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The climate reconstruction in Shandong Peninsula, North China during the last millennia based on stalagmite laminae

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Abstract

Stalagmite ky1 was collected from Kaiyuan Cave in coastal areas of Shandong Peninsula, northern China, located at warm temperate zone and East Asia monsoon area, it was 75 mm in length, and the top 42.77 mm developed 678 laminae. Based on high precision dating with U-^{230}Th technique, by continuous laminae counting, it can be confirmed that the 1st and 678th layer were 1217 and 1892 AD from top to bottom respectively. By the measurement of layer thickness and δ^{18}O values, we got the layer thickness data and δ^{18}O value time series data from 1217 to 1892 AD, analyzed the climatic significance of layer thickness variation on the basis of comparison. The result show that, in the 678 years from 1217 to 1892 AD, both the layer thickness variation of stalagmite ky1 and the variation of layer thickness fluctuation degree have obvious staged characteristic, and completely synchronized with the contemporaneous summer monsoon intensity/precipitation in time. Among, the thickness of layer and summer monsoon intensity/precipitation have negative correlation themselves. On the other hand, the layer thickness and the fluctuation degree of summer monsoon intensity/precipitation have positive correlation themselves. Therefore, Kaiyuan Cave, in the coastal area of warm temperate zone and East Asia monsoon area, the variation of layer thickness are relate to climatic factors variation themselves, and relate to climate stability degree in addition. For to achieve this, in the coastal area of warm temperate zone and East Asia monsoon area, the climate change between LIA and MWP, in addition to presented like less precipitation and low temperature that is to say dry and cold, also showed the climate stability degree obvious decreased.

1 Introduction

Calcareous speleothems, which have advantages in precisely dating and high-resolution sampling, are becoming one of the best geological archives for dating of major climate shifts (Burns et al., 2003; Cheng et al., 2009; Dykoski et al., 2005; Genty

CPD
11, 4643–4668, 2015

et al., 2003; Fairchild et al., 2006; Wang et al., 2001, 2008; Qin et al., 1999; Yuan et al., 2004) and high resolution reconstruction of past climate and environment (Committee on Surface Temperature Reconstructions for the Last 2000 Years and National Research Council, 2006; Fleitmann et al., 2003; Hou et al., 2003; McDermott et al., 2001; Paulsen et al., 2003; Tan et al., 2003; Tan, 2007; Wang et al., 2005; Zhang et al., 2008). Except for the most widely-used carbon and oxygen stable isotopes and trace elements, layers and growth rate of stalagmite could also be used as proxies for paleoclimate environment. However, different authors had very different climate and environment significance of layer thickness based on different climatic region. For instance, the layers of stalagmite were annual layers that was first confirmed (Baker et al., 1993), the structure of layers reflected the intensity of ancient rainfall (Baker et al., 1999), the growth rate of stalagmite had positive correlation with precipitation (Brook et al., 1999). However, the growth rate of stalagmite had negative correlation with precipitation (Proctor et al., 2000, 2002), the growth rate of stalagmite had response relation with temperature of winter (Frisia et al., 2003), and the growth rate of stalagmite were influenced by vegetation density in the top of cave (Baldini et al., 2005). Speleothem growth rates have a well-understood relationship with surface climate (Baldini, 2010; Mariethoz et al., 2012). The situations more complex in humid and semi-humid regions because other factors, such as drip rate, atmospheric P_{CO_2} in the cave, and the seasonality of the surface climate may also affect speleothem growth rates (Cai et al., 2011; Duan et al., 2012). The research of stalagmite layer in the middle reach of the Yangtze River indicate that the thickness of stalagmite layers may regard as the substitute index of the summer monsoon intensity of East Asia (Liu et al., 2005). The thickness variation had good response relation with the variation of rainfall (Tan et al., 1997; Ban et al., 2005). The growth rate of stalagmite had response relation with temperature of summer, the layer thickness may substitute the index of the intensity of East Asia monsoon (Tan et al., 2004). The δ^{18}O record of ZJD-21 indicates that δ^{18}O in the stalagmite was mainly influenced by rainfall amount and/or summer/winter rain ratio, with lighter values correspond to wetter climatic conditions and/or more summer monsoonal rains (Kuo et al., 2011). The Wanxiang Cave WX42B record indicated that while stalagmite δ^{18}O record represented local/regional moisture change (Li et al., 2011). The growth rate and the observed temperature had significant positive correlation (Tan et al., 2013).

The upper part of ky1 (from top to 42.769 mm depth, 0–42.769 mm) are consist of 678 continuous nonopaque annual layers clearly, its deposition time was from 1217 to 1892 AD, contained the whole LIA, the former late MWP and later early MCP (Modern Climate Period) (Lamp, 1965, 1972; Matthews, 2005; Ogilvie and Jónsson, 2001). This research is on the basis of high precision dating with U-^{230}Th technique, we observed and measured the thickness and dated the layers in the upper part of stalagmite ky1, compared and researched the time series data of layer thickness with the time series data of oxygen (O) stable isotope value. Because of the location of stalagmite ky1, it is located at the coastal area of warm temperate zone and East Asia monsoon area, containing the continuous layer thickness time series data of LIA (Little Ice Age), the transition period of LIA/MWP (Medieval Warm Period) and the transition period of LIA/MCP, it is first be found so far, so the result of this research can enrich the acquaintance about the climate environment significance of the layer thickness of stalagmite, and contribute to comprehend the specific manifestation of the MWP and LIA in the coastal area of warm temperate zone and East Asia monsoon area of northern China, especially the transition time of MWP/LIA and the sustaining time of LIA and the climate characteristic of LIA, and that may also deepen the research of climate change in Asian summer monsoon area based on the secondary carbonate record of karst cave.

2 Geological setting and sample description

Stalagmite ky1 was collected in 2008 AD from Kaiyuan Cave (35°43′35′′ N, 118°32′30′′ E) in the coastal area of western Shandong Peninsula, northern China, Kaiyuan cave. The cave is located in the northwest hilly area of Lushan Mountain in Zibo city, Shandong province, with elevation of 175 m above sea level (a.s.l.) (Fig. 1). As

CPD
11, 4643–4668, 2015

the largest peninsula in China, it was located between the Bohai sea and Yellow sea, widely distributed in its western region are Cambrian Middle Zhangxia group (the upper of oolitic shale, shale in clip to thin-layer limestone, oolitic limestone, algal clot limestone) and the Ordovician of Eight Steep and Gezhuang group, mainly for the gray-dark gray thick layer of mud wafer-thin limestone dolomitic limestone and marl, thickness of 24–238 m. Below section was integrated contacted with the Gezhuang group and upper section false intergrated contacted with the Carboniferous Benxi group (Shandong Provincial Bureau of Geology and Mineral, 1991), which were main mountains composition of the Lushan Mountain, Yishan Mountain, Mengshan Mountain with the highest elevation 1108, 1031 and 1150 m respectively. Comparisons with the cave landscape development of the Lushan Mountain, Yishan Mountain, Mengshan Mountain and surrounding carbonate rock mountain by the field investigation, the cave outcropping are numerous and large scale and most of caves had secondary carbonate sedimentary bodies that were typical development and morphological characteristics, such as stalagmites and so on.

Kaiyuan cave developed in the dolomite of the Ordovicia Zhifangzhuang group with the total strata thickness about 110 m. The total length of the cave is 6100 m, the overall distribution is northwest-southeast strike along with twists and turns, space width inside the cave is generally 2 to 8 m and can be up to 30 m. At the top of the cave that the surface of the bedrock covered soil about 50–80 cm thickness which can reach more than 1.0 m thick, and the soil type are calcareous rocky soil and drab soil (The soil and fertilizer workstation of Shandong Province, 1994), given priority to broad-leaved forest and xerophytic forest and grass vegetation, main tree species are locust tree and *populus davidiana*, constitute community is *platycladus orientalis–caragana frufex-ziziphus jujuba-themeda japonica*, shrub with *zizyphus jujube–cotinus coggygria-vitex negundo-lespedeza bicolor*, herbs with mainly *pennisetum flaccidum-roegneria kamoji* and so on, and scattered living trees have *ulmus pumila*, locust tree, *pistacia chinensis, populus* and so on. Original local vegetation consists of temperate deciduous and broad-leaved trees which was deforested anthropogenically and was currently replaced with

CPD
11, 4643–4668, 2015

shrubs and grasses including jujube, bramble, grass both riochloa and etc. The study site is currently influenced by both summer and winter monsoons with annual precipitation of ∼ 620 mm and annual mean temperature of ∼ 13° (Fig. 2). Summer monsoon prevails during July and August, contributing to half of the annual precipitation (Fig. 2).

The stalagmite ky1 is conical in shape and consists of very pure calcite. The polished surface of stalagmite and laminae observation by microscope show that stalagmite ky1 have no hiatus during development, the upper part (0–42.769 mm) developed 678 layers, overlain by continuous deposits, all layers were typical nonopaque annual layers. It has ^{232}Th concentrations ranging from 704.6 ± 5.1 to 1245.2 ± 5.0 ppt (Table 1), rendering high precision dating with U-^{230}Th technique which was conducted at the High-precision Mass Spectrometry and Environment Change Laboratory (HISPEC) of the National Taiwan University (Shen et al., 2002).

3 Analytical methods and data processing

3.1 Layer thickness measurement

First of all, the stalagmite ky1 should be cut along the growth axis, and pick a slice from the profile of stalagmite and then polishing the slice. Secondly, under the LEIKA DMRX microscope (magnification of 200×, eyepiece of 10×, objective of 20×), we used transmission light to observe characteristic of layers along the growth axis layer-by-layer. Then, we measured the thickness of 678 layers along three different path layer-by-layer, calculated every layer thickness data on average according to the three data of the each layer which had measured and dating layer-by-layer, we can get time series data of stalagmite layer thickness. At last, we contrasted the time series data and the $\delta^{18}O$ value data series, analyzed the paleoclimate environment characteristic of different stage, and discussed the climate significance of the variations of layer thickness.

3.2 Establish time scale

Considering stalagmite ky1 have no hiatus, the upper part (0–42.769 mm) developed 678 layers clearly and continuously, these continuous and ongoing layers has specific chronology pointing significance themselves. Therefore, based on high precision dating with U-^{230}Th technique, we used the method of laminae counting of annual layers, confirmed sedimentation time of each layer and sample of stalagmite ky1 layer-by-layer and established the time scale of stalagmite. In the upper part (0–42.769 mm) of stalagmite ky1, we counted along upward and downward direction according to many layer (marker bed) which has high precision dating results with U-^{230}Th technique continuously and annually, ensured forming times of 1–678 layers firstly, and then ensured date of each layer according to their horizons.

3.3 δ^{18}O isotopes test

In the first place, along the two layer that the horizons of 9.5 and 18.5 mm from top and perpendicular to growth axis, we collected 4 samples in 20 mm from growth center equally spaced that were used for Hendy test. Secondly, along development direction, we collected a 4 mm depth × 5 mm width × 75 mm length stone strip in development center, scraped samples with medical scalpel from top to bottom, sampling density of 7–8 samples mm^{-1} (separation distance of 0.1296 mm on average), 330 samples were scraped in total. In order to eliminate the mixed pollution among adjacent samples, following the principle of interval test, we chose 172 samples to measure their δ^{18}O value. Next, we confirmed the sedimentation time according to their horizons and formed the time series data of δ^{18}O and δ^{13}C value. δ^{18}O values were measured using an automated individual-carbonate reaction (Kiel) device coupled with a Thermo-Fisher MAT 253 mass spectrometer at the State Key Laboratory of Palaeobiology and Stratigraphy of Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences. Each powdered sample (∼ 0.08 to 0.1 mg of carbonate) was reacted with 103 % H_3PO_4 at 90 °C to liberate sufficient CO_2 for isotopic analysis. The standard used is NBS19 and one standard was analyzed with every ten samples. One sample out of ten was duplicated to check the replication. All isotope ratios are reported in permil (‰) deviations relative to the Vienna Peedee Belemnite (VPDB)standard in the conventional manner. The standard deviation (1σ) for replicate measurements on NBS-19 is $< \pm 0.10$ ‰.

4 Result and discussion

4.1 The layer thickness of stalagmite and dating results

In the upper part (0–42.769 mm) of stalagmite ky1, the dating result of age corrected in Table 1 show that the three samples of the horizons of 6, 15 and 25 mm were 251.1 ± 20.3, 316.4 ± 13.6 and 456.6 ± 13.6 B.P. (Table 1). Among, there are 221 layers between the horizons of 6 and 25 mm, their age interval were 206 years according to the U-^{230}Th dating results, the value difference of age between laminae counting and U-^{230}Th dating results was only 15 years. But there are 109 layers between the horizons of 6 and 15 mm, their age interval were 67 years according to the result of U-^{230}Th dating, and there are 112 layers between the horizons of 15 and 25 mm, their age interval were 141 years according to the result of U-^{230}Th dating. On the other hand, if we use the horizon of 6 mm as benchmark to reckon, the age of 1st and 678th layer were 1894 ± 20 and 1217 ± 20 AD respectively; if we use the horizon of 25 mm as benchmark to reckon, the age of 1st and 678th layer were 1909 ± 14 and 1232 ± 14 AD respectively; the results were only 14 years differs. In consider of the error of layer thickness measurement accumulated downward layer by layer, we chose the 133 layer correspond to the horizons of 6 mm as datum mark, calculated other layers in the upper part of stalagmite ky1. The result showed that deposition time of 1st and 678th layers were 1894 ± 20 and 1217 ± 20 AD respectively, the age of other layers calculated and so on, hereby we got the time series data of layer thickness of stalagmite ky1 (Fig. 3).

CPD
11, 4643–4668, 2015

4.2 Layer shape characteristic

Stalagmite ky1 developed continuous nonopaque layers obviously (Fig. 4). Under the microscope, first, the thickness of layer is rather changeable, the maximum thickness reached more than 800 µm, and the minimum thickness reached less than 15 µm (Fig. 5a). Because of layer thickness variation may correspond to the climate environment change when layers were developing, show the potential value of these nonopaque layers of stalagmite in rebuilding the paleoclimate environment. Secondly, most boundary of layers are straight, but some layers were obvious curved (Fig. 5b). Hereby when we analyzed the environment significance of the stalagmite layer thickness, we measured the same layer and calculated on average along multiple paths, in order to get substituted index information of climate environment in statistical significance. Third, color in some boundaries of nonopaque layers were deepen obviously (Fig. 5c), confirmed special structure similar to supera annual layer. This may hint that climate environment had season variation, it also had multi-interannual variation. Fourth, the light transmission of some nonopaque layers were obvious different from adjacent layers, the color of later layers were deeper and rich of dark spots (Fig. 5d). Whether these dark layers had some mineralogy and geochemistry characteristic that different from other nonopaque layers, and how their climate environment significant like, these may need further research in the future.

4.3 Layer thickness variation

The thickness variation of 678 layers in stalagmite ky1 (upper part) were 872.8 ~ 13.03 µm. The formed age of maximum thickness (872.8 µm) layer was 1551 AD, the formed age of the minimum thickness (13.03 µm) of layer was 1245 AD, the thickness of all layers were 63.08 µm on average (Fig. 6a). In the 678 years from 1217 to 1892 AD, the layer thickness of stalagmite ky1 had obvious staged variation, it had undergone the transition that from low value to high value and again to low value, and both the layer thickness itself and the fluctuation degree variation of layer thickness

CPD
11, 4643–4668, 2015

had obvious staged variation (Fig. 6). From 1217 to 1471 AD, it was the low value of layer thickness that sustaining 254 years (the average value of 46.08 µm). Among, the stage between 1217 to 1372 AD was low fluctuation period relatively; the stage between 1372 to 1471 AD was high fluctuation period relatively, presented the variation trend that rise first and then fall. From 1471 to 1744 AD, it was the high value of layer thickness and high fluctuation period that sustaining 273 years (the average value of 88.8307 µm). Among, this stage could be divided into three high value and high fluctuation period, 1471–1548, 1548–1637 and 1637–1744 AD, every period has the trend that increases firstly and then decreases, their average value of layer thickness were 82.2027, 82.5491 and 98.8252 µm successively. From 1744 to 1892 AD, it was the low value of layer thickness that sustaining 150 years (the average value of 45.1164 µm). Among, the stage between 1217 to 1372 AD was low fluctuation period relatively; the stage between 1744 to 1831 AD was high fluctuation period relatively, presented the variation trend that rise first and then fall; the stage between 1831 to 1880 AD was high fluctuation period relatively and did not had a trend of rise or fall obviously; it was a short rising period during 1880 to 1892 AD.

4.4 δ^{18}O value variation

The δ^{18}O value variation range of the 172 samples above was −8.599 ~ −6.247 ‰, the maximum value (−6.247 ‰) appeared in 1603 AD, the minimum value (−8.599 ‰) appeared in 1460 AD, the value of all samples were −7.674 ‰ on average (Fig. 6b). In the 678 years from 1217 to 1982 AD, the δ^{18}O value variation had obvious staged variation, it had undergone the transition that from low value to high value and again to low value, and both the δ^{18}O value and the fluctuation degree of δ^{18}O value had obvious staged variation (Fig. 6b). From 1217 to 1480 AD, it was the low value of δ^{18}O value that sustaining 263 years (the average value of −8.104 ‰). Among, the stage between 1217 to 1384 AD was low fluctuation period relatively, had a trend that slowly declined in total; the stage between 1384 to 1480 AD was high fluctuation period relatively, presented the trend that rise first and then fall. From 1480 to 1746 AD, it was

CPD
11, 4643–4668, 2015

the high value of $\delta^{18}O$ value and high fluctuation period that sustaining 269 years (the average value of −7.301 ‰). Among, this period could be divided into three subprime high value and high fluctuation period: 1480–1542, 1542–1633 and 1633–1746 AD, every subprime period has the trend that increased firstly and then decreased or decreased firstly and then increased, their inflection points appeared in the age of 1498, 1603 and 1663 AD, their average value of $\delta^{18}O$ were −7.393, −6.953 and −7.513 ‰ successively. From 1764 to 1892 AD, it was a low value period that sustaining 146 years (the average value of −8.199 ‰). Among, the stage between 1746 to 1831 AD was a high fluctuation period relatively, presented the variation trend that rise first and then fall; the stage between 1831 to 1880 AD was a low fluctuation period relatively and did not had a trend of rising or falling obviously; it was a short rising period during 1880 to 1892 AD.

4.5 Climate significance of layer thickness variation

Owing to the difference of homologous layer thickness stage and $\delta^{18}O$ value stage ranged 2 to 14 years, in consideration of the error of dating technique was 20 years and the resolution of $\delta^{18}O$ sample was 3.9 years, we could say the two synchronize with time variation, mean that the low value period and high value period of $\delta^{18}O$ value period correspond to the low value period and high value period of the stalagmite layer thickness, the low fluctuation period and high fluctuation period of $\delta^{18}O$ value were correspond to the low fluctuation period and high fluctuation period of layer thickness of stalagmite (Fig. 6a and b). On the other hand, the analysis result of $\delta^{18}O$ value showed that, $\delta^{18}O$ value of the 4 samples were −7.506, −7.753, −7.981 and −7.691 ‰ which were collected 9.5 mm distance from the top of stalagmite, 5, 10, 15 and 20 mm distance from the growth axis respectively; $\delta^{18}O$ value of the 4 samples were −6.571, −6.671, −6.540 and −6.542 ‰ which were collected 18.5 mm distance from the top of stalagmite, 5, 10, 15 and 20 mm distance from the growth axis respectively; the $\delta^{18}O$ form were similarly in the same layer position. Hence, the Hendy Test carried out about

CPD
11, 4643–4668, 2015

Ky1 indicate that calcite in Ky1 should be deposited under isotopic equilibrium conditions, the possibility of its kinetic fractionation in the sedimentary process is small, so the stalagmite $\delta^{18}O$ mainly reflected the original external climate signal (Hendy, 1971). Therefore, the $\delta^{18}O$ of stalagmite can use to collect and reconstruct the information of climate change.

The obvious synchronization relation between the layer thickness change of stalagmite ky1 and $\delta^{18}O$ value variation shows e closely relationship between the deposition rate variation of layers and climate change (Fig. 6). Kaiyuan Cave, located at warm temperate zone and East Asia monsoon area, rainy season which coincided with high temperature and precipitation are concentrate on summer, it was carried by summer monsoon from Pacific Ocean of low latitude; when the winter monsoon from the interior Asian continent of high latitude is prevailing, rare precipitation and cold weather. In this research, We has interpreted the $\delta^{18}O$ record of ky1 in term of the Asian summer monsoon intensity as is assumed in monsoonal China by Cheng et al. (2009) and the precipitation as is assumed by Zhang et al. (2008), with lower $\delta^{18}O$ values representing stronger summer monsoon and higher $\delta^{18}O$ values weaker summer monsoon and $\delta^{18}O$ values anti-correlating with precipitation. Hereby, it was strong summer monsoon/more precipitation period from 1217 to 1480 AD, it was weak summer monsoon/less precipitation period from 1480 to 1746 AD, and it was strong summer monsoon/more precipitation period from 1746 to 1892 AD again. On the other hand, the fluctuation degree of summer monsoon intensity/precipitation was not the same in different period. As a whole, the fluctuation degree was low when the summer monsoon were strong/the precipitation were more, the fluctuation degree was high when the summer monsoon were weak/the precipitation were less. Among, the stage from 1217 to 1480 AD can be divided into prior low fluctuation period and latter high fluctuation period; the stage from 1480 to 1746 AD can be divided into three high fluctuation period, the stage from 1746 to 1892 AD included a high fluctuation period, a low fluctuation period and a weaker/less period.

According to the layer thickness of stalagmite ky1 and $\delta^{18}O$ value record, the thickness of layer and summer monsoon intensity/precipitation value have negative correlation themselves, the high value period of layer thickness are correspond to weak summer monsoon/less precipitation, and low value are correspond to strong summer monsoon/larger precipitation. On the other hand, the thickness of layer and the fluctuation degree of summer monsoon intensity/precipitation have positive correlation themselves, the high value period of layer thickness are correspond to high fluctuation degree of summer monsoon intensity/precipitation, and low value are correspond to low fluctuation degree of summer monsoon/precipitation. Therefore, Kaiyuan Cave, in littoral of warm temperate zone and East Asia monsoon area, the change of layer thickness are not only relate to climatic factors variation themselves, but also relate to climate stability degree. This is because karstic water cycled faster and detention time was shorter in the fracture of rock, the dissolution was insufficient and weak, so the deposition rate and layer thickness of stalagmite were low, and more outstanding in the years that raining continuous and more. But karstic water cycled slower and detention time was longer in the fracture of rock, the dissolution was sufficient and strong, so the deposition rate and layer thickness of stalagmite were high. However, karstic water would less or dried up if the years of less precipitation continuous appeared, this is also bad for dissolution and stalagmite layer developing. So in the background of weaker summer monsoon and less precipitation, the fluctuation degree of summer monsoon intensity/precipitation value goes higher, and beneficial to enlarge the average value of the layer thickness of stalagmite, but their fluctuation degree goes higher. Because of the fluctuation degree of summer monsoon intensity/precipitation mirrored the stabilized degree of climate, according to the layer thickness of stalagmite ky1 and $\delta^{18}O$ value record, Kaiyuan Cave, in the littoral of warm temperate zone and East Asia monsoon area, the climate variation between LIA and MWP, in addition to present like less precipitation and lower temperature, also show that the climate stability degree was obvious decreased.

CPD

11, 4643–4668, 2015

The climate reconstruction in Shandong Peninsula

Q. Wang et al.

5 Results

The upper part of stalagmite ky1 (0–42.769 mm) are consist of 678 continuous nonopaque annual layers clearly, its deposition time were from 1217 to 1892 AD, contained the climate environment variation information of the whole LIA, the former late MWP and later early MCP. The analysis show that both the changes of layer thickness of stalagmite ky1 and the variation of layer thickness fluctuation degree have obvious characteristic of stage, from 1217 to 1892 AD, it had undergone the transition that from low value to high value and again to low value, and synchronize with the contemporaneous variation of $\delta^{18}O$ value and fluctuation degree. According to the comparison analysis between the layer thickness variation and synchronous $\delta^{18}O$ value of stalagmite ky1, the thickness of layer and summer monsoon intensity/precipitation value have negative correlation themselves, the high value period of layer thickness are correspond to weak summer monsoon/less precipitation, and low value are correspond to strong summer monsoon/larger precipitation. On the other hand, the thickness of layer and the fluctuation degree of summer monsoon intensity/precipitation have positive correlation themselves, the high value period of layer thickness are correspond to high fluctuation degree of summer monsoon intensity/precipitation, and low value are correspond to low fluctuation degree of summer monsoon/precipitation. Therefore, Kaiyuan Cave, in the coastal area of warm temperate zone and East Asia monsoon area, the relation between the variation of layer thickness and climate change, is not simply present that the effect of one climate factor variation like temperature and precipitation to the layer thickness, and closely related to the fluctuation degree of summer monsoon intensity and climate stability degree in addition. As a whole, it was a period of strong summer monsoon from 1217 to 1470 AD. Among, the climate stability was high from 1217 to 1370 AD firstly, and the climate stability reduced from 1217 to 1370 AD. From 1470 to 1740 AD was weak summer monsoon-low stability period, it could be divided into three subprime period that strengthen firstly and then weaken or weaken firstly and then strengthen by the boundaries of 1550 and 1640 AD. Begin with

CPD
11, 4643–4668, 2015

1640 AD, summer monsoon entered into strong stage again. Among, the stability degree is high from 1740 to 1830 AD, the stability degree reduced from 1830 to 1880 AD, the summer monsoon weakened shortly begin with 1880 AD.

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CPD
11, 4643–4668, 2015

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CPD
11, 4643–4668, 2015

Table 1. U-series isotopic results and ages for stalagmite ky1 from Kaiyuan Cave, Shandong peninsula, Northern China.

Sample ID	1	2	3
Dist. from top (mm)	6.0	15.0	25.0
^{238}U ppb[a]	347.47 ± 0.63	434.45 ± 0.92	334.58 ± 0.61
^{232}Th ppt	1245.2 ± 5.0	959.9 ± 4.9	704.6 ± 5.1
δ^{234}Umeasured	1457.9 ± 5.5	1341.2 ± 5.1	1320.3 ± 4.6
[^{230}Th/^{238}U] activity[c]	0.00652 ± 0.00014	0.00732 ± 0.00011	0.01021 ± 0.00013
[^{230}Th/^{232}Th] ppm[d]	30.0 ± 0.68	54.63 ± 0.89	79.9 ± 1.2
Age uncorrected	289.6 ± 6.5	341.4 ± 5.4	480.6 ± 6.3
Age corrected [c, e]	251.1 ± 20.3	316.4 ± 13.6	456.6 ± 13.6
δ^{234}U$_{\text{initial}}$ corrected[b]	1458.9 ± 5.5	1342.4 ± 5.1	1322.1 ± 4.6

Chemistry was performed on 8 July 2013 with the analysis method of Shen et al. (2003), and instrumental analysis on MC-ICP-MS (Shen et al., 2012). Analytical errors are 2σ of the mean.

[a] [^{238}U] = [^{235}U] × 137.818(±0.65 ‰) (Hiess et al., 2012) δ^{234}U = ([^{234}U/^{238}U]$_{\text{activity}}$ − 1) × 1000.

[b] δ^{234}U$_{\text{initial}}$ corrected was calculated based on ^{230}Th age (T), i.e., $\delta^{234}\text{U}_{\text{initial}} = \delta^{234}\text{U}_{\text{measured}} \times e^{\lambda 234 \times T}$, and T is corrected age.

[c] $[^{230}\text{Th}/^{238}\text{U}]_{\text{activity}} = 1 - e^{-\lambda 230 T} + (\delta^{234}\text{U}_{\text{measured}}/1000)[\lambda_{230}/(\lambda_{230} - \lambda_{234})](1 - e^{-(\lambda 230 - \lambda 234)T})$, where T is the age. Decay constants are 9.1705×10^{-6} yr^{-1} for ^{230}Th, 2.8221×10^{-6} yr^{-1} for ^{234}U (Cheng et al., 2013, EPSL), and 1.55125×10^{-10} yr^{-1} for ^{238}U (Jaffey et al., 1971).

[d] The degree of detrital ^{230}Th contamination is indicated by the [^{230}Th/^{232}Th] atomic ratio instead of the activity ratio.

[e] Age corrections for samples were calculated using an estimated atomic ^{230}Th/^{232}Th ratio of 4 ± 2 ppm. Those are the values for a material at secular equilibrium, with the crustal ^{232}Th/^{238}U value of 3.8. The errors are arbitrarily assumed to be 50 %.

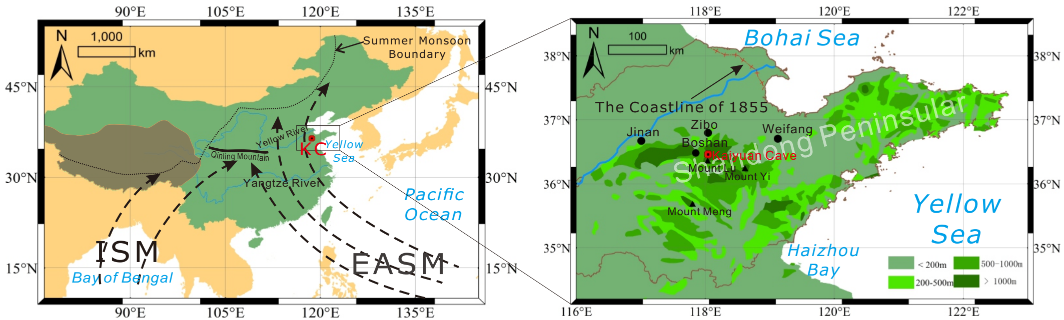

Figure 1. Location of Kaiyuan Cave and Shandong peninsula in monsoonal China. KC: Kaiyuan Cave (36°25′ N, 119°36′ E). The dashed black thin line indicates the northwestern boundary of the Asian summer monsoon. The dashed thick black lines with arrows indicate routes of the summer monsoon. The brown area is the Qinghai-Tibet Plateau.

CPD

11, 4643–4668, 2015

The climate reconstruction in Shandong Peninsula

Q. Wang et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

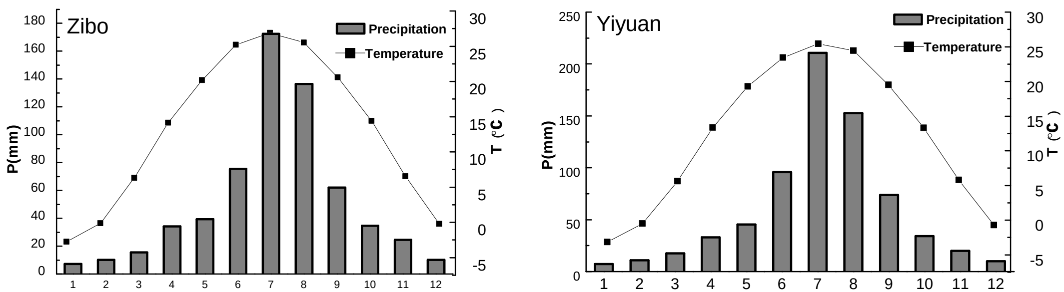

Figure 2. Monthly mean temperature (T) and precipitation (P) at Zibo Station (1952–1980) and Yiyuan (1958–2005) at Yiyuan Station, two meteorological stations close to the study site (Fig. 1).

CPD
11, 4643–4668, 2015

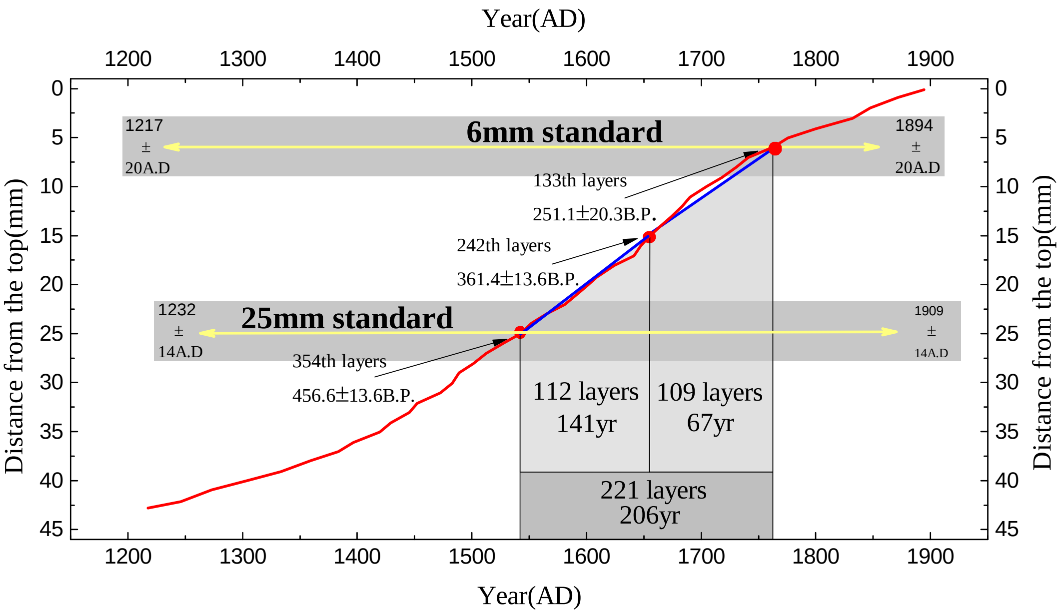

Figure 3. The age model for stalagmite ky1 established by the connection of lamina counting and linear interpolation/extrapolation based on the average growth rate between dated points. The blue line was the high precision dating results with U-^{230}Th technique and their connect lines. The red line was the age scale established by this article, the age of other laminas was determined by annually upward and downward counting based on the 133 lamina which was 1762 ± 20 AD that had known by high precision dating results with U-^{230}Th technique.

CPD
11, 4643–4668, 2015

Figure 4. Polished longitudinal cross-sections of stalagmites ky1.

CPD
11, 4643–4668, 2015

The climate reconstruction in Shandong Peninsula

Q. Wang et al.

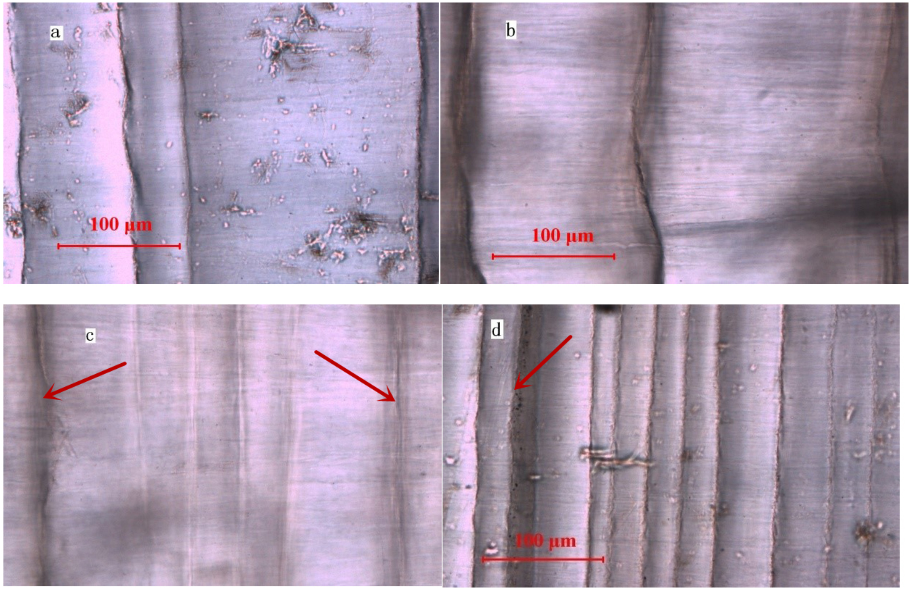

Figure 5. The characteristic of the nonopaque lamina in the upper part of stalagmite ky1, show that thickness of layers had obvious changed, the boundary was curved and the color near the boundary was deepened and the dark nonopaque lamina. Among, **(a)** thickness of layers had obvious changed; **(b)** the curve of the boundary of nonopaque lamina; **(c)** the color changing of the boundary of nonopaque lamina, the arrows indicate the darker boundaries, the boundary in the middle were whiter obviously; **(d)** dark nonopaque lamina (the arrows indicated in the figure).

CPD
11, 4643–4668, 2015

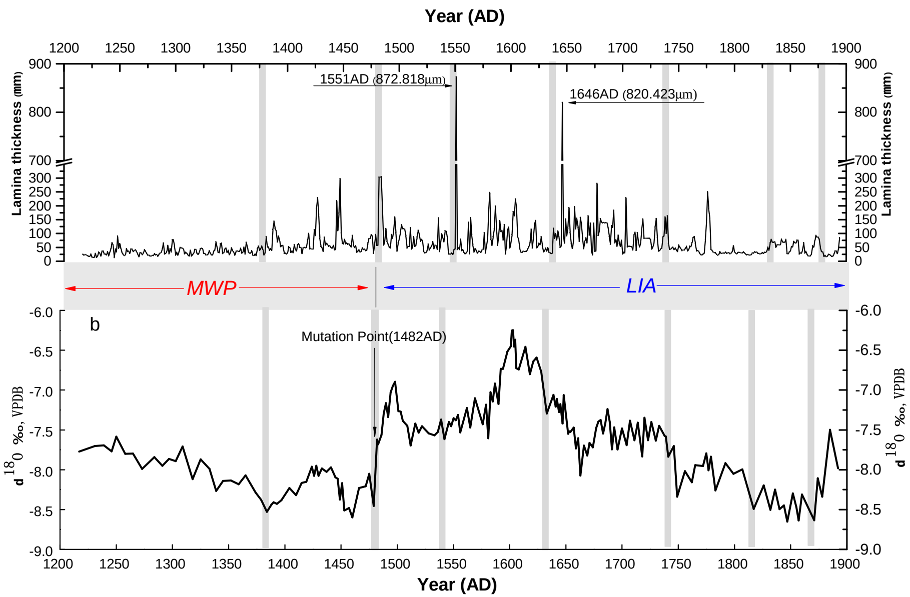

Figure 6. The formed year and thickness data series of the 678 layers in upper part (0–42.769 mm) of stalagmite ky1 **(a)** and the δ^{18}O value data series of 172 samples **(b)**. Among, the thickness of layers formed in 1551 and 1646 AD were up to 872.8183 and 820.4226 µm, they are much more higher than other layers, in order to reveal the total variation characteristic of layer thickness comprehensively, the figure was not determine the ordinate according to size of the two data and not show the two data in the curve, instead of indicated in the corresponding position respectively.

CPD
11, 4643–4668, 2015