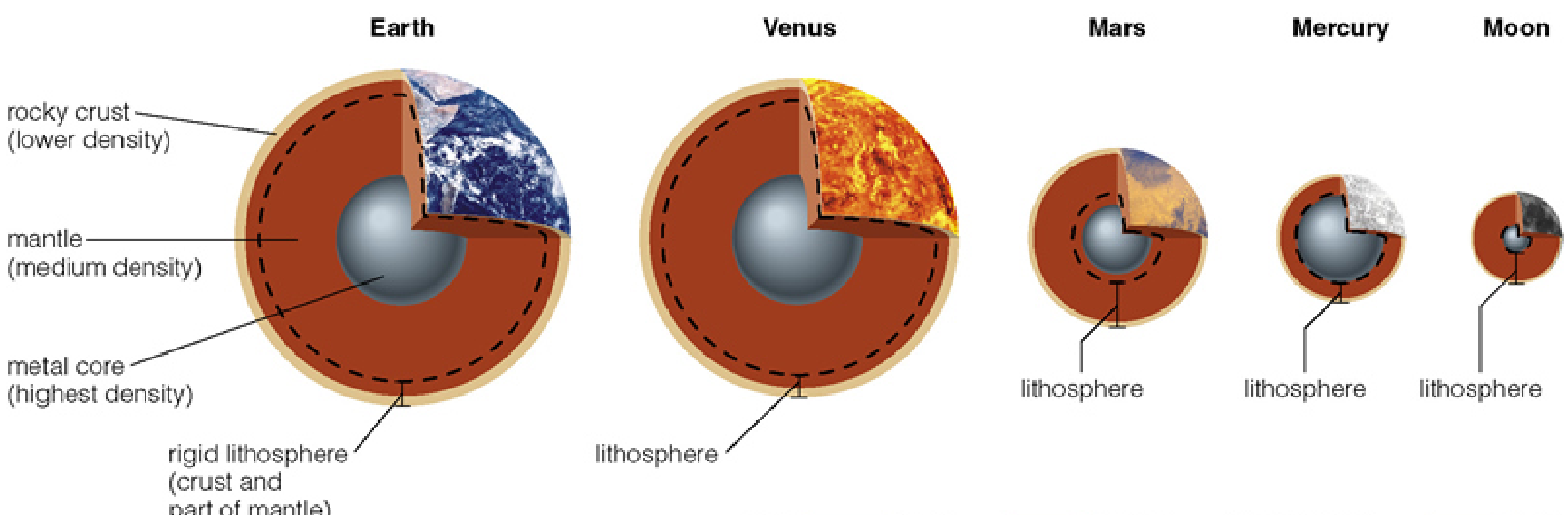
# Terrestrial planets

1) Interiors
2) Vulcanism, plate tectonics
3) Surface temperatures
4) Atmospheres: densities, temperatures, composition
5) Optics: colours, clouds
6) What happened to Venus?

# Interiors of the terrestrial planets

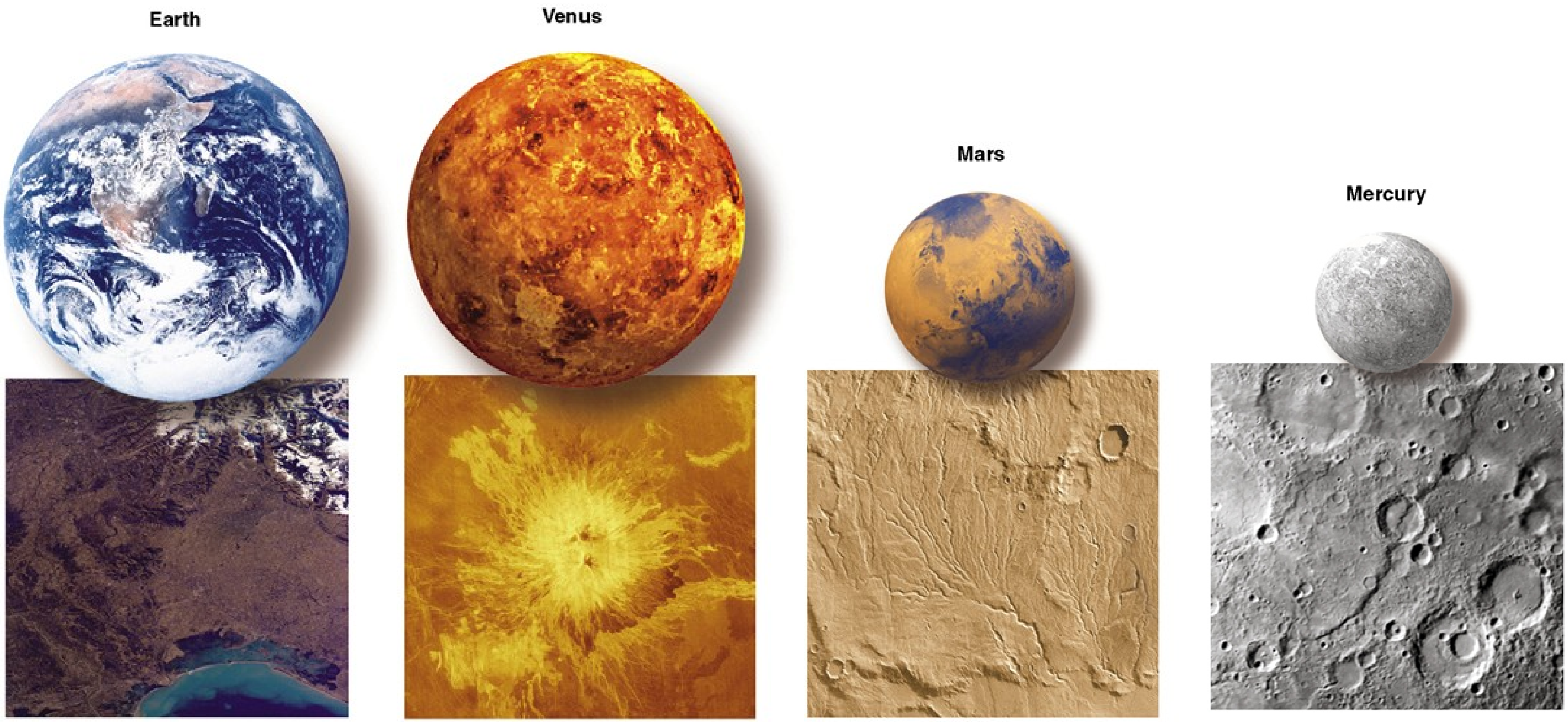
- Differentiated: dense, metallic core; inner part solid, outer fluid.
  lighter, mostly rocky mantle (*not* liquid, but can flow)
  even lighter rocky crust.
- Heat sources: accretion
  *(other than residual heat)*
  differentiation/contraction
  radioactive decay
  tidal
- Heat flow: conduction in core
  convection in (outer) mantle ("rock creep"; ~100 Myr timescale)
  conduction through rigid lithosphere



# Exteriors of the terrestial planets

Shaped by four main processes:

- Impacts (many early on, now rare; can be used to "date" surfaces)
- Volcanism (Earth, Venus active; Mars maybe, maybe not; Mercury inactive)
- Plate tectonics (still active on Earth, not on Venus(?), Mars, Mercury)
- Erosion (wind, water, ...) (active on Earth, Mars; not on Venus, Mercury)




Earth has a variety of geological features visible in this photo from orbit.

The central structure is a tall, twin-peaked volcano on Venus.

Mars has impact craters like the one near the upper right, but it also has features that look much like dried up riverbeds.

Mercury is heavily cratered, but also has long, steep cliffs—one is visible here as the long curve that passes through the center of the image.

# Continental Drift



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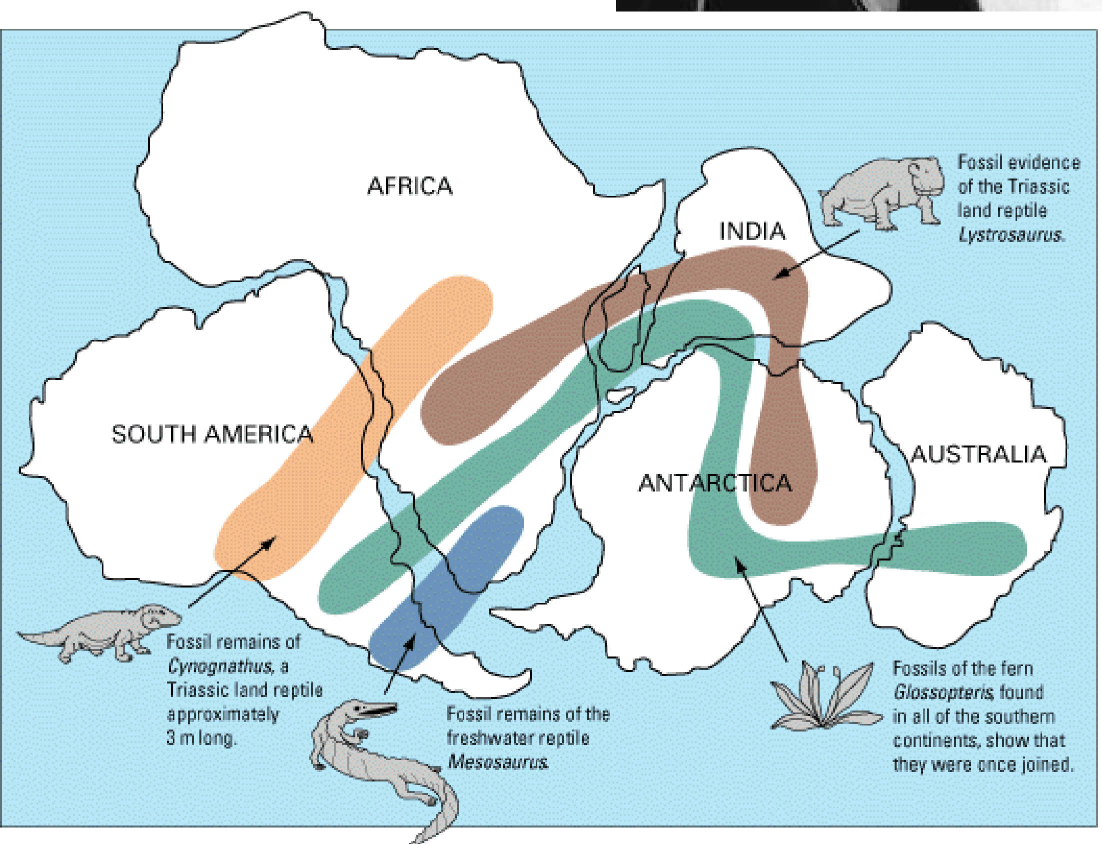
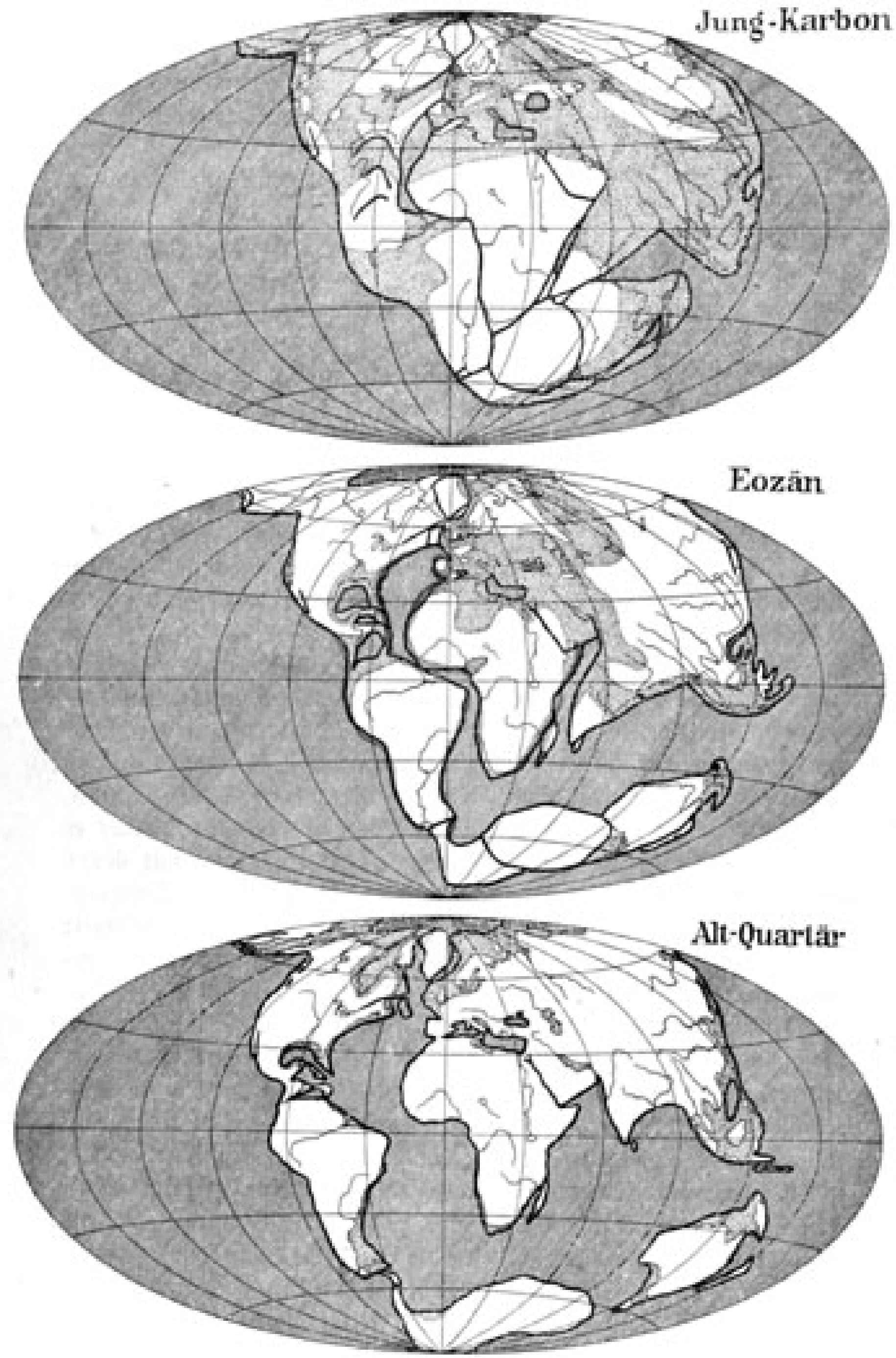


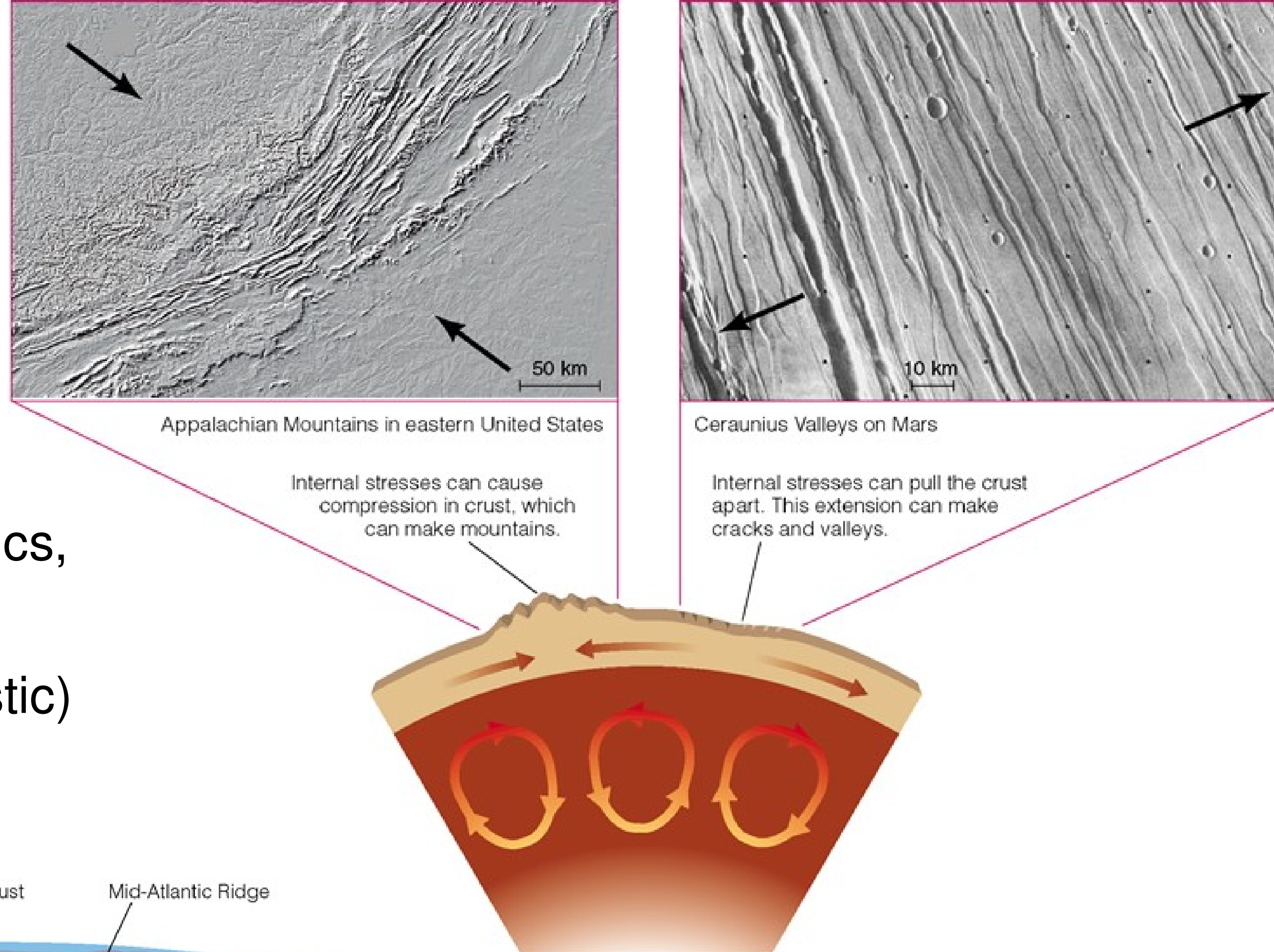

Abb. 4.



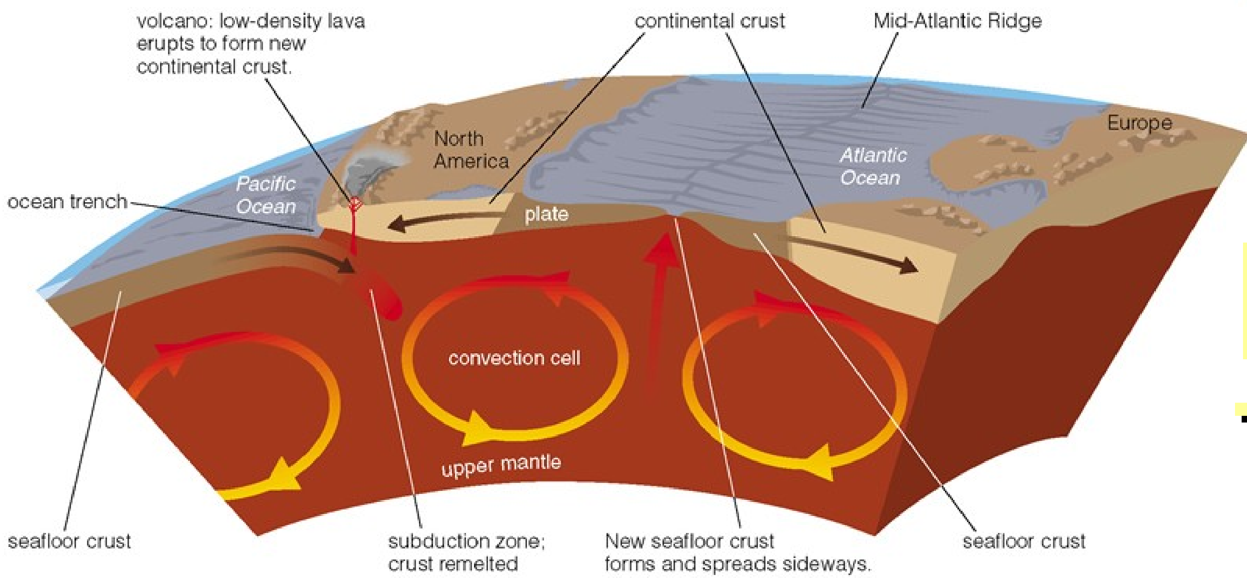

Rekonstruktionen der Erdkarte nach der Verschiebungstheorie für drei Zeiten.

Schraffiert: Tiefsee; punktiert: Flachsee; heutige Konturen und Flüsse nur zum Erkennen. Gradnetz willkürlich (das heutige von Afrika).

# Tectonics

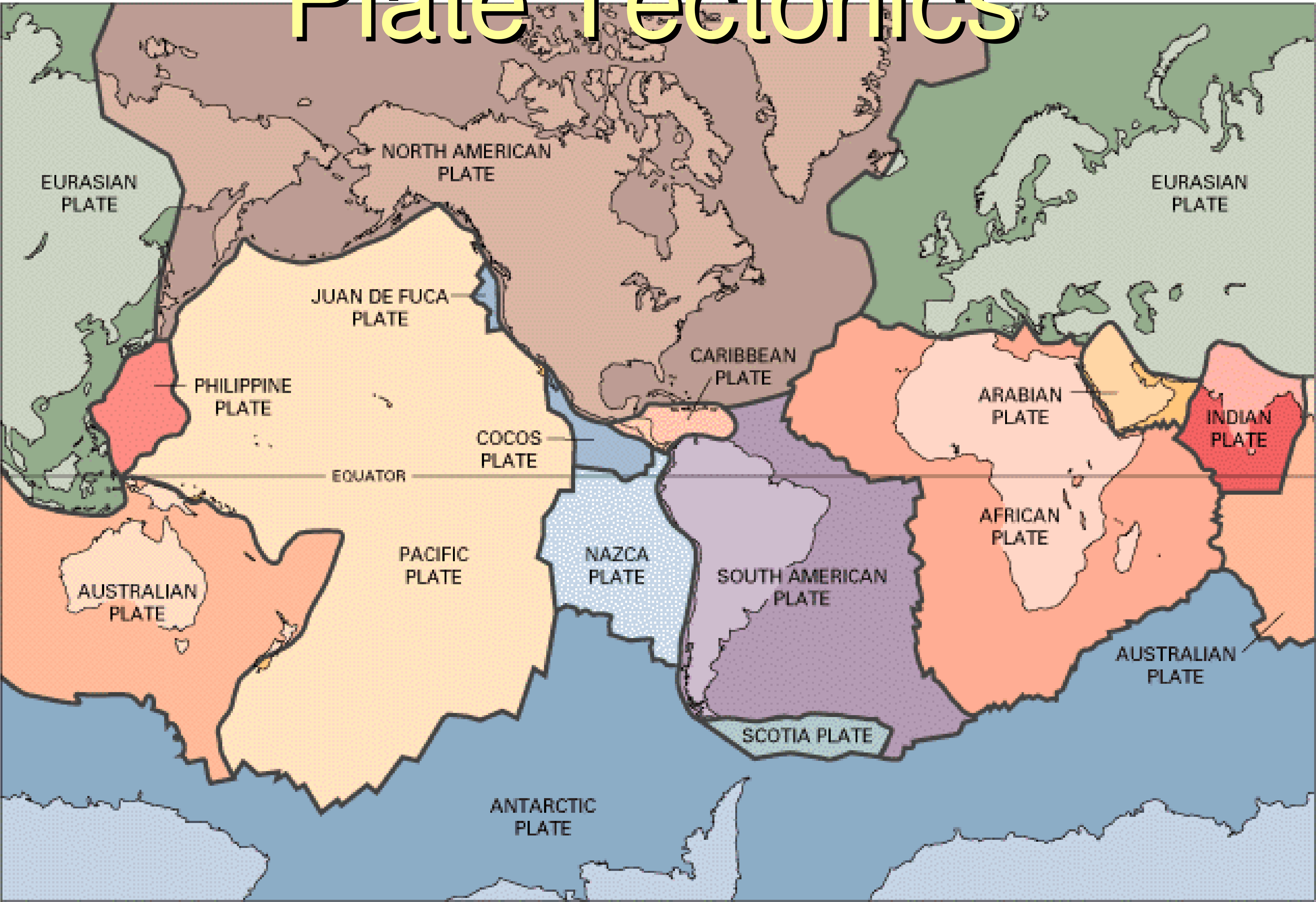



Venus shows signs of tectonics, but not plate tectonics.
Due to absence of water?
(water makes rock more plastic)

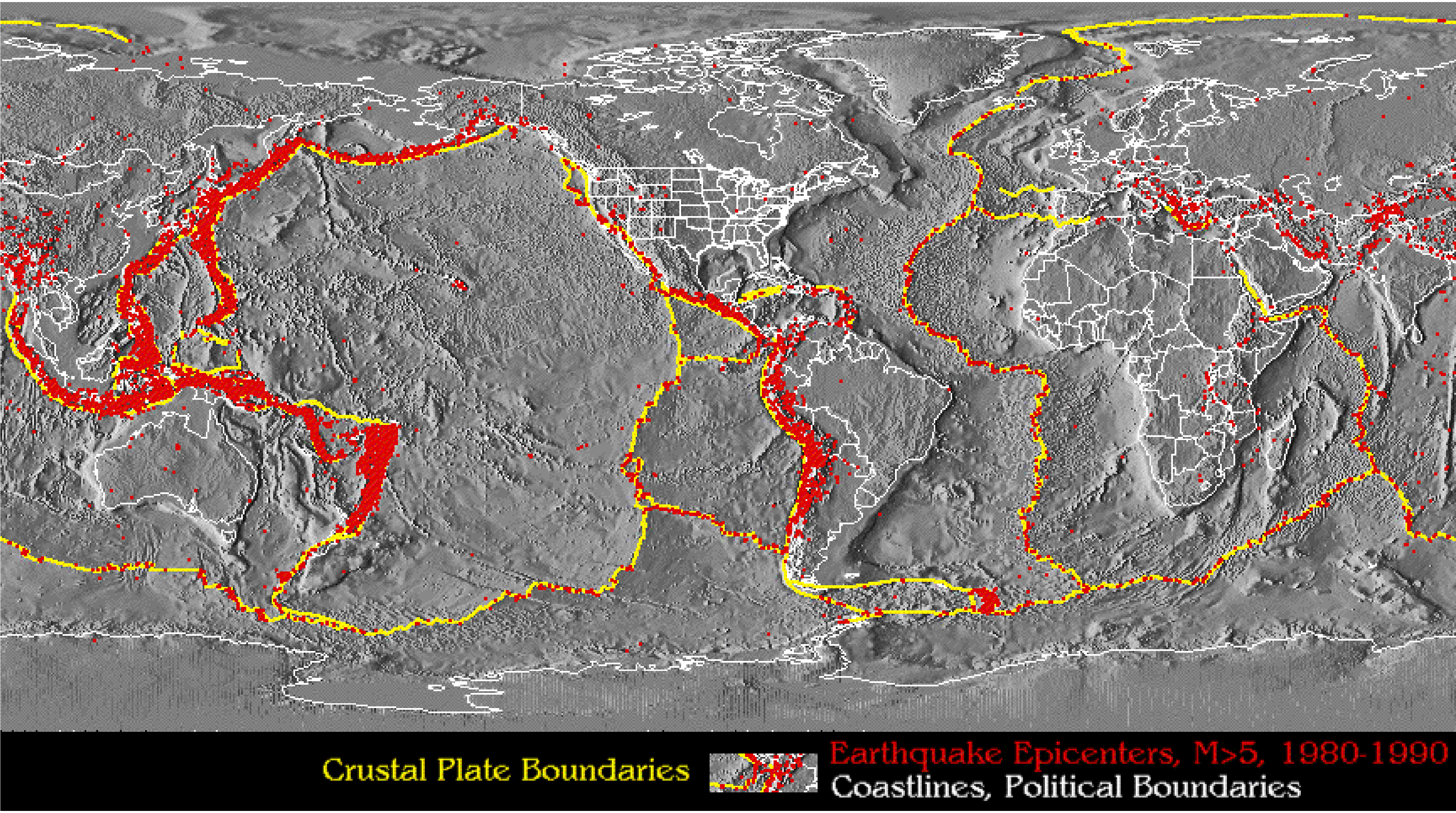



# Plate Tectonics

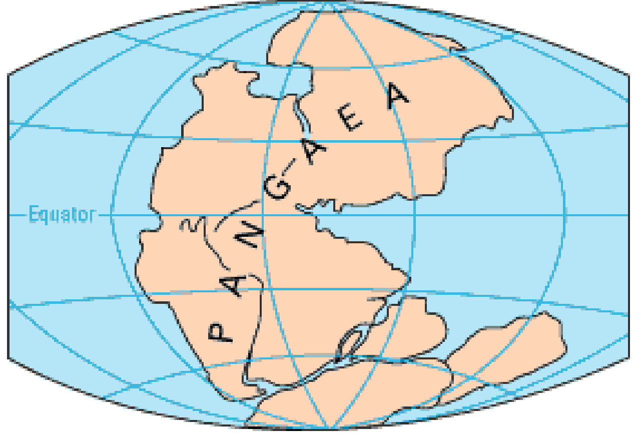
# Plate Tectonics



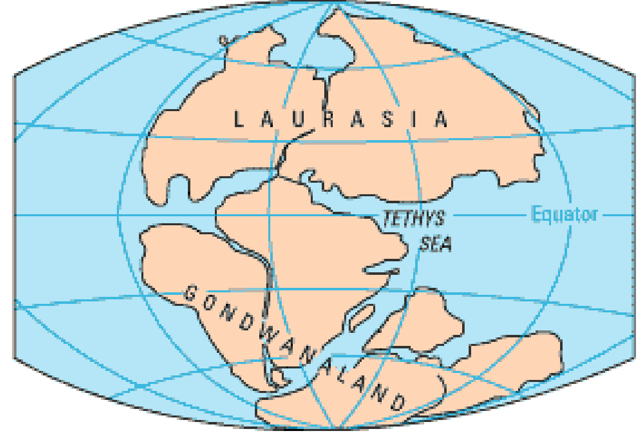
# Plates and Earthquakes



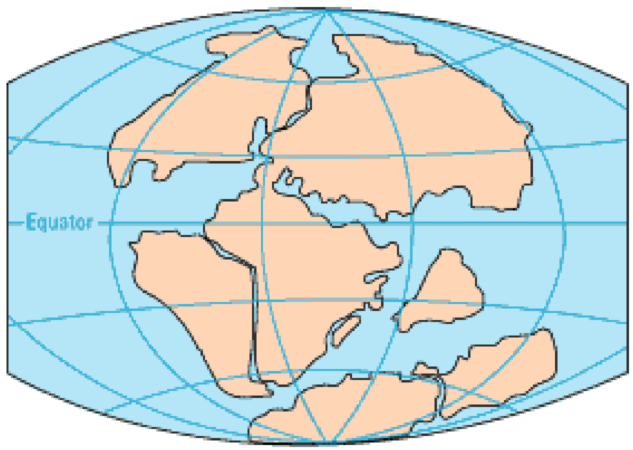
# Long Term Effects



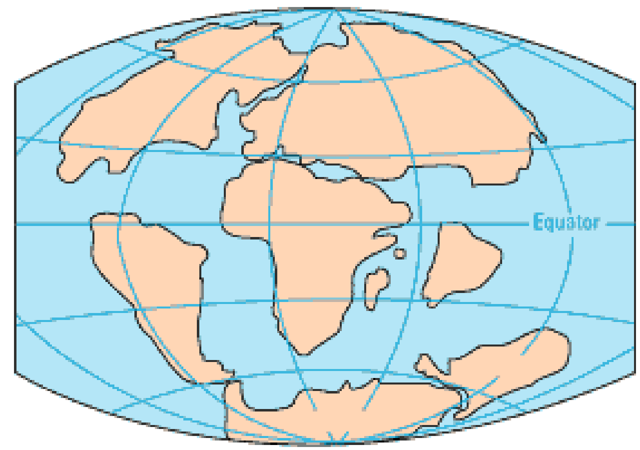

PERMIAN
225 million years ago



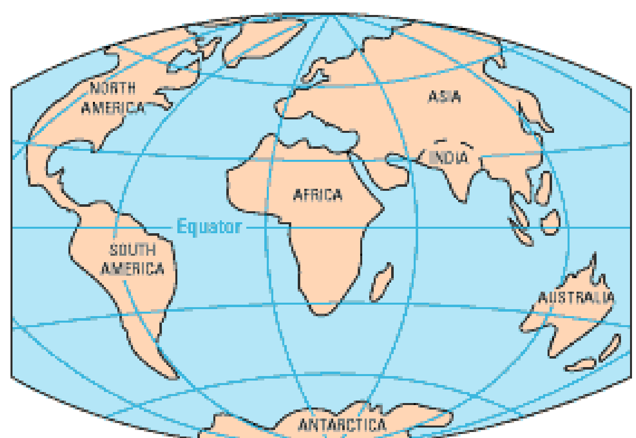

TRIASSIC
200 million years ago




JURASSIC
135 million years ago




CRETACEOUS
65 million years ago




PRESENT DAY

# Passively Heated by the Sun *--- the further the cooler*

Typically we observe objects in reflected light, however, all objects emit re-processed thermal radiation which is observable at longer wavelengths.

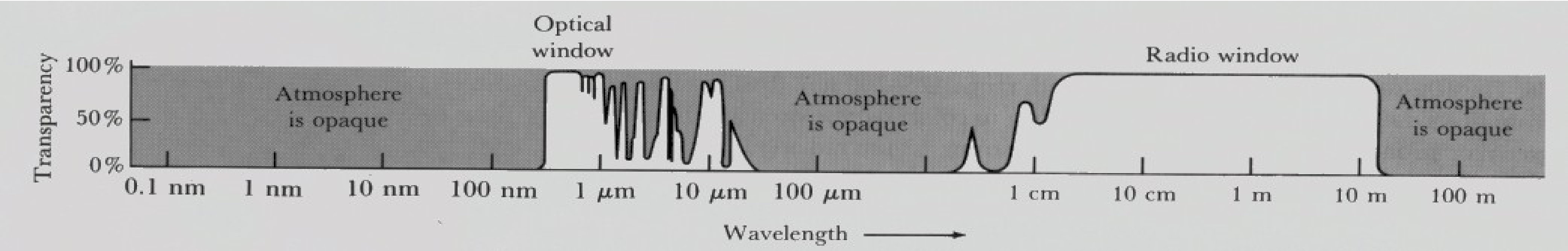
Blackbody temperature for a non-self-luminous spherical body at distance **a** away from the Sun (with albedo A -- reflectivity)

$$L_{abs} = (1-A)\frac{\pi R_p^2}{4\pi a^2}\, 4\pi R_s^2 \sigma T_s^4; \qquad L_{em} = 4\pi R_p^2 \sigma T_p^4$$

$$If \quad L_{abs} = L_{em}, then \quad \boxed{T_p = \left(\frac{R_o}{2a}\right)^{1/2} T_s (1-A)^{1/4}}$$

| | a (AU) | A | $T_{pred}$(K) | $T_{act}$(K) | |
|---|---|---|---|---|---|
| Mercury | 0.4 | 0.06 | 422 K | 100-725 | (?) |
| Venus | 0.7 | 0.77 | 230K | 733 | (?) |
| Earth | 1 | 0.30 | 255K | 288 | (?) |
| Mars | 1.5 | 0.25 | 218K | 223 | good |

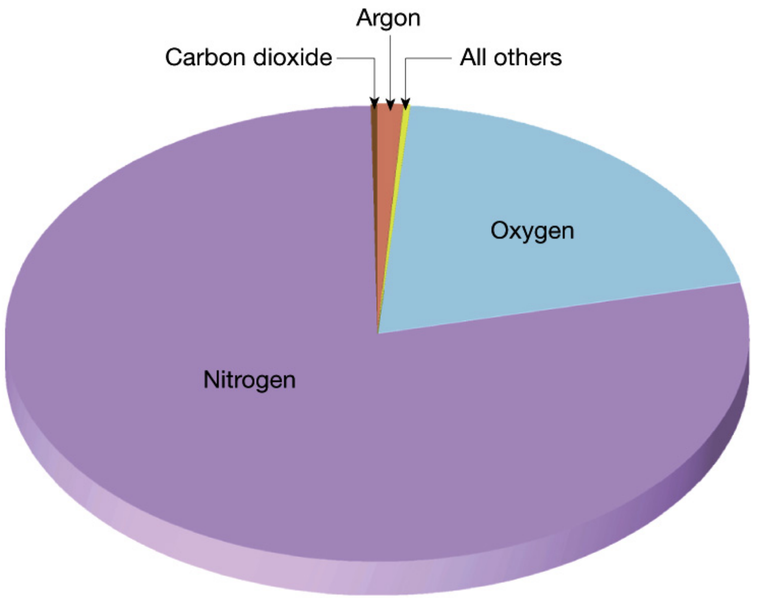
Greenhouse effect: optical radiation from the Sun reaches the ground, but the infrared radiation from the ground cannot easily escape.



# Atmospheres: Terrestrial Planets

| | Composition | surface pressure/T | |
|---|---|---|---|
| Mercury | -- | $< 10^{-12}$ bar | 100-725 K |
| Venus | 97% $CO_2$, 3% $N_2$ | 92 bar | 733 K (460°C) |
| Earth | 78% $N_2$, 21% $O_2$, 1% Ar | 1 bar | 288 K (15°C) |
| Mars | 95% $CO_2$, 3% $N_2$, 1.6% Ar | 0.006 bar | 223 K (-50°C) |
| Titan (@S) | 95% $N_2$, few% $CH_4$, Ar | 1.5 bar | 93 K (-180°C) |

Most atmospheres are reasonably well-mixed
(no molecular weight separation)




Earth's atmospheric composition
*From http://www.ux1.eiu.edu/~cfjps/1400/atmos_origin.html*

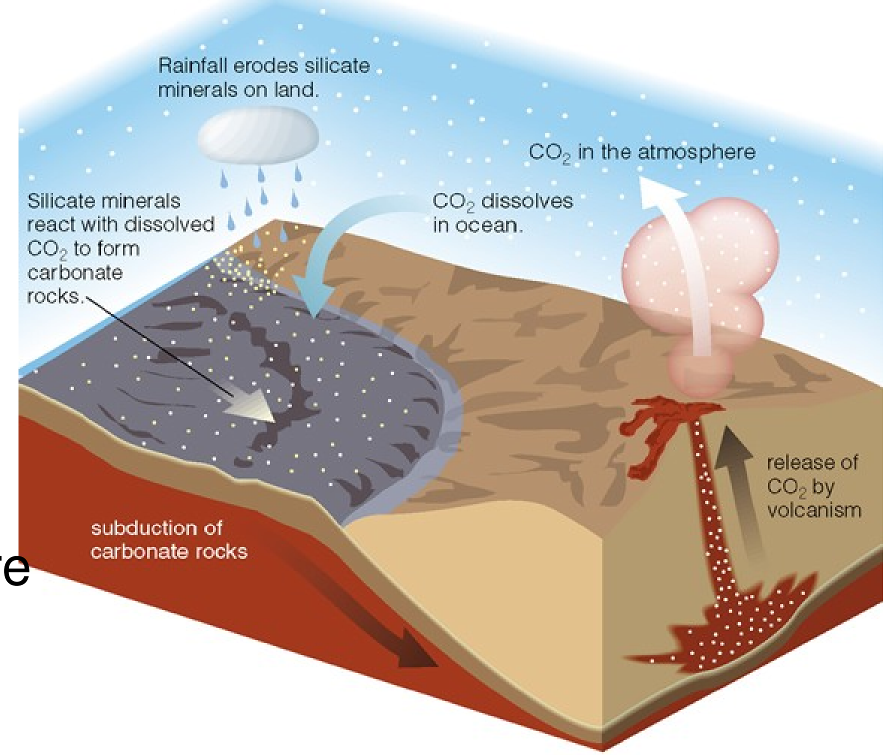
# $CO_2$ cycle and Earth's Thermostat

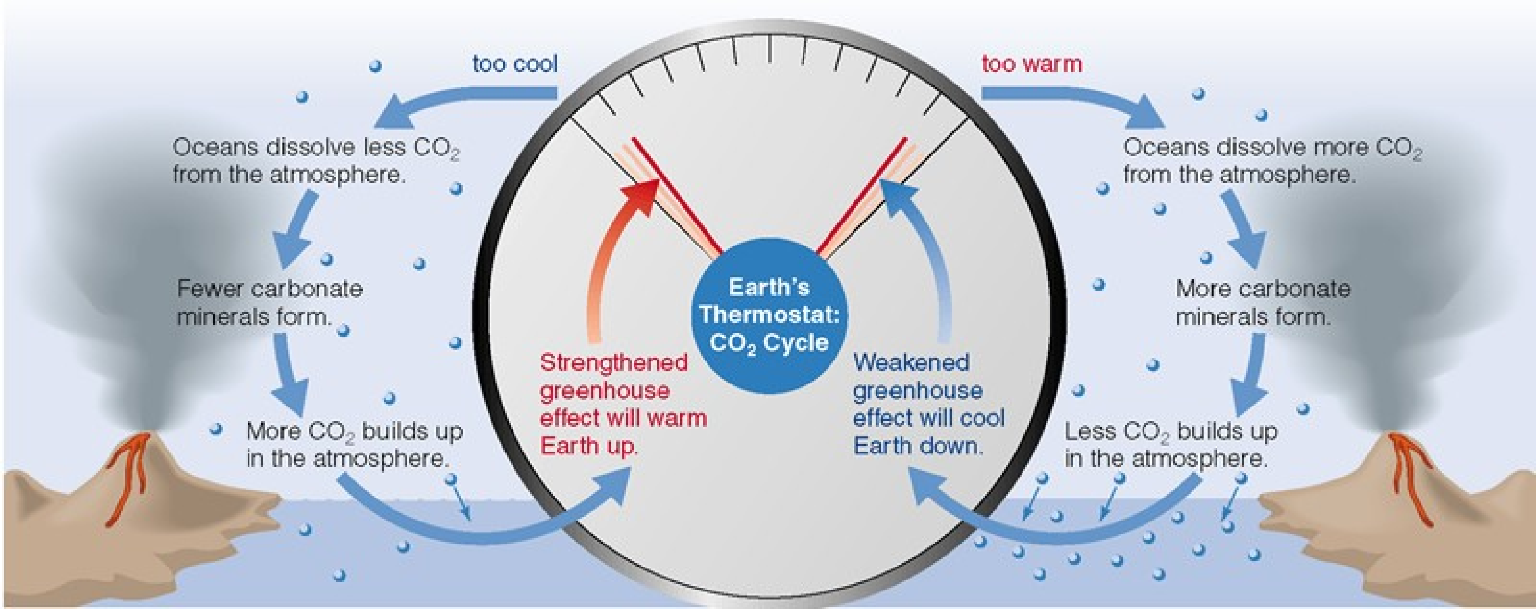
Venus has so much $CO_2$; where has it gone on Earth?

Sink: $CO_2$ dissolves in water, and reacts with silicates eroded by rain. Forms *carbonate rocks.*

Source: volcanoes.

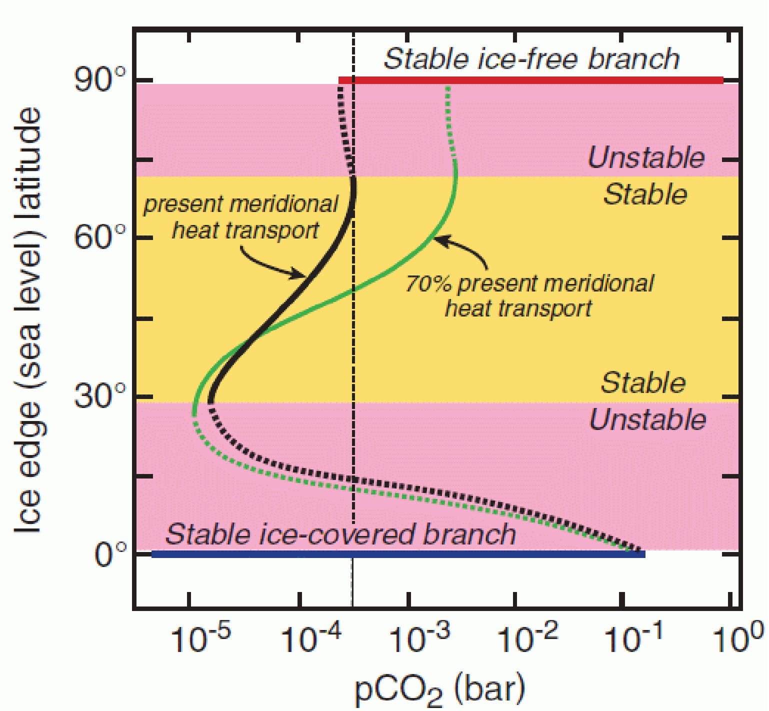
*Earth's thermostat*: Sink depends on temperature (source does not)

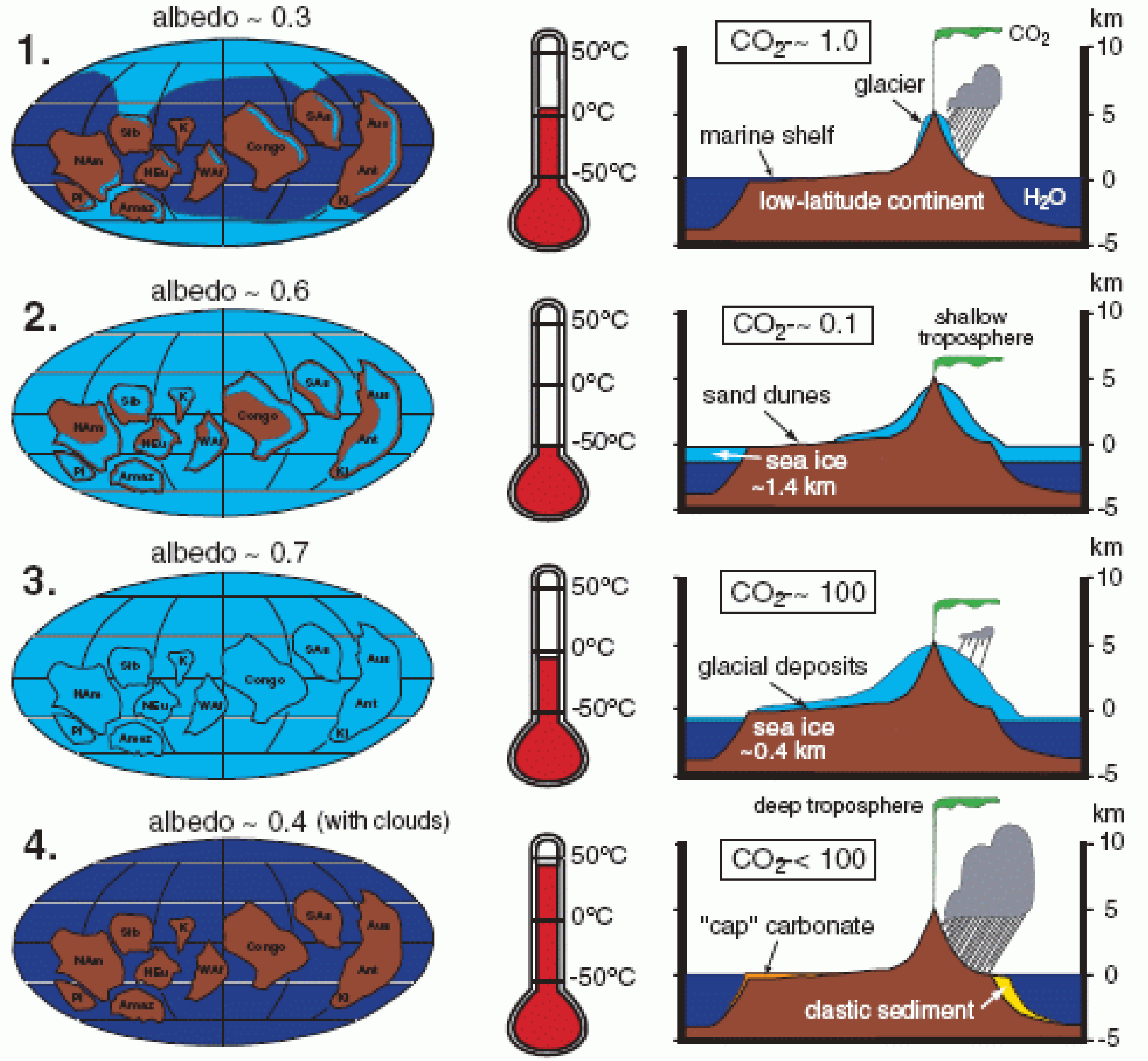


For details, see http://www.snowballearth.org/
Figures taken from a paper by Hoffman & Schrag
(the link to which has disappeared).

# SNOWBALL FREEZE-FRY SCENARIO




Cartoon of one complete 'snowball' episode, showing variations in planetary albedo, atmospheric carbon dioxide, surface temperature, tropospheric depth, precipitation, glacial extent, and sea ice thickness. Stage 1. incipient glaciation; 2. runaway ice-albedo (onset of 'snowball'); 3. end of 'snowball'; 4. transient 'hothouse' aftermath.

# Density & Temperature of our atmosphere

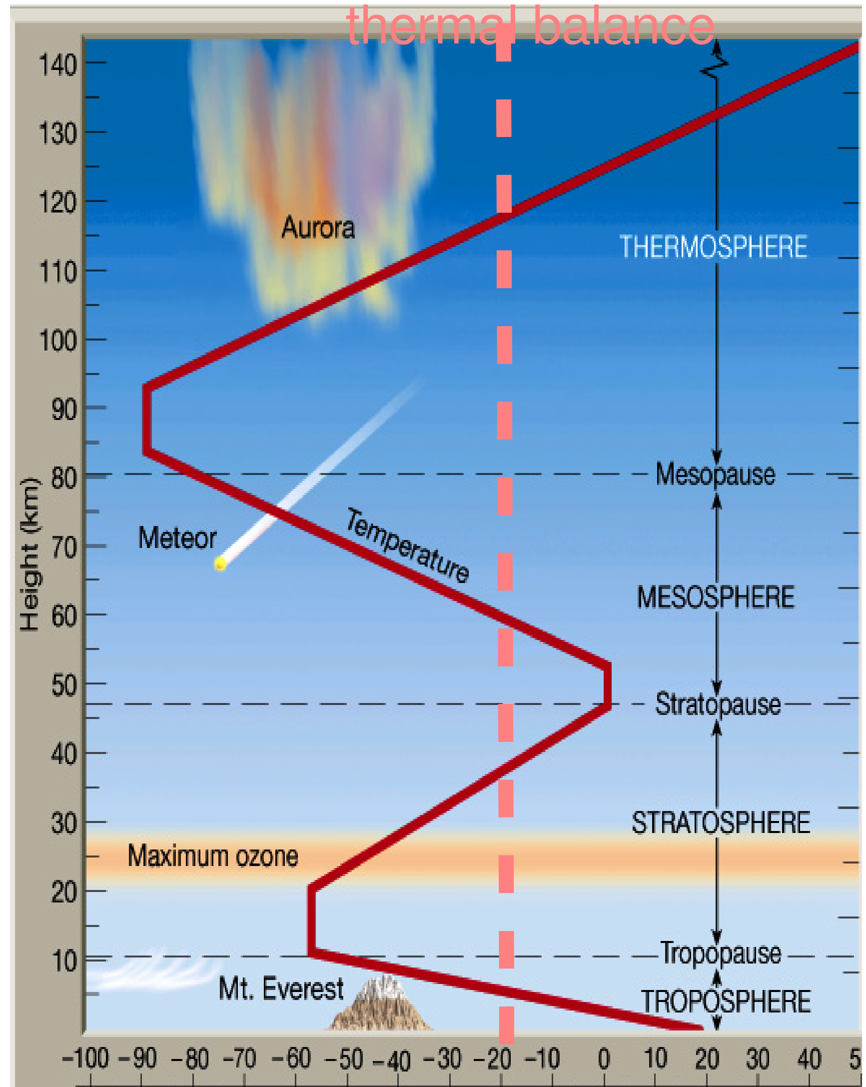
1) Temperature roughly **isothermal;** density decreases exponentially, H ~ 8 km

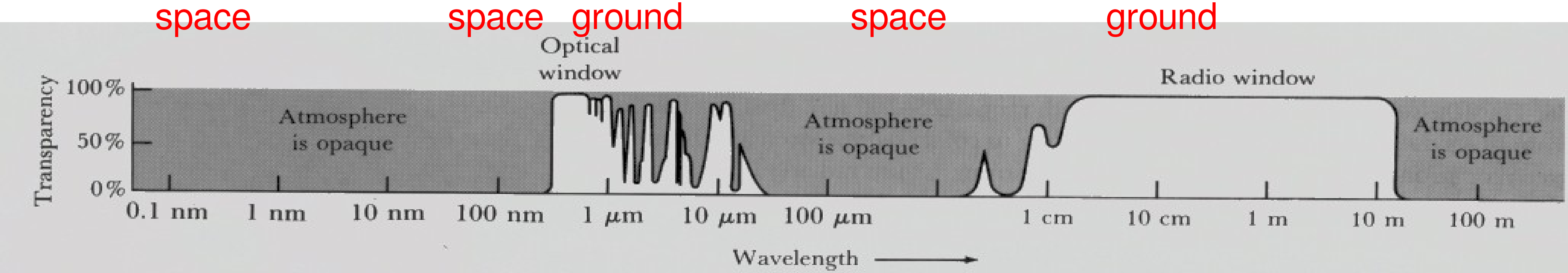
   Three local departures (T maxima)

   - Thermosphere absorbs X rays (~2000 K)
   - Stratosphere absorbs UV ($O_3$)
   - Ground absorbs whatever passes

2) Atmosphere largely transparent in optical, but opaque in infrared → green-house effect

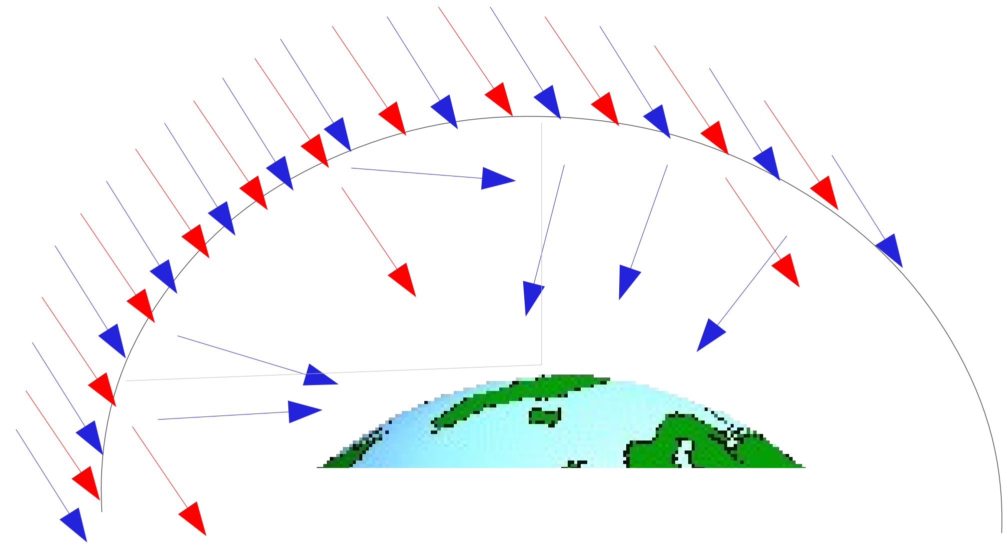
   - Troposphere heated by ground → turbulent → twinkling stars, planes fly @ ~10km
   - Astronomical observations: overcome turbulence & avoid absorption



# Atmospheric optics: I) Why is the sky blue on Earth? Rayleigh scattering

air molecules & other constituents ($N_2$, $O_2$, $H_2O$ droplets, dust...) all have sizes smaller than optical $\lambda$, and they preferentially scatter short-$\lambda$ photons: $\sigma \sim 1/\lambda^4$



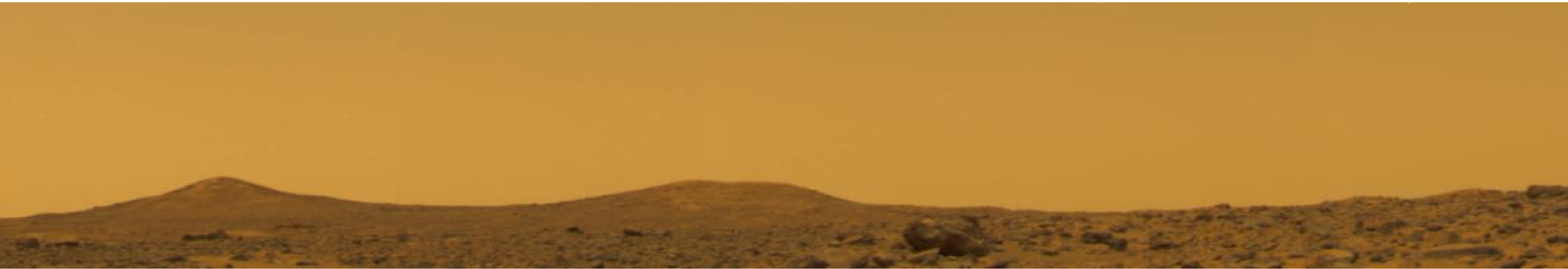
Earth: *sky is blue (--> ocean blue)*
*sunset is red (reddened)*
*horizon whiter than zenith*
*Fall/Winter sky dark blue*
*UV is diffuse*

Moon: *sky is black*

Mars: *sky is reddish yellow*

*fine-dust (1-10µm) Mie scattering --> white*
*iron oxide mineral absorption in the blue --> reddish*

*Mars Pathfinder true-color picture of Martian noon*



## Example of Rayleigh Scattering: *Interstellar Reddening*

1. interstellar space not empty
2. interstellar molecules & dust grains r < $\lambda$
3. scattered away – blue; transmitted – red

blue reflection nebula of Pleiades

Barnard 68

why is the Moon red during a lunar eclipse?

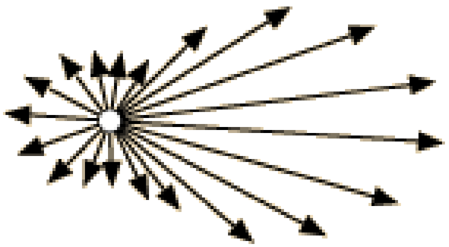
# Atmospheric optics: II) Clouds

What are clouds? Aggregates of water or ice droplets suspended in air
In troposphere: low clouds-- water; high clouds-- ice

How do they form? 100% hum. + condensation nuclei (dust, cosmic-rays)
e.g., rising air that cools (--> humidity increases)

Why are clouds white? Water droplet colorless, solar light white
Mie scattering (droplets size r ~ 10μm > λ),
nearly geometric optics, no λ dependence
(at sunset, cloud is red)
soap foam: geometric scattering, also no λ dep.

Mie Scattering



Why don't clouds fall from the sky?
Tiny droplets, fall slowly; updraft mixing?
Fall and evaporate and form new ones?
Electrically charged clouds?

## Origin of Earth's atmosphere

Our (& Venusian) atmosphere cannot be primordial

1) $N_2$, $CO_2$, $H_2O$ are not condensed at 1AU from Sun, $O_2$ does not naturally occur

2) Earth too low in mass to accrete gas directly

3) Gas is unlikely to have been trapped in solids and dragged to Earth, since noble gases (Ne, Kr, Xe) are heavily depleted relative to solar abundance.

4) New-born Earth molten and hot ($10^3$K) --> most gases can escape thermally.

Some relief only in that in the early bombardment period (~ 700 Myr) water can be brought in by comets & asteroids.
*(Note: D/H ratio in comets ~2 higher than ocean, so these cannot do it alone)*

# Origin of Earth's atmosphere (cont'd)

Our atmosphere is obtained gradually: volcanic outgassing & invaders

| | 1st atmosphere | 2nd atmosphere | 3rd atmosphere |
|---|---|---|---|
| | **thermal escape** | **outgassing/accretion** | **absorbing $CO_2$** |
| | H & He(?) | $CO_2$/$NH_3$ outgassed<br>$H_2O$ accreted/outgassed<br>*(solid crust/ocean, 3.5Gyrs ago)* | most $H_2O$ liquid<br>$CO_2$ got locked in<br>$O_2$ produced |
| P: | ? | ~100 bar (like Venus!) | ~1 bar |
| T: | $\sim 10^3$K | $0^oC < T < 100^oC$ | $\sim 15^oC$ |

**sinks of $CO_2$**: sedimentary rock via $H_2O$, life (carbon) via photon-synthesis
**sources of $CO_2$**: volcanic outgassing (+human activities)
**sinks of $H_2O$**: subducting plates
**sources of $H_2O$**: outgassing, comets/asteroids?

**Currently sensitive balance reached, mild green-house**
*run-away green-house: too much $CO_2$, $H_2O$ can all disappear*
*$\rightarrow$ sink disappears as well while outgassing produces yet more $CO_2$*

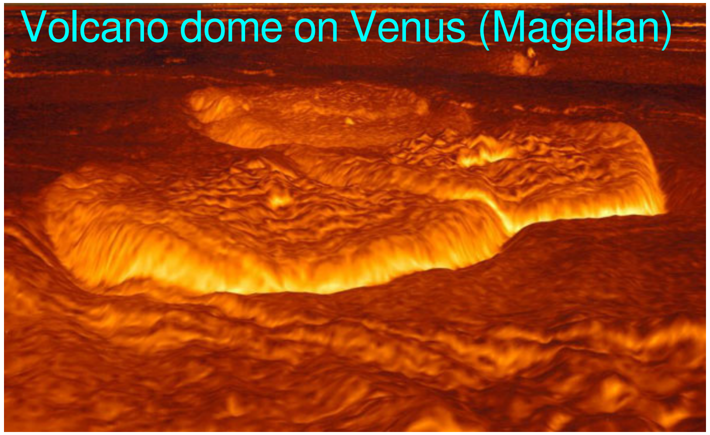
# Venus: divergent evolution from Earth

| | a(AU) | mass($M_E$) | spin | atm. Pressure | T | plate tect. | ocean |
|---|---|---|---|---|---|---|---|
| Earth: | 1 | 1 | 1 day | 1bar | 288 K | Yes | Yes |
| Venus: | 0.7 | 0.8 | 243 day | 92bar | 770 K | No | No |

1) 97% $CO_2$ in the atmosphere, ~ 700K, *no $CO_2$ sink due to dryness*

2) Why so dry? high D/H ratio indicates past large $H_2O$ reserve
Green-house runaway and $H_2O$ photo-evaporated

3) Cratering no older than ~0.8 Gyr → tectonics stopped recently




**A planet is a nonlinear system.**
**Strongly divergent evolution can occur.**

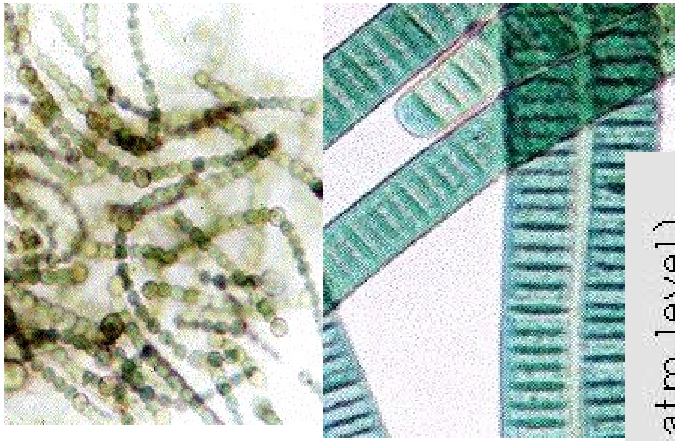
Cause & Effect?

1) Slightly closer to the Sun and got torched?
Or formation site had naturally less $H_2O$?

2) Too much $CO_2$ to start with and $H_2O$ never condensed
(But: Initial Earth atm. ~100 bar, mostly $CO_2$ --> would require *fine tuning*?)

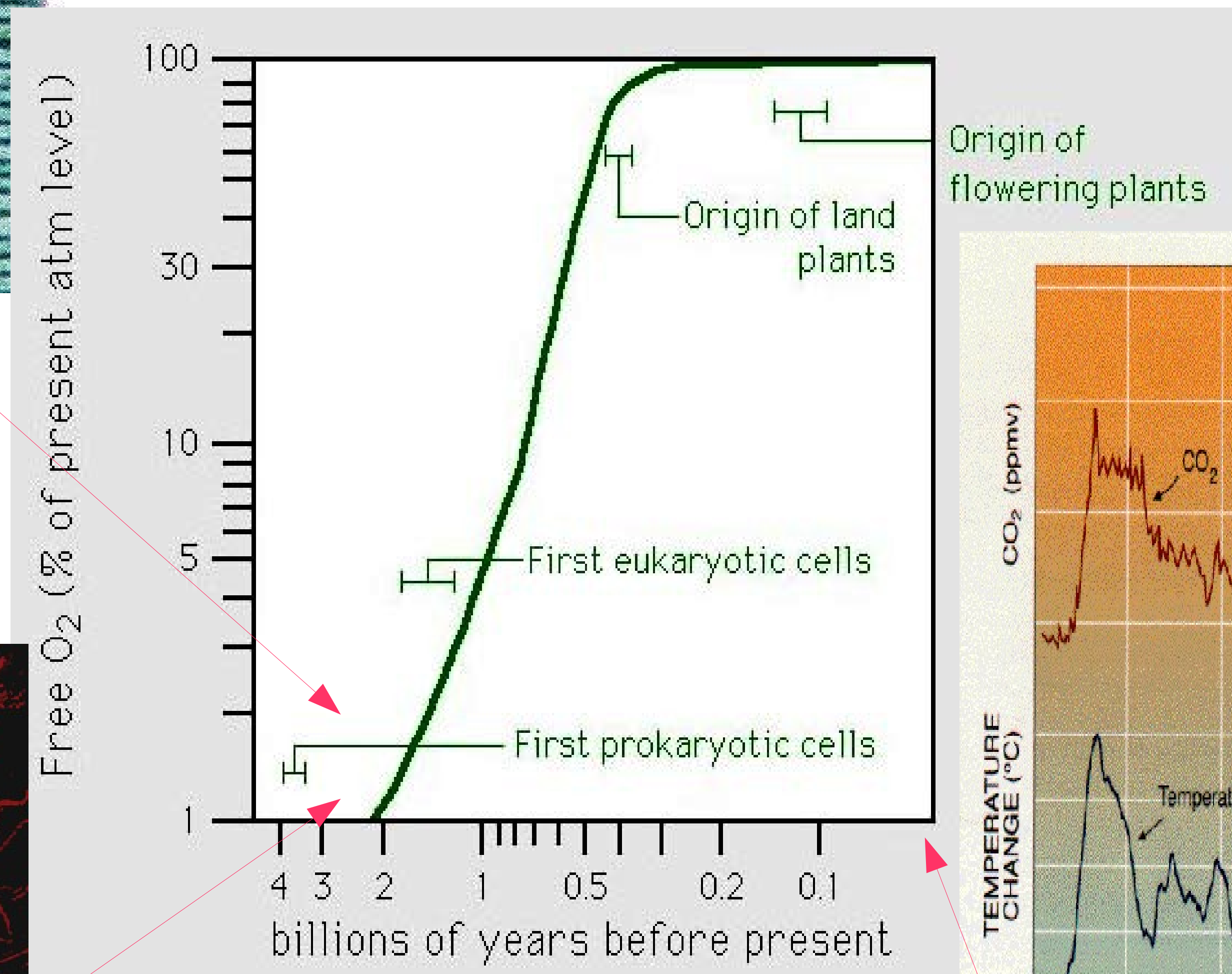
The Story for Mars: 2$^{nd}$ atmosphere gradually lost, no outgassing (tectonics)

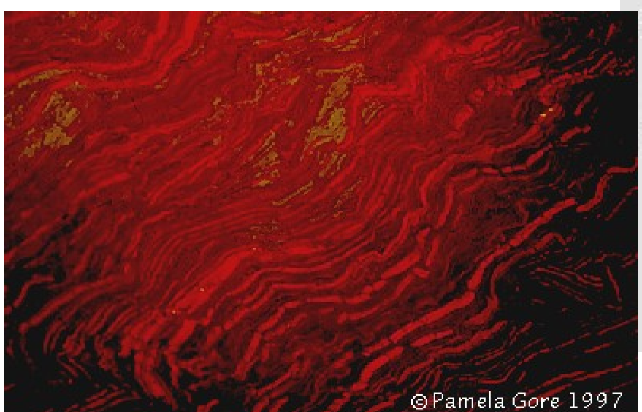
# Origin of $O_2$ on Earth: photosynthesis; $CO_2 + H_2O + h\nu \rightarrow O_2$ + carbo-hydrate



Archean Life: blue-green 'algae' or cyanobacteria (3.5-2.2 BYA) anerobic

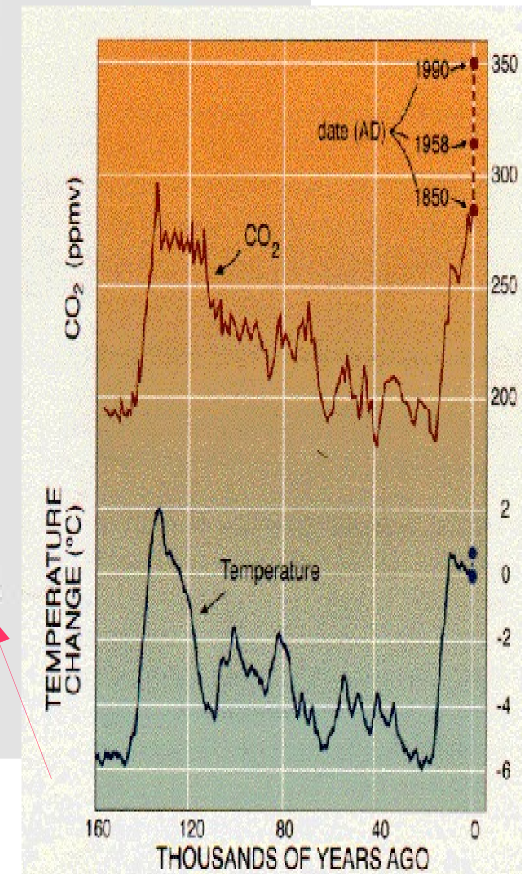
From http://www.clas.ufl.edu/users/mrosenme/Oceanography




Red-banded un-oxidized iron-rich rocks, pre-cambrian, ~2.5BYA

http://www.dc.peachnet.edu/~pgore/geology/geo102/precamb.htm




$CO_2$ and atm. T correlation

(April 1989, Scientific. American)