

## Auxiliary Material

### Response of atmospheric CO<sub>2</sub> to the abrupt cooling event 8200 years ago

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#### Methods for CO<sub>2</sub> analysis

Replicate measurements were typically done on different days within 3 months. Each ice sample weighed about 8~9 g after trimming >0.5 cm from all surfaces. The analytical methods were greatly improved from the previous ones [Ahn *et al.*, 2004] and the details are reported in [Ahn *et al.*, 2009]. Briefly, samples were placed in a double-walled stainless steel vacuum chamber at -35°C, cooled using cold ethanol circulation between the walls, and then crushed with steel pins, affixed to a pneumatically actuated linear motion feedthrough. Air liberated from the ice was dried in a cold stainless steel coil at -85°C and then cryotrapped in ~6 cm<sup>3</sup> stainless steel sample tubes at -262°C. After warming the trapped air to room temperature, and expanding to a 5 cm<sup>3</sup> stainless steel sample loop, the CO<sub>2</sub> mixing ratio was measured with an Agilent 6890N Gas Chromatograph (GC) with flame ionization detector, with nickel catalyst conversion of CO<sub>2</sub> to CH<sub>4</sub> prior to measurement. The pressure in the loop was measured with an MKS Baratron capacitance manometer (accuracy better than 0.15%). CO<sub>2</sub> peak area was divided by the sample pressure and the results quantified with similar measurements of standard air. Daily calibration curves used several measurements of standard air with 291.13 ppm CO<sub>2</sub> (WMOX2007 CO<sub>2</sub> mole fraction scale). Each air sample was measured twice. Daily corrections for the dry extraction and GC analysis were done using several air standards (291.13 ppm) that were introduced over the ice samples and transported to sample tubes mimicking the procedure of the air samples from ice.

Data reproducibility for the same depth intervals measured 1-3 months apart shows a pooled standard deviation of 0.5 ppm (Figure S1). We also analyzed Taylor Dome samples and compared our results with those previously analyzed at the University of Bern [Indermühle *et al.*, 1999]. We find that our results are 1.5 ppm higher than those from the University of Bern (Figure S2). Assuming the difference is an inter-laboratory offset, we find that our Siple Dome CO<sub>2</sub> record agrees well with those from Taylor Dome and Dome C within 4 ppm, part of which could be attributed to the relative age

uncertainty on multi-centennial to millennial timescales and aliasing of the atmospheric signal in the low resolution Dome C and Taylor Dome (Figure S3).

Figure S1. Reproducibility of CO<sub>2</sub> analysis. Different symbols represent experiment time periods. The measurements for the same depth intervals measured 1-3 months apart have a pooled standard deviation from the mean of 0.5 ppm.

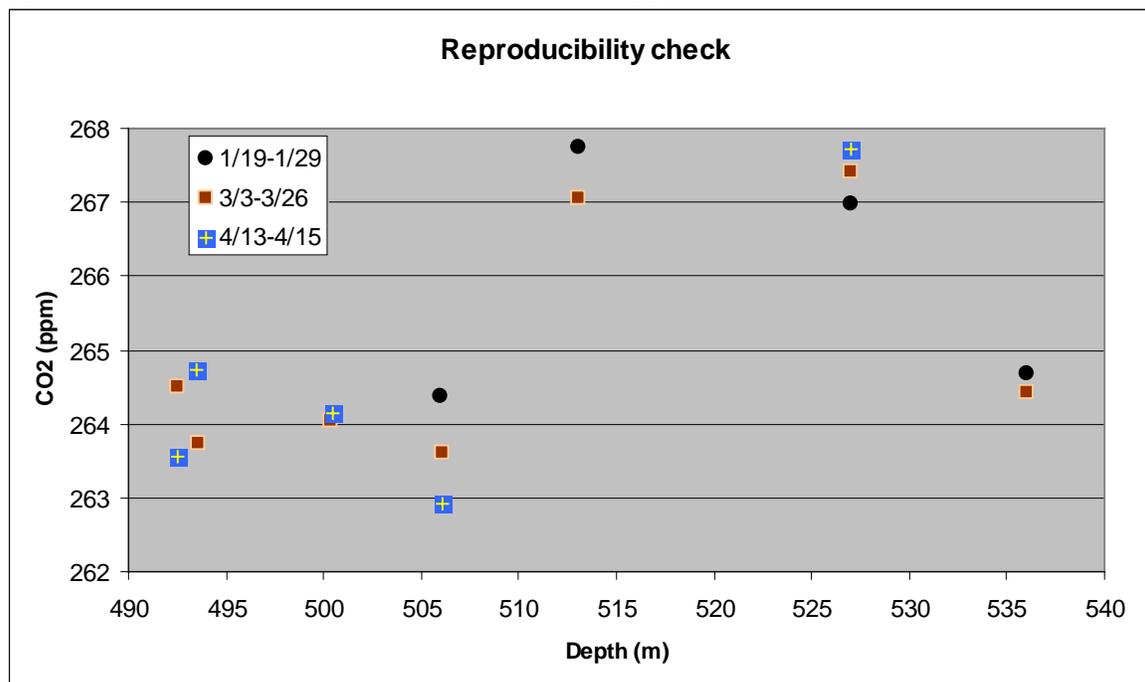


Figure S2. Interlaboratory comparison for CO<sub>2</sub> analysis between Oregon State University (OSU) and University of Bern (Bern) [Indermühle *et al.*, 1999] using Taylor Dome ice. At OSU, the Taylor Dome ice was analyzed during the same time period that the Siple Dome ice for this study was analyzed. On average, OSU CO<sub>2</sub> results are 1.5 ppm higher than those of Bern.

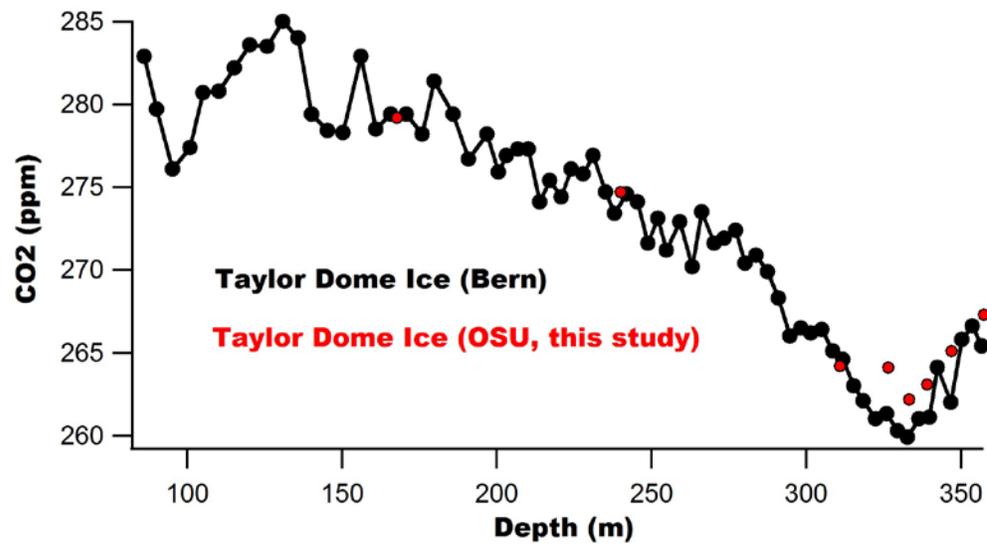
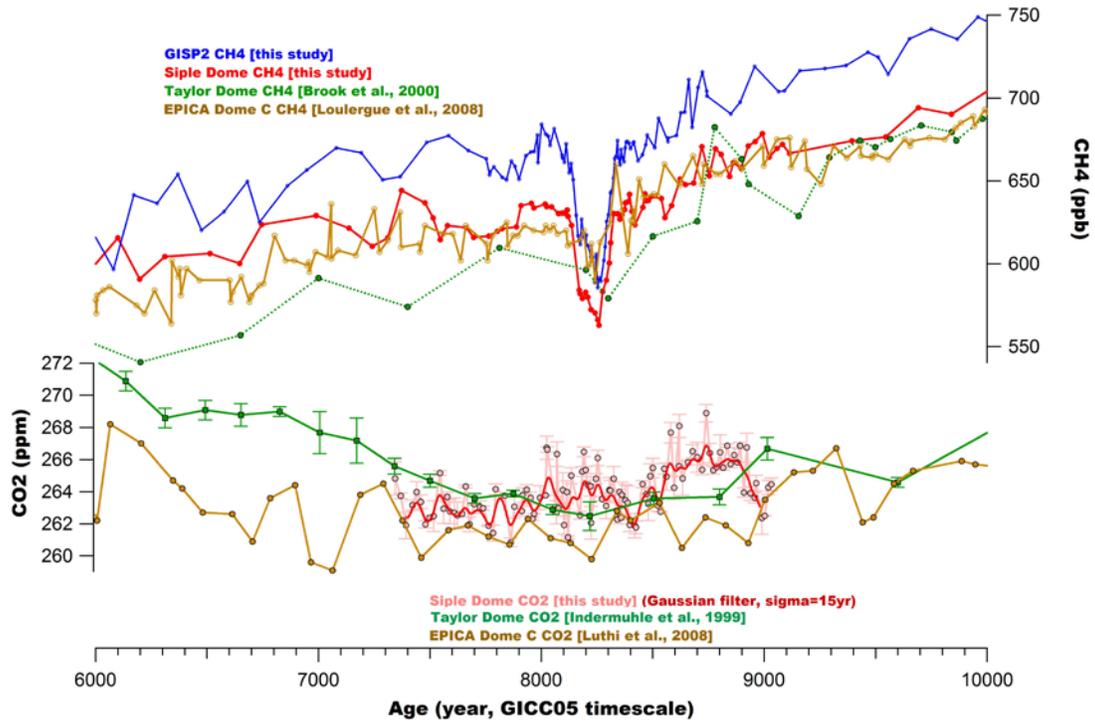


Figure S3. Comparison of ice core records for the early Holocene. In the upper panel CH<sub>4</sub> records are used to compare how well ages are constrained around the 8.2k event. GISP2 and Siple Dome ages are well constrained, but this is not the case for the EPICA Dome C and Taylor Dome ice cores. The lower panel shows CO<sub>2</sub> records from three different cores. Considering the relative age uncertainty, the CO<sub>2</sub> records agree well. In order to account for inter-laboratory offset, we added 1.5 ppm to the Taylor Dome and Dome C records (see Figure S2).



### Model for gas age distribution in Siple Dome ice core records.

We use the Center for Ice and Climate (CIC) firn air transport model [Buizert, 2011; Buizert *et al.*, 2012; Buizert *et al.*, 2013] to model gas transport in the open pores of the firn layer, as well as bubble trapping in the firn-ice transition zone. The model solves the diffusion-advection partial differential equation using Crank-Nicolson implicit time stepping in an Eulerian (i.e. static) reference frame. The model physics include molecular diffusion, gravitational enrichment, near surface convective mixing, advection with the ice matrix and a small amount of deep firn dispersive mixing. We assume a steady state, isothermal firn column at  $-25.4^{\circ}\text{C}$ ; atmospheric pressure is 937 hPa. We run the model with 0.25 m spatial resolution and 0.01-year time step. The density profile is a fit to Siple Dome density data [Severinghaus and Battle, 2006]. The effective diffusivity profile with depth was calibrated to optimize the fit to Siple Dome  $\text{CO}_2$  and  $\delta^{15}\text{N}$  firn air data (Figure S4).

The bubble trapping is based on a recently developed stochastic parameterization that includes the effect of firn density layering [Mitchell *et al.*, in prep.]. We use a close-off density of  $833.4 \text{ kg m}^{-3}$ , which is based on Martinerie *et al.* [1994], with a correction for the skewness of the trapping distribution. For the layering we use a  $1\sigma$  distribution width of  $12.5 \text{ kg m}^{-3}$ ; this value was found for the nearby WAIS-Divide site. Given that the magnitude of density variability depends, among other things, on accumulation rate [Hörhold *et al.*, 2011], we expect that Siple Dome may have slightly less layering than WAIS. Layering widens the age distribution in the closed bubbles by increasing the depth range over which bubbles are trapped, and therefore our method represents an upper bound, conservative estimate of firn smoothing of atmospheric records at Siple Dome.

The Age distributions are shown in Figure S5. The blue curve shows the age distribution in the open pores at the lock-in depth ( $z=52 \text{ m}$ ). The width of this distribution represents the amount of smoothing introduced by diffusive transport in the firn layer. The red curve gives the age distribution in the closed bubbles. The difference between the red and blue curves roughly represents the smoothing effect of gradual bubble trapping. Age distributions for Dome C and BAS depot/DML are calculated in the same way, using publicly available density and firn air data from the FIRETRACC project [Atlas *et al.*, 2006]. The closed pore age distributions at these two sites were evaluated at 110 and 80 m depth, respectively.

Figure S4. Siple Dome firn model tuned to density and CO<sub>2</sub> measurements [Severinghaus and Battle, 2006]. The lower green curve shows where the bubbles are trapped. We used a new parameterization [Mitchell *et al.* in prep.] using a firn density layering of 12.5 kg m<sup>-3</sup> obtained from nearby WAIS Divide coring site (the layering is set to the 1 standard deviation to high resolution lock-in zone density measurements). The trapping rate has dimensions of m<sup>3</sup> kg<sup>-1</sup>.

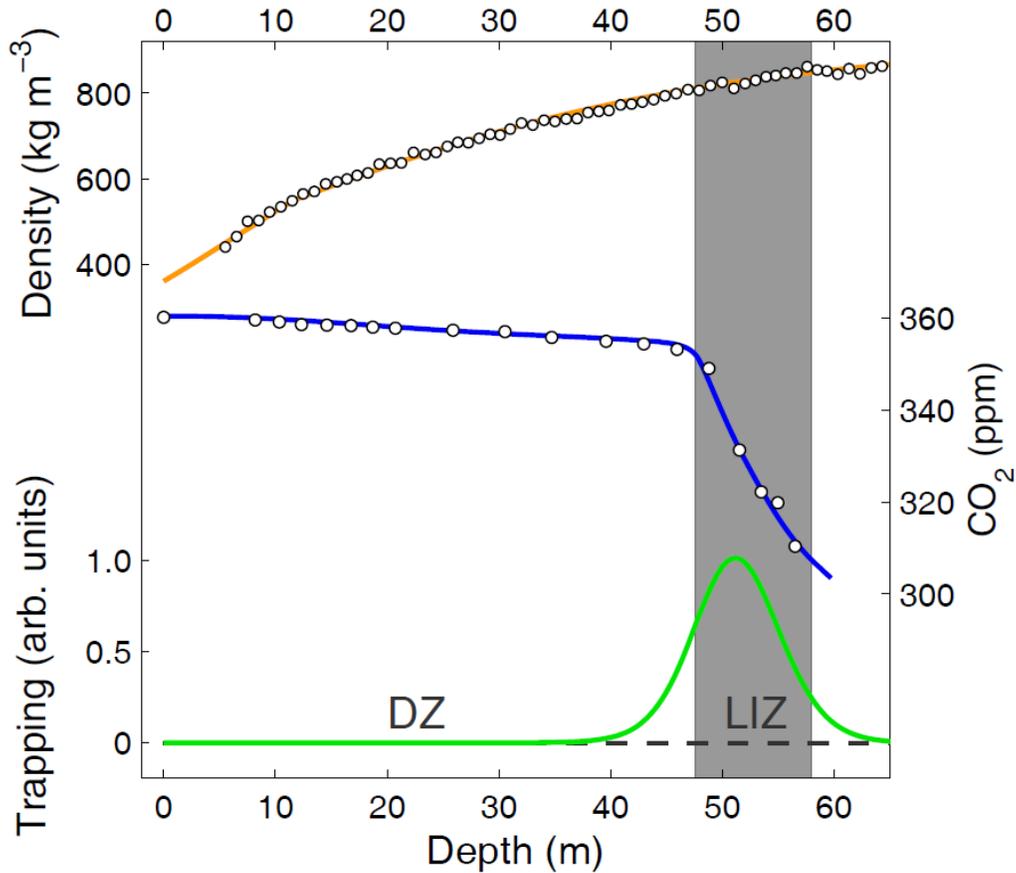


Figure S5. CO<sub>2</sub> age distribution in Siple Dome ice core. The blue curve shows smoothing of CO<sub>2</sub> age distribution in the middle of lock-in-zone (LIZ) by gas diffusion. The red line represents CO<sub>2</sub> age distribution in bubble by smoothing due to diffusion and gradual bubble trapping. Both curves have been shifted along the age axis to have a mean age of zero.

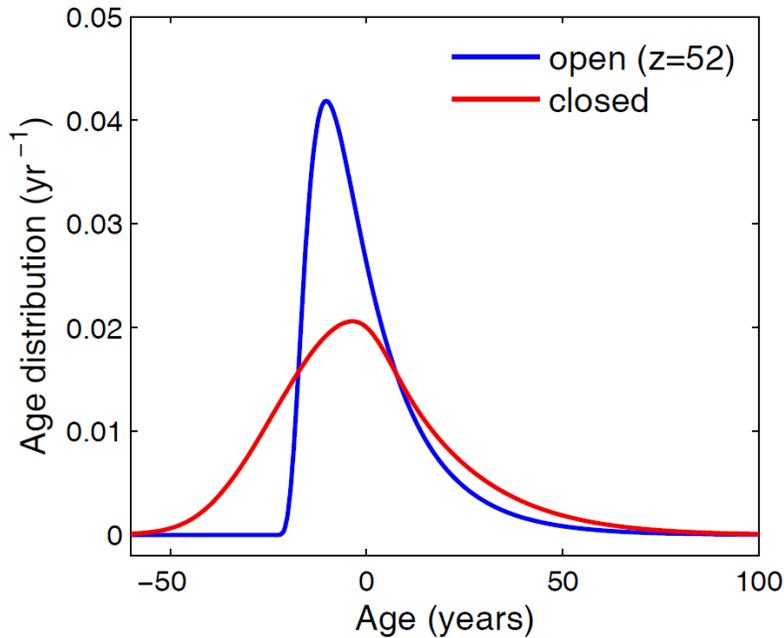


Table S1. Glaciological characteristics of Antarctic ice cores discussed in this paper.

Core name	Modern surface temperature(°C)*	Modern snow acc. rate (cm we/yr) *	CO <sub>2</sub> age distribution (yr) ** Full width at half maximum
EPICA-Dome C	-54	2.5	137
Taylor Dome	-42	6.4	52
Siple Dome	-25.4	12.4	42

\* [Siegenthaler *et al.*, 2005] for EPICA-Dome C; [Steig *et al.*, 1998] for Taylor Dome; [Brook *et al.*, 2005] for Siple Dome. \*\*CO<sub>2</sub> age distributions are calculated in this study. For details, see *Model for gas age distribution in Siple Dome ice core records*. To obtain the Taylor Dome age distribution, firn air data from BAS depot (-39°C, 7.6 cm we/yr) is used because the climatic conditions at BAS depot are similar to Taylor Dome [Atlas *et al.*, 2006]. The true Taylor Dome age distribution is probably wider, as the accumulation is lower than at BAS depot.

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