Mantle dynamics, tectonics, volatiles and climate

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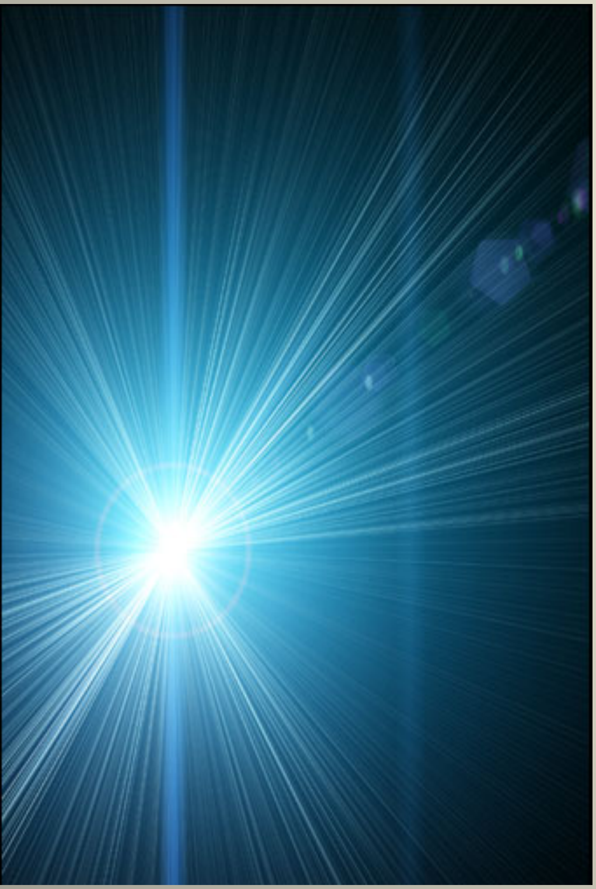
Unique Earth?

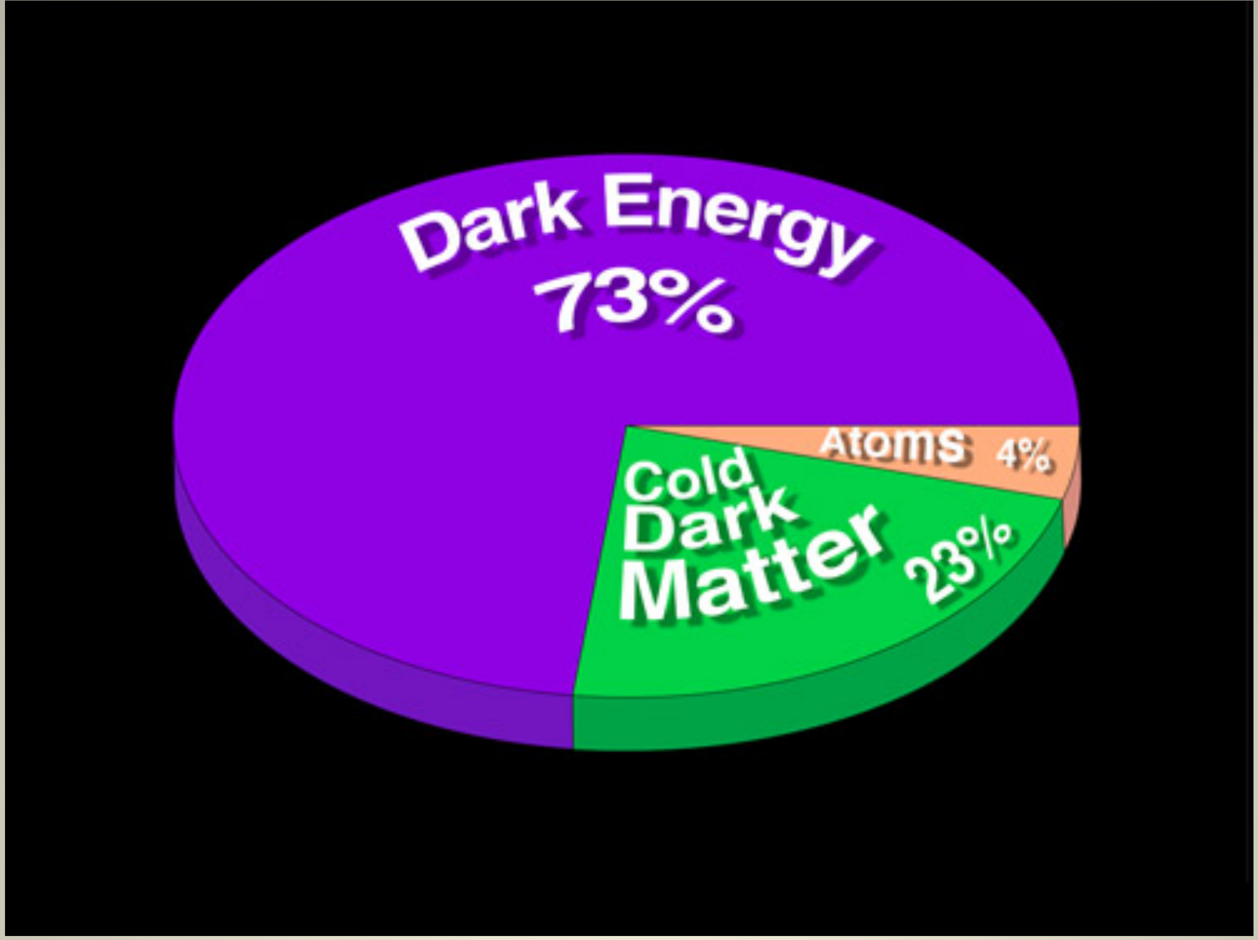
- **Why is Earth the only terrestrial planet in our solar system with…**
  - plate tectonics,
  - liquid water,
  - temperate climate,
  - …and life?

In the beginning… Big Bang

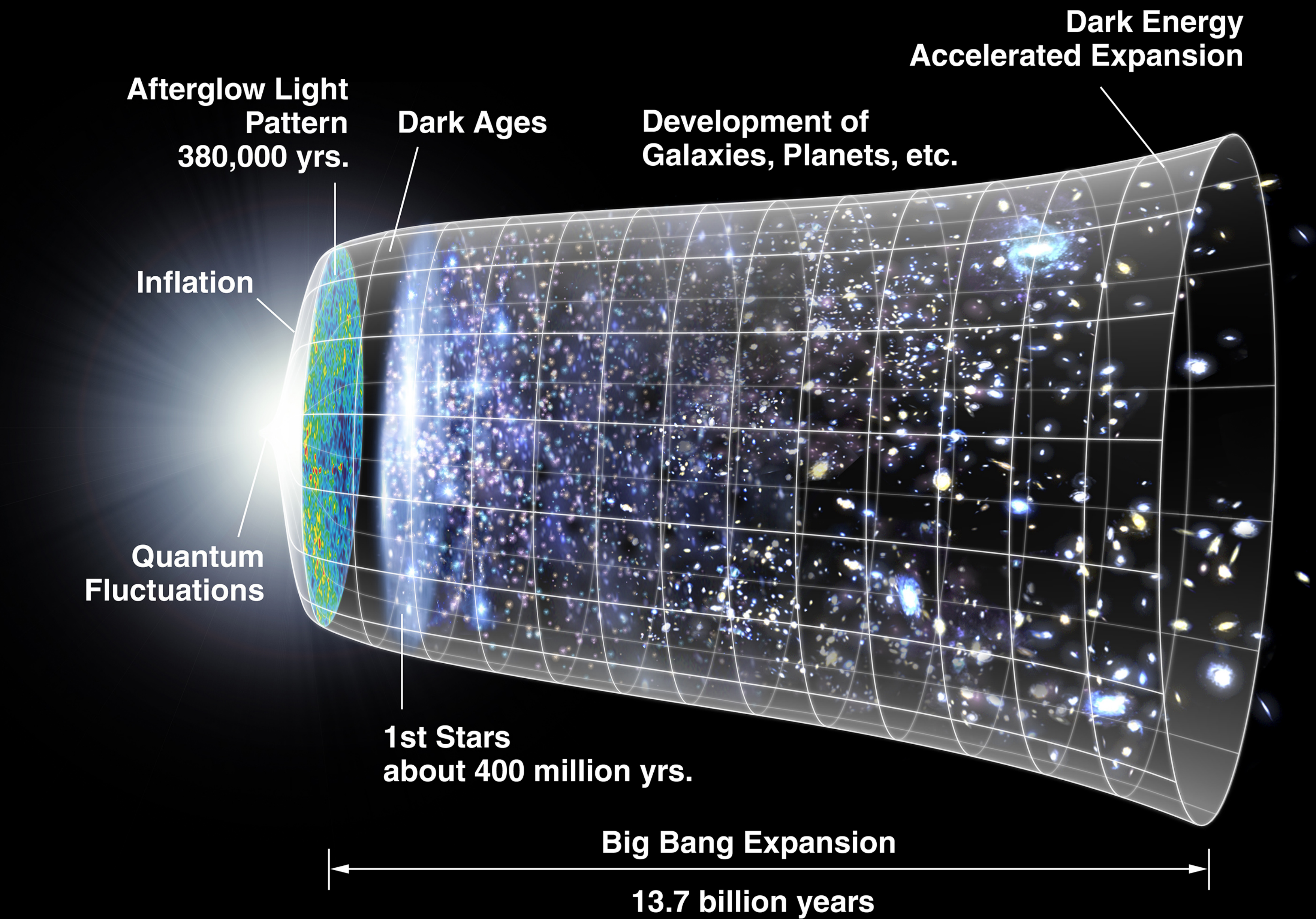


- Motivation: Hubble expansion, night-time sky, "CMB" = 3K space
- 0-10^{-43} s – Planck 'epoch'
- 10^{-35} s – Inflation 'epoch' (expansion *v*>*c*)
- 10^{-5} s – quark soup, matter-antimatter annihilation, Hadron epoch (e.g., neutrons, protons)
- 1 s – Lepton 'epoch' (e.g., electrons, neutrinos)
- 1-100s –nuclei; free neutrons unstable so only 1 in 8 hadrons are neutrons, rest protons; 75% mass H, 25% He; trace amount of other light ones (Li)
- 100kyrs – Radiation 'epoch' : matter, energy high density and coupled; ends when light "escapes"
- 380kyrs – atoms form, release energy now seen in CMB; Matter 'epoch' starts
- 300-400Myrs – Dark Ages; ends with formation of first giant H-He stars called Population III stars (perhaps only recently first observed)
- 1-3Gyrs – peak star formation, galaxies and galactic clusters

See M. Turner, Scientific American, September 2009, pp36-43.

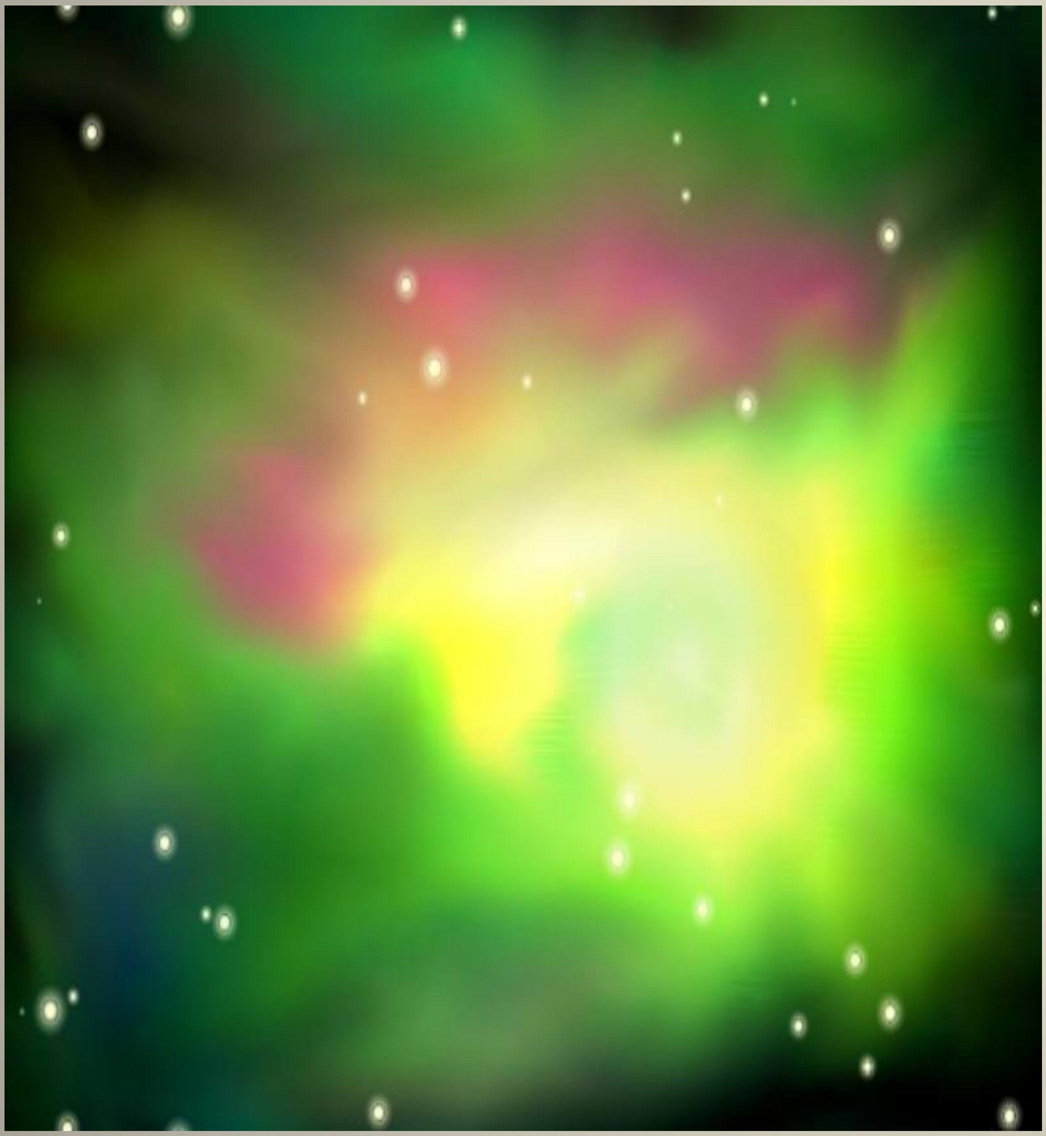


- Gravitational interaction between and within galaxies implies presence of **Dark Matter** (but doesn't radiate and doesn't collapse)
- Hubble telescope observations imply Universe expansion is *accelerating* (since about 4Ga) fuel for which is **Dark Energy**
- Energy,volume means >70% of universe made of Dark Energy
- Atomic matter only makes 4%



Wikimedia commons; from WMAP probe project

Pre-solar nebula collapse



- Gravitational collapse of cloud fragment about 1-3 light yrs across
- Gravitational Potential Energy exchanged for Kinetic Energy and Heat
- *Higher T and P resists collapse!*
- Need impulse (e.g. super nova?)
- Energy sinks (“phase changes”) to stabilize T and facilitate collapse

H_2 to H

H to H^+

Cloud-core mass > $0.08M_{sun}$ reaches T >10^7K

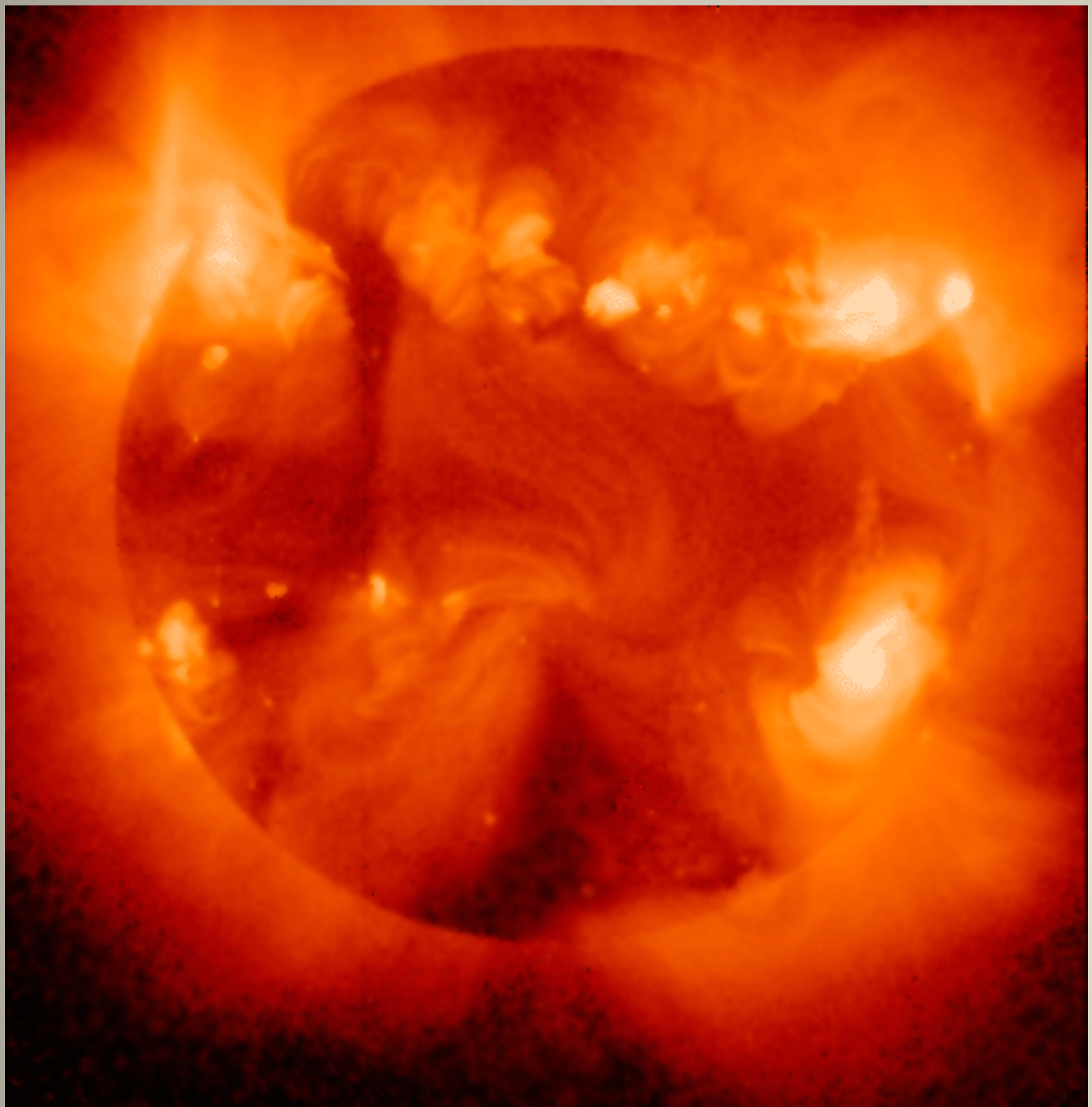
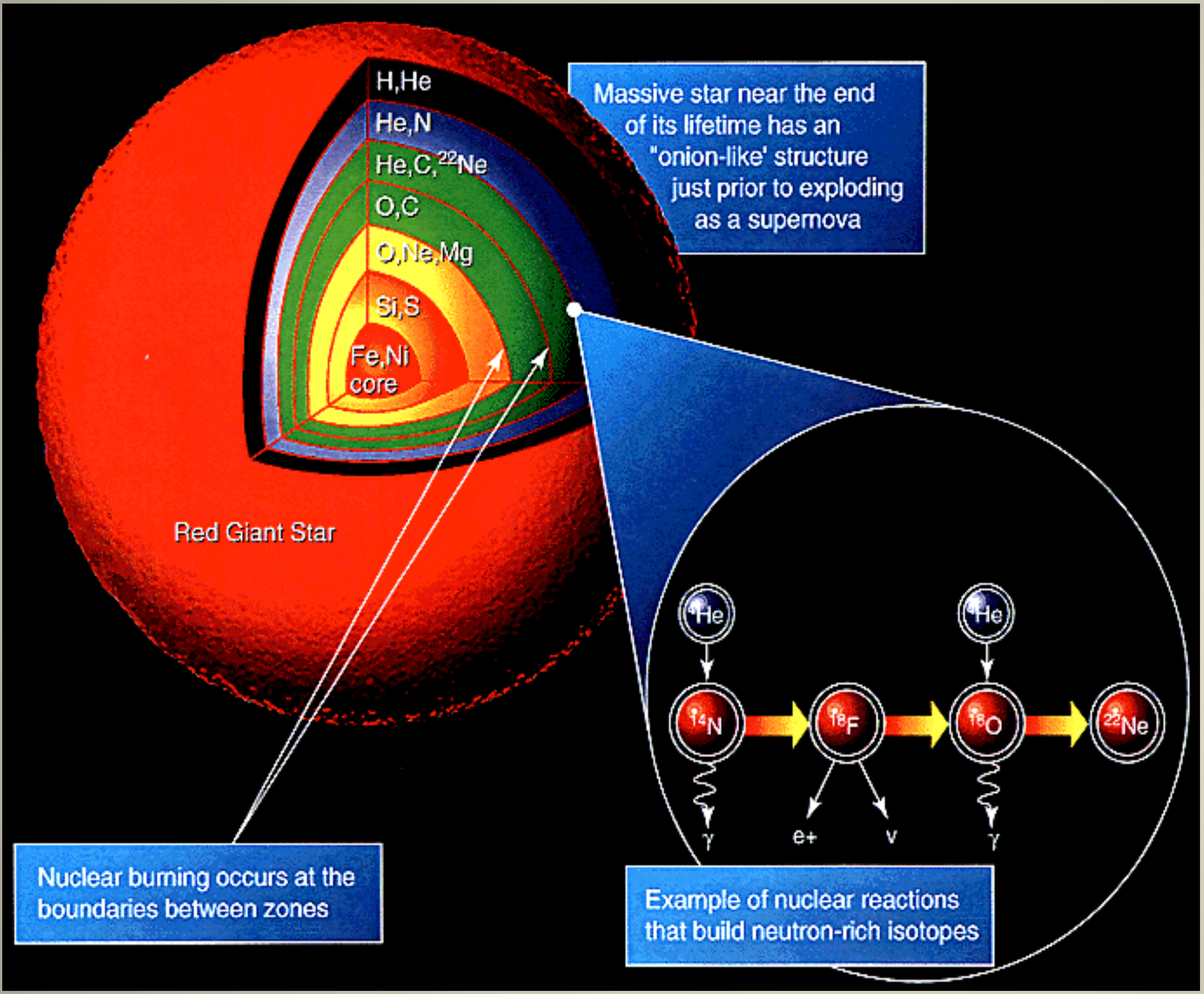


Image of the Sun in x-ray spectrum

- H to He nuclear fusion reactor
    - Fusion releases energy, stops collapse
    - Powers stars like our Sun ("Sol")
    - H-He fusion (proton-proton reaction) is slow
    - Uses up H in 10Gyrs (10 billion years) and collapses again
- Collapses and reheats; at $T=10^8$C fusion again:
    - He to oxygen (O) and carbon (C)

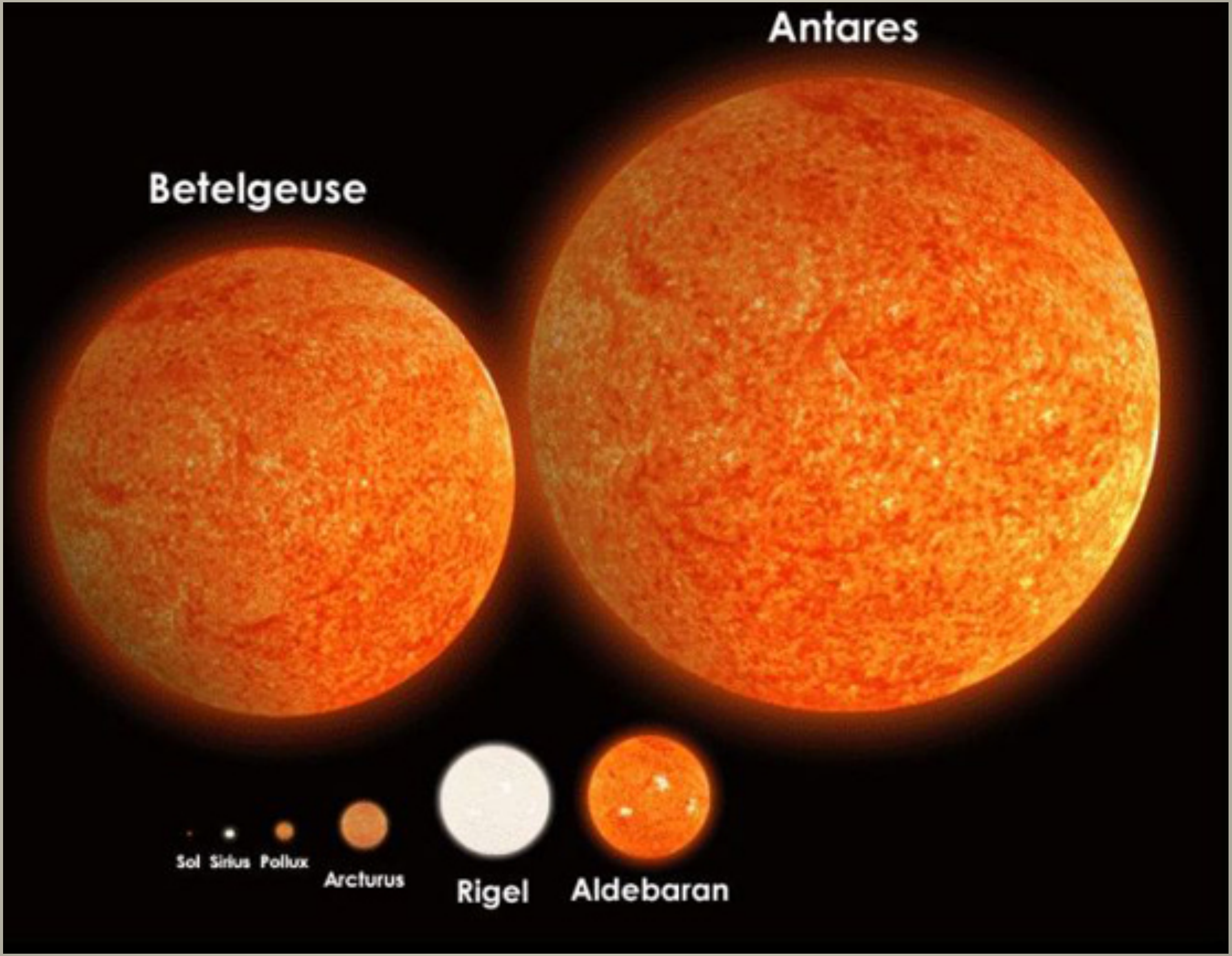
Red Super Giant Star



Stars > 15 solar masses

- Burn much hotter and faster (10^6yrs)
- Start off fusing elements up through silicon (Si), mag-nesium (Mg), etc - releases more and more energy
- Stops at iron (Fe) –beyond which fusion absorbs energy

Star comparisons



Alpha and CNO Processes

- Triple alpha process (slow) – carbon bottleneck
  - $^{4}He + {}^{4}He \rightarrow {}^{8}Be$
  - $^{8}Be + {}^{4}He \rightarrow {}^{12}C$
- Alpha process (alpha chain) – needs C above
  - $^{4}He + {}^{12}C \rightarrow {}^{16}O$
  - $^{4}He + {}^{16}O \rightarrow {}^{20}Ne$
  - $^{4}He + {}^{20}Ne \rightarrow {}^{24}Mg$
  - $^{4}He + {}^{24}Mg \rightarrow {}^{28}Si$
  - …… to ^{56}Fe
- CNO process
  - He "feed" to lower levels:
  - catalyze H to He conversion in stars > 1.3Msun
  - Fuse H + C to make N, again to make O
  - Eventually decay to leave C and He

Elements heavier than iron (uranium, thorium...) made by neutron capture

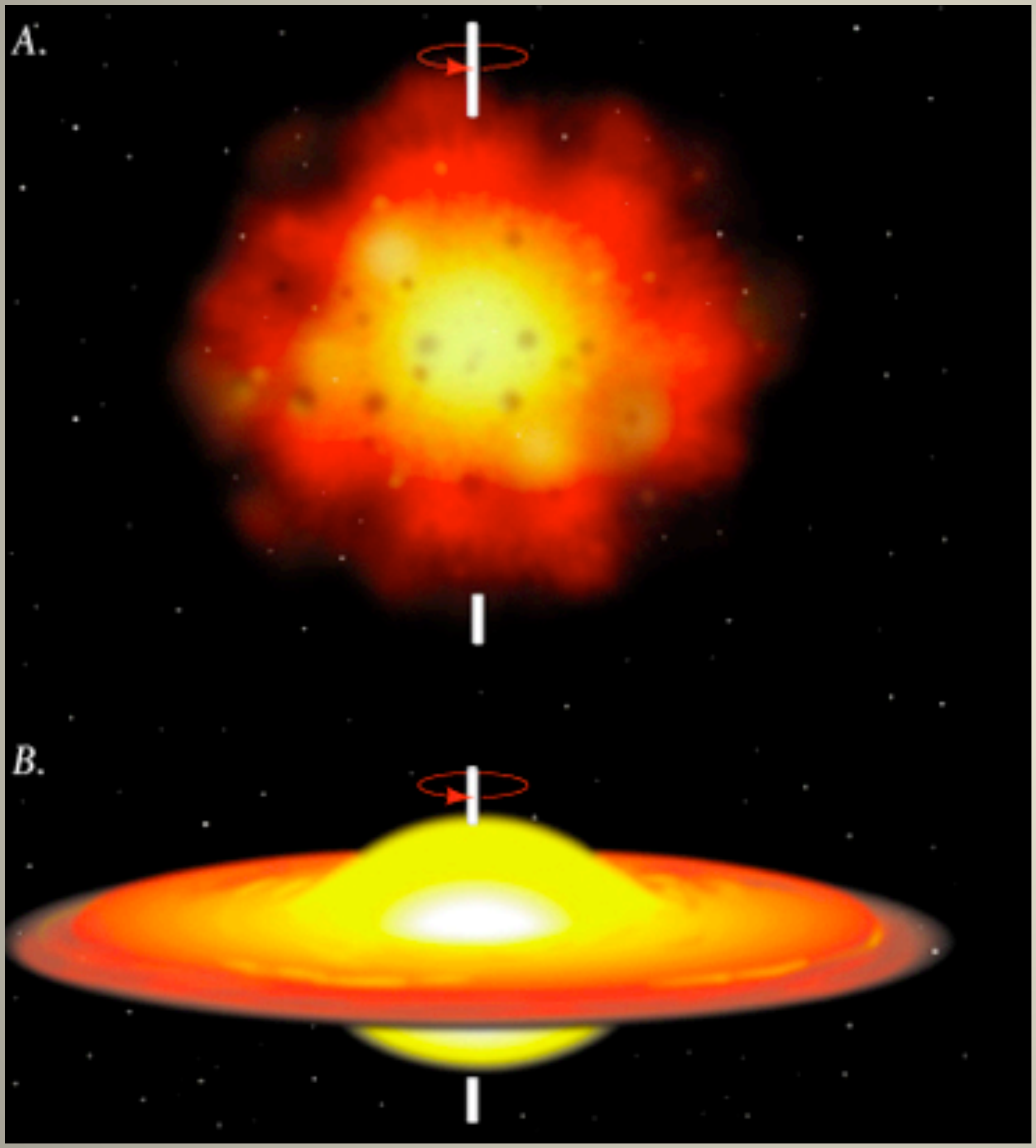
- Slowly inside large stars (s process)
- And rapidly after all fuel used up, final collapse and explosion as Super Nova (r process)
- Evidence of ^{60}Fe in meteorite dust grains implies our solar system cloud collapse started by super nova

What's left?

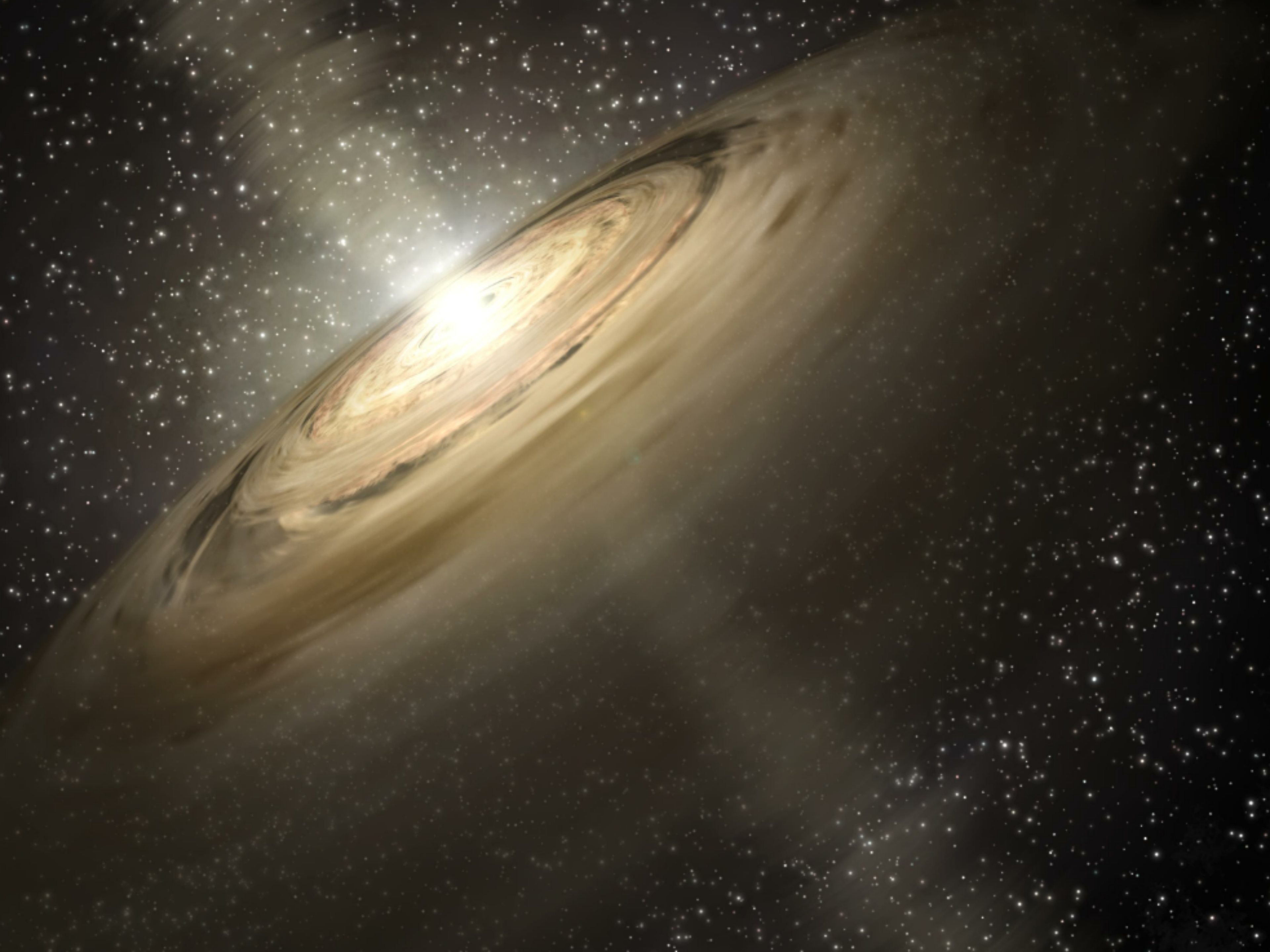
neutron star or black hole

- Giant stars form and die frequently
- Peak giant star formation ~11Ga
- Provide C, O,N, P, Si, Mg, Fe, etc
- “Dust” nebula accumulate from solar wind and SuperNova ejecta to make planetary systems

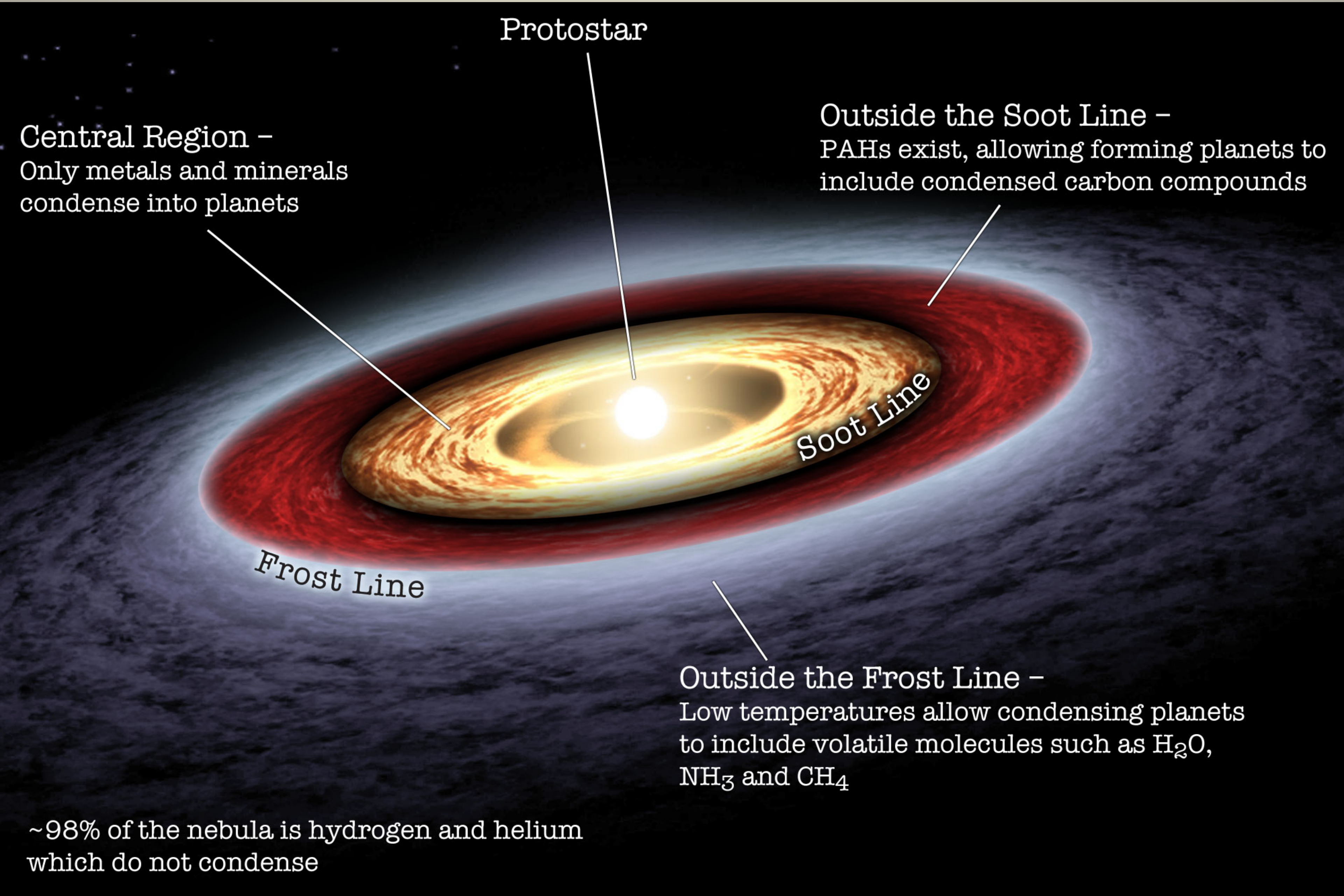
Cloud collapse into disk



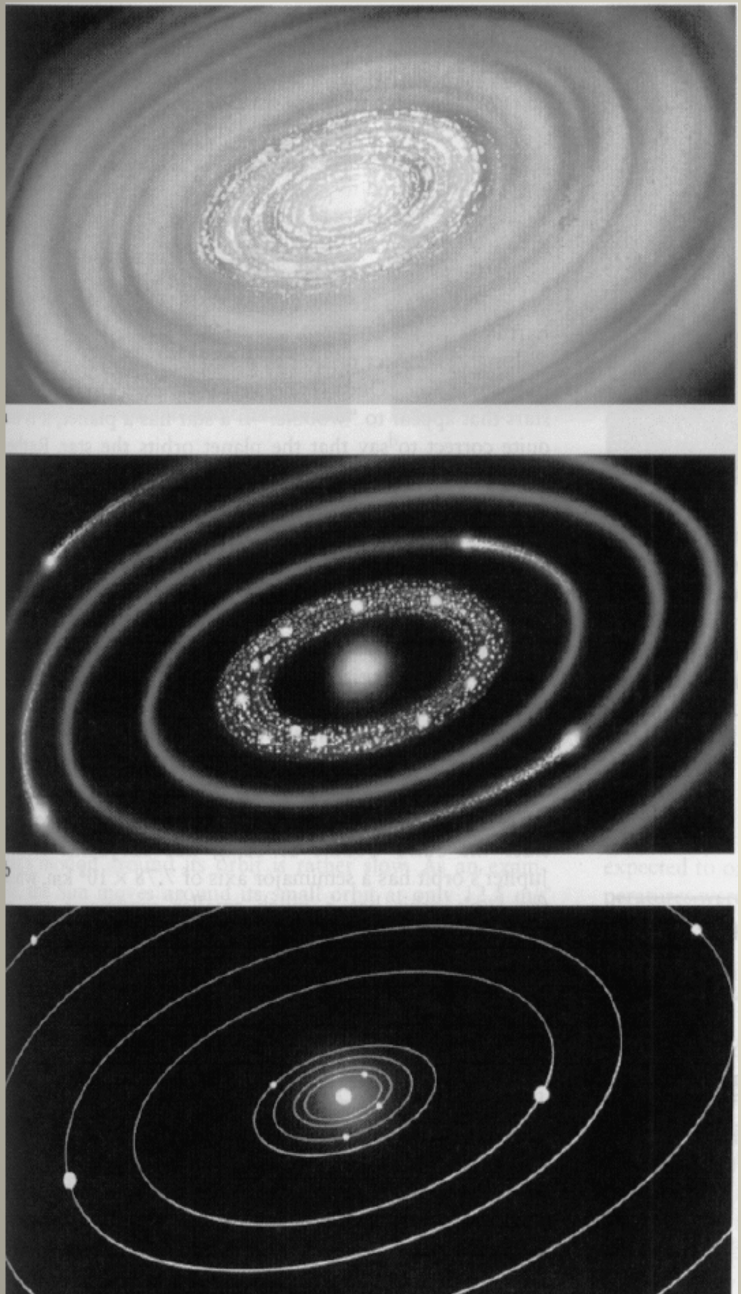
- Spin of initial cloud causes collapse into disk
- Most of disk spinning around central mass (star)
- Mass of disk about 0.1% of Solar mass



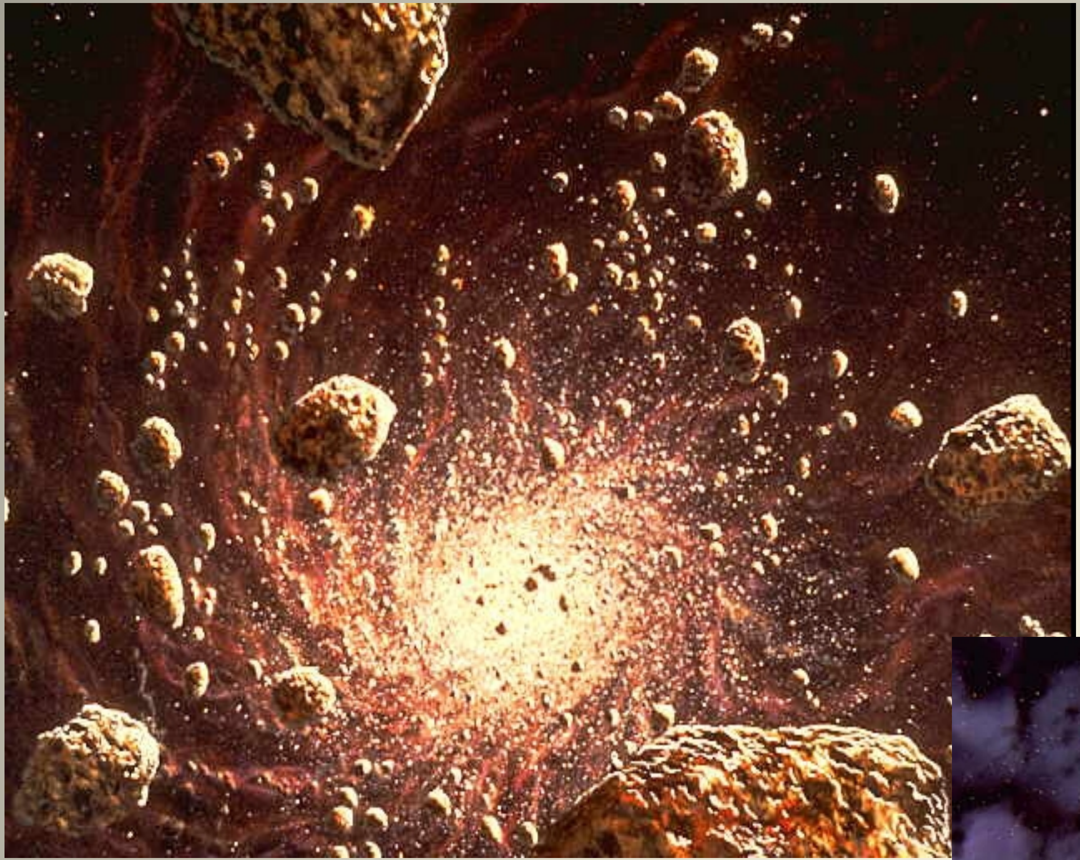
Frost line ~ 2.7-4AU



Planet formation



- Small particles (1μ-1m) stick by electrostatic, Van der Waals forces; grow quickly or spiral in b/c of gas drag
- When big enough (1km): less gas drag, gravitational clumping and sweeping up mass in orbital paths
- Planets further from Sun have bigger gravitational sweep
- Must all happen “fast” before pre-solar-ignition and solar wind blow out….(T-Tauri phase) 10-100Myrs



- Solar system forms and Earth “accretes” about 4.6 billion yrs ago
- Energy of colliding/ sticking bodies stored as PRIMORDIAL HEAT

Components from something like asteroids, more specifically chondrites make up bulk Earth (arguably)

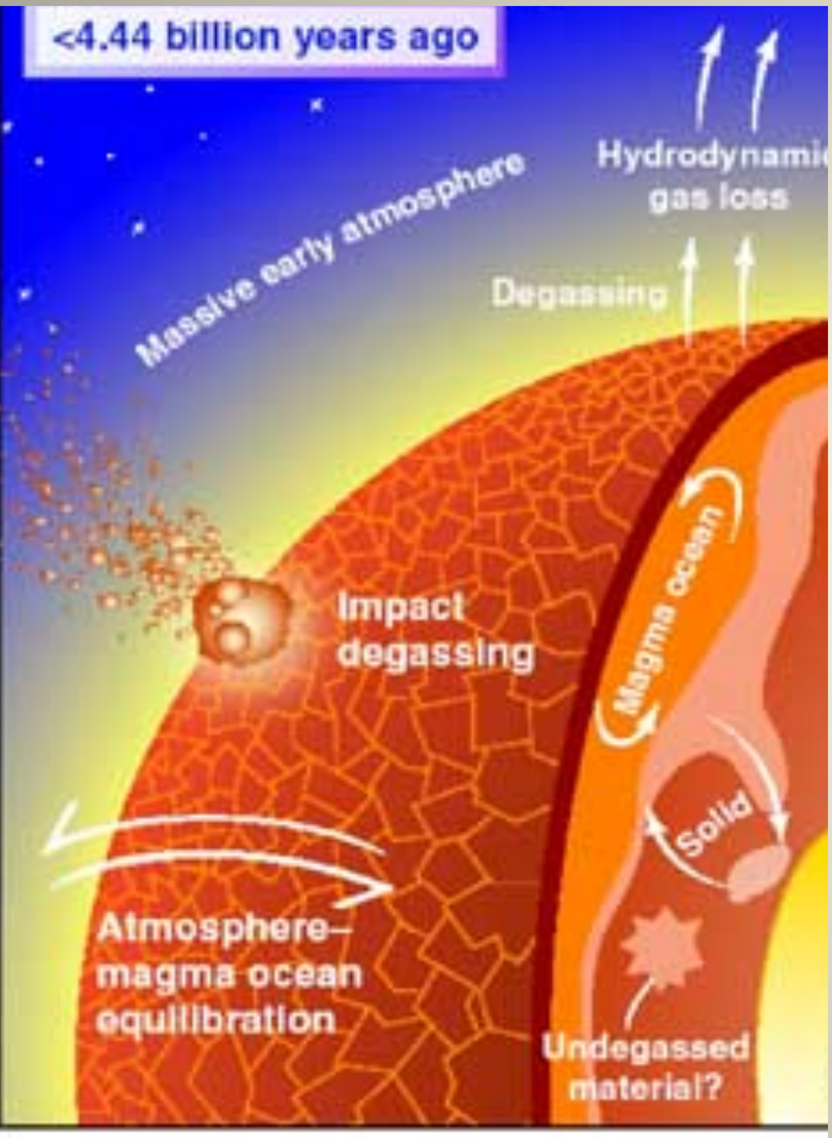
Origin of atmosphere and oceans?

Are they from outer cometary material? (exogenic)

Late veneer hypothesis

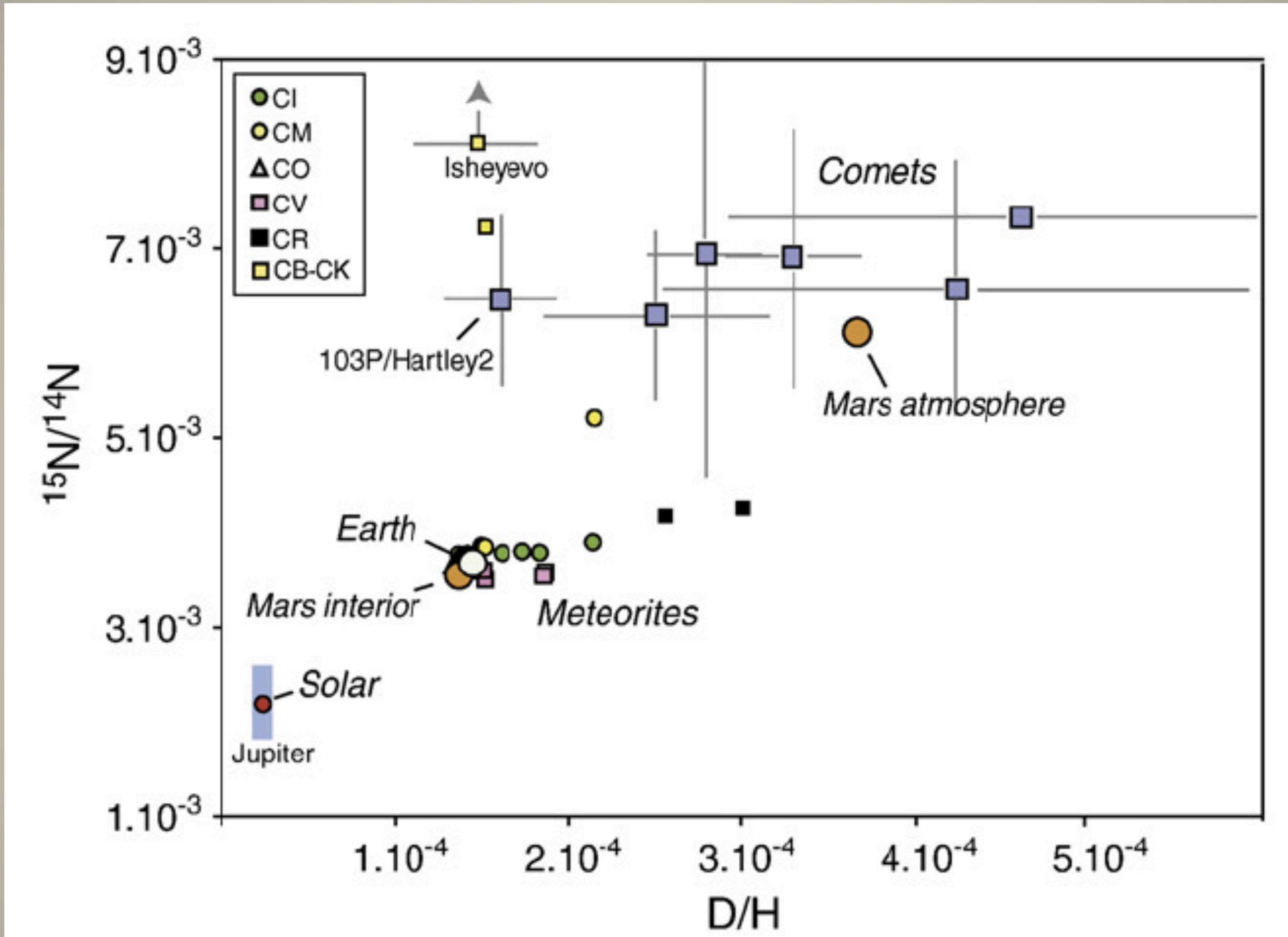
- Inner solar system dry
- Early earth with frequent impacts, too hot to keep surface water
- Came late from accumulation of volatile-rich impactors (comets)
- Comets from outer solar sysem (Kuiper Belt and Oort Cloud)

Origin of atmosphere and oceans?



Ballentine (Science 2002)

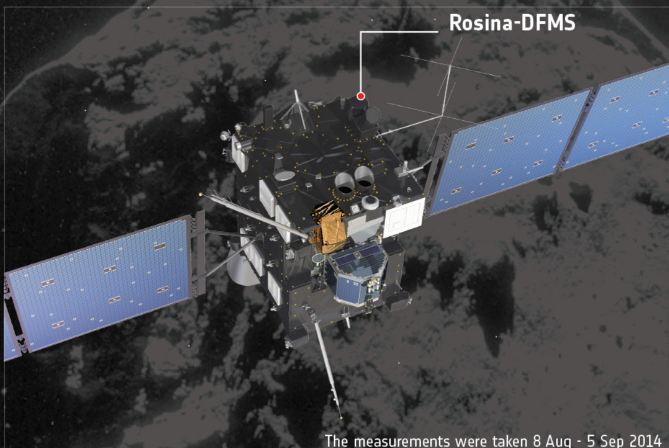
- **Are they from interior (endogenic)?**
- Water content of bulk Earth is tiny (0.02% by mass); in bulk very dry. Don't need much to make oceans, etc
- Freezing of early magma ocean…
  - Releases gases as it crystallizes
  - Mantle degasses through volcanism as planet cools

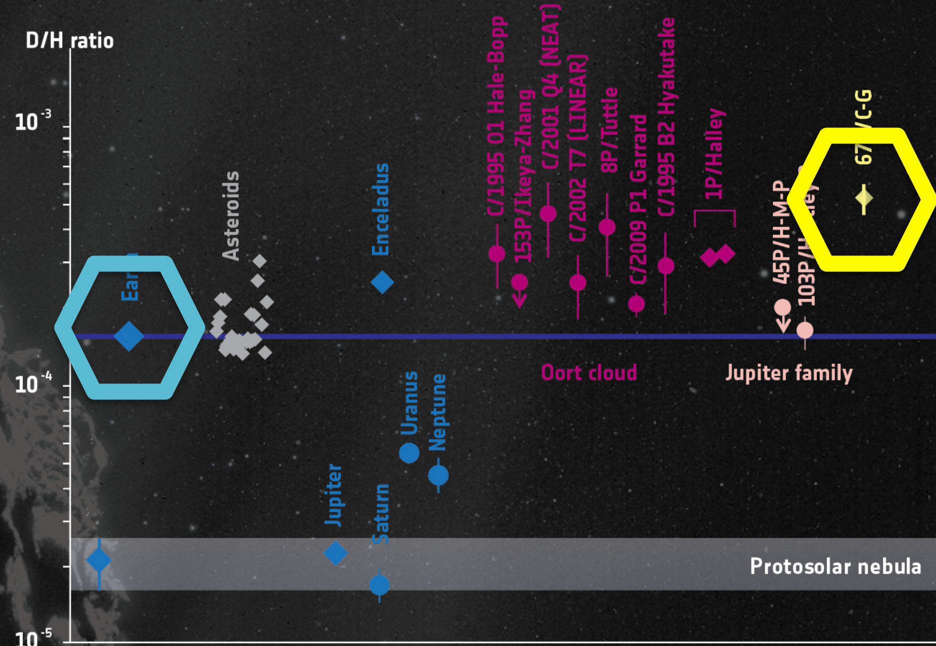


Isotopic signature of D/H most like meteorites (chondrites)
Implies oceans degassed from interior, not from comets
(Recent “exception” Hartley comet has different N isotope signature)

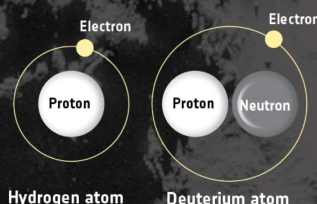
Marty (2012)

Rosetta's ROSINA instrument finds Comet 67P/Churyumov-Gerasimenko's water vapour to have a significantly different composition to Earth's oceans.



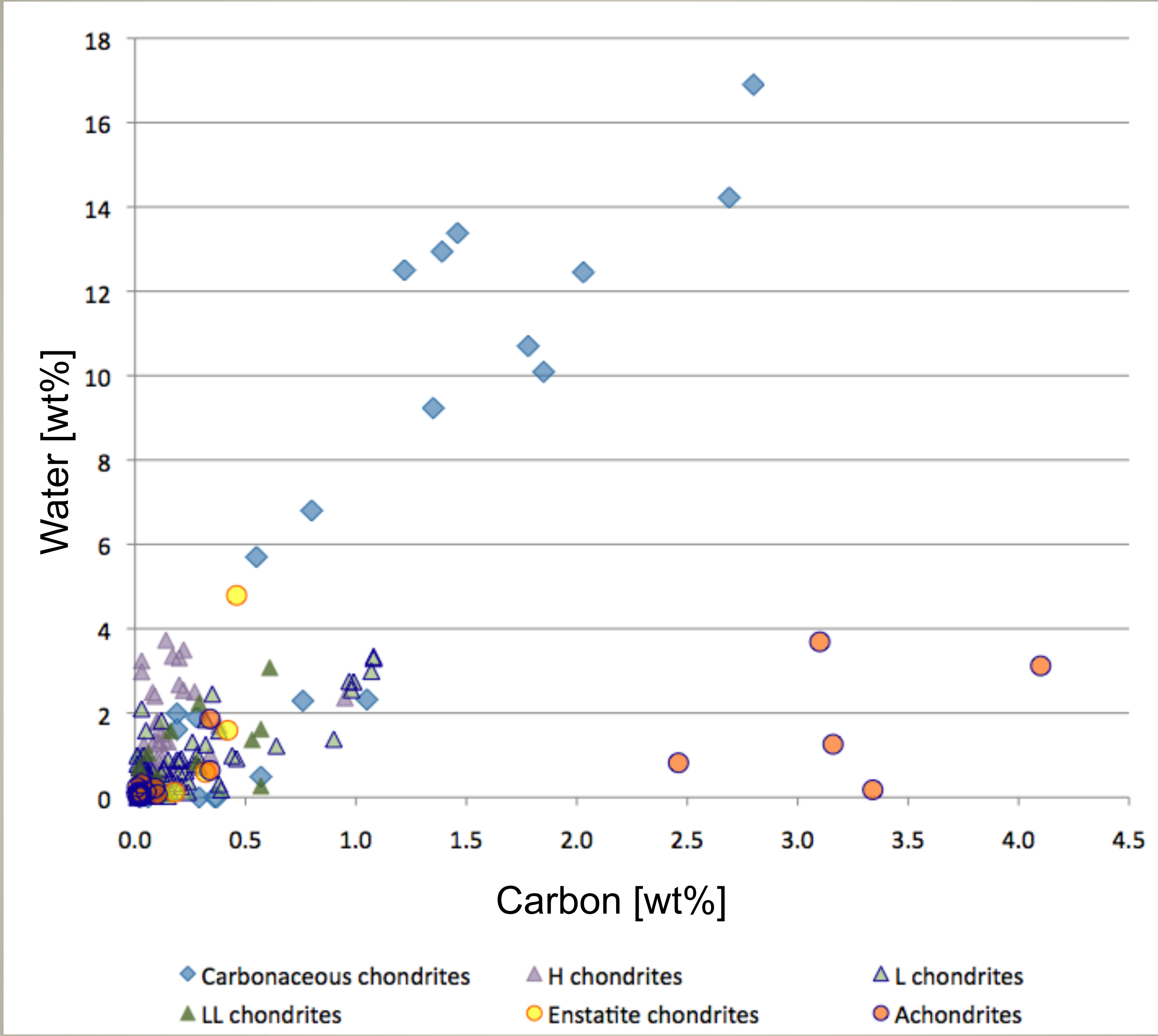


The ratio of deuterium to hydrogen in water is a key diagnostic to determining where in the Solar System an object originated and in what proportion asteroids and comets may have contributed to Earth's oceans



D/H ratio for different Solar System objects, grouped by colour as planets and moons (blue), chrondritic meteorites from the Asteroid Belt (grey), comets originating from the Oort cloud (purple) and Jupiter family comets (pink). Comet 67P/C-G, a Jupiter family comet, is highlighted in yellow. ◆ = data obtained in situ ●= data obtained by astronomical methods

Spacecraft: ESA/ATG medialab; Comet: ESA/Rosetta/NAVCAM; Data: Altwegg et al. 2014 and references therein.



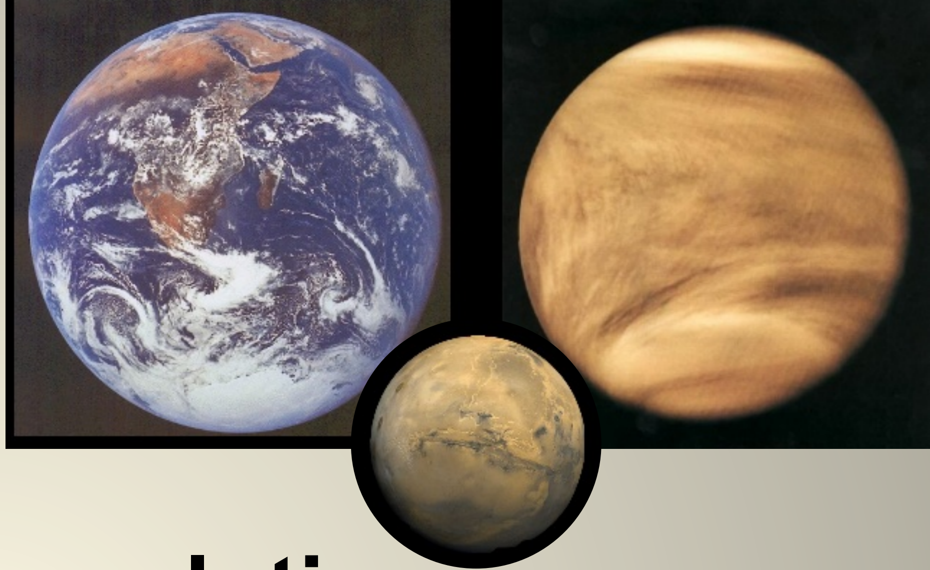
Data from Jarosewich (1990)

Chondrites are good candidates for source of water and carbon

Planetary atmospheres

- **Early terrestrials, Venus, Earth, Mars**
- All started (probably) with CO_2 rich atmospheres from degassing
  - Plus also modern volcanic output (H_2O, SO_2, Cl_2,N_2..)

Early Planetary Atmospheres



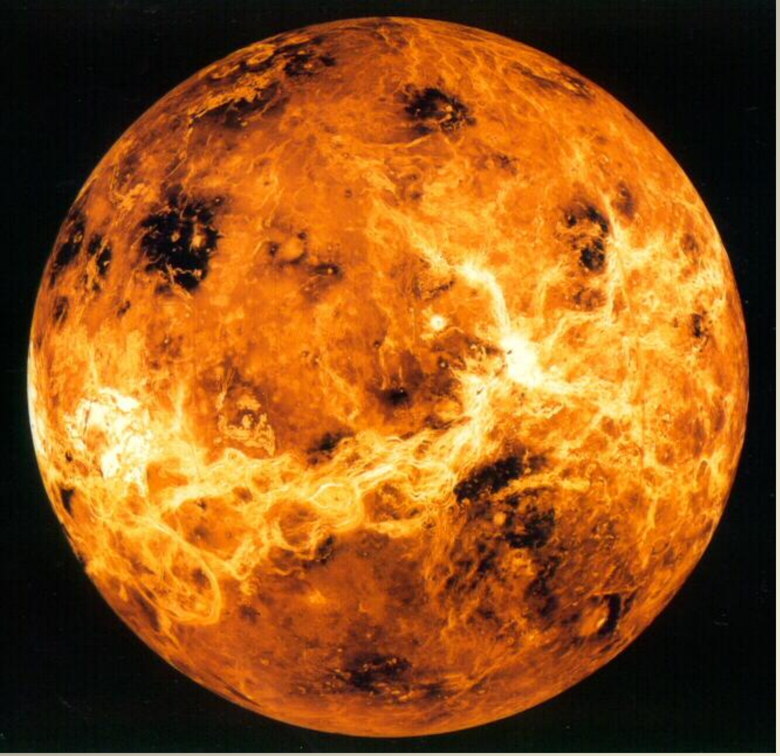
- **Divergent planetary evolutions**
- Venus now:
  - Thick CO_2 atmosphere, trace amount of water, super-hot surface
- Mars now
  - Thin CO_2 atmosphere, probably significant water in permafrost, ice-caps, very cold surface
- Earth now
  - Moderately thin atmosphere of mostly N_2 (inert) and O_2 (life) instead of CO_2; temperate climate, large liquid water oceans
  - Carbon now mostly in ocean and crustal carbonates and kerogen

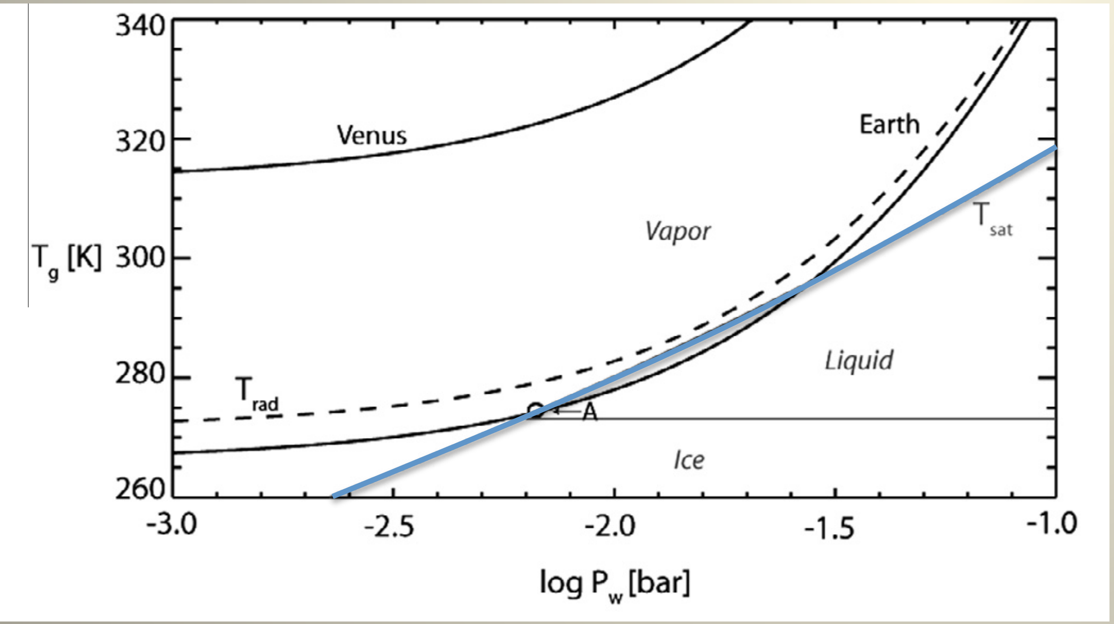
Atmospheres of the Inner Planets

	Venus	Early Earth	Mars	Earth Today
CO_2	96.5%	98%	95.3%	0.0401%(*)
N_2	3.4%	1.9%	2.7%	78%
O_2	trace	trace	0.13%	21%
Ar	0.01%	0.1%	1.6%	0.93%
Temperature °C	477	290	−53	16
Pressure (bars)	92	60	0.006	1

*401.24ppm as of April 2015
http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html#global_data

Venus and the runaway Greenhouse





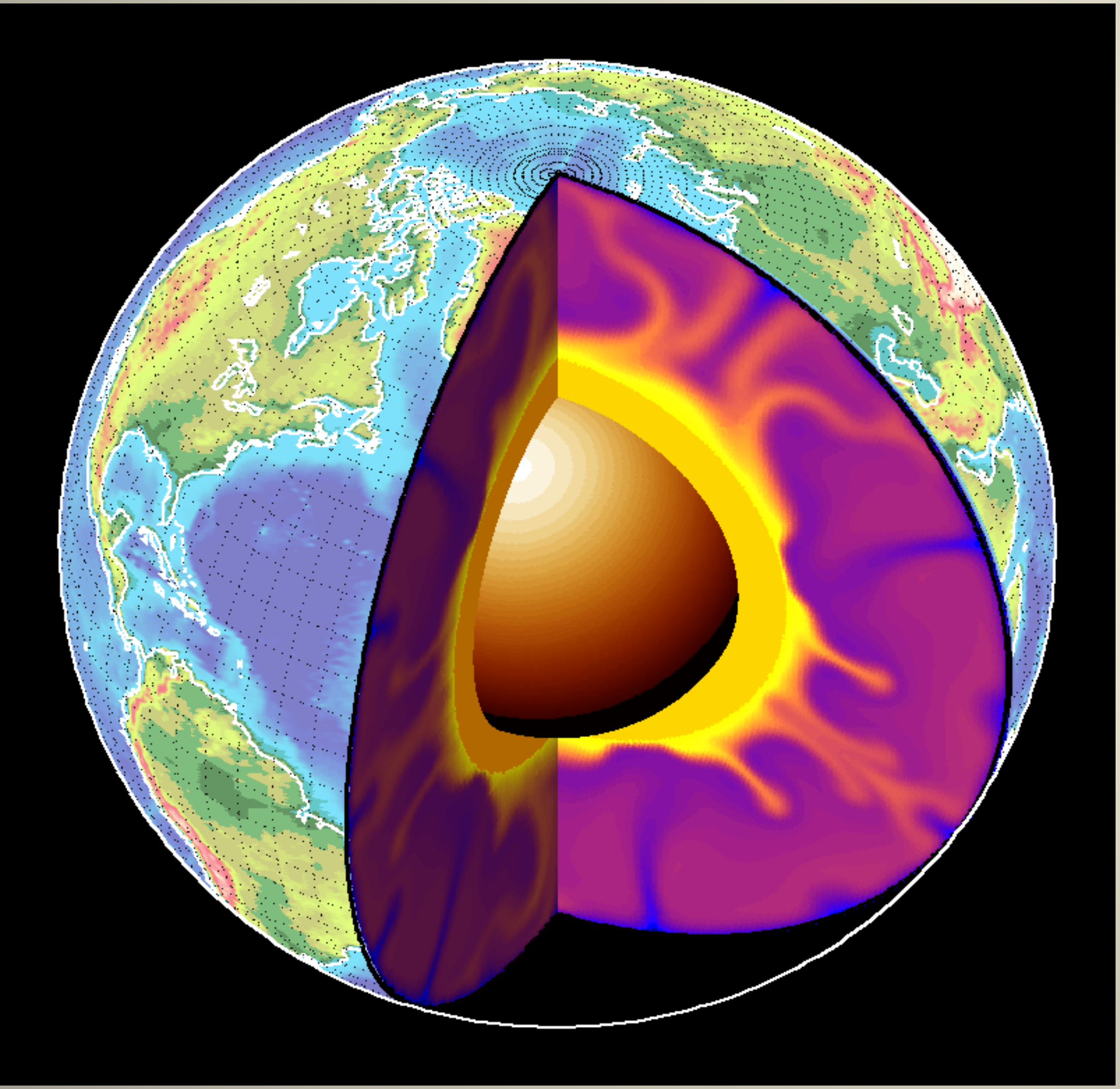
Driscoll & Bercovici 2013 after Ingersoll 1969

- CO_2 and H_20 are both strong GH gases
- Degassing of both increases atmospheric pressure and temperature
- If T(P) rises faster than and/or misses Tc(P) of water
  - atmosphere never saturated, no condensation and removal of water to oceans
  - just keeps getting hotter
- UV dissociates H_2O and H escapes
- O_2 locked up in rocks
- Present T 480^{o}C
  - **Rocks glow at night**

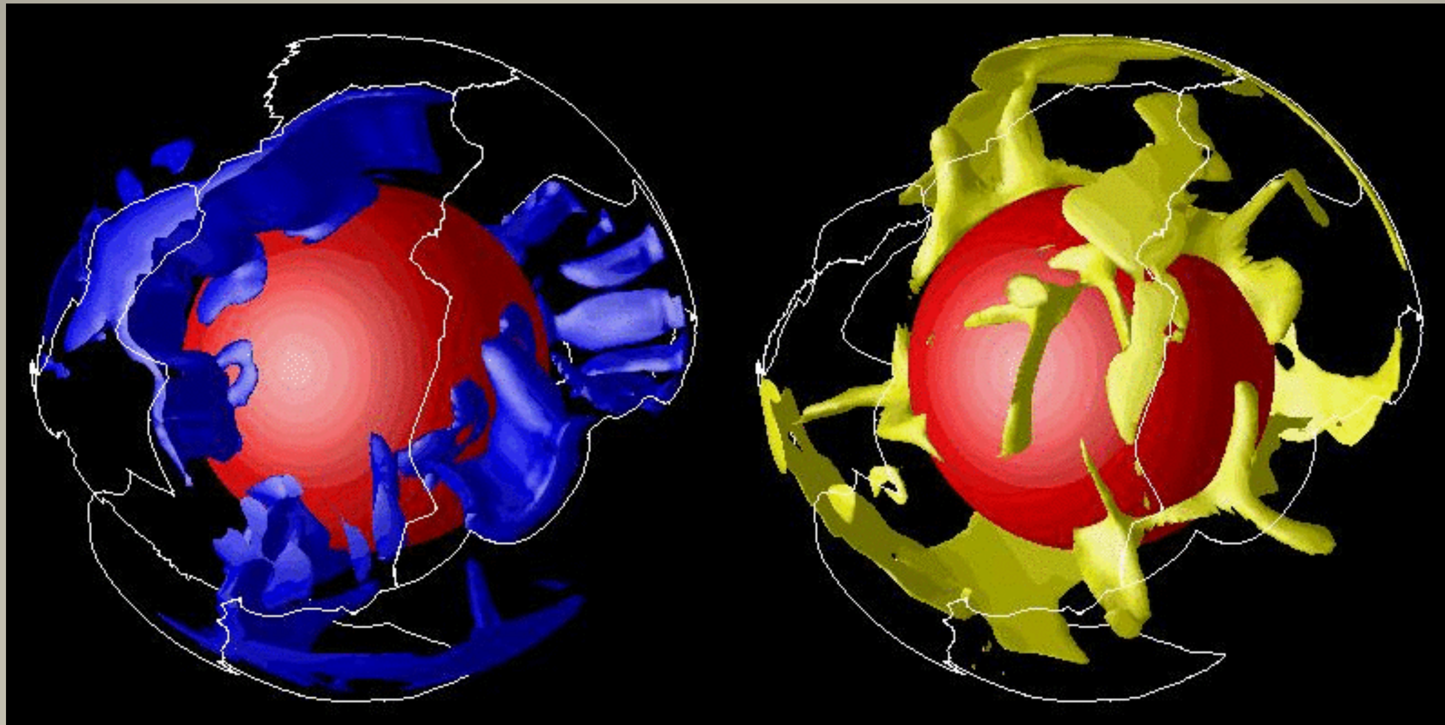
Early Earthy

- High CO_2 levels would have made initial ~300^{o}C atmosphere
- Evidence from *zircons* suggests Earth had “cool” liquid oceans soon after magma ocean >4Gyrs ago, after cooling of “magma ocean”
- First life by 3.5Gyr ago:
- CO_2 levels and temperature became low enough by 4Gyr for “cool” liquid water and by 3.5Gyr to allow life .
- **What drew down CO_2?**

Earth cools to space



- Total heat output from Earth about 46TW
  - 1 TeraWatt = 1 trillion Watts
  - More than ½ from primordial heat
  - Less than ½ from radioactive decay (e.g., of Uranium, Thorium)
- **Fuel for plate tectonic activity**
- Compare: solar heating is about 170,000TW



S. Zhong, Univ. Colorado

- ## Terrestrial mantle convection
- Thick layer of solid rock between crust and core
- Rock near surface cools and is heavy
- Rock near molten iron core heats and is light
- **Mantle convects slowly (on Earth: 1-10cm/yr)**
- **Governs how fast the entire planet cools to space**
- **Only Earth (as far as we know) has convective circulation interacting with the surface, i.e., plate tectonics**

Plate Tectonics and Convection

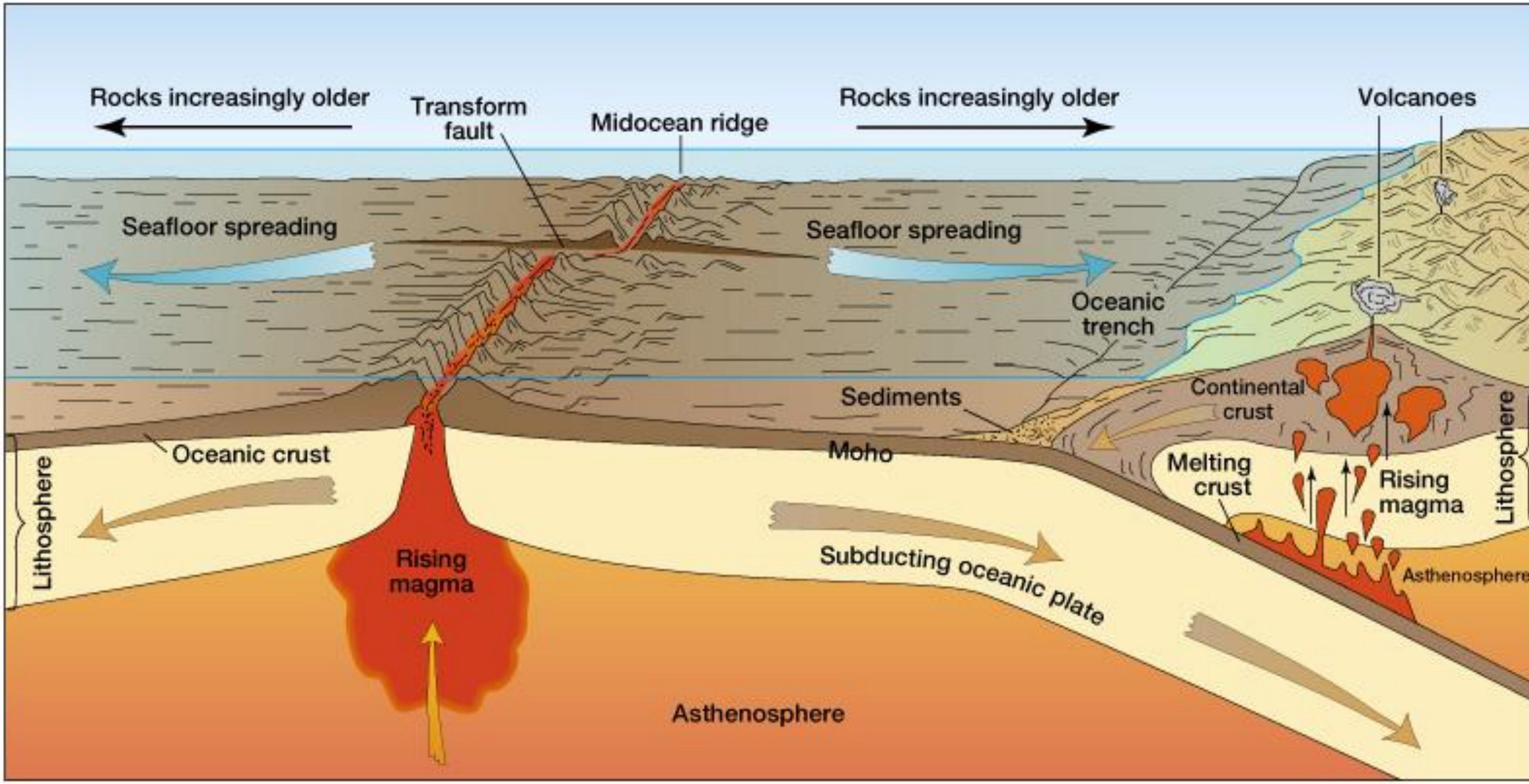
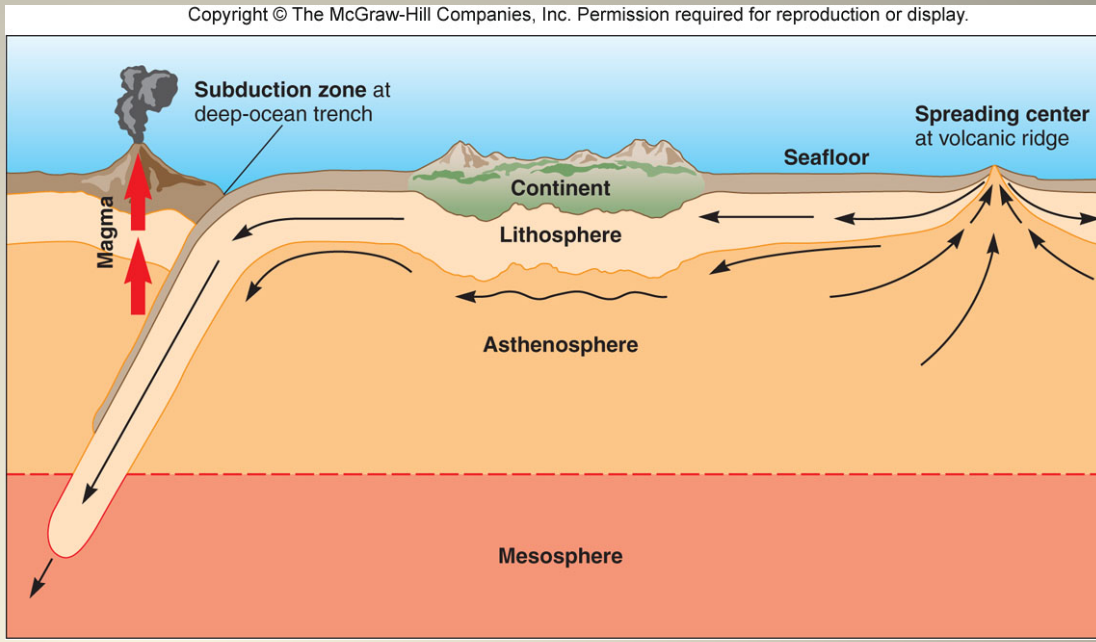


Plate tectonics (aka continental drift) is the top of the convecting mantle where near surface layer of rock (plates) are pulled along by the cold, heavy stuff sinking into the mantle along subduction zones, which are marked by deep ocean trenches

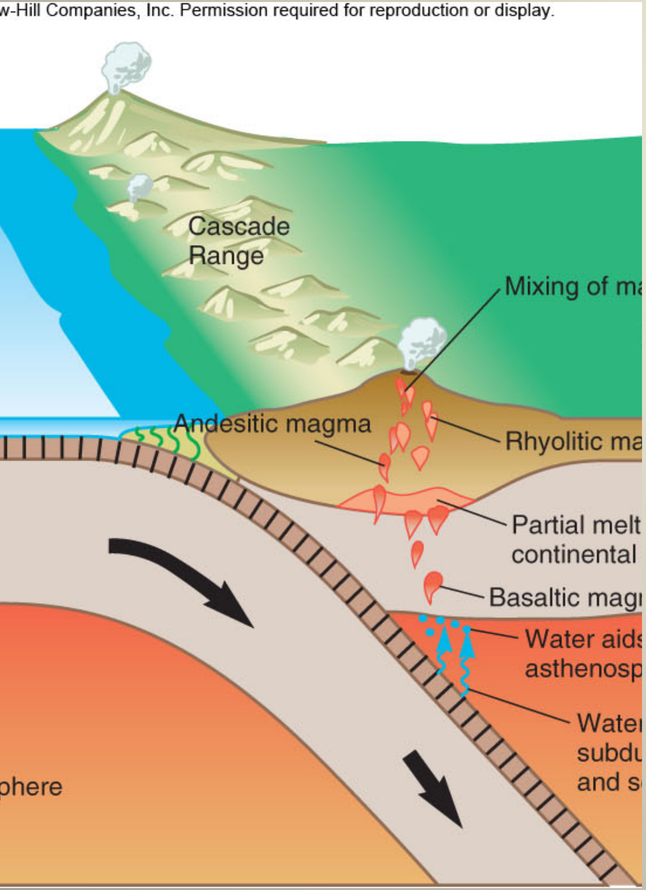
Plate Tectonic Carbon Cycle

Plate tectonics exposes fresh minerals to atmosphere and ocean

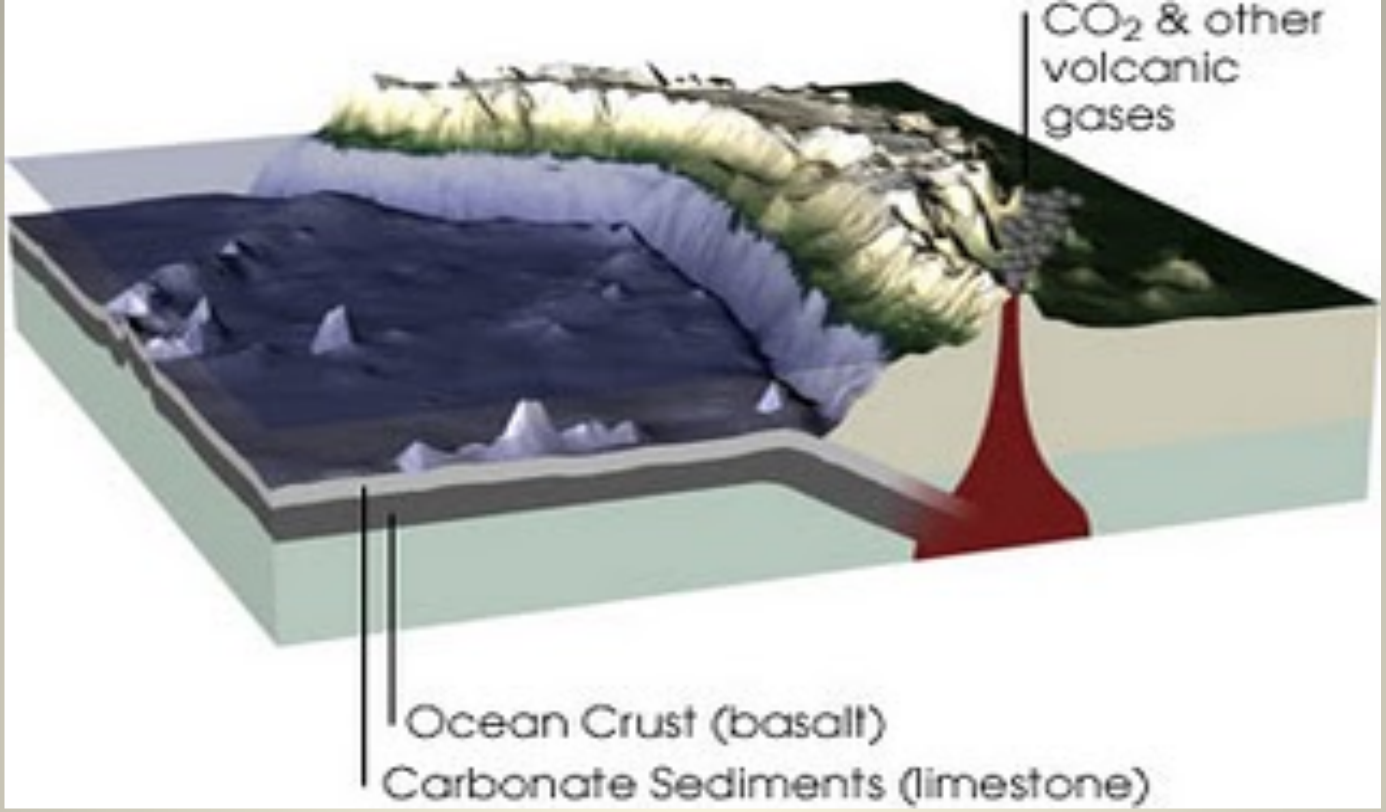


- Volcanism and mountain building expose fresh minerals (i.e., in chem equilibrium with subsurface, not atmosphere)
- CO_2 dissolved in rain, river and sea water makes weak carbonic acid H_2CO_3
- Erosion weathering of mountains washes minerals into rivers, oceans – react with acid and make carbonates
- Today – biologically mediated: organisms use these carbonates to make shells; 80% of today's CO_2 bound up in limestone (20% in kerogens)

Arc Volcanism Returns CO_2



- If all CO_2 were drawn down without being returned, the Earth would get too cold and freeze over
- Subduction zones drag down sea-floor carbonates, cook out CO_2 into mantle wedge (along with water), melts mantle, etc…
- Returns CO_2 by arc volcanism



- Important negative feedback stabilizes climate over
- 10s-100s of Myrs
- **If CO_2 levels rise then temperature rises**
  - Ocean evaporation and precipitation drives weathering and carbonation of minerals and draws down CO_2 and cools climate
- **If CO_2 levels fall then temperature drops**
  - Lower precipitation limits CO_2 draw-down, but volcanoes continue to pump out CO_2 and re-warm the climate
- **Need the hydrologic cycle (gas ⬌ liquid) for this to work**

Table 1. Carbon pools in the major reservoirs on Earth.

Pools	Quantity (Gt)
Atmosphere	720
Oceans	38,400
Total inorganic	37,400
Surface layer	670
Deep layer	36,730
Total organic	1,000
Lithosphere	
Sedimentary carbonates	>60,000,000
Kerogens	15,000,000
Terrestrial biosphere (total)	2,000
Living biomass	600–1,000
Dead biomass	1,200
Aquatic biosphere	1–2
Fossil fuels	4,130
Coal	3,510
Oil	230
Gas	140
Other (peat)	250

Present surface carbon budget

~ 10^8 Gt

(1Gt = 10^{12}kg = 1Pg)

Mostly in continental lithosphere as limestone

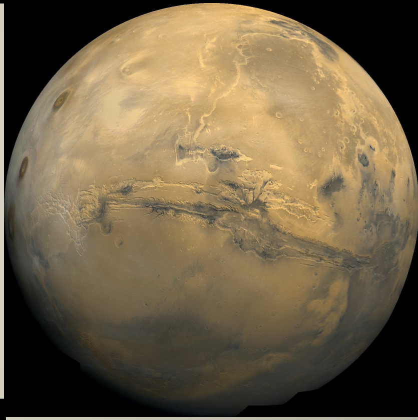
(Falkowski et al, Science 290, p291-296, 2000)

1-10 times this total stored in Mantle

20-80 times this perhaps stored in core

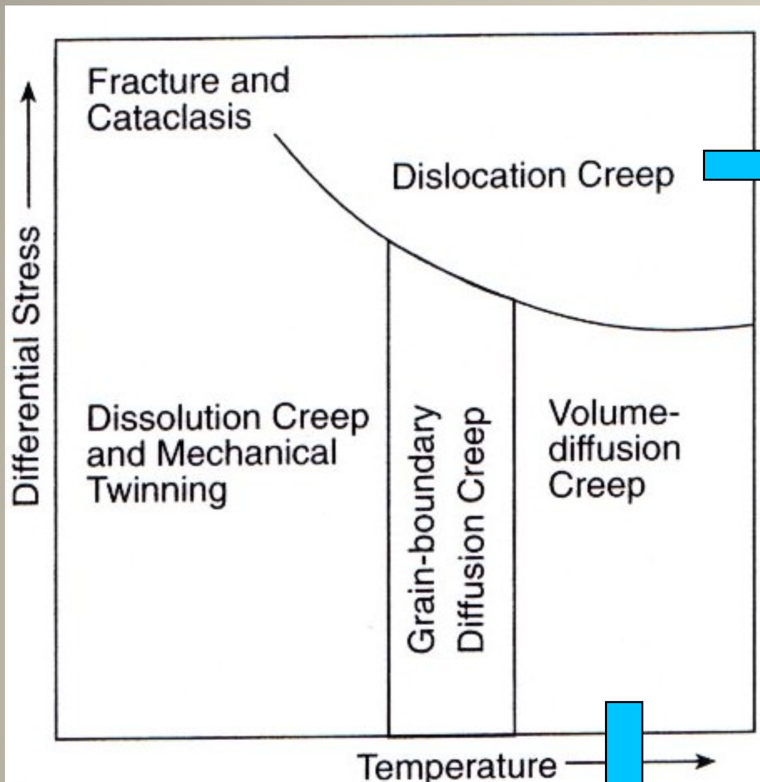
(Dasgupta & Hirschmann 2010)

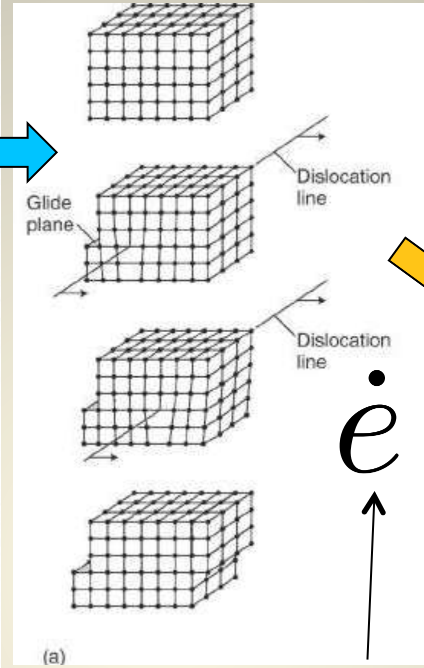
Plate tectonics: Why only Earth?



- Mars and Venus (and Mercury and Moon) are in stagnant lid, or one-plate planet
- Mars perhaps once had plate tectonics early in its history, but not anymore
- Venus’ surface appears to about 500Myrs old suggesting a resurfacing event, but no other sign of active plate tectonics (some arguable signs of subduction)
- What makes a planet’s mantle convection “plate-tectonic” vs “stagnant-lid”?

Mantle rock “creep” rheology





$$\dot{e} = A(T)\sigma^n$$

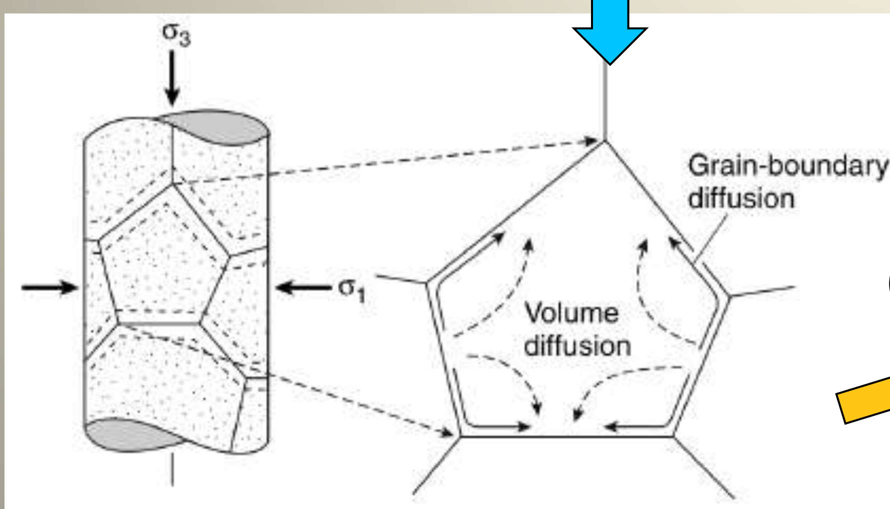
strain-rate

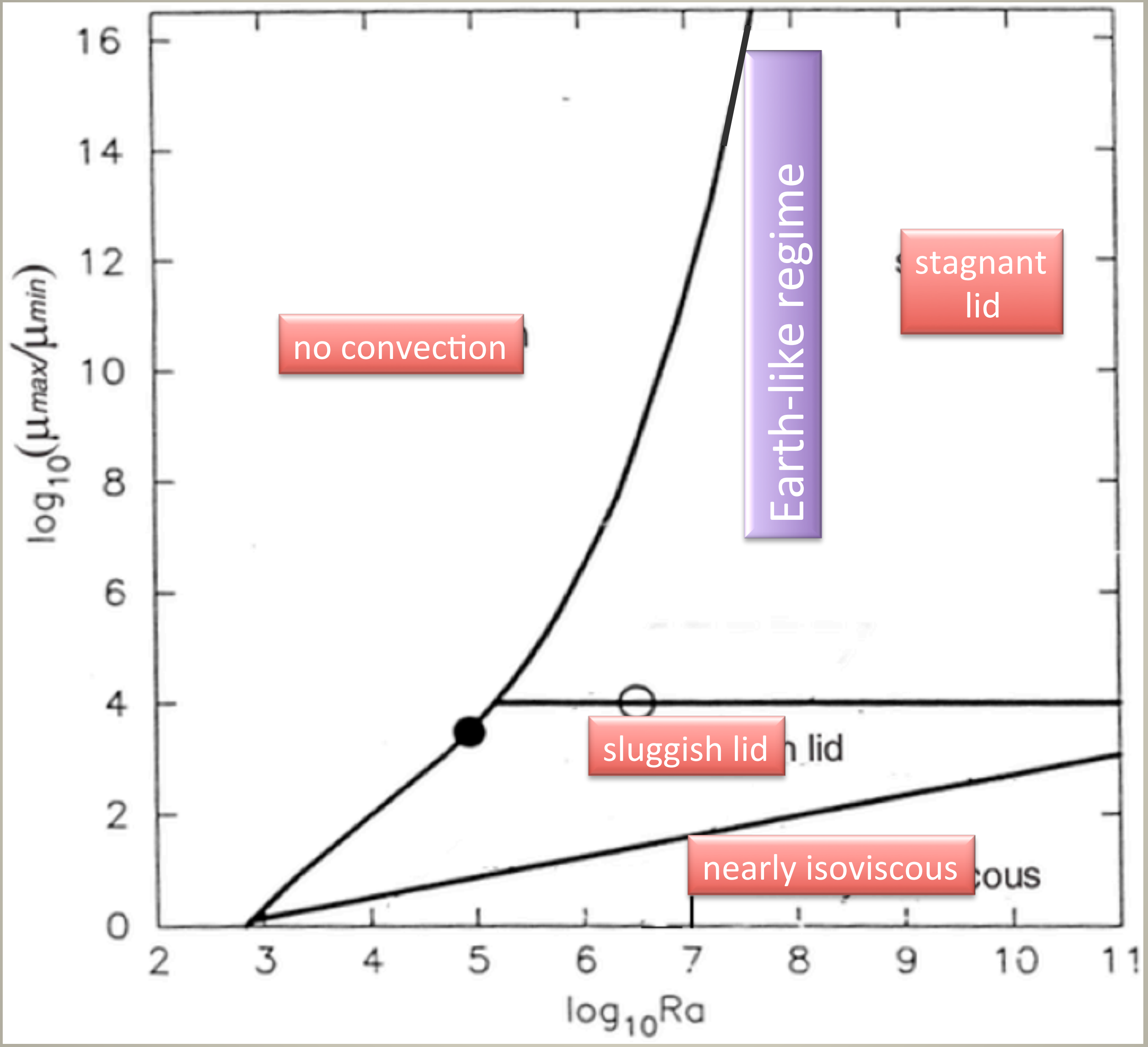
stress

temperature

grain-size

$$\dot{e} = B(T)\sigma/\mathcal{R}^m$$





16
14
12
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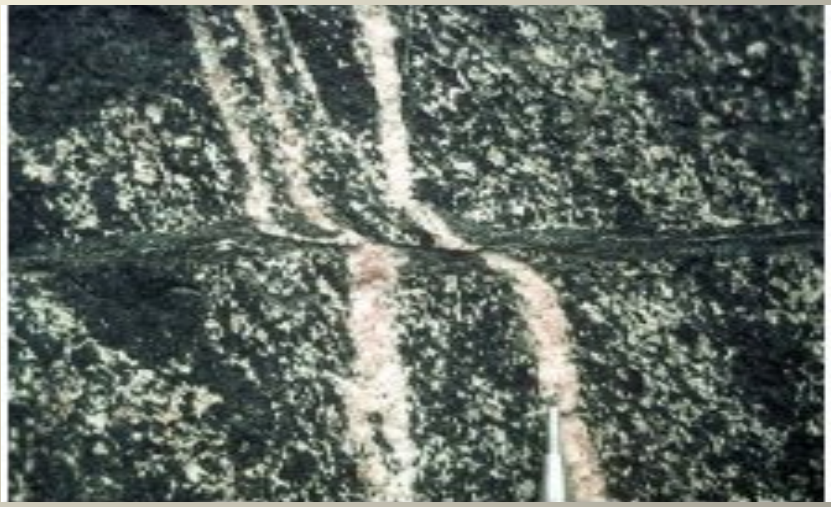
9
10
11
$\log_{10}(\mu_{max}/\mu_{min})$
$\log_{10}Ra$
no convection
Earth-like regime
stagnant lid
sluggish lid
nearly isoviscous

V. Solomatov

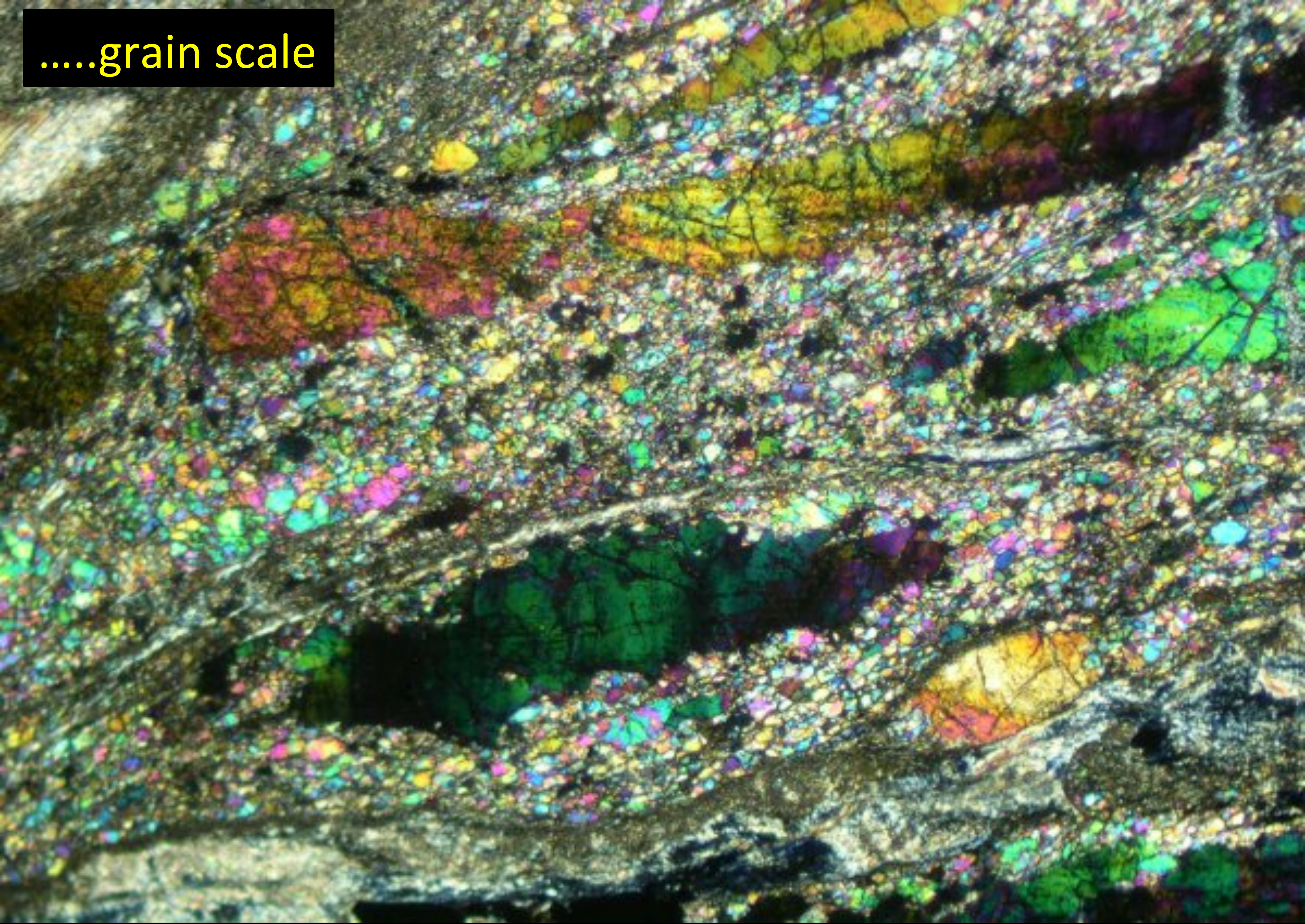
Plate Generation Mechanisms

- Most terrestrial mantles undergo *stagnant lid* convection
- Earth has self-softening feedbacks
- deformation softens material
- weak zones focus deformation
- causes more softening, more focusing: shear-localization
- Allows convecting mantle to generate
- strong broad plates,
- narrow, weak **long-lasting boundaries**
- **localized strike-slip shear**



Need to go from global scale to …..

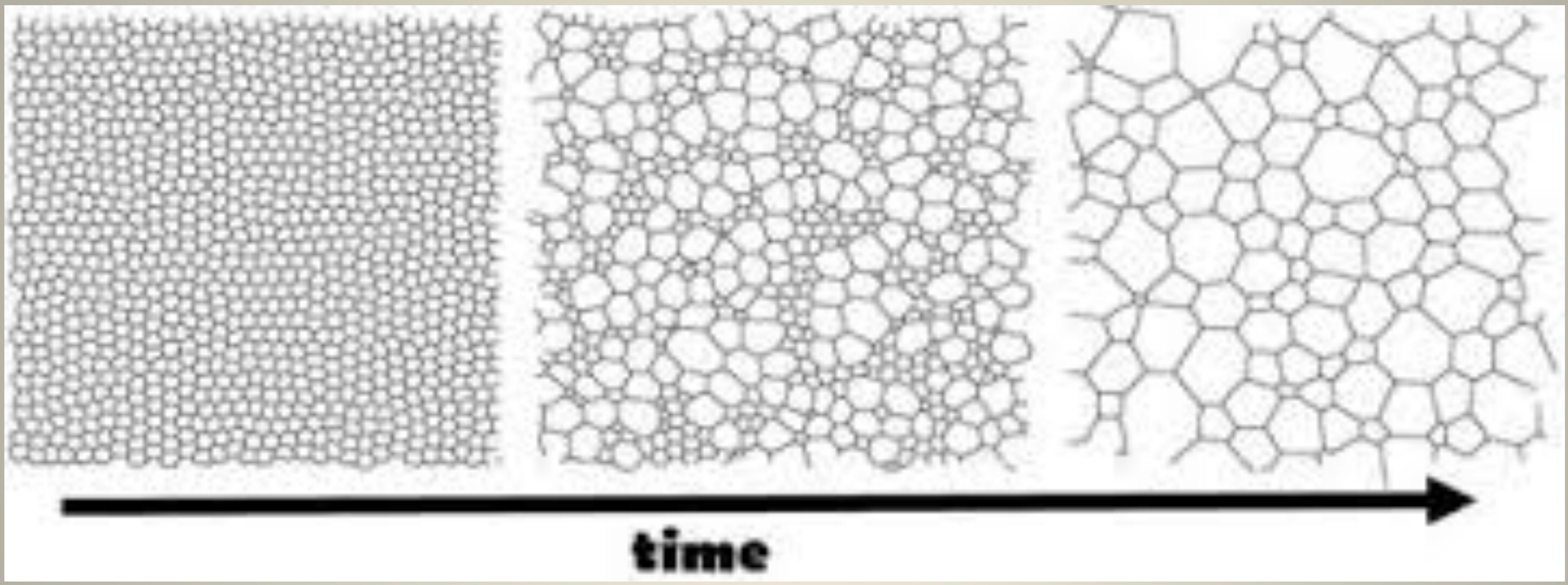
.....grain scale



Peridotite mylonite (Lars Hansen)


dreamstime

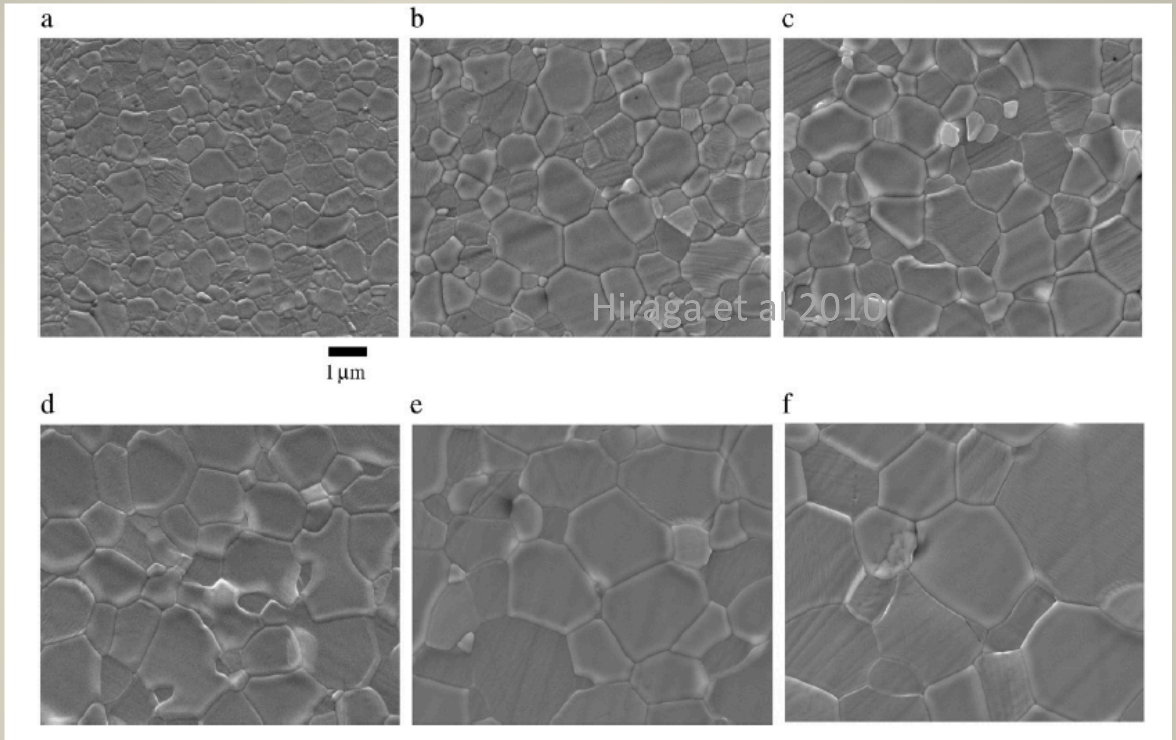
Foam coarsening



Surface tension and high curvature on small bubbles relative to large ones squeezes fluid from small to large grains: *big bubbles eat the small bubbles*

Grain-scale Processes

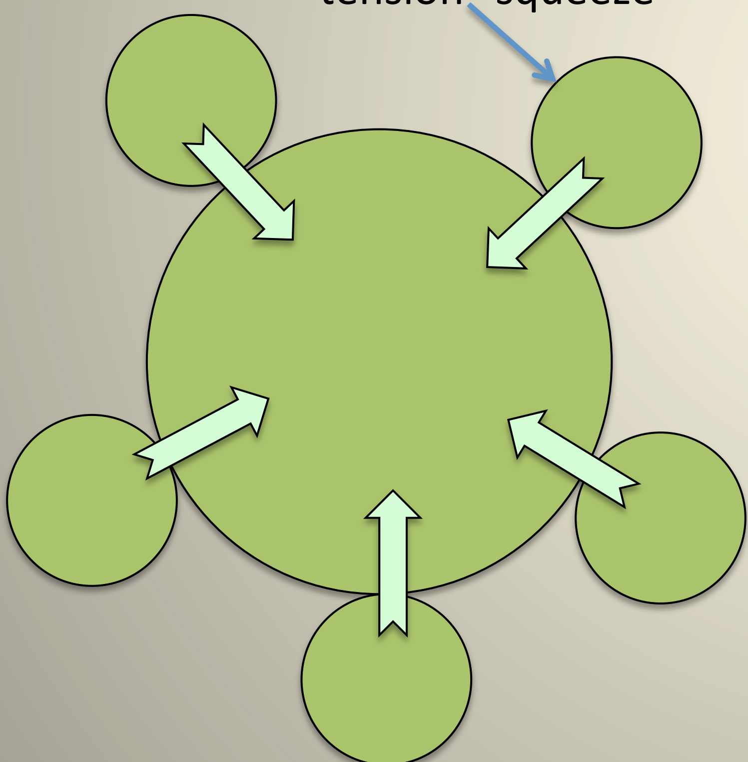
- Mineral grains grow if "static" and get stronger



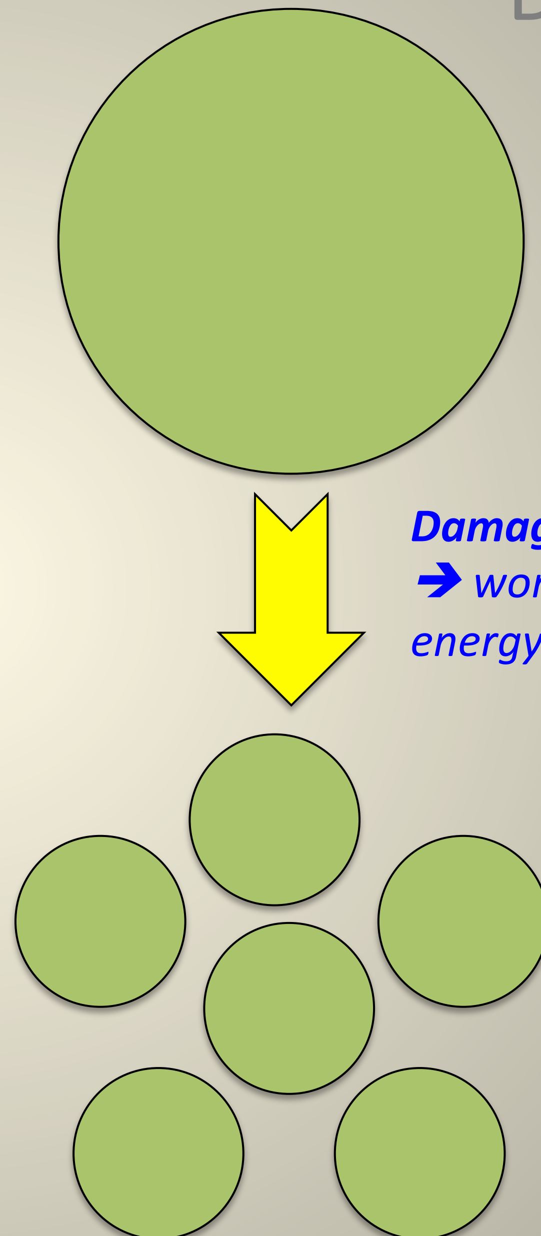
- With deformation and *damage* (dislocations), grain-size reduces
- Rocks apparently soften as grains "shrink" ➔ **positive feedback**
- **"Deep" lithospheric mechanism**
- **Evident in mylonites**

Healing and Damage

Grain-growth or coarsening



Damage



Grain evolution and damage laws

Grainsize (R) evolution: healing vs damage

$$\frac{dR}{dt} = \frac{\mathcal{C}}{pR^{p-1}} - \mathcal{D}R^2 \boldsymbol{\tau} : \dot{\mathbf{e}}$$

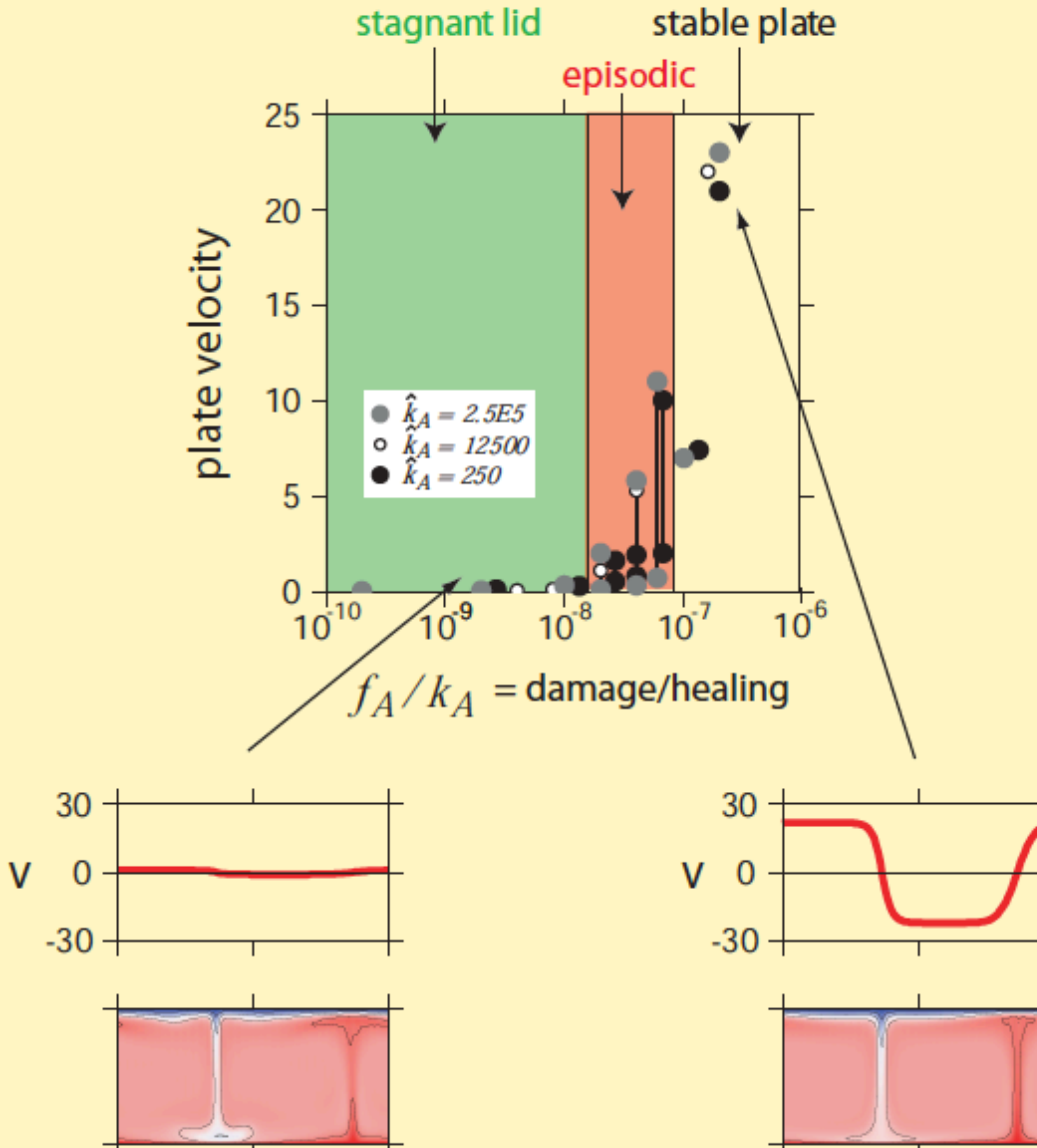
Composite dislocation + diffusion creep rheology

$$\underline{\dot{\mathbf{e}}} = \left(a\tau^{n-1} + bR^{-m}\right)\underline{\boldsymbol{\tau}}$$

- Strain rate increases with decreasing R, more damage, smaller R, more strain-rate…
- Get localization, weakening AND with slow healing, weakening history
- Healing rate C = func(T); higher/lower T promotes/suppresses healing

Convection with damage*

- As **damage to healing ratio** ***f_A* : *k_A* increases**
- **stagnant surface transitions to plate-like surface**

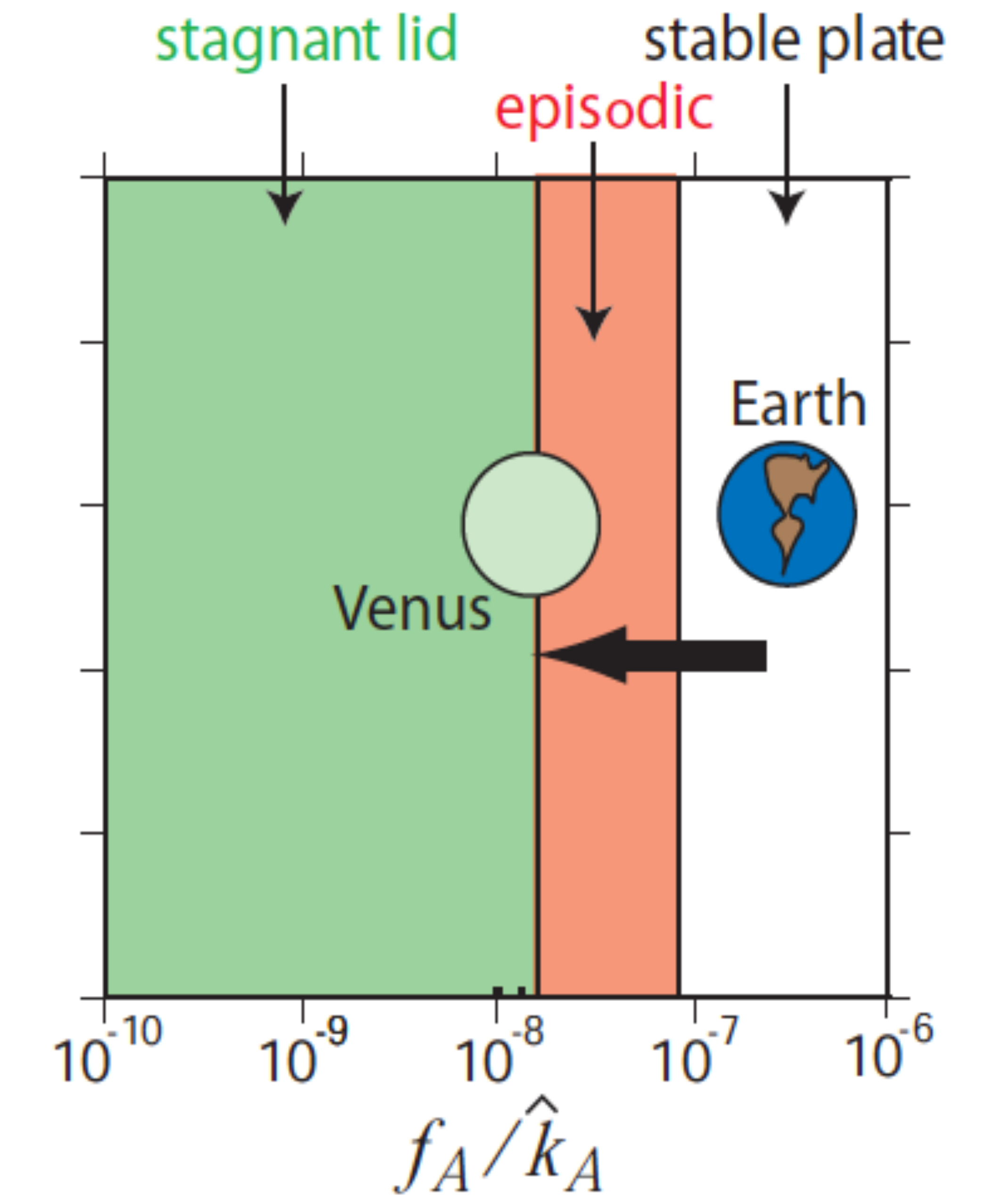


*Landuyt & Bercovici 2009

Planetary Climate and Tectonics?

- Higher surface T promotes healing, suppresses damage
- ➔ *low damage:healing ratio* ➔ **Venus**

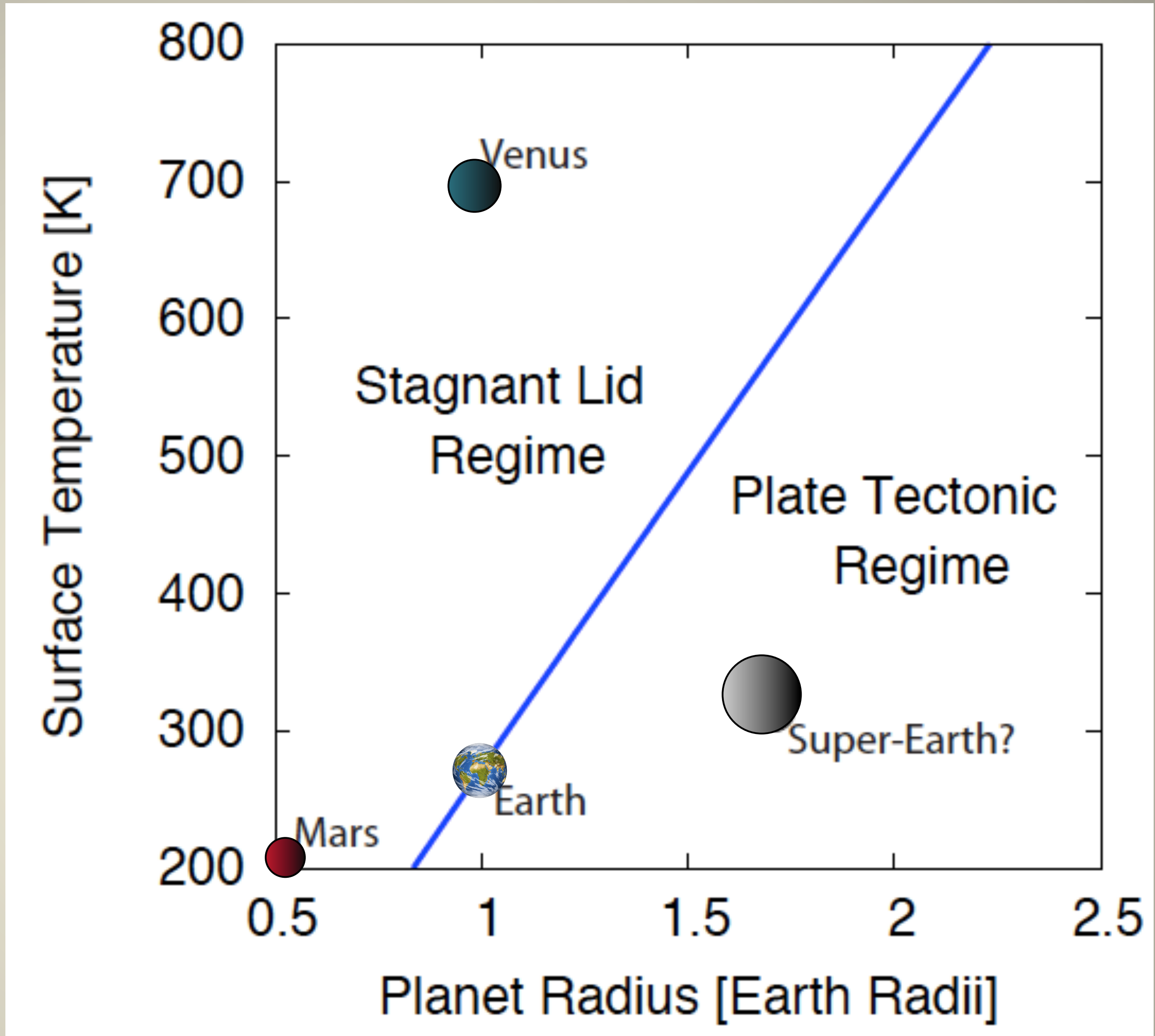
- Lower surface T reduces healing promotes damage ➔ *high damage:healing ratio* ➔ **Earth**



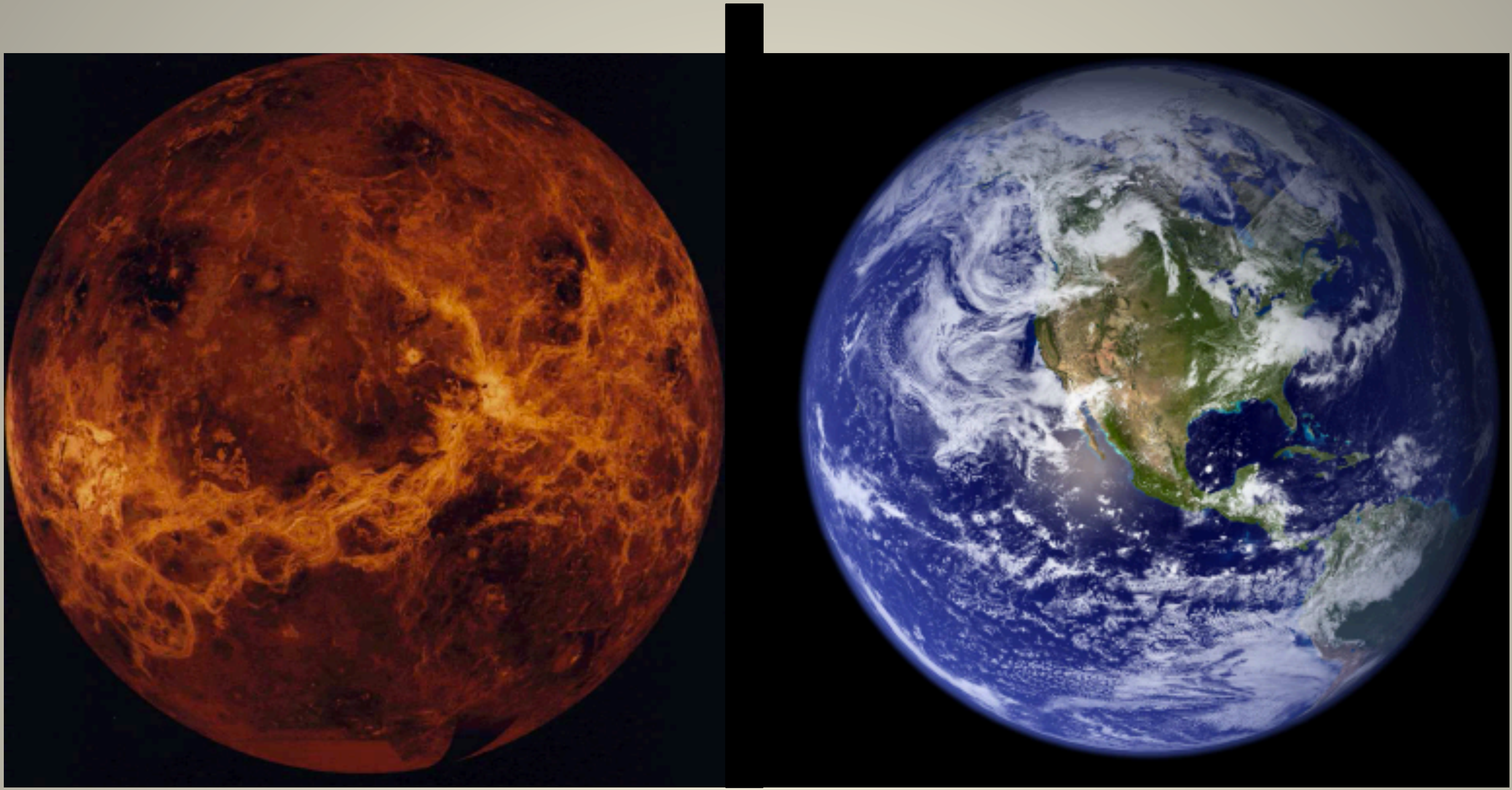
See also Lenardic et al EPSL 2008

Planetary plate generation phase diagram

- Convection models with grain damage: “plate” state depends on ratio of damage to healing
- Healing is surface T dependent
- Convection, damage depend on size (Ra number)
- Yields a “*phase boundary*” defining when planet’s surface is plate-like or stagnant

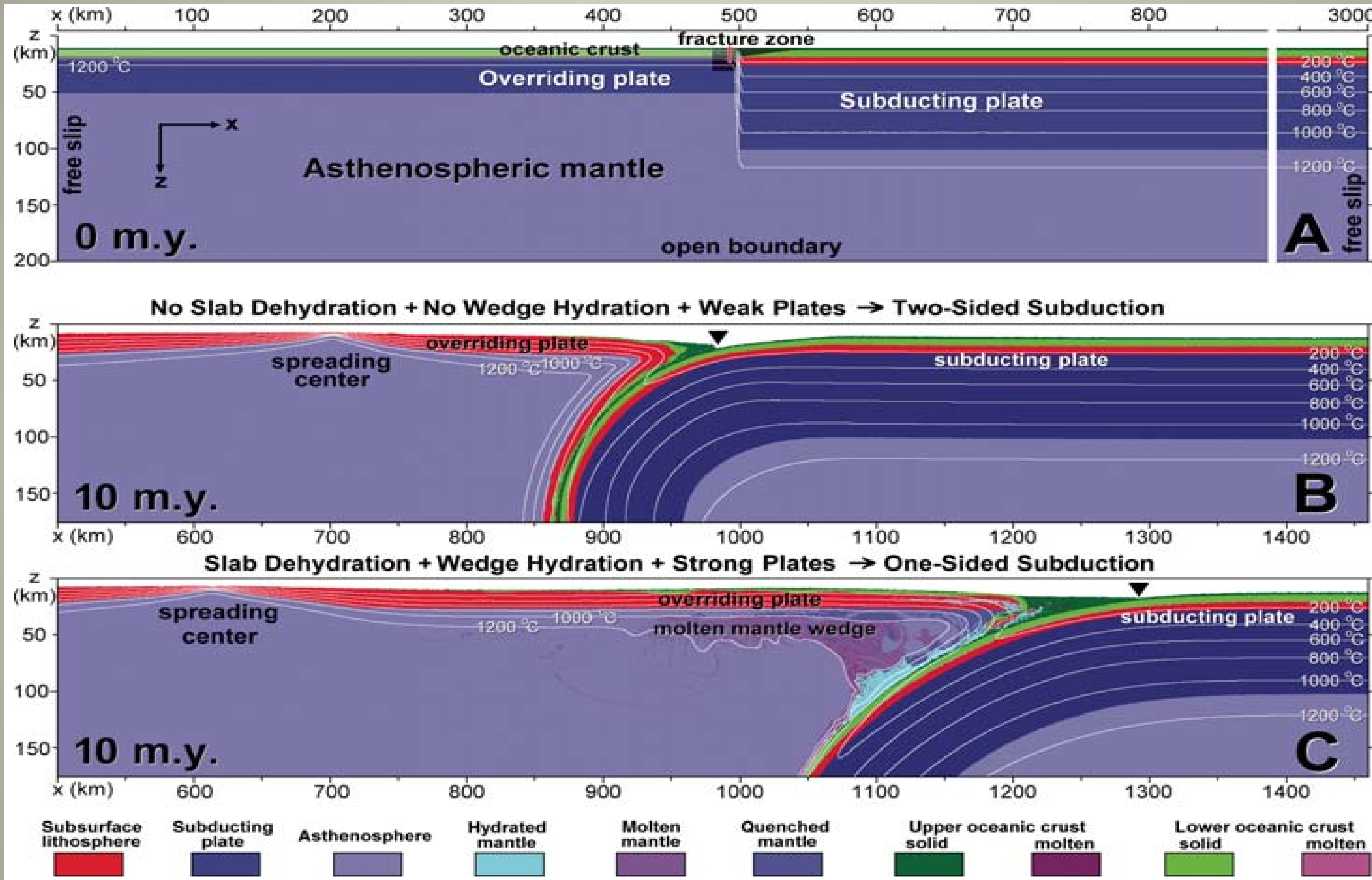


Foley et al (EPSL2012)



- An important role of liquid water is to keep moderate climate through promoting carbon cycle, not necessarily only through weakening
- Plate tectonic feedback likewise stabilizes carbon cycle

Water ingestion & plate tectonics



Gerya et al Geology 2008

Wedge hydrous melting allows asymmetric subduction

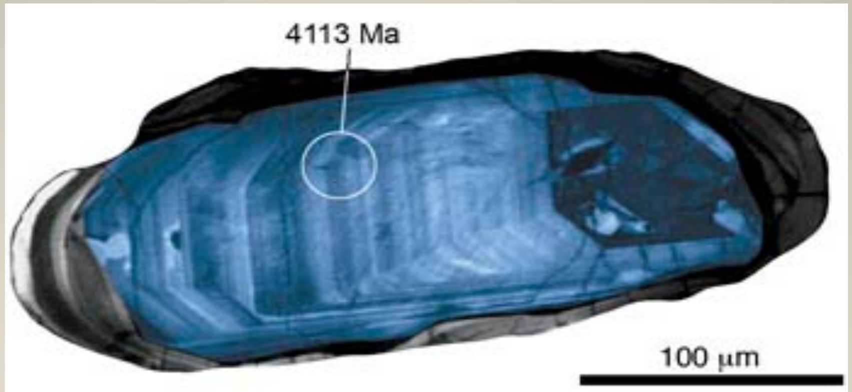
Chicken or Egg Paradox

What came first?
Plate Tectonics or Liquid Water?

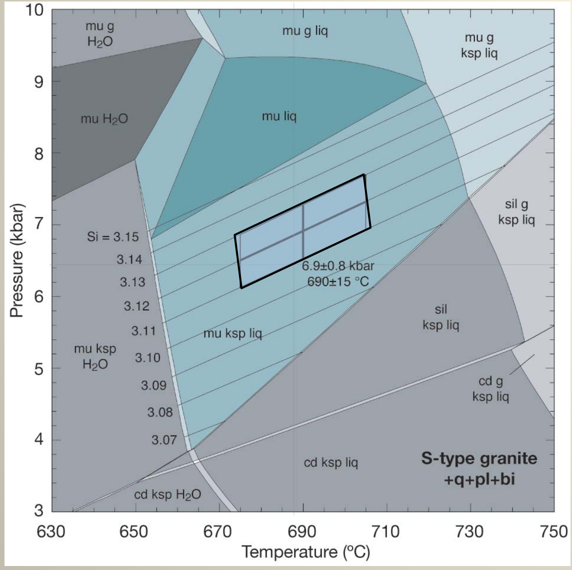
- Liquid water and cooler climate first? Because it's needed to promote plate tectonics?
- Plate tectonics first? Needed to draw down CO_2 and promote liquid water and cooler climate?

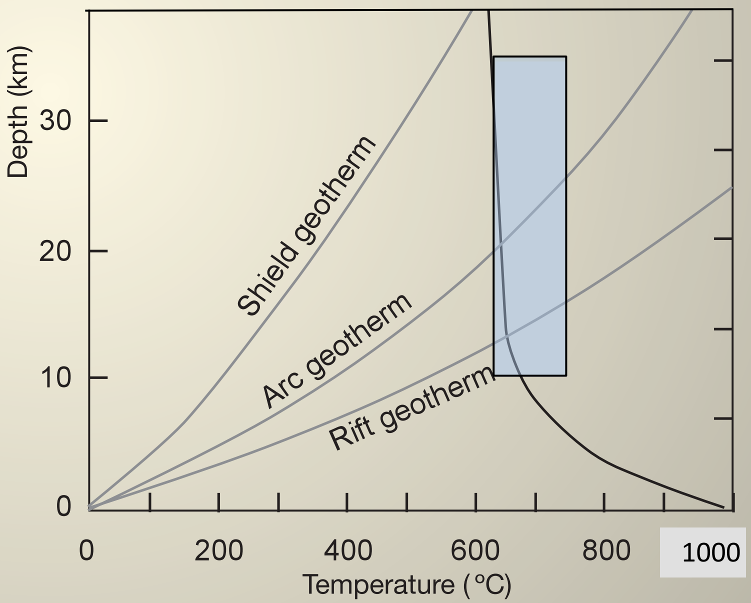
Hadean-Eoarchean Water AND Proto-subduction?

- Zircon granites: liquid water and crustal production and proto-subduction at >4Ga



False-color microscope image of a 4Gyr-old zircon, (Photo: M. Diman and J. Valley , Univ. Wisconsin)

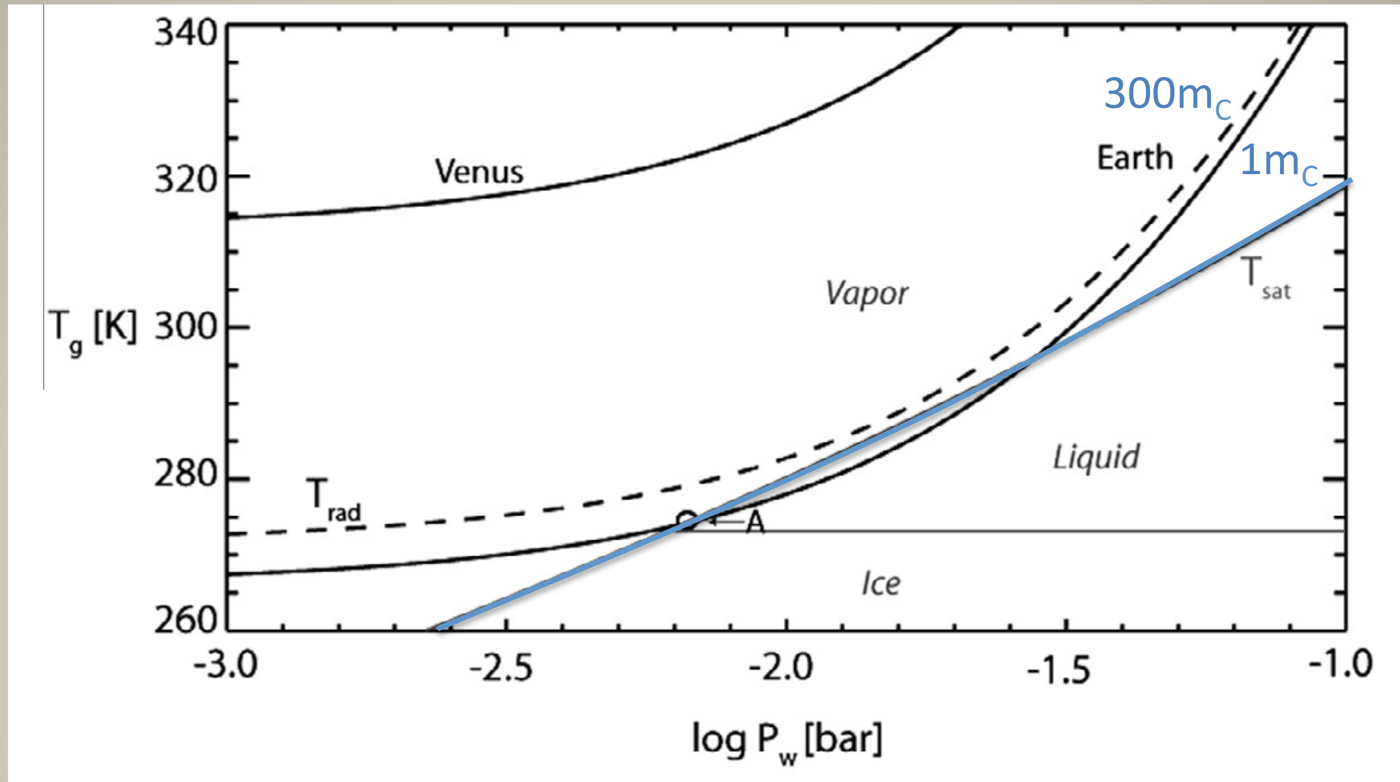




S-granite thermo-barometry: formation in low heatflow "convergent-zone" environment At 4Ga (Hopkins et al, Nature 2008)

BUT – see Kemp et al EPSL 2010 – who says granitic signature is due to remelting of floating crust

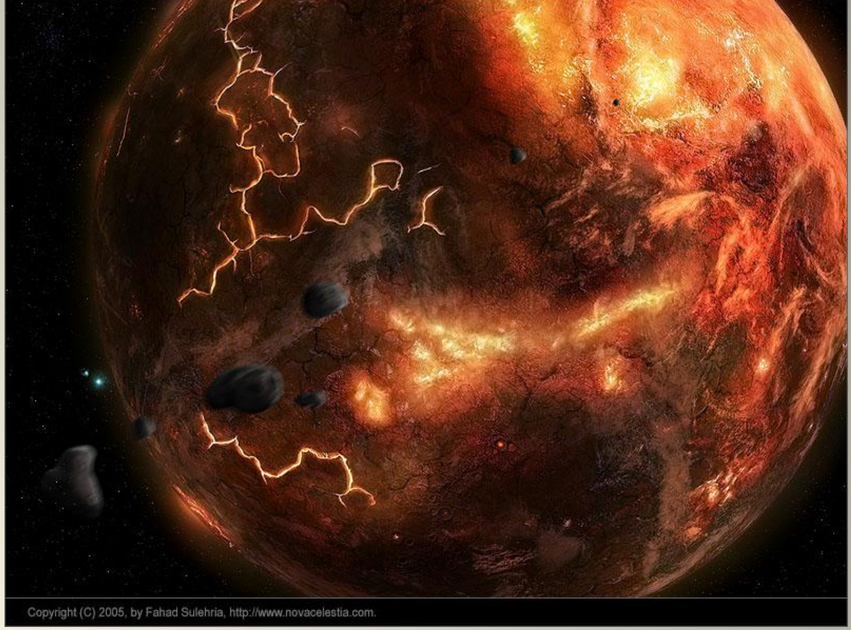
Water first? Greenhouse Earth



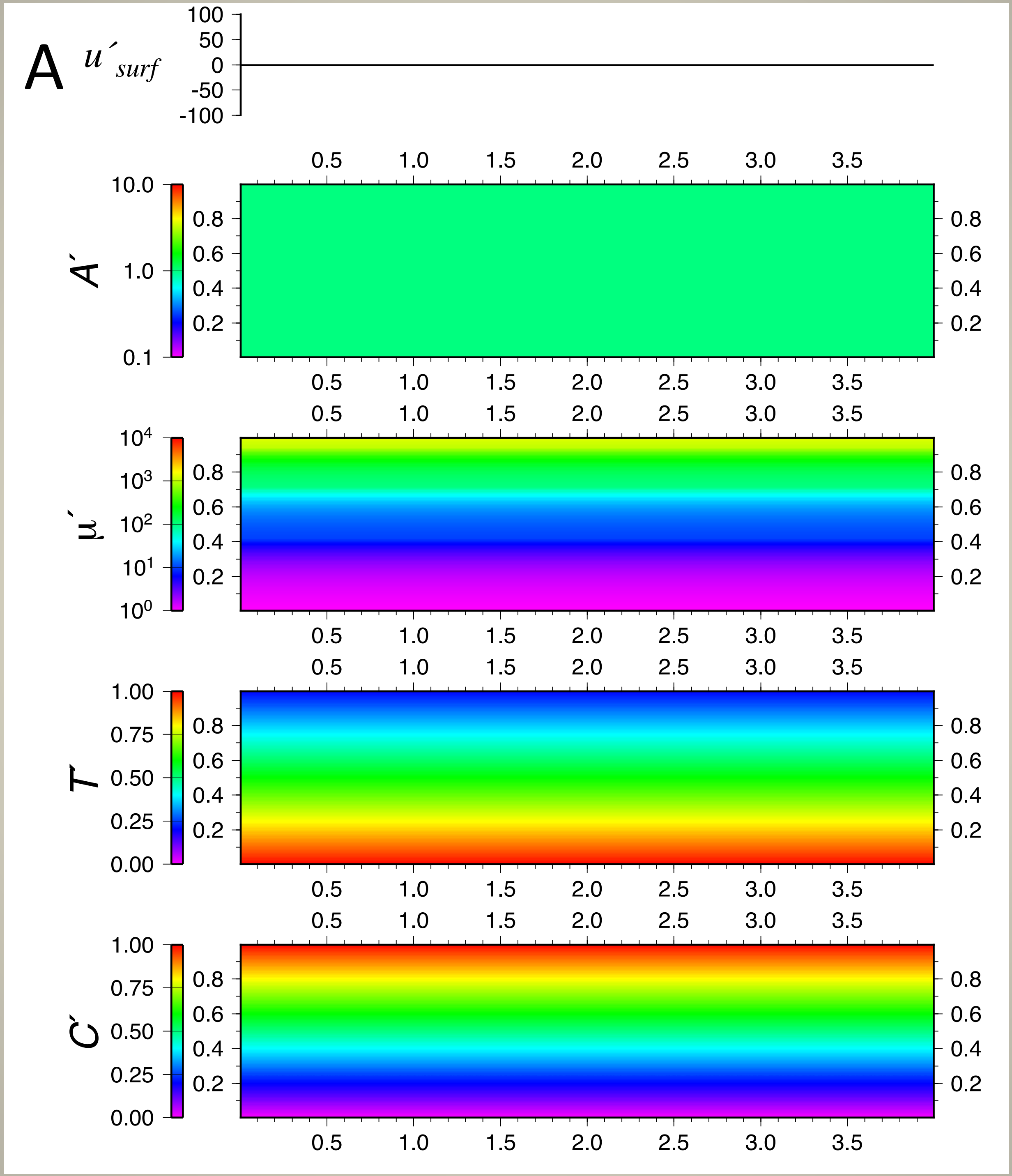
- Early degassing of CO_2 and H_2O increases T (GH radiative model) and P
- Starting from black-body radiative equilibrium it could intersect Tc(P):
  - Atmosphere became saturated in H_2O, drives condensation, limits H_2O GHG effect
  - CO_2 levels and T could increase but still some liquid remain if T stays on Tc(P)
  - (Earth currently in H_2O saturation, equilibrium with oceans; H_2O is still most important GHG but no runaway since short residence time – what goes in comes out; not so with CO_2)

Driscoll & Bercovici, 2013 after Ingersoll 1969

“Plates” first? Post-magma ocean convection



- Thermo-chemical convection models with simplified grain-damage (Foley et al, 2014)
  - Unstable chemical stratification during magma ocean crystallization (Elkins-Tanton, 2003)
  - Rapid chemical overturn followed by build up to thermal convection
  - What is lag from first overturn to mantle convection?
  - Is first mantle convection stagnant lid?



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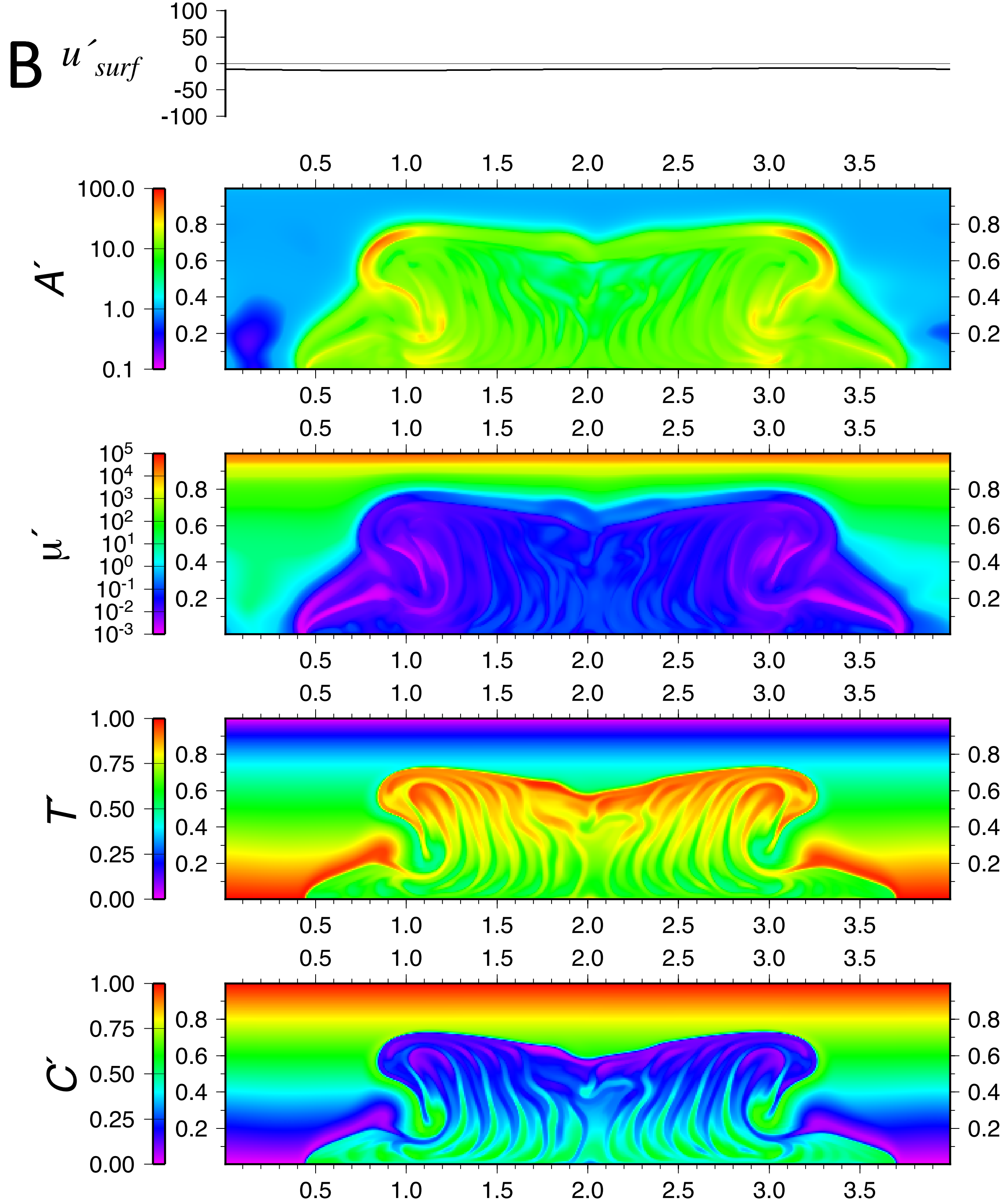

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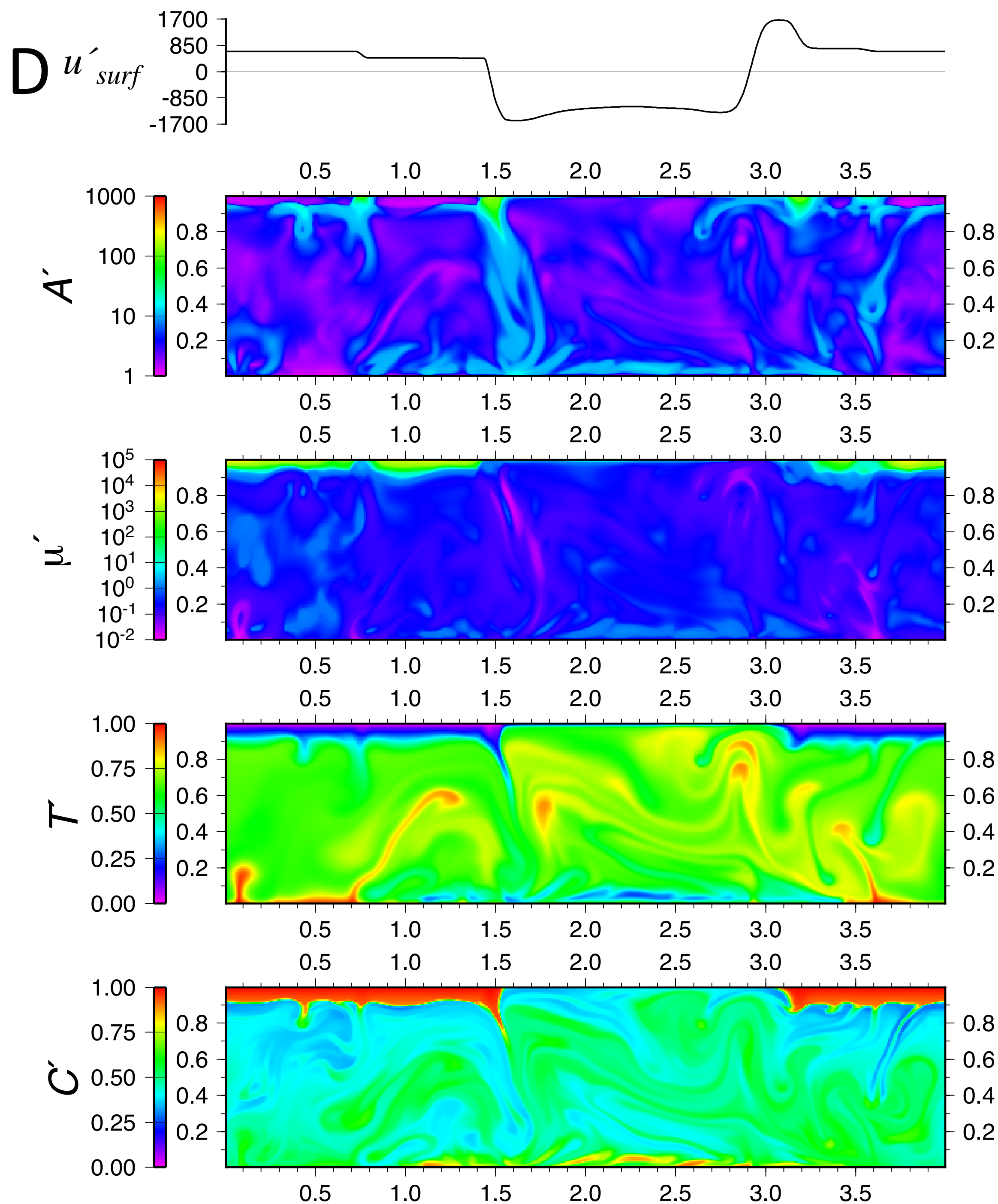

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T
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C´

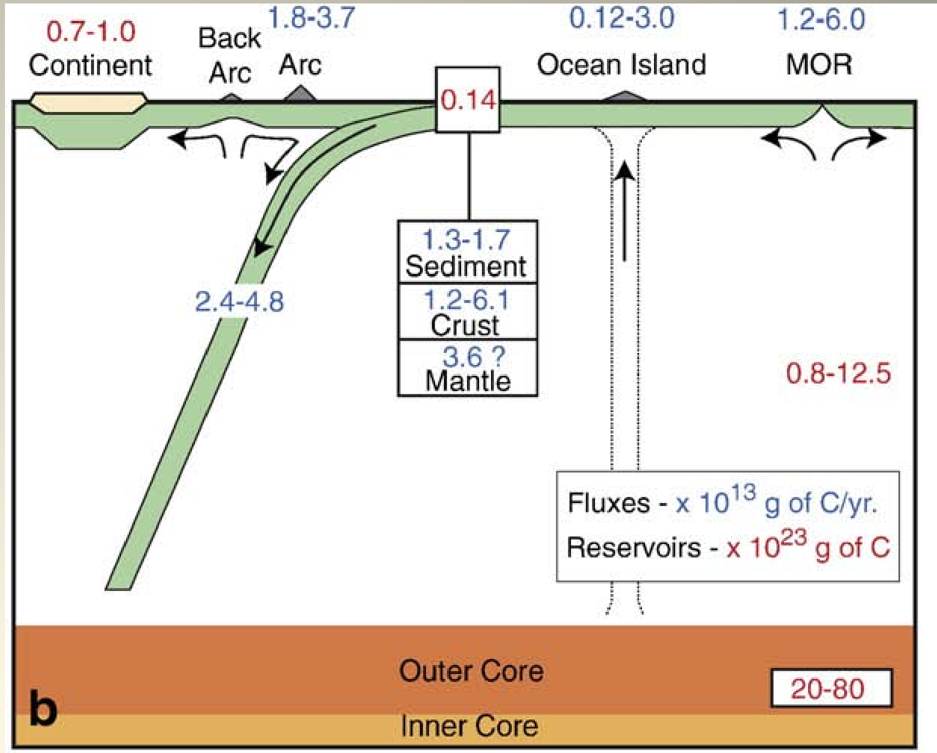
Plates or Water first?

- Even if water condensation first it's still not enough to draw down CO_2 alone. Need mineral exposure also.
  - Raw mafic surface? Highly reactive but "armors" and saturates
  - Basalt volcanism? Flux high enough? Why not Mars?
  - Lithospheric drips? The base drips, no surface ingestion?
- If plates first, can it draw down CO_2 without water?
  - Need hydrologic cycle and carbonic acid reactions?
- **Is their co-occurrence at the right temperature (T=300C???) required????**

Eoarchean CO_2 drawdown

- Currently modest CO_2 level draw-down into rocks is biologically mediated to create and sustain limestone reservoir
- What about draw-down of thick CO_2 atmosphere (before life began)?
- Was CO_2 being ingested by bigger reservoir, i.e. the mantle? (Sleep & Zahnle, 2001)

Carbon ingestion



- CO_2 ingestion is possibly large:
  - ***Slab influx ≈ 60-110 Mt C/yr***
  - ***Ridge efflux ≈ 10-60 Mt C/yr***
  - ***Arc efflux ≈ 20-40 Mt C/yr***
  - ***Net influx < 30 Mt C/yr***

    (Dasgupta & Hirschmann 2010; note *Mt=10^9kg)*
- This ingestion rate suggests a huge CO_2 sink
  - Large carbon ingestion implies degassing of primordial atmosphere is a problem
    - perhaps subduction not significant then? (DH2010))
- **Sleep and Zahnle (2001) propose large influx buffers out early CO_2**

Carbon flux (latest)

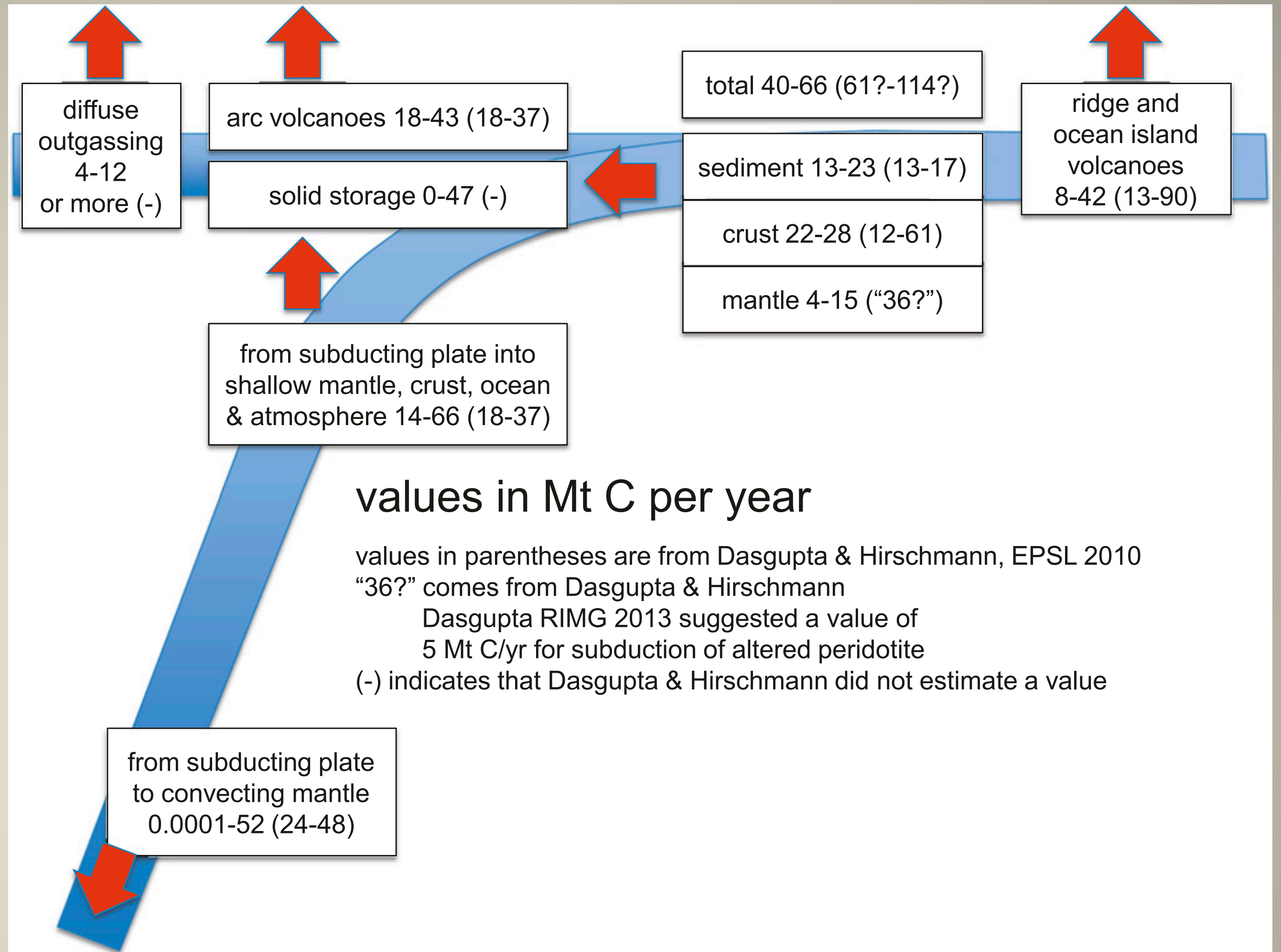
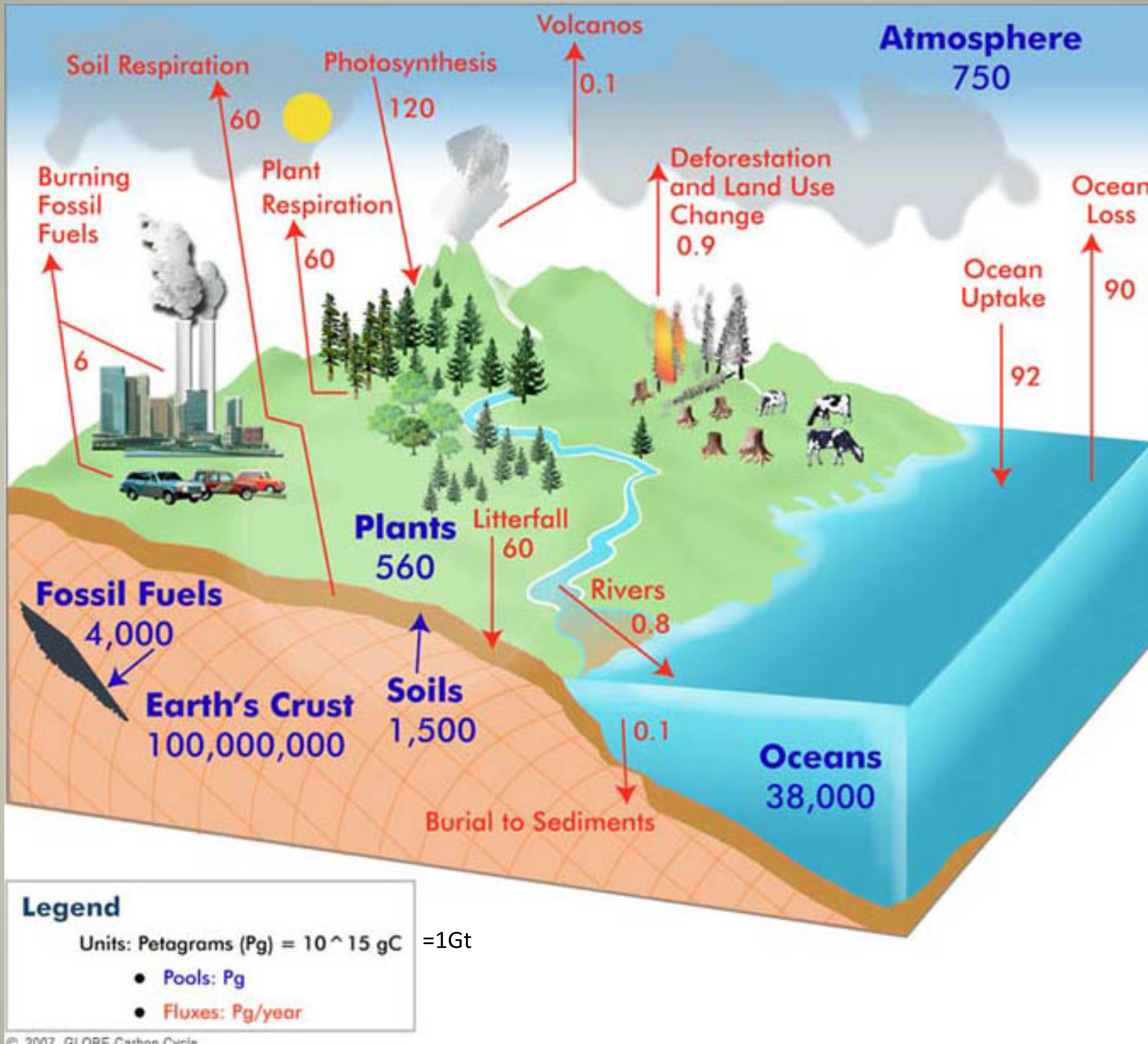


Fig. 5. Major fluxes of carbon estimated in this paper, with values from Dasgupta and Hirschmann (1) for comparis

- Accounting for carbonate solubility in aqueous solutions and sediment upwelling:
- Possibly little flux goes into mantle, but then too much to account for arcs
- Possibly stored in lithosphere

(Kelemen, Manning, PNAS 2015; Ague,Nicolescu NatGeo 2014)



=1Gt

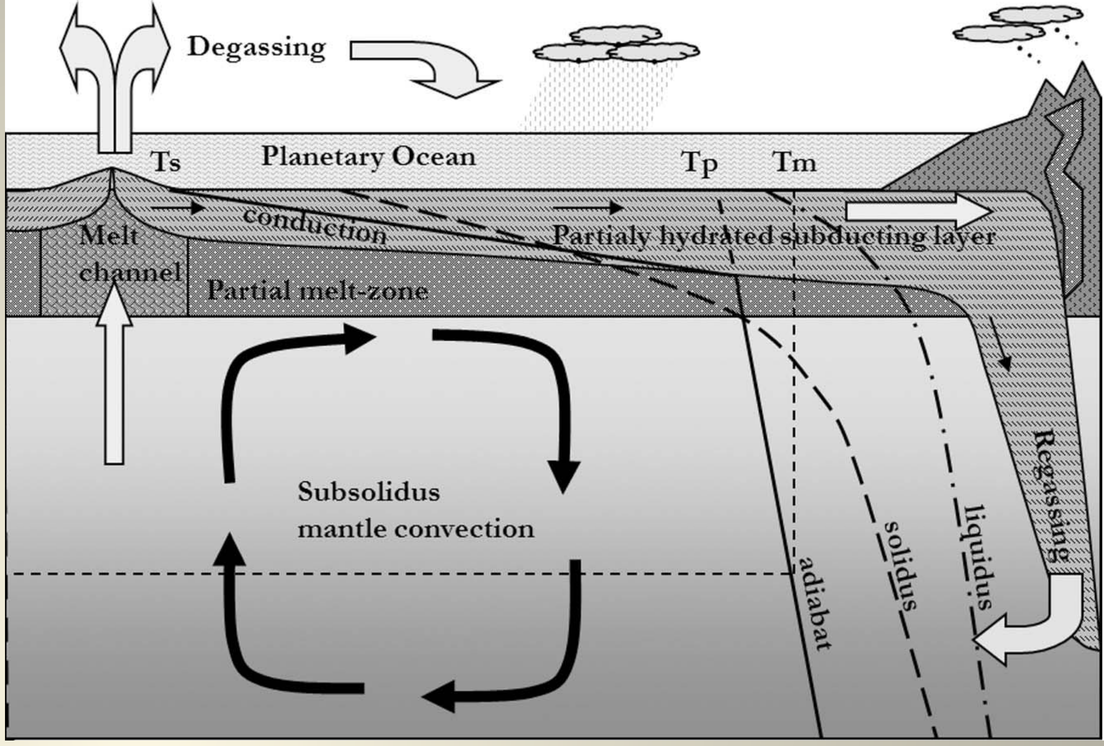
University of New Hampshire (http://globecarboncycle.unh.edu/diagram.shtml)

CO_2 Draw-down Quandaries

1. Drawdown or regassing requires significant plate tectonic cycling and subduction
   - But chondrite model that explains “endogenic” degassing volatile origin…
   - Also suggests weak radiogenic heat sources and hence mantle heat loss mostly primordial heat (>60%)
   - *Begs for plate tectonics to be slower or even stagnant* to slow down cooling and retain primordial heat longer (or else Earth is too young or molten not long ago)

2. If initial atmosphere came via degassing from freezing magma ocean and cooling Earth, <u>why would it regas</u>?
   - Freezing MO and cooling mantle can’t hang on to volatiles
   - Degas until chemical equilibrium with surface
   - Why would it then redisolve volatiles from surface (unless it over-shot equilibrium, which is hard to imagine in a slowly cooling and moving planet)?

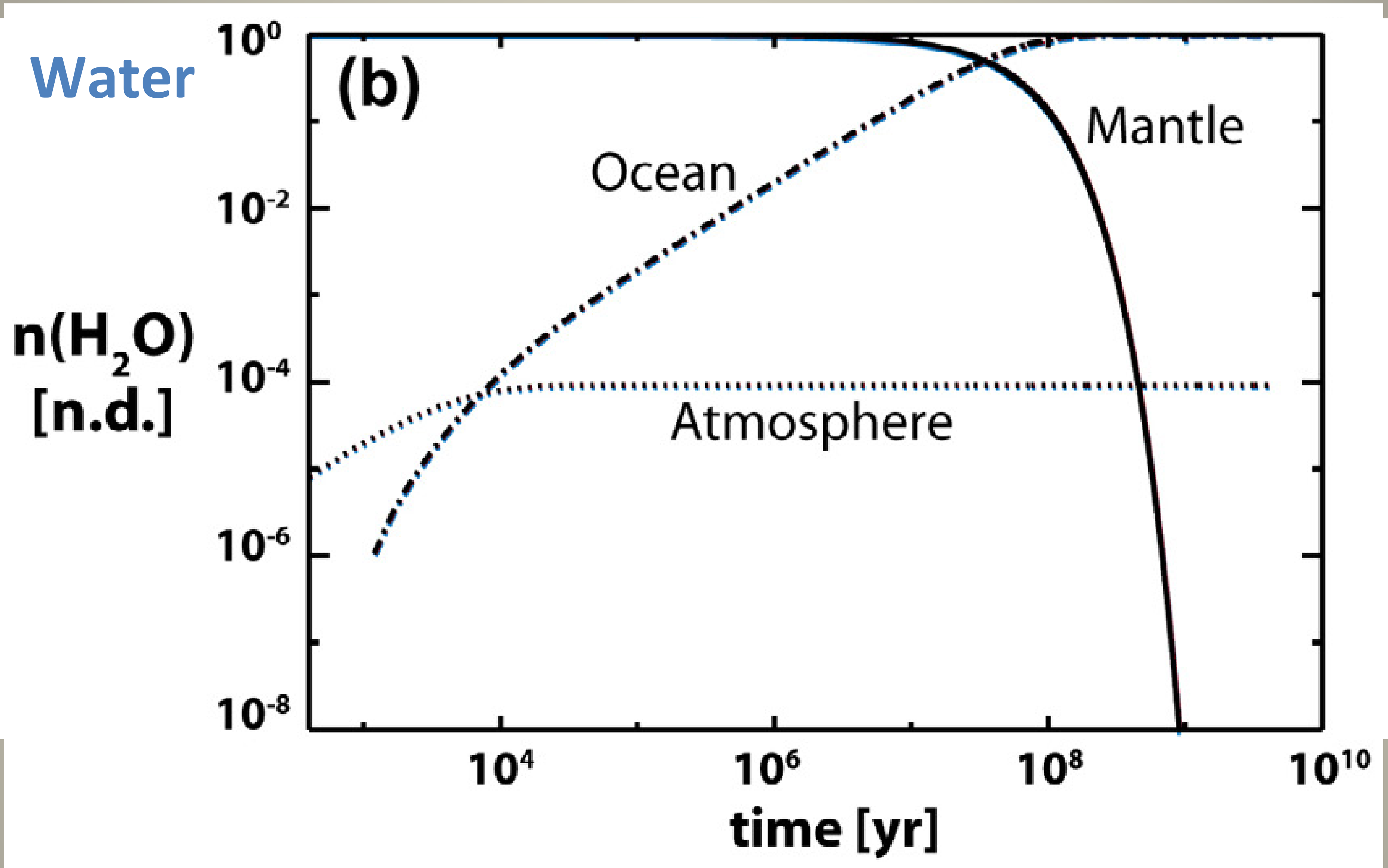
Lessons from dynamics of damp mantle



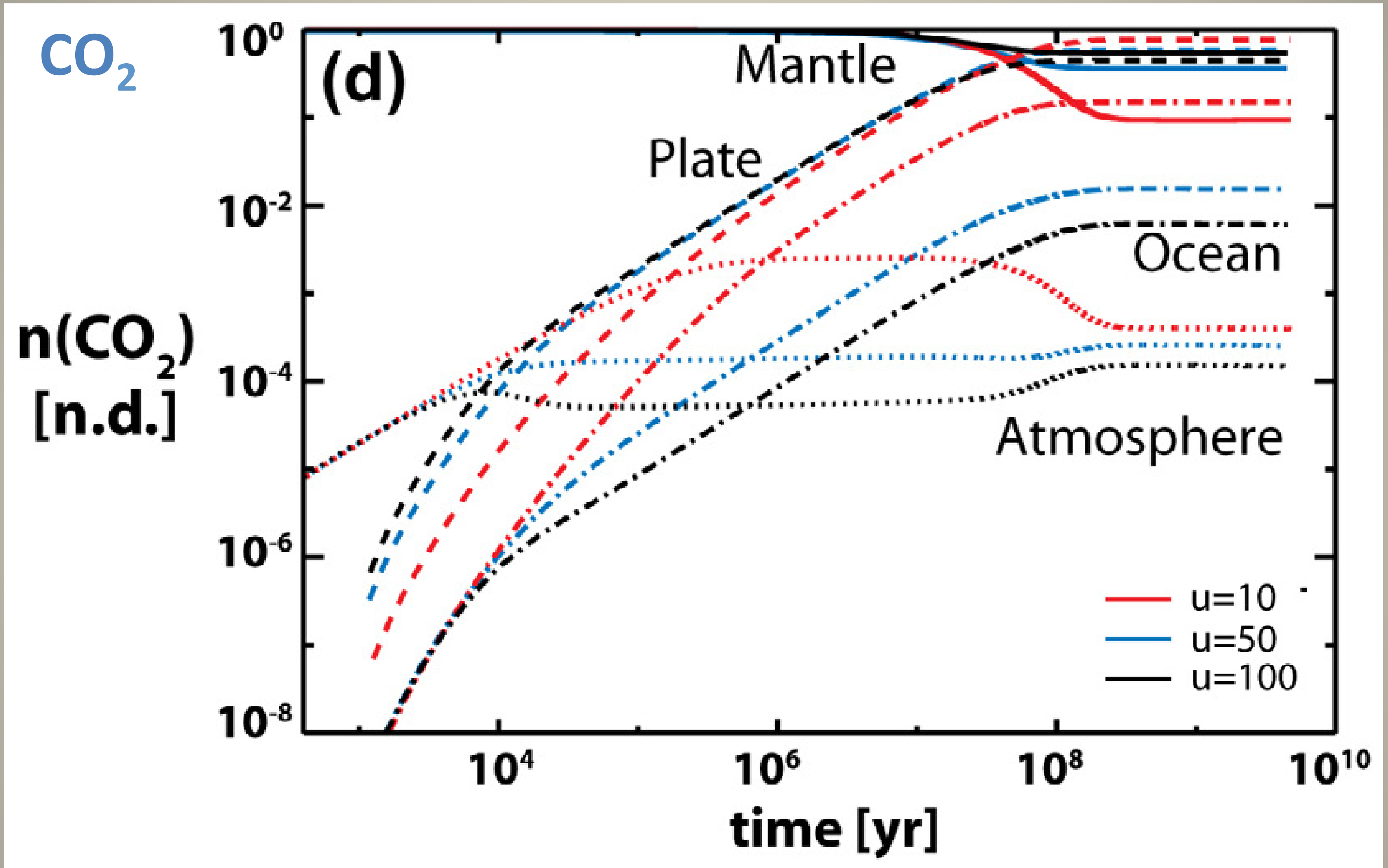
Sandu et al JGR 2011

- Regassing-degassing models of mantle circulation with water
- Water lowers mantle viscosity so causes self regulating feedback
  - If it gets too wet by too much regassing then convection is more vigorous and degasses
- Sensitivity of viscosity and melting to water makes degassing more efficient than regassing and so keeps mantle dry
- **Goes to equilibrium with surface early and stays there**
- CO_2 is different since it has little effect on viscosity, but still causes melt

- (McGovern & Schubert 1989, Bounoma et al 2001; Sandu, Lenardic, McGovern 2011; Driscoll Bercovici 2013



Degassing/regassing system model (Driscoll & Bercovici Icarus 2013)



Degassing/regassing system model (Driscoll & Bercovici Icarus 2013)

Summary

- Why Earth? Plates? Water? Clement climate? Life?
- Origin of volatiles (and everything else)
- Divergent evolution of terrestrial planets
  - What drew down CO_2 on Earth?
- Mantle convection and plate tectonics
  - Plate tectonic (geological) carbon cycle
  - Why only plates on Earth?
    - Plate generation and "damage"
  - Climate possibly also controls conditions for plates
- If climate/water needs plates and plates need climate/water, **which came first?**
    - What drew down CO_2? Deep carbon flux?
    - Why regas after degassing?