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

Shugui Hou[1,2], Theo M. Jenk[3,4], Wangbin Zhang[1], Chaomin Wang[1], Shuangye Wu[5], Yetang Wang[6], Hongxi Pang[1] and Margit Schwikowski[3, 4]

[1]School of Geographic and Oceanographic Sciences, Nanjing University, Nanjing, 210023, China.

[2]CAS Center for Excellence in Tibetan Plateau Earth Sciences, Beijing, 100101, China.

[3]Laboratory of Environmental Chemistry, Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland.

[4]Oeschger Centre for Climate Change Research, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland.

[5]Department of Geology, University of Dayton, Dayton, OH 45469, USA.

[6]College of Geography and Environment, Shandong Normal University, Jinan, 250358, China.

Correspondence to: Shugui Hou (shugui@nju.edu.cn)

Abstract. An accurate chronology is the essential first step for a sound understanding of ice core records, however, dating of ice cores drilled from the high elevation glaciers is challenging and often problematic, leading to great uncertainties. The Guliya ice core, drilled to bedrock (308.6 m in length) from the western Kunlun Mountains on the northwestern Tibetan Plateau (TP) and widely used as a benchmark for paleoclimate research, is believed to reach > 500 ka (thousand years) at its bottom. Meanwhile other Tibetan ice cores (i.e., Dasuopu and East Rongbuk in the Himalayas, Puruogangri in the central TP, and Dunde in the northeastern TP) are mostly of the Holocene origin. In this study, we drilled four ice cores to bedrock (216.6 m, 208.6 m, 135.8 m and 133.8 m in length, respectively) from the Chongce ice cap ~30 km from the Guliya ice core drilling site. We performed measurements of ^{14}C, ^{210}Pb, tritium and β-activity for the ice cores, and used these values in a two-parameter flow model to establish the ice core depth-age relationship. We suggested that the Chongce ice cores might be of Holocene origin, consistent to the other Tibetan ice cores except Guliya. The remarkable discrepancy between the Guliya and all the other Tibetan ice core chronology implies that more effort is necessary to explore multiple dating

techniques to confirm the age ranges of the TP glaciers, including those from Chongce and Guliya.

1 Introduction

Ice cores from the Tibetan Plateau (TP) provide a wealth of information for past climatic and environmental conditions that extends beyond the instrumental period (e.g., Thompson et al., 1989; 1997; 2000). An accurate chronology is the essential first step for a sound understanding of such ice core records. However, ice core dating is always a challenging task because seasonal signals suitable for annual layer counting are usually only observable in top sections of ice cores. For deeper (older) sections, annual cycles cannot be identified due to rapid thinning of ice layers. If sufficient organic matter (e.g., plant or insect fragments) is found inside the ice cores, the conventional radiocarbon (^{14}C) dating can be used (Thompson et al., 2002). Unfortunately, the presence of such material is far from guaranteed, which limits its application for ice core dating. Recently, a novel method was developed to extract water-insoluble organic carbon (WIOC) particles at microgram level from carbonaceous aerosol embedded in the glacier ice for Accelerator Mass Spectrometry (AMS) ^{14}C dating (Jenk et al., 2007; Uglietti et al., 2016). Carbonaceous aerosol is constantly transported to the glaciers, where it is deposited and finally incorporated in glacier ice. Consequently, carbonaceous aerosol in ice cores can provide reliable dating at any given depth when the samples contain sufficient carbon mass (> 10 μg). Here we applied this recently established technique for dating the Tibetan ice cores.

2 Chronology of previous ice cores

There are quite a few ice cores to the bedrock ever drilled from TP (Fig. 1). Below we review briefly information available about the bottom ages of these ice cores. Please refer to their original literatures for more details.

The Dunde ice cores: In 1987, three ice cores to bedrock (139.8 m, 136.6 m and 138.4 m in length) were recovered at an altitude of 5325 m a.s.l from the Dunde ice cap (38° 06′ N, 96° 24′ E) in the Qilian Shan on the northern TP (Fig. 1). Surface and basal borehole temperatures were -7.3 °C and -4.7 °C, respectively. The 2 ‰ shift in $\delta^{18}O$, concurrent with a sudden increase in dust concentration 14 m above the bedrock was interpreted as evidence of glacial-stage ice (Thompson et al., 1989). The core was extrapolated to 40 ka B.P. at the depth of 5 m above the bedrock by applying a two dimensional flow model, and was suggested to be potentially more than 100 ka B.P. at the ice-bedrock contact (Thompson et al., 1989). Later, Thompson et al. (2005) provided a single ^{14}C date of 6.24±0.33 ka B.P. for a sample collected close to the ice–bedrock contact (exact distance above the contact unavailable), and suggested the possibility that this core may be of Holocene origin.

The Guliya ice core: In 1992, a 308.6 m ice core to bedrock was recovered at an elevation of 6200 m a.s.l. from the Guliya ice cap (35° 17′ N, 81° 29′ E) in the western Kunlun Mountains on the northwestern TP (Fig. 1). The Guliya ice cap is surrounded by vertical ice walls 30 to 40 m high and has internal temperatures of -15.6 °C at 10 m, -5.9 °C at 200 m, and -2.1 °C at its base. Top 266 m of the Guliya core was dated to a period spanning 110 ka B.P., and the ice below 290 m was suggested to be >500 ka B.P., or to ~760 ka B.P. at the ice-bedrock contact based on ^{36}Cl-dead ice at the bottom section (Thompson et al., 1997).

The Dasuopu ice cores: In 1997, three ice cores were drilled from the Dasuopu glacier (28° 23′ N, 85° 43′ E) in the Himalayas. The first core (159.9 m in length) was drilled at an altitude of 7000 m a.s.l., and two more cores (149.2 and 167.7 m in length, respectively) were drilled to bedrock 100 m apart on the col at an altitude of 7200 m a.s.l. (Thompson et al., 2000). Borehole temperatures were -16 °C at 10 m and –13 °C at the ice/bedrock contact (Yao et al., 2002). The δ^{18}O record of the Dasuopu ice core lacks the 5 to 6 ‰ depletion that characterises glacial stage ice from the tropics to the polar regions (Yao et al., 2002). Furthermore, Dasuopu's basal ice does not contain as low as 0.4 ppmv (parts per million by volume) methane levels that characterise glacial ice in polar ice cores (Raynaud et al., 2000). Thus, it was suggested that the Dasuopu ice field accumulated entirely during the Holocene (Thompson et al., 2005).

The Puruogangri ice cores: In 2000, three ice cores (118.4 m, 214.7 m and 152 m in length) were recovered at an altitude of 6070 m a.s.l. from the Puruogangri ice cap (33° 55′ N, 89° 05′ E) on the central TP (Fig. 1). Borehole temperatures were –9.7 °C at 10 m and –5 °C at the ice/bedrock contact. The measured oldest ^{14}C date is 6.44±0.16

ka B.P. at 210.5 m depth of the 214.7 m ice core. The dating was extrapolated another 0.5 m further down to 7 ka B.P. (Thompson et al., 2006). The Puruogangri ice cores were suggested to be of Holocene origin (Thompson et al., 2005).

The East Rongbuk ice cores: In 2001, one ice core to bedrock (117.1 m in length) was drilled on the col of East Rongbuk Glacier (28º 1′ N, 86º 58′ E, 6518 m a.s.l.) on the north slope of Qomolangma (Mount Everest) in the Himalayas. In 2002, two more ice cores (108.8 m and 95.8 m in length, respectively) were drilled to bedrock nearby the previously drilling site. In a previous study, we matched the CH_4/ $\delta^{18}O_{atm}$ phase record of both the East Rongbuk 117.1 m and 108.8 m cores to the GRIP CH_4 and the GISP2 $\delta^{18}O_{atm}$ of the Greenland summit ice cores, and the results suggest a Holocene origin of the East Rongbuk ice cores (Hou et al., 2004).

The Grigoriev ice core: In 2007, an ice core to bedrock (86.87 m long) was recovered at an altitude of 4563 m a.s.l at the top of the Grigoriev ice cap (41° 59′ N, 77° 55′ E) in the west Tien Shan (Fig. 1). Borehole temperatures were was -2.7 °C at 10 m and –3.9 °C at the ice/bedrock contact. Takeuchi et al. (2014) suggested that the bottom age of the Grigoriev ice core coincides with the Younger Dryas cold period

(YD, 11.7 - 12.9 ka B.P.). However, the oldest ^{14}C age (12.58±0.10 ka) is obtained from a soil sample collected underneath the glacier, which should be considered as an upper constraint for the age of ice at the ice-bedrock contact.

3 The Chongce ice cores

In 2012, we drilled two ice cores to bedrock with length of 133.8 m (Core 1) and 135.8 m (Core 2) and a shallow core (Core 3) of 58.8 m at an altitude of 6010 m a.s.l. from the Chongce ice cap on the northwestern TP (35º14′ N, 81º7′ E; Fig. 1). The direct distance between the Chongce and the Guliya ice core drilling sites is ~30 km (Fig. S1). In 2013, two more ice cores were recovered to bedrock with the length of 216.6 m (Core 4) and 208.6 m (Core 5) at an altitude of 6100 m a.s.l. on the Chongce ice cap (35° 15′ N, 81° 5′ E). The detailed positions of the five Chongce ice cores are shown in Fig. S2. Borehole temperatures are -12.8 °C, -12.6 °C and -12.6 °C at 10 m depth for Core 1, Core 2 and Core 3, -8.8 °C and -8.8 °C at 130 m depth for Core 1 and Core 2, respectively (Fig. S3), suggesting that the Chongce ice cap is frozen to its bedrock. The Density profiles of the Chongce Core 2, Core 3 and Core 4 are shown in Fig. S4. All the ice cores were transported frozen to the cold room in the Nanjing University for further processing. The basal sediment collected from the bottom of Core 4 was measured for the first luminescence dating, resulting in an age of 42±4 ka B.P., which was regarded as an upper constraint for the age of the bottom ice at the drilling site (Zhang et al., 2018).

4 Measurements

^{14}C

We performed ^{14}C measurements on WIOC extracted from 22 samples collected discretely along the 216.6 m Chongce Core 4 and 9 samples along the 135.8 m Chongce Core 2, as well as 5 samples collected from the East Rongbuk 95.8 m ice core. The ^{14}C sample decontamination was performed at Paul Scherrer Institute by removing the ~3 mm outer layer with a bandsaw in a -20 °C cold room and rinsing with ultra-pure water in a class 100 laminar flow box. The WIOC fraction of carbonaceous particles in the sample was filtered onto freshly preheated quartz fiber filters (Pallflex Tissuquartz, 2500QAO-UP), then combusted stepwise (10 min at 340 °C; 12 min at 650 °C) using a thermal-optical carbon analyzer (Model4L, Sunset Laboratory Inc., USA) for separating organic carbon (OC) from elemental carbon (EC), and the resulting CO_2 was measured by the Mini Carbon Dating System (MICADAS) with a gas ion source for ^{14}C analysis at the University of Bern LARA laboratory. Details about sample preparation procedures and analytical methods can be found in previous studies (Jenk et al., 2007, 2009; Sigl et al., 2009; Uglietti et al., 2016). The overall procedural blanks were estimated using artificial ice blocks of frozen ultra-pure water, which were treated the same way as real ice samples. The average overall procedural blank is 1.34 ± 0.62 μg carbon with a $F^{14}C$ of 0.69 ± 0.13 (Uglietti et al., 2016). Conventional ^{14}C ages were calibrated using OxCal v4.2.4 software with the IntCal13 calibration curve (Bronk Ramsey and Lee, 2013; Reimer et al., 2013).

^{210}Pb

The accessible time range using radioactive isotope ^{210}Pb dating is ~150 years due to the 22.3-year half-life of ^{210}Pb, a product of the natural ^{238}U decay series. Here ^{210}Pb dating was performed on the Chongce 216.6 m Core 4, with a total of 52 samples collected from the depth of 0-76.6 m. Each sample (~100 - 200 g) was cut parallel to the drilling axis in a -20 °C cold room. The samples were processed according to the standard method established by Gäggeler et al. (1983). The samples were melted for 24 hours after adding 0.05% (V:V) analytical reagent HCl (30%). Afterwards, 100 μL ^{209}Po tracer was added to the solution to determine the yield of the separation. Spontaneous deposition of Po on an Ag disk (15 mm diameter), which was fixed on a wire and immersed in the liquid, was achieved during ~7 hours at 95 °C in 500 mL Erlenmeyer flasks using a magnetic stirrer. After drying, the disks were measured by α-counting at the Paul Scherrer Institute. The samples were positioned in vacuum chambers at a distance of 1mm from silicon surface barrier detectors (ORTEC, ruggedized, 300 and 450 mm^2) having an α-energy resolution of ~23 keV full width at half-maximum at 5.3 MeV. The yield of ^{209}Po tracer was measured via its 4.9 MeV α-line. Typical chemical yields were ~75%.

Tritium

Tritium measurements were performed on the Chongce 216.6 m Core 4, with 51 samples collected successively from the depth range of 6.7-11.8 m (corresponding to a sampling resolution of ~ 0.1 m per sample), and 42 samples from the depth range of 11.8-32.0 m (corresponding to a sampling resolution of ~ 0.5 m per sample). Each sample is ~10 g. Samples were analyzed at the Paul Scherrer Institute using liquid scintillation counting (TriCarb 2770 SLL/BGO, Packard SA). The detection limit for 3H measurements is <10 TU.

β-activity

Twenty-two samples were collected successively from top to the depth of 10.3 m of the Chongce 58.8 m Core 3. Each sample is ~1 kg. The β-activity was measured using Alpha-Beta Multidetector (Mini 20, Eurisys Mesures) at the National Key Laboratory of Cryospheric Sciences, China. More details can be found in An et al. (2016).

5 Results

The β-activity profile of the Chongce 58.8 m Core 3 is shown in Fig. 2a. A β-activity peak at the depth of 8.2-8.4 m was referenced as 1963 AD, while a second β-activity peak at the depth of 4.8-5.1 m was set as 1986 AD, corresponding to the 1986 Chernobyl nuclear accident. Both β-activity peaks were also observed in the Muztagata ice core from the eastern Pamir (Tian et al., 2007). The calculated mean annual accumulation rate is 140 mm w.e. (water equivalent) /year for the period of 1963–2012 AD.

The tritium profile of the Chongce 216.6 m Core 4 is shown in Fig. 2b. The tritium activity was corrected for decay to the time of deposition, because our purpose is to identify the apparent tritium peak (3237±89 TU) at the depth of 21.4 m. The depth of the sample with the highest activity was related to the year 1963, the year that the atmospheric test ban treaty was signed and tritium levels in precipitation began to decline gradually because of radioactive decay and the cessation of atmospheric testing (e.g. Kendall and Doctor, 2003). The calculated mean annual accumulation rate is 297 mm w.e./year for the period of 1963-2013 AD.

The ^{210}Pb activity profile of the Chongce 216.6 m Core 4 is shown in Fig. 3, which shows an exponential decrease as a function of depth in line with the radioactive decay law. The ^{210}Pb activity concentrations are in the range 7.5-317 mBq/kg, but keep relatively stable for the lower 16 samples, with an average of 11.2±2.1 mBq/kg (not shown). This average was taken as background ^{210}Pb (BGD) from the mineral dust contained in the ice core and was subtracted from the measured ^{210}Pb activity concentrations. From the linear regression of the logarithmic ^{210}Pb activities (BGD subtracted) against depth (Fig. 3), the value of the axis intercept (236±33 mBq/kg) corresponds to the ^{210}Pb activity at the surface of the Chongce ice cap. Following the widely applied approach described by Gäggeler et al. (1983), the ice age was derived using the constant initial concentration (CIC) model of equation (1). We calculated 1891±15 AD at the depth of 44.09 m (i.e. 34.36 m w.e.), resulting in a mean annual net accumulation rate of 280±47 mm w.e./year for the period of 1891-2013 AD. This value is in very good agreement with the 297 mm w.e./year for the period of 1963-2013 AD derived from the tritium profile of the same ice core (i.e., the Chongce 216.6 m Core 4, Fig. 2b).

$$t_s = \lambda^{-1} ln(\frac{C_0}{C_S}) \qquad (1)$$

Where, t_s stands for the age of ice at a certain depth with ^{210}Pb activities (subtracted) Cs, λ for the decay constant of ^{210}Pb (0.03114 a^{-1}), and C_0 for the ^{210}Pb surface activity.

The ^{14}C age profiles of the Chongce 216.6 m Core 4 and the 135.8 m Core 2 are shown in Figs 4 and 5, and the results are given in Tables S1 and S2, respectively. We initially collected the ^{14}C samples taking into consideration of the chronology of the Guliya ice core, but finally realized that most of the samples, especially those collected from the upper sections, are too young to be dated with an acceptable uncertainty. For instance, we obtained 1891±15 AD at the depth of 44.09 m from the ^{210}Pb measurements (Fig. 3), and the ^{14}C ages are 0.013-0.269 ka cal B.P. at the depth of 40.11-40.97 m, and modern to 0.430 ka cal B.P. at 50.06-50.82 m. Even though all obtained calibrated age ranges of the uppermost four samples include the expected ages based on the ^{210}Pb dating results, they have large uncertainties due to the young age and the relatively flat shape of the calibration curve in the past 500 yrs. Furthermore, anthropogenic contribution for samples younger than 200 yrs is likely introduce an old bias in ^{14}C ages due to fossil fuel (^{14}C dead) contribution (Jenk et al., 2006). Only 2% fossil contribution would shift the mean of the calibrated age ranges for these samples by up to 200 yrs towards younger ages, resulting in a smaller age range close to the ages estimated by ^{210}Pb dating. The ^{14}C age profile in the depth range of 80-180 m shows large scatter and no clear increase in age (Fig. 4). This is likely caused by the relatively young age of samples in combination with relatively large analytical uncertainties due to the presence of high mineral dust load in the Chongce ice core.

We made use of the ^{14}C ages (excluding the top four samples for the reasons discussed above), the ^{210}Pb results (Fig. 3), and the tritium horizon (Fig. 2) to establish the depth-age relationship for the Chongce 216.6 m Core 4 (Fig. 4), by applying a two-parameter flow model (2p model) (Bolzan, 1985 and Supplement). To avoid overfitting of the data and giving to much weight to individual data points, we prefer not to make assumptions about changes in accumulation, such as by applying a Monte-Carlo approach (Uglietti et al., 2016; Gabrielli et al., 2016). However, we understand that the 2p model, though widely used for establishing the ice core chronology including the Dunde (Thompson et al., 1989) and the Puruogangri (Thompson et al., 2006) ice cores, is limited and cannot account for the complex flow regimes close to the glacier bedrock. Therefore, we simply used the flow model to fit the dating points for obtaining a continuous age-depth scale. In order to make full use of the information available, we estimated the age at the ice-bedrock by extrapolating 2p model to the bedrock. The results of the bottom ages were provided in Supplement.

6 Discussion

We have notice the apparent incoherence between the depth-age relationship of Core 2 and Core 4, which may be caused by their surface topography, resulting in different accumulation rate at their respective drilling sites. The mean annual accumulation rate of Core 3 (several meters away from Core 2 drilling site) is calculated to be 140 mm w.e. /year for the period of 1963–2012 AD, while the mean annual accumulation rate of Core 4 is 297 mm w.e./year for the period of 1963-2013 AD. It is possible that the Core 4 drilling site may receive extra snow supplies, such as snow drifting, whereas part of the snow deposition at the Core 3 drilling site may be blown away due to wind scouring (Fisher et al., 1983). The impact of wind scouring on the ice core drilled from the Dasuopu summit was also suggested (Thompson et al., 2018). Nevertheless, a full understanding of this difference will require a long-term *in situ* observation that is unavailable at this moment.

It was previously suggested that the Himalayan ice cores (Dasuopu and East Rongbuk) were of Holocene origin (Thompson et al., 2005; Hou et al., 2004). The oldest cal. ^{14}C age for a sample collected down to the ice-bedrock contact of the East Rongbuk 95.8 m ice core, is 6.72±0.43 ka B.P., confirming its Holocene origin. The ice cores from Puruogangri in the central TP, and, to a less degree, Dunde in the northeastern TP are of Holocene origin, too (Thompson et al., 2005). For the Chongce ice cores, the measured oldest cal. ^{14}C ages are similar to what are measured for the East Rongbuk, Puruogangri and Dunde ice cores (Fig. 1). Our estimated ages at the ice-bedrock contact ($8.3\pm^{6.2}_{3.6}$ ka B.P. for the Chongce 216.6 m Core 4 and $9.0 \pm ^{7.9}_{3.6}$ ka B.P. for the Chongce 135.8 m Core 2 respectively, see details in Supplement) are either of Holocene origin, or, less possible, origin of late deglaciation period, similar to the result of the Grigoriev ice core in the west Tien Shan (Takeuchi et al., 2014). In both cases, the results confirm the upper constraint of 42±4 ka B.P. derived from the luminescence age of the basal sediment sample collected from the bottom of the Chongce 216.6 m Core 4 (Zhang et al., 2018).

It is apparent that the age range of the Guliya ice core is, at least, an order of magnitude older than that of the other Tibetan and the Tien Shan ice cores. Thompson et al. (2005) previously considered this as evidence that the growth (glaciation) and decay (deglaciation) of large ice fields in the lower latitudes are often asynchronous. However, our new understanding of the chronology of the Chongce ice cores suggests a similar age range of the ice cores in the western Kunlun Mountains in comparison to the other Tibetan cores. Though the validity of the Guliya chronology has been assumed since its publication (Thompson et al., 2005, 2017), Cheng et al. (2012) argued that the Guliya ice core chronology should be shortened by a factor of two in order to reconcile the difference in the $\delta^{18}O$ variations between the Guliya ice core and the Kesang stalagmite records (Fig. 1 and Supplement). Although, at this moment, we cannot give the final word on the age ranges of the Tibetan ice cores, it is necessary to explore more indepentant evidences to decipher the age dilemma of the ice cores from the western Kunlun Mountains on the northwestern TP.

We notice that, in 2015, a new Guliya ice core to bedrock (309.73 m in length) was drilled close to the location of the 1992 Guliya core drill site. Thompson et al. (2018) suggested that future analyses will include ^{14}C, ^{36}Cl, ^{10}Be, $\delta^{18}O$ of air in bubbles, and argon isotopic ratios ($^{40}Ar/^{38}Ar$) on deep sections of the new Guliya ice core to determine more precisely the age of the Guliya ice cap. We look forward to their new results.

7 Conclusions

We provided cal. ^{14}C ages and age estimation at the ice-bedrock contact of the Chongce ice cores drilled from the western Kunlun Mountains on the northwestern Tibetan Plateau, where exceptional length of the ice core record was previously suggested. Our results suggest that the age ranges of the Chongce ice cores is similar to the other Tibetan ice cores except the Guliya ice core, confirming the recent conclusion derived from the luminescence age of the Chongce ice core. The current work may has wide implications, such as whether or not existance of asynchronous glaciation on the Tibetan Plateau. Undoubtly, more effort is necessary to explore multiple dating techniques to confirm the ages of the Tibetan glaciers, including those from Chongce and Guliya.

Data availability. The ^{14}C data of the Chongce ice cores is provided in Supplement.

Author contribution. SH conceived this study, drilled the Chongce ice cores, and wrote the paper. CW, TMJ and MS measured the ^{14}C, ^{210}Pb, β-activity and tritium. All authors contributed to discussion of the results.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgments. Thanks are due to many scientists, technicians, graduate students and porters, especially to Yongliang Zhang, Hao Xu and Yaping Liu, for their great efforts in the high elevations, to Chiara Uglietti and Heinz Walter Gäggeler for help to measure the ^{14}C and the ^{210}Pb samples, to Guocai Zhu for providing the ground penetrating radar results and to Lonnie Thompson for providing the coordinates of the 1992 Guliya ice core drilling site. We are grateful to Paul Mayewski, Lonnie Thompson, an anonymous reviewer and the editor Joel Savarino for their constructive comments, which helped to improve the paper. This work was supported by the National Natural Science Foundation of China (41330526).

References

An, W., Hou, S., Zhang, W., Wu, S., Xu, H., Pang, H., Wang, Y., and Liu, Y.: Possible recent warming hiatus on the northwestern Tibetan Plateau derived from ice core records, Sci. Rep., 6, 32813, doi:10.1038/srep32813, 2016.

Bolzan, J.: Ice flow at the Dome C ice divide based on a deep temperature profile, J. Geophys. Res., 90, 8111-8124, 1985.

Bronk Ramsey, C. and Lee, S.: Recent and planned developments of the program Oxcal, Radiocarbon, 55, 720-730, doi:10.2458/azu_js_rc.55.16215, 2013.

Cheng, H., Zhang, P. Z., Spötl, C., Edwards, R. L., Cai, Y. J., Zhang, D. Z., Sang, W. C., Tan, M., and An, Z. S.: The climatic cyclicity in semiarid-arid central Asia over the past 500,000 years, Geophys. Res. Lett., 39, L01705, doi:10.1029/2011GL050202, 2012.

Fisher, D., Koerner, R., Paterson, W., Dansgaard, W., Gundestrup, N., and Reeh, N.: Effect of wind scouring on climatic records from ice-core oxygen-isotope profiles, Nature, 301, 205-209, doi: 10.1038/301205a0, 1983.

Gabrielli, P. et al.: Age of the Mt. Ortles ice cores, the Tyrolean Iceman and glaciation of the highest summit of South Tyrol since the Northern Hemisphere Climatic Optimum, The Cryosphere, 10, 2779–2797, doi:10.5194/tc-10-2779-2016, 2016.

Gäggeler, H., von Gunten, H., Rössler, E., Oeschger, H., andSchotterer, U.: ^{210}Pb-dating of cold Alpine firn/ice cores from Colle Gnifetti, Switzerland, J. Glaciol., 29, 165-177, 1983.

Hou, S., Qin, D., Jouzel, J., Masson-Delmotte, V., von Grafenstein, U., Landais, A., Caillon, N., and Chappellaz. J.: Age of Himalayan bottom ice cores, J. Glaciol. 50, 467-468, 2004.

Jenk, T., Szidat, S., Schwikowski, M., Gäggeler, H., Brütsch, S., Wacker, L., Synal, H., and Saurer, M.: Radiocarbon analysis in an Alpine ice core: record of anthropogenic and biogenic contributions to carbonaceous aerosols in the past (1650–1940), Atmos. Chem. Phys., 6, 5381–5390, doi:10.5194/acp-6-5381-2006, 2006.

Jenk, T., Szidat, S., Schwikowski, M., Gäggeler, H., Wacker, L., Synal, H., and Saurer, M.: Microgram level radiocarbon (^{14}C) determination on carbonaceous particles in ice, Nucl. Instrum. Methods Phys. Res. Sect. B, 259, 518-525, doi:10.1016/j.nimb.2007.01.196, 2007.

Jenk, T., Szidat, S., Bolius, D., Sigl, M., Gäggeler, H., Wacker, L., Ruff, M., Barbante, C., Boutron, C., and Schwikowski, M.: A novel radiocarbon dating technique applied to an ice core from the Alps indicating late Pleistocen ages, J. Geophys. Res., 114, D14, doi:10.1029/2009jd011860, 2009.

Kendall, C. and Doctor, D. H.: Stable isotope applications in hydrologic studies, Treatise on Geochemistry, 5, 319-364, doi:10.1016/B0-08-043751-6/05081-7, 2003.

Raynaud, D., Barnola, J., Chappellaz, J., Blunier, T., Indermühle, A., and Stauffer, B.: The ice core record of greenhouse gases: a view in the context of future changes, Quat. Sci. Rev., 19, 9–17, 2000.

Reimer, P., Bard, E., Bayliss, A., Beck, J., Blackwell, P., Ramsey, C., Buck, C., Cheng, H., Edwards, P., Friedrich, M., Grootes, P., Guilderson, T., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T., Hoffmann, D., Hogg, A., Hughen, K., Kaiser, K., Kromer, B., Manning, S., Niu, M., Reimer, R., Richards, D., Scott, E., Southon, J., Staff, R., Turney, C., and van der Plicht, J.: IntCal13 and Marine13 radiocarbon age calibration curves 0-50,000 years cal B.P., Radiocarbon, 55, 1869-1887, doi:10.2458/azu_js_rc.55.16947, 2013.

Sigl, M., Jenk, T., Kellerhals, T., Szidat, S., Gäggeler, H., Wacker, L., Synal, H., Boutron, C., Barbante, C., Gabrieli, J., and Schwikowski, M.: Towards radiocarbon dating of ice cores, J. Glaciol., 55, 985-996, doi:10.3189/002214309790794922, 2009.

Takeuchi, N., Fujita, K., Aizen, V., Narama, C., Yokoyama, Y., Okamoto, S., Naoki, K., and Kubota, J.: The disappearance of glaciers in the Tien Shan Mountains in Central Asia at the end of Pleistocene, Quat. Sci. Rev., 103, 26-33, doi:10.1016/j.quascirev.2014.09.006, 2014.

Thompson, L. G., Mosley-Thompson, E., Davis, M., Bolzan, J., Dai, J., Klein, L., Yao, T., Wu, X., Xie, Z., and Gundestrup, N.: Holocene-late pleistocene climatic ice core records from Qinghai-Tibetan Plateau, Science, 246, 474-477, doi:10.1126/science.246.4929.474, 1989.

Thompson, L. G., Yao, T., Davis, M. E., Henderson, K. A., Mosley-Thompson, E., Lin, P.-N., Beer, J., Synal, H.-A., Cole-Dai, J., and Bolzan, J.F.: Tropical climate instability: the last glacial cycle from a Qinghai-Tibetan ice core, Science, 276, 1821-1825, doi: 10.1126/science.276.5320.1821, 1997.

Thompson, L. G., Yao, T., Mosley-Thompson, E., Davis, M., Henderson, K., and Lin, P.: A high-resolution millennial record of the south Asian monsoon from Himalayan ice cores, Science, 289, 1916-1919, 2000.

Thompson, L. G., Mosley-Thompson, E., Davis, M., Henderson, Brecher, H., Zagorodnov, V., Mashiotta, T., Lin, P., Mikhalenko, V., Hardy, D., and Beer, J.: Kilimanjaro ice core records: evidence of Holocene climate change in tropical Africa, Science, 298, 589-593, 2002.

Thompson, L. G., Davis, M., Mosley-Thompson, E., Lin, P., Henderson, K., and Mashiotta, T.: Tropical ice core records: evidence for asynchronous glaciation on Milankovitch timescales, J. Quat. Sci., 20, 723-733, 2005.

Thompson, L. G., Yao, T., Davis, M., Mosley-Thompson, E., Mashiotta, T., Lin, P., Mikhalenko, V., and Zagorodnov, V.: Holocene climate variability archived in the Puruogangri ice cap on the central Tibetan Plateau, Ann. Glaciol., 43, 61-69, 2006.

Thompson, L.: Past, present, and future of glacier archives from the world's highest mountains, Proc. Am. Philos. Soc., 161, 226-243, 2017.

Thompson, L., Yao, T., Davis, M., Mosley-Thompson, E., Wu, G., Porter, S., Xu, B., Lin, P., Wang, N., Beaudon, E., Duan, K., Sierra-Hernández, M., and Kenny, D.: Ice core records of climate variability on the Third Pole with emphasis on the Guliya ice cap, western Kunlun Mountains, Quat. Sci. Rev., 188, 1-14, doi:10.1016/j.quascirev.2018.03.003, 2018.

Tian, L., Yao, T., Wu, G., Li, Z., Xu, B., and Li, Y.: Chernobyl nuclear accident revealed from the 7010 m Muztagata ice core record, Chin. Sci. Bull., 52, 1436-1439, doi: 10.1007/s11434-007-0188-y, 2007.

Uglietti, C., Zapf, A., Jenk, T., Sigl, M., Szidat, S., Salazar, G., and Schwikowski, M.: Radiocarbon dating of glacier ice: overview, optimisation, validation and potential, The Cryosphere 10, 3091-3105, doi:10.5194/tc-10-3091-2016, 2016.

Yao, T., Duan, K., Xu, B., Wang, N., and Pu, J.: Temperature and methane changes over the past 1000 years recorded in Dasuopu glacier (central Himalaya) ice core, Ann. Glaciol., 35, 379–383, 2002.

Yao, T., Masson-Delmotte, V., Gao, J., Yu, W., Yang, X., Risi, C., Sturm, C., Werner, M., Zhao, H., He, Y., Ren, W., Tian, L., Shi, C., and Hou, S.: A review of climatic controls on $\delta^{18}O$ in precipitation over the Tibetan Plateau: Observations and simulations, Rev. Geophys., 51, 525–548, doi:10.1002/rog.20023, 2013.

Zhang, Z., Hou, S., and Yi, S.: The first luminescence dating of Tibetan glacier basal sediment, The Cryosphere, 12, 1-6, doi:10.5194/tc-12-1-2018, 2018.

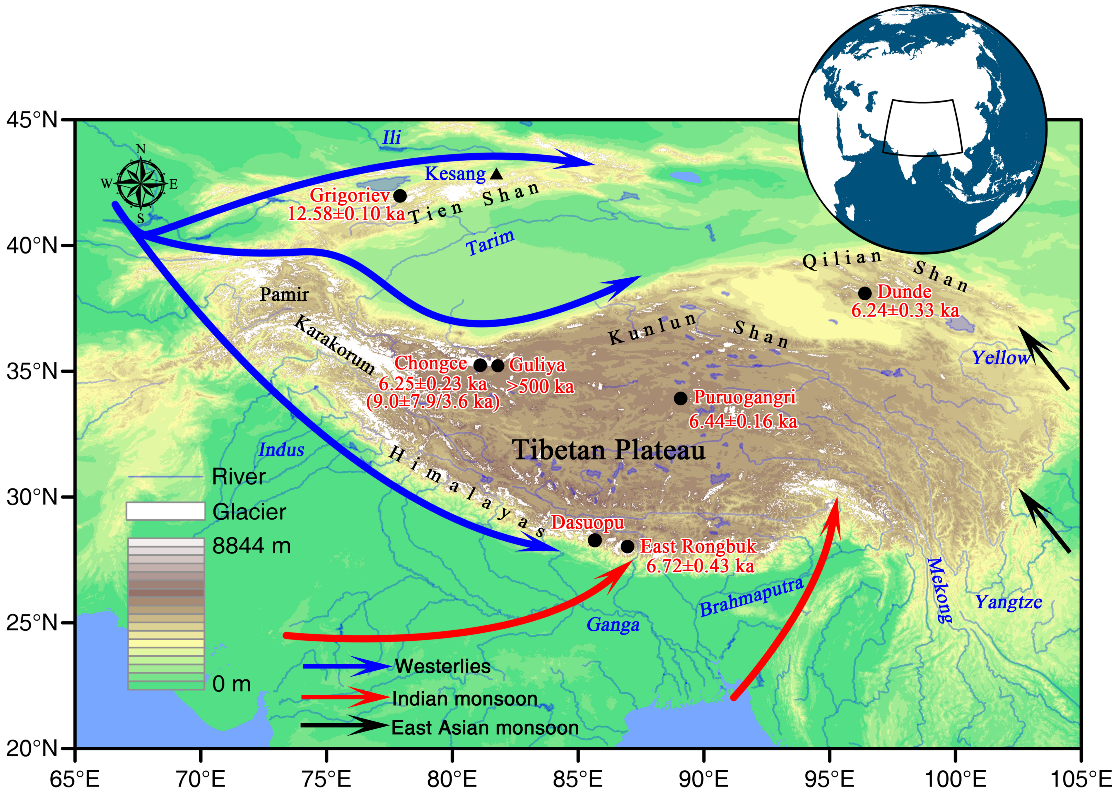

Figure 1: Map showing the locations of ice core drilling sites. The numbers for each site except Guliya are the measured oldest ^{14}C ages, while the number inside the bracket below the Chongce site is the estimated ice age at the ice-bedrock contact. The schematic positions of the westerlies and the monsoon circulations are from Yao et al. (2013). Data of glaciers are from the Global Land Ice Measurements from Space (GLIMS, available at http://www.glims.org). The topographic data were extracted using ETOPO1 elevations global data, available from National Oceanic and Atmospheric Administration at http://www.ngdc.noaa.gov/mgg/global/global.html.

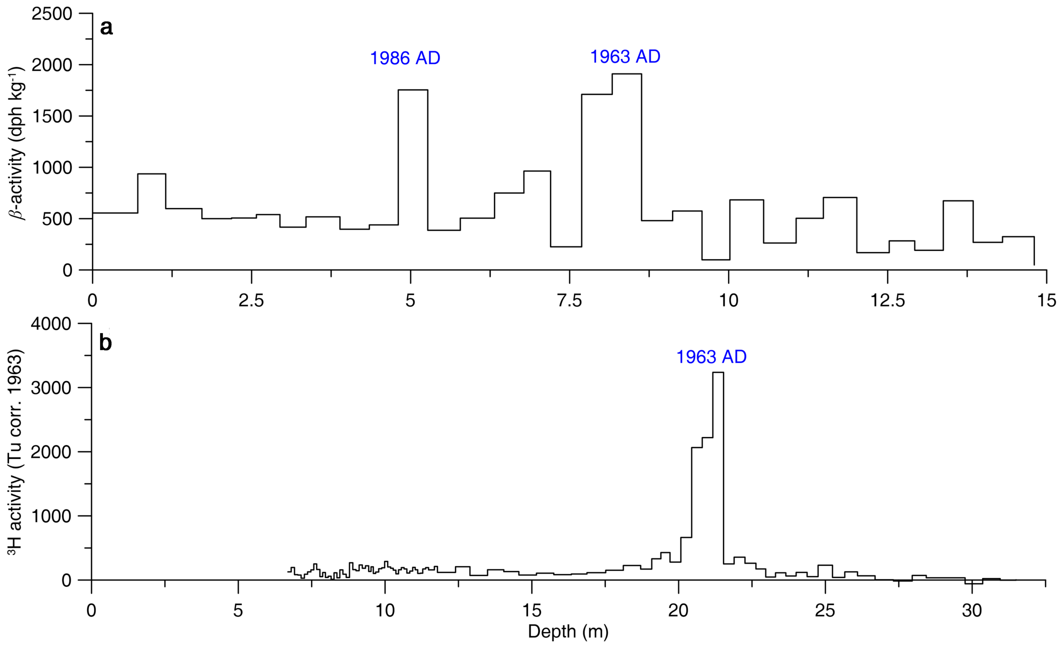

Figure 2: The β-activity profile of the Chongce 58.8 m Core 3 (a) and the tritium (corrected for the decay) profile of the Chongce 216.6 m Core 4 (b). TU (tritium units) is one tritium atom/1018 hydrogen atoms.

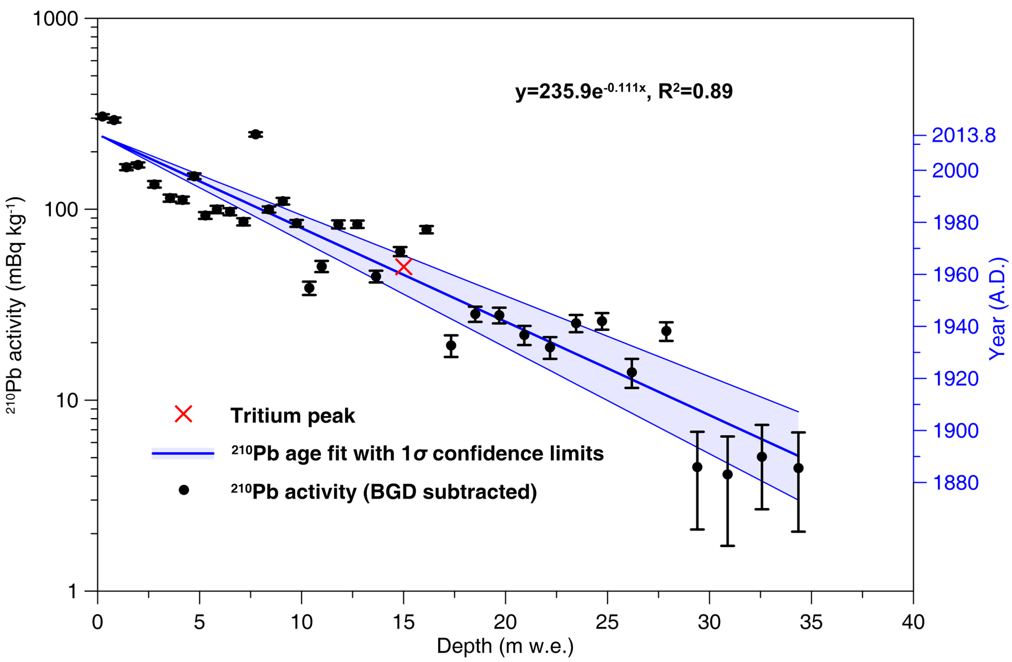

Figure 3: ^{210}Pb activity profile of the Chongce 216.6 m Core 4 and the derived age-depth relationship. The ^{3}H fallout horizon indicating the year 1963 A.D. is located within the uncertainty of the ^{210}Pb results. Please note that the 1 σ confidence band is related to the right hand y-axis only.

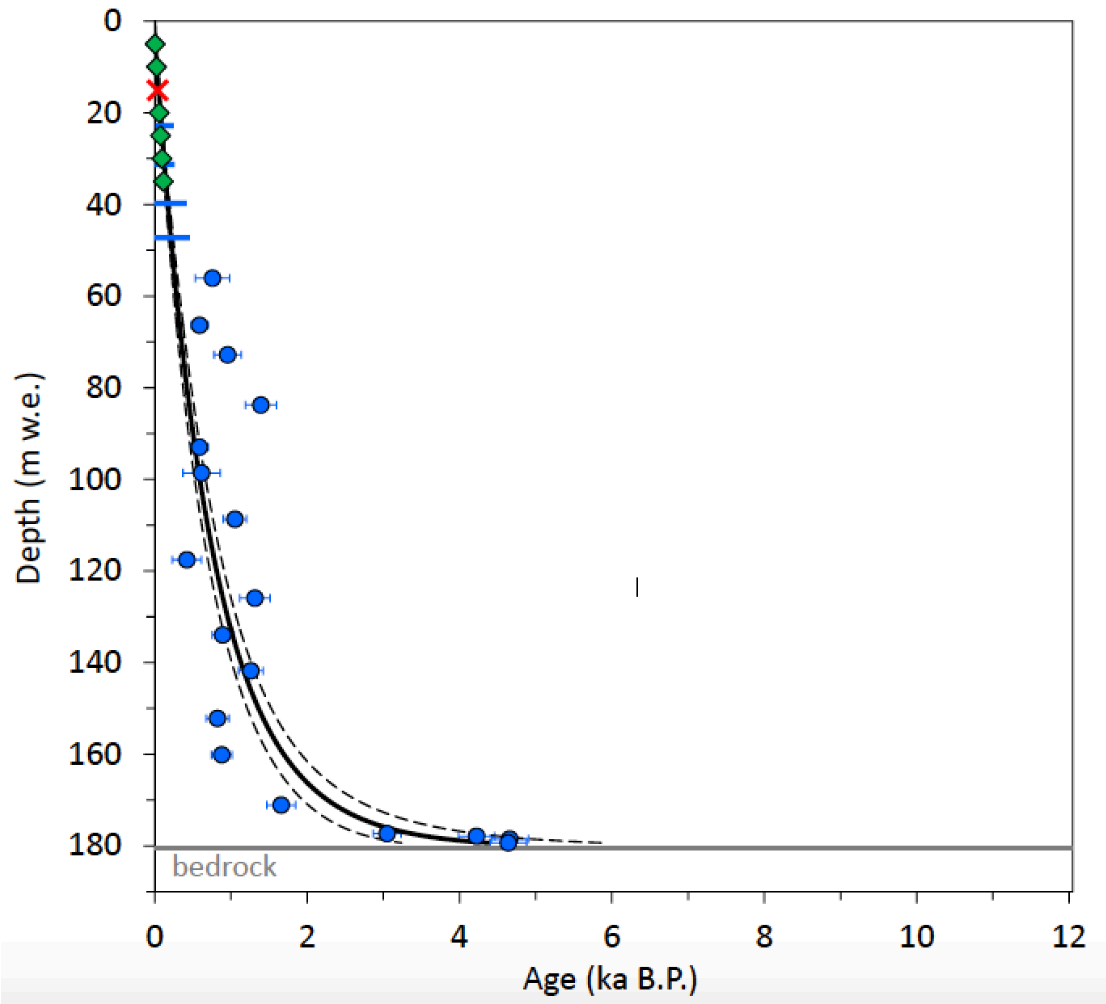

Figure 4: The depth-age relationship of the Chongce 216.6 m Core 4. The dashed lines represent the 1 σ confidence interval of the 2p model fit (solid line). The red cross stands for the tritium horizon, green diamonds for the ^{210}Pb ages calculated at intervals of 5 m w.e. (Fig. 3), and the blue dots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

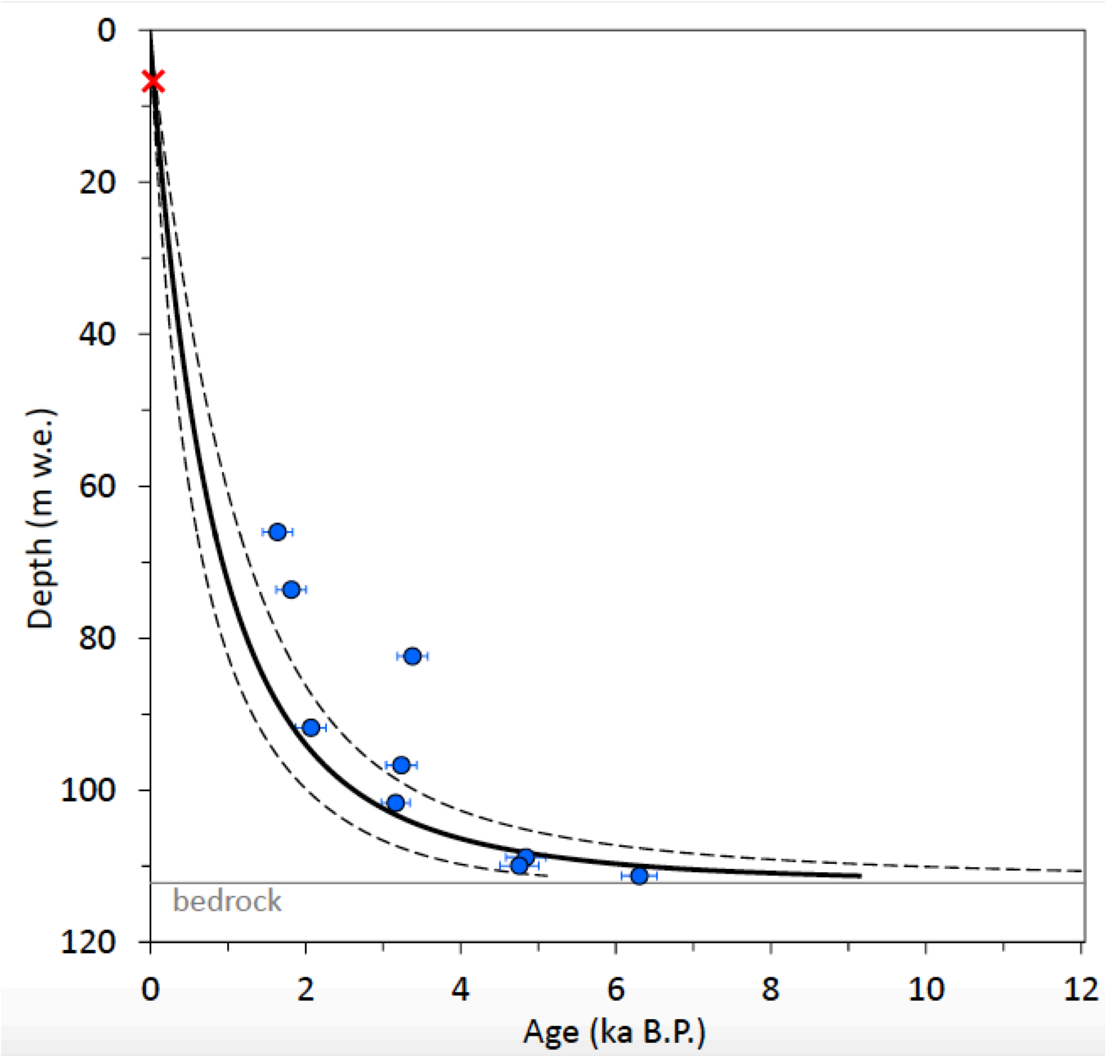

Figure 5: The depth-age relationship of the Chongce 135.8 m Core 2. The dashed lines represent the 1σ confidence interval of the 2p model fit (solid line). The red cross stands for the β-activity horizon (Fig. 2) and the blue dots for the cal. ^{14}C ages with 1σ error bars.