Natural Climate Change

Lecture 4: Fundamentals of Energy and Mineral Resources

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2017

Read Eddy and Bond papers on blackboard

Biggest worry is climate change

Steps to solve any problem:

- Perspective
- Observations

This Lecture (L4)

- Understanding
- Predictions
- Proscription

Lecture 5

- Challenges

Lecture 6

PERSPECTIVE

Climate requires **time** Perspective

- Geologic history (4.56 billion years) is to all of recorded human history (6 thousand years) as 1 day is to the last 0.1 seconds of that day: We must use geological evidence to gain perspective.

4.56 Ga	Solar System	24 hrs
3.8	Amitsog Gneiss	20 hrs
0.57	Skeletal Creatures	3 hrs
0.066	Dinosaurs Extinct	21 min
0.050	Tropical England	16 min
0.003	Humanoids	1 minute
0.000006	Recorded History	0.1 sec

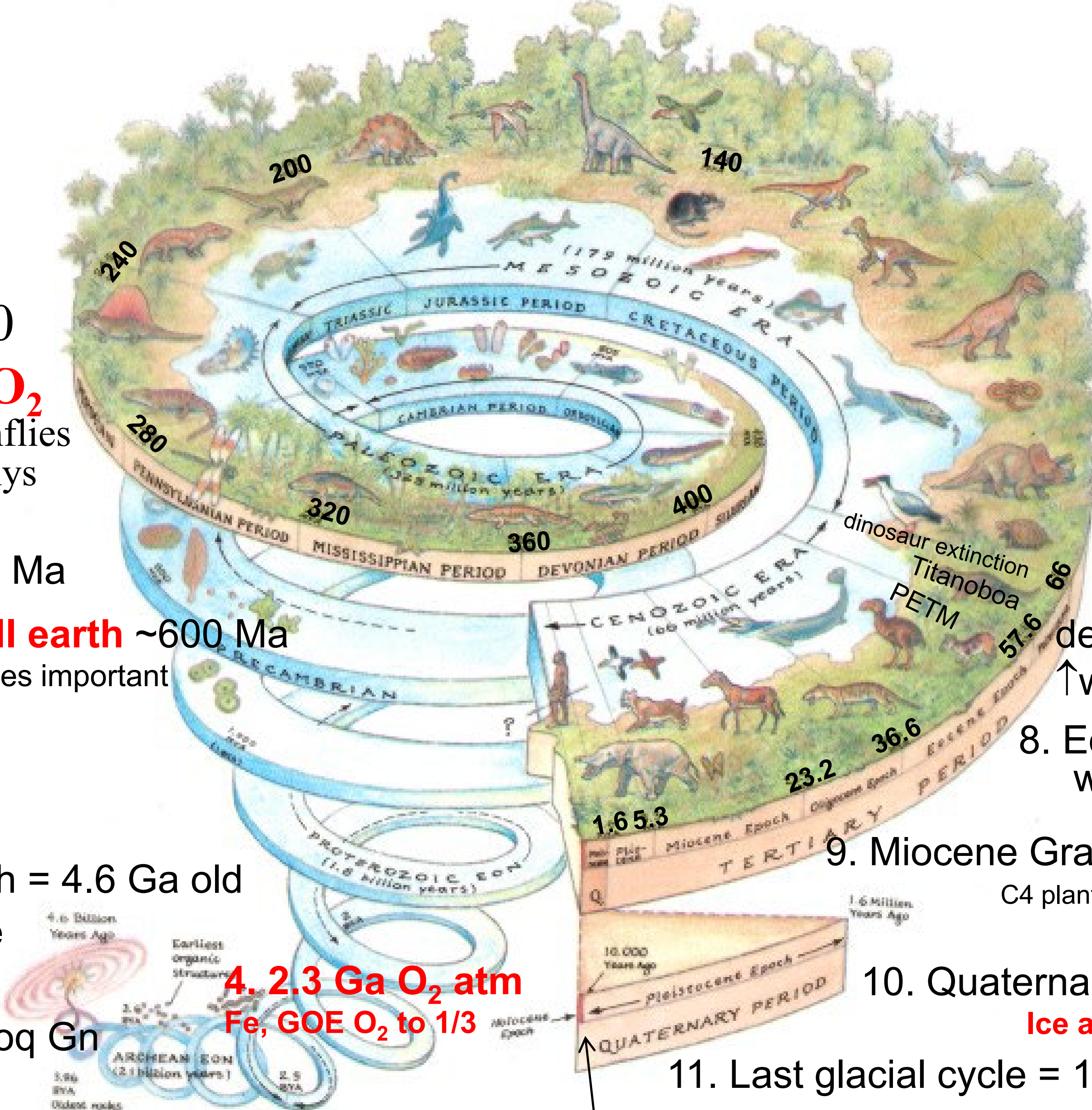
7. 340-260

35 vol% O_2

70 cm dragonflies
coal, oil, Tethys

6. Life~550 Ma

5. **Snowball earth** ~600 Ma
O_2 ↑, sulfates important



Cocoliths shift carbonate deposition to oceans

deciduous trees
↑weathering

8. Eocene 50 Ma
warm

9. Miocene Grasses ↓erosion
C4 plants, decreasing CO_2,T

1. Earth = 4.6 Ga old

2. Fe core

3. 3.8 Amitsoq Gn

4. 2.3 Ga O_2 atm
Fe, GOE O_2 to 1/3

10. Quaternary = humans
Ice ages

11. Last glacial cycle = 100 ka

12. Holocene = last 10,000 yrs

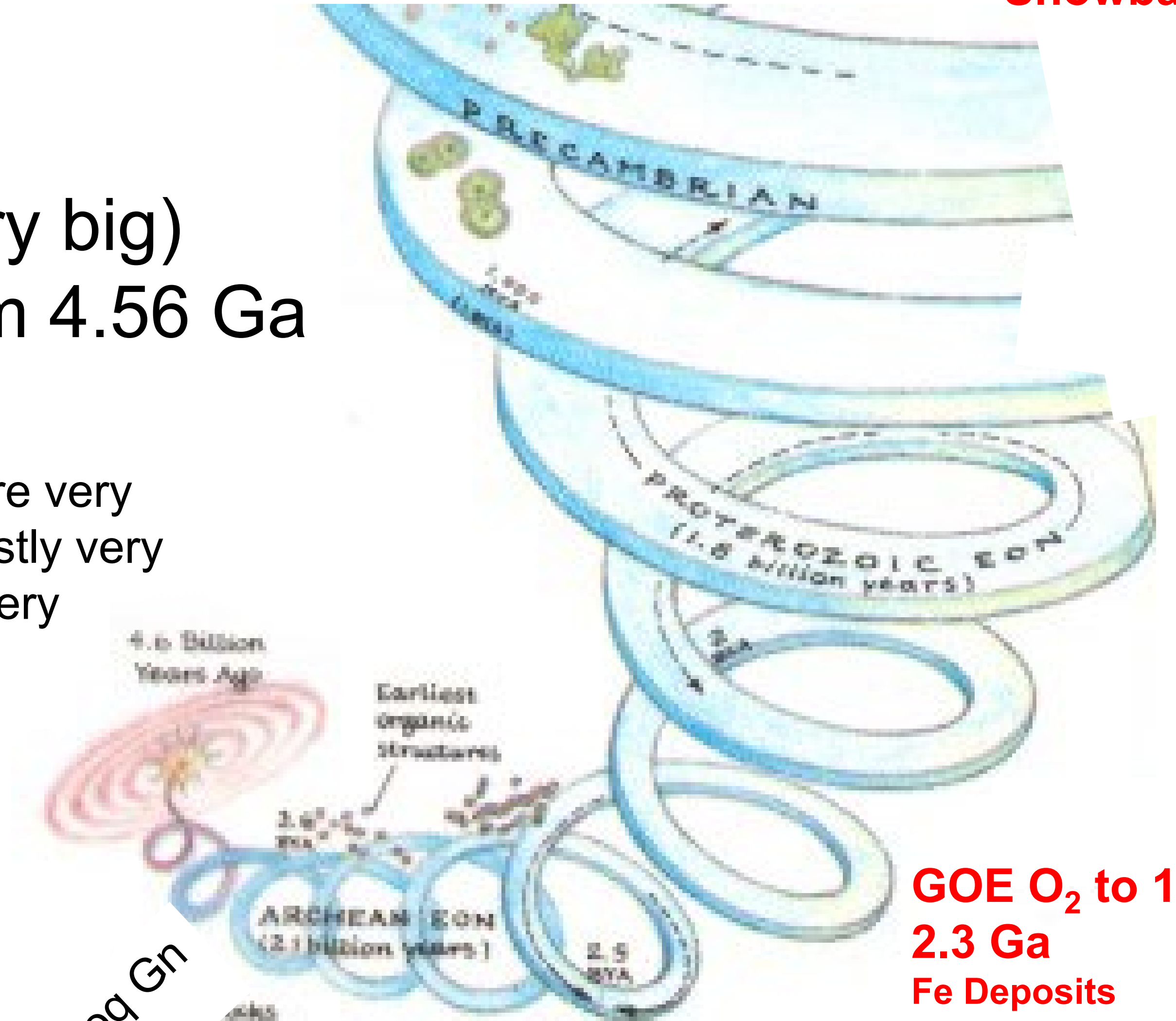
Outline

- Formation to Cambrian (Snowball Earth)
- Cambrian to first ice age cycles
- The ice age cycles (Quaternary)
- The Holocene (our current interglacial)

Changes to the Cambrian

Only 2 (very big) events from 4.56 Ga to ~0.6 Ga

Changes were very slow and mostly very boring until very recently.



Snowball earth

GOE O_2 to 1/3 present
2.3 Ga
Fe Deposits

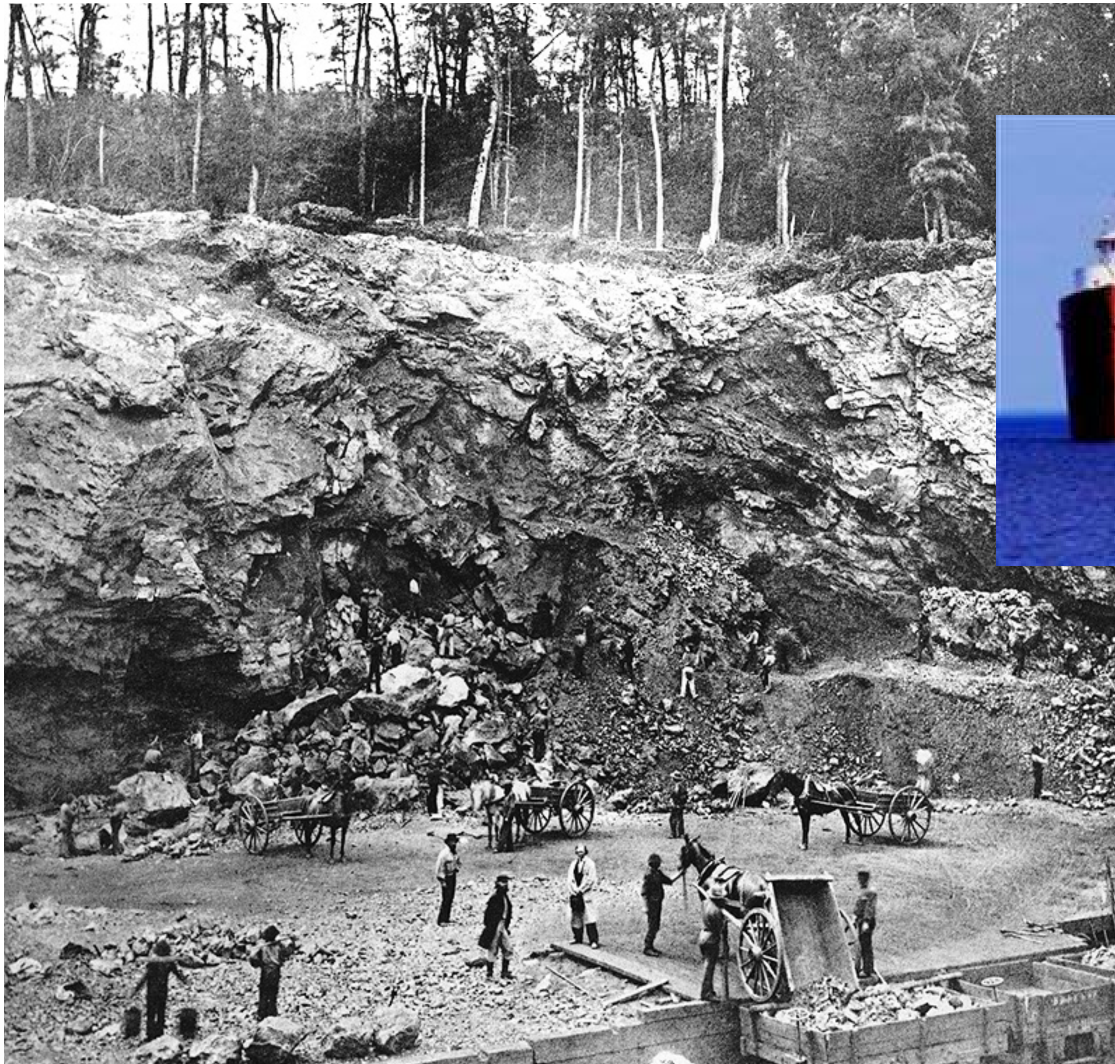
3.8 Ga Amitsoq Gn

3.8 Ga Amitsoq Gneiss, Greenland

Metamorphosed volcanics, sediments, banded ironstones, and conglomerates

GOE O_2 to 1/3 present
2.3 Ga
Fe Deposits

Lake Superior Iron Ore

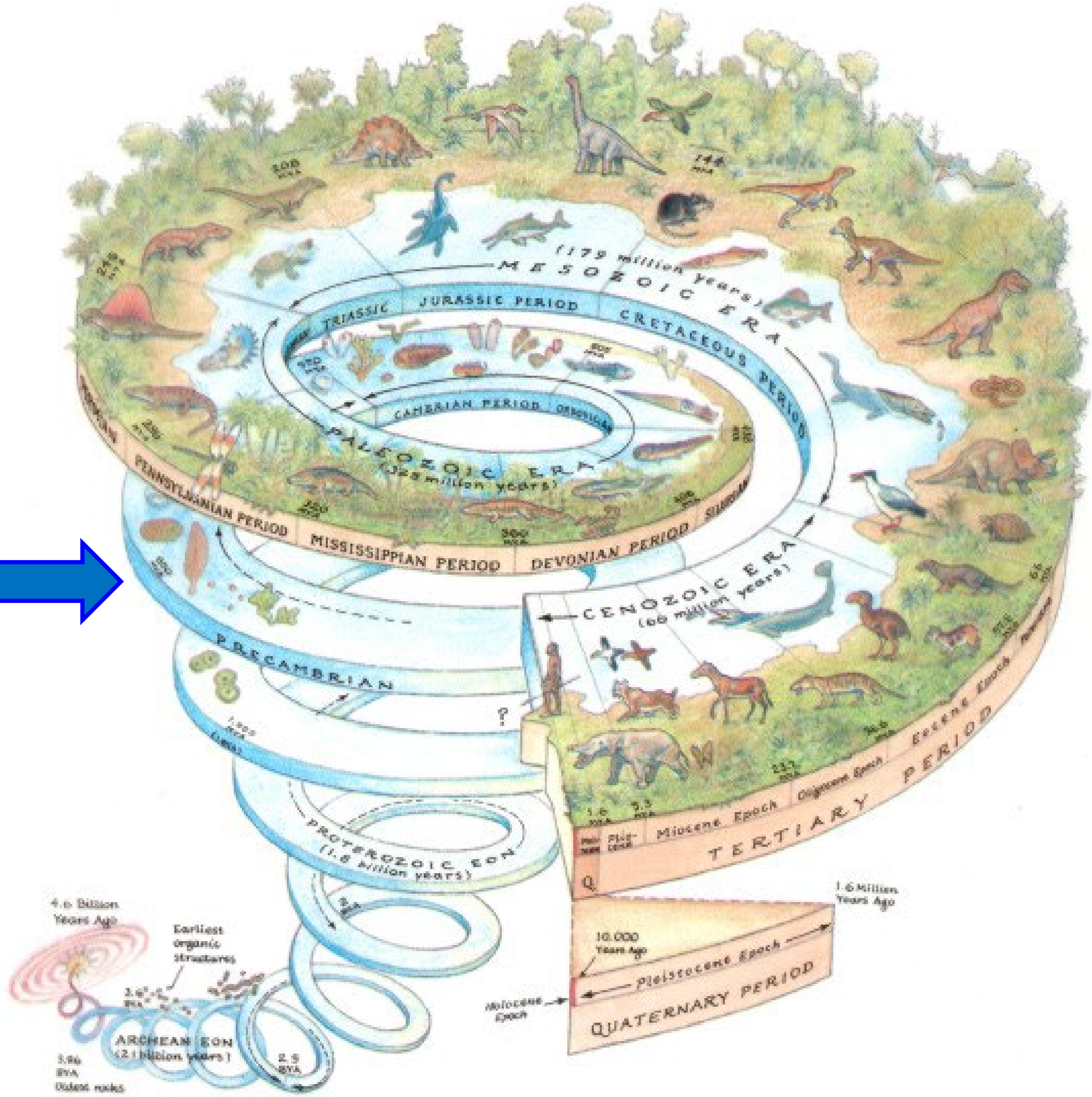


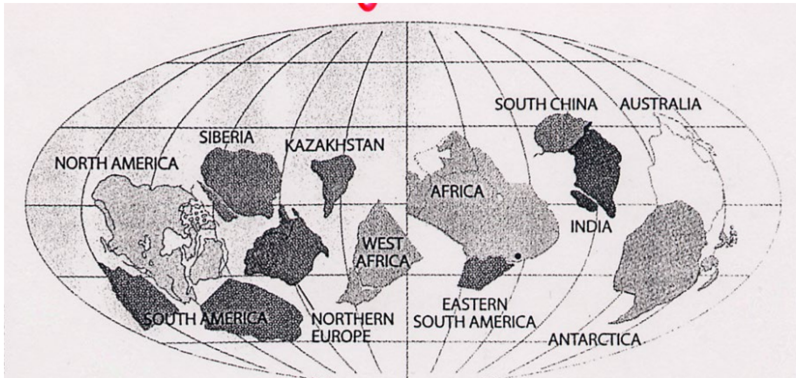
Leaching of the continents
by oxygenated atmosphere

Snowball earth

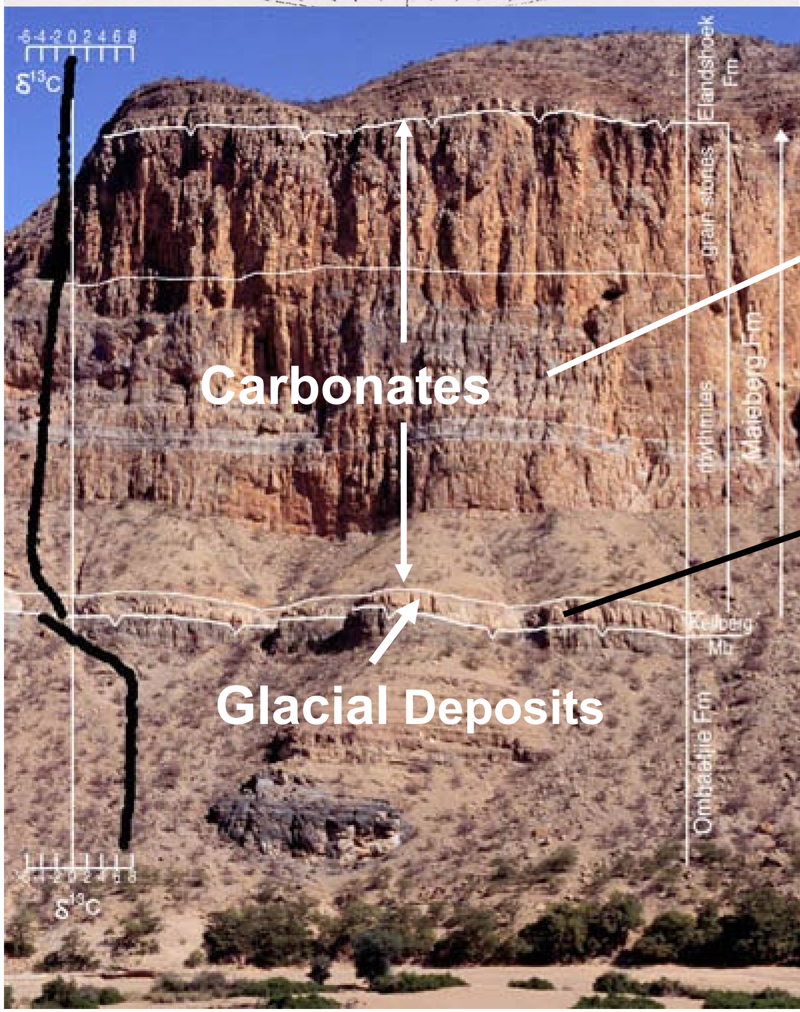
~700 ma

Then all hell broke loose starting with snowball earth





Hoffman & Schrag, Jan 2000. *Scientific American*



5. **Snowball earth** ~600 Ma

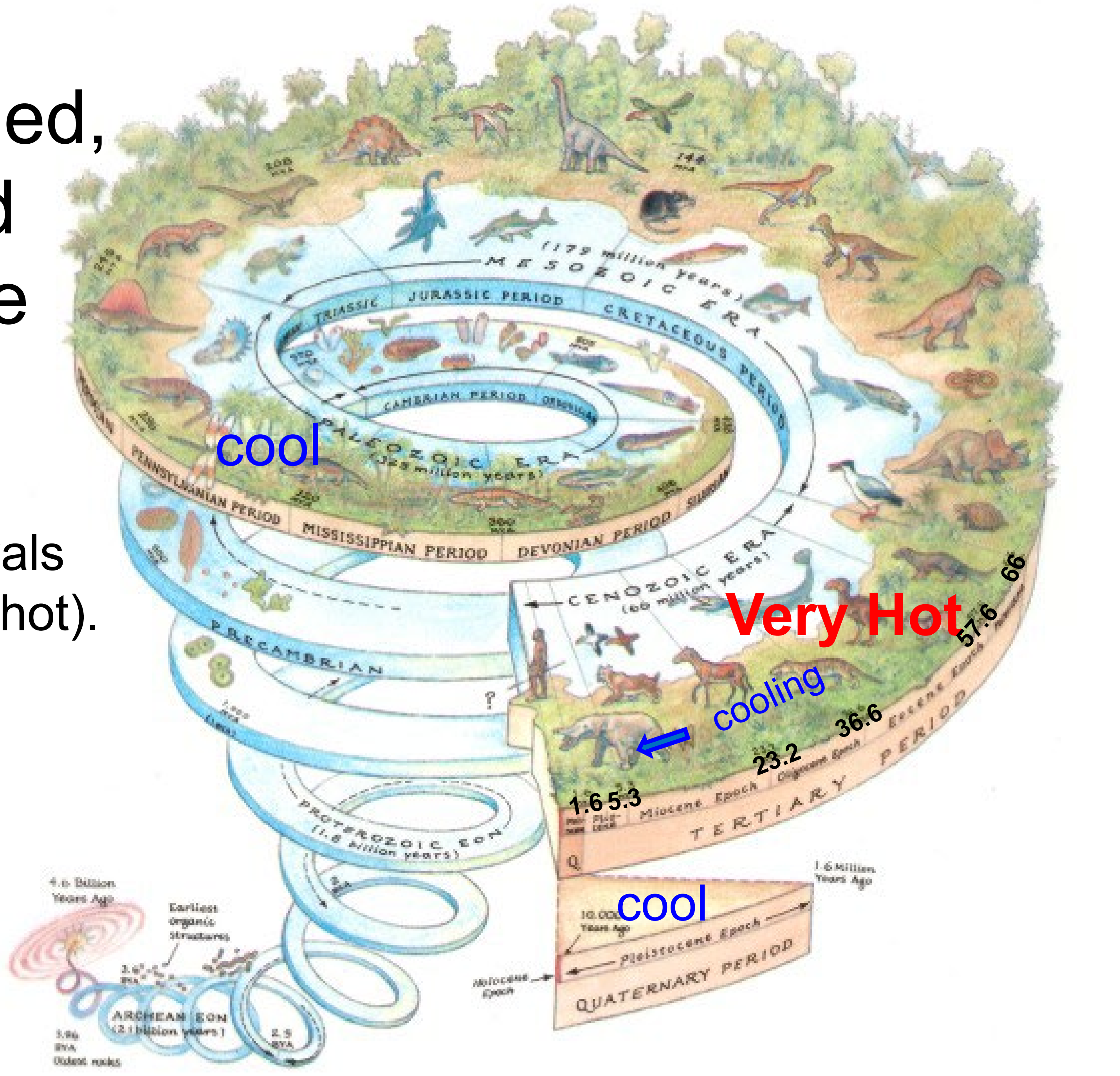
O_2 ↑, sulfates important

"Rock Layer that represents the abrupt end Of a 700-million-year old snowball [earth] event. Pure carbonate layers stacked above the glacial deposits precipitated in the warm shallow seas of the hothouse aftermath [of a completely frozen earth]." 4-5 cycles of –50°C to +50°C may have bread super-adaptable biota and triggered the explosive evolution that followed.

Phanerozoic

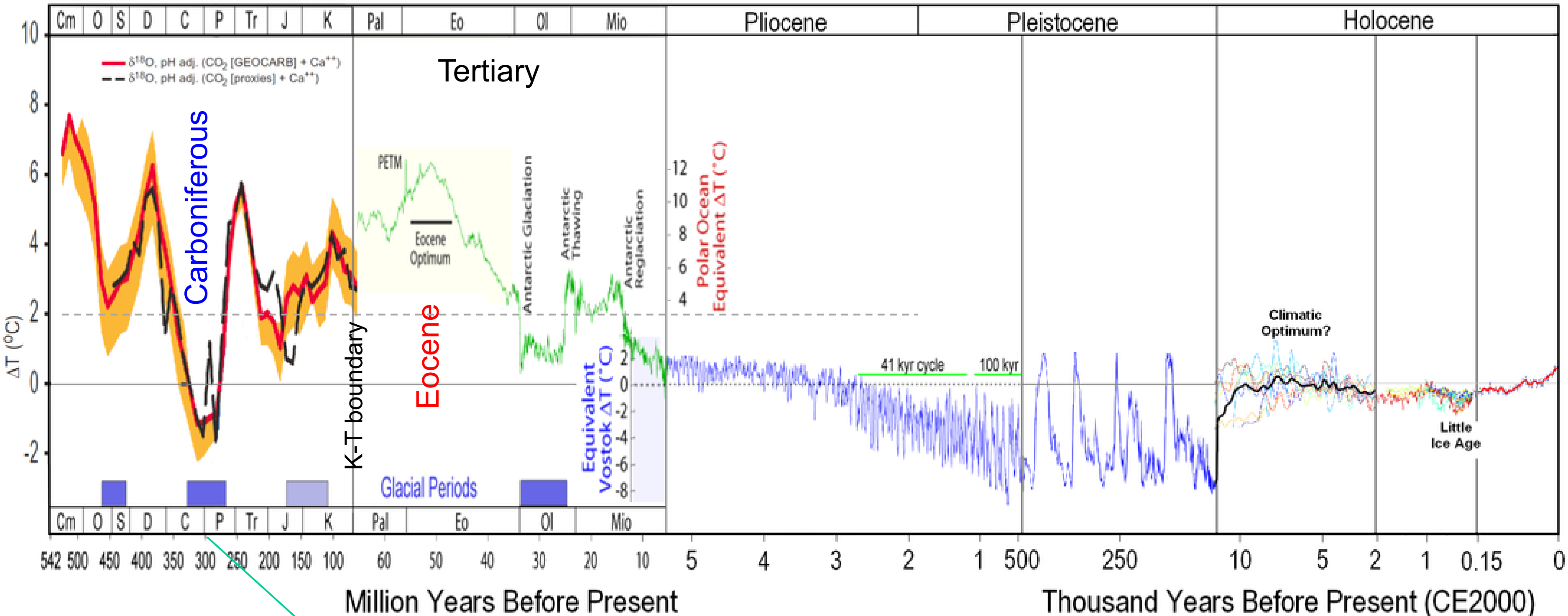
Life Exploded, climate and atmosphere changed.

T hot (with intervals of cool and very hot).

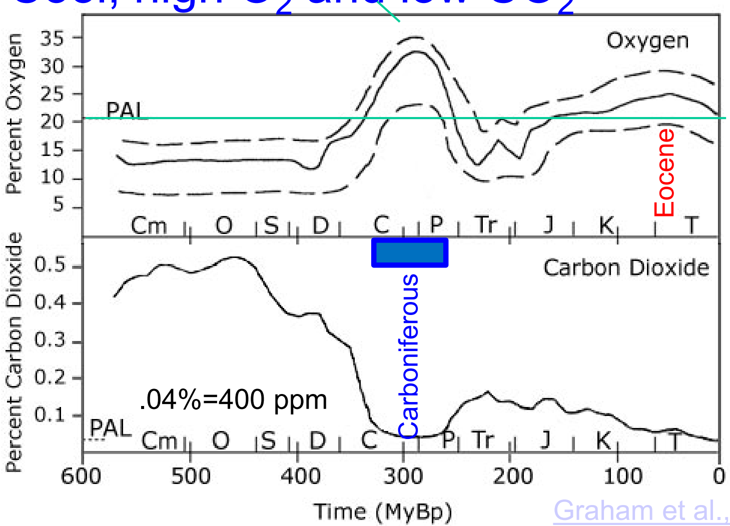


Overview of Phanerozoic

Temperature of Planet Earth

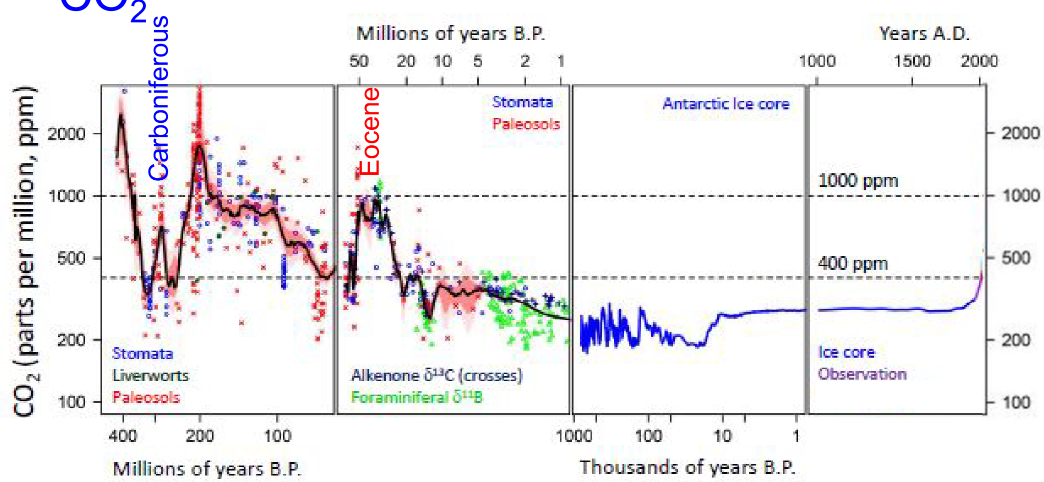


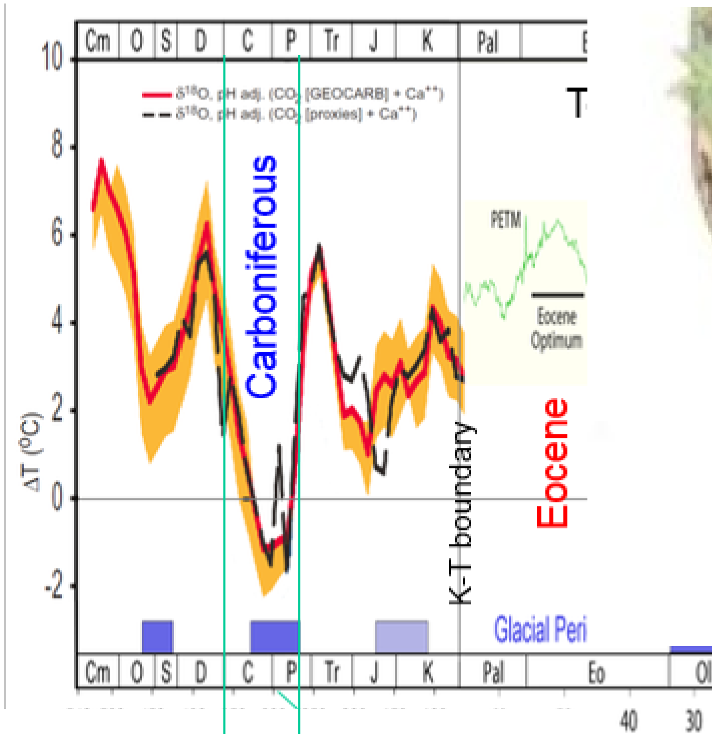
Cool, high O_2 and low CO_2

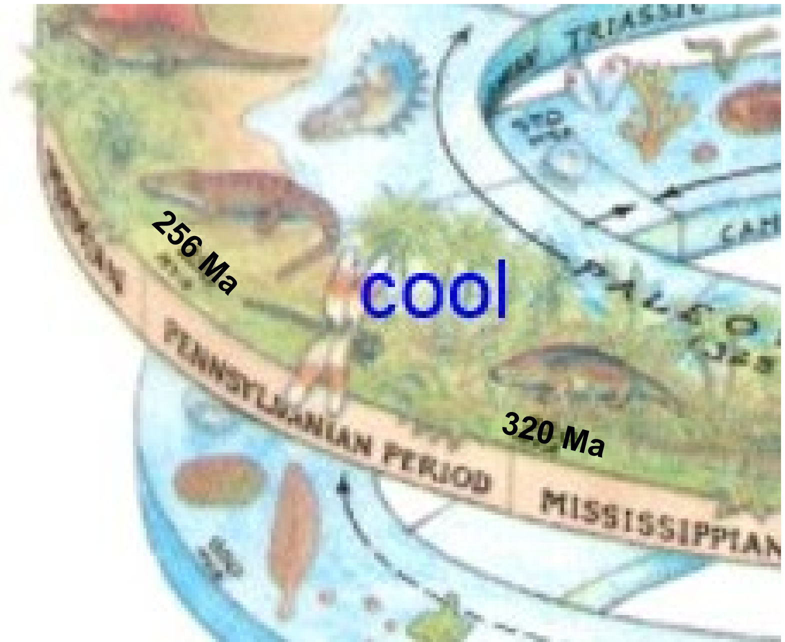


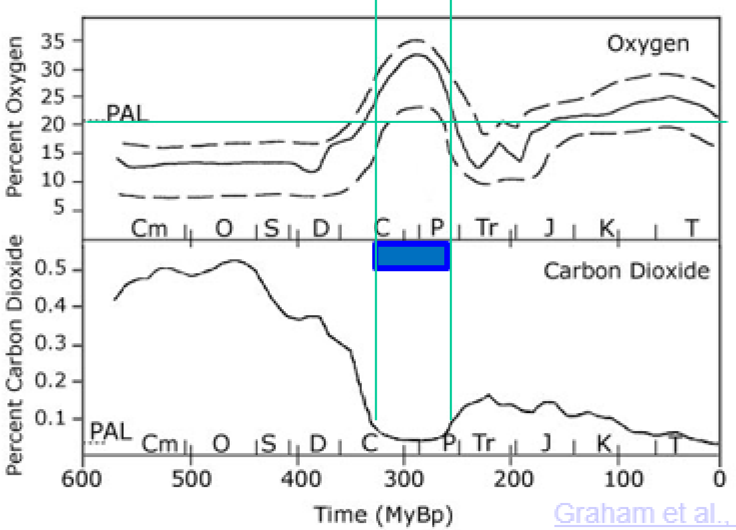
Graham et al., 1997

CO_2









Carboniferous

- Cold, Glaciers
- 35% O_2
- Low CO_2
- **¾ World's Oil and gas**
- Giant Dragon Flies

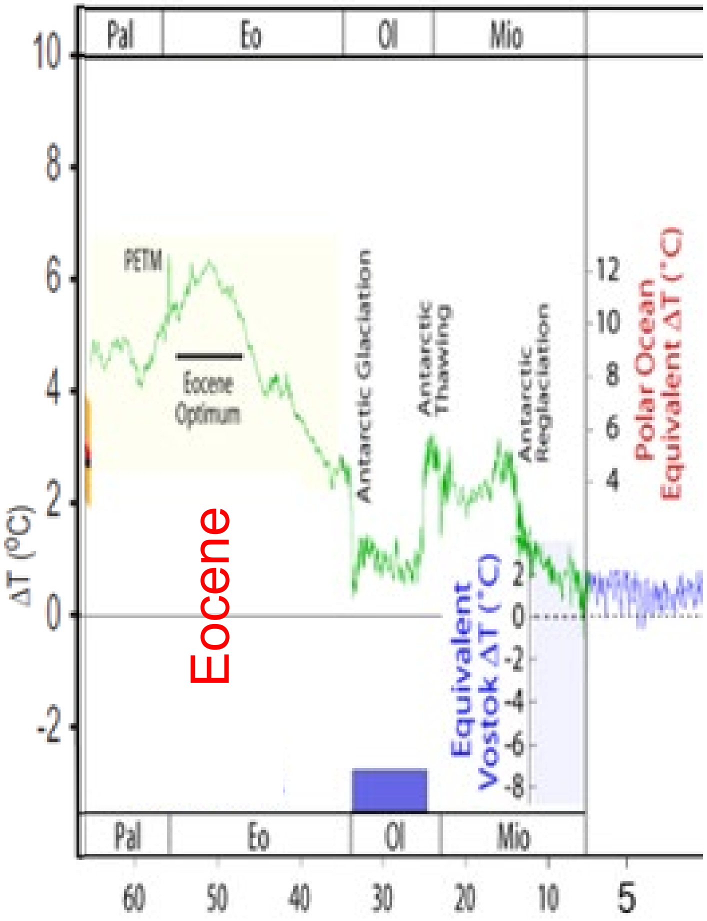
Permo-carboniferous 35% O_2

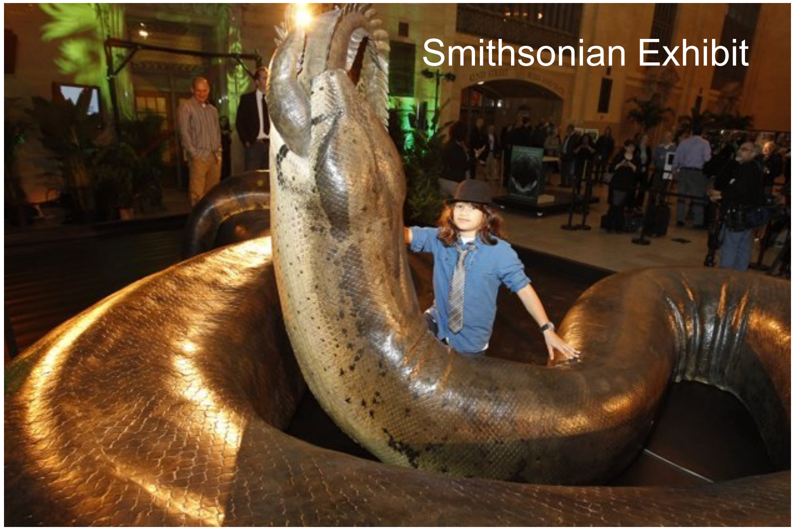
Vascular plants buried C and O_2 increased

340-260 Ma

Eocene (~50 Ma)

- Very Hot
- Sudden thermal spikes (PETM)
- Titanoboa (giant snakes)
- Then cooling

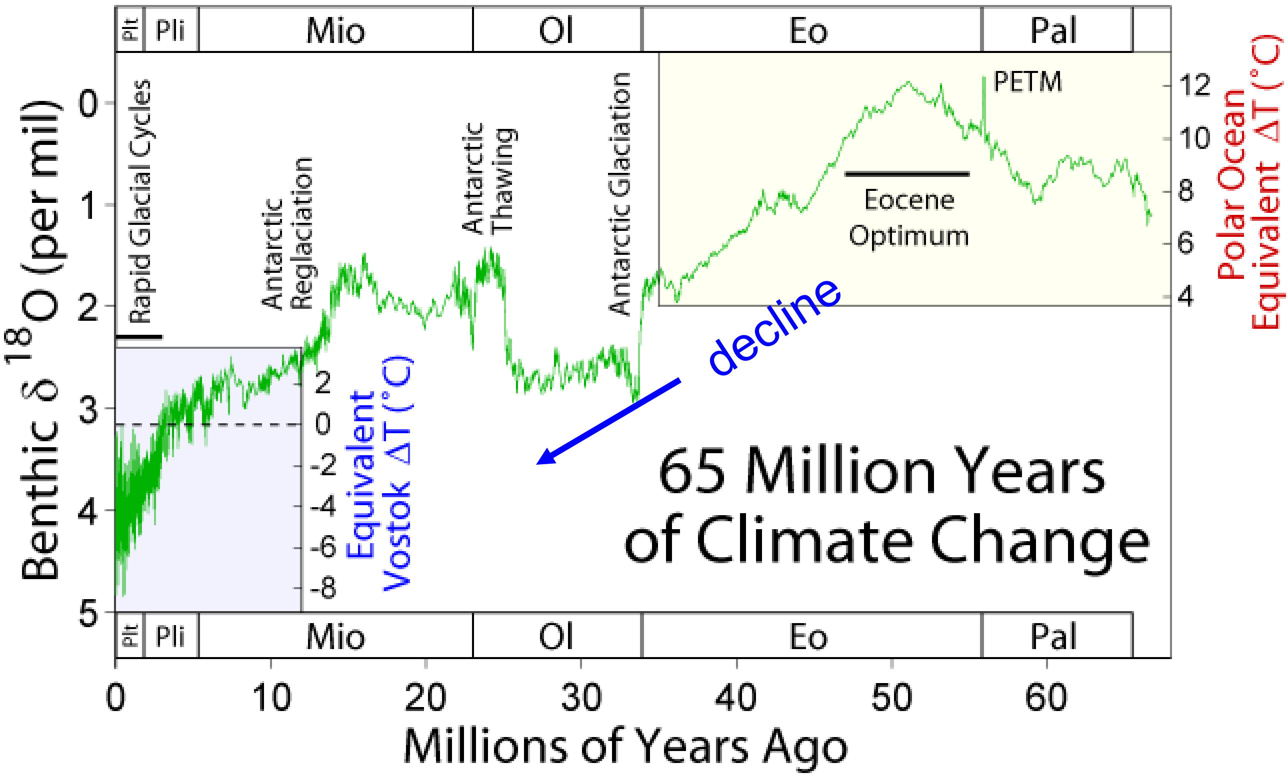




…then Decline into ice ages

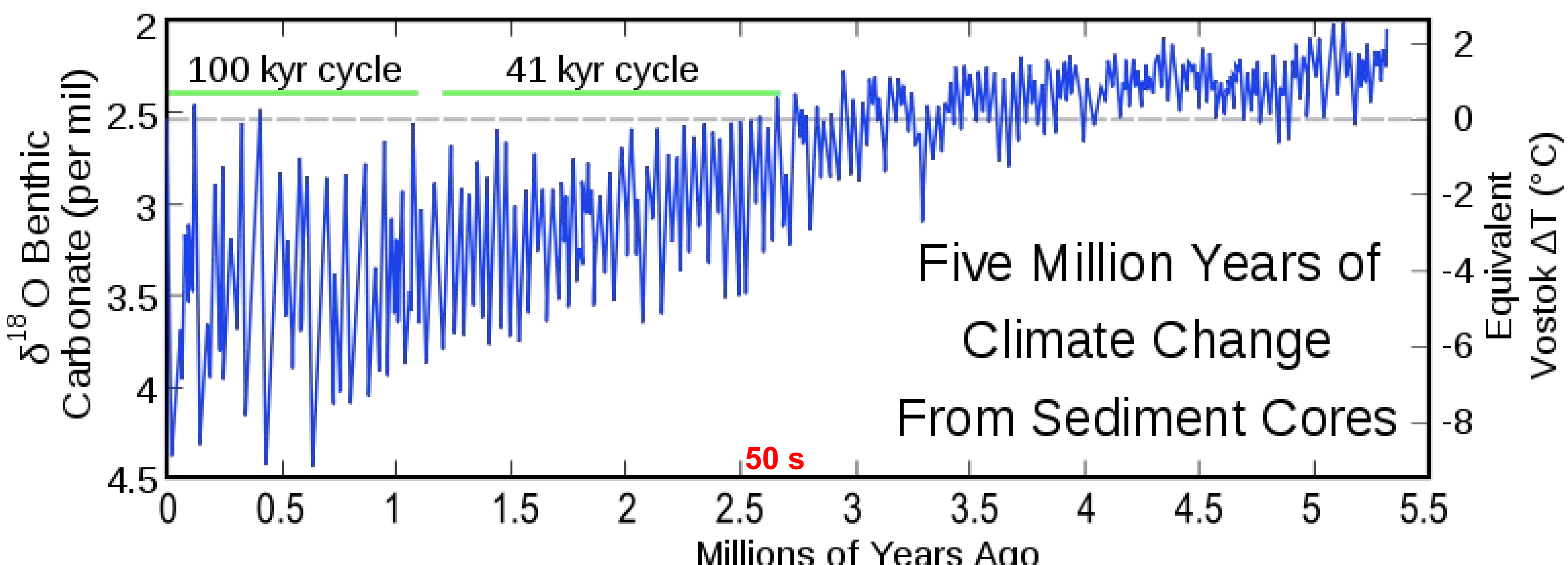
1. High sed. ^{18}O = cold (ice takes up ^{16}O)

2. Present T warmest ~1% of last 2.5 Ma



warm→

Cold →

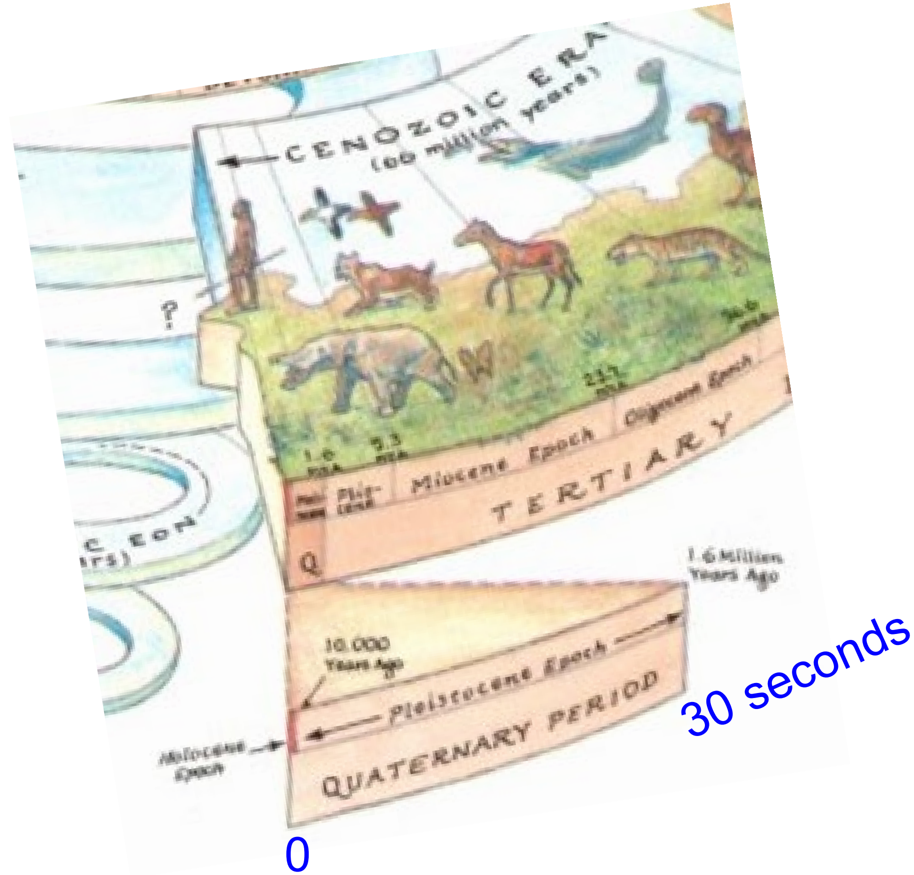


http://en.wikipedia.org/wiki/File:Five_Myr_Climate_Change.png

Pictures from museum in Lucern, Cathles, 2006

The Quaternary

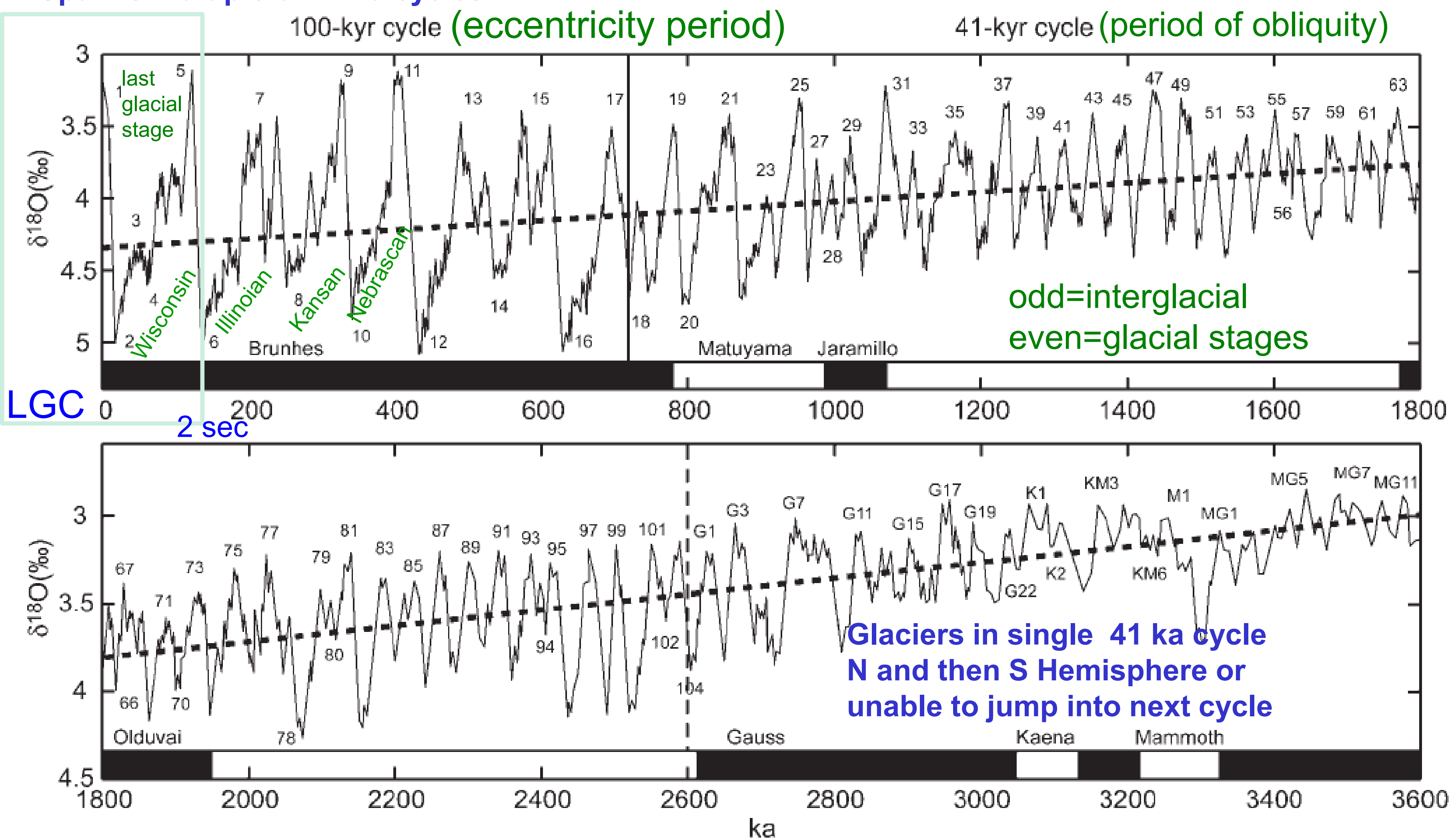
- 100s of glacial cycles
- Appearance of humans



57 stacked benthic marine $\delta^{18}O$ profiles

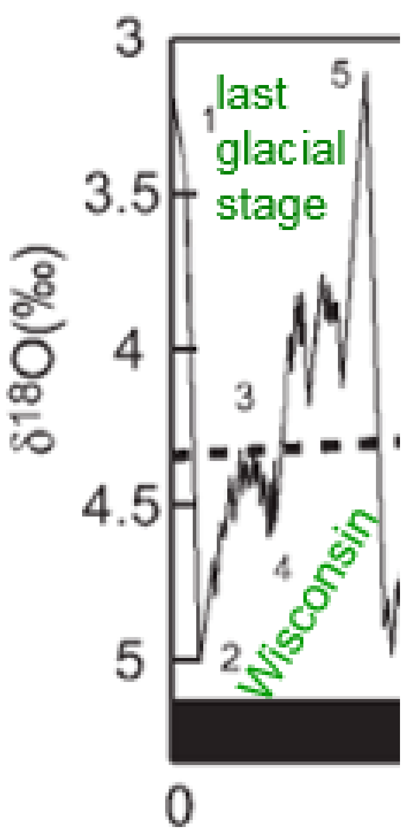
- steady decrease T over 3.6 Ma
- many glacial stages
- shift from 41 to 100 ka period
- getting longer and more severe

Glaciers synchronous in both hemispheres
Span is multiple of 41 ka cycles



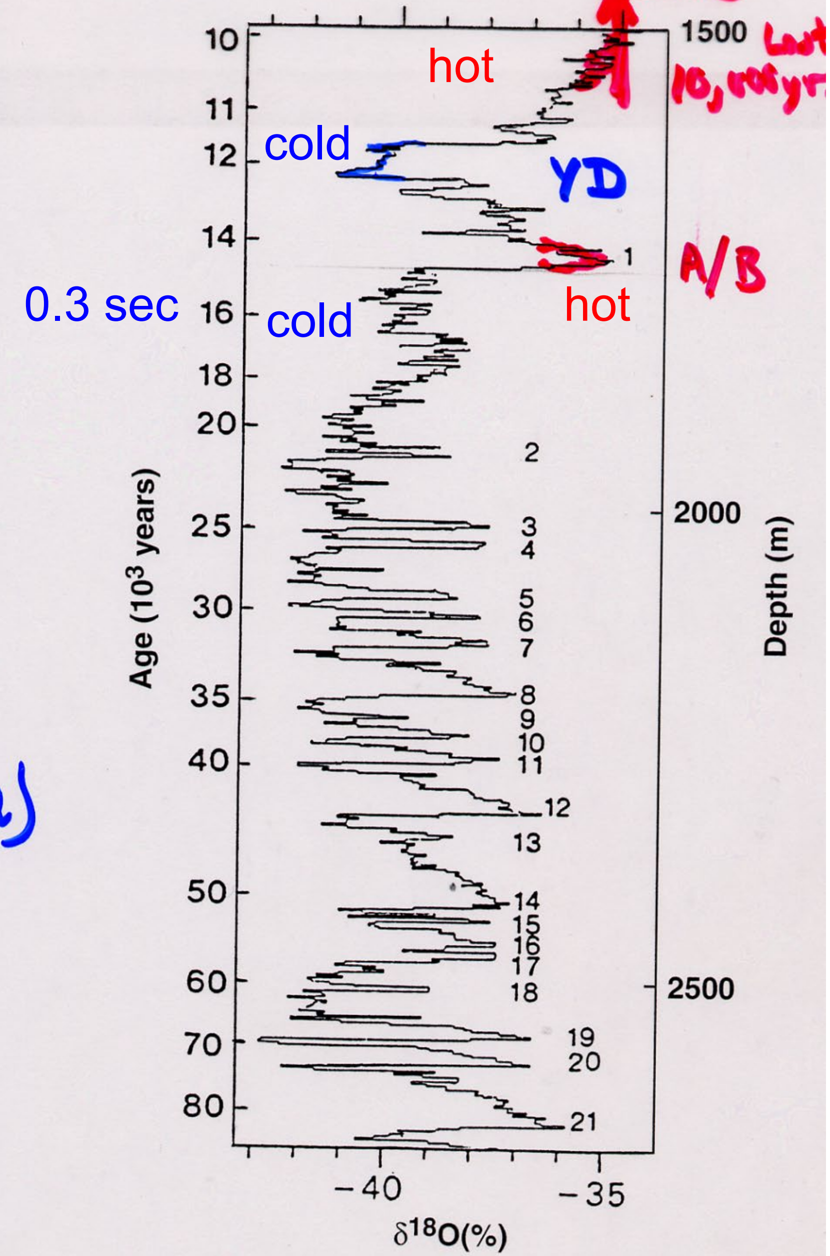
Walker and Lowe, Quaternary Science, 2007

The end of the last glacial cycle was irregular and abrupt



Greenland δ18O Ice Core

FIGURE 18-6. $\delta^{18}O$ record from the GRIP ice core, Summit, Greenland, between depths of 1500 to 2675 m, covering a time span from 10,000 to 87,000 years ago. Linear depth scale; time scale established by counting annual layers back to 14,500 years; beyond that by ice flow modeling. In the upper 1500 m of the ice core that covers 10,000 years of Holocene time $\delta^{18}O$ values are nearly constant at $-35 \pm 1‰$. Warm peaks of Dansgaard-Oescher cycles 1 to 21 are numbered for reference. The late glacial cold interval known as the Younger Dryas followed warm peak no. 1 (modified from Dansgaard et al., 1993, Figure 1).



Ice isotopically light (18O depleted) when cold

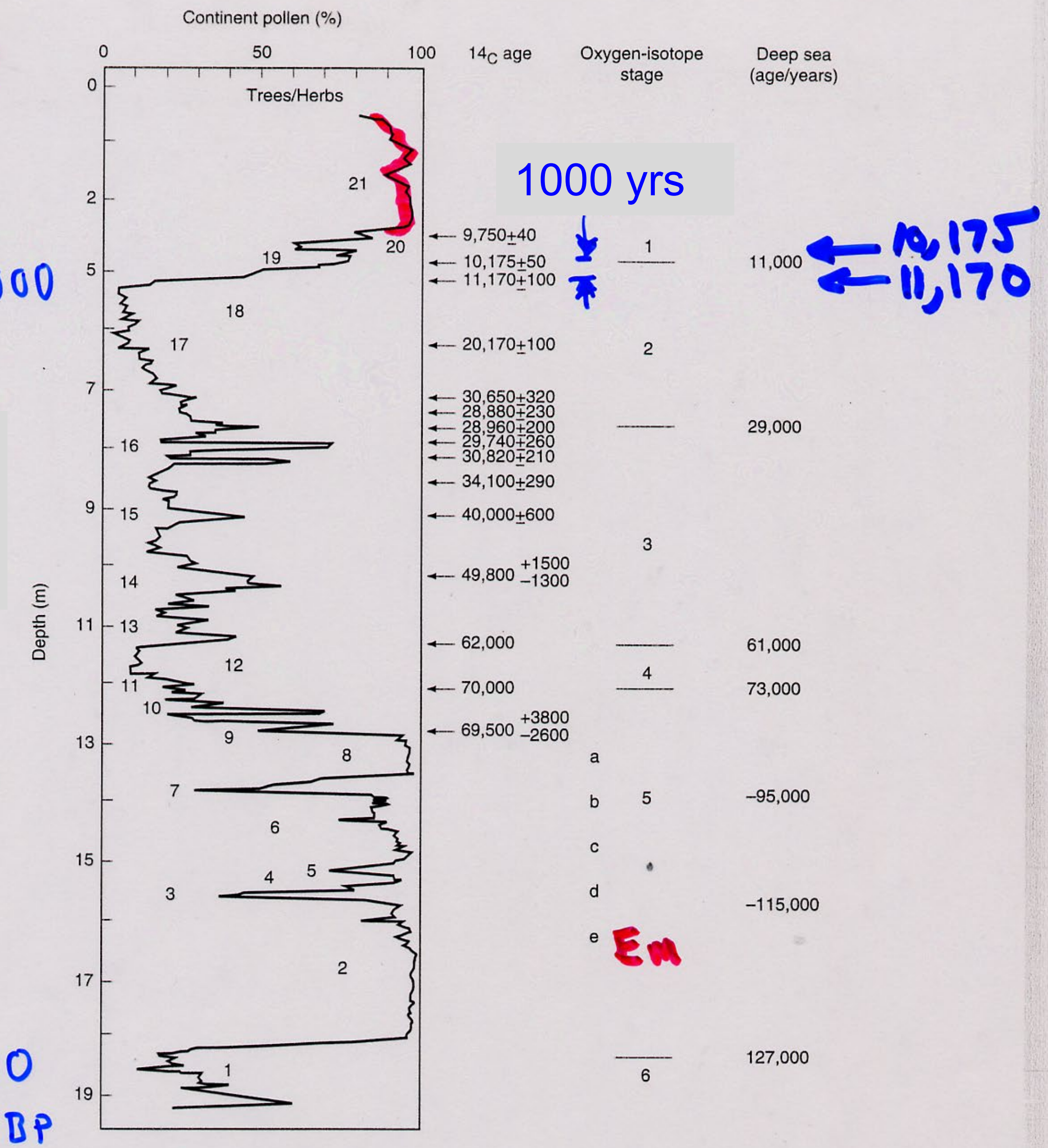
Pollen @ Grande Pile, France

FIGURE 18-5. Diagram of total tree and shrub pollen versus herb pollen from Grande Pile, France. Depth scale (m). Radiocarbon dates at various levels are shown, with suggested correlations with the deep-sea oxygen-isotope record (simplified from Woillard and Mook, 1981, Figure 1).

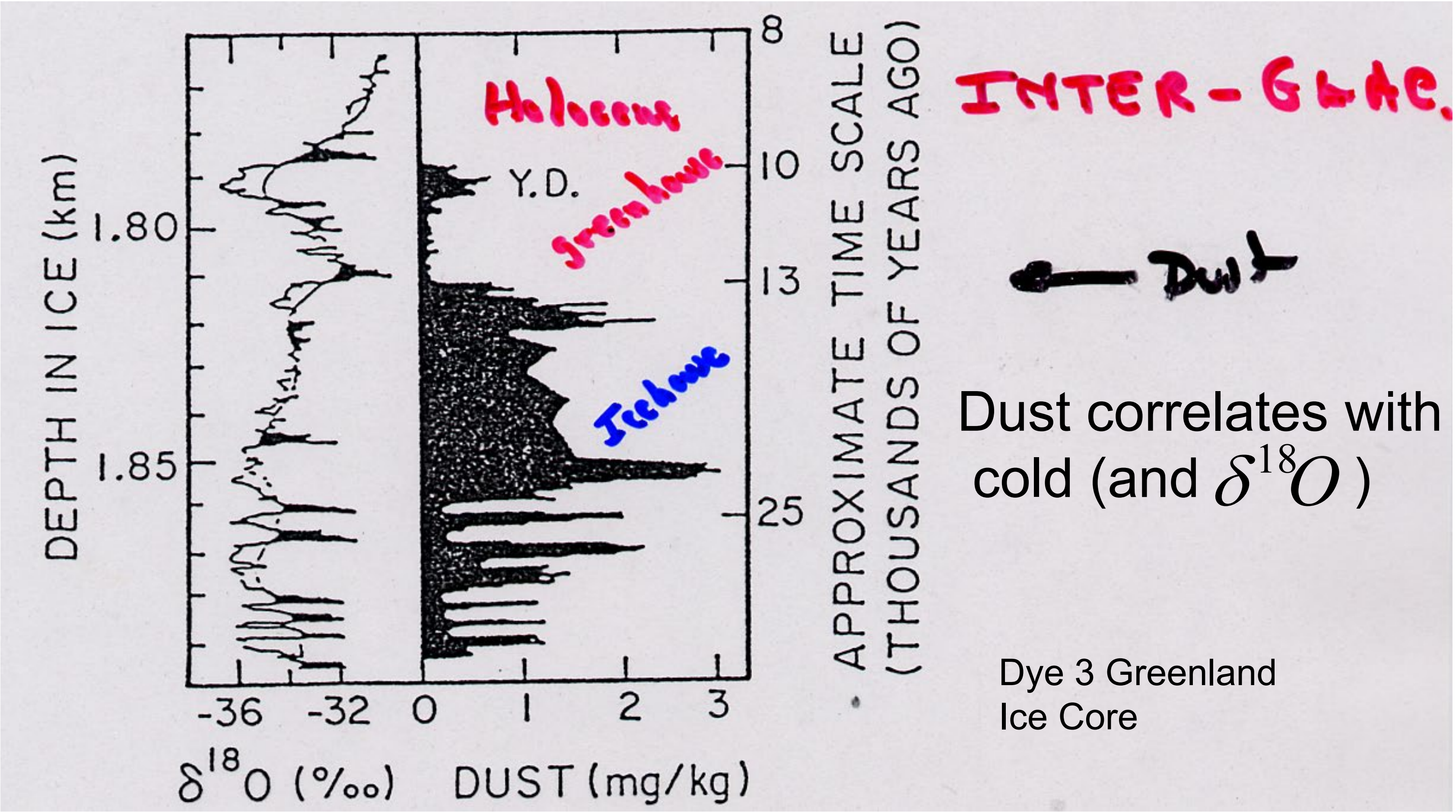
11,000

127,000
years BP

Temperature changes were sudden



Dust proxy suggests T changes were **very** sudden



The **flickering switch**

There is a high resolution oxygen isotope and dust record for the period from ~8,000 to ~40, 000 years ago

Dust in ice core

"Greenland ice sheet Project 2"

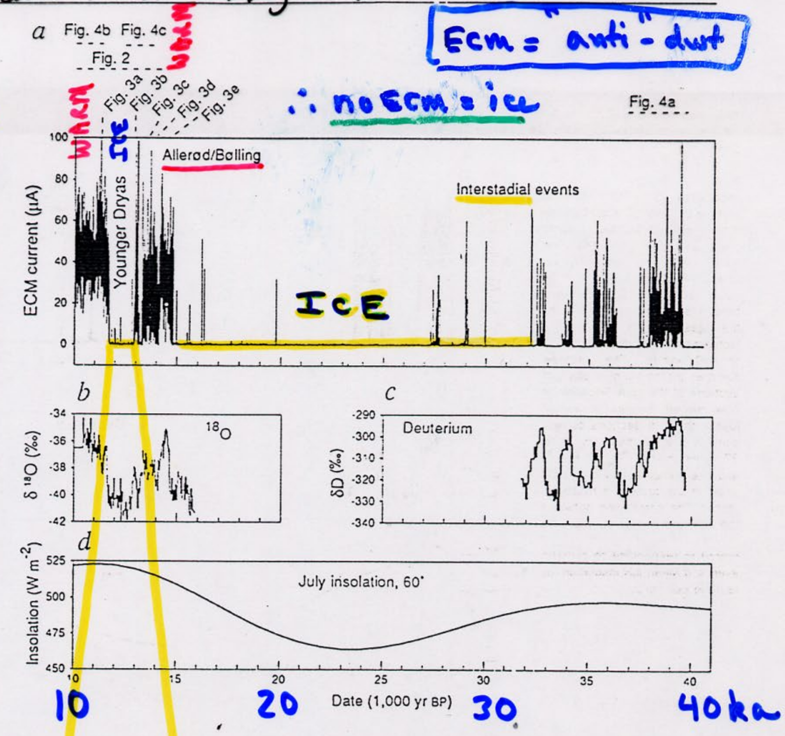


FIG. 1 *a*, GISP2 electrical conductivity measurement (ECM) record for the period of 10–40.5 kyr BP. Low current levels indicate that alkaline dust has neutralized the acidity of the ice. The record is resampled to a rate of one sample per year. The ages of the other expanded-scale figures (Figs 2–4) are indicated. The years indicated are calendar years. We adopt the carbon-14 datum of AD 1950 as present time. *b*, Isotopic ratio $^{18}O/^{16}O$ for the ages 10.5 to 16 kyr BP. *c*, Isotopic ratio D/H for the ages 32 to 40.5 kyr BP. The isotope samples are from contiguous 1-m sections of the core. Because of flow-induced thinning of annual layers, the 1-m sections correspond to one sample every 15 to 37 years in the $^{18}O/^{16}O$ record and one sample every 65 to 80 years in the deuterium/hydrogen record. The correlation between the ECM and the isotope records demonstrates that the ECM record is responding to climatic events. *d*, Mean July insolation for latitude 60° north[23].

acidic and alkaline conditions, the effect of small amounts of additional dust on the magnitude (but not the frequency) of the ECM signal may be disproportionately large. In the GISP2 core, however, detailed chemical analysis shows that the order-of-magnitude decreases in ECM that we consider here are associated with order-of-magnitude increases in calcium. The source for the calcium is believed to be airborne calcium carbonate dust. The ECM record has the highest time resolution (>15 samples per year) of available measurements, and together with the sensitivity to dust, this makes ECM suitable for investigating the rate of rapid atmospheric circulation changes.

The ECM record discussed here covers the time period 10 to 42 thousand years before present (kyr BP), and allows climate variability to be investigated on timescales of seasons to

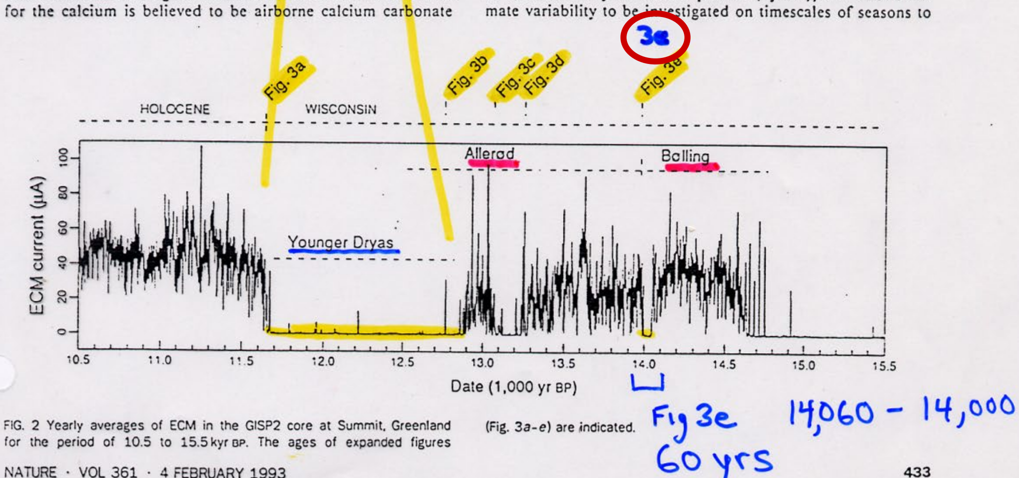
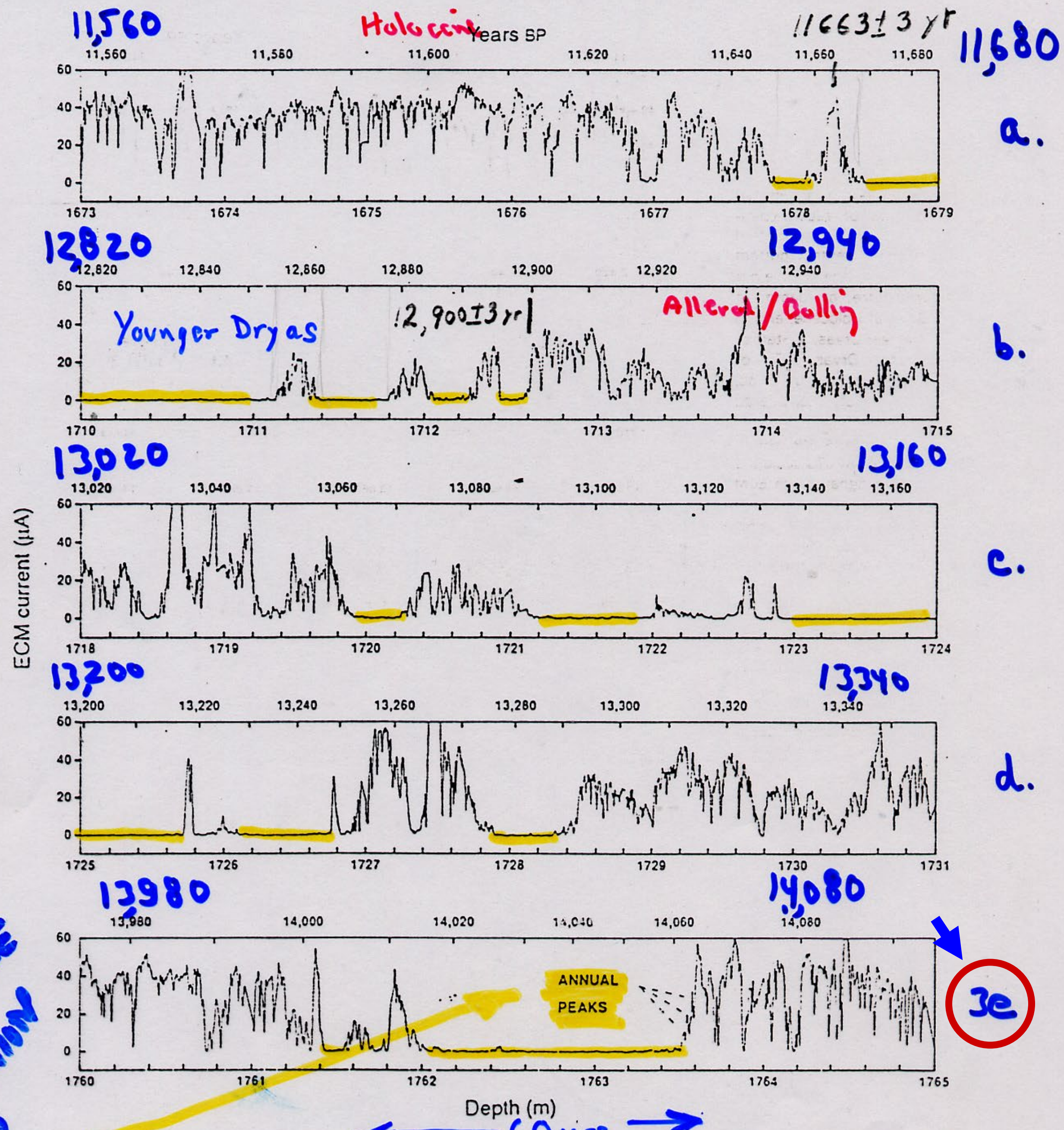


FIG. 2 Yearly averages of ECM in the GISP2 core at Summit, Greenland for the period of 10.5 to 15.5 kyr BP. The ages of expanded figures (Fig. 3*a*–*e*) are indicated.

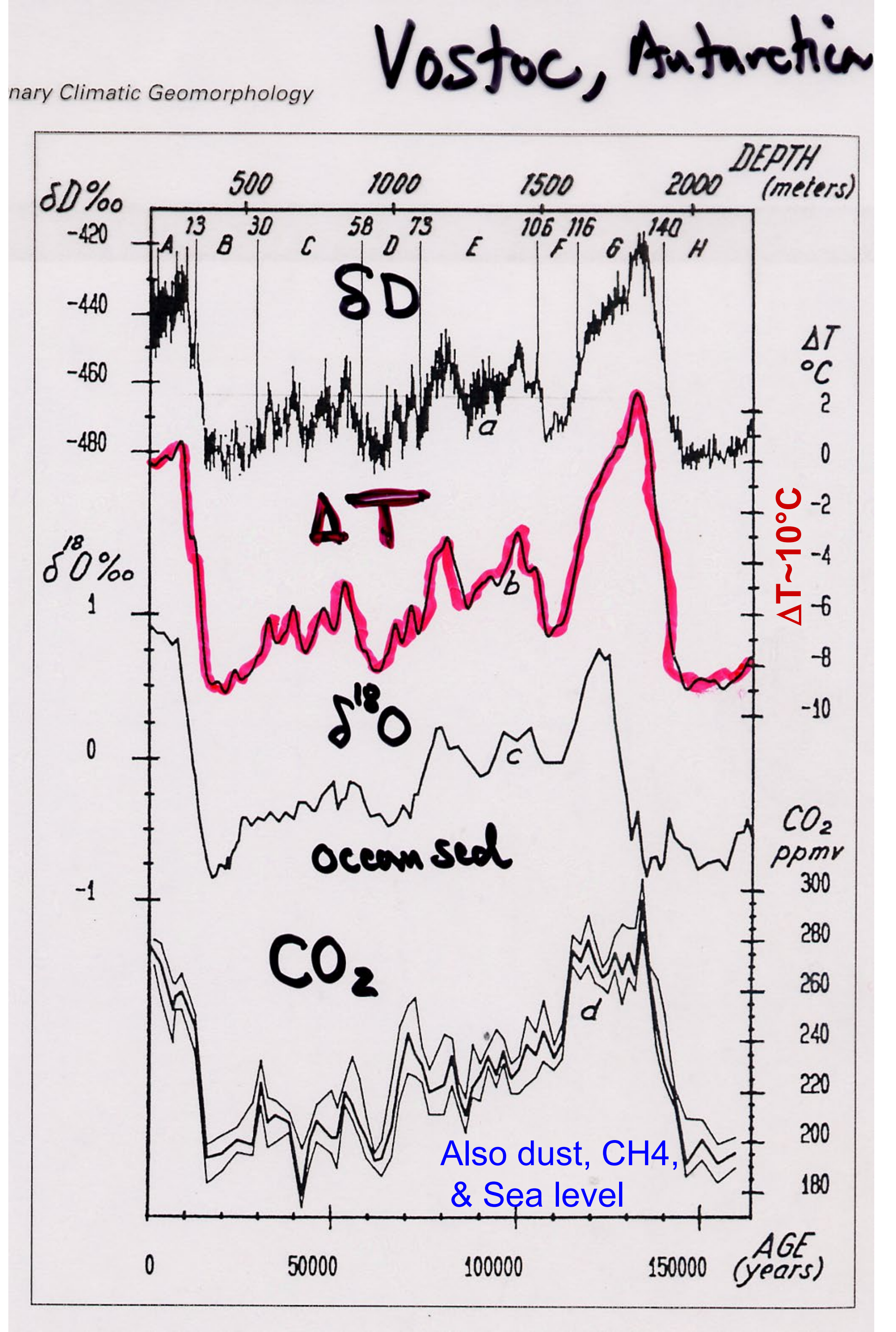
Taylor, et al., "flickering switch"

FIG. 3 *a–e*, Expanded ECM records of recent climate transitions plotted against depth (bottom axis) with one sample per millimetre of depth. *a*, Start of Holocene, end of Younger Dryas. *b*, Start of Younger Dryas. *c*, End of inter-Allerød cold period. *d*, Start of inter-Allerød cold period. *e*, Transition. The top axes are age, in years BP. At this scale the annual signal in the ECM can occasionally be resolved as small local peaks that occur once per year. During the transition at 14,060 BP (*e*), three annual peaks can be resolved. The annual layer thickness is ~6 cm per year during warmer, less dusty conditions and 3 cm per year during colder dusty conditions. Occasionally the number of ECM annual peaks and annual layers in a given segment differ slightly because particulate and visual stratigraphy records were also considered when annual layers were identified.



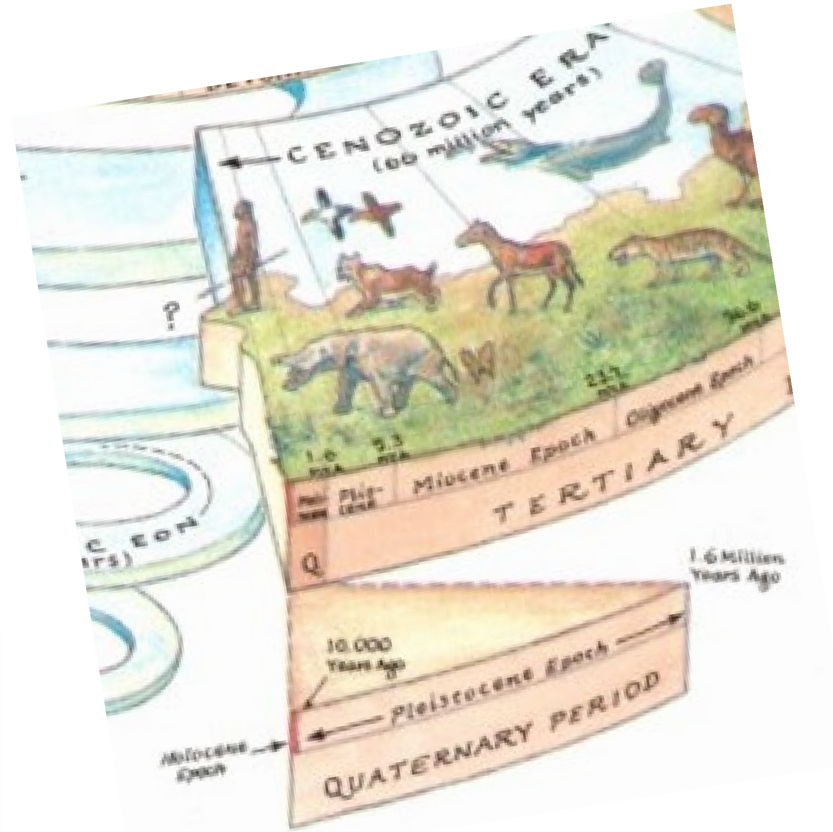
Taylor et al., "flickering switch"

Over ice age cycles, everything correlates with everything



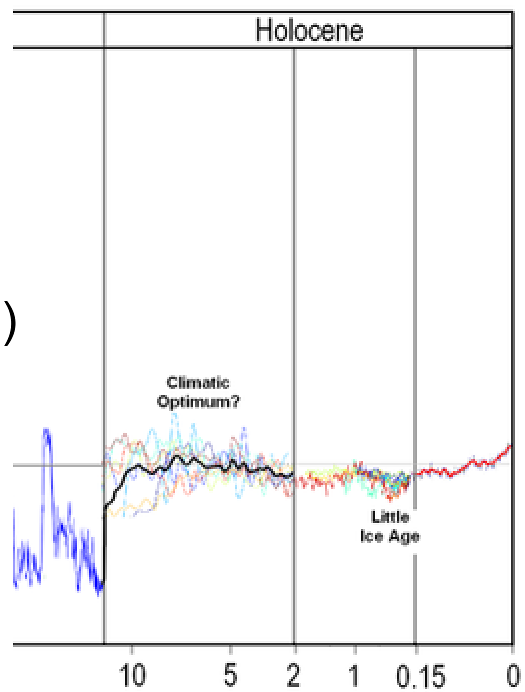
The Holocene

- The current interglacial (last 10 ka)
- Dominance of humans
- Anthropogenic climate change

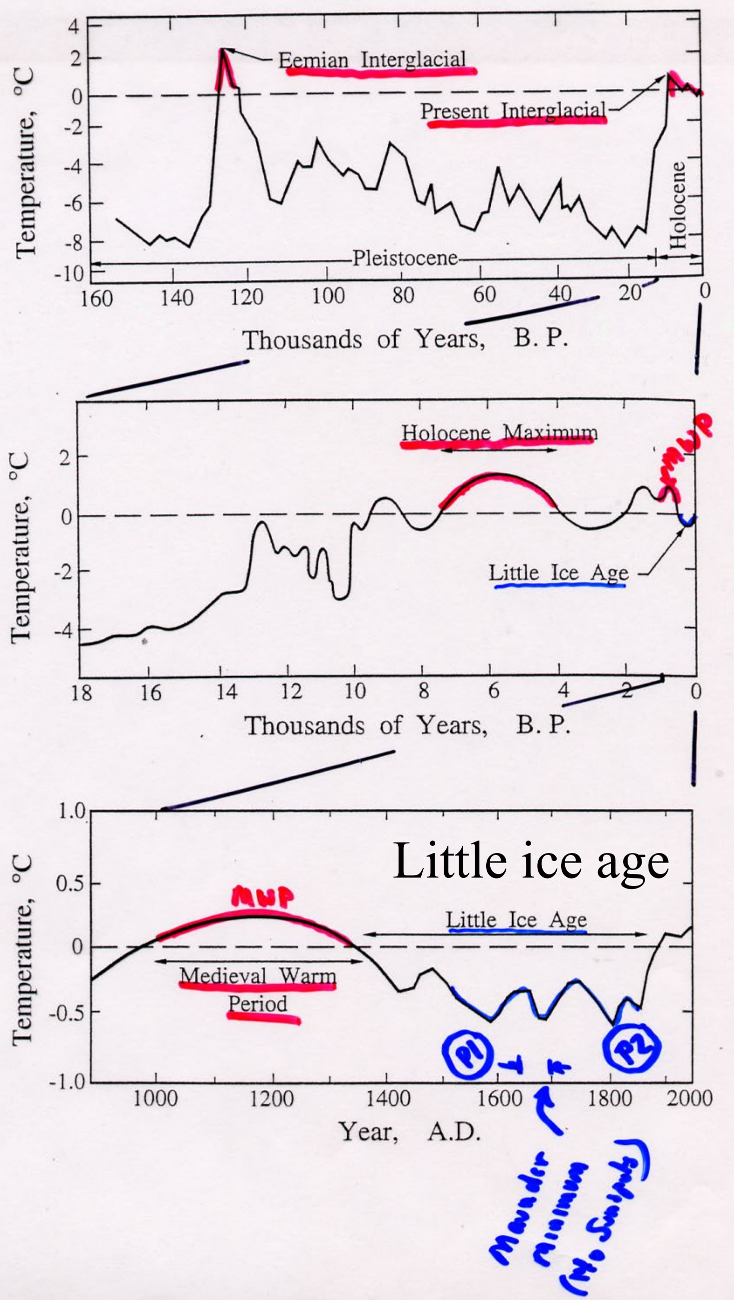


Last 0.2 seconds

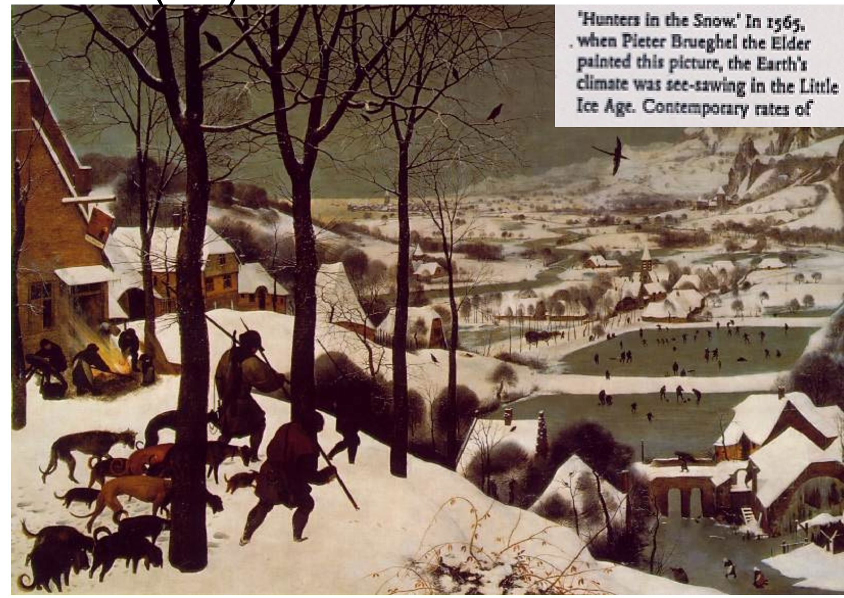
Holocene T is significantly (for us) variable



Historical Zoom:



1565 (P1)

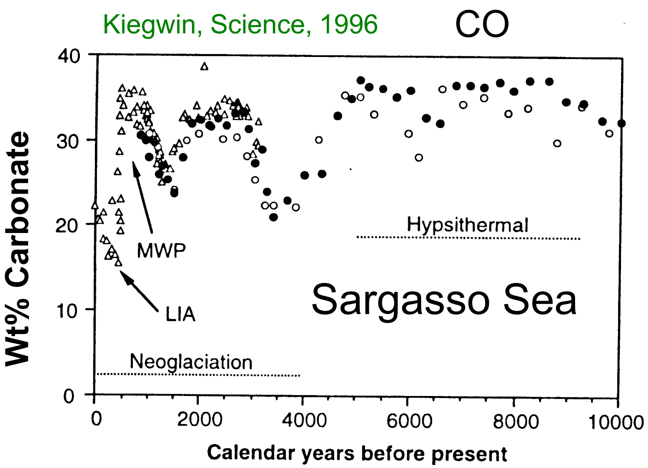


1895 (P2) Thames

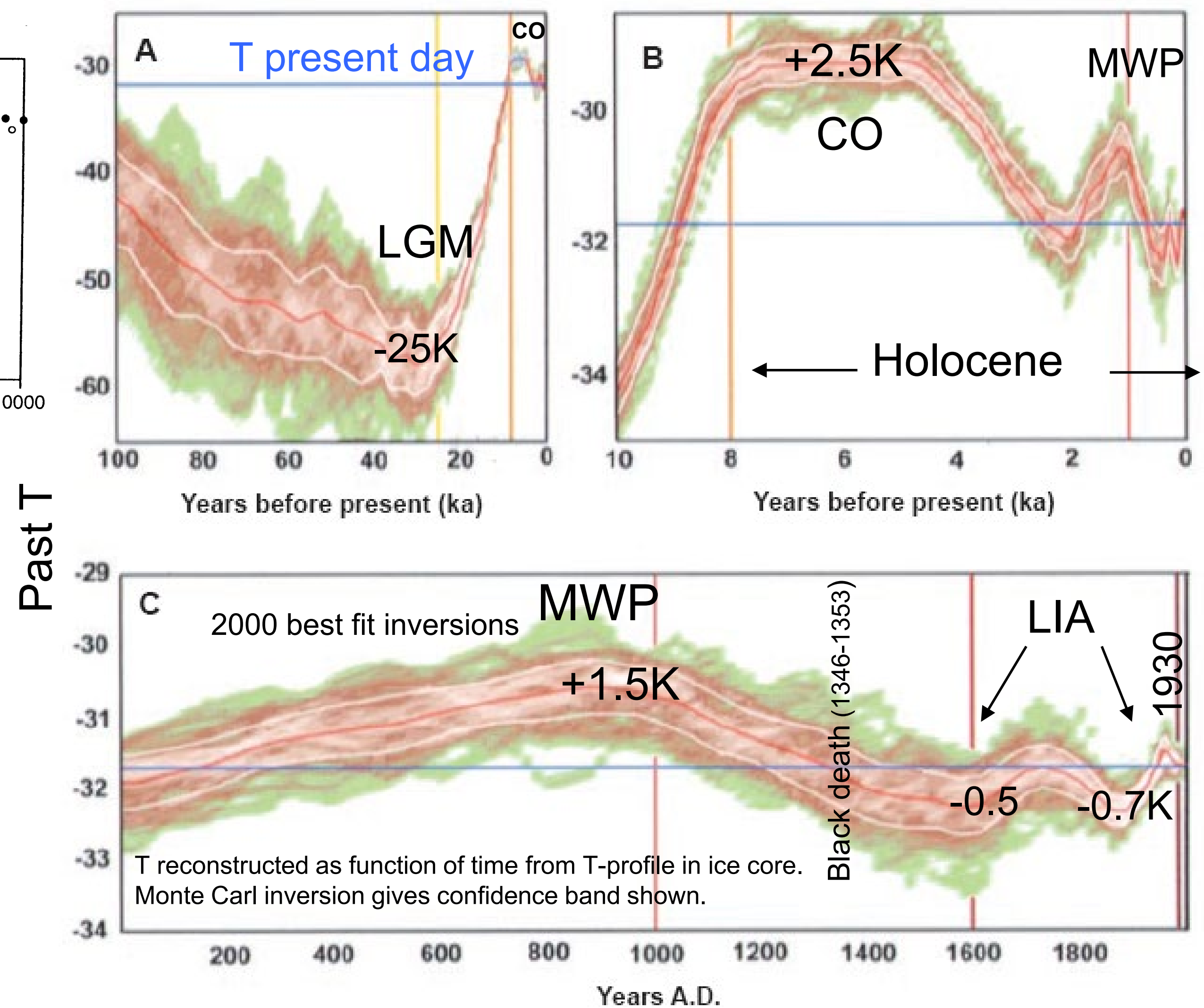
Before the global warming. In the 1890s the world was, on average, about 0.5 degree cooler than the 1990s. The Sun was in a lazy mood, as shown by the low sunspot counts (Opposite).

Royal Meteorological Society, Bracknell

Clear evidence of Climate Optimum, Medieval Warm Period, Little Ice Age:



Monte Carlo inversion of GRIP T(z) for $T_{surf}(t)$ and Heat Flux Greenland



Dahl-Jensen et al, Science 1998

MWP

- Farming to 200 m higher elevation
- > 50 vineyards in England
- Since 1000 AD we have been going into or emerging from LIA

Explaining Observations

The Black Body Temperature of the Earth

J_{sun} = energy flux from the sun = 1340 $W\,m^{-2}$

R_{bb} = black body radiancy = σT^4 $W\,m^{-2}$

T = temperature in °K = T[°C]-273.15

σ= Boltzman's constant = 5.65×10^{-8} $W\,m^{-2}\,K^{-4}$

A= Albedo = fraction sunlight reflected = 0.3

Black body temperature of the earth is the temperature the earth must have to radiate back into space the energy it receives from the sun

Energy Balance

$$4\pi r^2 \sigma T^4 = \pi r^2 (1-A) J_{sun}$$

Black body radiation from earth radiation from sun

albedo

$$T[°C] = \left(\frac{1}{4}\frac{(1-A)J_{sun}}{\sigma}\right)^{0.25} - 273.15$$

geom factor

The earth is made clement by 35°C greenhouse warming:

Case	**Geom Fact**	**T[C]**
Base: global black body	1/4	-19.3
equatorial black body	1/π*	-3.8
Cloudier A=0.4	1/4	-28.9
1.67 J_{sun}	1/4	15.3

35°C

Natural greenhouse warming

Average temperature of earth is 15°C

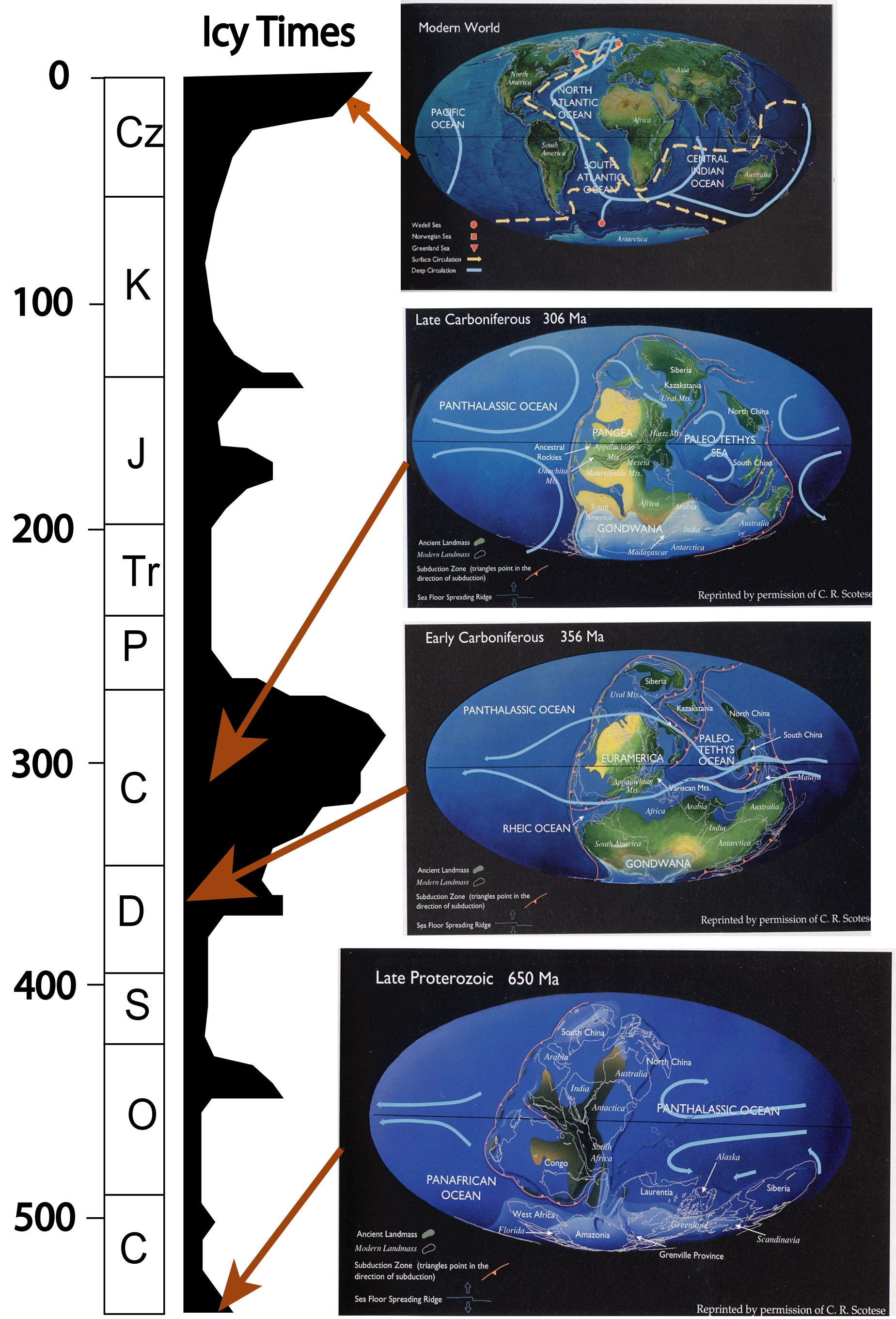
$$^{*}2\pi rL\,\sigma T^{4} = 2rL(1-A)J_{sun}\text{ , geometric factor} = \frac{2\mathrm{rL}}{2\pi\mathrm{rL}} = \frac{1}{\pi}$$

Snowball Earth

- Burial of C cause cooling
- As ice caps grew albedo increased cooling
- Earth froze
- Continued subduction-related CO_2 venting incerased CO_2 in atmosphere, raising T untill ice melted
- Albedo change led to over-warming and burial of Carbonate carbon

Glacial conditions seem to have occurred when ocean circulation was blocked by a N-S band of continents

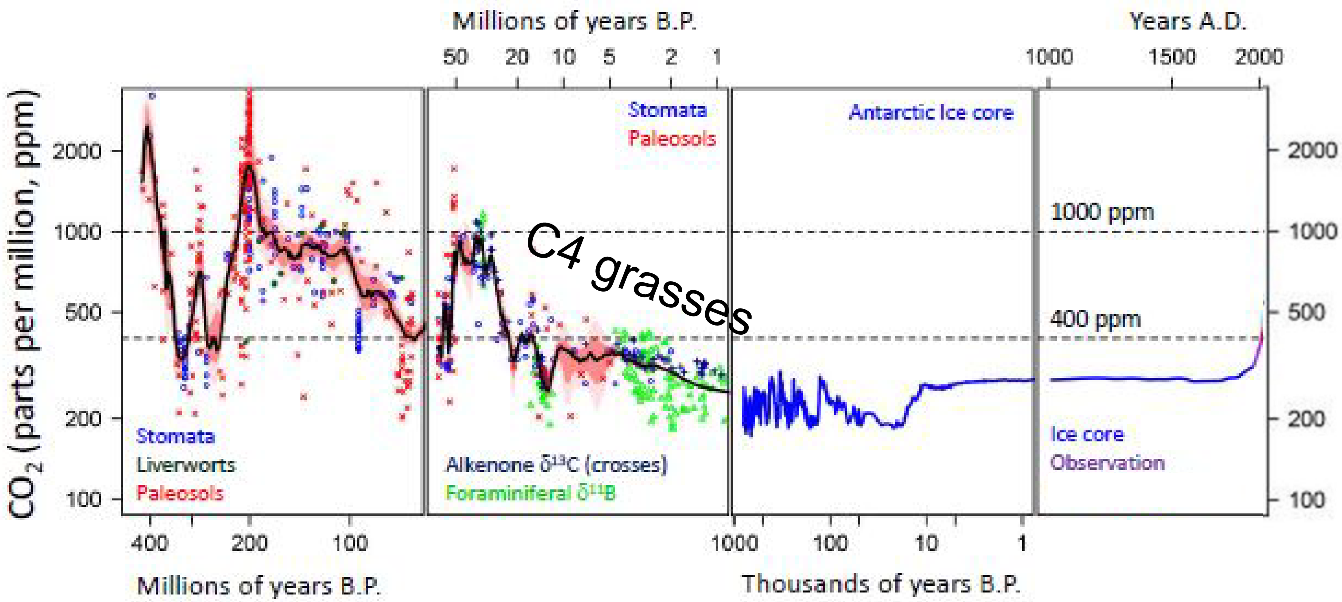
…or when earth was passing through dusty spiral arms of galaxy



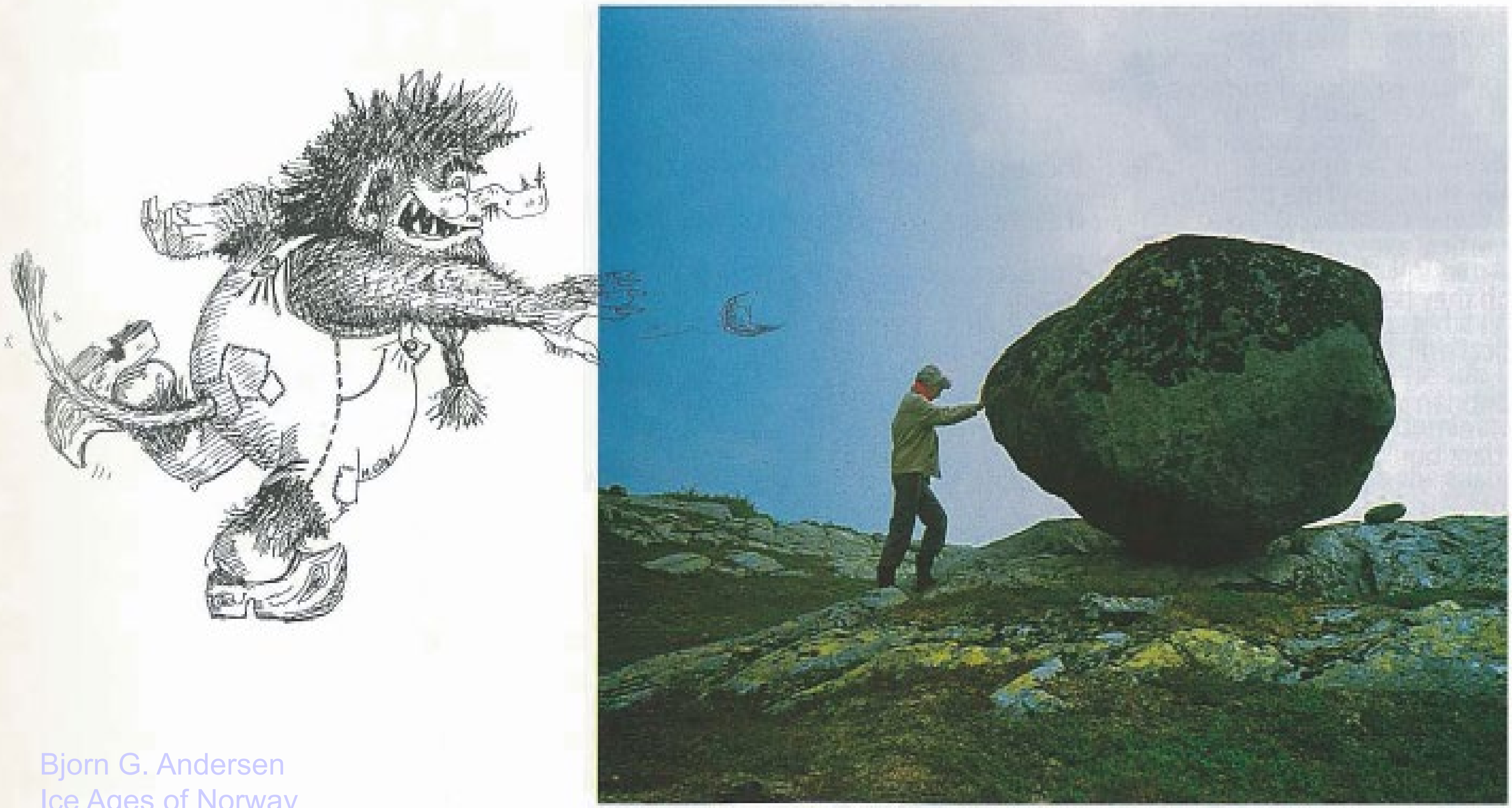
Gerhard and Harrison, 2001

Drop in T from Eocene may be due to development of C4 grasses

Able to grow at lower CO_2 concentrations

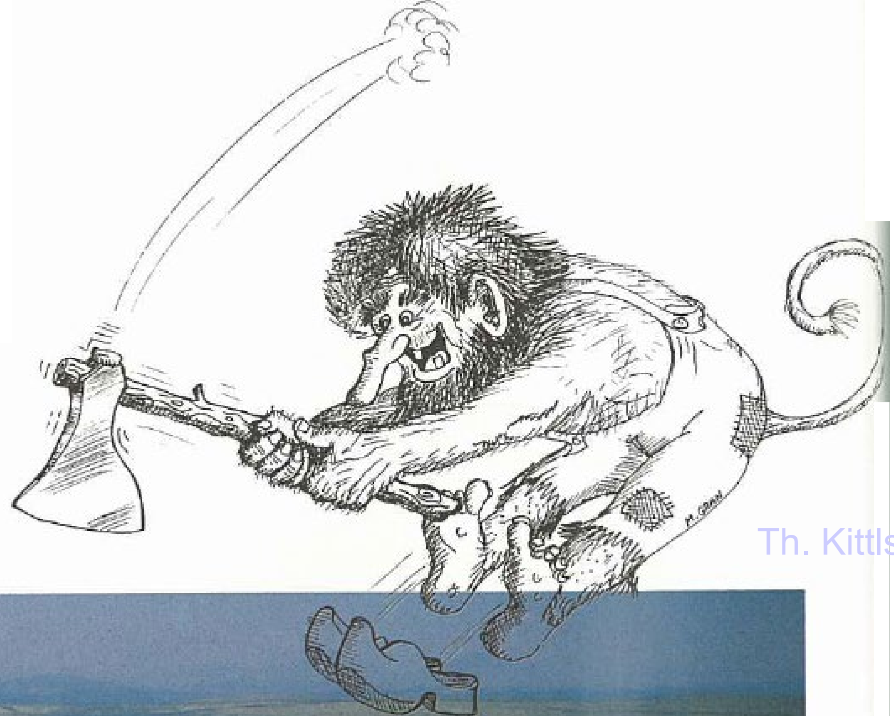


… to 1940 some thought trolls best explanation for many ice-related observations



Bjorn G. Andersen
Ice Ages of Norway
2000

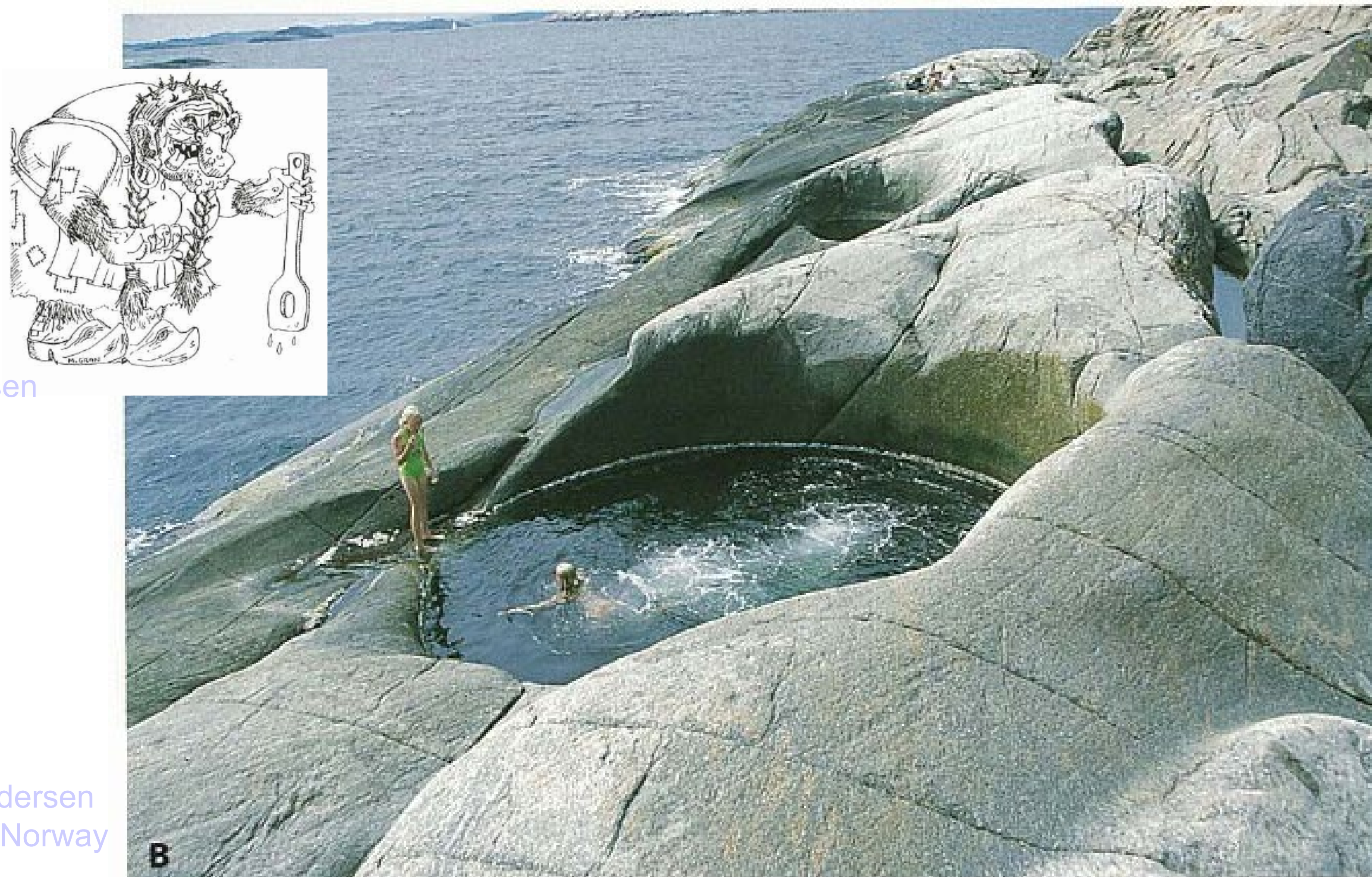
Gorges without source



Th. Kittlsen

Bjorn G. Andersen
Ice Ages of Norway
2000

cauldrons



Th. Kittlsen

Bjorn G. Andersen
Ice Ages of Norway
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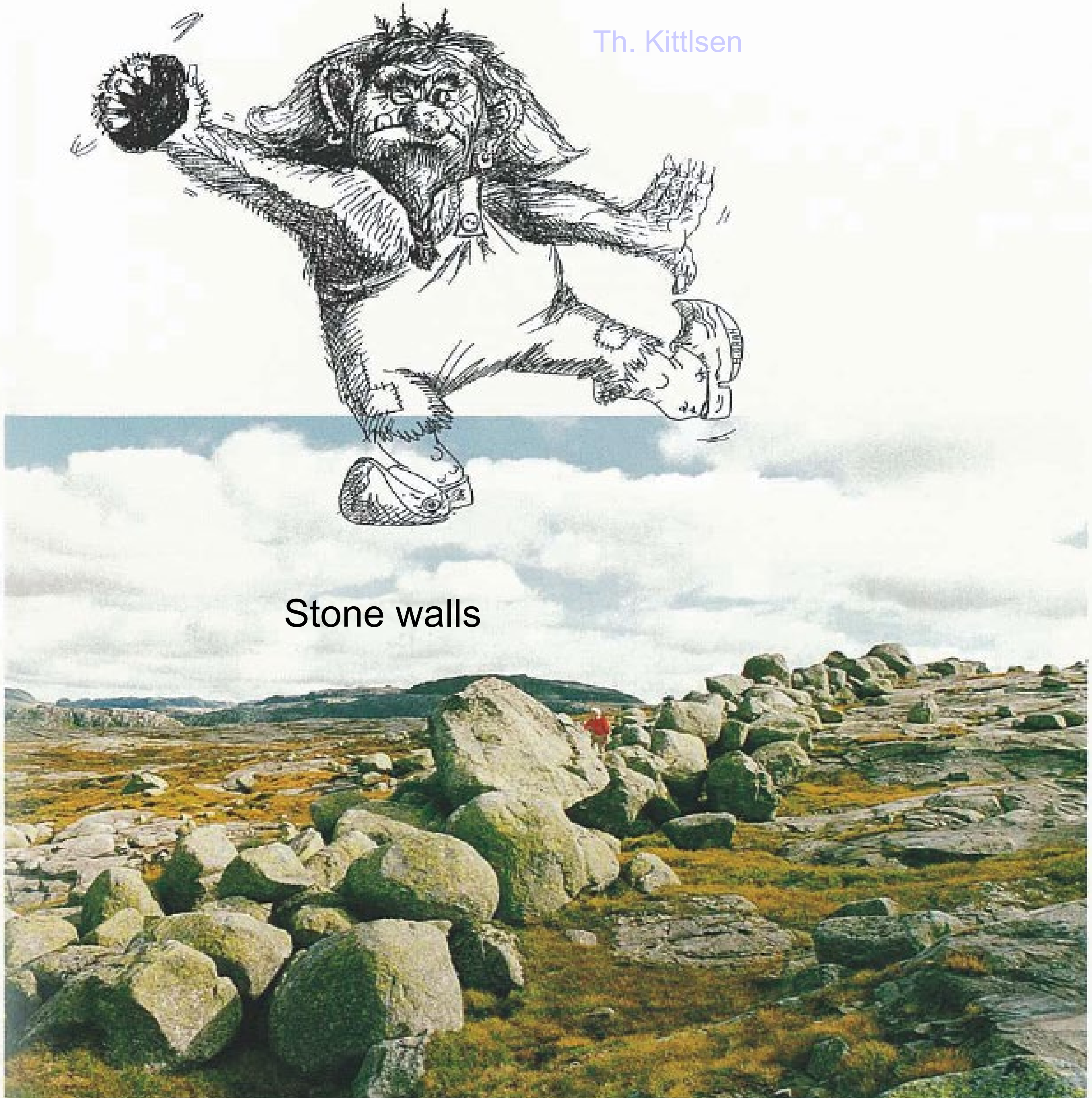


Bjorn G. Andersen
Ice Ages of Norway
2000

Now know ice ages caused by Milankovitch cycles

- Variations in N Hemisphere Insolation at 65°N
- Orbital perturbations drove T change
- CO_2 was slave to orbital temperature changes

Broad geological reflection of Milankovitch cycles:

- Cyclothems
- Lake level fluctuations (e.g., Great Salt Lake in Utah)
- Isotopes in stalagmites

Milankovitch Forcings caused ice ages

A. Seasons: ~170 W m^{-2} @ 65° N, yearly
summer-winter

B. Precession of seasons (tilt relative to orbit position) relative to stars (Platonic year 25,765 y)
21 kyr period relative to seasons
(shortening of seasons when earth closer to sun cancels increased solar irradience. Thus this signal ~0. Huybbers (2006))

C. Obliquity to ecliptic (magnitude of tilt)
tilt: 21.5 – 23.44 – 24.5°

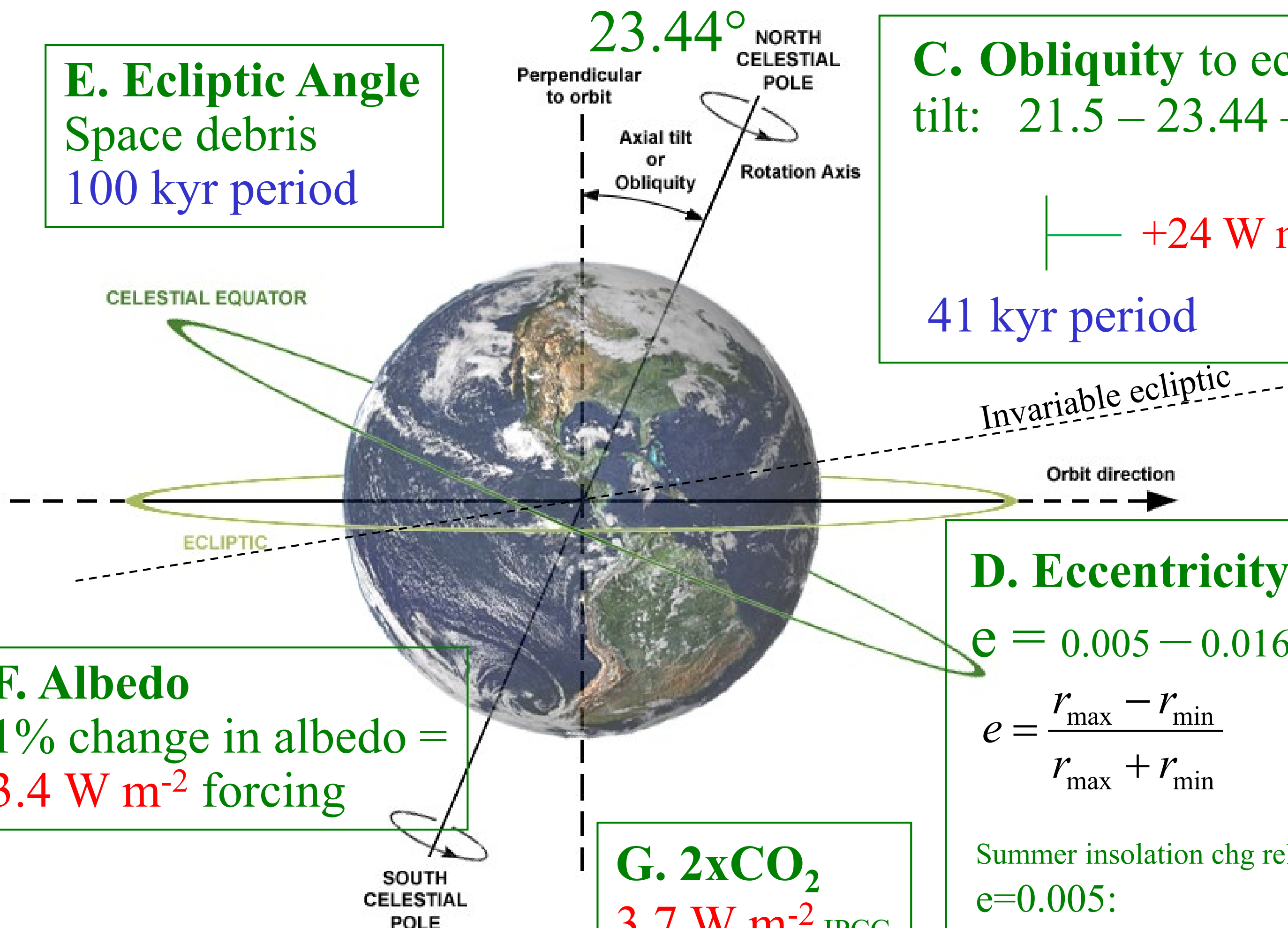
Explains 70% of early Pleistocene ice volume change variance

+24 W m^{-2} in summer

41 kyr period

Huybers(2006)

E. Ecliptic Angle
Space debris
100 kyr period



D. Eccentricity or orbit

e = 0.005 – 0.0167 tdy (0.028 mean) – 0.058

$$e = \frac{r_{max} - r_{min}}{r_{max} + r_{min}}$$

147.5 x 10^6 km
152.6 x 10^6 km

3.4% radius difference today:

Summer insolation chg rel present e=0.058: +24.5 W m^{-2}
e=0.005: -20 W m^{-2}

95, 125, 400 kyr period

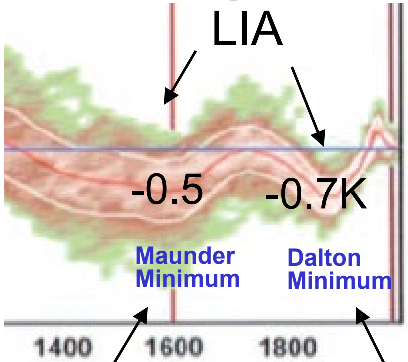
(Huybers, 2006)

F. Albedo
1% change in albedo =
3.4 W m^{-2} forcing

G. 2xCO_2
3.7 W m^{-2} IPCC

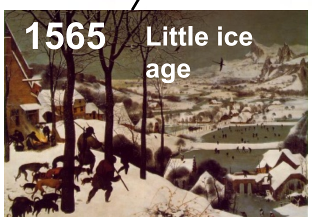
http://en.wikipedia.org/wiki/Image:AxialTiltObliquity.png

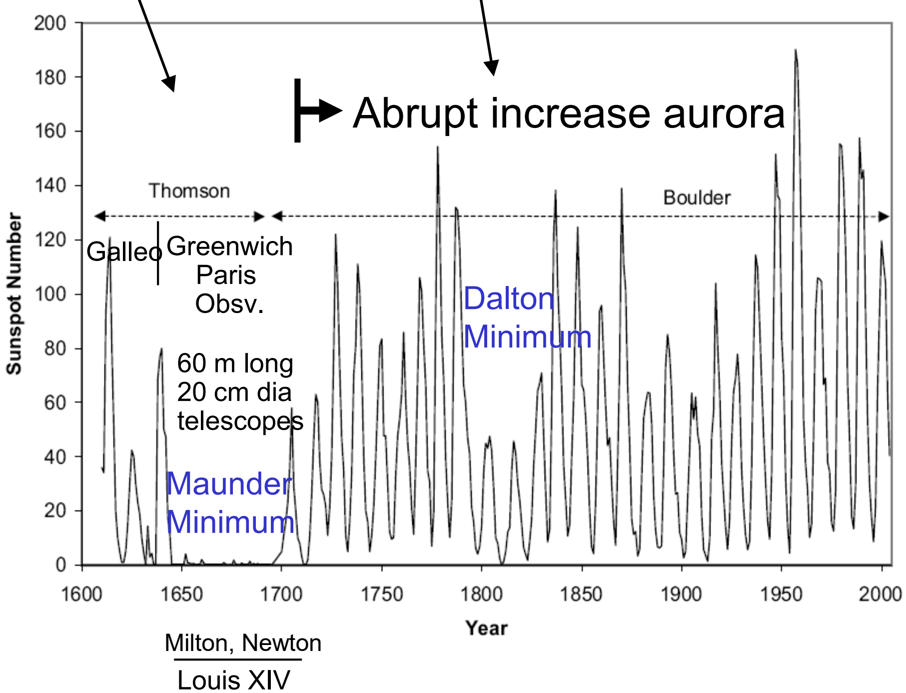
Sun implicated in Holocene climate changes…

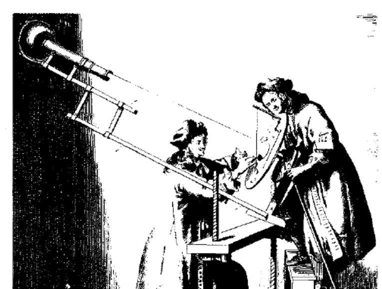


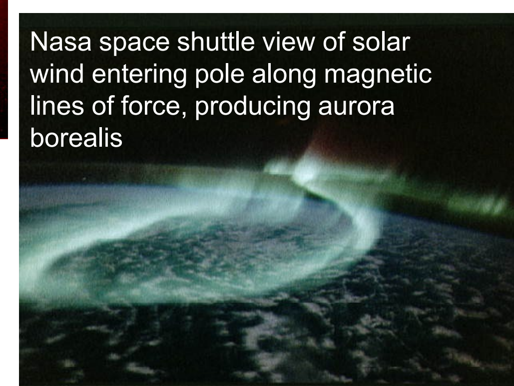
During Maunder Minimum:

There were no sunspots, no solar corona during eclipses, and no aurora displays- sun was "off"

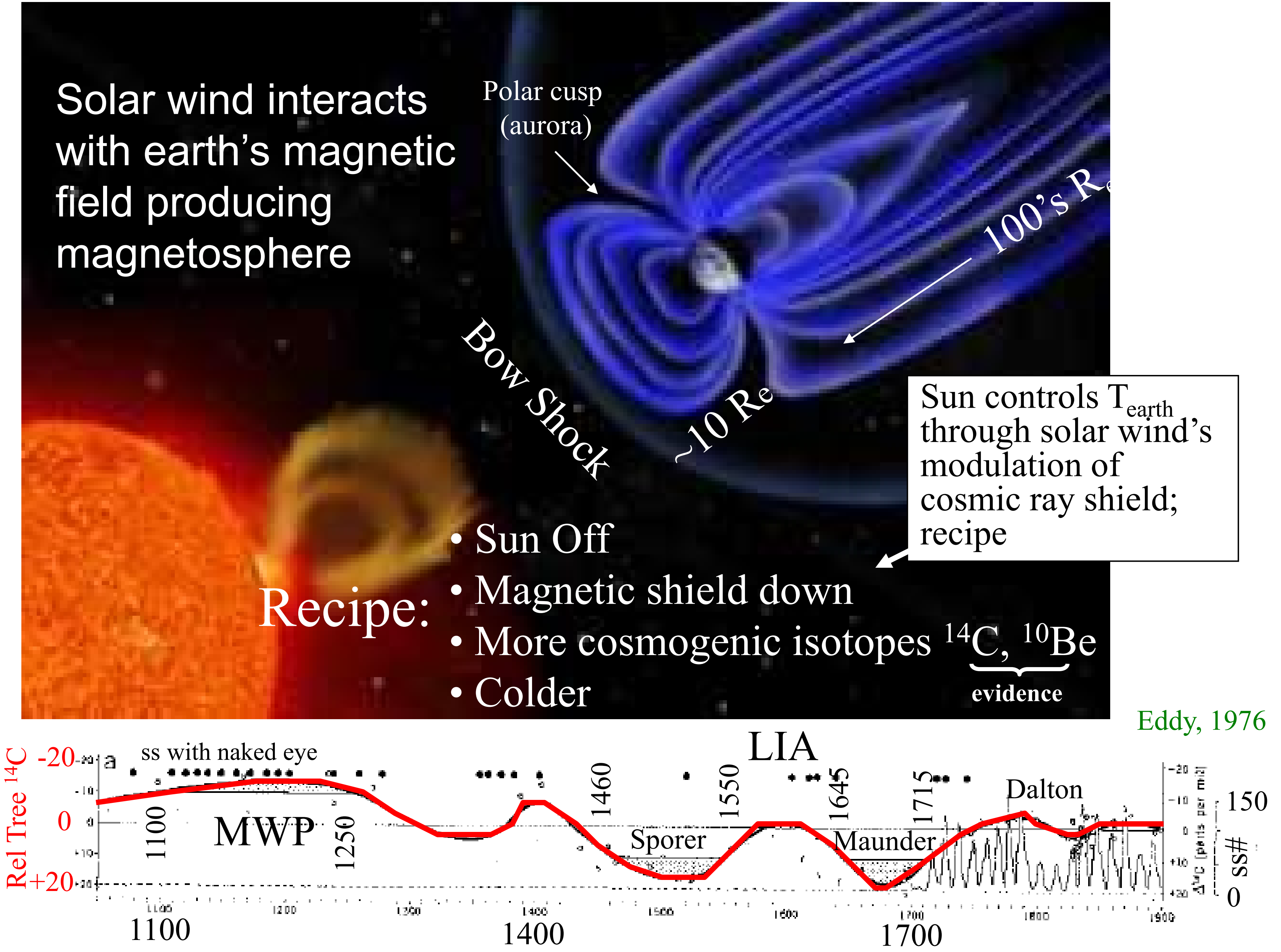






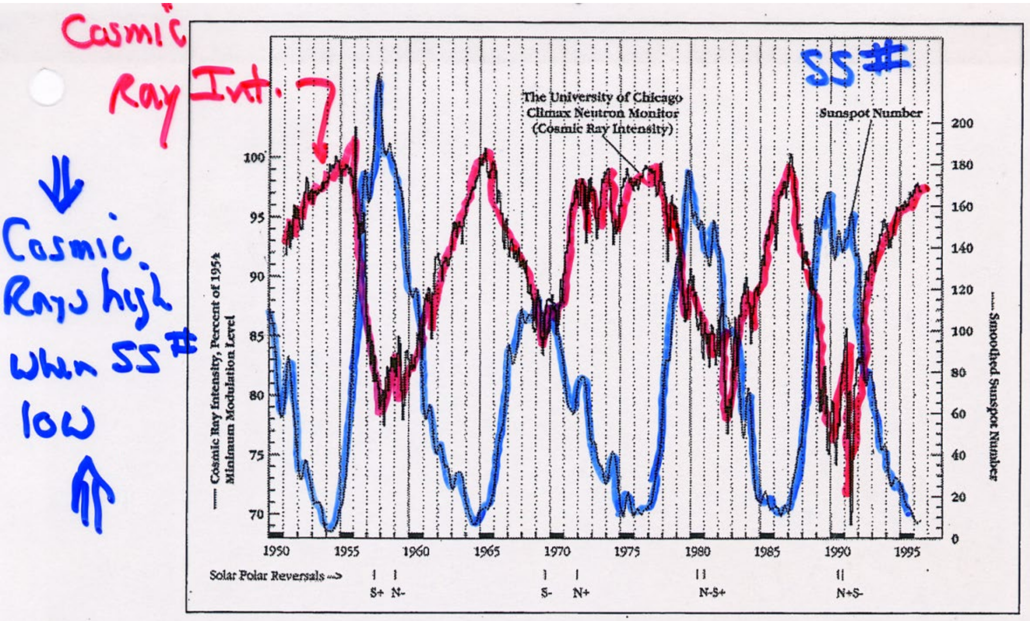


Eddy, The Maunder Minimum, Science, 1976

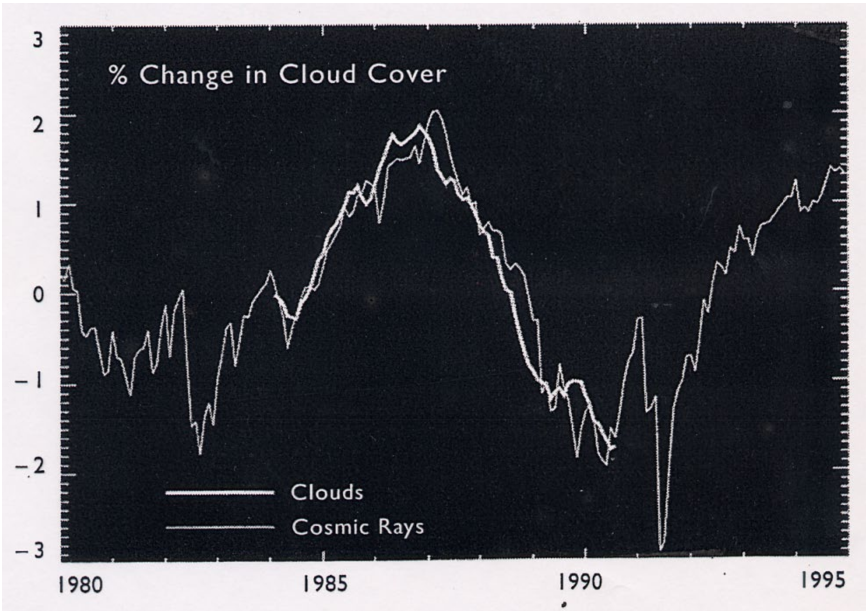


Solar wind interacts with earth's magnetic field producing magnetosphere
Polar cusp (aurora)
100's Re
Bow Shock
~10 Re
Sun controls T_{earth} through solar wind's modulation of cosmic ray shield; recipe
Recipe:
• Sun Off
• Magnetic shield down
• More cosmogenic isotopes ^{14}C, ^{10}Be
evidence
• Colder
Eddy, 1976
LIA
Rel Tree ^{14}C
-20
0
+20
ss with naked eye
MWP
1100
1250
1460
1550
1645
1715
Sporer
Maunder
Dalton
150
ss#
0
1100
1400
1700

Cosmic Ray Intensity correlates with Sunspot activity



Clouds correlate with cosmic ray intensity (climate connection?)

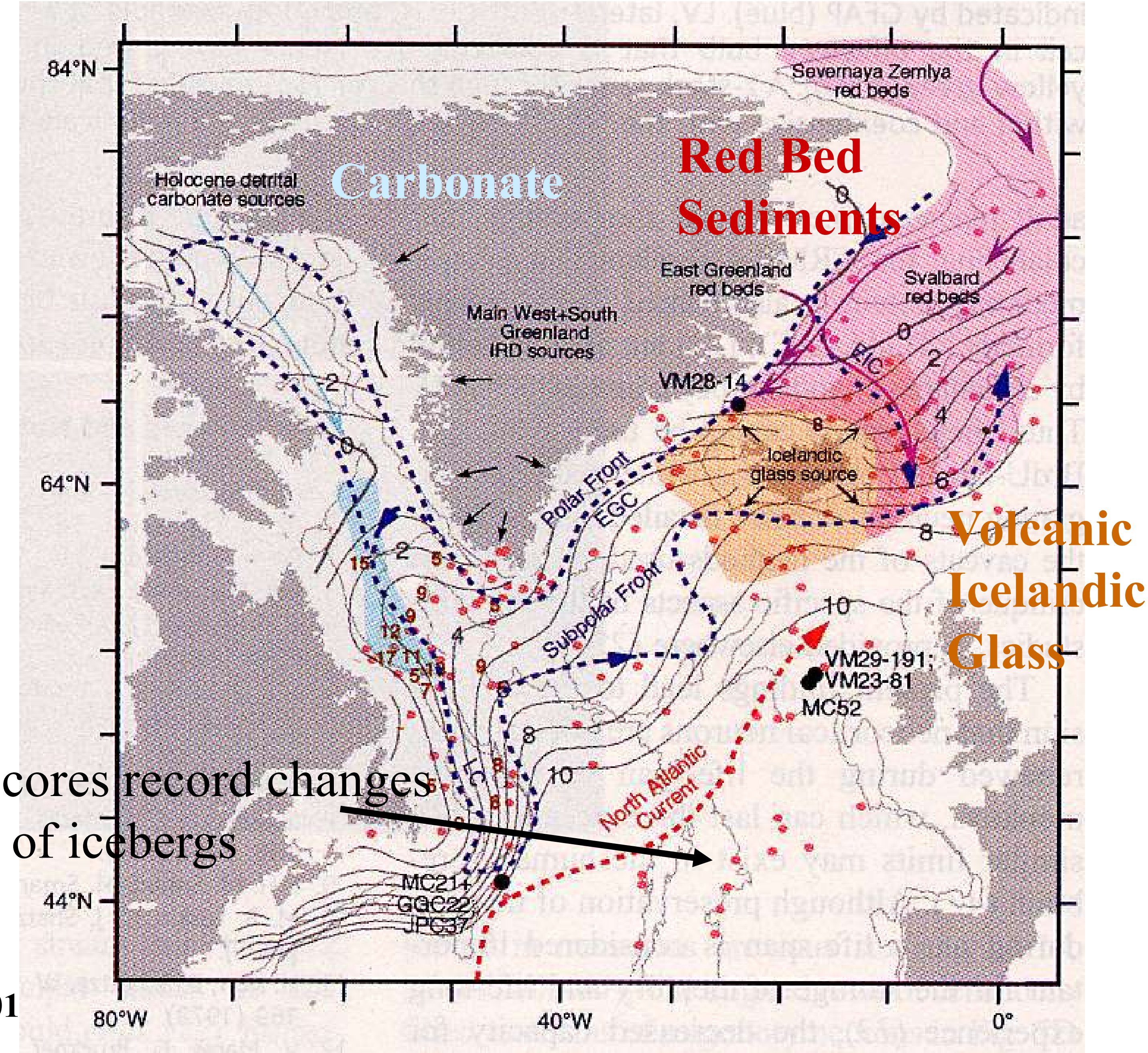


Current testing: CLOUD experiment in CERN

Can you think of a test of solar forcing?

A test of the solar cause of Holocene Climate Change:

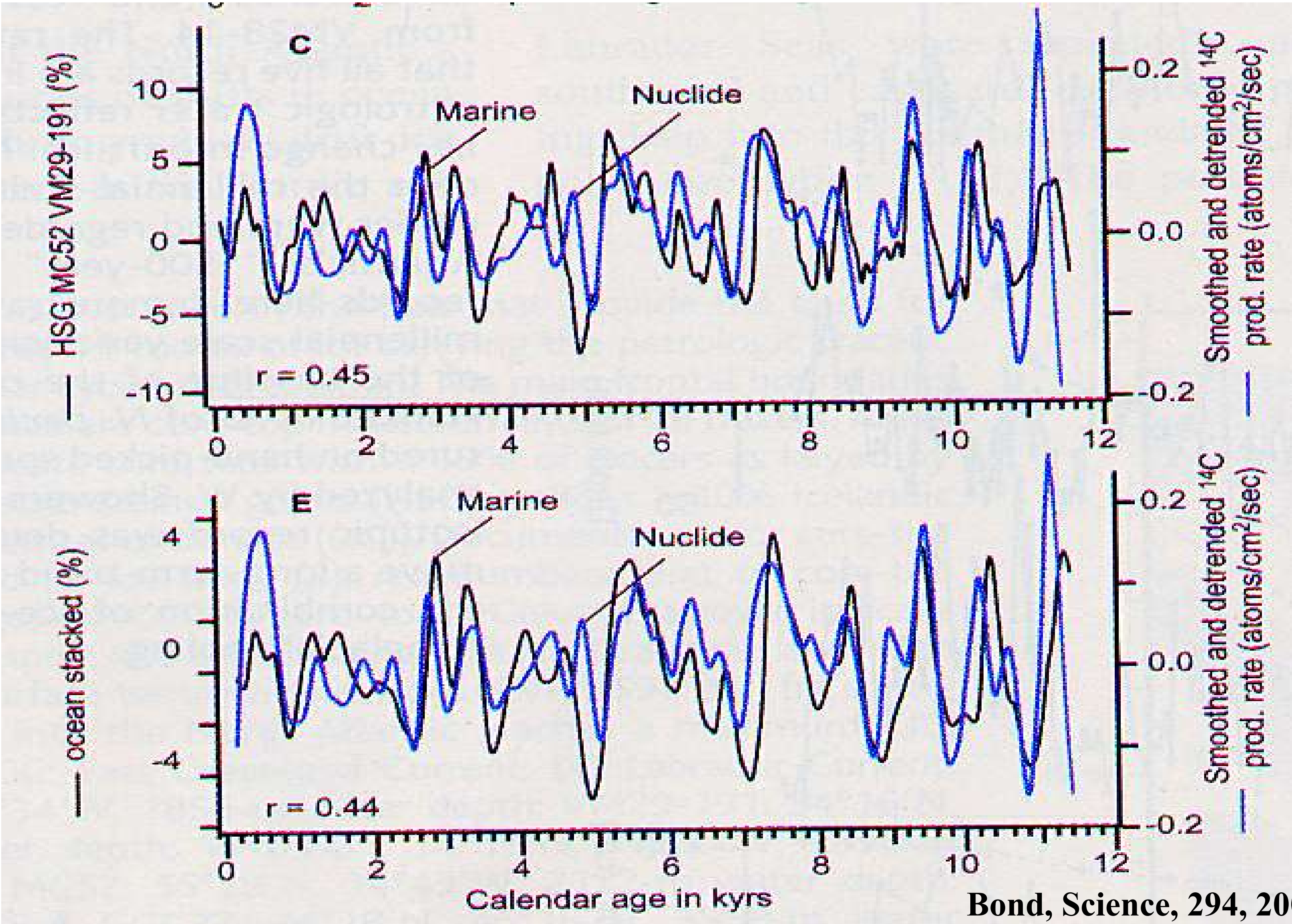
Sources of ice-rafted material in Canada and Iceland:



Ocean sediment cores record changes in southern limit of icebergs

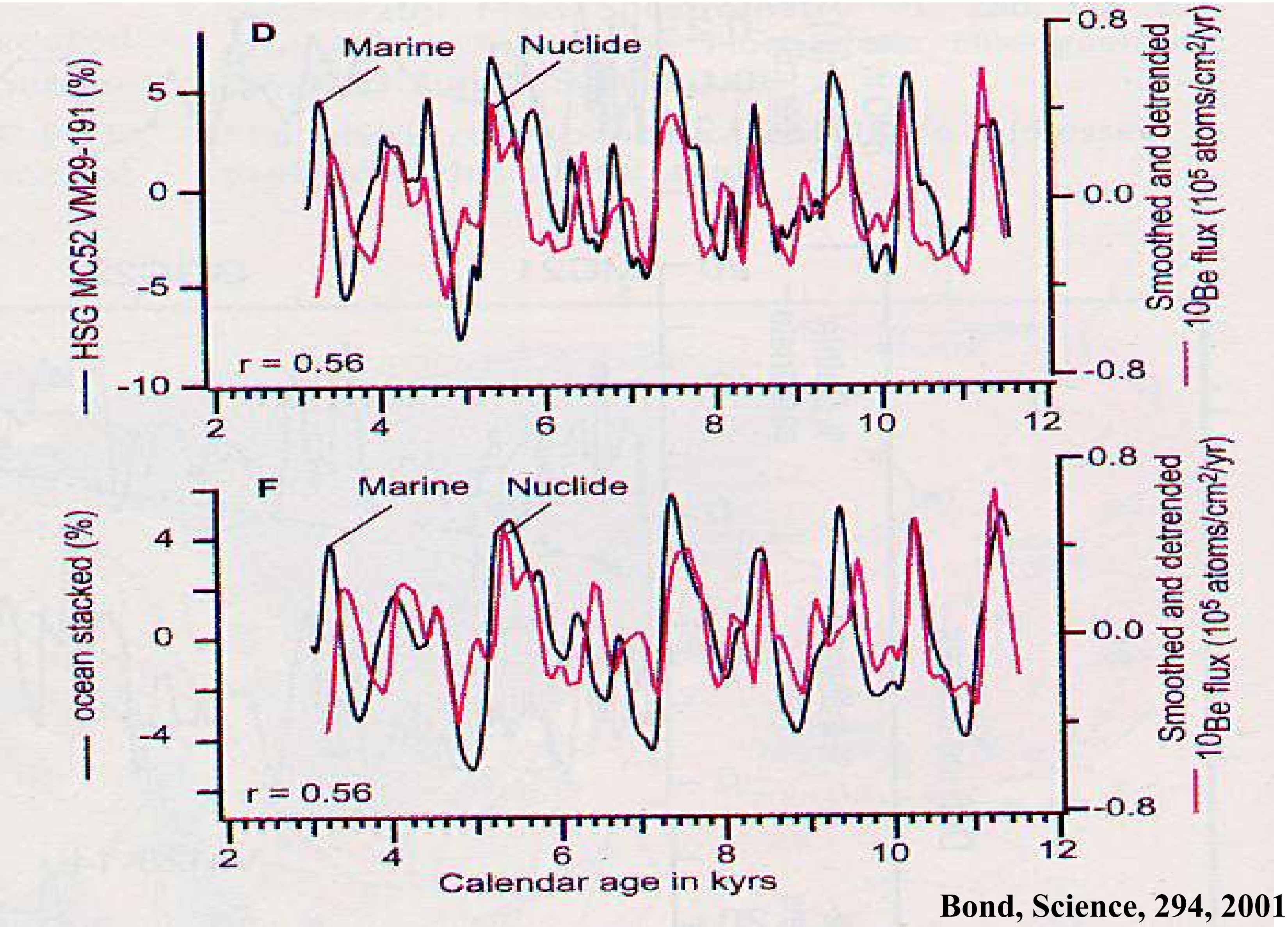
Bond, Science, 294, 2001

Comparison marine and ^{14}C timeseries from tree rings indicates solar control of iceberg limit



Bond, Science, 294, 2001

Comparison marine and cosmogenic ^{10}Be timeseries from ice cores indicates solar control



Bond, Science, 294, 2001

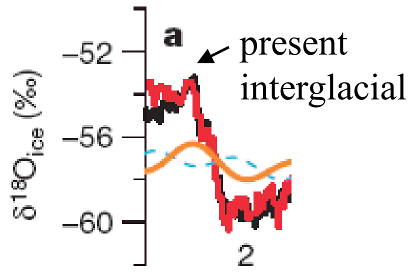
Summary of pre-quaternary

- 35°C greenhouse warming makes earth habitable
- Evolution (burial of C) produced snowball earth cycles
- Galactic dust or alignment of continents caused relatively infrequent glacial periods
- Except for ~3 ice ages at 800-600, 320-250, and 35-0 Ma, earth has been hotter than present and thermally more stable (no ice at poles)
- Steady drop in temperature from Eocene (possibly due to C4 plants)

Quaternary = Milankovitch

- N Hemisphere Insolation at 65°N drive ~100 ice age cycles
- CO_2 amplifies insolation forcing
- Temperature change "simultaneous" in both hemispheres
- 41 ka Obliquity is principle driver (Huybers, Science, 2006)
- Late Pleistocene ice ages 100 ka cycle and colder and better organized because:
  - encompass 2 or 3 41 ka cycles
  - forced by orbit passing through ecliptic plane?
- Interglacials warmest 1% of Pleistocene

But even interglacials have T-variability



- Holocene (current interglacial) changes in climate were:
  - historically significant
  - geologically recorded in areas of high sedimentation (Sargasso Sea) and in Greenland ice
  - associated with changes in solar activity
  - lots of areas for research

- Holocene Maximum (7000-4000 BP)
- Medieval Warm Period (1000-1400 AD)
- Little Ice Age (1400-1860 AD)
- Current Warm Period (1860-present)
- Anthropogenic forcing since ~1950

Implications for Sustainability?

- Last ~100 yrs unusually climatically stable
- Should not assume this is typical
- Natural switch is likely to flicker again
- Natural changes related to sun (Milankovich, radiogenic isotopes)

References

read

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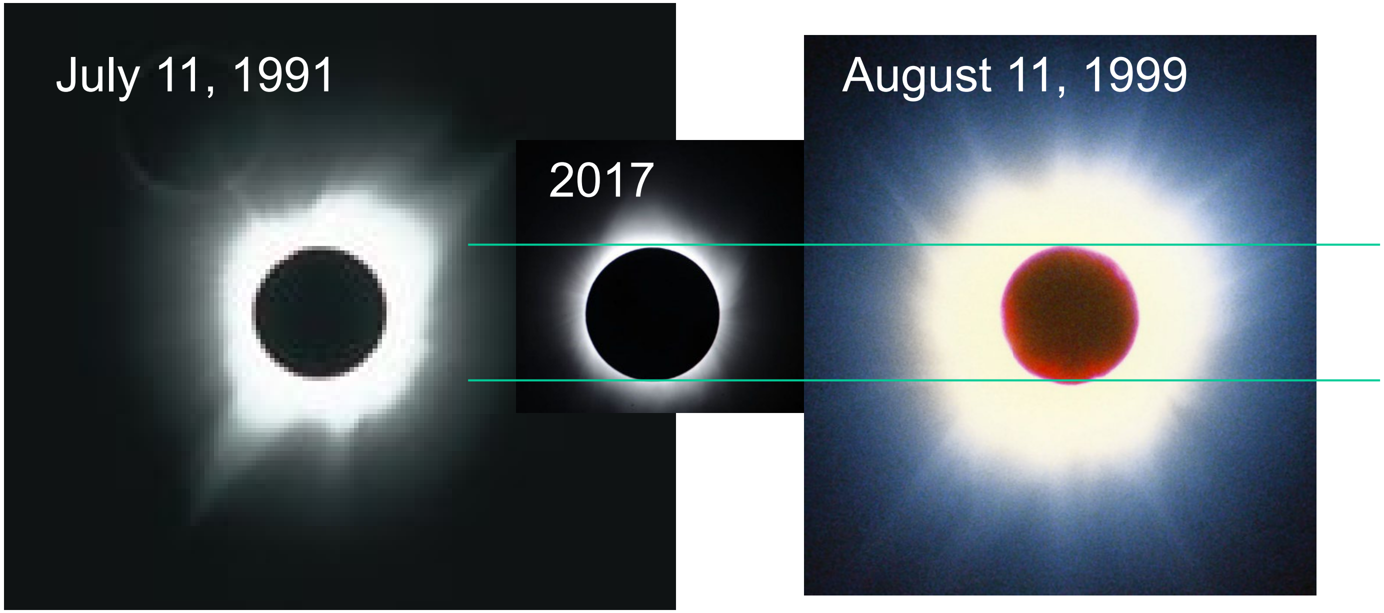
July 11, 1991
2017
August 11, 1999