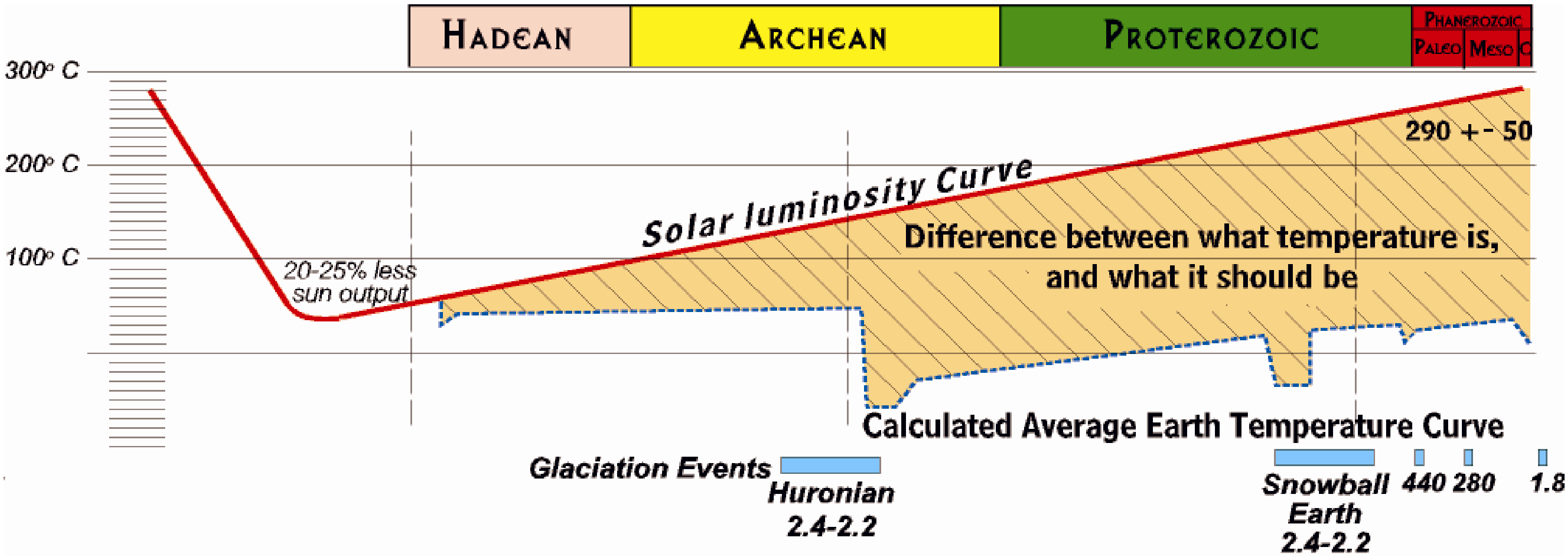
4.0 Billion Years of Earth Environmental Change

We have already explored the various ways the Earth has evolved over the past 4 billion years.

1. Volcanic arcs, to proto-continents, to micro-continents, to continents, to Wilson and supercontinent cycles.
2. Climate Evolution: changes in the atmosphere from CO_2 choked to methane rich, to our present nitrogen/oxygen rich atmosphere.
3. Increasing complexity of biogeochemical cycling and Gaia Theory.

We will begin by looking at the record of some major environmental changes in Earth history, and them examine some mechanisms.

The Solar Luminosity Curve and Long Term History of Earth Environments

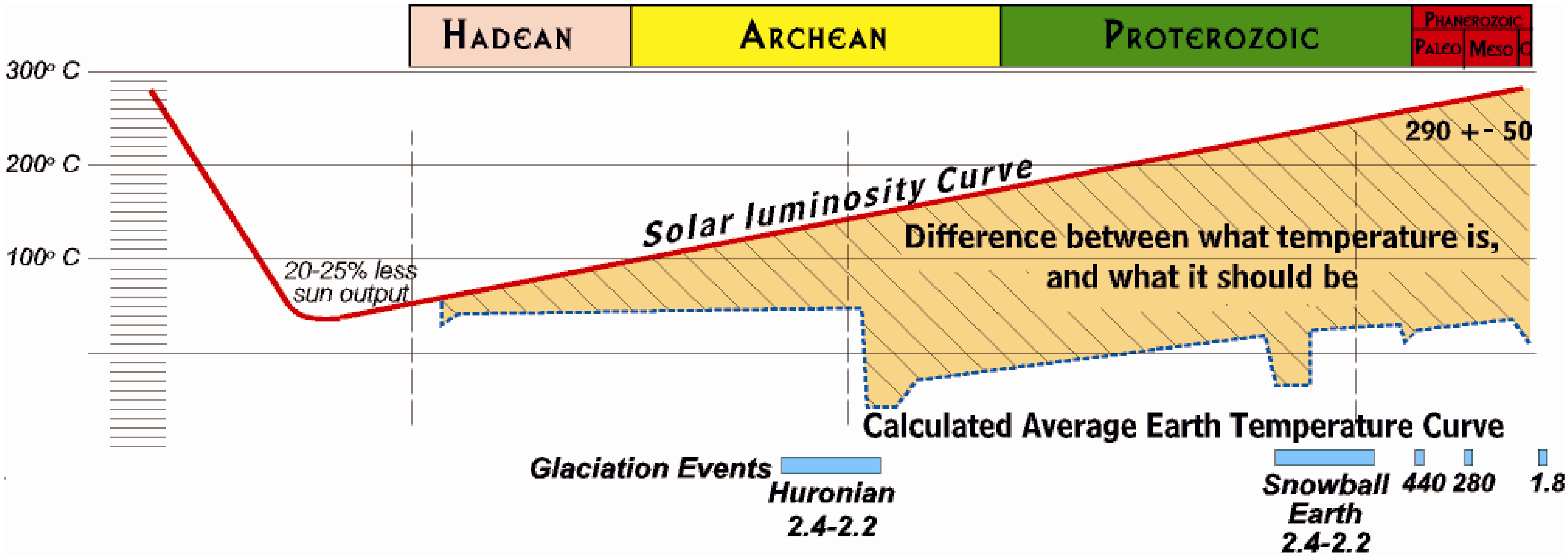


The solar luminosity curve shows steadily increasing temperature with time.

The calculated average Earth temperature curve shows how the temperature actually changed.

According to Gaia theory life processes have moderated Earth temperature, keeping it low enough for life to thrive.

The Solar Luminosity Curve and Long Term History of Earth Environments

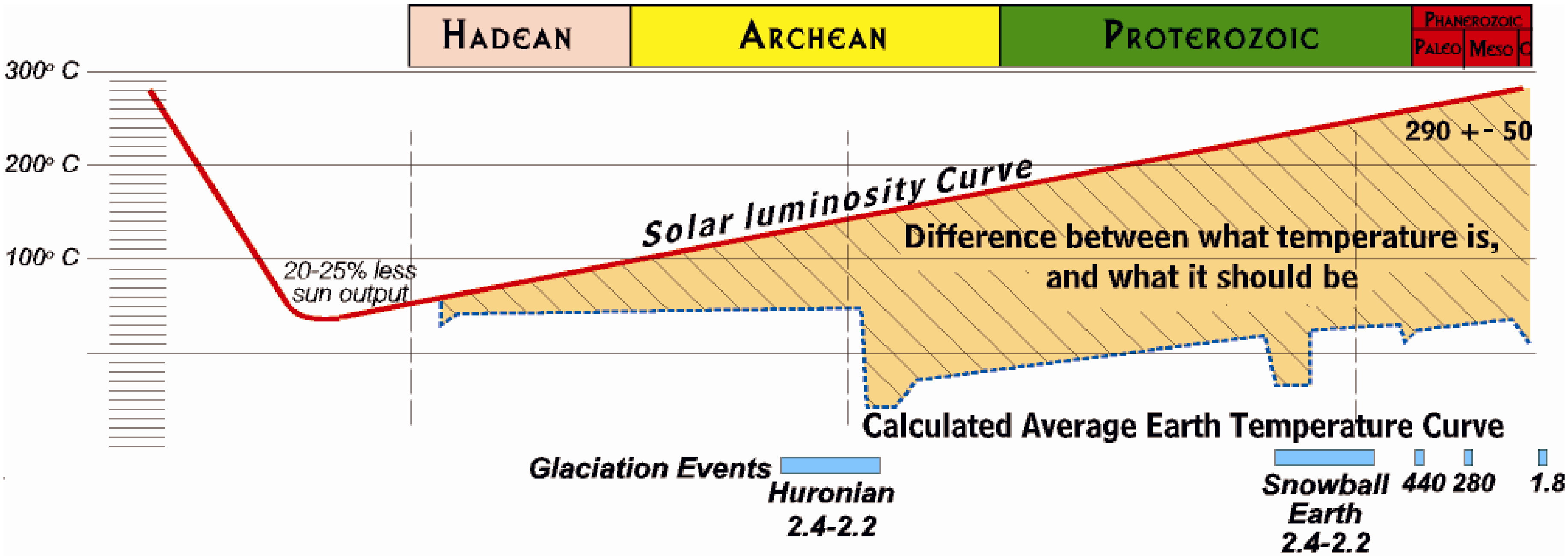


But, the regulation has not been perfect. Earth temperatures do fluctuate at all scales of observation, and . . .

Several times in Earth history Earth has plunged into partial or complete glaciations – times of large to extreme cold on the planet.

This points out that the regulation of temperature is far from perfect, . . . the question is, "What causes the destabilization that leads to fluctuations.

The Solar Luminosity Curve and Long Term History of Earth Environments

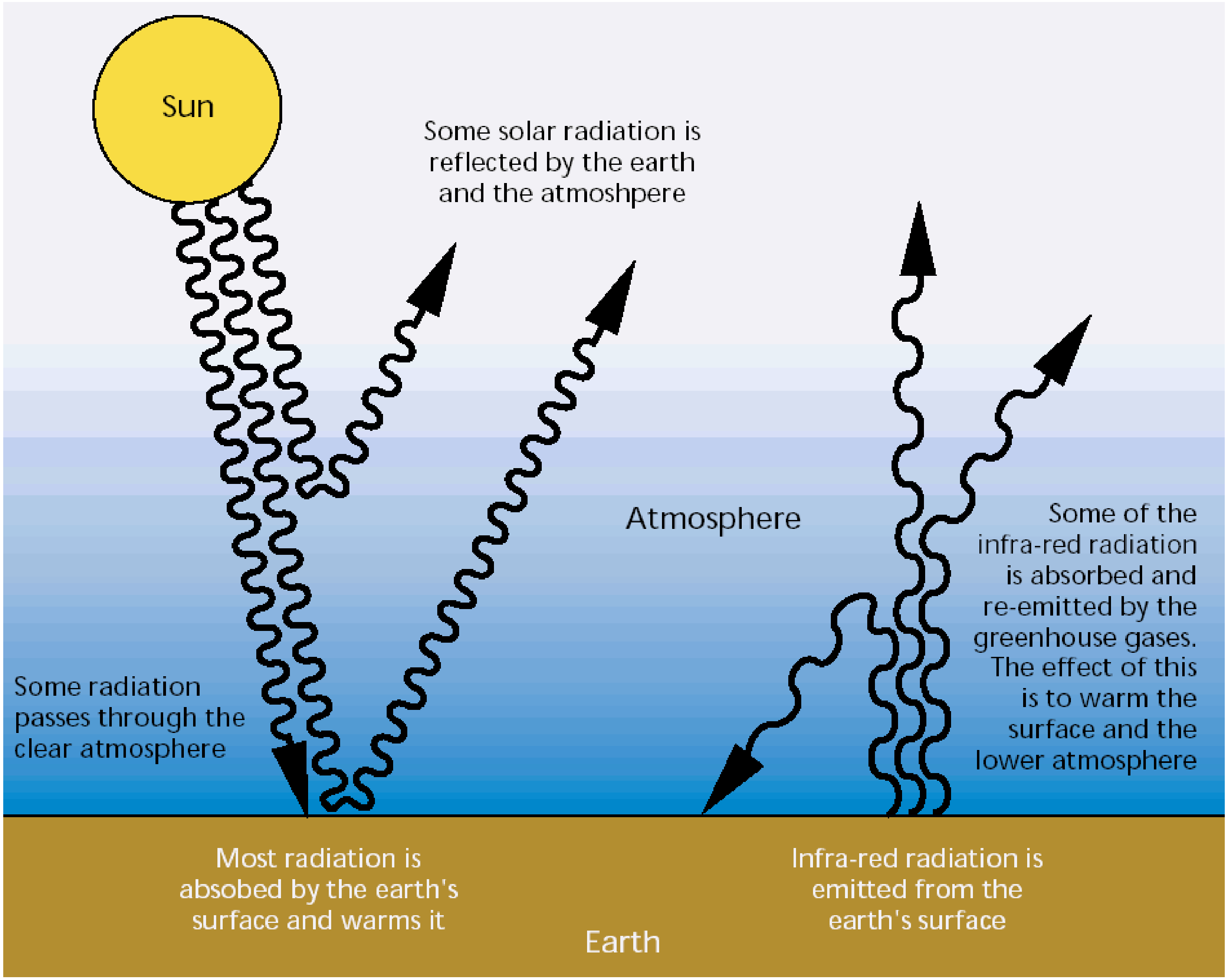


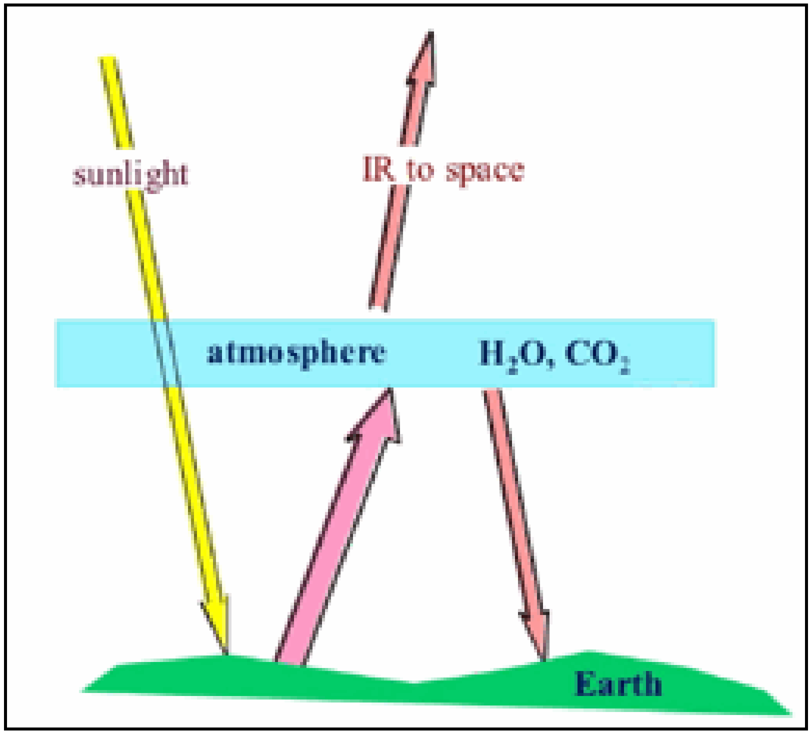
The simple answer is, . . . It ain't simple.

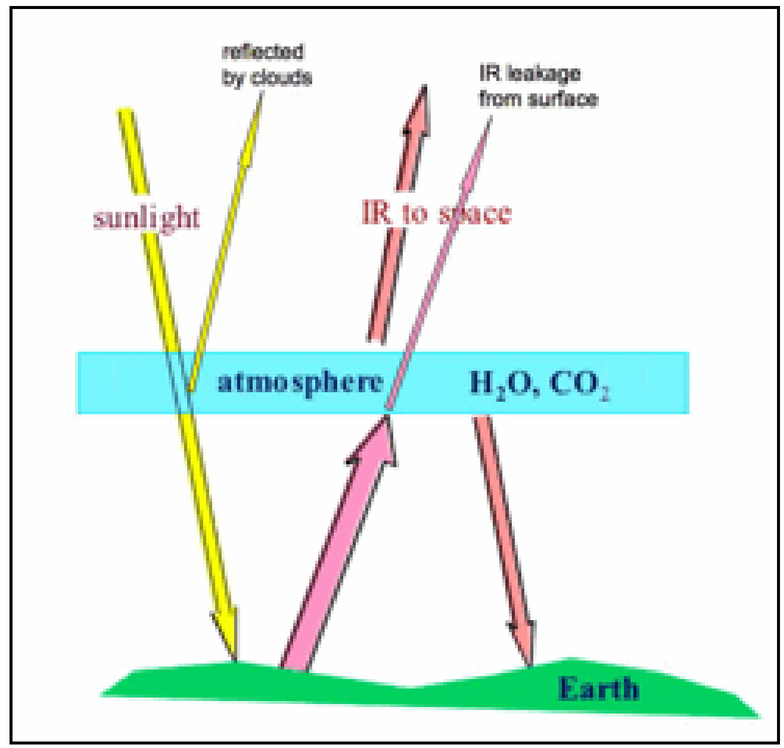
There are some general principles, but they are best understood by looking at specific examples.

But, climate is related to greenhouse gas abundance, the position of the continents, and albedo.

Greenhouse Gasses and The Carbon History of the Earth


Sun
Some solar radiation is reflected by the earth and the atmoshpere
Atmosphere
Some of the infra-red radiation is absorbed and re-emitted by the greenhouse gases. The effect of this is to warm the surface and the lower atmosphere
Some radiation passes through the clear atmosphere
Most radiation is absobed by the earth's surface and warms it
Infra-red radiation is emitted from the earth's surface
Earth

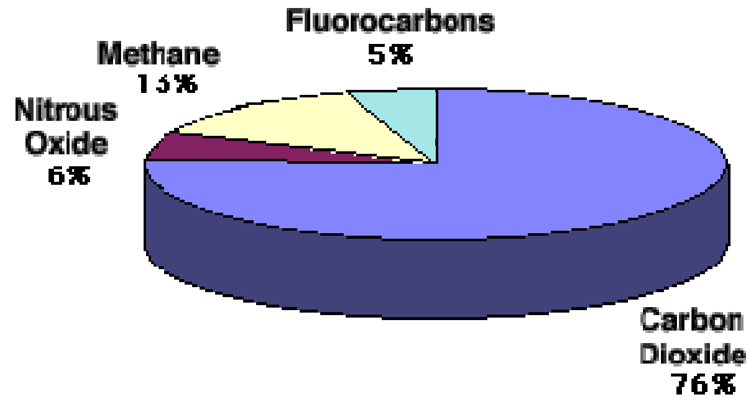




http://muller.lbl.gov/teaching/physics10/PffP_textbook/PffP-10-climate.htm

On earth, the most abundant greenhouse gases are, in order of relative abundance:

* water vapor
* carbon dioxide
* methane
* nitrous oxide
* ozone
* CFCs

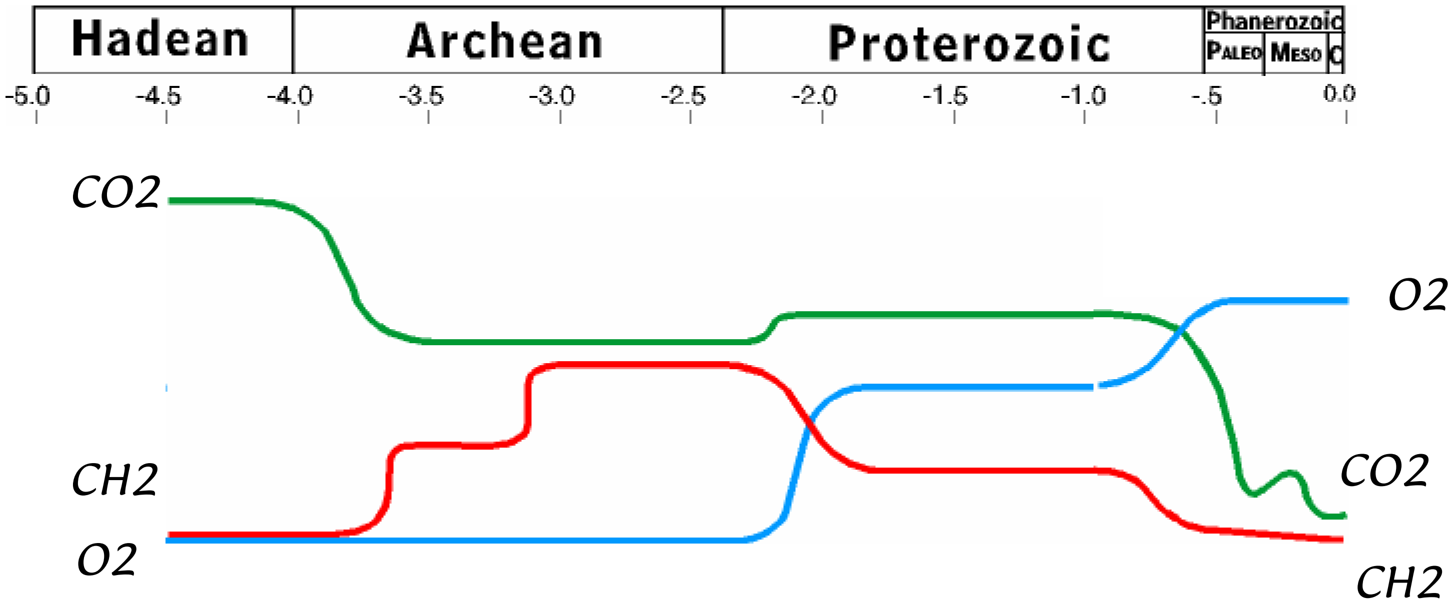


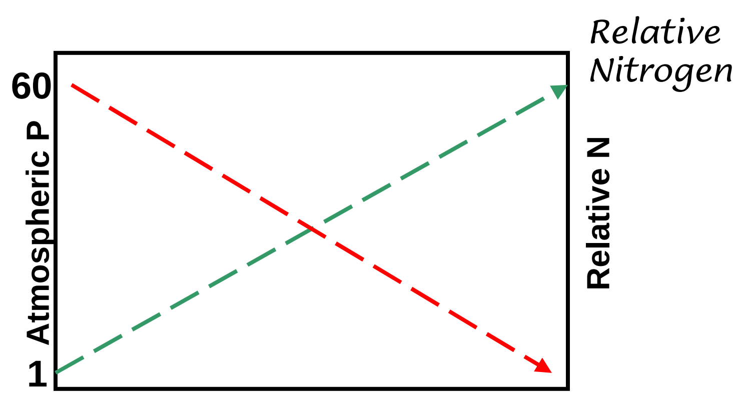
The most powerful greenhouse gases are

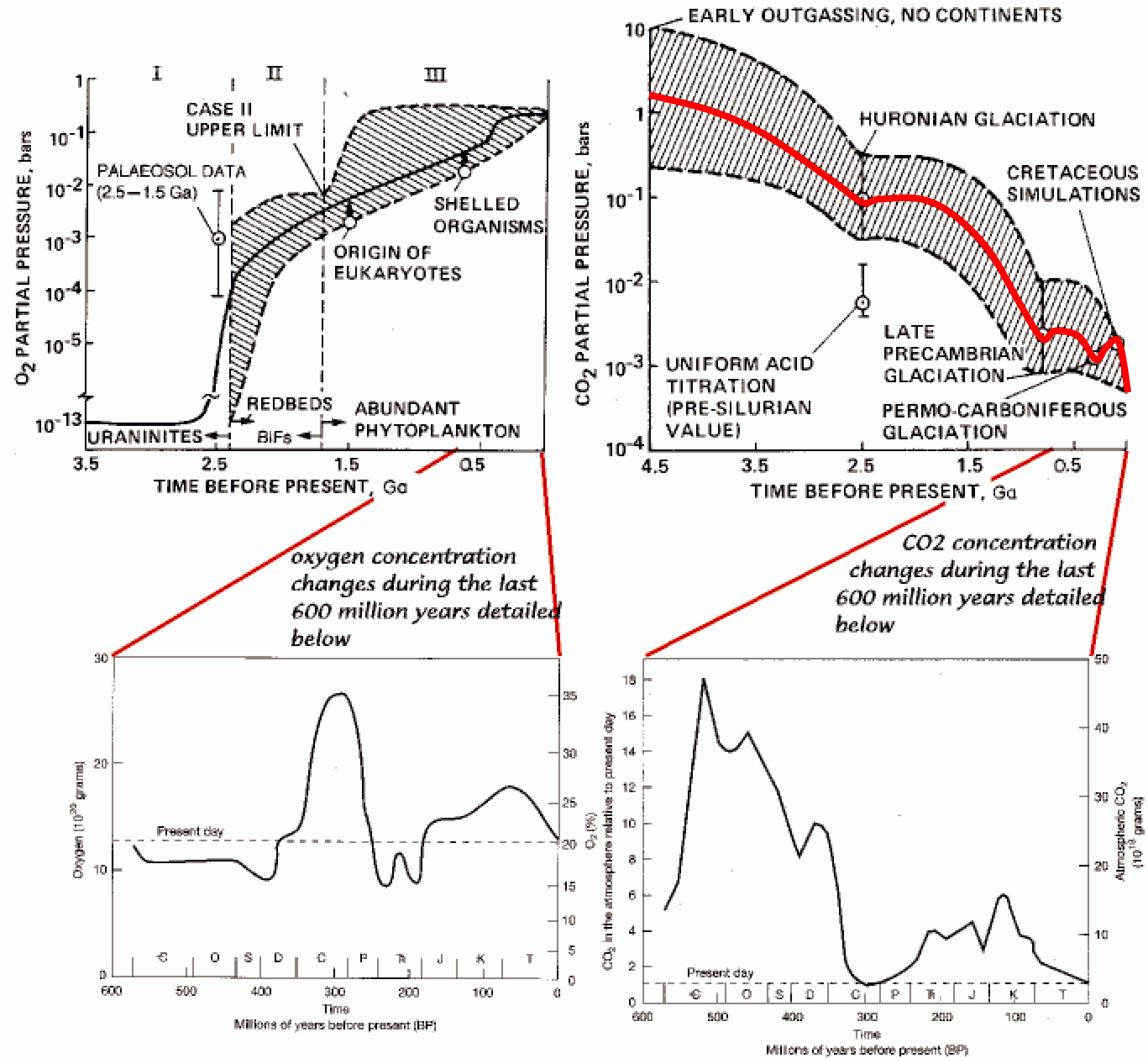
* water vapor, which causes about 36–70% of the greenhouse effect on Earth. (Note clouds typically affect climate differently from other forms of atmospheric water.)
* carbon dioxide, which causes 9–26%
* methane, which causes 4–9%
* ozone, which causes 3–7%

Methane is 21 times more effective at capturing infrared heat than carbon dioxide so less of it has more effect.

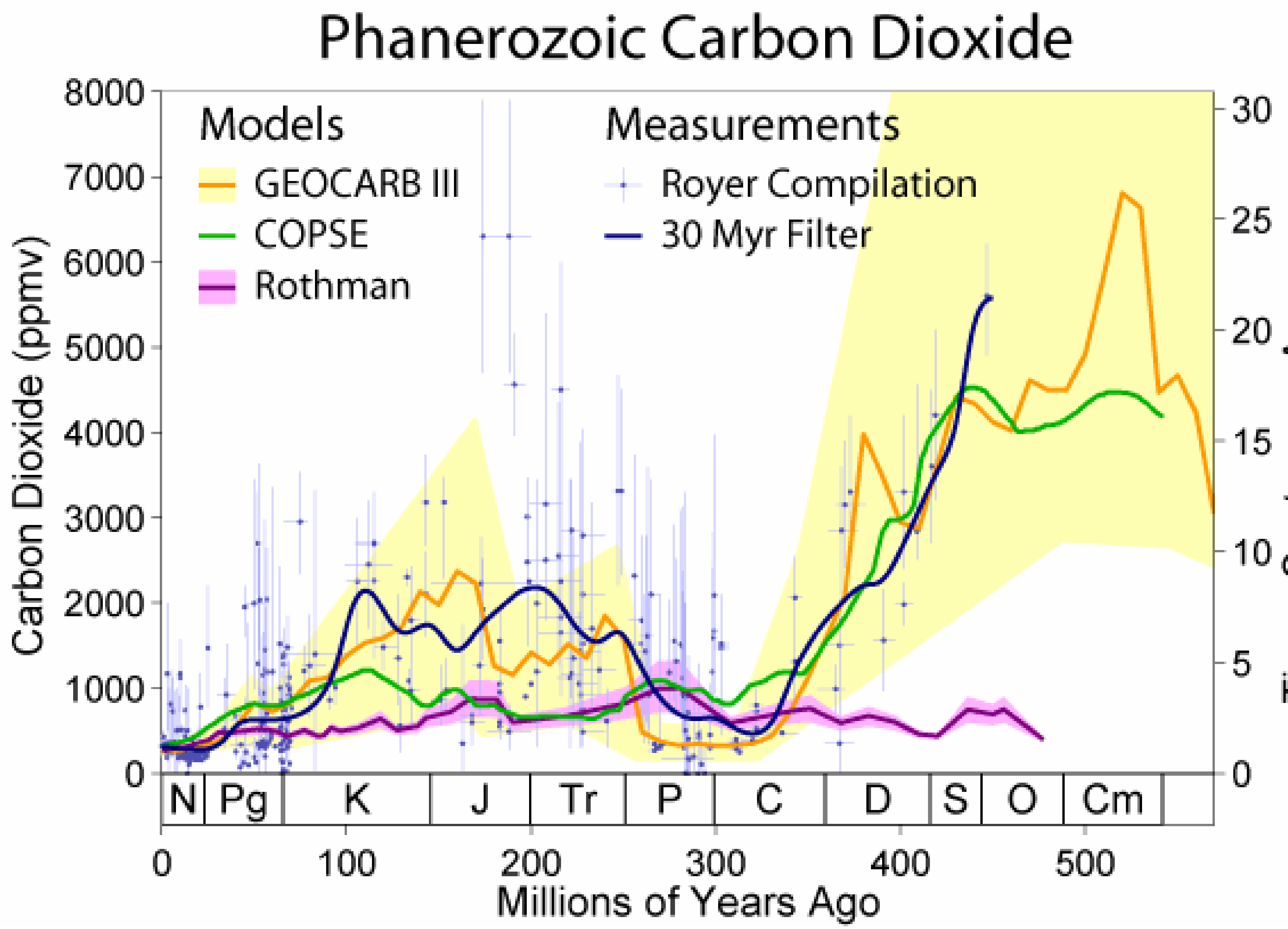
Carbon dioxide has declined more or less continuously in Earth history, being captured by life processes and sequestered in the sediments as carbonate rocks and petroleum.



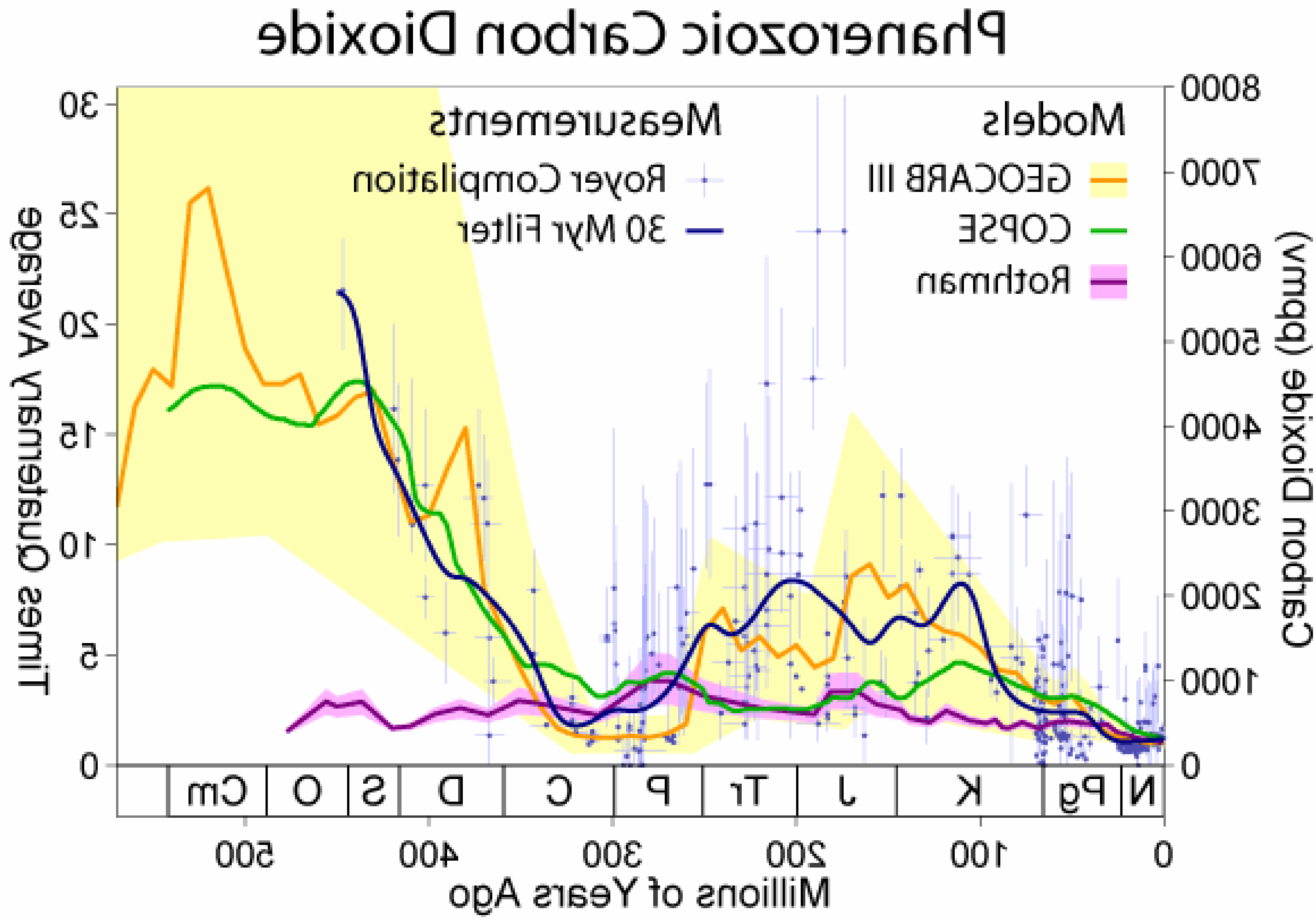




I
II
III
CASE II
UPPER LIMIT
PALAEOSOL DATA
(2.5—1.5 Ga)
SHELLED
ORGANISMS
ORIGIN OF
EUKARYOTES
REDBEDS
ABUNDANT
PHYTOPLANKTON
URANINITES
BIFs
O2 PARTIAL PRESSURE, bars
TIME BEFORE PRESENT, Ga
EARLY OUTGASSING, NO CONTINENTS
HURONIAN GLACIATION
CRETACEOUS
SIMULATIONS
LATE
PRECAMBRIAN
GLACIATION
UNIFORM ACID
TITRATION
(PRE-SILURIAN
VALUE)
PERMO-CARBONIFEROUS
GLACIATION
CO2 PARTIAL PRESSURE, bars
TIME BEFORE PRESENT, Ga
oxygen concentration
changes during the last
600 million years detailed
below
CO2 concentration
changes during the last
600 million years detailed
below
Present day
Oxygen (10^{20} grams)
O_2 (%)
Time
Millions of years before present (BP)
CO_2 in the atmosphere relative to present day
Atmospheric CO_2 (10^{18} grams)



Phanerozoic Carbon Dioxide
Models
GEOCARB III
COPSE
Rothman
Measurements
Royer Compilation
30 Myr Filter
Carbon Dioxide (ppmv)
Times Quaternary Average
Millions of Years Ago
8000
7000
6000
5000
4000
3000
2000
1000
0
30
25
20
15
10
5
0
N
Pg
K
J
Tr
P
C
D
S
O
Cm
0
100
200
300
400
500



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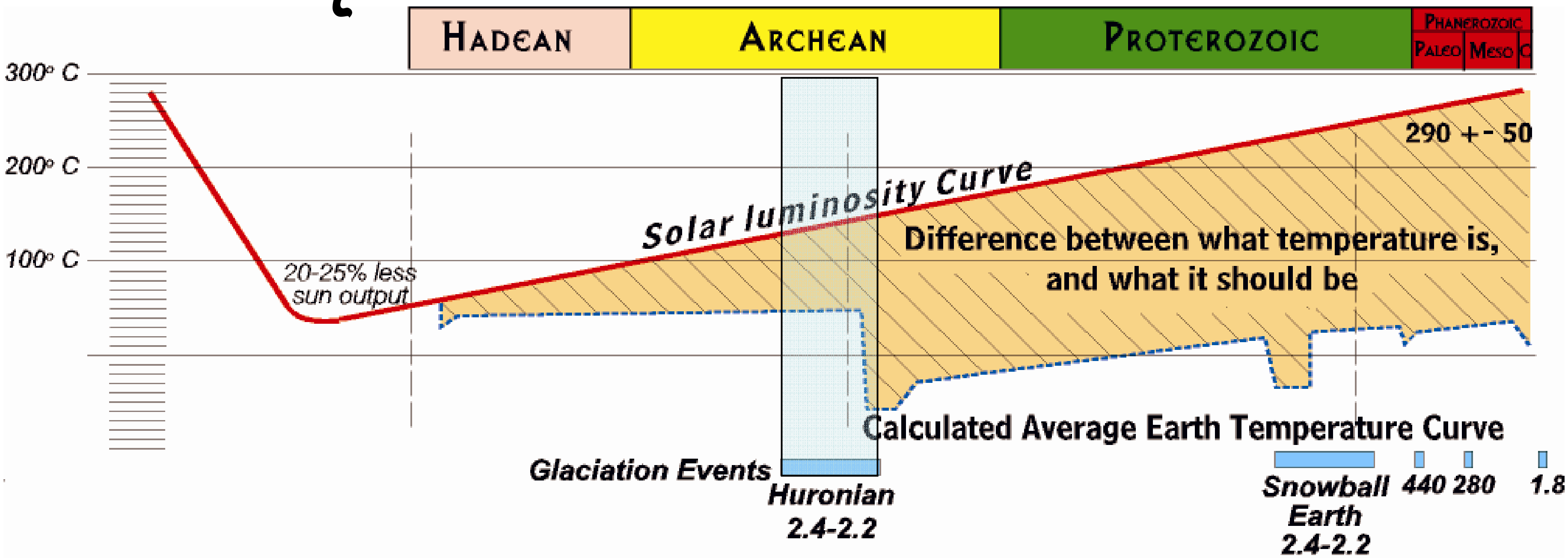
S
D
C
P
Tr
J
K
Pg
N
500
400
300
200
100
0
30
25
20
15
10
5
0
8000
7000
6000
5000
4000
3000
2000
1000
0

Glaciation Events

Huronian Glaciation

Huronian Glaciation

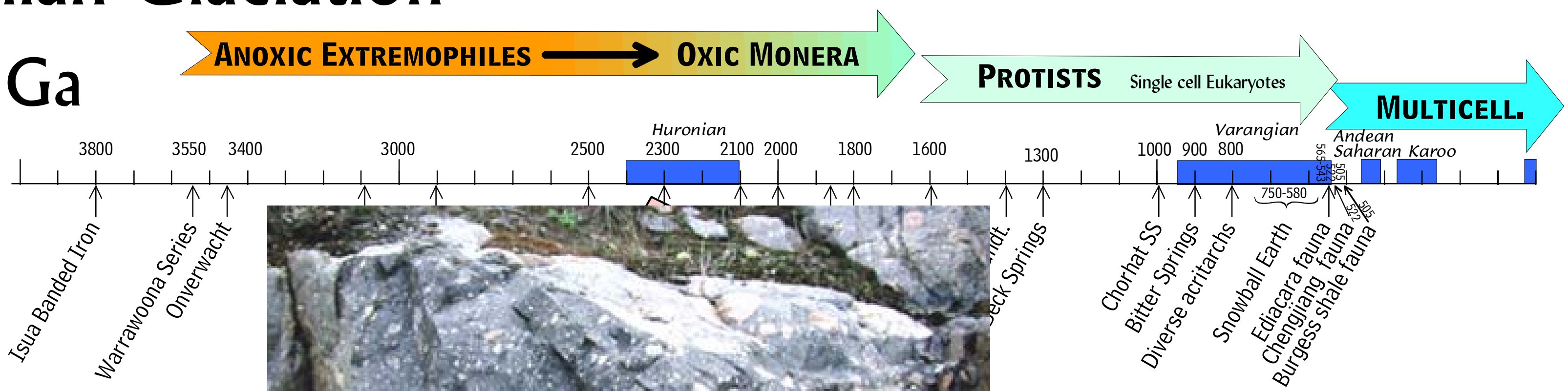


- Earliest glaciation for which we have good evidence.
- 2.4-2.2 Ga (billion years ago)

Proterozoic Earth Environments

Huronian Glaciation

2.4-2.2 Ga



http://abyss.elte.hu/users/segeusc/arhivum/2001_Kanada/Kanada.htm

Gowganda

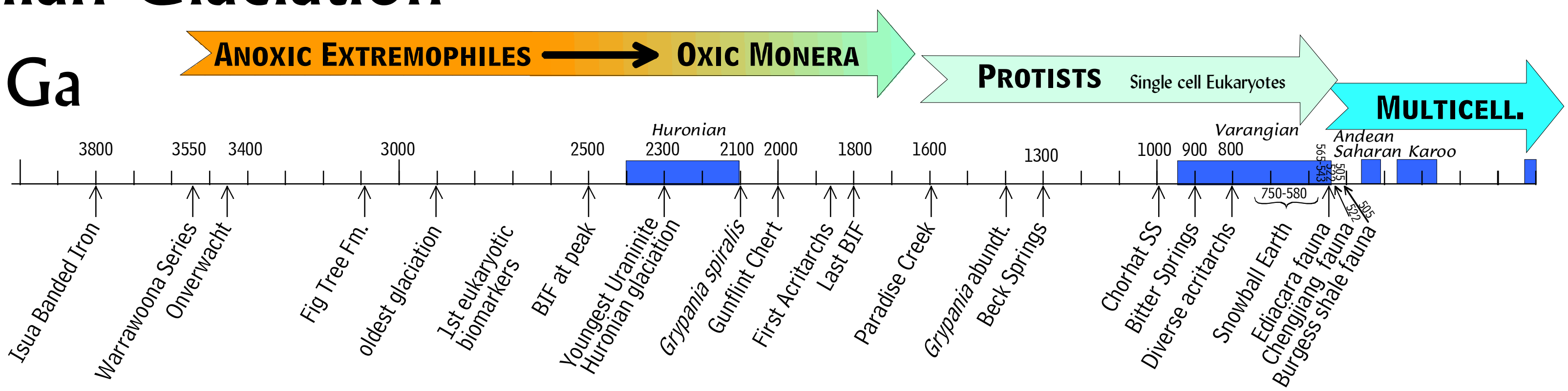
formation

http://www.gps.caltech.edu/~rkopp/photos/Huronian2002/

Proterozoic Earth Environments

Huronian Glaciation

2.4-2.2 Ga

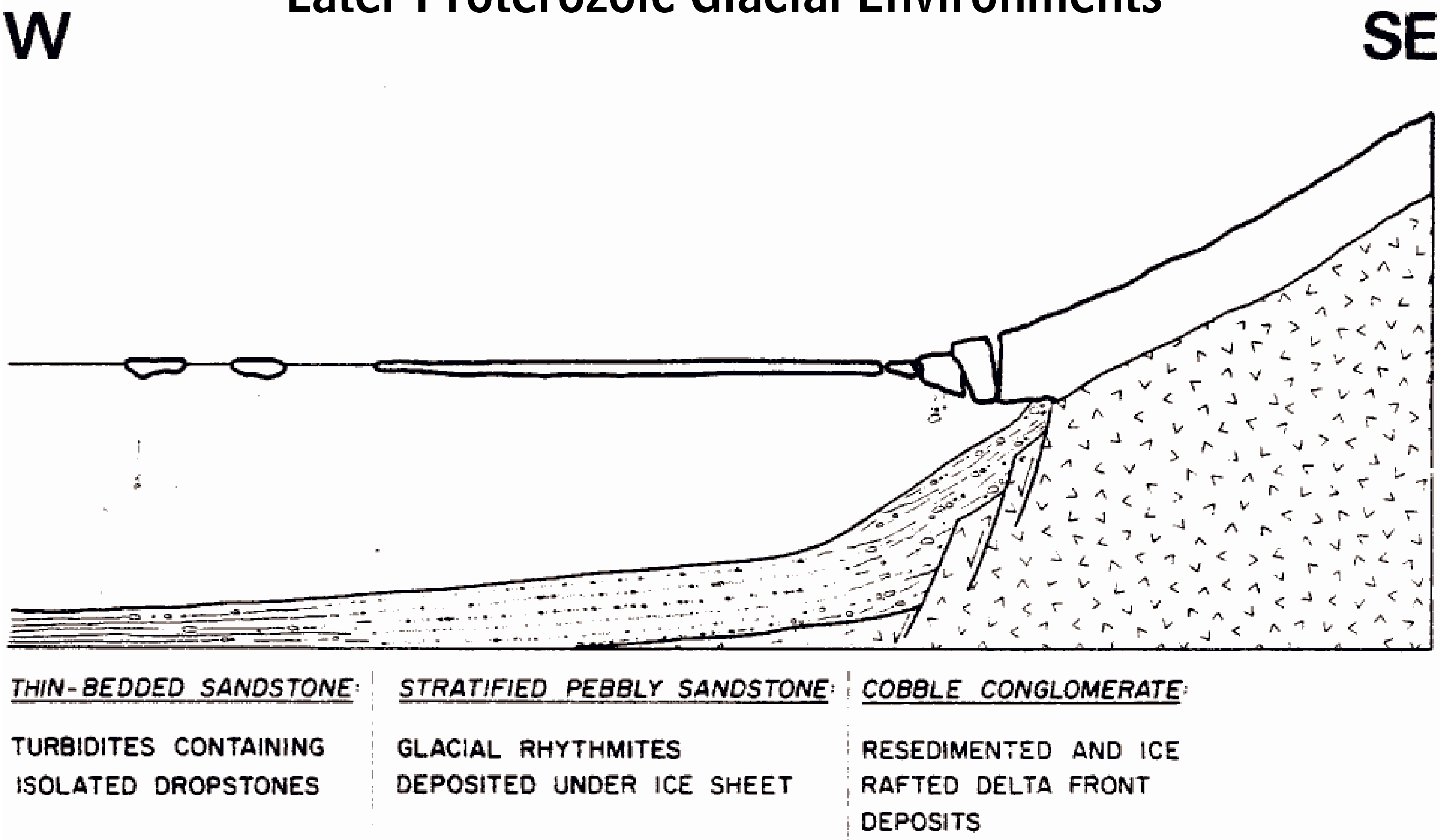


http://maps.unomaha.edu/maher/plate/week11/supracrustals.html

Glacial Dropstones

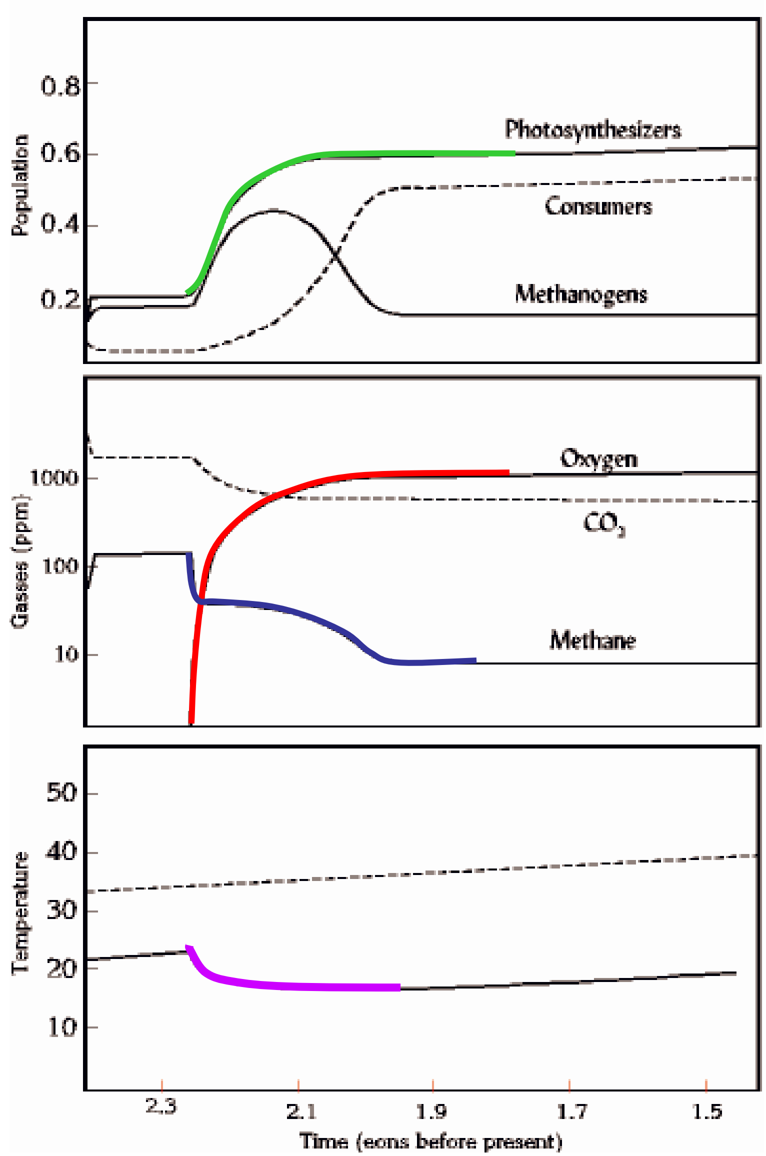
Glacial Dropstones

Formation of Dropstones in the Virginia Later Proterozoic Glacial Environments

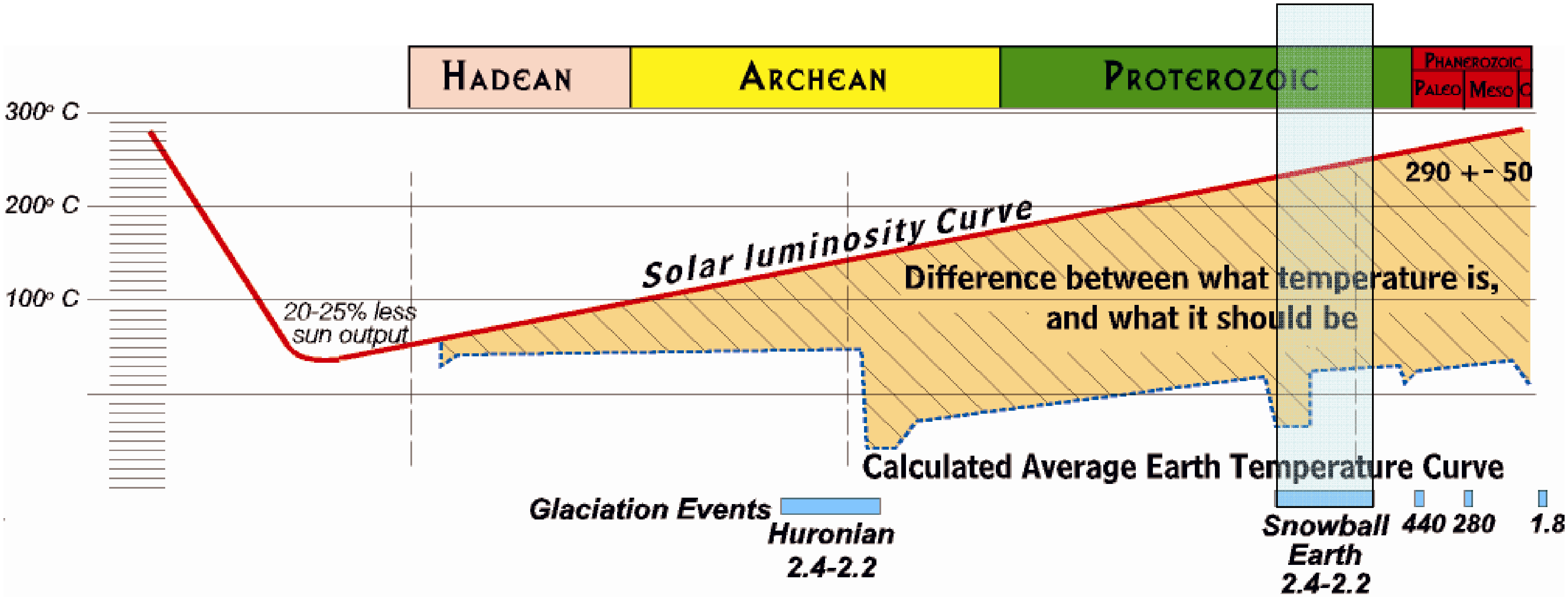


Huronian Glaciation

- Earliest glaciation for which we have good evidence.
- 2.4-2.2 Ga (billion years ago)
- It is likely that the temperature drop causing the glaciation was precipitated by a change in atmospheric composition, likely the decline of the strong greenhouses of CO_2 and CH_4 rich atmosphere associated with the rise of photosynthesizing Blue Green Algae and oxygen in the atmosphere.



Snowball Earth



The World of Unintended Consequences

Snowball Earth

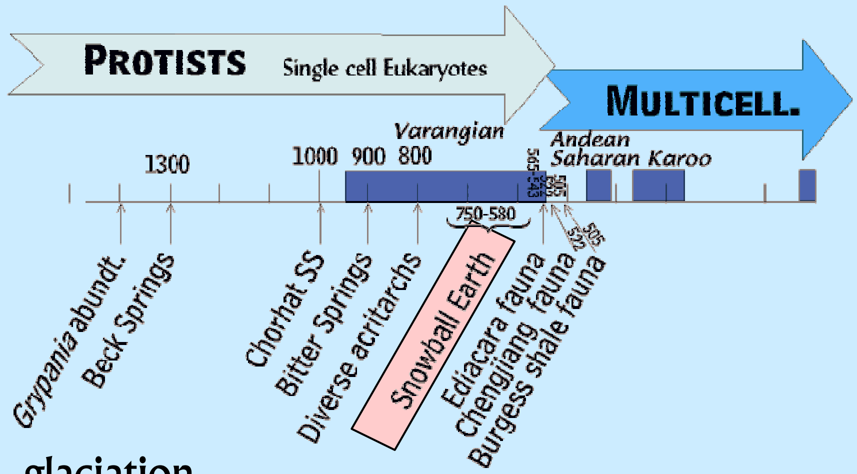
750-580 Ma

Link 1 for Snowball Earth

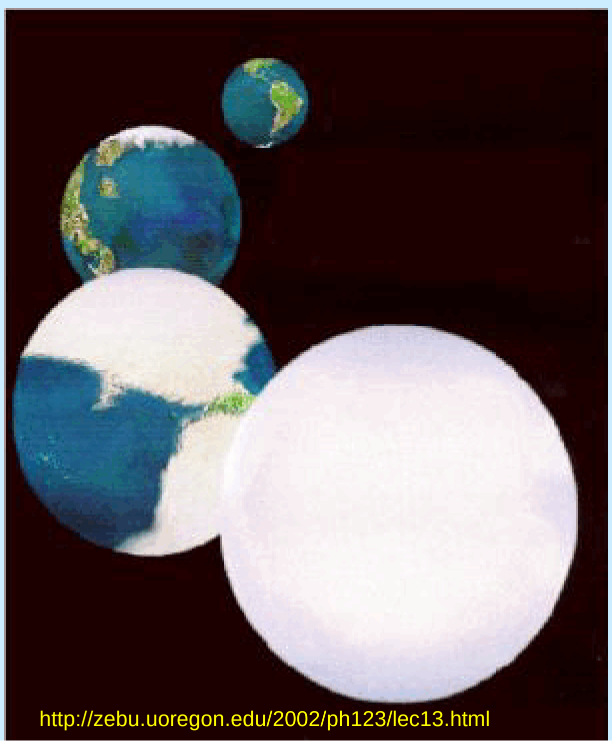
Link 2 for Snowball Earth

Link 3 for Snowball Earth

Link 4 for Snowball Earth



- Earth underwent four extremely severe, global-wide, glaciation events, each lasting about 10 million years. Temperatures dropped to -50 degrees Celsius. Oceans froze 1 km thick at equator.



http://zebu.uoregon.edu/2002/ph123/lec13.html

The existence of two very severe glaciations near the end of the Proterozoic Eon, approximately 730 and 640 million years ago, has long been inferred from geological observations. Recent paleomagnetic measurements reliably indicate that glaciers extended to sea level close to the equator for millions of years during these events. How could such a dire situation have come about?

In the last five years, physical and geochemical observations of sedimentary rock layers on virtually all of Earth's ancient continents provide compelling evidence for unique greenhouse conditions following each of the two great Late Proterozoic ice ages.

http://www.utah.edu/unews/releases/03/nov/snowball.html

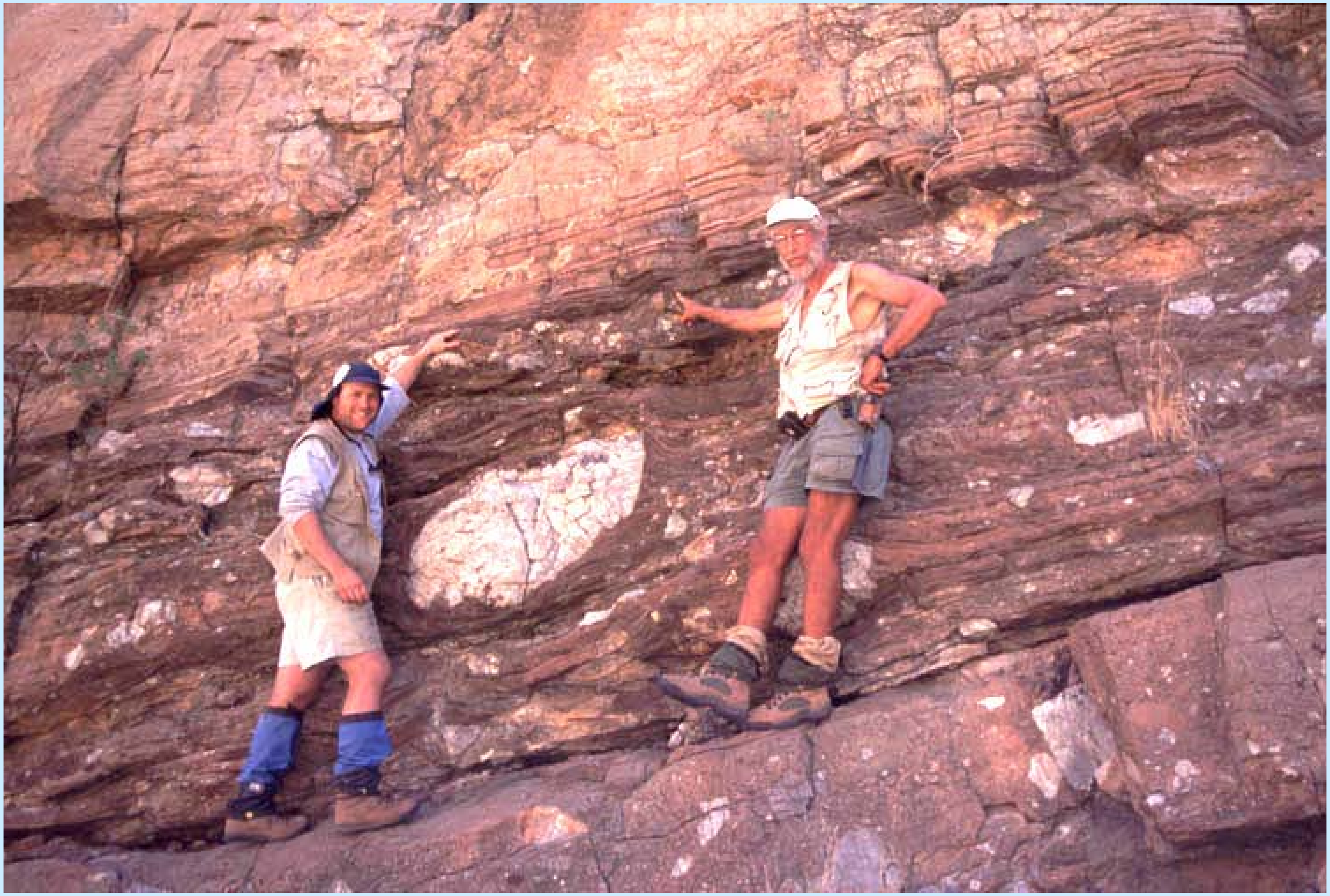
Paul Hoffman - Sturgis Hooper professor of geology, Harvard University

Evidence from Namibia (in Africa), Svalbard (in Norway) and northern Canada will be highlighted in this talk. The case for the snowball Earth hypothesis is strong: It provides satisfactory explanations for a diversity of unique and otherwise enigmatic observations. But vigorous criticism continues. Hoffman states: "In my view, improved understanding of snowball ice dynamics and its evolution over time will go far to reconcile the hypothesis with geological observations."

PreCambrian Record of Life And Associated Geologic Deposits

Snowball Earth

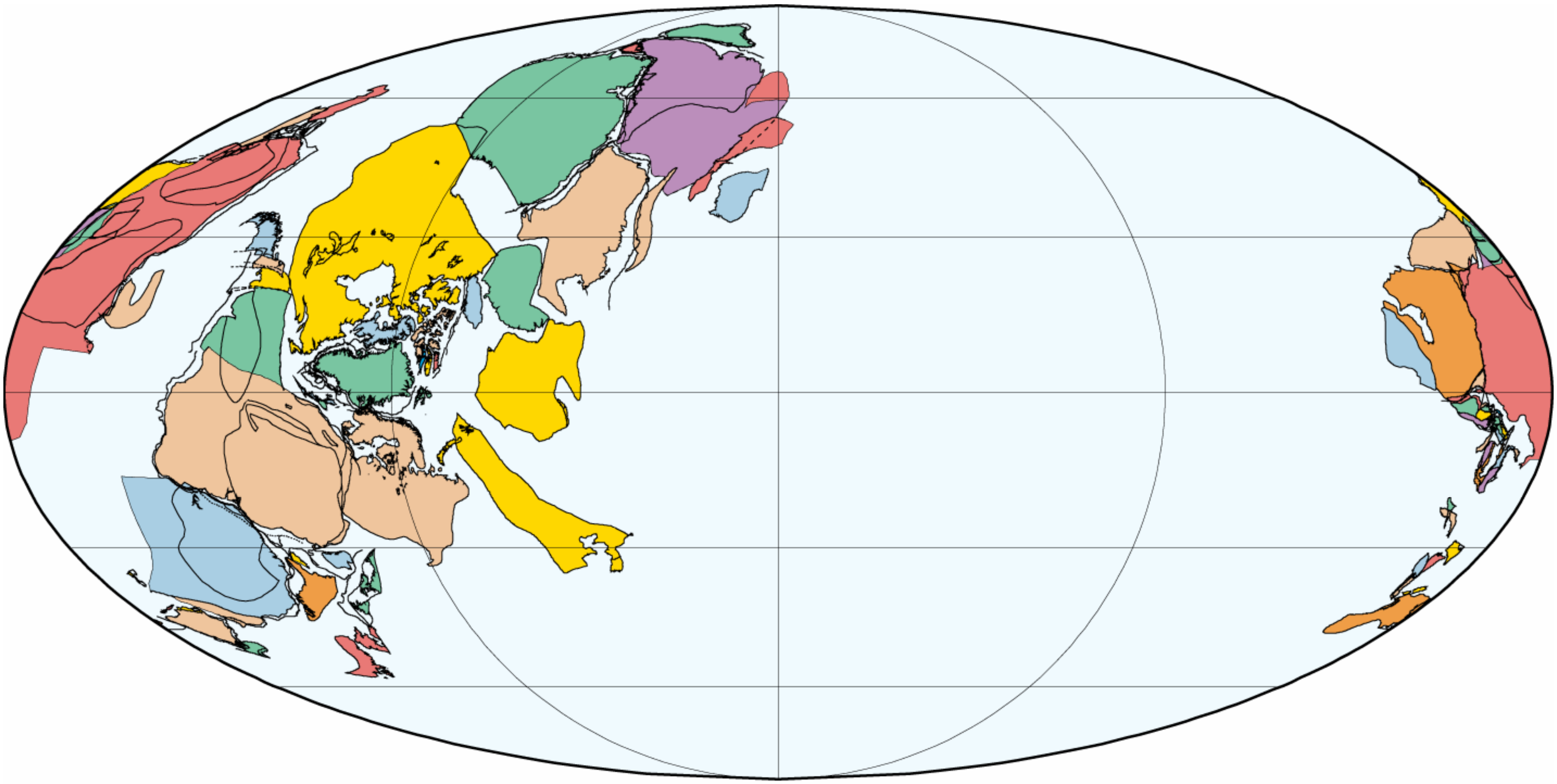
750-580 Ma



What Caused Snowball Earth, And Could It Happen Again?

Continents gather at equator.

1. Increased tropical weathering draws down CO_2
2. Tropical bioproductivity sequesters CO_2 (high C^{13} burial)



750 Ma
Late Proterozoic

PLATES/UTIG
August 2002

What Caused Snowball Earth, And Could It Happen Again?

Continents gather at equator.

1. Increased tropical weathering draws down CO_2
2. Tropical bioproductivity sequesters CO_2 (high C^{13} burial)

This is the basalt weathering reaction, likely one of the most common geological reactions on the early Earth.

$$2FeO + 3CO_2 + H_2O \rightarrow Fe_2CO_3 + H_2$$

The weathering sucks CO_2 out of the atmosphere, and it ends up either dissolved in sea water, or sequestered in the sediments.

What Caused Snowball Earth, And Could It Happen Again?

Continents gather at equator.

1. Increased tropical weathering draws down CO_2
2. Tropical bioproductivity sequesters CO_2 (high C^{13} burial)

The feldspar weathering reaction also sucks CO_2 out of the atmosphere.

$$KAlSi_3O_8 + H_2CO_3 + 12\ H_2O \longrightarrow$$

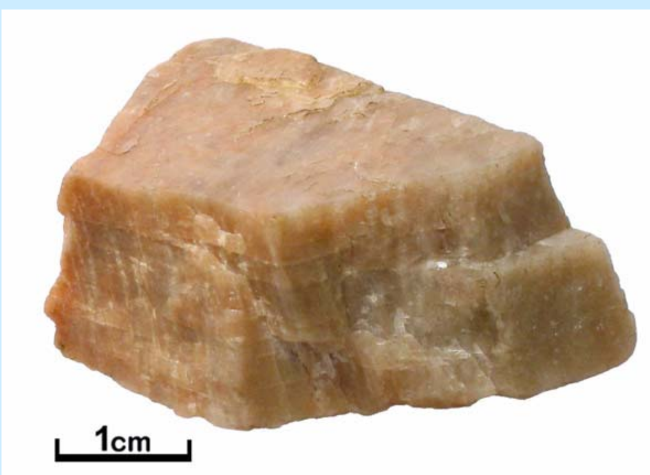
Orthoclase

Dissolved Silica

$$2K^+ + 2HCO_3^- + 5H_4SiO^4 +$$

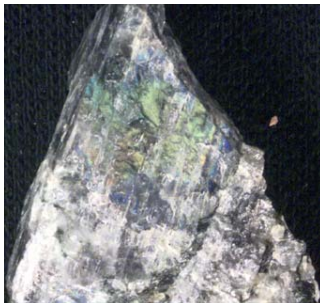
$$+ Al_2Si_2O_5(OH)$$

Kaolinite Clay



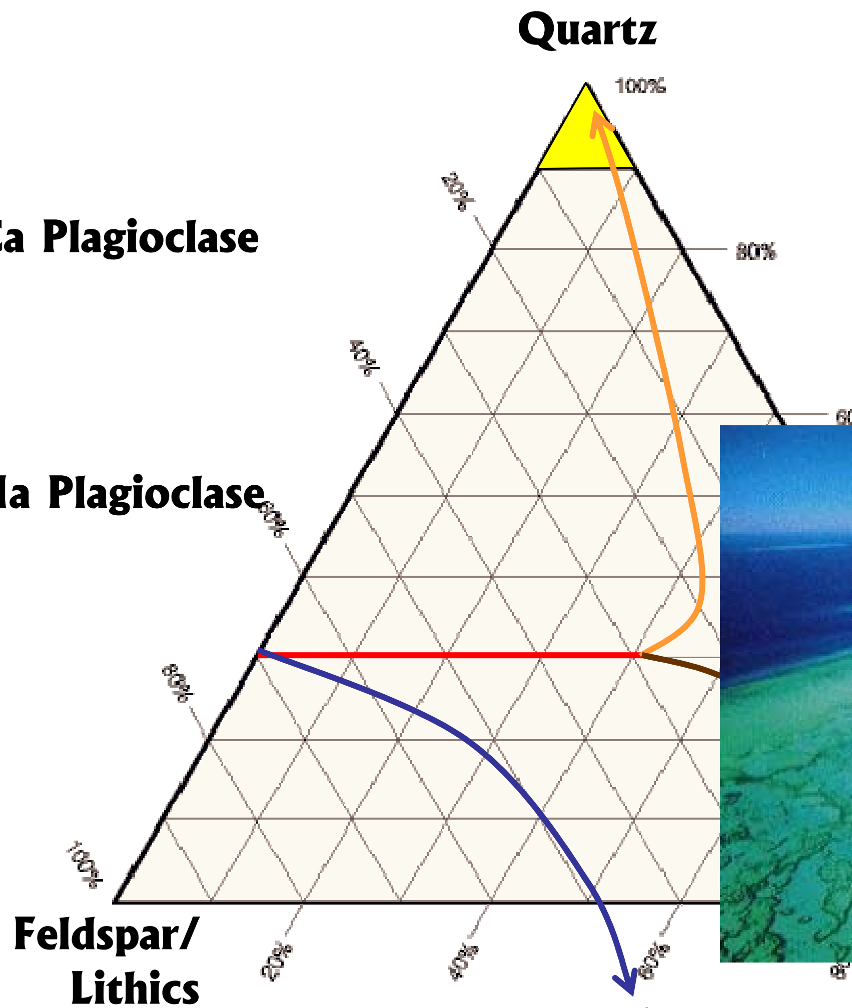
Sediment Evolution on a Ternary Diagram

Carbonates and Evaporates



Ca Plagioclase

Na Plagioclase



And Ca goes into sea water
Where it precipitates . . .

To form vast limestone
deposits

Biogeochemical Carbon Cycling

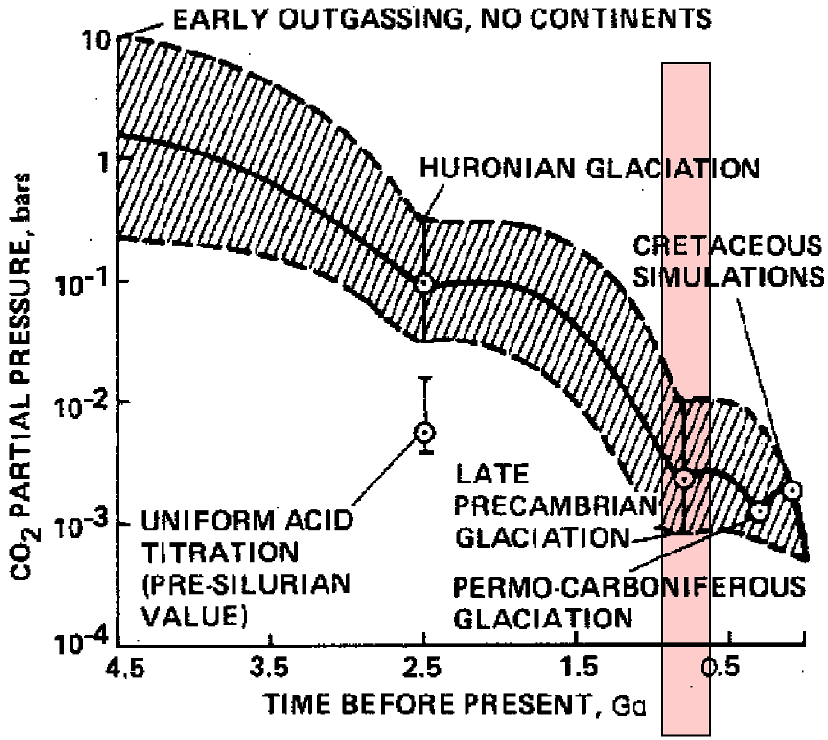
Carbon Reservoirs on Earth

	Mass in billion metric tons	
Carbonate rocks	10,000,000	LITHOSPHERE
Oceans	36,000	HYDROSPHERE
Fossil Fuels	6000	LITHOSPHERE
Soils	1500	LITHOSPHERE
Atmosphere	735	ATMOSPHERE
Plants (land and ocean)	560	BIOSPHERE

LITHOSPHERE = 10,750,000

HYDROSPHERE = 36,000

BIOSPHERE = 560



Estimated changes in pCO_3 over geologic time. The shaded area represents the climatically reasonable range of pCO_3.

What Caused Snowball Earth, And Could It Happen Again?

Continents gather at equator.

1. Increased tropical weathering draws down CO_2
2. Tropical bioproductivity sequesters CO_2 (high C^{13} burial)

Earth temperature drops
- Polar oceans begin to freeze
- Albedo increases

Runaway positive feedback drives temperature down.

Absence of mitigating conditions
- No continental ice sheet to shut down weathering sink for CO_2

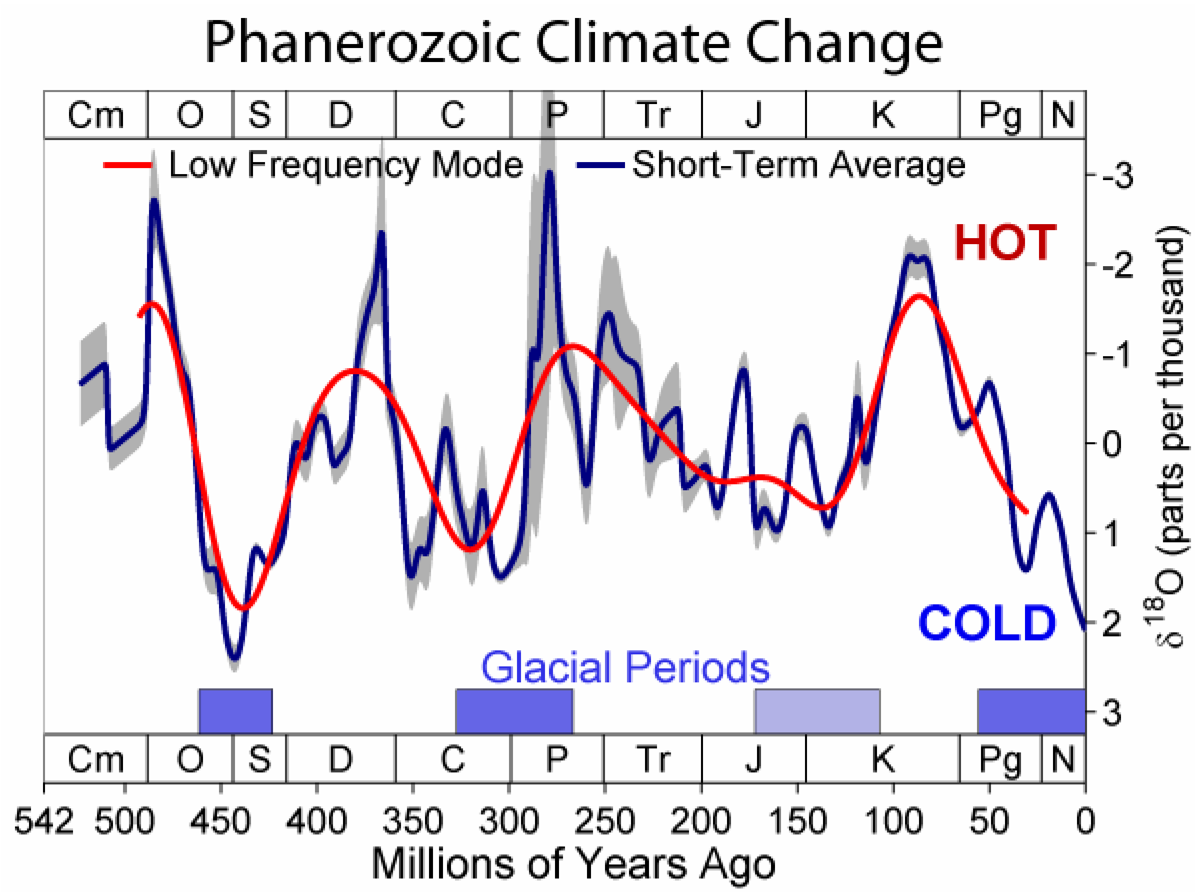
CH_4 becomes more important greenhouse gas than CO_2
(It is less stable than CO_2)

Leading to increased instability, further plunging system into runaway + feedback

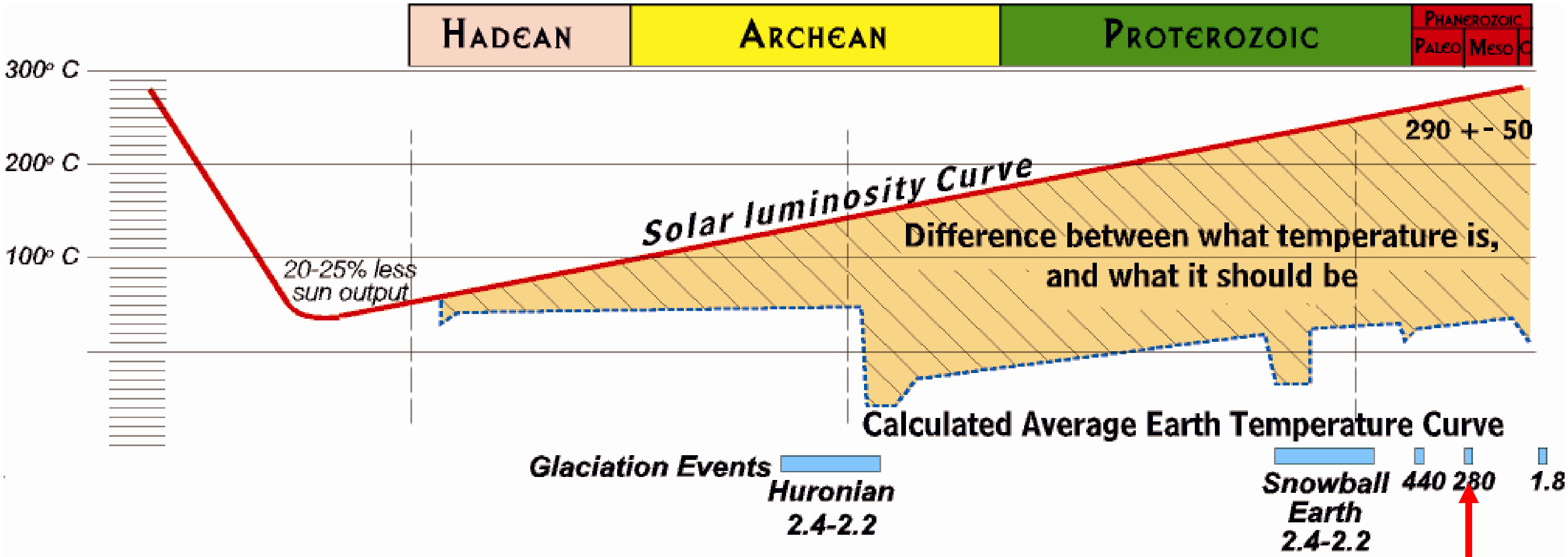
On a tectonically dead planet this condition is irreversible.

- But ongoing volcanic activity pumps CO_2 into the atmosphere, eventually reversing the system, leading to oscillations.

More Recent Glaciations

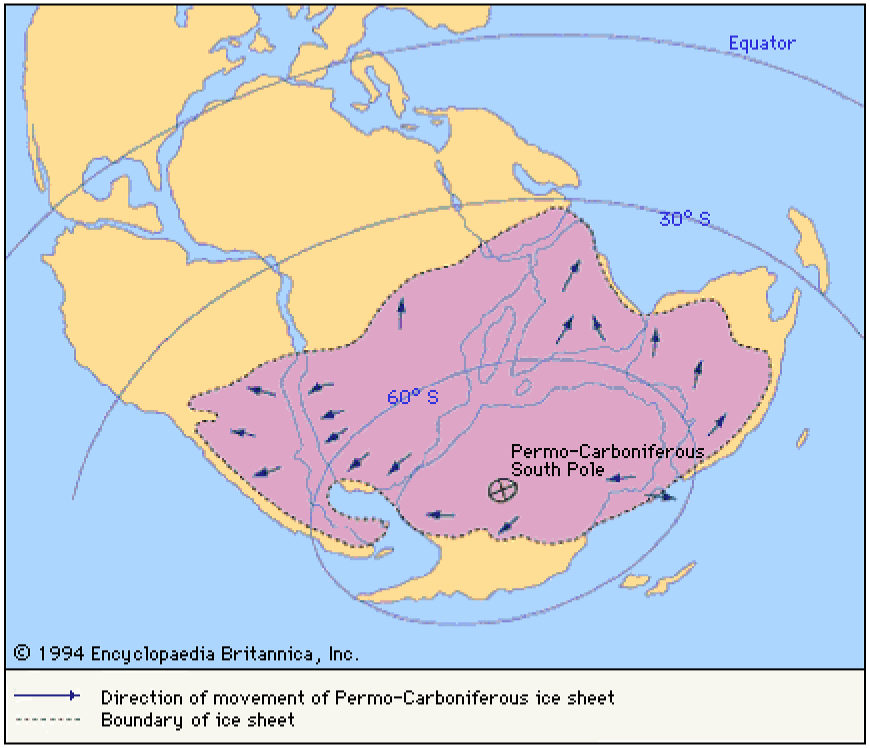

Phanerozoic Climate Change
Cm O S D C P Tr J K Pg N
Low Frequency Mode
Short-Term Average
HOT
COLD
Glacial Periods
-3 -2 -1 0 1 2 3
δ18O (parts per thousand)
542 500 450 400 350 300 250 200 150 100 50 0
Millions of Years Ago

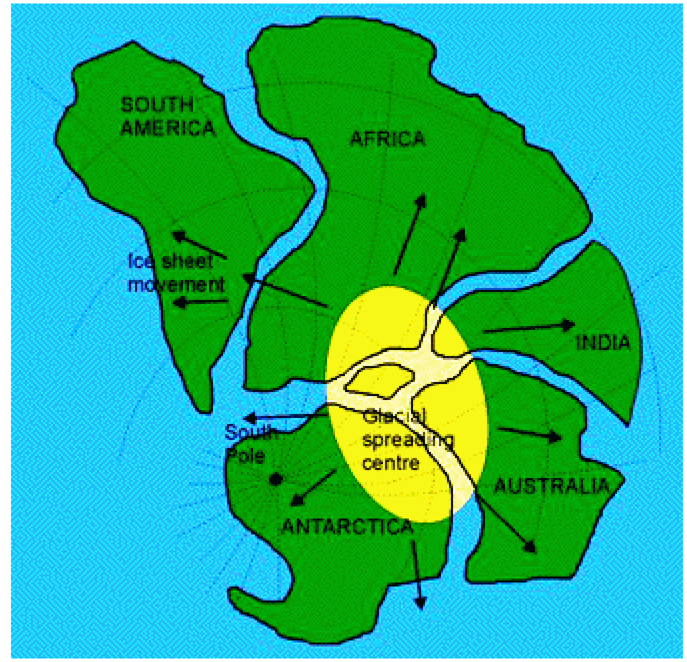
More Recent Glaciations



Carboniferous Glaciation

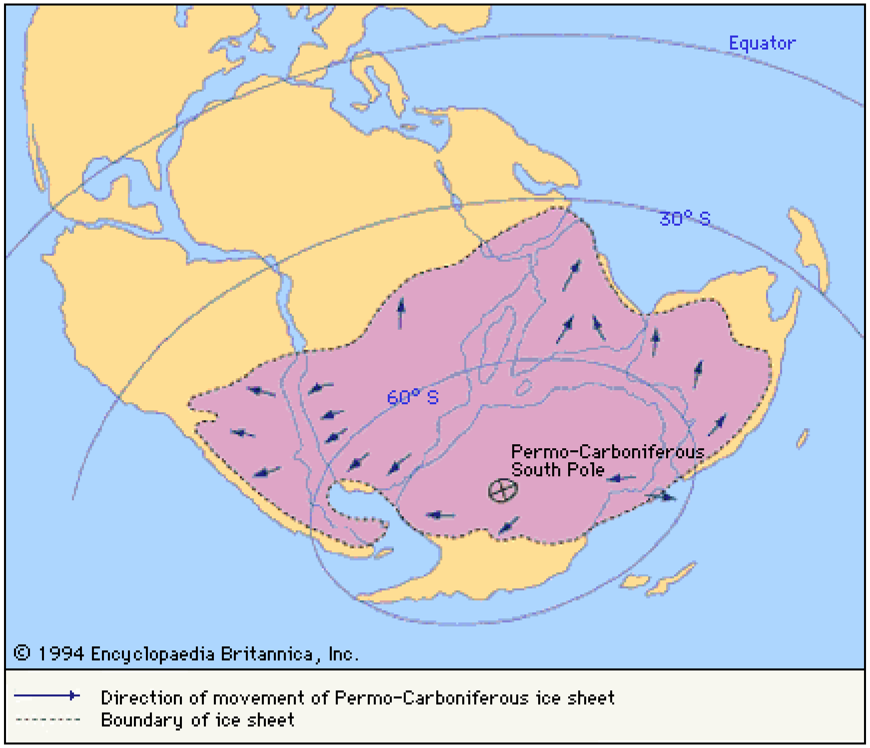
Pangaea Supercontinent

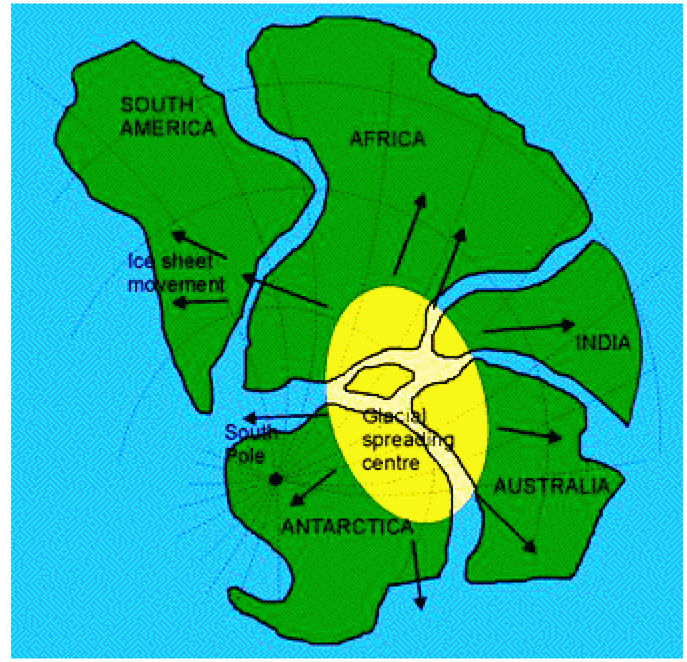




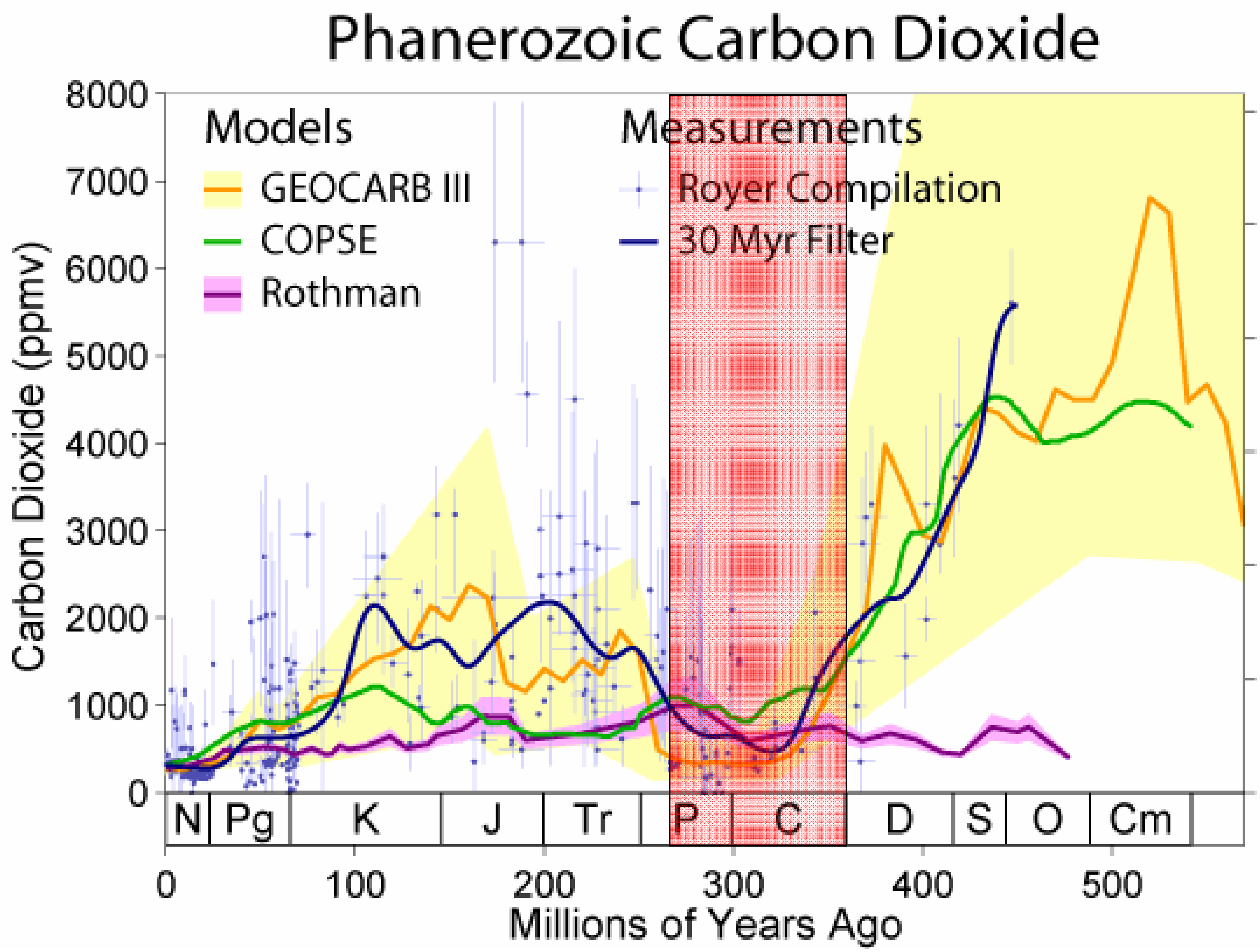
During the Carboniferous Period, the climate of various landmasses was controlled by their latitudinal position. Since prevailing wind patterns were similar to those on Earth today, tropical conditions characterized the equatorial regions; the midlatitudes were dry, and higher latitudes were both cooler and moist.

Pangaea Supercontinent





In contrast, the bulk of Gondwana was below 30° South latitude and experienced colder conditions that allowed the formation of continental glaciers. These glaciations were similar to those occurring in the Northern Hemisphere during the Pleistocene Epoch. Coeval (parallel) continental glaciations did not occur in the high latitudes of the Northern Hemisphere, probably because the landmasses were too small to sustain large ice fields.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Carbon Dioxide (ppmv)
Times Quaternary Average
Millions of Years Ago
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6000
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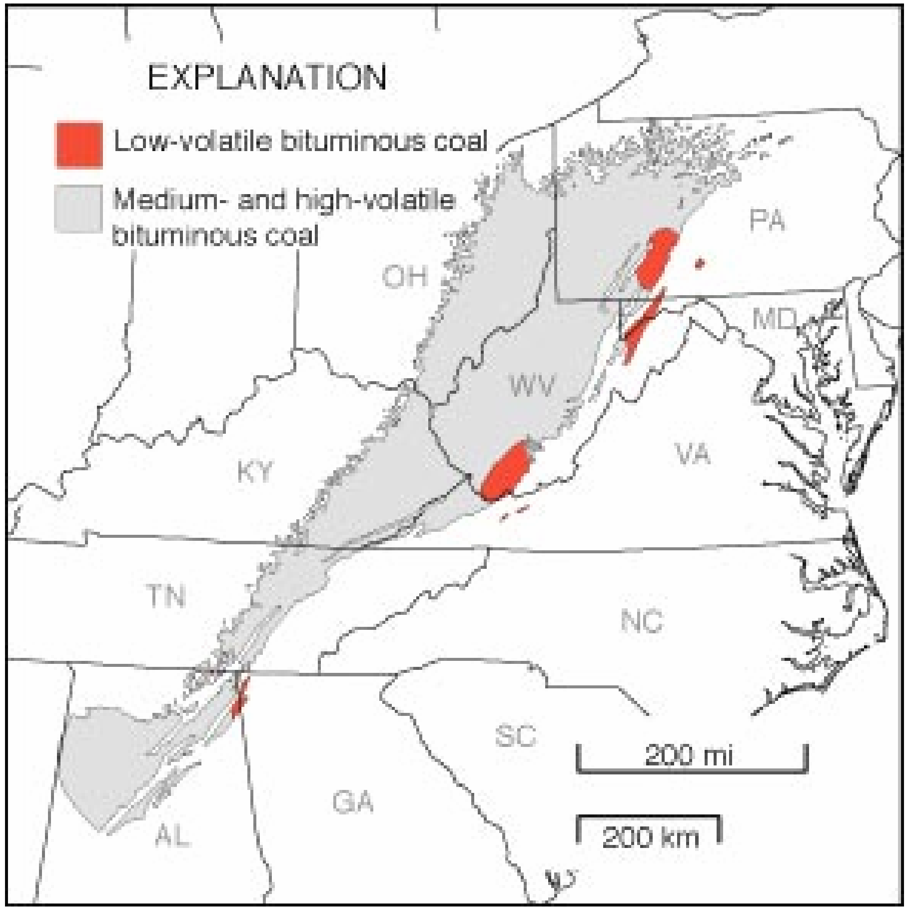


The Appalachian basin coal region. The USGS assessment is focused in the northern and central parts of the Appalachian coal region (Kentucky, West Virginia, Virginia, Maryland, Pennsylvania, and Ohio) because about 93 percent of Appalachian coal is produced here.

http://pubs.usgs.gov/fs/fs115-99/fs115-99.html

http://picasaweb.google.com/irenko11/GeologicalFieldTripsKentuckyUSA2007

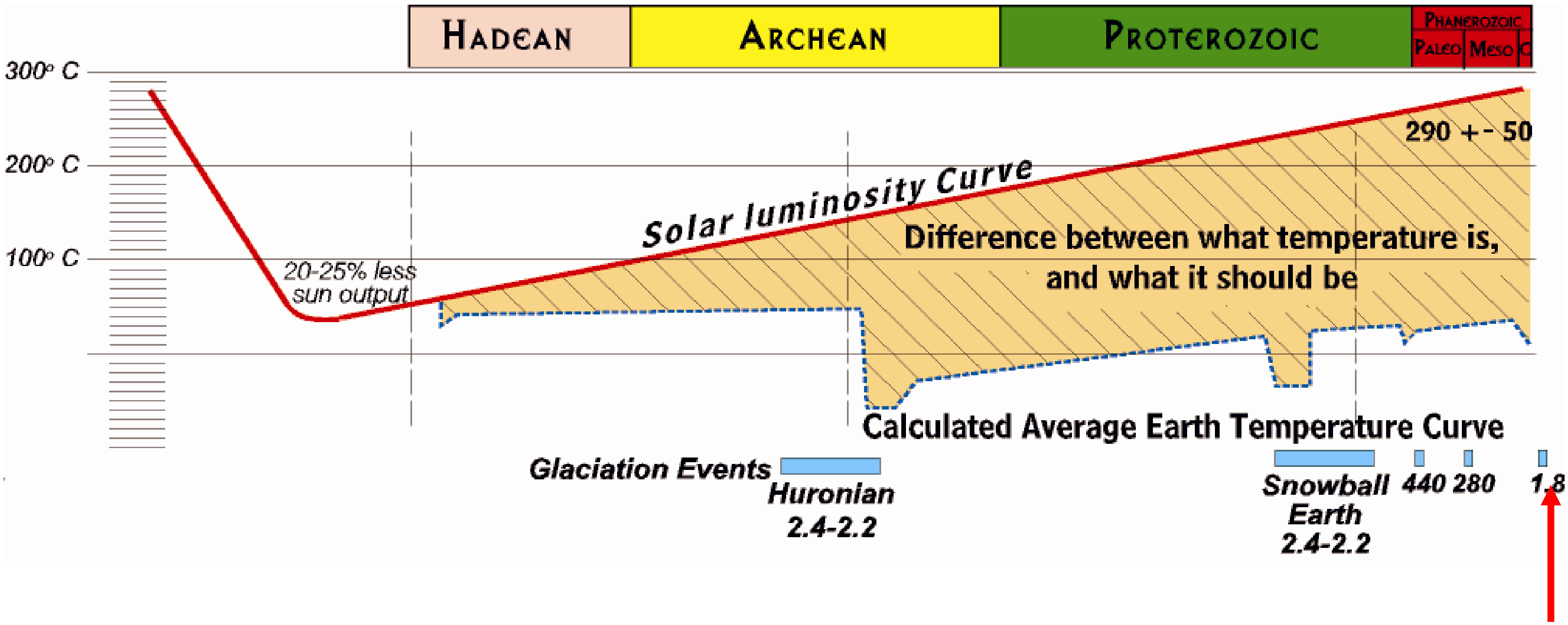
Pennsylvanian Coal Swamps

http://www.fieldmuseum.org/research_collections/ecp/ecp_sites/NPI_web/models_coal.htm

Pennsylvanian Coal Swamps

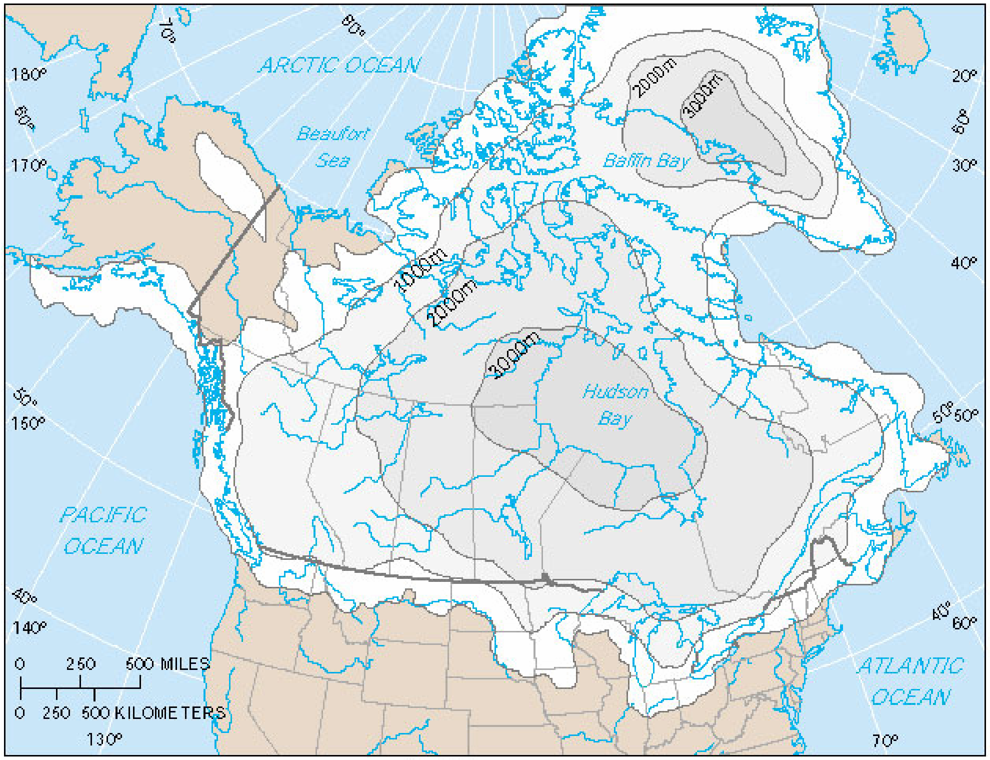
lInks to Online coal swamp dioramas

More Recent Glaciations



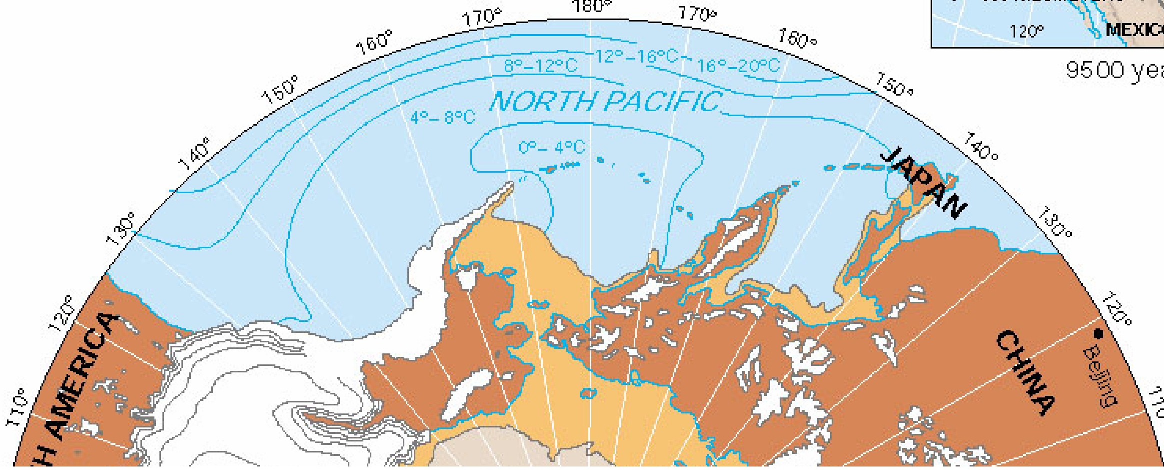
Pleistocene
Glaciation

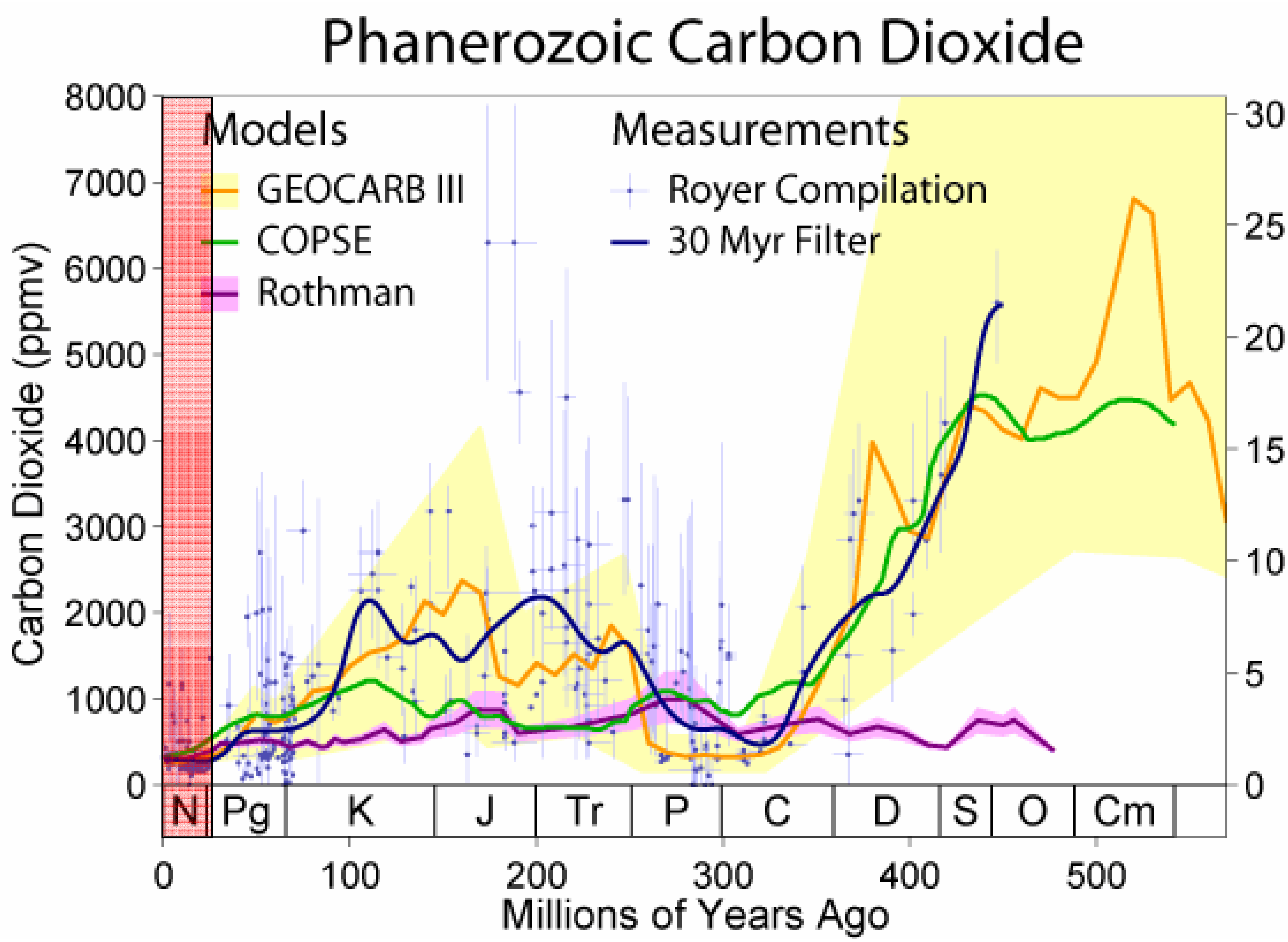
Pleistocene Glaciation



18,000 years ago

9500 years ago

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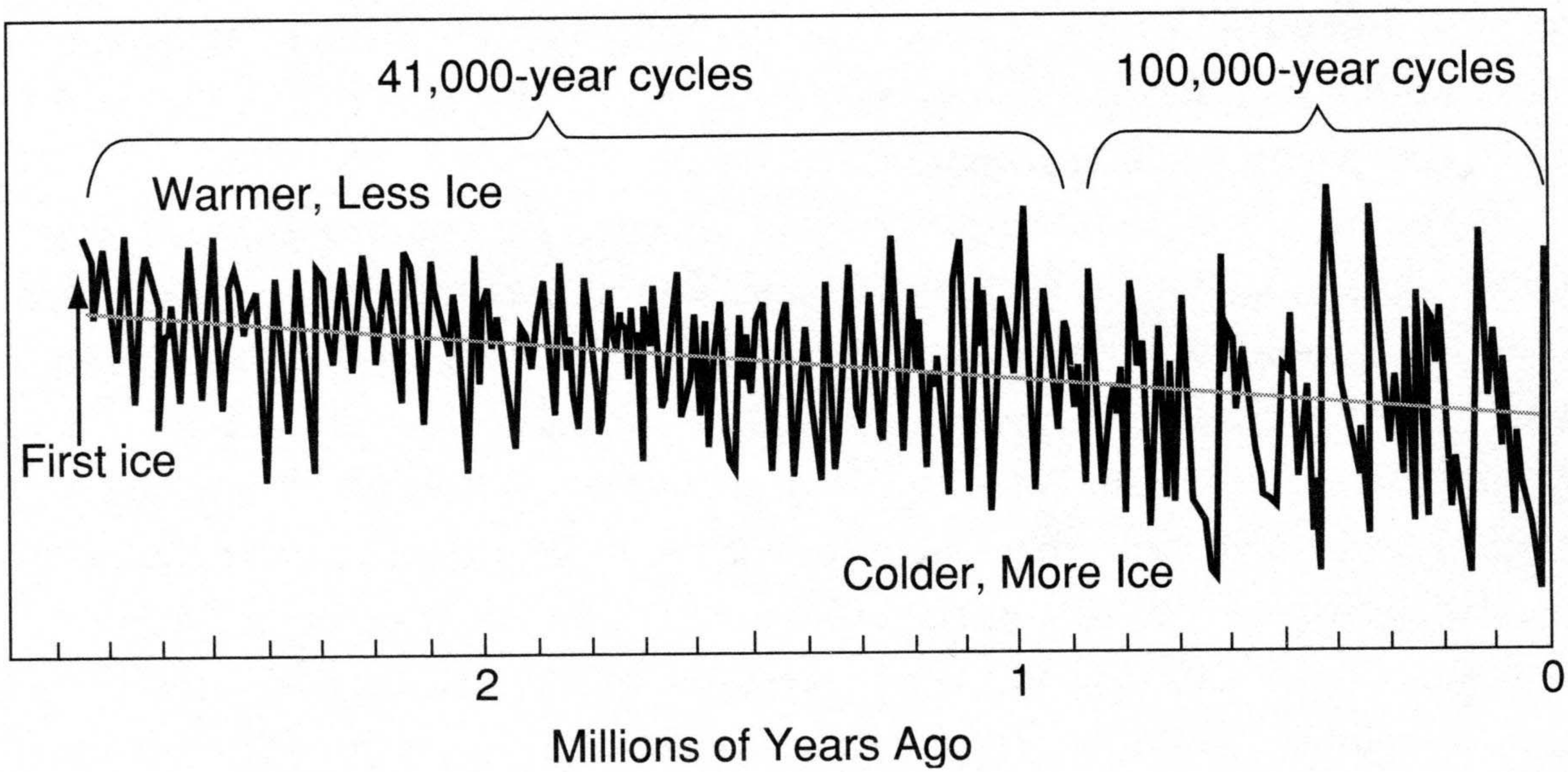
0
100
200
300
400
500
Millions of Years Ago

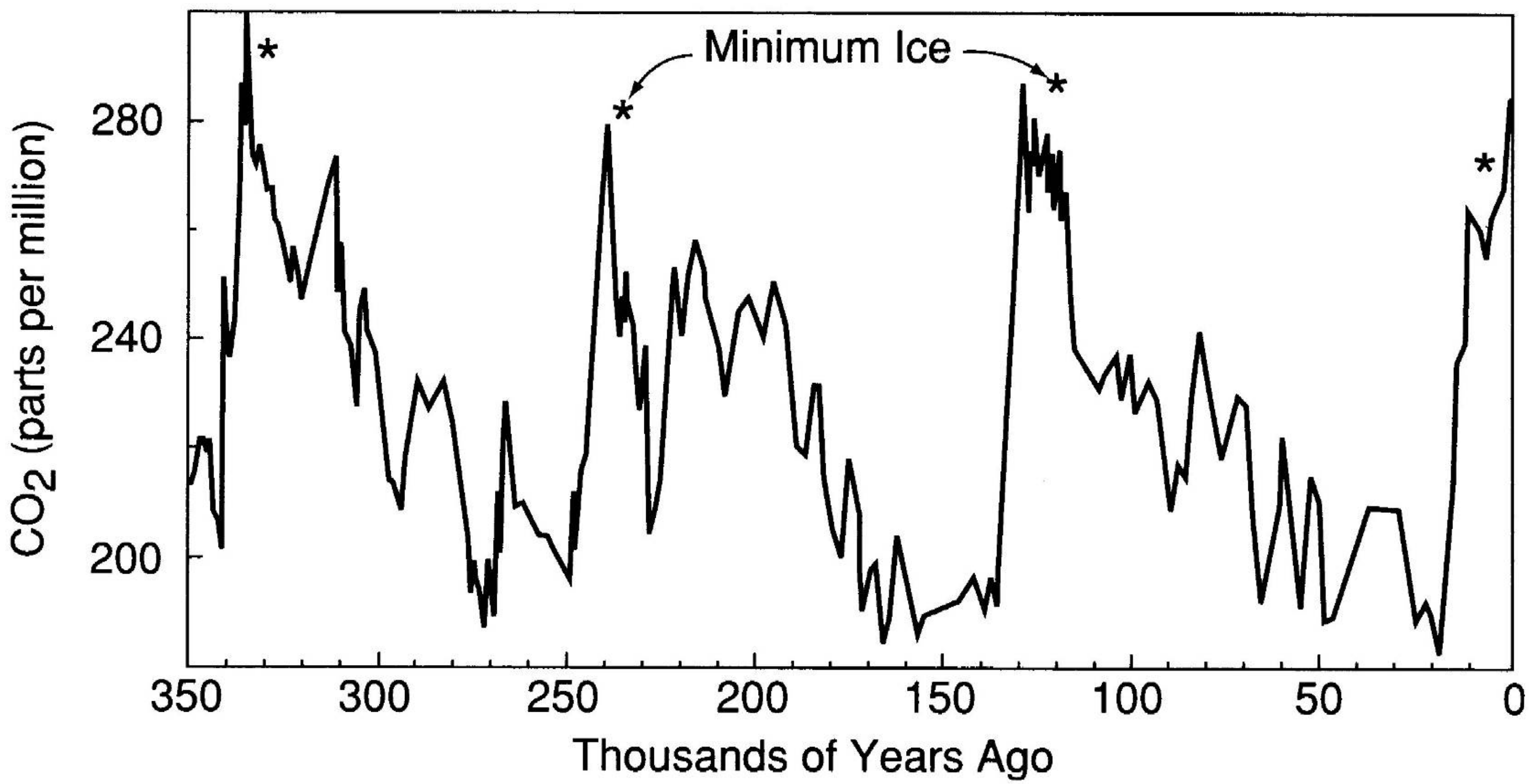
The Pleistocene glaciation began about 2.75 million years ago, and the ice has waxed and waned about 40 times.

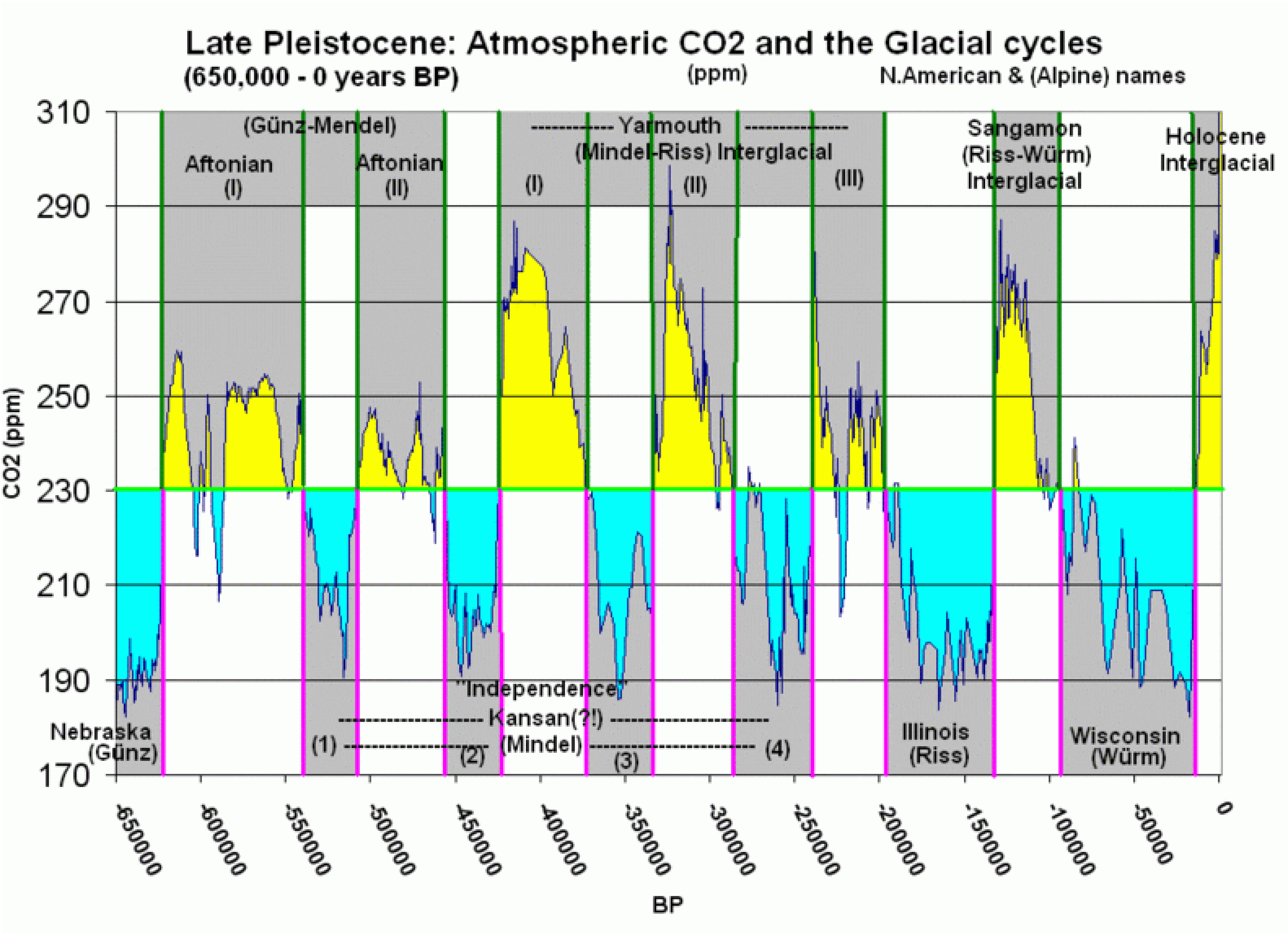


4.2. Large ice sheets first appeared in the Northern Hemisphere nearly 2.75 million years ago and grew and melted at the 41,000-year cycle of orbital tilt until about 0.9 million years ago. Since that time, the major cycle of ice-sheet changes has been at a cycle of 100,000 years.

The advances and retreats are fractal, patterns within patterns within patterns.

We see little cooling events within larger cooling events within even larger cooling events.




Late Pleistocene: Atmospheric CO2 and the Glacial cycles
(650,000 - 0 years BP)
(ppm)
N.American & (Alpine) names
(Günz-Mendel)
Aftonian (I)
Aftonian (II)
------------ Yarmouth ---------------
(Mindel-Riss) Interglacial
(I)
(II)
(III)
Sangamon (Riss-Würm) Interglacial
Holocene Interglacial
"Independence"
Kansan(?!)
(1) (Mindel) (4)
(2)
(3)
Nebraska (Günz)
Illinois (Riss)
Wisconsin (Würm)
CO2 (ppm)
310
290
270
250
230
210
190
170
-650000
-600000
-550000
-500000
-450000
-400000
-350000
-300000
-250000
-200000
-150000
-100000
-50000
0
BP