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Timing of millennial-scale climate change at Siple Dome, West Antarctica, during the last glacial period

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Abstract

Using atmospheric methane and the isotopic composition of O_2 as correlation tools, we place the δD record of ice from the Siple Dome (West Antarctica) ice core on a precise common chronology with the GISP2 (Greenland) ice core for the period from 9 to 57 ka. The onset of major millennial warming events in Siple Dome preceded major abrupt warmings in Greenland, and the pattern of millennial change at Siple Dome was broadly similar, though not identical, to that previously observed for the Byrd ice core (also in West Antarctica). The addition of Siple Dome to the database of well-dated Antarctic paleoclimate records supports the case for a coherent regional pattern of millennial-scale climate change in Antarctica during much of the last ice age and glacial–interglacial transition.

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1. Introduction

Abrupt, millennial-scale climate change during the last glacial period is now recognized from a variety of paleoclimate archives (Voelker et al., 2002). Many mechanisms have been proposed to explain the abrupt changes, but constraints on competing hypotheses are limited, in part, by the scarcity of records with precise chronologies. One topic of major interest is the relative timing of abrupt climate changes in Greenland ice cores (Dansgaard–Oeschger or D–O events) and putative counterparts in Antarctica. Precise comparison of Greenlandic and Antarctic records can be accomplished using atmospheric gas records as correlation tools, but cores with high ice accumulation rates are required to minimize uncertainties in the difference between the age of the gas and the ice phases (Δage) (Schwander et al., 1997). Two published Antarctic ice core records have suitably high accumulation rates and suitable atmospheric gas records: the Byrd core (Sowers and Bender, 1995; Blunier and Brook, 2001) and the DSS core at Law Dome (Morgan et al., 2002). Of these, only the Byrd record currently extends well into the last ice age. Modern Δage values for the Byrd and DSS cores are ~270 years (Blunier et al., 1998) and 50 years (Morgan et al., 2002), respectively. For comparison, modern Δage for the low accumulation rate east Antarctic Vostok core is ~3400 years (Goujon et al., 2003). Siple Dome

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conditions are similar to those at Byrd. The modern ice accumulation rate is ~0.124 m water equivalent/yr, and Δage under modern conditions (average $T = -24.5\,^{\circ}\mathrm{C}$) is ~242 years. Δage was larger at all sites during the glacial period because temperatures and accumulation rates were lower.

Blunier and Brook (2001) used atmospheric methane variations to create a common time scale for the GISP2 and Byrd ice cores from 10 to 90 ka. This common chronology allows analysis of the timing of temperature changes in Greenland and West Antarctica over this time period. Visual comparison of the Byrd and GISP2 ice stable isotope records suggests that the abrupt warming at the onset of the larger and longer D–O events in Greenland was preceded by slower warming in Antarctica, and that Antarctic temperatures peaked, at about the time of abrupt warming in Greenland, then declined (Blunier et al., 1998; Blunier and Brook, 2001).

Conceptual and numerical models attribute warming of high southern latitudes at times when Greenland cooled to decreases in the North Atlantic overturning circulation, which diminished heat transport to high northern latitudes while leaving more heat in the southern hemisphere (e.g., Crowley, 1992; Stocker et al., 1992; Ganopolski and Rahmstorf, 2001; Stocker, 2002; Vellinga and Wood, 2002; Schmittner et al., 2003; Knutti et al., 2004). The Byrd–Greenland comparison has been used to support this mechanism of abrupt climate change.

A variety of quantitative analyses have been applied to the GISP2–Byrd data set with varying conclusions. Steig and Alley (2002) used lag correlation analysis of filtered data to examine the relationships between the records. They concluded that the data are consistent with either a southern hemisphere lead of 1000–1600 years or a 400–800 year southern hemisphere lag, and emphasized that neither is a complete description of the data. Schmittner et al. (2003), also using correlation analysis of filtered data, argued that temperature changes in Greenland led changes of the opposite sign in Antarctica. Their analysis also revealed high correlation for Antarctica leading Greenland by ~1300 years, but they emphasized that this observation need not require a trigger for abrupt climate change in the Southern hemisphere. Huybers (2004), commenting on Schmittner et al., and using a different model analysis, argued that a small Antarctic lead was statistically superior to a Greenland lead. Wunsch (2003) analyzed the records in the frequency domain, and concluded that at periods longer than about 2500 years Antarctic temperature changes led those in Greenland by 1400–1800 years, but suggested that evidence for mechanistically significant relationships between the records on shorter time scales is weak or absent. Stocker and Johnsen (2003) developed a simple "thermal bipolar seesaw" model which allowed them to predict the Byrd isotope curve fairly accurately from the Greenland (GRIP in this case) record by incorporating a heat reservoir (the Southern Ocean), which delays and integrates the impact of a northern hemisphere climate changes on the southern hemisphere. They argued that almost all D–O events between 25 and 65 ka have a recognizable counterpart in the Byrd record. Knutti et al. (2004) elaborated on this approach with a more sophisticated model, and reached similar conclusions. Roe and Steig (2004) argued for a significant relationship between the Byrd and GISP2 records, but only for the largest and longest of the millennial-scale fluctuations, consistent with the visual interpretation of the data described above.

Given the attention that the Greenland–Antarctic comparison has received, it is important to develop other records with the goal of examining how spatially consistent the relationships are. In particular, it would be valuable to demonstrate that the observed relationships are not limited to the Byrd record, but represent some larger spatial domain, as is generally assumed to be the case. In Greenland the combination of the GISP2, GRIP, North GRIP, and older records supports the pattern of abrupt climate change inferred from GRIP and GISP2 (Johnsen et al., 2001). In this paper we discuss data from a portion of the new Antarctic record from Siple Dome, West Antarctica (Fig. 1) for the period from 9 to 57 ka B.P. We use atmospheric methane (Blunier and Brook, 2001) and the isotopic composition of O_2 (Bender et al., 1994) to create a time

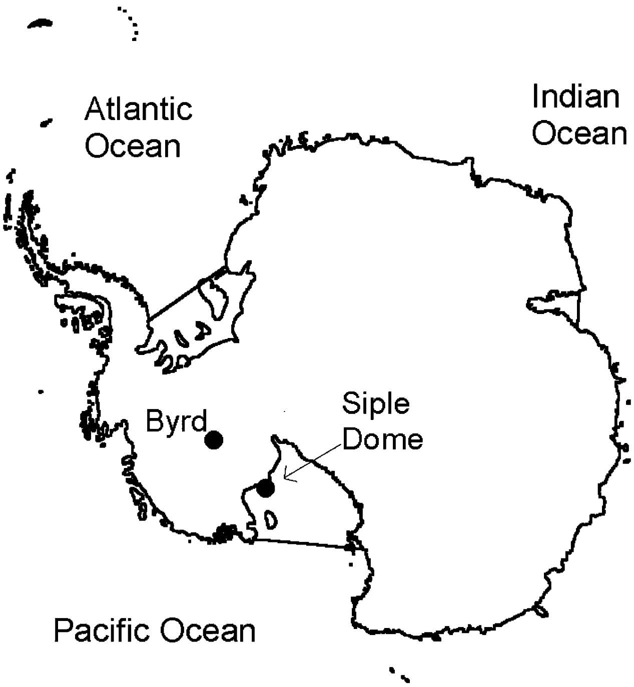

Fig. 1. Location of Siple Dome and Byrd ice cores.

scale that allows direct comparison with the Greenland records. A robust empirical result of our work is that there are four intervals between 9 and 57 ka during which we observe slow Antarctic warming while Greenland remained cold, followed by rapid warming in Greenland at about the time of maximum warmth in Antarctica. These periods correspond to the largest and longest interstadial events in Greenland and Antarctica in this time interval.

2. Methods

We determine the Siple Dome chronology from 8.7 to 42.7 ka by first correlating the methane–depth curve of Siple Dome with that of GISP2 and GRIP (Blunier and Brook, 2001). We use the GISP2 time scale of Meese et al. (1994). Where GRIP methane data are used, they are placed on the GISP2 time scale as reported by Blunier and Brook (2001). The Siple Dome methane record over this time period consists of duplicate measurements from 281 depths in the interval from 514.8 m (gas age 8.3 ka) to 854.5 m (gas age 42.7 ka). The GISP2 record consists of results published by Brook et al. (1996, 2000) and additional measurements made since that time. Before 42.7 ka the existing methane record is sparse, with insufficient data to precisely match the numerous oscillations during this time period. We extend the chronology presented here to 57 ka employing a control point at 919.9 m (56.7 ka) based on $\delta^{18}O$ of O_2 ($\delta^{18}O_{atm}$). In general, $\delta^{18}O_{atm}$ values are heavier at Siple Dome than at GISP2. The probable cause is gas loss from Siple Dome samples, with isotope fractionation, due to poor core quality. We validate the gas-age time scale for the methane-dated interval by demonstrating that the curve of $\delta^{18}O_{atm}$-age at Siple Dome agrees with that of GISP2 (Fig. 2) within the uncertainty of the $\delta^{18}O_{atm}$-based age control (± 2000 years) during times of major variation in $\delta^{18}O_{atm}$. The 0–8.7 ka chronology for Siple Dome is based on annual layer counting (Taylor et al., 2005). The match of the existing Siple Dome methane data between 42.7 and 57 ka with GISP2 is equivocal due to the small number of Siple Dome data points, but within the ± 2000 year uncertainty of the chronology based on $\delta^{18}O_{atm}$ the methane records are not inconsistent. The full data sets and time-scale description are archived at www.nsidc.org.

Methods for methane measurements are described in Brook et al. (2000), with the only major differences being that we employed an air standard of 850.1 ppb CH_4 (calibrated by NOAA CMDL), we analyzed each of the duplicate samples only once, and we used a Hewlett Packard 6890 Series II gas chromatograph for the analysis. Full procedural blanks ranged from 12 ± 5 to 27 ± 7 ppb depending on the time period of the measurements. Data for a depth interval were accepted if the methane concentration measurements in duplicate ice samples differed by less than 40 ppb. Sixteen samples were reanalyzed in duplicate based on this criterion. $\delta^{18}O_{atm}$ of paleoatmospheric O_2 was determined at Princeton using the method of Sowers et al. (1989). Air was extracted using only a single melt-refreeze step, as for recent GISP2 and Vostok samples (Bender et al., 1999).

We established time control points for Siple Dome at inflection points that can be identified in both the Siple Dome and Greenland methane or $\delta^{18}O_{atm}$ records (Fig. 2; Table 1). We interpolated linearly between these control points to provide a record of gas age vs. depth. Gas ages are younger than ice ages because air is trapped at depth in the firn (Schwander et al., 1993). To create an ice age time scale we calculated the gas age–ice age difference (Δage) using the Herron and Langway (1980) empirical model. This steady-state model requires temperature and accumulation input. One can estimate these terms from proxy data (δD_{ice} and $\delta^{18}O_{ice}$).

Temperature was estimated from the δD_{ice} and $\delta^{18}O_{ice}$ records, scaling from the modern mean annual temperature ($-24.5\,^{\circ}C$) and correcting for changes in moisture source temperature and ocean isotopic changes (Schilla et al., 2005). We first corrected for changes in the isotopic composition of the ocean using a $\delta^{18}O_{seawater}$ record from core TR163-22 in the eastern tropical Pacific (D.W. Lea, personal communication, 2003). Deuterium excess (d) was used as a proxy for the air temperature at the moisture source, which we also corrected for. To make that correction we chose a sensitivity of d to moisture source temperature of $+1.1‰/^{\circ}C$ based on simple 1D (Petit et al., 1991) and more complex 3D models of isotopes in polar precipitation (Stenni et al., 2001; Vimeux et al., 2001). These models were also used to scale the sensitivity of δD_{ice} to moisture source temperature, which we fixed as $-4‰/^{\circ}C$ for the near-coastal Siple Dome site. The δD_{ice} record was corrected for moisture source temperature changes based on these scaling factors, and surface temperatures were calculated using an apparent δD_{ice}/surface temperature sensitivity of $+6‰/^{\circ}C$ based on models and spatial observations in West Antarctica. Accumulation rates were estimated from temperature using the Lorius et al. (1985) relationship that predicts accumulation rate from surface temperature and the modern accumulation rate (0.124 m water equivalent per year). We are aware that accumulation and temperature may not always covary in coastal Antarctica (Monnin et al., 2004; van Ommen et al., 2005). However, we know of no better way to estimate past accumulation for which data are fully available at this point.

The Herron and Langway model does not explicitly incorporate the impact of changes in temperature or accumulation on densification. To account for changing temperatures and accumulation, we estimated the

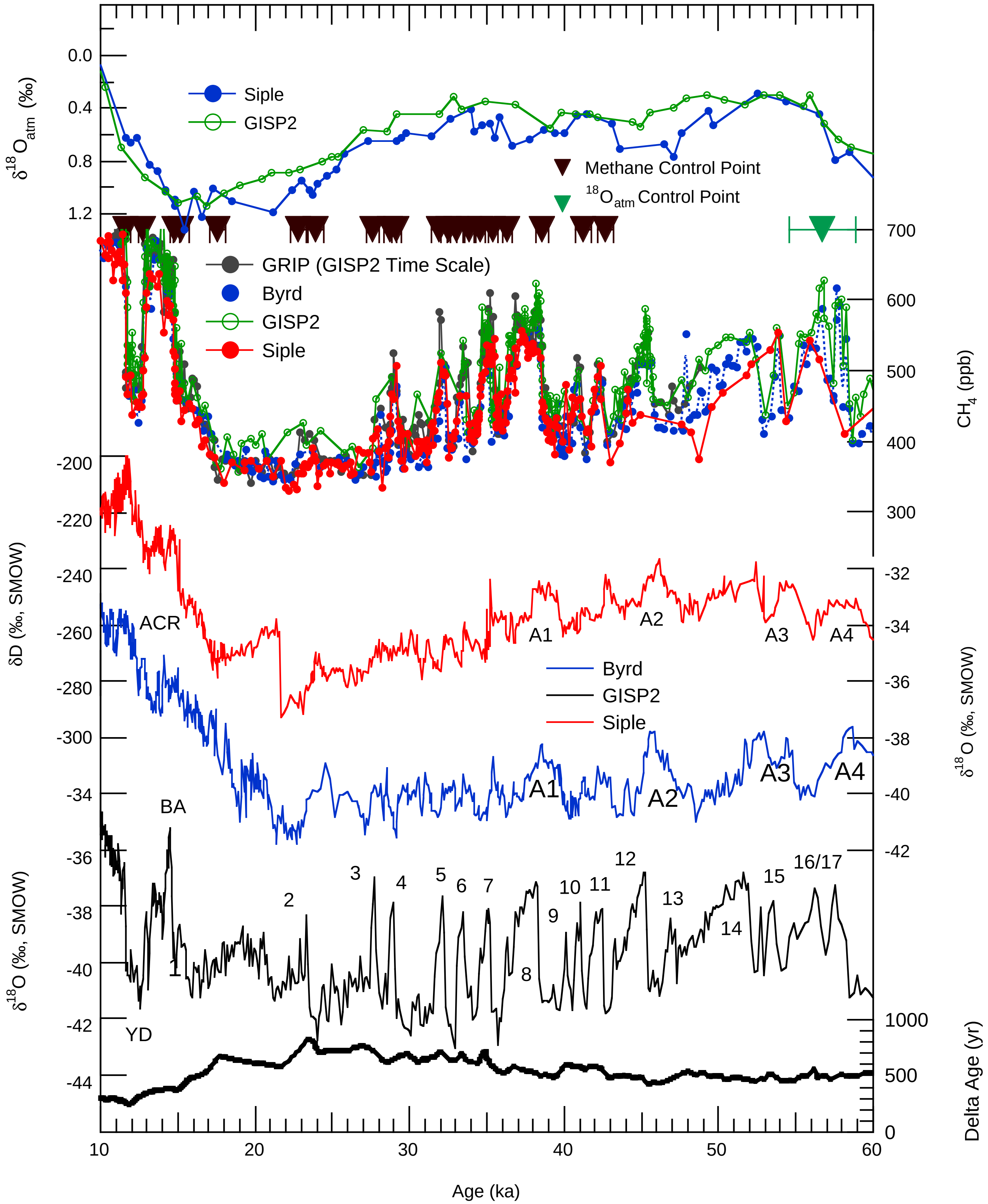

Fig. 2. Time series records discussed in text, with age control points plotted at the top of figure (solid triangles). The youngest control point used (8.33 ka at 514.78 m based on CH_4) is not shown. Methane data for GRIP and Byrd and their chronologies from Blunier and Brook (2001); Siple δD record from Taylor et al. (2004) and White et al. (in prep.), Byrd $\delta^{18}O$ from Blunier and Brook (2001), GISP2 $\delta^{18}O$ record from Grootes et al. (1993) on chronology from Meese et al. (1994). Numbers indicate D–O events, BA = Bølling/Ållerød, YD = Younger Dryas. The apparent abrupt warming at ~15.2 ka occurs in an interval in the core where nitrogen and argon isotopic data suggest firn thinning or deep convection in the firn (Fig. 3), and possibly a hiatus in deposition, and should be interpreted cautiously.

Table 1
Control points for Siple Dome gas-age time scale, Δage, and estimated uncertainties

Depth	Corr. variable	Gas age (ka)	Δage (yr)	Ice age (ka)	Δage unc. (ka)	Correlation unc. (ka)	GISP vs. Siple, total unc	GISP unc. (ka)	Absolute unc. (ka)
514.78	CH_4	8.33	282	8.61	0.08	0.20	0.38	0.17	0.55
621.73	CH_4	11.63	243	11.88	0.07	0.12	0.30	0.23	0.53
646.71	CH_4	12.79	351	13.14	0.11	0.17	0.38	0.26	0.63
674.88	CH_4	14.78	381	15.16	0.11	0.13	0.35	0.30	0.64
680.38	CH_4	15.21	442	15.65	0.13	0.12	0.35	0.30	0.66
708.08	CH_4	17.56	645	18.20	0.19	0.32	0.61	0.35	0.97
729.15	CH_4	22.81	815	23.63	0.24	0.27	0.61	0.46	1.07
739.72	CH_4	23.95	719	24.67	0.22	0.27	0.58	0.48	1.06
757.84	CH_4	27.61	729	28.34	0.22	0.26	0.58	0.55	1.13
765.48	CH_4	28.72	670	29.39	0.20	0.15	0.45	0.57	1.03
767.89	CH_4	29.21	689	29.90	0.21	0.18	0.48	0.58	1.07
786.93	CH_4	31.97	633	32.60	0.19	0.06	0.35	0.64	0.99
789.02	CH_4	32.52	683	33.21	0.20	0.30	0.60	0.65	1.25
793.57	CH_4	33.05	629	33.68	0.19	0.33	0.62	0.66	1.28
795.20	CH_4	33.85	599	34.45	0.18	0.21	0.49	0.68	1.17
803.82	CH_4	34.60	672	35.28	0.20	0.14	0.44	0.69	1.13
809.26	CH_4	35.45	599	36.05	0.18	0.13	0.41	0.71	1.12
815.94	CH_4	36.30	572	36.87	0.17	0.10	0.37	0.73	1.09
825.87	CH_4	38.56	496	39.05	0.15	0.20	0.44	0.77	1.22
846.92	CH_4	41.21	572	41.78	0.17	0.29	0.56	0.82	1.38
854.53	CH_4	42.65	482	43.13	0.14	0.32	0.57	0.85	1.42
919.88	$\delta^{18}O_{atm}$	56.70	463	57.16	0.14	2.00	2.24	1.13	3.37

See text for further explanation.

average temperature and accumulation rate for the firn column at the time of bubble close off for each depth of interest. To make this estimate we assumed a constant firn thickness with time (50 m) and used the thinning function of Nereson et al. (1996) to calculate, for each depth, the thickness of ice that would have composed the firn column at the time of bubble close off. We then calculated the average temperature and accumulation rate over this interval.

The densification model also requires the density at bubble close off. We calculated close-off density using the temperature-dependent relationship of Martinerie et al. (1992). We reduced the close-off density by 14 kg m^{-3} to account for the impact of the zone of alternating permeable and impermeable layers that obviate vertical transport near the close-off depth (Schwander et al., 1997). The Herron and Langway calculation then yields the age of the ice when air is isolated from the overlying atmosphere. A final correction is necessary for the diffusion time of gases from the ice sheet surface to the air isolation depth. Schwander et al. (1997) determined a 10-year diffusion time for the 70 m modern firn column at the GRIP and GISP2 sites. We scaled this value for Siple Dome assuming diffusion time varies as the square of firn thickness (e.g., Siple diffusion time = $10^*(H/70)^2$, where H is firn thickness). H was determined from the Herron and Langway equations.

We calculated Δage on 0.5 m spacing for the whole core. From 8.7 to 57 ka Δage ranges from approximately 230 to a maximum of 820 years, with most values between 400 and 700 years. The gas-age time scale was interpolated linearly to the 0.5 m grid and ice ages were calculated for each depth by adding Δage to gas age. An alternate interpolation scheme (Bender et al., 1999) that determines the shape of the age vs. depth curve between the control points by using the relative variations in calculated accumulation rates (in this case based on the ice isotope data), results in a time scale that differs from the linear interpolation by less than 0.13 ka above 920 m (56 ka). Below, there are four excursions. At 930 m (60 ka), the difference is 0.3 ka; at 950 m (68 ka), 0.21 ka; at 960 m (79 ka), 0.41 ka; and at 967 m (89 ka), 0.3 ka. Given uncertainties in estimating accumulation rates, we retain the linear interpolation and use these deviations as one measure of error due to interpolation.

An alternate calculation of Δage, employing a dynamic densification model incorporating heat transport (Goujon et al., 2003) and the same accumulation and temperature input, produced values within 100 years of the Herron and Langway model for most of the record, and within 200 years during the coldest parts of the last ice age (Fig. 3).

The chronology presented here allows a precise comparison of Siple Dome with Greenland records. The relative uncertainty of the ice chronology between GISP2 and Siple Dome depends on the gas correlation uncertainty as well as uncertainties in Δage for the two cores (Table 1). The latter uncertainty arises for GISP2 because the layer-counted ice chronology is translated to the GISP2 gas-age time scale using models for Δage

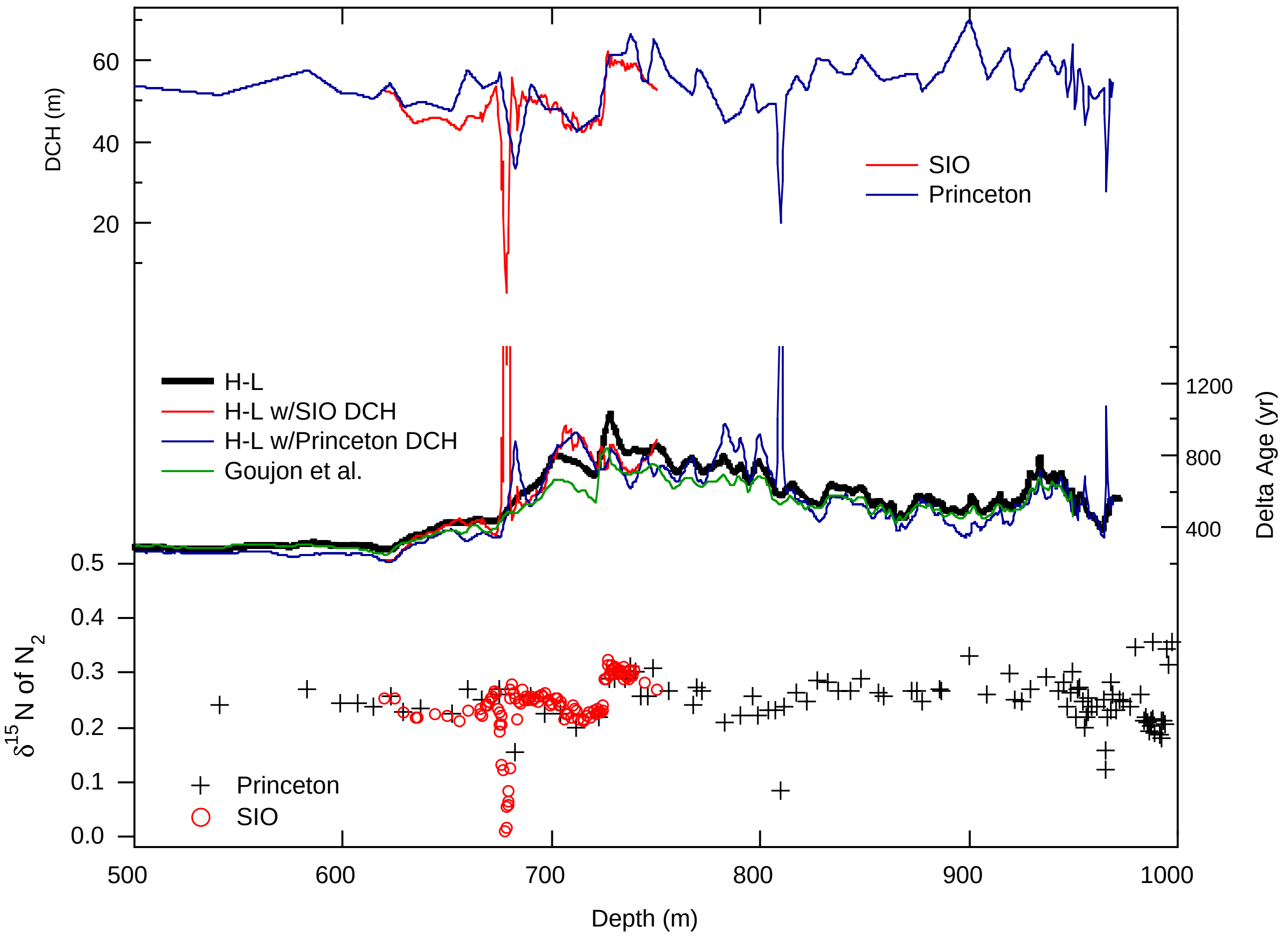

Fig. 3. Bottom: Siple Dome Nitrogen isotope data from Princeton and SIO (Severinghaus et al., 2003). Top: Estimates of DCH for Siple Dome based on δ^{15}N data and barometric equation. Middle: Various Δage estimates for Siple Dome. H–L = Herron and Langway (1980) densification model with temperature and accumulation estimated from ice isotope record (see text). H–L/SIO or HL/Princeton uses Herron and Langway model and the same temperature estimates, with the depth close-off constrained by the DCH estimates in the top panel. Goujon et al. (2003) is a dynamic densification model run with the temperature and accumulation rates estimated from the ice isotope record. See text for more details.

similar to those employed here for Siple Dome. To estimate the GISP2 vs. Siple Dome uncertainty, we assume a 100-year uncertainty in GISP2 Δage (Blunier and Brook, 2001), and estimate correlation uncertainty as the larger of the GISP2 or Siple Dome sample spacing at the match points. Uncertainty in Δage is the main source of uncertainty in the Siple Dome chronology. It results from inaccuracies in the model and uncertainty in both the temperature reconstruction and its impact on accumulation estimates. The possibility that changes in accumulation are not related to temperature in an obvious way is problematic for this and other studies that use temperature reconstructions to estimate accumulation rates. These uncertainties are difficult to quantify in the absence of independent measures of accumulation and/or calibration of the isotope thermometer specifically for Siple Dome. A conservative estimate of the Δage uncertainty is ±30%. For the most part the uncertainties discussed here are not random, but are ranges of probable values for the parameters used in the Δage model. We therefore conservatively express total uncertainty at the control points as the sum of the individual uncertainties (Table 1). As described above, interpolation between control points adds additional uncertainty.

A caveat for the Siple Dome chronology concerns correlation of the small methane oscillation at 22–24 ka (Fig. 2). We use this feature for correlation to be consistent with its use in correlating Byrd with GISP2/GRIP by Blunier and Brook (2001). The oscillation is small, however, reducing confidence in the match between the records, and we cannot with complete confidence rule out alternate chronologies in the 18–28 ka region.

One nearly independent check on the Δage calculations is available from the nitrogen and argon isotopic measurements in Siple Dome air from Severinghaus et al. (2003) and similar nitrogen isotope measurements made at Princeton. Nitrogen and argon isotopes are fractionated by gravity, and the degree of heavy isotope enrichment depends on the thickness of the diffusive part of the firn column (Craig et al., 1988; Schwander et al., 1988). This thickness (called Diffusive Column Height or DCH) can be estimated using the isotope data and the barometric equation (Sowers et al., 1989). In Fig. 3, we plot DCH based on both $\delta^{15}N$ data sets. Neither data set is corrected for thermal diffusion effects, but these should be relatively small at Siple Dome (Severinghaus et al., 2003).

To calculate Δage from DCH we assumed that near-surface convection was negligible, so that gravitational fractionation was expressed throughout the firn column. We also assumed that the Herron and Langway model describes the paleo depth–density profiles. Close off density and ice surface temperature were estimated as described above. We then used the Herron and Langway equations to calculate Δage from DCH, with accumulation rate as a free parameter. Essentially, this calculation uses the DCH to find the accumulation rate consistent with the specified firn thickness (DCH), close-off density, and temperature. Δage is then determined from these parameters. The results are plotted in Fig. 3. In general, Δage calculated from DCH agrees reasonably well with the Herron and Langway calculation, and the trends of the two estimates are broadly similar. There are two clear exceptions. One is the interval between 675 and 689 m (15.2–15.7 ka) where the nitrogen and argon isotope data are consistent with firn thinning or extremely deep convection in the firn (Severinghaus et al., 2003; Taylor et al., 2004). Very low accumulation rates and high values of Δage are predicted for this interval using DCH as a constraint. Although these predictions may be artifacts of the influence of deep convection in the firn column, it is also possible that they represent a brief hiatus in deposition (Severinghaus et al., 2003; Taylor et al., 2004). This interval is also associated with an apparent abrupt change in δD (Fig. 2). The sequence of events in this section of the core is therefore complex, and the chronology of this interval should be interpreted cautiously. The second exception is an apparently similar, but brief, interval at about 810 m, where $\delta^{15}N$ of N_2 reaches values less than +0.1 ‰. This oscillation is not associated with any major events in the δD record and has not yet been examined in detail.

3. Results and discussion

In Fig. 2 we plot the methane records, GISP2 $\delta^{18}O_{ice}$, Siple Dome δD_{ice}, Byrd $\delta^{18}O_{ice}$, and Siple Dome Δage. As the Byrd chronology was also constructed by correlation to Greenland using methane (Blunier and Brook, 2001), all three records are on the same time scale. The isotope records are taken primarily as records of surface temperature variations at the core sites. We recognize that this is not strictly true, as the isotope ratios respond to temperature changes at the moisture source, as well as other factors such as changes in the seasonal distribution of snowfall (Dansgaard, 1964; Cuffey and Brook, 2001). As we lack the deuterium excess record at Byrd needed to correct $\delta^{18}O_{ice}$ for changes in moisture source temperature (Jouzel and Merlivat, 1984; Petit et al., 1991), the raw isotope records, rather than ice sheet temperature estimates, are compared. For this purpose, we assume that factors such as changes in seasonality and multiple moisture sources either are small or make approximately equal contributions to the records at both sites.

As described above, previous analysis of the Byrd record showed that millennial-scale climate fluctuations at Byrd were not synchronous with the Greenland D–O events (Blunier et al., 1998; Blunier and Brook, 2001). Instead, at least for the larger events, warm periods in the Byrd record clearly began during or at the onset of cold stadial periods in Greenland (Blunier and Brook, 2001).

The timing of major millennial events in Siple Dome between 10–16 and 26–57 ka is very similar to that in Byrd. For example, we identify the A1, A2, A3, and A4 Antarctic warm events (Blunier and Brook, 2001) in Siple Dome with the same timing as Byrd (Fig. 2). The Siple Dome record has a prominent plateau from 13 to 15 ka, similar to the Antarctic Cold Reversal identified in Byrd and other Antarctic ice core records (Jouzel et al., 1995; Morgan et al., 2002). The apparent abrupt warming just prior to the start of the ACR in Siple Dome is described further by Taylor et al. (2004) and Severinghaus et al. (2003) and may in part be due to an interruption of deposition. Given the good match between the details of the Siple Dome, Byrd, and Greenland methane records we believe that a hiatus in the record, if any, probably was short, on the order of 500 years or less. The main impact on the stratigraphy would be to make the apparent abrupt event at 15.2 ka more pronounced. A forthcoming paper from the Siple Dome project will examine this interval in more detail. Warming at the end of the ACR started at about 13 ka in the Siple record. Within chronological uncertainties, this warming is synchronous with the Younger Dryas onset.

Visual inspection of the Siple and Byrd records suggests that they share additional common features, e.g., the broad peak centered at 24–25 ka, the sequence of oscillations between 30 and 36 ka, and possibly the oscillations between A1 and A2 (Fig. 2). There are differences between the records also. The slight cooling in Siple Dome from 22 to 18 ka does not appear to match the Byrd record. The abrupt event at 22 ka is absent or diminished in the Byrd record, and may be a local phenomenon (Taylor et al., 2004). However, there is a subtler warming trend at ~21 ka in the Byrd record, and given chronological uncertainties at this time of low methane variability these two features could be correlative. Taylor et al. (2004) discuss the 22 ka event in more detail. Finally, the warm event identified as A3 in Byrd appears to be two distinct warm phases at Siple Dome.

The correlation coefficient between the Byrd and Siple records for the 10–57 ka period is 0.78, significant at the 95% confidence interval. The similarities on millennial scales are more visually apparent after applying a high-pass filter (cut off 1/7000 yrs) to both records (Fig. 4). The correlation between the filtered records is 0.60 (significant at 95% confidence).

Comparison of the GISP2 isotope record with Siple Dome reveals the clear differences apparent in the Byrd vs. GISP2 comparison (Blunier and Brook, 2001; Sowers and Bender, 1995). The onset of the A1 and A2 events clearly preceded the GISP2 D–O events 8 and 12 (by about 1.2 and 1.4 ka, respectively) and cooling of A1 and A2 apparently began at the onset of D–O events 8 and 12. For A3 the relationships are more subjective. As indicated above, the event identified as A3 in Byrd could be considered a sequence of two warm events, and this split is more pronounced in the Siple record (Fig. 2). Turning to the younger part of the record, in Greenland the coldest temperatures of the past 30,000 years occurred at 24 ka. Greenland temperatures then warmed, while Antarctic temperatures began falling, reaching a minimum at 23 ka, 1000 years after Greenland (Alley et al., 2002). Byrd began a steady warming by 19 ka, and Siple Dome, at 17.5 ka. At both sites most of the deglacial warming was complete before the large step warming into the Bølling at GISP2. The ACR in Siple Dome occurred prior to the Younger Dryas in GISP2, during the Bølling–Allerød warm period, as observed for Byrd (Sowers and Bender, 1995). The Siple Dome record also indicates a cooling trend at the start of the Holocene, at a time when the GISP2 record indicates warming.

There are important limitations to the precision of the Greenland–Antarctic comparison. To illustrate this point we project the times of several abrupt warmings in GISP2 onto the Siple Dome record, showing the uncertainty in that projection (Fig. 5), as derived from uncertainty estimates in Table 1. This plot shows that we can be confident in stating that the onset of longer millennial warmings in Antarctica occurred before the onset of longer millennial warmings in Greenland, but for shorter events the relative timing is more difficult to constrain. Reducing the uncertainties in Δage will require sites with higher accumulation rates and methods of determining accumulation that are independent of temperature proxies (e.g., layer counting, cosmogenic isotopes, or bubble number density proxies [Alley and Fitzpatrick, 1999]).

On the other hand, we can gain some further confidence in the timing of Greenlandic vs. Antarctic events by examining the methane and ice isotope data in the depth domain. In Fig. 6 we plot both variables for the section of Siple Dome from 780 to 840 m, roughly 32–41 ka B.P, encompassing Greenland D–O events 5–8. The sharp increases in methane mark the Greenland

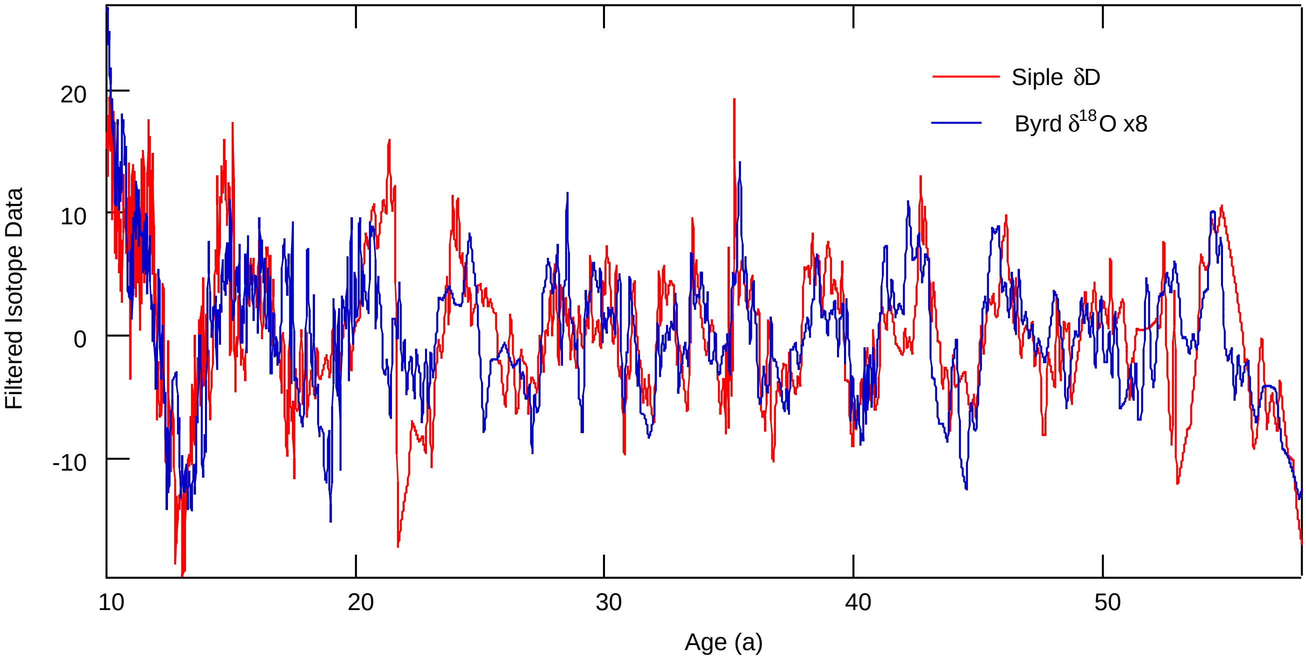

Fig. 4. High-pass filtered isotope data for Siple Dome and Byrd, using a cut-off frequency of 1/7 ka. The data were linearly interpolated to a 10-year spacing and normalized to the mean of each time series prior to filtering. The Byrd record is multiplied by 8 to facilitate the comparison.

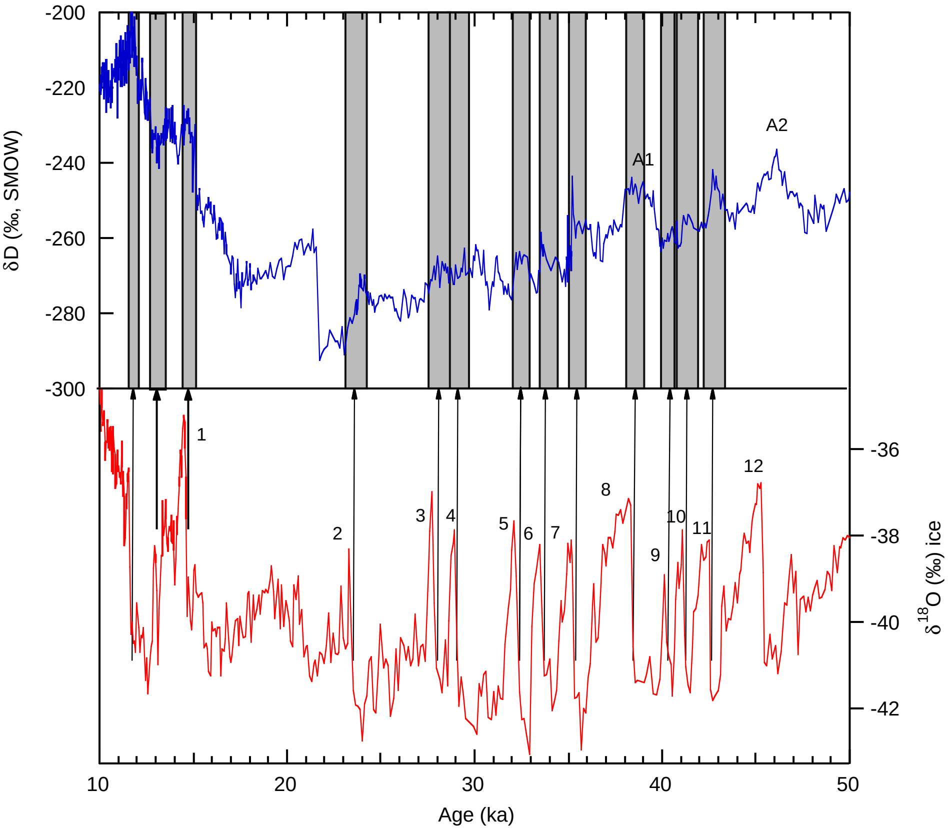

Fig. 5. Illustration of uncertainty of Siple Dome time scale relative to GISP2. The shaded boxes are the estimated uncertainty in placing the timing of GISP2 warming on the Siple Dome time scale. The arrows do not necessarily suggest genetically related events, they simply show the projection of GISP2 chronology on Siple Dome. Numbered interstadial events as in Fig. 2. BA = Bølling/Ållerød, YD = Younger Dryas.

D–O events (Fig. 2). We assume, based on previous work (Severinghaus et al., 1998; Severinghaus and Brook, 1999), that these methane increases were coincident (within several decades) with Greenland temperature change at the onset of the D–O events indicated in Fig. 6. Due to the gas age–ice age difference, the location of an event in the gas phase in an ice core record will be physically displaced below the ice that was deposited at the time of that event. We observe that the warming events in Siple Dome that may be associated with D–O 7 and 8 are actually below the associated methane increases (Fig. 6). This stratigraphic relationship rules out synchronous climate changes at Siple Dome and GISP2 for these events, and requires that the onset of the Siple Dome events preceded the onset of D–O events 7 and 8 in Greenland. At the two shallower events the methane increases are nearly coincident in depth with the warmings in the isotope record. Again, warming at Siple Dome must lead the methane increase, since the gas age–ice age difference must be >0. It is important to note that finding a methane increase below an Antarctic warming would not prove a Greenland lead vs. Antarctica. For those situations we must rely on models of Δage to examine the phasing.

By making these stratigraphic arguments we do not make any specific inference about causes of phasing for the events associated with D–O 7 and 8, nor can we demonstrate that these few observations prove a systematic difference in timing between Greenland and Antarctica for all millennial events. Nevertheless, for these events the phasing is clear. With a core from a higher accumulation rate site it is possible that this approach could help define the Greenland–Antarctic relationship more accurately for many of the D–O events.

4. Conclusions

We provide a chronology for the Siple Dome ice core for the period from 9 to 57 ka based on correlating records of atmospheric methane and $\delta^{18}O_{atm}$ between GISP2 (Greenland) and Siple Dome (Antarctica). This places Siple Dome on the common chronology of the GISP2, GRIP, and Byrd ice cores established by Blunier and Brook (2001). We find four intervals between 9 and 57 ka where we observe slow Antarctic warming while Greenland remained cold, followed by rapid warming in Greenland at about the time of maximum warming in

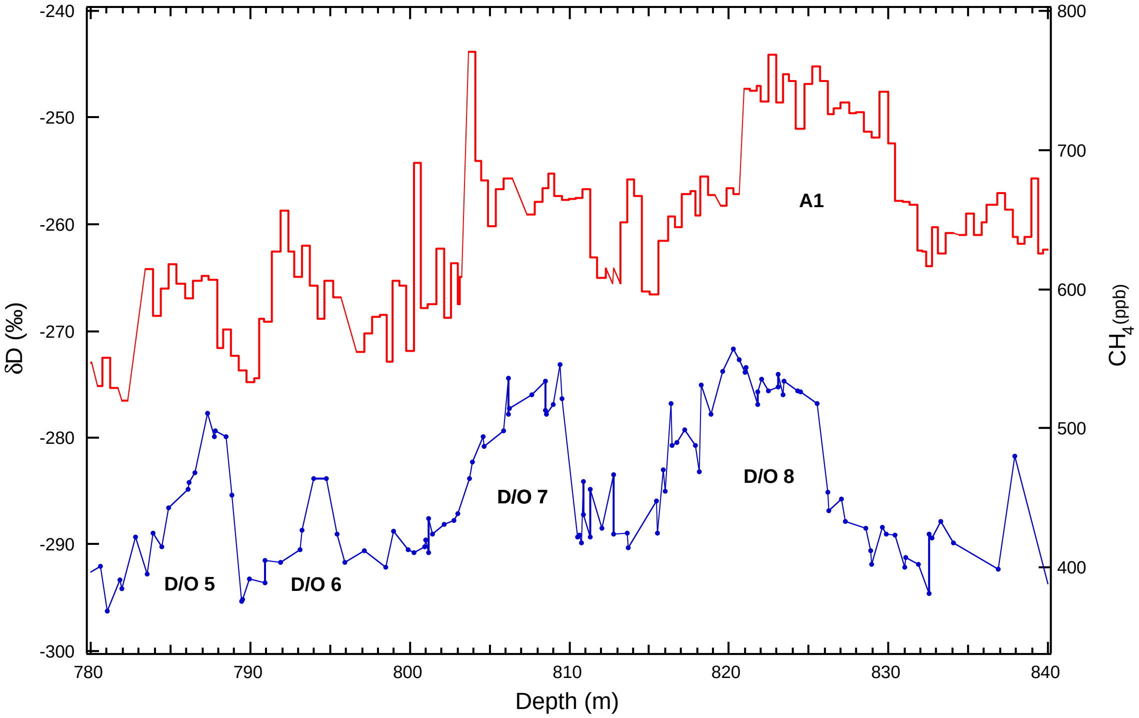

Fig. 6. Methane and δD record from Siple Dome plotted as a function of depth. The methane increases mark the timing of abrupt warming in Greenland. The methane increases associated with D–O 7 and 8 are stratigraphically above the warming events in the Siple Dome δD record, providing definitive evidence that the Siple Dome events are not synchronous with D–O events in GISP2. At the two shallower events in Siple Dome, the methane increases (associated with D–O 5 and 6) are nearly coincident in depth with the warmings in the isotope record. Warming at Siple Dome must also lead the methane increase (and therefore the D–O events) for these events, since the gas age–ice age difference must be >0.

Antarctica. These periods correspond to the largest and longest interstadial events in Greenland and Antarctica in this time interval. It is not possible to establish, with these data, if this relationship holds for shorter-lived D–O events and possible Antarctic counterparts. Additional records are needed, particularly from higher accumulation rate sites in Antarctica.

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