Dear Editor,

Many thanks for the constructive comments. Below I have made a point-to-point response to the comments. The comments are in black, and our response is in blue. I have revised the original manuscript following the comments, and hope that the revision can be accepted by The Cryosphere.

Sincerely yours,

Hou Shugui

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response to J. Gombiner' comments

This is an interesting paper that should eventually be published.

However, the authors could give more thought to the calculation of dose rate and the meaning of the optical age for basal sediment.

The OSL age is the equivalent dose divided by the dose rate. In calculating the OSL age, the authors calculated a lower limit age for dehydrated sediment, containing air in the pore space, and an upper limit age, for hydrated sediment containing water in the pore space. The dose rate is lower for hydrated sediment because water attenuates radiation transfer from grain to grain. The actual sample came from sediment embedded within ice. The authors should calculate a dose rate for the real situation of sediment in ice.

There are potentially two additional sources of radiation that are not included in the dose rate calculation.

(1) Radiation from the bedrock or subglacial sediment.

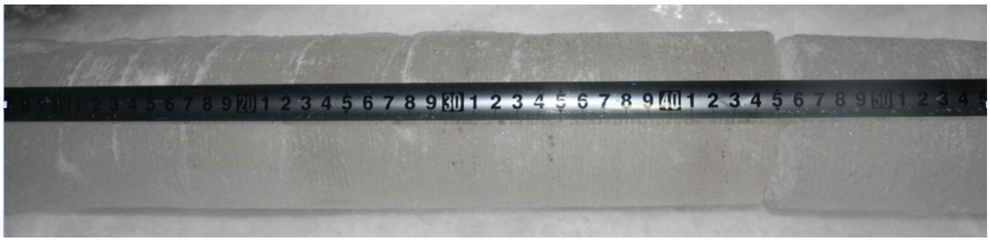
(2) Radiation from dust layers in the core.

The authors should add these sources of radiation to the dose rate, or show that they are insignificant. If these other sources are included, the higher radiation dose rate would lower the calculated age.

Yes we fully agree that the dose rate is determined by many factors, including the potentially two additional sources of radiation as indicated above.

Willerslev et al. (2007) provided the first luminescence measurements on the single grains of quartz and feldspar extracted from a sample cut out of an opaque part of the Greenland Dye 3 basal ice containing dispersed sandy and silty particles. They found that the dose rate contribution from the underlying bedrock was negligible following calculations based on radiation transport modelling software (MCNP5). Because no literature values are available to calculate the dose rate contribution from the underlying bedrock at our drilling site, we, for the moment, assume that its contribution to the dose rate was insignificant.

The sediment sample was collected from the very bottom several centimeters of Core 4. Its high particle content (~70%) suggests a similar condition as shown by the inset photo of Figure S1. Though dust layers are frequently observed along the Core 4, they are much weaker than the bottom section, as shown by the photo below with typical dust layers along the core.



A 18.7 m ice core drilled at the summit (6530 m a.s.l.) of the Chongce ice cap in 1992 gives a maximum dust mass concentration of 955 $mg.kg^{-1}$ (Li et al., 2006). This provides a general impression of dust layers along the Chongce ice cores, which is ~3 orders of magnitude lower than the bottom sediment, suggesting insignificant influence of radiation from dust layers in the core, given a similar radiation intensity of the dust layers in the core and the bottom sediment.

As discussed above, slightly increased dose rate would be expected if these additional sources of radiation were included, thus resulting in a slightly younger age. Therefore, our upper limit age may be over estimated.

Li, Y., Yang, Y., Han, J., Xie, Z., Nakawo, M., and Goto-Azuma, K.: Persistent decrease of dust burden for about 100 years over middle-upper Troposphere of the southern Taklimakan Desert, China, J. Glaciol. Geocryol., 28, 873-878, 2006. (in Chinese with English abstract).

Willerslev, E., Cappellini, E., Boomsma, W., Nielsen, R., Hebsgaard, M. B., Brand, T. B., Hofreiter, M., Bunce, M., Poinar, H. N., Dahl-Jensen, D., Johnsen, S., Steffensen, J. P., Bennike, O., Schwenninger, J.-L., Nathan, R., Armitage, S., de Hoog, C.-J., Alfimov, V., Christl, M., Beer, J., Muscheler, R., Barker, J., Sharp, M., Penkman, K. E. H., Haile, J., Taberlet, P., Gilbert, M. T. P., Casoli, A., Campani, E., and Collins, M. J.: Ancient biomolecules from deep ice cores reveal a forested southern Greenland, Science, 317, 111-114, doi: 10.1126/science.1141758, 2007.

Finally, I am not sure that the OSL age of the basal sediment directly relates to the age of the ice cap. The authors suggest that the sand-sized quartz grains are sourced from subglacial erosion. If true, it seems likely that some of the silt-sized quartz is also derived from subglacial erosion. Thus, it is conceivable that the dated aliquots are a mixture of eolian quartz and subglacially derived quartz.

Yes the dated aliquots are a mixture of eolian quartz and subglacially derived quartz. But because the distance from the summit of the Chongce ice cap to the drilling site is only several kilometers, and the ice cap is much shallower in comparison to the ice sheets, the scoured sediment experienced weak grinding. This suggests that even some of the silt-sized quartz is also derived from subglacial erosion, its portion might be very small. Thus the dated aliquots are mostly an eolian origin.

If the ice flow at the core site is dominated by downward vertical motion, then the OSL age of the eolian component of the dated aliquots would represent the time for the ice to move from the surface to the bed, not the age of the ice cap itself.

Yes we agree with the comment, and this will be clarified in the revision.

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comments by Anonymous Referee #1

The manuscript by Zhang et al. provides interesting and new data which justify publication in The Cryosphere. It is relatively well structured and well written. However, English wording is partly not sufficient and some language editing will be required (for example in lines 15: "…. interpretation this information….", "….highland over the world….", line 21 "its sounding regions.").

We have accordingly revised these sentences.

Lines 14-15: We revised this sentence as:

A precise chronology is the essential first step for a reliable interpretation of the ice core records.

Lines 15-16: We revised this sentence as:

The Tibetan Plateau, sometimes called "the Roof of the World", is the world's highest and largest plateau with an average elevation exceeding 4000 m above sea level (a.s.l.) and an area of 2.5 Million square kilometers.

Lines 20-21: Following Cheng et al. GRL 2012, we revised this sentence as:

During the past two decades, the Guliya ice core record has been widely used as a benchmark for correlating regional climate variables in the Westerlies region of the central Asia and the northern Tibetan Plateau.

There are three major deficiencies which need to be addressed before publication:

1) The implications of the Kesang Cave record for the reliability of the Guliya ice core chronology are barely touched in the manuscript. The issue is mentioned but not explained in detail. Unexperienced readers will not understand the point. So, why is Kesang Cave and also the new study supporting the opinion that the Guliya ice core chronology is not correct. What is the evidence from Kesang Cave? This is not explained in sufficient way.

Yes we include a short introduction about the records of the Kesang Cave and the Guliya ice core in the Supplement in order to make the communication as concise as possible.

The Guliya ice core and the Kesang Cave core

In 1992, a 308.6 m ice core to bedrock was recovered from the Guliya ice cap located at 35°17’N, 81°29’E on the northwest Tibetan Plateau (Figure 1). The drilling site is at an elevation of 6200 m a.s.l. Top 266 m of the core was dated to a period spanning 110 ka, and ice below 290 m depth was suggested to be more than 500 ka old due to ^{36}Cl-dead in the ice (Thompson et al., 1997). Three Guliya interstadials (Stages 3, 5a, and 5c) are marked by increases in δ^{18}O values similar to that of the Holocene and Eemian (~124 ka ago) (Thompson et al., 1997).

The Kesang Cave is located in the Tekesi County,western China (42°52′ N, 81°45′ E, elevation ~2000 m a.s.l.) (Figure 1). Eight samples from the Kesang Cave were collected to establish the Kesang δ^{18}O record with three covering the Holocene and five covering the rest of the Pleistocene portion. Cheng et al. (2012) obtained precise ages (~150 dates), all in stratigraphic order within errors, using a ^{230}Th dating technique in the University of Minnesota. The stalagmite δ^{18}O variations largely reflect changes in the δ^{18}O of meteoric precipitation (Cheng et al., 2012).

To reconcile the difference in the δ^{18}O variations between the Guliya and the Kesang records, Cheng et al. (2012) suggested that the Guliya record needs to be younger about a factor of two.

2) The authors state that the Chongce ice cap is not older than 42 ka. They also argue that this age is much younger than those assumed for the lower parts of the Guliya ice cores. However, what are the paleoclimatic implications of their findings for the Chongce ice cap? Are the new data evidence for an ice-free region in the Chongce region in Marine Isotope Stage (MIS) 3? If so, what are the implications for the snow and ice accumulation rate at Chongce since the establishment of the ice cap sometime in MIS 3 or later? What does the statement that Chongce subglacial sediments are much younger than Guliya basal ice imply? Are the two ice caps comparable in terms of altitude, exposure, underlying relief, etc.?).

We have thought seriously about these constructive comments.

The luminescence dating of the basal sediment of the Chongce ice cap provides an upper limit of 42 ± 4 ka. This might imply that the ice age at the bottom of the drilling site should be younger than this upper limit, although we do not know the exact age of the bottom ice at the drilling site. The new data does not imply for an ice-free region in the Chongce region in Marine Isotope Stage (MIS) 3, but for an ice-free condition at and below the elevation of the bottom at the drilling site during a (or more) warm period (or periods) since the upper limit age (e.g., MIS3, the Bølling-Allerød period, Holocene Climate Optimum). Given the surface elevation of the Chongce drilling site of 6100 m a.s.l. and the ice core length of 216.6 m, the elevation at the bottom of the Chongce drilling site should be 5883.4 m a.s.l. As to the Guliya ice core, the surface elevation of the drilling site of 6200 m a.s.l. and the ice core length of 308.6 m result in an elevation at the bottom of the Guliya drilling site to be 5891.4 m a.s.l., suggesting that the age of the bottom ice at the Chongce and the Guliya drilling sites might be comparable. Thus our new data can not support the previously suggested age of more than 500 ka old at the Guliya ice core bottom (Thompson et al., 1997).

We will clarify this information in the revision.

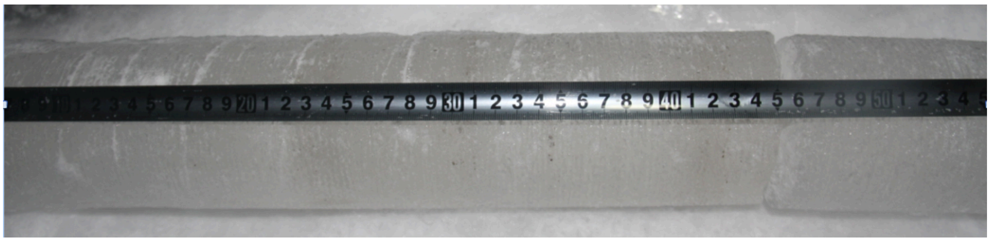
3) The authors state that the bottom sediments beneath Chongce ice cap are a combination of sediment and ice. What is the evidence that the base of the ice cap was actually reached? Are the sediments possibly representing a higher concentration of sediments within the ice but not necessarily basal sediments? The authors do not state that bedrock was drilled.

We have several pieces of evidences that the base of the ice cap might be actually reached.

① The bottom sediment is consisted of particles with wide range of size, including a high fraction of coarse particles. We had roughly measured the size distribution of a bottom sediment sample, with the results as shown in the table below. These coarse particles can not be an eolian origin. Moreover, the mountains surrounding the ice core drilling sites are snow and ice covered, thus eliminating the possibility that these coarse particles are from the surrounding high mountains. Therefore, these coarse particles should be scoured from the bed ground beneath the glacier, implying that the base of the ice cap might be actually reached.

size (μ m)	< 150	150 - 900	900 - 2000	> 2000
quality (g)	4.0	4.28	3.97	9.68
percent (%)	18.2	19.5	18.1	44.1

② Due to the limit of luminescence test, we can not take a photo the bottom section of the Core 4, but the high particle content (~70%) of the bottom sediment of Core 4 suggests a similar condition as shown by the inset photo of Figure S1. Though dust layers are frequently observed along the Core 4, they are much weaker than the bottom section. The photo below with typical dust layers along the core, when compared to the inset photo of Figure S1, makes clear the uniqueness of the bottom sediment section.

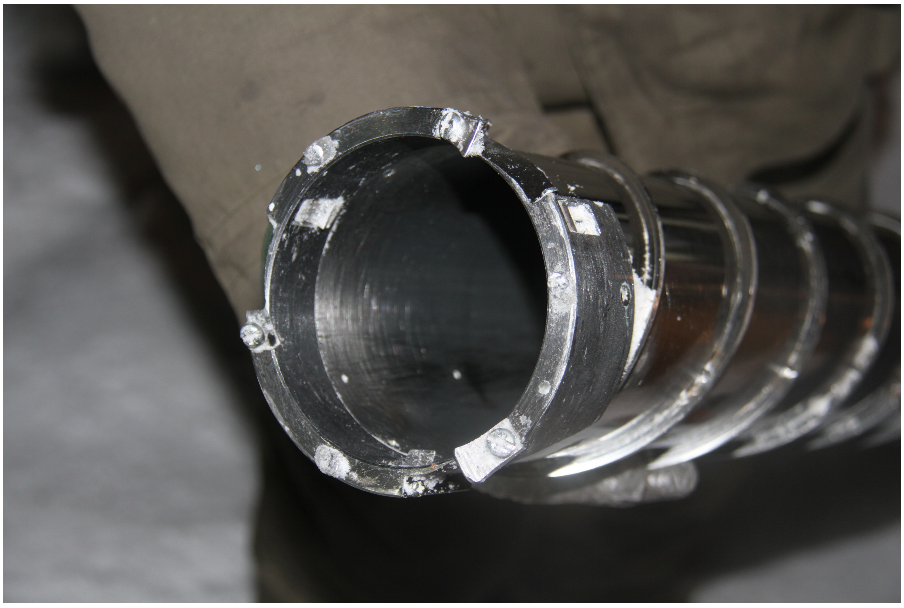


A 18. 7 m ice core drilled at the summit (6530 m a.s.l.) of the Chongce ice cap in 1992 gives a maximum dust mass concentration of 955 mg kg^{-1} (Li et al., 2006). This provides a general impression of dust layers along the Chongce ice cores, which is ~3 orders of magnitude lower than the bottom sediment, confirming the uniqueness of the bottom sediment section.

Li Y., Yang Y., Han J., Xie Z., M. Nakawo, K. Goto-Azuma. Persistent decrease of dust burden for about 100 years over middle-upper Troposphere of the southern Taklimakan Desert , China. J. Glaciol. Geocryol., 28(6), 873-878, 2006. (in Chinese with English abstract)

③ Radio sounding gives an ice thickness of ~ 214 m at the drilling site, which is very close to our ice core length of 216.6 m.

④ We drilled the ice cores by using an electromechanical drill in a dry hole. Unfortunately, this kind electromechanical drill is not designed to penetrate into bedrock. But when the cutters of the drill reached the bedrock, a unique vibrating movement can be felt through the cable by our experienced engineer, who has experience of drilling ice cores for >20 years. Below I attach a photo of the cutters after the last run of drilling, showing the blade fractures that were caused by the high-speed spinning cutters bounced from the bedrock.



Minor comments:

Are lines 9-14 on page 2 relevant? They could be removed.

This gives basic information about the Chongce ice cores. For the convenience of the readers, we think it better to keep this information.

Page 2, line 26: ice or water content? make clear

The total bottom sediment including ice is 1431.7 g. We first took a small portion of the sediment (13.4 g) for measuring ice content, which is determined by weighting the mass before and after drying, resulting in ~30% ice (water equivalent) content.

Page 3, line 20: what is “obvious”?

We have revised this sentence to make it clear.

Samples with IRSL (infrared stimulated luminescence) vs. blue OSL signal ratios over 10% of unity would be re-treated with fluosilicic acid again until the ratio was within 10% of unity.

Page 3, line 20: what are the dots in the unit here?

We have revised it as “IRSL (infrared stimulated luminescence) vs. blue OSL signal ratios”.

Page 4, line 9: What is the result if the first case is assumed? Explain the age result for this scenario too.

The OSL dating results of the coarse grain (90-150μm) quartz are shown below. Water content is assigned an absolute uncertainty of ±7%. The slightly older ages of the coarse grains in comparison to the fine grain quartz may imply that the former were more affected by the local scoured particles that were partly bleached. Another disadvantage for the coarse grain aliquots is that their medium and slow components accounts for a significant part of the natural OSL signal.

Sample	U (ppm)		Th (ppm)		K (%)		Water content	D_e	Dose rate	Age
	Gamma[1]	NAA	Gamma	NAA	Gamma	NAA	(%)	(Gy)	(Gy/ka)	(ka)
CCICE	3.66±0.15	3.45±0.12	11.21±0.42	11.40±0.32	3.52±0.10	3.48±0.08	0	238±51	5.25±0.45	45 ±11
CCICE	3.66±0.15	3.45±0.12	11.21±0.42	11.40±0.32	3.52±0.10	3.48±0.08	30	238±51	3.85±0.24	62 ±14

Page 4, lines 11-12: how is the study of Takeuchi et al. related with the new study here?

Takeuchi et al. (2014) reported radiocarbon dating of organic soil from the bottom of an 86.87 m ice core drilled at the top of the Grigoriev Ice Cap (41°58’33” N, 77°54’48” E. Fig. 1) in the Tien Shan Mountains, showing that the age of the soil is 12 656 -12 434 cal years before present. This age is apparently younger than our luminescence dating, suggesting that our upper limit age may be over estimated because potentially additional sources of radiation were not considered for calculating the dose rate.

Page 6, line 17: abbreviation should be probably “Geochron.”

Revised accordingly.

Page 7, line 7: no issue numbers

Revised accordingly.

Page 7, line 30: no capitalized letters if not for names or at beginning of sentence

Revised accordingly.

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comments by Anonymous Referee #2

General comments:

The Manuscript by Zhang et al. is interesting, original and well written and suitable for publishing in the cryosphere after a few minor adjustments.

Specific comments:

1) The inconsistency in chronology between the Guliya ice core record and the Kesang stalagmite mentioned in the introduction, should be described.

We include a short introduction about the records of the Kesang Cave and the Guliya ice core in the Supplement in order to make the communication as concise as possible.

The Guliya ice core and the Kesang Cave core

In 1992, a 308.6 m ice core to bedrock was recovered from the Guliya ice cap located at 35°17’N, 81°29’E on the northwest Tibetan Plateau (Figure 1). The drilling site is at an elevation of 6200 m a.s.l. Top 266 m of the core was dated to a period spanning 110 ka, and ice below 290 m depth was suggested to be more than 500 ka old due to ^{36}Cl-dead in the ice (Thompson et al., 1997). Three Guliya interstadials (Stages 3, 5a, and 5c) are marked by increases in $\delta^{18}O$ values similar to that of the Holocene and Eemian (~124 ka ago) (Thompson et al., 1997).

The Kesang Cave is located in the Tekesi County, western China (42°52′ N, 81°45′ E, elevation ~2000 m a.s.l.) (Figure 1). Eight samples from the Kesang Cave were collected to establish the Kesang $\delta^{18}O$ record with three covering the Holocene and five covering the rest of the Pleistocene portion. Cheng et al. (2012) obtained precise ages (~150 dates), all in stratigraphic order within errors, using a ^{230}Th dating technique in the University of Minnesota. The stalagmite $\delta^{18}O$ variations largely reflect changes in the $\delta^{18}O$ of meteoric precipitation (Cheng et al., 2012).

To reconcile the difference in the $\delta^{18}O$ variations between the Guliya and the Kesang records, Cheng et al. (2012) suggested that the Guliya record needs to be younger about a factor of two.

2) It seems that the dating has been performed on basal ice, however it is a little unclear and should be more clear!

Yes the dating was performed on the basal sediment. In fact, this sediment is a mixture of particles and ice. We will clarify this content in the revision.

3) "Ice content" and "water content" seem to be used randomly. This should be more clear.

We took a small portion of the sediment (13.4 g) for measuring ice content, which is determined by weighting the mass before and after drying, resulting in ~30% ice (water equivalent) content.

4) The influence of the ice matrix on the dose rate should be accounted for in detail and explained and an evaluation of dose rate for each scenario should be performed.

The infinite matrix dose rate was estimated using concentration-to-dose rate conversion constants presented by Adamiec and Aitken (1998) and the estimate of the dilution of the external dose rate by ice was assumed to be consistent with calculations recommended by Aitken (1985). Water, if present in the sediment matrix, absorbs radiation differently from mineral sediment, and has to be accounted for in the dose rate calculations. Since we have, for the moment, no information about the influence of the ice matrix on the dose rate, we use two extreme cases as our bounding scenarios, i.e., no water under the frozen condition and 30% water content if the sediment is saturated with water. The latter case (with high water content) results in a lower dose rate. Thus our upper limit age may be over estimated.

Adamiec, G. and Aitken, M.J.: Dose rate conversion factors: update, Anc. TL, 16, 37-50, 1998.

Aitken, M. J.: Thermoluminescence dating, Academic Press, London. 1985.

5) The photograph of the Core 2 show a very clear transition to basal ice in the core, however Core 4+5 are retrieved at a different place at the ice-cap where the contourlines in the map of Figure S1 suggest more ice dynamics, and the bottom part of the cores can be much more mixed. The 4-11 micro-metres fin-grained quartz used for the dating could be eolean material deposited onto the ice and therefore younger than the ice-cap. If this is the case, the grains would recieve most of their dose after mixing with the basal ice. The authors should discuss this possibillity.

Yes the 4 -11 μm fine quartz grains used for the dating are mostly an eolian origin. The OSL age of the eolian component would represent the time for the ice to move from the surface to the bed, which is younger than the ice cap. In fact, this OSL age, as an upper limit, does not imply for an ice-free region in the Chongce region, but for a retreat of the ice cap above the elevation of the bottom at the drilling site during a (or more) warm period (or periods) since the upper limit age (e.g., MIS3, the Bølling-Allerød period, Holocene Climate Optimum). Because only limited results are gained, and many processes (each with its uncertainty) are involved in affecting the final age, we are cautious to avoid over-explaining the results at this moment.

6) In the conclusion the authors suggest collecting more suitable glacier basal sediment. It should be explained what "suitable" means.

We have drilled ice cores from several glaciers and ice caps on the Tibetan Plateau. This is the first time to collect sufficient amount of sediment at the Chongce ice core bottom for the luminescence dating. To avoid misunderstanding, we revised this sentence as the following.

The major limitation of the current work is the very small number of absolute datings, but this preliminary work provides potential implications for exploring age of mountainous glacier bottom ice. Future work should include collecting more glacier basal sediment samples for the luminescence dating....

Technical corrections:

page 1, line 9: more than one order of magnitude younger

Revised accordingly.

page 1, line 15: interpretation of this information.

Revised accordingly.

page 5, line 5-6: The sentence "We have no information about the behavior of ice in the sediment" should be refrased.

We revised this sentence as the following.

Since we have, for the moment, no information about the influence of the ice matrix on the dose rate, we use two extreme cases as our bounding scenarios, i.e., no water under the frozen condition and 30% water content if the sediment is saturated with water.

The first luminescence dating of Tibetan glacier basal sediment

Zhu Zhang, Shugui Hou, Shuangwen Yi

School of Geographic and Oceanographic Sciences, Nanjing University, Nanjing, 210093, China

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

Abstract. Dating of ice cores drilled in the high mountain glaciers is difficult because seasonal variations cannot be traced at depth due to rapid thinning of the ice layers. Here we provide the first luminescence dating of the basal sediment of the Chongce ice cap in the northwest Tibetan Plateau. Assuming the sediment is of similar (or older) age as the surrounding ice, the luminescence dating of 42 ± 4 ka provides an upper limit for the age of the bottom ice at the drilling site. This result is more than one order of magnitude younger than the previously suggested age of the basal ice of the nearby Guliya ice cap (~40 km in distance).

1 Introduction

Ice cores from the high elevation regions provide a wealth of information for past climatic and environmental conditions that extends beyond the instrumental period. A precise chronology is the essential first step for a reliable interpretation of the ice core records. The Tibetan Plateau (TP), sometimes called "the Roof of the World", is the world's highest and largest plateau with an average elevation exceeding 4000 m above sea level (a.s.l.) and an area of 2.5 Million square kilometers. It has the largest number of glaciers outside the polar regions. In 1992, a 308.6 m ice core to bedrock was recovered from the Guliya ice cap on the northwest TP (Fig. 1). Top 266 m of the core was dated to a period spanning 110 ka, and the ice below 290 m was suggested to be more than 500 ka old due to ^{36}Cl-dead in the ice (Thompson et al., 1997). This makes it the second oldest continuous ice core, only younger than the Antarctic EPICA Dome C ice core. During the past two decades, the Guliya ice core record has been widely used as a benchmark for correlating regional climate variables in the Westerlies region of the central Asia and the northern Tibetan Plateau. However, Cheng et al. (2012) suggested a substantial revision of the Guliya chronology due to the enormous inconsistence between the δ^{18}O records of the Guliya ice core and the Kesang stalagmite (Fig. 1 and Supplement).

Luminescence dating can be readily applied to most terrestrial sediments and can be used to date sediments on timescales from 10^1 to 10^5 years, encompassing the entire late Quaternary (Fuchs and Owen, 2008). Dating errors within a few percent of the age can be achieved depending upon the nature of the sediment and the laboratory methods. During the recent decades, optically stimulated luminescence (OSL) method has been successfully used for dating glacial sediments on the TP and surrounding regions (e.g., Owen et al., 2003; Ou et al., 2014; Hu et al., 2015). Willerslev et al. (2007) provided the first luminescence measurements on the single grains of quartz and feldspar extracted from a sample cut out of an opaque part of the Greenland Dye 3 basal ice containing dispersed sandy and silty particles. To our knowledge, this is the only published luminescence dating of glacier basal ice so far. As pointed out by the authors, at the time when the Dye 3 ice core was drilled (1979–1981), no standard apparatus or procedures were used to avoid inadvertent exposure to light during the drilling and subsequent handling, inspection and storage of the ice cores. For this reason, the sample may be considered to be highly problematic for luminescence dating (Willerslev et al., 2007).

2 The Chongce ice cores

In 2012, we drilled two ice cores to the bottom with the length of 133.8 m and 135.8 m respectively, and a shallow ice core with length of 58.8 m at an altitude of 6010 m a.s.l. from the Chongce ice cap (Fig. S1). The Chongce ice cap is located in the west Kunlun Mountains on the northwest TP, with a snowline altitude about 5900 m a.s.l.. It is 28.7 km in length, covering an area of 163.06 km^2, with a volume of 38.16 km^3. The measured ice temperature is about -8.8 °C at depth of 130 m for both the 133.8 m and 135.8 m core boreholes. The drilling sites are about 40 km away from the Guliya drilling site (Fig. 1). The very bottom of the core is a combination of sediment and ice (see picture in Fig. S1). No special precautions were taken to avoid exposure to light during the drilling operation. Therefore, in 2013, two more ice cores to the bottom were recovered with the length of 216.6 m and 208.6 m respectively at an altitude of 6100 m a.s.l. (35°14'57" N, 81°5'28" E. Fig. S1). This time we paid special attention to avoid exposure to light during the drilling and subsequent procedures. The drilling was performed at night. When it was close to the bottom, the cores, together with chips, were recovered in faint red light. They were directly sacked into opaque plastic bags and immediately wrapped with aluminium foil and adhesive tape. The ice cores were kept frozen and transported to the cold room in the Nanjing University for further processing.

3 Sample preparation and measurements

Sample preparation was performed under the safe red light in the Luminescence Dating Laboratory of the Nanjing University. The total bottom sediment including ice is 1431.7 g. We first took a small portion of the sediment (13.4 g) for measuring ice content, which is determined by weighting the mass before and after drying, resulting in ~30%

ice (water equivalent) content. As the water content may have varied over the entire burial period of the sample, we assigned a relative uncertainty of 50% to allow for possible fluctuations. Afterwards, this part of sediment was dried in oven (<60 °C). About 5 g dried sediment was ground to fine powder for determining U, Th and K concentrations by neutron activation analysis (NAA) at the China Institute of Atomic Energy, Beijing. The results are given in Table 1. As the measured concentrations are normally low, the accuracy of the dose rates, calculated from the NAA results, may have been affected by the inhomogeneity of the deposits. Therefore, ~ 100g sample was also measured for >24 h using the high-resolution gamma spectrometry (Table S1). The sample was ignited at 450 °C, cast in wax and stored for >3 weeks to assure equilibrium conditions for ^{226}Ra–^{222}Rn decay (Murray et al., 1987).

The rest of the sediment (~1300 g) was put into a beaker and melted in the Luminescence Dating Laboratory at room temperature (~ 20 °C). The melt water was carefully extravasated. This process was repeated to leave as little water inside the beaker as possible. Then the sediment was filtered through the 200 μm wet sieve. The filtered sediment was successively soaked in the 10% hydrochloric acid and 30% hydrogen peroxide to remove carbonate and organic matters. Afterwards, the residual was wet-sieved to separate the coarse grains (90 - 150 μm) from the fine grains (<40 μm).

The coarse grains were then separated by dense liquid (2.58 g.cm^{-3}), resulting in the coarse quartz grains at the bottom. After purified with deionized water, the coarse (90 - 150 μm) quartz grains were immersed in 40% hydrofluoric acid for 40 minutes to remove any remaining feldspar contamination, and in 10% hydrochloric acid for 40 minutes to remove residual fluoride. The purity of the quartz was determined using the OSL-IR depletion ratio method (Duller, 2003). Even after being etched (40% HF, 40 minutes) twice, it was not possible to remove feldspar completely. So, a post-IR measurement with blue LED stimulation (Banerjee et al., 2001) was applied to the coarse grain quartz measurements.

As for the fine grains (<40 μm), a fraction (4 - 11 μm) was further isolated according to 'Stocks' law. To extract pure fine quartz grains, the sample was submerged first in the 40% fluosilicic acid for 10 days, and then in the 10% hydrochloric acid to remove any fluorides. The purity of treated fine grains was checked by the same method as that used with the coarse grains quartz (Duller, 2003). Samples with IRSL (infrared stimulated luminescence) vs. blue OSL signal ratios over 10% of unity would be re-treated with fluosilicic acid until the ratio was within 10% of unity. The coarse quartz grains (90 - 150 μm) were then mounted on stainless steel discs (~2 mm in diameter) using the Silkospray silicone oil, and the fine quartz grains (4 - 11 μm) were settled on discs using pure water with a pipette. Measurements were performed on a Risø TL/OSL reader (model DA-20C/D), fitted with blue LEDs (470 nm, ~80 mW.cm^{-2}), infrared LEDs (870 nm, ~135 mW.cm^{-2}) and a ^{90}Sr/^{90}Y beta source (Bøtter-Jensen et al., 2010).

The OSL signal from the quartz grains was detected by a 9235QA photomultiplier tube through a 7.5 mm Schott U-340 detection filter.

The quartz equivalent doses (D_e) were determined using the single aliquot regeneration (SAR) protocol (Murray and Wintle, 2000). A preheat temperature of 260 °C with a cutheat of 220 °C was selected for D_e measurement with an elevated temperature (280 ˚C) blue light bleach at the end of each cycle. The early background subtraction (first 0.16 s minus background from 0.16 - 0.32 s interval) was used for signal integration, and to minimize the influence of slow and medium components (Cunningham and Wallinga, 2010).

Individual D_e values were obtained using a single-saturating exponential fitted in Analyst version 4.31.7 (Duller, 2015). The uncertainty of individual D_e values was calculated using counting statistics and an instrumental uncertainty of 1.5%.

4 Results and discussion

The basic assumption of the OSL dating technique is that the mineral grains were fully bleached before deposited. The possibility of complete bleaching of the grains decreases for materials from supraglacial debris, to englacial debris, to basal debris (Fuchs and Owen, 2008), suggesting that extreme care should be taken when applying the luminescence dating techniques to basal debris. The OSL dose-response and decay curves of the quartz aliquots are shown in Fig. 2. It's apparent that parts of the coarse grain (90 - 150 μm) quartz aliquots approach the saturated level, but all the fine grain aliquots are similar and well below the saturated level. The decay curves of the fine grain (4 - 11 μm) show that the OSL signal decreases very quickly and approaches to background level during the first seconds of stimulation. We further decomposed the natural OSL signal of the fine grain aliquots into fast, medium and slow components (Fig. S2). Fast component accounts for around 87% of the natural signal, indicating that the signal is fast component dominant. However, the OSL decay curves of the coarse grain aliquots display a relatively slow trend (Fig. 2). We also performed scanning electron microscope of the sediment sample. A typical coarse grain quartz is shown in Fig. S3. Its angular texture and low degree of deformation suggest that this coarse grain quartz might have been scoured from bedrock, which mainly consists of Triassic high-K granitoids in the west Kunlun Mountains (Wang et al., 2013). In addition, the D_e distribution presented in Fig. 3 shows a narrow and nearly symmetric shape for the fine quartz grains, indicating sufficient bleaching of the fine quartz grains. Based on these results, we believe that only the fine grain quartz is appropriate for luminescence dating of our sample, hence excluded the coarse grain quartz from further calculation. The same conclusion was also reached in some previous studies on Himalayan glacial deposits (e.g. Hu et al. 2015).

We further evaluate the reliability of the fine quartz (4 - 11 μm) grain measurements by their recuperation and recycling ratios. The recuperation values of all the fine grain quartz aliquots are below 5% (Fig. S4). The recycling ratios range from 0.82 to 1.2, with 9 of the 12 fine grain quartz aliquots having recycling ratios within the acceptable range of 0.9 to 1.1. Only the aliquots with recycling ratios within the acceptable range were used for further analysis. Among these, one additional aliquot was also excluded because its D_e value fell outside 2σ of the distribution (Fig. 3). In the end, 8 fine grain quartz aliquots were used for OSL age calculation, resulting in an average equivalent dose (D_e) of 178 ± 9 Gy (Table 1).

Annual dose rate (D) can be estimated from the U, Th and K concentrations, water contents and cosmic ray contribution (Guérin et al., 2011). An alpha efficiency factor (a-value) of 0.04 ± 0.02 for quartz (Rees-Jones, 1995) was used to calculate the alpha contribution to the total dose rate. The cosmic dose rate is negligible because the sediments are covered by thick ice and multiple dust layers, hence largely insulated from light and cosmic rays. There are potentially two additional sources of radiation that are not included in the dose rate calculation: (1) radiation from the bedrock or subglacial sediment, and (2) radiation from dust layers in the core. Willerslev et al. (2007) suggested that the dose rate contribution from the underlying bedrock at the Greenland Dye 3 ice core drilling site was negligible following calculations based on radiation transport modelling software (MCNP5). Because no literature values are available to calculate the dose rate contribution from the underlying bedrock at our drilling site, at the first stage we assume that its contribution to the dose rate was insignificant. As to radiation from dust layers in the core, we have not measured the dust concentrations of our Chongce ice cores, but A 18.7 m ice core drilled at the summit (6530 m a.s.l.) of the Chongce ice cap in 1992 gives a maximum dust mass concentration of 955 $mg.kg^{-1}$ (Li et al., 2006). This provides a general impression of dust layers along the Chongce ice cores, which is ~3 orders of magnitude lower than the bottom sediment, suggesting insignificant influence of radiation from dust layers in the core, given a similar radiation intensity of the dust layers in the core and the bottom sediment. Therefore, slightly increased dose rate would be expected if these additional sources of radiation were included, thus resulting in a slightly younger age.

The converted U, Th and K concentrations from the gamma measurements are close to the NAA results (Table 1), affirming the accuracy our element measurements. Water, if present in the sediment matrix, absorbs radiation differently from mineral sediment, and has to be accounted for in the dose rate calculations. Since we have, for the moment, no information about the influence of the ice matrix on the dose rate, we use two extreme cases as our bounding scenarios, i.e., no water under the frozen condition and 30% water content if the sediment is saturated with water. The latter case (with high water content) results in a lower dose rate, hence an older age (Table 1).

The dated fine grain quartz aliquots are a mixture of eolian quartz and subglacially scoured quartz. But because the distance from the summit of the Chongce ice cap to the drilling site is only several kilometers, and the ice cap is much shallower in comparison to the ice sheets, the scoured sediment experienced weak grinding. This suggests that even some of the fine grain quartz is derived from subglacial erosion, its portion might be very small. Thus the dated aliquots are mostly an eolian origin, implying that the luminescence dating would represent the time for the ice to move from the surface to the bed

Our new data does not imply for an ice-free region in the Chongce region since 42 ± 4 ka ago, but for an ice-free condition below the elevation of the bottom at the drilling site during a (or more) warm period (or periods) since this upper limit age (e.g., Marine Isotope Stage (MIS) 3, the Bølling-Allerød period, Holocene Climate Optimum). Takeuchi et al. (2014) reported radiocarbon dating of organic soil from the bottom of an 86.87 m ice core drilled at the top of the Grigoriev Ice Cap (41°58’33” N, 77°54’48” E) in the Tien Shan Mountains, showing that the age of the soil is 12 656 - 12 434 cal years before present. Takeuchi et al. (2014) suggested that the Grigoriev Ice Cap did not exist in the Bølling-Allerød period.

Given the surface elevation of the Chongce drilling site of 6100 m a.s.l. and the ice core length of 216.6 m, the elevation at the bottom of the Chongce drilling site is 5883.4 m a.s.l.. As to the Guliya ice core drilling site, its surface elevation of 6200 m a.s.l. and its length of 308.6 m result in an elevation at the bottom to be 5891.4 m a.s.l., suggesting that the age of the bottom ice at the Chongce and the Guliya drilling sites might be comparable. Thus our new data can not support the previously suggested age of more than 500 ka old of the Guliya bottom ice (Thompson et al., 1997).

~~Finally, it is worthy pointing out that our dose rates are quite consistent with the results of many previous studies in region. Examples include the OSL dating of the eolian sediments from the terrace of the Keriya River (about 110 km northeast away from our drilling site) (Han et al., 2014), the glacial deposits in the eastern Himalaya (Hu et al., 2015), the glacial sediments and adjacent loess from moraines in the Tien Shan Mountains (Narama et al., 2009), and the glacial till sediment in the Altai Mountains (Xu et al., 2009).~~

5 Conclusions

We provide an OSL age estimate of the basal sediment sample from the Chongce ice cap in the west Kunlun Mountains on the northwest TP, which gives an upper limit age of 42 ± 4 ka. The age is more than one order of magnitude younger than the previously suggested age of bottom ice in the west Kunlun Mountains. The major limitation of the current work is the very small number of absolute datings and simple assumptions, but this preliminary work provides potential implications for exploring age of mountainous glacier bottom ice. Future work should include collecting more glacier basal sediment samples for the luminescence dating, and better understanding the unique processes for preserving the luminescence signal in the glacier basal sediment. ~~However, the current work provides an important step towards better understanding the TP ice cores and more accurate interpretation of their records.~~

Author contribution

Shugui Hou designed this work and drilled the ice cores. Zhu Zhang and Shuangwen Yi performed the measurements. Shugui Hou wrote the draft of the paper. All authors contributed to discussion of the results.

Competing interests

The authors declare that they have no conflict of interest.

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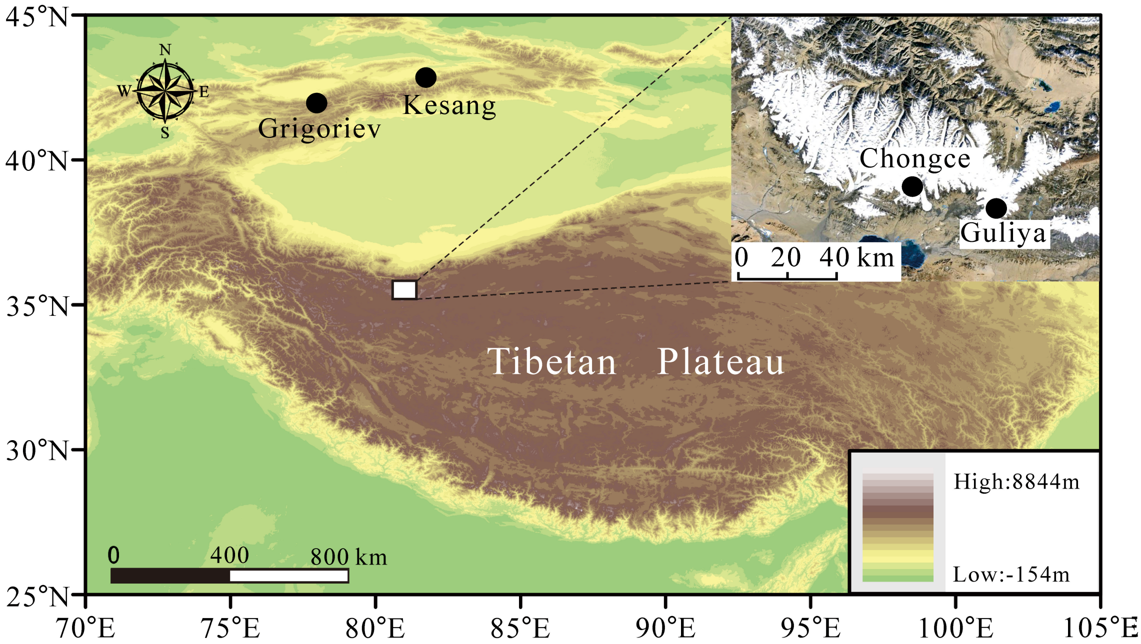

Figure 1: Study area map showing the locations of the Chongce and Guliya ice caps in the west Kunlun Mountains, the Kesang cave and the Grigoriev Ice Cap.

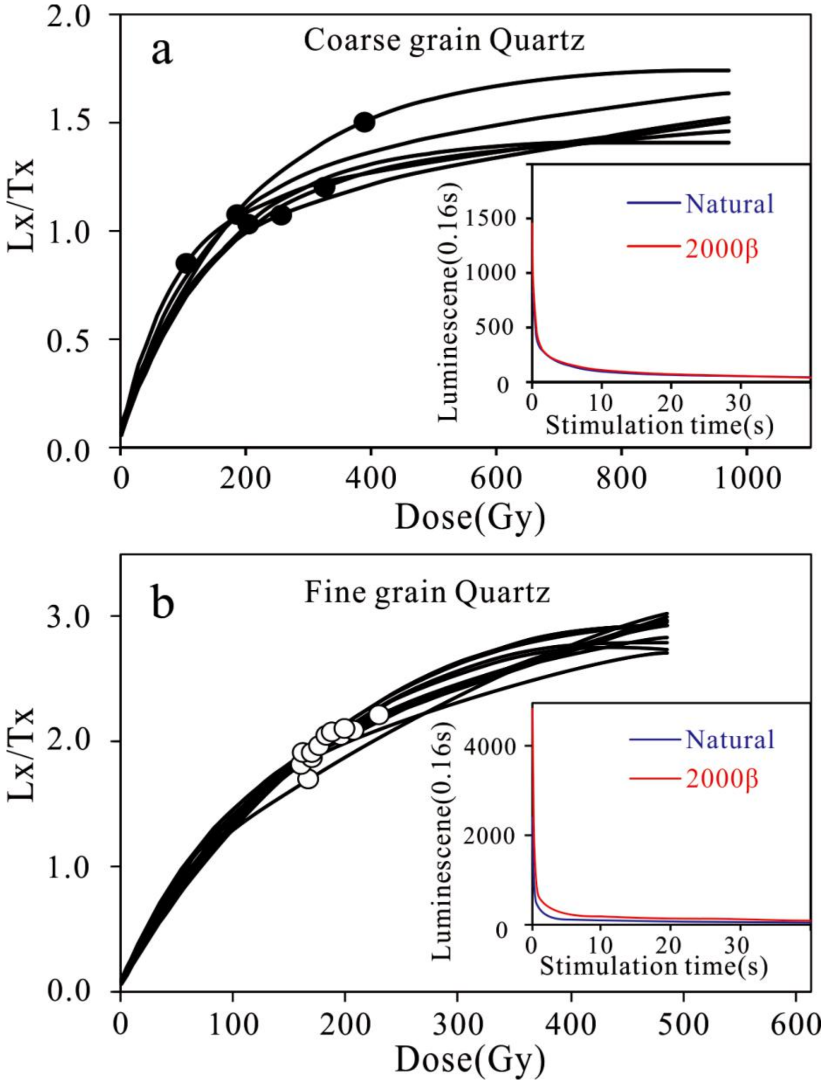

Figure 2: The OSL dose-response and decay curves of the coarse and fine grain quartz aliquots. Inserts show decay curves of the natural and regenerated dose (2000β) of the sample.

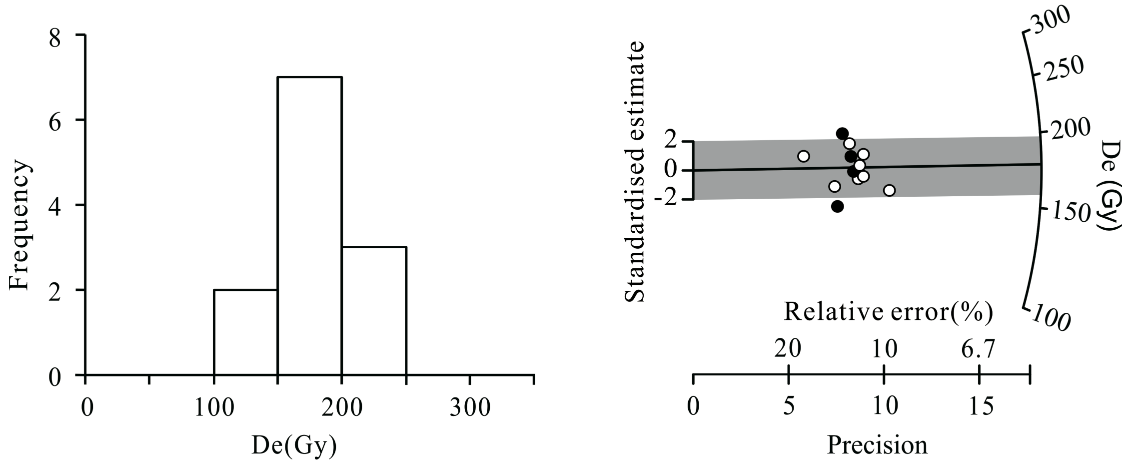

Figure 3: D_e distribution histogram (left) and radial plot (right) showing the distribution of D_e results for the fine grains. The shaded region represents 2σ width of the distribution. The filled symbol represents the aliquots that were excluded in the final age calculation.

Table 1. Results of the fine quartz grains with their corresponding OSL ages.

Sample	U (ppm)		Th (ppm)		K (%)		D_e	Water content	Dose rate	Age
	Gamma	NAA	Gamma	NAA	Gamma	NAA	(Gy)	(%)	(Gy/ka)	(ka)
CCICE	3.66 ± 0.15	3.45 ± 0.12	11.21 ± 0.42	11.40 ± 0.32	3.52 ± 0.10	3.48 ± 0.08	178 ± 9	0	5.81 ± 0.46	31 ± 3
								30 ± 15	4.24 ± 0.37	42 ± 4