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Age ranges of the Tibetan ice cores with emphasis on the Chongce ice cores, western Kunlun Mountains

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Two-parameter flow model (2p model)

The 2p model is based on a simple analytical expression for the decrease of the annual layer thickness $L_{(z)}$ (m w.e.) with depth:

$$L_{(z)}=b\left(1-\frac{z}{H}\right)^{p+1}$$

where z is depth (m w.e.), H the glacier thickness (m w.e.), b the annual accumulation (m w.e.) and p a thinning parameter (dimensionless). The age $T_{(z)}$ as a function of depth can be calculated when the inverse layer thickness is integrated over depth:

$$T_{(z)}=\int \frac{\mathrm{d}z}{L_{(z)}}=\frac{1}{b}\int\left(1-\frac{z}{H}\right)^{-p-1}$$

Solving the integral and setting the age at the surface to be T (0) = 0, the final age-depth relation is obtained:

$$T_{(z)}=\frac{H}{bp}\left[\left(1-\frac{z}{H}\right)^{-p}-1\right]$$

The thinning rate (vertical strain rate) is the first derivative of the layer thickness:

$$L'_{(z)}=\frac{\mathrm{d}L_{(z)}}{\mathrm{d}z}=-\frac{b(p+1)}{H}\left(1-\frac{z}{H}\right)^{p}$$

The model has two degrees of freedom, the net annual accumulation rate b and the thinning parameter p, both of which are assumed to be constant over time. This allows us to fit the model by a least squares approach through the available reference horizons if the glacier thickness H is known (if drilled to the bedrock) or can be reasonably well estimated (e.g. from radar sounding). In order not to overweigh the data from the deepest horizons, the model is fitted using the logarithms of the age values (Uglietti et al., 2016).

Age estimate at the ice-bedrock

We made use of the ^{14}C ages, the ^{210}Pb results and the tritium horizon of the Chongce 216.6 m Core 4 to establish the depth-age relationship down to the bedrock (Fig. S5). The derived age estimate just above the ice–bedrock contact (10 cm w.e. above) is $7.0\pm^{4.4}_{2.7}$ ka B.P.. At the ice-bedrock contact the estimated age is $8.3\pm^{6.2}_{3.6}$ ka B.P. Since the model approaches infinity as the depth gets close to bedrock, this bottom age was derived by assuming no further thinning with depth for the last 10 cm w.e.. The model derived annual accumulation rate is 248±36 mm w.e./year and the model derived age at the depth of the oldest ^{14}C sample is $4.3\pm^{1.5}_{1.1}$ ka B.P., both in good agreement with the accumulation rate of 280-300 mm w.e./year deduced from ^{210}Pb and tritium (Figs

2 and 3) and cal. ^{14}C age of 4.5±0.2 ka B.P.. This indicates reasonable reliability of the model results.

For the Chongce 135.8 m Core 2, a depth-age relationship using the 2p model was also attempted down to the bedrock (Fig. S6). In this case the model is constrained by the ^{14}C cal. ages and the β-activity horizon of the Chongce 58.8 m Core 3 (Fig. 2), assuming a similar depth-age relationship for the upper parts of Core 2 and Core 3, which is reasonable given that their drilling sites are only several meters apart (Fig. S2). Although the derived annual accumulation rate of 137±54 mm w.e./year is in good agreement with the 140 mm w.e./year derived from the β-activity horizon (Fig. 2), we find the model to be poorly constrained for this simulation. For instance, the derived age at the depth of the oldest ^{14}C sample is $9.1 \pm^{7.2}_{4.0}$ ka B.P., much older than the actual ^{14}C age (6.3±0.2 ka B.P.) at that depth. The large uncertainty (Fig. S6) further indicates that the model is poorly constrained. Given the close proximity between the Chongce 216.6 m Core 4 and the Chongce 135.8 m Core 2 and similar bottom altitude of their drilling sites, we used the estimated age at bedrock derived for the Chongce 216.6 m Core 4 as an additional constraint (Fig. S7). With the additional age constraint at the bottom, the 1σ confidence interval for the model is significantly reduced. The ice age at the bedrock for the Chongce 135.8 m Core 2 is thus estimated to be $9.0 \pm ^{7.9}_{3.6}$ ka B.P.. This seems to be a reasonable estimate considering 1) the so derived accumulation rate (103±34 mm w.e./year) is in relative agreement with the *β*-activity based estimate (140 mm w.e./year); and 2) the modeled age at the depth of the oldest ^{14}C sample is now $5.2 \pm ^{1.9}_{1.4}$ ka B.P., similar to the actual ^{14}C age of 6.3±0.2 ka B.P. given the uncertainty range. Although this result is far from satisfying, it is much better than the result obtained from the model without the additional bottom age constraint. However, more independent evidence, such as $\delta^{18}O$ of air in bubbles (Hou et al., 2004), might be very helpful to determine more precisely the age ranges of the ice cores.

The Kesang stalagmite core

The Kesang Cave is located in the Tekesi County, the western China (42°52′ N, 81°45′ E, ~2000 m a.s.l., Fig. 1). Eight samples from Kesang Cave were used to establish the Kesang $\delta^{18}O$ record with three covering the Holocene and five covering the rest of the

Pleistocene portion. The Kesang stalagmite $\delta^{18}O$ records characterize a dynamic precipitation history over most of the past 500,000 years (Cheng et al., 2012).

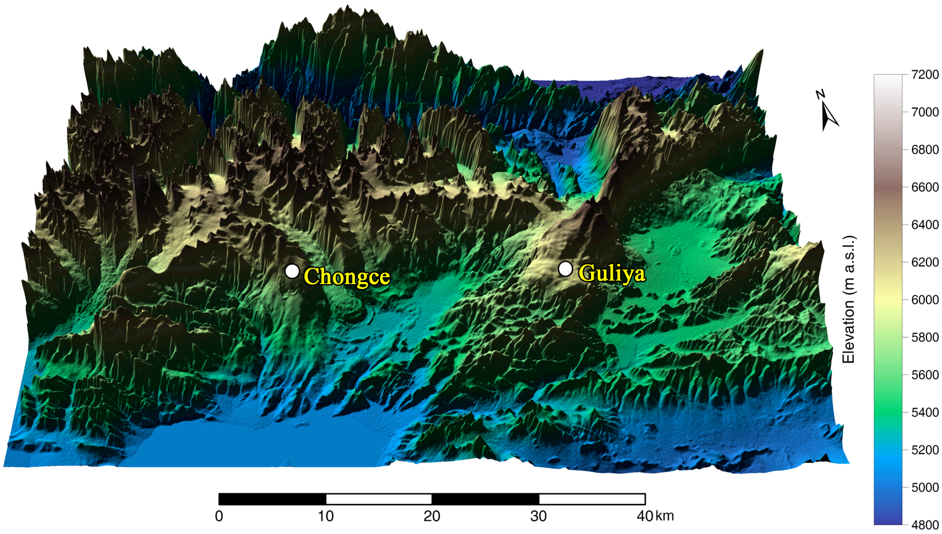

Figure S1: Three-dimensional topography for the locations of the Chongce and the Guliya ice caps. It was constructed from the Shuttle Radar Topography Mission (SRTM) digital elevation data, available from the Consultative Group for International Agricultural Research-Consortium for Spatial Information (CGIAR-CSI) at http://srtm.csi.cgiar.org/.

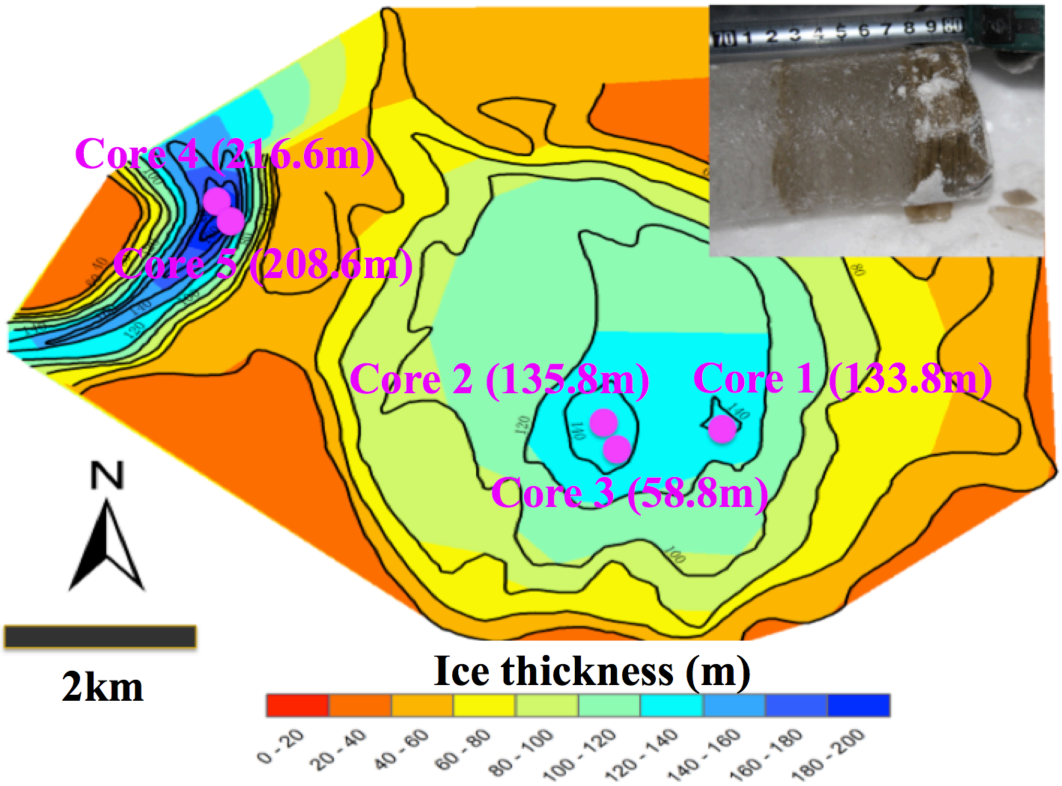

Figure S2: Map showing the ice thickness of the Chongce ice cap with drilling sites. Core 1 (133.8 m) and Core 2 (135.8 m) to bedrock and Core 3 (58.8 m) were drilled in 2012. Core 4 (216.6 m) and Core 5 (208.6 m) to bedrock were drilled in 2013. Inset picture shows the bottom section of Core 2. The ice thickness was measured by ground penetrating radar with relatively high accuracy. For instance, the thickness measured at the drilling site of the 216.6 m core is ~214 m.

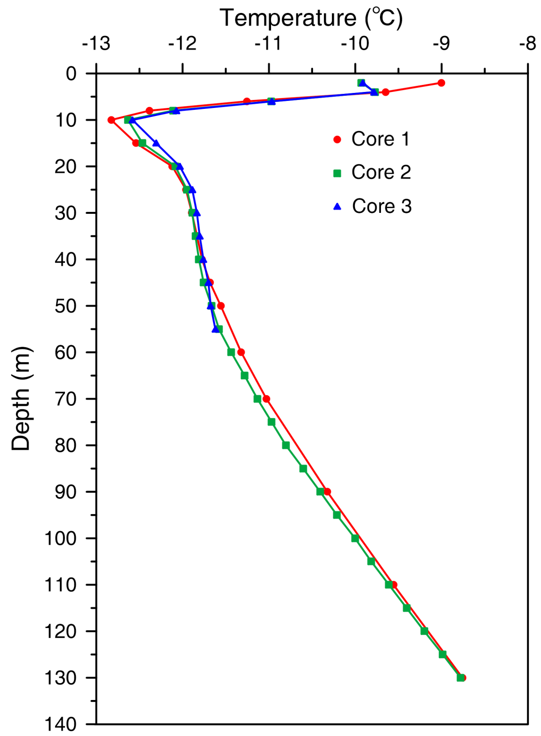

Figure S3: Borehole temperature profiles of the Chongce Core 1, Core 2 and Core 3.

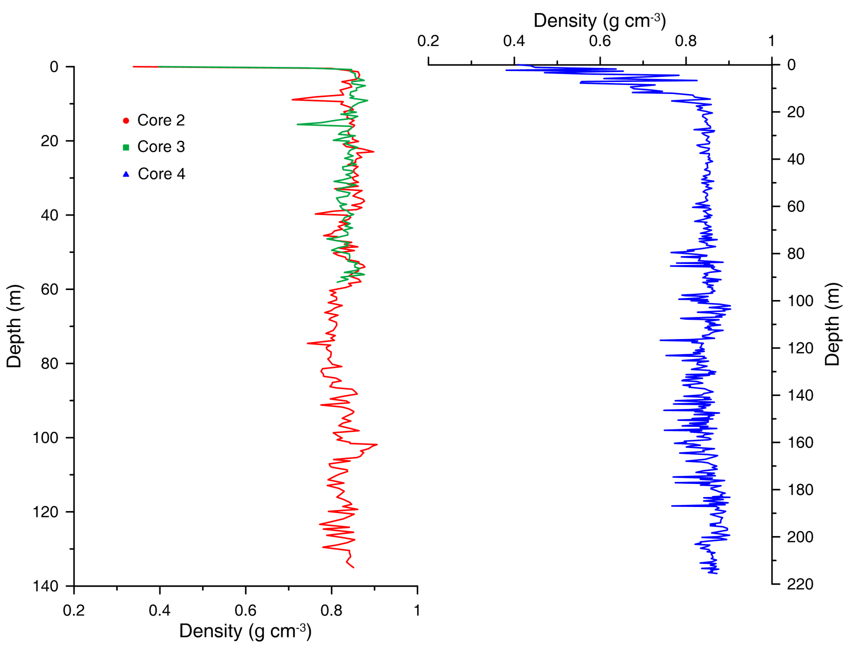

Figure S4: Density profiles of the Chongce Core 2, Core 3 and Core 4.

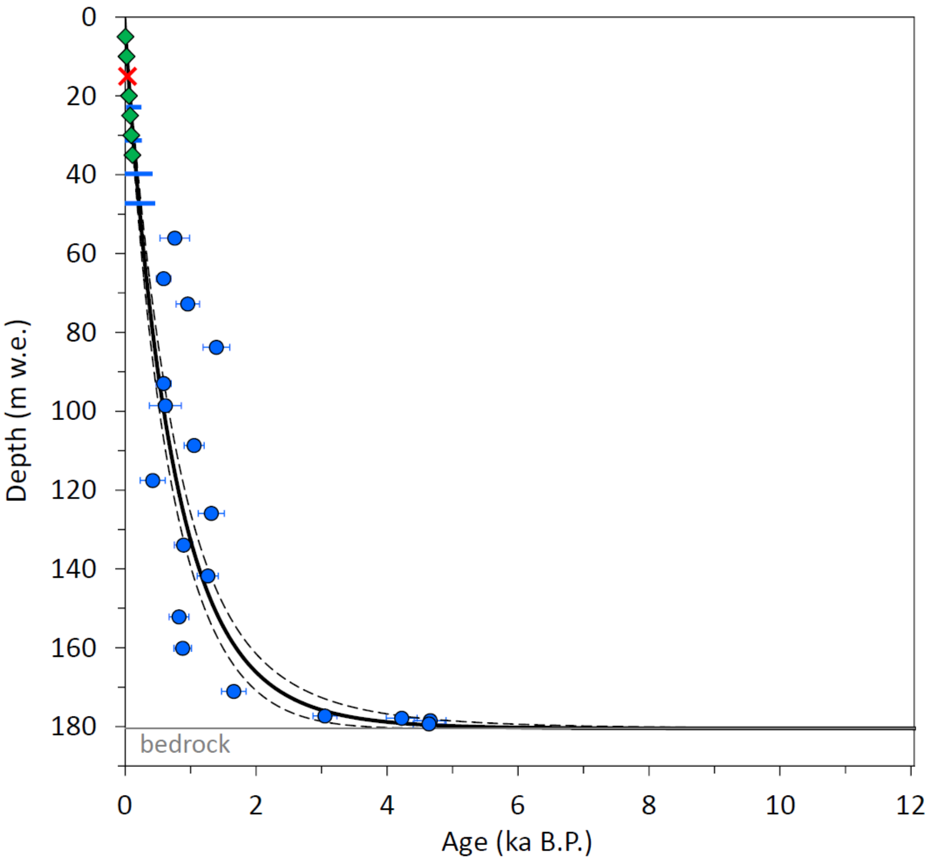

Figure S5: The depth-age relationship of the Chongce 216.6 m Core 4. The dashed lines represent the 1σ confidence interval of the 2p model fit (solid line). The red cross stands for the tritium horizon, green diamonds for the ^{210}Pb ages calculated at intervals of 5 m w.e. (Fig. 3), and the blue dots for the cal. ^{14}C ages with 1σ error bar.

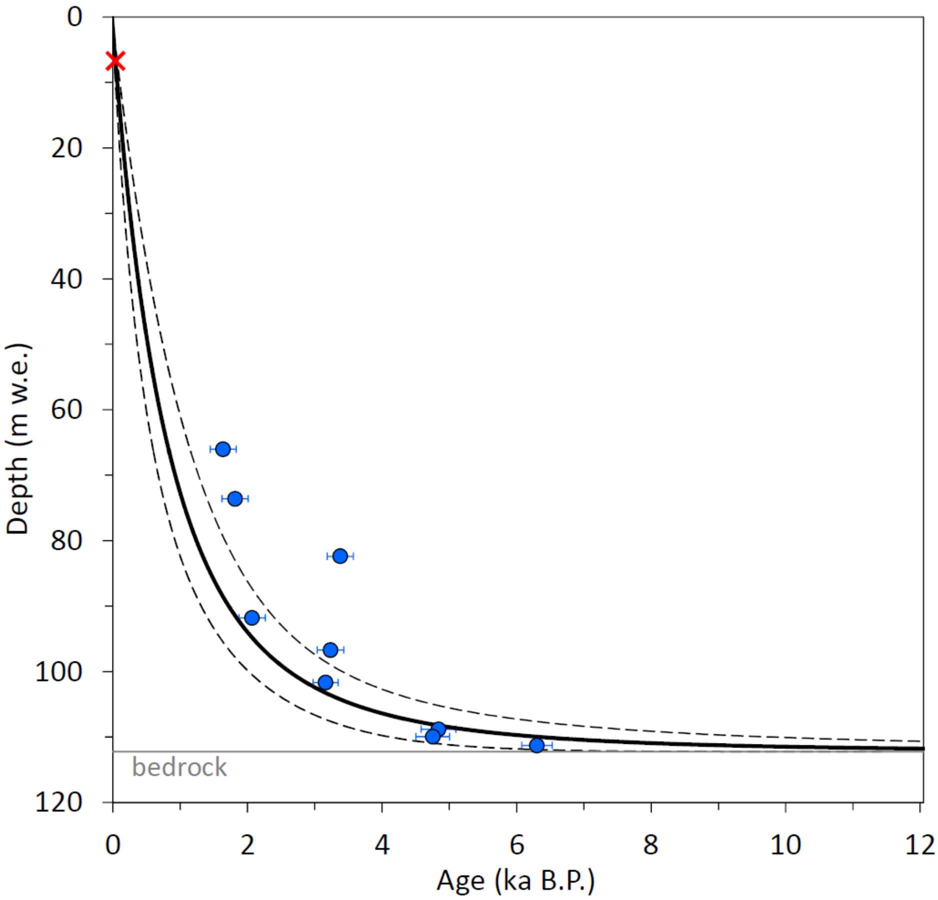

Figure S6: The poorly constrained depth-age relationship of the Chongce 135.8 m Core 2. The dashed lines represent the 1σ confidence interval of the 2p model fit (solid line). The red cross stands for the *β*-activity horizon (Fig. 2) and the blue dots for the cal. ^{14}C ages with 1σ error bars.

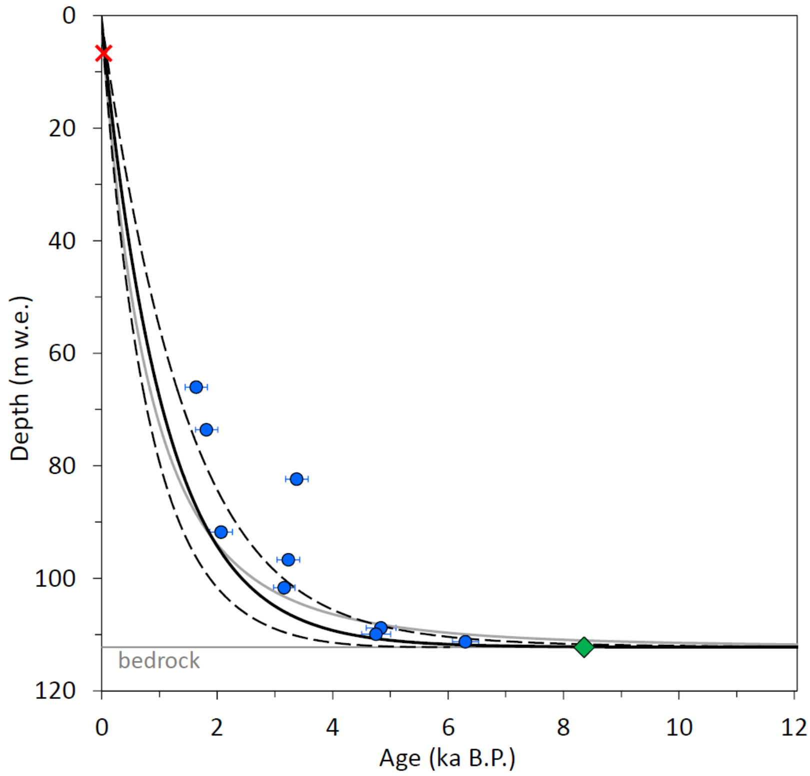

Figure S7: The depth-age relationship of the Chongce 135.8 m Core 2 using additional age constraint (i.e., age at bedrock estimated from the Chongce 216.6 m Core 4, green diamond). The dashed lines represent the 1σ confidence interval of the 2p model fit (solid line). The red cross stands for the β-activity horizon (Fig. 2) and the blue dots for the cal. ^{14}C ages with 1σ error bars. The grey line indicates the depth-age relationship derived without additional bottom age constraint. Please note that the ^{14}C data are all above the fitted line except the deepest point (green diamond) due to the strong thinning close to ice-bedrock contact.

Table S1. The ^{14}C dating of 216.6 m Chongce ice core. Absolute uncertainties are given as 1σ range.

Sample #	Depth (m)	Mass (g)	WIOC (μg)	$F^{14}C$	^{14}C age (ka B.P.)	Cal. age (ka B.P.)
CC-1	30.49-32	1178.5	49.8±3.8	1.00±0.01	0.002±0.010	0.025-0.26
CC-2	40.11-40.97	445.7	13.6±0.7	1.04±0.03	-0.297±0.236	0.013-0.269
CC-3	50.06-50.82	426.2	10.2±0.6	0.98±0.04	0.148±0.318	< 0.430
CC-4	58.88-59.72	464.1	22.0±1.2	0.97±0.02	0.248±0.154	< 0.470
CC-5	69.37-70.09	407.5	13.2±0.7	0.91±0.03	0.717±0.241	0.513-0.921
CC-6	81.41-82.52	312.2	18.6±1.6	0.94±0.01	0.537±0.129	0.479-0.667
CC-7	88.98-90.20	345.6	30.0±2.7	0.89±0.02	0.950±0.198	0.687-1.055
CC-8	102.13-102.85	479.2	16.6±0.9	0.84±0.02	1.418±0.193	1.090-1.548
CC-9	112.51-113.69	394.3	17.8±1.4	0.94±0.02	0.537±0.133	0.469-0.669
CC-10	119.13-120.53	386.1	17.9±1.5	0.93±0.03	0.576±0.261	0.310-0.781
CC-11	131.55-132.32	390.5	23.1±1.4	0.87±0.02	1.073±0.154	0.800-1.177
CC-12	142.33-142.95	316.4	15.1±1.0	0.95±0.03	0.374±0.211	< 0.629
CC-13	152.22-152.99	411.8	16.7±1.0	0.85±0.02	1.348±0.191	1.013-1.516
CC-14	161.93-162.66	432.2	21.6±1.3	0.89±0.02	0.892±0.154	0.679-0.935
CC-15	171.35-172.05	430.0	20.2±1.2	0.85±0.02	1.303±0.160	1.010-1.355
CC-16	183.46-184.16	411.8	20.6±1.2	0.91±0.02	0.800±0.172	0.567-0.920
CC-17	192.56-193.32	452.5	25.7±1.5	0.90±0.02	0.879±0.148	0.684-0.927
CC-18	205.38-205.99	343.3	18.9±1.1	0.81±0.02	1.673±0.174	1.394-1.805
CC-19	212.48-213.36	511.9	28.5±1.6	0.70±0.01	2.837±0.152	2.787-3.156
CC-20	213.36-214.10	382.6	24.6±1.4	0.62±0.01	3.778±0.167	3.930-4.413
CC-21	214.10-215.08	412.8	23.4±1.4	0.60±0.01	4.100±0.173	4.408-4.854
CC-22	215.08-216.03	367.1	23.6±1.4	0.60±0.01	4.086±0.172	4.360-4.846

Table S2. The ^{14}C dating of 135.8 m Chongce ice core. Absolute uncertainties are given as 1σ range.

Sample #	Depth (m)	Mass (g)	WIOC (μg)	$F^{14}C$	^{14}C age (ka B.P.)	Cal. age (ka B.P.)
CB-1	79.46-80.21	307.7	20.3±1.2	0.81±0.01	1.679±0.078	1.445-1.704
CB-2	88.82-89.56	302.9	24.3±1.4	0.80±0.01	1.831±0.138	1.572-1.921
CB-3	99.44-100.10	304.6	13.8±0.9	0.68±0.01	3.133±0.161	3.157-3.560
CB-4	110.58-111.35	342.6	24.9±1.4	0.78±0.01	2.037±0.142	1.827-2.296
CB-5	116.62-117.43	330.9	9.1±0.7	0.69±0.01	3.012±0.164	2.978-3.377
CB-6	122.64-123.36	338.6	17.6±1.1	0.69±0.01	2.944±0.157	2.892-3.331
CB-7	131.41-132.10	324.6	22.6±1.3	0.59±0.01	4.228±0.176	4.451-5.036
CB-8	132.65-133.51	392.7	23.6±1.4	0.60±0.01	4.169±0.175	4.424-4.951
CB-9	134.31-135.03	292.4	23.0±1.4	0.51±0.01	5.466±0.201	5.997-6.443