A new radiometric timescale challenges the chronology of the iconic 1992 Guliya ice core

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**Abstract:** Tibetan ice cores provide essential data about the regional paleoclimate. Among them, the Guliya Plateau ice core (GP1992, 308.6 m in length), drilled in 1992 through the Guliya ice cap, has elicited exceptional interest, because of its inferred antiquity. The base of GP1992 was tentatively dated to 760 ka based on 36Cl-depleted ice in its bottom section. A companion core (GP2015, 309.7 m in length) was drilled in 2015 nearby the GP1992 drilling site. GP2015 was dated to ~41 ka at 187.4 m depth by assuming, in part, that a cosmogenic 36Cl maximum represented the Laschamps geomagnetic excursion at ~ 41 ka. In this paper, we revisit the timescales of GP1992 and GP2015. To do this, we exhaustively date a new Guliya ice core (GP2021) drilled in 2021 close to the previous GP drilling sites. GP2021 did not reach bedrock, but terminated at 175.1 m depth. We apply an ice flow model constrained by multiple dating methods, including the bomb 3H horizon, 210Pb, 39Ar, 14C, and stratigraphic correlation based on the oxygen isotopic composition of ice and O2. All our data are compatible with a bottom age of < 3 ka for GP2021. The bottom of GP2021 is stratigraphically equivalent to a depth of 253 m in GP1992, where the age is ~ 100 ka in the original GP1992 chronology. Based on this discrepancy, conclusions about climate history and dynamics deduced from GP1992, as well as GP2015, need to be reevaluated before they can be used as a regional reference of Tibetan paleoclimate.

**Main Text:**

The GP1992 ice core, 308.6 m in length, was drilled in 1992 to bedrock on the Plateau area of the Guliya ice cap in the northwestern Tibetan Plateau at 35°14′N, 81°28′E (Fig. 1 and Fig. S1) (*1*). The timescale of GP1992 proposed by Thompson et al. (*1*) invokes an age at the base of > 500 ka or 760 ka (thousand years before present; where present = 1950 C.E.). This basal age is far older than all other extra-polar ice cores. It would make GP1992 the second oldest stratigraphically continuous ice core in the world, after only the Antarctic ice cores EPICA Dome C (*2*).

Thompson et al. (*1*) derived a timescale for GP1992 through a number of steps. They derived an age for the ice at the bed by assuming that the decreasing 36Cl concentration of ice in the very bottom of the core is due predominantly to radioactive decay. They matched variations in the δ18Oice (*3*) of GP1992 to variations of paleo-atmospheric CH4 concentrations and δ18Oice in the Greenland GISP2 ice core (*4*). By this matching, they derived a timescale for the past 110 ka. They also identified high 36Cl activity at the section of 178-187 m, which dated to 35-40 ka in their timescale (*1*).

In 2015, another ice core (GP2015, 309.7 m in length) was drilled close to GP1992 (Fig. 1C and Fig. S1). In addition, three ice cores were drilled to bedrock at the Summit of the Guliya ice cap (hereafter referred as GS2015, 50.72 m, 51.38 m and 50.86 m in length, respectively) (Fig. 1B). Thompson et al. (*5*) established a chronology of the 50.86 m GS2015 core by matching the profile of the paleo-atmospheric isotopic composition of O2 (δ18Oatm, ref. *3*) preserved in air bubbles with the well-dated δ18Oatm record of the West Antarctic Ice Sheet (WAIS) ice core (*6*). They then transferred this GS chronology to GP2015 by matching their profiles of δ18Oice (*5*). They inferred an age of 15 ka at 144.4 m depth in GP2015 (*5*). Furthermore, Thompson et al. (*7*) inferred another featured age of 41 ka, based on a 36Cl peak at 187.4 m of GP2015, which they attributed to the Laschamp Geomagnetic Event. They also argued that a 36Cl peak at 179 m depth could, given their timescale, be associated with the Mono Lake event, a possible geomagnetic event dated to 30-36 ka (*7*). Although the timescale below 187.4 m of GP2015 has not been determined, the high consistency between timescales proposed for GP2015 and GP1992, at least until the inferred age of 41 ka, was invoked to support the accuracy of the GP ice core chronology at millennial to precessional timescales (*7*). Finally, Thompson et al. (*8*) counted snow layers in the upper part of GP1992, tracking these measurements back to an age of about 0.2 ka.

According to the timescale outlined above, the Guliya Plateau must have been continuously glaciated for the past 500 ka or 760 ka (*1*). GP1992 would provide a continuous climate record during the last glacial stage. This record was punctuated by a sequence of stadial and interstadial events, as well as abrupt climate changes, such as ~100 oscillations with an average period of 200 years between 15 and 33 ka (*1*). The timescale suggests an important role for orbital variations in the Tibetan climate record (*7*). This record has since been widely cited by numerous studies (e.g., *9*-*13*), and used for climate reconstructions. For example, the PAGES2k initiative employed GP1992 record as a regional proxy (*14*).

The 36Cl profiles of GP1992 and GP2015 are subject to alternative interpretations, and might not provide a reliable constraint on their timescales (*1*, *7*). The 36Cl excursion of GP2015, attributed to the Laschamps event, is not a unique feature of the record. For example, there are two enigmatic excursions to very high 36Cl values at shallower depths (*7*). The 36Cl decrease in the bottom ice of GP1992 gives information about ice age only if no processes except radioactive decay cause 36Cl concentrations to decrease. However, Cl- decreases progressively at the base of the ice cap, to remarkably low levels (Fig. S3). This feature suggests a nonradioactive pathway to Cl- loss, which presumably removes 36Cl as well as Cl-. Snow metamorphism and ventilation in the firn layers were assumed to be the main physical processes responsible for the instability of gaseous Cl- deposits (*15*). Given these phenomena and observations, 36Cl is not a robust tool for dating deep ice cores from low accumulation areas (*15*). In fact, the measured 36Cl accumulation rate of GP1992 was clearly lower than those of the other mid-latitude ice cores, and the measured 36Cl flux was also significantly lower than the modeled 36Cl deposition fluxes, partly due to low accumulation rate at the GP1992 drilling site (*16*), causing the instability of gaseous Cl- deposits in the firn layers (*15*).

Other studies favor a much younger timescales for the GP ice cores. Tian et al. (*17*) used radiometric 81Kr to date discharging ice, sampled at the outlets of the Guliya ice cap, to attain an upper age limit of the Guliya ice in the range of 15-74 ka. The large uncertainties may suffer from a consequence of the long 81Kr half-life (2.29\*105 years) when measuring 81Kr concentrations in young samples. The GP1992 chronology was also questioned by the results from other Tibetan ice cores (*18*-*20*). For instance, the basal ages of two ice cores that were drilled to bedrock from the Chongce ice cap, ~30 km from the Guliya ice cap (Fig. 1), were calculated to be ka and ka, respectively (*18*). Hou et al. (*19*) further suggested that the GP1992 and Chongce ice cores might cover a similar temporal span because of the significant similarity of their relative depth profiles of δ18Oice (Fig. S4).

In order to examine the credibility of the GP1992 and GP2015 timescales, we retrieved a new Guliya ice core in 2021 (GP2021) close to GP1992 and GP2015 (Fig. 1 and Fig. S1). GP2021 did not reach bedrock, but terminated at 175.1 m depth. We measured 210Pb, 39Ar, 14C and 3H for samples collected from GP2021 in order to establish its depth-age relationship. We also measured the isotopic composition of atmospheric O2 (δ18Oatm) to further constrain the age-depth curve. Moreover, we made continuous measurements of 3515 ice samples for stable isotopes (δ18Oice) with a sampling resolution of ~5 cm/sample for the purpose to directly compare variations of δ18Oice vs. depth in GP2021, GP2015 and GP1992 by matching their δ18Oice profiles. More details about drilling site, sample processing and measurements are provided in the Supplementary Materials (Figs. S5-S13 and Tables S1-S5).

**Fig. 1. Ice-core drilling locations on the Tibetan Plateau.** (**A**) Topographic map showing the Tibetan ice core drilling sites. The numbers below each drilling site except Guliya indicate the oldest 14C calibrated ages for each corresponding ice core, and the numbers inside the brackets below the Chongce, Zangser Kangri, and Shulenanshan ice cores are the bottom ice ages estimated by a two-parameter glacier flow model (*18*, *20*). Glacier data are from the Global Land Ice Measurements from Space (GLIMS; available at: http://www.glims.org, last access: 4 August 2020) (*21*). The topographic data are extracted from ETOPO1 elevation global data, available from National Oceanic and Atmospheric Administration at: http://www.ngdc.noaa.gov/mgg/global/global.html (last access: 4 August 2020) (*22*). (**B**) A three-dimensional satellite map showing the locations of the Guliya ice core drilling sites. GP cores stand for the GP1992, GP2015 and GP2021 drilling sites that are too close to be distinguished, and GS cores for the GS2015 drilling site at 6710 m above sea level. (**C**) A schematic depicts ice thicknesses and locations of the GP1992, GP2015 and GP2021 drilling sites. Ice thickness data are from ref. *23* deposited in the NOAA National Climate Data Center.

**Depth-age relationship of GP2021**

We made use of the radiometric 210Pb, 39Ar, 14C measurements and the 3H horizon corresponding to 1963 C.E. to establish the depth-age relationship of GP2021 (Fig. 2). The dating ranges of the respective radionuclides vary according to their different half-lives, with ~150 years for 210Pb (*24*), ~0.1 ka to ~1.8 ka for 39Ar (*25*), and ~0.5 ka to ~50 ka for 14C (*26*, *27*). The method of 210Pb has been reliably applied to date Tibetan ice cores within its age range (*18*, *20*). More recently, 39Ar has also been applied for Tibetan ice core dating by Atom Trap Trace Analysis (ATTA), a newly improved laser-based detection method (*25*). With this apparatus, ice core samples younger than 1.8 ka can now be dated with a precision of ±20% (*25*). For the GP2021 core, two organic carbon fractions, i.e., water insoluble organic carbon (WIOC) and dissolved organic carbon (DOC), have been used for 14C measurements (*28*). This 14C approach is particularly challenging for our work, because the proximity of our drilling site to the Taklamakan desert (Fig. 1A), leads to the exceptionally high mineral dust content in the Guliya glacier ice (Fig. S6). However, samples collected from the deep section (around 170-174 m) of GP2021 displayed good agreement between the 14C calibrated ages derived from the WIOC and DOC fractions. This result indicates high reliability of 14C calibrated ages in the deep section of GP2021.

The experimental timescale of GP2021 is compared with simulations of the D-J glacier model (*29*) as shown in Fig. 2A. The ice becomes older with increasing depth, reaching ~2.7 ka at the bottom of GP2021 (175.1 m). No dramatic thinning was simulated or observed in the 14C or 39Ar dates (Fig. 2). This is expected, because GP2021 terminated at 175.1 m depth, about 55 m above bedrock, which lies at ~230 m below the surface of the ice cap (Fig. S8).

We further compared the timescales of GP2021 and GP1992 (*1*) as shown in Fig. 2B. The depth-age relationships of GP2021 and GP1992 are quite comparable for their upper layers of tens meters (Fig. 2B). However, beneath the upper layers of tens meters, an obvious discrepancy is observed between the independently established chronologies of GP2021 and GP1992 (Fig. 2B), because exceptionally rapid thinning, reflected in the timescales of GP1992 and GP2015, begins at ~80 m depth for GP1992, and ~90 m depth for GP2015 (Fig. 2B), which was neither observed nor simulated for GP2021 (Fig. 2A). While some variability is expected for the timescales of the three GP cores, it is not plausible that authentic ages differ by more than an order of magnitude within their overlapping depth range (Fig. 2B). Therefore, either the GP1992 and GP2015 timescales are in error, or the GP2021 timescale is in error.

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**Fig. 2. The depth-age relationship of GP2021 (A), in comparison with previously established chronologies of GP1992 and GP2015 (B).** The depth-age relationship of GP2021 (thick blue line) constrained by the age points determined by absolute ages deduced from 210Pb, 39Ar, 14C and the 3H horizon of 1963 C.E. The dashed line stands for the GP2021 timescale based on ice flow modeling (D-J model, ref. *29*) allowing for a certain variability in annual net accumulation rates (±15%). The blue shading stands for the confidence band assuming a steady state of the Guliya ice cap. 14C results are either from the WIOC or DOC fraction, or a combination of both for the deep section of GP2021. The open symbols of 14C were considered as outliers, evaluated independently from the other dating methods applied in this study. The 39Ar ages at the depths of ~147 m, ~170 m, and ~174 m display large uncertainties due to contamination correction. Therefore, only their lower age limits could be established at these depths (horizontal black fading bars). The depth-age relationship of GP1992 is from ref. *1*, complemented with results from ref. *30* for its top 80 m section. The depth-age relationship of GP2015 is from refs. *6* and *9*.

**Age constraint of GP2021 from the isotopic composition of atmospheric O2 (δ18Oatm)**

O2 is a well-mixed gas in the atmosphere, given that its residence time (>1000 years) is much longer than the mixing time of the atmosphere (~ 1 year). Its paleoatmospheric value closely tracks northern hemisphere summer insolation (*31*). We can determine the timescale of an undated ice core by matching its δ18Oatm stratigraphy to the well-documented global record. This dating approach was recently applied to GP2015 by Thompson et al. (*5*) and the Chongce ice core by Hu et al. (*32*). Fig. 3 shows the δ18Oatm depth profile of GP2021, plotted against the δ18Oatm record of the West Antarctic ice sheet (WAIS) ice core (*6*). The GP2021 record is much noisier than WAIS, especially above 100 m depth. The greater scatter is common when comparing polar and extra-polar ice core δ18Oatm records. This is because extra-polar cores are generally recovered from warmer areas where respiration, melting, and other post-depositional processes alias δ18Oatm (*5*, *32*). Therefore, we identified samples affected by melting based on δAr/N2 values of trapped gases (*33*). We rejected all samples with δAr/N2 values higher than +30‰ (*32*), which corresponds to an anomalous Ar enrichment of about 3%. For reference, Thompson et al. (*5*) included samples with much larger δAr/N2 anomalies in constructing their GP2015 timescale after a correction for meltwater effects in their samples that was not performed in ref. *32*. The remaining δ18Oatm values (mean value = 0.13±0.05‰, N=46 including duplicate or triplicate analysis of samples) are slightly above the atmospheric value of the past ~3 ka (~0‰), as recorded in the WAIS record (*6*). This is likely a consequence of respiration, which has been observed in the upper sections of Tibetan ice cores (*32*). Respiration consumes the heavy isotope (18O) more slowly than 16O, thereby elevating δ18Oatm of residual O2 (more details in Supplementary Materials). Comparing GP2021 with the WAIS δ18Oatm record gives an age at 174.475 m of GP2021 (the depth for the deepest δ18Oatm sample) younger than 3 ka. This constraint reflects the fact that δ18Oatm decreases between 3 and 6 ka for WAIS (*6*), but no such trend was observed in the GP2021 δ18Oatm record (Fig. 3). This age constraint is entirely compatible with the age-depth scale of GP2021 as shown in Fig. 2A.

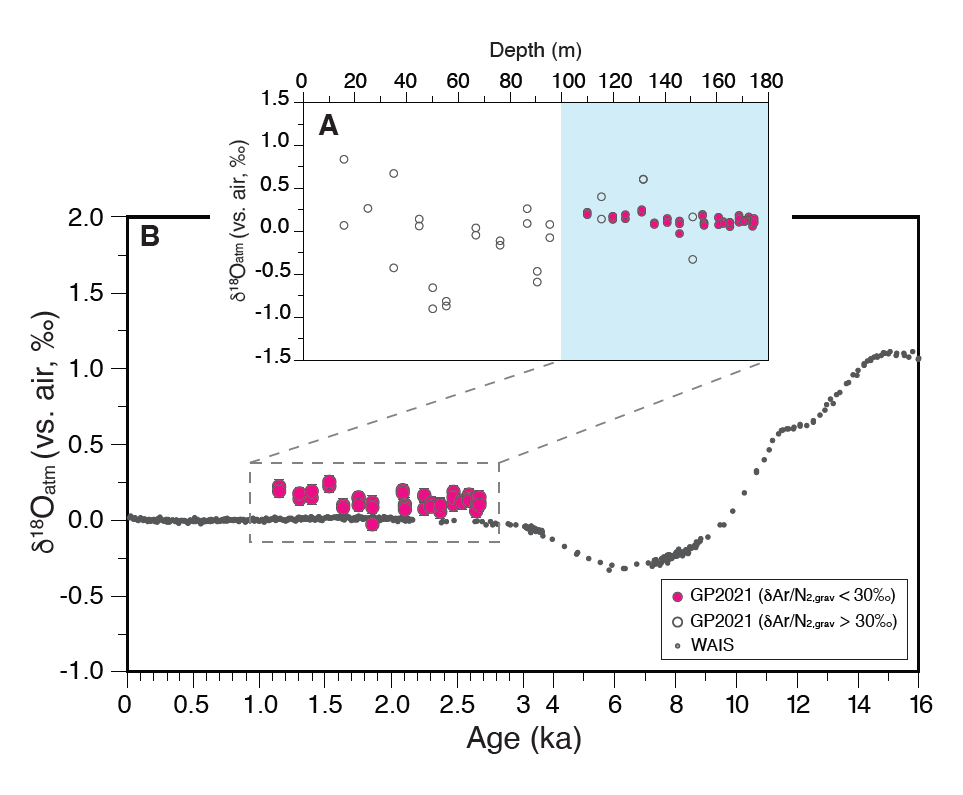


Fig. 3. The depth profile of δ18Oatm in GP2021 (A). Selected δ18Oatm values least affected by melting, as inferred by δAr/N2 ratios < 30 ‰, shown as red dots (B) overplotted on the WAIS δ18Oatm age profile (*6*). Please note that the scale of X-axis varies before and after 3 ka.

**A comparison of δ18Oice profiles for the GP ice cores**

We matched the δ18Oice profiles by depth between GP2021 and GP1992 (Fig. 4A), as well as between GP2015 and GP1992 (Fig. 4B) using the Match software (*34*). This Match software utilizes dynamic programming to find the optimal alignment of two stratigraphic geochemical data or two paleoclimate proxy data using penalty functions, which produces objective and high-resolution results without pre-existing automated correlation techniques or hand tuning (*34*). Based on the Match result, the 175.1 m GP2021 core correlates with GP1992 down to ~253 m depth (Fig. 4A), while GP2015 at 187.4 m depth corresponds to GP1992 core at ~191 m depth (Fig. 4B). The depth correspondence is understandable given that GP1992 and GP2015 were drilled adjacently to the valley underneath sites with a similar ice thickness (Fig. 1C), while GP2021 was drilled from the slope where the ice thickness is about 230 m (Fig. 1C; see SM for the ice thickness estimation at the GP2021 drilling site). We calculated a significantly positive correlation (*r* = 0.75, *n* = 188, *p* < 0.0001) between GP2015 and GP1992 (Fig. 4B), while a marginally better positive correlation (*r* = 0.77, *n* = 254, *p* < 0.0001) was identified between GP2021 and GP1992 (Fig. 4A). If we choose the section between 135-253 m depth of GP1992 for calculating its correlation coefficient with the overlapping depth of GP2021 (Fig. 4A), we get an even higher coefficient of 0.81 (n=119, p<0.0001). The significant similarities of the three GP δ18Oice profiles by depth (Fig. 4A and Fig. 4B) imply high reproducibility of the Guliya Plateau δ18Oice records, and consequently comparable timescales for their stratigraphically equivalent overlapping depth intervals.

Based on the excellent agreement of their δ18Oice profiles by depth (Fig. 4A and Fig. 4B), we further compared the δ18Oice profiles of GP2021 and GP1992 (Fig. 4C), as well as GP2015 and GP1992 (Fig. 4D), plotted on their respectively established timescales. The time scales of GP2015 and GP1992 are generally consistent, or slightly older of GP2015 than GP1992 at their certain stratigraphically equivalent depth intervals (Fig. 4D). For example, the Younger Dryas (YD) episode (12.9-11.7 ka) identified for GP2015 (*7*) is located well above the depth of the YD episode identified for GP1992 (*1*) (Fig. 4D). Nevertheless, the time scale of GP1992 (*1*) is dramatically different from that of GP2021 at their stratigraphically equivalent depths (Fig. 4C). For example, the bottom depth of 175.1 m (corresponding to ~2.7 ka) for GP2021 is stratigraphically equivalent to the depth of ~253 m for GP1992, where the ice age of GP1992 is ~100 ka according to the original timescale of GP1992 (*1*). We also highlighted an emblematic 39Ar age of for GP2021 that corresponded an age of 12 ka for GP1992 at their stratigraphically equivalent depth (Fig. 4C). To further examine the age discrepancy of the GP ice cores, we compiled the original ages of GP1992 at its selected depths (*1*) in comparison to the corresponding ages at each stratigraphically equivalent depth of GP2015 (*5*, *7*) and GP2021 (Fig. 2A) as summarized in Table 1. It is apparent that the timescales of GP1992 and GP2015 should be remarkably overestimated below their upper tens meters ice layers (Fig. 2B, Fig. 4C and Fig. 4D), and the dating overestimation deteriorates along the ice core depth downwards.



**Fig. 4. The δ18Oice profiles of GP2021 (blue lines), GP1992 (red lines) and GP2015 (black lines).** The Match software (*24*) was employed for matching the δ18Oice.depth profiles between GP2021 and GP1992 (A); and between GP2015 and GP1992 (B). Comparison of the δ18Oice age profiles between GP2021 and GP1992 (C), and between GP2015 and GP1992 (D) was based on their respectively established timescales after matching the δ18Oice profiles by depth as shown respectively in (A) and (B). The δ18Oice profile of GP1992 was digitalized from ref. *35*. The δ18Oice profile of GP2015 was from ref. *7*, publicly available for the top 187.4 m only. The age scale of GP2021 is from the depth-age relationship shown in Fig. 2A. The age scale of GP1992, with its distinctive YD episode, is from ref. *1*, and the age scale of GP2015, with its three distinctive ages of the YD episode, 15 ka and 41 ka, from refs. *5* and *7*. For comparison, we also identified the distinctive ages of 15 ka and 41 ka for GP1992 after matching the δ18Oice profiles by depth of GP1992 and GP2015 as shown in (B).

Table 1. Comparison of ages at selected stratigraphically equivalent depths of GP1992, GP2015 and GP2021 after matching their δ18Oice profiles by depth. Ages of GP1992 are from ref. *1* except those numbers with a star from ref. *11*, ages of GP2015 from ref. *7*, and ages of GP2021 from Fig. 2A.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Depth of GP1992 (m) | age of GP1992  (ka) | equivalent depth of GP2015 (m) | age of GP2015  (ka) | equivalent depth of GP2021 (m) | age of GP2021 (ka) |
| 20 | ~0.07\* | 27.0 | 0.07 | 22.6 | 0.07 |
| 40 | ~0.24\* | 41.6 | 0.14 | 42.6 | 0.24 |
| 60 | ~0.45\* | 53.6 | 0.19 | 64.6 | 0.50 |
| 80 | ~0.76\* | 72.2 | 0.53 | 78.4 | 0.68 |
| 100 | 3.25 | 97.2 | 2.01 | 91.4 | 0.88 |
| 120 | 5.70 | 119.2 | 5.81 | 103.2 | 1.06 |
| 140 | 8.20 | 139.6 | 13.56 | 114.2 | 1.22 |
| 144 | 10.40 | 144.4 | 15 | 117.4 | 1.27 |
| 160 | 19.60 | 160.2 | 20.86 | 127.8 | 1.46 |
| 180 | 34.40 | 182.0 | 35.44 | 138.4 | 1.70 |
| 187 | 38.30 | 187.4 | 41 | 141.0 | 1.76 |
| 200 | 46.00 | / | / | 144.4 | 1.83 |
| 220 | 71.60 | / | / | 156.8 | 2.15 |
| 240 | 87.60 | / | / | 168.0 | 2.46 |
| 253 | ~100.00 | / | / | 175.1 | 2.70 |

**Implications for climate reconstruction**

We have argued that the original timescales of GP1992 and GP2015 (*1*, *5*, *7*) are seriously in error. Given the fact that age of ~100 ka at the 253 m depth of GP1992 equivalently corresponds to age of ~2.7 ka at the 175.1 m of GP2021 (Table 1), the previously reconstructed climate history from GP1992 (*1*) should be seriously compressed, such as what has already been suggested from the comparison of the δ18O profiles of GP1992 and Chongce ice cores (Fig. S4, ref. *19*). As a result, conclusions of studies based on these timescales need to be reconsidered. For example, according to the GP1992 and GP2015 timescales, the δ18Oice at Guliya shows an excursion to heavy values during the YD episode. This result is unexpected because the YD episode was a cold interval in the northern Hemisphere (*36*), whereas increasing δ18Oice suggests warmer temperature in the northern TP (*37*). Thompson et al. (*7*) proposed an inverse relationship between δ18Oice and temperature during the YD episode, as well as Heinrich Event 1 (H1). They suggest that this inversion might be due to a glacial/post glacial isotopic switch, resulting in 18Oice enrichment during the cold YD episode and H1 event (*7*). However, this interpretation is not supported by a transient simulation of climate-isotope coevolution over the last deglaciation (20 to 11 ka) that simulated modest δ18Oice depletion during the H1 and YD periods (*38*).

Our robust timescale for GP2021 gives us a new tool for climate reconstructions of the past two millennia. For example, the GP2021 δ18Oice record suggests a millennial warming trend during the Common Era (Fig. S13A). This evidence for warming in the northwestern TP was supported by the δ18Oice record of the neighboring Chongce ice cores (*39*). Additionally, our new dating results revealed the large δ18Oice variations (up to ~8‰ depending on the averaging intervals), at multi-decadal to multi-centennial scales prior to ~800 C.E. (Fig. S13C, Fig. S14). These events date to ~1.2-1.4 ka, 1.7 ka, 2.0 ka, 2.2 ka, and 2.6 ka (Fig. 4C). Taking account of the observed slope of 0.62‰/°C for daily δ18O in precipitation vs. temperature at Delingha, a site located in the northern TP (*37*), this large δ18Oice variations of GP2021 at multi-centennial scales cannot be solely interpreted as a temperature signal, because a variation of up to 8‰ in δ18Oice would imply implausible temperature excursions of 13˚ C. We therefore suggest that these large δ18Oice variations could be the response of other potential factors. One such candidate might account for the specific location of the Guliya ice cap, situating in the transition zone between the mid-latitude westerlies and the Indian Summer Monsoon (ISM) (*37*). Both paleoclimate data and model studies have revealed strong variability of the Atlantic Meridional Overturning Circulation (AMOC) at multidecadal to centennial scales (*40*, *41*), which significantly shifts the position of westerlies and the intertropical convergence zone (ITCZ, and hence ISM) by altering the temperature gradient between low and high latitudes (42, 43). As a result, large δ18Oice variations for ice cores from this climatic transition domain are expected due to interplay between westerlies and ISM (*44*).

The high-resolution, absolutely-dated calcite *δ*18O record of the Kesang stalagmites (see Fig. 1A for the Kesang location) also shows large amplitude fluctuations at multi-decadal to multi-centennial timescales superimposed on an increasing *δ*18O trend over the past 3 ka (*45*), very similar to the δ18Oice profile of GP2021 (Fig. S15). A significantly positive correlation (r=0.462, p<0.001, n=90) is observed between the Kesang calcite *δ*18O record and the GP2021 δ18Oice record (Fig. S15A), and the correlation can be improved after matching the GP2021 δ18Oice record to the Kesang calcite *δ*18O record (Fig. S15B), resulting in a better r=0.618 (p<0.001, n=89). Interestingly, Cheng et al. (*45*) firstly argued that the GP1992 timescale needed to be shortened by half in order to reconcile the discrepancies between the GP1992 δ18Oice and the Kesang stalagmite δ18O profiles. This is certainly not shortened enough. It was suggested that the Kesang observations show clear evidence of possible incursions of ISM rainfall or related moisture into the Kesang site and adjacent areas during former wet periods (*45*, *46*), while changes of moisture source (*47*) and moisture pathways (*44*) play an important role in controlling the Tibetan ice core δ18Oice variations. Therefore, the Guliya δ18Oice may reflect a final outcome of regional hydroclimate in the northwestern TP, rather than a solely temperature signal (*1*, *7*). It is worth pointing out that the current work focused primarily on the chronologies of the GP ice cores, with emphasis on the previously misunderstanding of GP1992 and GP2015. Future work will deal with the detailed forces and mechanism of past climate on the Tibetan Plateau.

**Conclusions and perspective**

In this study, we report the collection and chronology of a new 175.1 m ice core from the Guliya ice cap. Based on the water isotope stratigraphy, our data covers the equivalent depths of 0-253 m in the GP1992 core. We have authoritatively dated GP2021 by bomb tritium, 210Pb, 14C, 39Ar, and 18Oatm stratigraphy. Timescales from the various properties are in good agreement, and the timescale is robust in the context of its uncertainties. The original timescales for GP1992 and GP2015 differ from GP2021 by an order of magnitude or more in the range of overlapping depth intervals. We argue that these timescales of GP1992 and GP2015 are seriously in error, and conclusions about climate history and dynamics based on GP1992 and GP2015 need to be reconsidered. At the same time, GP2021 serves as a new archive of climate during the last two millennia. We further suggest that measurements of δ18Oatm, 14C, 81Kr, and possibly 41Ca for the deeper sections of the GP1992, GP2015 and, hopefully, new GP cores will provide a complete and more reliable timescale for the Guliya ice cores.

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**SUPPLEMENTARY MATERIALS**

Materials and Methods

Figs. S1 to S15

Tables S1 to S7

References and notes (48-\*\*)