Mon Nov 10

Announcements:
9.0 earthquake in Puget Sound! (in 1700)

TALK TODAY: Monday 10 Nov **3:30 310 ATG**

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Prof Lyatt Jaegle, UW, "Space-based observations of
biomass-burning emissions of NOx" [a pollutant gas]
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Where we're going:
This week:

KKC Chaps 8,9 (selected) and Snowball Earth article (web)

Solid Earth Circulation (wrap-up last week)

Ancient Climates (or "History of Planet Earth in 3 Easy Lessons")

Tues: HOLIDAY (free talk by veteran in Kane 120, 7pm)

Wed: HW#4 DUE

Fri: *review, tutorial*

but first, some first-grade wisdom...

Continental drift: Fig 6-1

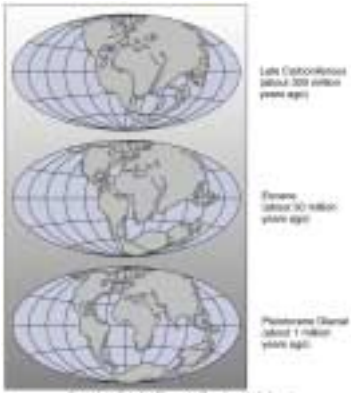
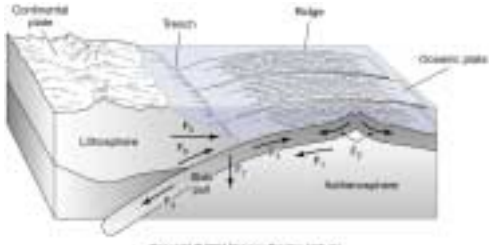


Plate tectonics: Fig 6-21

- the third of our three BIG pumps
- driven by circulations in the upper mantle; ultimately, by radioactive decay, releasing heat within the Earth's interior
- recycles key substances like mineralized carbon



Wilson Cycle: Fig 6-27

- continents group together then spread apart
- timescale is ~500 million years
- major climatic consequences (location of continents affects atmos/ocean currents; ice-albedo feedback, etc)

Circulation Summary

Three BIG Pumps

- Atmosphere/Surface Ocean
  - distributes heat poleward
  - cause of regional and seasonal climates
  - mixing timescale is ~1 week
- Thermo-haline circulation (THC)
  - mixes deep ocean
  - timescale of mixing is about 1000 years
  - may shut on and off as conditions change in N. Atlantic
  - possible "trigger" for global climate
- Solid Earth circulation: Wilson Cycle
  - continents group and then spread
  - cycle timescale is ~500 million years
  - major climatic effects (e.g. sets boundaries for the other two circulations)
  - mixes key elements like carbon and recycles them from rocks back to the atmosphere

Ancient Climates: Readings (info on website)

Introduction/Overview	8:152-153, Fig 8-1
Formation of Early Atmosphere	8:158-159, Fig 8-7
Faint Young Sun paradox	8:159-161, Figs 8-8, 8-9
Long Term Climate Record	8:161-164, Fig 8-10, 8-11
Low Latitude Glaciation BOX	8:165
"Snowball Earth" article	available on web
Warm Mesozoic Era	8:167-169, Fig 8-15
Cooling During Cenozoic Era	8:169-170, Fig 8-17
Modern Controls on Atmos. O2	9:188-189, Fig 9-17

Ancient Climates: Stories

Paleoclimate record
- fossils, clues and mysteries

Grand Sweep of Earth History
- 4.6 billion years (so far)
- marker events (to memorize)

Faint Young Sun paradox
- good illustration of scientific method

Rise of Atmospheric Oxygen
- greatest global pollution event ever
- but made life on land possible
- oxygen and fire

Snowball Earth >>>read from article
- something new in ancient history

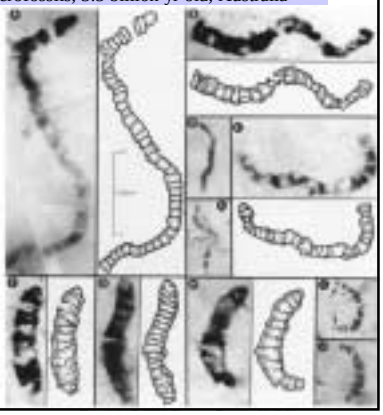
Failure of planetary life support
- Venus and Mars
- Snowball Earth
- asteroids

Fig 9-5: microfossils, 3.5 billion yr old, Australia

Origin of life:
~4 billion yrs ago

prokaryote (bacteria):
single-celled organisms
with no cell nucleus
- only form of life for most of Earth history
- still dominates

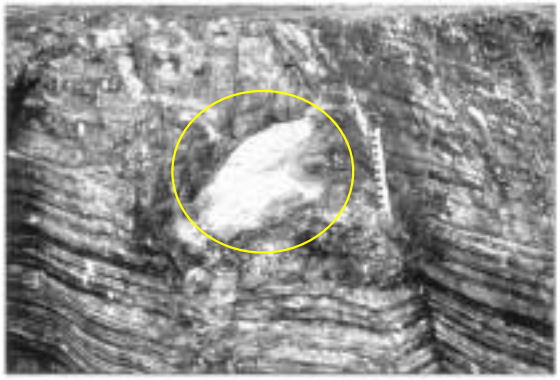
eukaryote:
organism whose cells
have a nucleus
- includes all multicellular organisms
- came much later



Evidence of glaciations: tillite, 2.4 billion yrs old, Fig 8-10a

Evidence of glaciations: striations, 650 million yr old, Fig 8-10b

Evidence of glaciations: dropstone, Fig 8-10c

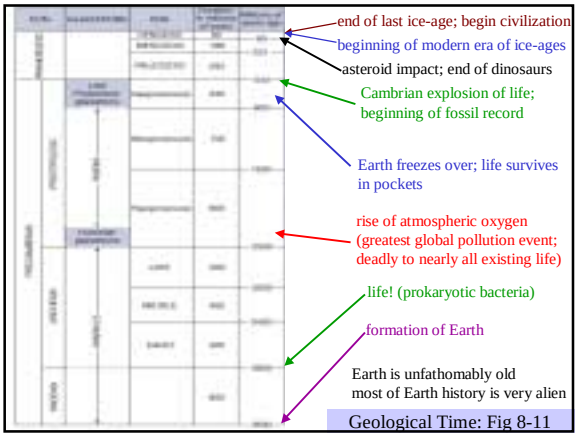


Wed Nov 12

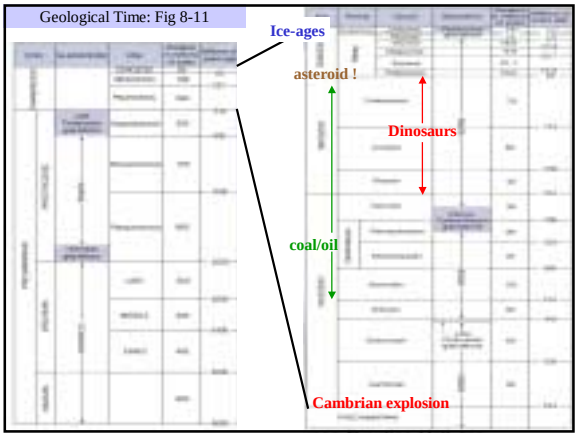
Announcements:
- grades on web
- HW#4 due today; HW#5 due next thursday
- Tad gone Tues-Thurs next week

Today:
- marker events in Earth history
- Faint Young Sun paradox

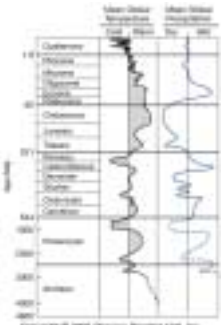
but first, tribute to a life of self-sacrifice...



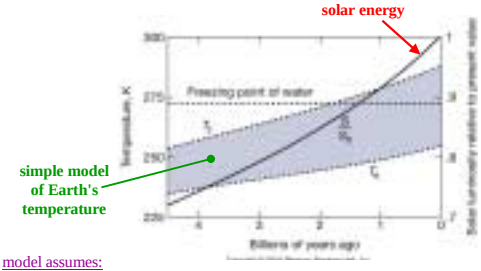
Geological Time: Fig 8-11



Temperature/Precipitation History



Faint Young Sun paradox: Fig 8-8

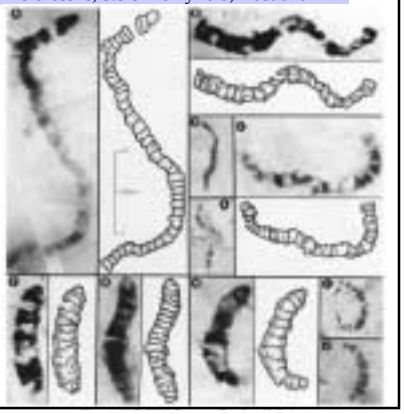


model assumes:
- CO2 in atmosphere same as today
- Earth albedo same as today

Why do we know this model is wrong?

Fig 9-5: microfossils, 3.5 billion yr old, Australia

Answer:
Archeon life!
Requires liquid water



Faint Young Sun paradox: p159-161

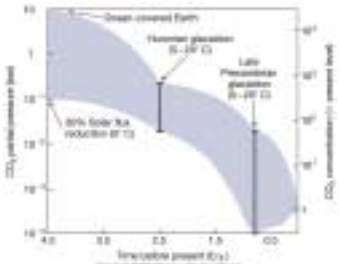
paradox: despite less solar energy, Archean was warm enough to support photosynthetic life

conceptual framework:
$T_s = f(S_o, A, \Delta T_g)$

Possible explanations
- sun... ?
- albedo... no
- geothermal energy... no
- > greenhouse...
  - H2O... no
  - NH3... no
  - > CO2... [see figure]
    less land
    more volcanism
    plenty of carbon [see inorganic carbon cycle figure]
  - > CH4 methane? (CH4) [recent Kasting proposal]
    early life would have produced it
    far longer atmospheric lifetime than today due to lack of oxygen

Illustrates nature of scientific knowledge/progress (draw figure)

CO2 over Earth History: Fig 8-9



Thurs Nov 13

Announcements:
?

Today:
- marker events in Earth history
- Mesozoic Warmth
- Cenozoic Cooling
- Sister planets
- Snowball science history (and some pretty pictures)

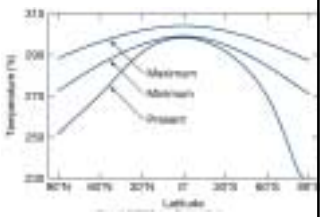
but first, a few late-breaking headlines...

Earth History: Marker Events

1. Origin of Earth	4.6 billion ybp (years before present)
2. Origin of Life	~4 billion ybp
3. Rise of Oxygen to ~ modern levels	~2 billion ybp
4. Snowball Earth events	600-900 million ybp
5. Beginning of fossil record (Cambrian explosion)	540 million ybp
6. Extinction of Dinosaurs by asteroid	65 million ybp
7. Beginning of modern glaciations	3 million ybp
8. End of last ice-age	10 thousand ybp

Mesozoic Warmth (250-65 million ybp)

What:
- Warmer global-mean temperature.
- Much warmer Polar Regions; no ice-caps.
- Much warmer deep ocean.



Evidence:
- Lush ferns and alligators in Siberia.
- Carbon isotopes in ocean sediments

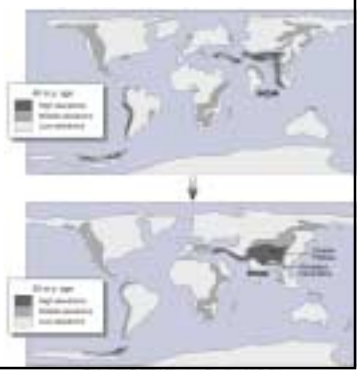
Cause:
- Higher CO2 is leading suspect.
- sea-floor spreading rate was greater
- higher sea level (no ice caps)

Remaining mysteries:
- Ocean/atmos heat transport must have been much more efficient.
- latitudinal and vertical
- this is not understood

Cenozoic cooling, 65 million ybp to present

What:
- Earth cools, beginning ~60 million ybp.
- Life retreats from Poles.
- Polar ice caps form.
- Eventually, ice-ages begin.

Cause (one leading theory):
- India collides with Asia.
- Himalayas form.
- Silicate weathering increases.
- Atmospheric CO2 goes down.



Sister planets

Venus (runaway greenhouse)	Earth ("just right")	Mars (virtually no greenhouse)

- Oceans boiled away	- has oceans	- farther from Sun; too cold for liquid water
- No more weathering	- hydrological cycle	
- Carbon partitions to atmosphere	- weathering returns CO2 to lithosphere	- no water vapor greenhouse
- CO2 is ~100,000 times that on Earth	- plate tectonics (volcanoes) return carbon to atmos.	- too small for plate tectonics - no carbon cycle
- T_s = 427 C; ΔT_g = 466C	- negative feedback	- CO2 is ~10 times Earth - T_s = -53C; ΔT_g = ~3C

Mars, CO2 and Greenhouse

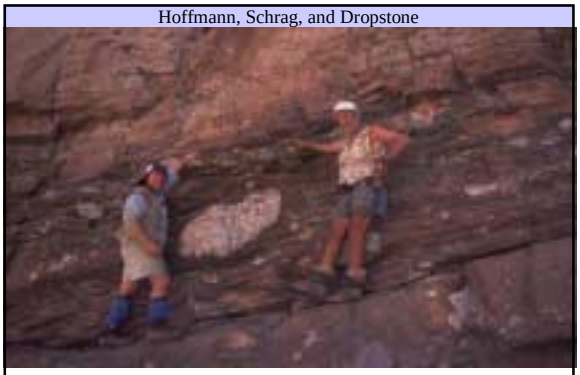
Mars
(virtually no greenhouse)

- CO2 is ~10 times Earth
- ΔT_g = ~3C

Do you notice something strange about these facts???

What can we conclude about the cause of the greenhouse effect on Earth???

Hoffmann, Schrag, and Dropstone



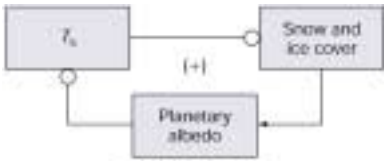
http://www-eps.harvard.edu/people/faculty/hoffman/snowball_paper.html

Snowball Science History -1

1960's: Mikhail Budyko (theoretical climate modeling)
- "run-away" ice-albedo feedback if Earth freezes below 30-degree latitude
- this must never have happened for two reasons...
  1. continuous life
  2. Earth could never recover

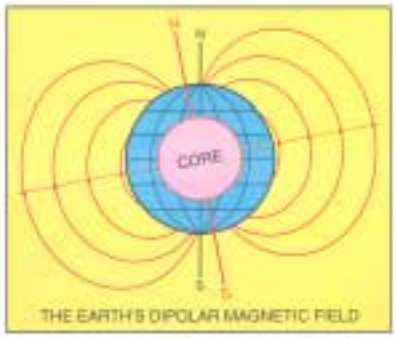
1964: Brian Harland (geologist)
- Late proterozoic glacial deposits on almost every continent
- magnetic alignment of grains indicate continents were near Equator

ice-albedo feedback



Positive feedback loop:
- amplifies an initial perturbation
- potentially causes current equilibrium state to be unstable

Earth's Magnetic Field



Possible continental positions during Late Proterozoic Glaciations: Fig 8-12

Critical latitude for "runaway" ice-albedo (~30 degrees):
Why would ice-albedo feedback get stronger as the ice-line got to lower and lower latitudes???

Answer: - more sunlight to reflect at lower latitudes
- the amount of area per degree latitude gets much larger (major factor)

Snowball Science History -2

1960's: Martin Rudwick (biologist) with Brian Harland
- Recovery from global glaciation may have spurred Cambrian explosion
- "all 11 animal phyla ever to inhabit the earth emerged within a narrow window of time" after the end of the last glaciation

1970's: more biology
- discovery of life in extreme environments
- organisms near geothermal vents at ocean bottom have no need of sunlight
- bacteria and algea living in snow, ice, and rock pores under extreme cold, heat, and pressure
- overcomes argument (1), above

1992: Joseph Kirschvink (geophysicist)
- Atmospheric CO2 would build up during a global glaciation
- CO2 removal by silicate weathering would cease, but
- CO2 input from volcanoes would continue unabated
- overcomes argument (2), above

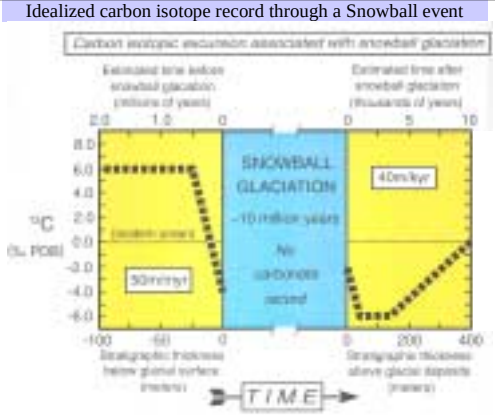
Snowball Science History -3

1992: Kenneth Caldeira and James Kasting
- Calculate that CO2 would have to be 350 times current levels to melt a global glaciation
- This would take about 10 million years

1992: Kirschvink
- Iron deposits mixed with glacial debris indicate ocean lacked oxygen
- This implies ice-covered oceans

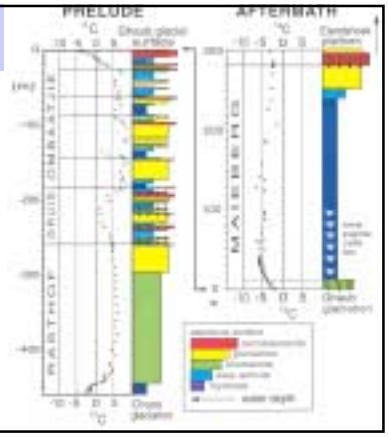
1990's: Hoffman and Schrag
- Carbon isotopes in rocks surrounding glacial deposits indicate a virtual shut-down of biological activity
- Massive carbonate deposits on top of the glacial deposits ("cap carbonates") indicate very warm water and sudden deposition of huge amounts of carbon
- Apparently, the glaciation events were immediately followed by a global hothouse period
- This is consistent with huge buildup of atmospheric CO2.

Idealized carbon isotope record through a Snowball event

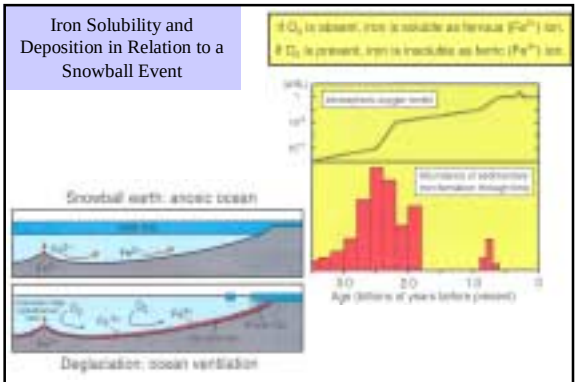


Measured carbon isotope record through a Snowball event

Ghaub Glaciation, Otavi Group, NW Namibia



Iron Solubility and Deposition in Relation to a Snowball Event



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Namibia cliffs, snowball record