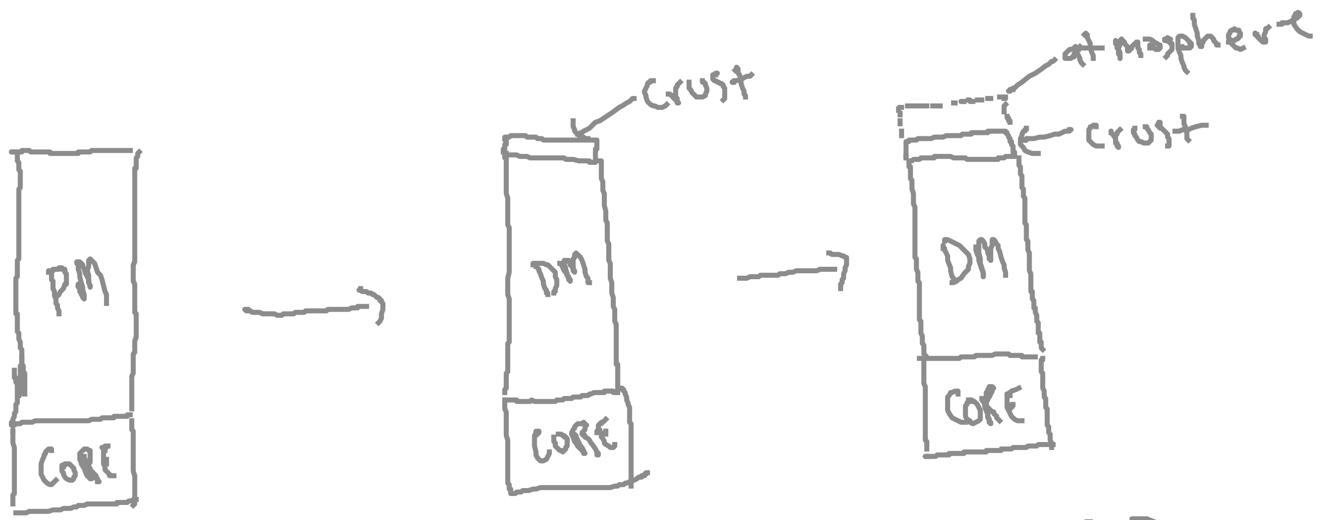
Lecture 14-20: the Atmosphere and Oceans

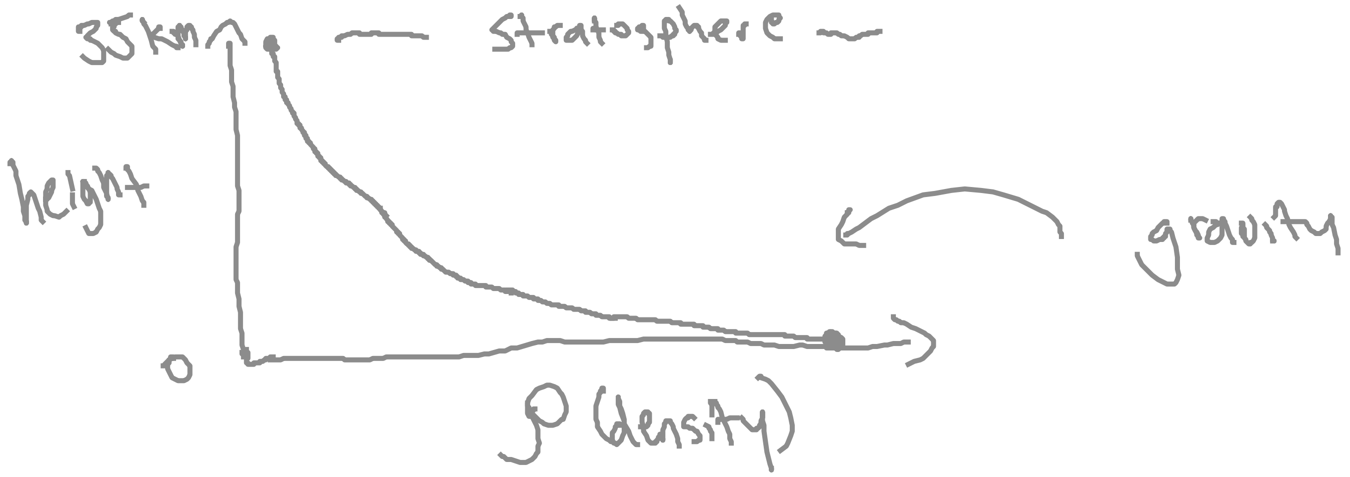
1. The atmosphere
2. Planetary habitability
    - A. Mysterious water
3. The temperature of the Earth
4. A faint young Sun
    - A. The necessity of a negative feedback
5. The (long-term) Carbon cycle
6. Changing climate
7. Stable isotopes
8. Cenozoic Climate
9. Pleistocene Climate

We acknowledge and respect the lək̓ʷəŋən peoples on whose traditional territory the university stands and the Songhees, Esquimalt and W̱SÁNEĆ peoples whose historical relationships with the land continue to this day.

The atmosphere



What is the atmosphere (physically)?



What is the atmosphere chemical composition?

78% Nitrogen

21% Oxygen

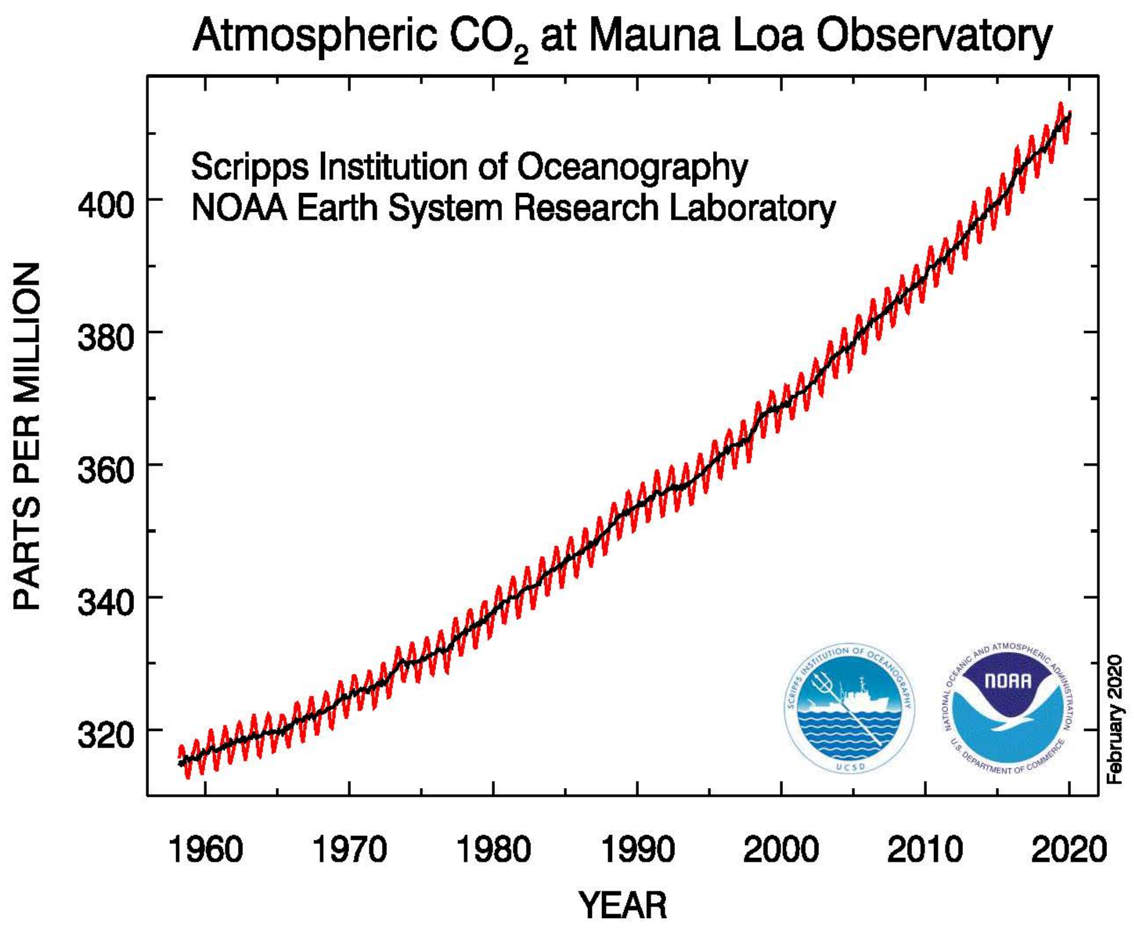
0.9% Argon

0.04% CO_2 (400 ppm)

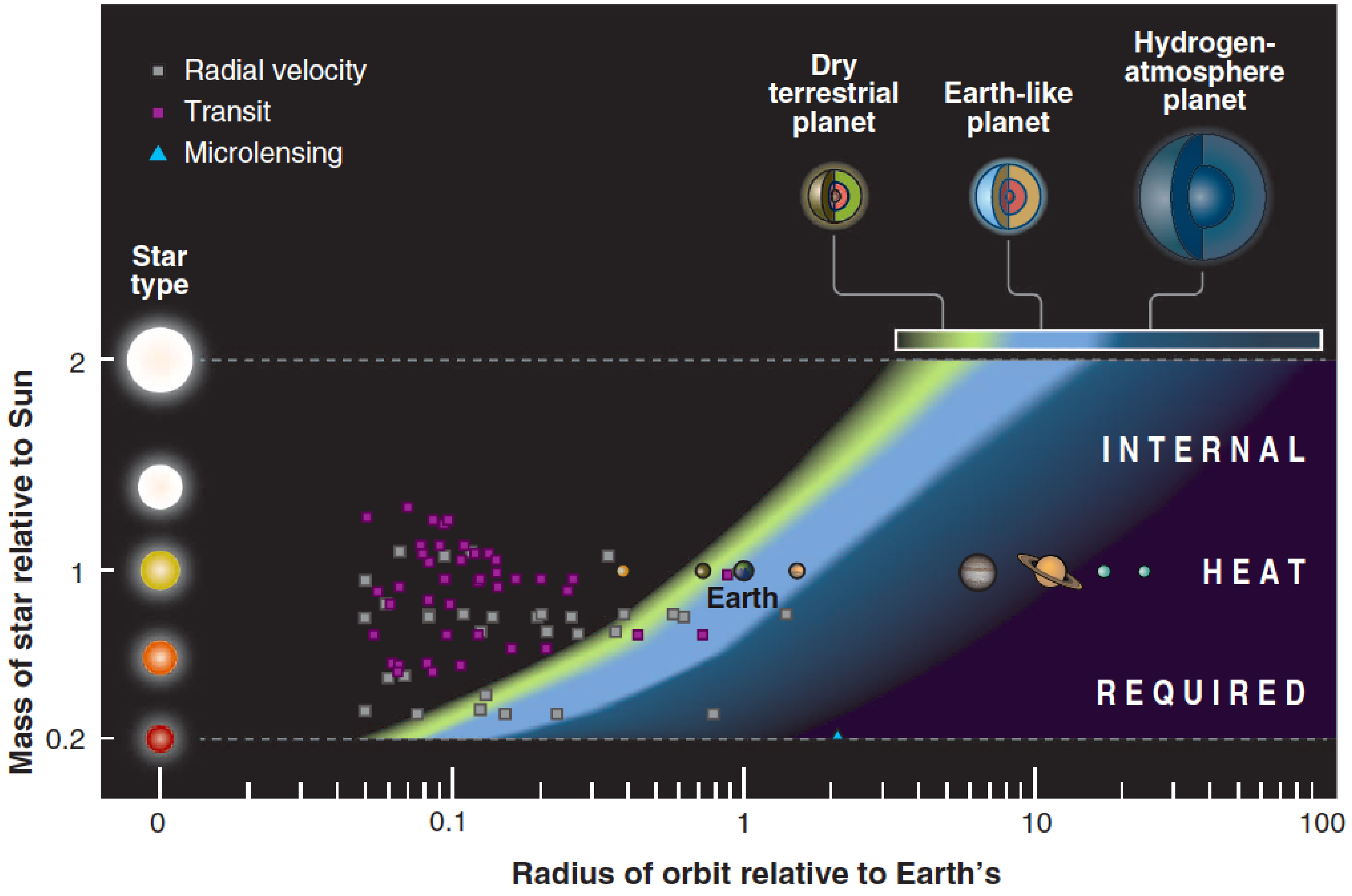
~1% water vapor at sea level

↳ temp dependant

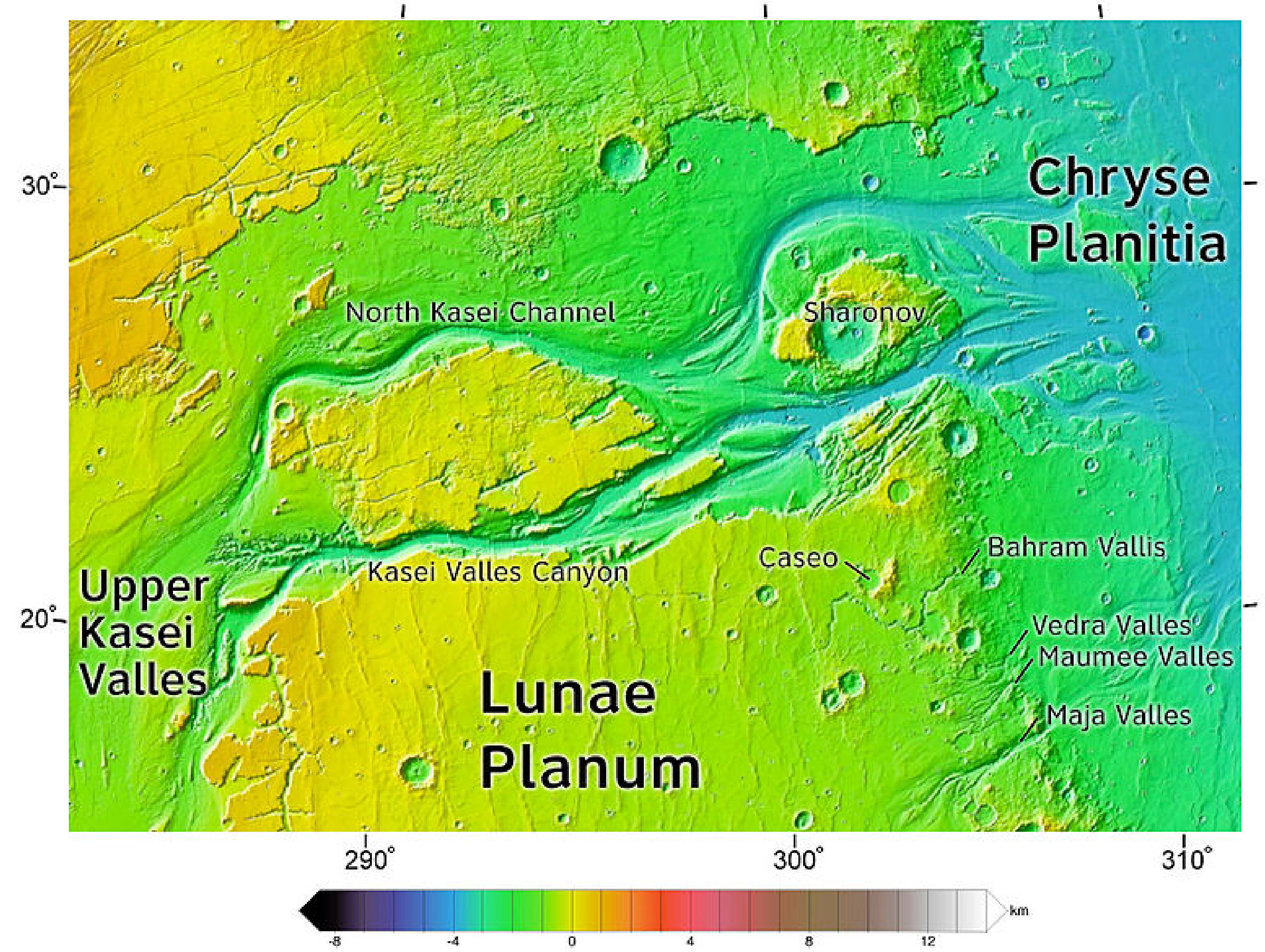
GOE:
Great Oxygenation
Event ~ 2.5 Ga
> 0.01%



Atmospheric CO_2 at Mauna Loa Observatory
Scripps Institution of Oceanography
NOAA Earth System Research Laboratory
PARTS PER MILLION
400
380
360
340
320
1960
1970
1980
1990
2000
2010
2020
YEAR
February 2020



Radial velocity
Transit
Microlensing
Dry terrestrial planet
Earth-like planet
Hydrogen-atmosphere planet
Star type
INTERNAL
HEAT
REQUIRED
Earth
Mass of star relative to Sun
2
1
0.2
0
0.1
1
10
100
Radius of orbit relative to Earth's

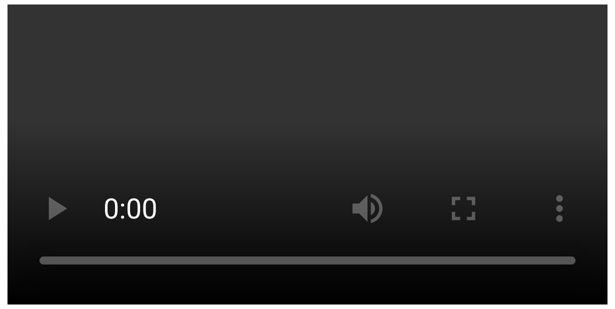


Chryse Planitia
North Kasei Channel
Sharonov
Kasei Valles Canyon
Caseo
Bahram Vallis
Upper Kasei Valles
Vedra Valles
Maumee Valles
Maja Valles
Lunae Planum
30°
20°
290°
300°
310°
-8
-4
0
4
8
12
km

In [3]:

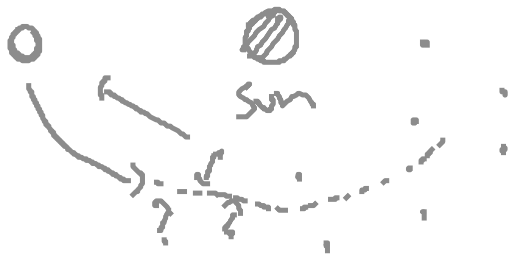
```
Video("videos/planet_formation.mp4")
```

Out[3]:

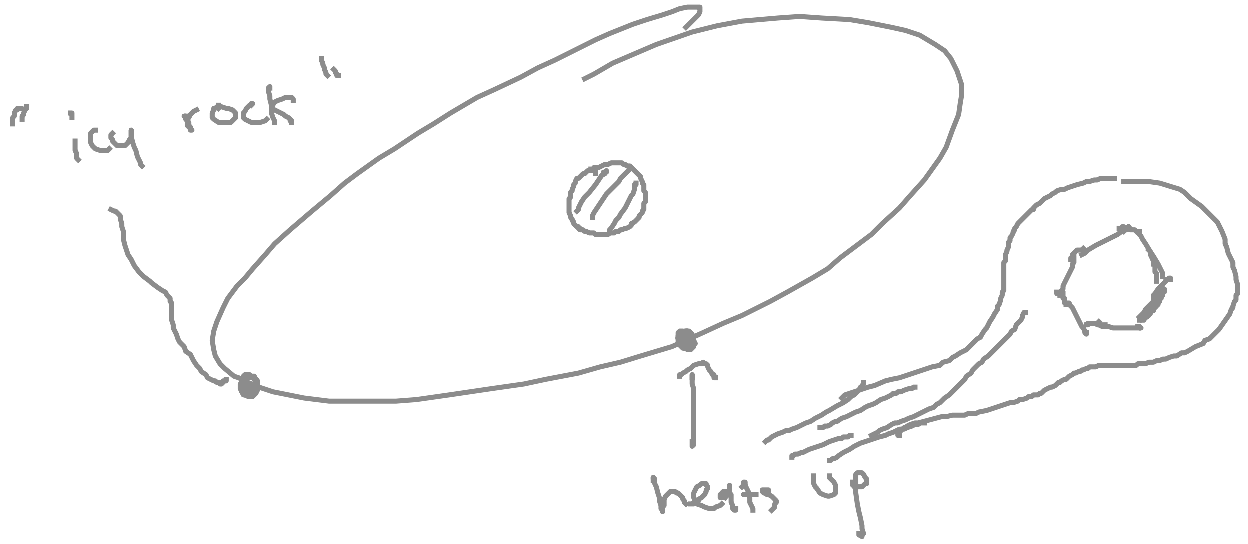


Where does our water come from?

1. Started with it
   - → during accretion major heating which releases volatiles
2. Late heavy bombardment – many impactors from 4.5 to 4.0 Ga
   - → collected "late"



3. Captured from comets

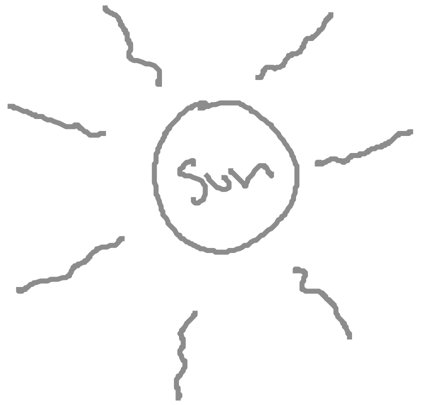


What sets the temperature of the Earth?

of any planet?

- incoming radiation
- interior heating (radioactive decay)

$3.87 \times 10^{26}\ W = Q$

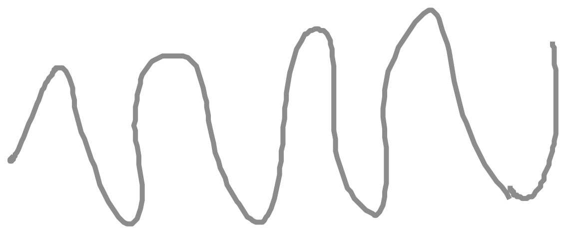


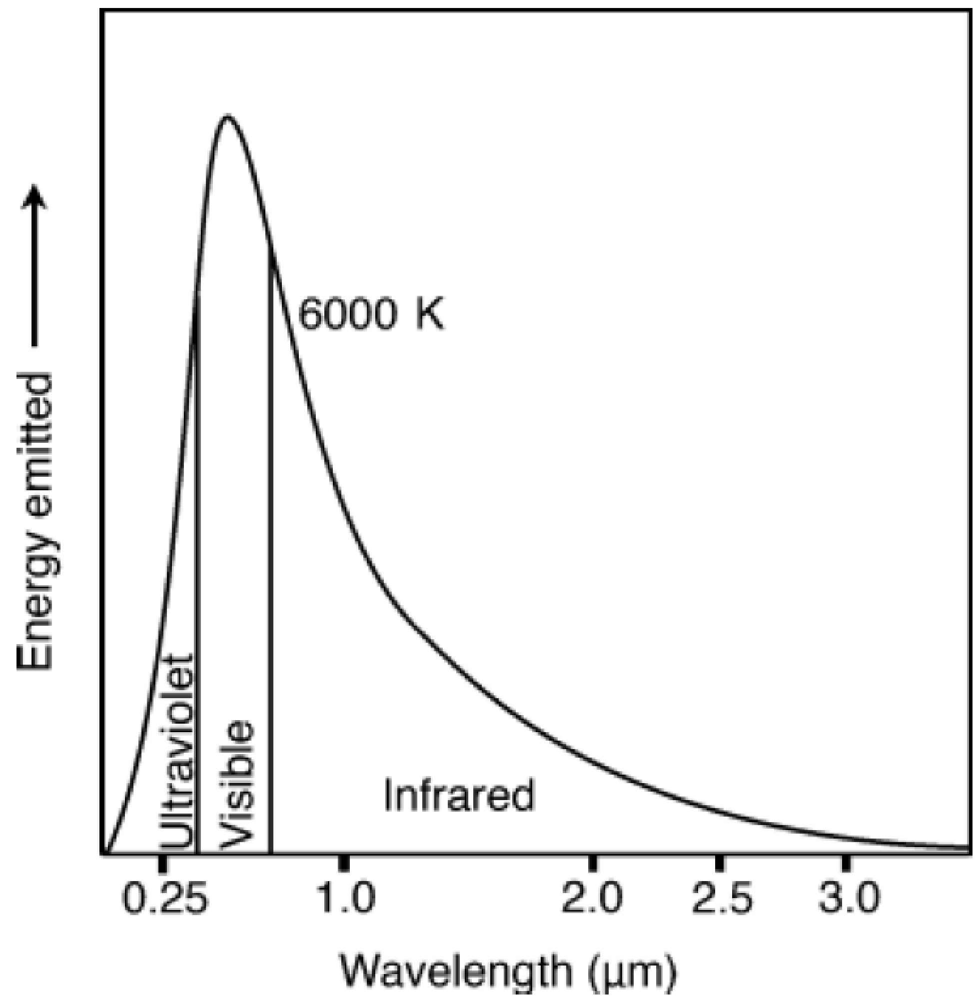
how much energy does Earth see?
- function of radius

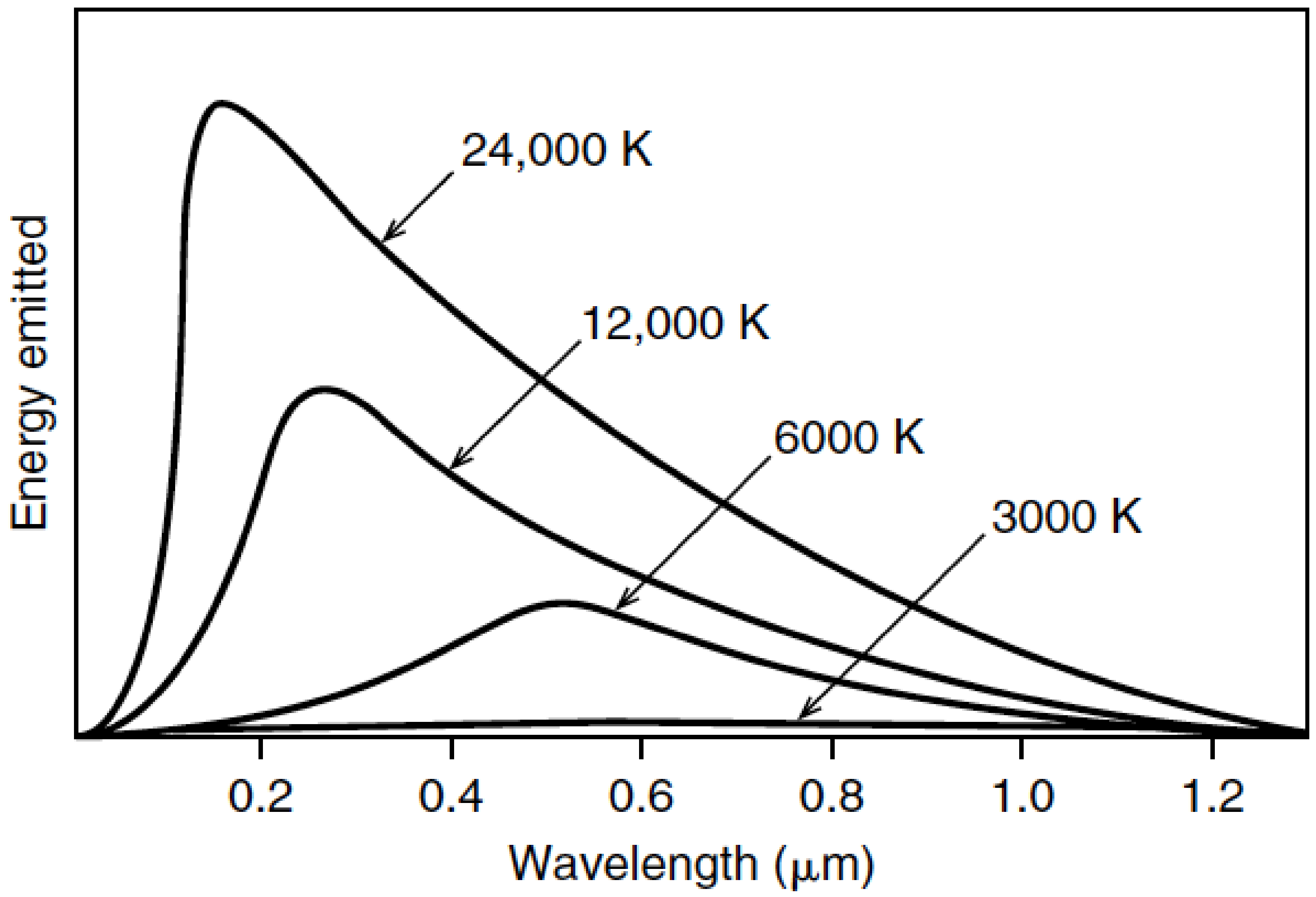
$\frac{Q}{4\pi r^2} = S_0$ ← solar constant

$S_0 = 1367\ W\ m^{-2}$ for Earth

Spectrum of frequencies



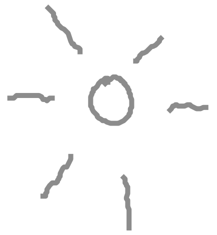

Energy emitted
6000 K
Ultraviolet
Visible
Infrared
0.25
1.0
2.0
2.5
3.0
Wavelength (μm)


Energy emitted
24,000 K
12,000 K
6000 K
3000 K
0.2
0.4
0.6
0.8
1.0
1.2
Wavelength (μm)

Calculating the 'emission' temperature of Earth

- incoming radiation
- interior heat (radio active decay)
- other heat from accretion

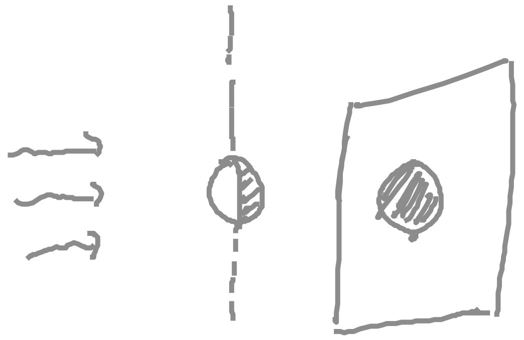
$Q = 3.87 \times 10^{26}$ W



Solar constant $= S_0$

$\frac{Q}{4\pi r^2} = S_0$ distance from sun

$S_0 = 1367$ W m^{-2} for Earth today



πr^2 Earth radius

incoming radiation on the surface

$S_0 \cdot \pi r^2 (1 - \alpha)$ α = albedo

outgoing radiation

σT_E^4

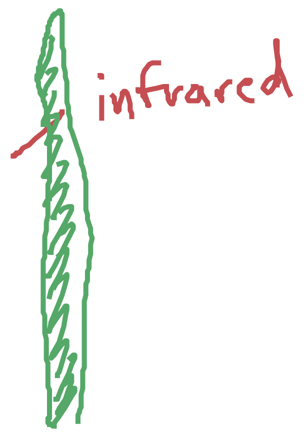
Stefan-Boltzman law

$\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}

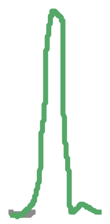
$T_E = 255$ K ($-18°$ C)

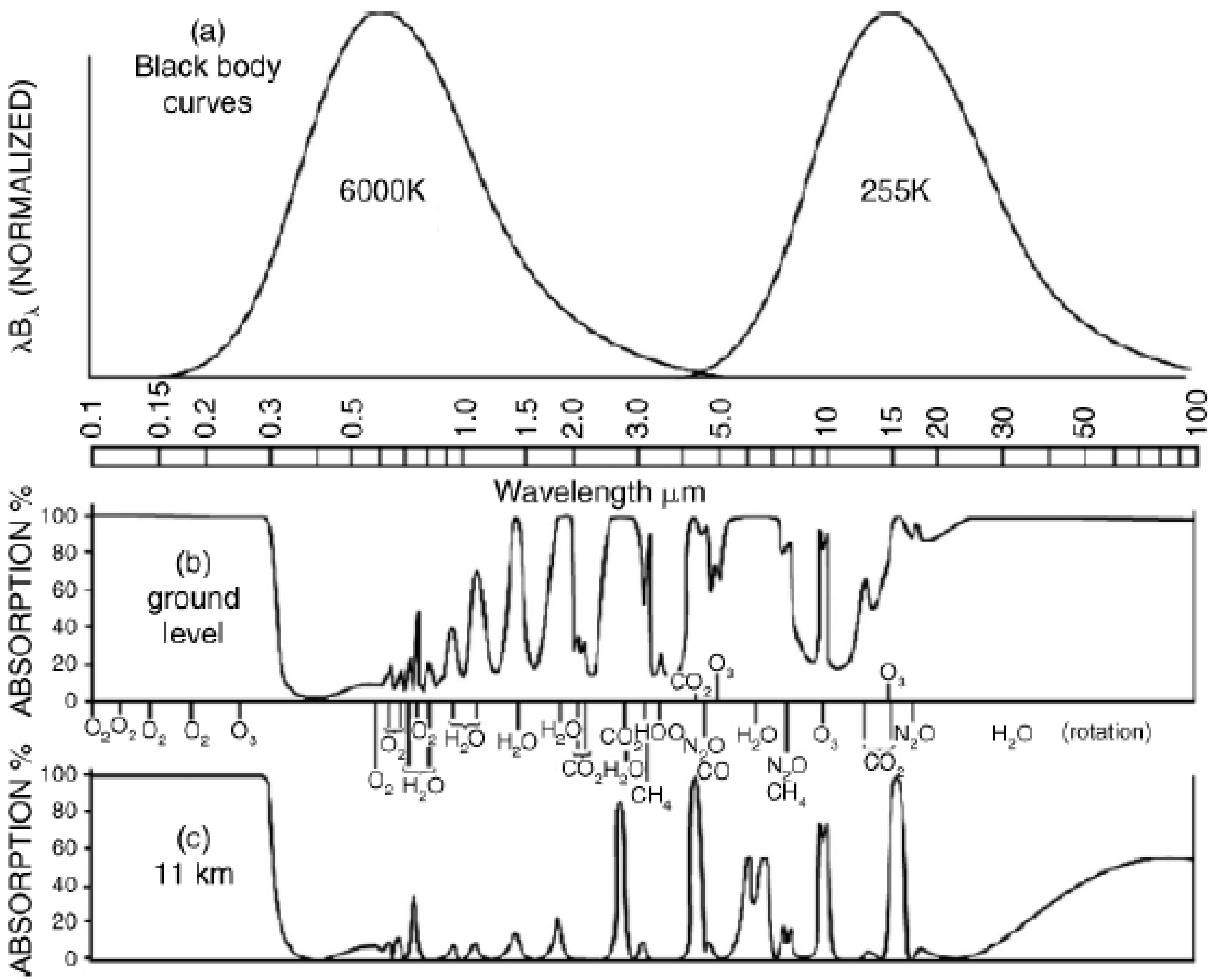
$T_S = 288$ K ($15°$ C)

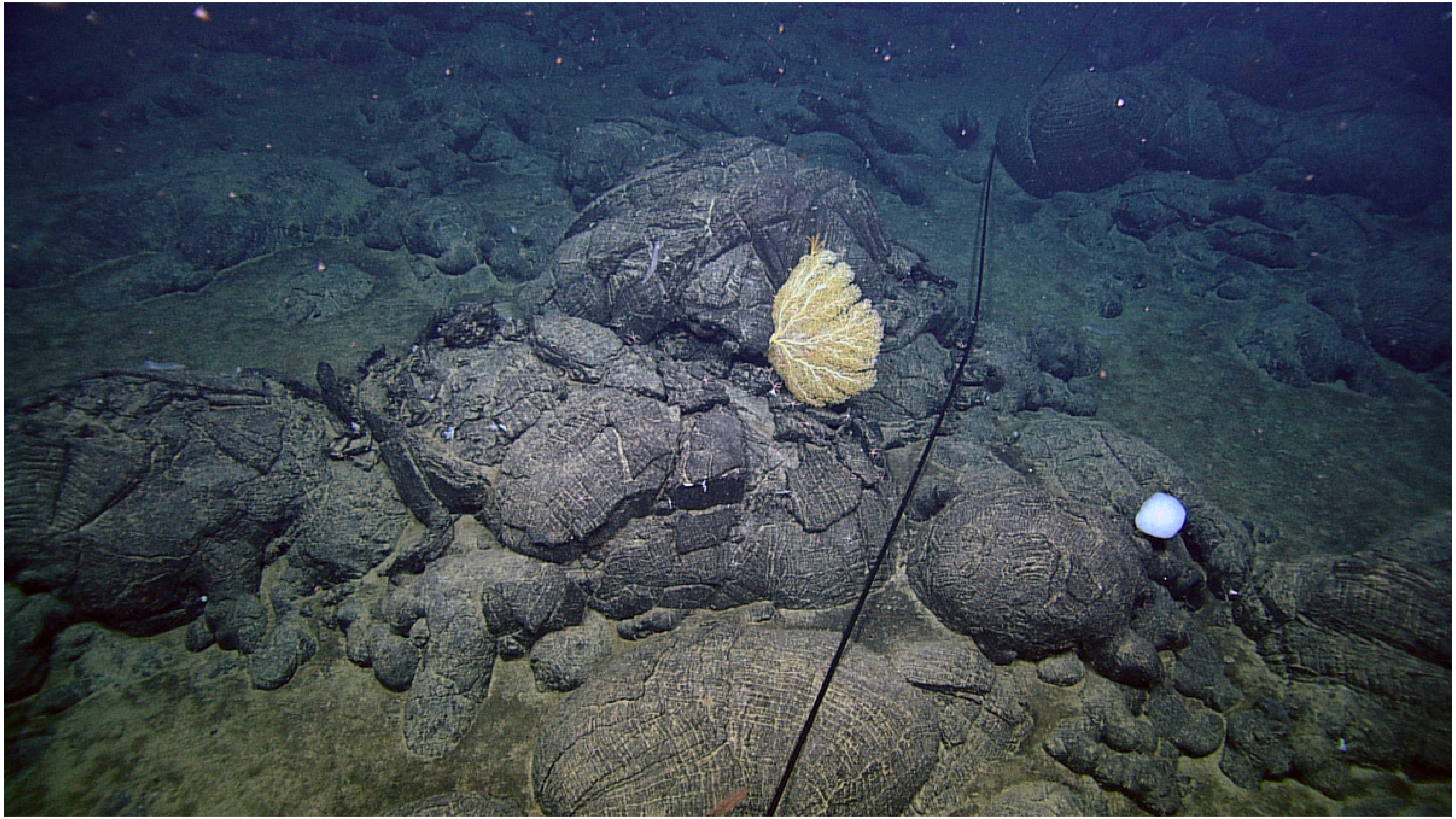
- Difference is the "greenhouse" effect


infrared

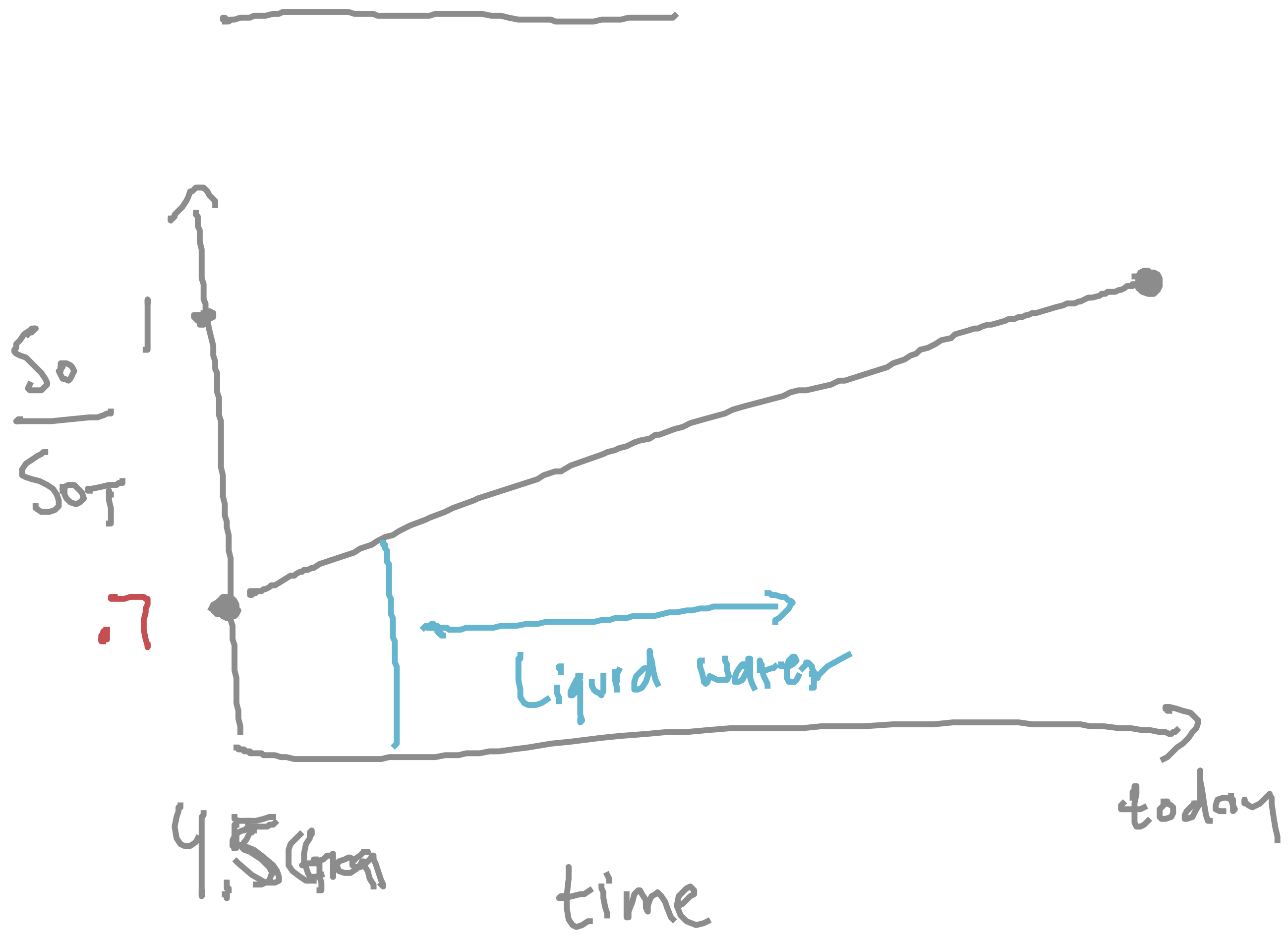

255 K
CO_2 absorbs
>255 K
255 K




(a)
Black body
curves
6000K
255K
λB_λ (NORMALIZED)
0.1
0.15
0.2
0.3
0.5
1.0
1.5
2.0
3.0
5.0
10
15
20
30
50
100
Wavelength μm
ABSORPTION %
(b)
ground
level
(c)
11 km
(rotation)



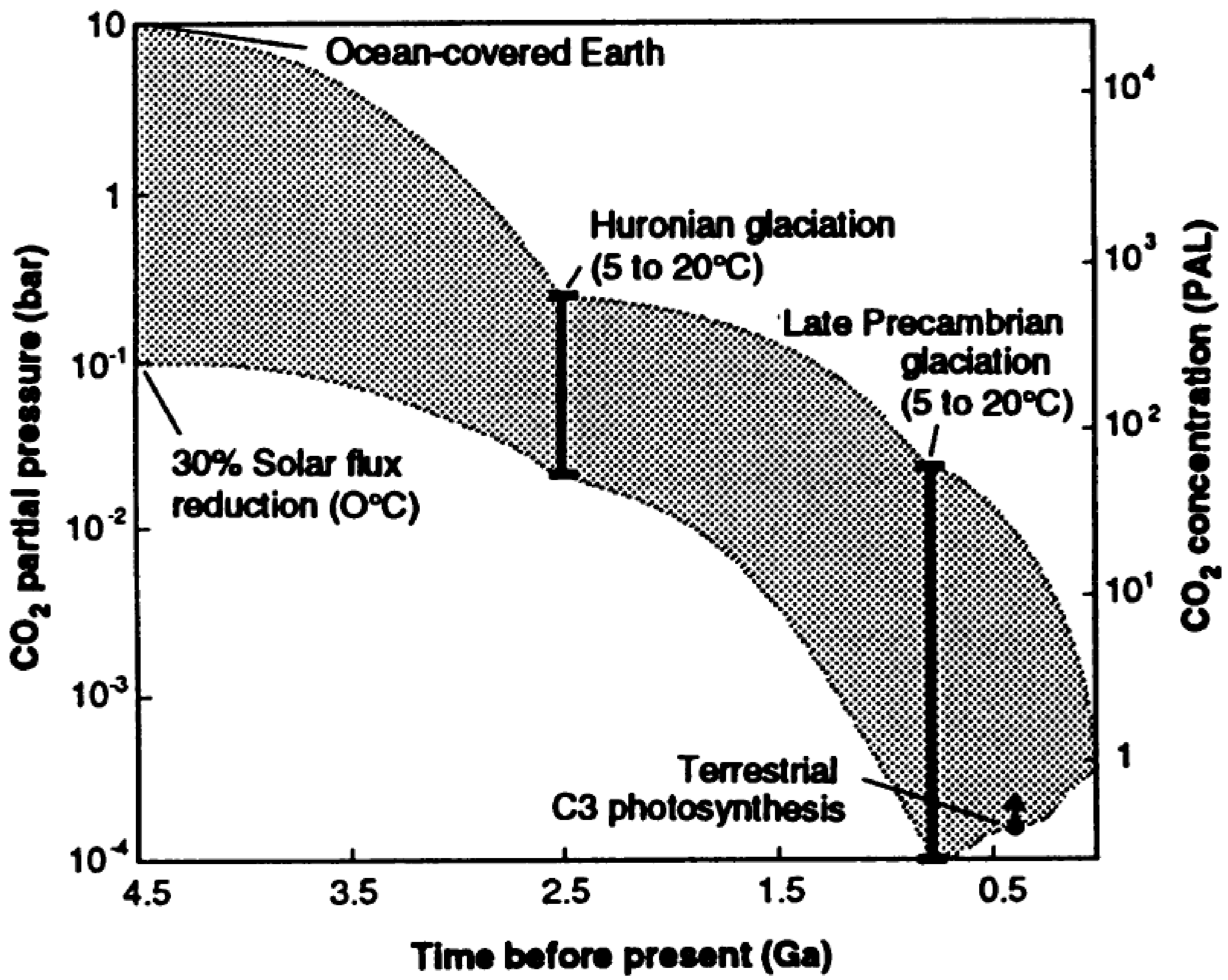
A faint young Sun and possible solutions



Solar constant increased by 30%

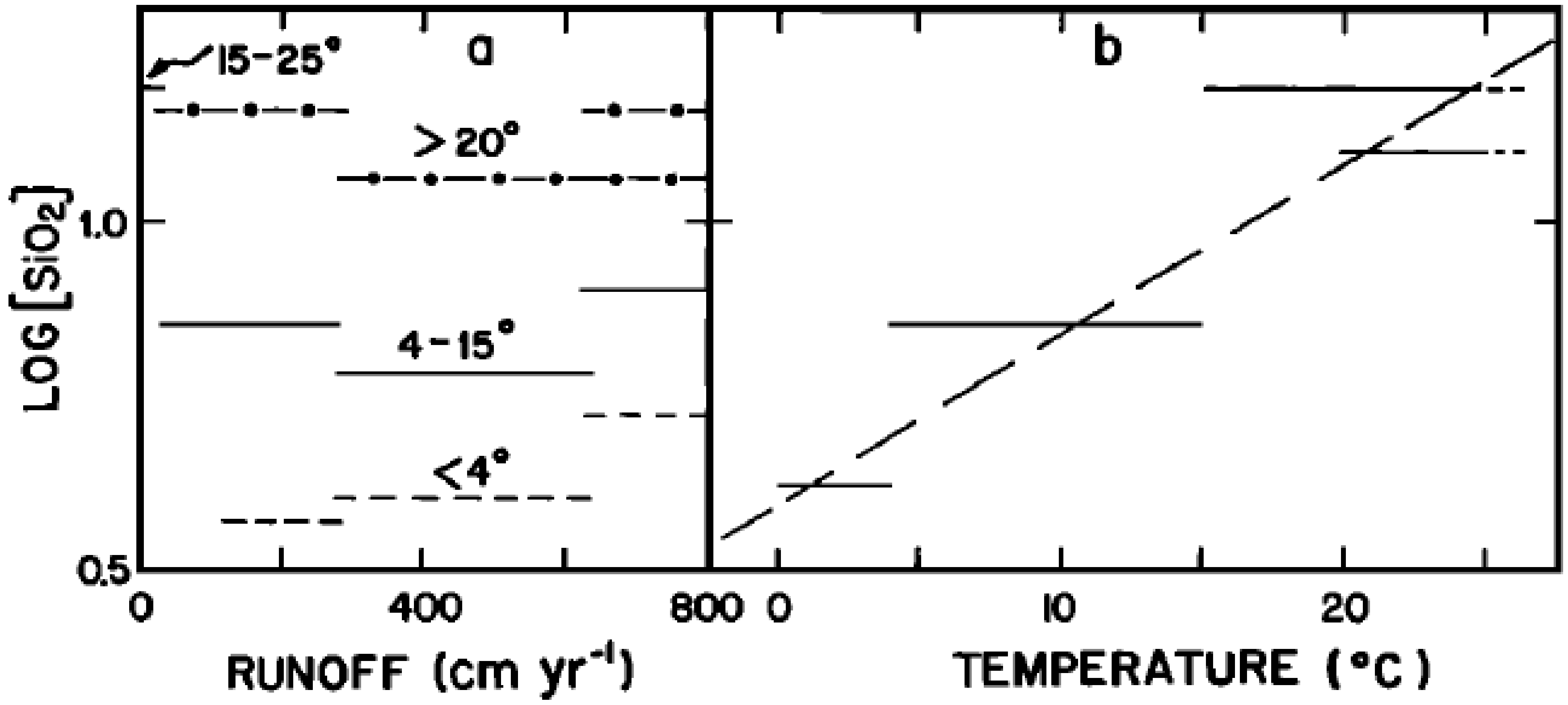
↳ we need 72 W/m^2

- Larger GHG effect
- radioactive decay
  - Today: 0.06 W/m^2
  - 4.5 Ga: 0.3 W/m^2



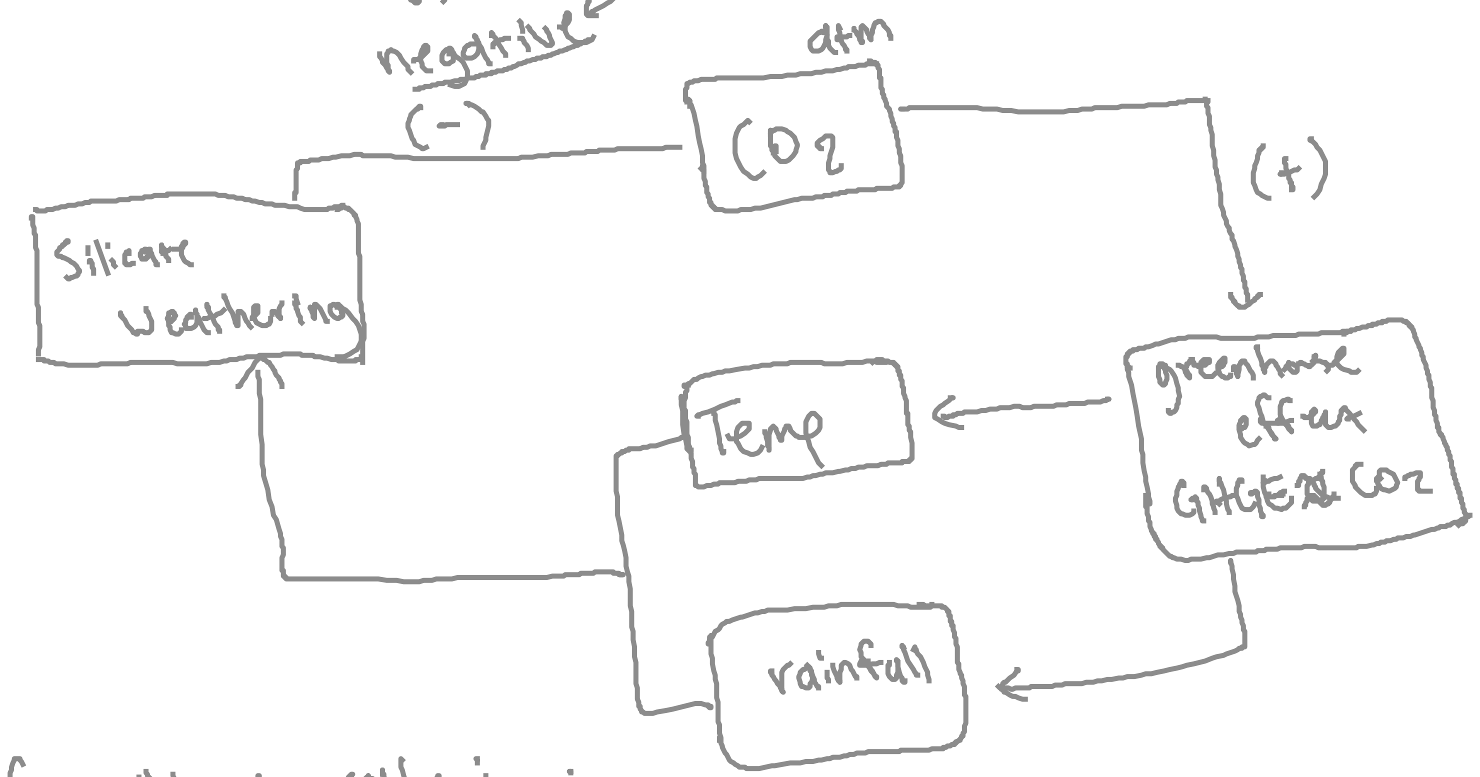
Ocean-covered Earth
Huronian glaciation
(5 to 20°C)
Late Precambrian
glaciation
(5 to 20°C)
30% Solar flux
reduction (O°C)
Terrestrial
C3 photosynthesis
CO_2 partial pressure (bar)
CO_2 concentration (PAL)
Time before present (Ga)
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^4
10^3
10^2
10^1
1
4.5
3.5
2.5
1.5
0.5

The silicate weathering feedback



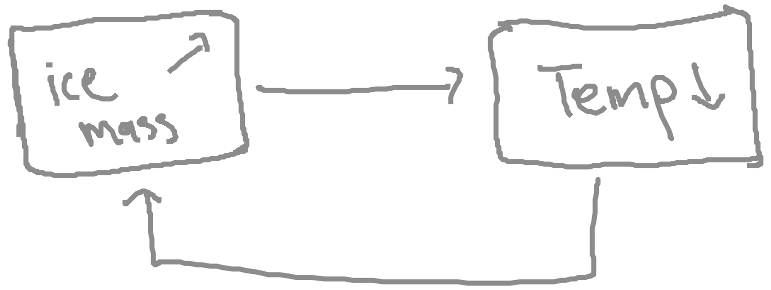
Feedbacks

positive
vs
negative



if silicate weathering:
↗ then CO_2 ↘
↘ then CO_2 ↗

ice - Albedo feedback (positive)



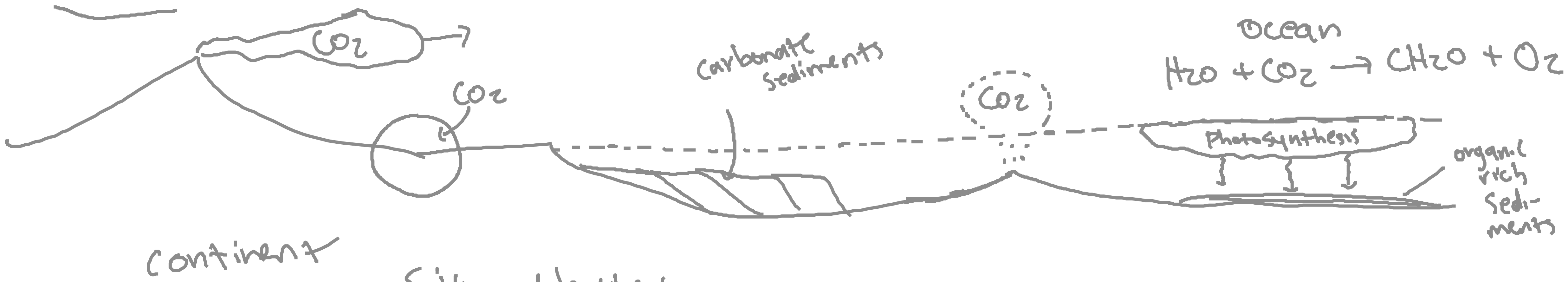
The long term carbon cycle (conceptual)

million - billion years

$CO_2 + H_2O \longleftrightarrow H_2CO_3$

Ocean

$H_2O + CO_2 \longrightarrow CH_2O + O_2$



Silicate Weathering

$CaSiO_3 + 2H_2CO_3 \longrightarrow \underline{Ca^{2+} + 2HCO_3^-} + SiO_2 + H_2O$

Carb. weathering

└→ carb. precipitation

no change in CO_2

Carbonate Weathering

$CaCO_3 + H_2CO_3 \underset{\text{precipitation}}{\overset{\text{carbonate weathering}}{\rightleftharpoons}} \underline{Ca^{2+} + 2HCO_3^-}$

Silicate weathering

└ $-1CO_2$

└→ carb. precipitation

The long term carbon cycle (a model)

box model

Steady state : mass doesn't change over time

Volcanic degassing → Carbon mass ocean + atmosphere → Carbonates and organic sediments

K: weatherability "efficiency of weathering"

Flux out = K · M

$$\frac{dM}{dt} = \text{Flux in} - \text{Flux out}$$

when we have steady state

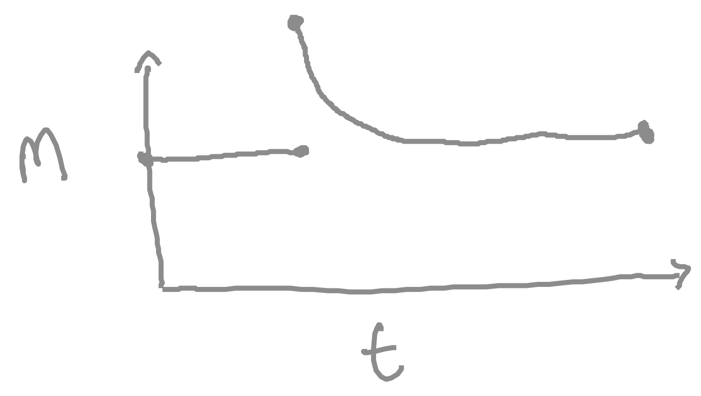
$$\frac{dM}{dt} = 0$$

w/ a negative feedback

$$\frac{dM}{dt} = \text{Flux in} - K \cdot M$$

$$0 = \text{Flux in} - K \cdot M$$

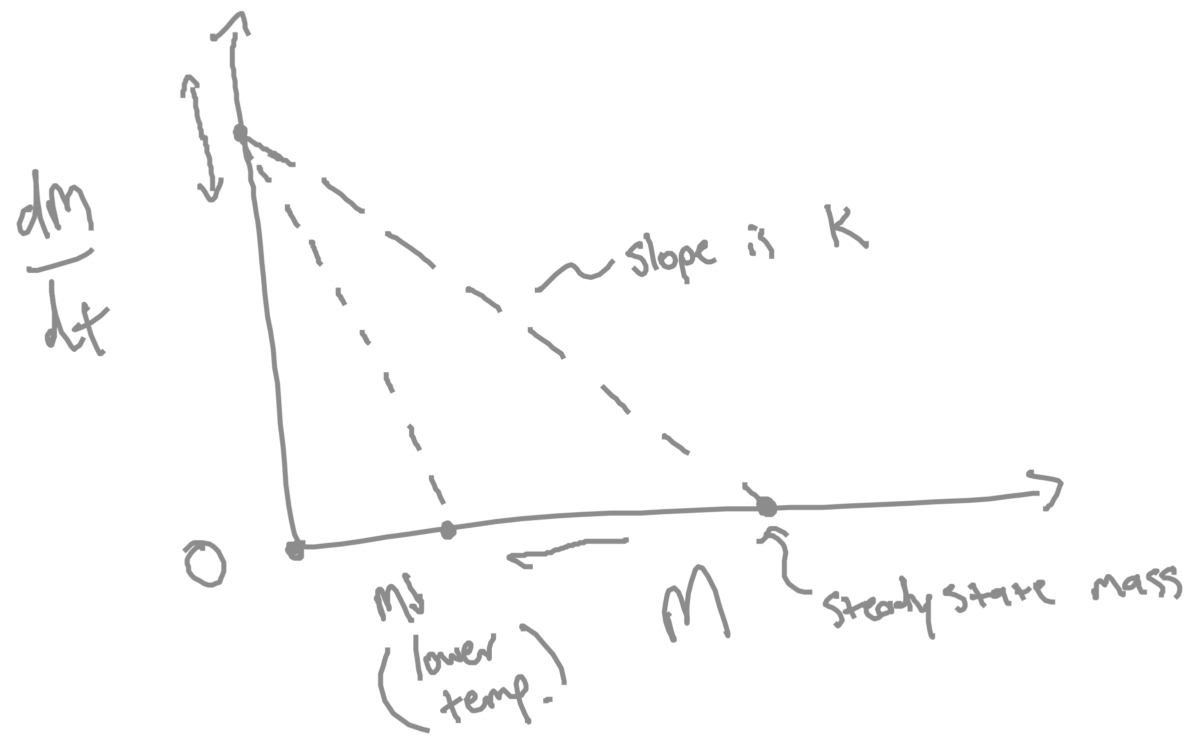
$$K M = \text{flux in}$$



How does climate change?

• change steady state M

$$\frac{dM}{dt} = F_{in} - KM \qquad (Y = b - mx)$$

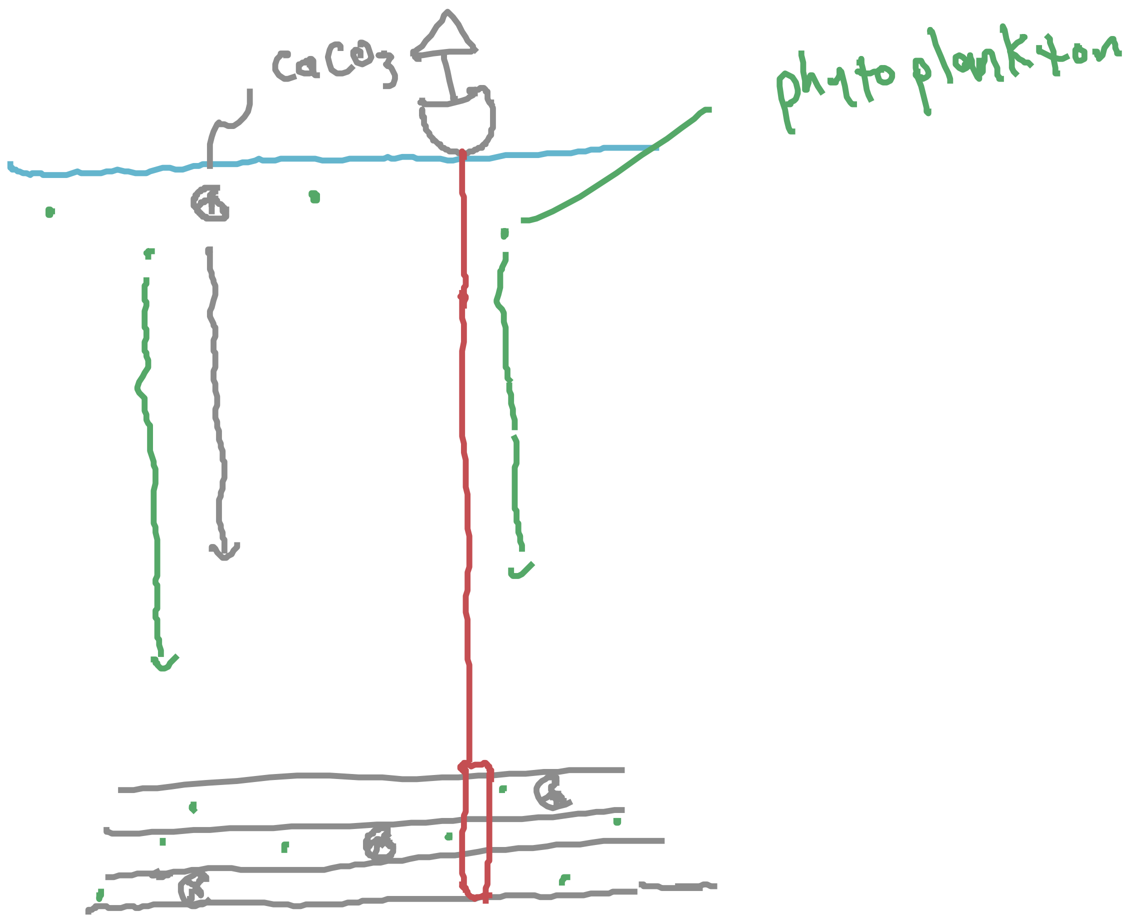


How do we measure past climate change?

Sediment hold records of the past surface conditions

- we look at "proxies"
  - ↳ paleo sea level elevations
  - ↳ organic molecules
  - ↳ Stable isotopic composition of sediments

- Direct measurements
  - ice cores have trapped gas bubbles that hold old atmosphere



Stable isotopes: notation

mass number for an isotope

$$R^{13}_{C} = \frac{C^{13}}{C^{12}}$$

always the lowest mass for a given element

oxygen comes as 16, 17, 18 ;

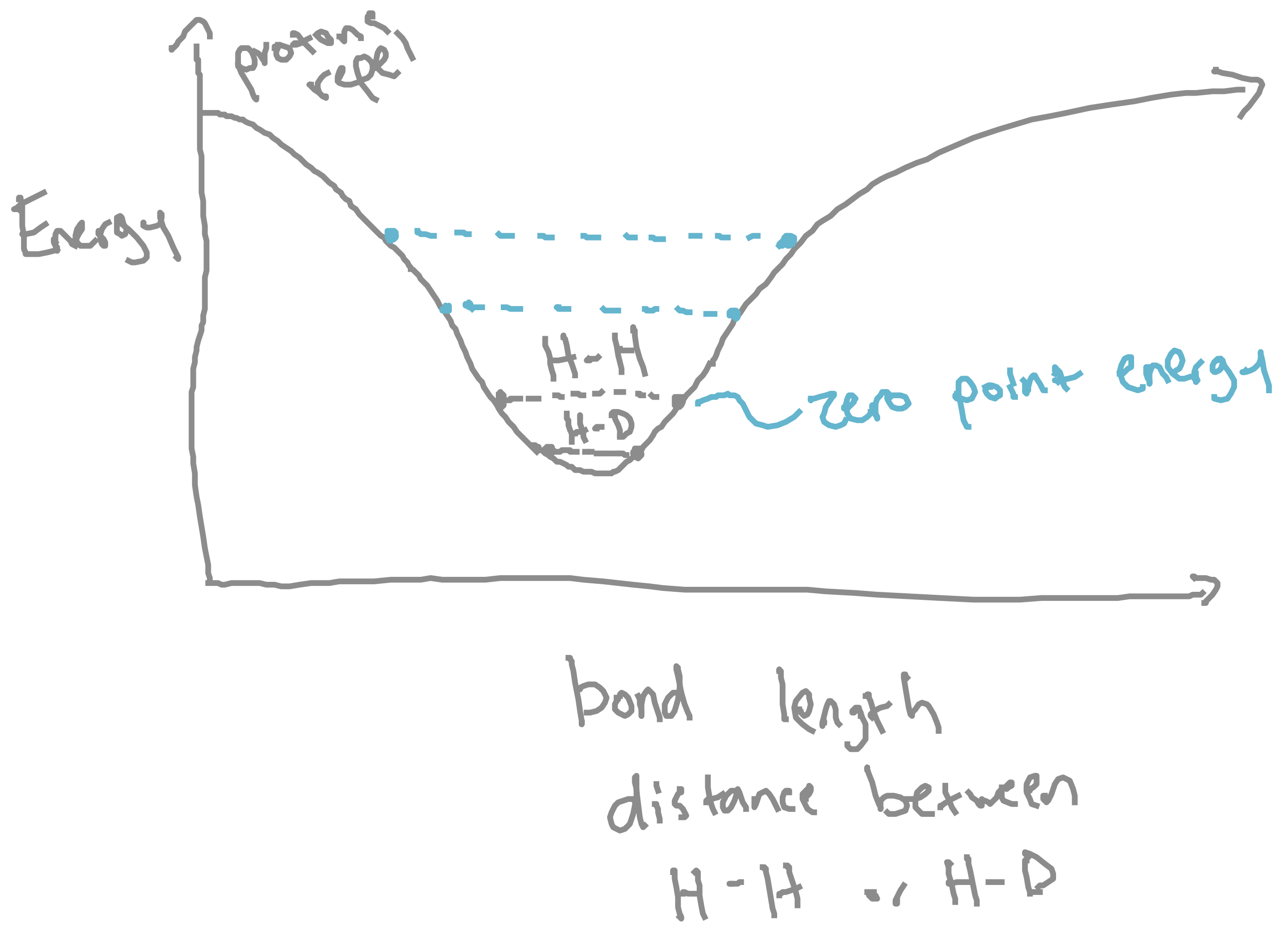
$$R^{17}_{O} = \frac{[O^{17}]}{[O^{16}]}$$

$$\frac{R^{13}_{CO_2}}{R^{13}_{HCO_3^-}} = \alpha$$ = fractionation factor

$$\delta = \left(\frac{(R^{13}_{CO_2})_{sample}}{(R^{13}_{CO_2})_{standard}} - 1 \right) \times 10^{3}$$

$$\delta^{13}C_{PDB} = +4.1$$

Stable isotopes: equilibrium and zero point energy



$^1H - ^1H$ $\quad$ $^2D - ^1H$ $\quad$ $D = {^2H}$

$$F = -Kx$$

$$freq = \nu = \frac{1}{2\pi}\sqrt{\frac{K}{\mu}}$$ ← reduced mass

high freq = high energy

$$\mu = \frac{M_1 \cdot M_2}{M_1 + M_2}$$

$$\mu_{H_1-H_1} = \frac{1 \cdot 1}{2} \quad 0.5$$

$$\mu_{D-H_1} = \frac{1 \cdot 2}{3} = .\overline{6}$$

Stable isotopes: equilibrium example

$$H_2O(l) + HDS(g) \rightleftharpoons HDO(l) + H_2S(g)$$

K is equilibrium constant $K = \frac{[HDO][H_2S]}{[HDS][H_2O]} \neq 1 = \alpha$ "fractionation factor"

* $\cancel{\Delta G}^{\,0} = \Delta G_0 + RT \ln Q$

equilibrium

$\Delta G_0 = -RT \ln K$

$\Delta E_2 - \Delta E_1 \approx -RT \ln K$

$-1(\Delta E_2 - \Delta E_1) \approx -RT \ln K$

$$\frac{\Delta E_1 - \Delta E_2}{RT} \approx \ln K$$

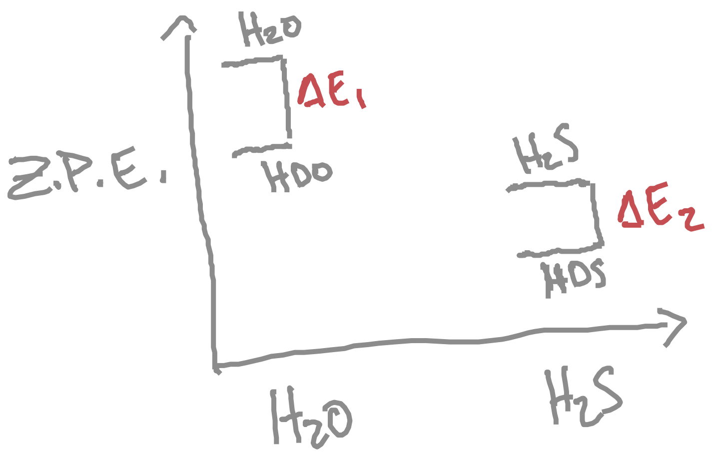
General Rule: heavy isotopes prefer to go into the chemical compound that is more strongly bonded

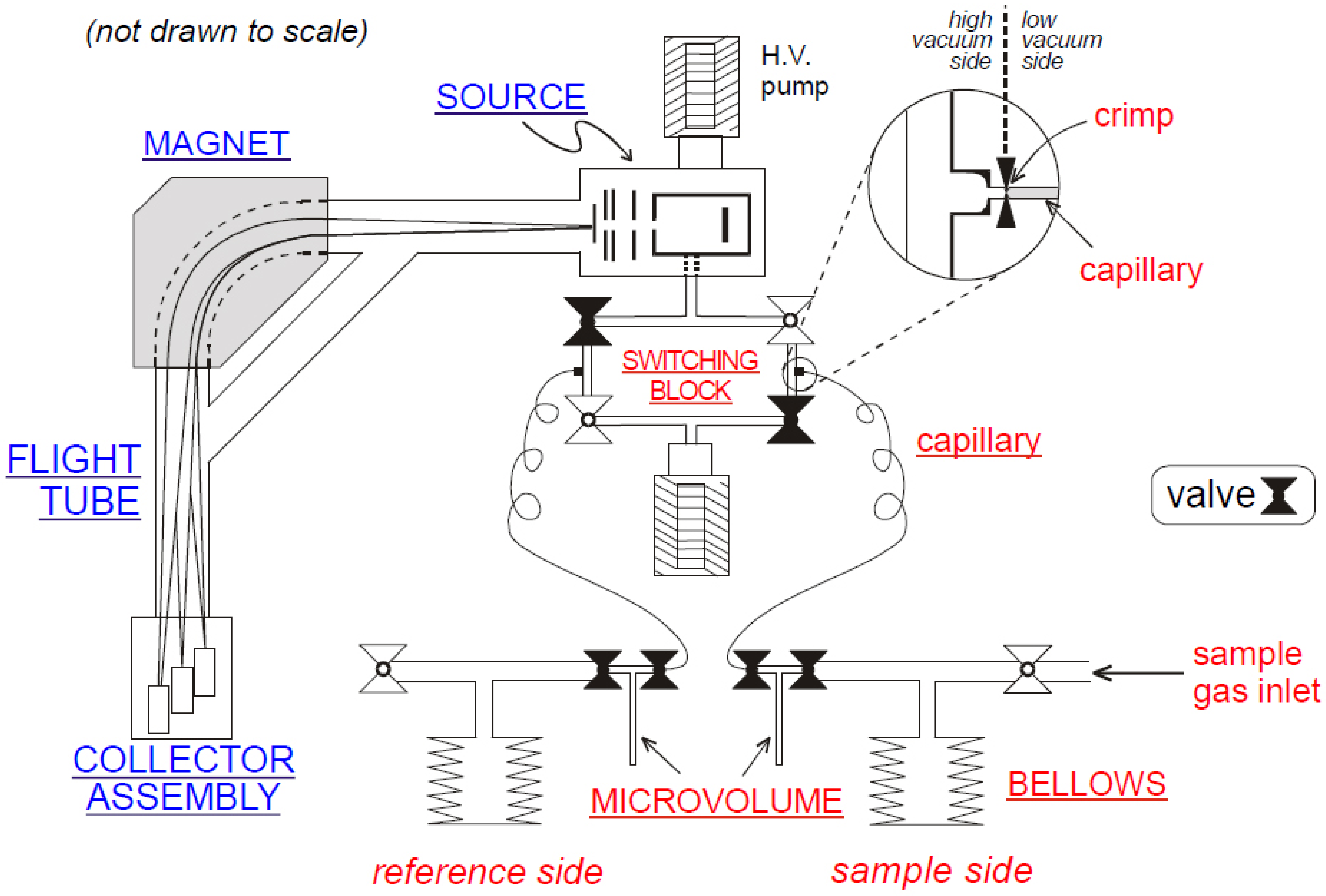
to get to products ΔG_0 reactants

$H_2S + HDO - HDS - H_2O$

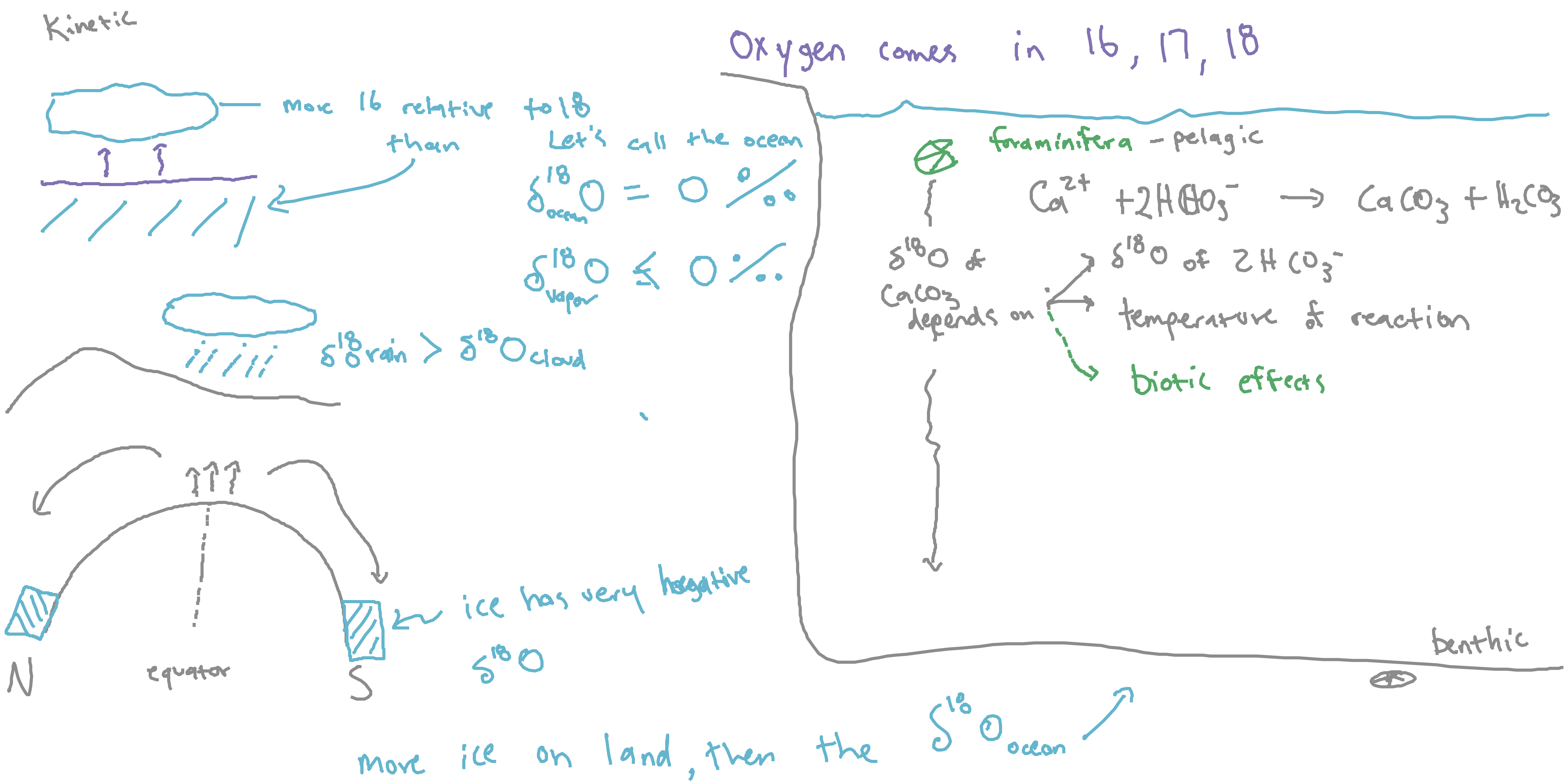
$H_2S - HDS + HDO - H_2O$ $\boxed{-1(H_2O - HDO)}$

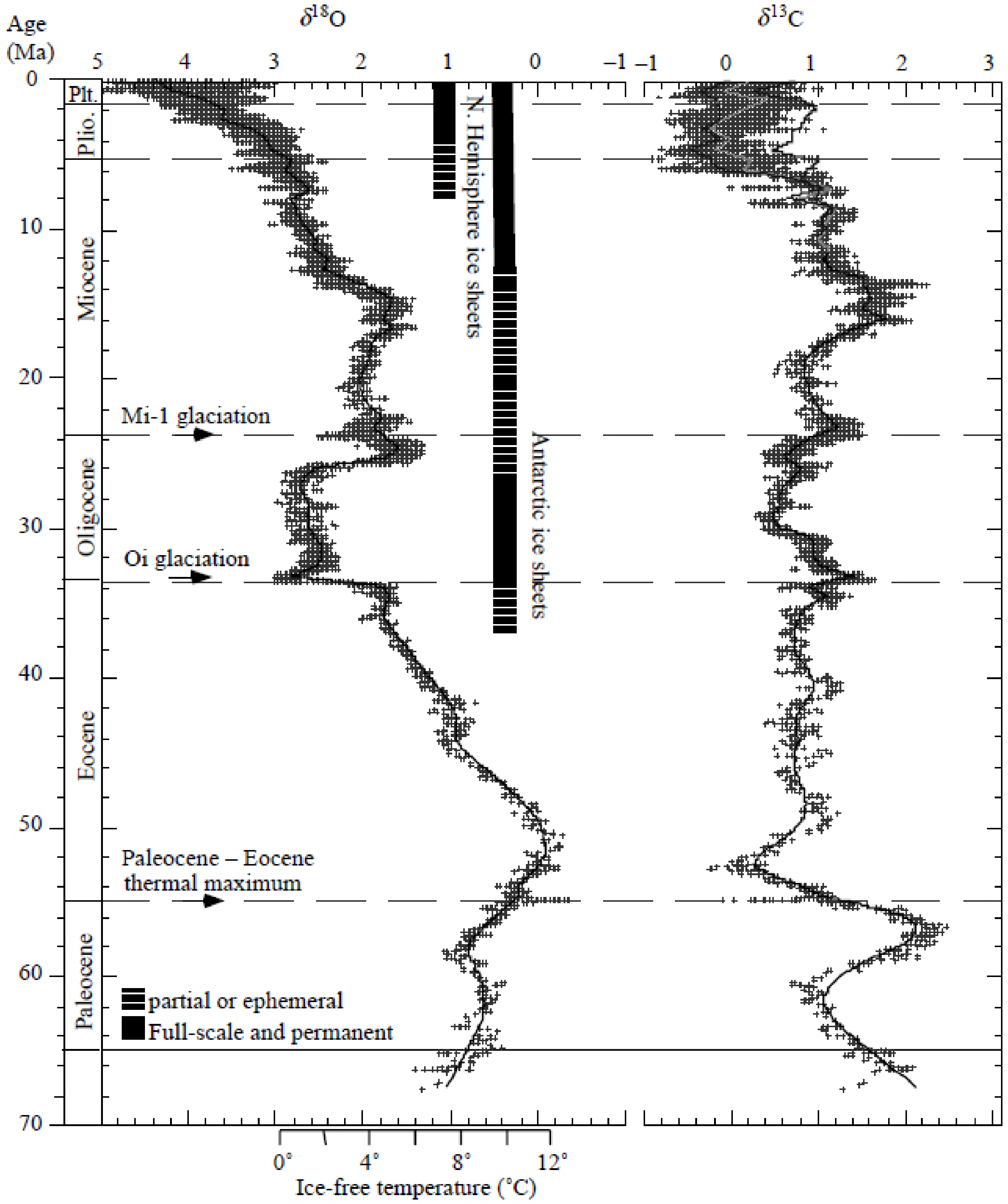
$\underbrace{(H_2S - HDS)}_{\Delta E_2} - \underbrace{(H_2O - HDO)}_{\Delta E_1}$




(not drawn to scale)
SOURCE
H.V. pump
high vacuum side
low vacuum side
crimp
capillary
MAGNET
SWITCHING BLOCK
capillary
FLIGHT TUBE
valve
COLLECTOR ASSEMBLY
MICROVOLUME
BELLOWS
sample gas inlet
reference side
sample side

Stable isotopes: oxygen isotopes in the ocean





Compilation from Zachos *et al.*, 2001

colder
+

warmer
↓ −

$\delta^{18}O$ of forams ↗
↳ ice volume ↗
↳ lower temp.

icehouse

↓
greenhouse

hot

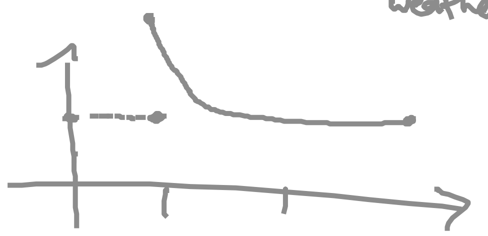
hypothesis 1: Volcanic degassing decreases over the last 50 mA

recall

mass of CO_2

$$\frac{dM}{dt} = F_{in} - K M$$

↑
weatherability

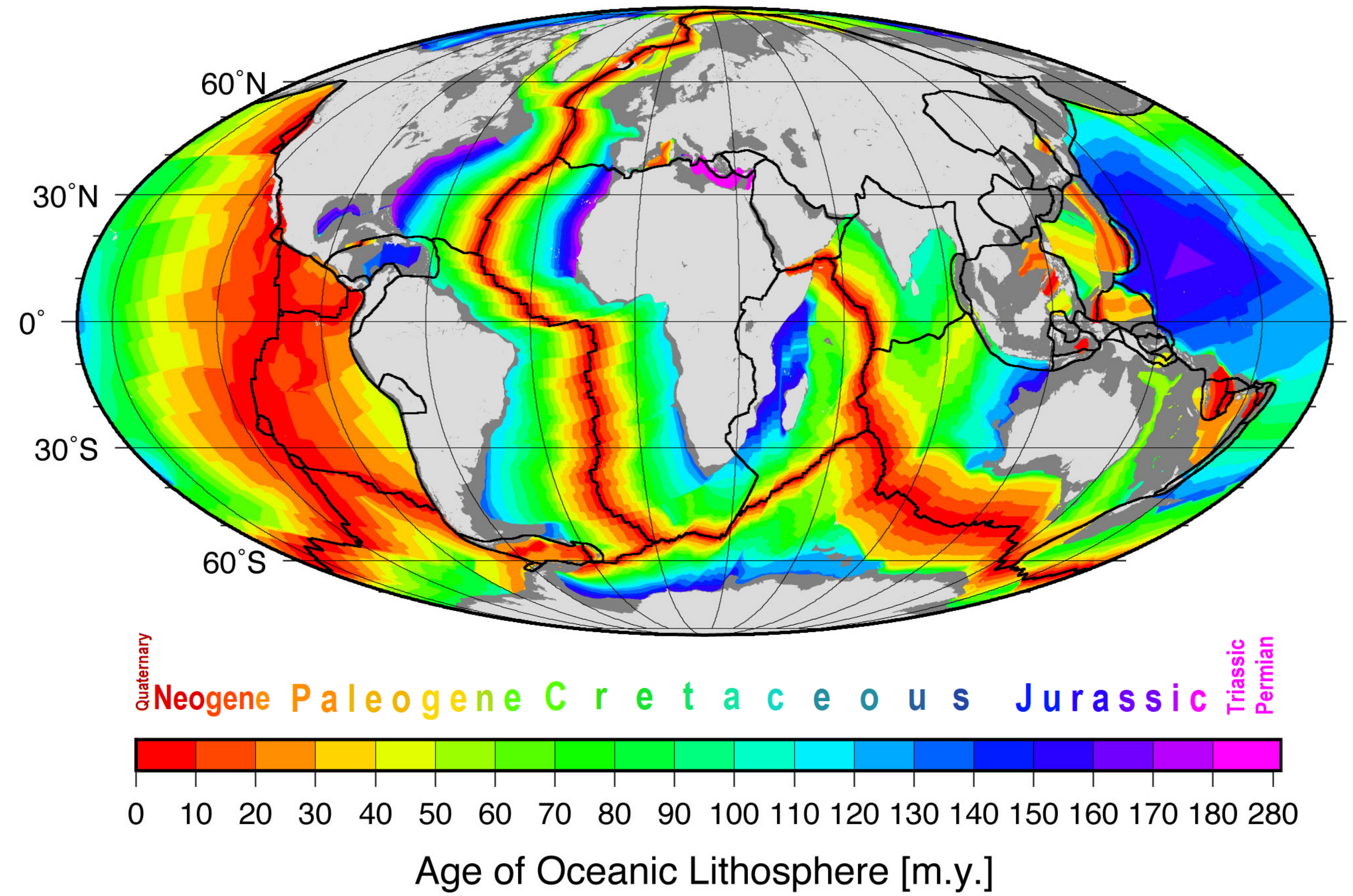


$$\frac{dM}{dt} = 0 \quad \text{at steady state}$$

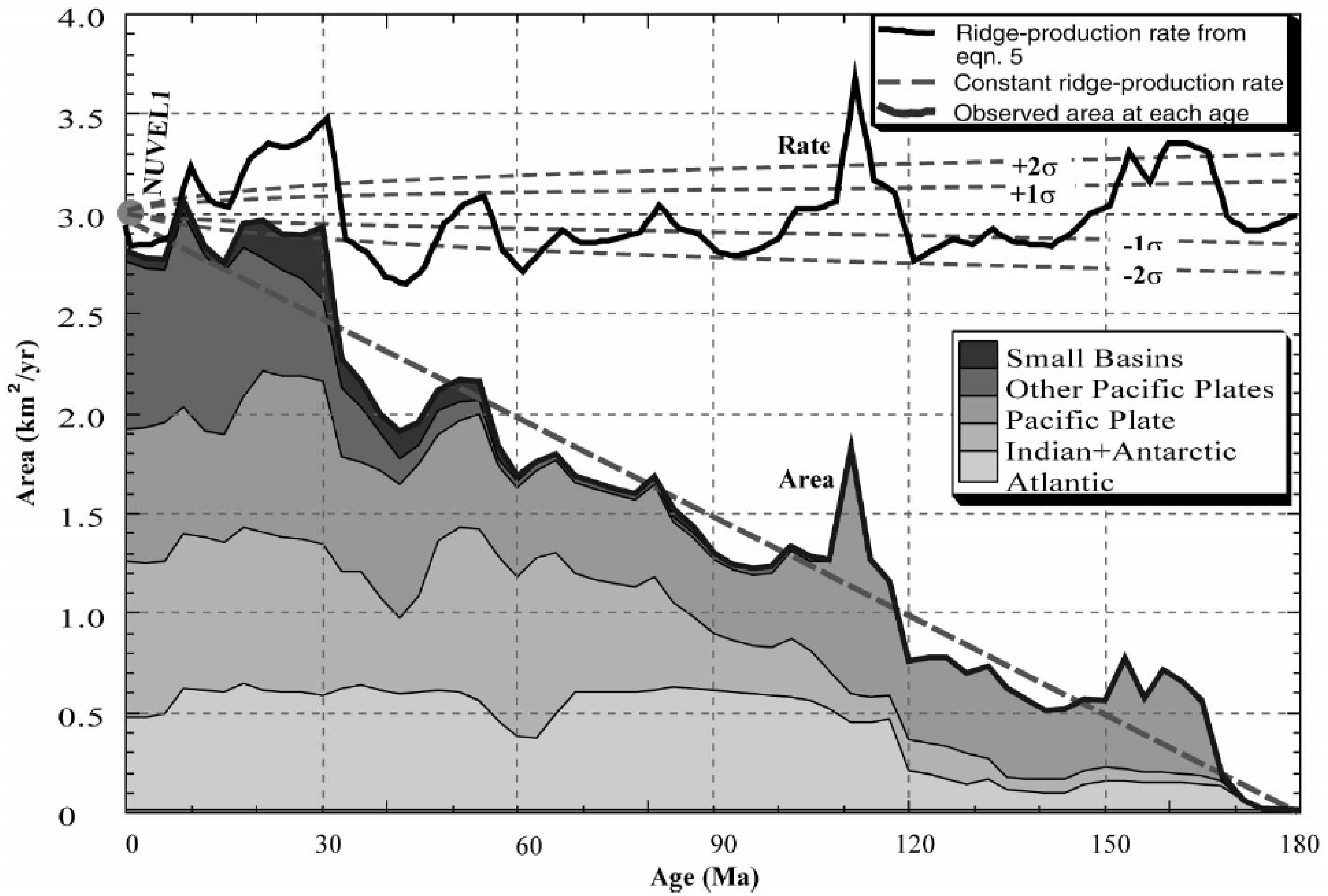
$$0 = F_{in} - K \cdot M$$

$$F_{in} = K M$$

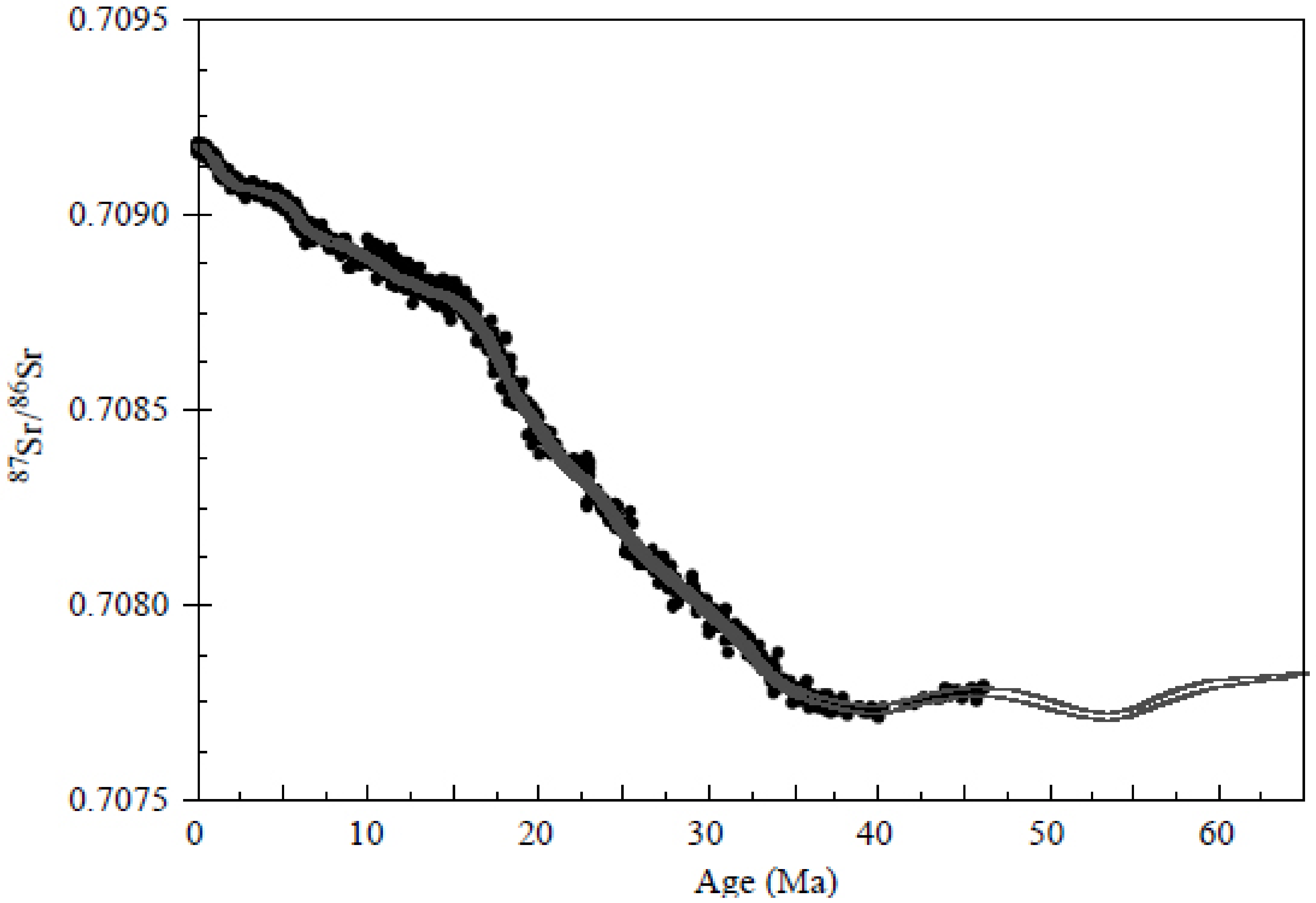
$$\frac{F_{in}}{K} = M$$



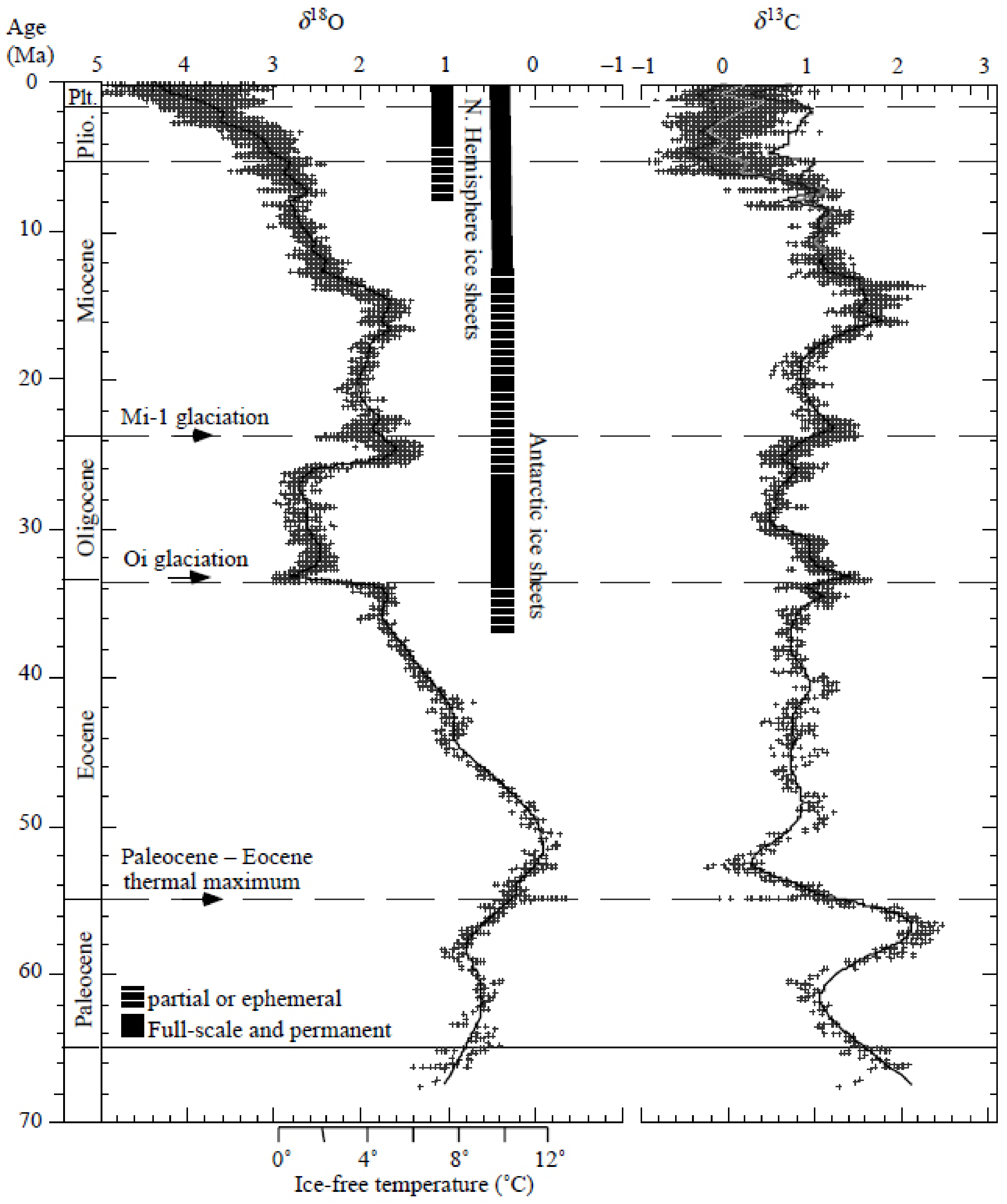
60˚N
30˚N
0˚
30˚S
60˚S
Quaternary
Neogene
Paleogene
Cretaceous
Jurassic
Triassic
Permian
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 280
Age of Oceanic Lithosphere [m.y.]



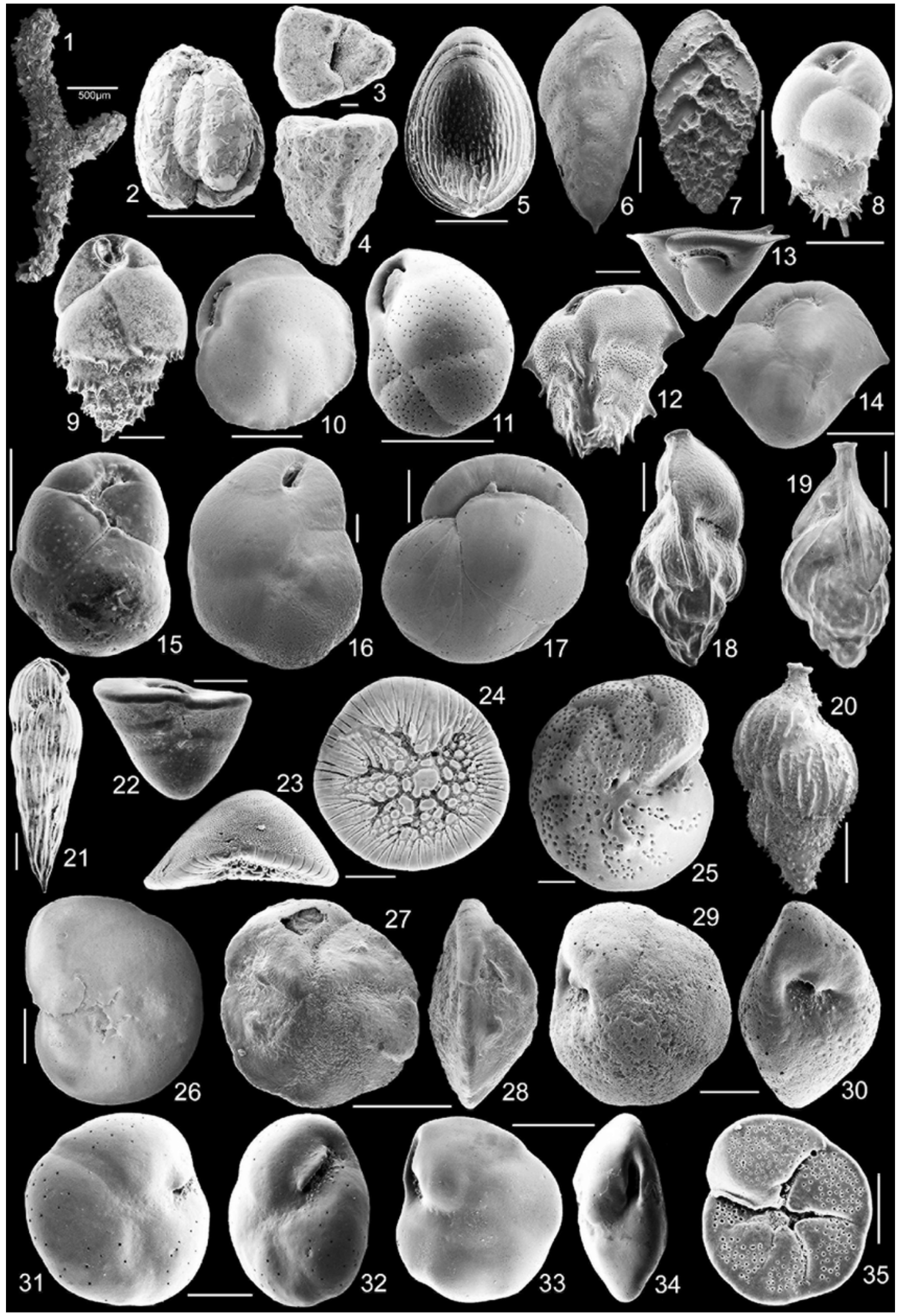
Ridge-production rate from eqn. 5
Constant ridge-production rate
Observed area at each age
NUVEL1
Rate
+2σ
+1σ
-1σ
-2σ
Small Basins
Other Pacific Plates
Pacific Plate
Indian+Antarctic
Atlantic
Area
Area (km^2/yr)
Age (Ma)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
0
30
60
90
120
150
180



Compilation from Ravizza and Zachos, 2003



Compilation from Zachos *et al.*, 2001


1
500µm
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
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21
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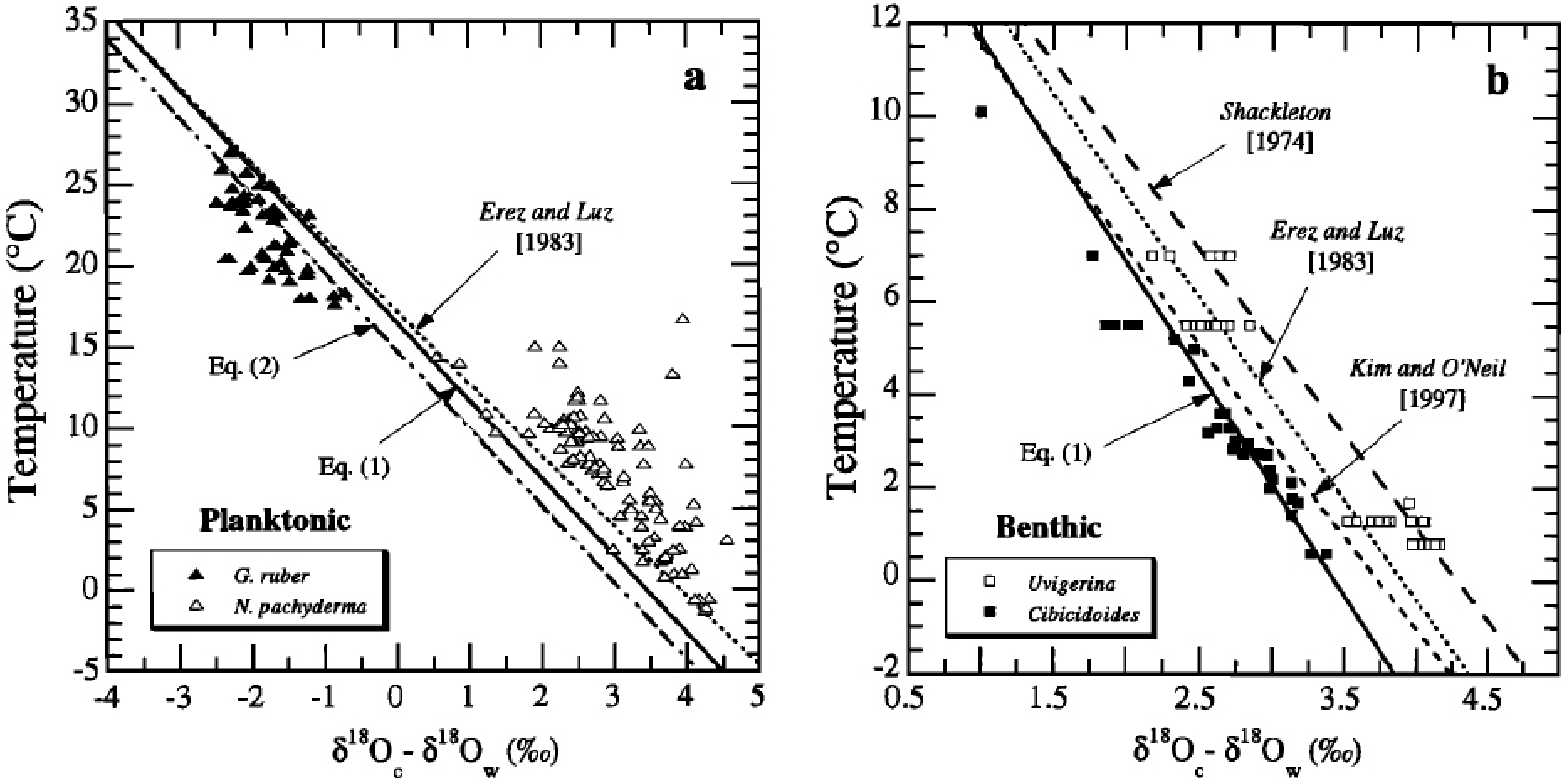
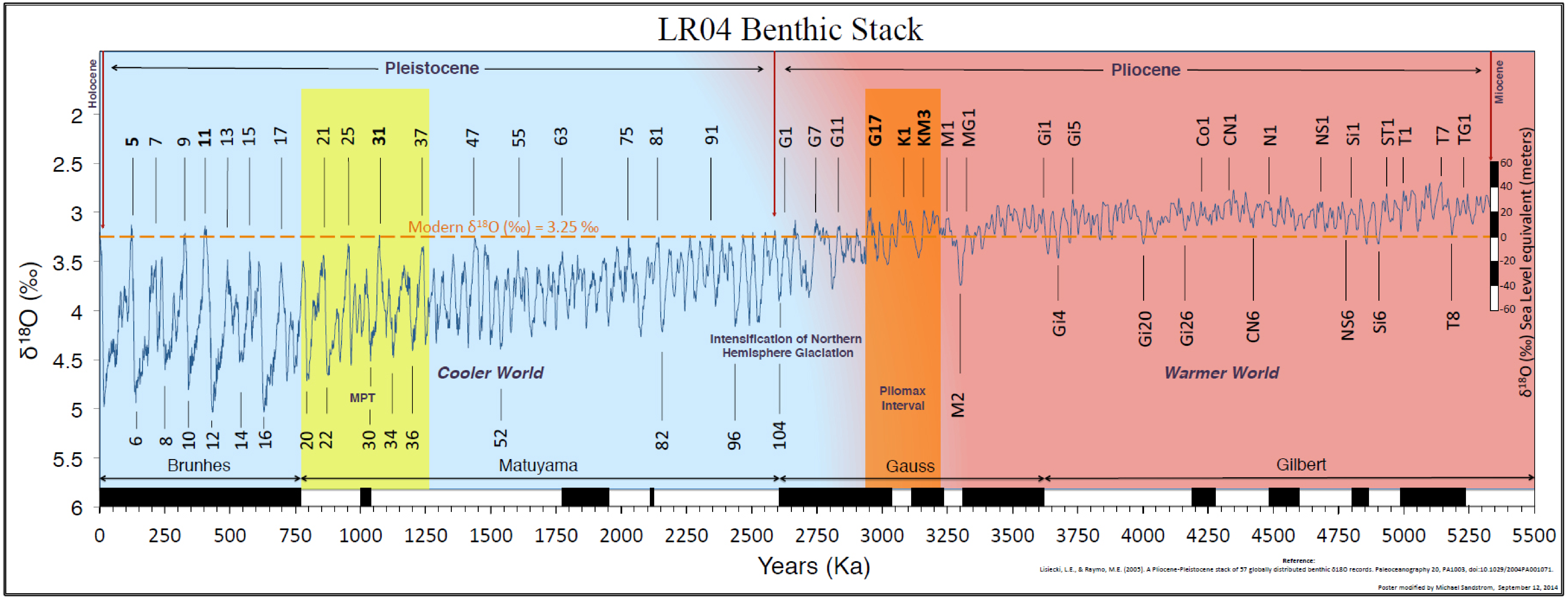
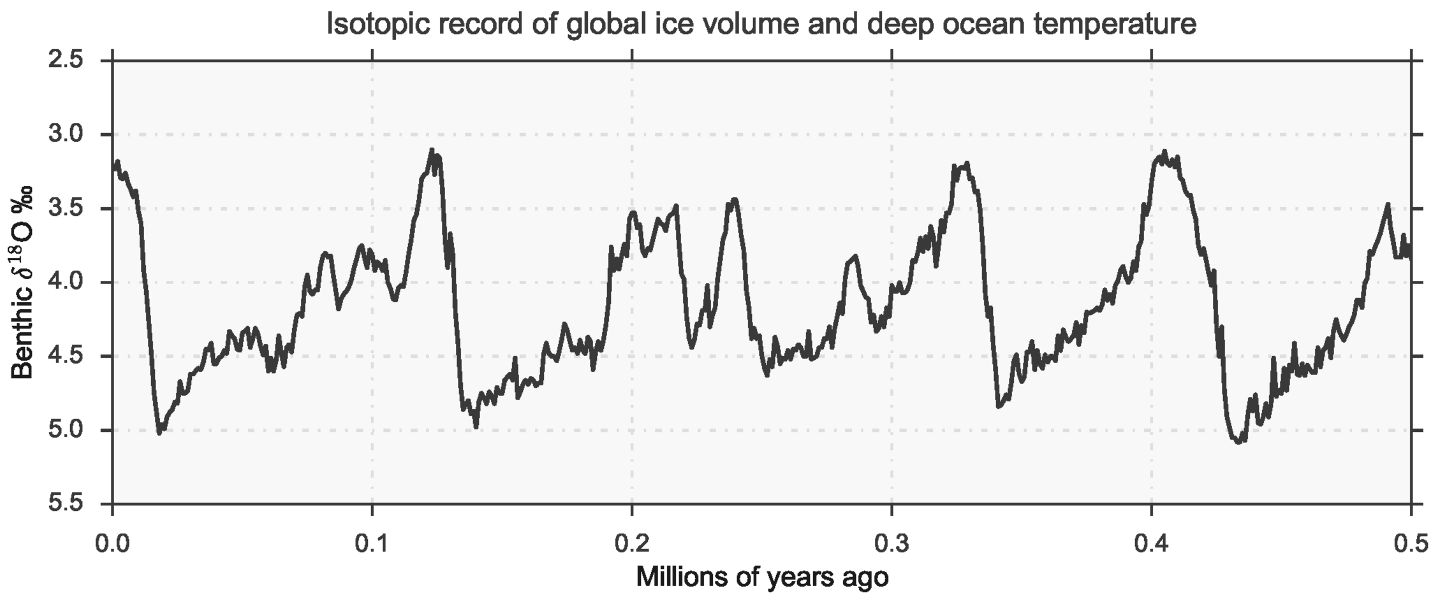
34
35



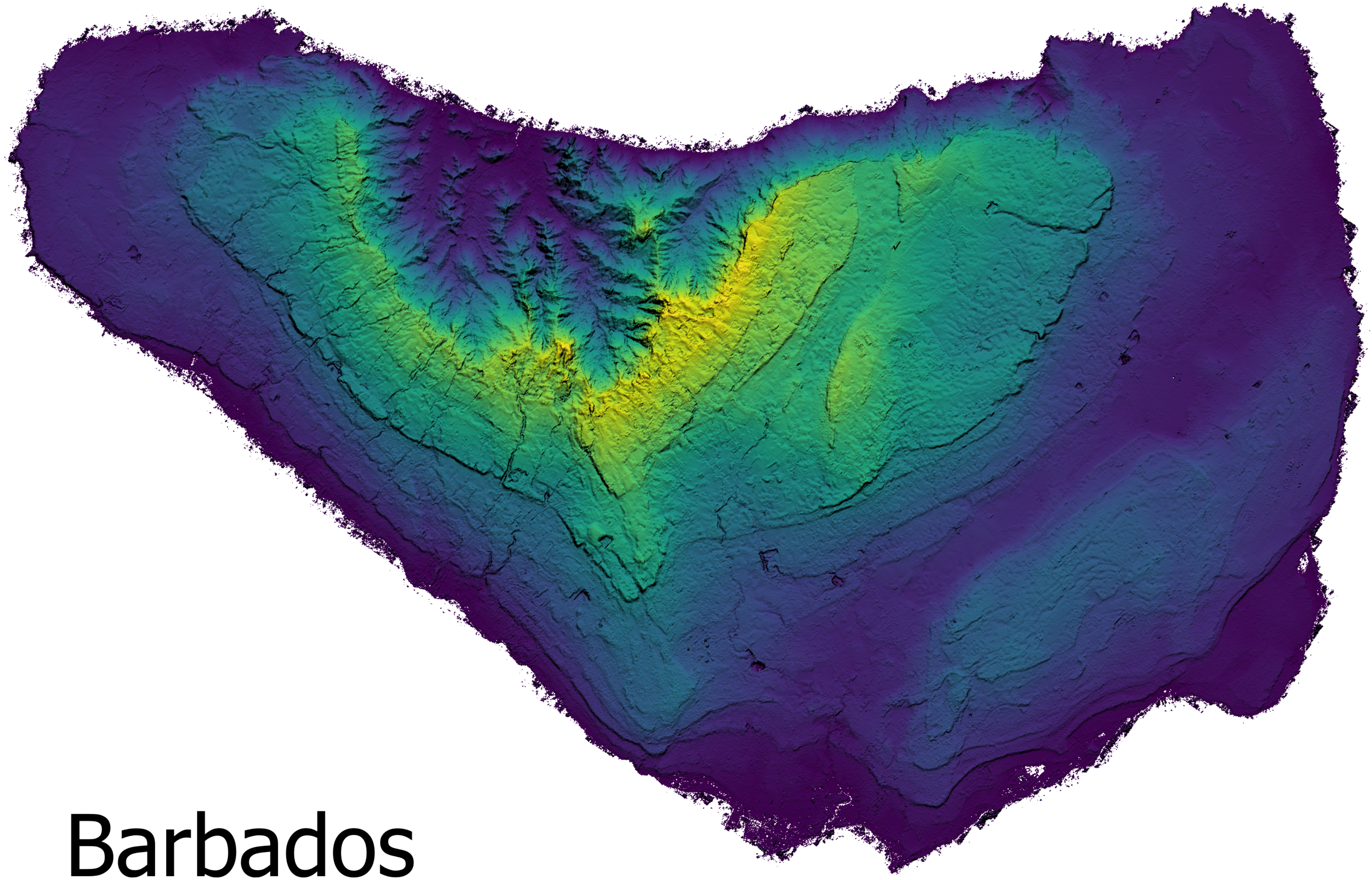
from Bemis et al., 1998



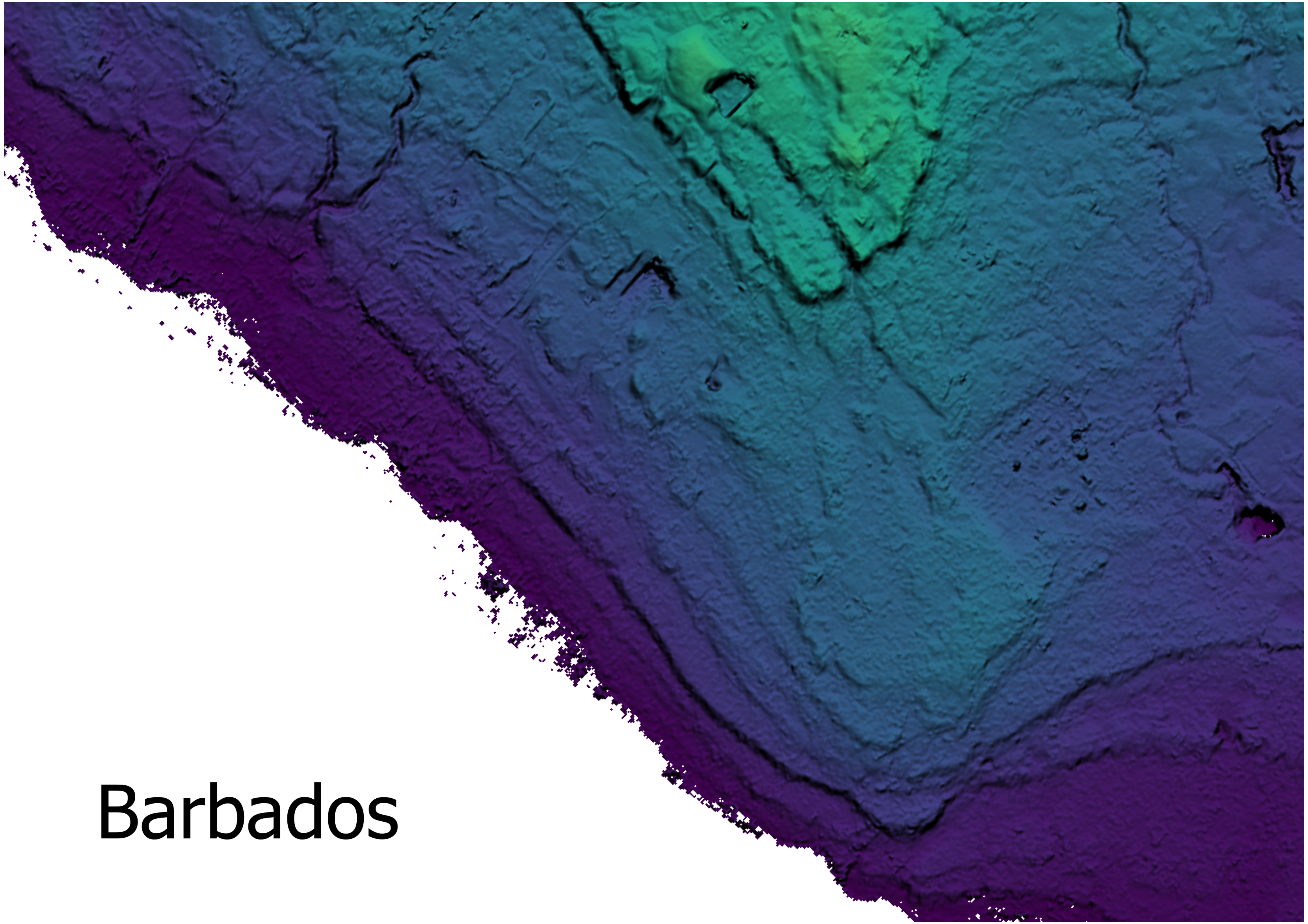
from Lisiecki and Raymo, 2004


Isotopic record of global ice volume and deep ocean temperature
Benthic δ18O ‰
2.5
3.0
3.5
4.0
4.5
5.0
5.5
0.0
0.1
0.2
0.3
0.4
0.5
Millions of years ago

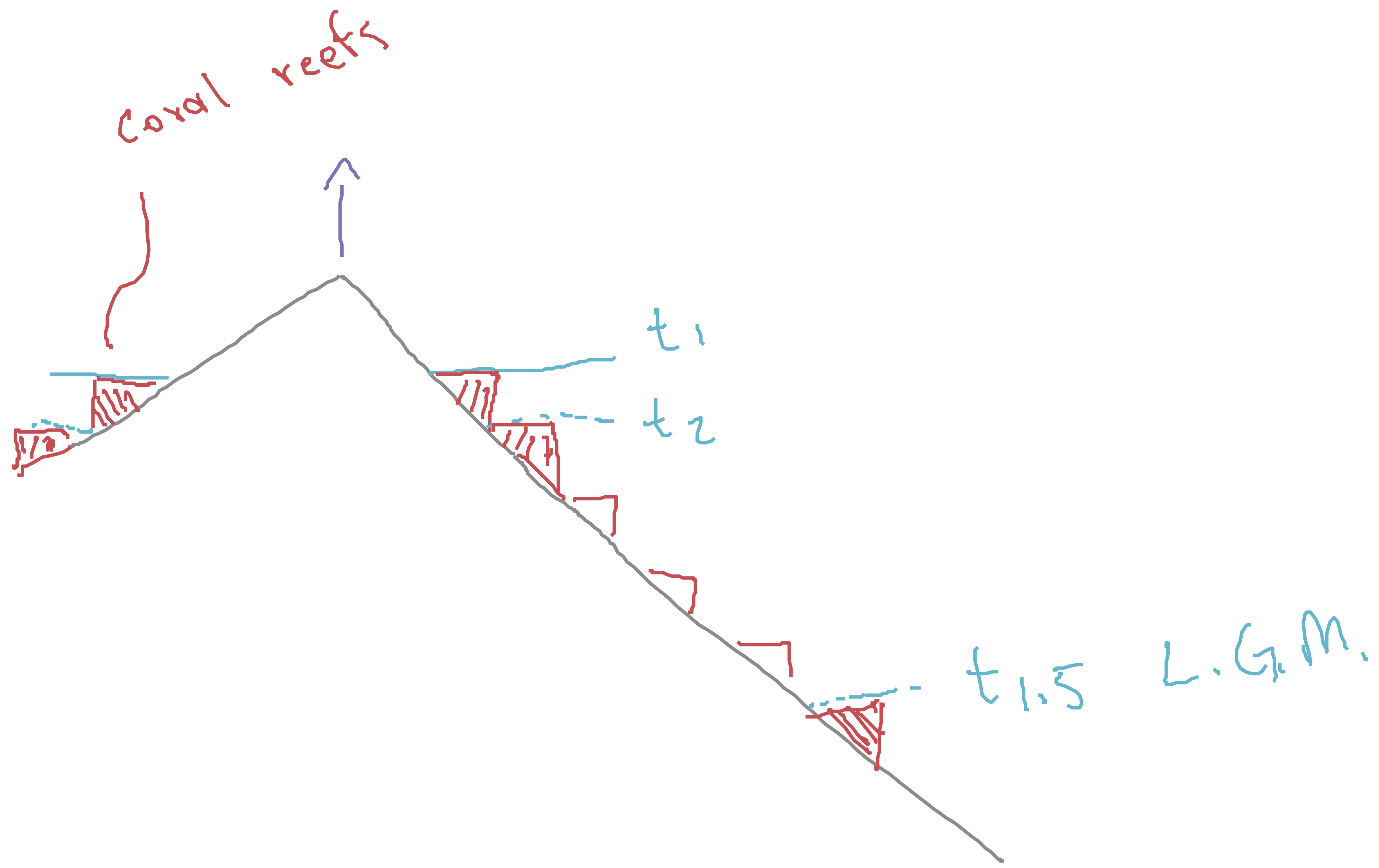

Barbados



Barbados



Barbados



Coral reefs
t1
t2
t1.5 L.G.M.