

Dear Referee,

Many thanks for your constructive comments. Below a point-to-point response to the comments. The comments are in black, and our response is in blue.

This manuscript brings new valuable information about the Chongse glacier ice core extracted in Tibet that can be published in TC by making major corrections with a neutral review and comparison with other tibetan sites. However, the author needs to clarify his objectives. If through the information of Chongse, the author seeks to discredit the information extracted from other sites like that from Guliya ice core without bringing new, precise and concrete information on this same site, because Guliya doesn't fit with his conclusion, the manuscript has to be rejected.

Response: We thank the reviewer for the positive viewpoint of our results. We have to say that, from the beginning, it is beyond our intention to discredit the chronology of the Guliya ice core. In fact, we had initially been inspired by the exceptional length of the Guliya core to drill the nearby Chongce ice cores. This is also the reason for us to collect a total of 22 samples from the longest Chongce core (216.6 m Core 4) for ^{14}C measurement, by sampling from as shallow as 30.49 m depth to the bottom (0.57 m above the ice-bedrock contact).

When we got the cal. ^{14}C ages of these 22 samples, we were puzzled by the results that the measured oldest cal. ^{14}C age is only 4.59 ± 0.24 ka B. P.. Moreover, several samples from the upper ice core sections are, in fact, not ideal for ^{14}C measurements due to their relatively

young ages of around ~1 ka or younger (see discussion in lines 203-214 and Fig. 4 in our TCD manuscript). Afterwards, we collected 9 samples from the Chongce 135.8 m Core 2 by sampling from 79.46 m depth to the bottom (0.77 m above the ice-bedrock contact). Although the measured oldest cal. ^{14}C age (6.25 ± 0.23 ka B. P.) is slightly older than that of Core 4, it is apparent that the measured oldest cal. ^{14}C ages for both the Chongce Core 2 and Core 4, as well as other Tibetan ice cores except Guliya (i.e., Dunde, Puruogangri, East Rongbuk, Fig. 1), fall within a similar age range.

To meet the reviewer's comments for "a neutral review and comparison with other tibetan sites", we would like to change the title from "Age of the Tibetan ice cores" to "Age ranges of the Tibetan ice cores with emphasis on the Chongce ice cores, western Kunlun Mountains".

We would also like to present, in a neutral way, the results of the Chongce ice cores, the results of other Tibetan ice cores from their original literatures, the remarkable age range difference of the Guliya and other Tibetan ice cores, and finally to conclude that "more effort is necessary to explore multiple dating techniques to confirm the ages of the TP glaciers, including those from Chongce and Guliya" (Thompson, 2018a).

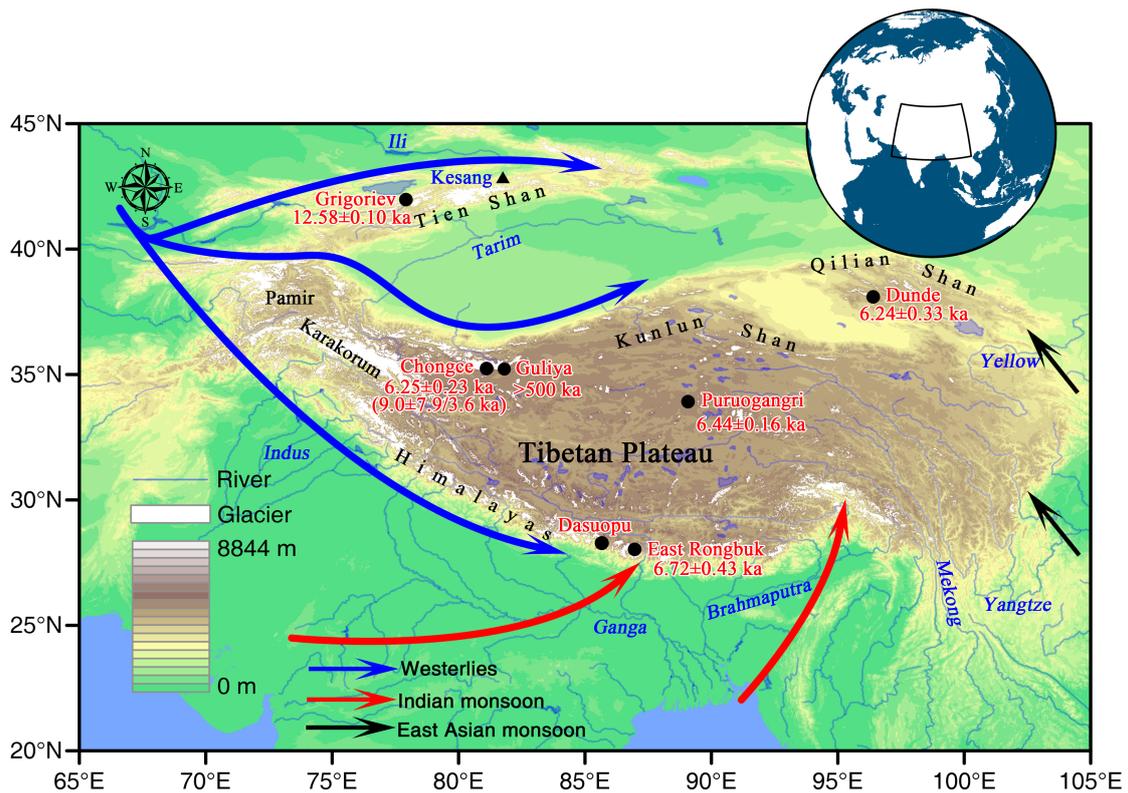


Fig. 1. Map showing the locations of ice core drilling sites. The numbers for each site except Guliya are the measured oldest ^{14}C ages, while the number inside the bracket below the Chongce site is the estimated ice age at the ice-bedrock contact. The schematic positions of the westerlies and the 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>.

General comments

In this manuscript, Hou et al. presents preliminary results of dating a new ice cores extracted from the Chongce glacier in Tibet. Based on three radiogenic dating methods (^3H , ^{210}Pb , and

^{14}C), the cores extracted from two different sites on the glacier would preserve samples dating as far back as the Holocene. This conclusion is mainly based on the deepest samples dating using a robust ^{14}C dating method extracted from WIOC. The extrapolated dating on bedrock age is based on a simple 2-p flow model. The second discussion of this manuscript concerns the comparison of the various ice cores extracted in this Himalayan region and in particular the maximum age preserved in these archives. The author argues that since the majority of these archives, including Chongse, do not preserve more than Holocene ice, the particular site of Guliya displaying 700ky must be questioned.

General comments on both main manuscript sections:

1) Chongse ice cores dating: Chongse ice cores were dated using three different radiogenic methods, ^3H , ^{210}Pb and ^{14}C covering different age scales with their own limitations. All methods were applied and results used in an adequate way for their interpretation. ^{14}C method based on WIOC extraction allows to date quasi continuously over the oldest part of the core, reaching an age of 7.0 ka ten centimeters above bedrock for deepest core (C4). At this stage of the dating, the use of a very simplistic model 2-p does not bring complementary information in view of the uncertainties related to the parametrization like constant accumulation over time. Using the maximum age of C4 to constrain the C2 model is not appropriate. What seems to be ignored in the manuscript concerns the difference in ^{14}C age obtained between C4 and C2 at intermediate depths, between 2 and 4 ka on C2 (60-110m we) whereas they have rather 0.5-2ka on C4 (80-175m we). These data would rather show that there is no coherence between the two cores and that their records are discontinuous.

Considering the data that appears to be available (surface and bedrock topography, surface flow velocity, temperature profile), the application of a 2D or 3D flow model should help to constrain the conclusions on the dating of ice layers.

Response: We agree that the two dimensional flow 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. We have to point out that it is always a challenge to model the glacier bottom regime very close to bedrock, and the application of a more complex 2D or 3D glacier flow model faces a similar difficulty for dating the glacier bottom ice due to its very complex behavior without constraints (e.g. Luthi and Funk, 2000).

In our approach, the flow model is simply used to obtain a continuous age-depth scale by fitting to the dating points. Regarding the available age constraints and the uncertainties of the individual dating points we refrained from applying a more sophisticated fitting procedure that would allow, for instance, changes in accumulation over time in order not to over fit (or over interpret) the available data points. Based on the chosen approach, the age constrained 2p-model results in a reasonable fit. The derived average annual accumulation rate is similar to the values obtained from the $^3\text{H}/\beta$ -activity peak and the ^{210}Pb dating methods. This suggests that the underlying assumptions of this approach seem reasonable. In any case, more independent constraints are needed to improve the present results.

Regarding the extrapolation to the very bedrock and the constrain of the age model for Core 4 using information from Core 2, we fully agree, that this approach is far from satisfactory, as we already discussed in the manuscript. We decided to use this additional constraint in order

to get the most reasonable age estimate combining all available dating information we have got from both Chongce cores. The limitation of this approach was appropriately reflected in the large uncertainties of the age estimates and discussed accordingly. However, we do understand the reviewer's concerns. Since we have cal. ^{14}C ages very close to the bottom of both cores, which are in agreement with each other and in-line with the general discussion and conclusions of the paper, we thus decided to remove this approach from the revised version of the manuscript as no significant loss in information will result. Nevertheless, to make full use of the information available, this part will instead be moved to the supplement. In any case, independent evidence such as stable isotopes might be very helpful, which is under way for the Chongce ice cores.

The incoherence between Core 2 and Core 4 may be caused by their surface topography, resulting in different accumulation rate at their drilling sites. Based on the β -activity reference of 1963 AD, the mean annual accumulation rate of Core 3 (several meters away from Core 2 drilling site) is calculated to be 140 mm w.e. (water equivalent) /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., 2018b). Nevertheless, a full understanding of this difference will require a long-term *in situ* observation that is unavailable at this moment. Further, a possible explanation for the determined ages at intermediate depths of Core 2 was discussed in the

manuscript (lines 203-214). Generally for the ^{14}C dating by WIOC, it is not recommended to discuss individual dating points. With the accumulation of Core 4 being approximately twice as high compared to Core 2, the ages of around $\sim 1.7 \pm 0.2$ ka for Core 4 seem to be not perfect but still in agreement with the ages determined for Core 2 when considering the uncertainties. The single data point of $\sim 3.3 \pm 0.2$ ka in Core 4 is indeed outside the expected range but as stated above, it should be avoided to overrate the relevance of a single data point considering all uncertainties and potential bias from sample composition and preparation in this highly sensitive analytical approach.

2) Tibetan ice cores comparison: This paragraph summarizes the maximum ages obtained from the different sites of this region. In order to get a better idea of these points, it is necessary to provide a better description of each of the studied sites (topography, bedrock temperature, flow) and to describe which methods were applied for the core dating. Special attention seems to be given to the Guliya site, which has an age of up to 700ka and is exceptional for this region. It is not acceptable in this discussion that the author calls into question Guliya's record without providing any additional new information on Guliya glacier, only based on the conclusion of a nearby and very different Chongse glacier.

Response: We will include the following basic information for each of the ice cores in the manuscript, and encourage the readers to find details in their respective references. For a neutral review of the result, we will delete the discussion for calling into question Guliya's chronology, but just reminding the remarkable temporal range difference of the Guliya and other Tibetan ice cores.

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, as well as three cores to bedrock (50.72 m, 51.38 m, 50.86 m in length) from the Guliya Summit. Thompson et al. (2018b) suggested that future analyses will include ^{14}C on organic material trapped in the ice, and ^{36}Cl , beryllium-10 (^{10}Be), $\delta^{18}\text{O}$ of air in bubbles trapped in the ice, and argon isotopic ratios ($^{40}\text{Ar}/^{38}\text{Ar}$) on deep sections of the 309.73 m core to determine more precisely the age of the ice cap. We look forward to their new results.

Information for the ice cores that will be included in the revised manuscript:

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 ($35^{\circ} 17' \text{ N}$, $81^{\circ} 29' \text{ E}$) 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 Dundee 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 Dundee ice cap ($38^{\circ} 06' \text{ N}$, $96^{\circ} 24' \text{ E}$) 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 $\delta^{18}\text{O}$, 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, and suggested the possibility that this core may be of Holocene origin.

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 ($33^{\circ} 55' \text{ N}$, $89^{\circ} 05' \text{ E}$) 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 may be of Holocene origin (Thompson et al., 2005).

The Dasuopu ice cores: In 1997, three ice cores were drilled from the Dasuopu glacier ($28^{\circ} 23' \text{ N}$, $85^{\circ} 43' \text{ E}$) 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 $\delta^{18}\text{O}$ 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 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 -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 ¹⁴C 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. A close examination of the Grigoriev ice core $\delta^{18}\text{O}$ profile (Fig. 4 in Takeuchi et al., 2014) reveals that the lowest $\delta^{18}\text{O}$ values occurred ~8 ka B.P., between two cal. ¹⁴C dates of 8.00±0.04 ka B.P. and 8.07±0.06 ka B.P., but the bottom section, corresponding to the age between 8.07±0.06 ka B.P. and 12.58±0.10 ka B.P., shows no further decrease of $\delta^{18}\text{O}$ below the low values around 8 ka B.P.. Given the high sensitivity of $\delta^{18}\text{O}$ to temperature for the Grigoriev ice core (Takeuchi et al., 2014), significantly more negative $\delta^{18}\text{O}$ values towards the bottom section of the Grigoriev core should have been observed if the bottom age indeed reaches YD. Therefore, the Grigoriev bottom ice is very likely younger than YD, and could be deposited during the early Holocene.

Specific comments

Title: Not adapted to the content, too general. Suggestion “Chongse ice core, a contribution to Tibetan ice core age review”

Response: We consider to change the title as “Age ranges of the Tibetan ice cores with emphasis on the Chongce ice cores, western Kunlun Mountains”.

Abstract: To review according to the objectives of the manuscript (see introductory comment to editor).

Response: We will delete the last sentence in the abstract “The significant discrepancy between the Guliya and all the other Tibetan ice core chronology calls for a revisit of the Guliya ice core”. Instead, we include the following sentence “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 ages of the TP glaciers, including those from Chongce and Guliya.”

2) Chronology of previous ice cores”: Dunde ice core: explain how original chronology was established and what led to the new dating.

Response: We will include the following information in the manuscript.

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 are -7.3 °C and -4.7 °C, respectively. The 2 ‰ shift in $\delta^{18}\text{O}$, 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, and suggested the possibility that this core may be of Holocene origin.

Guliya ice core: if this record seems to disturb the author, it will be necessary to provide explanations and more complete arguments. Yao (1997) indicates ages at different depths (AC 1700 at 120m, LGM at 170m, 110ka at 268m) and explain how they were established. It should be noted at this point that the age of Guliya at 170m is of the same order of magnitude as that of Chongse for the same depth, but that Guliya has 100m of additional older ice. The deep dating of Guliya is established by a simple model passing by dated points (^{36}Cl instead of ^{14}C), the technique is similar to that proposed in this manuscript for Chongse, with just as many uncertainties. Even if the last point of ^{36}Cl is very uncertain because of a low chloride concentration, the fact remains that the complete record could only reach 300ka. But in any case, an indisputable point is that the record of Guliya is more than 110ka and calls into question the inappropriate discussions on this point in this manuscript with inexistent ice older than Holocene in Tibetan region.

Response: Many thanks for providing a different perspective. We will simply remind the remarkable discrepancy between the Guliya and all the other Tibetan ice core chronology, and leave the question open.

Dasuopu ice core: explain how this core was dated? Give references like Yao (2002), on CH₄ comparison, $\delta^{18}\text{O}$ depletion missing...

Response: We will include the following information in the manuscript.

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 $\delta^{18}\text{O}$ 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).

Gregoriev ice core: according to Takeuchi (2014), there is an important difference between deepest ice core age (8.155 ka at 81.54m) and soil (12.656 ka). Take care on that potential important difference also on Chongse in your discussion.

Response: We will include the following information in the manuscript.

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 ¹⁴C 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. A close examination of the Grigoriev ice core $\delta^{18}\text{O}$ profile (Fig. 4 in Takeuchi et al., 2014) reveals that the lowest $\delta^{18}\text{O}$ values occurred ~8 ka B.P., between two cal. ¹⁴C dates of 8.00±0.04 ka B.P. and 8.07±0.06 ka B.P., but the bottom section, corresponding to the age between 8.07±0.06 ka B.P. and 12.58±0.10 ka B.P., shows no further decrease of $\delta^{18}\text{O}$ below the low values around 8 ka B.P.. Given the high sensitivity of $\delta^{18}\text{O}$ to temperature for the Grigoriev ice core (Takeuchi et al., 2014), significantly more negative $\delta^{18}\text{O}$ values towards the bottom section of the Grigoriev core should have been observed if the bottom age indeed reaches YD. Therefore, the Grigoriev bottom ice is very likely younger than YD, and could be deposited during the early Holocene.

Other cores are available, like from Geladaindong (0.5ka at 110m, total core 147m). Check all available data if you want to compare all regional ice core archives.

Response: There are quite a few ice cores ever drilled from the TP other than what discussed in our manuscript. But most of them didn't reach bedrock. Even for those reaching bedrock, there is no information available about age of their bottom sections (e.g., Geladaindong and

Nyainqêntanglha (Kang et al., 2015)). Therefore, we consider to change the title as “Age ranges of the Tibetan ice cores with emphasis on the Chongce ice cores, western Kunlun Mountains”.

3) Chongce ice core What are the other characteristics of the Chongse site and ice cores?

Density and temperature profiles useful for dating and modelling? From temperature profile, estimate the bedrock potential melting.

Response: We will include the density profiles of the Chongce ice cores (Fig. 2) and borehole temperature profiles (Fig. 3) in the manuscript.

Borehole temperatures are $-12.8\text{ }^{\circ}\text{C}$, $-12.6\text{ }^{\circ}\text{C}$ and $-12.6\text{ }^{\circ}\text{C}$ at 10 m for Core 1, Core 2 and Core 3, $-8.8\text{ }^{\circ}\text{C}$ and $-8.8\text{ }^{\circ}\text{C}$ at 130 m for Core 1 and Core 2, respectively, suggesting that the Chongce ice cap is frozen to its bedrock.

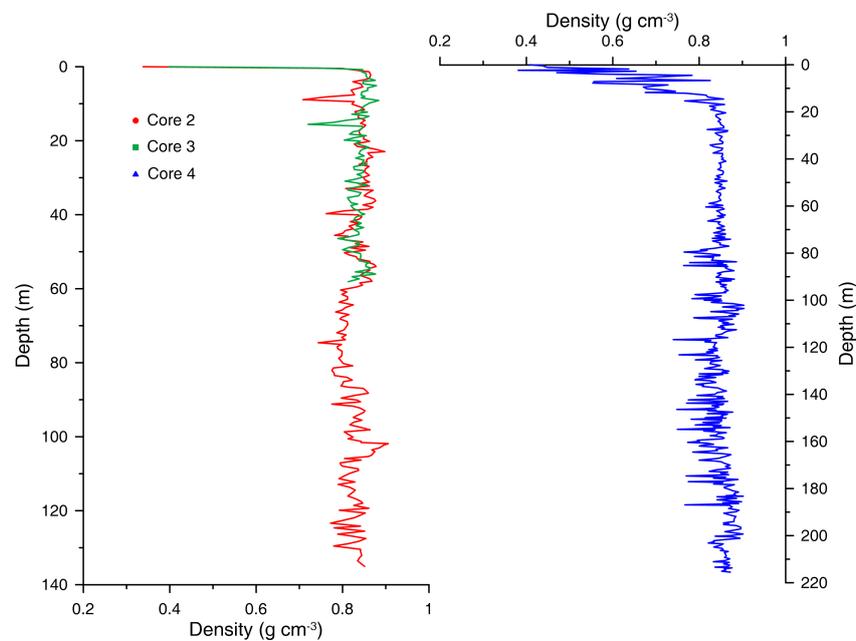


Fig. 2. Density profiles of the Chongce Core 2, Core 3 and Core 4 (see Fig. S2 in the TCD manuscript for location of these ice cores).

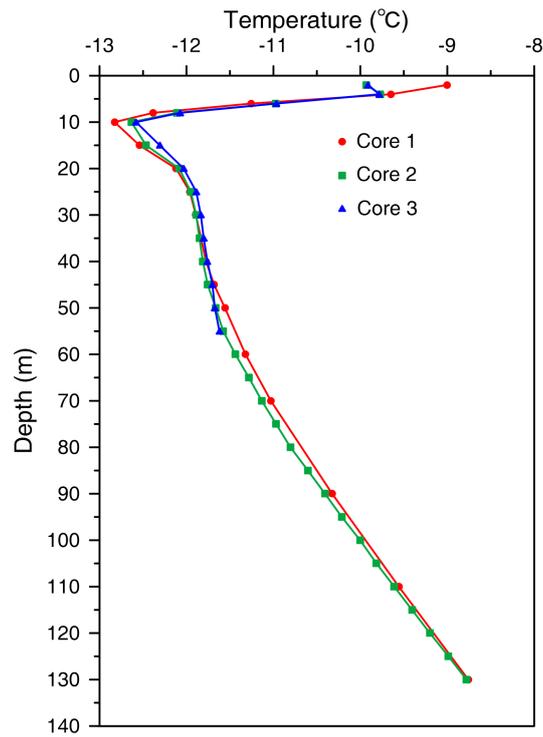


Fig. 3. Borehole temperature profiles of the Chongce Core 1, Core 2 and Core 3 (see Fig. S2 in the TCD manuscript for location of these ice cores).

4) Measurements Provide a depth distribution table for the ^{14}C samples. How deep were the last samples, how far from bedrock?

Response: We will include the following tables for the ^{14}C measurements in the Supplement.

The lowest ^{14}C samples are 0.77 m (Core 2) and 0.57 m (Core 4) above the bedrock. This information will be included in the revision.

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

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

For ^3H and ^{210}Pb methods, provide uncertainties and references.

Response: ^3H uncertainties will be included in Figure 2b. The detection limit for ^3H measurements is <10 TU.

^{210}Pb uncertainties are shown in Figure 3 and the related reference is included as:

“Following the widely applied approach described by Gägger et al. (1983), the ice age was derived using the constant initial concentration (CIC) model.”

5) results About β -activity profile, how are you sure about the date of each peak without additional information? Did you use annual layer counting to these depth? What do you know about surface age, did any annual layers disappeared?

Response: We did have annual layer counting from stable isotopes to back up the β -activity horizons. For more details, please see our previous paper (An et al., 2016).

As to the surface age, we have examined the area changes of glaciers on the Western Kunlun Mountain (including the Chongce ice cap) since the 1970s (Wang, Y., Hou, S., Huai, B., An, W., Pang, H., Liu, Y.: Glacier anomaly over the Western Kunlun Mountains, northwestern Tibetan Plateau, since the 1970s, *J. Glaciol.*, 3rd revision). For the whole area, change of the glacier area reveals insignificant shrinkage by $0.07 \pm 0.1\% \text{ yr}^{-1}$ from the 1970s to 2016.

Although the Chongce glacier retreated between 1977 and 1990, and advanced from 1990 to 2011, then remained stable until 2016, the Chongce ice cap remained static from the 1977 to 2016 (Fig. 4), confirming the stability of the ice cap where our ice cores were recovered. The estimate of elevation changes over the West Kunlun Mountain by Lin et al. (2017) and Zhou et al. (2018) (Figs 5 and 6) is also roughly in balance between 1973 and 2014. Therefore, we regard the surface age as the drilling time, and no annual layer disappeared. Moreover, the ice core density profiles (Fig. 2) and the borehole temperature profiles (Fig. 3) also suggest a sounding condition for preserving the ice core records.

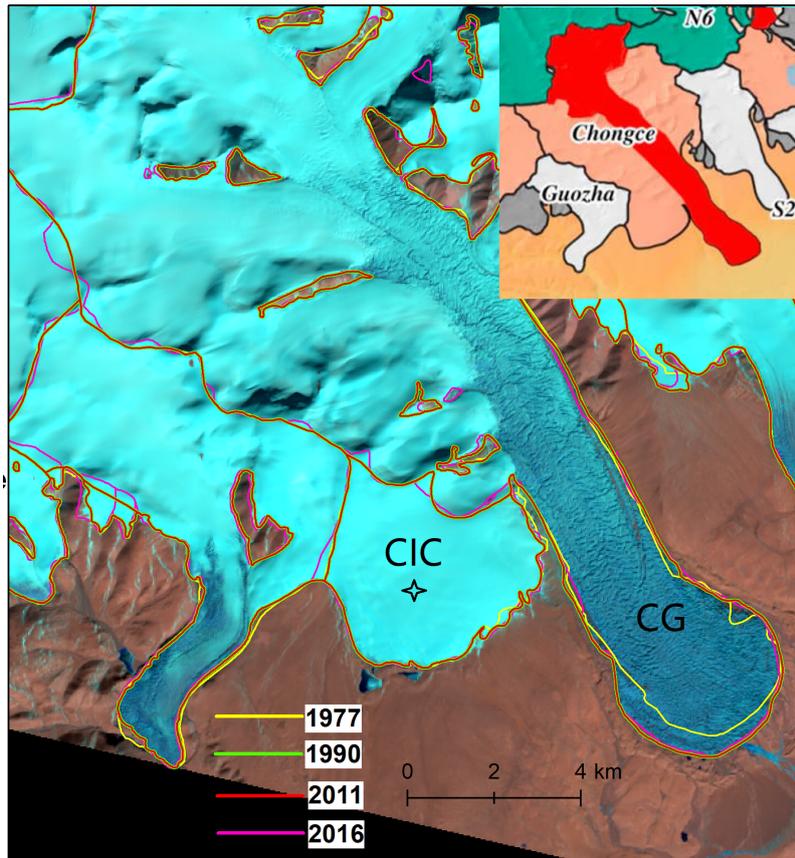


Fig. 4. Map showing the Chongce Ice Cap (CIC) and the Chongce Glacier (CG), with the terminus positions at different time. The star shows the position of the drilling site of the Chongce Cores 2 and 3, which might be an optimal site for retrieving an undisturbed paleoclimate record. The inset is from Fig. 3 of Yasuda and Furuya (2015) with the red area showing the surged area confined within the Chongce glacier.

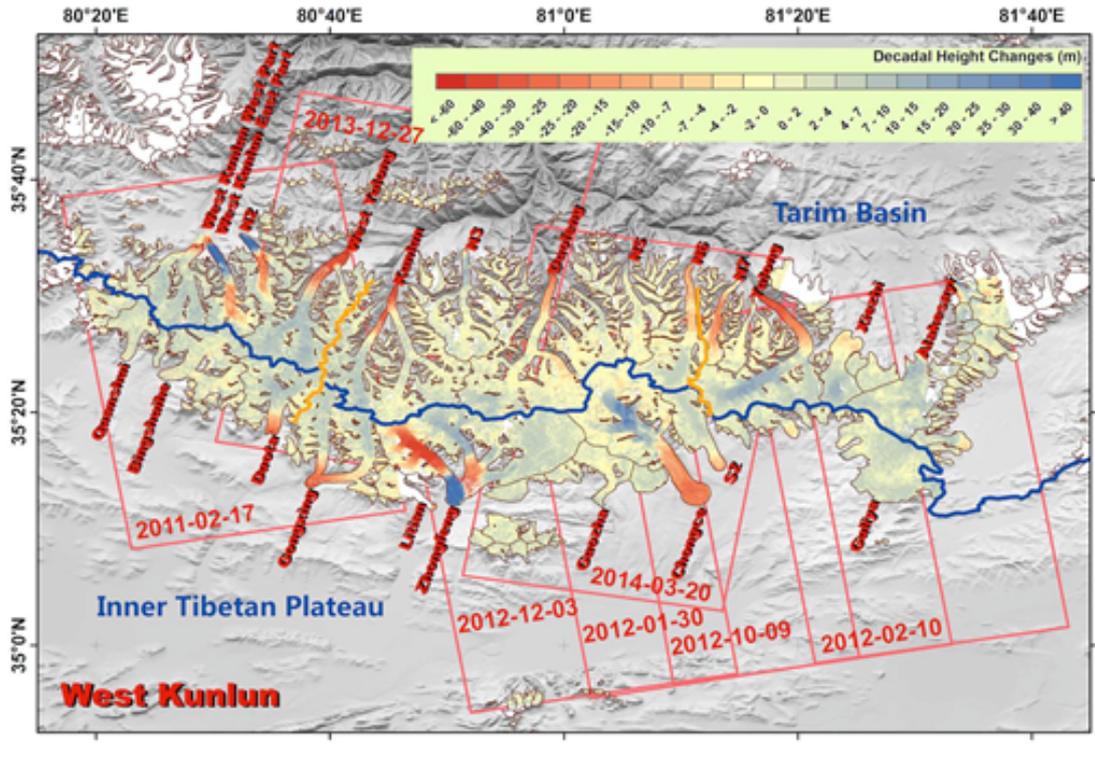


Fig.5. Glacier height changes from 2000 to the 2010s from Lin et al. (2017)

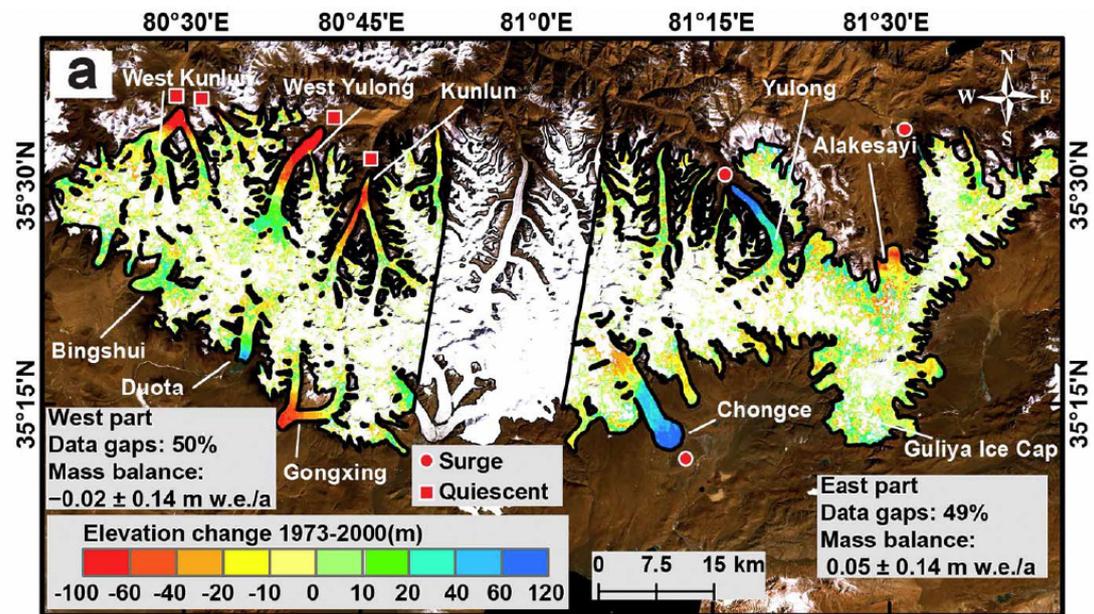


Fig.6. Glacier elevation change from 1973 to 2010 from Zhou et al. (2018)

For ^3H profile in figure 2b, it seems for me that the plotted values are corrected from decay to reach such high numbers? 3237TU for the 1963 peak value is very high in comparison with other ice core data, mostly around few hundreds TU today value for the 1963 peak, see Gelaidaindong core (Kang, 2015). Give reference on the identification of maximum peak.

Response: Yes the values are corrected for the decay since 1963 as indicated on the y-axis in manuscript Fig. 2b. 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). We will make a revision accordingly.

^{14}C data interpretation: can you argue why in C4, ^{14}C dates are only around 1-2ka for the intermediate depth (80-170m) and between 2-4ka in C2 at 60-110m? For me C4 is discontinuous, may be because of the particular bedrock topography (presence of bedrock canyon), with recent ice on the 0-110m over older dead ice.

Response: ^{14}C measurements for samples with relatively young ages are challenging and limited by the currently achieved analytical precision using WIOC in combination with the relatively flat ^{14}C calibration curve, especially for samples younger than ~1 ka. For more details addressing this comment please see response to comment 1) above. In any case, we agree that additional independent evidences (e.g., stable isotopes, methane) would be beneficial to decipher the ^{14}C results obtained for the intermediate depth, which will be presented in a separate manuscript.

The use of a simplistic 2-p model is not appropriate for this kind of site where you know that the accumulation is not constant through the Holocene, but especially to be used on the bottom of the glacier where in principle its exponential approach is unrealistic. You have enough ^{14}C data to trigger glacier bottom age using a simple exponential regression down to bedrock depth for C4.

Response: We agree that the applied 2-p model is limited, especially for the bottom of the glacier where it becomes infinite as described in the manuscript. As discussed above (see response to point 1), we used the flow model by constraining it to fit the dating points in order to obtain a continuous age-depth scale. To avoid overfitting of the data and giving too 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). We are confident that our careful and rather conservative approach results in a robust estimate with sufficient precision for the general discussion and conclusions.

Nevertheless, we are aware that the approach of extrapolating the age scale from the oldest ^{14}C sample down to bedrock is far from satisfactory, a fact clearly stated in the manuscript.

Therefore, this part will be moved to the supplement.

If applying a simple exponential regression, the simulated ages at bedrock are 3.987 ka B.P. and 5.395 ka ka B.P. for Core 4 and Core 2, respectively, younger than their respective oldest cal. ^{14}C ages (Figs 7a and 8a), which may be biased by the younger ^{14}C measurements.

Taking this into consideration, we performed more runs of exponential regression by subsequently deleting the uppermost ^{14}C measurement in each consecutive run. So the last run was based on the lowest cal. ^{14}C age and the ages from the tritium horizon and ^{210}Pb for Core

4). For Core 2, the last run was based on the lowest cal. ^{14}C age and the age from β -activity horizon, as well as the surface age in order to fix the regression. The simulated ages at bedrock for each run are presented in Tables 3 and 4, giving age ranges of 3.99-5.59 ka B. P. for Core 4 and 5.40-7.67 ka B. P. for Core 2, respectively. These results, although at the lower end, are well within the 1 sigma range of our results presented in the initial manuscript and based on the approach discussed therein.

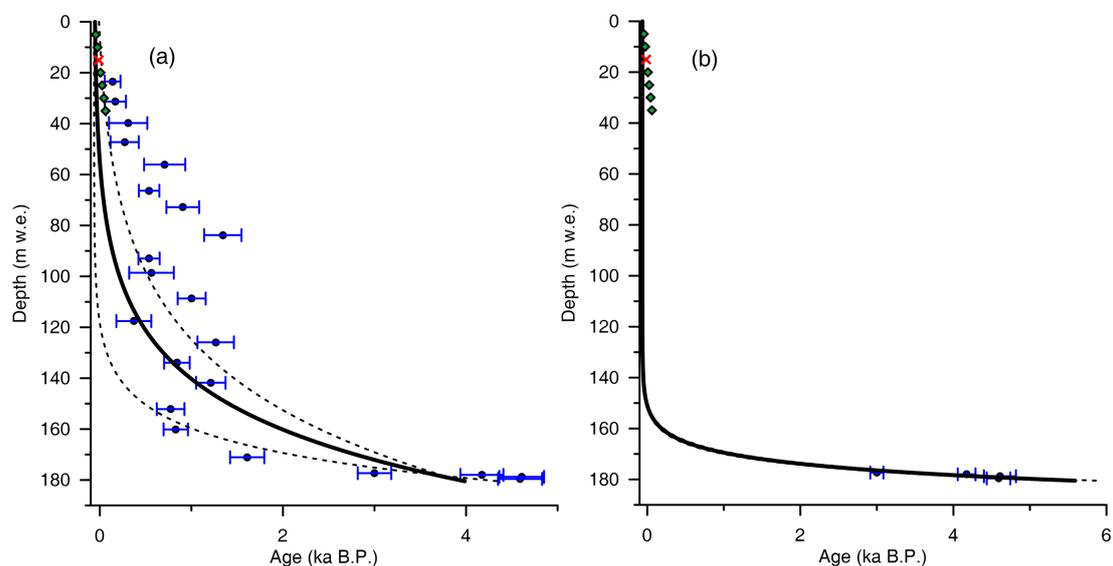


Fig. 7. Profiles of an exponential regression for Core 4, (a) including all the cal. ^{14}C ages, (b) including the four lowest cal. ^{14}C ages to result in the oldest age at the bottom among all the runs (Table 3). The dashed lines represent the 1σ confidence interval of the regression (solid line). The red cross stands for the tritium horizon, green diamonds for the ^{210}Pb ages calculated at intervals of 5 m w.e., and the blue dots for the cal. ^{14}C ages with 1σ error bar.

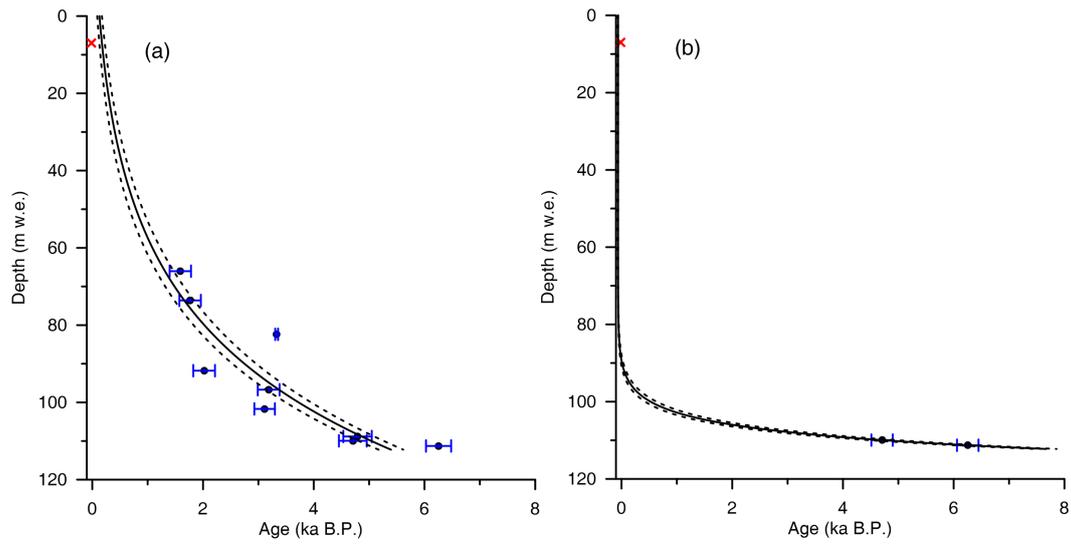


Fig. 8. Profile of an exponential regression for Core 2, (a) including all the cal. ¹⁴C ages, (b) including the two lowest cal. ¹⁴C ages to result in the oldest age at the bottom among all the runs (Table 4). The dashed lines represent the 1σ confidence interval of the regression (solid line). The red cross stands for the β-activity horizon and the blue dots for the cal. ¹⁴C ages with 1σ error bars.

Table 3. The simulated ages at bedrock by applying an exponential regression ($y=ae^{bx}$) for

Core 4.

No. of cal. ^{14}C ages used	a	b	R^2	Simulated ages at bedrock (ka B. P.)
22	0.00999	0.03327	0.79756	3.99
21	0.00956	0.03352	0.79466	3.99
20	0.00902	0.03386	0.79182	4.00
19	0.00802	0.03453	0.79121	4.02
18	0.00714	0.03520	0.78944	4.04
17	0.00507	0.03716	0.79961	4.08
16	0.00371	0.03895	0.80400	4.13
15	0.00212	0.04214	0.82176	4.20
14	818311×10^{-9}	0.04754	0.86176	4.30
13	525863×10^{-9}	0.05004	0.86651	4.34
12	313385×10^{-9}	0.05298	0.87189	4.39
11	975051×10^{-10}	0.05958	0.89357	4.50
10	581575×10^{-10}	0.06249	0.89367	4.54
9	581236×10^{-11}	0.07547	0.92826	4.72
8	104984×10^{-11}	0.08509	0.94233	4.85
7	588197×10^{-13}	0.10128	0.97316	5.05
6	554846×10^{-14}	0.11453	0.98125	5.20
5	266867×10^{-15}	0.13153	0.98595	5.39
4	694579×10^{-17}	0.15195	0.98657	5.59
3	0.03597	0.02704	0.99826	4.67
2	0.04418	0.02600	0.99968	4.76
1	0.04255	0.02614	0.99987	4.70

Table 4. The simulated ages at bedrock by applying an exponential regression ($y=ae^{bx}$) for Core 2.

No. of cal. ^{14}C ages used	a	b	R^2	Simulated ages at bedrock (ka B. P.)
9	0.19181	0.02983	0.84957	5.40
8	0.16245	0.03139	0.83787	5.45
7	0.13711	0.03297	0.82107	5.49
6	0.02219	0.04981	0.94779	5.88
5	0.02555	0.04852	0.94051	5.86
4	0.00269	0.06904	0.96654	6.18
3	922368×10^{-11}	0.12049	0.97807	6.83
2	414342×10^{-15}	0.21070	0.99977	7.67
1	0.00247	0.07051	1	6.70

Lines 234 and 245, you indicate tritium when it is from β -activity data.

Response: We apologize for this negligence. Correction will be made accordingly.

Dating of C2: you are absolutely trying to match a curve from an unsuitable model with data from real measurements, and in addition you add values from other sites to try to force your conclusions. This reasoning and this method are not acceptable. Given the weakness of the model, it is reasonable to remove it from this manuscript.

Response: Although we understand the concern of the reviewer regarding the use of additional constraint for Core 2, our main point is the aim to get the most robust age estimates based on the available data without overfitting or overweighting individual dating points

considering all the potential uncertainties. Since a more advanced glacier ice flow model (i.e. 3D) model is not available and in fact would face similar uncertainties close to the bedrock (e.g. Luthi and Funk, 2000), what we did is to carefully evaluate our age model output by taking advantage of all available data, rather than trying to derive results in order to force our conclusions. For Core 2, the model is clearly under constrained due to too few dating points. This result in giving a questionable weight to one single data point (3.3 ± 0.2 ka at ~ 100 m depth) which, for currently unknown reasons, might simply be an analytical outlier or be biased (also see response to comments 1 and 5). Partly because of this reason, the model is fitted poorly to the oldest/deepest dating point (in manuscript line 235 “the derived age at the depth of the oldest ^{14}C sample is $9.1 \pm \frac{7.2}{4.0}$ ka B.P., much older than the actual ^{14}C age (6.3 ± 0.2 ka B.P.) at that depth.”). By adding additional constraint based on the results from Core 4, this misfit decreases but we fully agree with the reviewer in the sense that this part of the approach is far from satisfactory. As discussed above, we prefer to move the extrapolation down to bedrock into the Supplement.

6) Discussion This chapter is to be reviewed in its entirety. The author must clearly state the objectives of this manuscript. If it comes to presenting new results from the Chongse Core, in this case with major corrections these results could be published. If it's a matter of depressing previous works like those on Guliya glacier, as this manuscript does not bring any innovative data to this site, not the least substantiated discussion, there is no reason to publish it in TC. On that stage of the review, various technical corrections can wait for a revised version of the manuscript.

Response: We will revise the manuscript according to the aforementioned discussion. We will, in a neutral way, present the results of the Chongce ice cores and from other Tibetan ice cores based on their original literature. We will remind the remarkable age range difference of the Guliya and other Tibetan ice cores, and conclude that “more effort is necessary to explore multiple dating techniques to confirm the ages of the TP glaciers, including those from Chongce and Guliya” (Thompson, 2018a).

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Dear Prof. Paul Mayewski,

Many thanks for your positive comments. We appreciate.

Best regards,

Hou

Interactive comment on “Age of the Tibetan ice cores” by Shugui Hou et al.

P. A. Mayewski (Referee)

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Received and published: 25 May 2018

1. Does the paper address relevant scientific questions within the scope of TC? – Yes, it calls into question conclusions based on the interpretation of a single water soluble ³⁶Cl measurement that has been used to provide a reference point in following publications to assert timing and extent of past glacial age ice cover and associated climate interpretations. 2. Does the paper present novel concepts, ideas, tools, or data? Yes it provides an impressive rationale and data assembly for dating a relatively new Tibetan ice core record – Chongce. 3. Are substantial conclusions reached? Yes, the authors present a clear and straightforward comparison of existing Tibetan ice core records. 4. Are the scientific methods and assumptions valid and clearly outlined? Yes.

5. Are the results sufficient to support the interpretations and conclusions? The interpretations and conclusions are based on significant spatial and temporal data and the basic conclusion is very professionally stated calling for more work, ideally similar to that presented in this paper, re dating of the Guliya ice core. 6. Is the description of experiments and calculations sufficiently complete and precise to allow their reproduction by fellow scientists (traceability of results)? Yes 7. Do the authors give proper credit to related work and clearly indicate their own new/original contribution? Yes 8. Does the title clearly reflect the contents of the paper? Yes 9. Does the abstract provide a concise and complete summary? Yes 10. Is the overall presentation well structured and clear? Absolutely. 11. Is the language fluent and precise? Yes 12. Are mathematical formulae, symbols, abbreviations, and units correctly defined and used? Yes 13. Should any parts of the paper (text, formulae, figures, tables) be clarified, reduced, combined, or eliminated? No. 14. Are the number and quality of references appropriate? Yes. 15. Is the amount and quality of supplementary material appropriate? Yes.

Dear Prof. Lonnie Thompson,

Many thanks for your constructive comments. Below a point-to-point response to the comments. The comments are in black, and our response is in blue.

Comments: Hou, et al. Age of Tibetan ice cores by L.G. Thompson

The authors raise an important point about the age of the Guliya record as it is unusual in light of previous Tibetan Plateau (TP) records from the Dunde ice cap, Dasuopu Glacier (col) and Puruogangri ice cap. For their Chongce ice cores, the authors used a novel method of radiocarbon dating water-insoluble organic carbon (WIOC) particles at the microgram level from carbonaceous aerosols embedded in the glacier ice from 44 meters to 216.6 meters depth.

They import these dates into a simple two dimensional flow model to develop a time-depth profile. Questions should be raised concerning the use of such a model, given the complex flow regimes in these western Kunlun glaciers. More importantly the authors do not show any climate record derived from stable isotopes from these ice cores so that the reader can evaluate the quality and continuity of the record and how it compares to the other TP climate records (especially the 1992 Guliya record). Guliya is unusual in that it shows large and abrupt variations in $\delta^{18}\text{O}$ below ~150 m, which other TP records do not contain. Does the longest record from Chongce show similar variations?

Response: We agree that the two dimensional flow model, though widely used for establishing the ice core chronology including the Dunde (Thompson et al., 1989) and the Puruogangri (Thompon et al., 2006) ice cores, is too simple to account for the complex flow regimes close to the glacier bedrock. We will therefore remove the extrapolation from the oldest (and deepest) ^{14}C data point to the bedrock. Otherwise, we simply used the flow model to fit the dating points for obtaining a continuous age-depth scale. We agree that independent evidence such as the stable isotopes from these ice cores would be helpful to support the dating. We just finished the measurement of stable isotopes of the Chongce 135.8 m Core 2 and the 58.8 m Core 3 and they suggest Holocene origin in agreement with our dating. We are preparing the corresponding manuscript and therefore cannot post these $\delta^{18}\text{O}$ profiles here and make them public at this moment. Nevertheless, we will provide a copy of these $\delta^{18}\text{O}$ profiles for the review purpose only.

Another concern about the Chongce record is geophysical in nature. In 1991 Chinese scientists published a Quaternary Glacial Distribution Map of the TP. According to this map, the terminal moraines around the Guliya ice cap are very close to their maximum position during the last two glaciations. However, this is not the case for the Chongce ice cap located just ~30 km to the west. Chongce shows the greatest variations in ice extent of any of the ice caps in this region. In addition, the Chongce glacier, which flows from the Chongce ice cap, surged between 1992 and 2014 while the Guliya ice cap remained static (Yasuda and Furuya, 2015; Fig. 3). Therefore, it might be inaccurate to assume that the timescale developed for the Chongce cores should reflect that of Guliya. In light of the evidence indicating the instability

of the Chongce's ice flow, the longest core drilled in the deepest section of a valley glacier which flows through a bedrock trough (fig. S2) is very unlikely to be an optimal site for retrieving an undisturbed paleoclimate record. In light of the geophysical considerations discussed above it would be premature to conclude that these results invalidate the much longer Guliya timescale.

Response: Thank you for bringing to our attention of Yasuda and Furuya's work on the dynamics of surge-type glaciers in West Kunlun Shan. From Fig. 3 of their paper, it is clear that the surged area is confined within the Chongce glacier (Fig. 1). Using topographical maps, Shuttle Radar Topography Mission (SRTM) and Landsat data, we have examined the area changes of glaciers on the Western Kunlun Mountain (including the Chongce and Guliya ice caps) since the 1970s (Fig. 1. Wang, Y., Hou, S., Huai, B., An, W., Pang, H., Liu, Y.: Glacier anomaly over the Western Kunlun Mountains, northwestern Tibetan Plateau, since the 1970s, *J. Glaciol.*, 3rd revision). For the whole area, change of the glacier area reveals insignificant shrinkage by $0.07 \pm 0.1\% \text{ yr}^{-1}$ from the 1970s to 2016. The Chongce glacier retreated between 1977 and 1990, and advanced from 1990 to 2011 (period of surge), then remained stable until 2016. In contrast, the Chongce ice cap remained static from the 1977 to 2016 (Fig. 1), confirming the stability of the ice cap where our ice cores were recovered. Moreover, we observed similar mass changes of surge-type and non-surge-type glaciers over the Western Kunlun Mountains, suggesting that the flow instabilities seem to have little effect on the glacier-wide mass balance. Similar mass budgets for surging and non-surging glaciers have also been reported in the Pamirs and Karakoram (Gardelle et al., 2013). Based on the estimate of elevation changes over the West Kunlun Mountain by Lin et al. (2017) and Zhou

et al. (2018) (Figs 3 and 4), it is reasonable that Chongce ice cap is in balance between 1973 and 2014. Therefore, the impact of surge over the Chongce glacier is minimal, if any, on the stratigraphy of the Chongce ice cap, especially in its accumulation zone where our Chongce ice cores were drilled.

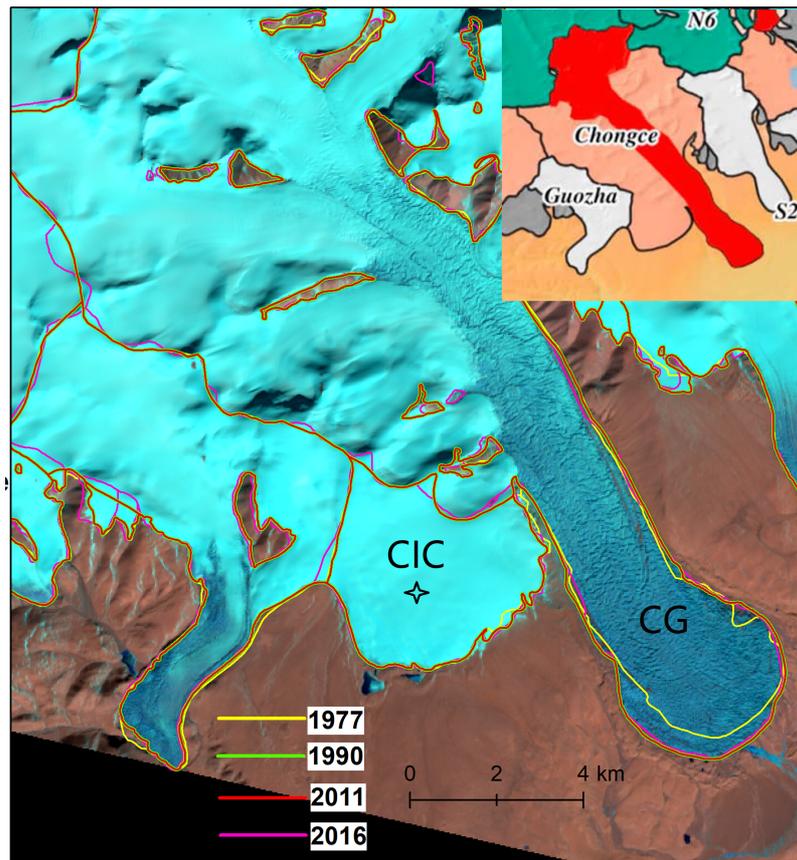
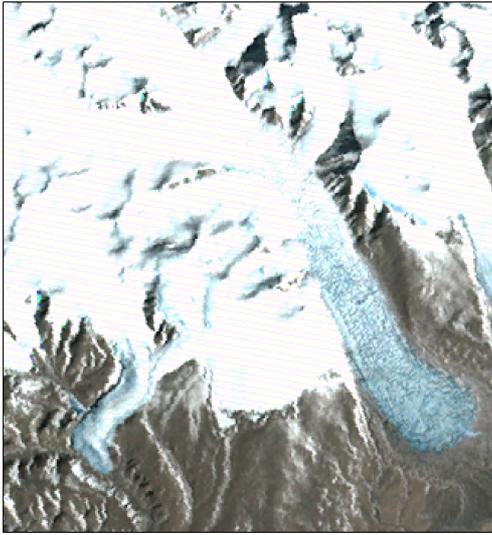
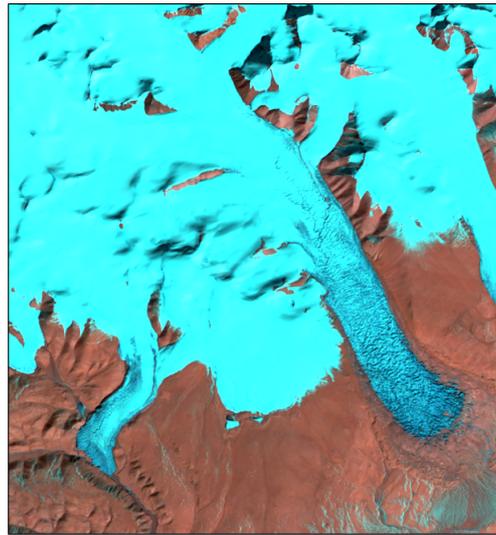


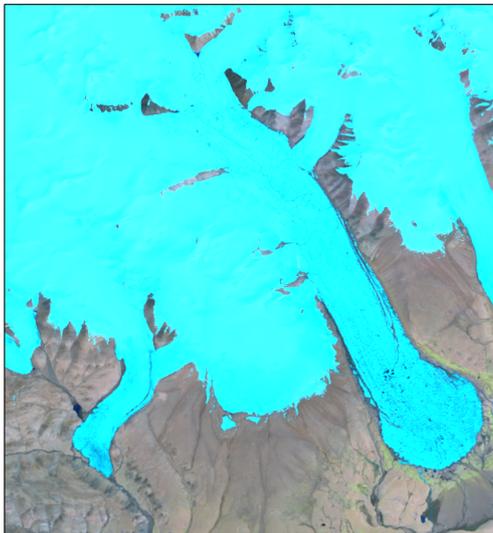
Fig.1. Map showing the Chongce Ice Cap (CIC) and the Chongce Glacier (CG), with the terminus positions at different time. The star shows the position of the drilling site of the Chongce Cores 2 and 3, which might be an optimal site for retrieving an undisturbed paleoclimate record. The inset is from Fig. 3 of Yasuda and Furuya (2015) with the red area showing the surged area confined within the Chongce glacier. Terminus positions are determined from Landsat images as shown in Fig. 2.



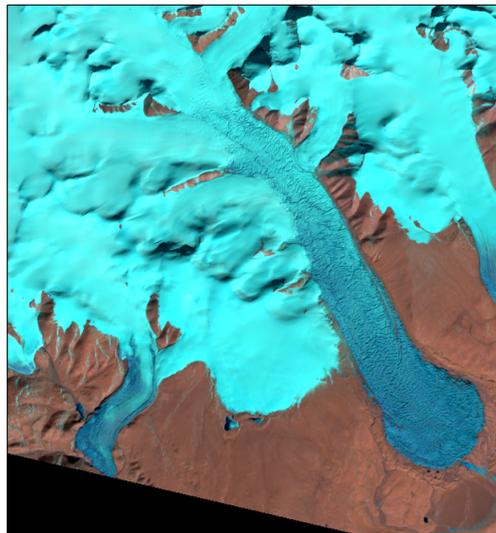
Landsat MSS (17, Feb, 1977)



Landsat TM (15, Nov. 1990)



Landsat TM (5, Aug. 2011)



Landsat 8 (5, Oct. 2016)

Fig. 2. Data for Chongce glacier and ice cap terminus position assessment. They are co-registered to the topographical maps and the accuracy of co-registration is about 20 m (slightly more than half of one pixel of Landsat images)

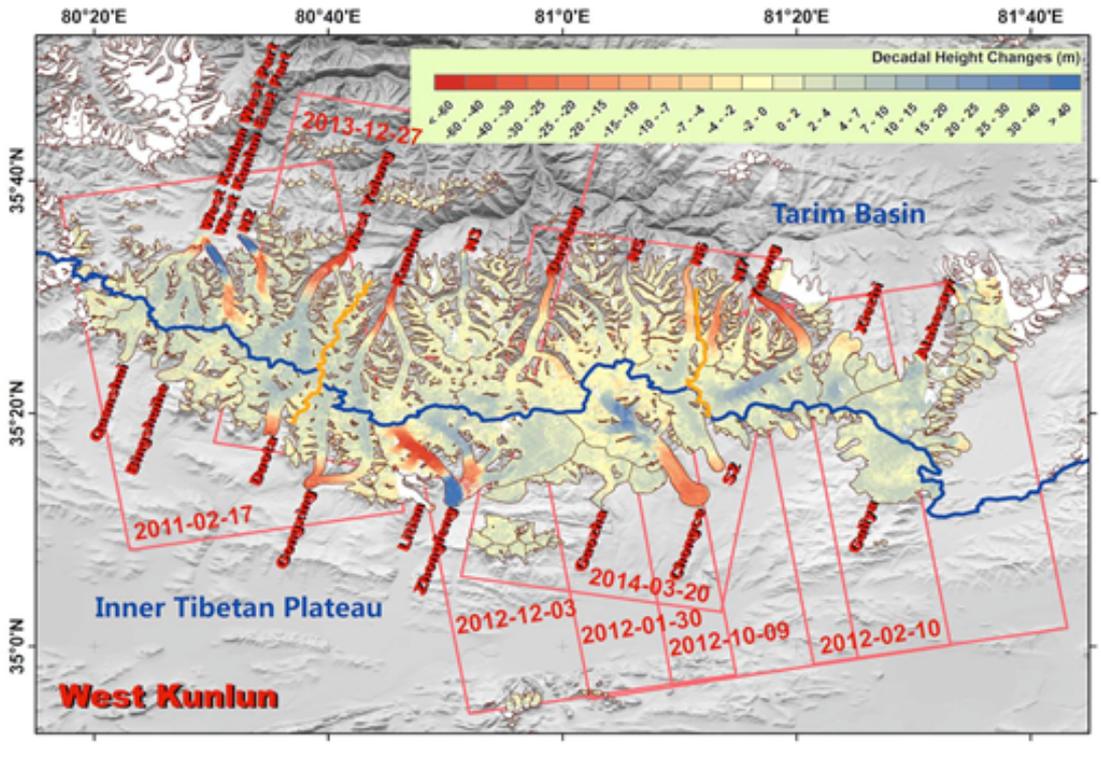


Fig.3. Glacier height changes from 2000 to the 2010s from Lin et al. (2017)

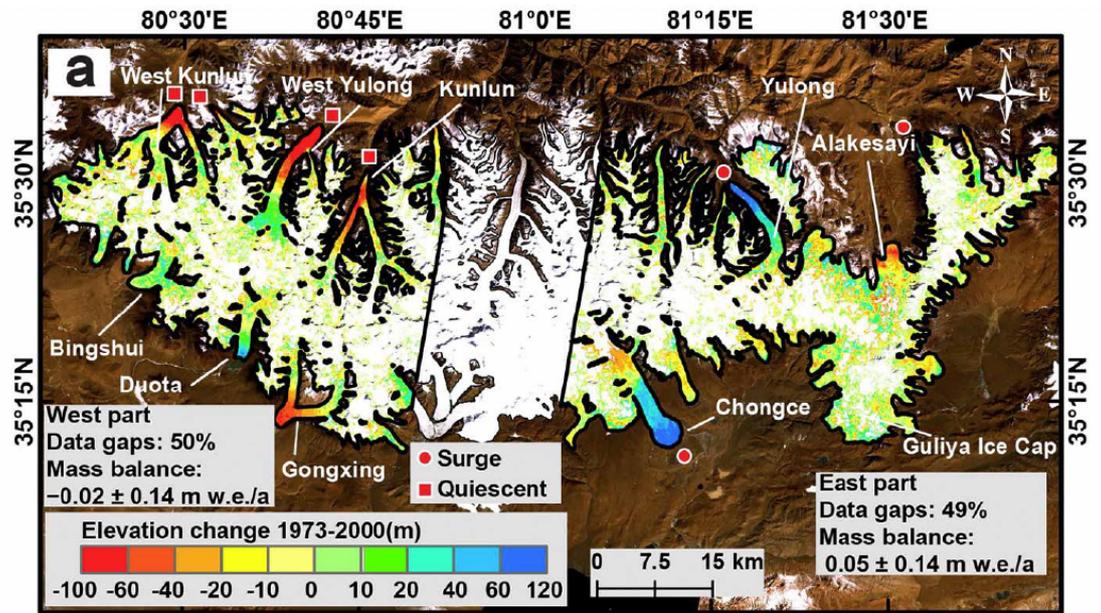


Fig.4. Glacier elevation change from 1973 to 2010 from Zhou et al. (2018)

Note that the location shown for the 1992 Guliya core in Fig. S1 is incorrect. This should be corrected.

Response: We used the coordinates (35°17' N, 81°29' E) published in Thompson et al. (1997) for the location of the 1992 Guliya core. We would be happy to make a correction if more accurate coordinates can be provided.

We strongly agree with the authors that more effort is necessary to explore multiple dating techniques to confirm the ages of the TP glaciers, including those from Chongce and Guliya.

The Western Kunlun region, located at the intersection of the regions dominated by the westerlies and the SW Monsoon, is climatologically complex and the interactions of multiple air masses makes stable isotope interpretation challenging. Multiple aerosol sources also complicate the reconstruction of the paleo-environmental records preserved in these ice fields.

Response: We fully agree with this comment. Thanks to the new analytical techniques, we should have more opportunities to decipher the complexity of the Tibetan ice core records.

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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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Abstract. An accurate chronology is the essential first step for a sound understanding

20 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.

25 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

30 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

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已删除: The modeled ages of two Chongce ice cores at the ice-bedrock contact are $8.3 \pm_{3.6}^{6.2}$ ka B.P. and $9.0 \pm_{3.6}^{7.9}$ ka B.P. respectively.

techniques to confirm the age ranges of the TP glaciers, including those from

Chongce and Guliya

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已删除: The significant discrepancy between the Guliya and all other Tibetan ice core chronologies calls for a revisit of this legend ice core record.

40

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

45 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,

50 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

60 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 ($> 10 \mu$

g). Here we applied this recently established technique for dating the Tibetan ice

cores.

65

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.

70

The Dundee 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 Dundee 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 $\delta^{18}\text{O}$.

75 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
80 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 ($35^{\circ} 17' \text{ N}$, $81^{\circ} 29' \text{ E}$) in the
western Kunlun Mountains on the northwestern TP (Fig. 1). The Guliya ice cap is
85 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).

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~~已删除: The Dunde ice cores are the first ones ever drilled on the TP (Fig. 1). In 1987, three ice cores (139.8 m, 136.6 m and 138.4 m in length) were drilled to bedrock at an altitude of 5325 m a.s.l. (above sea level) from the Dunde ice cap ($38^{\circ}06' \text{ N}$, $96^{\circ}24' \text{ E}$) in the Qilian Shan mountains on the northeastern TP (Fig. 1). Their original chronology was suggested to be 40 ka B.P. (before present, i.e., before 1950 AD) at the depth of 5 m above the ice-bedrock contact, and 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, and suggested the possibility that the Dunde cores may have a Holocene origin.~~

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 $\delta^{18}\text{O}$ 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

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已删除: The Guliya ice core: In 1992, a 308.6 m ice core to bedrock was drilled at an altitude of 6200 m a.s.l. from the Guliya ice cap (35° 17' N, 81° 29' E) on the northwestern TP (Fig. 1). 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. based mainly on ^{36}Cl -dead ice at the bottom section (Thompson et al., 1997).

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已删除: 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). It was suggested that the Dasuopu ice field accumulated entirely during the Holocene (Thompson et al., 2005).

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 (28° 1' N, 86° 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 CH₄/δ¹⁸O_{atm} phase record of both the East Rongbuk 117.1 m and 108.8 m cores to the GRIP CH₄ and the GISP2 δ¹⁸O_{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

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已删除: The Puruogangri ice cores: In 2000, three ice cores (118.4 m, 214.7 m and 152 m in length) were drilled 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). The measured oldest ¹⁴C 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), indicating its Holocene origin (Thompson et al., 2005).

170 (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

175 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 ($35^{\circ}14' \text{ N}$, $81^{\circ}7' \text{ E}$; 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
180 216.6 m (Core 4) and 208.6 m (Core 5) at an altitude of 6100 m a.s.l. on the Chongce
ice cap ($35^{\circ} 15' \text{ N}$, $81^{\circ} 5' \text{ E}$). 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
185 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 CO₂ was measured by the Mini Carbon Dating System (MICADAS) with a gas ion source for ¹⁴C 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 $1.34 \pm 0.62 \mu\text{g}$ carbon with a $F^{14}\text{C}$ of 0.69 ± 0.13 (Uglietti et al., 2016). Conventional ¹⁴C ages were calibrated using OxCal v4.2.4 software with the IntCal13 calibration curve (Bronk Ramsey and Lee, 2013; Reimer et al., 2013).

215

²¹⁰Pb

The accessible time range using radioactive isotope ²¹⁰Pb 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

220 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.

225 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, 230 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

235 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
240 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
245 the Chongce 58.8 m Core 3. Each sample is ~1 kg. The β -activity was measured
using Alpha-Beta Multidetector (Mini 20, Eurisy Mesures) at the National Key
Laboratory of Cryospheric Sciences, China. More details can be found in An et al.
(2016).

250 **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

260 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

265 rate is 297 mm w.e./year for the period of 1963-2013 AD.

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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 Gaggeler 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).

$$t_s = \lambda^{-1} \ln\left(\frac{C_0}{C_s}\right) \quad (1)$$

Where, t_s stands for the age of ice at a certain depth with ^{210}Pb activities (subtracted)

C_s , λ for the decay constant of ^{210}Pb (0.03114 a^{-1}), and C_0 for the ^{210}Pb surface

290 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

295 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

300 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

305 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
310 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

315 applying a two-parameter flow model (2p model) (Bolzan, 1985 and Supplement). To avoid overfitting of the data and giving too 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

320 chronology including the Dundee (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.

325

6 Discussion

330 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

335 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.

340 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. ¹⁴C

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
345 measured oldest cal. ¹⁴C 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 ($8.3 \pm_{3.6}^{6.2}$ ka B.P. for the Chongce 216.6 m Core 4 and $9.0 \pm_{3.6}^{7.9}$ 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
350 result of the Grigoriev ice core in the west Tien Shan (Takeuchi et al., 2014). In both

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cases, the results confirm the upper constraint of 42 ± 4 ka B.P. derived from the

355 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

360 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)

365 argued that the Guliya ice core chronology should be shortened by a factor of two in

order to reconcile the difference in the $\delta^{18}\text{O}$ 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

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from the Guliya ice core drilling site

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375 necessary to explore more independent 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 , $\delta^{18}\text{O}$ of air in bubbles,
380 and argon isotopic ratios ($^{40}\text{Ar}/^{38}\text{Ar}$) 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

385 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
390 conclusion derived from the luminescence age of the Chongce ice core. The current

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已删除: It is worth pointing out that the ^{36}Cl -dead in the bottom section of the Guliya core provided the key evidence for the existence of ice older than 500 ka (Thompson et al., 1997). Since ^{36}Cl is presumably present as water-soluble ion, it can be easily removed from the snow or firn layer by meltwater percolation. Thus, the absence of ^{36}Cl could have resulted from its leaching with glacier meltwater, as indicated by the abnormally low chloride concentrations in the bottom section of the Guliya record (Thompson et al., 1997), although a thorough explanation is beyond the scope of the current work. Nevertheless, much work is necessary for conviction of the exceptional length of the Guliya ice core.

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work may has wide implications, such as whether or not existence 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

415 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

420 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.

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已删除: reexamination of the Tibetan ice core records,

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已删除: more reliable chronologies of the Tibetan ice cores to bedrock are necessary and urgent, thanks to the new development of dating techniques

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measure the ^{14}C and the ^{210}Pb samples, and to Guocai Zhu for providing the ground penetrating radar results. This work was supported by the National Natural Science Foundation of China (41330526).

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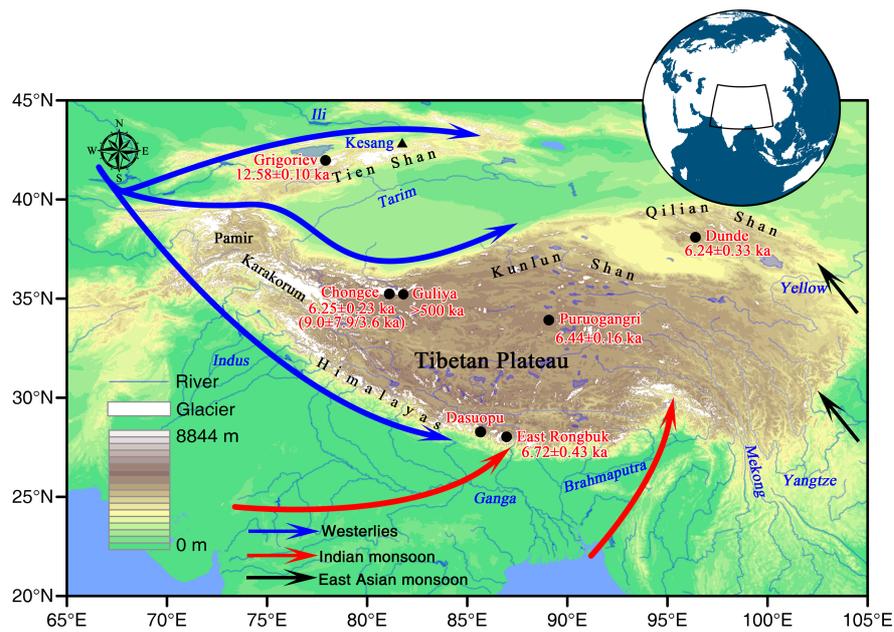


Figure 1: Map showing the locations of ice core drilling sites. The numbers for each

site except Guliya are the measured oldest ^{14}C ages, while the number inside the

550 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

555 Atmospheric Administration at <http://www.ngdc.noaa.gov/mgg/global/global.html>.

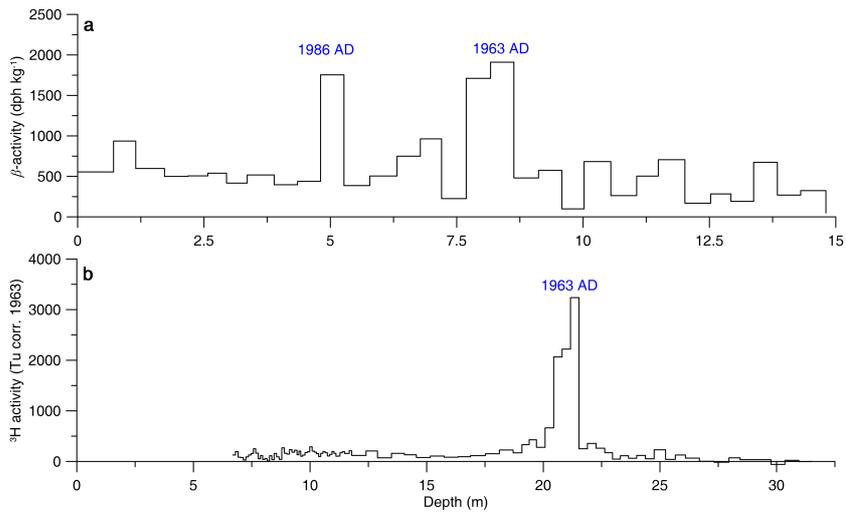


Figure 2: The β -activity profile of the Chongce 58.8 m Core 3 (a) and the tritium (corrected for the decay) profile of the Chongce 216.6 m Core 4 (b). TU (tritium units)

560 is one tritium atom/1018 hydrogen atoms.

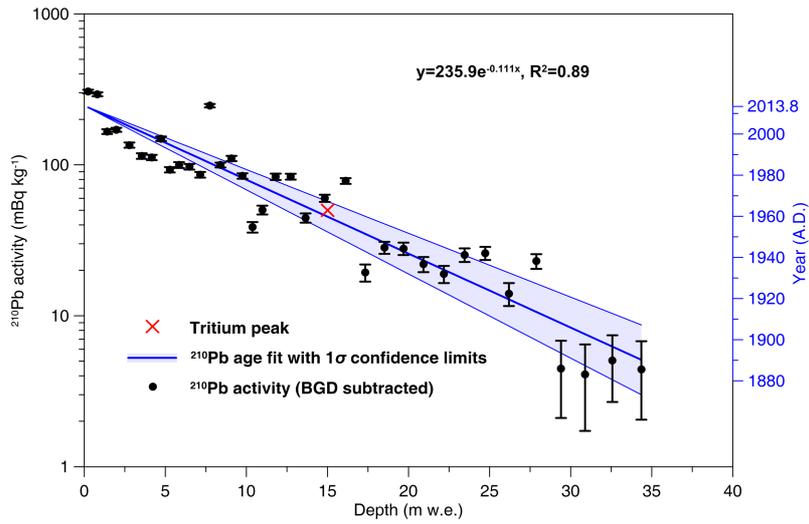


Figure 3: ^{210}Pb activity profile of the Chongce 216.6 m Core 4 and the derived age-depth relationship. The ^3H fallout horizon indicating the year 1963 A.D. is

565 located within the uncertainty of the ^{210}Pb results. Please note that the 1σ confidence band is related to the right hand y-axis only.

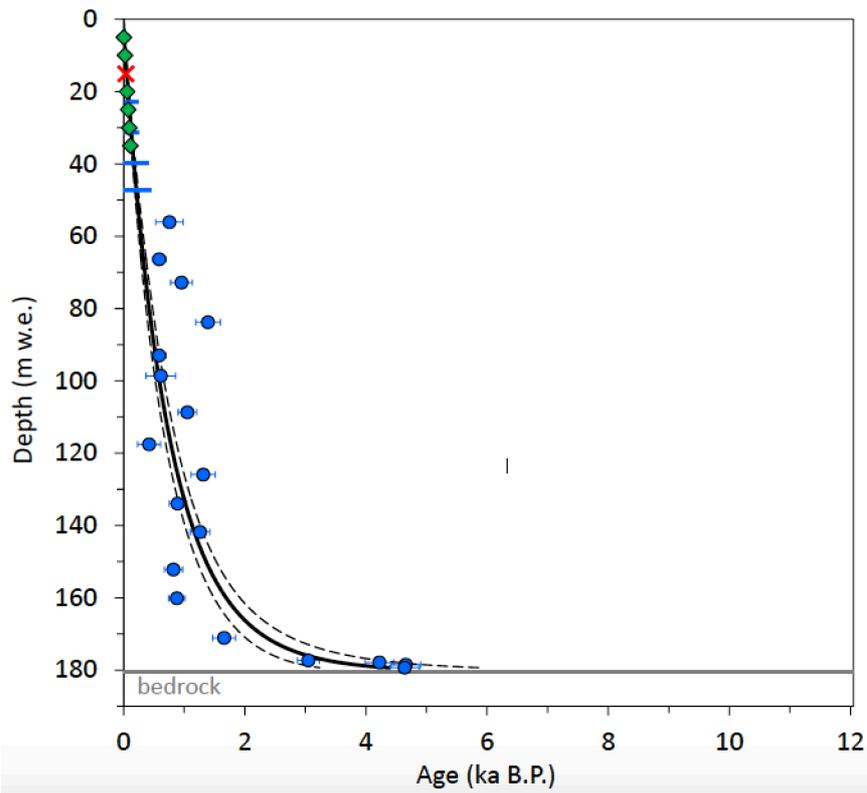
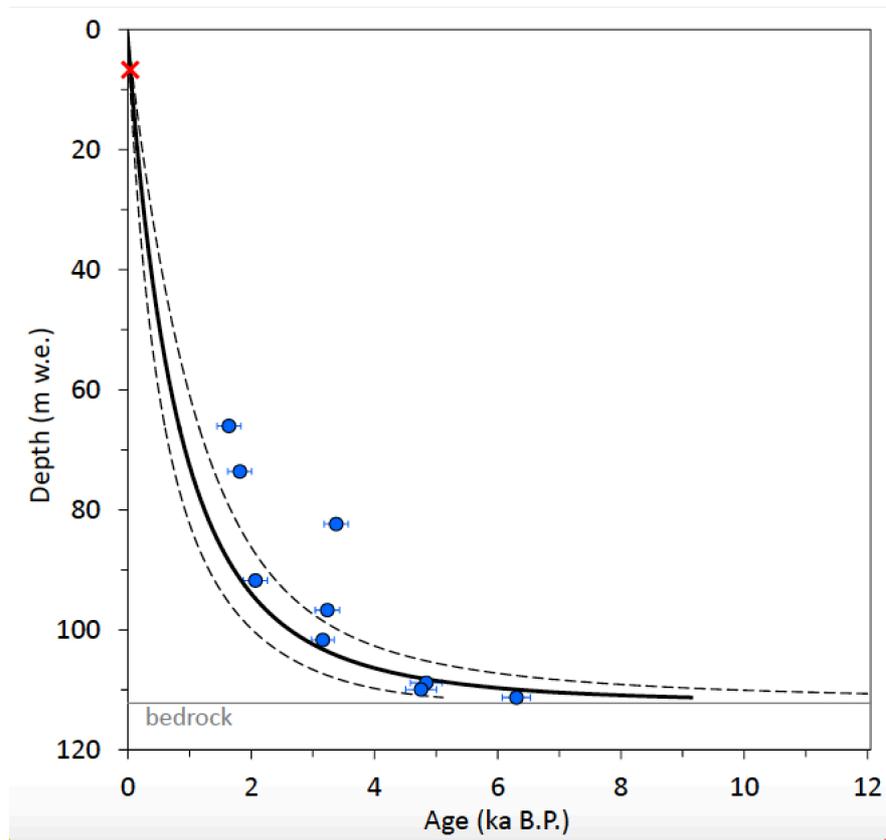


Figure 4: The depth-age relationship of the Chongce 216.6 m Core 4. The dashed lines represent the 1σ confidence interval of the 2p model fit (solid line). The red cross stands for the tritium horizon, green diamonds for the ^{210}Pb ages calculated at intervals of 5 m w.e. (Fig. 3), and the blue dots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

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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. ¹⁴C ages with 1σ error bars.

