Evidence for Abrupt Climate Change in the Paleo-record

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Acknowledgments

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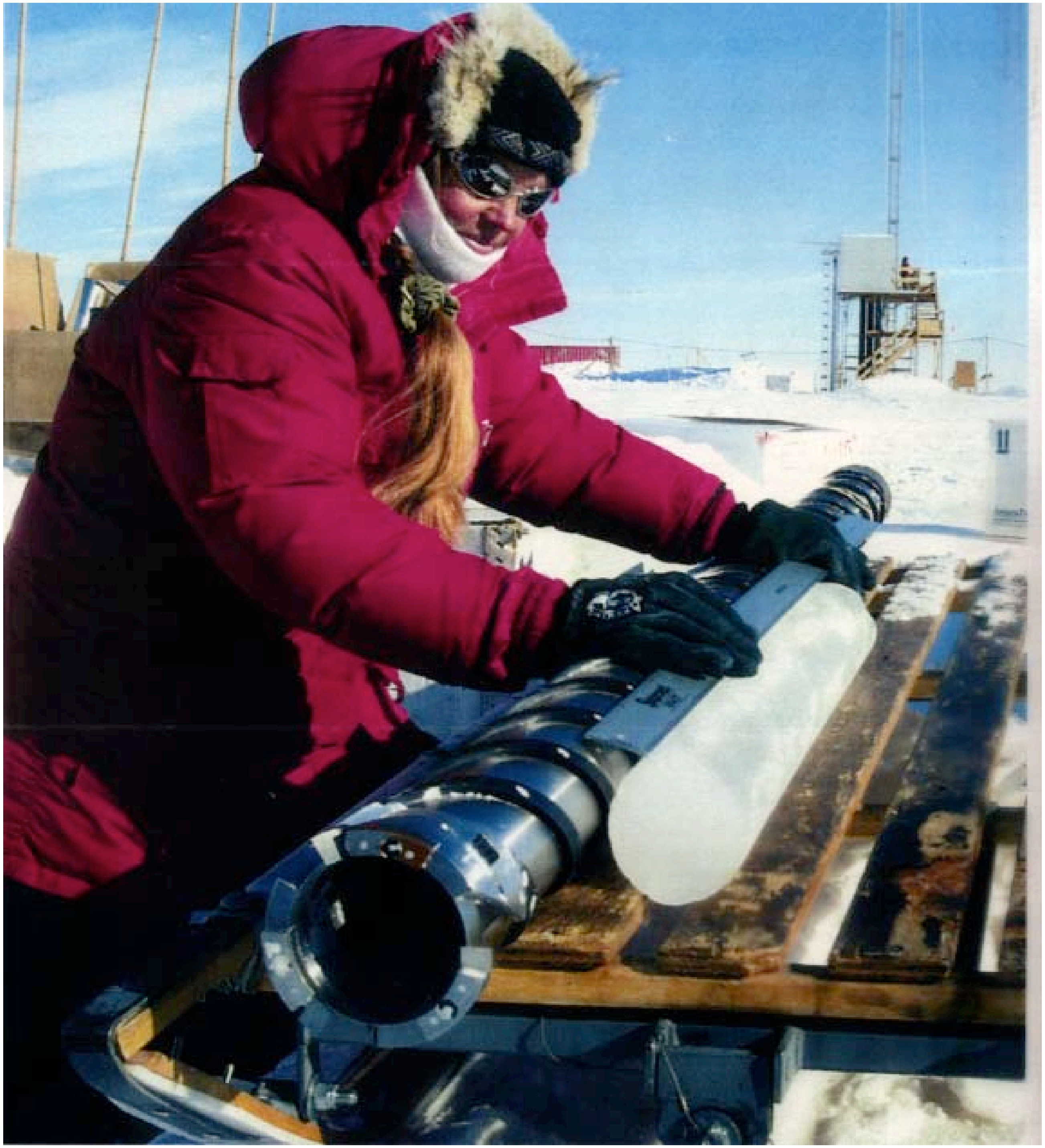
Packard Foundation

National Ice Core Laboratory, USGS/NSF

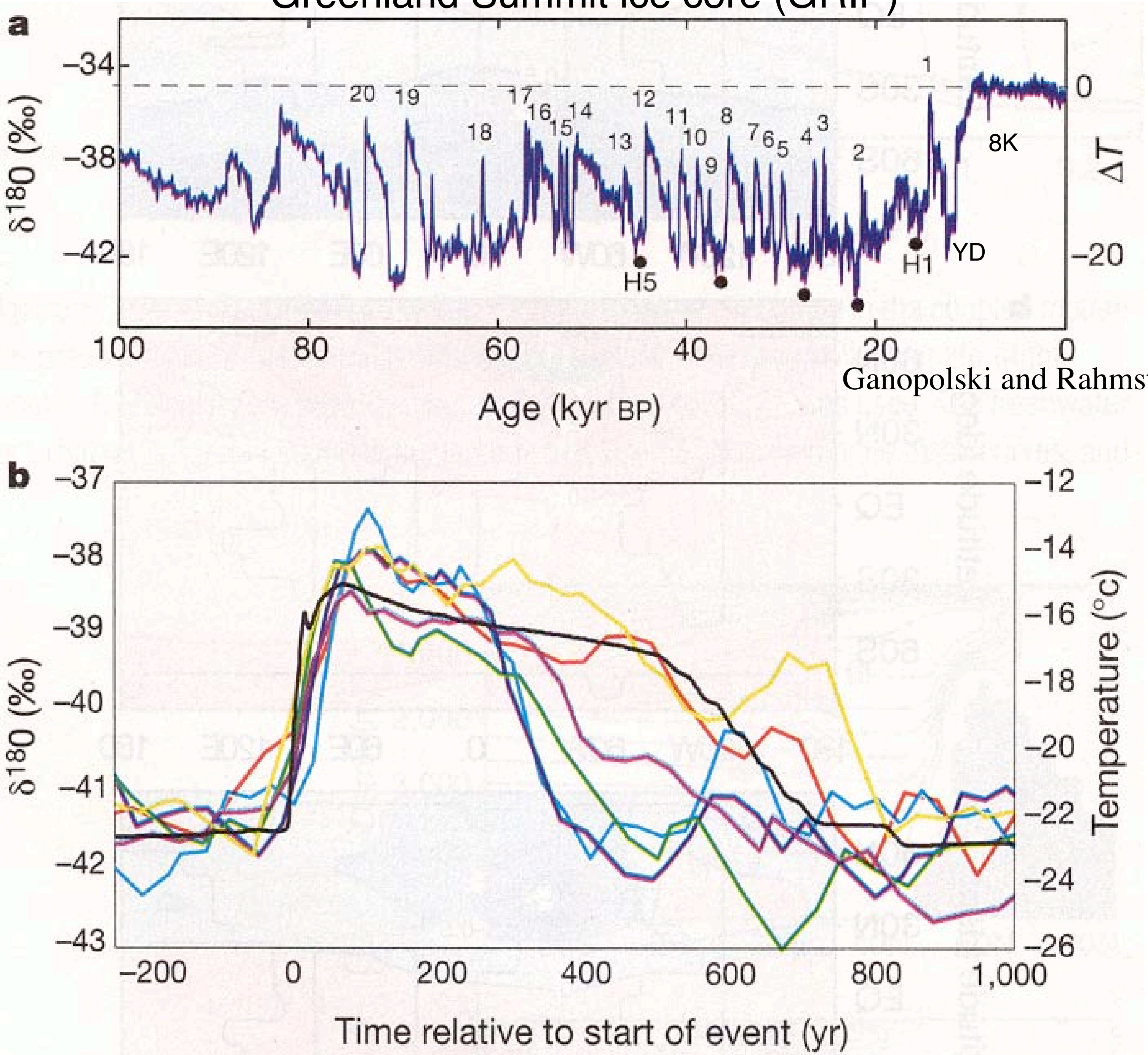
Gary Comer Science and Education Foundation



Greenland ice cores:

- Annually resolved
- Well-dated to 40 kyr BP

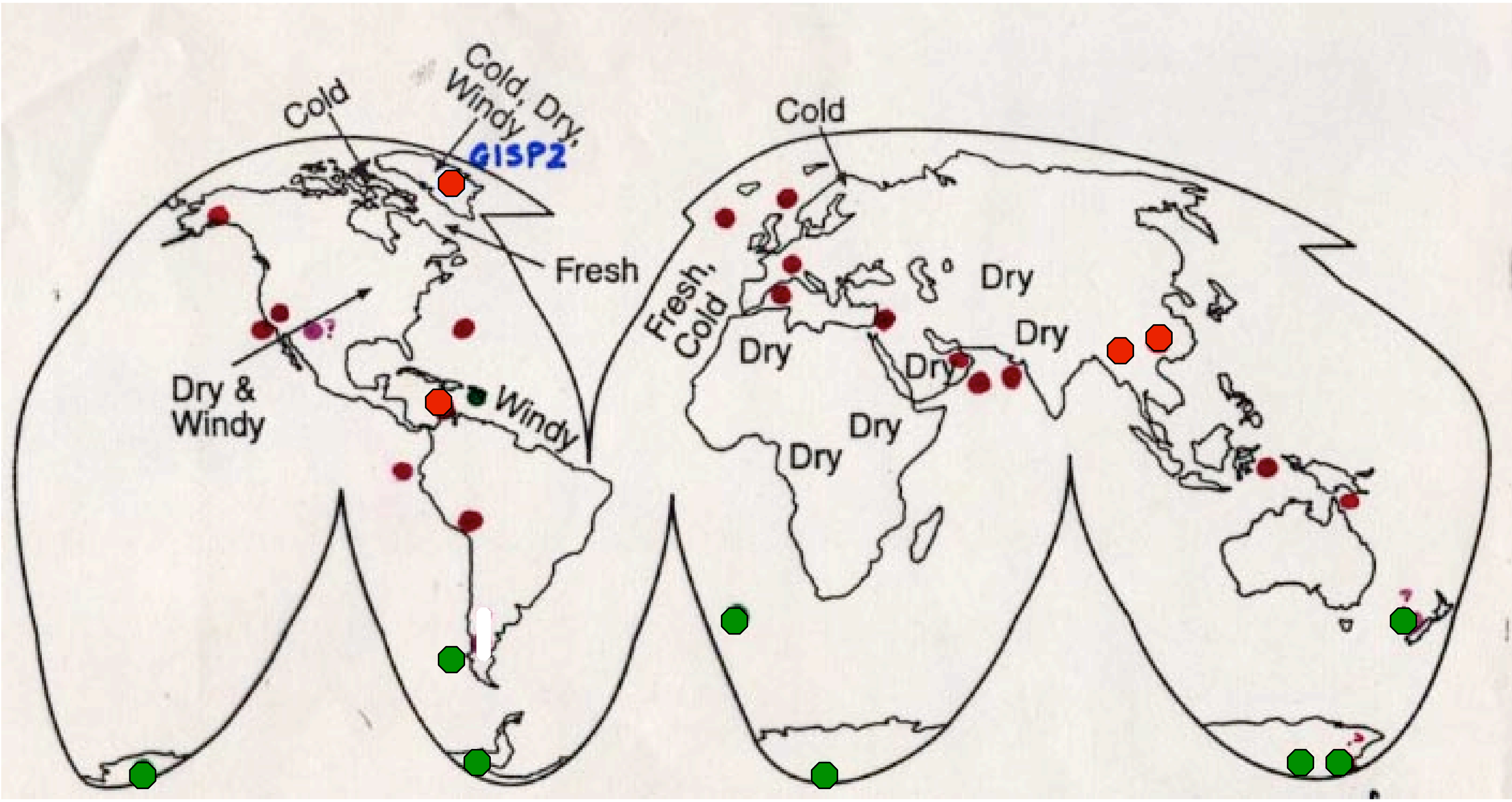
Greenland Summit ice core (GRIP)



Ganopolski and Rahmstorf, 2001

How spatially extensive were the events?

Was it just Greenland?



Locations of proposed Dansgaard-Oeschger signals

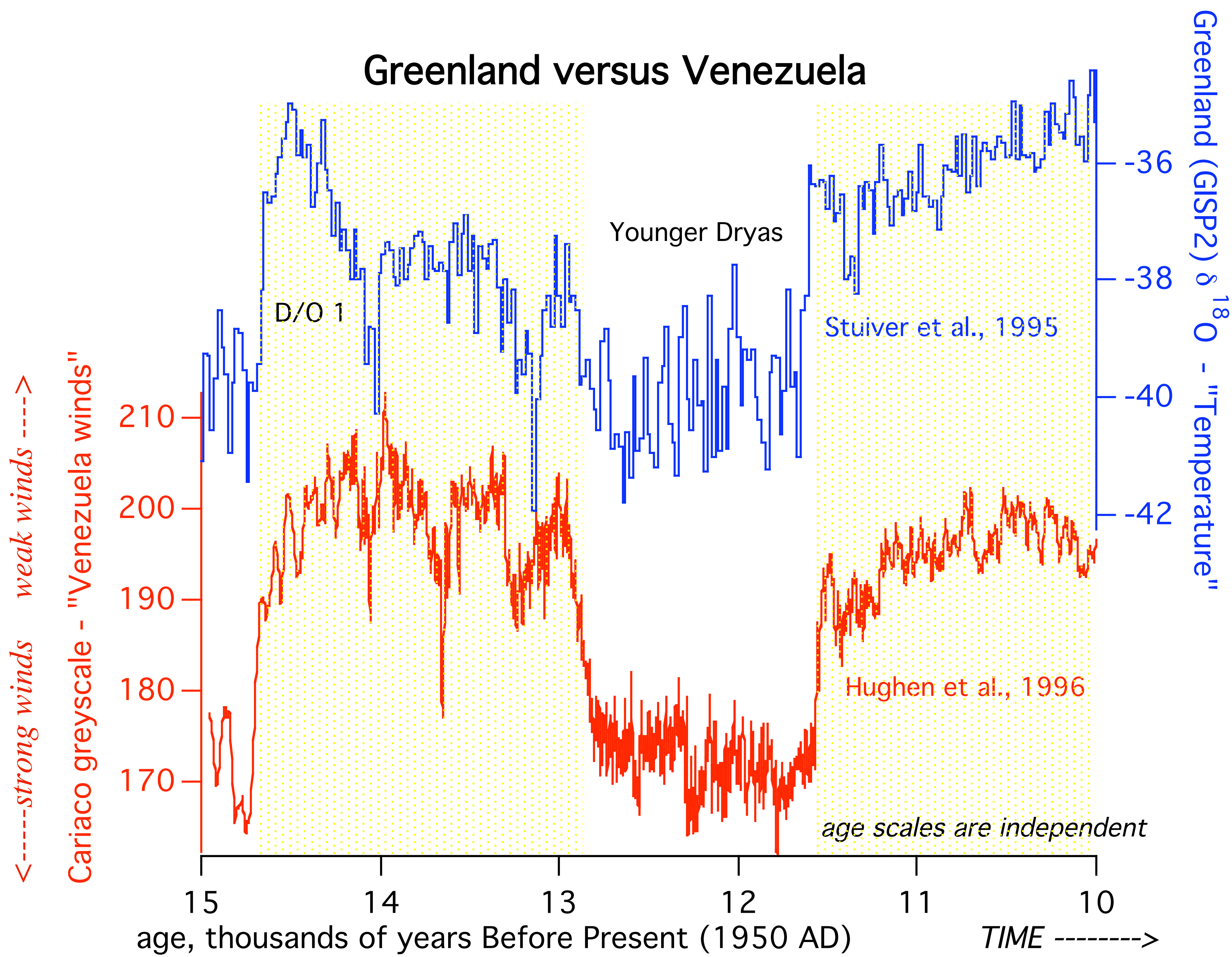
"Antiphased" event

Problem: dating of most non-ice core D-O records is poor enough that it is not possible to tell from them if the D-O events were truly hemispheric in extent.

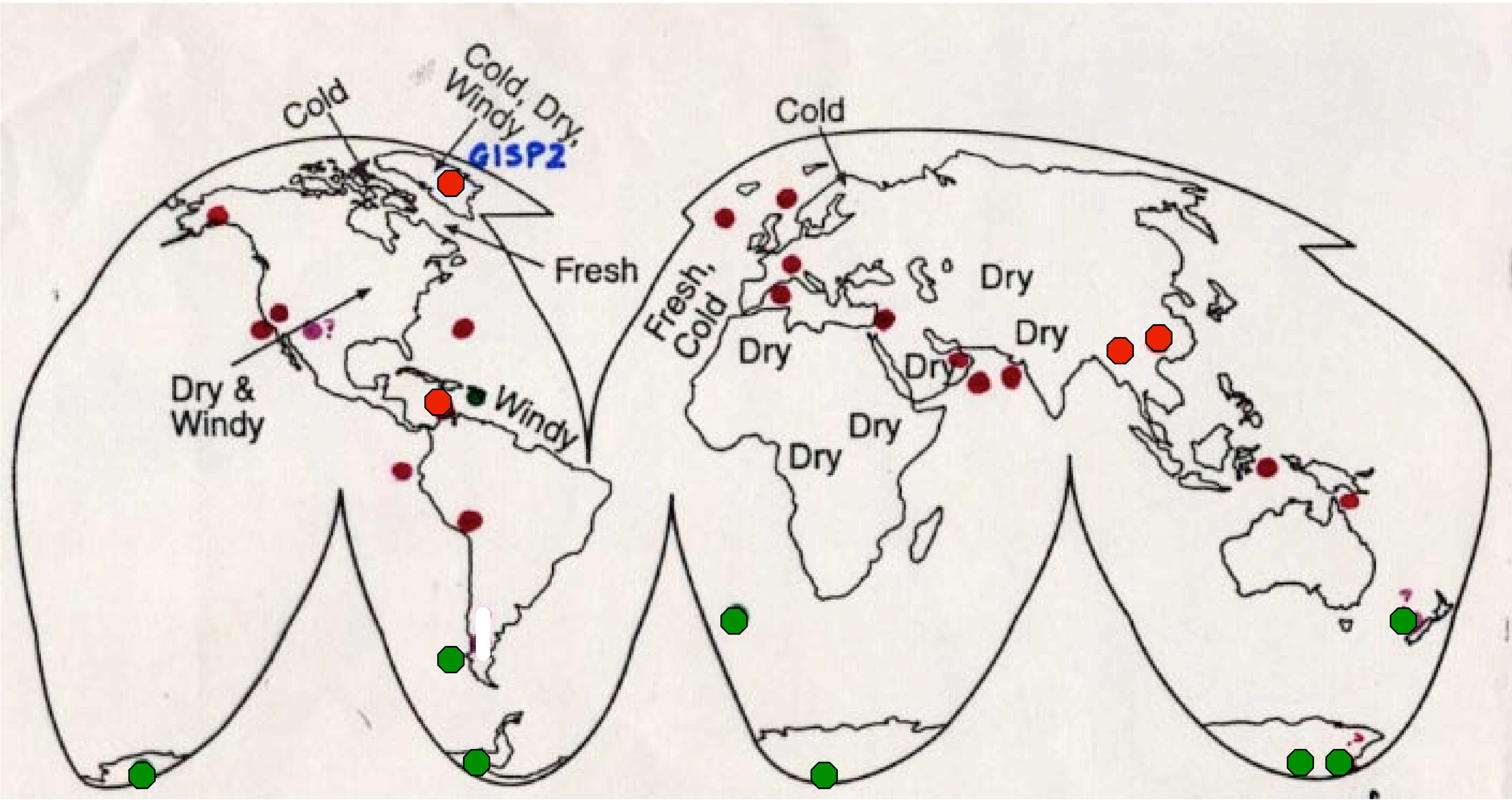
Exceptions:

- Annually-laminated layer-counted sediment records (e.g. Cariaco Basin, Venezuela, between 9-15 kyr BP)
- Uranium-Thorium-dated cave deposits (Hulu Cave and Dongge Cave, China)

Problem: interpretation of the proxies is often not straightforward.

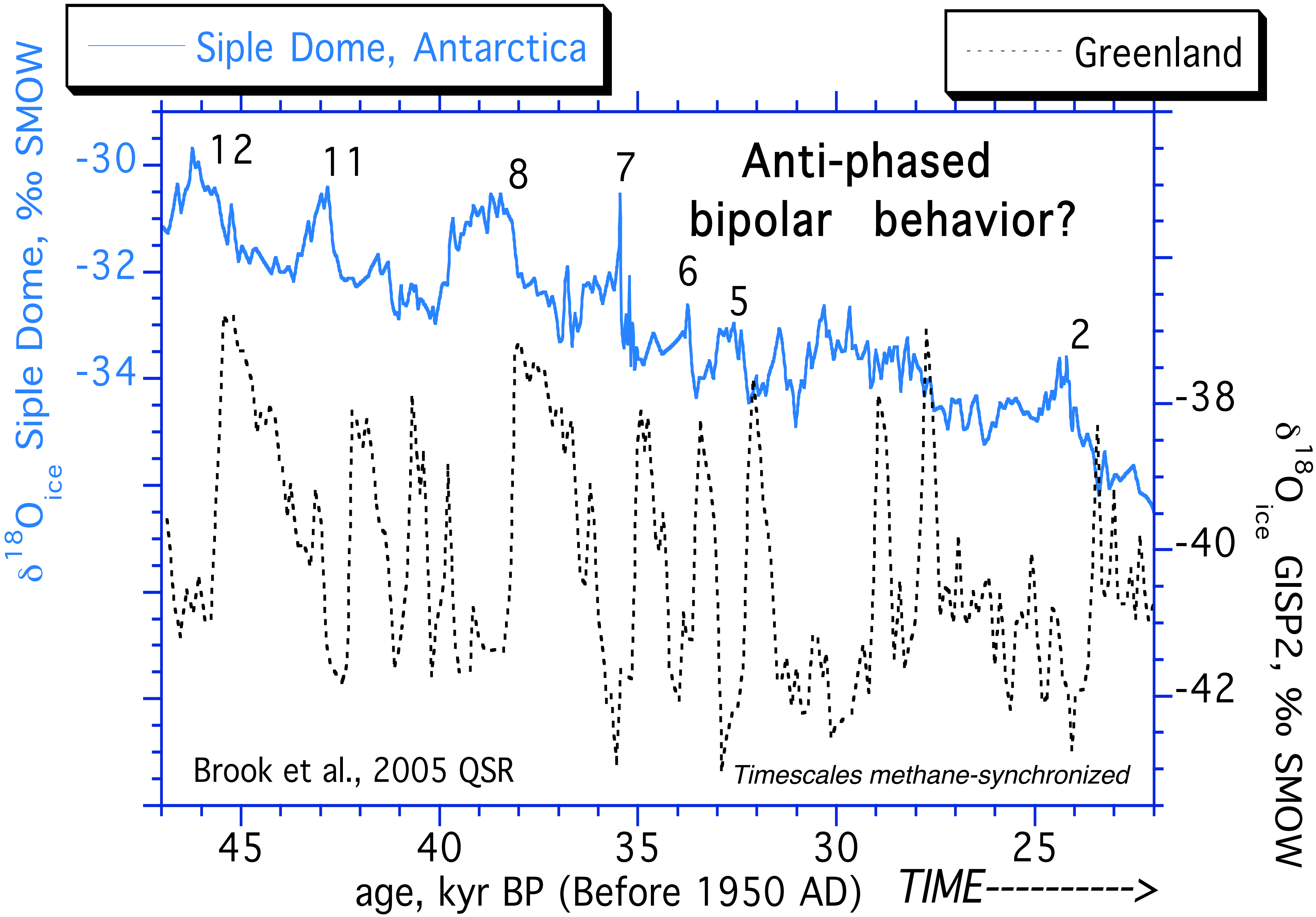


Greenland versus Venezuela
Younger Dryas
D/O 1
Stuiver et al., 1995
Hughen et al., 1996
age scales are independent
Greenland (GISP2) δ 18O - "Temperature"
-36
-38
-40
-42
Cariaco greyscale - "Venezuela winds"
<----strong winds   weak winds ---->
210
200
190
180
170
15
14
13
12
11
10
age, thousands of years Before Present (1950 AD)
TIME -------->



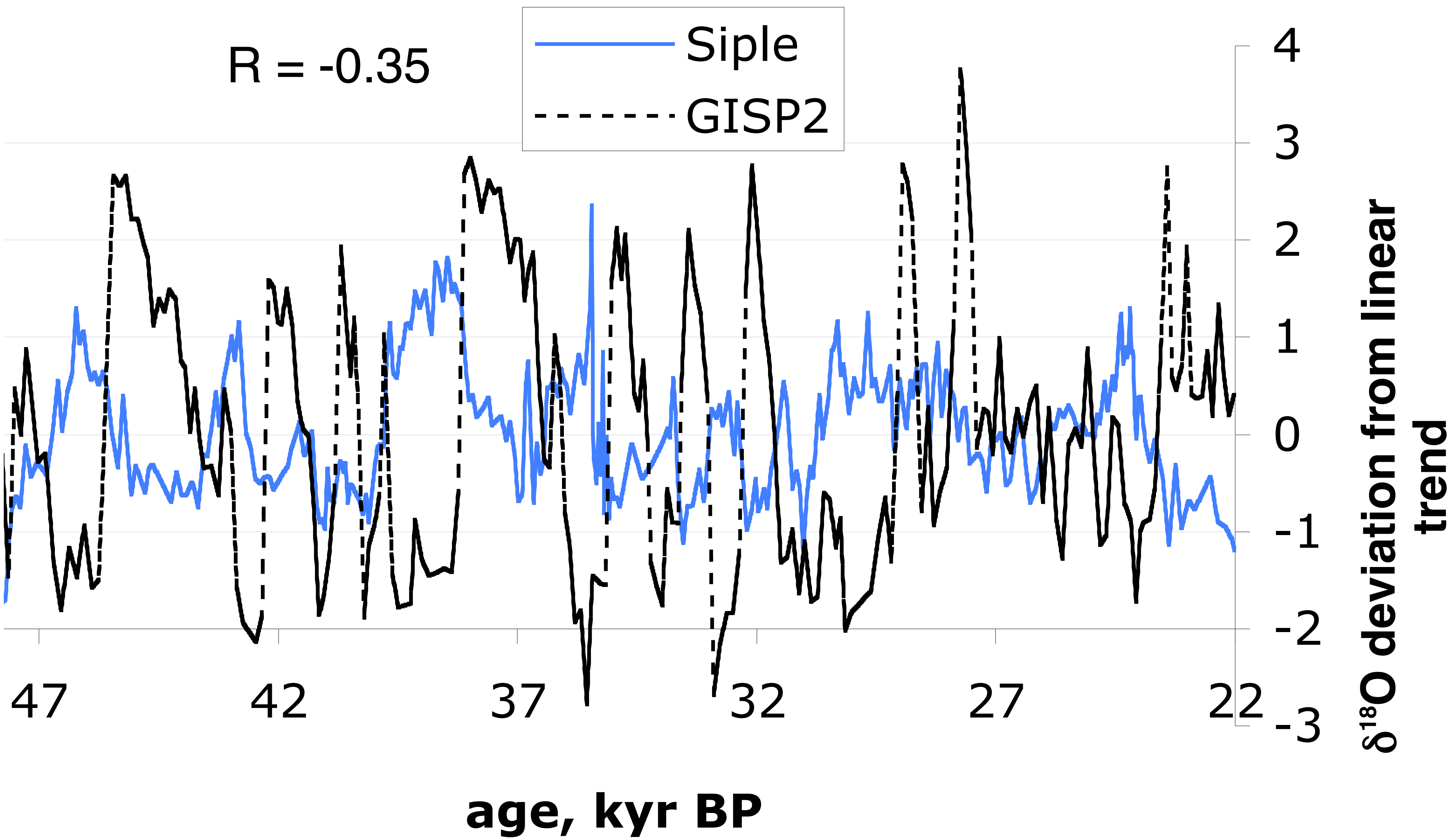
Locations of proposed Dansgaard-Oeschger signals

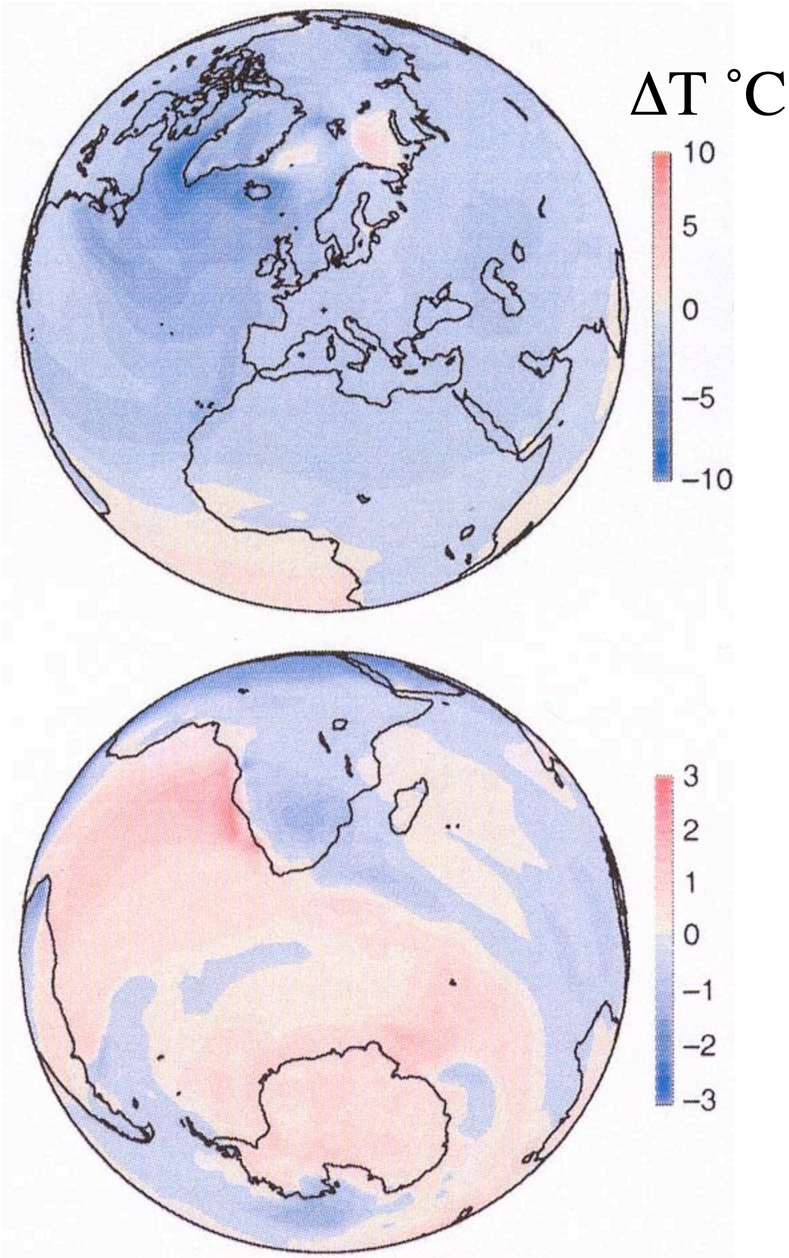
“Antiphased” event



Siple Dome, Antarctica
Greenland
12
11
8
7
6
5
2
Anti-phased
bipolar behavior?
-30
-32
-34
-38
-40
-42
δ18O ice Siple Dome, ‰ SMOW
δ18O ice GISP2, ‰ SMOW
Brook et al., 2005 QSR
Timescales methane-synchronized
45
40
35
30
25
age, kyr BP (Before 1950 AD)
TIME---------->

DETRENDED SIPLE DOME & GISP2 $\delta^{18}O_{ice}$



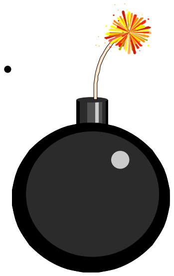


Stocker, 2003

“Bipolar seesaw” hypothesis:

Explains ice core observations of asynchronous polar behavior

Problem: Small Antarctic $\delta^{18}O_{ice}$ variations have not been conclusively shown to represent temperature (no Ar-N_2 data yet… WAIS Divide core in 2007-2011 will provide). In principle, $\delta^{18}O_{ice}$ should be affected by processes other than local temperature...



Atmosphere is well-mixed, so gases provide another indication of the spatial extent of the events

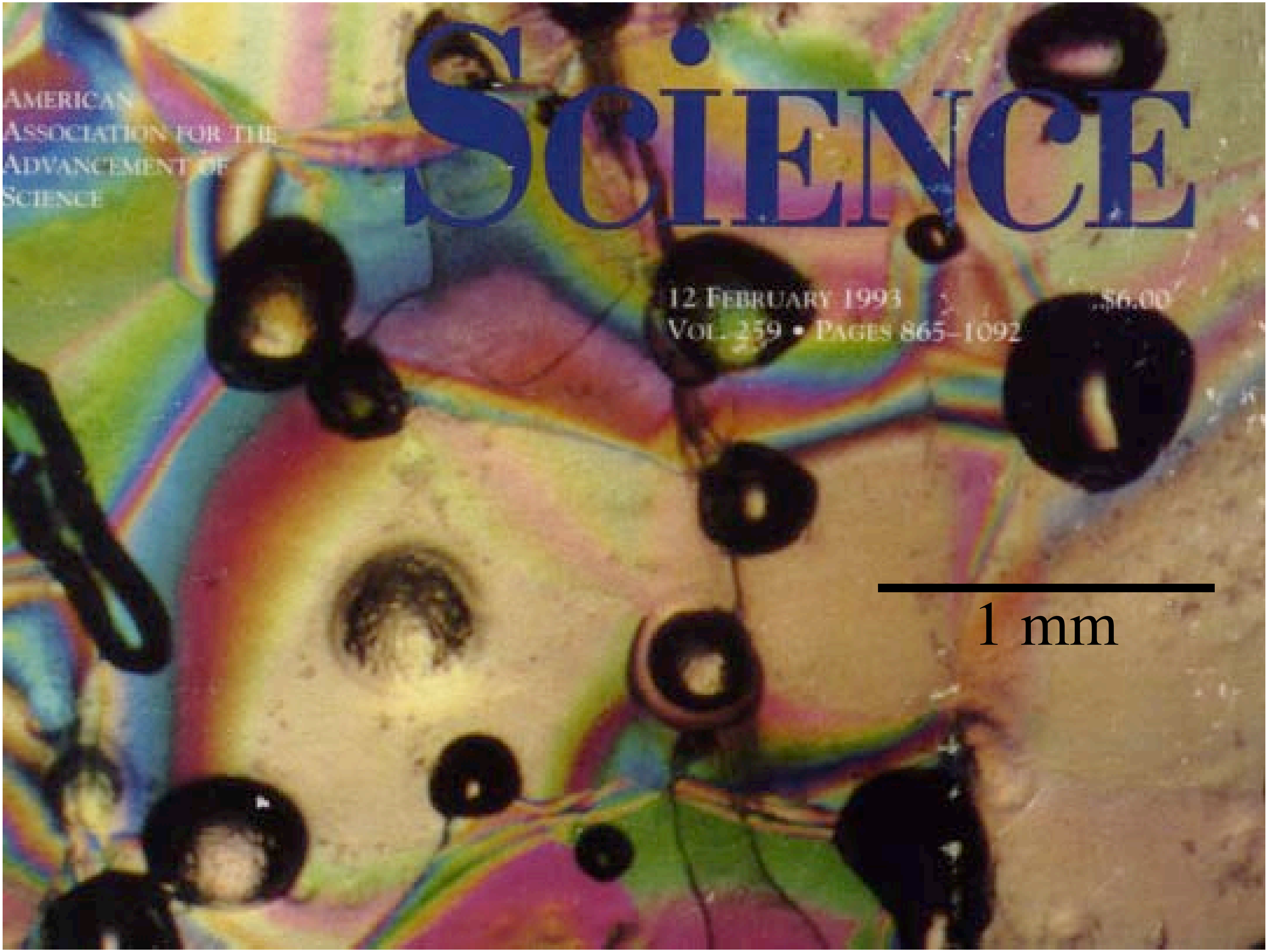
(same core, so no relative dating problem!)

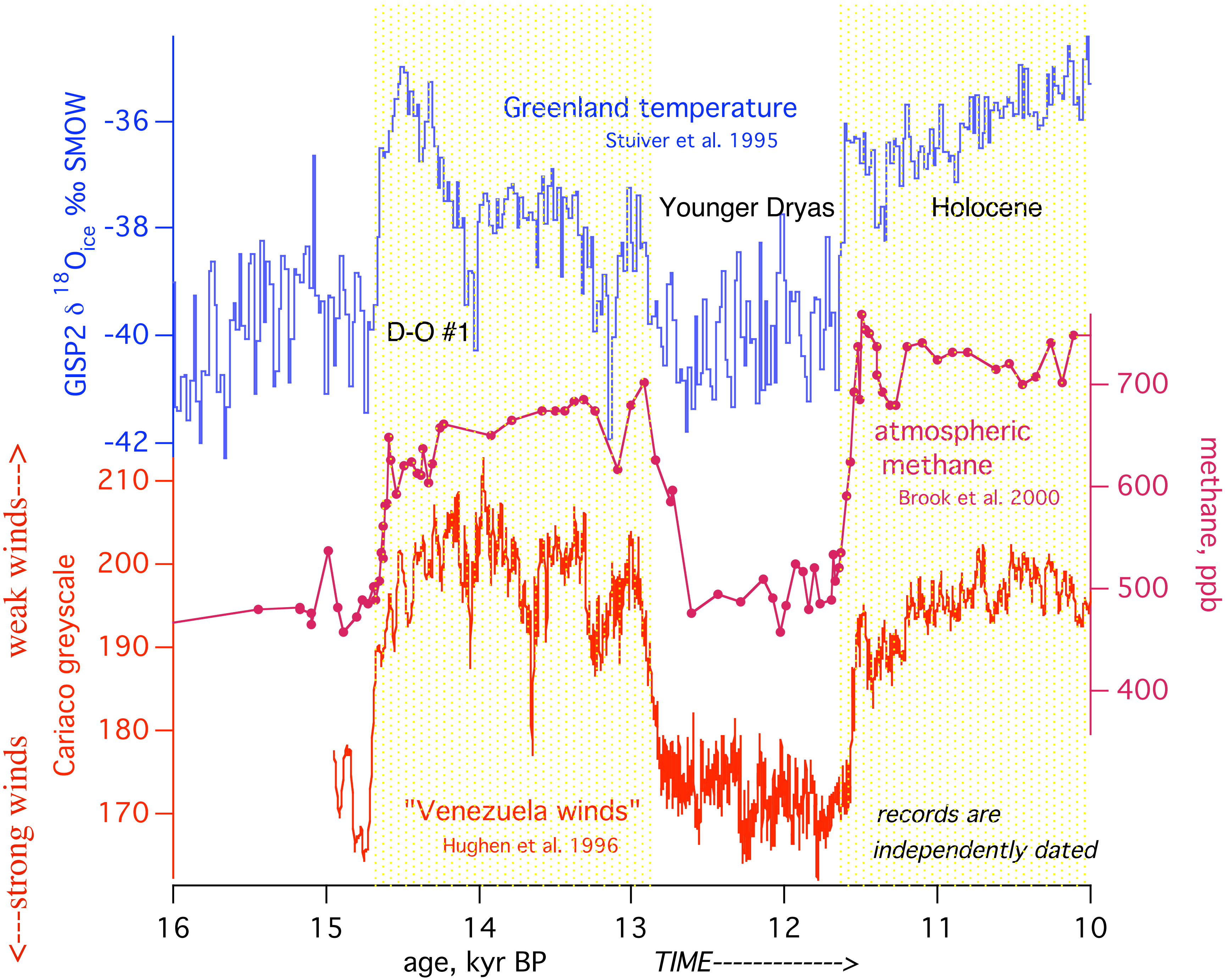
Methane responds rapidly due to short lifetime (8 yr)

N_2O lifetime 120 yr

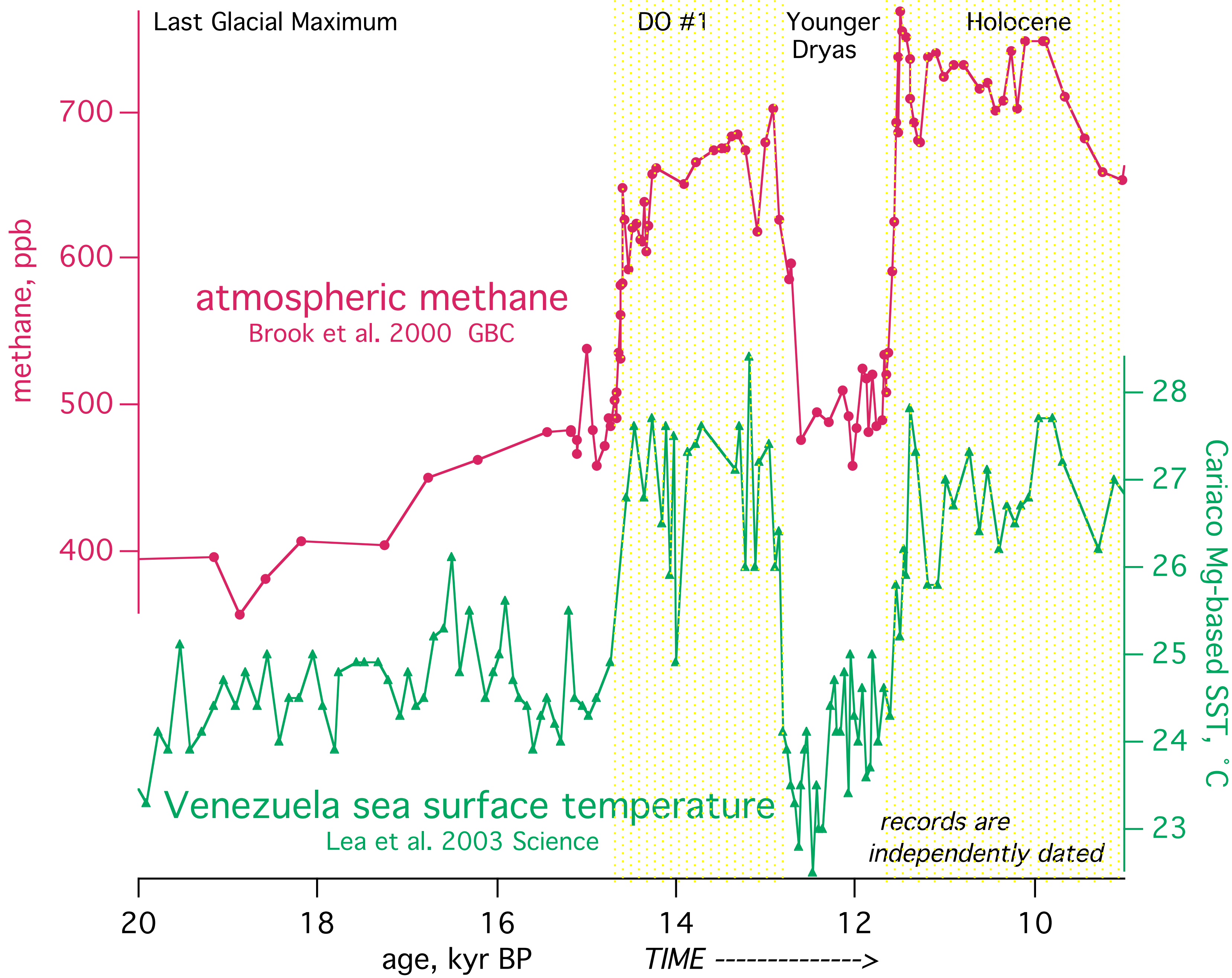
O_2 lifetime ~1000 yr

CO_2 lifetime ~5 yr


American Association for the Advancement of Science
Science
12 February 1993
$6.00
Vol. 259 • Pages 865–1092
1 mm



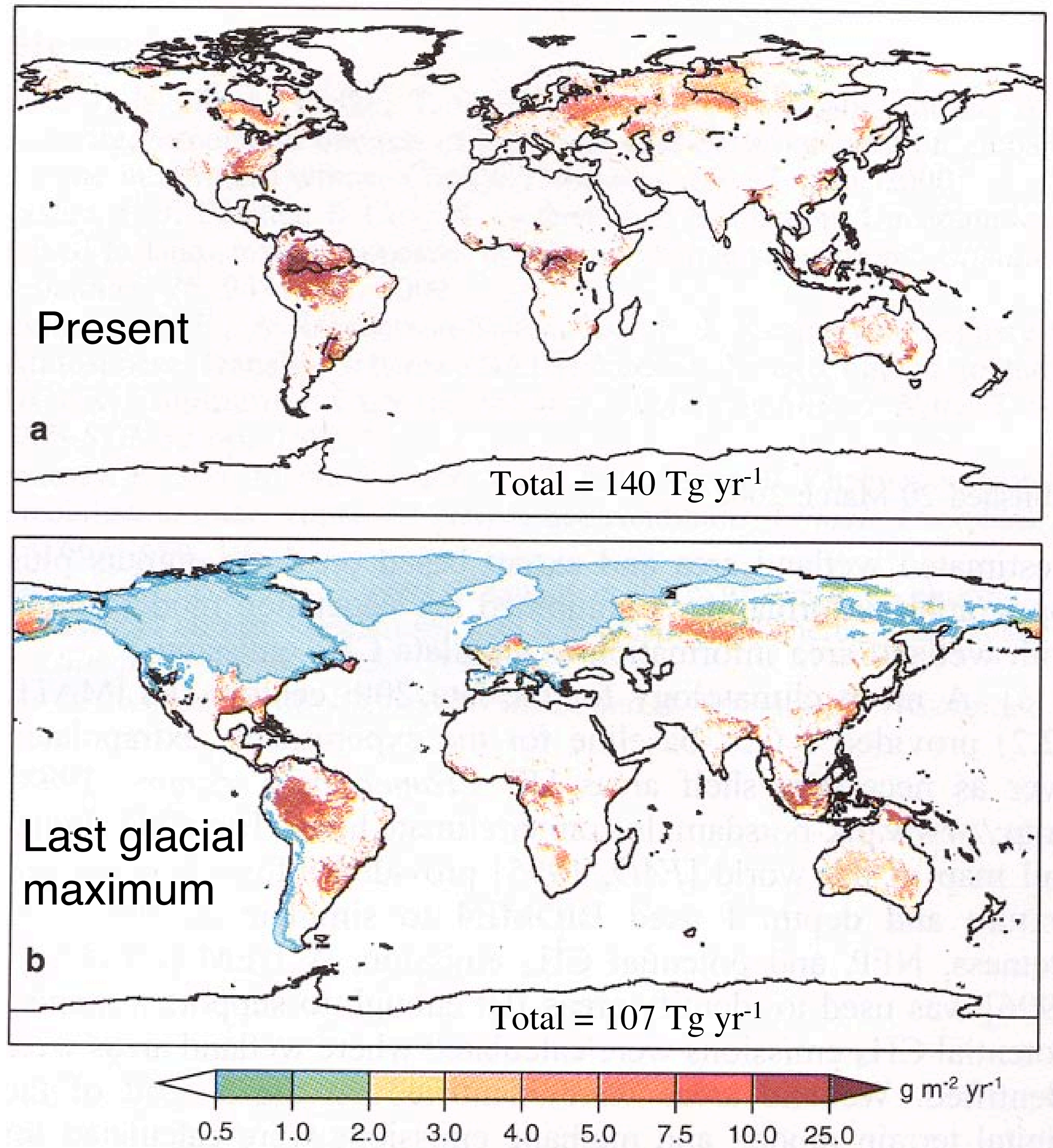
Greenland temperature
Stuiver et al. 1995
Younger Dryas
Holocene
D-O #1
GISP2 δ 18Oice ‰ SMOW
-36
-38
-40
-42
atmospheric
methane
Brook et al. 2000
methane, ppb
700
600
500
400
weak winds--->
<---strong winds
Cariaco greyscale
210
200
190
180
170
"Venezuela winds"
Hughen et al. 1996
records are
independently dated
16
15
14
13
12
11
10
age, kyr BP
TIME------------->



Last Glacial Maximum
DO #1
Younger Dryas
Holocene
methane, ppb
700
600
500
400
atmospheric methane
Brook et al. 2000 GBC
Venezuela sea surface temperature
Lea et al. 2003 Science
records are independently dated
28
27
26
25
24
23
Cariaco Mg-based SST, °C
20
18
16
14
12
10
age, kyr BP
TIME -------------->

Modeled natural wetland methane emissions

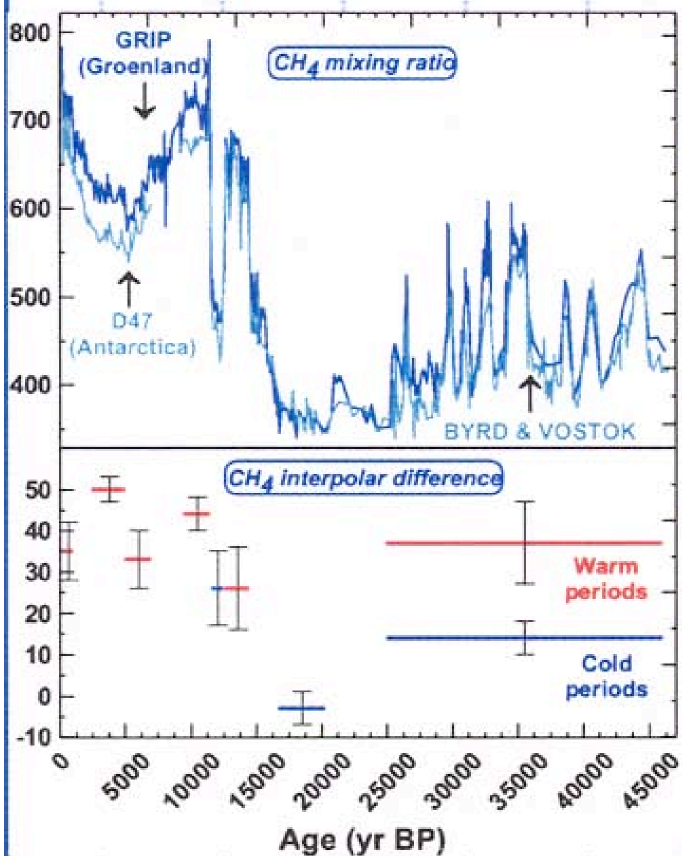
Kaplan, 2002 GRL



Latitudinal distribution of methane sources in the past inferred from the difference between Greenland and Antarctic ice core records

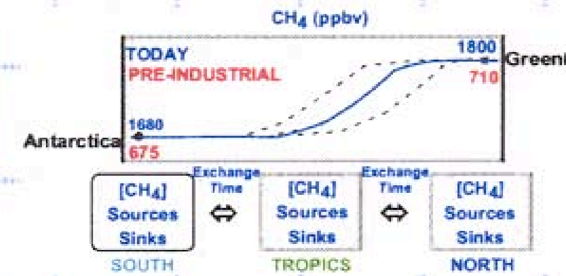
Chappellaz et al. 2001

Interpolar gradient measurements



Simple 3-box atmospheric model

Model variables prescribed from today: South box natural source, Exchange times, Intra-box CH_4 lifetimes (-20% for preindustrial times)

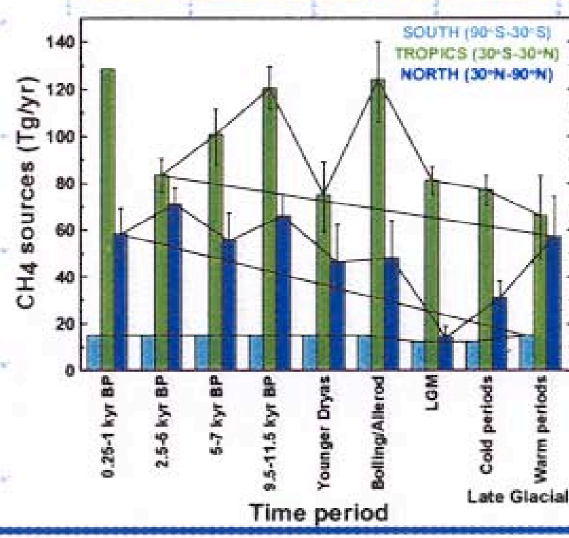


Variations in the difference of CH_4 mixing ratio between Greenland and Antarctica suggest that the Tropics always had a dominant contribution to the natural methane budget

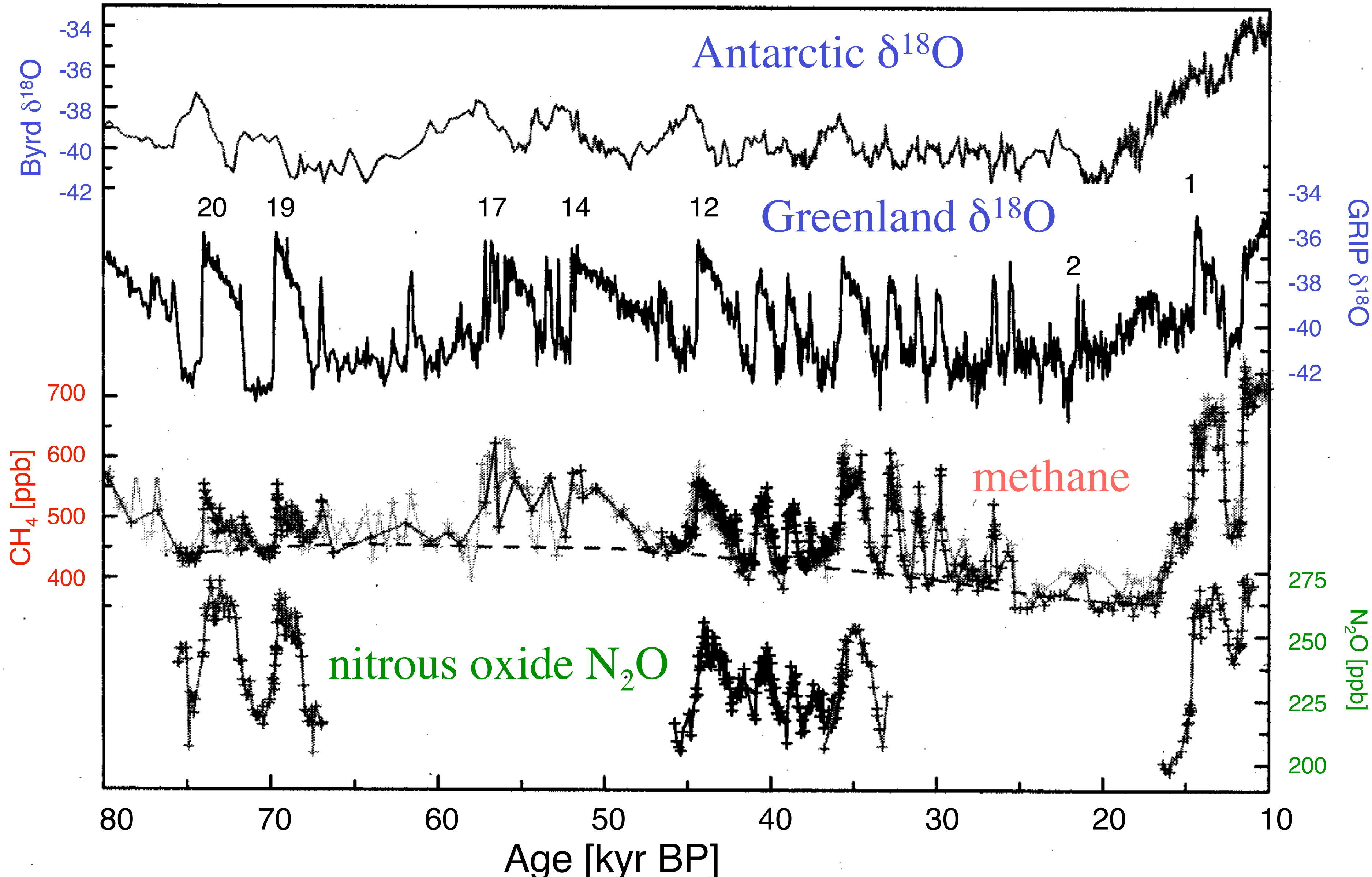
The atmospheric CH_4 fluctuations since the Bolling/Allerod period (14 kyr BP) appear to be mainly driven by the Tropics as well

But late glacial and early deglacial changes are paralleled with variations of the northern source (clathrates or periglacial wetlands ?)

3-box source distribution



Nitrous oxide (N_2O) provides additional clues:



Flückiger et al., 2004 *GBC*

N_2O sources and sinks to atmosphere:

SOURCES:

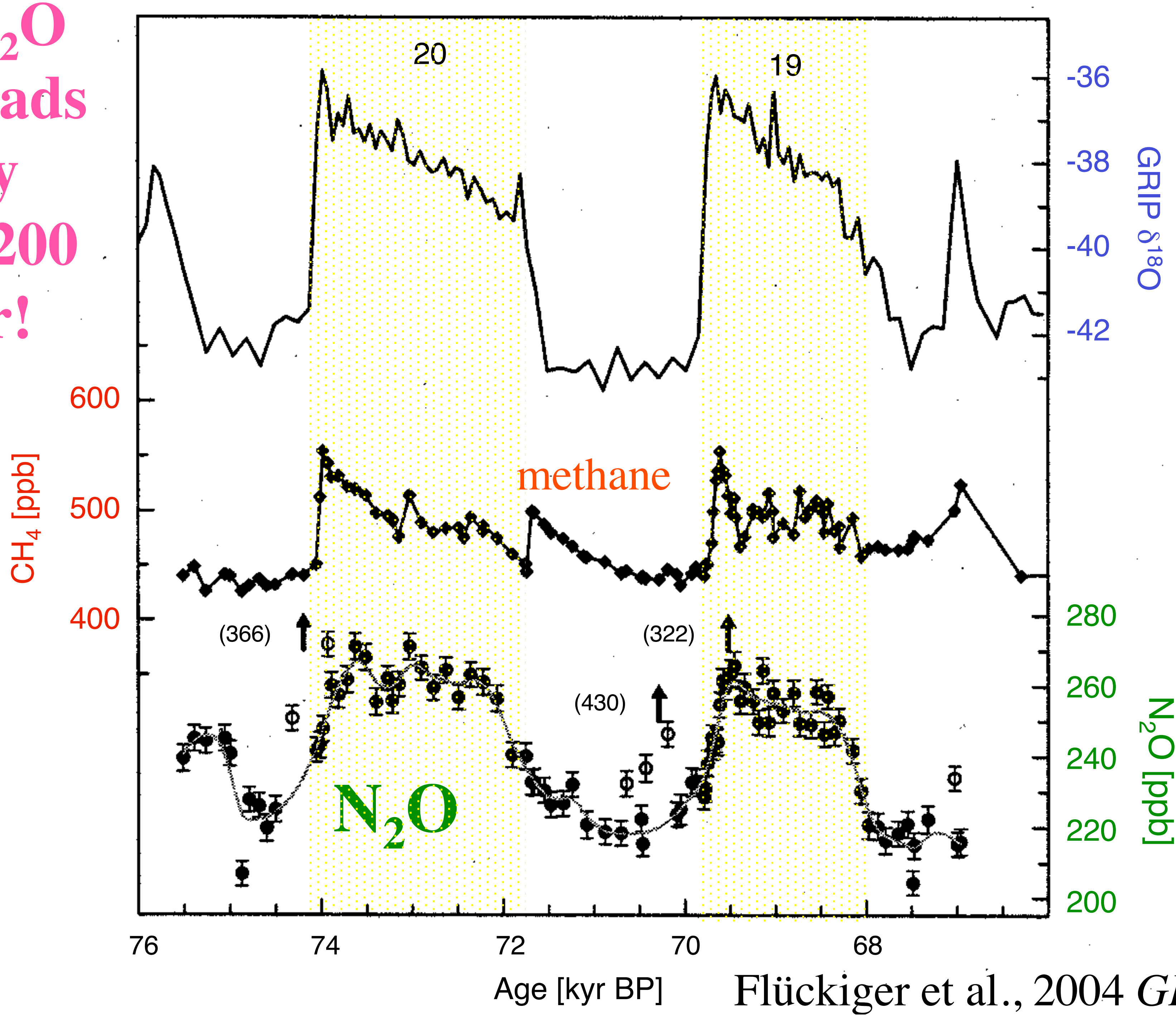
- Tropical soils (50-90% water saturated)
- Oceanic subtropical oxygen-minimum zones (denitrification)

SINKS:

- Stratosphere (photolysis)

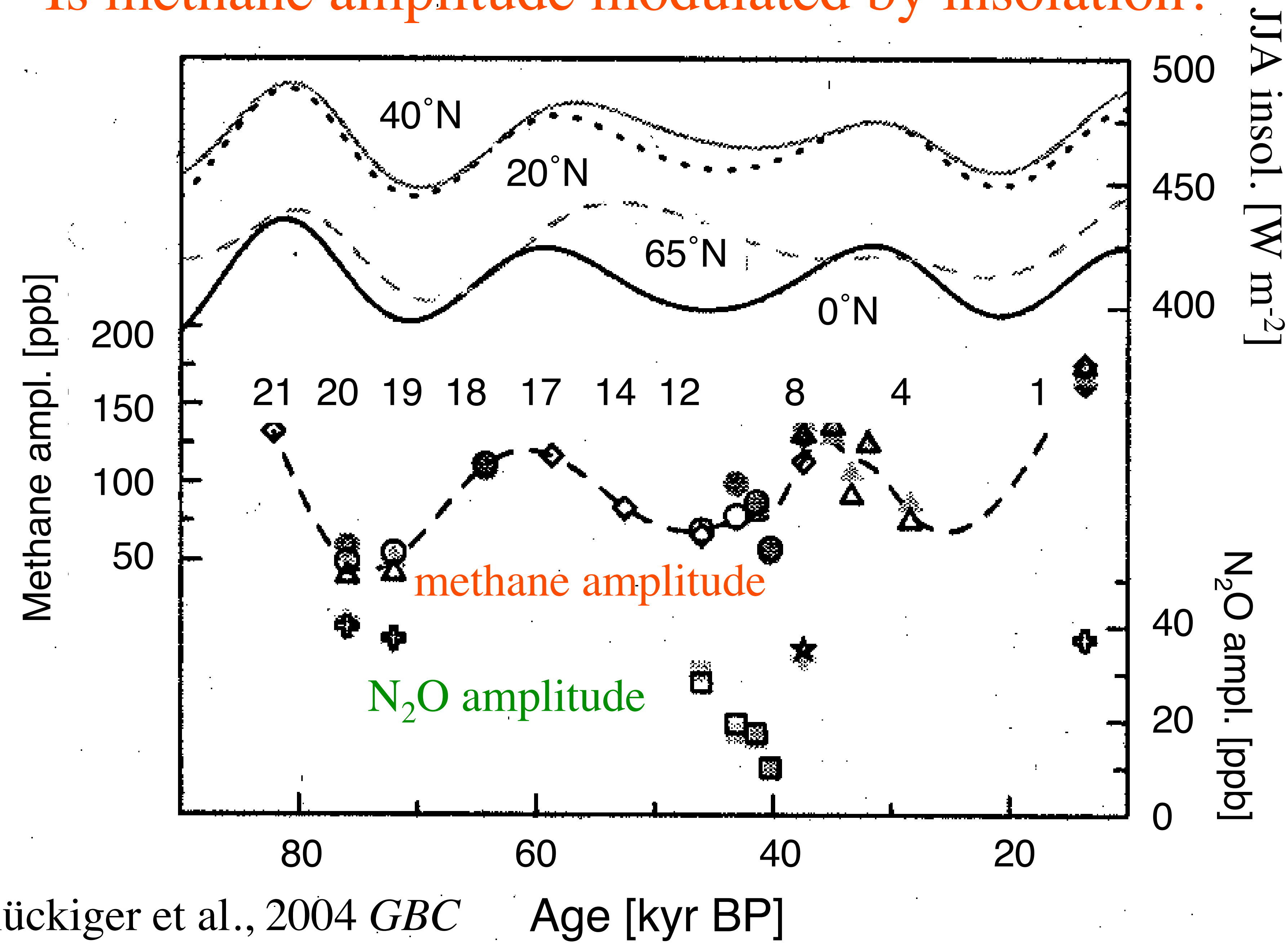
SINKS PROBABLY CONSTANT IN TIME

N_2O leads by ~200 yr!



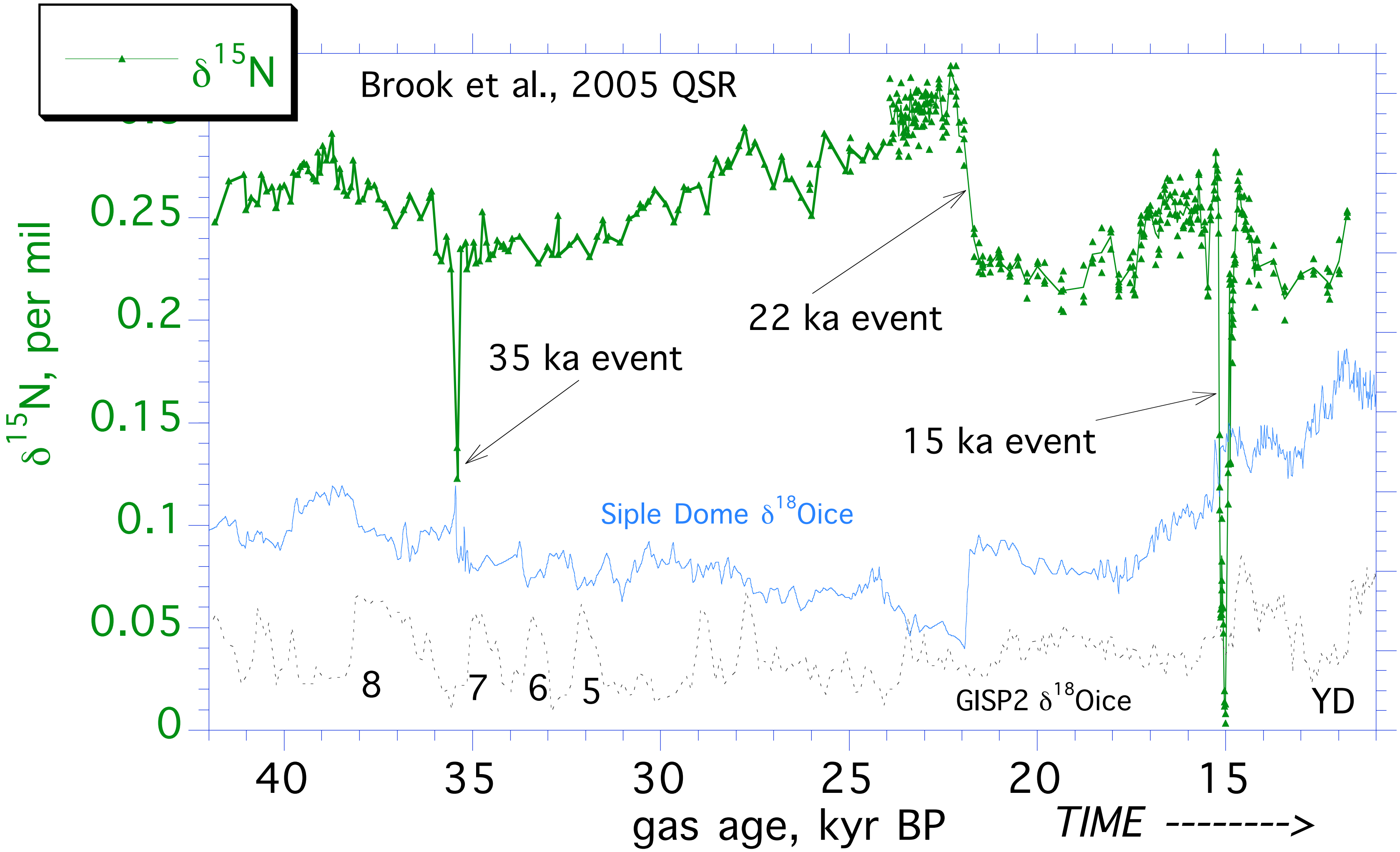
Flückiger et al., 2004 *GBC*

Is methane amplitude modulated by insolation?

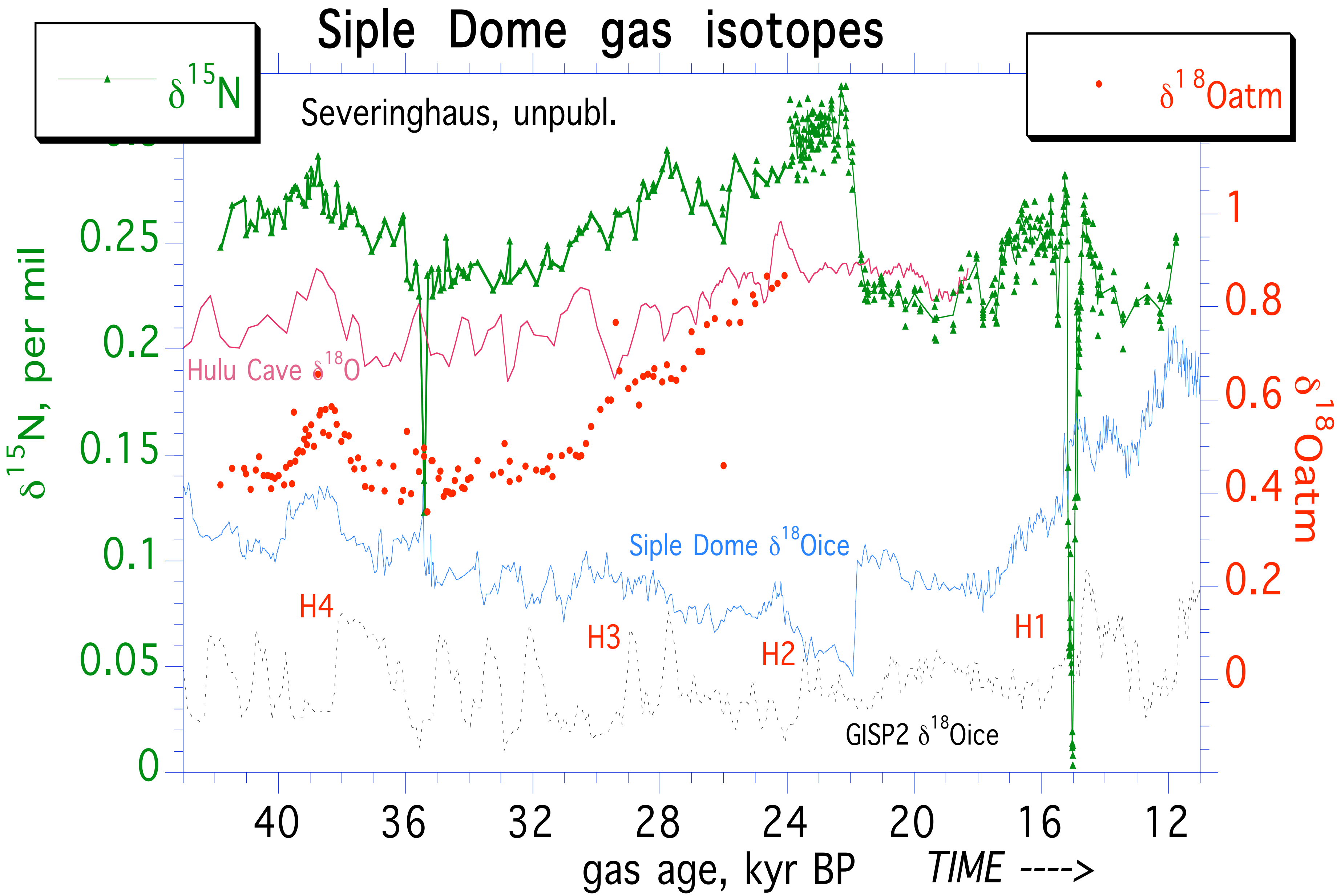


Flückiger et al., 2004 *GBC*

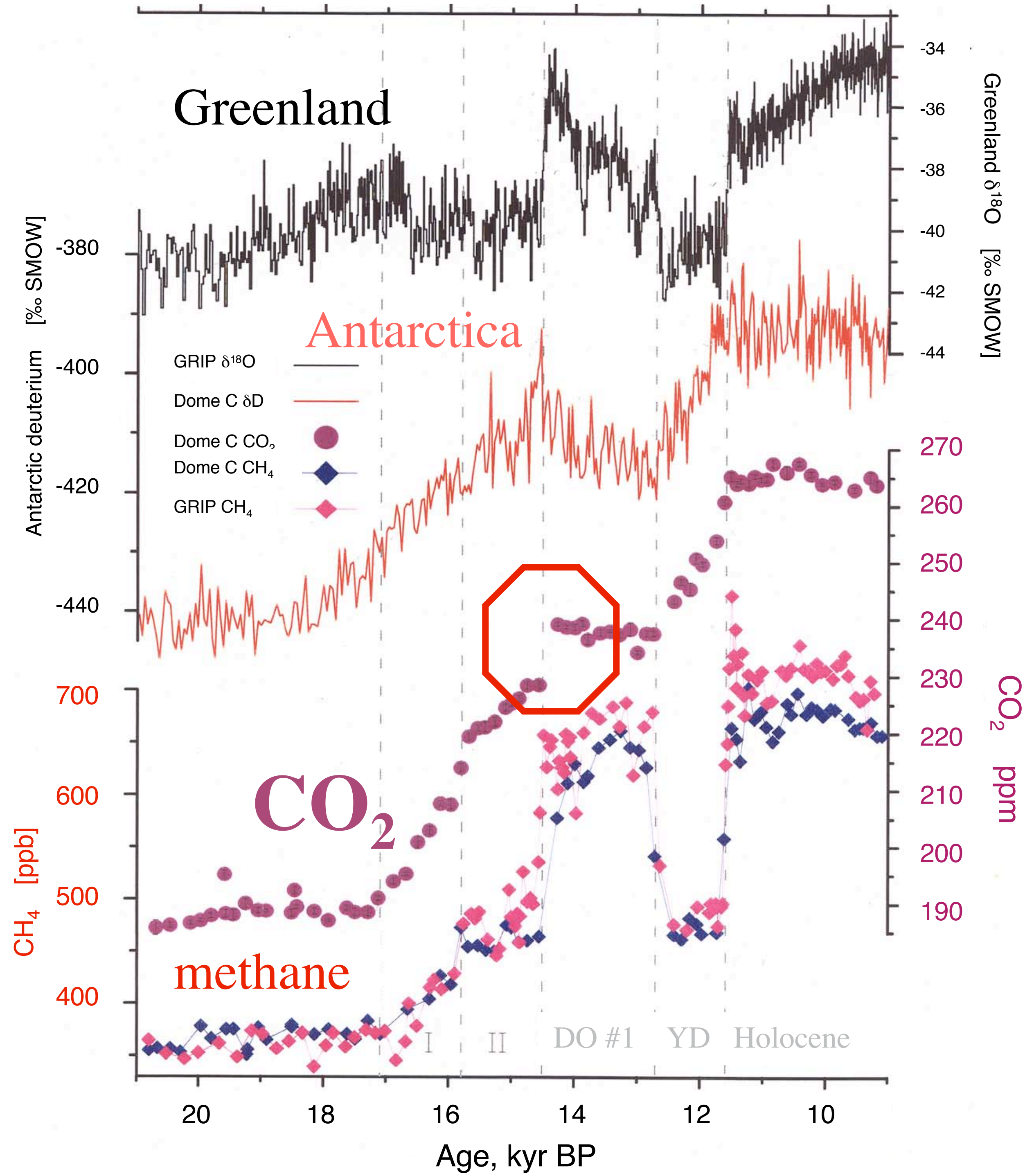
Isotopic records from Siple Dome, Antarctica



O-18 of atmospheric O_2 also varies with Heinrich events:



CO_2 shows some abrupt changes



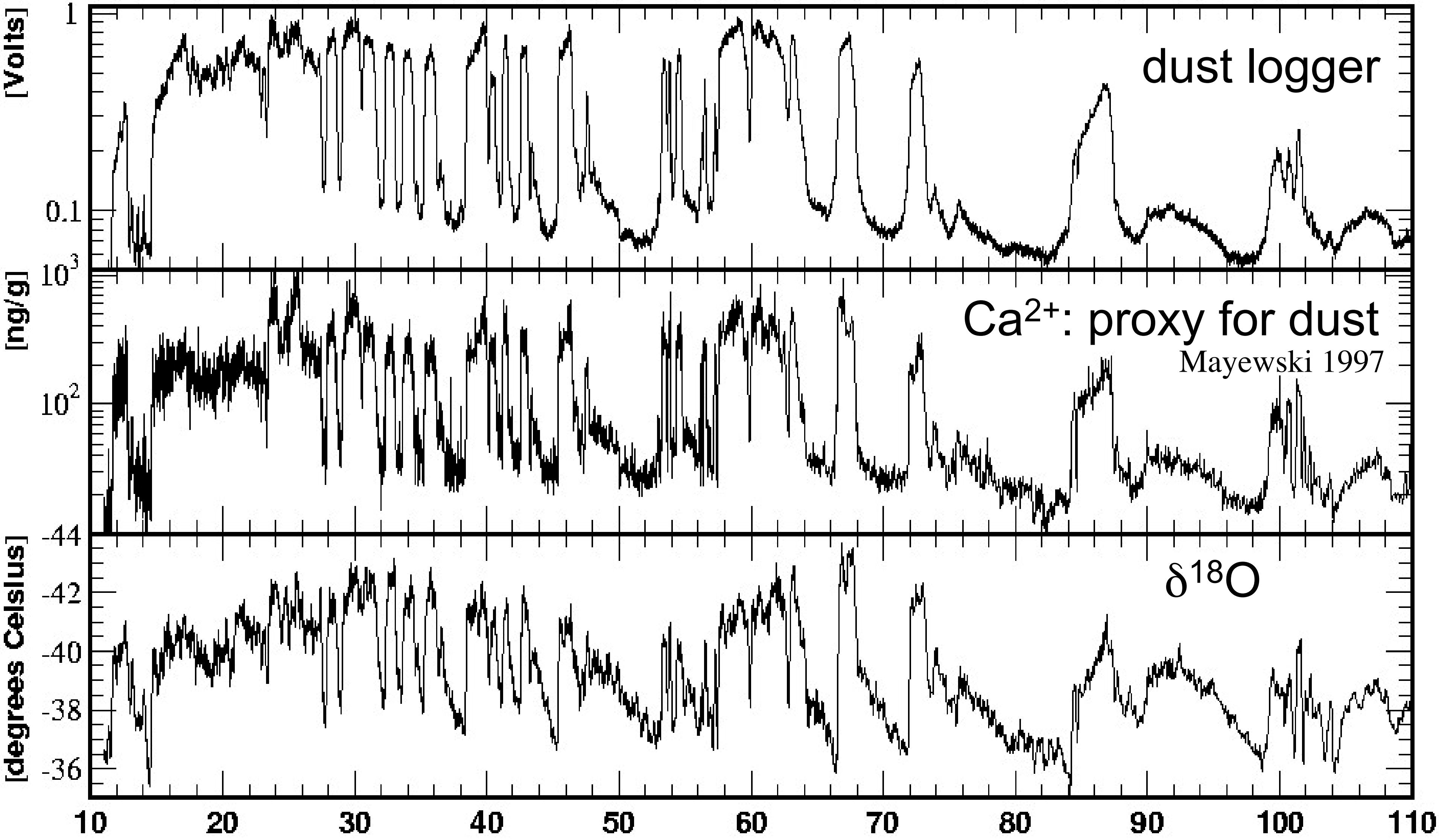
Monnin et al., 2001 *Science*

Ice matrix contains other indicators of far-field climate:

- dust (Asian deserts for Greenland, Patagonian deserts for Antarctica)
  -isotopic fingerprint identifies regions uniquely (Biscaye 1997)
- particle sizes give wind velocity
- calcium: dry lake bed- and arid soils-indicator
- sodium: from sea-salt; a sea-ice indicator
- chloride: from sea-salt; a sea-ice indicator

Calcium in Greenland ice cores varies by 2 orders of magnitude - must have been source changes, implying precipitation/evaporation changes in central Asia that were synchronous with Greenland temperature

Abrupt climate changes recorded in GISP2, with optical dust logger sent down borehole



Bay, Price et al. 2003

Kiloyears before present

Summary of spatial extent evidence:

- Atmospheric methane suggests large-scale abrupt hydrological change in low- and/or mid-latitudes.
- Calcium plus dust-isotopic records require abrupt hydrological change in Takla Maklan and Gobi deserts, China
- Venezeula trade winds abruptly weakened with Greenland abrupt warming - probable migration of ITCZ over site
- Atmospheric N_2O suggests tropical soil warmth/moisture and/or subtropical ocean dysoxia in phase with Greenland on millennial timescale
- Atmospheric O_2 isotopic composition implies perturbation to global-average chloroplast water O-18 on millennial timescale
- Atmospheric CO_2 suggests abrupt terrestrial-biospheric and/or SST change at some events (D-O #1)

How large were the warmings?

Oxygen-18 of ice is affected by factors other than temperature, such as vapor source conditions and seasonality

Solution: new thermometer using gas isotopes

$\delta^{15}N$ indicates temperature change via thermal diffusion

	Concentration gradient	Temperature gradient
Mass transport	"ORDINARY" MOLECULAR DIFFUSION	THERMAL DIFFUSION
Heat transport		HEAT DIFFUSION

Thermal diffusion

$$\delta = \Omega \, \Delta T$$

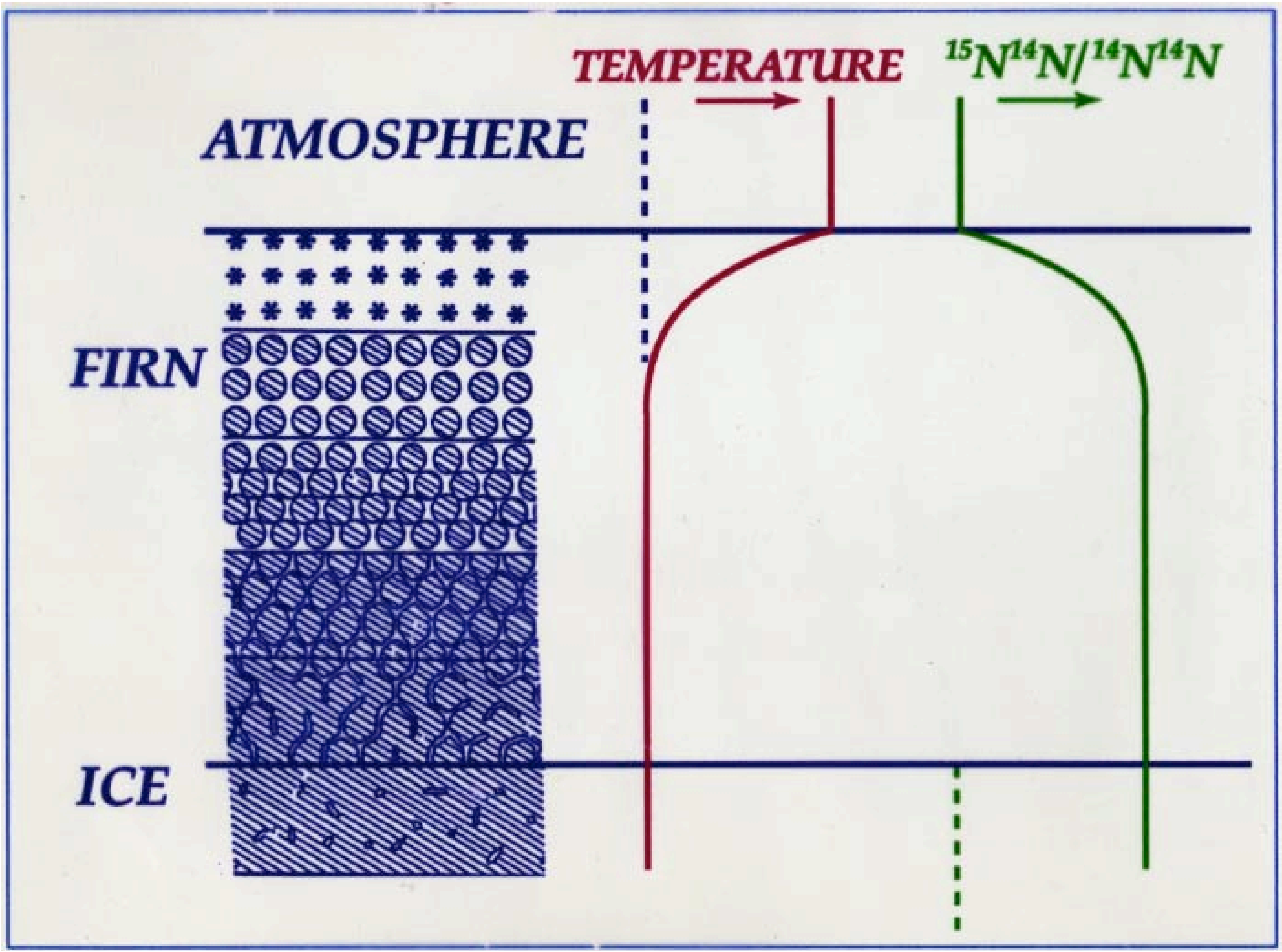
δ isotopic enrichment

Ω thermal diffusion sensitivity

ΔT temperature difference

$\delta^{15}N = [^{15}N/^{14}N_{sample}]/ [^{15}N/^{14}N_{atmosphere}]$

$\delta^{40}Ar = [^{40}Ar/^{36}Ar_{sample}]/ [^{40}Ar/^{36}Ar_{atmosphere}]$


TEMPERATURE
$^{15}N^{14}N/^{14}N^{14}N$
ATMOSPHERE
FIRN
ICE

Gravitational fractionation

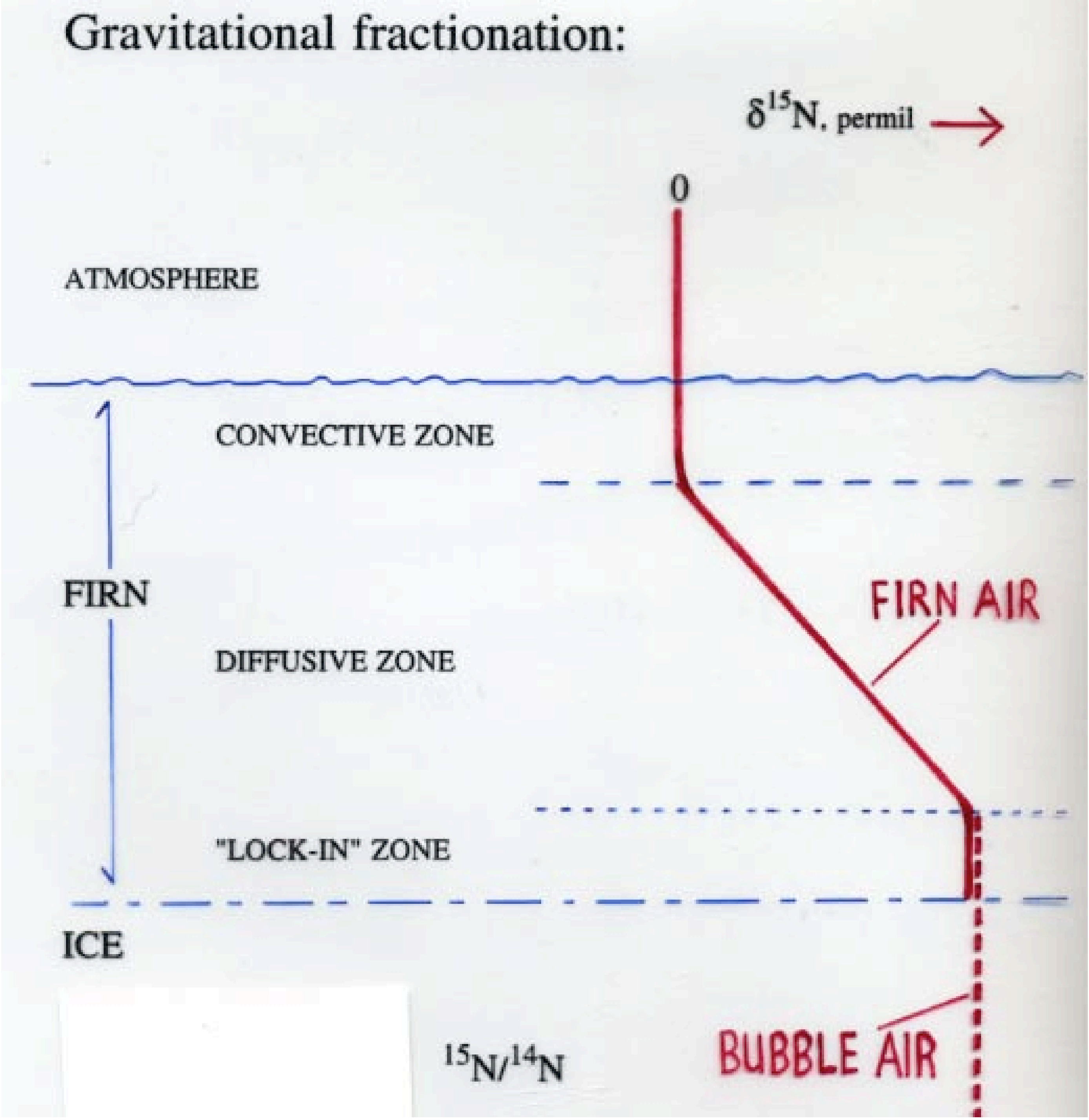
(Dalton, 1826; Gibbs, 1928; Craig + Sowers, 1988)

$$\delta = [\ \exp(\Delta mgz/RT) - 1\ ]\ 10^3\ ‰$$

Δm	mass difference
g	gravitational accelleration
z	depth
R	gas constant
T	temperature, K

Example: $\Delta m = 1$, $z = 80$ m, $T = 230$ K

$\delta^{15}N = +0.4$ ‰


Gravitational fractionation:
δ15N, permil →
0
ATMOSPHERE
CONVECTIVE ZONE
FIRN
DIFFUSIVE ZONE
FIRN AIR
"LOCK-IN" ZONE
ICE
15N/14N
BUBBLE AIR

Gas model:

Fractionation terms:

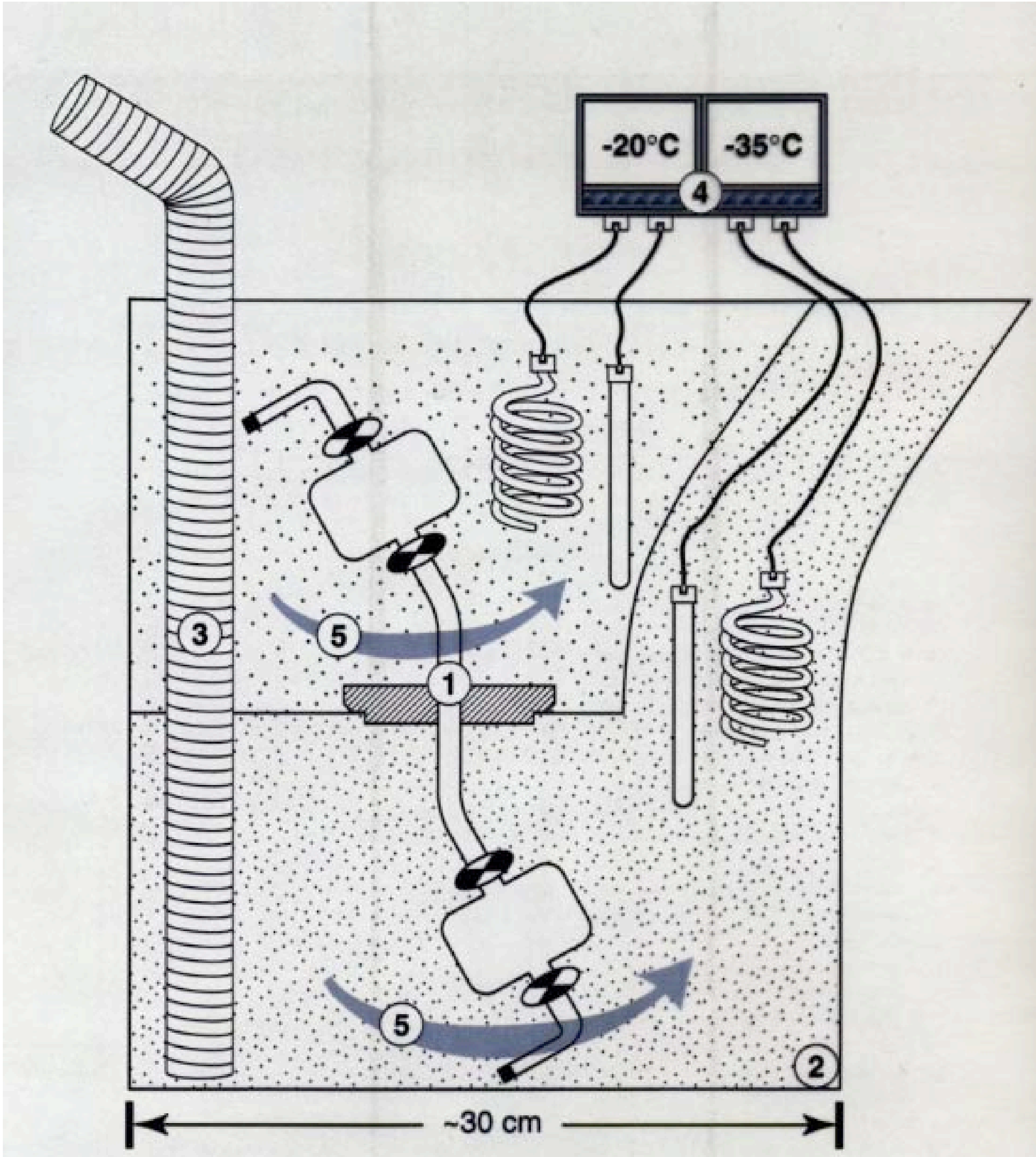
Gravitational ↓ Thermal ↓

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial z}\left(D(z,T)\left[\frac{\partial C}{\partial z} - \frac{\Delta m g}{RT} + \Omega\frac{dT}{dz}\right]\right)$$

C	isotope delta value (e.g., $\delta^{15}N$)
t	time
z	depth
D	molecular diffusivity of gas in porous snow
T	temperature
Δm	mass difference between isotopes
g	gravitational acceleration
R	gas constant
T	absolute temperature
Ω	thermal diffusion sensitivity, ‰ K^{-1}

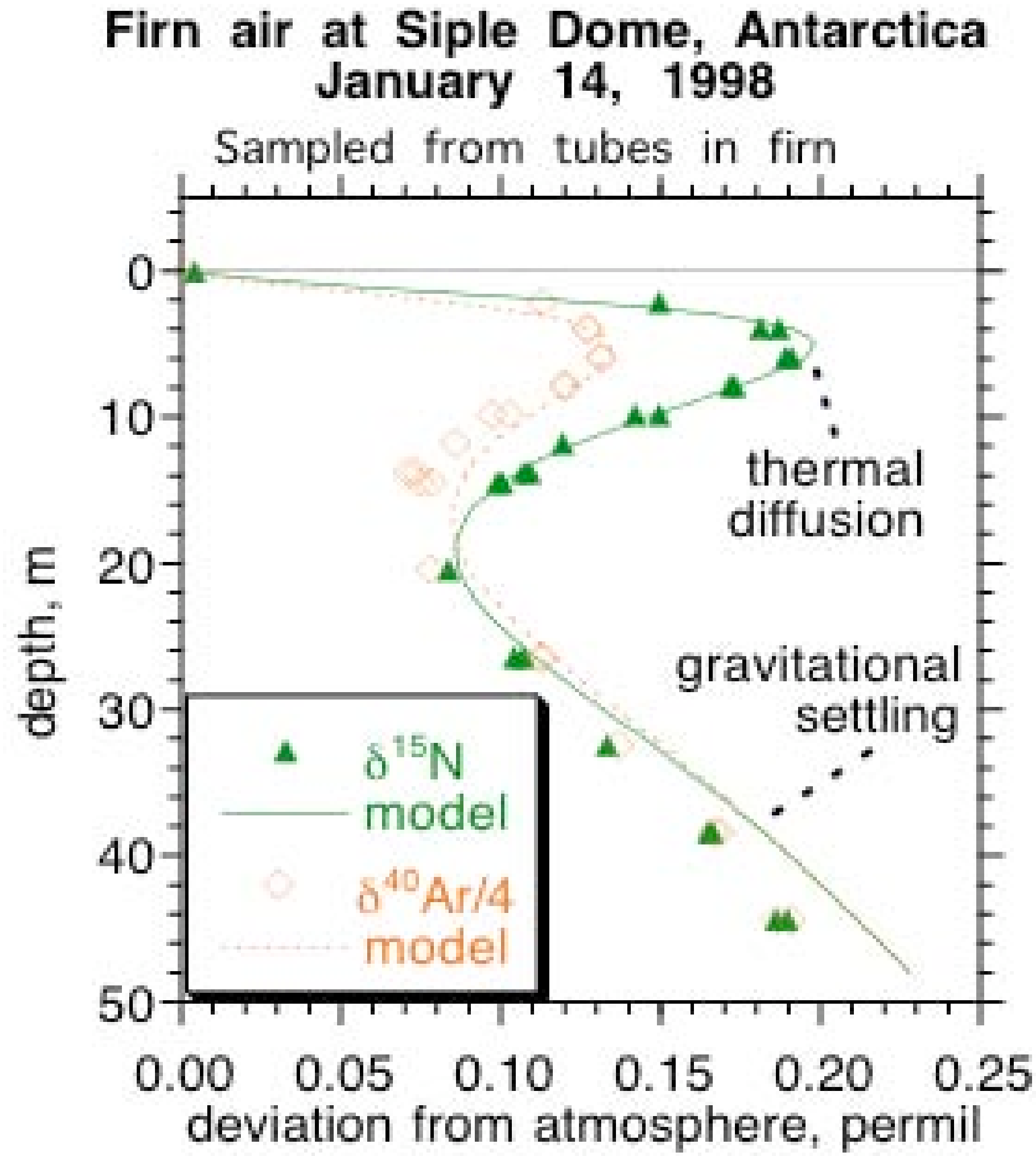
$\Omega(\delta^{15}N)$	$\Omega(\delta^{40}Ar)$
+0.0144	+0.0390
±0.0005	±0.0004

@230K

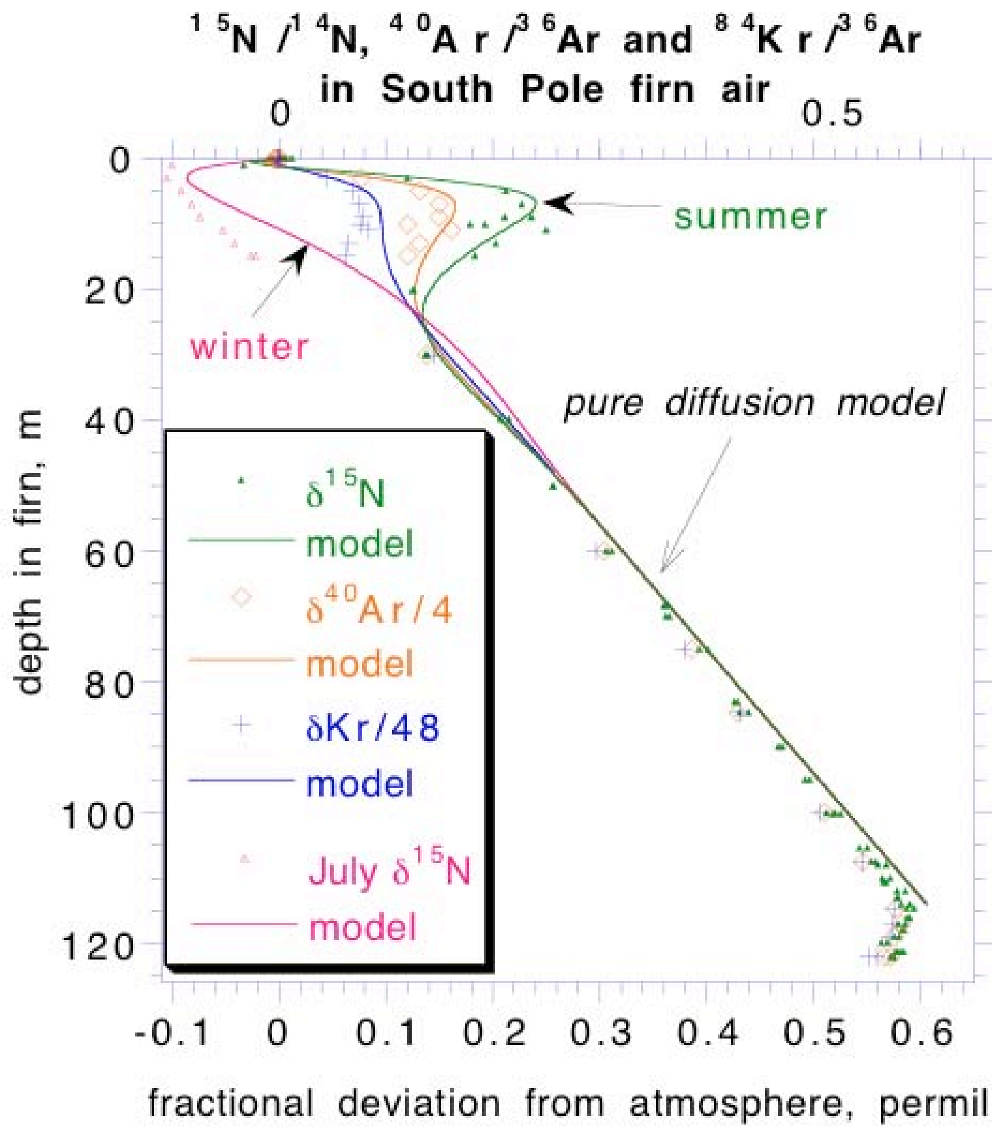


-20°C
-35°C
4
3
5
1
5
2
~30 cm

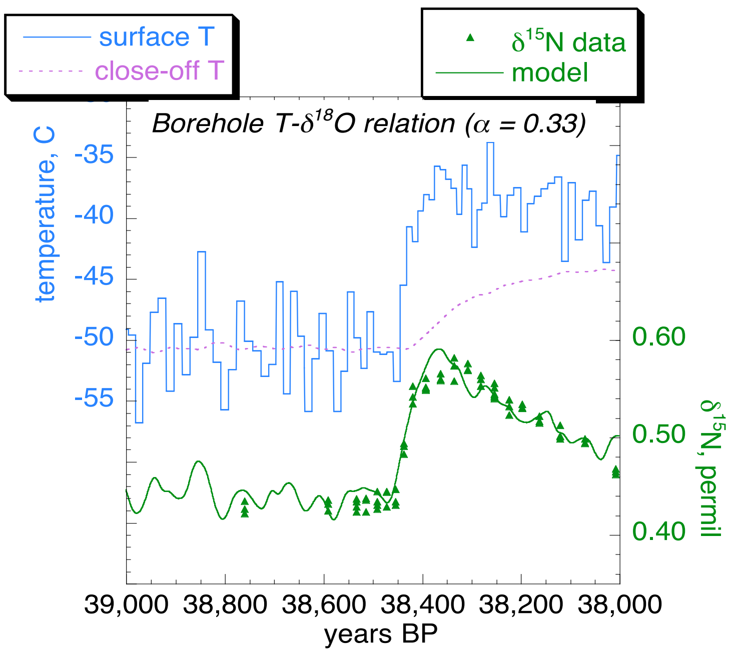

ECLIPSE Ice Drill

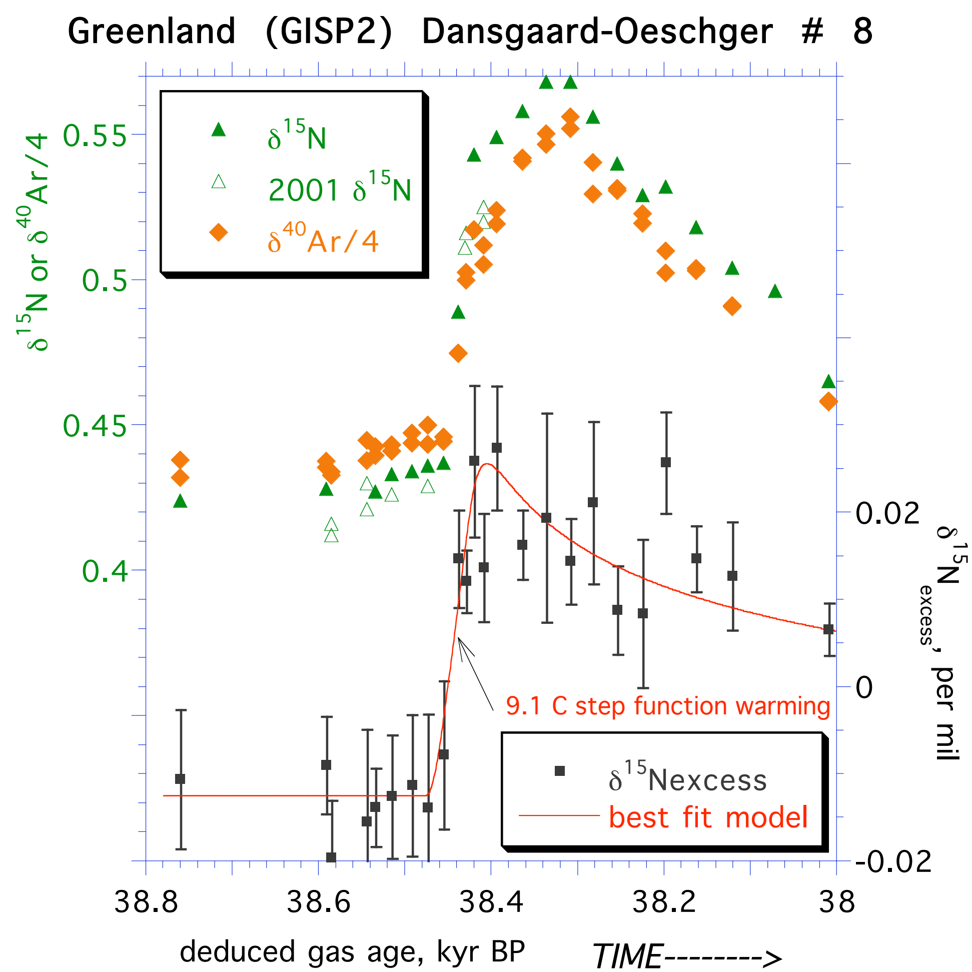


Firn air at Siple Dome, Antarctica
January 14, 1998
Sampled from tubes in firn
thermal
diffusion
gravitational
settling
δ15N
model
δ40Ar/4
model
depth, m
0
10
20
30
40
50
0.00
0.05
0.10
0.15
0.20
0.25
deviation from atmosphere, permil


15N/14N, 40Ar/36Ar and 84Kr/36Ar
in South Pole firn air
0
0.5
summer
winter
pure diffusion model
depth in firn, m
0
20
40
60
80
100
120
δ15N
model
δ40Ar/4
model
δKr/48
model
July δ15N
model
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
fractional deviation from atmosphere, permil

Thermal-diffusion-based magnitude estimates of abrupt Greenland warmings are mostly 10° C





Isolate temperature signal by solving two simultaneous equations with two unknowns:

$$\delta^{15}N_{obs} = \delta^{15}N_{grav} + \delta^{15}N_{therm}$$

$$\delta^{40}Ar_{obs} = \delta^{40}Ar_{grav} + \delta^{40}Ar_{therm}$$

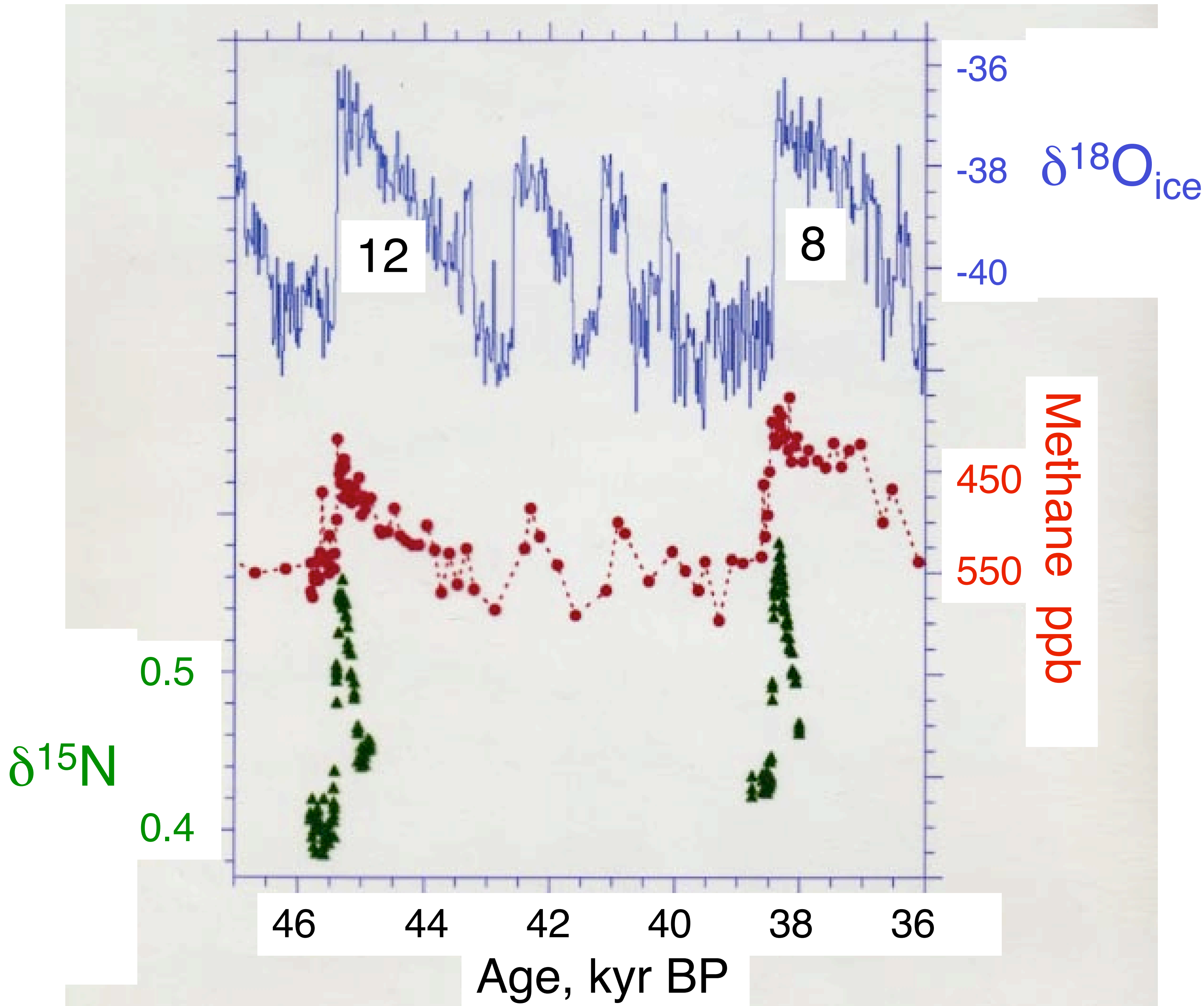
$$\delta^{15}N_{obs} - \delta^{40}Ar/4_{obs} = \Delta T(\Omega^{15} - \Omega^{40})$$

$$\delta^{15}N_{excess} = \delta^{15}N - \delta^{40}Ar/4$$

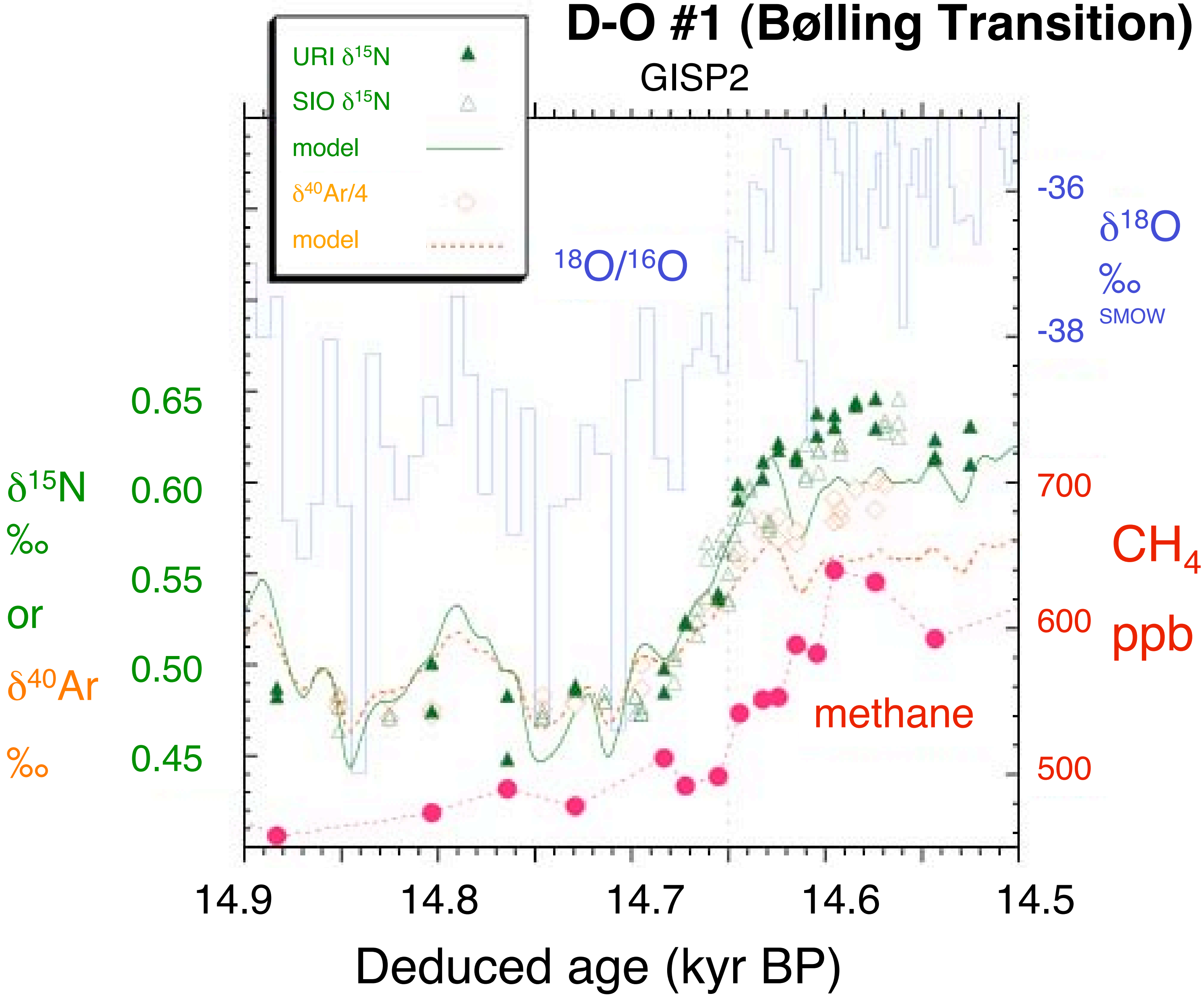
Timing of methane vs. temperature

With $\delta^{15}N$, one can compare gases directly with gases - no issues with gas age-ice age difference

Dansgaard-Oeschger #8 and 12#, Greenland summit (GISP2)

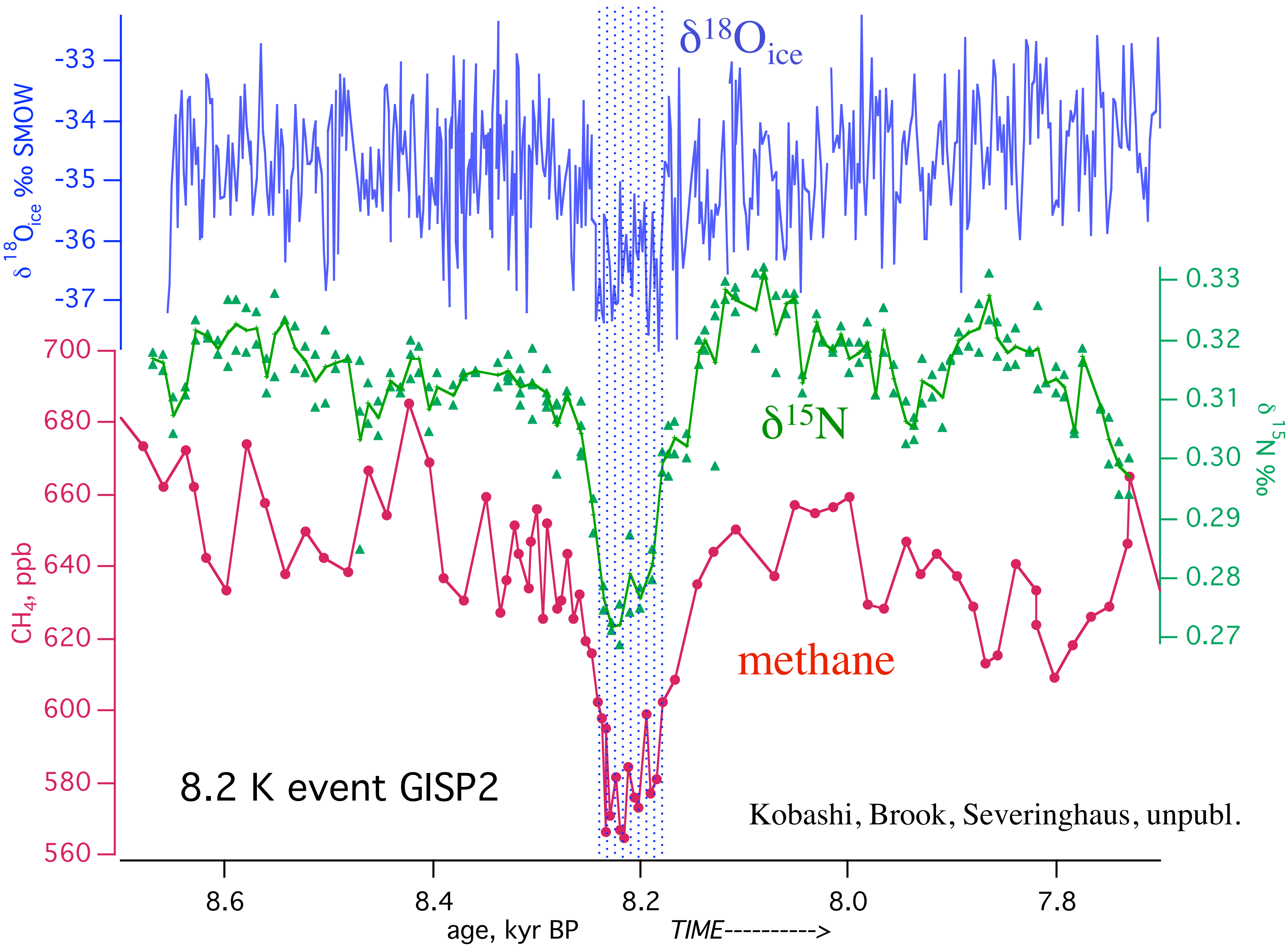


D-O #1 (Bølling Transition)



The beginnings of the methane changes are synchronous with Greenland temperature change, within our ability to measure it (± 30 yr). In some cases methane lags slightly and/or rises more gradually than temperature, taking ~150 years to reach maximum values (Severinghaus et al., 1998; Severinghaus and Brook, 1999; Brook et al, 2000).

Abrupt climate change in a background climate like today:

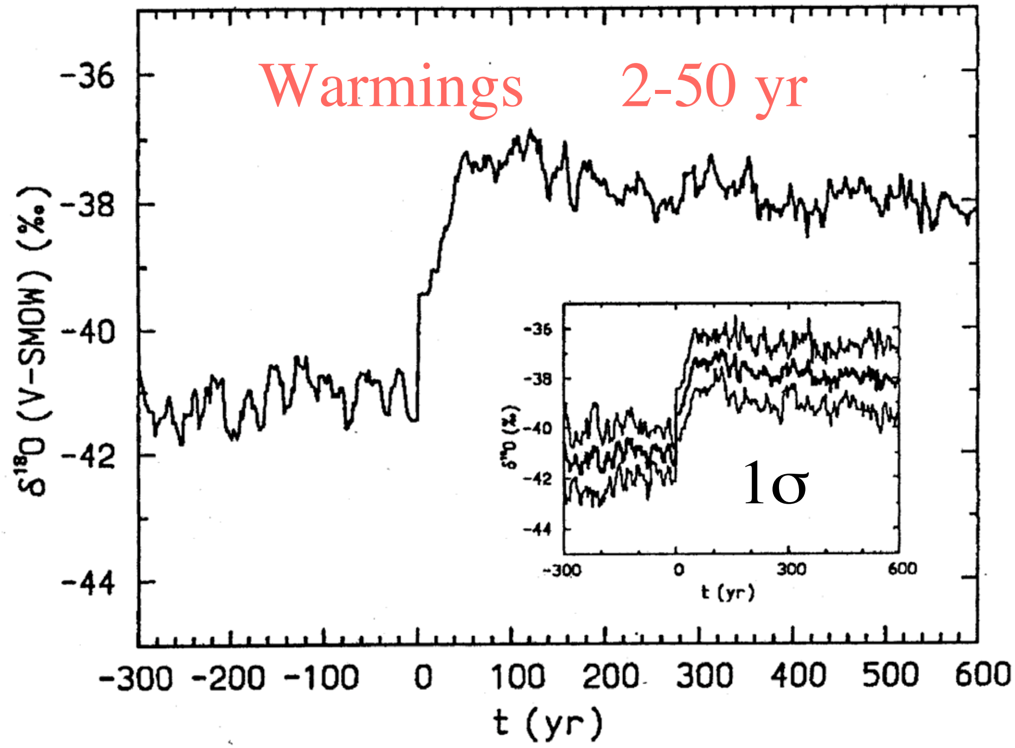


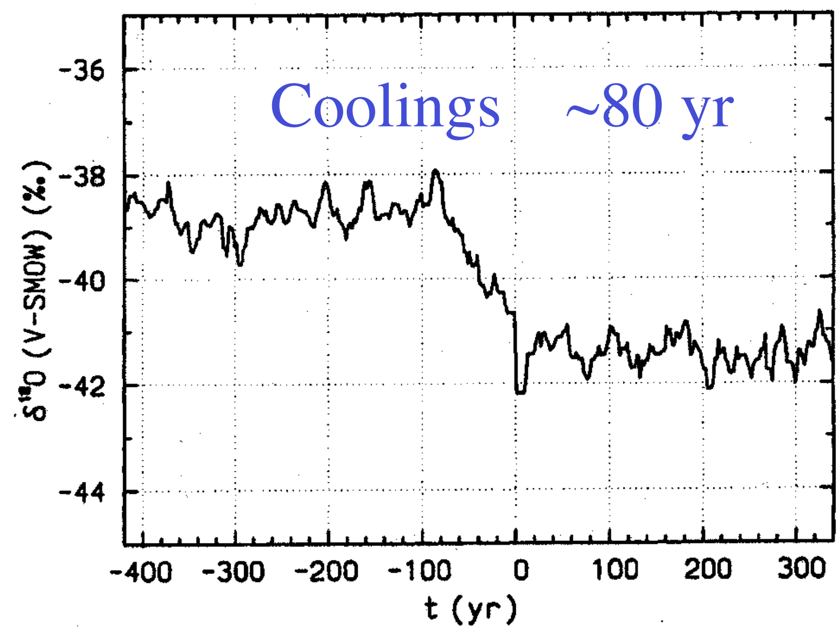
A clue?

Speed of warmings
versus coolings?

Stacked ^{18}O
records of 13
D-O events

Stuiver and Grootes,
2000, *QR*





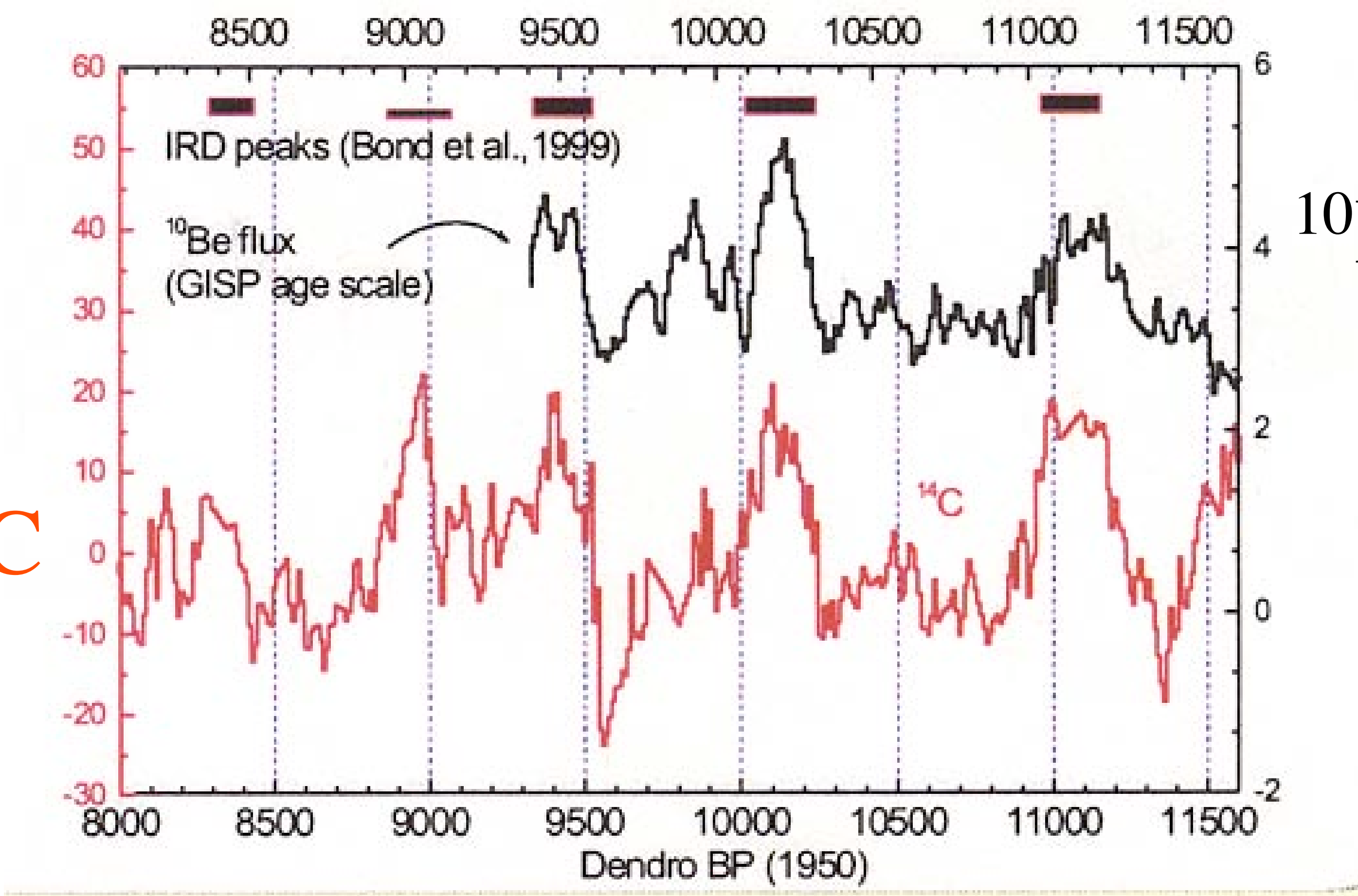
Is there a solar role in climate variability?

Does the sun act as the 1470-yr pacemaker of abrupt climate change?

Solar proxies: Greenland ^{10}Be and tree-ring ^{14}C

^{10}Be

^{14}C



Friedrich et al., 2001, *QSR*

CONCLUSIONS

D-O abrupt warmings were large (10˚C in Greenland), rapid (1 to 50 years), accumulation doubled, typically in 1-3 years; temperature change in Greenland and Europe large, elsewhere changes are smaller and temperature data are less certain

8.2 k event was an abrupt Greenland cooling of ~5˚C over probably just 5 years; lasted 65 yr in cold phase, and ended more gradually than it began; "different animal"

Atmospheric methane shows that hydrology changed abruptly over large areas;
--->implies that drought may be biggest impact of future abrupt change.

Ice core dust and major ions imply abrupt China dust-source hydrology changes

Low latitudes had changes in wind, rainfall; temperature less certain; Bolivian ice core (Sajama) signal could be hydrology not temperature; New Zealand, Chile, Antarctica asynchronous with Greenland

D-O footprint appears to have been semi-global, affecting biogenic atmospheric gases whose sources are dominantly in low latitudes (CH_4, N_2O, O_2, CO_2)

Nitrous oxide is not modulated by precession as methane is; Leads abrupt warmings by several hundred years - a hot clue?

Solar role in climate looks probable. Precise clock/pacemaker unlikely. Megadroughts occurred at times of high solar activity.

THANK YOU