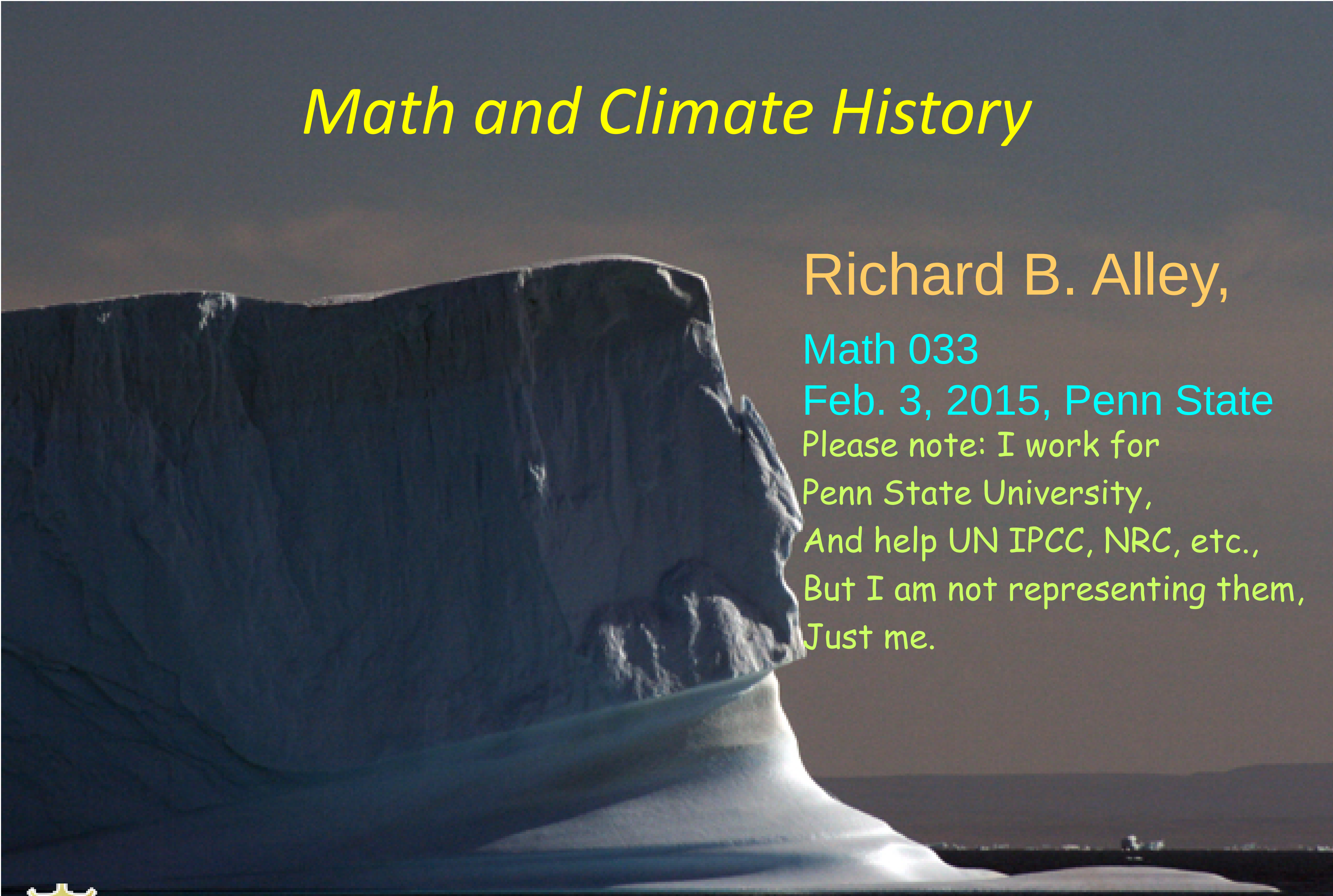
Math and Climate History



Richard B. Alley,

Math 033

Feb. 3, 2015, Penn State

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

G. Comer Foundation

Paleoclimatology

- What happened? Reconstruct past climate;
- When did it happen? Date past events;
- Why did it happen? Reconstruct possible causes of climate change, such as drifting continents, changes in the sun's output, shifts in Earth's orbit, eruptions of sun-blocking dust or fall of meteorite dust, changes in greenhouse gases, etc.

History of Climate

- No instruments way back, so use proxies
- Find sediment-climate relations
- Past sand dunes, glaciers, or lakes easy to identify, tell different things about climate
- Some are mainly physics (Greenland's ice is colder a mile down than ice above or below because still warming from ice age, tells how cold ice age was)
- Some based on assuming little change in modern correlations (e.g., relation between temperature and who lives where)—for such, we look for agreement among multiple independent indicators

History of Climate

- Find ages of sediments in many ways
- Oldest tree ~5000 years, but overlapping pattern of thick and thin rings in living and nearby dead wood to >12,000 years; we counted >100,000 years in Greenland ice (match historical volcanic fallout, etc. as far back as written history goes)
- Older, a host of damage-accumulation and radiometric-dating techniques (and yes, you use math to make them work—isochrones, exponential decay curves, etc.)
- Again, look for agreement among multiple ways

What might control Earth's temperature?

- Changes in LOTS of things

→Brightness of Sun

→Distance of Earth from Sun

→Blockage of sunlight on its way to us

→Reflection of sunlight by Earth (albedo)

→Greenhouse effect

What might control Earth's temperature?

- Changes in LOTS of things

→Brightness of Sun—Fast changes small (whew!); slow ones offset by thermostat

→Distance of Earth from Sun

→Blockage of sunlight on its way to us

→Reflection of sunlight by Earth (albedo)

→Greenhouse effect

What might control Earth's temperature?

- Changes in LOTS of things

→Brightness of Sun

→Distance of Earth from Sun—No worry!—dino-killer moved Earth ≤1" (2.5 cm) out of ~93 million miles (CALCULATE momentum!)

→Blockage of sunlight on its way to us

→Reflection of sunlight by Earth (albedo)

→Greenhouse effect

What might control Earth's temperature?

- Changes in LOTS of things

→Brightness of Sun

→Distance of Earth from Sun

→Blockage of sunlight on its way to us—tiny tiny tiny (not enough to matter)

→Reflection of sunlight by Earth (albedo)

→Greenhouse effect

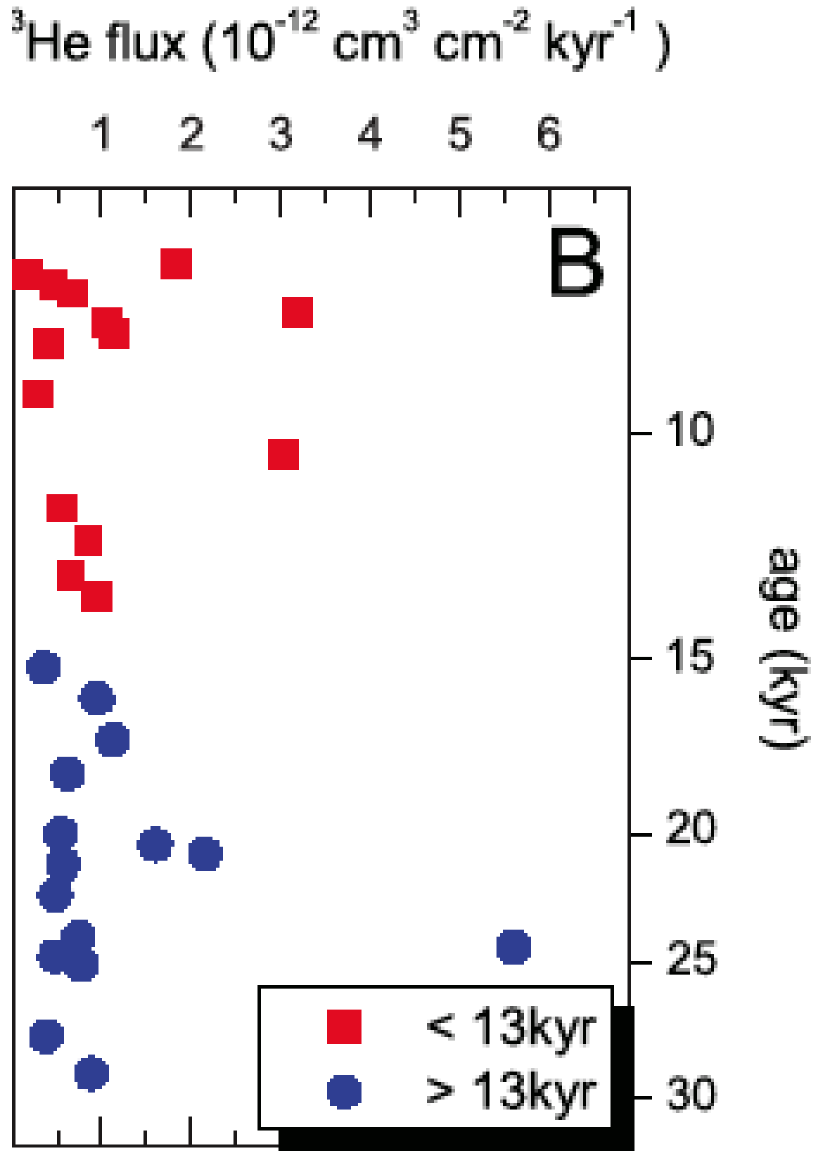
Changes in space dust have been small, and haven't affected climate much.

Helium-3 is mostly from space dust.

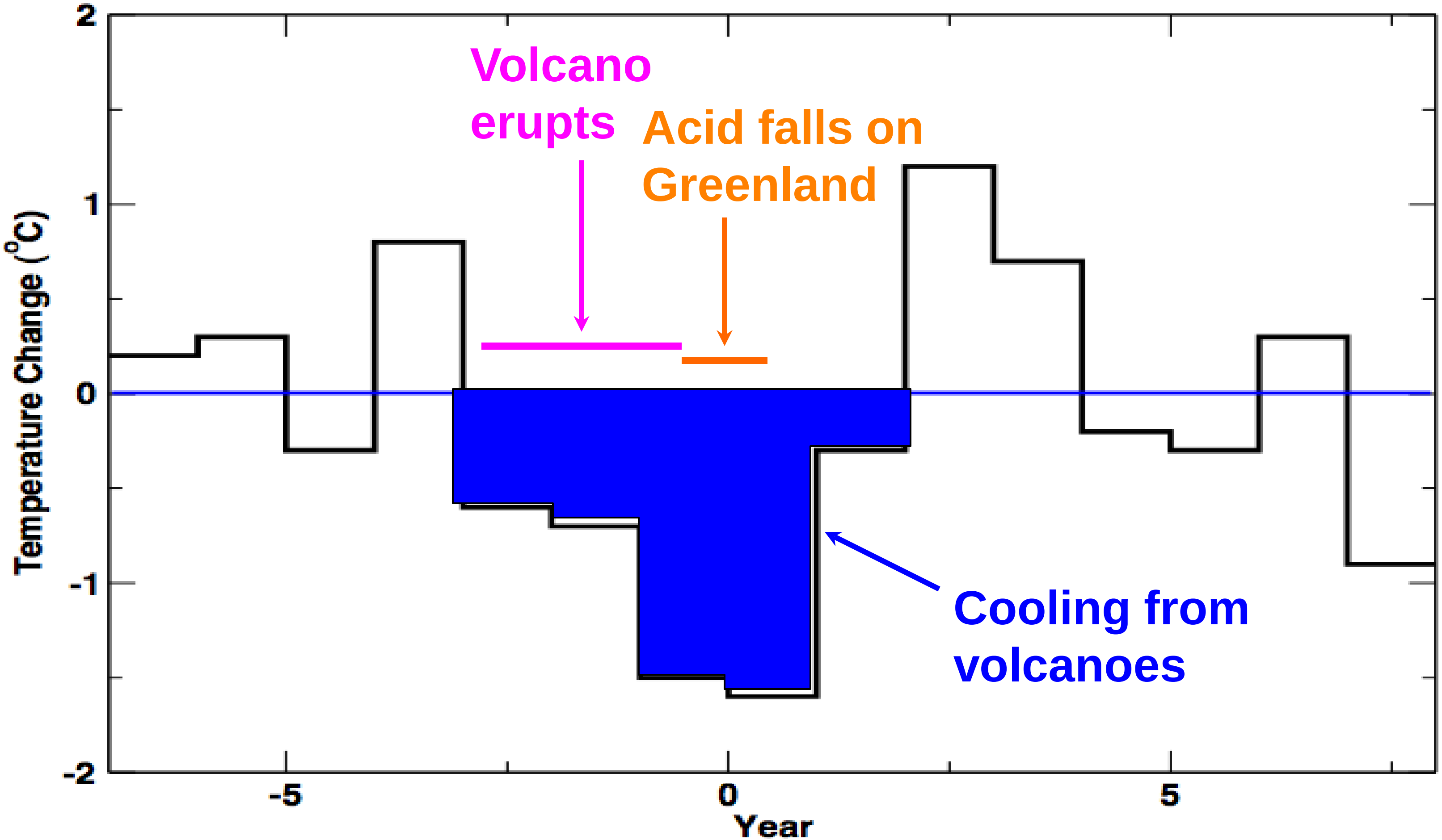
If space dust changed a lot, that might affect climate some.

But there has been little change in space dust over last 30,000 years (ice-core data shown here) and beyond (other data not shown).

(Very rarely, a big meteorite does matter, such as the one that killed the dinosaurs 65 million years ago.)



Winckler & Fischer, 2006, *Science*



Big volcanoes cool (1-2°C for 2-3 years). But, big volcanoes don't get really organized (a little; Huybers & Langmuir, 2009), so explosive volcanoes don't control climate. (Note that flood-basalt eruption does seem to warm.)

(Stack of GISP2, Greenland $\delta^{18}O$ records from 7 VEI 6-7 eruptions; Stuiver et al. 1995.)

What might control Earth's temperature?

- Changes in LOTS of things

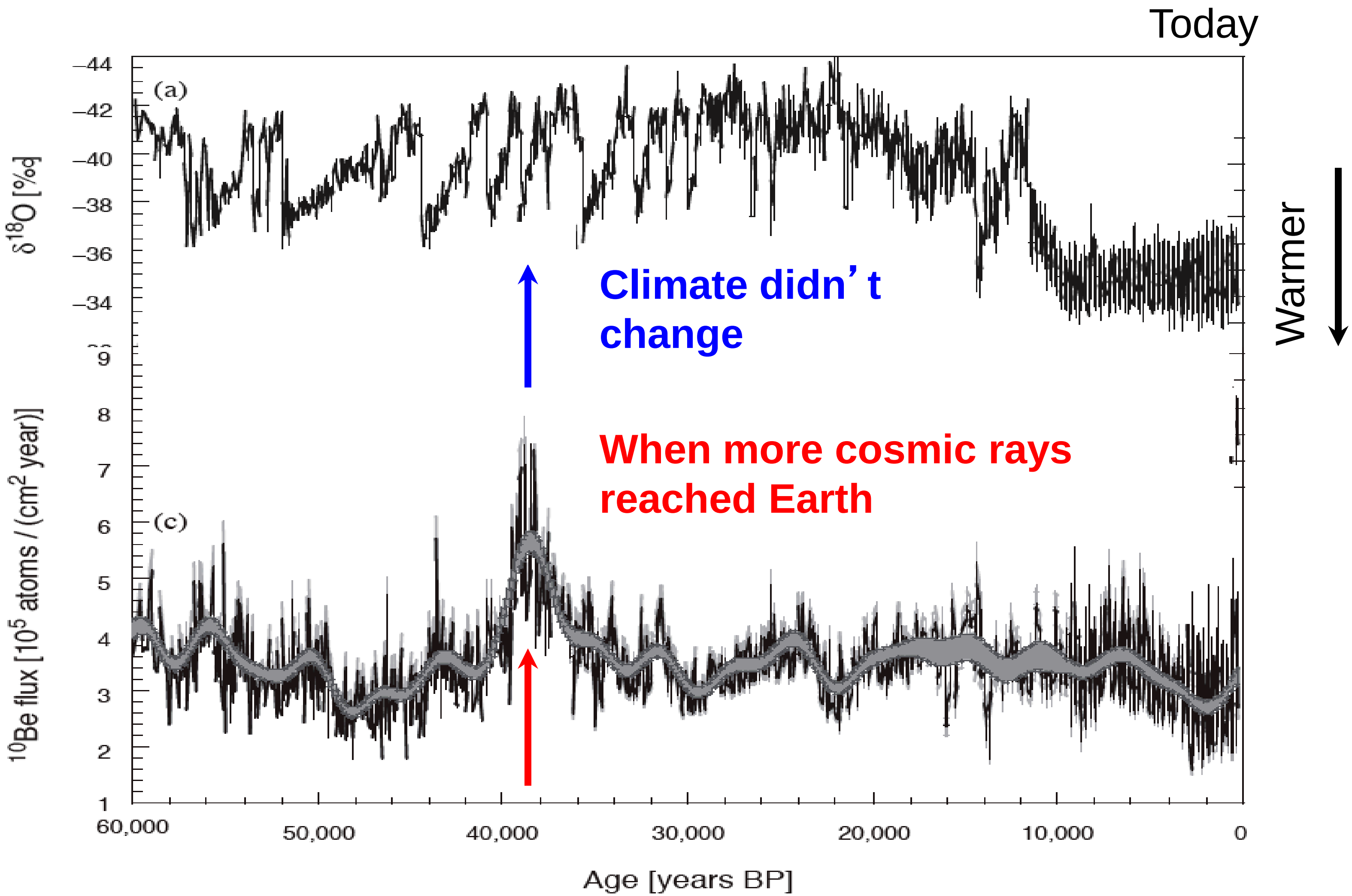
→Brightness of Sun

→Distance of Earth from Sun

→Blockage of sunlight on its way to us

→Reflection of sunlight by Earth (albedo)—can matter; hard to change much by itself

→Greenhouse effect



Cosmic rays, magnetic field don't matter much to climate.

From Muschler et al., 2005, QSR. $\delta^{18}O$ (proxy for temperature) from GRIP core (top), the concentration of ^{10}Be (middle), and the flux of ^{10}Be (bottom). The Laschamp event of near-zero magnetic field (red arrow) allowed increased cosmic-ray flux producing more ^{10}Be, but with no apparent effect on climate.

What might control Earth's temperature?

- Changes in LOTS of things

→Brightness of Sun

→Distance of Earth from Sun

→Blockage of sunlight on its way to us

→Reflection of sunlight by Earth (albedo)

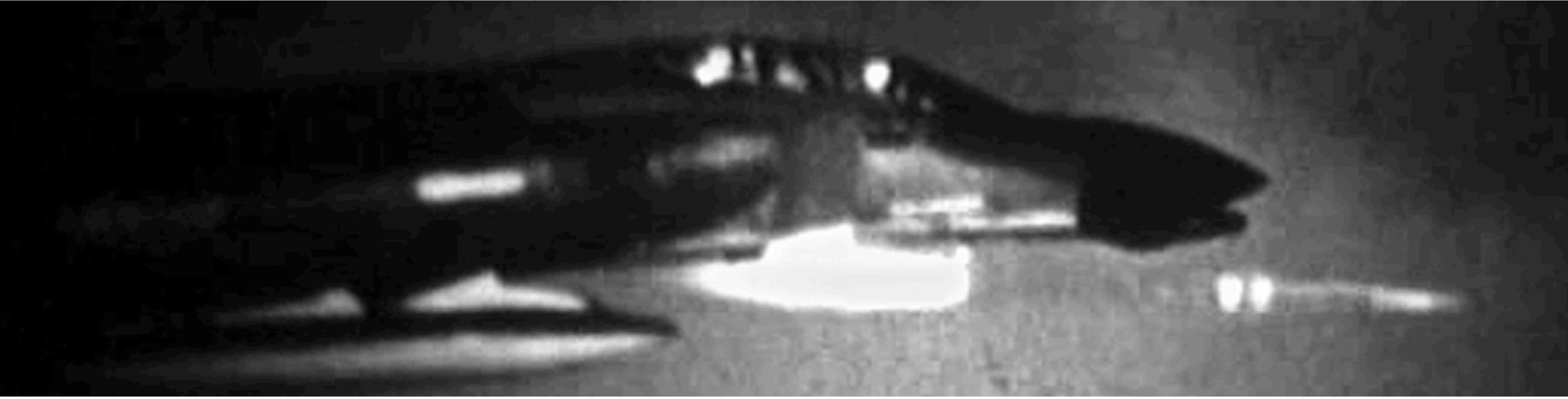
→Greenhouse effect—can matter a lot (Venus…), and easy to change, as we'll see

Greenhouse Effect

- Amount of stuff that goes into a factory is almost exactly equal to what comes out, but little pieces go in and big cars come out
- Total energy reaching Earth almost exactly equal to energy leaving, but mostly shortwave arrives and longwave leaves
- A pothole can stop a car tire while allowing a giant truck tire or a kid's toy car to pass
- Some gases absorb longwave, not shortwave, and pass energy to other gases in collisions.

Greenhouse gases

- Of greenhouse gases, water vapor absorbs most energy, CO_2 next, others minor
- But, changing water vapor very hard except by warming air over vast, wet ocean
- Fossil fuel burn→CO_2—stays up millennium or so, & water vapor—stays up week or so
- Models: remove water vapor and evap. restores in few days; remove CO_2 and Earth freezes over (Pierrehumbert et al, 2007; Voigt and Marotzke, 2009)



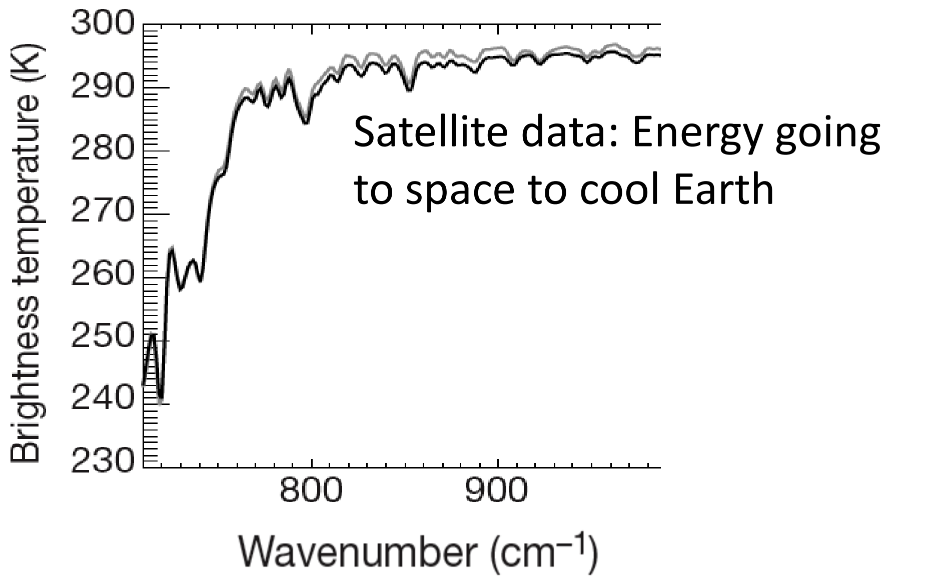
Basis for expecting global warming is PHYSICS

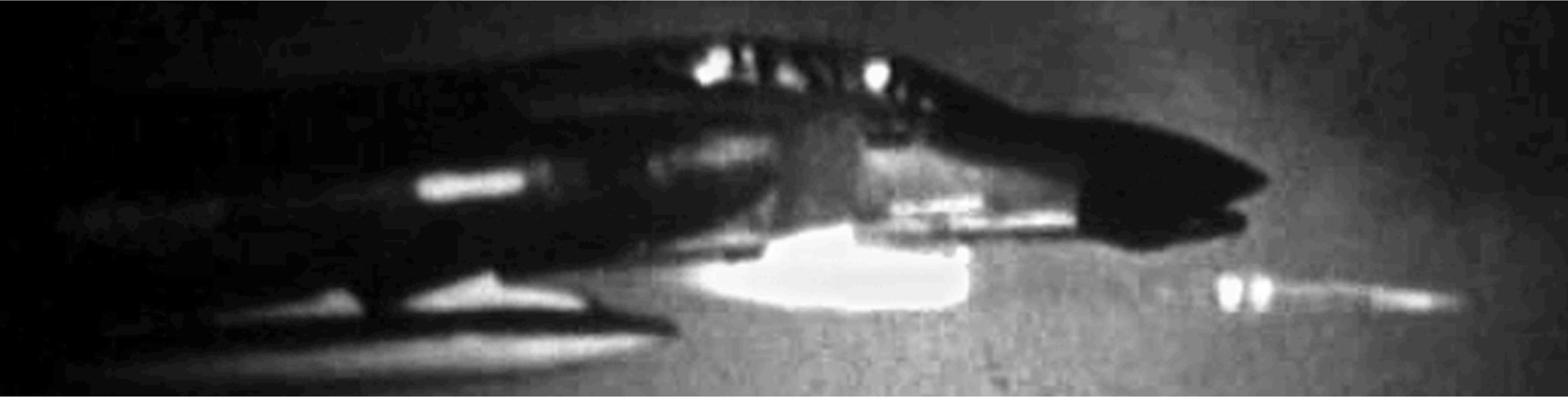
**Known for over a century

**Refined by Air Force after WWII (operations, communications, heat-seeking missiles)

**Observed today by satellites, etc.

**Confirmed by history





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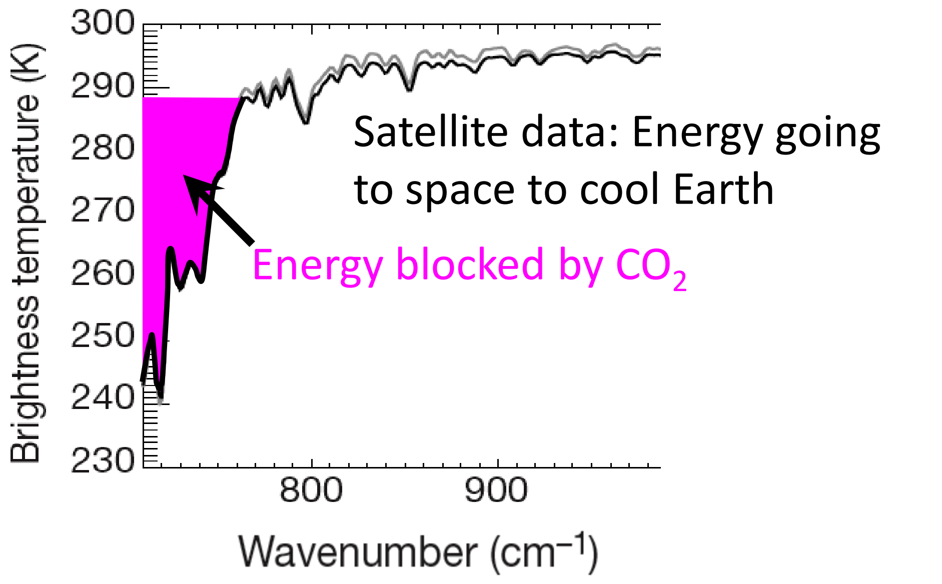

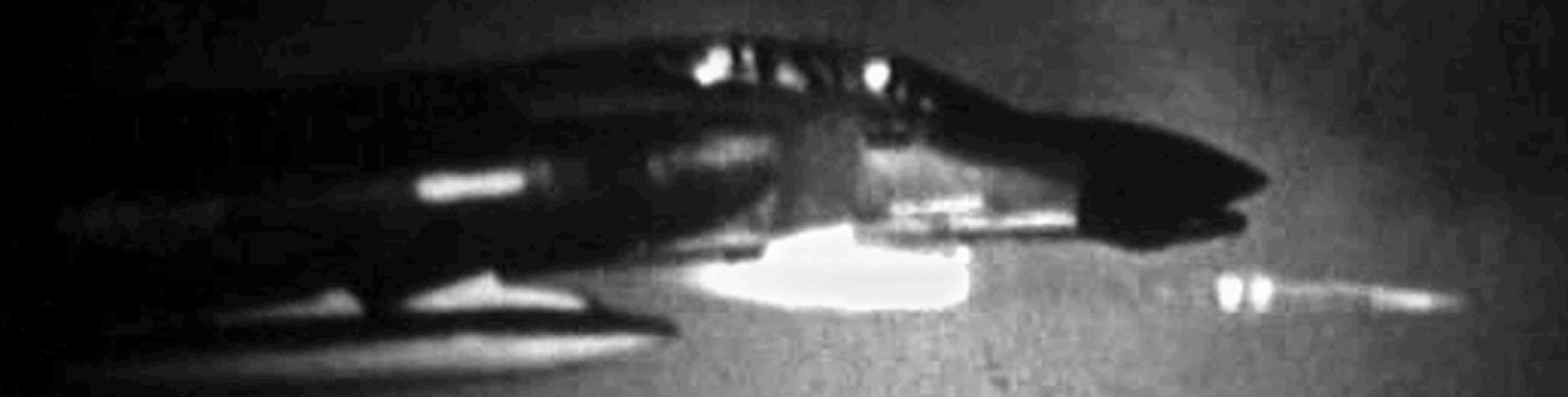

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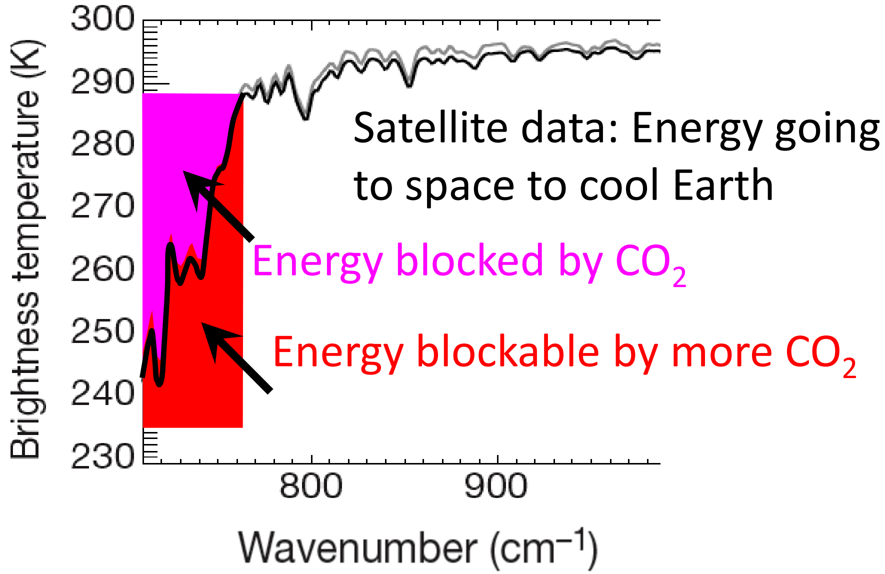
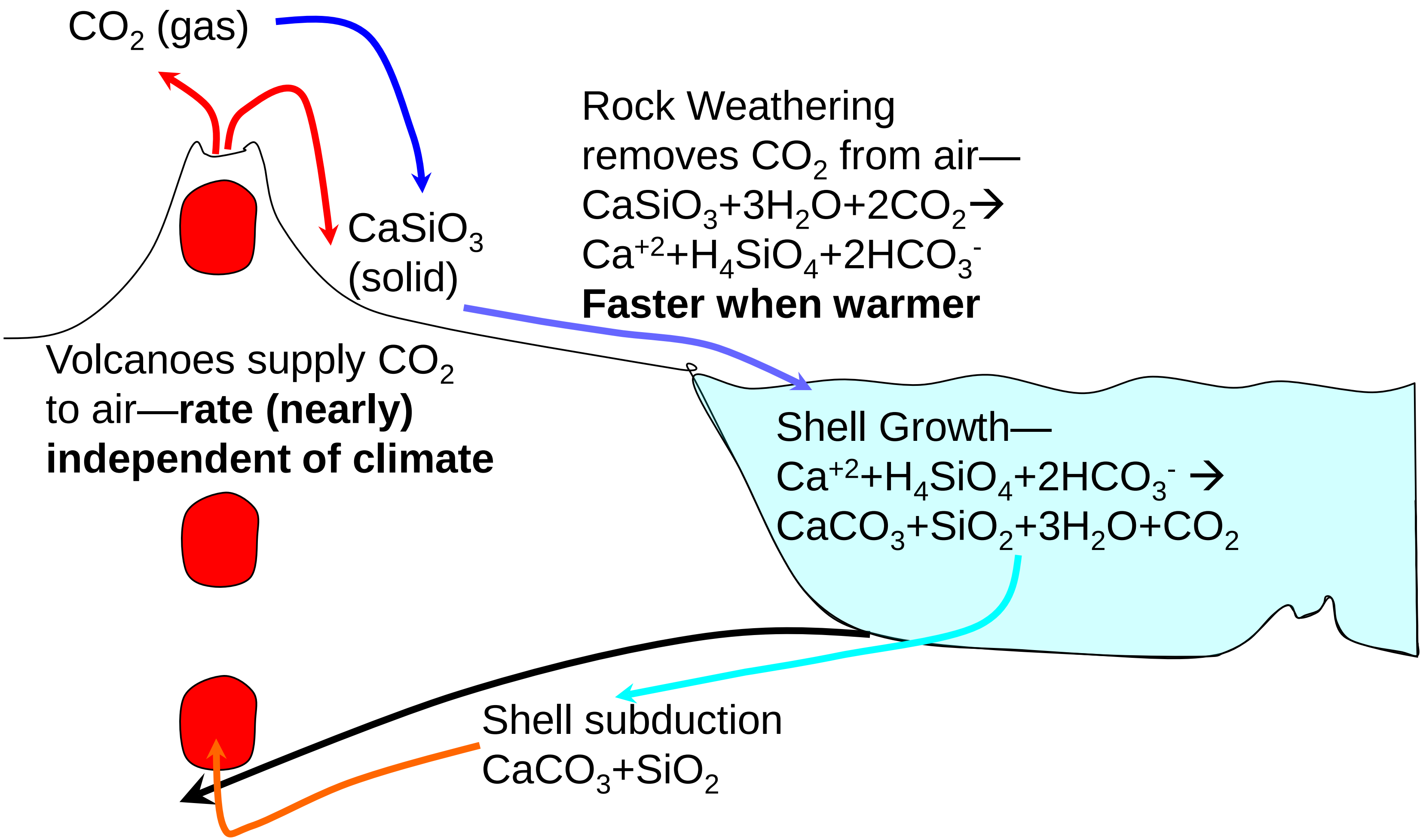


Faint Young Sun "Paradox"

- Sun's output ~70% of modern 4.6 billion years ago—fusing hydrogen to helium increases solar core's density, so faster fusion occurs, balancing gravity;
- Yet evidence of liquid water on Earth as far back as we have records (~4.4 billion years);
- Earth reflects ~30% of sun now, so would need perfectly black early Earth (didn't happen) to offset changing sun;
- So, physics plus data point to stronger early greenhouse (Sagan, C. and G. Mullen, 1972).

Rock-Weathering Thermostat—When Earth cold, CO_2 builds up in air, warming; when Earth warm, CO_2 removed from air, cooling



Walker, J.C.G., P.B. Hays and J.F. Kasting, 1981

Rock-Weathering Thermostat—Simpler Version

At surface, faster when warmer

$CaSiO_3$
$+CO_2$

$CaCO_3$
$+SiO_2$

Deep in Earth, doesn't care
about surface temperature

Walker, J.C.G., P.B. Hays and J.F. Kasting, 1981

Snowball Earth

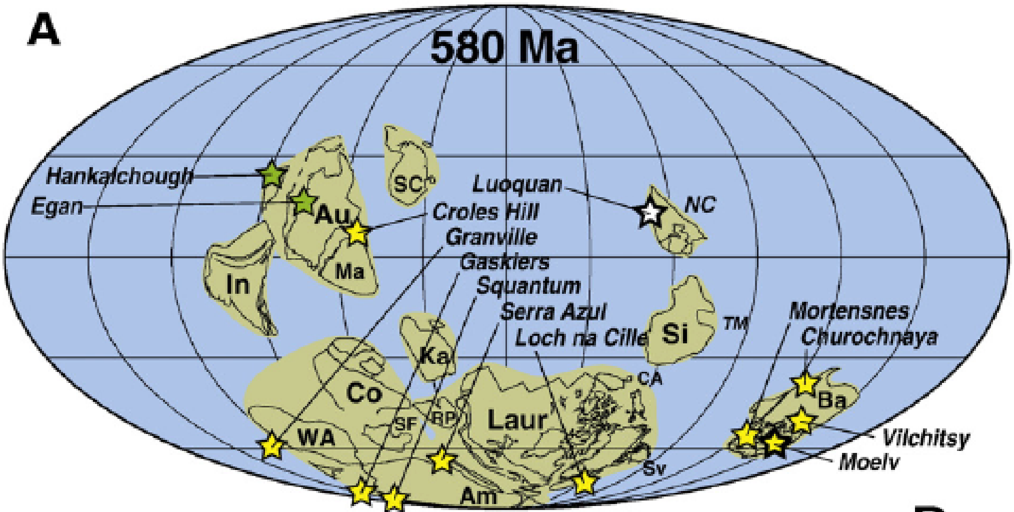
- Extensive low-elevation, low-latitude glacial deposits from some times on middle-aged Earth;
- Physical understanding: if CO_2 warms & rock-weathering thermostat works, then

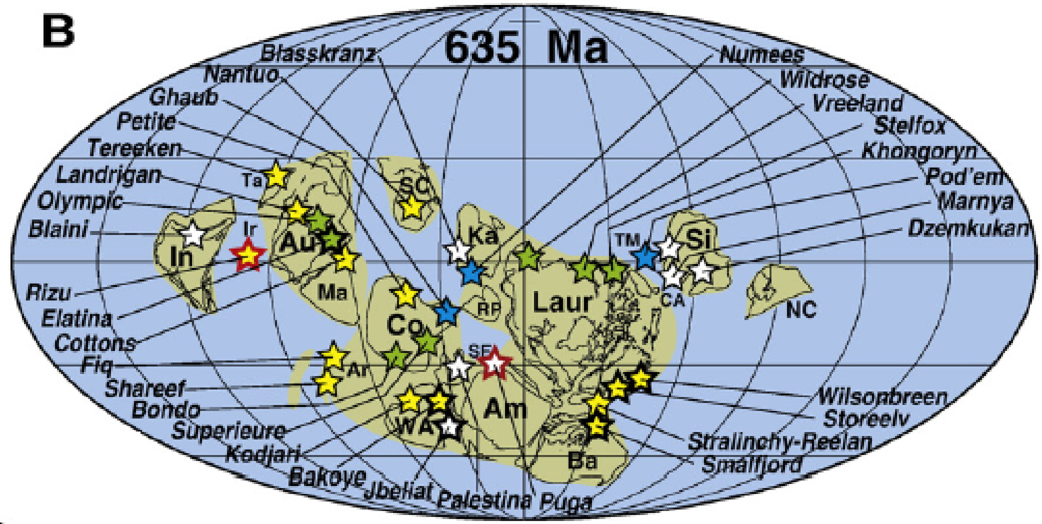
→Can get into a snowball with a faint sun if fast (thermostat takes ~0.5 million years to work);

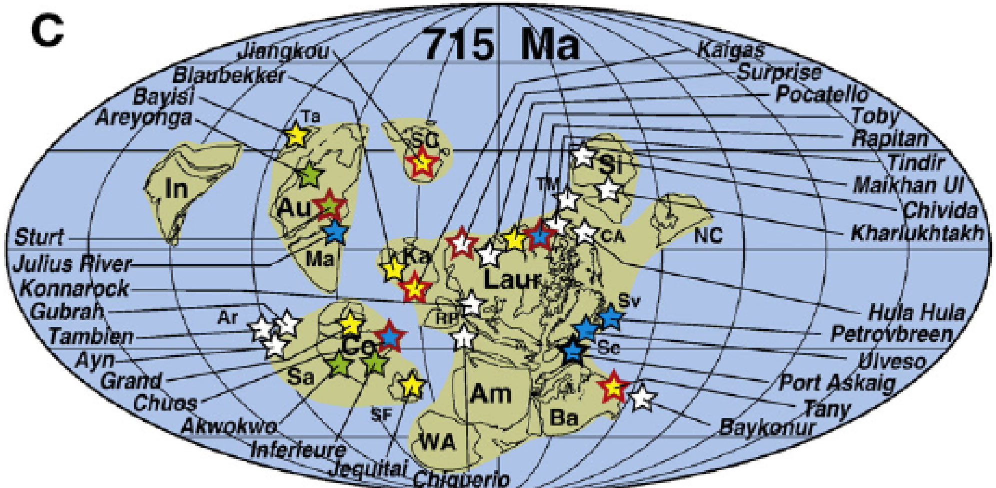
→Then high snow albedo needs lots of CO_2 to thaw;

→Then lots of warming and rapid weathering should have deposited carbonate rocks rapidly

- And, cap carbonates sit atop snowball deposits.



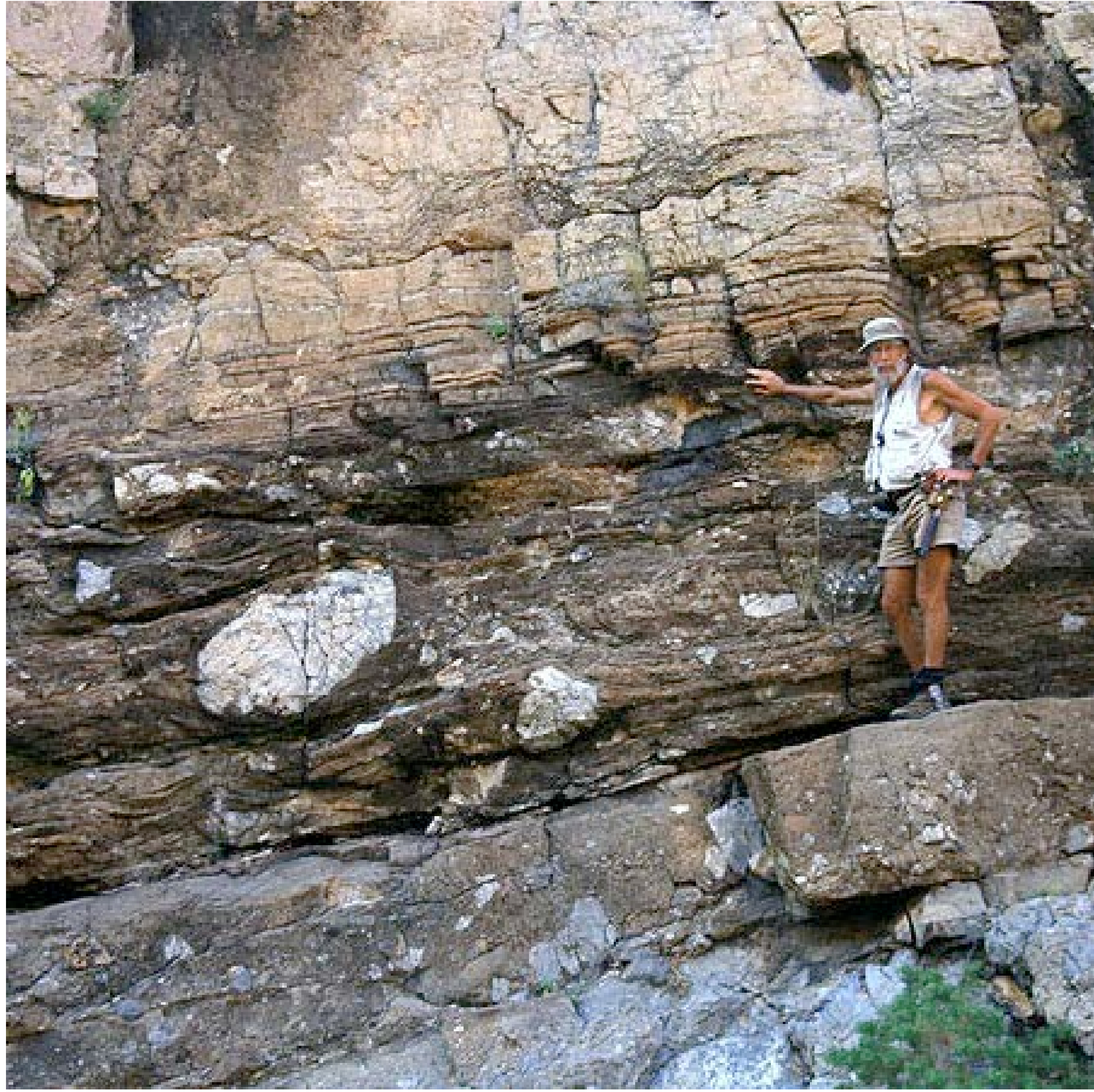




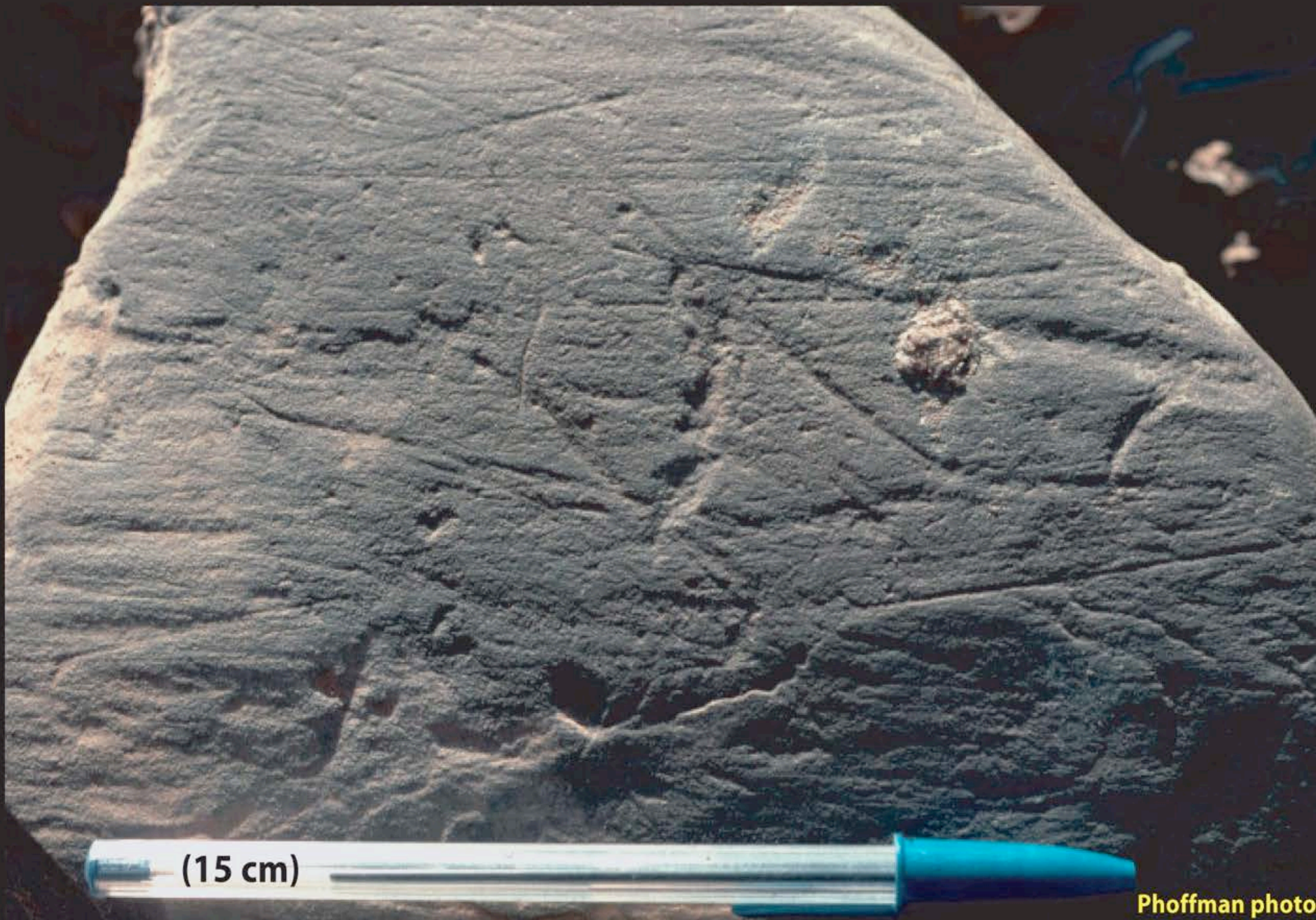
Where the ice was at different times (colors of stars relate to geologic setting) (Hoffman and Li, 2009, Paleo[3])

http://www.snowballearth.org/week1.html

Boulders dropped by icebergs into laminated marine sediment in late Precambrian time, Narachaampspos, Kaokoveld, Namibia. The chief proponent of the Snowball Earth hypothesis, Paul Hoffman, points to the transition to carbonate rocks which indicate the sudden termination of this frigid event. Photo M. J. Hambrey. http://www.swisseduc.ch/glaciers/glossary/snowball-earth-en.html



See Hoffman, P.F. and D.P. Schrag. 2002. The snowball Earth hypothesis: testing the limits of global change. Terra Nova 14, 129-155.



Scratched pebble from Jbéliat tillite, Mauritania

http://www.snowballearth.org/week1.html

Contact between Egan tillite and basal Yurabi cap dolostone, Margaret River (at Stockyard Crossing, Great Northern Highway) Kimberley Region, Western Australia (P.F. Hoffman photo)

http://www.snowballearth.org/capcarbs.html

Resetting the Thermostat

- More CO_2 from volcanoes (e.g., more volcanism, or shallower oceanic subduction zones so more shells subducted rather than dissolved);
- Slower weathering—colder or drier climate, or less-weatherable materials (e.g., shale at surface, vs. basalt), or less plant activity (e.g., pre-land-plants less CO_2 in soil);
- Less fossil-fuel burial, or more fossil-fuel burning (e.g., higher-oxygen oceans because colder or less-fertilized);
- Change greatly over time-scales of plate tectonics and evolution—100 million years or so.

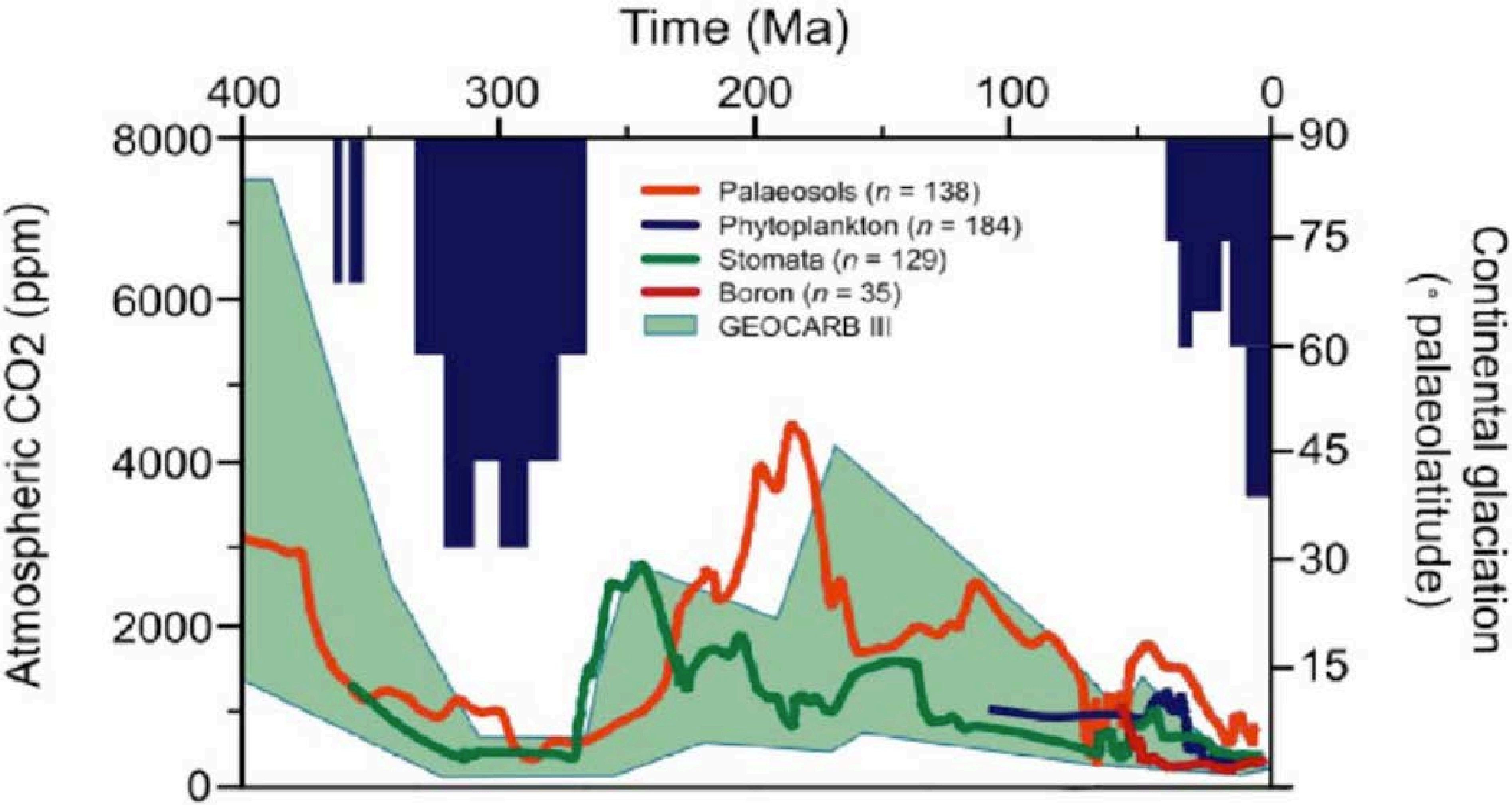
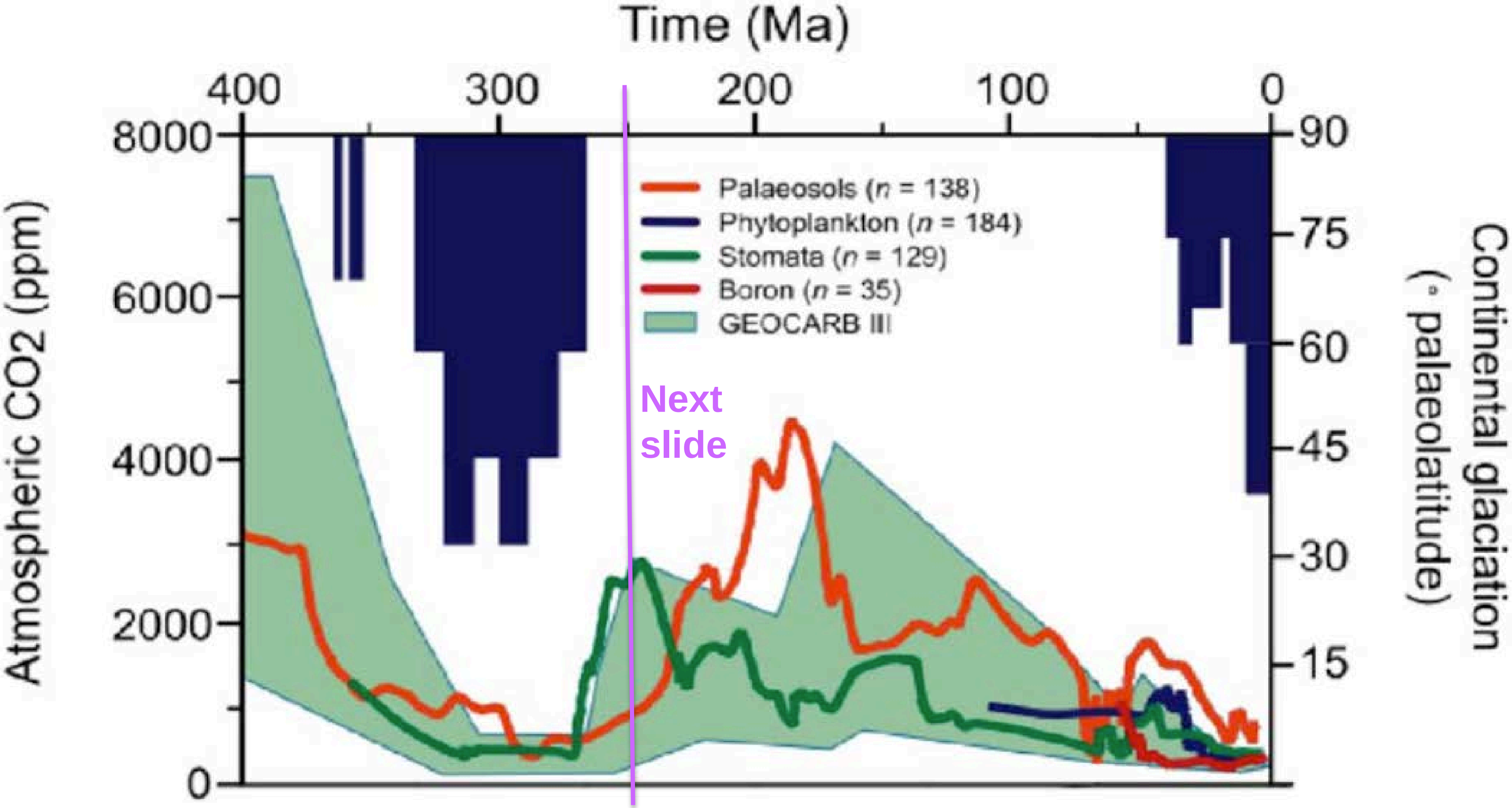


Figure 4.24 Atmospheric CO2 and continental glaciation 400 Ma to present. Vertical blue bars, timing and palaeolatitudinal extent of ice sheets (after Crowley, 1998). Plotted CO2 records represent five-point running averages from each of four major proxies (see Royer, 2006 for details of compilation). Also plotted are the plausible ranges of CO2 derived from the geochemical carbon cycle model GEOCARB III (Berner and Kothavala, 2001). All data adjusted to the Gradstein et al. (2004) time scale. Continental ice sheets grow extensively when CO2 is low. (after Jansen, 2007, that report's Figure 6.1)



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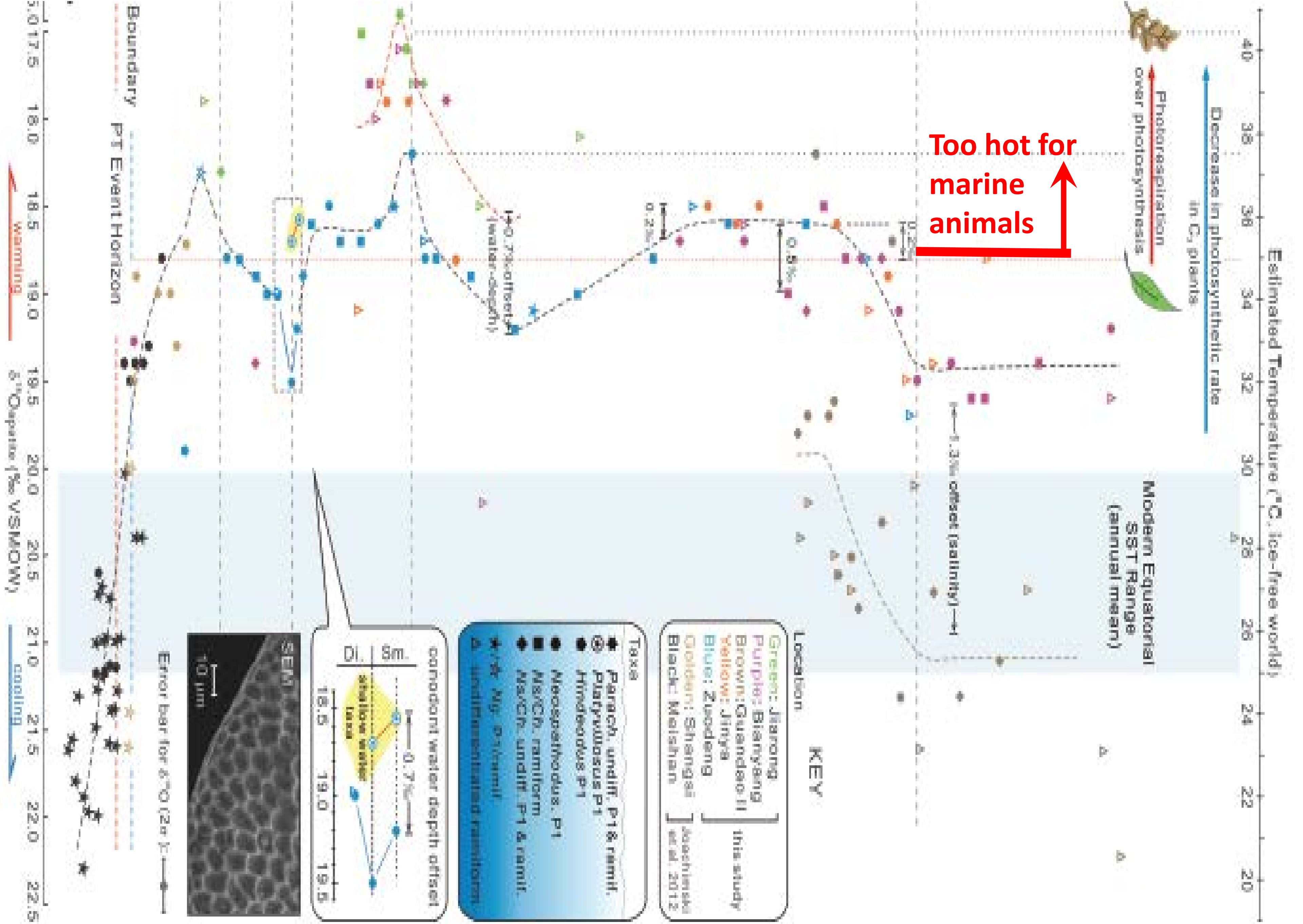
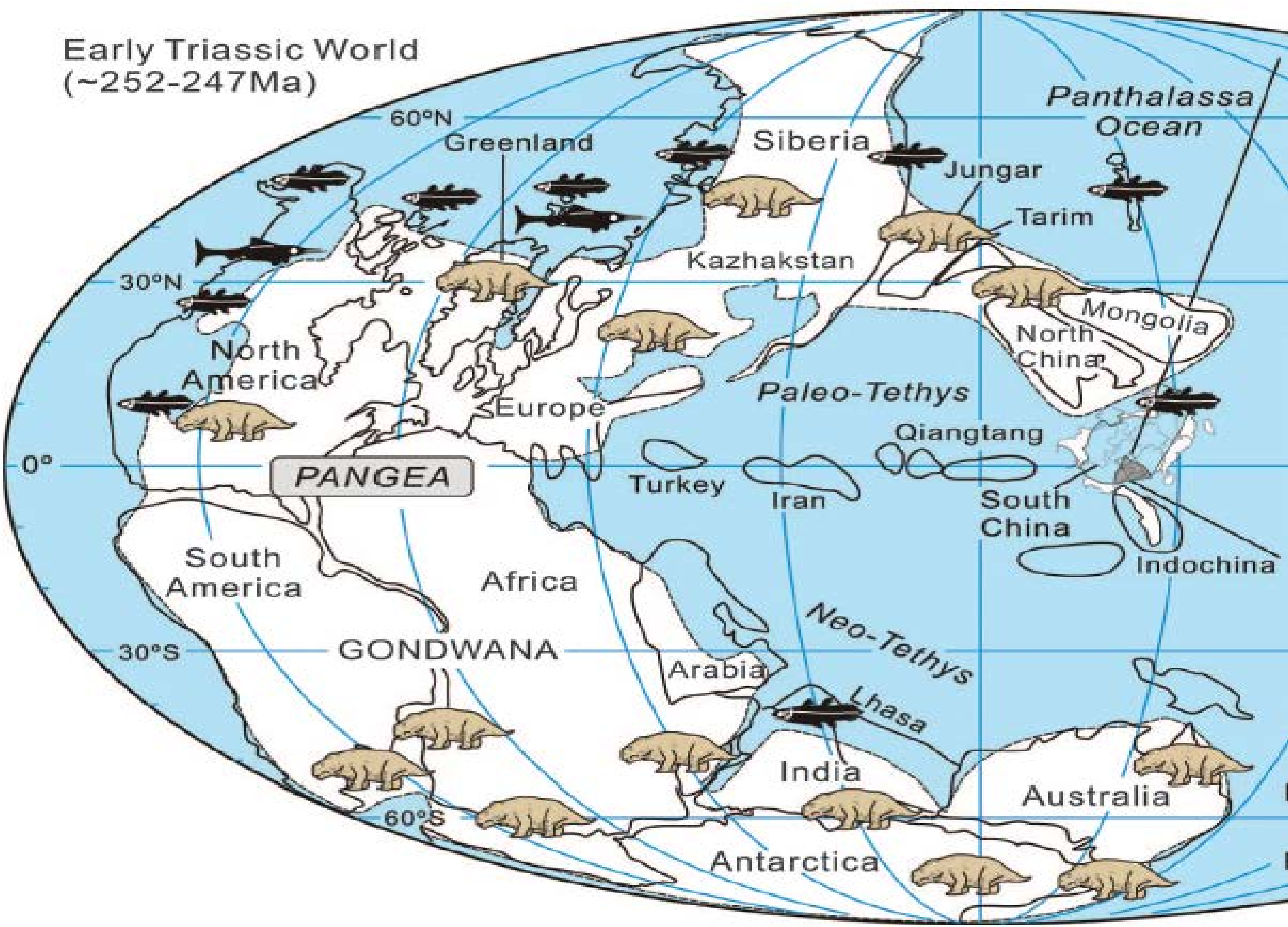
Events—The Great Dying

- End-Permian extinction, 251 million years, perhaps 95% of species became extinct;
- Widespread marine biomarkers of green sulfur bacteria that use H_2S for photosynthesis (100 ppm in air is immediate danger to life or health);
- Greatest volcanism in >500 million years (Siberian traps) (slow vs. human source, but protracted);
- CO_2-induced warmth, fertilization from basalt breakdown, sulfur from volcanoes seem to have contributed to anoxia and euxinia (H_2S) of ocean.



Yadong Sun et al., 2012, Lethally hot temperatures during the early Triassic greenhouse, Science 338, 366.



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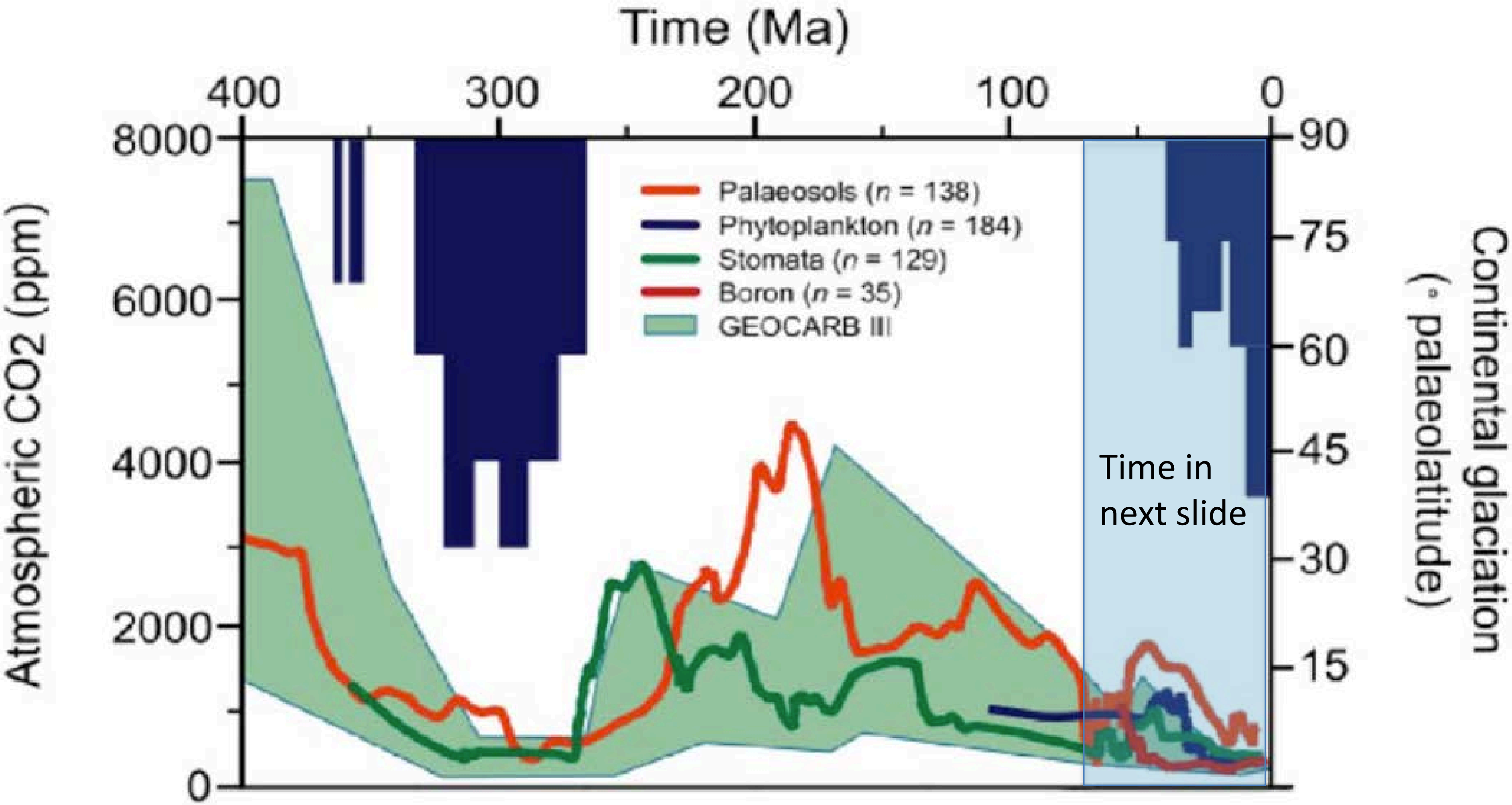

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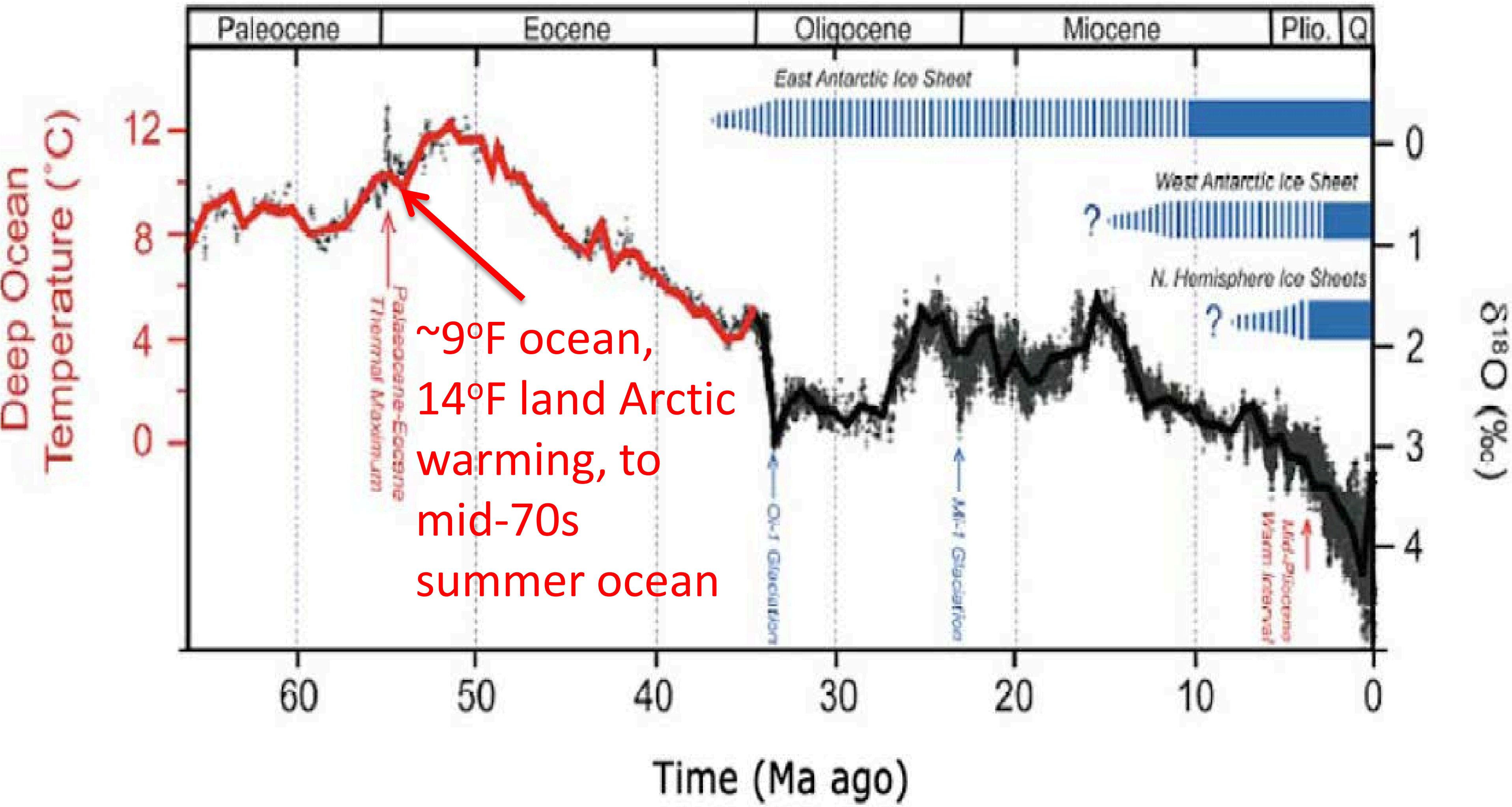


Figure 3.8. Global compilation of more than 40 deep sea benthic δ18O isotopic records taken from Zachos et al. (2001), updated with high-resolution Eocene through Miocene records from Billups et al. (2002), Bohaty and Zachos (2003), and Lear et al. (2004). Dashed blue bars, times when glaciers came and went or were smaller than now; solid blue bars, ice sheets of modern size or larger. (Figure and text modified from IPCC Chapter 6, Paleoclimate, Jansen et al., 2007.)

Events—Paleocene-Eocene Thermal Maximum

- Strong isotopic anomaly—formerly-living (isotopically light) CO_2 source (maybe at least partly CH_4, but event long enough to shift to CO_2);
- Widespread few-degree warming; models have trouble simulating as much warming as occurred;
- Acidic ocean (sea-floor dissolution & extinction);
- Many more effects—enhanced insect damage, plant and animal migration, animal dwarfing;
- Too short-lived to be caused by drifting continents, etc., probably some coincidences involved (nothing else this big for LONG times!);
- Recovery time matches carbon-cycle models well;

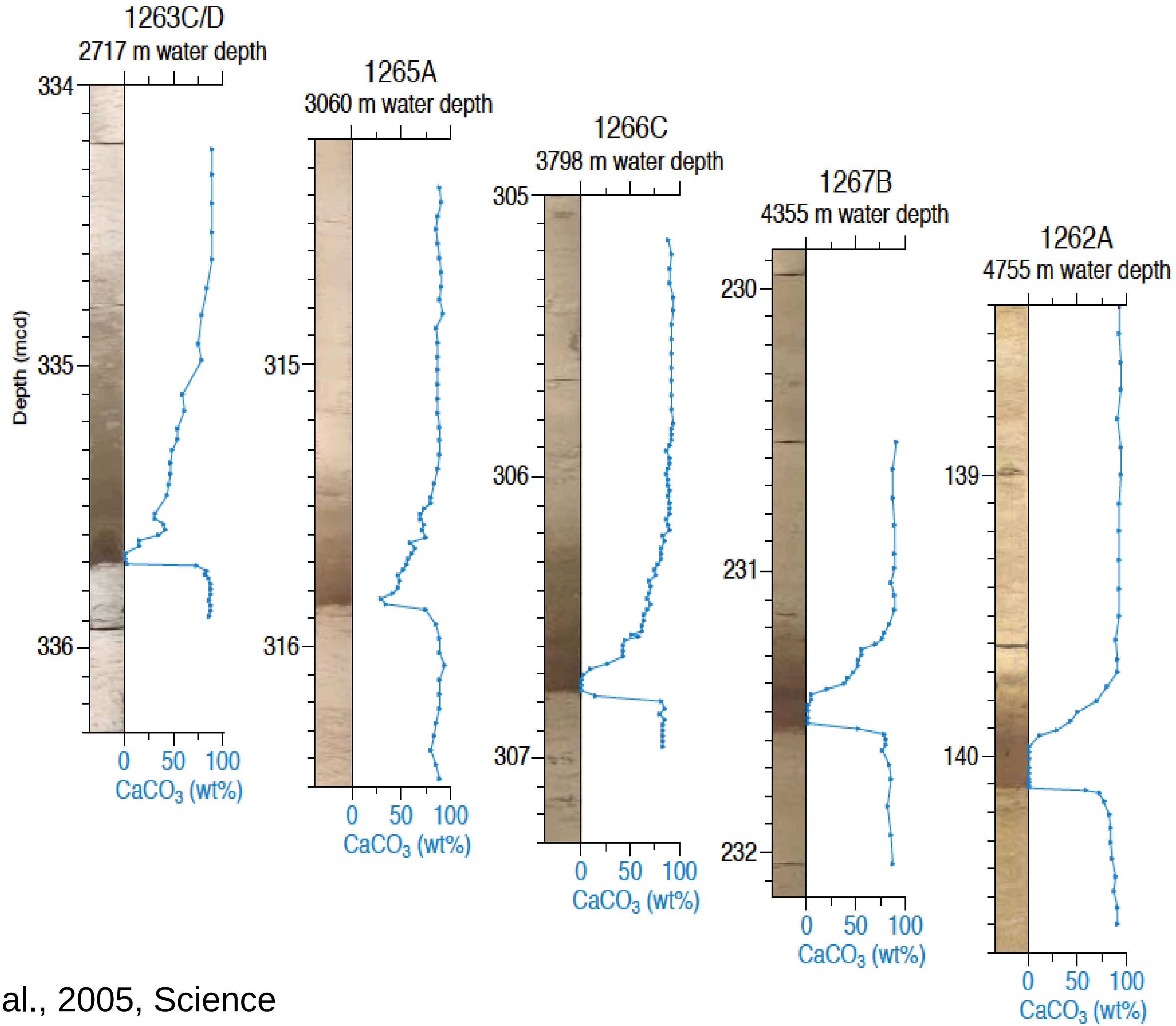
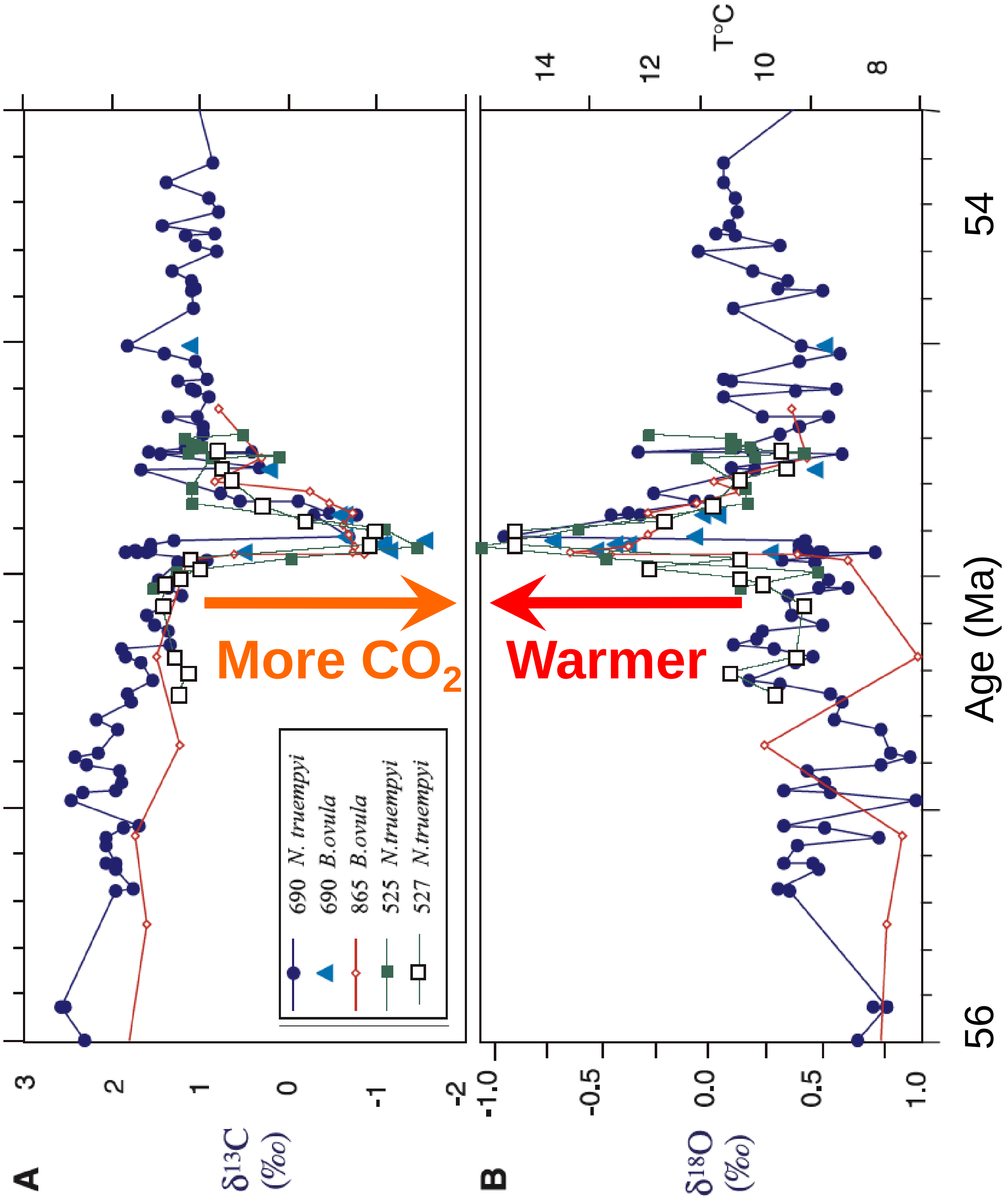


Fig. 1. Digital core photos and weight % $CaCO_3$ content plotted versus meters of composite depth (MCD) across the P-E boundary interval at ODP sites 1262 (hole A), 1263 (hole C/D), 1265 (hole A), 1266 (hole C), and 1267 (hole B) on Walvis Ridge (fig. S1) (*18*). Records are plotted from left to right in order of increasing water depth. The core photos for each site represent composites of the following sections: 1262A-13H-5 and -6; 1263C-14H-1 and core catcher (CC); 1263D-4H-1 and -2; 1265A-29H-6 and -7; 1266C-17H-2, -3, and -4; 1267B-23H-1, -2, and -3.

Zachos et al., 2005, Science

Still much slower than human release; maybe a similar amount.



Zachos et al., 2001, Science, PETM

The LPTM as recorded in benthic d13C and d18O records (A and B, respectively) from Sites 527 and 690 in the south Atlantic (73), and Site 865 in the western Pacific (26). The time scale is based on the cycle stratigraphy of Site 690 (30) with the base of the excursion placed at 54.95 Ma. The other records have been correlated to Site 690 using the carbon isotope stratigraphy. Apparent leads and lags are artifacts of differences in sample spacing. The oxygen isotope values have been adjusted for species-specific vital effects (118), and the temperature scale on the right is for an ice-free ocean. The negative carbon isotope excursion is thought to represent the influx of up to 2600 Gt of methane from dissociation of seafloor clathrate (111).

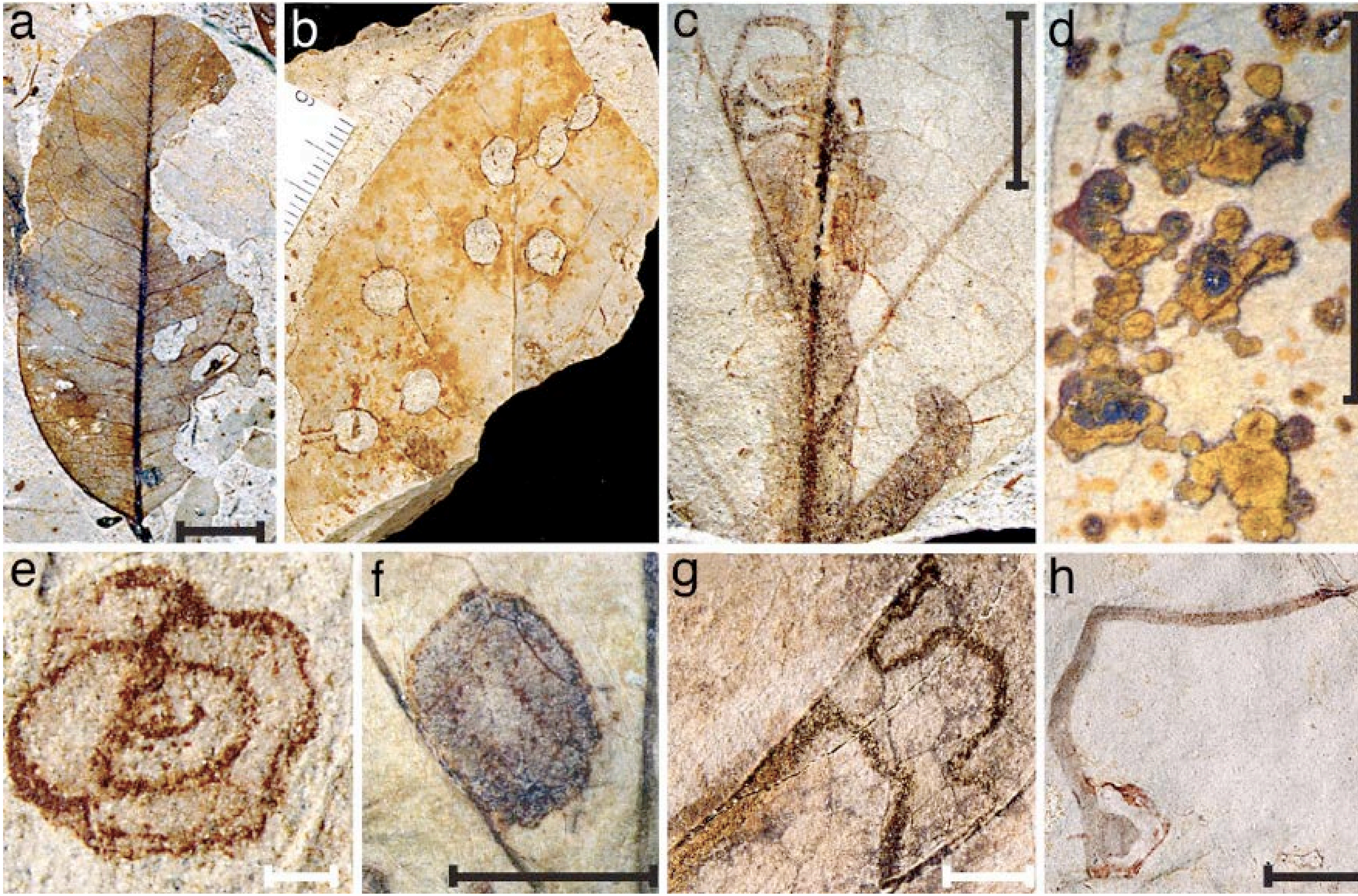
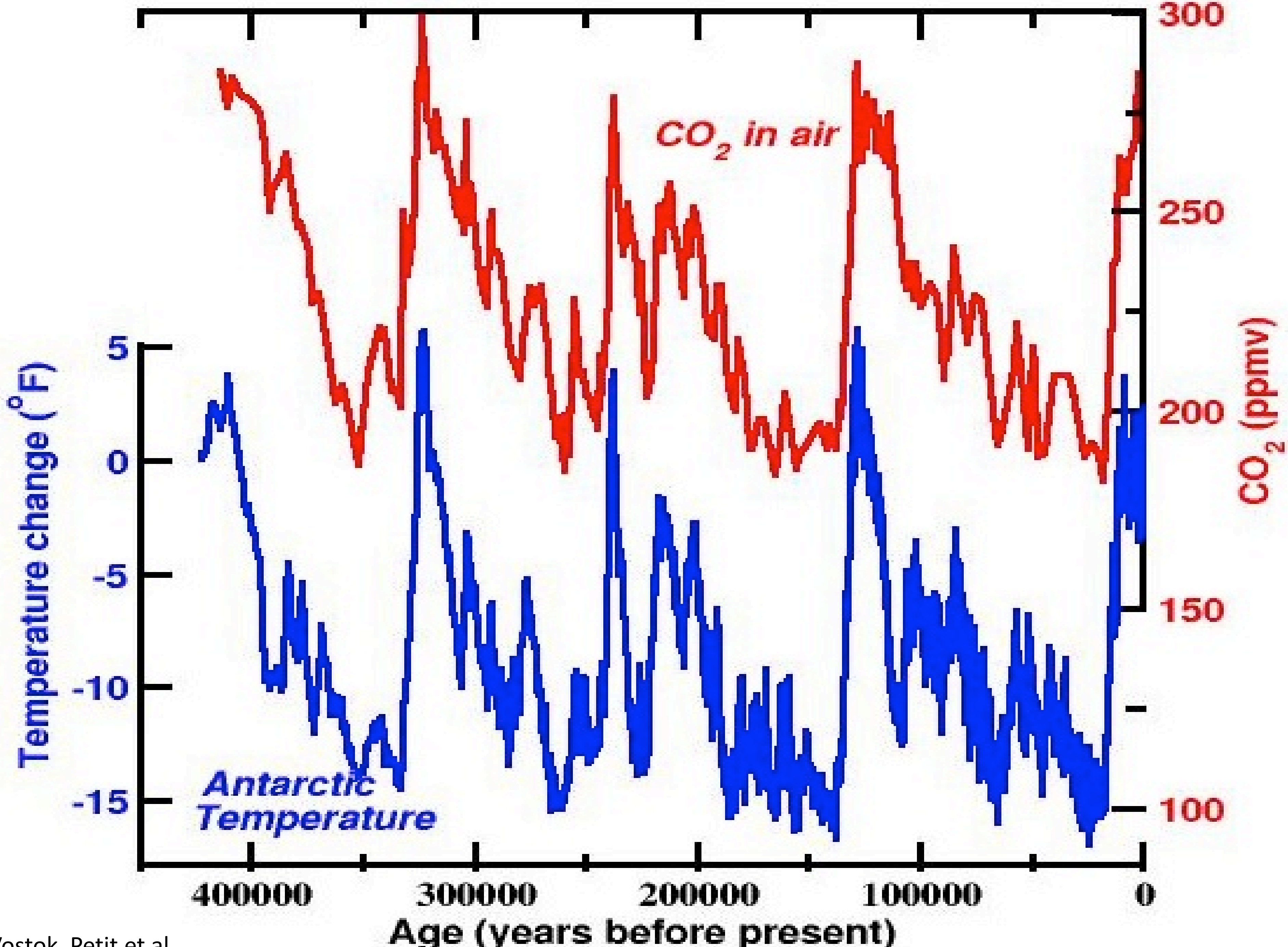


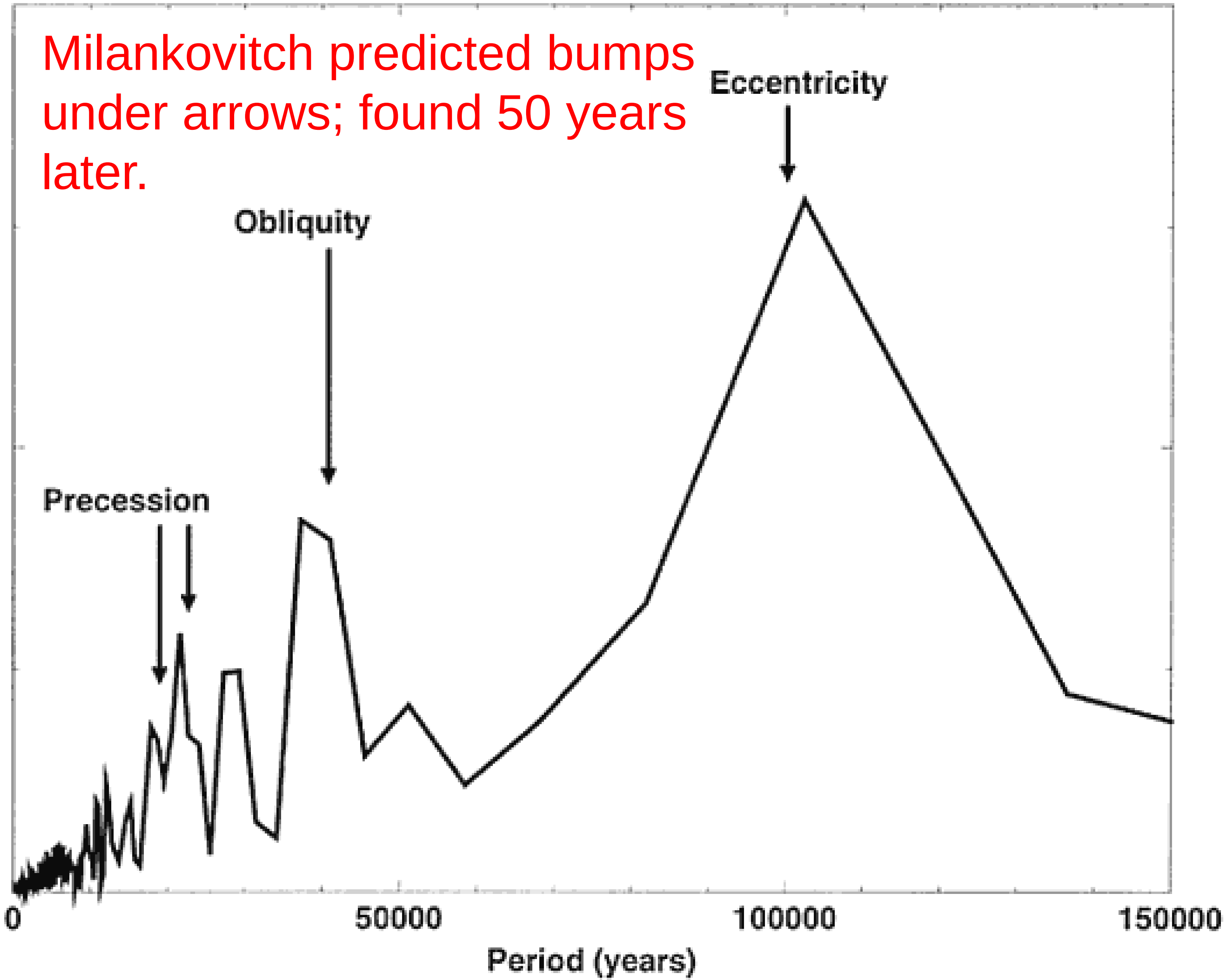
Fig. 1. Representative insect damage diversity on PETM leaves. (a) Dicot sp. WW007 (Fabaceae) leaf about one-third consumed by insect herbivores (USNM 530967). (b) Characteristic large, circular hole-feeding (DT4) found only on dicot sp.WW006(530968). (c) Serpentine mine with a solid frass trail becoming massive (DT43) on an unidentifiable dicot (530969). (d) Polylobate to clustered galls (DT125) on dicot sp. WW007 (Fabaceae, 530970). (e) Blotch mine with a sinusoidal frass trail (DT37) on dicot sp. WW003 (530971). (f) Blotch mine with distinct coprolites and terminal chamber (DT35) on dicot sp. WW006 (530972). (g) Serpentine mine with a solid frass trail (DT43) on dicot sp. WW004 (530973). (h) Semilinear serpentine mine with terminal chamber (DT40) on dicot sp. WW005 (530974). (Scale bars: white, 1 mm; black, 5 mm.) Currano et al., 2008, PNAS (>5000 fossil leaves, Wyoming)

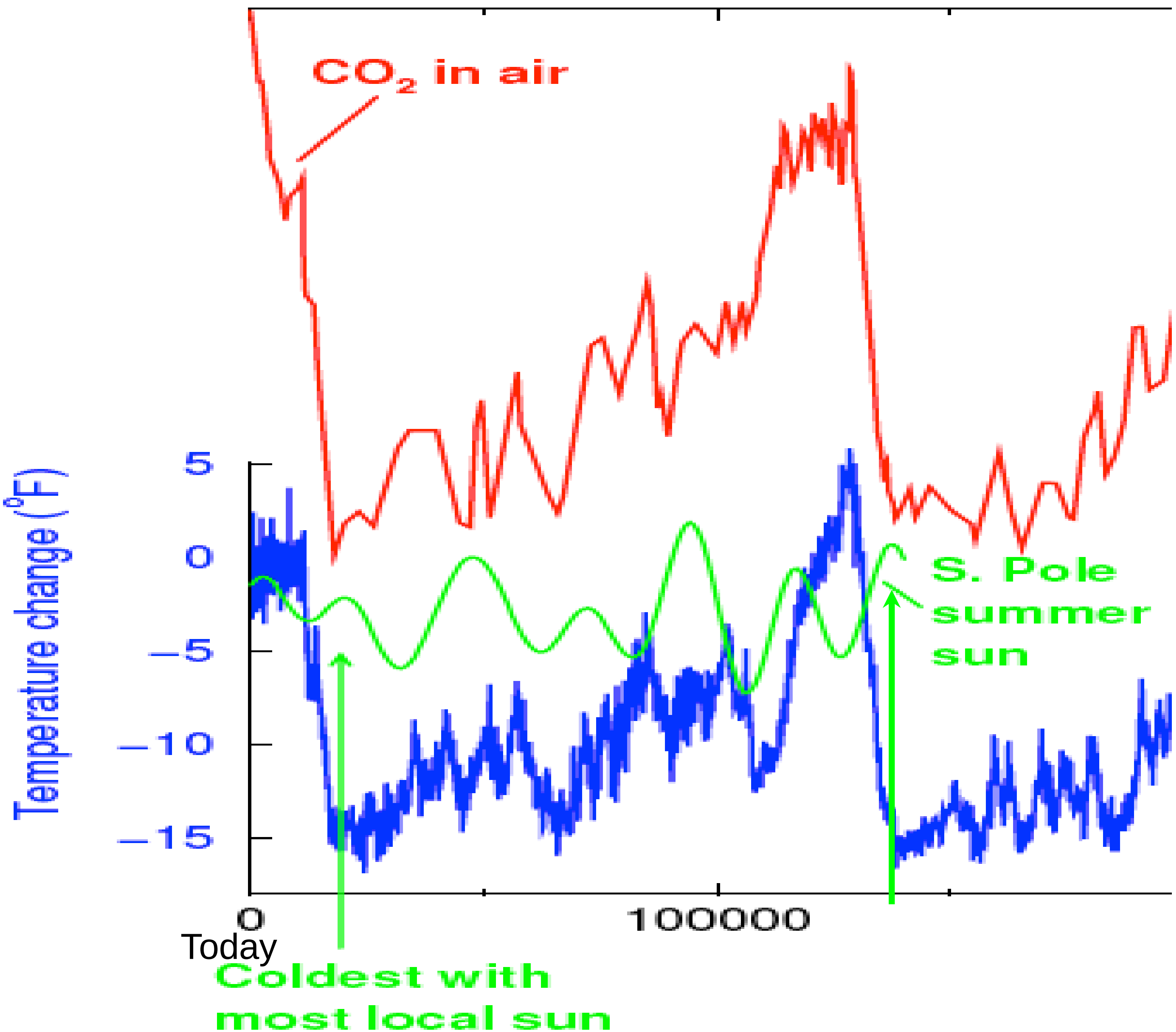


Vostok, Petit et al.

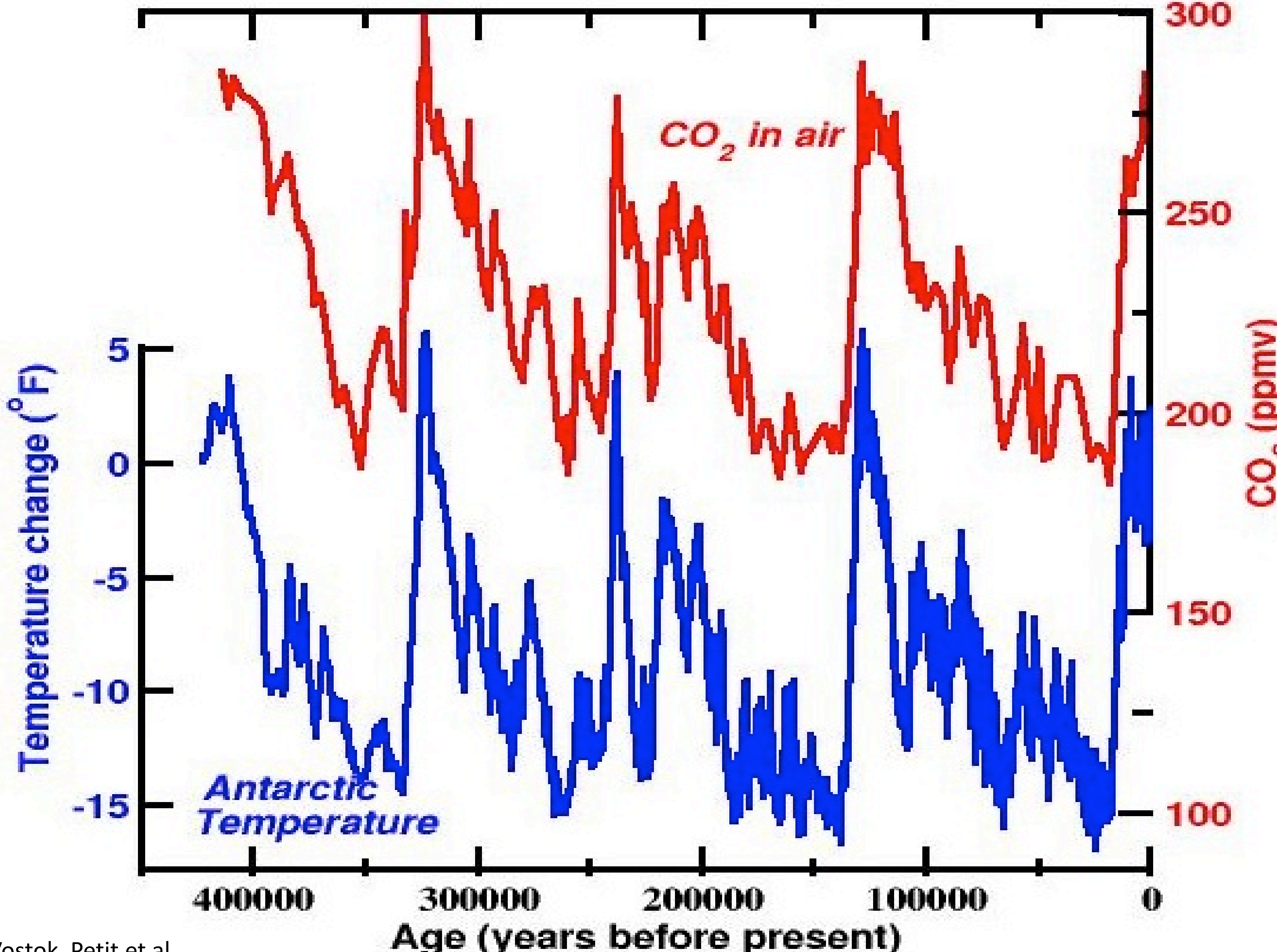
FFT of Vostok $\delta^{18}O$ data

Petit et al., 1999





Petit et al., 1999



Vostok, Petit et al.

So, where does that leave us?

- If higher CO_2 warms, climate history is sensible, and CO_2 caused or amplified most main changes;
- There is now no plausible alternative to this;
- If higher CO_2 doesn't warm, we must explain how physicists are so wrong, and how so many suddenly-unexplained events happened;
- CO_2 may be forcing or feedback—air is warmed by a CO_2 molecule regardless of how it got there;
- Paleoclimatic data show climate sensitivity similar to values in modern models (~3°C for doubled CO_2), perhaps with somewhat higher values over centuries or millennia especially in polar regions.

So, where does that leave us?

- Lots of knobs control the Earth's climate system;
- "Sun" knob isn't twiddled much over short times, and ineffective over long times because of CO_2;
- Magnetic-field, cosmic-ray, space-dust, other "space" knobs not shown to matter, and no more than fine-tuning (except very rare dinosaur-killer)
- Much on Earth matters regionally—a continent cools going from equator to pole, and North Atlantic ocean circulation is important—but global effect weak except through CO_2;

So, where does that leave us?

- The biggest of the past changes are on the same scale as what we might do in next centuries;
- Except for dinosaur-killer, from best estimates, if we keep burning fossil fuels (business as usual) we will change climate faster than nature did
- Slower, similar-sized natural changes had huge impacts on living things, often killing them

So, where does that leave us?

- Nature has always had fires, but arson exists
- We want arson investigators to understand natural fires, to tell the difference
- Understanding past climate changes increases confidence that humans are primarily driving now
- *A*nd increases confidence that we will have huge impacts on the Earth if we don't start moving away from fossil fuels
- Much to learn! But, the complex history of Earth's climate points to the power of human CO_2 release.