	237.4±0.6	1317±16	400.4±3.1	151.3±1.7
The interface of two sediment cycles between Q2u-13 and Q2u-14					

λ_{230} = 9.1577×10^{-6} a^{-1}, λ_{234} =2.8263×10^{-6} a^{-1}, λ_{238} = 1.55125×10^{-6} a^{-1}. $\delta^{234}U = ([^{234}U/^{238}U]_{active} - 1) \times 1000$. The error is 2$\delta$.

The lower parts of the three stalagmites in the penultimate glacial period are continuous deposits on the whole, with growth rates of 0.81 mm/100a for D3 stalagmite, 2.05 mm/100a for D4 stalagmite and 1.53 mm/100a for Q2 stalagmite, respectively. This displays that the growth rate of the stalagmite is slow and the dropping water amount from the top of cave is small but the dropping rate is stable. But the growth rates of sub-stages 5e and 5d in the last interglacial period are 6.88 mm/100a and 3.88 mm/100a, respectively, in the middle-upper parts of the D3 and D4 stalagmites. During this period, the dropping water amount from the top of cave was increased, so did the growth rate of the stalagmite. The ages of the three stalagmites in the south part of Guizhou Province can be compared with the ages of No. 1 stalagmite (which ranges from 80.70 kaBP to 229.10 kaBP) from Shuinan cave, stalagmite 82-9 (which ranges from 41.00 kaBP to 350.00 kaBP) from Maomao-toudayan cave in Guilin City, a stalagmite (from 18.00 kaBP to 215.00 kaBP) of the Tiane cave in Ninghua, Fujian Province, and the records of the marine oxygen isotope (V28-238 drill hole) at the middle-late phase of stage 6 , the Guliya ice core, the GRIP ice cores , the Antarctic ice core (since 150 kaBP) and the Lishi Loess beds (L2) in the north of China[10—21]. The general trend of climate change recorded in these stalagmites responds to the global changes, but the particular changes during this period of time are not fully consistent.

3 The paleoclimate significance of the carbon and oxygen isotopes

In recent years, the study on oxygen isotopic characteristics of the meteoric precipitation and the present stalagmite-carbonate in caves has shown that the variation of the δ^{18}O value of the stalagmites reflects the isotopic composition of the meteoric precipitation and the changes of the annual air temperature on the earth's surface over the cave which are obviously affected by the intensity of the East Asian monsoon[22—24] in this area when the oxygen isotope of the stalagmite-carbonate is formed under an oxygen isotope equilibrium condition. The isotope data of the recent meteoric precipitation from Guilin area and the southwest China have indicated that the meteoric precipitation in the summer season is mainly controlled by the East Asian summer monsoon and the properties of the precipitation-cloud cluster in the tropics. The meteoric precipitation in the winter season is mainly controlled by the cold fronts of the winter monsoon and the southwest warm-wet air masses. Therefore, the δ^{18}O values of the summer monsoon rainwater are much lower than those of the winter monsoon rainwater (for instance, the δ^{18}O values of the summer rainwater is much lower or more negative (from –2‰ to –3.5‰) than those of the winter rainwater in the area of Guilin) [25,26]. Moreover, the δ^{18}O value of the meteoric precipitation has a trend of gradual negative shift from the coastal cities such as Hong Kong and Guangzhou to the inland cities such as Guilin in Guizhou owing to the oxygen isotope fractionation of the meteoric precipitation[25,26]. The results indicate that the lower the δ^{18}O values are, the more intense the East Asian summer monsoon is, the higher the air temperature, and the richer the rainfall. These results indicate a warm and humid climate condition. On the contrary, relatively heavy δ^{18}O values of stalagmite calcites show that the winter monsoon may predominate over the East Asian summer monsoon, and hence indicating a dry and cold climate condition.

3.1 Paleoclimate records of the oxygen isotope

The oxygen isotope records from the middle and lower parts of the D3, D4 and Q2 stalagmites are shown in fig. 1. The mean δ^{18}O value from the lower part of the D3 stalagmite between 162.97 kaBP and 129.50 kaBP is –5.73‰ (PDB) and the mean δ^{18}O value from the middle-upper part of the D3 stalagmite after 129.50 kaBP is –8.36‰ (PDB). The mean δ^{18}O value from the lower part of the D4 stalagmite between 147.60 kaBP and 129.34 kaBP is –6.02‰ (PDB) and the mean δ^{18}O value from the middle-upper part of the D4 stalagmite after 129.34 kaBP is –8.42‰ (PDB). The mean δ^{18}O value from the lower part of the Q2 stalagmite between 151.30 kaBP and 130.60 kaBP is –4.74‰ (PDB) and the mean δ^{18}O value from the middle-upper part of the Q2 stalagmite after 129.34 kaBP is –7.9‰ (PDB). As a whole, the isotopic oscillation change trends of the three stalagmites are basically consistent with each other.

The curves of the oxygen isotope records from the three stalagmites, which range from 163.00 kaBP to 113.80 kaBP, indicate that there are two climatic cycles from a cold to a warm which are well coherent with the sediment cycles of the lower part and middle part of the stalagmites. The curves of the oxygen isotopes from the three stalagmites present a saw-toothed oscillation and form two maximum wave crests (with low value of δ) and a small wave crest, associated with two deep wave valleys (with high value of δ) and

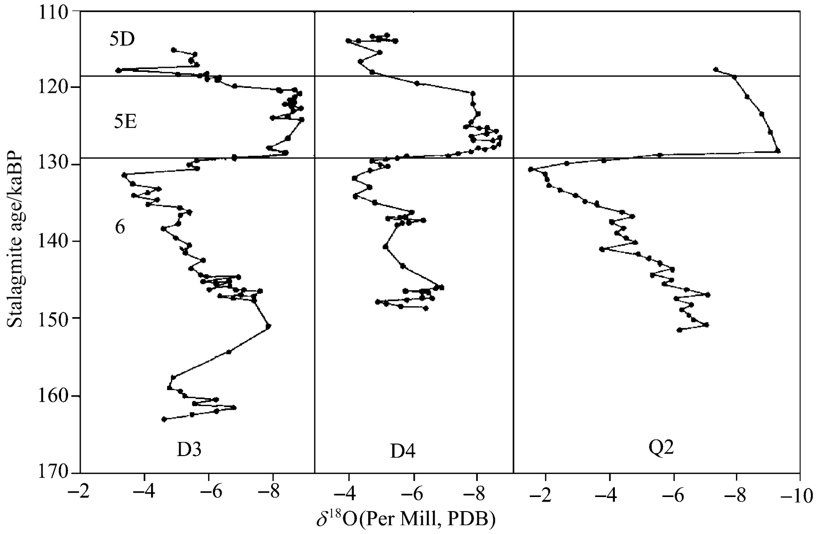

Fig. 1. Curves of oxygen isotope records from D3 and D4 stalagmites of Dongge cave and Q2 stalagmite of Qixing cave. D3 and D4, stalagmites from the Dongge cave; Q2, stalagmite from the Qixing cave.

a shallow wave valley. The two periods of the lowest wave valleys range from 135.15 kaBP to 130.53 kaBP and from 118.40 kaBP to 113.00 kaBP, respectively, and the two periods of the maximum wave crests (low value area of δ) range from 154.29 kaBP to 145.20 kaBP and from 129.28 kaBP to 119.00 kaBP, respectively. The climate changes from 163.00 kaBP to 113.80 kaBP can be divided into two climate types according to the fluctuation shape of the oxygen isotope records.

(i) The penultimate glacial period from 163.00 kaBP to 129.28 kaBP. The records of the TIMS-U series dating ages from the three stalagmites indicate that the period ranging from 163.00 kaBP to 129.28 kaBP is the penultimate glacial period, corresponding well to the marine oxygen isotope stage 6 which shifted from cold climate to warm one, with the coldest event existing during 135.15 kaBP and 130.53 kaBP. The climate change records during the penultimate glacial period can compare to those of ice cores, lake sediments, the adjacent (Sulu Sea) deep sea sediments and the Lishi loess (L2) from the north of China[17—21]. These can be divided into four intervals.

i) The relatively warm-cooling climate sub-stage from 163.00 kaBP to 160.00 kaBP. The growth of the D3 stalagmite began at 162.97 kaBP and the δ^{18}O value of the stalagmite changed gradually from –4.61‰ (PDB) to –5.48‰ (PDB). This suggests that the air temperature increased gradually from 5.4℃ to 8℃ (the air temperature is obtained according to the calculation of Craig H' Equation: $T℃ = 16.9 - 4.2 \times (\delta_c - \delta_w) + 0.13\,(\delta_c - \delta_w)^2$) and the climate changed from the dry-cold to the cold-cool. The δ^{18}O value for the period between 162.00 kaBP and 160.00 kaBP ranges from –5.48‰ (PDB) to –6.24‰ (PDB) which formed the low value area of δ^{18}O and lasted for about 2.00 ka. During this period the air temperature increased from 8℃ to 10.22℃, showing clearly that the marine or sea surface temperature had gone up again and is indicative of the semi-arid, warm-cooling climate.

ii) The relatively cold-cooling climate sub-stage from 160.00 kaBP to 154.29 kaBP. The δ^{18}O value of the stalagmites from 160.00 kaBP to 154.29 kaBP changes from –6.22‰ (PDB) to –5.28‰ (PDB), forming the high value area of δ^{18}O and lasting for about 5.71 ka. The result indicates that the air temperature in this period begins to go down again, falling from 10.22℃ to 7.2℃, and that the winter monsoon predominates over the East Asian summer monsoon, being indicative of the semi-arid, cold-cool climate.

iii) The warm-humid climate sub-stage from

154.29 kaBP to 145.20 kaBP. The Q2 and D4 stalagmites also began to grow at the very beginning of the period during 154.29 kaBP and 145.20 kaBP, so that during this period all the three stalagmites grew simultaneously. The $\delta^{18}O$ value for this period changes from –4.88‰ (PDB) to –6.59‰ (PDB), and the mean $\delta^{18}O$ value of the three stalagmites is –6.798‰ (PDB), the $\delta^{18}O$ value becomes much more negative than others, indicating that the duration is about 9.09 ka. During this period, the air temperature increased from 5.8℃ to 11.22℃ again and the mean air temperature was 12.28℃. This indicates that the East Asian summer monsoon was more intense than before, the sea surface temperature was high, and the rainfall was more plentiful. This was the warmest sub-stage of the penultimate glacial period.

iv) The severe-cold or dry-cold climate sub-stage from 145.20 kaBP to 129.28 kaBP. The $\delta^{18}O$ values for the period from 145.20 kaBP to 129.28 kaBP change from –6.93‰ (PDB) to –5.79‰ (PDB) and the mean $\delta^{18}O$ value shifts from –6.798‰ (PDB) to –4.62‰ (PDB). The $\delta^{18}O$ value is heavier than before, showing that the temperature dropped from 12.28℃ to 5.4℃. The mean $\delta^{18}O$ value for the period between 145.20 kaBP and 135.15 kaBP is –5.28‰ (PDB), showing that the mean air temperature was about 7.2 ℃. This condition lasted for about 10.05 ka, being indicative of a semi-arid, cold-cool climate. But the mean $\delta^{18}O$ value for the period between 135.15 kaBP and 130.53 kaBP is –3.96‰ (PDB). The $\delta^{18}O$ value is much heavier, showing that the mean air temperature was about 2.86℃ with the coldest temperature falling from 0.54℃ to –1℃. This condition lasted for about 4.62 ka and formed the coldest sub-stage in the penultimate glacial period. This result indicates that the cold front of the winter monsoon and the northwest cold air-current occupied a dominant position, the sea surface temperature fell dramatically, and the climate was drier for lack of rainfall. This period was of a severe cold or dry-cold climate. Then the air temperature began to go up again gradually and ended the deposit of the penultimate glacial period before129.28 kaBP.

(ii) The last interglacial period from 129.28 kaBP to 113.80 kaBP. The curves of the oxygen isotopes from the records of the stalagmites from 129.28 kaBP to 113.80 kaBP show a maximum peak (the low value area of $\delta^{18}O$) and a deep trough (the high value area of $\delta^{18}O$). The low values of $\delta^{18}O$ range from 129.28 kaBP to 118.40 kaBP and the high values of $\delta^{18}O$ range from 118.40 kaBP to 113.80kaBP, corresponding to sub-stages 5e and 5d of the marine oxygen isotope stage 5, respectively.

i) The warm-humid climate sub-stage from 129.28 kaBP to 118.40 kaBP. This sub-stage from 129.28 kaBP to 118.40 kaBP was analogous to the sub-stage 5e of the marine oxygen isotope stage 5 or Eemian of GRIS ice cores. The mean $\delta^{18}O$ values from D3, D4 and Q2 stalagmites in sub-stage 5e were –8.36‰ (PDB), –8.42‰ (PDB) and –7.9‰ (PDB), respectively, much lighter than previous, indicating the summer monsoon waxing and the winter monsoon waning in the area. The estimated mean air temperatures were 18.2℃, 18.7℃ and 17.5℃, respectively, and the highest air temperature was 21.6℃, showing a warm-humid climate. This sub-stage also was the warmest event during the last interglacial period in which the temperature began to reach the highest one for the fist time.

ii) The severe-cold or dry-cold climate sub-stage from 118.40 kaBP to 113.80 kaBP. The transition from 5e to 5d is very sharp at about 118.4 kaBP. This sub-stage from 118.40 kaBP to 113.80 kaBP was analogous to sub-stage 5d of the marine oxygen isotope stage 5. The mean $\delta^{18}O$ values of D3 and D4 stalagmites in sub-stage 5d are merely –5.22‰ (PDB) and –5.37‰ (PDB), respectively. The mean air temperatures were estimated to be 7.15℃ and 7.62℃, respectively, and the lowest air temperature was 0.63 ℃. The results suggest a winter monsoon prevailing period and a dry-cold climatic condition. This sub-stage was also the coldest event in the early stage of the last interglacial period.

Although our paleoclimatic records of stalagmites have their own features, as a whole, they are comparable with other records, e.g. the oxygen isotopic records of the deep-sea cores (V28-238), the Vostok ice core[27], other ice cores[2,17,18], the Lishi loess beds (L2) and the paleosol S1 in the north of China, lacustrine sediments, and the adjacent Sulu Sea sediments[28] in China.

3.2 Paleoclimatic records of carbon isotopes

The records of the carbon isotopes from the middle-lower part of the D3 and Q2 stalagmites in the south of Guizhou Province are shown in fig. 2. The mean δ^{13}C value from D3 and Q2 stalagmites from 162.97 kaBP to 113.90 kaBP was –4.12‰ (PDB) and –6.24‰ (PDB), respectively. This value may indicate the relative abundance of C3 plants over C4 plants. The carbon isotope records show that the changes of δ^{13}C values from the two stalagmites are nearly synchronous with the changes of δ^{18}O value, reflecting the ecological environment changes resulting from changes of the global climatic environments.

The mean δ^{13}C value from the D3 stalagmite is –2.97‰ (PDB) from 163.0 kaBP to 129.28 kaBP during the penultimate glacial period, implying that C4 plants were dominant over C3 plants in the dry and cool climate condition. The δ^{13}C value of this period has a much heavier drift trend and displays that C4 plants accounted for 78%, and C3 plants accounted for 22%.

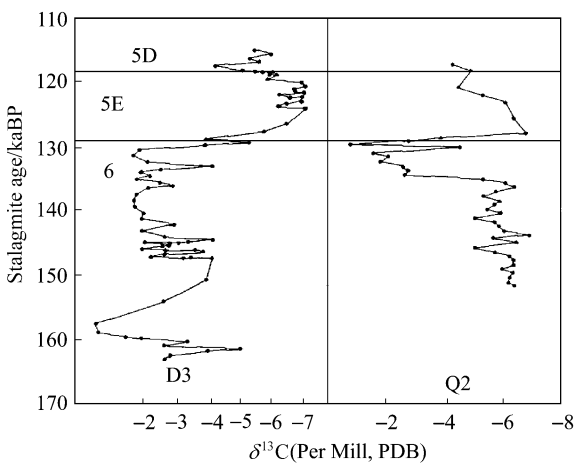

Fig. 2. The record curves of carbon isotope from D3 stalagmite of Dongge cave, Libo County and Q2 stalagmite of Qixing cave, Duyun City. D3, stalagmite from the Dongge cave; Q2, stalagmite from the Qixing cave.

The mean δ^{13}C value of the D3 stalagmite is –5.86‰ (PDB) in the last interglacial period from 129.28 kaBP to 113.8 kaBP, including sub-stages 5e and 5d, suggesting that the C3 plants dominated over C4 plants in a relatively warm and humid condition, especially in 5e period. From 129.28 kaBP to 118.40 kaBP, the C3 plants accounted for 87%, and C4 plants only accounted for 13%, showing that C3 plants recovered very well in the warm-humid climate environment. But during the period from 118.40 kaBP to 113.80 kaBP, analogous to the sub-stage 5d of the marine oxygen isotope stage 5, the C3 plants accounted for 65% and the C4 plants accounted for 35%, suggesting that the C3 plants were reduced as a result of falling air temperatures and rainfall decrease or drier conditions.

The mean δ^{13}C value of the Q2 stalagmite from the Qixing cave is –6.16% (PDB) from 151.3 kaBP to 129.28 kaBP during the penultimate glacial period, suggesting that C4 plants might be less than C3 plants at the plateau area. C4 plants only accounted for 38%, and C3 plants accounted for 62%. In particular, the mean δ^{13}C value from 151.30 kaBP to 135.36 kaBP is –7.05% (PDB). This δ^{13}C value has a negative drift trend, C3 plants accounted for 90.5% and C4 plants only accounted for 9.5%, indicating that C3 vegetation during this stage is exceedingly well preserved. But the δ^{13}C value from 135.36 kaBP to 129.28 kaBP in the dry-cold climate sub-stage is –4.72‰ (PDB) with a heavy drift. During this stage, C4 plants accounted for 57% and C3 plants accounted for 43%, indicating that C3 vegetation gradually dropped off and C4 vegetation increased relatively.

The mean δ^{13}C value of Q2 stalagmite from the Qixing cave is –6.76‰ (PDB) from 128.28 kaBP to 121.70 kaBP during the last interglacial period and has a negative drift trend. During this sub-stage, C3 plants accounted for 79% and C4 plants for 21%, implying C3 plants were again dominant in the warm-humid condition in the last interglacial period.

4 Precise determination and timing of termination II

Termination II is the onset time of the last interglacial period, i.e. the abrupt transition boundary between the cold penultimate glacial period and the warm last interglacial period. The termination II time has different estimates based on different records. For example, the termination II time is (140.00±3.00) kaBP in DH-11 vein calcite record [29]; (140.00±15.00) kaBP in the Vostok ice core record in the South Pole[27], 125.00 kaBP in the Guliya ice core[16], 128.00 kaBP or 130.00 kaBP in the deep sea sediment (V28-238 drill hole) isotope records[1,4]; (129.84±3.05) kaBP in SPECMAP (Geological chronology of the oxygen isotope from Martinson, D.G. et al., 1987)[2] in the sediments of WP7 drill hole; 128.00 kaBP in the Weinan Loess section and the Lishi loess (L2) in the north of China[30]; (130.00—132.00) kaBP in the coral records in the Atlantic Ocean[31]; (132.0±3.6) kaBP in the submerged speleothems and the coral records in Barbados[32] and 130.00 kaBP in the LFG-2 stalagmite from the Lithophagus cave in the northwestern Romania[33]. The determined ages of various sediment records have so great differences in the timing values, which may be caused by using different methods to calculate or measure ages and the different objects of collecting samples.

At the moment, the chronological records from various sediments show that termination II ages between 128.0 kaBP and 130.0 kaBP from the deep sea sediments——V28-238 drill hole and WP7 drill hole, the LFG-2 stalagmite from Romania and the Weinan Loess section and the Lishi loess (L2) from the northern China approached one another. In particular, the age of termination II from WP7 drill hole sediments is (129.84±3.05) kaBP which is the most accurate.

The boundary location of termination II in our three stalagmites is 185.7 cm, 260.75 cm and 185 cm from the top of the D3, D4 and Q2 stalagmite sections, respectively. The upper and lower parts of the three stalagmites all have obvious deposition interfaces and can be divided into upper and lower sediment cycles according to the deposit characteristics of stalagmites. The lithological characteristics of the upper and lower cycles from the stalagmites are very different. The lower cycle of stalagmite is dark in color and the calcite crystal is fine with micro-banding. The growth rate is smaller. In contrast, the upper sediment cycle is white or light-greyish white in color and the calcite crystal is coarse with rare lamination, and the growth rate is larger. The isotope records between the upper and lower cycle boundaries of termination II have an abrupt change. For instances, i)) the $\delta^{13}C$ values around the boundary change rapidly from –1.76‰ (PDB) to –4.01‰ (PDB) for the D3 stalagmite from 187.0 cm to 185.5 cm (only 1.5 cm apart) with a change of about 2.25‰, and the $\delta^{18}O$ values change rapidly from –3.73‰ (PDB) to –8.43‰ (PDB) with a change of about 4.7‰; ii)) the $\delta^{13}C$ values around the boundary change rapidly from –3.24‰ (PDB) to –5.51‰ (PDB) for the D4 stalagmite from 262.0 cm to 260.5 cm (also only 1.5 cm apart) with a change of about 2.27‰, and the $\delta^{18}O$ values change rapidly from –5.21‰ (PDB) to –7.44‰ (PDB) with a change of about 2.23‰; iii)) the $\delta^{13}C$ values around the boundary change rapidly from –3.39‰ (PDB) to –7.64‰ (PDB) for the Q2 stalagmite from 185.0 cm to 183.5 cm (only 1.5 cm apart) with a change of about 4.25‰, and the $\delta^{18}O$ values around the boundary change rapidly from –5.57‰ (PDB) to –9.16‰ (PDB) with a change of about 3.54‰. The boundary of termination II has been precisely determined by linear interpolating of dating results on the stalagmites according to the sudden change characteristics of sediment cycles, growth rate, the sudden change of the stable isotope component and so on.

Based on TIMS-U series dating results (tables 1 and 2), the dating ages from 185.1 cm to 185.9 cm on the D3 stalagmite are (127.80±1.00) kaBP and (129.50±1.80) kaBP, respectively. The dated ages from 259.00 cm to 261.00 cm on the D4 stalagmite are (128.50±0.80) kaBP and (129.34±0.90) kaBP, respectively. The dated ages from 183.0 cm to 187.0 cm on the Q2 stalagmite are (121.70±0.80) kaBP and (130.60±1.20) kaBP, respectively. According to linear interpolating of dating results (tables 1 and 2), the ages of termination II in the lower parts of the three stalagmites are (129.28±1.40) kaBP, (129.23±0.90) kaBP and (129.32±1.00) kaBP, respectively. The dating results of the three stalagmites are identical with an error range from 0.04 ka to 0.09 ka. The records of other sediments are very difficult to determine the precise age. Therefore, the final age of termination II in the penultimate glacial period obtained by averaging and synthesizing the age values of termination II from the D3, D4 and Q2 stalagmites from the southern of Guizhou Province should be (129.28±1.10) kaBP.

The age of termination II of the three stalagmites in the south of Guizhou Province is identical to the results obtained from the deep sea sediments, V28-238, V23-239 and WP7 drill holes, the stalagmite records of Romania, and the Weinan loess and the Lishi loess sections in the north of China, and in particular, is relatively close to the record age from WP7 drill hole and they both have only a 0.56-ka difference, suggesting that termination II of East Asian monsoon obtained from our stalagmites is synchronous within error with termination II determined by other records. The chronology determination of termination II is not only of stratigraphic significance, but also of chronological significance.

5 Conclusions

The East Asian monsoon records between 163.00 kaBP and 113.80 kaBP from the D3, D4 and Q2 stalagmites in the south of Guizhou Province are similar to the paleoclimate records of the deep-sea cores or sediments (V28-238), the WP7 drill hole, the GRIP ice cores, the adjacent Sulu Sea sediments, the lacustrine sediments and the Weinan loess or the Lishi loess (L2) section and the paleosol S1 in the north of China, particularly, some key events occurring in nearly the same time intervals. For instance, the dry-cold event between 135.15 kaBP and 130.53 kaBP in the penultimate glacial period (when the mean air temperature was only 2.86℃ and the lowest air temperature fell from 0.54℃ to −1℃) is comparable to that in deep-sea cores or sediments (i.e. V28-238).

In the last interglacial period, both warming event (5e or Eemian) and cooling event (5d) occurred between 129.28 kaBP and 113.80 kaBP. The warming event of the East Asian monsoon known from the three stalagmites occurred between 129.28 kaBP and 118.4 kaBP, corresponding to sub-stage 5e of marine oxygen isotope stage 5 or Eemian of the GRIP ice cores. The mean air temperature in sub-stage 5e was 18.16℃, and the highest air temperature was 21.64℃, suggesting a warmest time period in the last interglacial period. The cooling period (event) is between 118.40 kaBP and 113.80 kaBP, corresponding to sub-stage 5d of marine oxygen isotope stage 5. The mean air temperature in sub-stage 5d was 7.15℃ or 7.62℃, and the lowest air temperature was 0.63℃, suggesting a coldest time period in the last interglacial period.

The study results indicate that the changes of driving mechanism of the paleo-monsoon circulation recorded by the stalagmites were in accord with the global changes. The direct mechanism of the East Asian paleo-monsoon changes might result from the changes of the global ice volume or, in other words, mainly controlled by various factors, including the solar radiation strength at the low-latitude in the Northern Hemisphere, the ice-rafted events in the North Atlantic and changes of the Equatorial Pacific sea surface temperature. The East Asian summer monsoon in the eastern part of China was intensified when the global ice volume reduced and the temperature of the sea water in the South Pole and sea surface increased. The ice-rafted events in the North Atlantic are documented in the stalagmites from the south of Guizhou Province, the stalagmites in the Guilin area, the stalagmites of Fujian Provcince and Nanjing City[10,13,7] , as well as the Weinan loess or the Lishi loess section[34,35] in the north of China and the adjacent Sulu Sea sediments[26], suggesting that the paleo-monsoon circulation of China is related to the changes of the global ice amount and massive discharges of icebergs into the North Atlantic, causing the changes of the sea water temperature. In addition, the isotope records of the stalagmites from the Qixing cave and the Dongge cave in the south of Guizhou Province, stalagmites from the Xiangshui cave[36] and the Shuinan cave in the Guilin area and the stalagmite from the Tangshan cave of Nanjing are similar to and consistent with the global ice amount changes documented well by high resolution records from the Sulu

Sea sediments. This also supports the records from other evidence.

Both cold and warm events recorded in the three stalagmites from the south of Guizhou Province indicate that the changes of the Eastern Asian Paleomonsoon circulation in the area are also correlated to the climatic oscillation in the North Atlantic and, therefore, have strong teleconnection with the paleoclimate changes in the north pole region.

The temporal variations of paleoclimate since 163.00 kaBP in the south of Guizhou Province has been established on the basis of the TIMS-U series dating method and the data of the carbon and oxygen isotopes from the three stalagmites. The age of termination II between the penultimate glacial period and the last interglacial period is precisely determined at (129.28 ± 1.10) kaBP. The chronology determination of termination II is not only of stratigraphic and chronological significance, but also provides important information for discussing short-time scales of climate oscillation and the sudden change of paleoclimate in the region influenced by the East Asian monsoon.

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