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Supplementary Information for

Use of $\delta^{18}O_{atm}$ in dating a Tibetan ice core record of Holocene/Late Glacial climate

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Supplementary Information Text

S1. Timescale reconstruction

S1.1 Annual layer counting from 1840 to 2015 CE

Very low accumulation (0.2 to 0.3 m water equivalent a^{-1}) (1) and post-depositional alteration of the snow on the Guliya ice cap complicates the process of distinguishing annual layers with the degree of precision that is possible for higher accumulation ice cores. Annual time series for the GP core and a nearby shallow core were reconstructed from 1840 to 2014 CE (1). However, without well-defined seasonal variations and calibration horizons below the 1963 CE (12.0 m) beta horizon (from ^{90}Sr and ^{137}Cs decay) resulting from the 1962/63 Arctic thermonuclear tests, the range of age uncertainty increases with depth. Thus, we did not extend the annual layer counting below 1840 CE.

Surface snow on the Guliya plateau, which in the summer is only ~1 meter thick, is metamorphosed to ice within one year. Therefore, the Guliya plateau is composed of superimposed ice that lacks an upper firn section. The high levels of solar radiation, coupled with warm summer temperatures, melt the surface snow which quickly refreezes at this altitude. This is confirmed by the recovery of several shallow cores around the Guliya plateau in 1990 and 1991, in addition to the deep core drilled in 1992. Since each year's snow is at least partially melted and refrozen in place without lateral mass displacement, the water isotopes and aerosols are "fixed" in the column and elution of the major ions does not occur, although the partially melted and refrozen snow may be more enriched in ^{18}O.

In contrast to the Guliya plateau, the upper 25 m of the Guliya summit cores contain firn, albeit with numerous ice layers. A 1.5 m snow pit excavated and sampled on the Guliya summit in 1991 showed well-defined seasonal variations in $\delta^{18}O_{ice}$ and mineral dust over the previous 1.5 years (1). However, below the most recent snow layers, the $\delta^{18}O_{ice}$ records in the Guliya summit cores lack seasonal definition, i.e., the quasi-seasonal ^{18}O depletion (indicating winter) observed in the GP core record is absent from the summit cores (Fig. S1). Intense air circulation may ventilate the firn in the upper meters on the Guliya summit, resulting in removal of the lighter isotopes through sublimation. This type of isotopic enrichment has been observed in Antarctica (2).

Despite the stratigraphic differences between these two Guliya drill sites, many timescale horizons from 1840 to 2014 CE in the GP core (1) can be transferred to GS3 by broad $\delta^{18}O_{ice}$ matching (Fig. S1, Table S1). Note that the 1962/63 depth in the GP long core, marked by a beta activity peak, is deeper than that in the GP shallow core that was presented in Thompson et al. (2018) (1). These transferred points are used as timescale calibration markers in the development of the 5th order polynomial from which the GS3 timescale between -0.1 and 4.4 ka BP is calculated (Fig. 3*B*).

S1.2 Radiocarbon dating

Five plant fragments were observed and isolated in the GP core and in GS2. The samples were prepared at BPCRC for ^{14}C AMS analyses performed at WHOI NOSAMS and ETH in Zurich (Table S2). All sample masses were small (21.5 to 64 µg C) and the radiocarbon dates were calibrated using the CALIB Rev 8.0.1 radiocarbon calibration program (3) with the Intcal20.14c calibration data set (4). The ^{14}C ages of the plant fragments in the GP core at 35.67 and 51.40 m fell within the late 19th century and had ± errors nearly as large as the calibrated ages. The ^{14}C age for the lowest mass sample (21.5 µg C) found at 101.64 m (38.12 m in GS3) was stratigraphically anomalous and thus not used in the polynomial function between -0.1 and 4.4 ka BP.

S2. Abbreviations

CE	Common Era, more commonly referred to as AD
$\delta^{18}O_{air}$	Ratio of oxygen isotopes (^{16}O, ^{18}O) of O_2 in the air bubbles in the glacier ice
$\delta^{18}O_{ice}$	Ratio of oxygen isotopes (^{16}O, ^{18}O) of water in the glacier ice
GP	Guliya plateau
GP core	The core drilled to bedrock in 2015 on the Guliya Plateau

GS	Guliya summit
GS2, GS3	The cores drilled to bedrock on the Guliya summit (GS1 is archived at the ITP)
ka BP	thousands of years before present (before 1950 CE)
NWTP	northwest Tibetan Plateau
TP	Tibetan Plateau

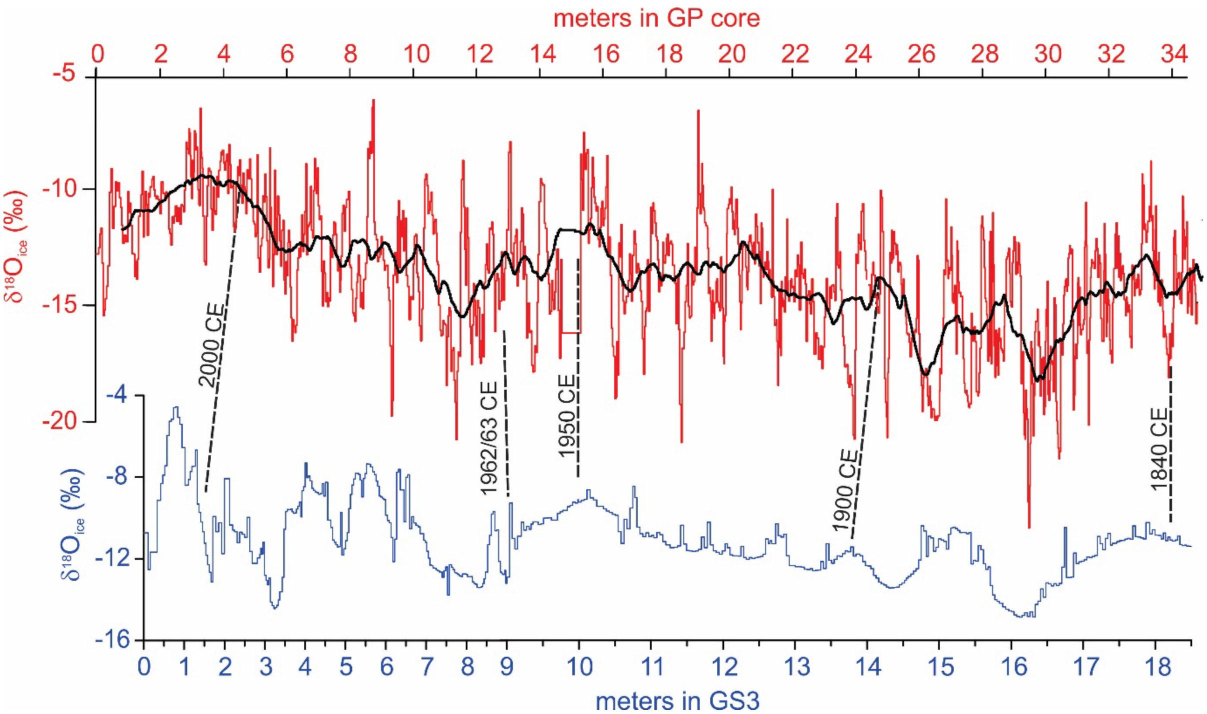

Fig. S1. $\delta^{18}O_{ice}$ matching between the GP core (red) and GS3 (blue) from 1840 to 2014 CE. The individual $\delta^{18}O$ samples for the GP core are shown along with 41-sample moving averages (black solid line). The individual $\delta^{18}O_{ice}$ samples for GS3 are shown without smoothing. The top meter of the GS3 core was composed of snow and low-density firn which had compacted during transport from the field to the lab. The 1962/63 CE thermonuclear horizon was identified in both cores by high levels of beta (β) activity, thus establishing a definite tie point.

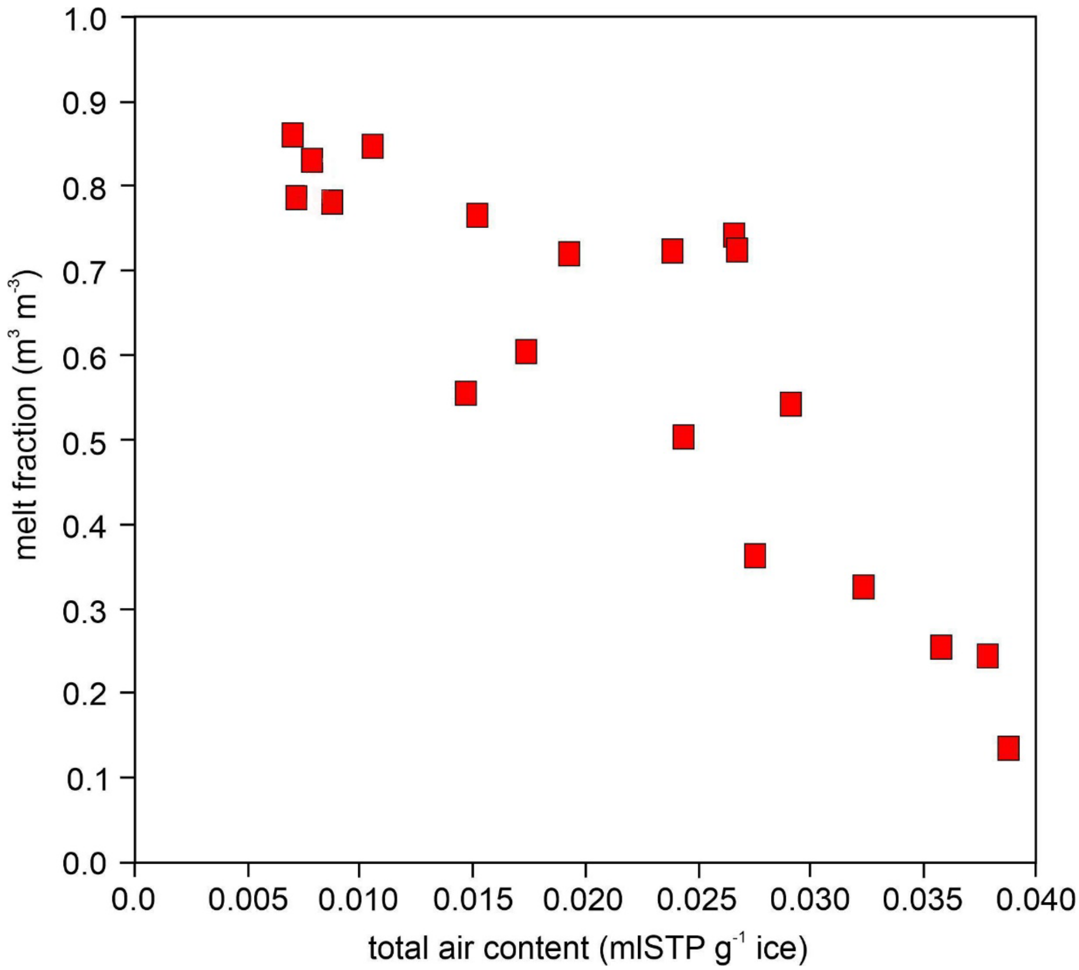

Fig. S2. Calculated melt fraction versus experimentally measured total air content in GS3 ice. The inverse correlation confirms that melt is the major reason for the very low air content. For comparison, a typical ~2 km altitude polar ice sample has an air content of 0.1 in these units.

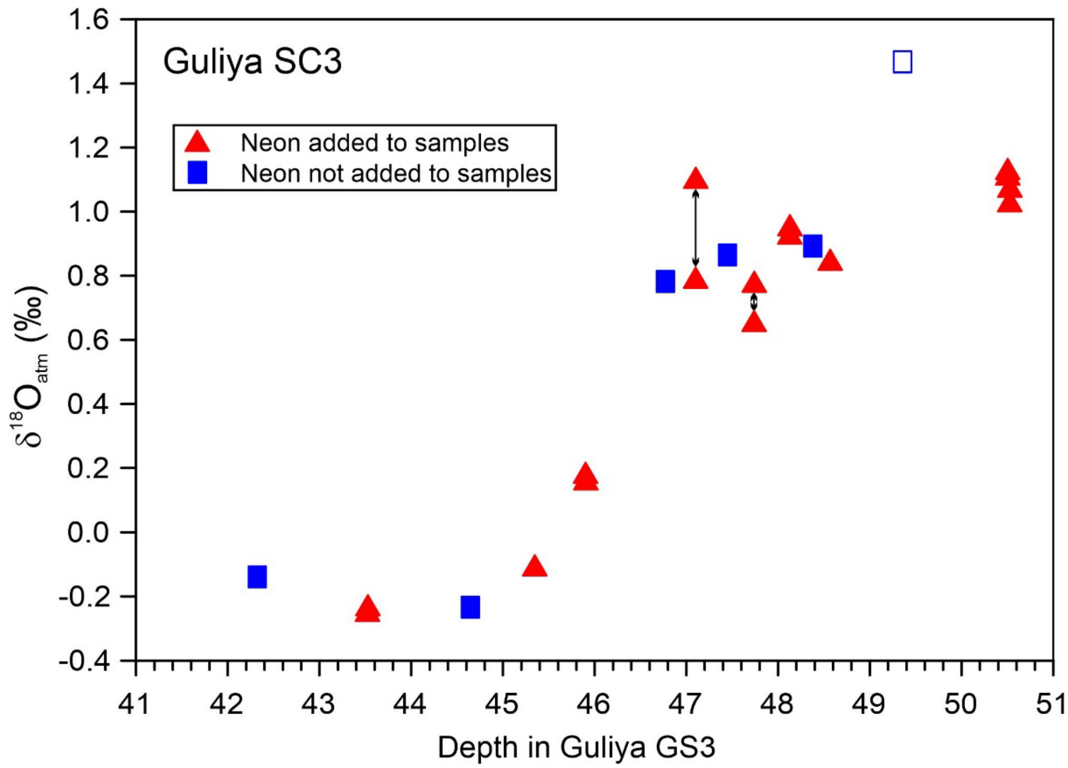

Fig. S3. GS3 $\delta^{18}O_{atm}$ corrected values plotted with depth. Closed red triangles indicate $\delta^{18}O_{atm}$ values from samples to which neon was added, while closed blue squares indicate values from samples to which neon was not added. Several of the samples were measured twice, including GS3-T48-1 (47.11 m) and GS3-T48-2 (47.74 m) (connected by double arrows). The data point (GS3-T50-1) marked by the open blue square, to which neon was not added, is anomalously high, possibly due to the inadvertent incorporation of ^{18}O enriched outer layers of the ice during sample preparation.

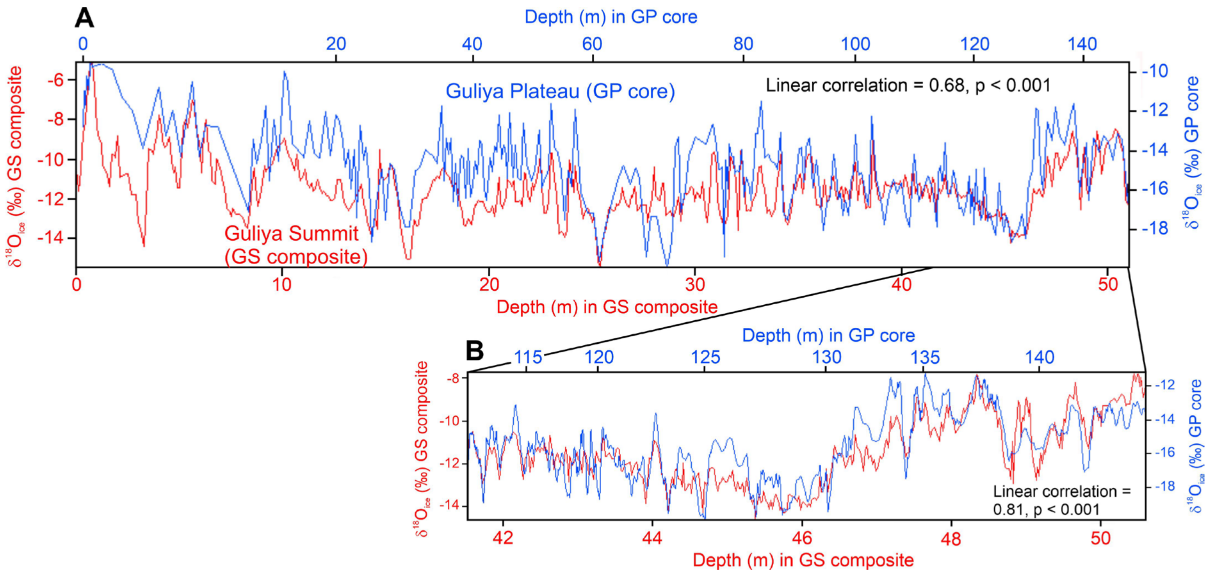

Fig. S4. Analyseries (5) match between the GP core and GS composite. (*A*) Match between $\delta^{18}O_{ice}$ from the GS composite (red curve, 0.10 m averages) and the GP core (blue curve, 0.50 m averages). (*B*) Detailed matching between $\delta^{18}O_{ice}$ from the bottom of the GS composite (red curve, each sample) and the GP core (blue curve, 11-sample running means).

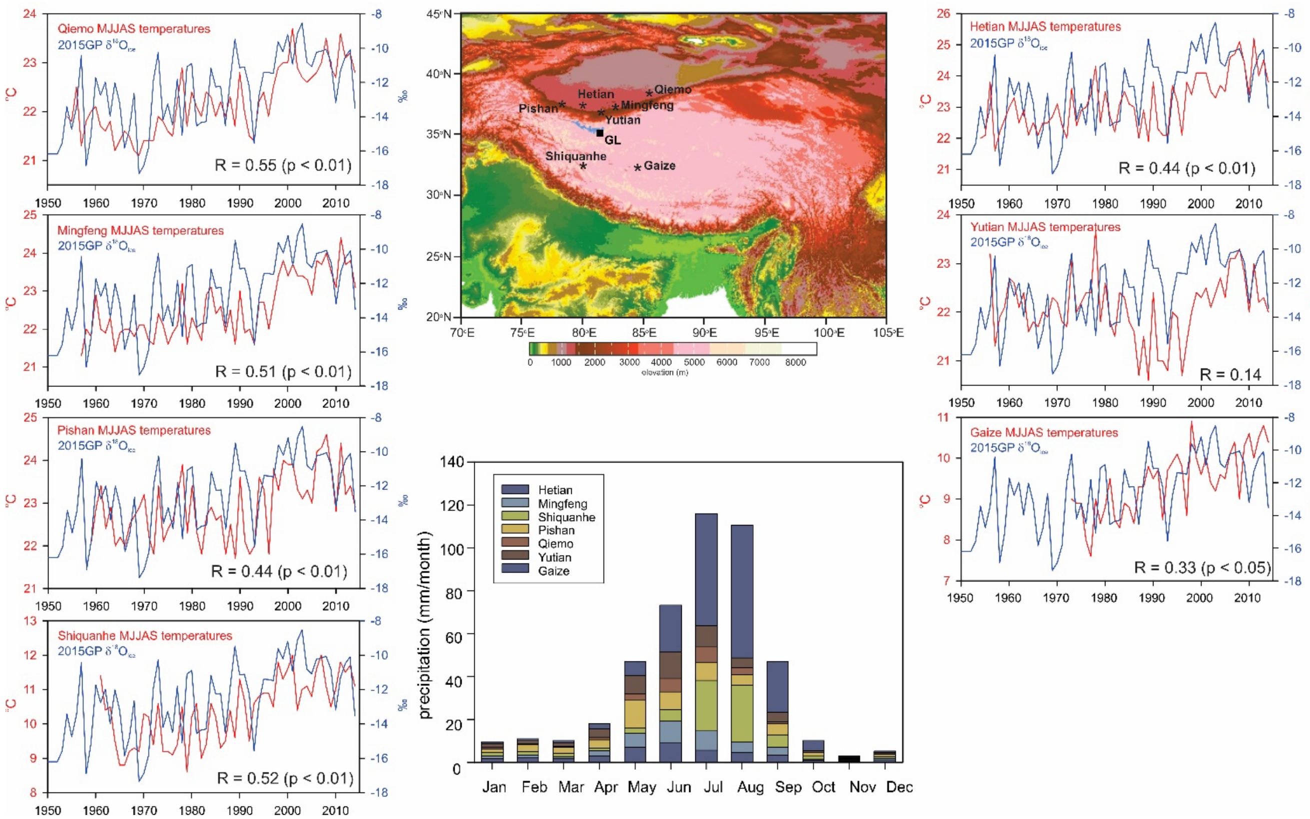

Fig. S5. Temperature records (average May to September) from seven meteorological stations (locations shown on map) in the western TP compared with annual averages of $\delta^{18}O_{ice}$ from the GP core since 1950 CE. The stacked bar graph shows monthly precipitation at these stations over the same time periods as the temperature records. Approximately 85% of the annual precipitation occurs between May and September. Temperature and precipitation data were obtained from the National Meteorological Information Center of the China Meteorological Administration (CMA) (http://data.cma.cn).

Table S1. Depths in the GP core and GS3 every 10 years from -0.06 to 0.11 ka BP (before 1950 CE) (1840 to 2010 CE).

Depth in 2015GP (m)	Corresponding depth in GS3 (m)	Calendar year CE	ka BP
1.79	0.47	2010	-0.06
4.26	1.41	2000	-0.05
6.84	3.82	1990	-0.04
8.65	5.36	1980	-0.03
11.10	7.49	1970	-0.02
13.47	8.91	1960	-0.01
15.35	9.99	1950	0
17.11	10.78	1940	0.01
18.59	11.37	1930	0.02
20.70	12.21	1920	0.03
22.94	13.09	1910	0.04
24.52	13.73	1900	0.05
26.61	14.57	1890	0.06
27.79	15.13	1880	0.07
29.22	15.80	1870	0.08
30.91	16.70	1860	0.09
32.84	17.76	1850	0.10
34.05	18.24	1840	0.11

Table S2. **^{14}C AMS data from plant fragments from GS2 and the GP core and their corresponding depths in GS3.**

Core	Depth (m)	Corresponding depth in GS3 (m)	Mass (µg C)	^{14}C age (yrs before 1950 CE)	Calibrated age (yrs before 1950 CE)	Lab
GS2	41.90	41.50	64	3940±35	4387±37	NOSAMS[#]
GP core	35.67	18.85	64	105±25	69±45	NOSAMS
	51.40	22.60	61.5	100±60	85±56	ETH[*]
	89.70	35.00	28	1430±45	1325±26	NOSAMS
	101.64	38.10	21.5	830±70	735±56	ETH

[#]National Ocean Sciences Accelerator Mass Spectrometry, Woods Hole Oceanographic Institution

*Swiss Federal Institute of Technology

Table S3. Conventional data measured on GS3 samples (to which neon was added) prior to making the corrections.

Lab sample ID	Depth (m)	$\delta^{15}N$ (‰)	$\delta^{18}O$ of O_2 (‰)	O_2/N_2	Ar/N_2	$*\delta^{18}O_{atm}$	Total air content mL STP/g
GS3-T30-1	29.96-29.99	0.080	0.699	32.52	106.78	0.540	0.008
GS3-T39-1	38.82-38.85	-0.006 -0.107	0.127 -0.113	-0.53 1.46	9.51 4.70	0.138 0.100	0.038 0.039
GS3-T41-1	40.09-40.12	-0.071	-0.123	-16.19	-8.40	0.020	0.012
GS3-T42-1	41.10-41.13	-0.014 -0.009	-0.049 -0.070	1.32 7.90	10.08 14.31	-0.022 -0.052	0.036 0.032
GS3-T44-1	43.51-43.54	-0.019 -0.006	-0.196 -0.197	15.17 4.32	29.59 16.81	-0.158 -0.185	0.024 0.027
GS3-T46-1	45.33-45.36	-0.023	-0.056	16.16	34.37	-0.011	0.029
GS3-T47-1	45.89-45.93	-0.020 -0.005	0.216 0.281	24.95 15.87	44.04 36.45	0.255 0.290	0.017 0.015
GS3-T48-1	47.09-47.13	0.035 0.017	0.946 1.381	65.41 28.18	90.64 73.43	0.875 1.347	0.015 0.024
GS3-T48-2	47.72-47.76	0.154 0.127	1.342 1.454	83.82 66.24	160.90 147.19	1.034 1.200	0.007 0.011
GS3-T49-1	48.11-48.15	0.039 0.057	1.143 1.242	49.78 38.72	79.87 73.22	1.065 1.128	0.027 0.027
GS3-T49-2	48.55-48.58	0.058	1.007	55.67	72.98	0.891	0.019
GS3-T51-1	50.48-50.51	0.080 -0.163	1.607 1.100	40.06 42.68	98.99 101.52	1.447 1.427	0.009 0.007
GS3-T52-1	50.51-50.544	0.175 0.194	1.827 1.828	56.33 46.02	132.93 122.35	1.476 1.441	0.008 0.008

$*\delta^{18}O_{atm}$ is used here as classically defined ($=\delta^{18}O-2\delta^{15}N$), but this is not the true atmospheric value.

Table S4. Computed values for correction of $\delta^{18}O_{atm}$ for the effects of melt and respiration.

Samples GS3-T30-1, GS3-T39-1, GS3-T41-1, and GS3-T42-1 were not used for the GS3 timescale construction because the atmosphere's $\delta^{18}O_{atm}$ has relatively little variation in this time interval, and because the record above ~6 ka BP can be dated using other techniques. Sample GS3-T52-1 was not used because of the extremely high age/depth interval ratio (>1000 yrs/2 cm).

Lab Sample ID	Depth (m)	$\delta^{15}N$ (‰)	$\delta^{18}O$ of O_2 (‰)	O_2/N_2 (‰)	Ar/N_2 (‰)	O_2/Ar (‰)	$\delta^{18}O_{atm}$ (‰)	Total air content mL STP/g	corrected $\delta^{18}O_{atm}$ (‰)	Inferred age ka BP
GS3-T30-1	29.96-29.99	0.080	0.699	32.52	106.78	-67.09	0.540	0.008	0.126	NA
GS3-T39-1	38.82-38.85	-0.006 -0.107	0.127 -0.113	-0.53 1.46	9.51 4.70	-9.95 -3.22	0.138 0.100	0.038 0.039	0.088 0.081	NA
GS3-T41-1	40.09-40.12	-0.071	-0.123	-16.19	-8.40	-7.86	0.020	0.012	-0.089	NA
GS3-T42-1	41.10-41.13	-0.014 -0.009	-0.049 -0.070	1.32 7.90	10.08 14.31	-8.67 -6.33	-0.022 -0.052	0.036 0.032	-0.071 -0.087	NA
GS3-T44-1	43.51-43.54	-0.019 -0.006	-0.196 -0.197	15.17 4.32	29.59 16.81	-14.01 -12.28	-0.158 -0.185	0.024 0.027	-0.239 -0.256	6.2
GS3-T46-1	45.33-45.36	-0.023	-0.056	16.16	34.37	-17.62	-0.011	0.029	-0.114	9.2
GS3-T47-1	45.89-45.93	-0.020 -0.005	0.216 0.281	24.95 15.87	44.04 36.45	-18.28 -19.85	0.225 0.290	0.017 0.015	0.154 0.173	10.2
GS3-T48-1	47.09-47.13	0.035 0.017	0.946 1.381	65.41 28.18	90.64 73.43	-23.14 -42.16	0.875 1.347	0.015 0.024	0.783 1.092	11.8
GS3-T48-2	47.72-47.76	0.154 0.127	1.342 1.454	83.82 66.24	160.90 147.19	-66.39 -70.57	1.034 1.200	0.007 0.011	0.647 0.771	12.4
GS3-T49-1	48.11-48.15	0.039 0.057	1.143 1.242	49.78 38.72	79.87 73.22	-27.86 -32.15	1.065 1.128	0.027 0.027	0.921 0.944	12.80
GS3-T49-2	48.55-48.58	0.058	1.007	55.67	72.98	-16.13	0.891	0.019	0.840	13.14
GS3-T51-1	50.48-50.51	0.080 -0.163	1.607 1.100	40.06 42.68	98.99 101.52	-53.62 -53.42	1.447 1.427	0.009 0.007	1.121 1.103	15.0
GS3-T52-1	50.51-50.54	0.175 0.194	1.827 1.828	56.33 46.02	132.93 122.35	-67.61 -68.01	1.476 1.441	0.008 0.008	1.062 1.021	>16

Table S5. Computed values for correction of $\delta^{18}O_{atm}$ for the effects of melt and respiration for 6 samples to which neon was not added.

Lab Sample ID	Depth (m)	$\delta^{15}N$ (‰)	$\delta^{18}O$ of O_2 (‰)	$\delta O_2/N_2$	$\delta Ar/N_2$	Total air content (mL STP/g)	$\delta^{18}O_{atm}$ (‰)	Inferred age ka BP
GS3-T43-1	42.30-42.33	0.021	0.000	-2.35	17.99	0.033	-0.137	3.9
GS3-T45-1	44.62-44.67	-0.016	-0.213	2.92	10.83	0.039	-0.236	8.1
GS3-T47-2	46.76-46.79	0.036	0.935	30.78	45.92	0.021	0.778	11.5
GS3-T48-3	47.44-47.47	0.066	1.034	50.92	63.36	0.017	0.861	12.1
GS3-T49-3	48.36-48.40	0.089	1.238	67.15	102.21	0.012	0.890	13
GS3-T50-1	49.34-49.37	0.059	1.596	-32.54	14.83	0.035	1.466*	13-15

*Anomalously high $\delta^{18}O_{atm}$ value

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