Evidence of WAIS loss during MIS 5e: Siple Dome and more

R.B. Alley, E.J. Brook, D. Pollard, J.P. Severinghaus, E.J. Steig, E.D. Waddington, J.W.C. White, J. Ahn

WAIS, near San Diego, Sept. 26, 2014

Please note: I work for
Penn State University,
And help UN IPCC, NRC, etc.,
But I am not representing them, just me.

PENNSTATE 1855

NASA

G. Comer Foundation

earth THE OPERATORS' MANUAL

A bit of history

- C. Bentley, IGY, found deep WAIS basins
- Bentley & Ostenso, 1961, said WAIS likely formed by ice-shelf bridging of basins
- Could be reversed (Robin 1958; Hollin 1962)
- Our CO_2 could do this (Mercer 1968, 1978)
- (Is it possible that less of recent work is novel than we sometimes like to believe…?)

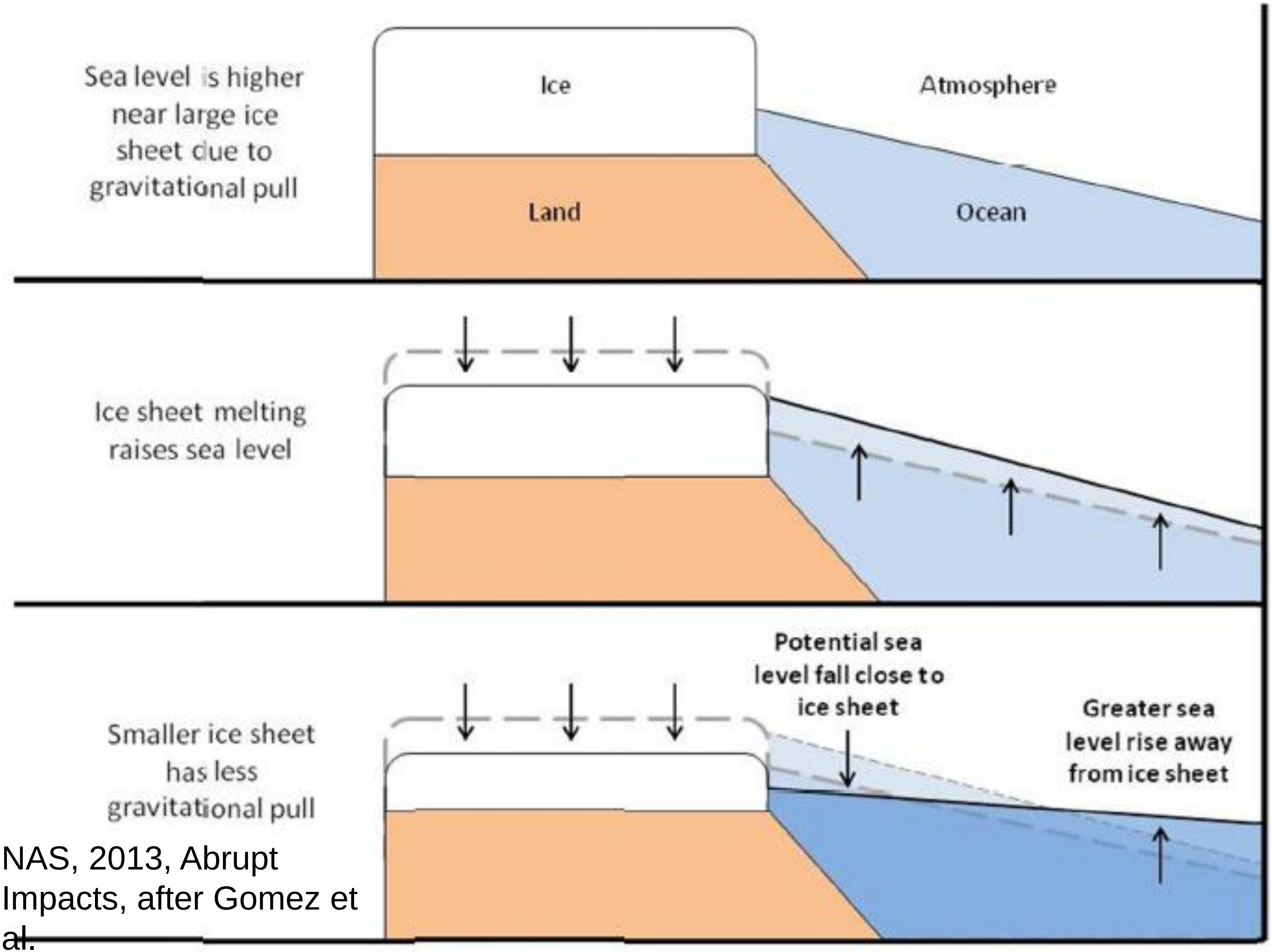
More history, Hollin 1962 suggested limits on cliff height, Hanson & Hooke 2003 estimated ~100 m, Bassis & Walker 2012, Bassis & Jacobs 2013 also 100 m or so…relevant to Deconto & Pollard’s simulations with Thwaites heading for a 200 m cliff…

Recent WAIS deglaciation?

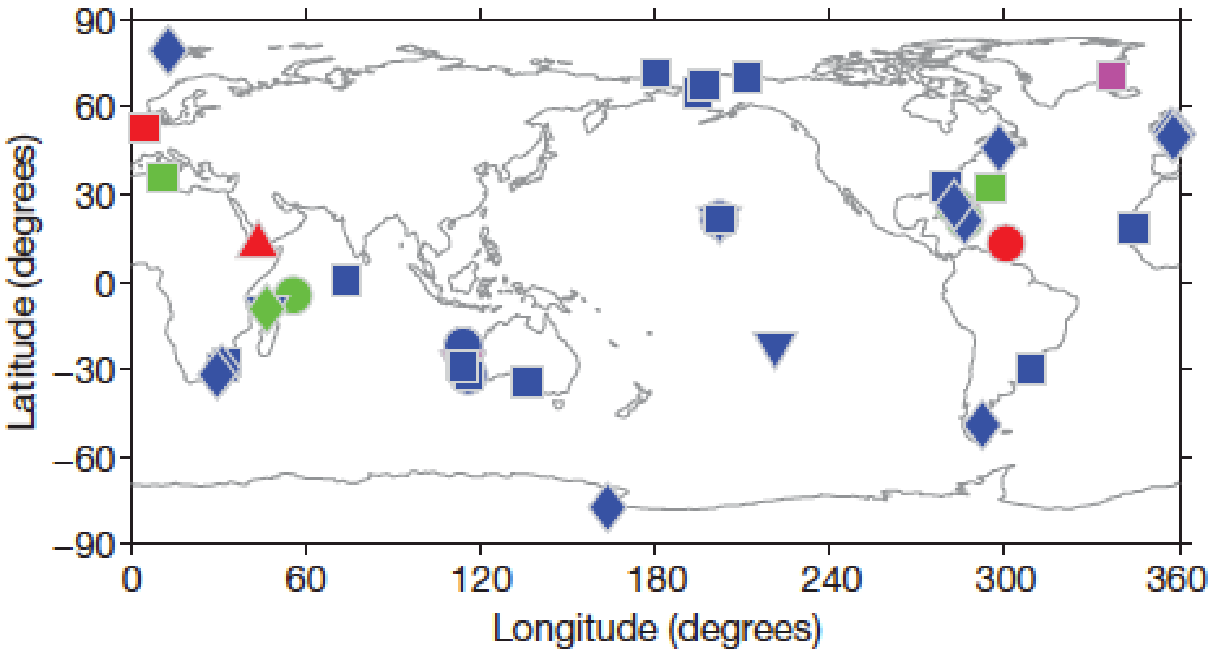
- Probably
- 5e likely most recent
- No “smoking gun” that WAIS died
- But several lines of evidence agree
- Getting stronger
- And no strong counter-evidence

Far-field sea level

- Mercer (1968) noted match between WAIS volume and MIS 5e far-field sea-level high stand
- Kopp et al. (2009) ≥95% confidence each pole contributed ≥2.5 m to total 6.6 m
- ~3.3 m marine WAIS (Bamber et al., 2009)
- (Note: Can't separate WAIS & EAIS)
- Dutton & Lambeck (2012), O'Leary et al. (2013) similar results to Kopp et al.



NAS, 2013, Abrupt Impacts, after Gomez et al.



Kopp et al., 2009, *Nature*, Sea-level fingerprinting

MIS 5e: 95% probability of at least 2.5 m of sea-level rise from Greenland and from Antarctic ice sheets to MIS 5e peak of at least 6.6 m above modern (67% probability peak exceeded 8.0 m)

McKay et al. (2011, GRL) modeled thermal expansion of ocean, argue for 4.1-5.8 m from Antarctic

Rate of rise may have been fast

- 5e level reached near or above modern, and then had a rapid-rise event
- Compare to recent rise of 0.3 m/century

→ ≥2.5 m/1000 yr (≥0.25 m/century) Thompson et al.

→ 3-7 m/1000 yr (0.3-0.7 m/century) Kopp et al.

- Maybe completed in <1000 yr resolution

→ 0.6 m/century (or more?) O'Leary et al.

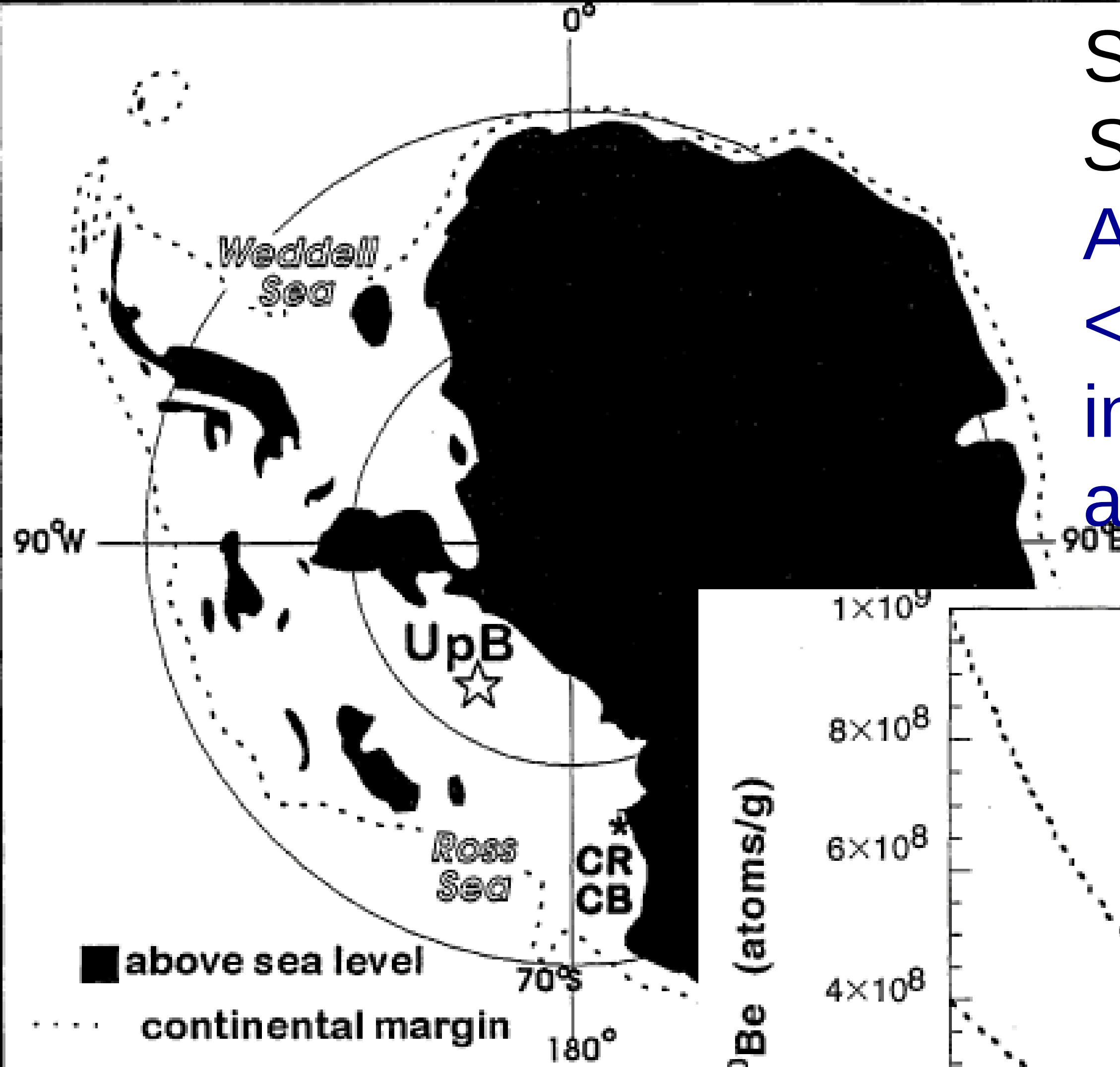
→ 2.5 m/century over ~300 yr after 750-year smooth applied to data Rohling et al.

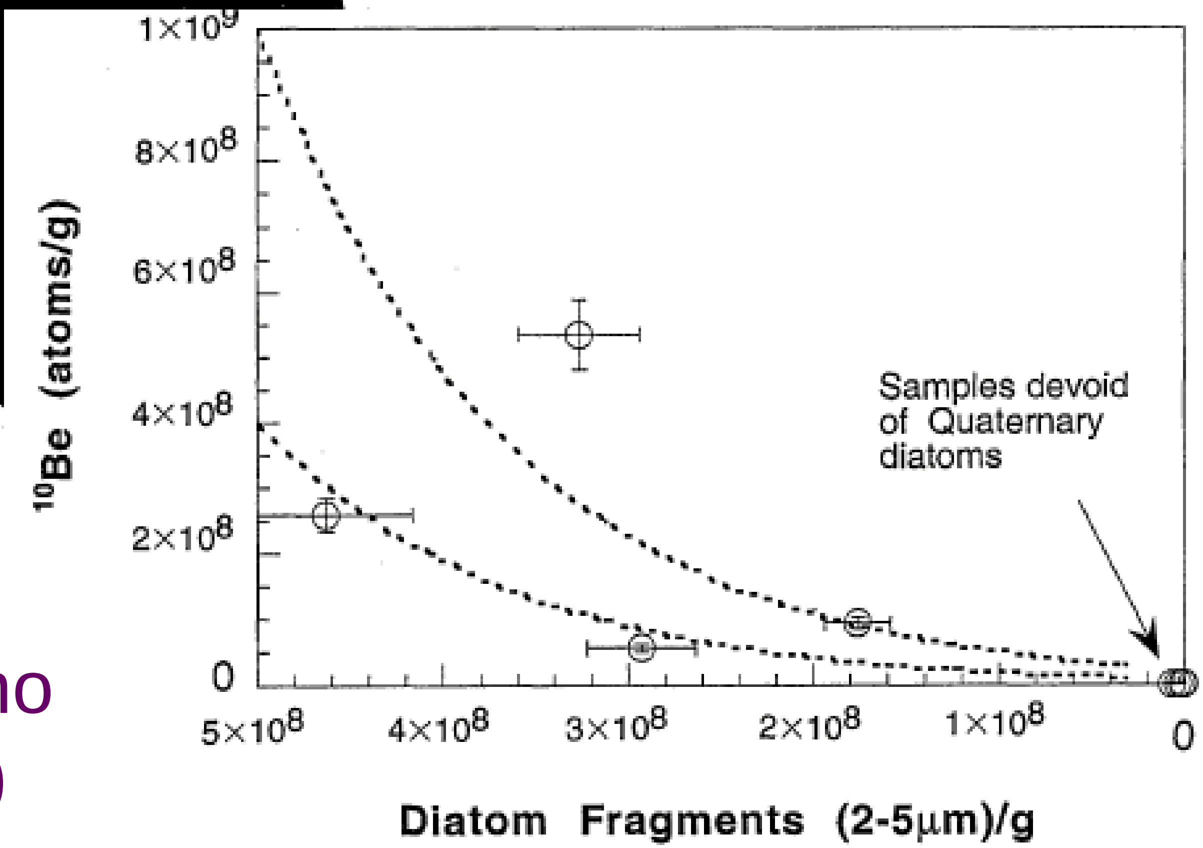
Fast collapse allowed, not required

- Mercer 1968, evidence shows “rise in sea level to above present levels took place during the Sangamon Hypsithermal [MIS 5e] and was very rapid”, which “suggests possible catastrophic disintegration of the West Antarctic Ice Sheet at that time, but further evidence is needed.”
- More evidence now, know more, but no big change in the suggested outcome yet

Scherer et al., 1998, *Science*, UpB,

Abundant diatoms <750ka (prob. <600ka) in some samples, with abundant ^{10}Be

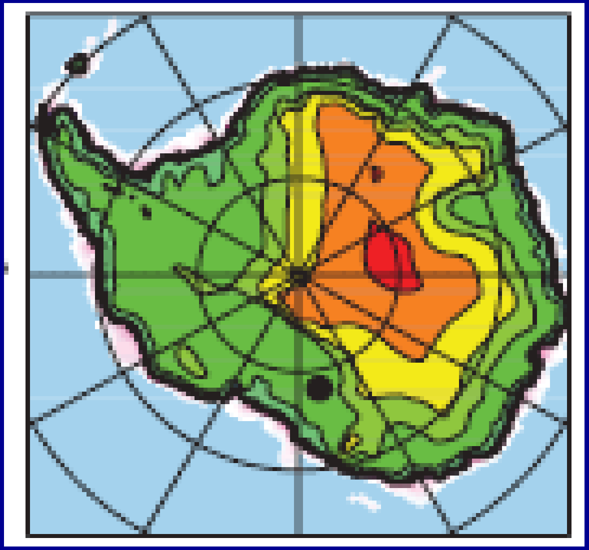


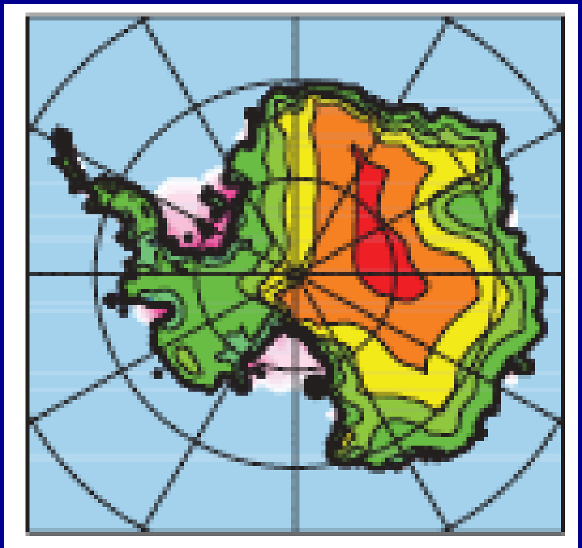


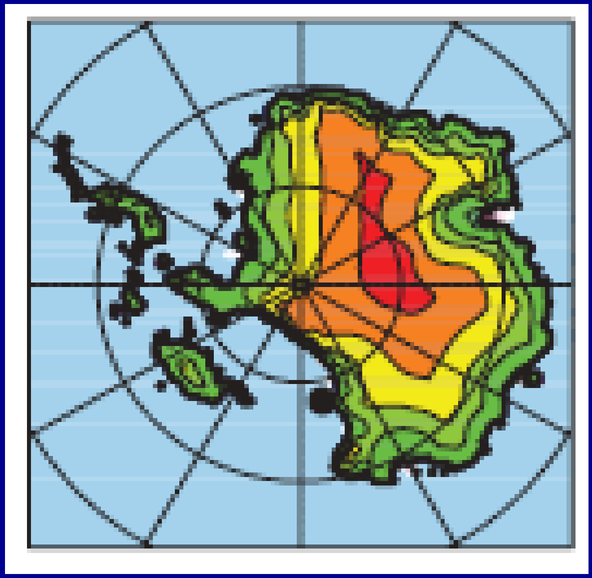
Fauna UNLIKE wind-blown (esp. no lacustrine species)

Has WAIS gone away recently?

- Andrill shows collapses (Pollard&DeConto, 2009)
- Unclear on 5e collapse (Naish+, 2009, Nature)







Quaternary Science Reviews 34 (2012) 93–112

Contents lists available at SciVerse ScienceDirect

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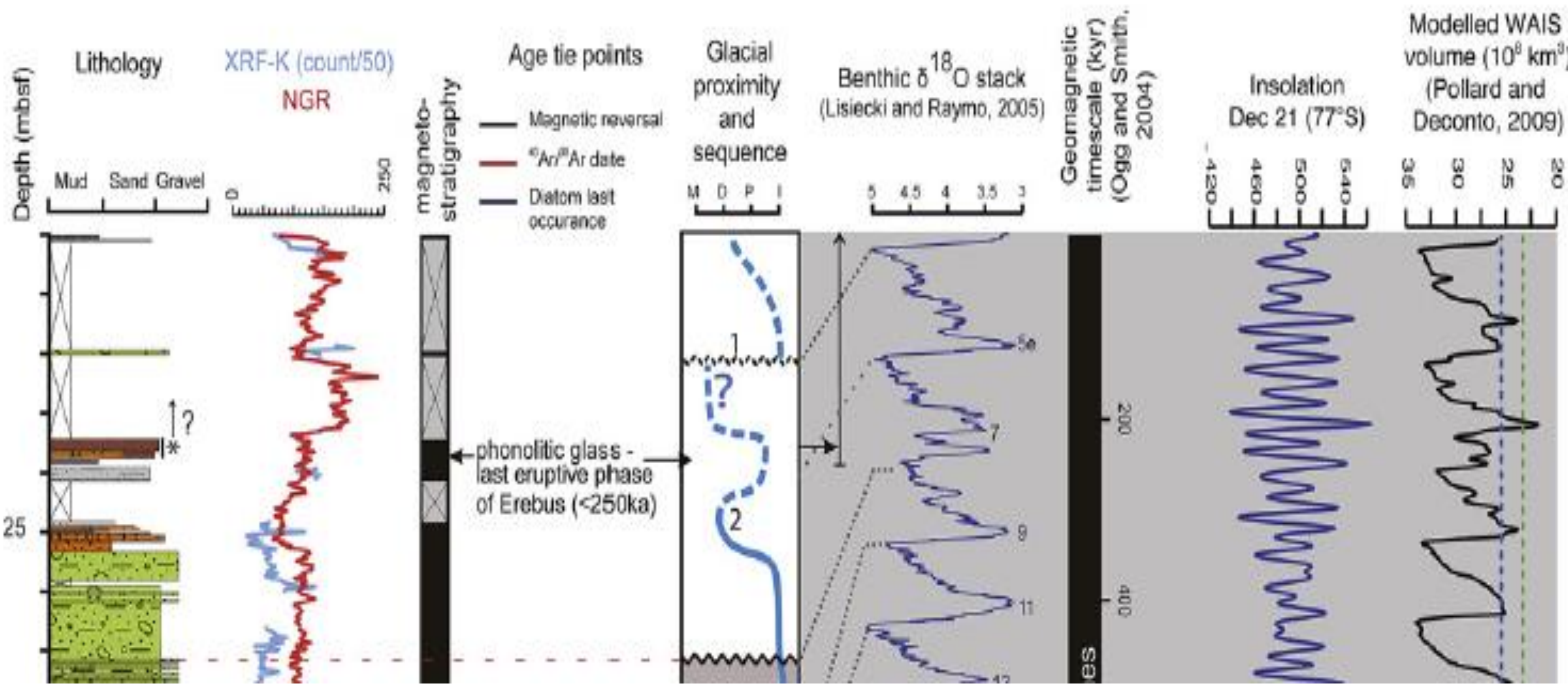
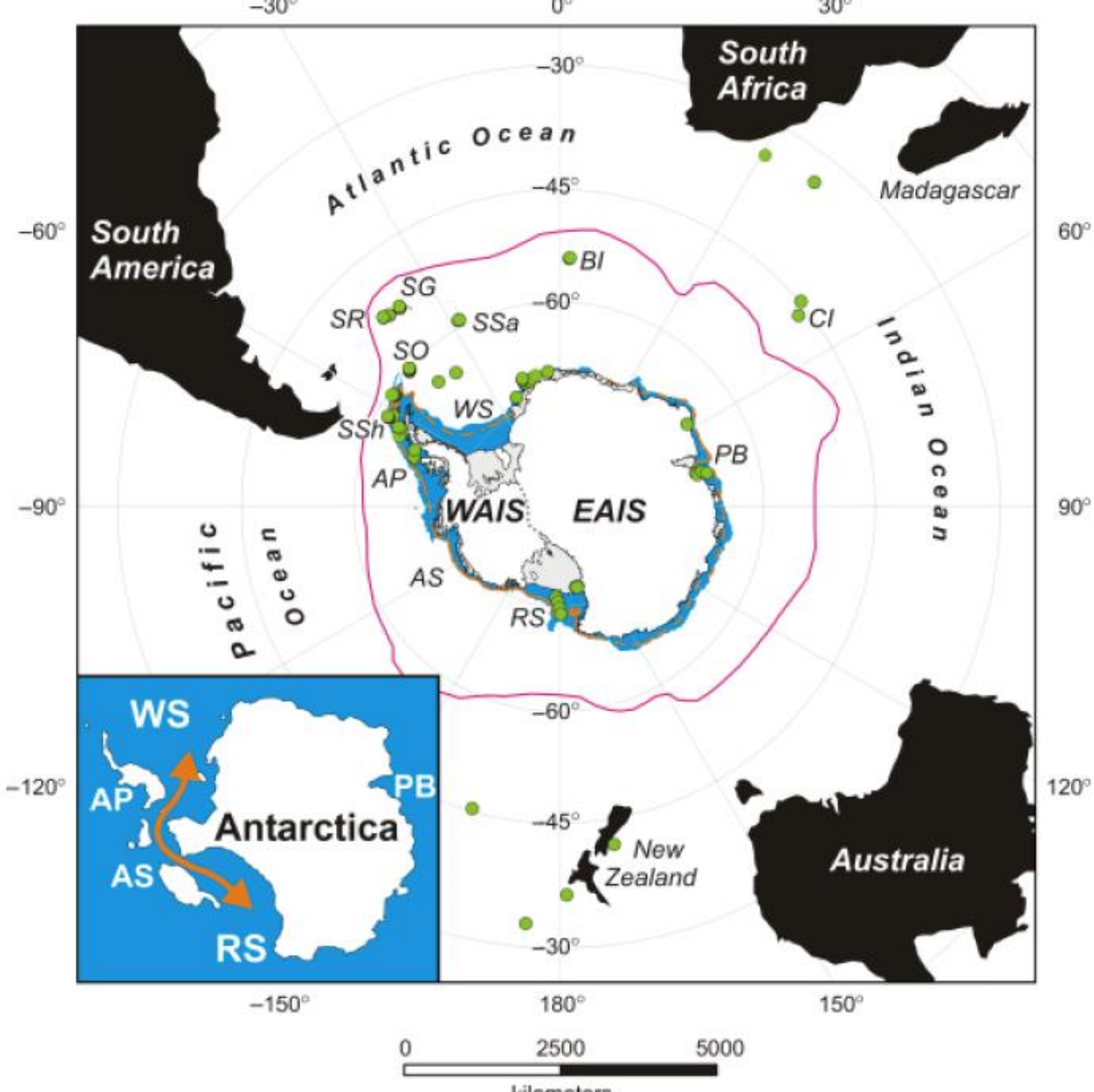
journal homepage: www.elsevier.com/locate/quascirev

Pleistocene variability of Antarctic Ice Sheet extent in the Ross Embayment

Robert McKay [a,*], Tim Naish [a], Ross Powell [b], Peter Barrett [a], Reed Scherer [b], Franco Talarico [c], Philip Kyle [d], Donata Monien [e,1], Gerhard Kuhn [e], Chris Jackolski [b], Trevor Williams [f]

Most-recent more-extensive open-water conditions stage 5 or 7…





Barnes & Hillenbrand 2010, *Global Change Biology*, looked at patterns of bryozoan relatedness.

Vaughan et al., 2011 suggest 5e as most likely.

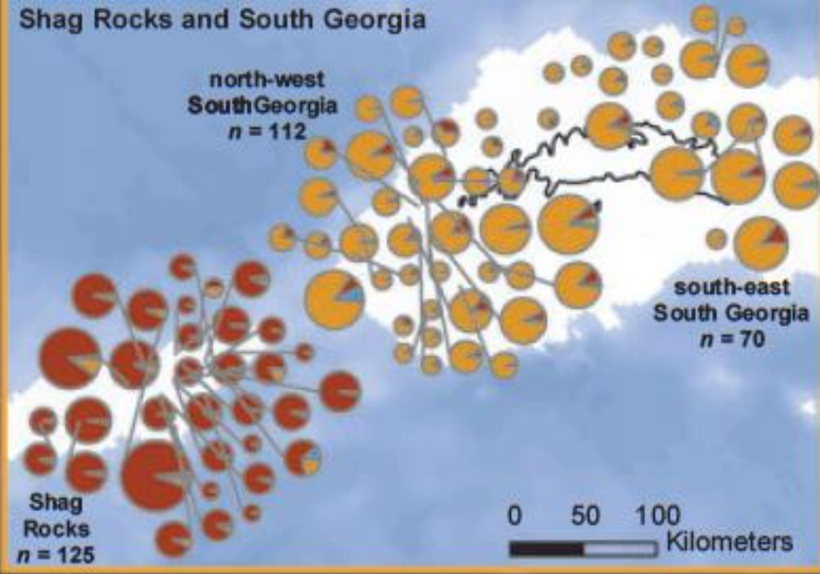
Ross and Weddell species most similar; suggests open seaway, perhaps within last few interglacials

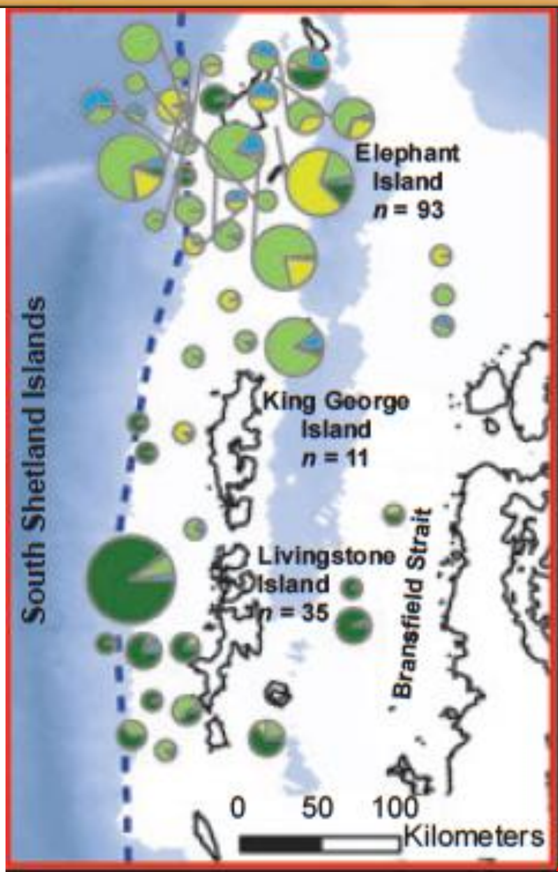
MOLECULAR ECOLOGY

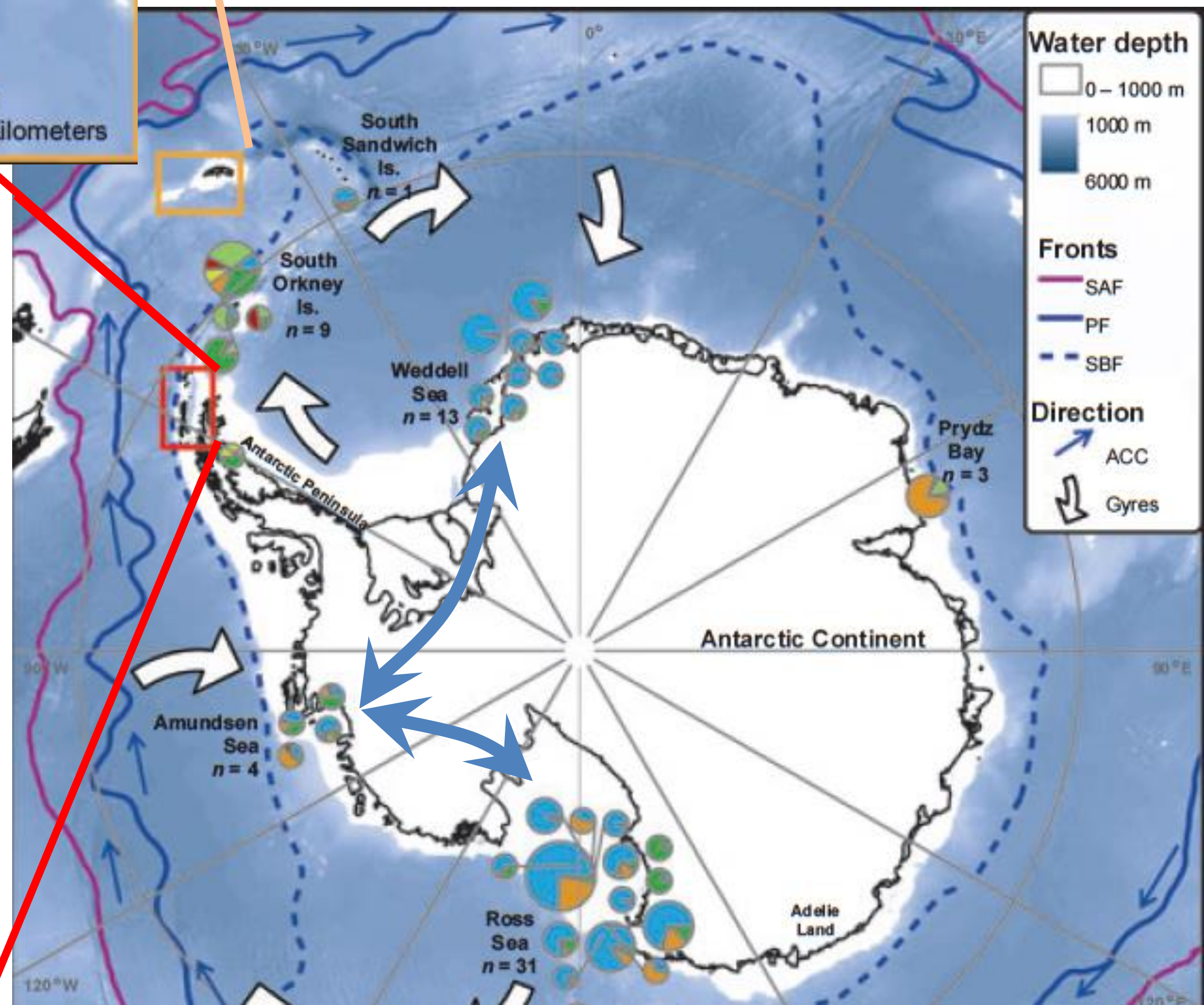
Molecular Ecology (2012) 21, 2775–2787 doi: 10.1111/j.1365-294X.2012.05572.x

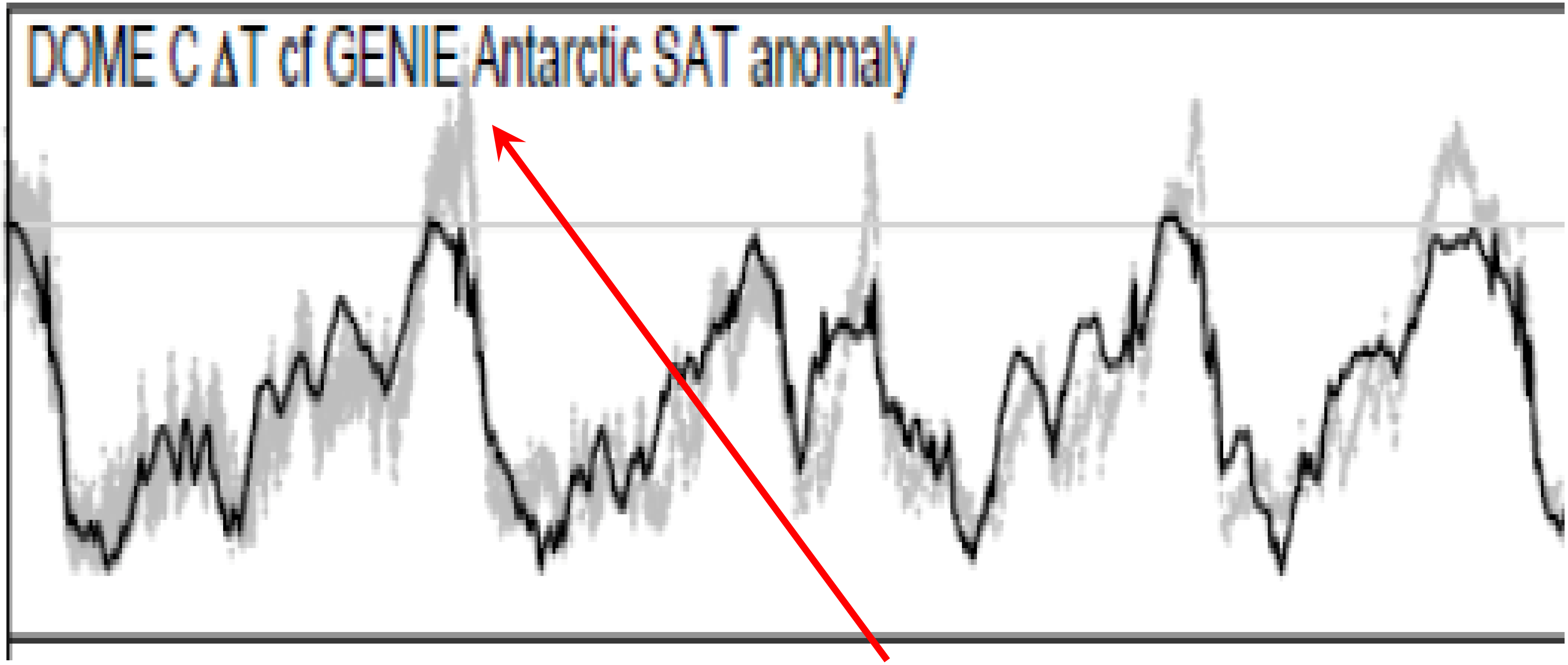
Persistent genetic signatures of historic climatic events in an Antarctic octopus

J. M. STRUGNELL,* P. C.WATTS,†[1] P. J. SMITH‡ and A. L. ALLCOCK§[1]





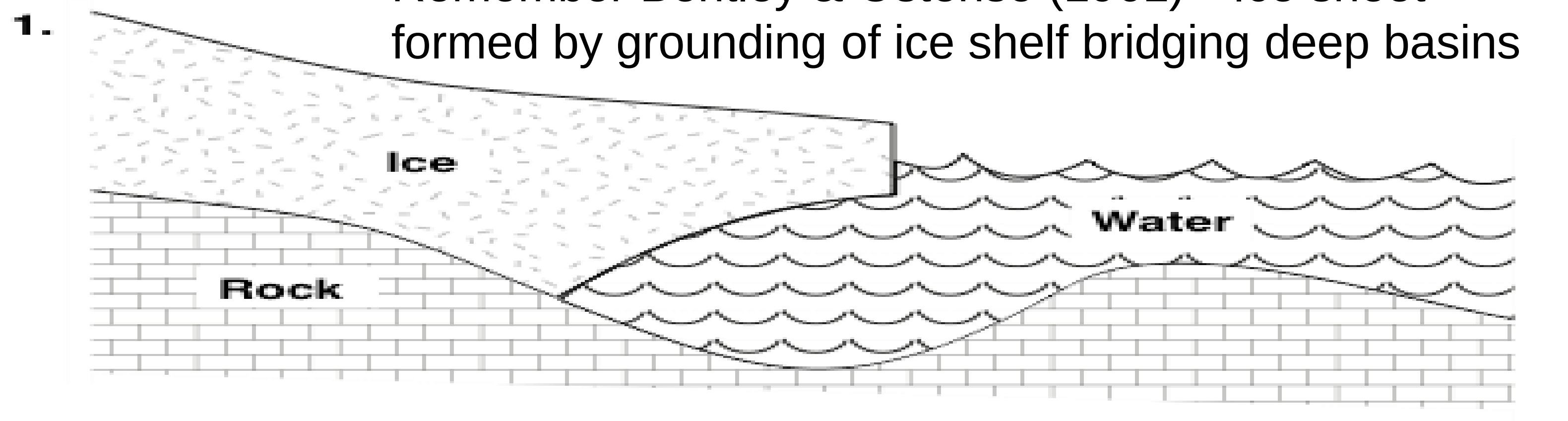


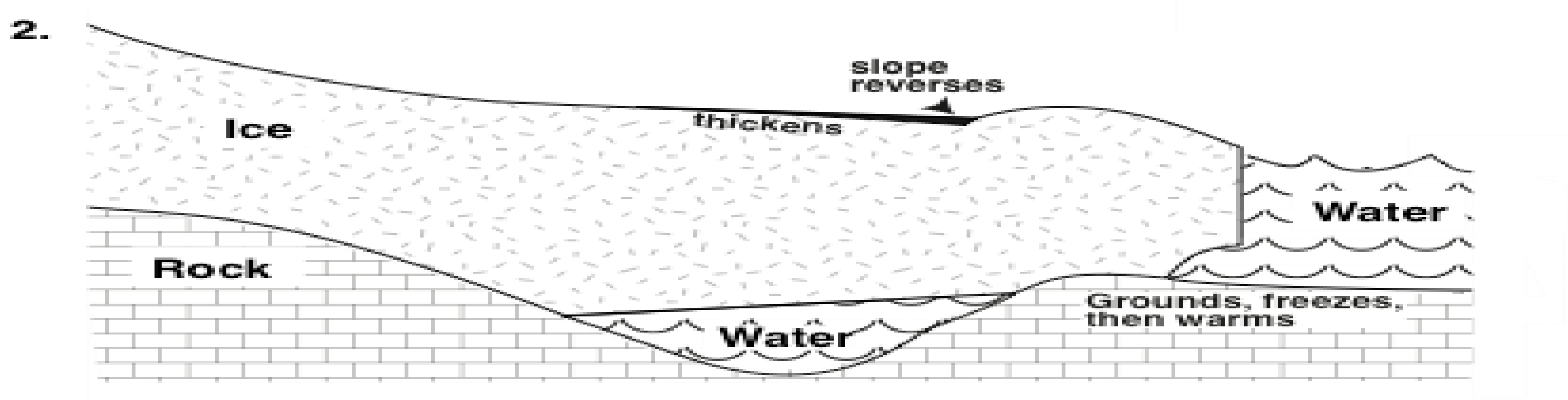


EAIS ice cores show "anomalous" interglacial warmth in 5e, and to a lesser extent 7, 9 and 11, compared to Holocene and to older interglacials. Hard to model through orbital forcing, CO_2, etc., but can match if WAIS greatly reduced or lost.

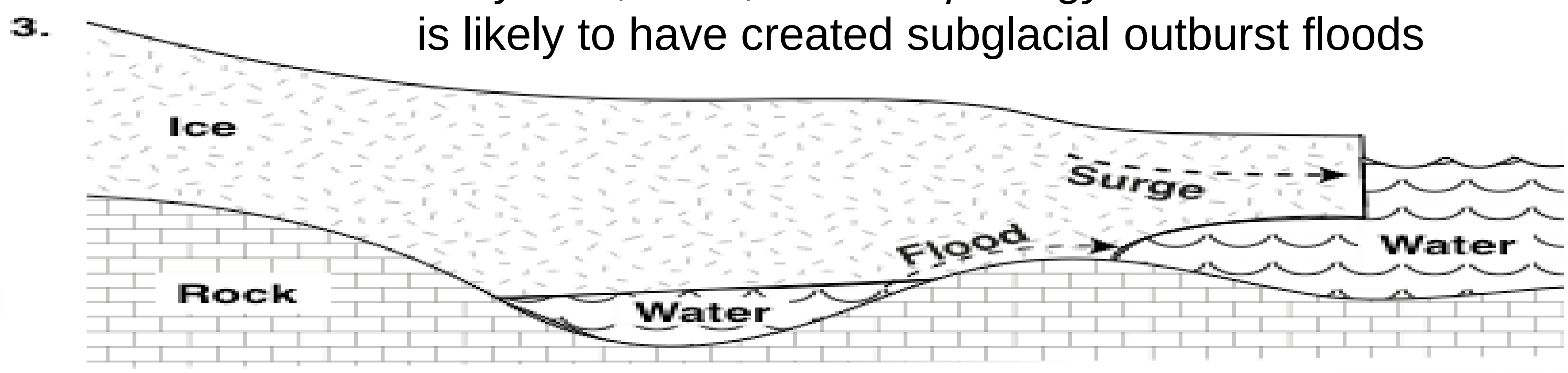
Holden et al., 2010, *Clim. Past.;* 2011, *J. Quat. Sci.*

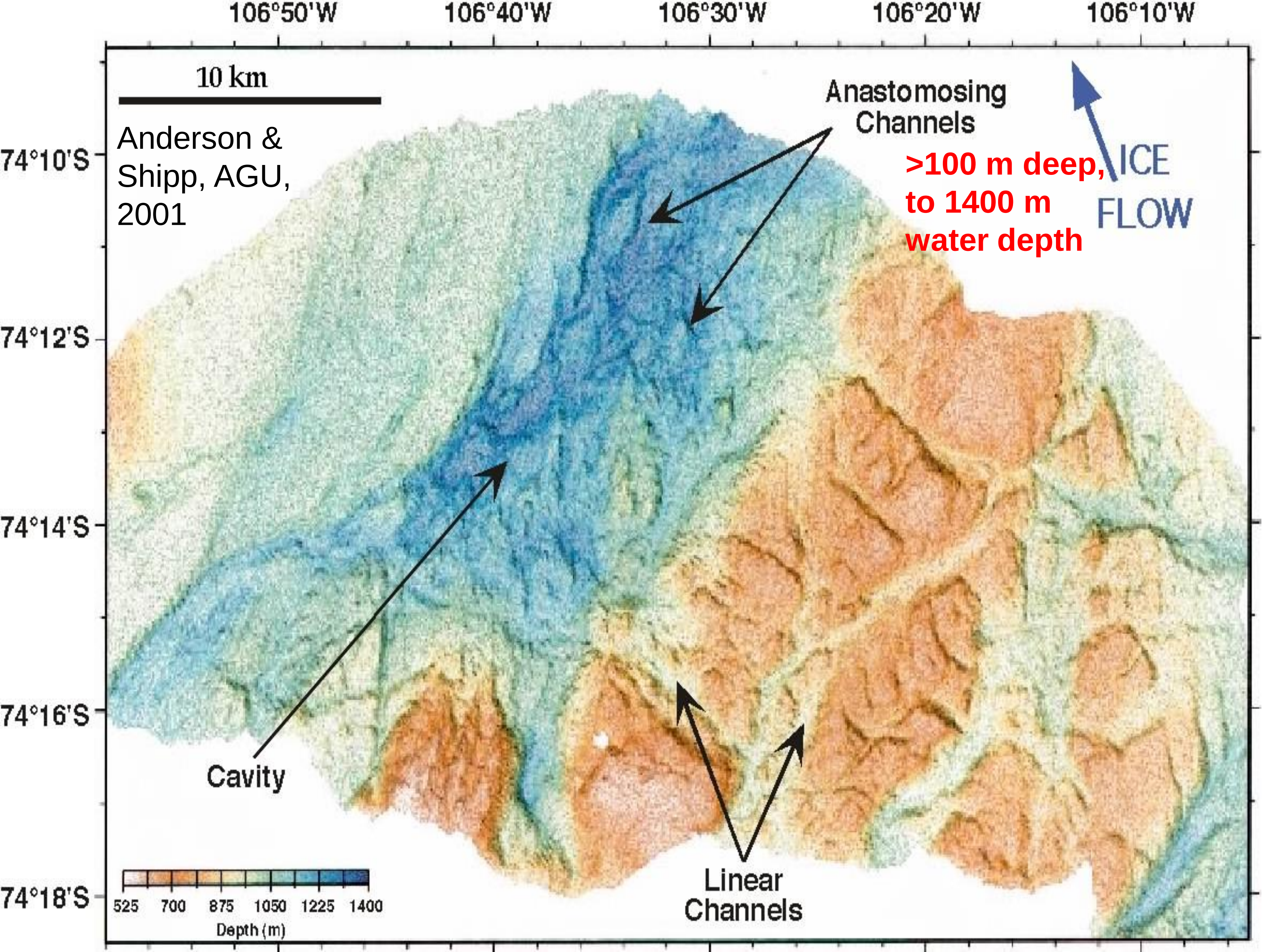
Remember Bentley & Ostenso (1961)—Ice sheet formed by grounding of ice shelf bridging deep basins



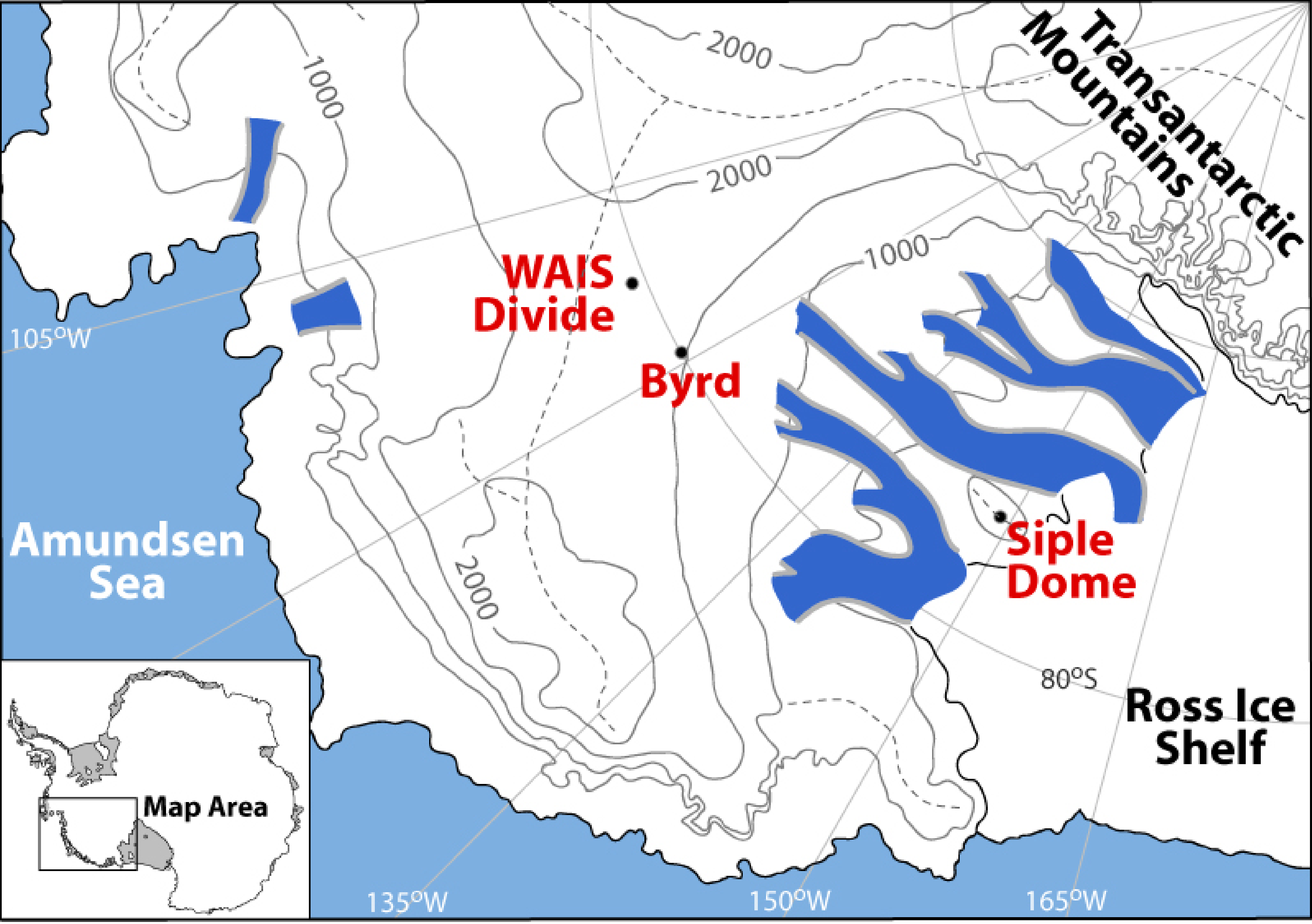


Alley et al, 2006, *Geomorphology* showed how this is likely to have created subglacial outburst floods

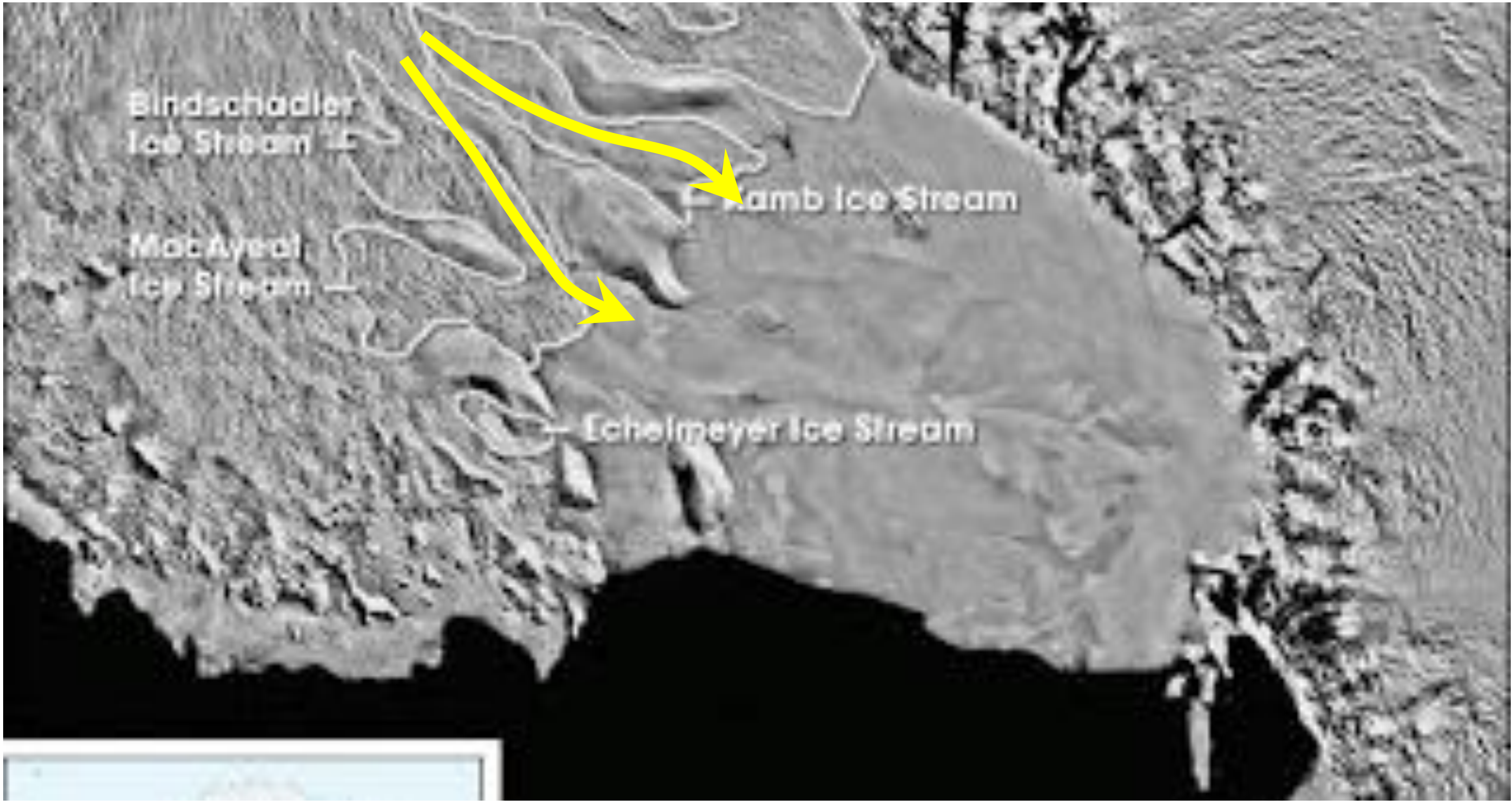




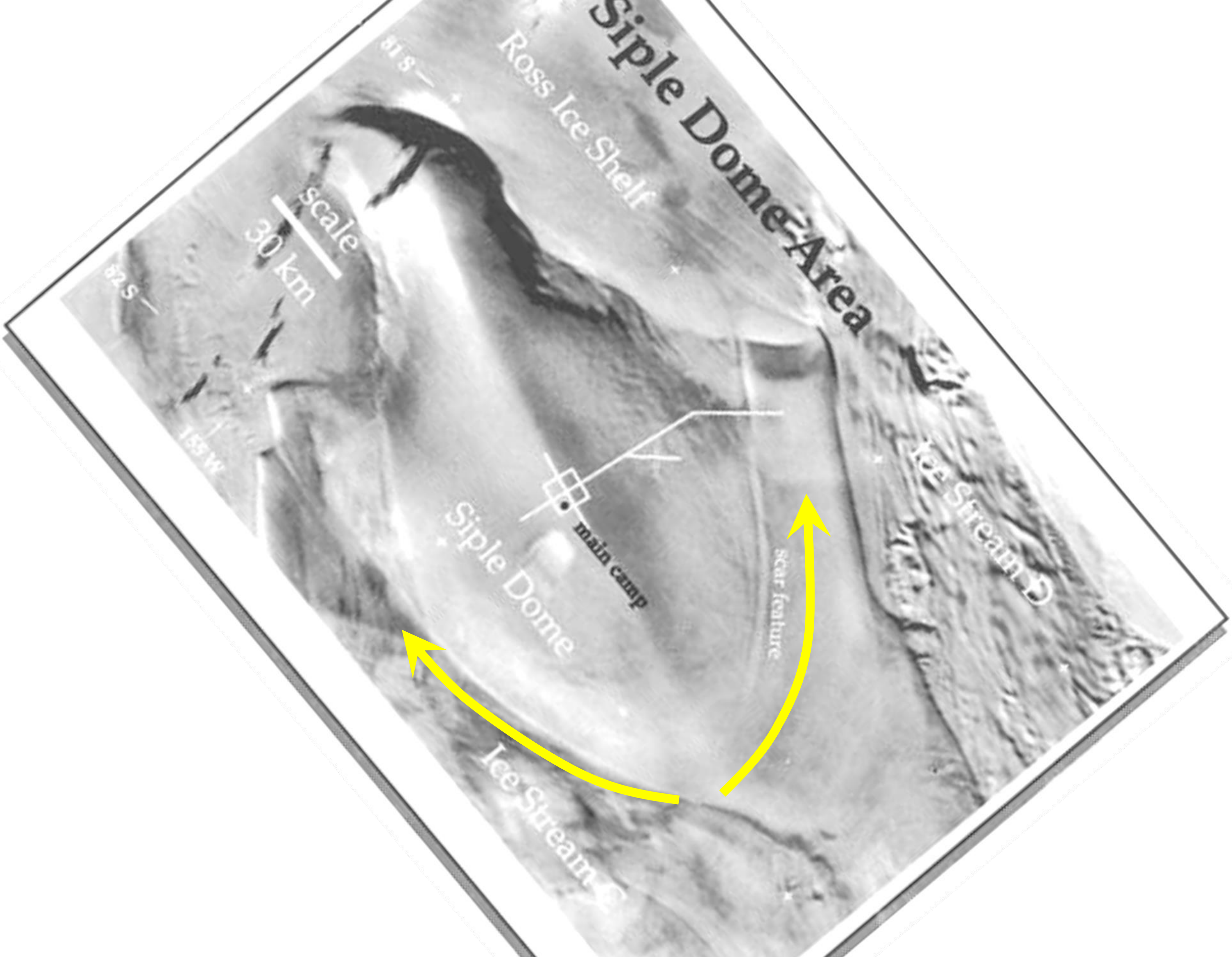
106°50'W
106°40'W
106°30'W
106°20'W
106°10'W
74°10'S
74°12'S
74°14'S
74°16'S
74°18'S
10 km
Anderson & Shipp, AGU, 2001
Anastomosing Channels
>100 m deep, to 1400 m water depth
ICE FLOW
Cavity
Linear Channels
525 700 875 1050 1225 1400
Depth (m)



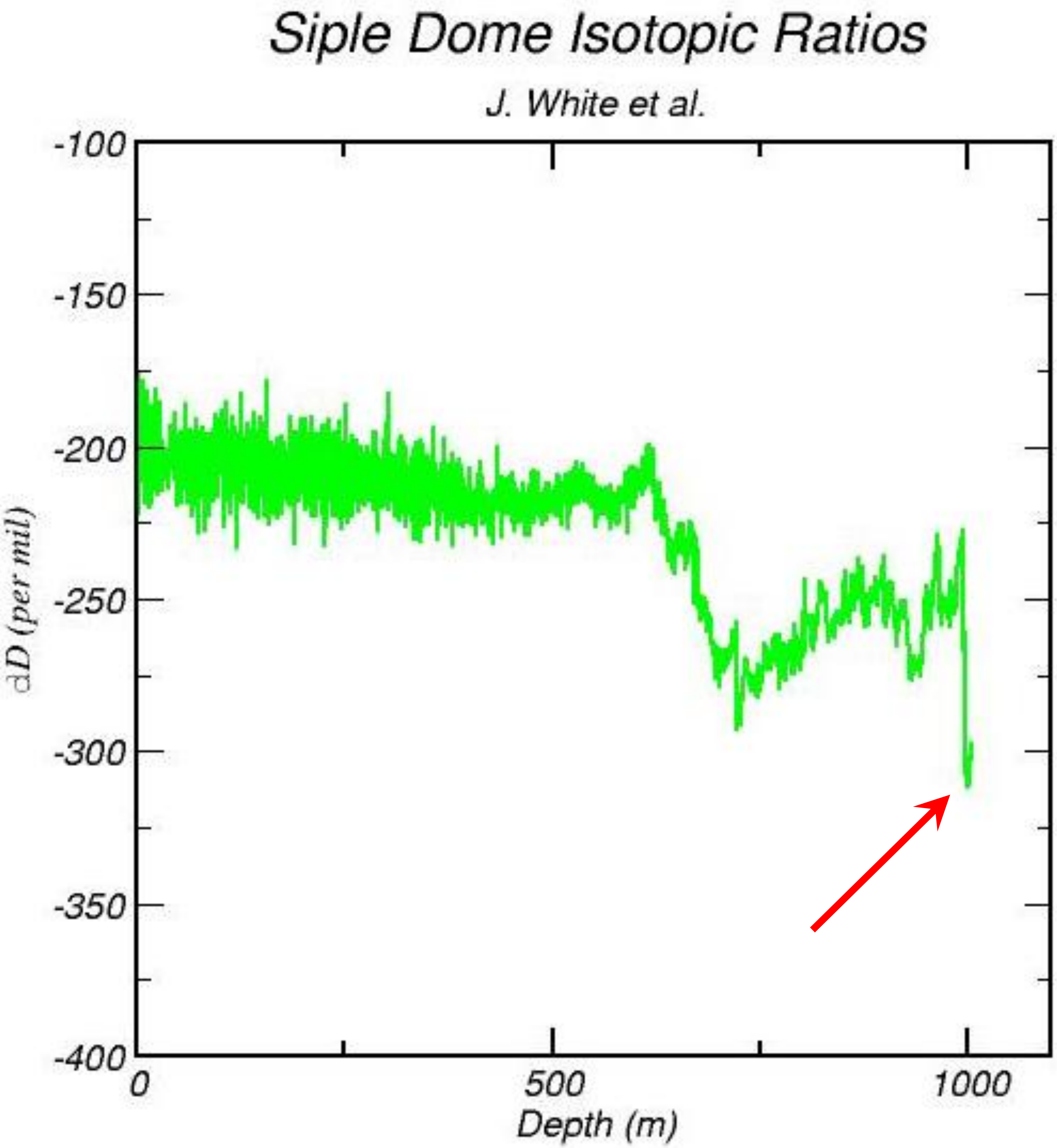
http://antarcticsun.usap.gov/science/contentHandler.cfm?id=1574, from WAIS Divide Project web site



Bindschadler Ice Stream
MacAyeal Ice Stream
Kamb Ice Stream
Echelmeyer Ice Stream

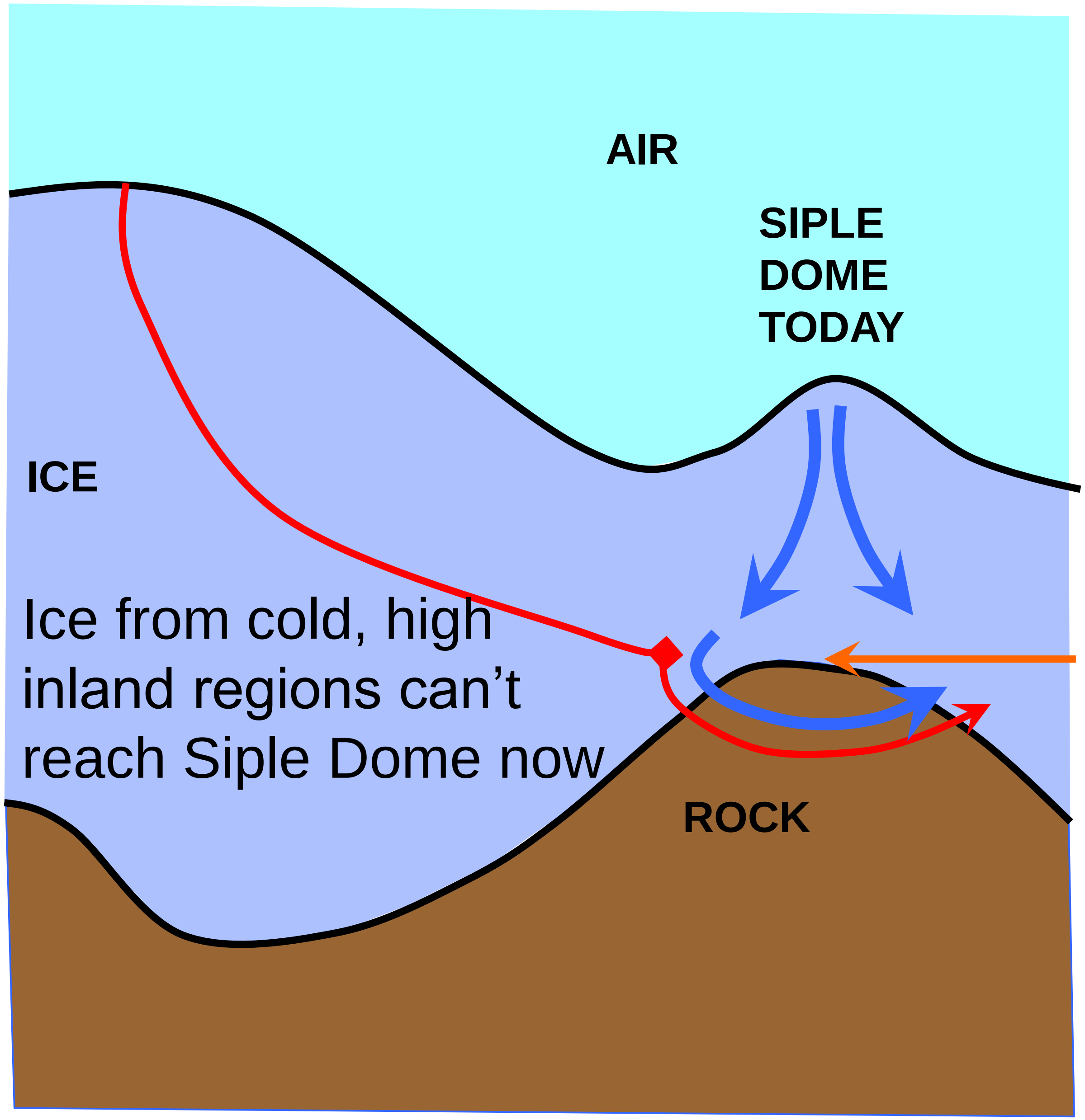


Siple Dome Area
Ross Ice Shelf
81 S
82 S
scale
30 km
155 W
Siple Dome
main camp
scar feature
Ice Stream C
Ice Stream D

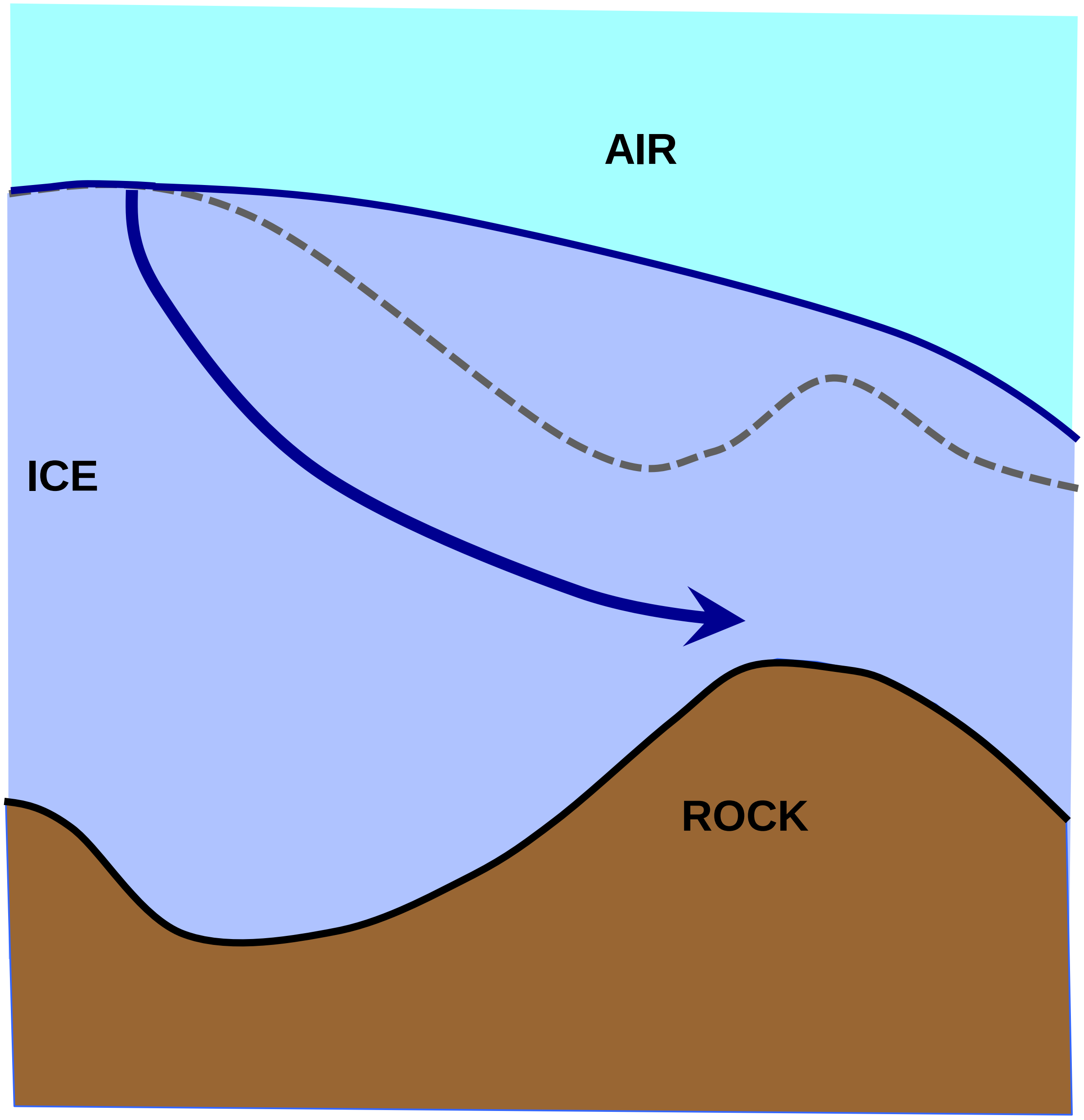


From Alley & White, WAIS Abstract, 2000

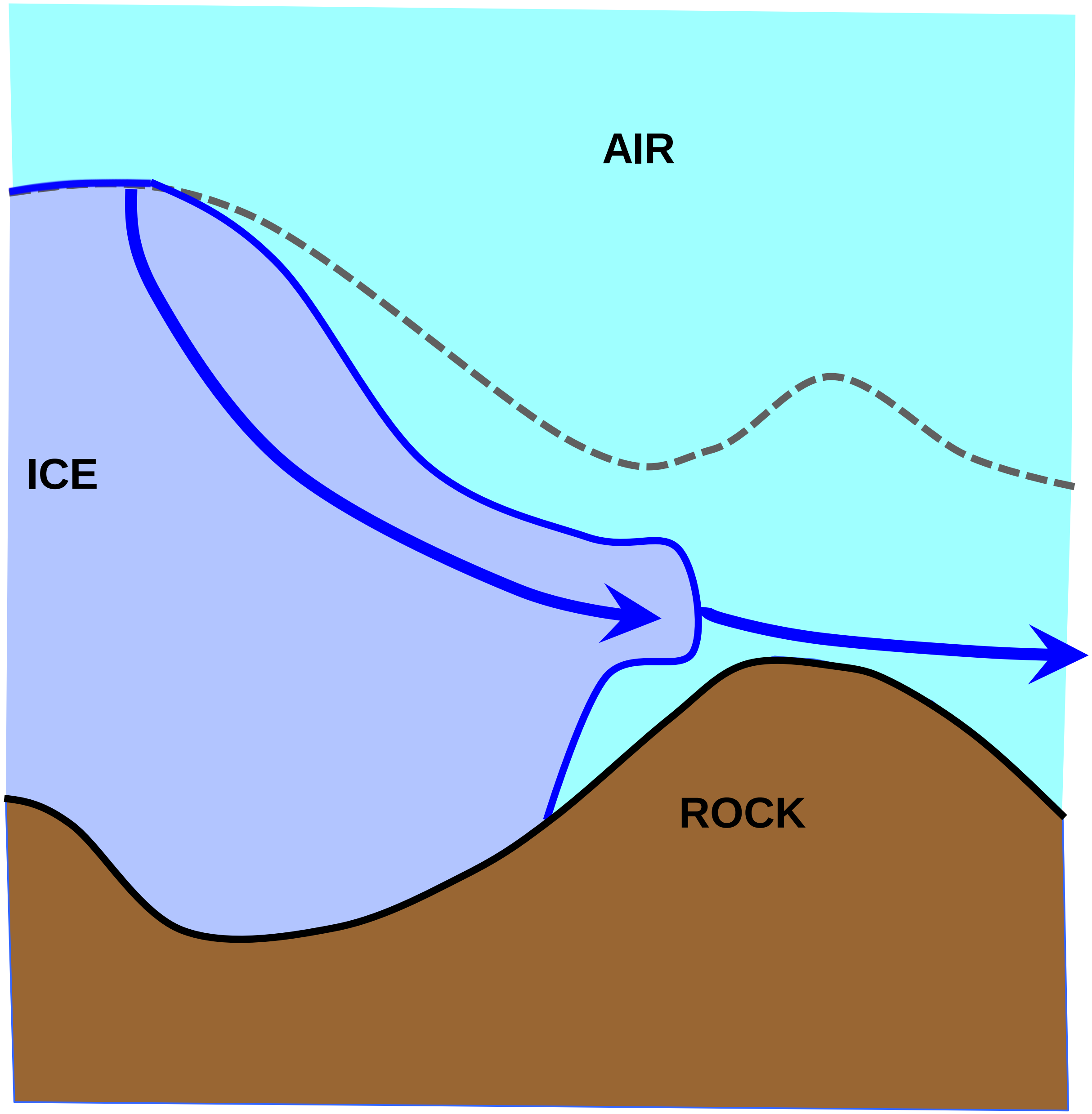
Basal Siple Dome--oldest well-dated ice is younger than Eem, atop a thin layer with isotopic values typical of ice-age Byrd—was the Dome overridden or gone?



Yet basal ice is
from a cold,
high region



Big ice in past would work, but no evidence for this, and some evidence against…



Small ice in past, then an ice shelf grounding, would also work, and agrees with other data

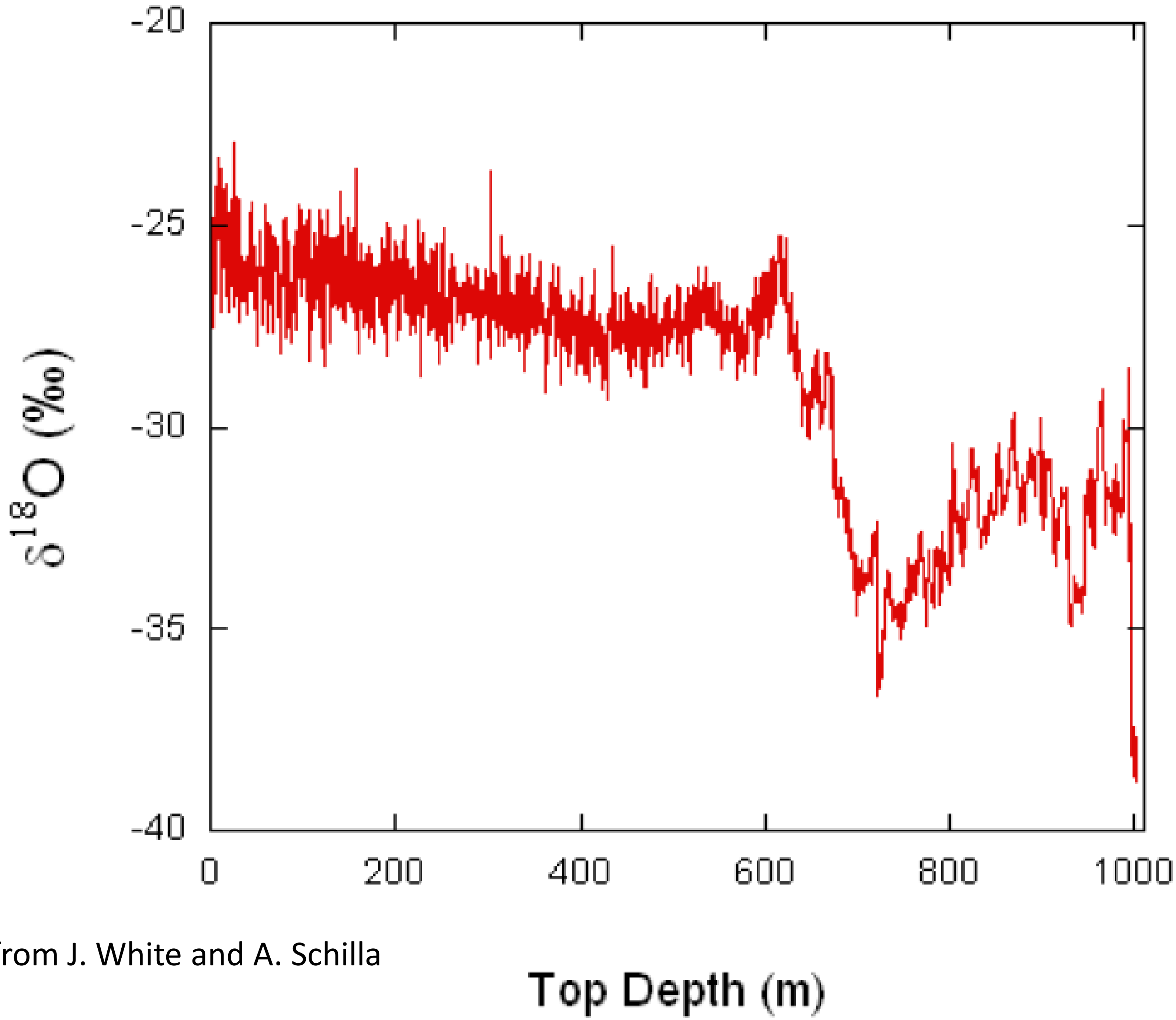


Fig. from J. White and A. Schilla

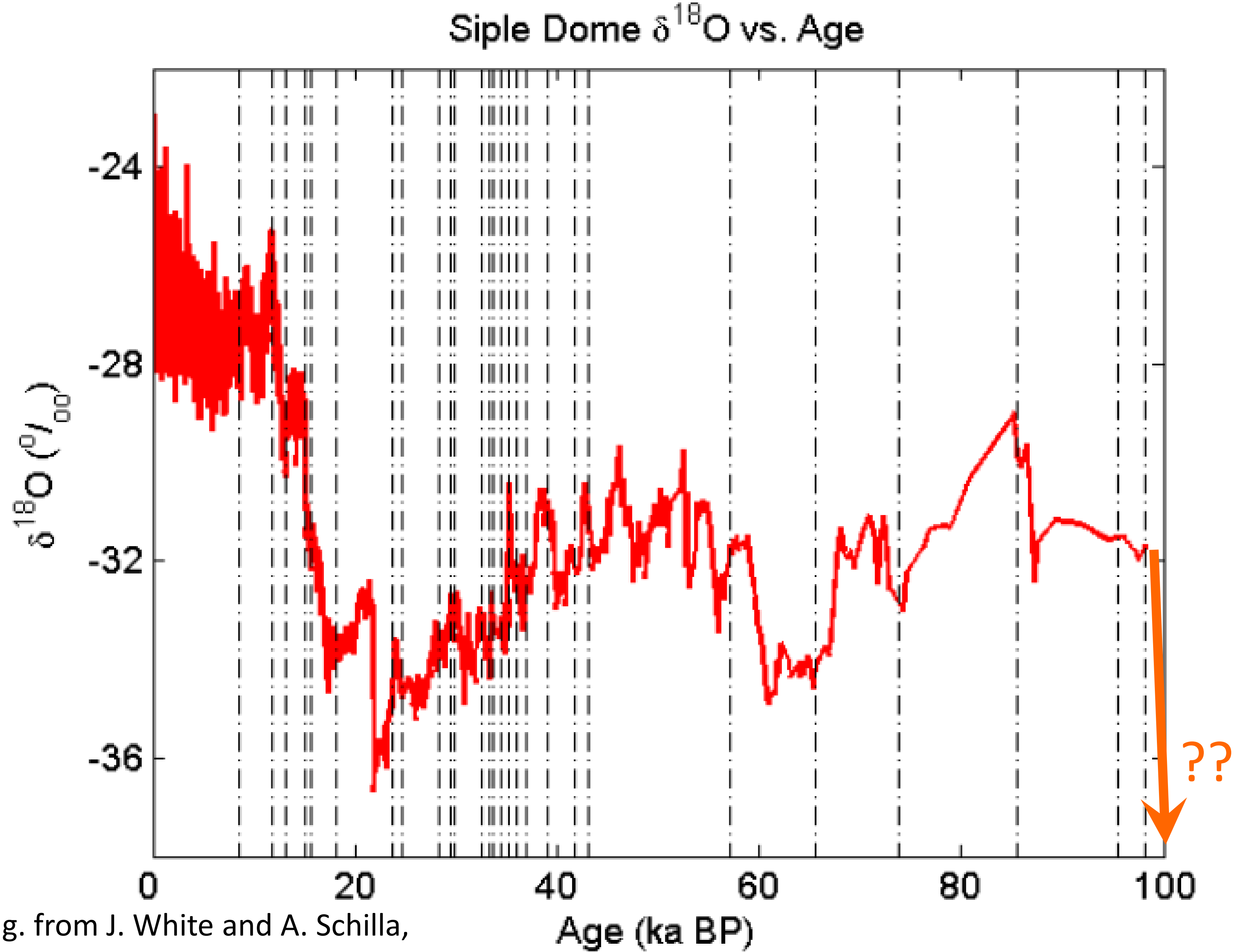
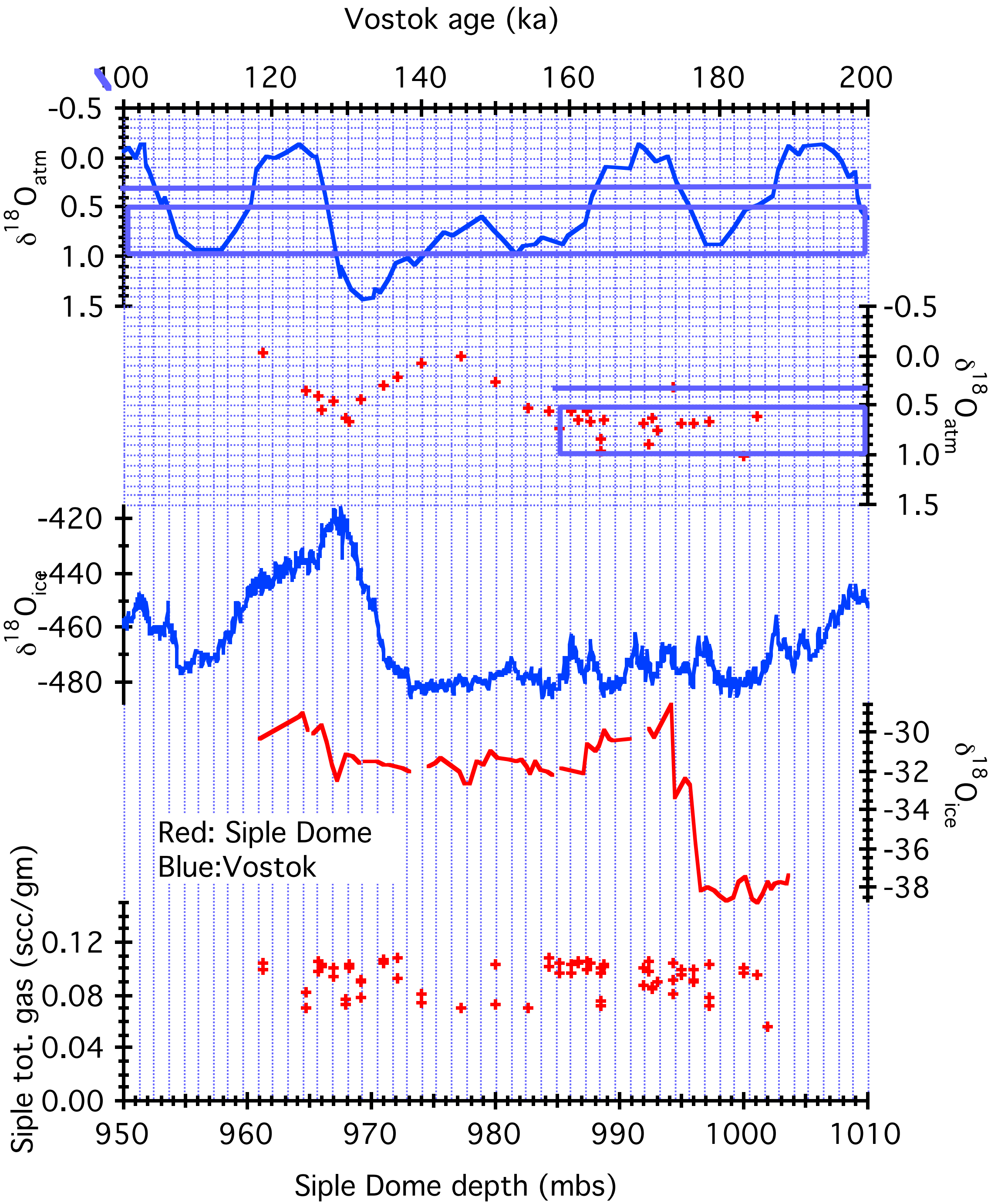


Fig. from J. White and A. Schilla, with Brook et al. tie points

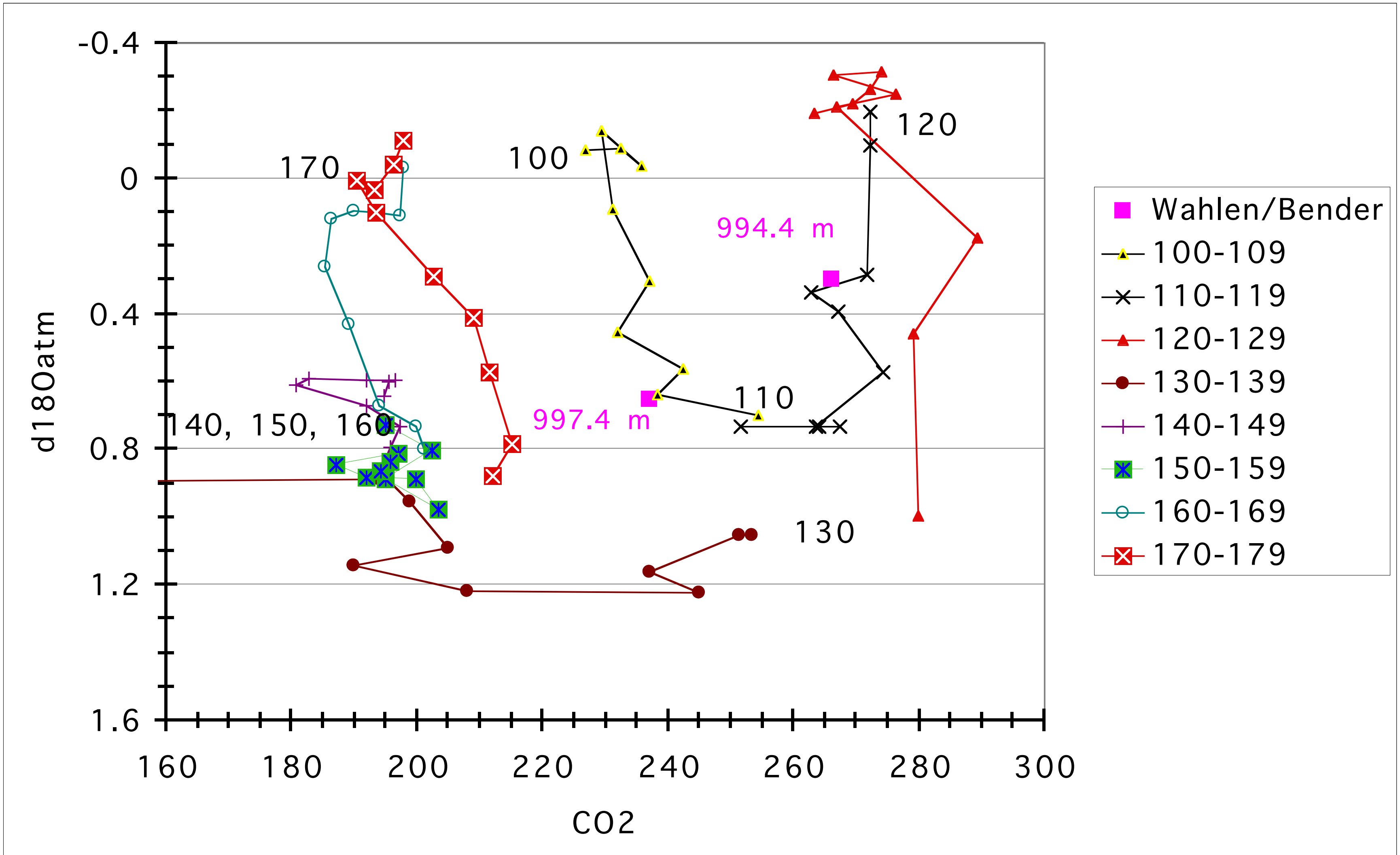
1.

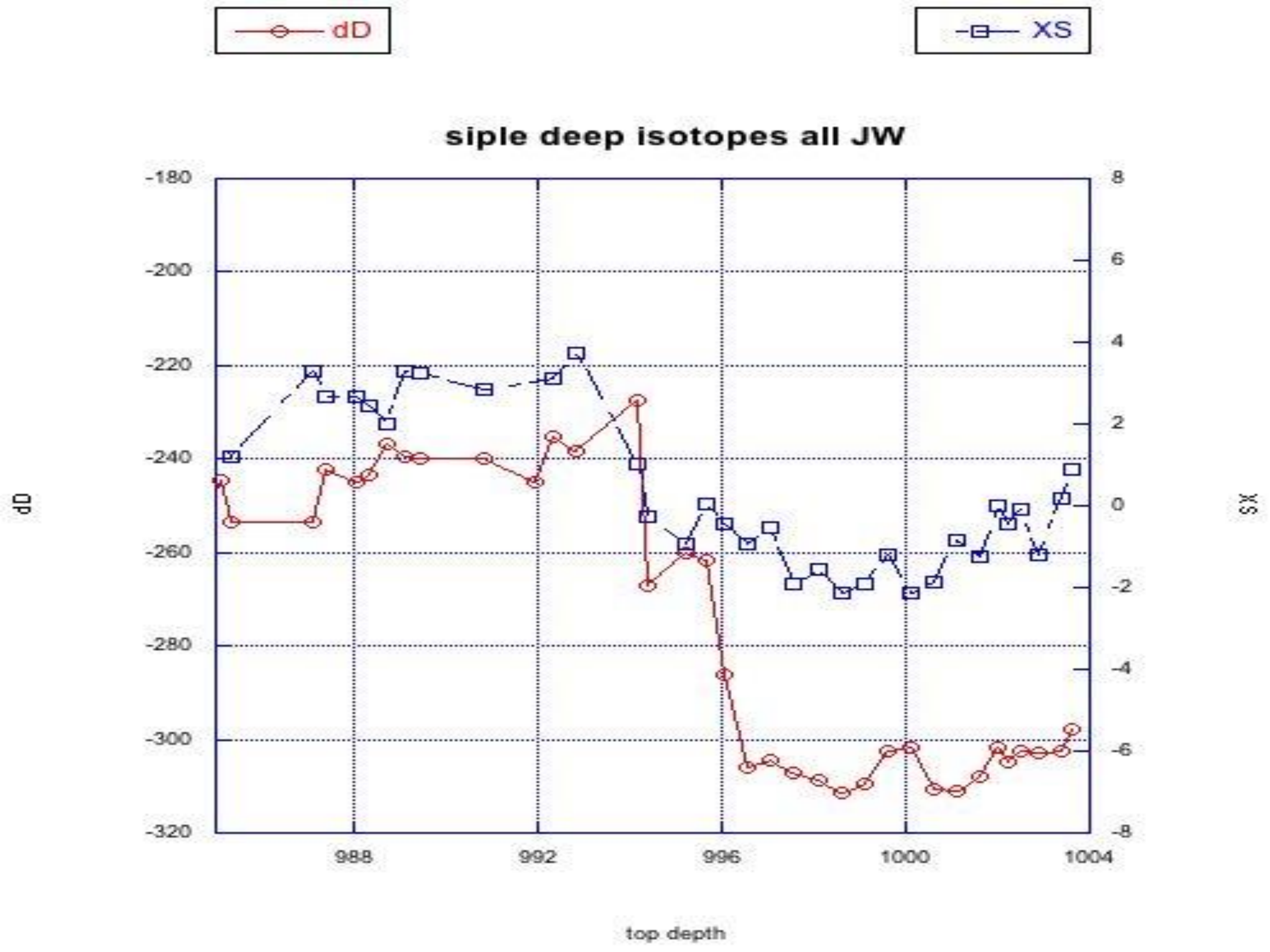
Deep Siple Dome unscrambling



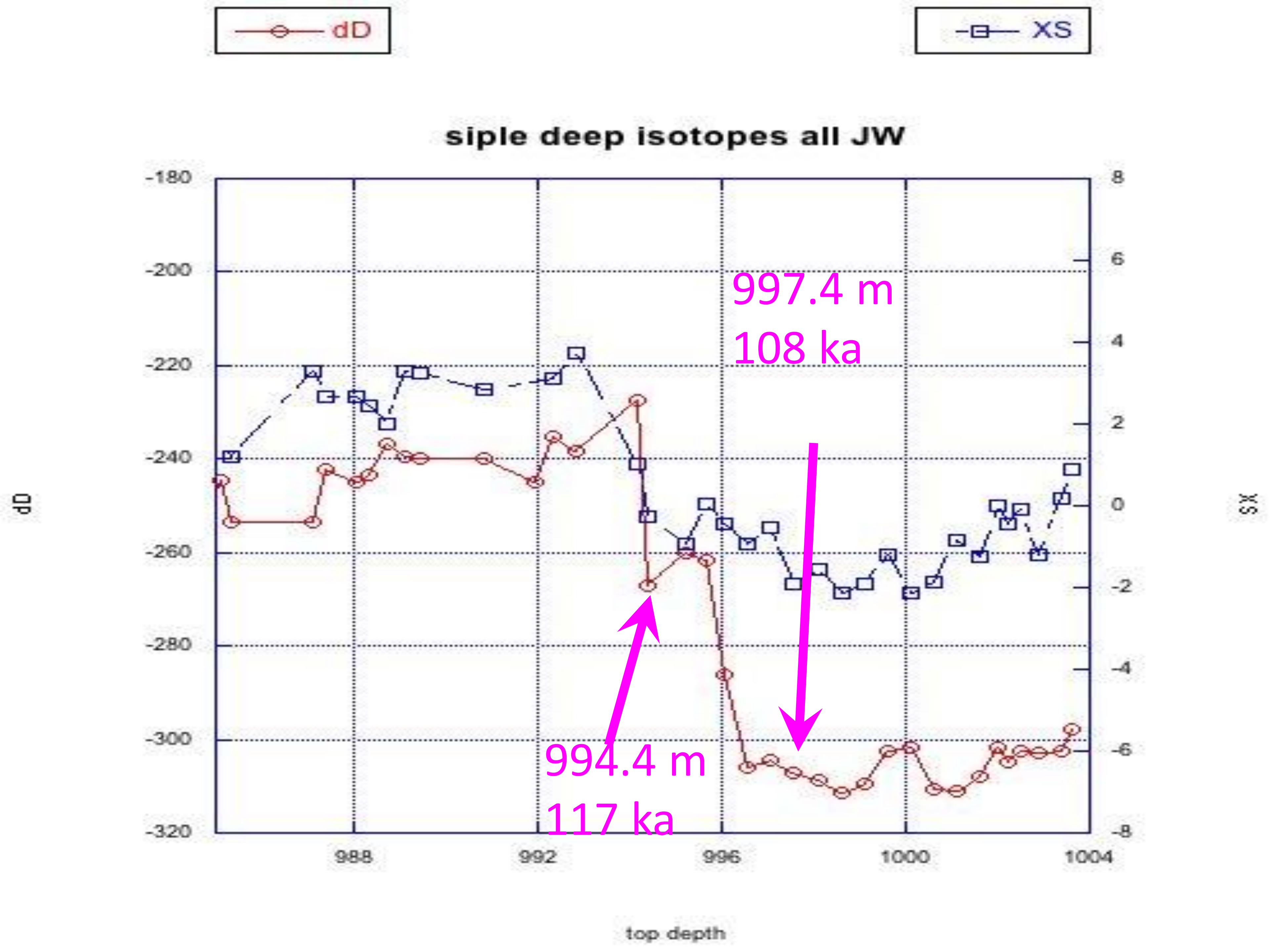
3.

Scrambled ice reconstruction

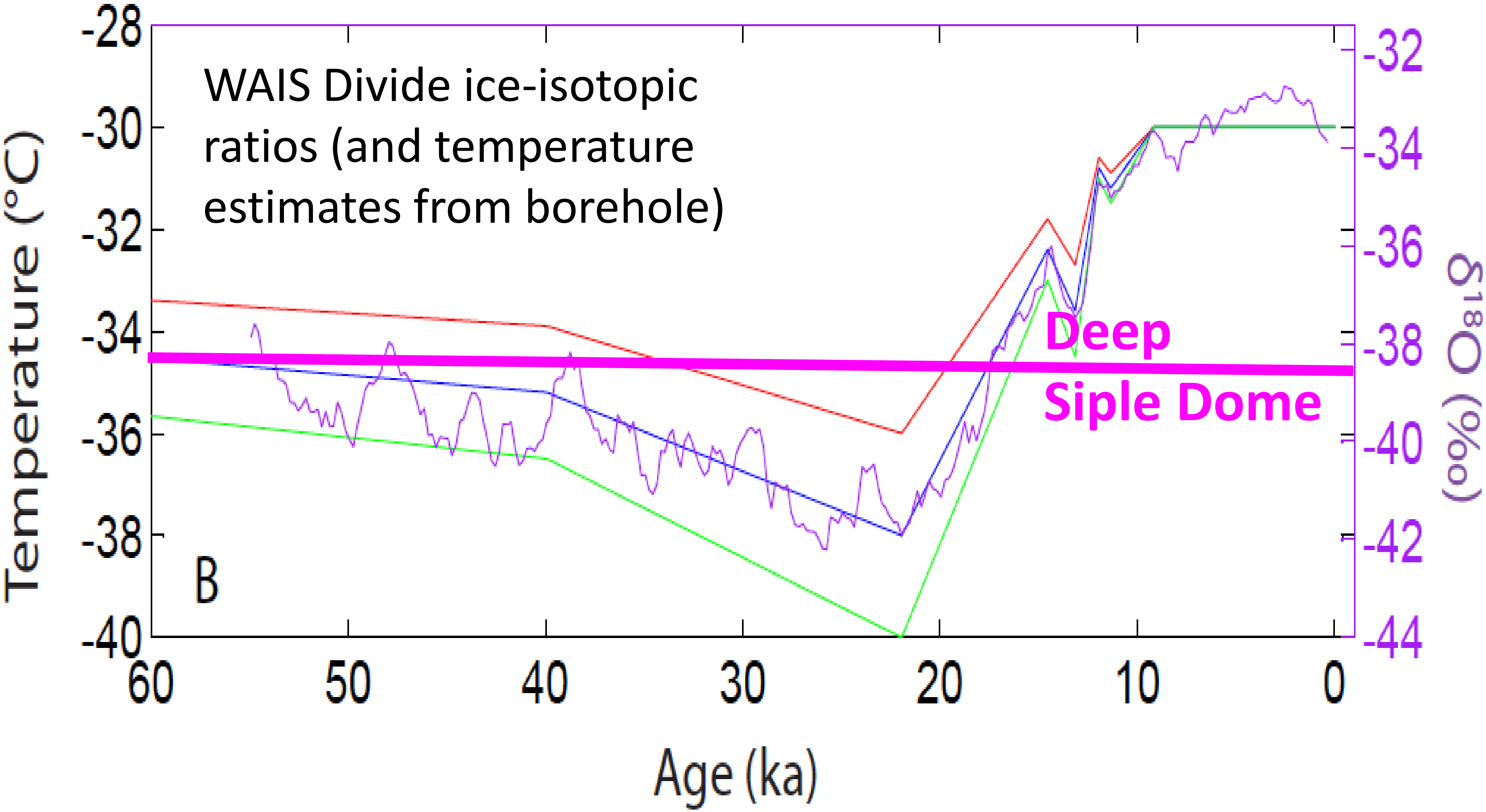




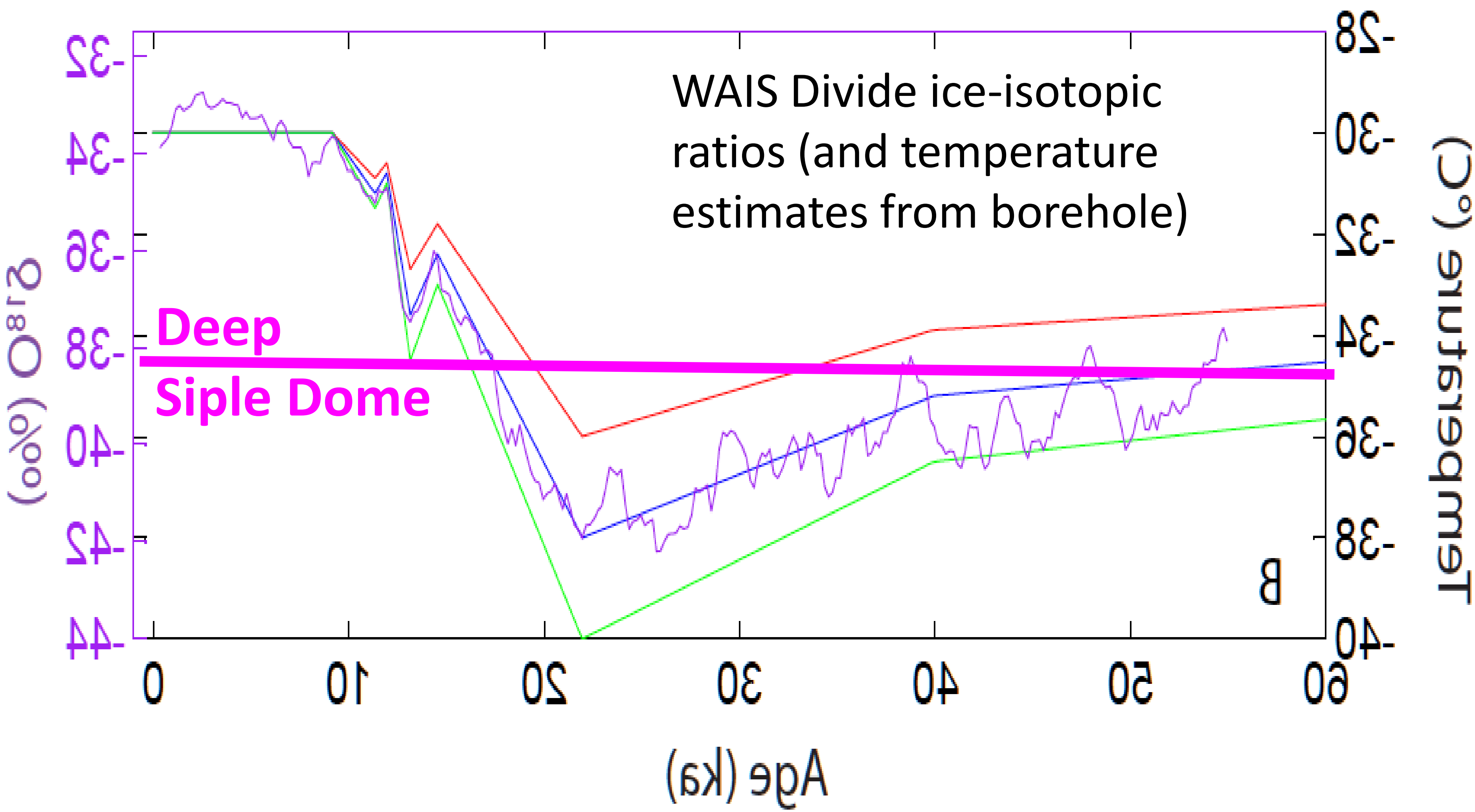
dD
XS
siple deep isotopes all JW
-180
-200
-220
-240
-260
-280
-300
-320
8
6
4
2
0
-2
-4
-6
-8
988
992
996
1000
1004
dD
XS
top depth



dD
XS
siple deep isotopes all JW
-180
-200
-220
-240
-260
-280
-300
-320
8
6
4
2
0
-2
-4
-6
-8
988
992
996
1000
1004
top depth
dD
XS
997.4 m
108 ka
994.4 m
117 ka



Fudge et al. (WAIS Divide Project Members), 2013, Nature



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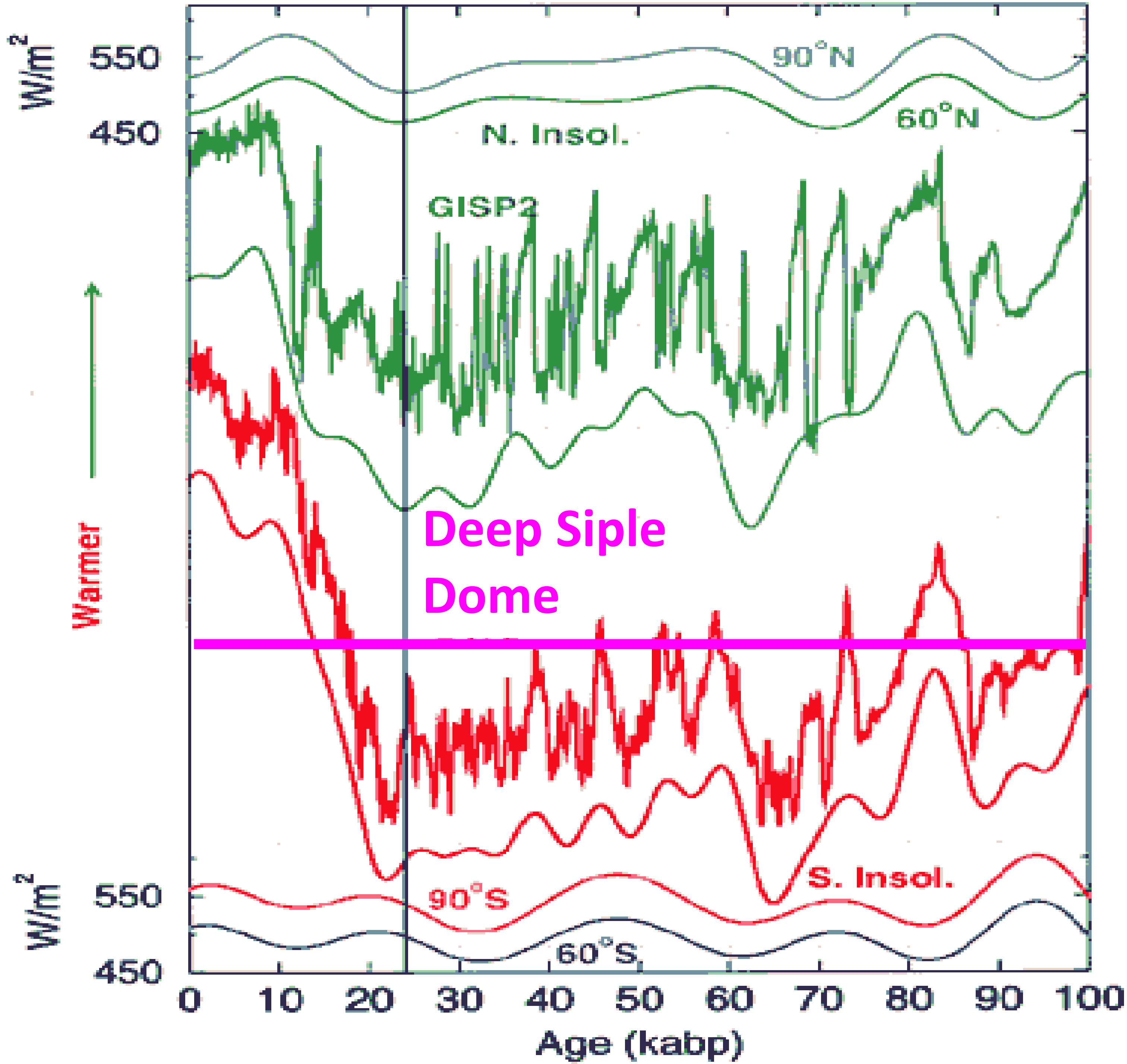
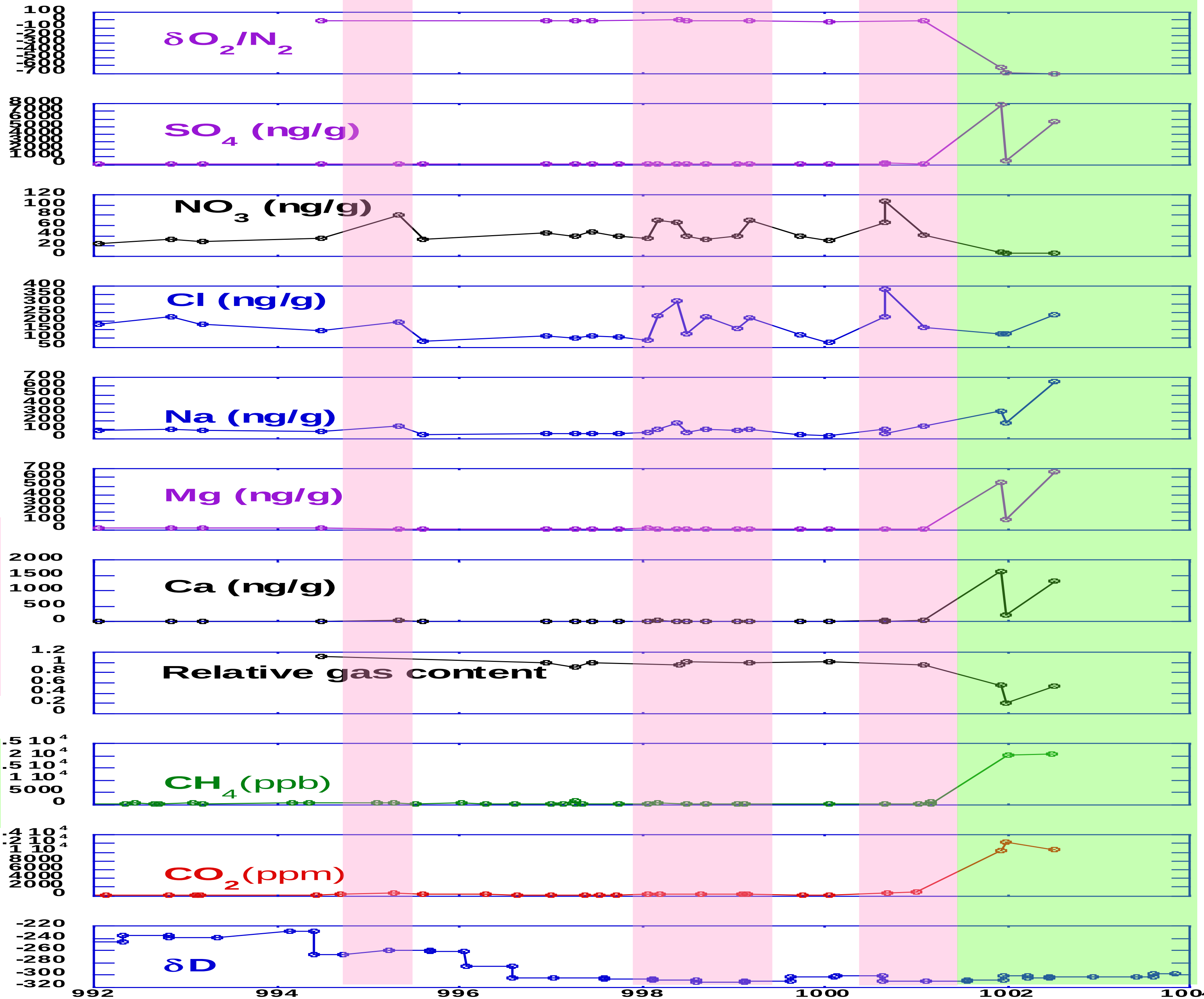


W/m²
550
450
90°N
60°N
N. Insol.
GISP2
Warmer
Deep Siple Dome
S. Insol.
90°S
60°S
W/m²
550
450
0
10
20
30
40
50
60
70
80
90
100
Age (kabp)

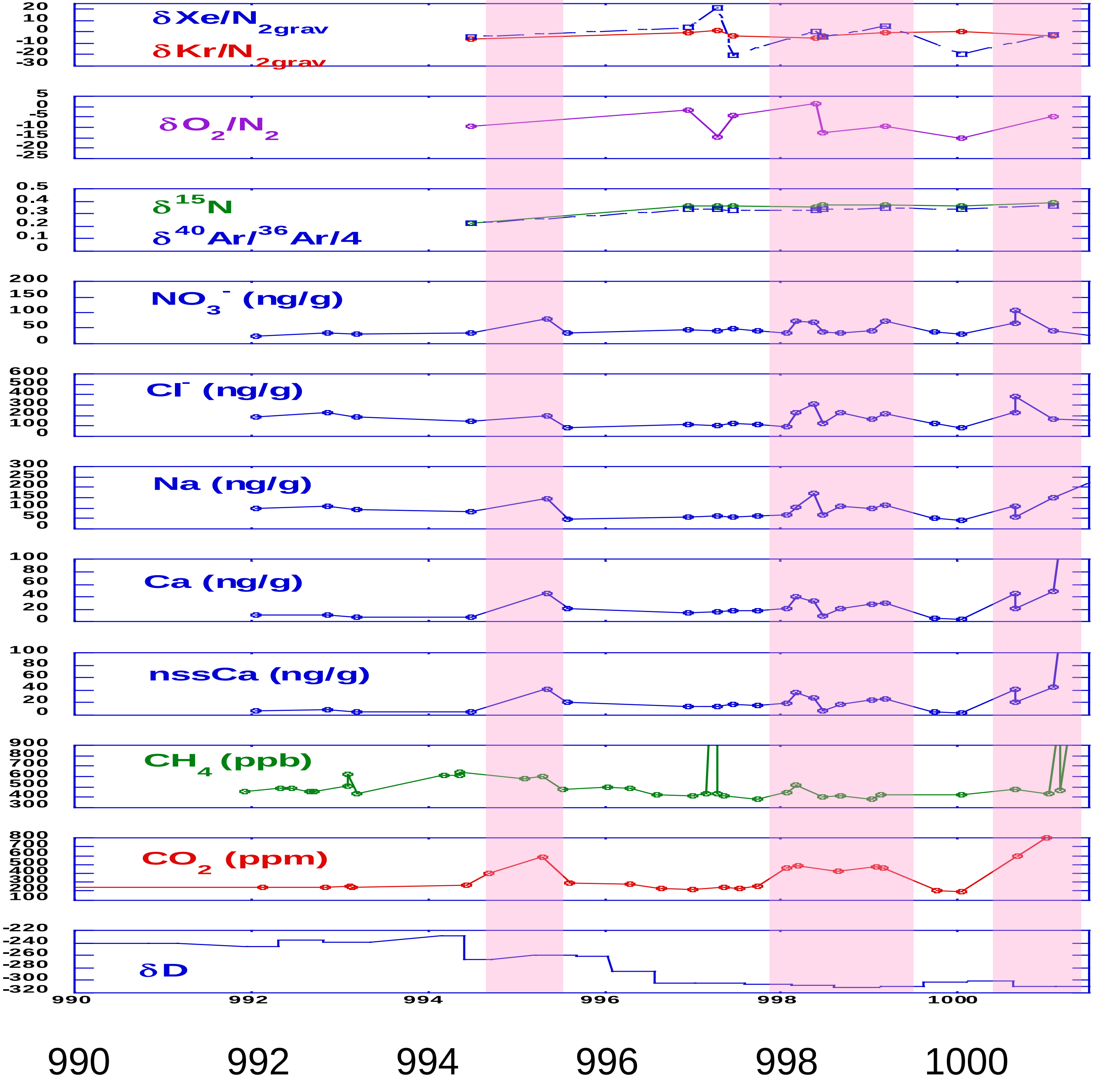
The causes of excess CO_2 at the base of the Siple Dome ice core, Antarctica, J. Ahn, J. Severinghaus, E.J. Brook, M. Headly, M. Wahlen, M. Suwa, P.A. Mayewski and J.W.C. White, Abstract, Fall AGU 2005



Anom-alously high CO2

Silty

The causes of excess CO_2 at the base of the Siple Dome ice core, Antarctica, J. Ahn, J. Severinghaus, E.J. Brook, M. Headly, M. Wahlen, M. Suwa, P.A. Mayewski and J.W.C. White, Abstract, Fall AGU 2005



Anomalously high CO2

Deep samples with low $\delta^{18}O$ and plausibly atmospheric CO_2

→ $\delta^{40}Ar/4 \approx 0.34$ per mil, similar to $\delta^{15}N \approx 0.36$ per mil (max $\delta^{15}N \approx 0.305$ over 100 kyr at Siple Dome)

→ firn column about 70 m thick

→ Would be consistent, for example, with a temperature of -34 C (from the $\delta^{18}O_{ice}$) and an accumulation rate of 16 cm/yr ice equivalent (using Herron and Langway).

→ These are values very unlikely to have occurred at Siple Dome, as we know it

→ Xenon/N_2 and krypton/N_2 do not look particularly anomalous, suggesting that there hasn't been major melting and refreezing, which could corrupt the $\delta^{15}N$ and $\delta^{40}Ar$ (from Jeff Severinghaus)

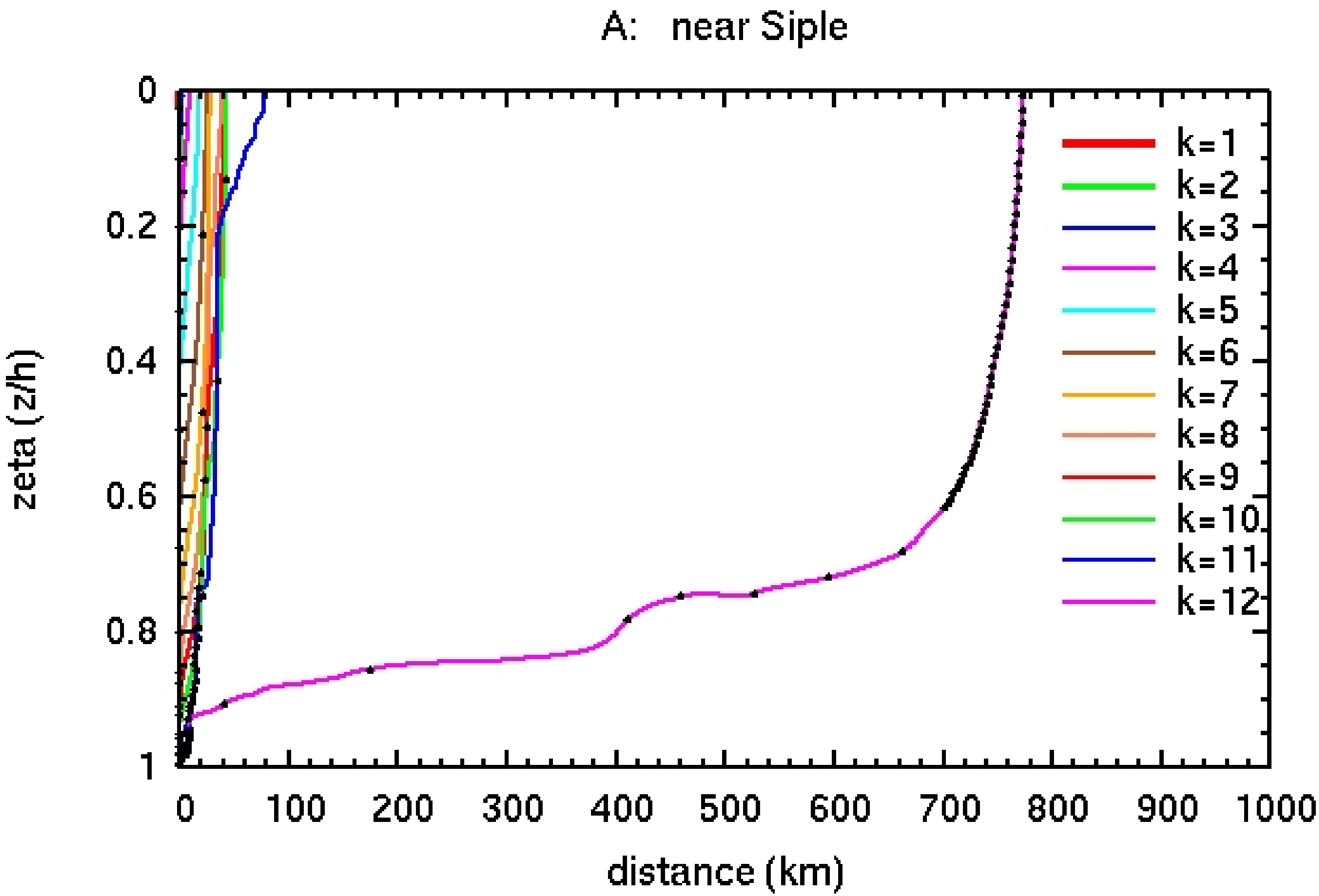
Total gas (if you believe it…) slightly lower in basal samples with light $\delta^{18}O_{ice}$, consistent with higher-elevation origin.

Modeling ongoing, and not finalized.

Dave Pollard does simulate WAIS deglaciations of marine basins with realistic forcing. (He usually doesn't find a 5e deglaciation, but can produce one easily by tweaking the forcing within the uncertainties).

In some runs (not all), ice-shelf growth and grounding occurs on Siple Dome.

Many runs bring deep Siple Dome ice from near the Ellsworth-Whitmore block.



x= 1047.5 y= 0.559488

In a favorable run, particle paths to modern Siple Dome core

Modeling annual-layer thickness in Siple Dome core

Waddington, E.D., H. Conway, E.J. Steig, R.B. Alley, E.J. Brook, K.C. Taylor and J.W.C. White. 2005. Decoding the dipstick: thickness of Siple Dome, West Antarctica, at the last glacial maximum. *Geology* **33**(4), 281-284; and other work from Ed's group, more ongoing

→Difficult to match deep Siple Dome thicknesses

→Would be easier if they had not been thinned by "normal" burial through whole ice sheet

→"Big ice" history for getting inland ice beneath Siple Dome does not solve this problem

→"Ice shelf" history more favorable

Note that Siple Coast ice streams today have meters of debris-rich basal ice everywhere (Kamb, 2001; Christoffersen, Tulaczyk and Behar, JGR, 2010)

If an ice STREAM brought the basal ice now trapped beneath Siple Dome, much debris-rich ice would be expected

If an ice SHELF brought the basal ice now trapped beneath Siple Dome, almost no debris-rich ice would be expected

We observe almost no debris-rich ice, favoring ice SHELF

Synopsis

- Still no “smoking gun” for WAIS 5e loss
- May never be
- Far-field sea-level records require

→ WAIS-sized loss in S (physics favors WAIS over EAIS)

→ Or, great researchers really wrong (I favor WAIS loss)

- Several other lines of evidence also point to WAIS 5e loss
- Importantly, no strong data against WAIS 5e loss (ice near Moulton would survive…much work including Holschuh et al in rev)

Synopsis

- Siple Dome—more analyses in progress, but unlikely to change basic idea
- Strong evidence that the basal ice originated much higher and farther inland
- Physical understanding, lack of frozen-on debris, thick deep layers argue against a much larger, overriding ice sheet
- Data consistent with ice-shelf grounding during WAIS regrowth after collapse
- Maybe the best evidence of recent (MIS 5e?) WAIS collapse

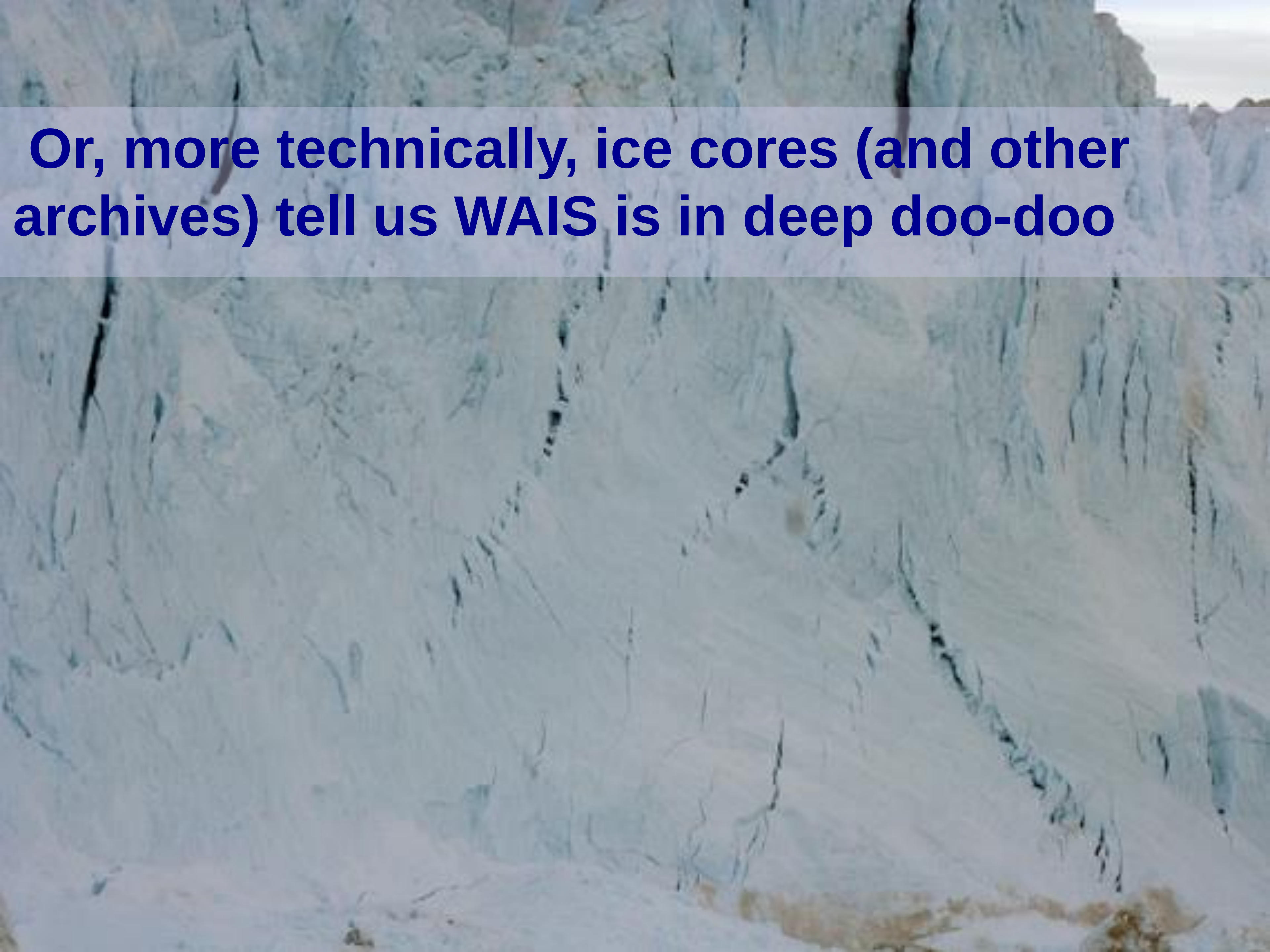
Report: Ocean Levels Could Rise Foot Or More If Lots Of People Go Swimming

NEWS IN BRIEF · Environment · Science & Technology · Science · ISSUE 50•10 · Mar 1

From ***The Onion***

All people on Earth ≈0.001 mm sea level, vs. 3 mm/yr rise now

Or, more technically, ice cores (and other archives) tell us WAIS is in deep doo-doo

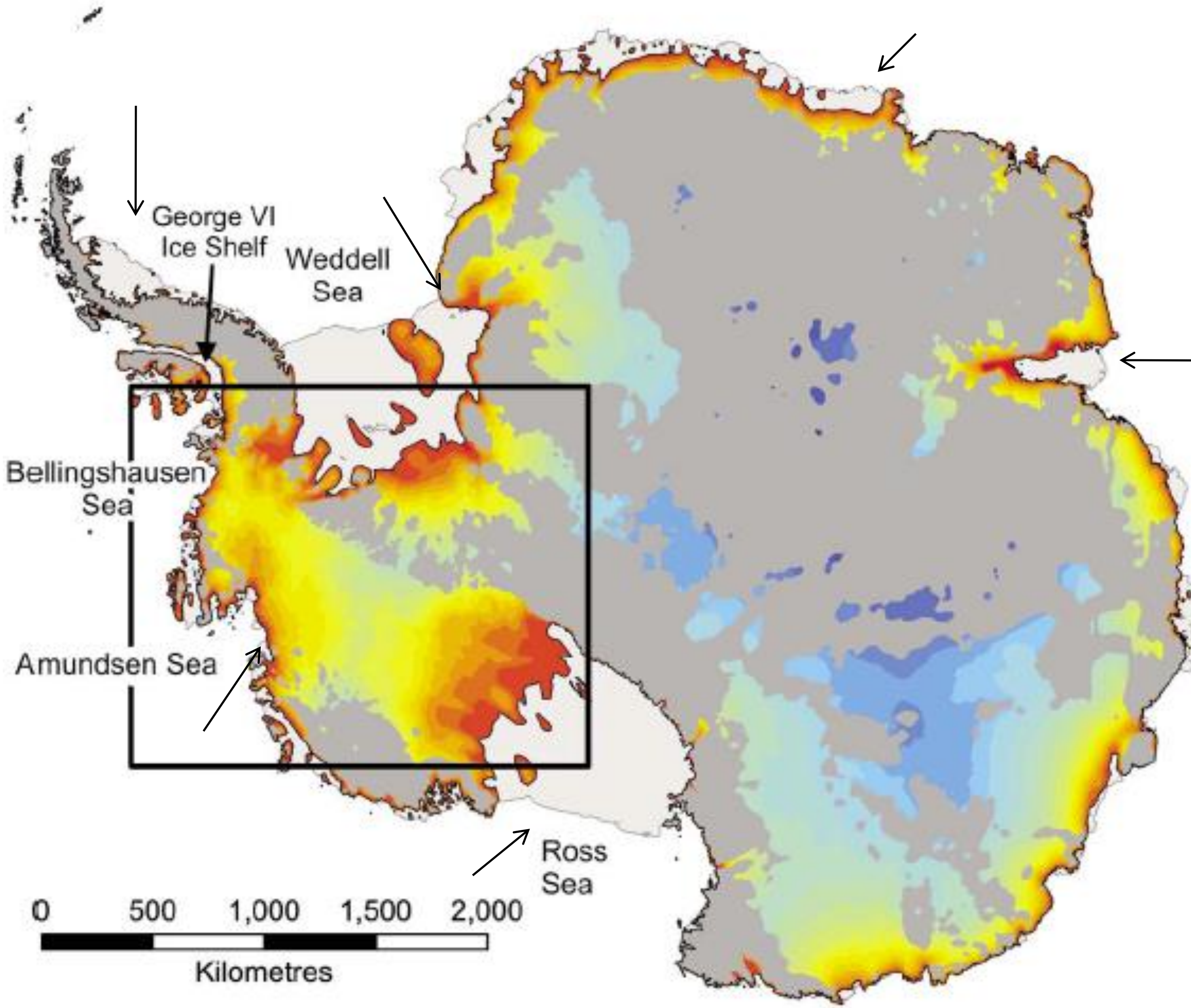


A bit of history

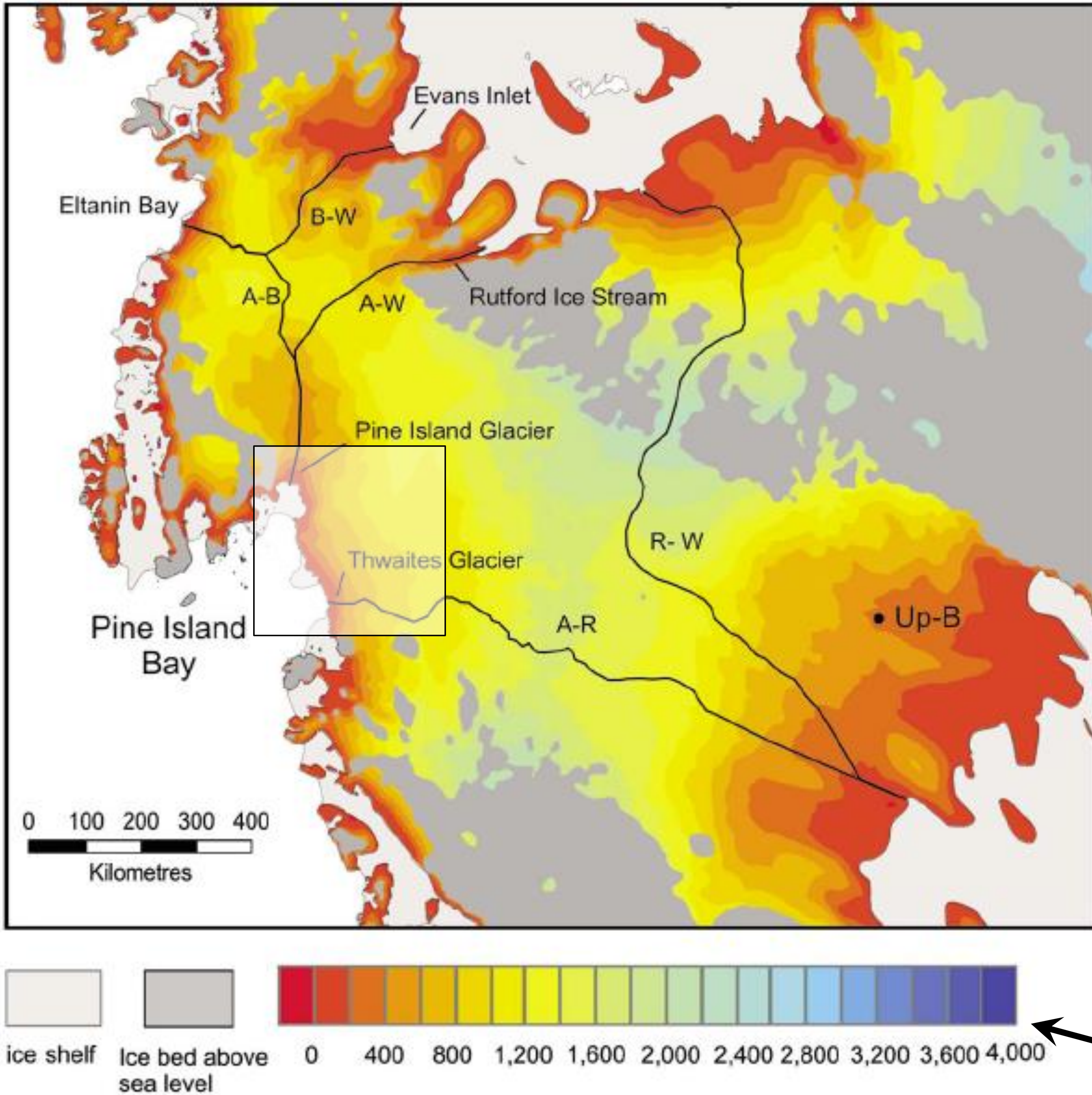
- Collapse may already have been triggered (Joughin et al., 2014, Rignot et al., 2014)
- By enhanced circulation of warmer waters beneath Amundsen Sea ice shelves
- From some combination of ozone hole, global warming, and natural variability
- Broader parameter exploration suggests possible survival (Parizek et al., 2013)—we find more-plastic bed reduces coastal thinning that allows retreat by tapping inland ice more rapidly

Framing the Issues…

Edge of Thwaites Ice Shelf, Icebridge NASA photo by Jim Yungel http://eoimages.gsfc.nasa.gov/images/imagerecords/79000/79533/thwaits_icebrige_2012.jpg



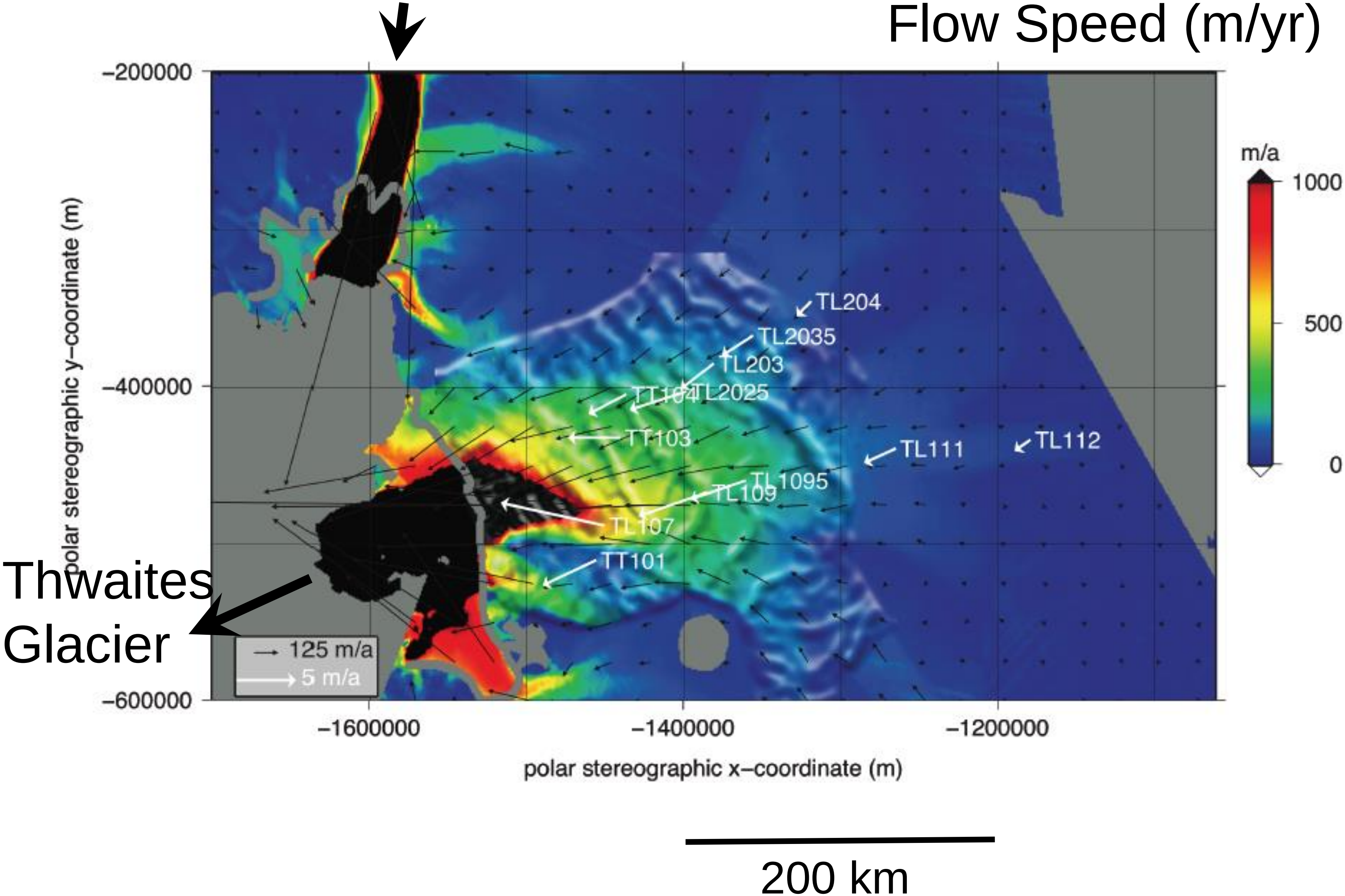
Colors—bed below sea level, can calve icebergs. Many"flying buttress" ice shelves—arrows point to just a few.



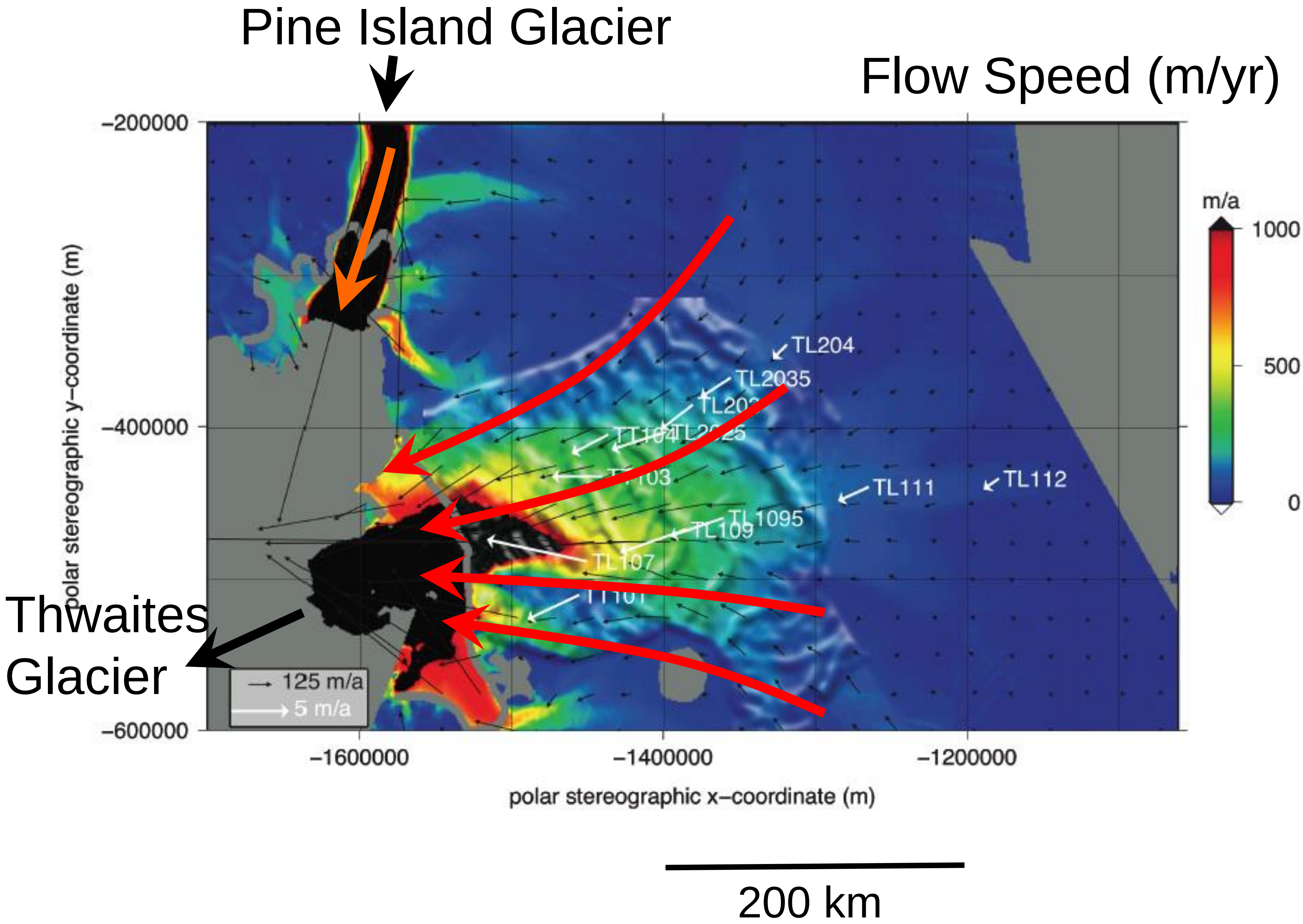
Big issue is Thwaites Glacier, “weak underbelly” of the West Antarctic ice sheet—wide ice stream leads into thick ice on a deep bed that could make icebergs FAST.

Vaughan, D.G., D K. A. Barnes, P.T. Fretwell & R.G. Bingham, 2011, Geochem. Geophys. Geosyst.

Thickness above sea level

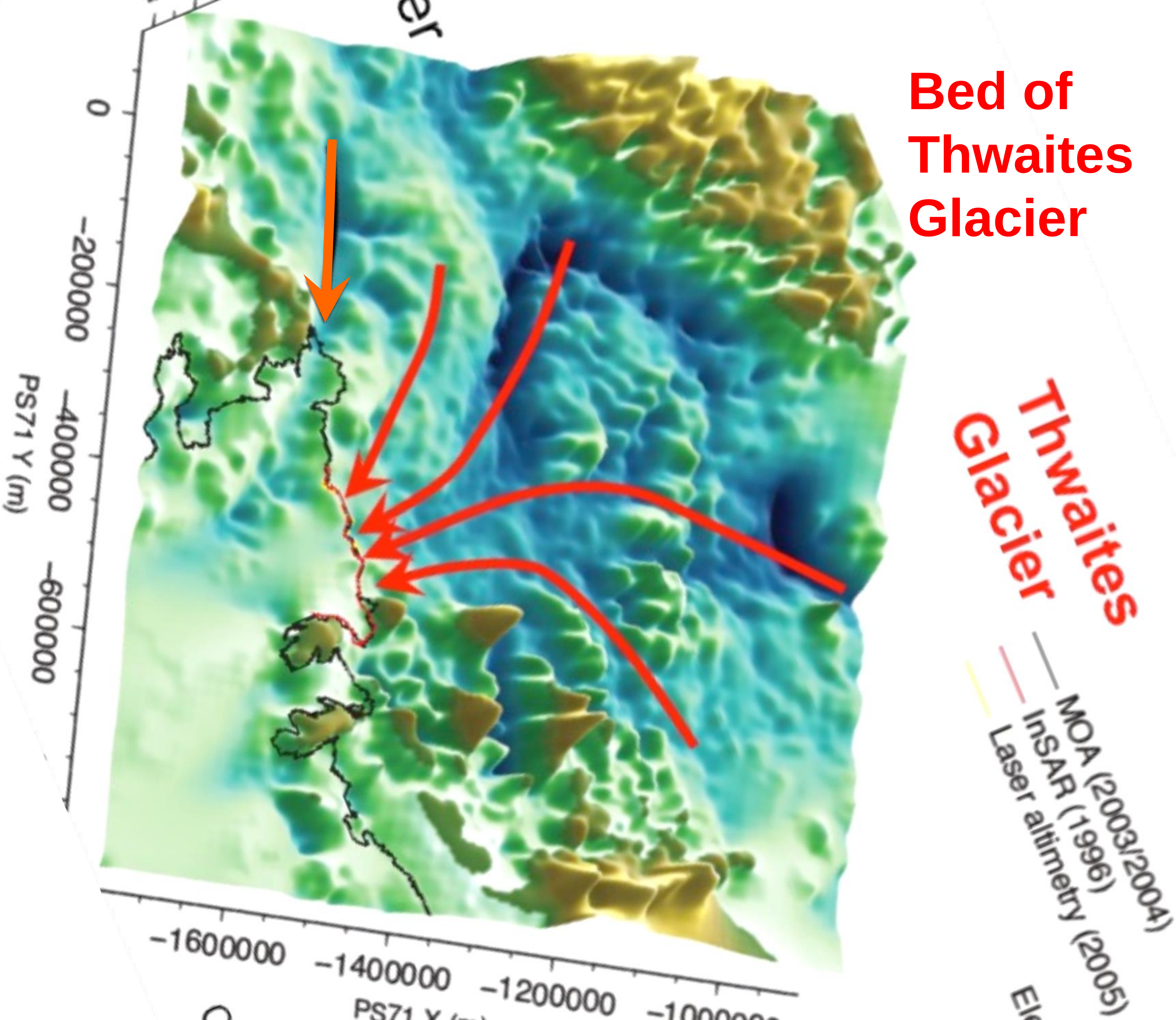


Christianson et al., 2011

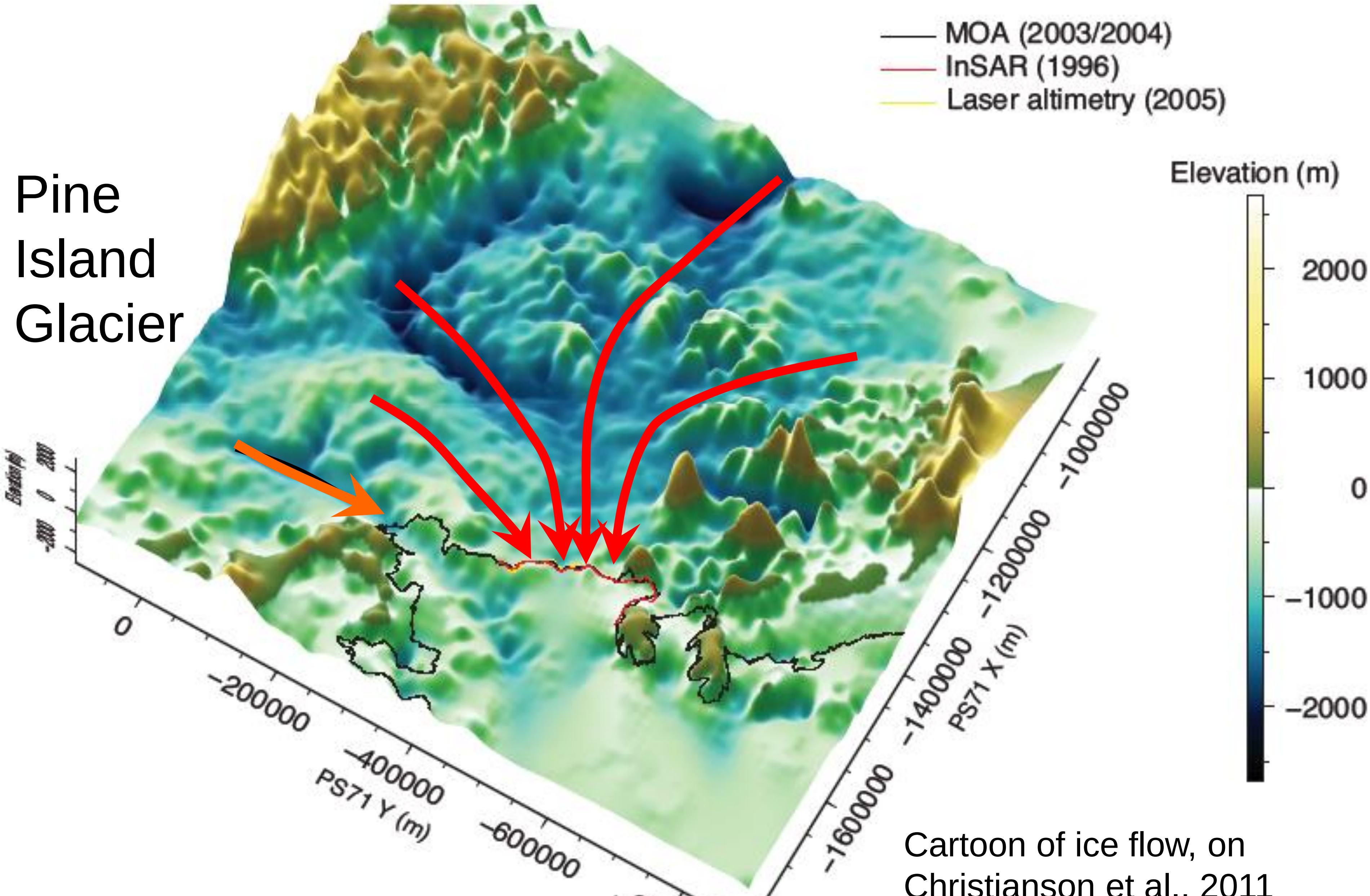


Christianson et al., 2011

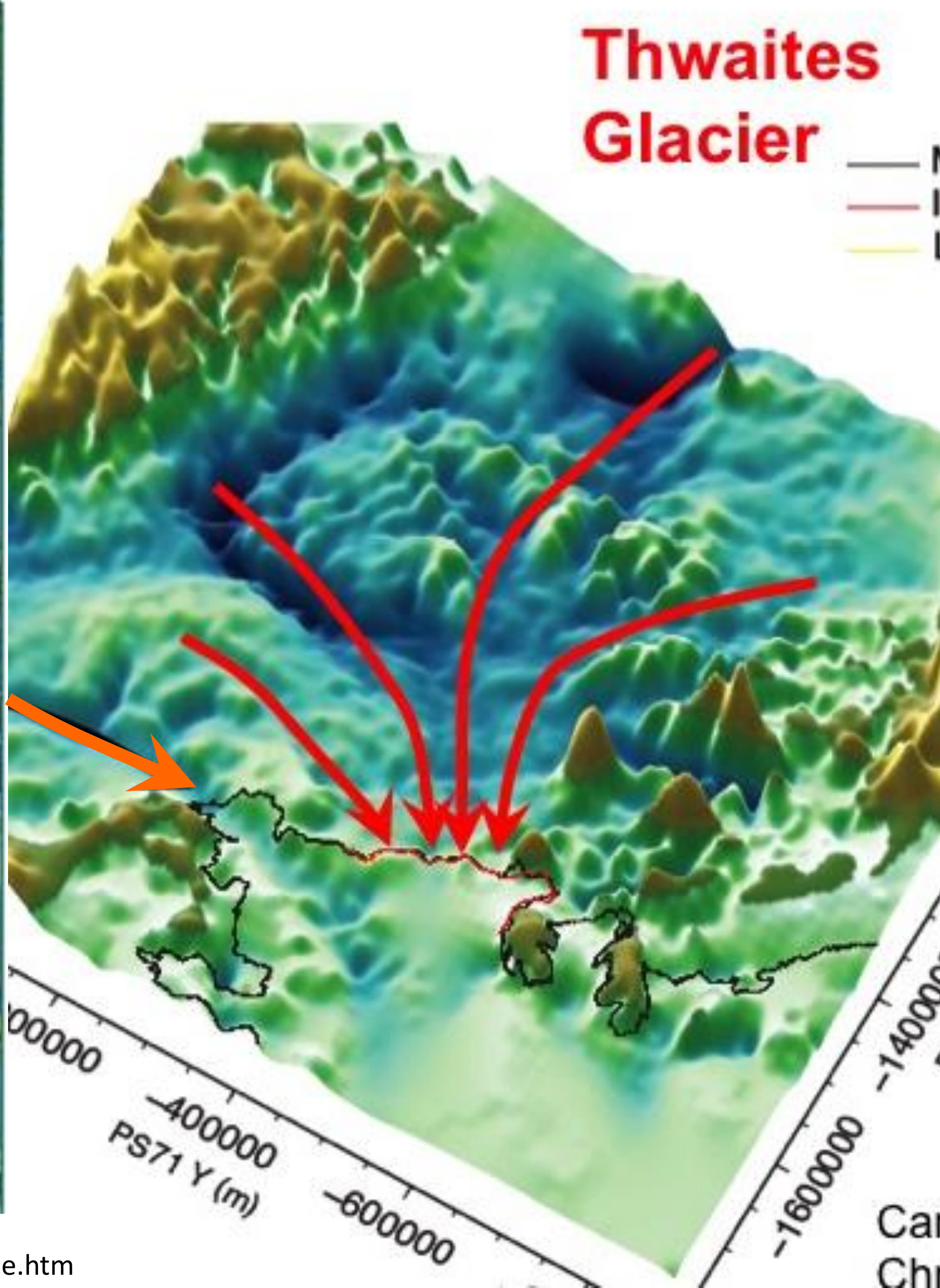
Bed of Thwaites Glacier



Bed of Thwaites Glacier



Cartoon of ice flow, on
Christianson et al., 2011



http://www.ops.fhwa.dot.gov/wz/p2p/pmwkshop053013/hayee/hayee.htm

Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica

Ian Joughin, Benjamin E. Smith, Brooke Medley

Resting atop a deep marine basin, the West Antarctic Ice Sheet has long been considered prone to instability. Using a numerical model, we investigated the sensitivity of Thwaites Glacier to ocean melt and whether its unstable retreat is already under way. Our model reproduces observed losses when forced with ocean melt comparable to estimates. Simulated losses are moderate (<0.25 mm per year at sea level) over the 21st century but generally increase thereafter. Except possibly for the lowest-melt scenario, the simulations indicate that early-stage collapse has begun. Less certain is the time scale, with the onset of rapid (>1 mm per year of sea-level rise) collapse in the different simulations within the range of 200 to 900 years.

“the simulations indicate that early-stage collapse has begun”

Science, 2014

Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica

Science, 2014

Ian Joughin, Benjamin E. Smith, Brooke Medley

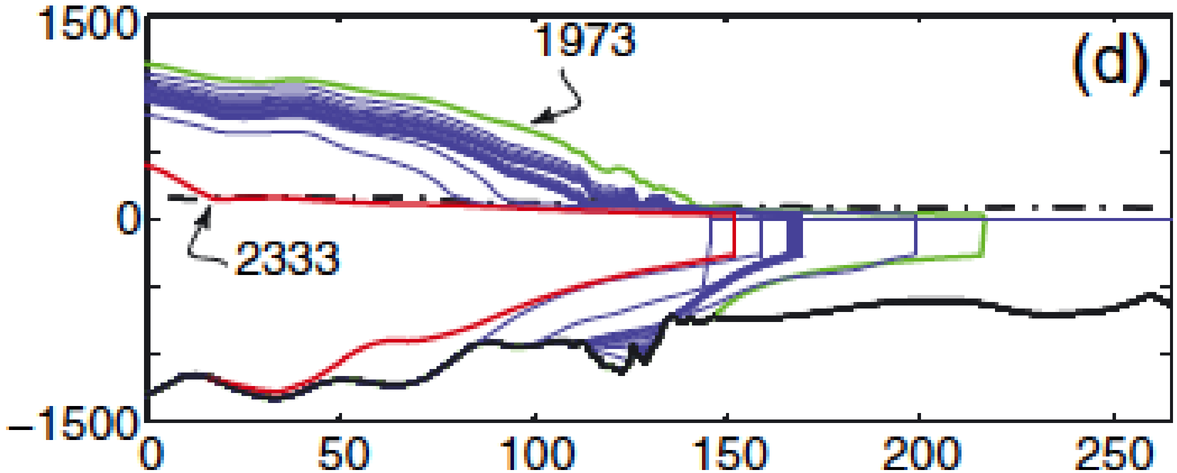
Our simulations provide strong evidence that the process of marine ice-sheet destabilization is already under way on Thwaites Glacier…although losses are likely to be relatively modest over the next century (<0.25 mm/year of sle), rapid collapse (>1 mm/year of sle) will ensue once the grounding line reaches the basin's deeper regions …undermining much of West Antarctica…unless CDW recedes sufficiently to reduce melt well below present levels, it is difficult to foresee a stabilization of the Thwaites system, even with plausible increases in surface accumulation. Although our simple melt parameterization suggests that a full-scale collapse of this sector may be inevitable, it leaves large uncertainty in the timing.

JOURNAL OF GEOPHYSICAL RESEARCH: EARTH SURFACE, VOL. 118, 1–18, doi:10.1002/jgrf.20044, 2013

Dynamic (in)stability of Thwaites Glacier, West Antarctica

B. R. Parizek,[1] K. Christianson,[2,3] S. Anandakrishnan,[2] R. B. Alley,[2] R. T. Walker,[2,4] R. A. Edwards,[5] D. S. Wolfe,[6] G. T. Bertini,[7] S. K. Rinehart,[8] R. A. Bindschadler,[9] and S. M. J. Nowicki[9]

Also, Nowicki et al., 2013, JGR,



If ocean melting of ice shelves is restricted to fully floating regions beyond a grounding line, no huge changes over ~100 years.

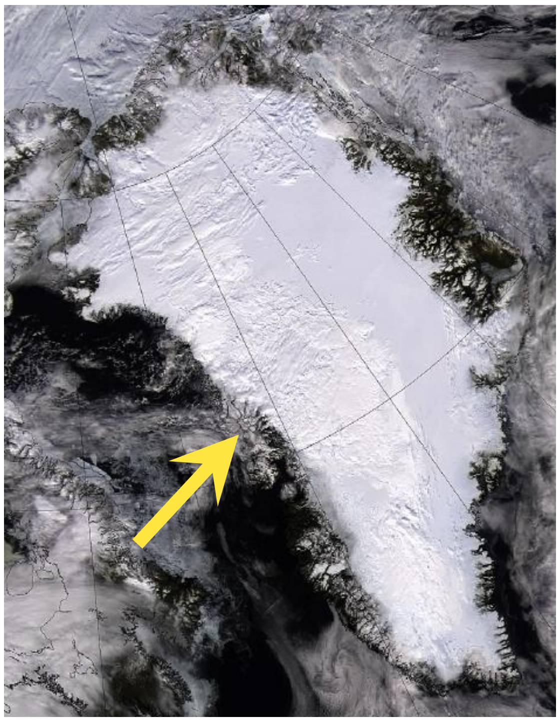
If ocean melting can reach inland across a grounding zone, large melting can cause huge

No plausible worst-case yet…

- The Pfeffer et al. “speed limits” apply to bedrock-controlled ice streams
- If Thwaites were to retreat notably while maintaining a small or zero ice shelf, it would have a deeper, wider grounding line than any on Earth today
- Likely with additional physical processes
- Usually not modeled; Pollard & DeConto modeled for AGU last year…
- Not good news for slow-small-expected ice-sheet retreat

Greenland shows this can matter a lot… Jakobshavn

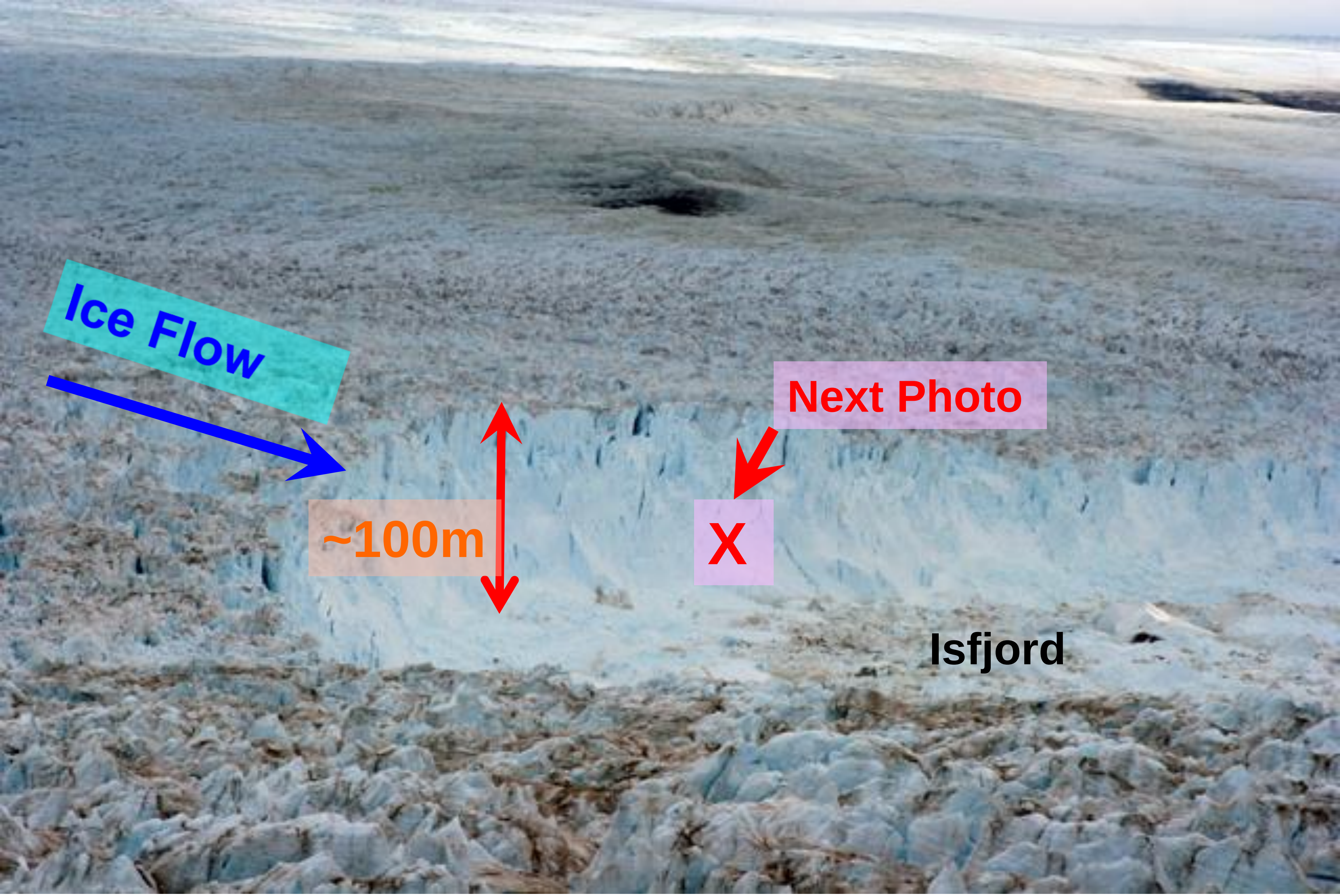
Discharge from many major Greenland ice streams has accelerated markedly.



http://www.gsfc.nasa.gov/gsfc/earth/pictures/earthpic.htm

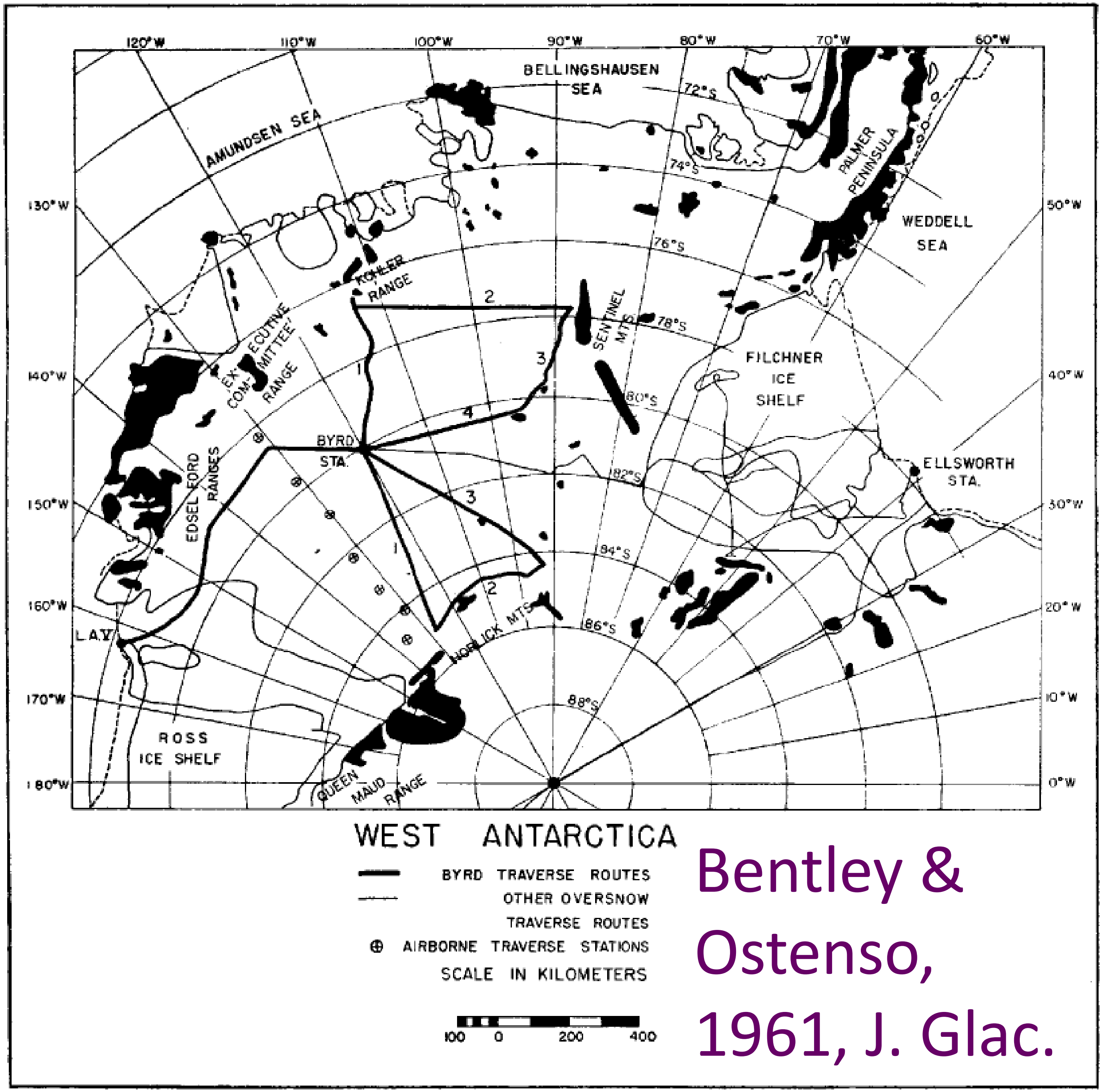
Source: Prof. Konrad Steffen, U of CO

Seal, in Jakobshavn Isfjord. The fjord is so clogged with ice calved from the glacier that it is sometimes hard to realize that deep seawater lies beneath. This seal, far up the fjord, is good evidence that indeed an appropriately equipped swimmer can get here.



The calving front of Jakobshavn. Ice flows down from the Greenland ice sheet on the left, along the arrow. On the right is the Isfjord, ocean water clogged with loose icebergs that have calved off. “X” marks the couple-hundred-foot-high cliff where icebergs form, falling down into the Isfjord where broken ice covers sea water.

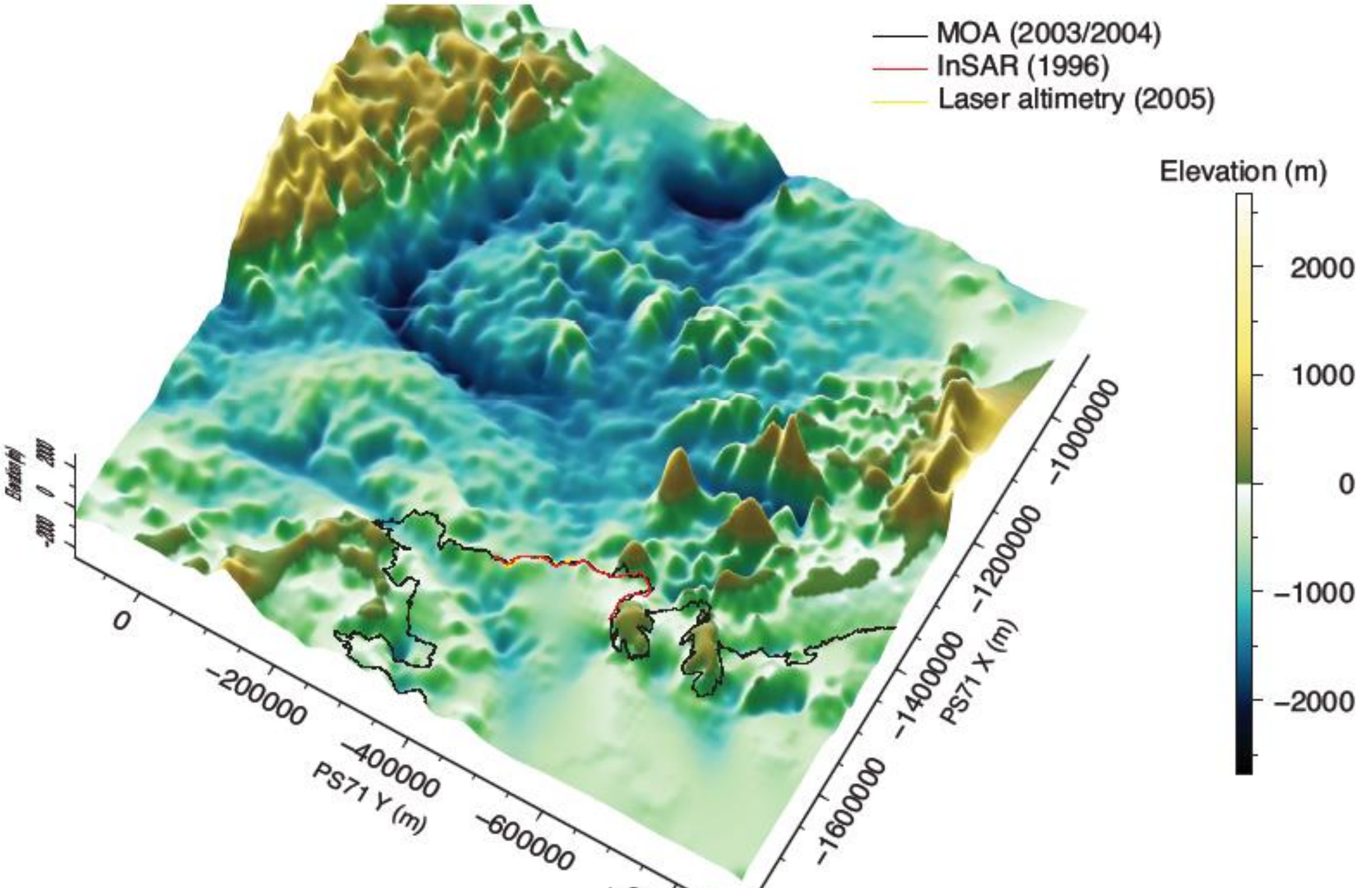
100-m Jakobshavn calving front is close to failure.

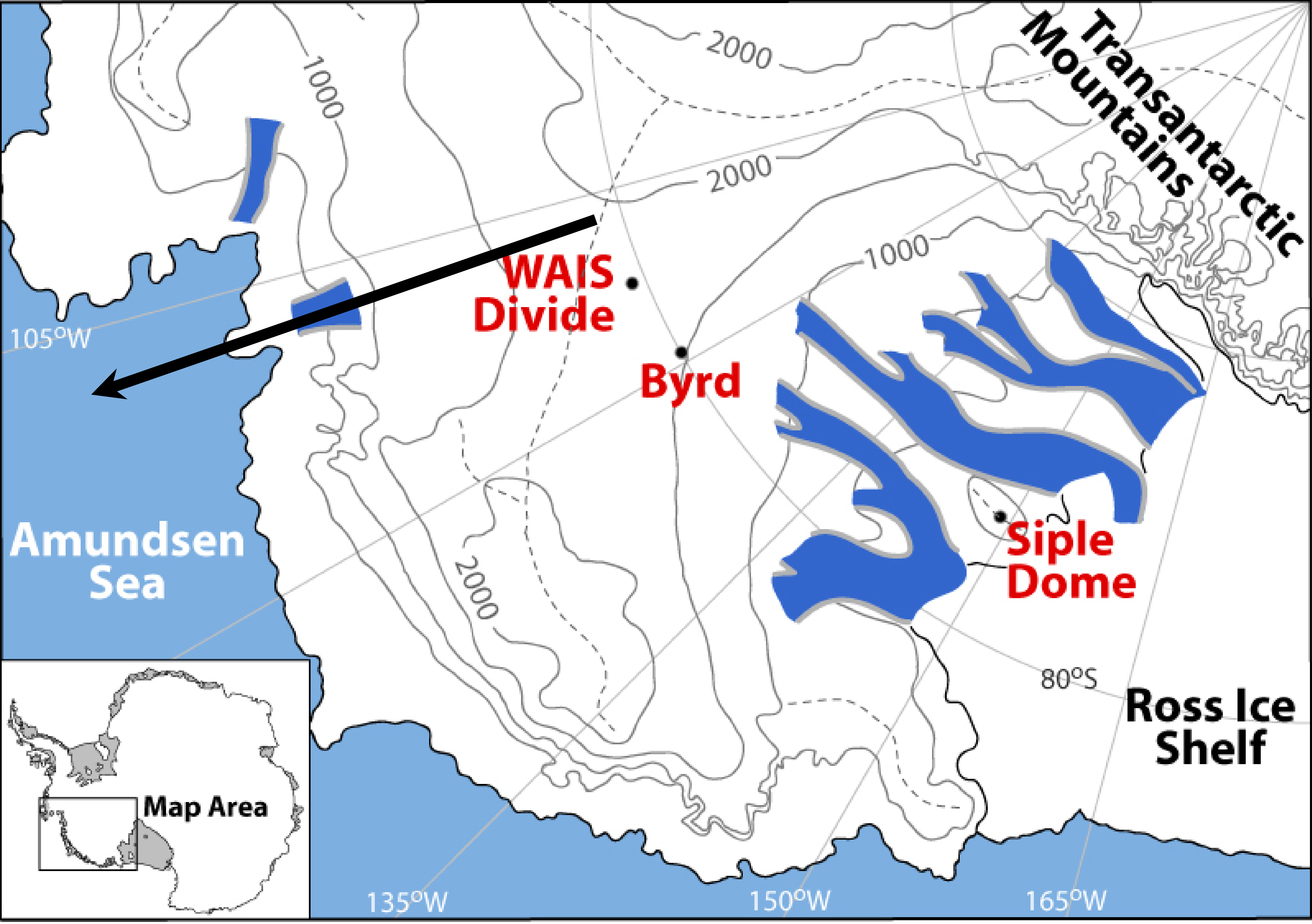


Bentley & Ostenso, 1961, J. Glac.

Fig. 1. Traverse routes in West Antarctica. Numbers refer to the various legs of the Sentinel Mountains and Horlick Mountains traverses

Christianson et al., 2011





http://antarcticsun.usap.gov/science/contentHandler.cfm?id=1574, from WAIS Divide Project web site

nature climate change
LETTERS
PUBLISHED ONLINE: 4 MAY 2014 | DOI: 10.1038/NCLIMATE2226

Ice plug prevents irreversible discharge from East Antarctica

M. Mengel[1,2] and A. Levermann[1,2]*

…we show here that the removal of a specific coastal ice volume equivalent to less than 80mm of global sea-level rise at the margin of the Wilkes Basin destabilizes the regional
ice flow and leads to a self-sustained discharge of the entire basin and a global sea-level rise of 3–4 m.

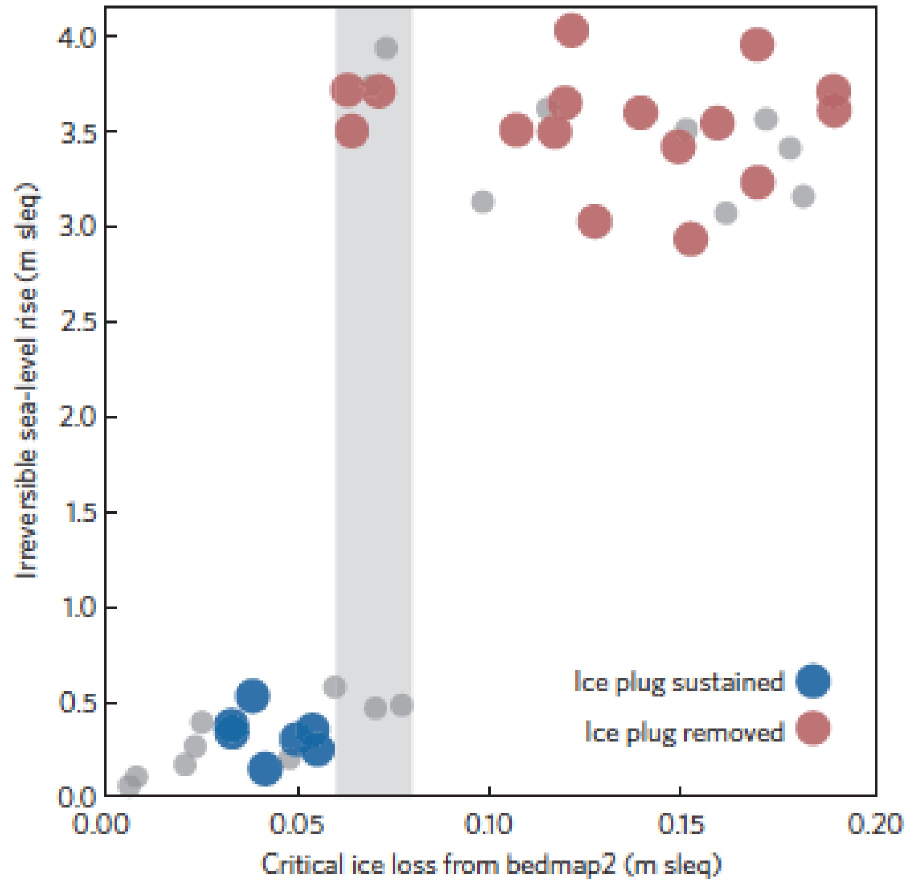


Figure 3 | Collapse condition. Long-term sea-level rise as a function of the ice volume removed from the state observed at present in the plug region. Stable states (blue) exist only below the threshold that corresponds to approximately 60 mm sea-level-relevant ice loss from the ice-plug region. The unstable states (red) feature self-sustained long-term sea-level rise of 3–4 m, defined as the sea-level-relevant ice loss 25 kyr after the forcing ended. All coloured dots are based on 7 km resolution, grey dots are based on 10 km resolution.

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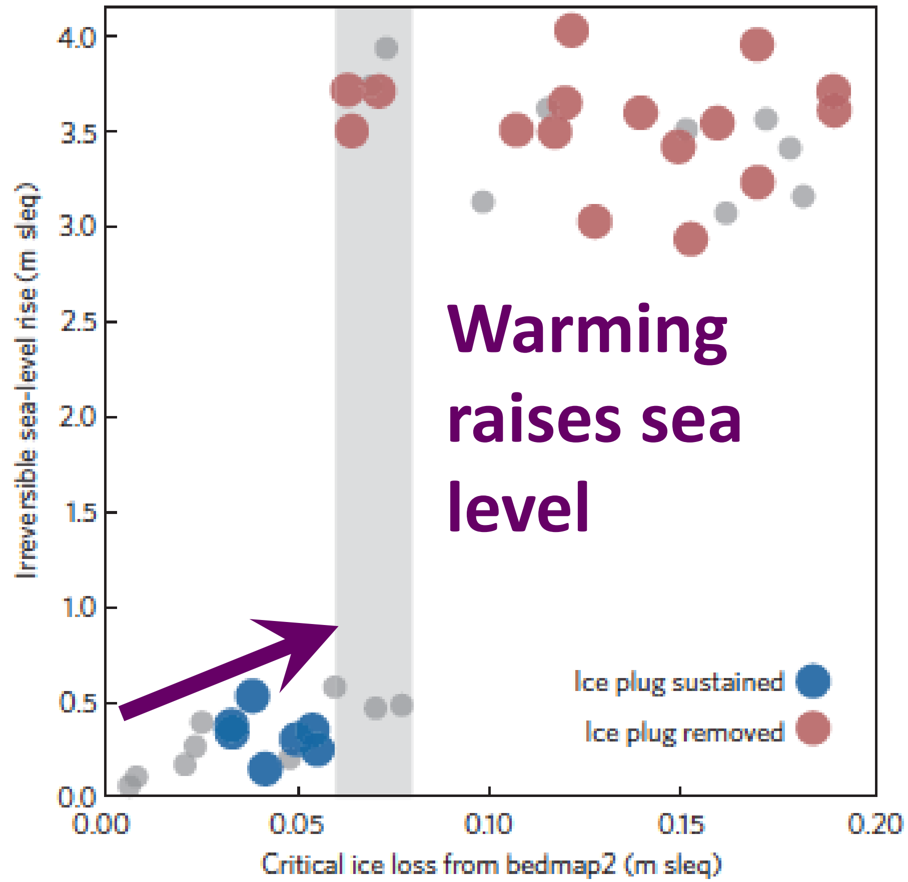

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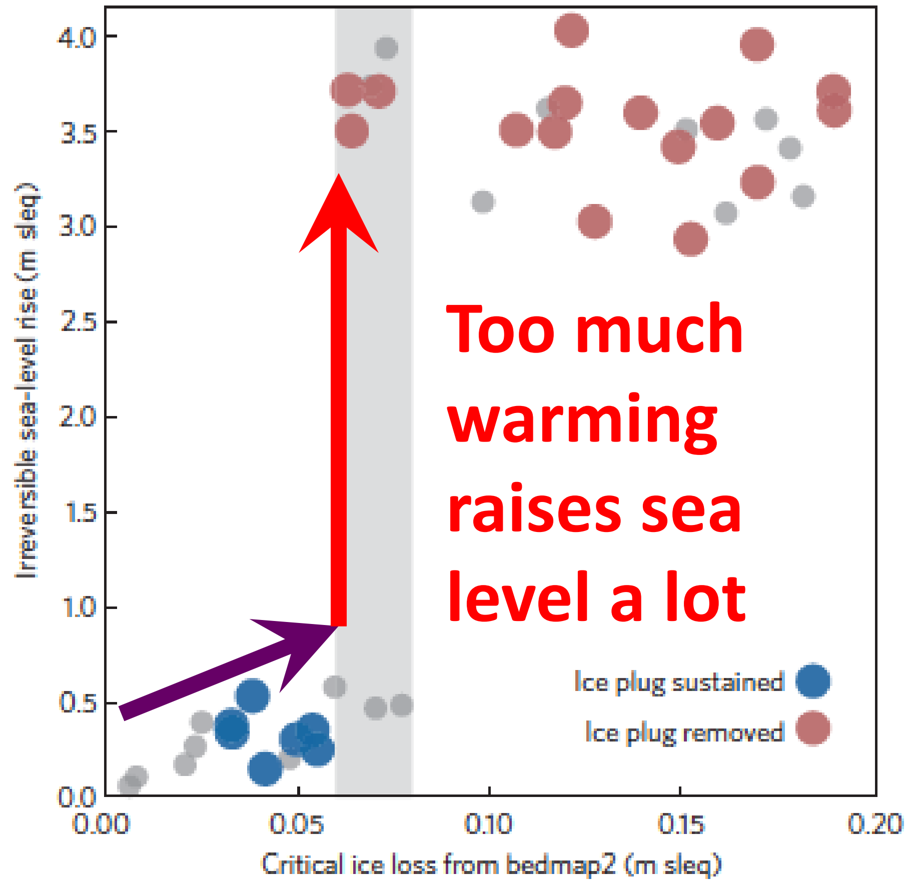

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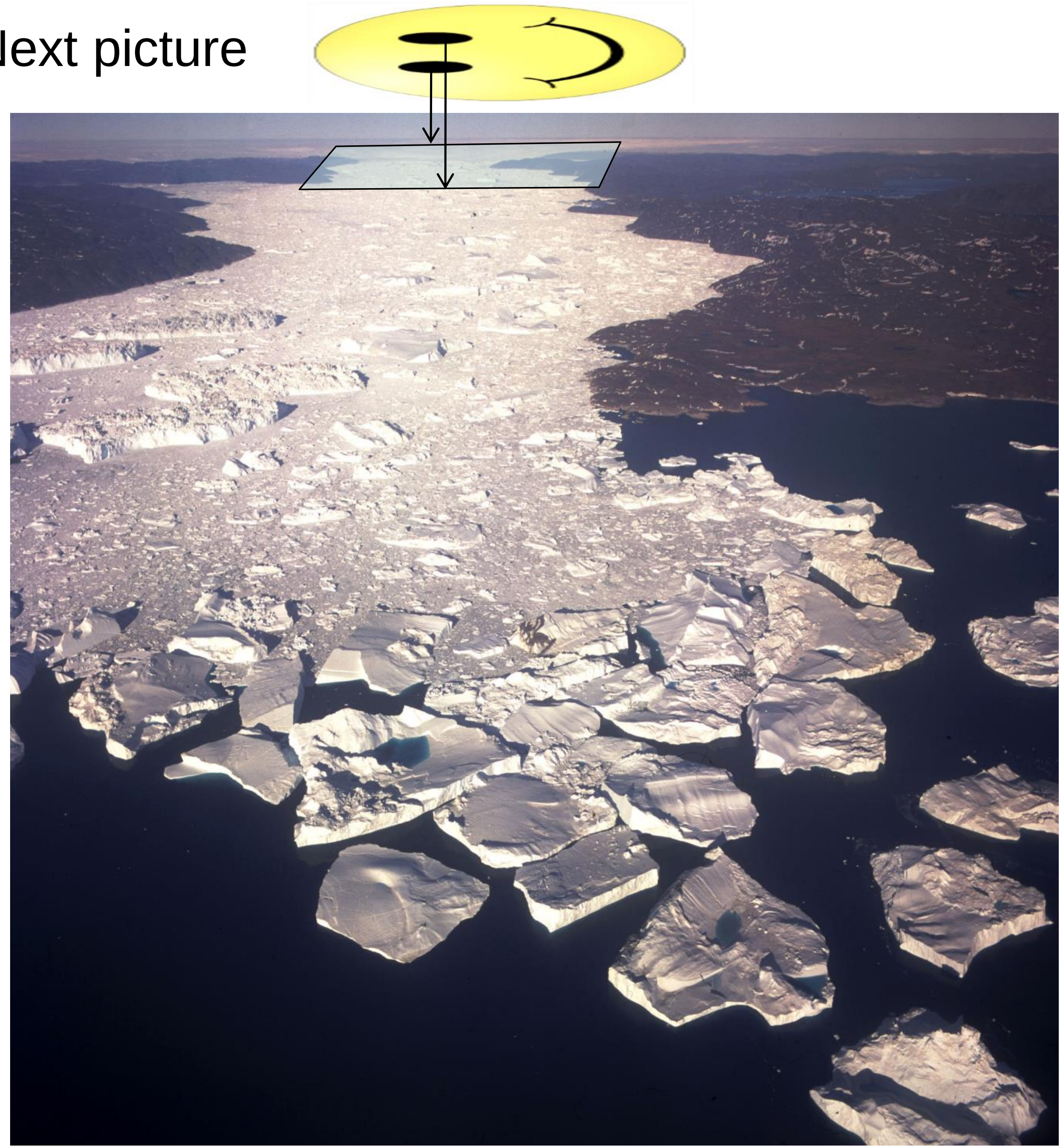
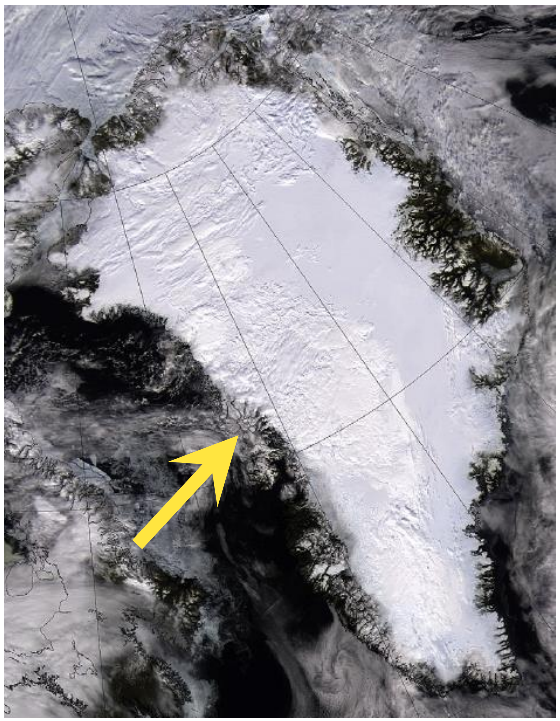
Next picture

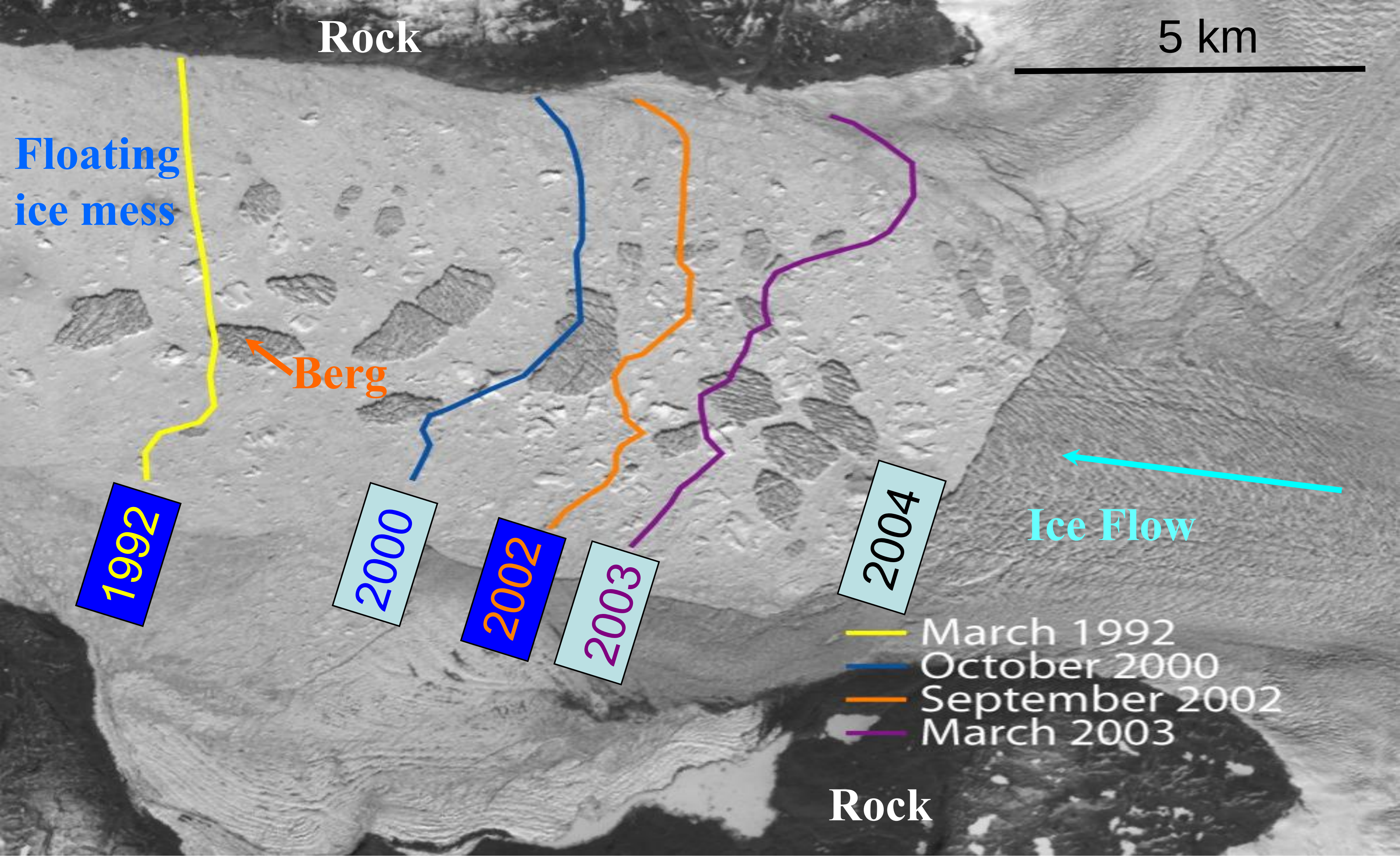


Discharge from many major Greenland ice streams has accelerated markedly.



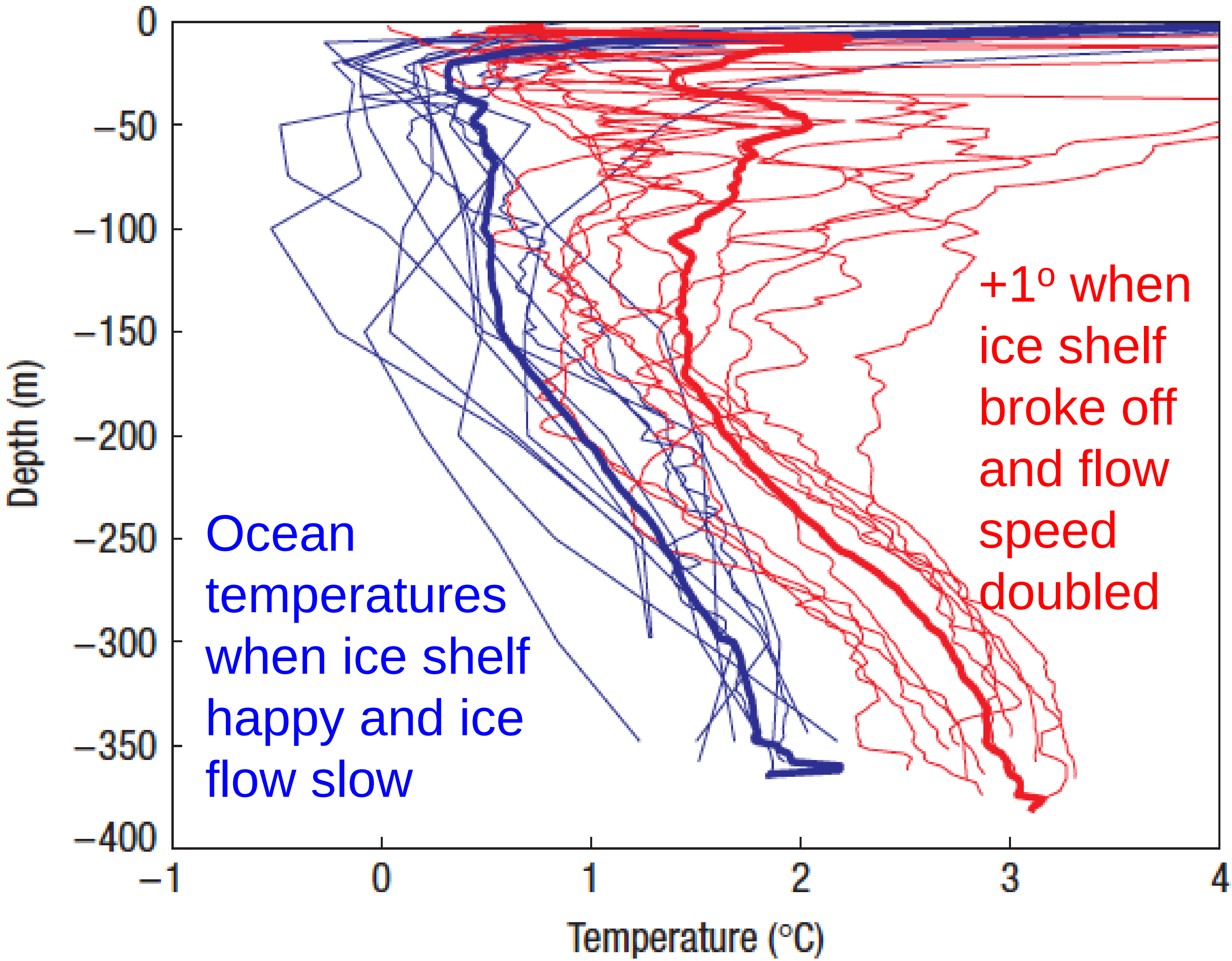
http://www.gsfc.nasa.gov/gsfc/earth/pictures/earthpic.htm

Source: Prof. Konrad Steffen, U of CO



Jakobshavn Isbrae, W. Greenland. Retreat and speed doubling During ice-shelf loss, which likely was caused by warming.

Image courtesy Ian Joughin (Alley et al., 2005).

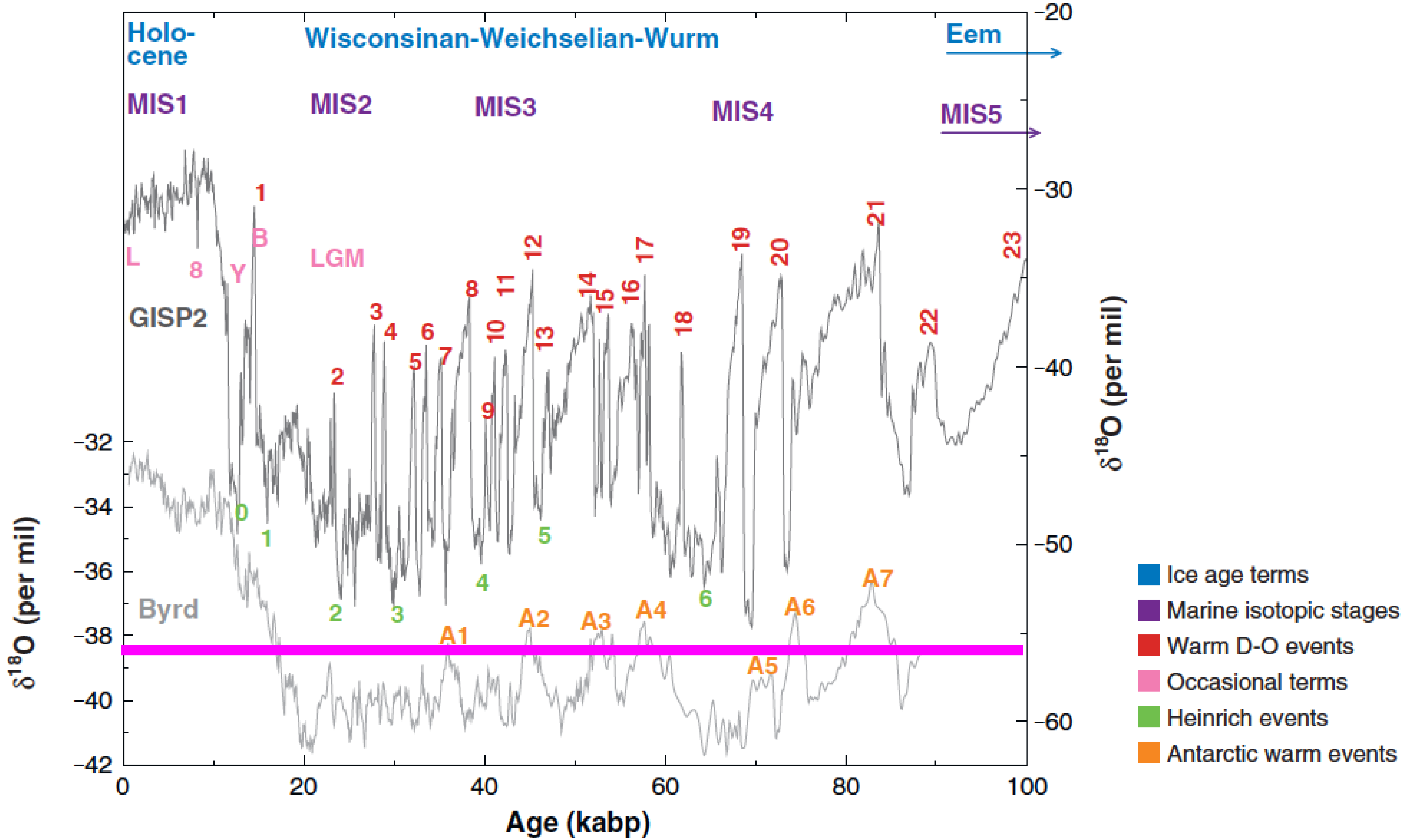


Blue—1954 and 1980-1990; red 1997-2007, heavy lines are averages, just N of mouth of Isfjord, Holland et al., Nature Geosci 2008. They say the wind did it.

What do the ice cores (and other archives) tell us about the stability of WAIS and its presence/absence during MIS 5e?

R.B. Alley, E.J. Brook, D. Pollard, J.P. Severinghaus, E.J. Steig, E.D. Waddington, J.W.C. White, J. Ahn

Available evidence strongly, although not unequivocally, points to loss of the marine portions of the West Antarctic Ice Sheet (WAIS) during one or more recent interglacials, and especially during Marine Isotope Stage 5e. The height and pattern of far-field sea-level records indicate a southern contribution to the 5e high-stand, of magnitude similar to the marine portions of WAIS (e.g., Kopp et al., 2009). Sedimentary records from under (Scherer et al., 1998) or just in front of (Naish et al., 2009) the Ross drainage of WAIS, coupled to ice-flow modeling (Pollard and DeConto, 2009), indicate Pleistocene deglaciation. Excess warmth in East Antarctica during 5e and earlier deglaciations (Holden et al., 2011), and the patterns of relatedness of bryozoans (Vaughan et al., 2011) and octopi (Strugnell et al., 2012) around the coast, are most easily explained if WAIS deglaciated recently. The meltwater channels incised into bedrock in deep water in Pine Island Bay, and rising away from the ice sheet, have been explained as resulting from: i) deglaciation of the marine basins but with ice remaining on the highlands; ii) cooling-induced ice-shelf formation fed by the ice on the highlands, bridging the deep basins and grounding on higher seafloor beyond; iii) thickening of this ice cover in response to the greater friction from the grounding



Holo-
cene
Wisconsinan-Weichselian-Wurm
Eem
MIS1
MIS2
MIS3
MIS4
MIS5
GISP2
Byrd
L
8
Y
B
LGM
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17
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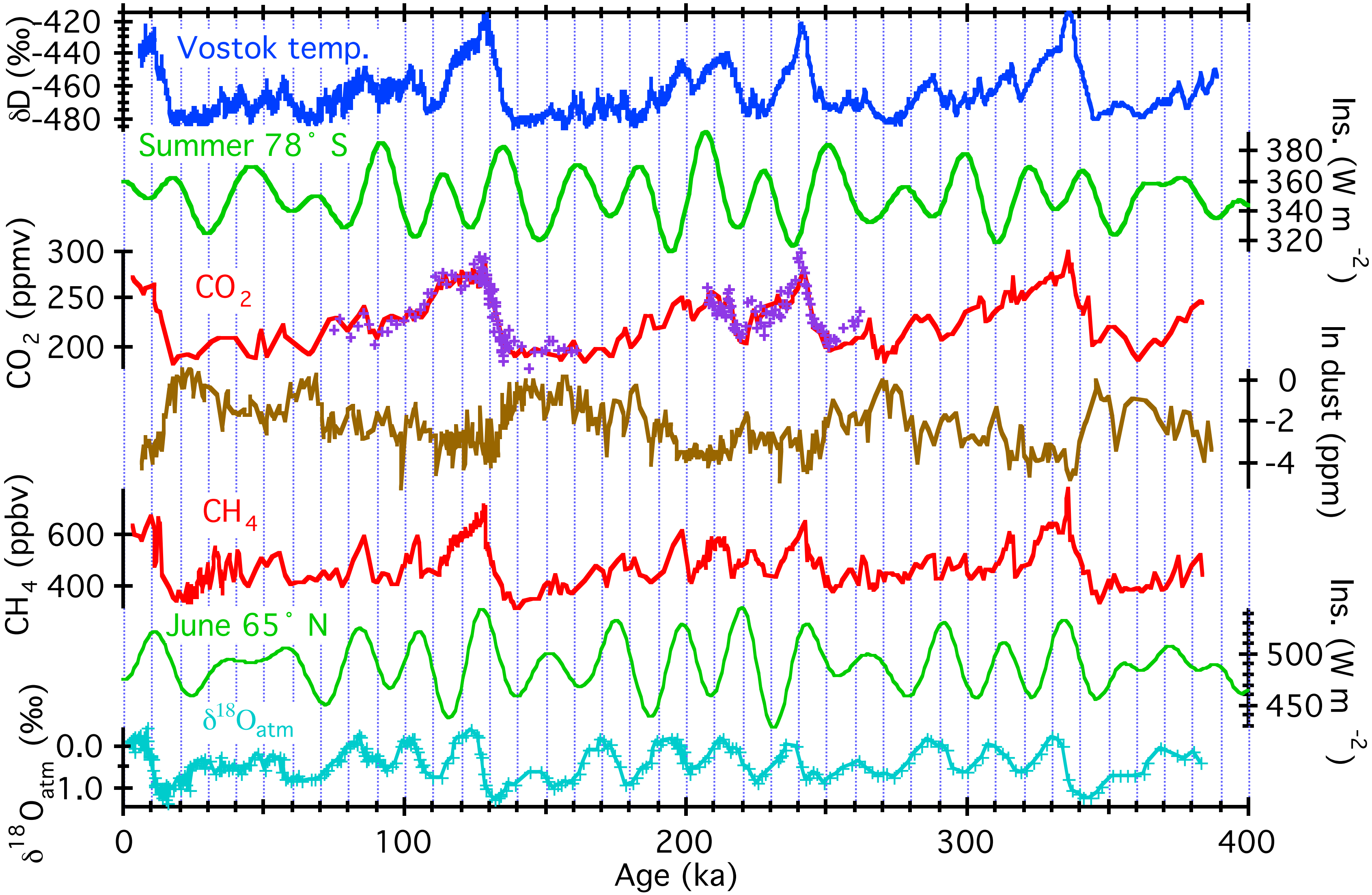
21
22
23
0
1
2
3
4
5
6
A1
A2
A3
A4
A5
A6
A7
δ18O (per mil)
Age (kabp)
Ice age terms
Marine isotopic stages
Warm D-O events
Occasional terms
Heinrich events
Antarctic warm events

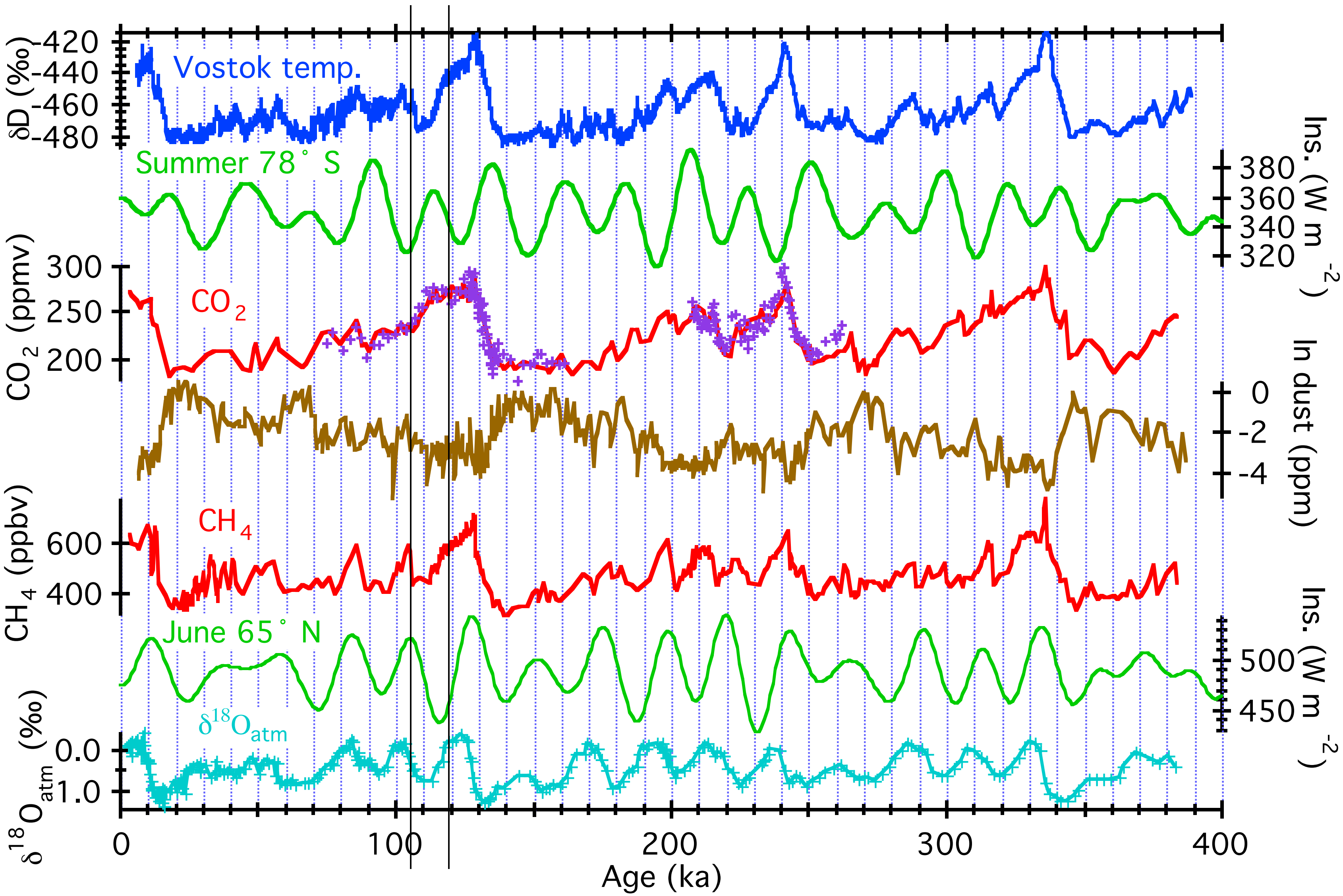
2.

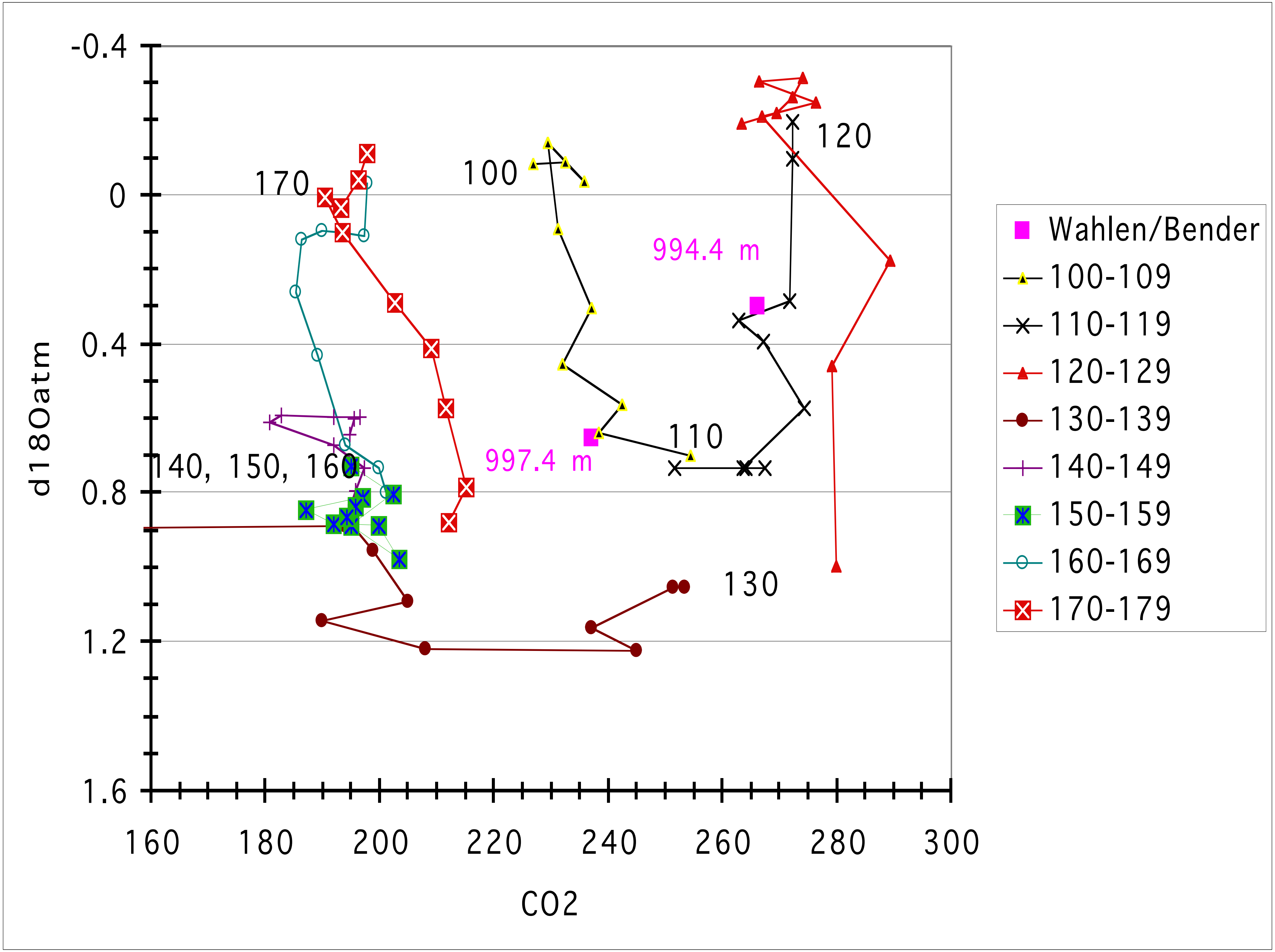
Vostok records



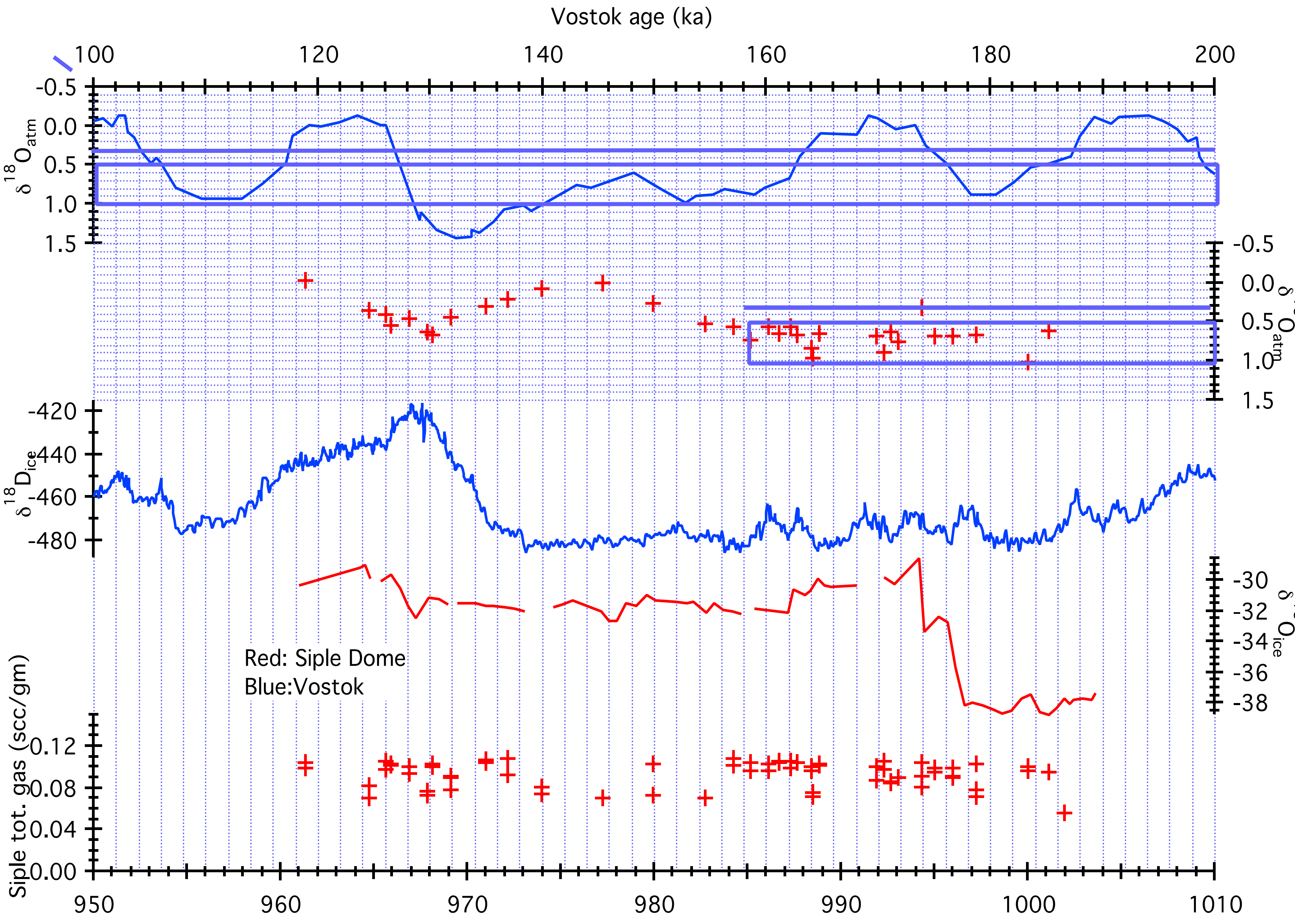
4.

Vostok records



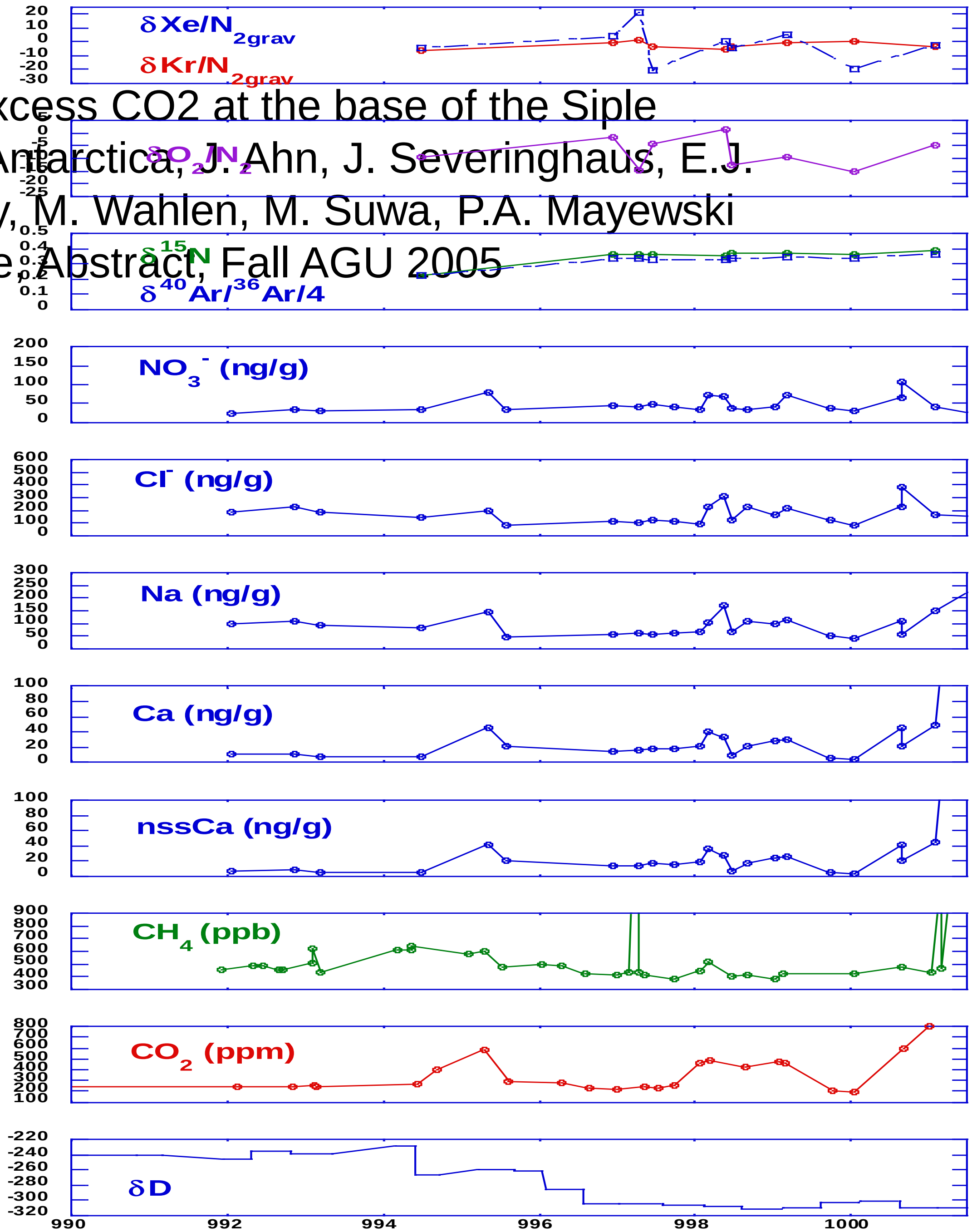


-0.4
0
0.4
0.8
1.2
1.6
d18Oatm
160
180
200
220
240
260
280
300
CO2
170
100
120
994.4 m
997.4 m
110
140, 150, 160
130
Wahlen/Bender
100-109
110-119
120-129
130-139
140-149
150-159
160-169
170-179



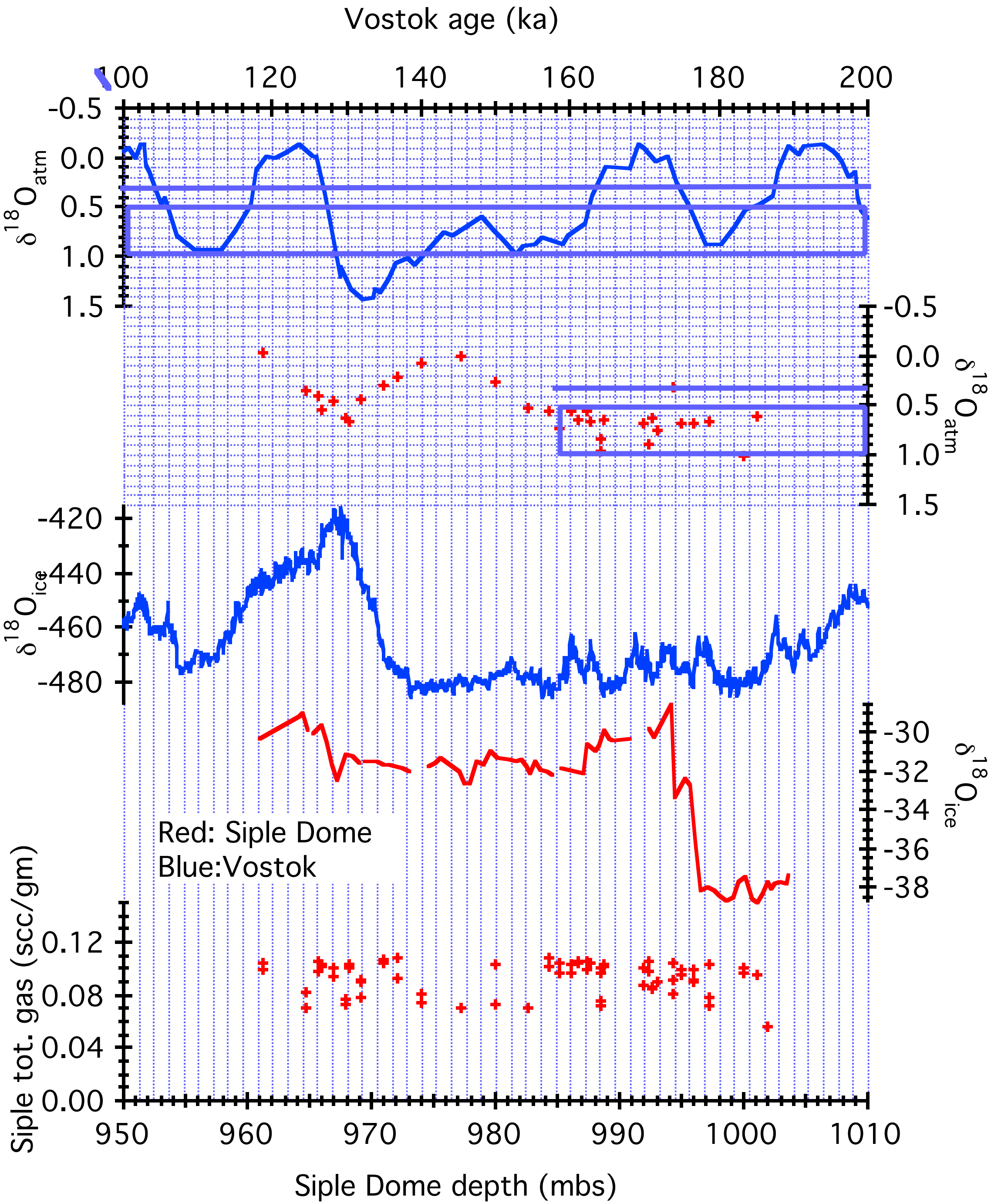
Vostok age (ka)
100
120
140
160
180
200
-0.5
0.0
0.5
1.0
1.5
$\delta^{18}O_{atm}$
-0.5
0.0
0.5
1.0
1.5
$\delta^{18}O_{atm}$
-420
-440
-460
-480
$\delta^{18}D_{ice}$
-30
-32
-34
-36
-38
$\delta^{18}O_{ice}$
Red: Siple Dome
Blue:Vostok
Siple tot. gas (scc/gm)
0.12
0.08
0.04
0.00
950
960
970
980
990
1000
1010
Siple Dome depth (mbs)

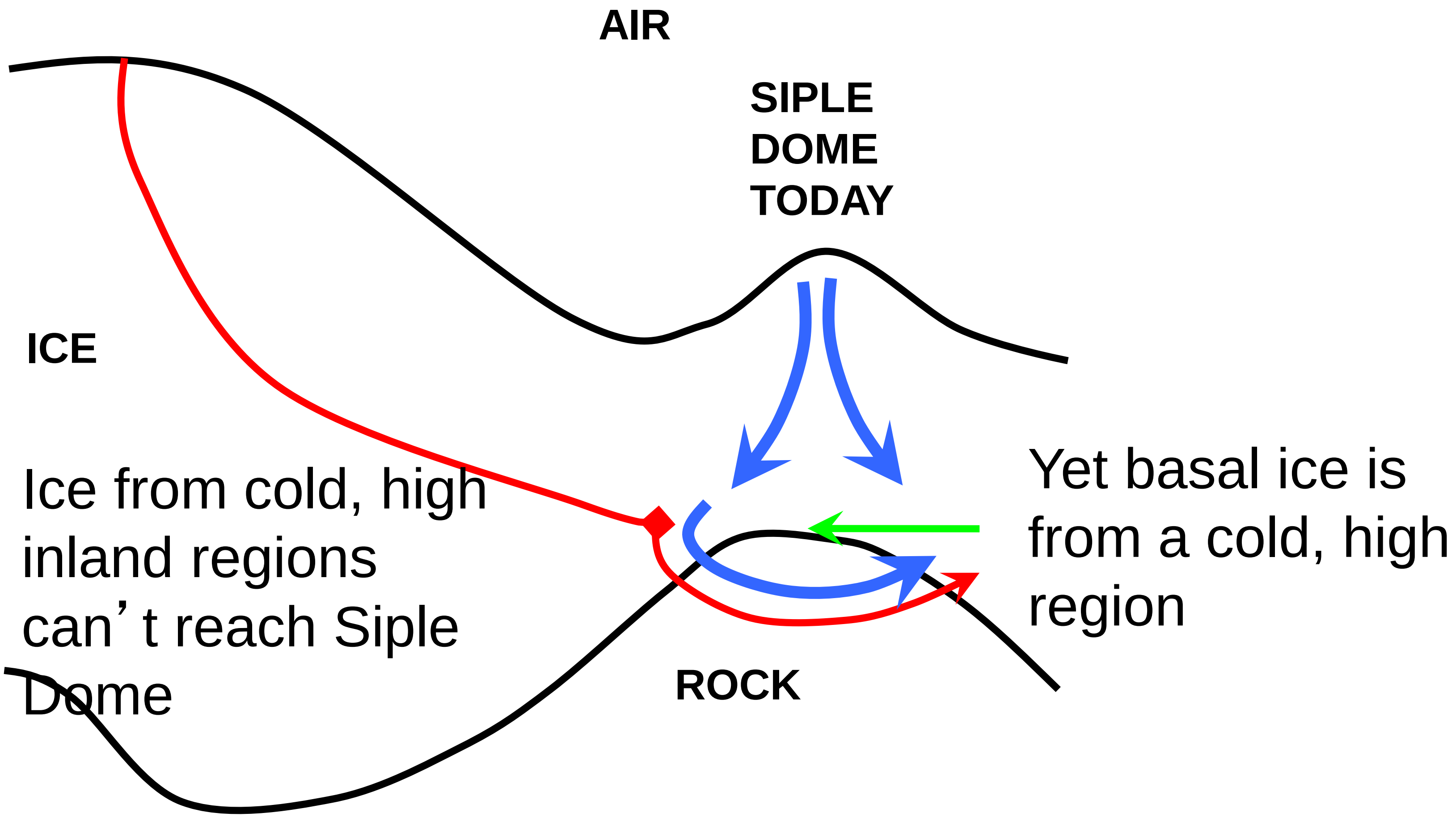
The causes of excess CO_2 at the base of the Siple Dome ice core, Antarctica, J. Ahn, J. Severinghaus, E.J. Brook, M. Headly, M. Wahlen, M. Suwa, P.A. Mayewski and J.W.C. White, Abstract, Fall AGU 2005

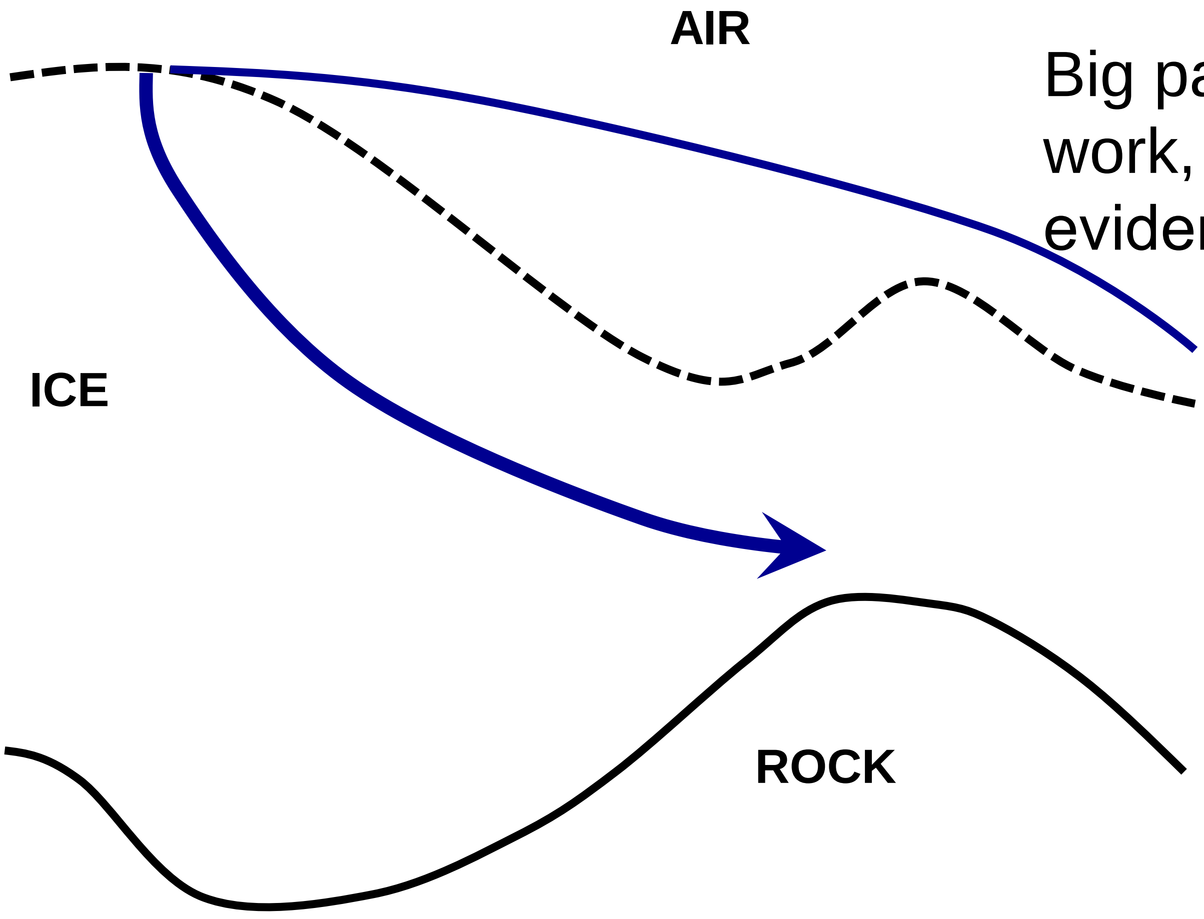


5.

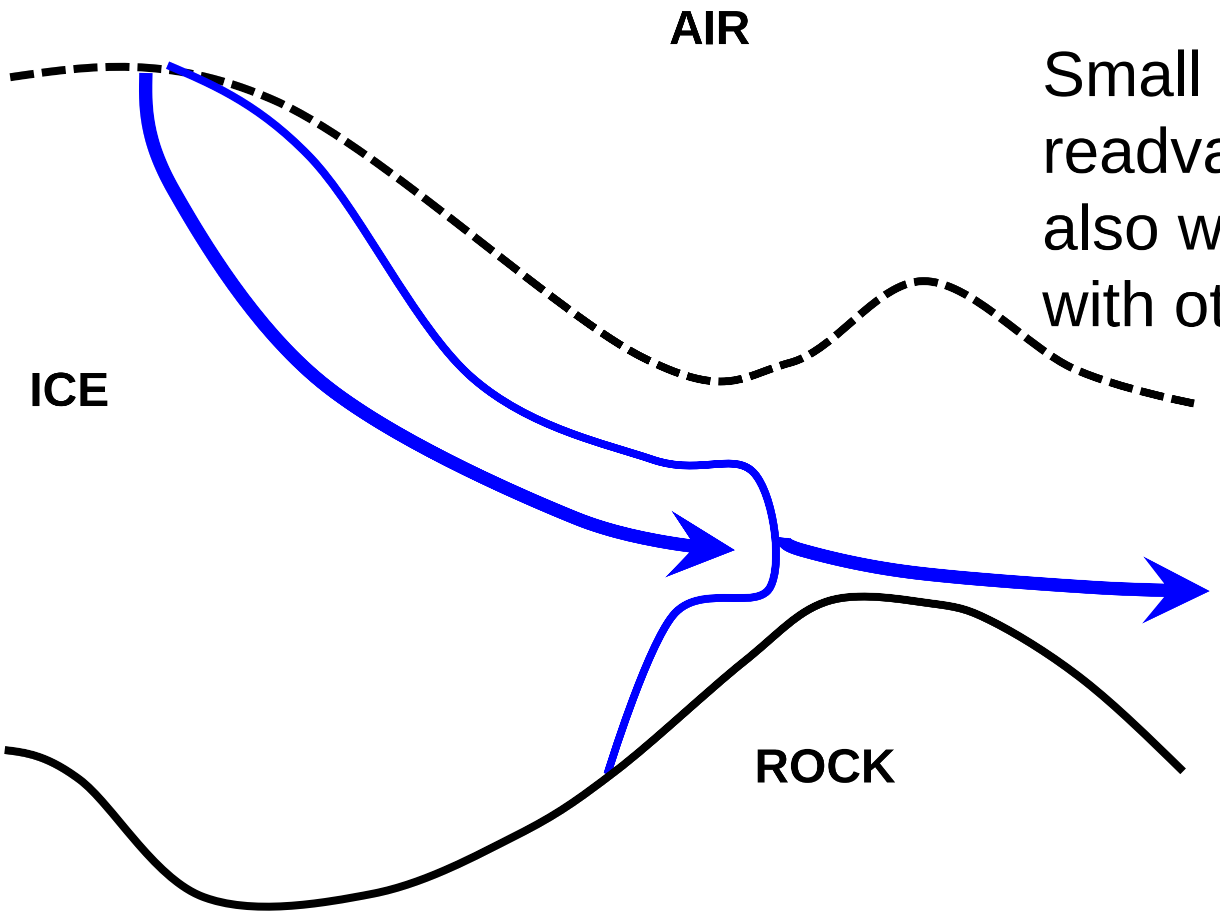
Deep Siple Dome unscrambling




AIR
SIPLE DOME TODAY
ICE
Ice from cold, high inland regions can’t reach Siple Dome
Yet basal ice is from a cold, high region
ROCK



Big past ice would work, but no evidence for this…



Small past ice readvancing would also work, consistent with other data

WAIS Divide core?

- As noted earlier, much useful work ongoing
- Not best place to look for big past changes
- Especially when core stopped far from bed
- But, the larger WAISCORES project IS a great one for looking at past changes
- We'll look, after a bit of background