



# Earth Sweet Earth

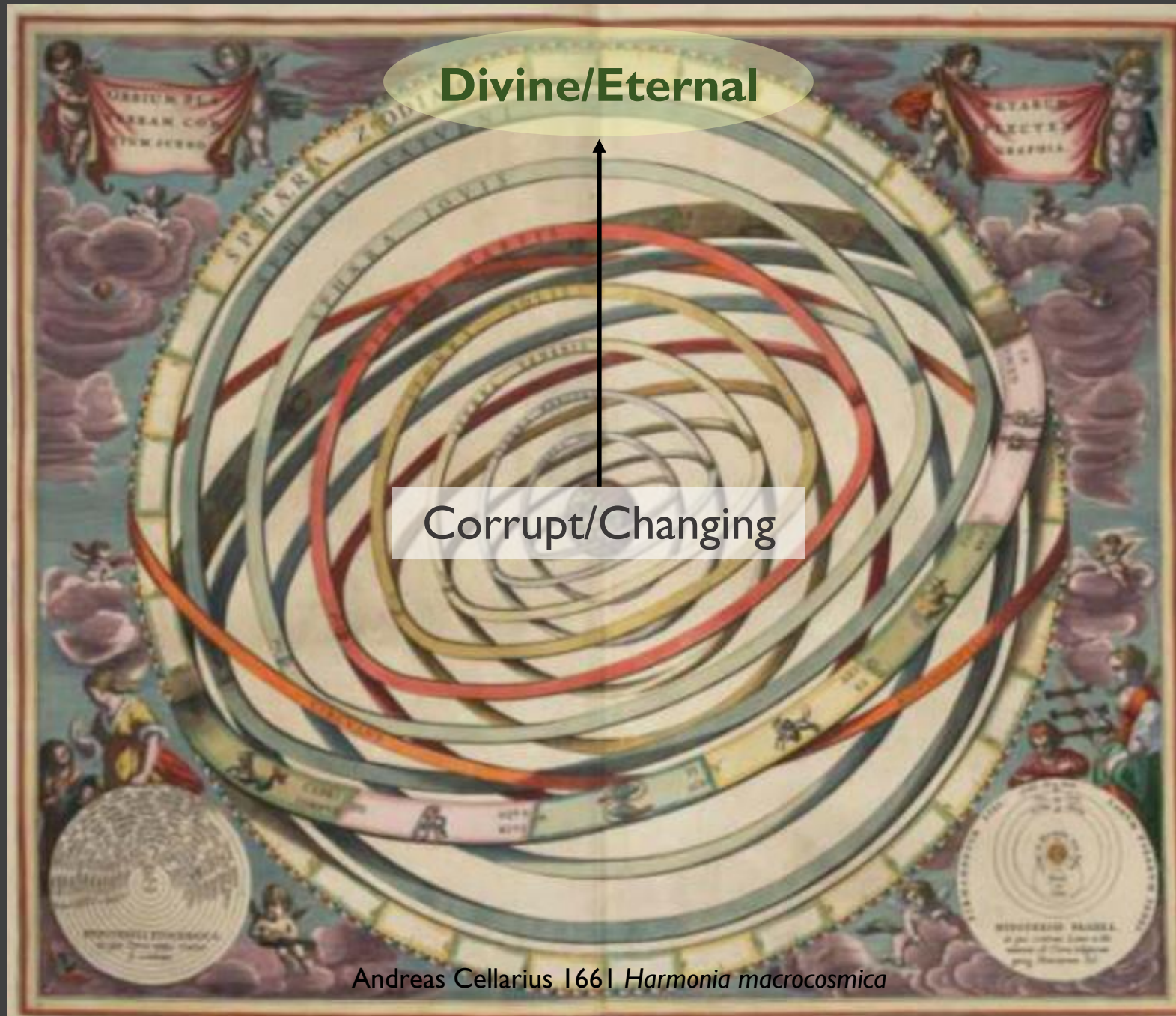
## The deep logic of the planet

Marcia Bjørnerud

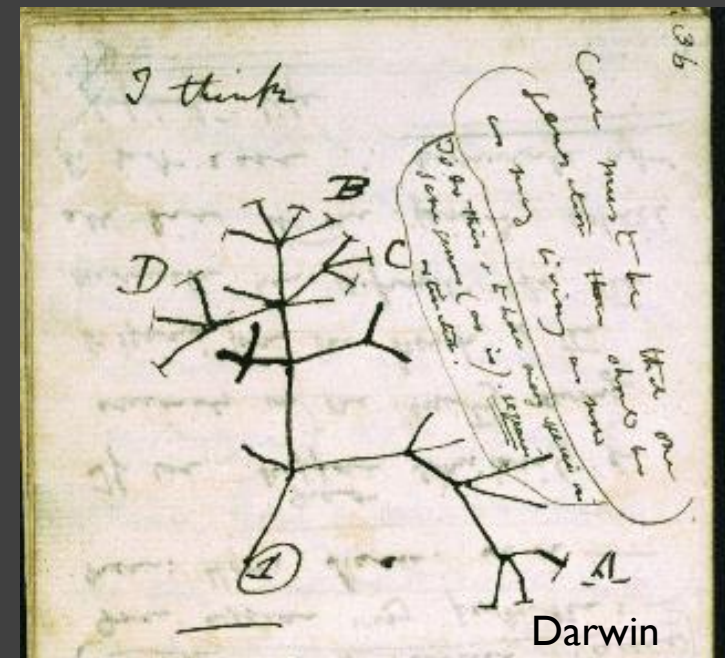
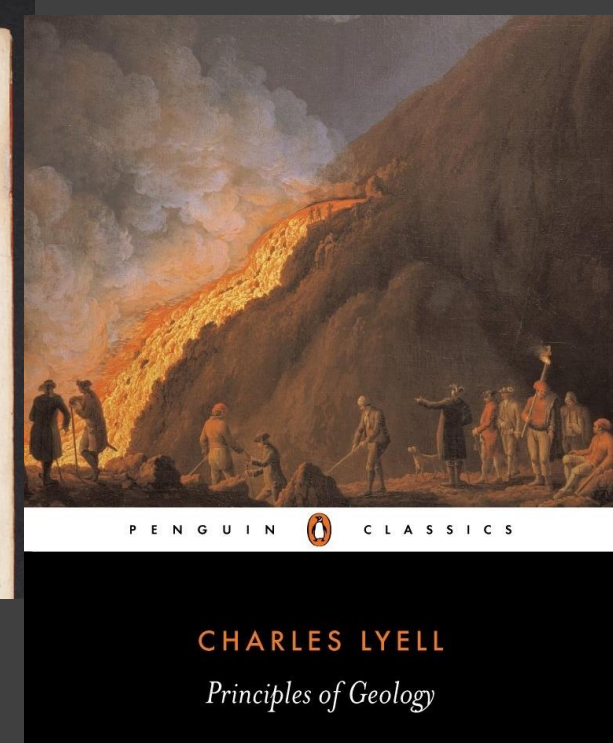
Professor of Geosciences

Lawrence University

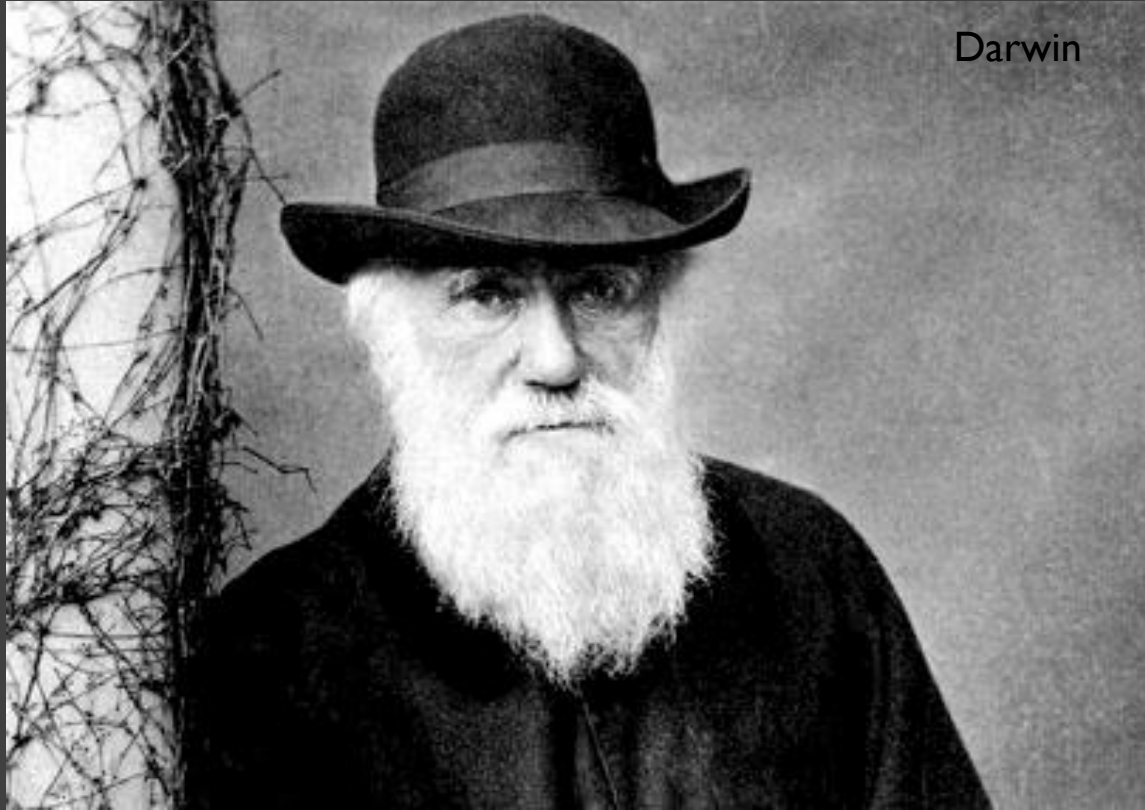
Appleton, Wisconsin



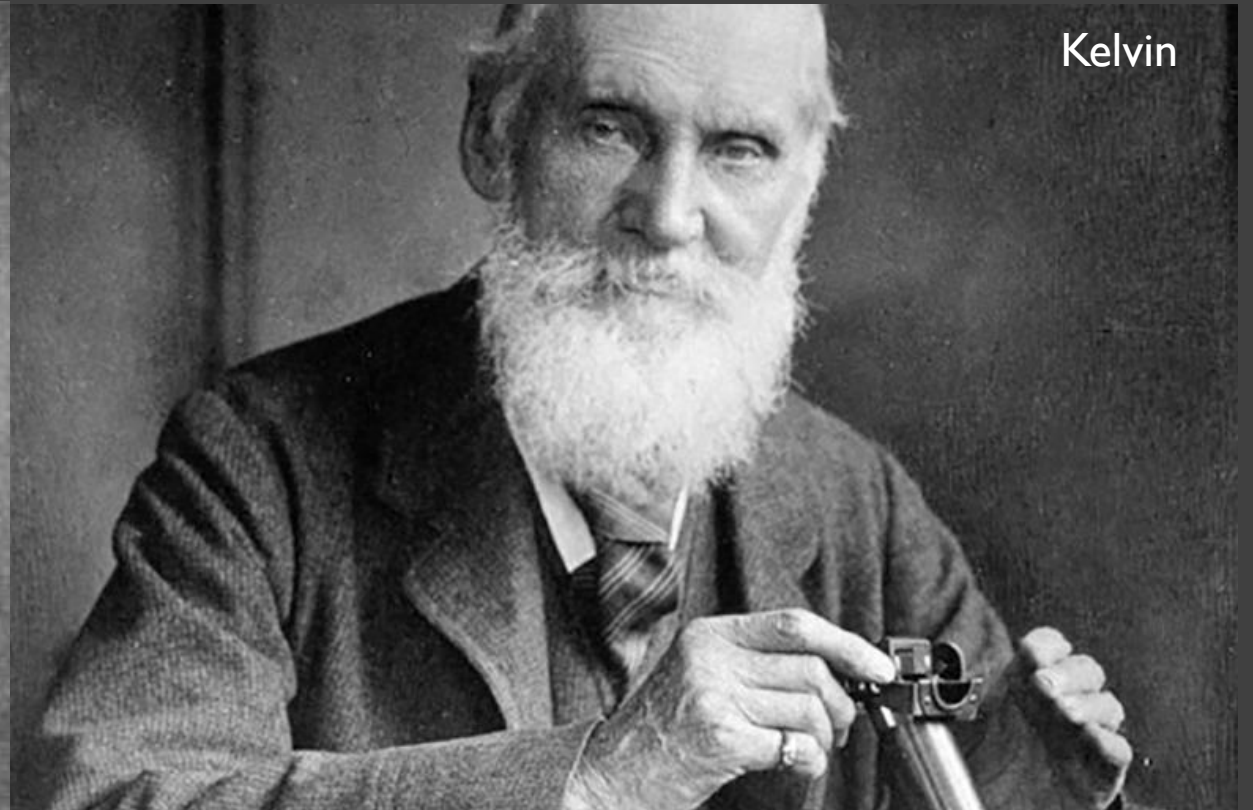
We've long had trouble seeing the planet in proper perspective



## Early glimpses of the whole



Darwin



Kelvin

But then, a shortage of time

## A century of myopia

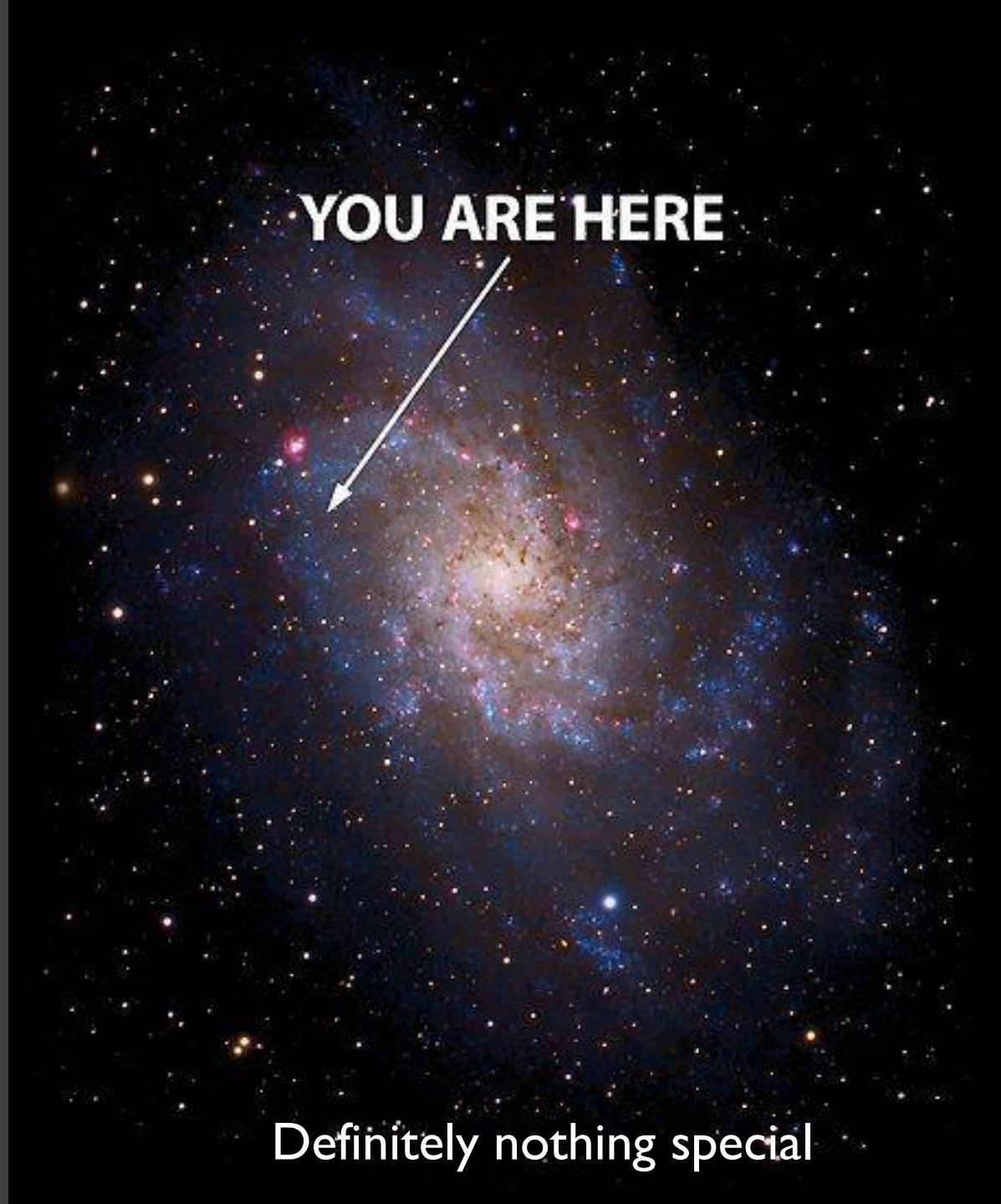


Old, dull and irrelevant –  
But also deeply threatening to  
cherished beliefs about ourselves



Venal, profit-driven

Humbling  
astronomical  
demotion



Definitely nothing special

© Tom Toro

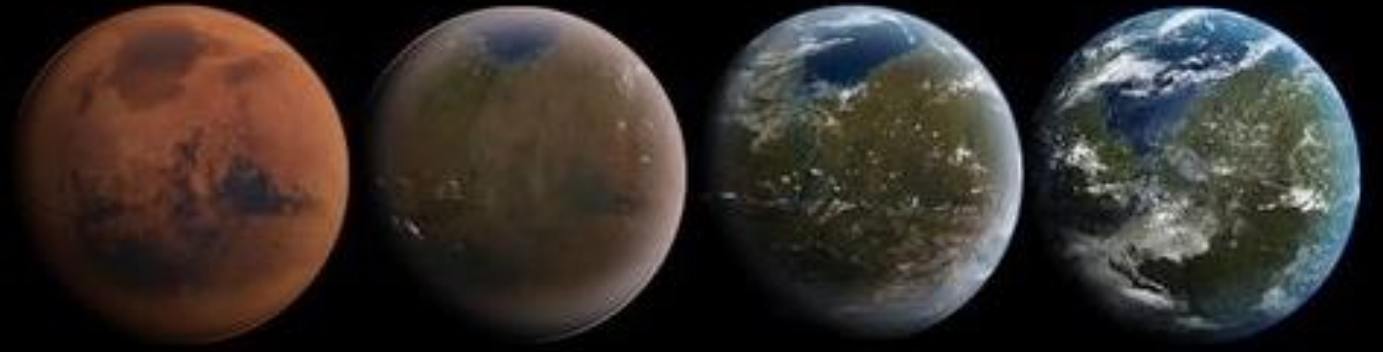
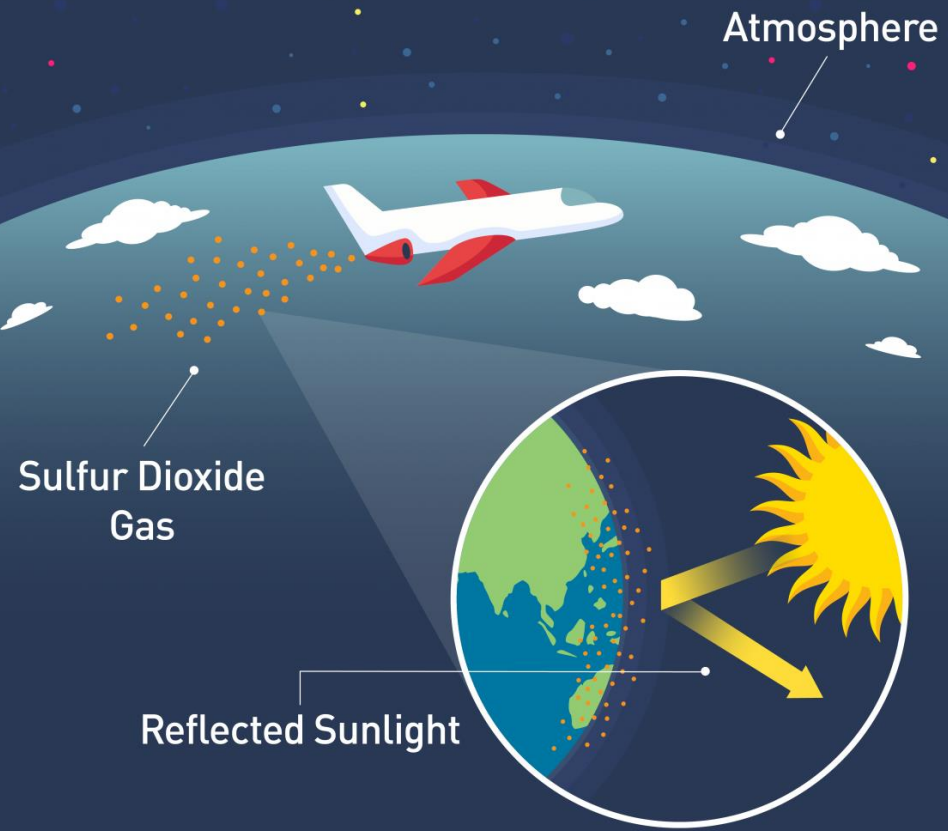


*“Yes, the planet got destroyed, but for a beautiful moment in time, we created a lot of value for shareholders”*

Economically  
motivated  
delusions

## Delusions (cont.)

### STRATOSPHERIC AEROSOL INJECTION




SpaceX.com



humanmars.net

Only recently have we  
had the conceptual  
framework and  
analytical tools to see  
the Earth clearly over a  
range of spatial and  
temporal scales

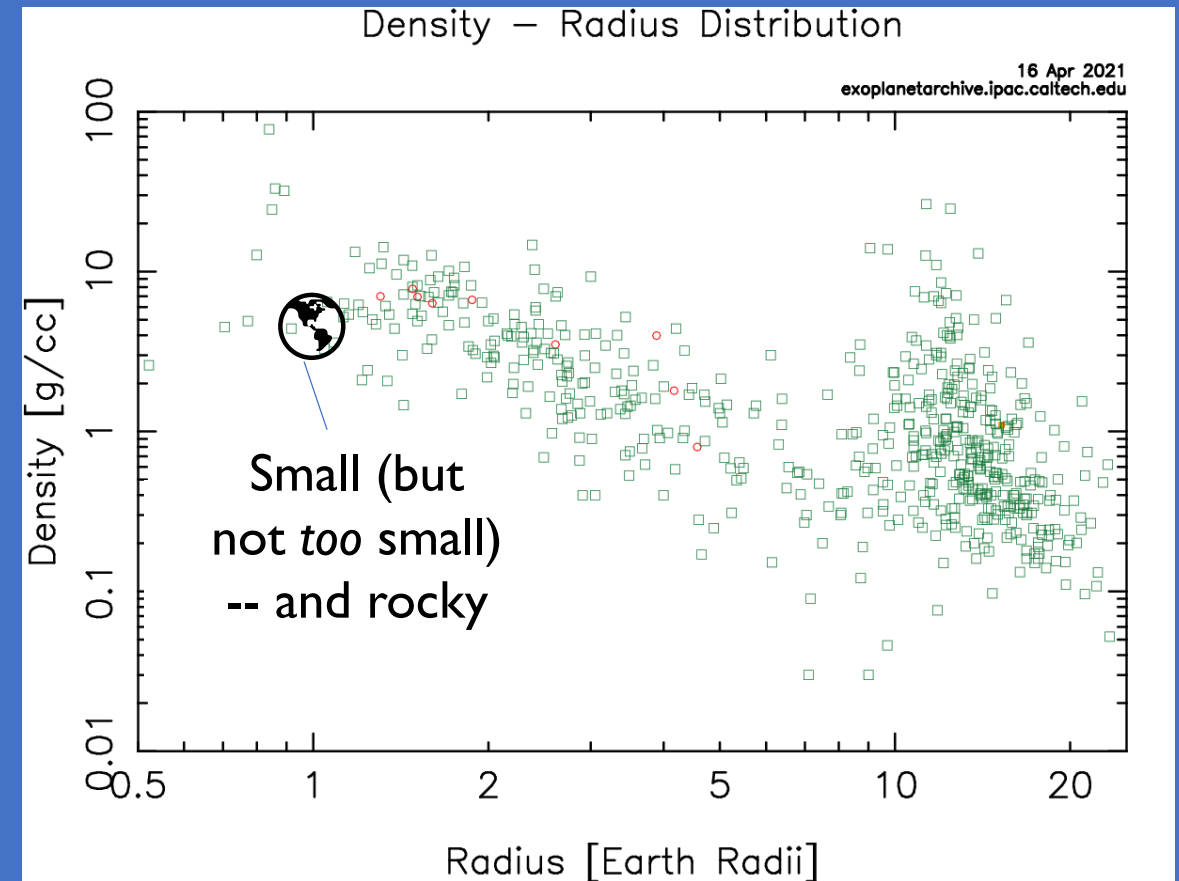
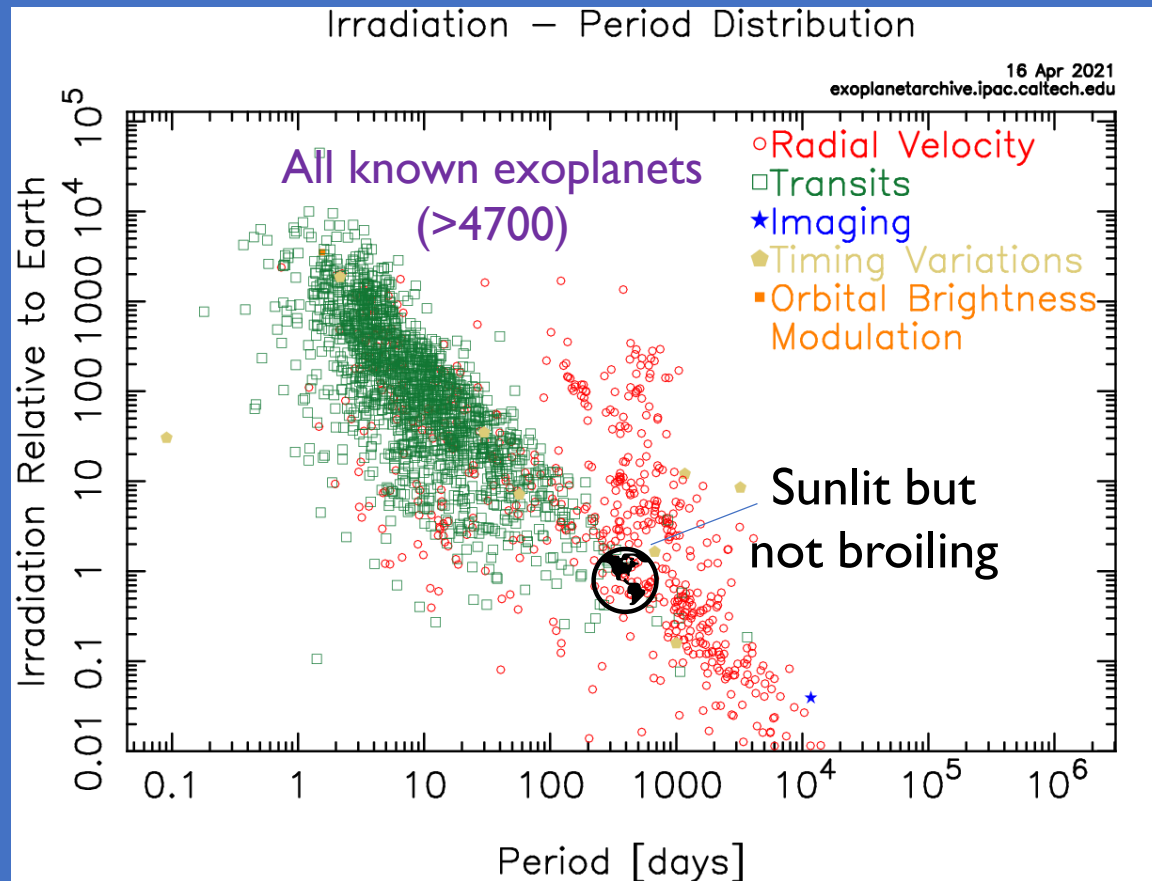




Only recently have we  
had the conceptual  
framework and  
analytical tools to see  
the Earth clearly over a  
range of spatial and  
temporal scales

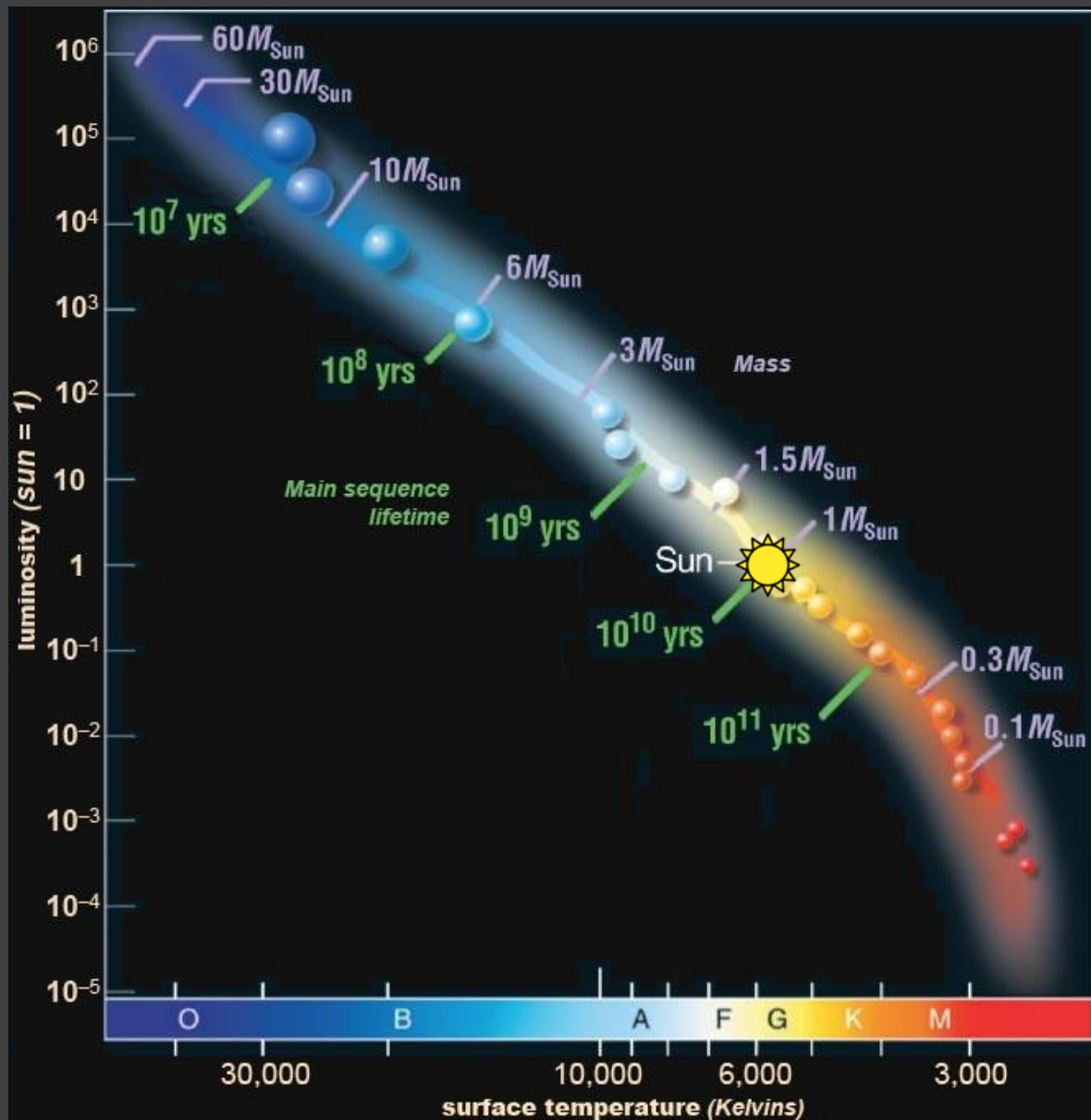
Old? Very.  
But responsive, resilient,  
subtle, sophisticated –  
far beyond our engineering  
capacity or design prowess

# A lucky start



Not too hot and not too cold

The right ingredients in the right amounts



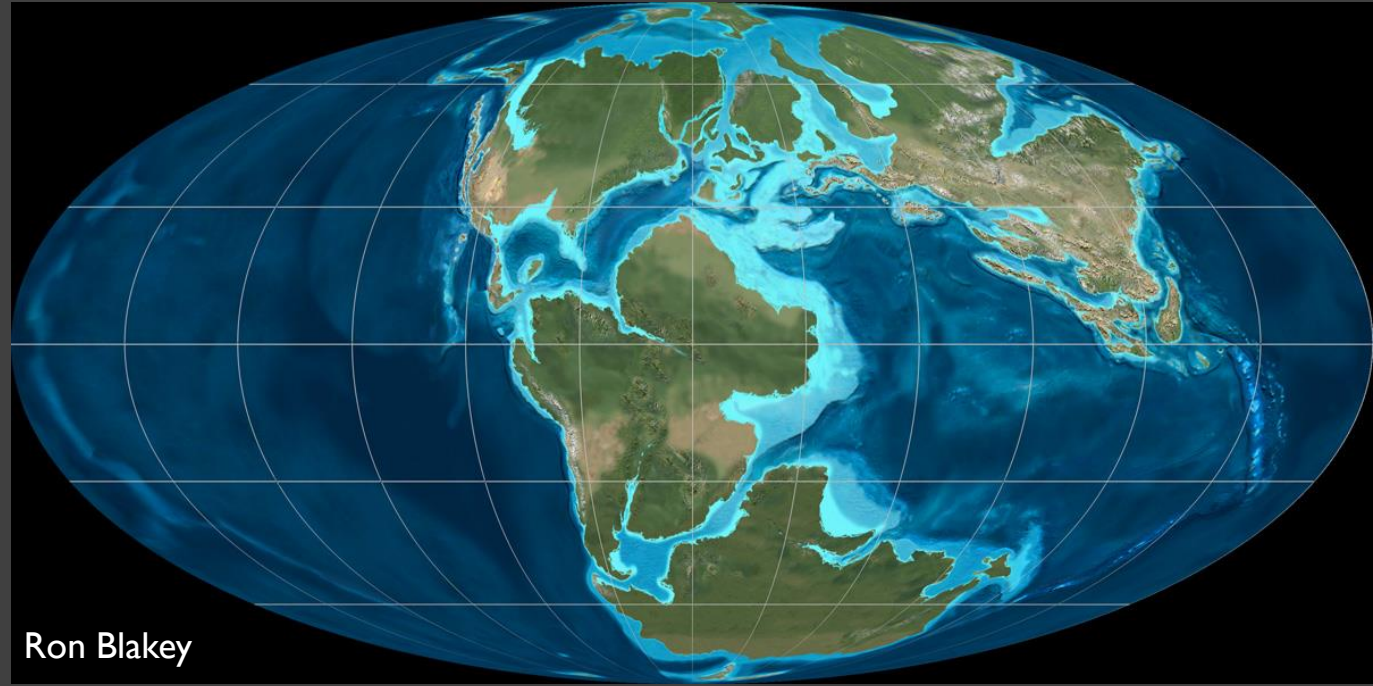
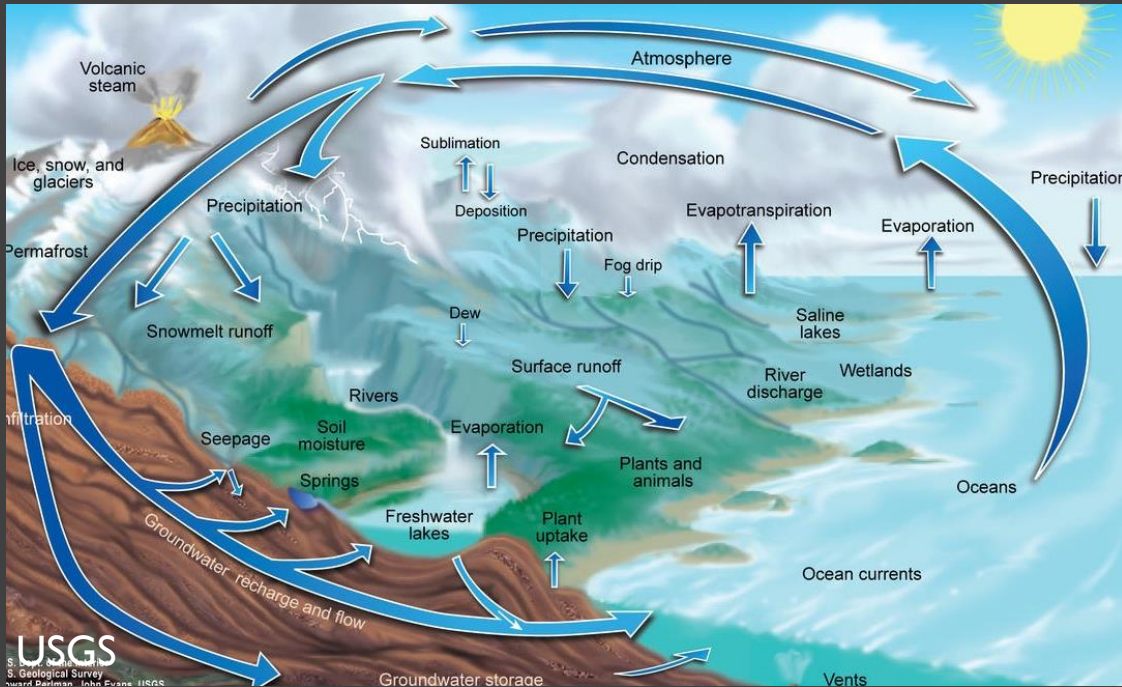
# Oceans of time



An aerial photograph of a massive ocean wave, likely a tsunami or a large storm surge, with a large plume of white foam at its crest. The water is a deep teal color, and the sky is a pale, hazy blue.

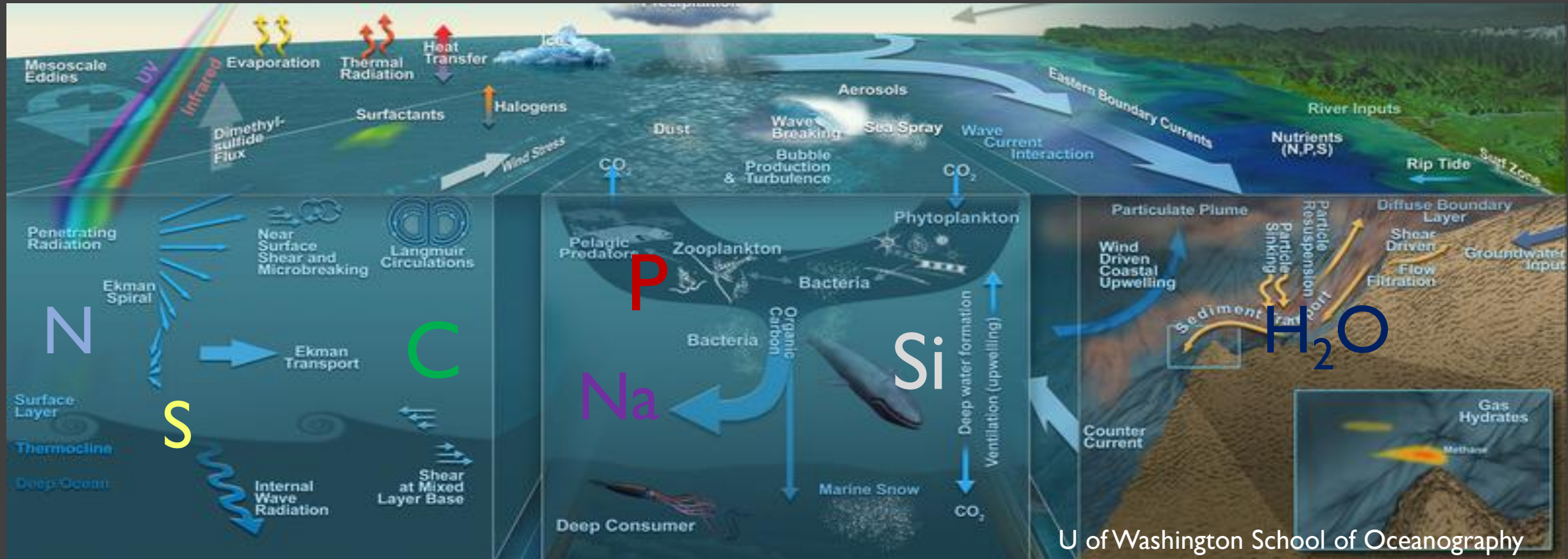
Eons of water 🌐

# Habits adopted and maintained over time 🌍





# The great biogeochemical cycles contradance



## Recycling Ratio

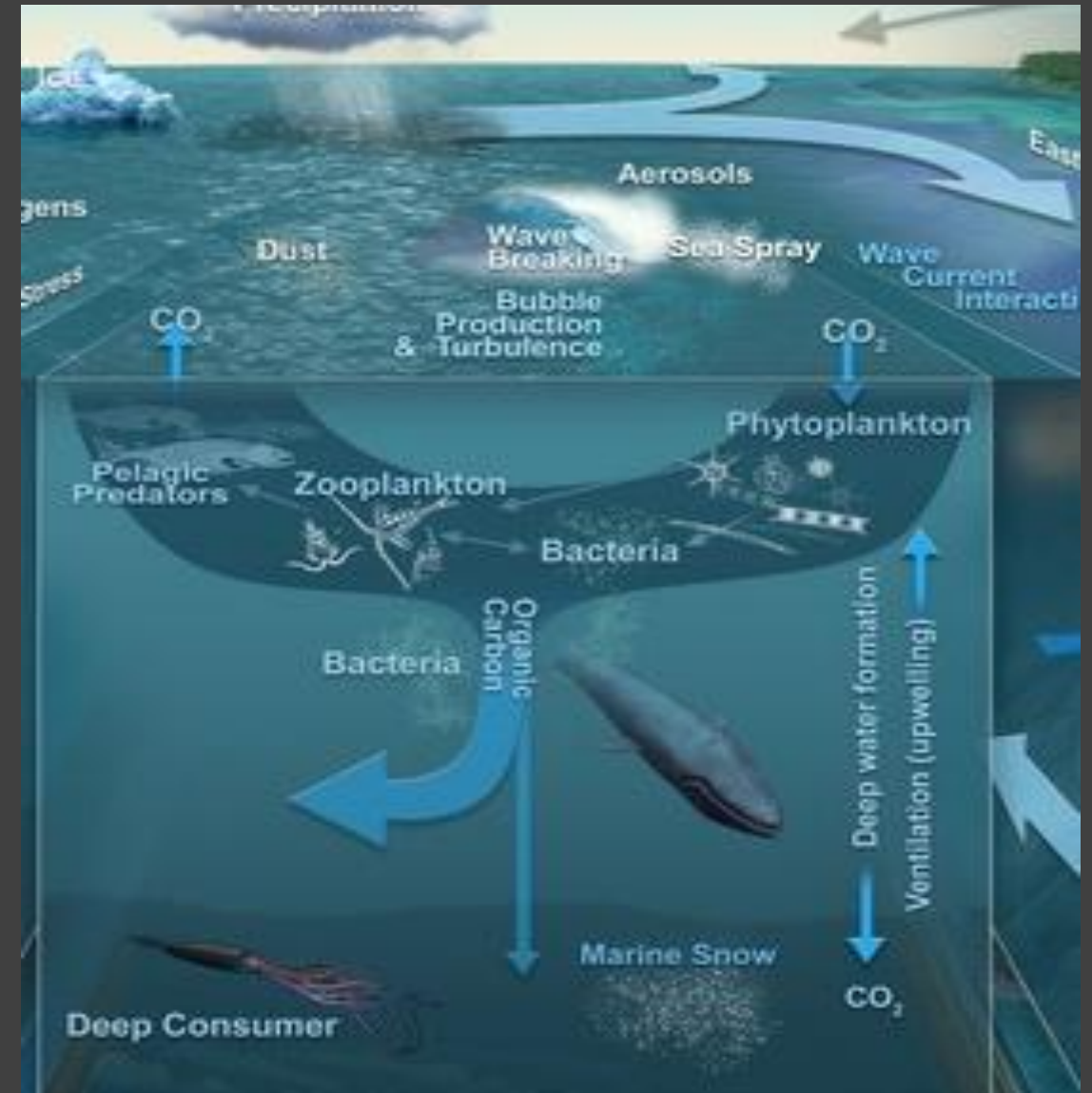
Ratio of amount of an element reused within biosphere to amount coming in from nonbiogenic sources

Calcium (4% of crust): 2

Potassium (2%): 10

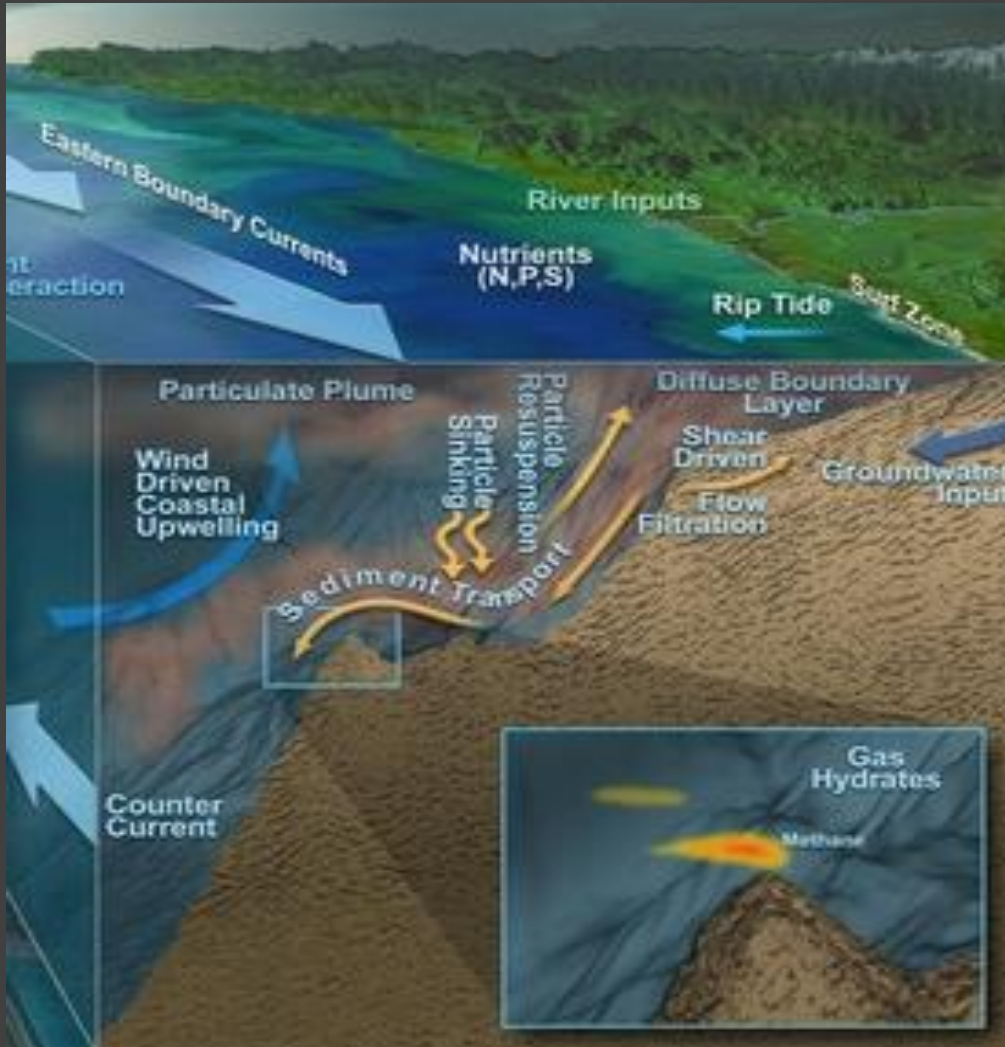
Phosphorous (<0.1%): 100

Schlesinger & Bernhardt, *Biogeochemistry*





$$\text{Residence time} = \frac{\text{Inflow or Outflow rate}}{\text{Reservoir size}}$$

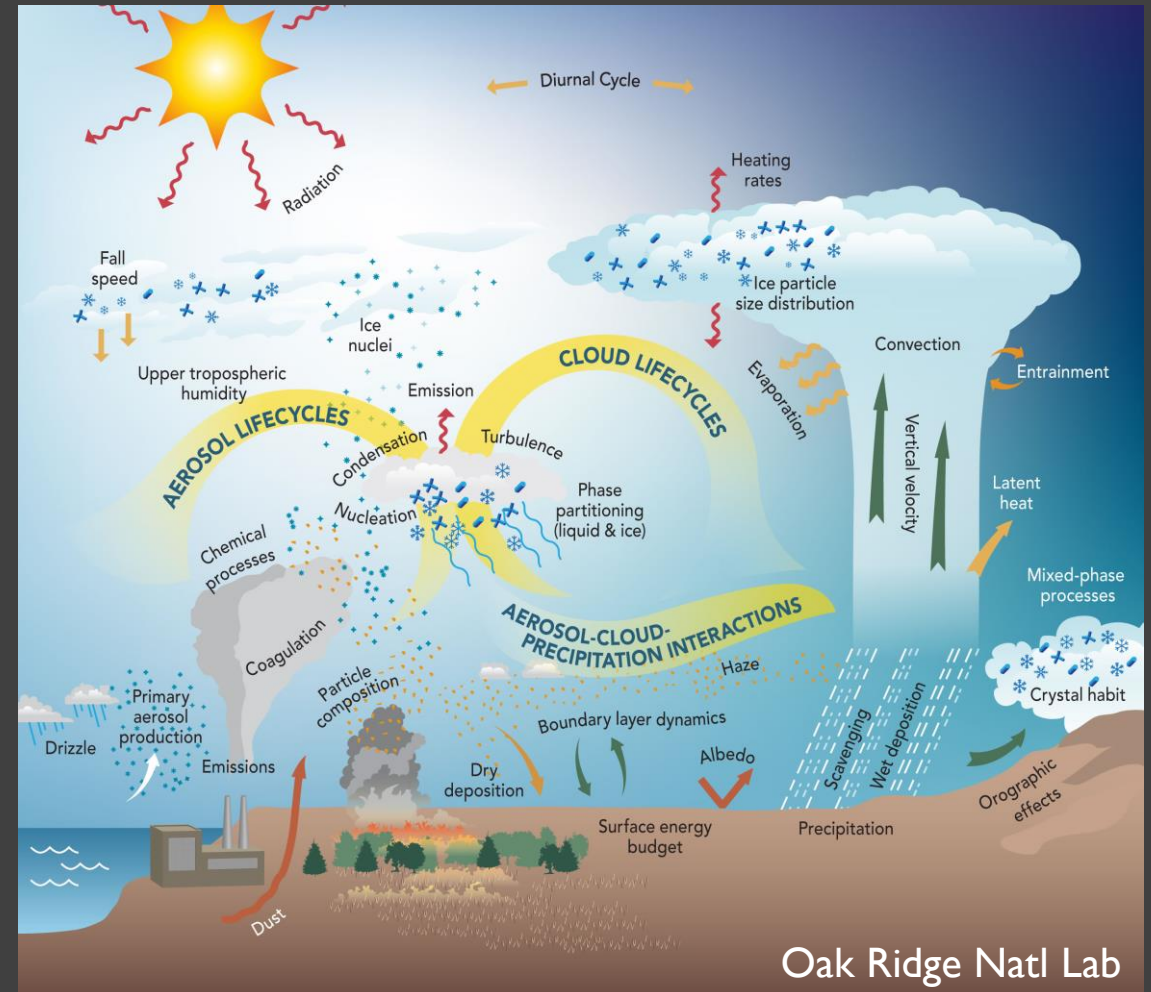


Of water in atmosphere: 9 days  
 water in oceans: 3000 yrs  
 water in the mantle:  $10^8$  yrs

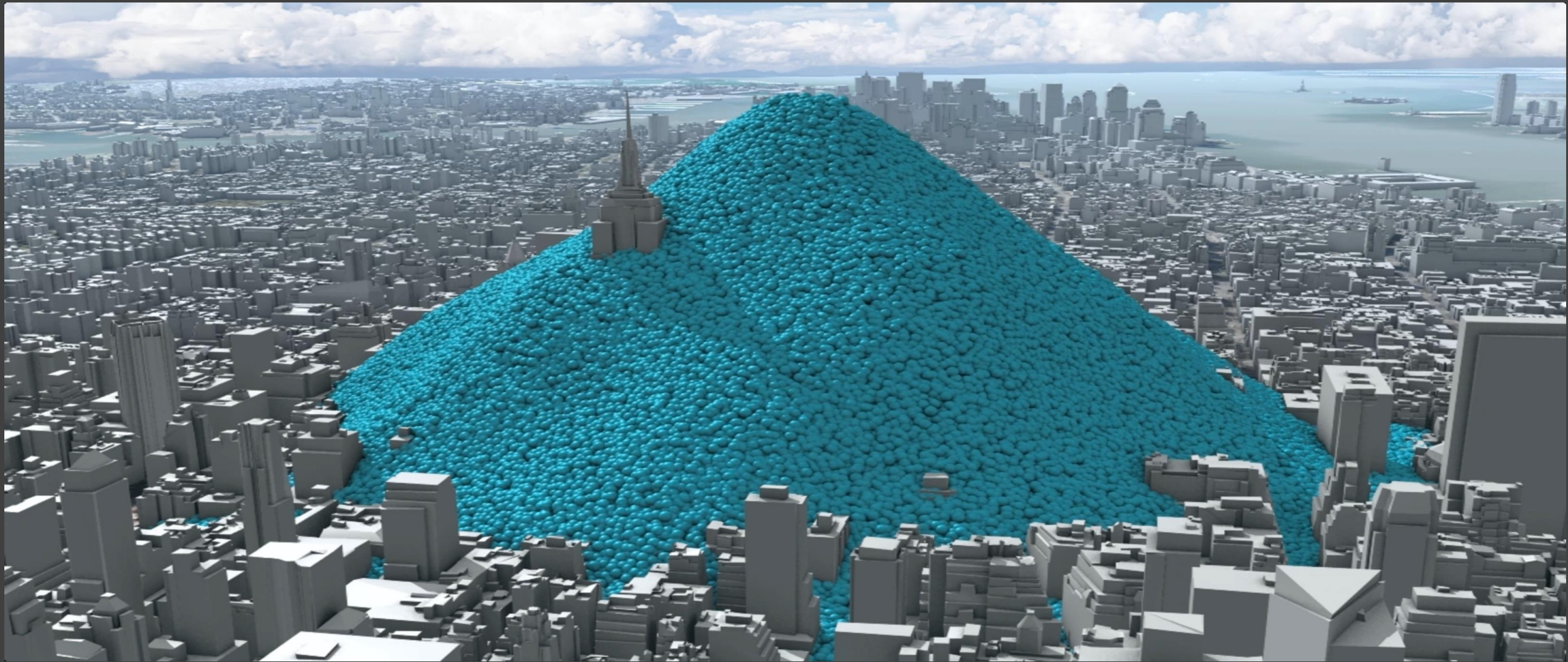
Of carbon in plants: 5 years  
 carbon in soils: 500 yrs  
 carbon in limestones:  $10^8$  yrs

Mixing time = Time for a component in a 'reservoir'  
to become homogeneously distributed

When  
Residence time < Mixing time,  
Concentrations vary spatially  
e.g., P in seawater;  
Coal-derived SO<sub>2</sub> in atmosphere  
Residence time > Mixing time,  
Reservoir is well-mixed  
e.g., Na in seawater;  
CO<sub>2</sub> in atmosphere



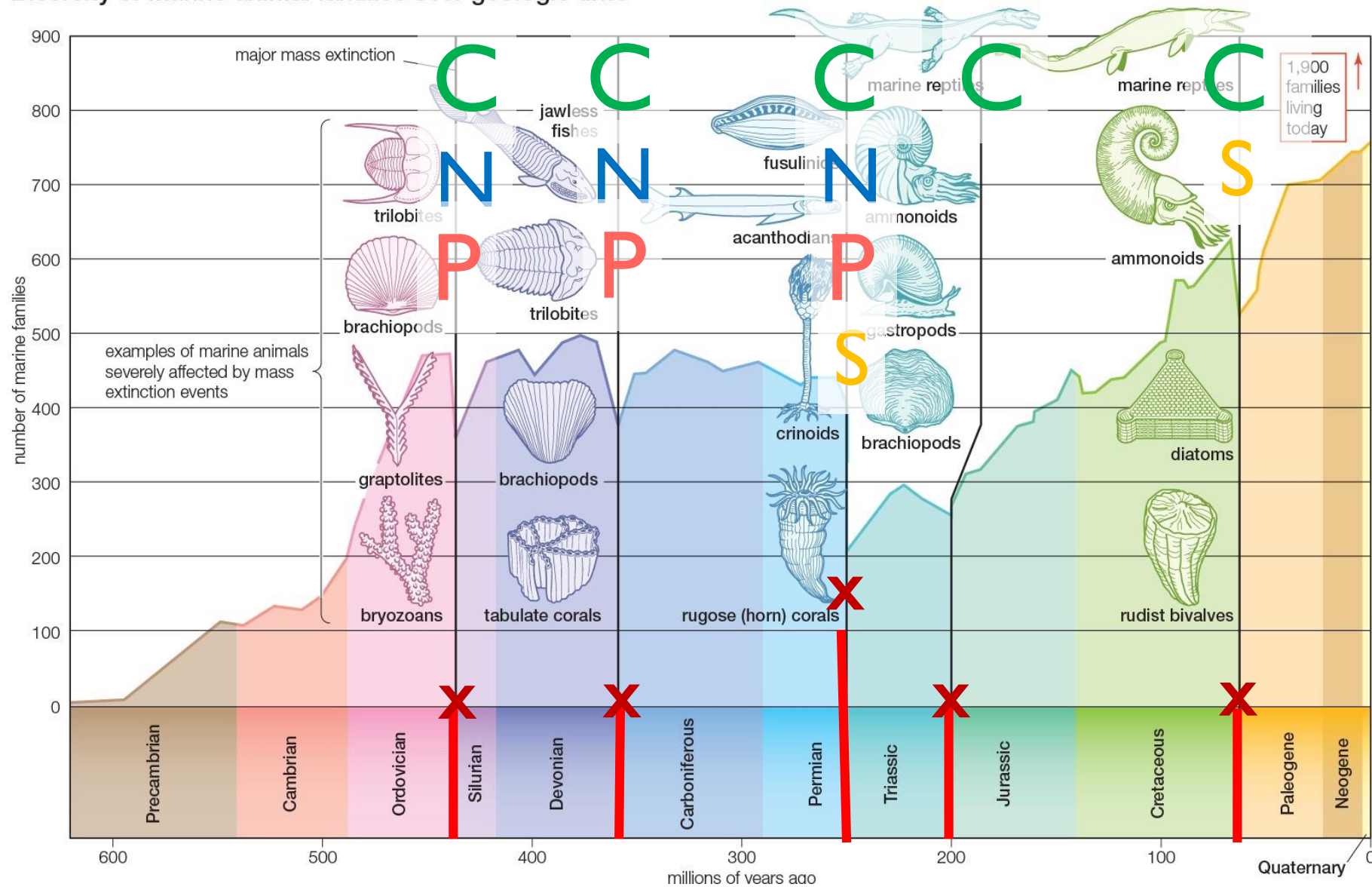
If CO<sub>2</sub> mixing time were *longer* than its residence time...



One year of CO<sub>2</sub> emissions in New York City as one-ton spheres

Adam Nieman & Chris Rabet

Diversity of marine animal families over geologic time



All of the great mass extinctions of the past 500 million years were linked with major disruptions of biogeochemical cycles (and ensuing climate and food web consequences)



Nekton (10 cm–2 m)

Macrozooplankton + micronekton (2 mm–10 cm)

Zooplankton (20–2000 μm)

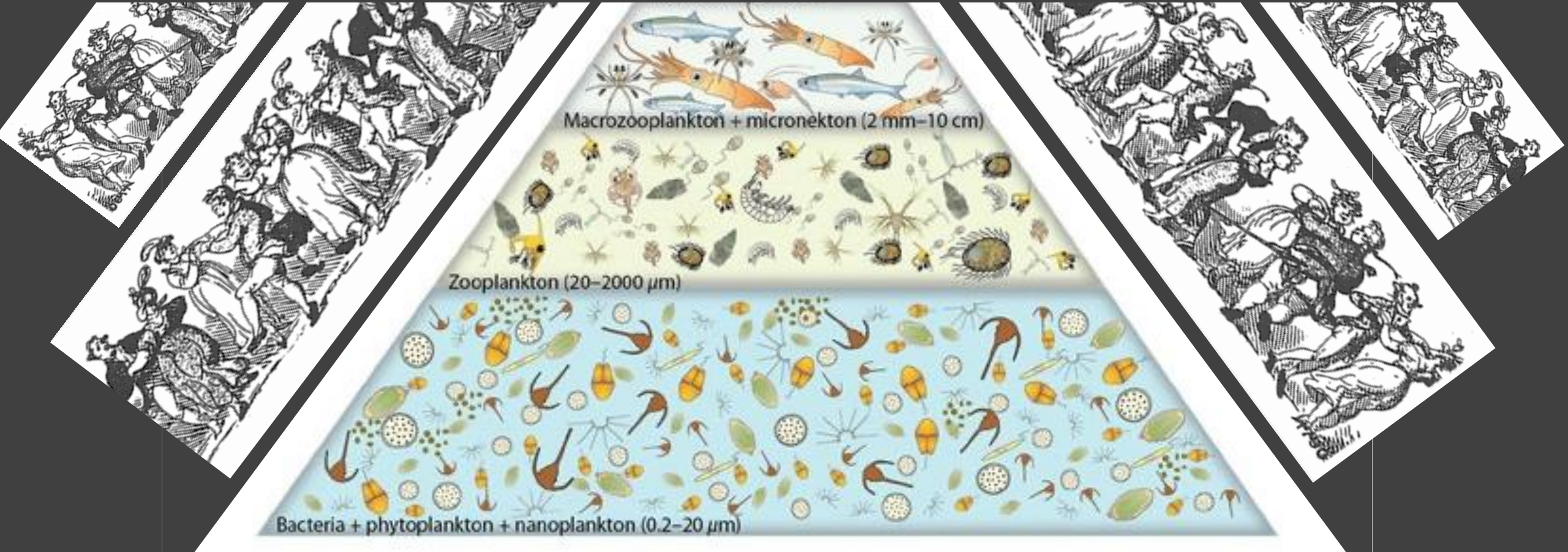
Bacteria + phytoplankton + nanoplankton (0.2–20 μm)

HAPPY TIMES

# MASS EXTINCTION







Same dance;  
New dancers



Nekton (10 cm–2 m)

Macrozooplankton + micronekton (2 mm–10 cm)



Zooplankton (20–2000  $\mu$ m)



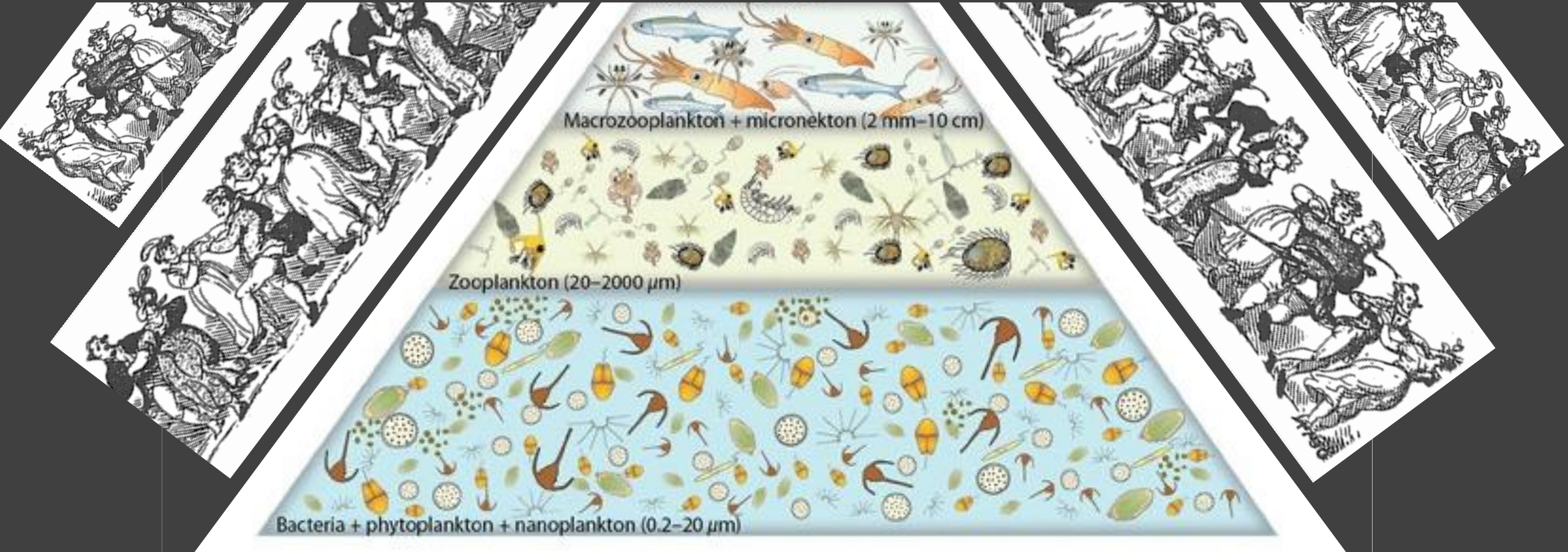
Bacteria + phytoplankton + nanoplankton (0.2–20  $\mu$ m)

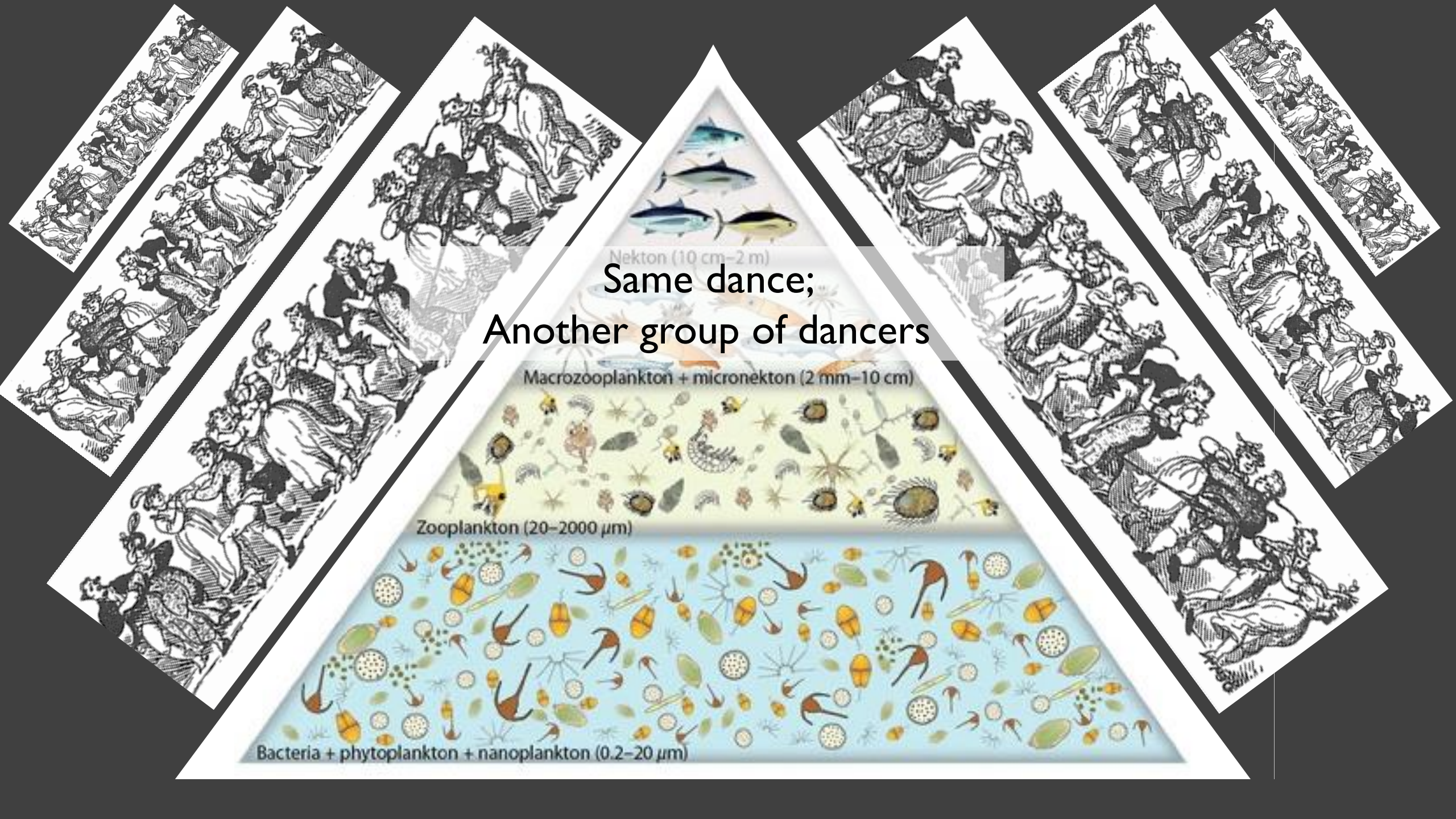


# MASS EXTINCTION









Same dance;  
Another group of dancers

Nekton (10 cm–2 m)

Macrozooplankton + micronekton (2 mm–10 cm)

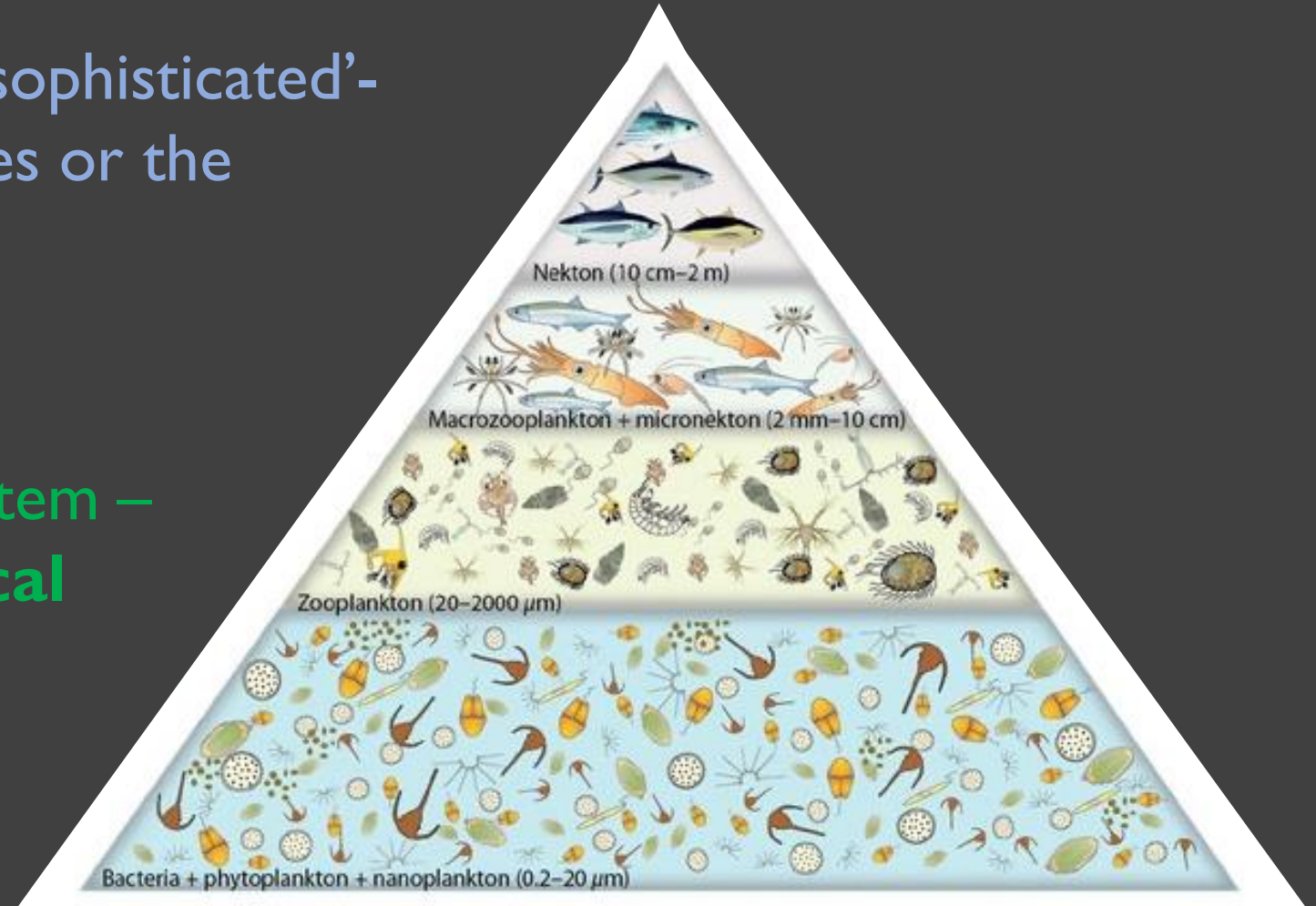
Zooplankton (20–2000  $\mu\text{m}$ )

Bacteria + phytoplankton + nanoplankton (0.2–20  $\mu\text{m}$ )

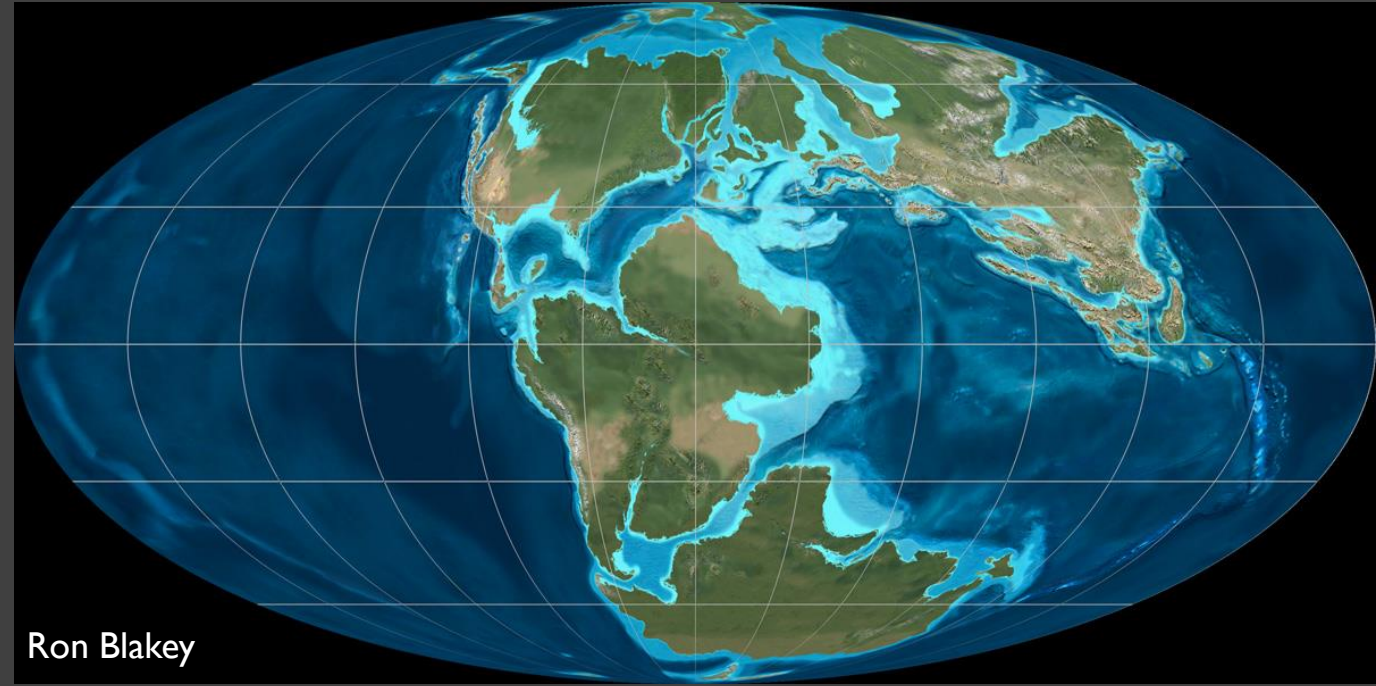
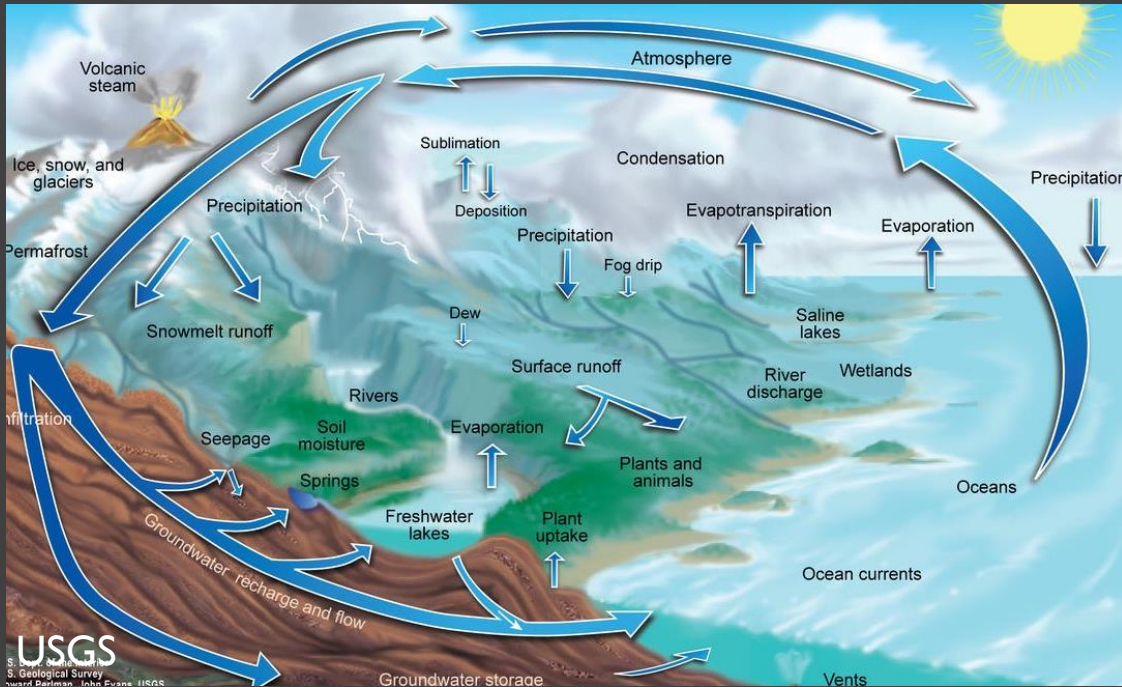
Is evolution in any absolute sense progressive?

Which organisms are more ‘sophisticated’-  
the elaborate but extinct ones or the  
‘primitive’ survivors?

Players come and go, but the  
dynamic character of the system –  
the **habit of biogeochemical  
cycling** -- persists



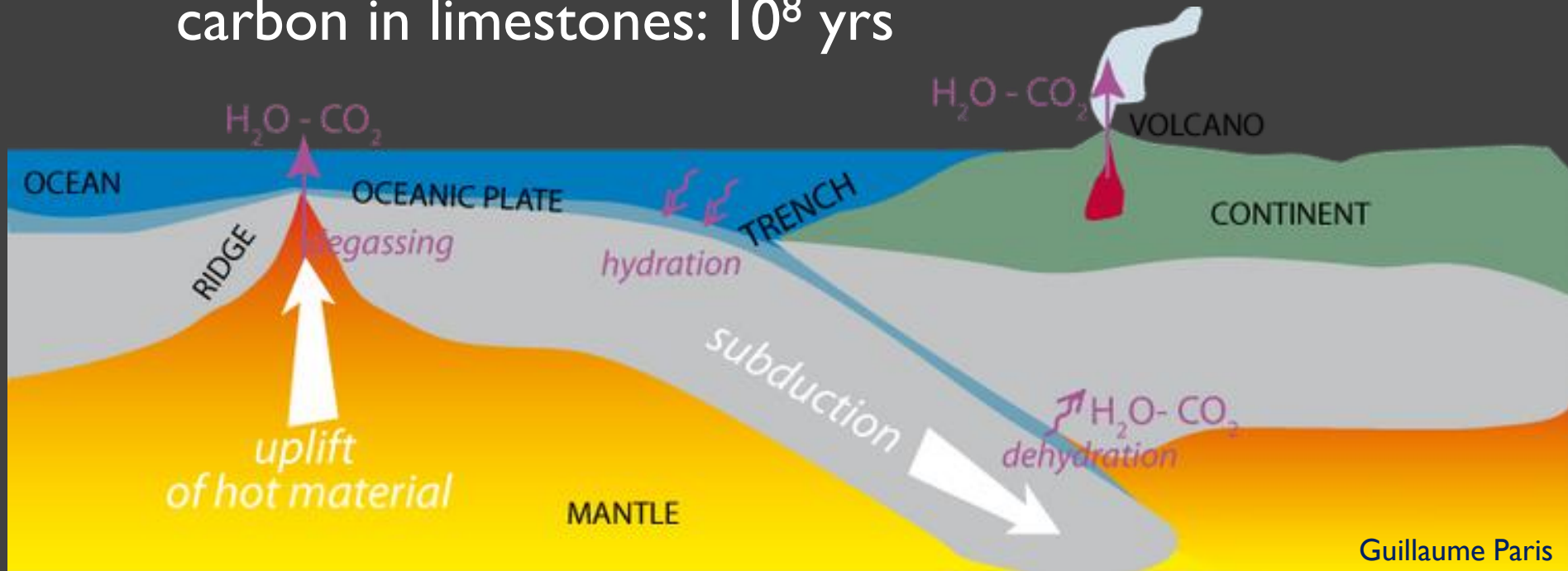
# Habits adopted and maintained over time (cont.) 🌍



Residence times

Of water in atmosphere: 9 days  
water in oceans: 3000 yrs  
water in the mantle:  $10^8$  yrs

Of carbon in plants: 5 years  
carbon in soils: 500 yrs  
carbon in limestones:  $10^8$  yrs



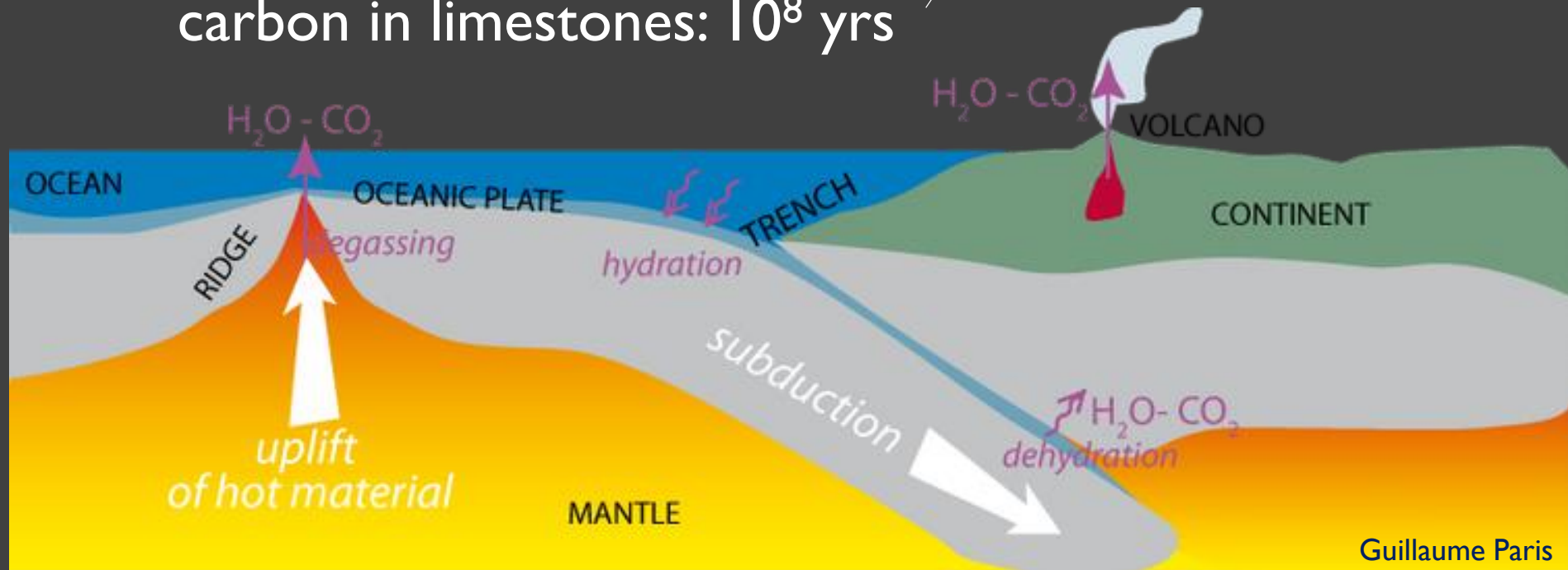
Residence times

Of water in atmosphere: 9 days  
water in oceans: 3000 yrs  
water in the mantle:  $10^8$  yrs

Of carbon in plants: 5 years  
carbon in soils: 500 yrs  
carbon in limestones:  $10^8$  yrs



The Tai Chi pace of  
**plate tectonics** 



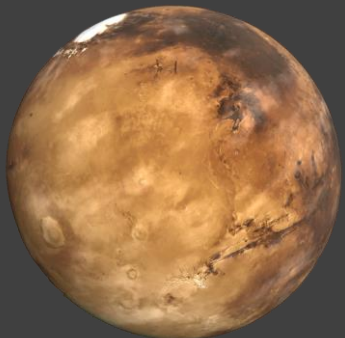
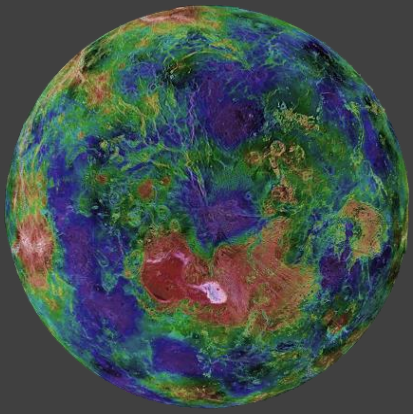
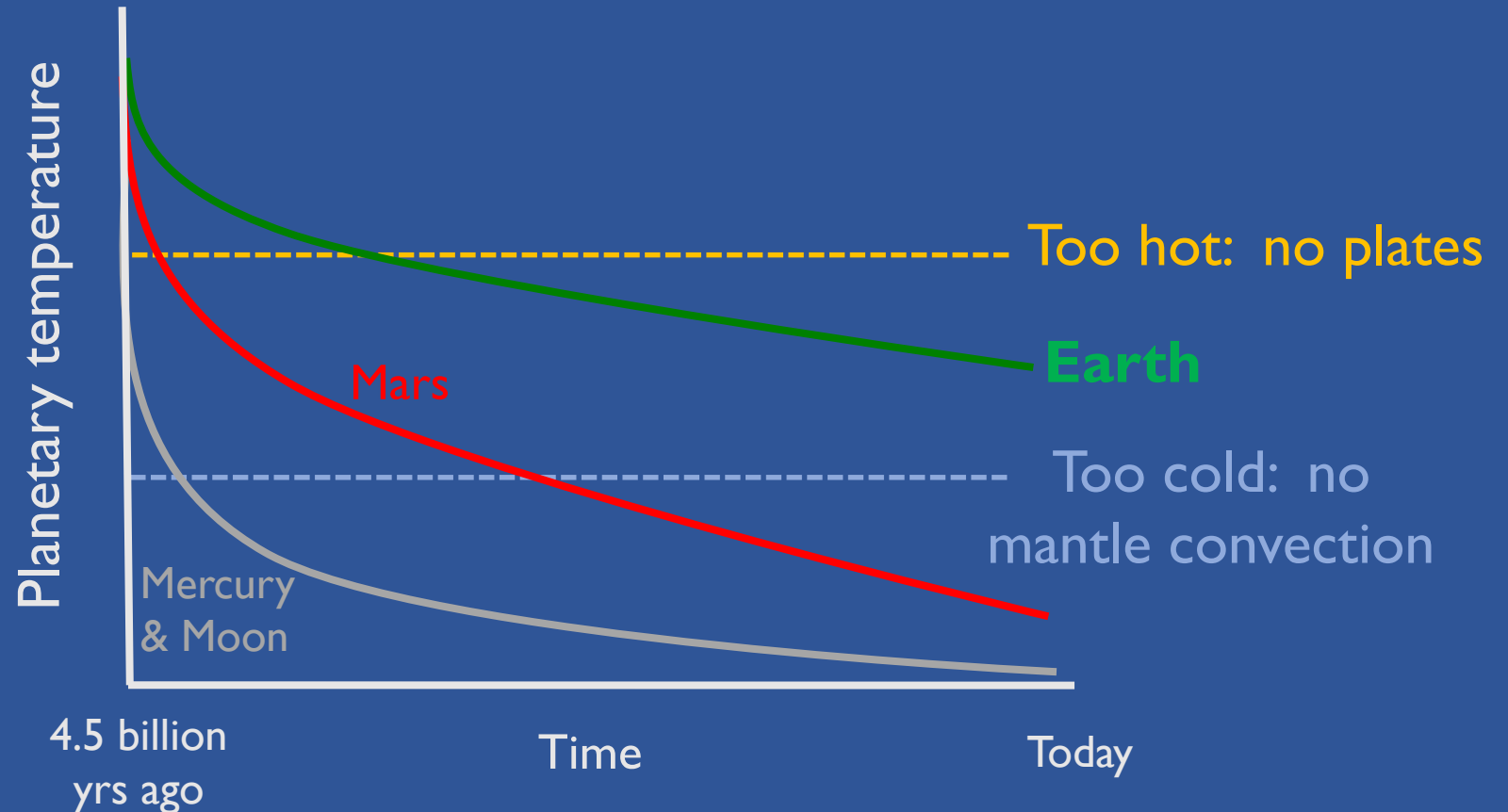


Plate tectonics is not inevitable for a rocky planet –  
Must be hot enough for mantle convection  
but cool enough for a rigid lithosphere  
-- and this must persist for  $>10^9$  years



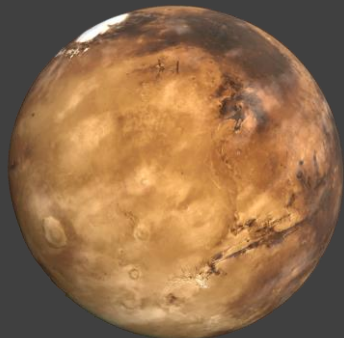
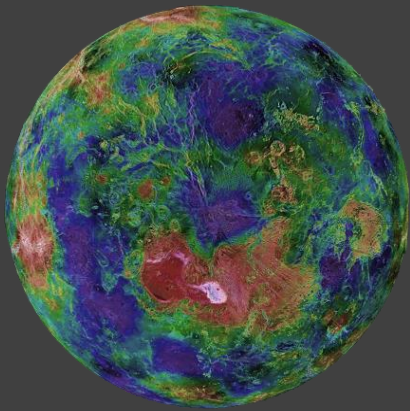
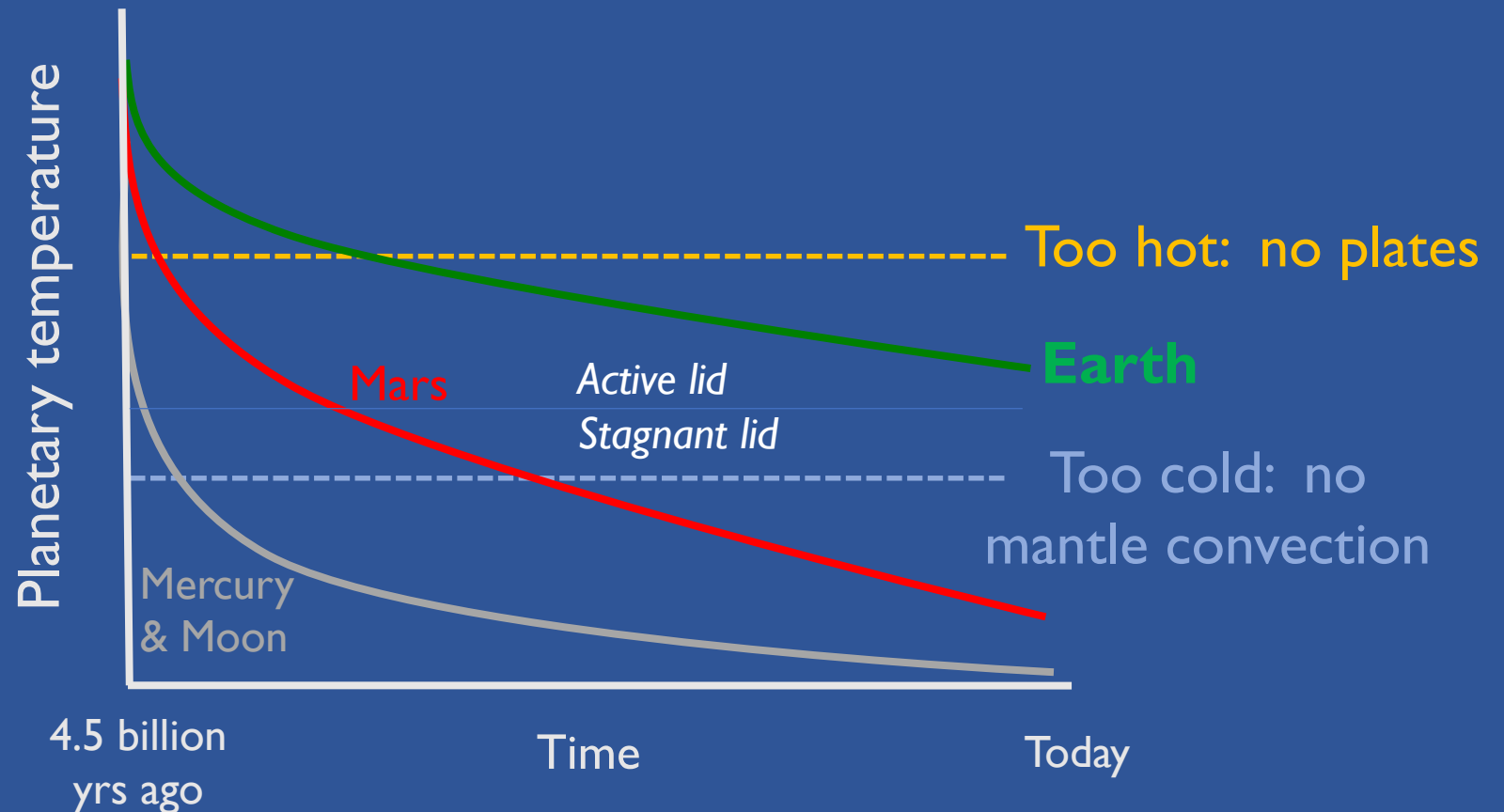
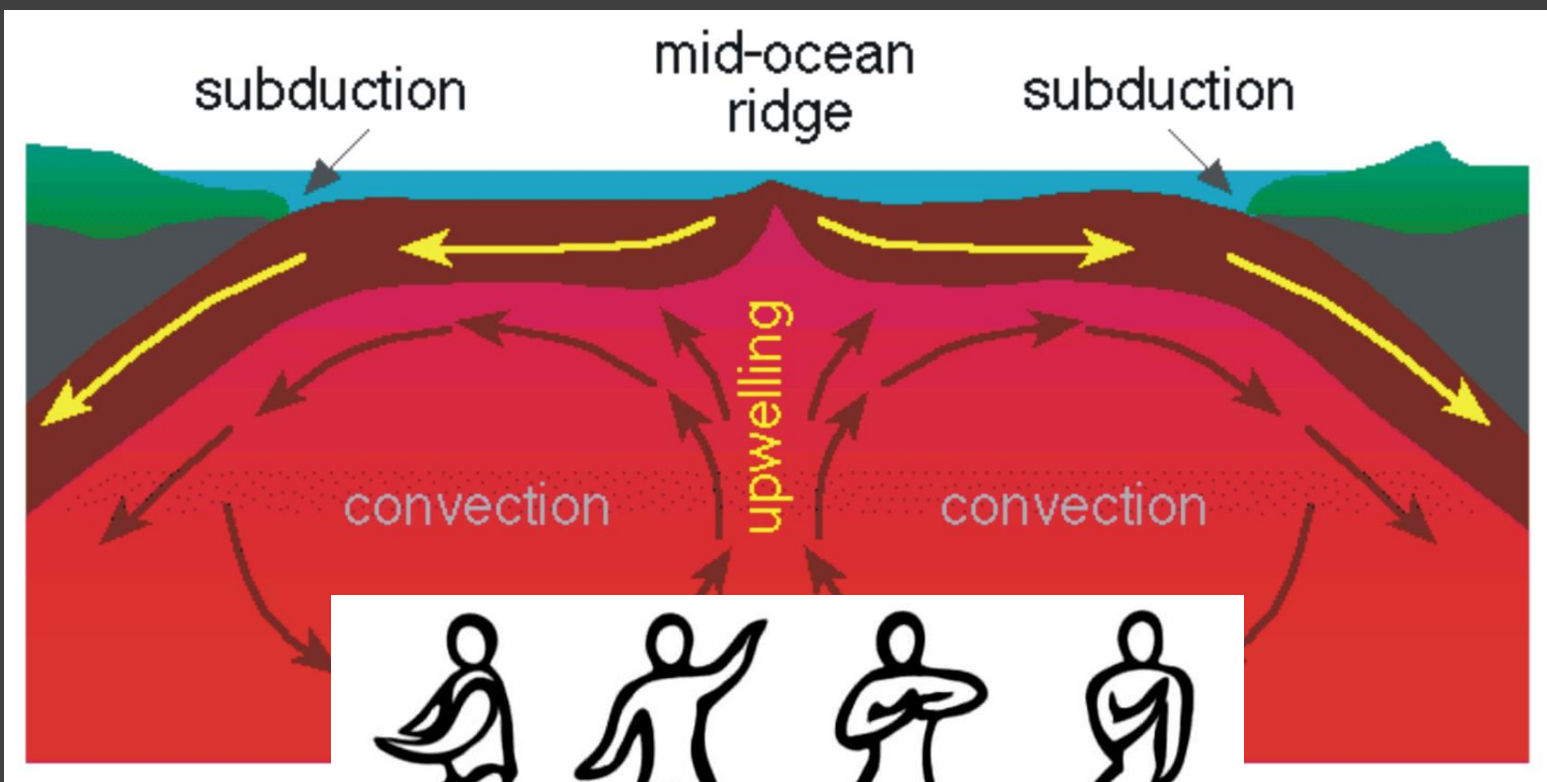


Plate tectonics is not inevitable for a rocky planet –  
Must be hot enough for mantle convection  
but cool enough for a rigid lithosphere  
-- and this must persist for  $>10^9$  years

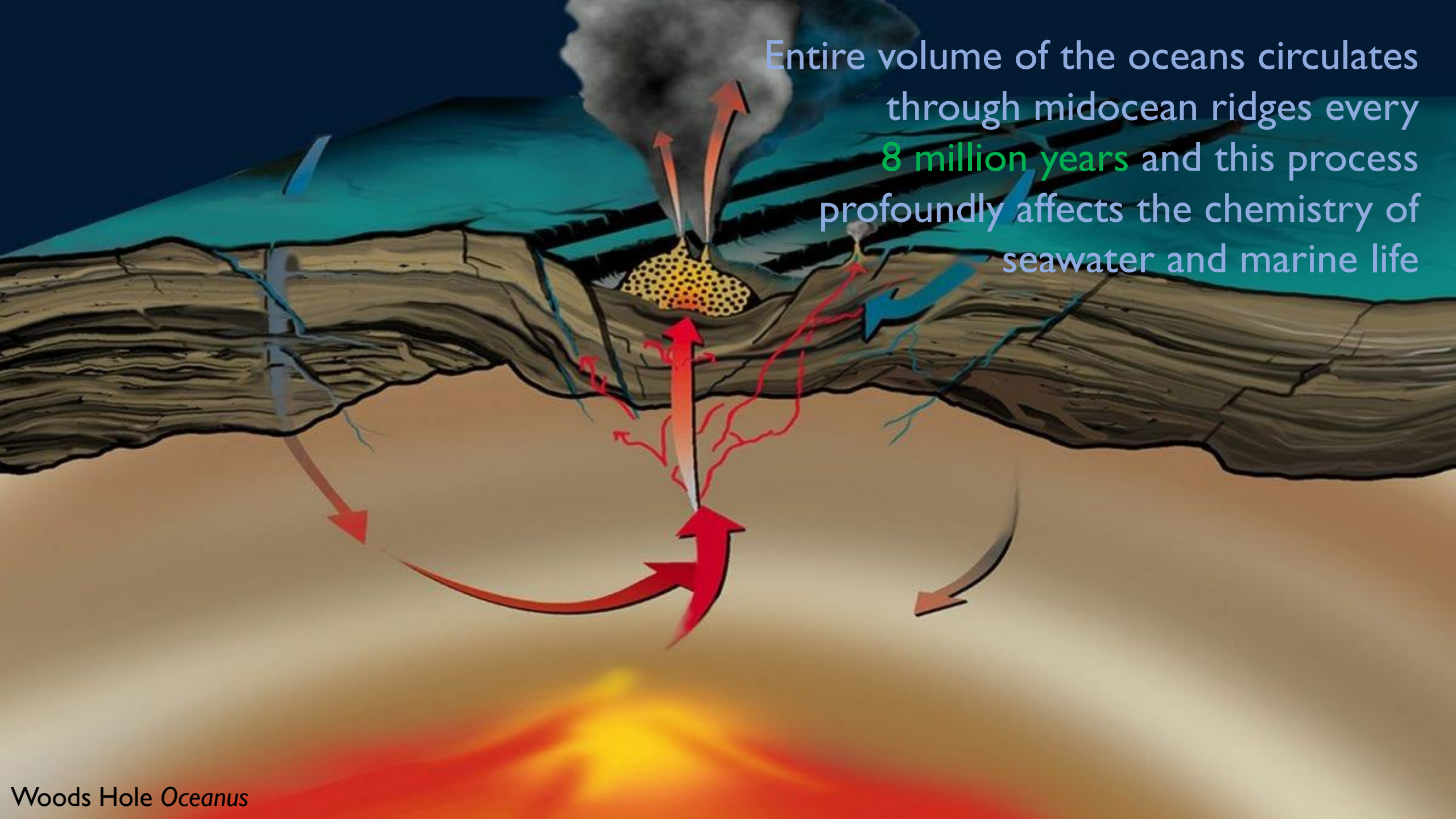




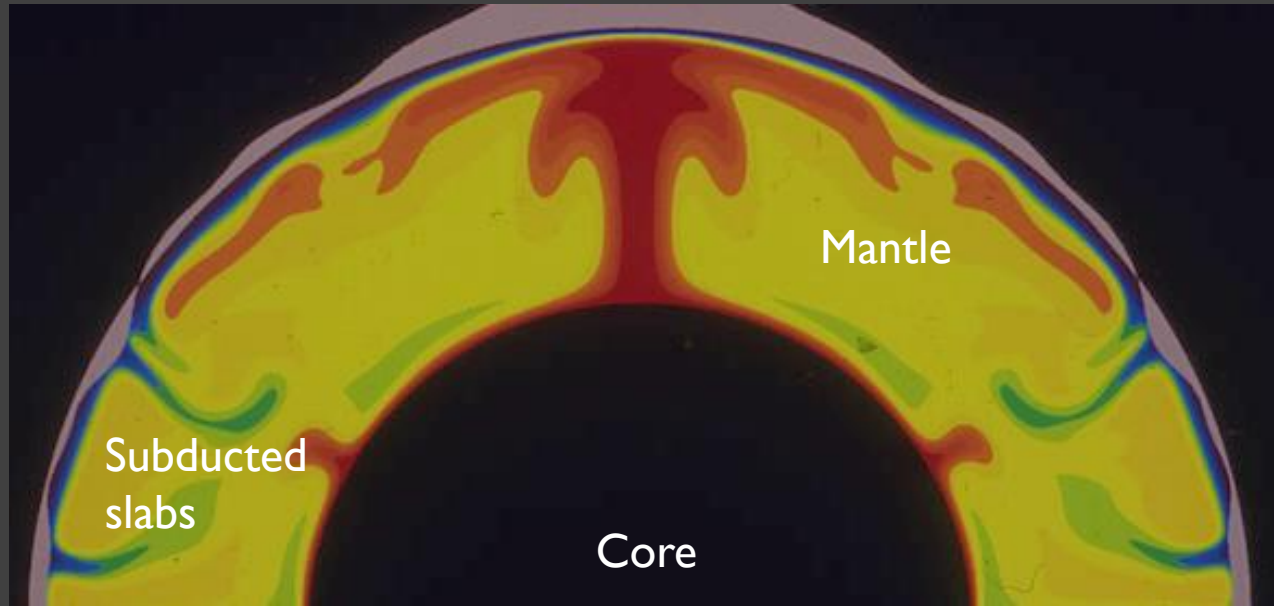
Earth has an **active-lid** tectonic system, with the oceanic crust involved in the convective process through **subduction**.

This keeps the **interior and exterior of the Earth** in **geochemical communication**

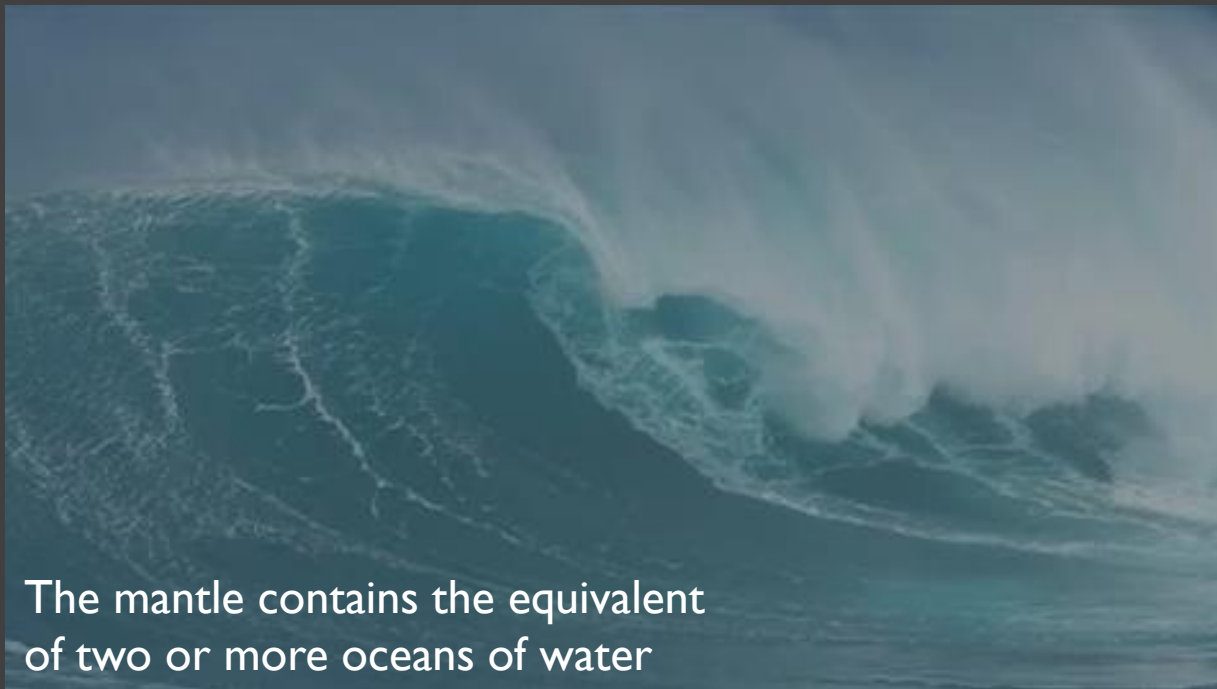


A cross-sectional diagram of a mid-ocean ridge. At the top, a volcano-like structure emits a plume of dark smoke. Below it, a yellow, porous, cone-shaped structure represents a magma chamber. Red arrows show magma rising from this chamber through cracks in the dark, layered oceanic crust. Blue arrows show seawater moving down the outer slopes of the ridge and then back up along the central axis. Large red arrows at the bottom indicate a large-scale circulation loop. The background is a gradient from dark blue at the top to orange and red at the bottom, representing the mantle.

Entire volume of the oceans circulates  
through midocean ridges every  
8 million years and this process  
profoundly affects the chemistry of  
seawater and marine life



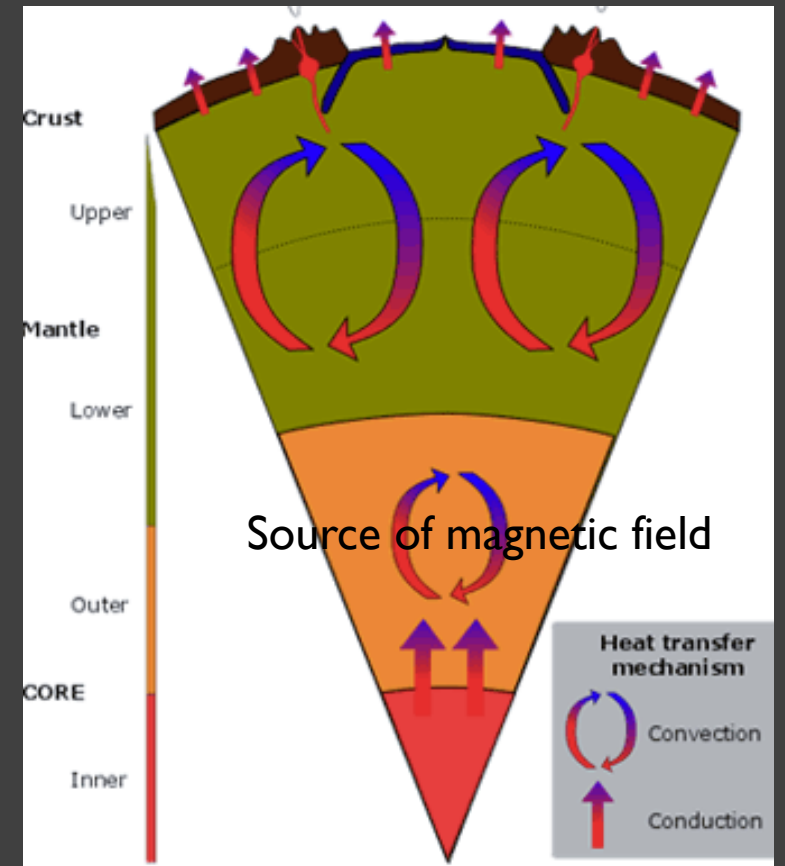
Water carried into the mantle by subducted slabs plays critical roles in the functioning of the tectonic system



The mantle contains the equivalent of two or more oceans of water

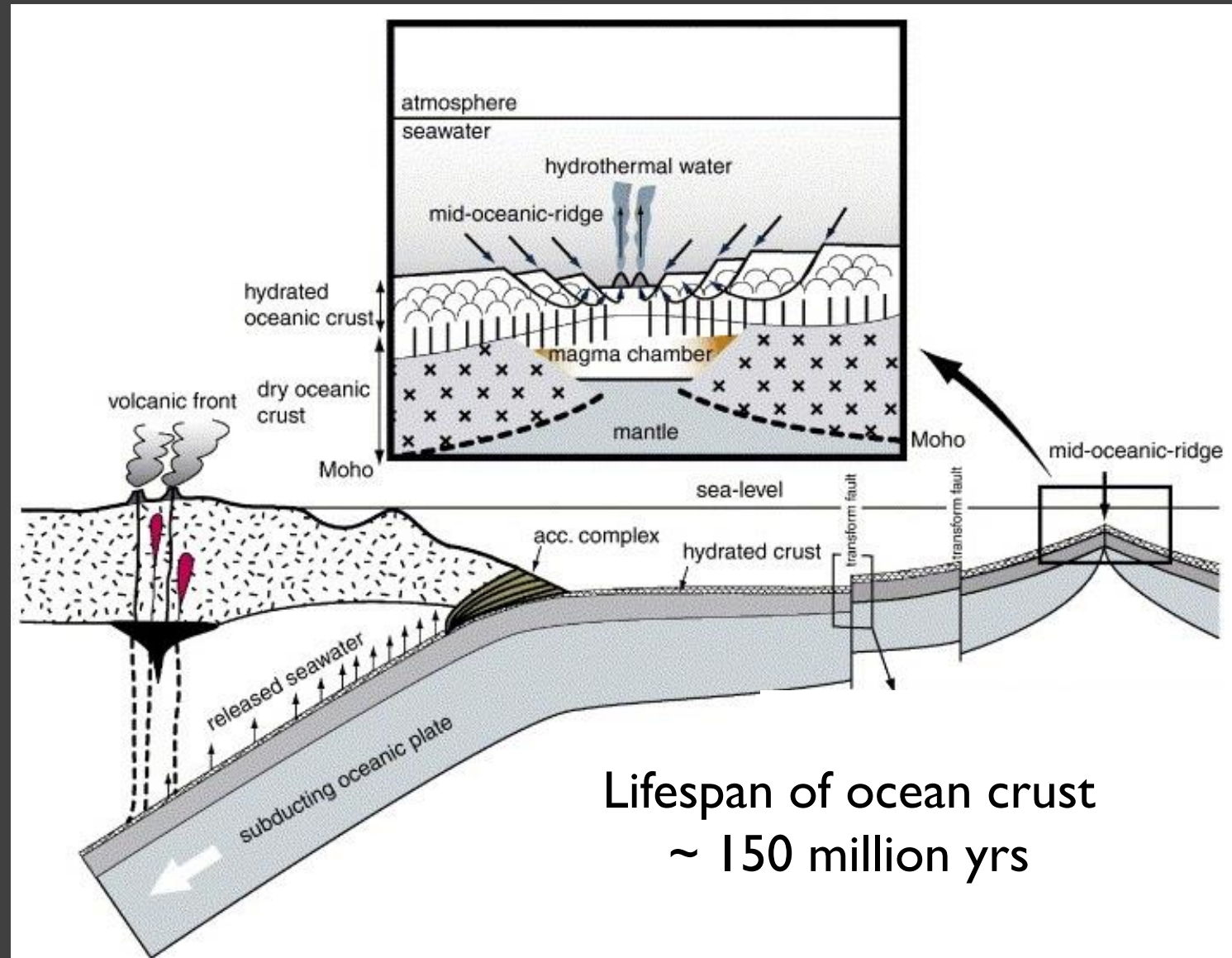
→ Subducted water **decreases the viscosity of the mantle** and allows mantle convection to continue even as Earth has cooled

As if returning the favor, mantle convection indirectly protects the hydrosphere and atmosphere by creating a temperature gradient in Earth's metallic core that drives core motion and generates the magnetic field



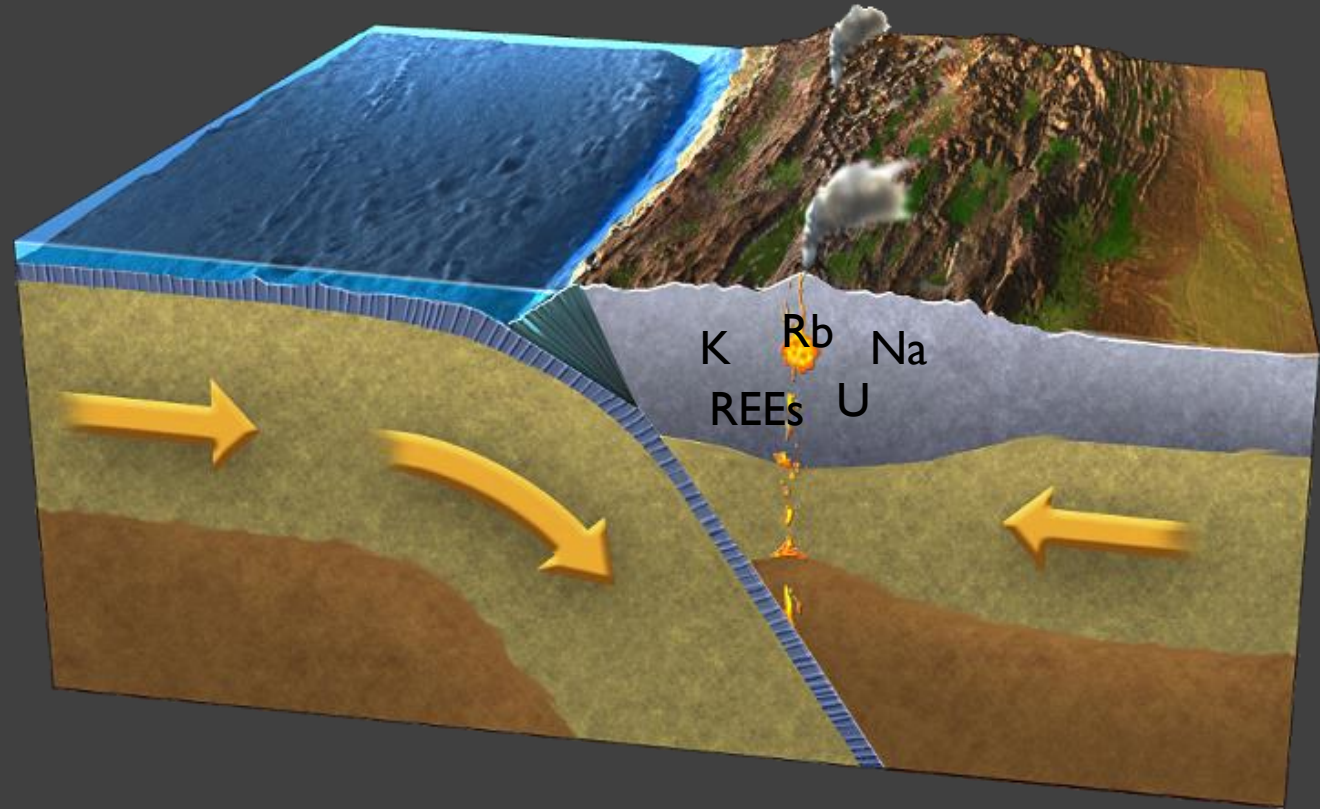
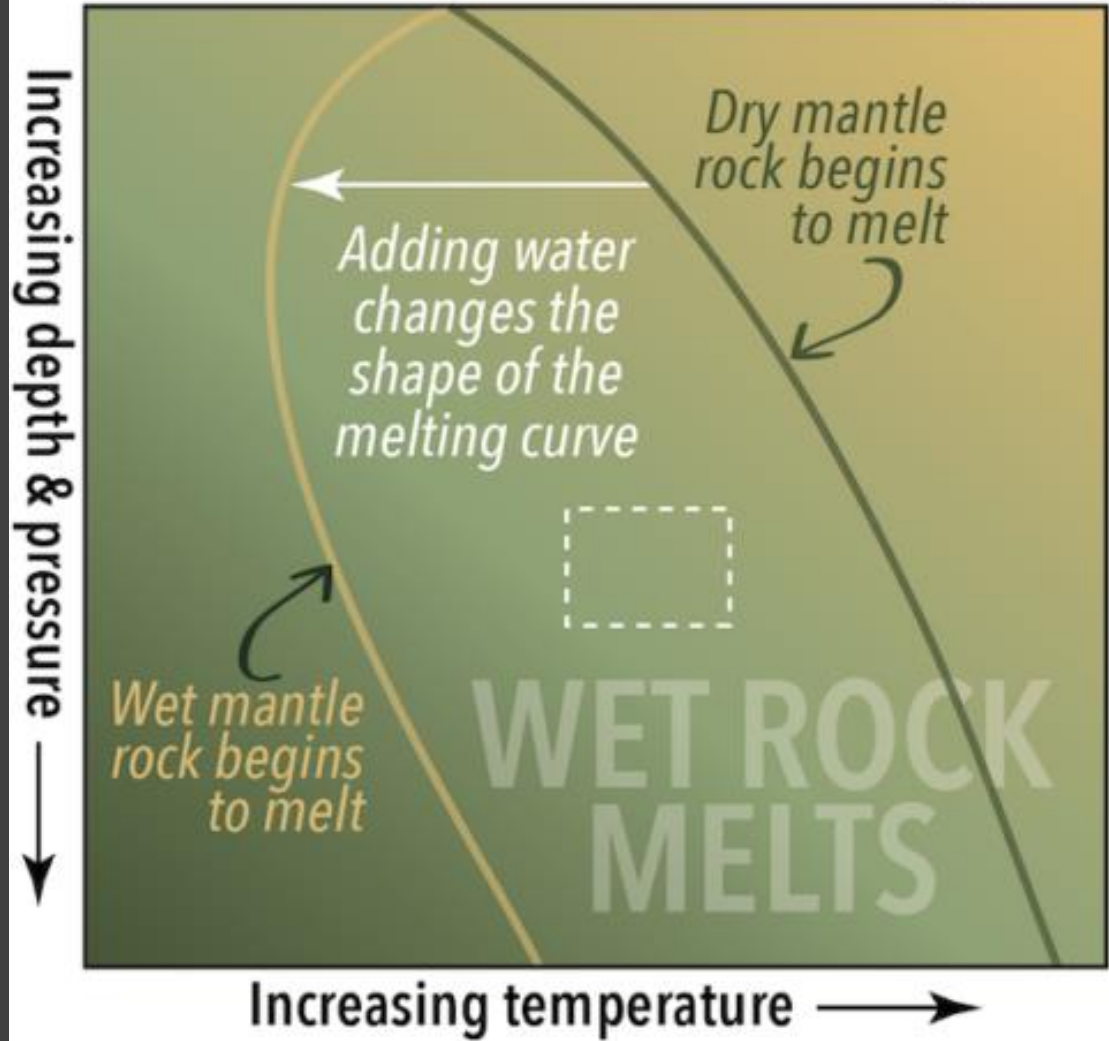
Without the magnetic field, Earth's atmosphere would be stripped by the solar wind and cosmic radiation

→ Subducted water **lowers the melting temperature of the mantle** and creates low-temperature melts that are the **first step in building continents**, whose composition (granitic) is very different from that of the mantle

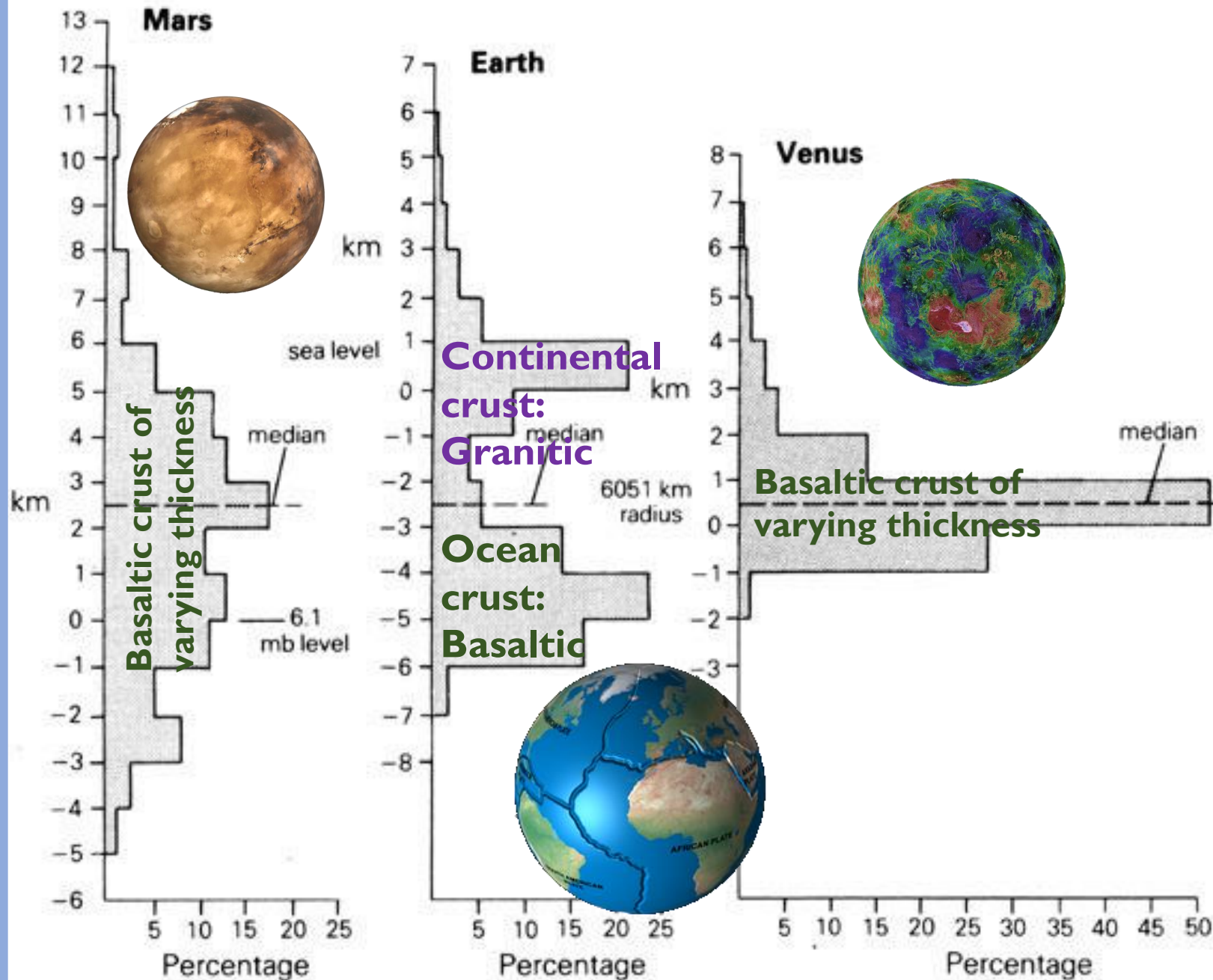


Lifespan of ocean crust  
~ 150 million yrs

# Flux-induced Melting



→ Water-assisted melting preferentially extracts elements including Na, K, Rb, U, Th and Rare Earths that are in trace concentrations in the mantle



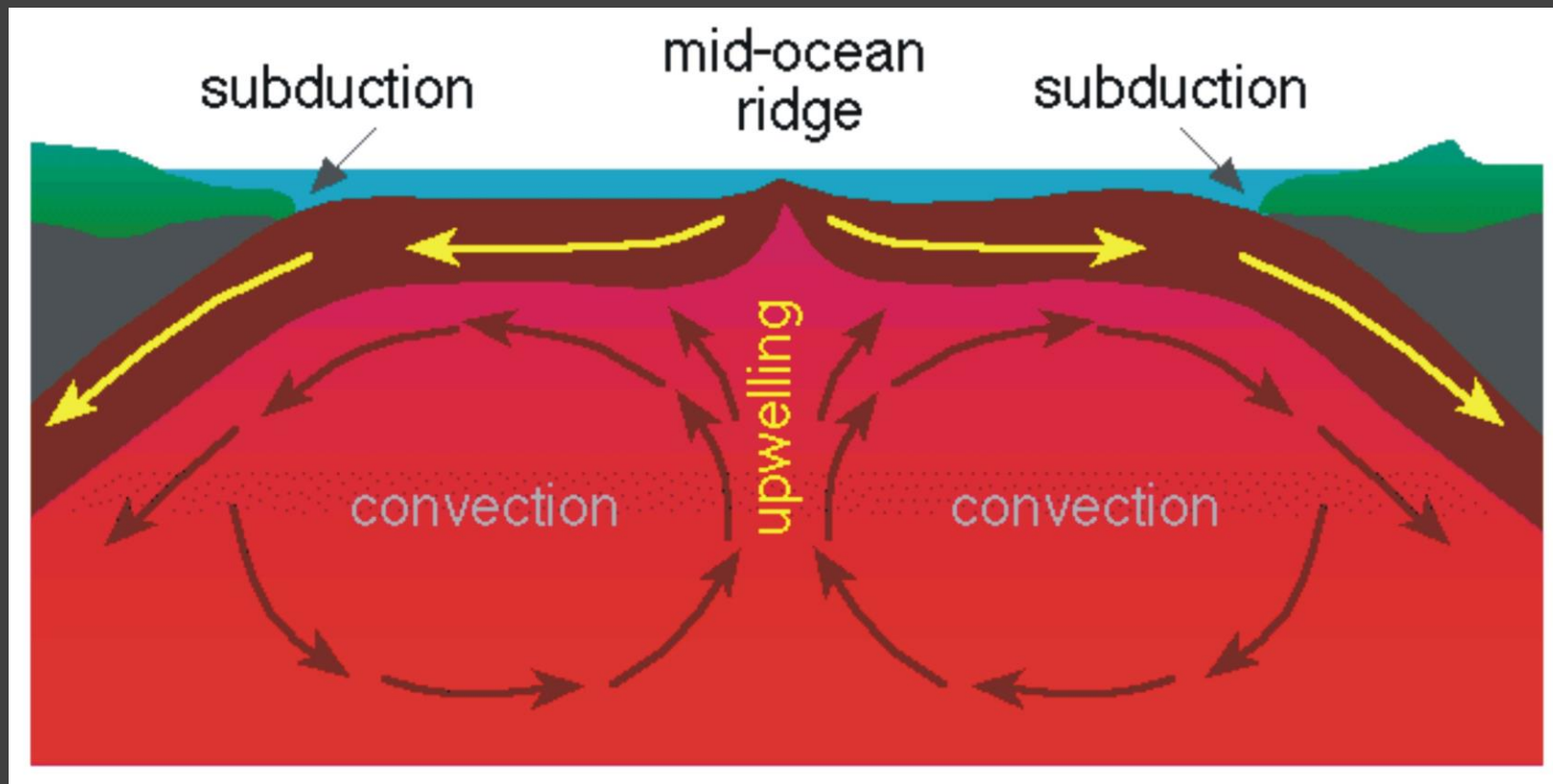
‘Hypsometric’ plots:  
Distribution of  
planetary surface  
elevations

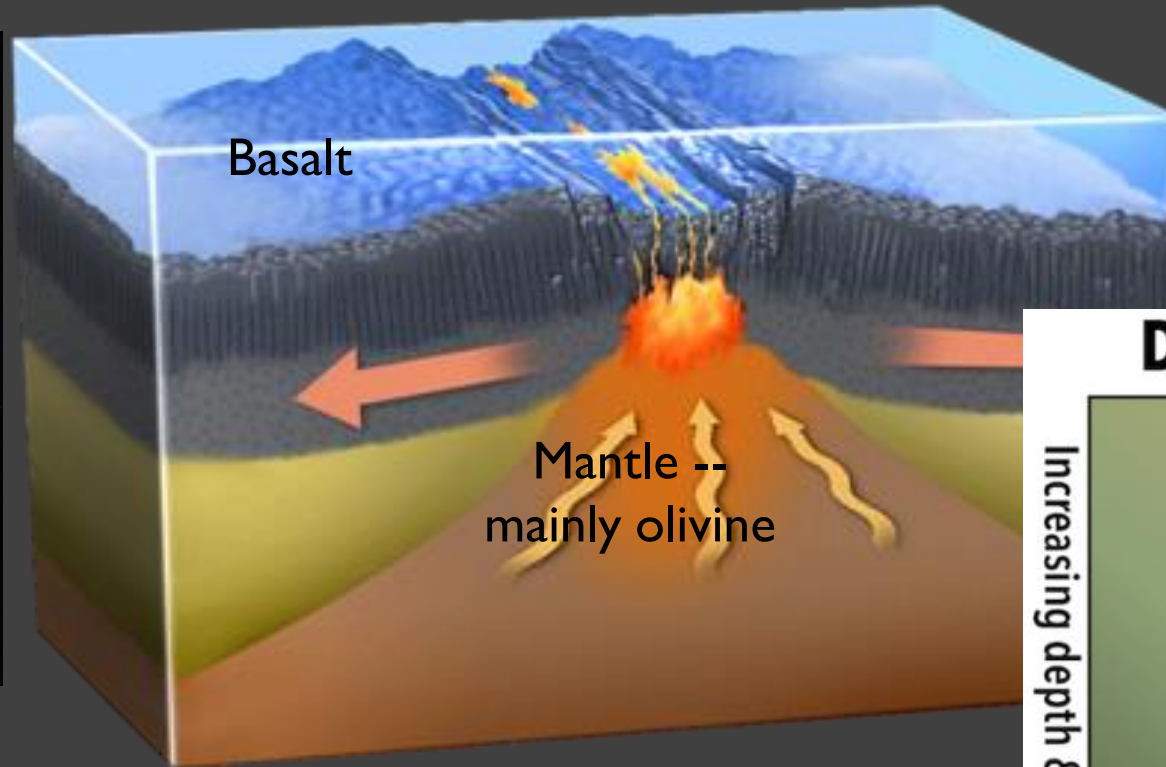
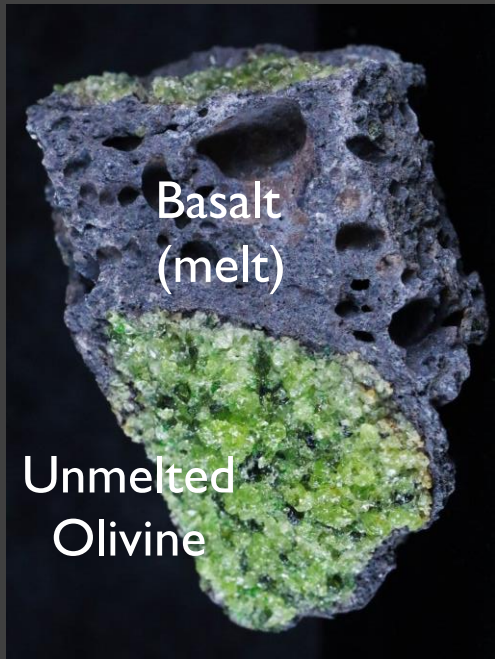
Only Earth has a  
**bimodal** distribution  
reflecting  
contrasting  
composition and  
density of the two  
types of crust

**Earth is the  
granite planet**

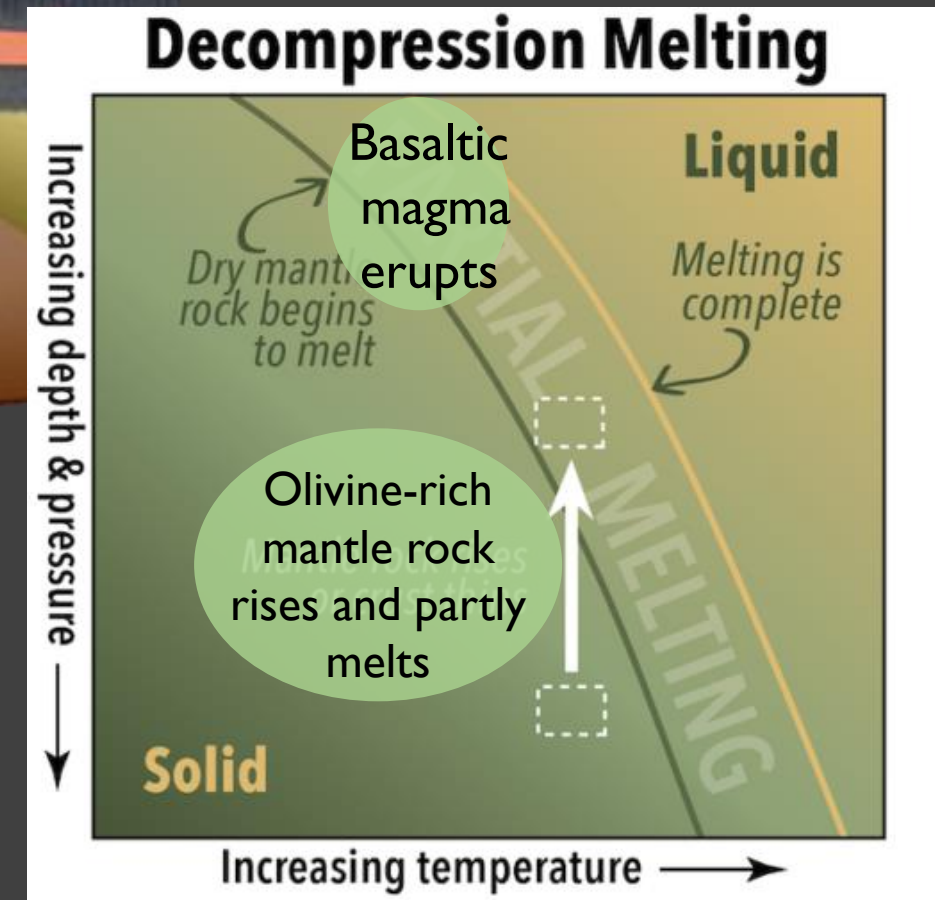
But why does subduction – the signature process of Earth's tectonic system -- happen at all?

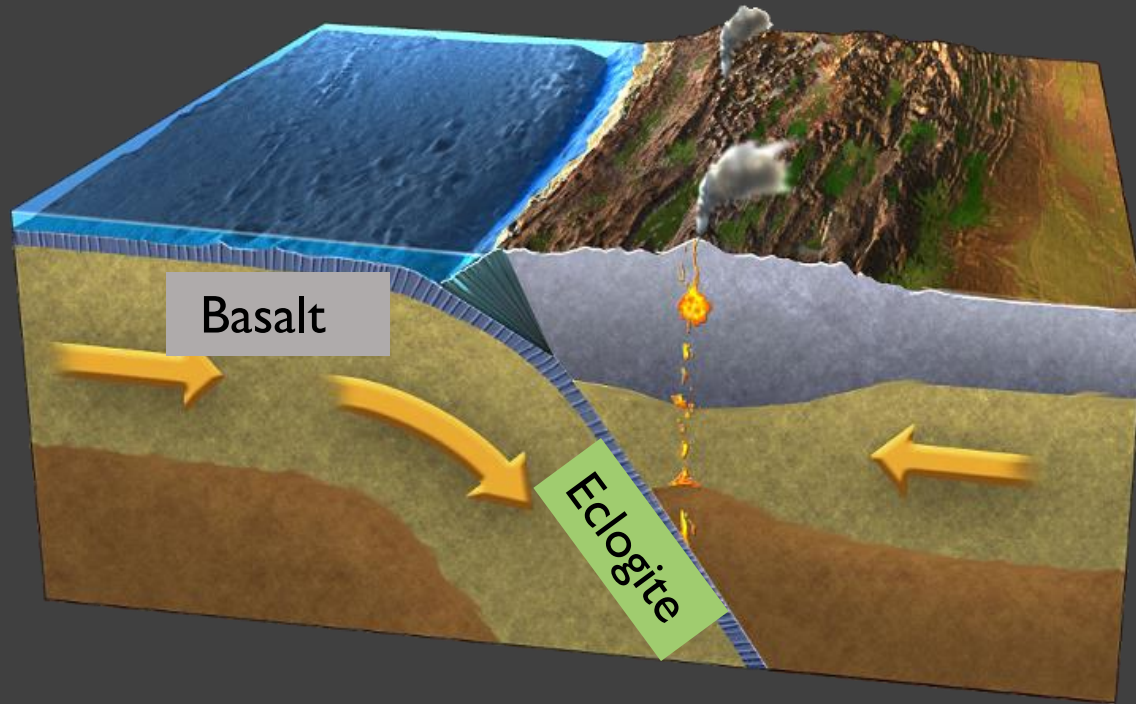
Ocean crust comes from the mantle, so how can it sink deep into the mantle?





Incomplete melting of olivine-rich mantle (peridotite) yields basaltic magma – richer in Si and Al than the mantle itself

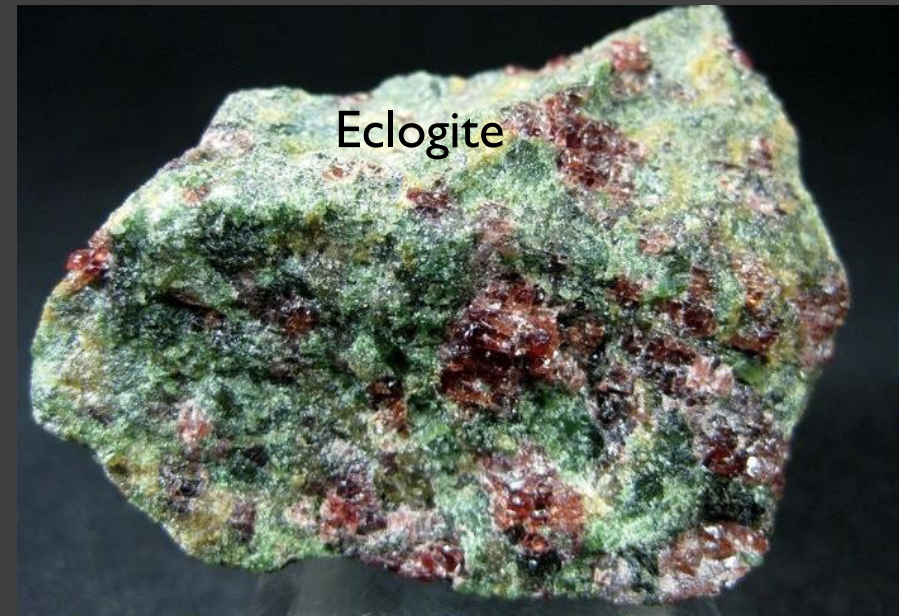
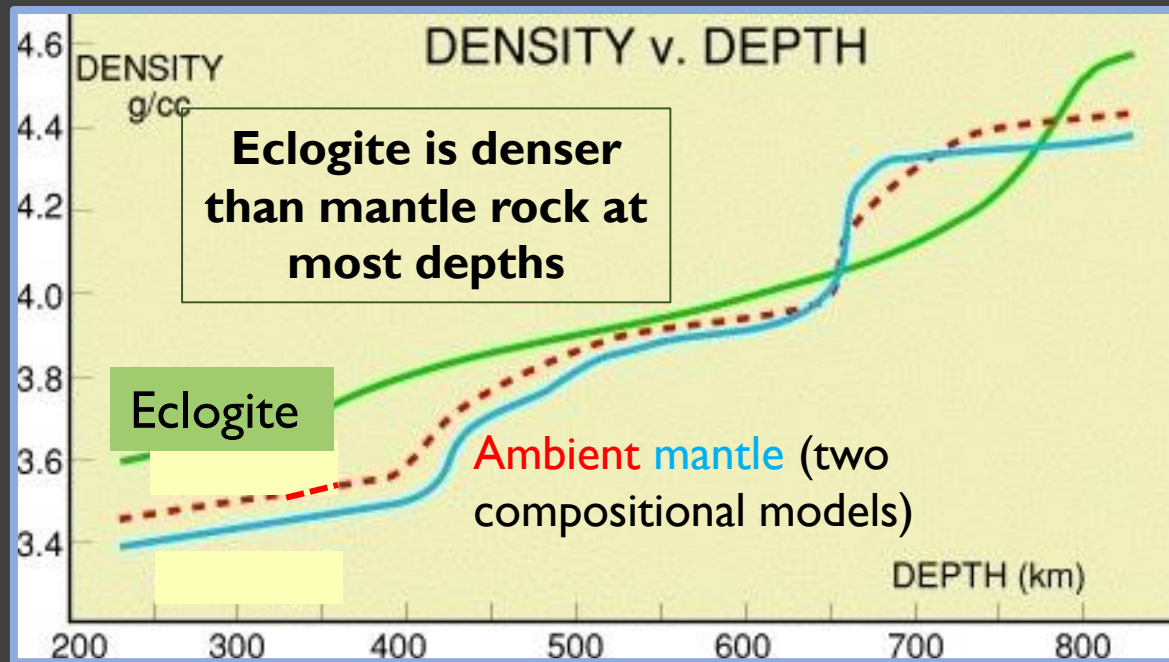


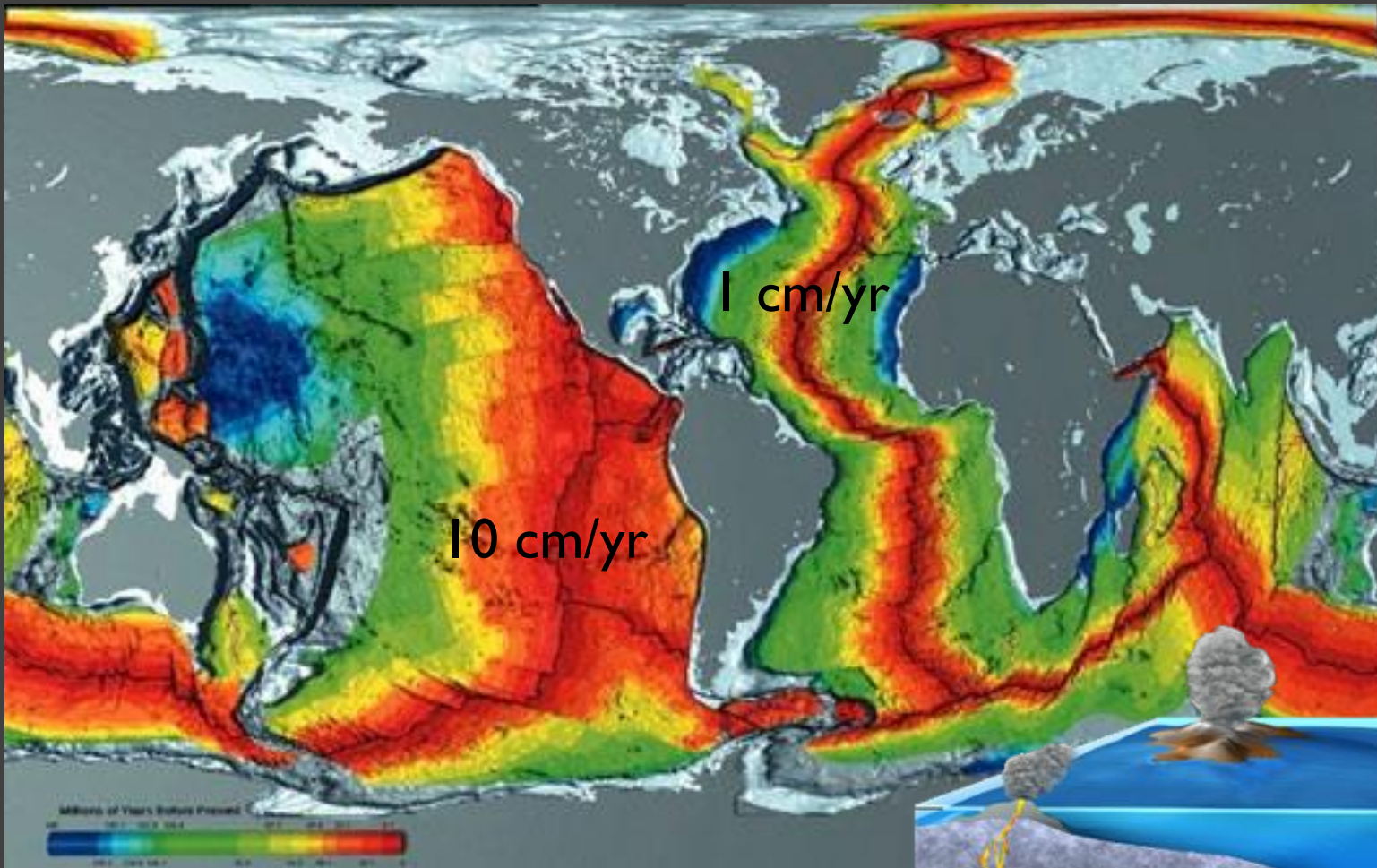


When basalt returns to the mantle via subduction, it is metamorphosed to a much denser rock -- **Eclogite**

Aluminum-rich **garnet** in eclogite is what pulls the slab down – i.e., the tectonic system is **powered by garnet**

**Earth is the garnet planet**



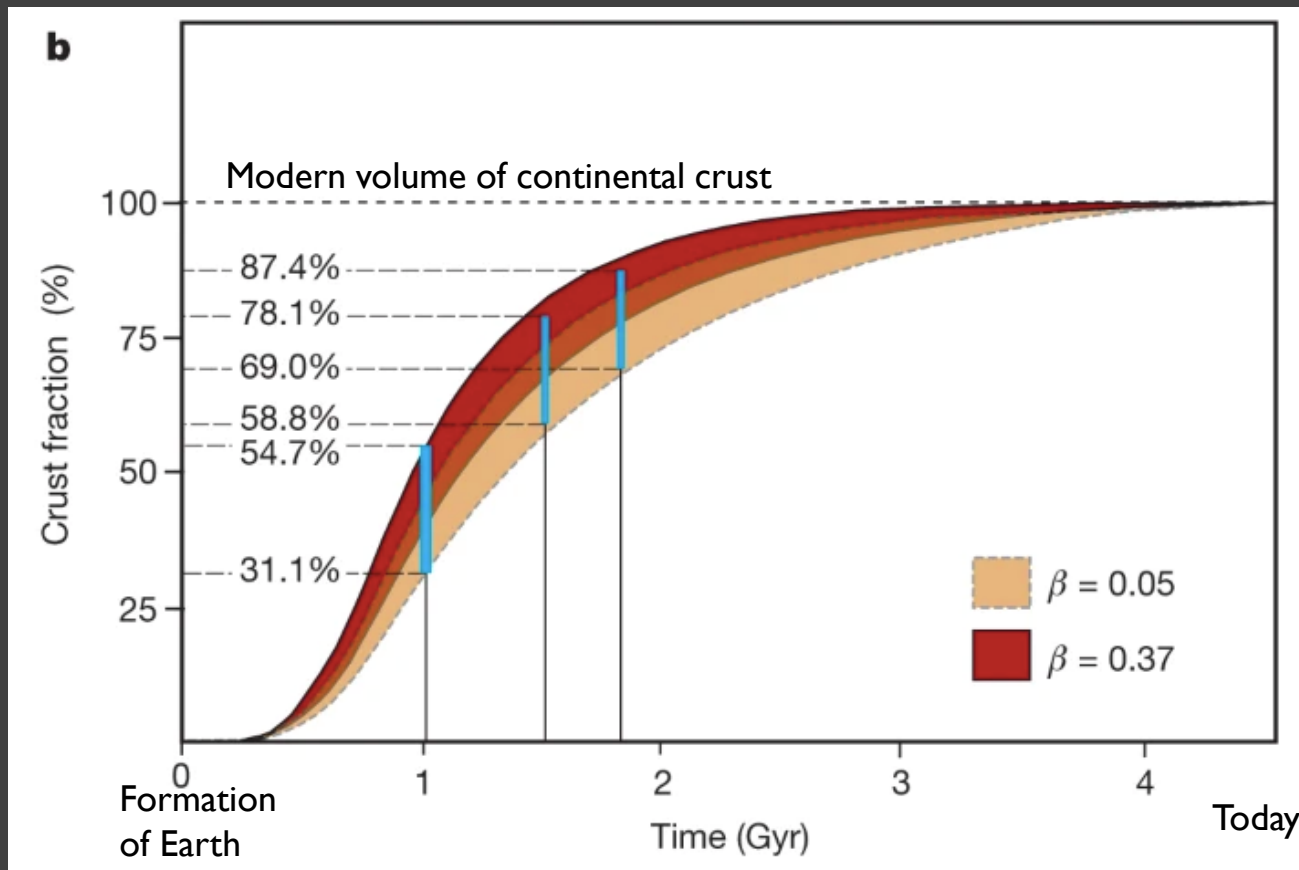


Evidence of **garnet power**:  
Seafloor spreading rates in  
Atlantic vs. Pacific



Volumes of continental & oceanic crust seem to have been constant for >2.5 billion yrs

→ Rates of creation and destruction are balanced



One model for the change in continental crust volume over time, based on changing ratios of  $^{40}\text{Ar}/^{36}\text{Ar}$  in hydrothermal minerals

( $^{40}\text{Ar}$  is a proxy for  $^{40}\text{K}$ , strongly concentrated in the continental crust)

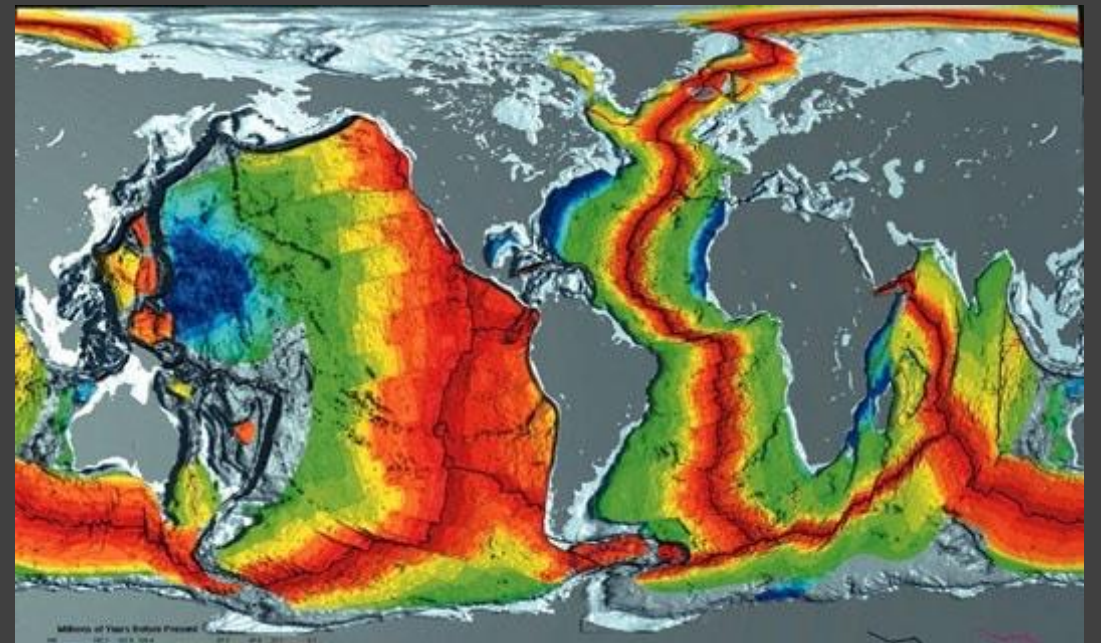
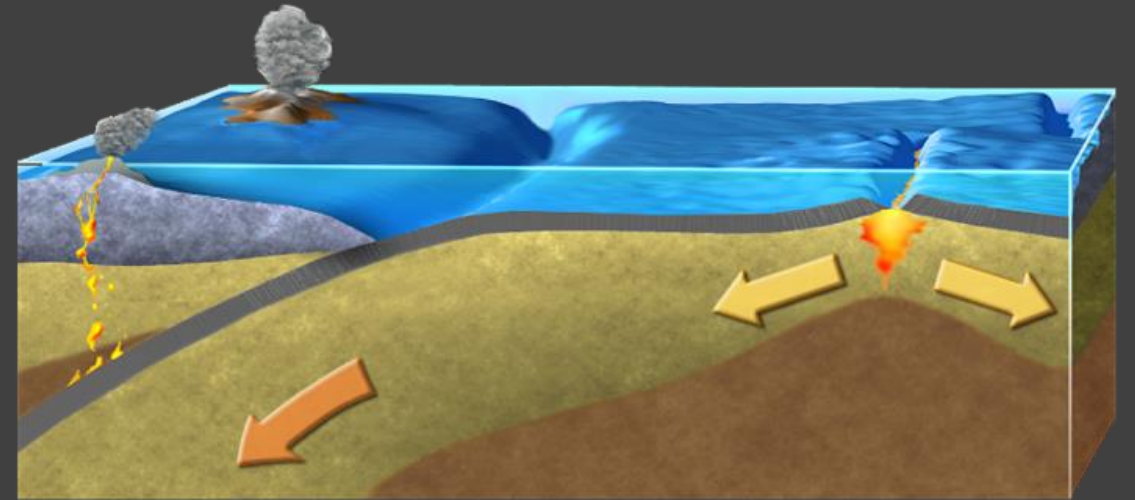
Pujol et al., *Nature* 2013

Volumes of continental & oceanic crust  
have been constant for >2.5 billion yrs

→ Rates of creation and  
destruction are balanced

Not too surprising for ocean crust,  
since processes of creation and  
recycling are genetically linked

Typical life span (residence time of  
ocean crust at the surface)  
~150 million years



Continental crust has an average life span of ~2.8 billion years – much longer than ocean crust

But if there is no net growth in continental crust, something is slowly destroying it

Continents are too light to be subducted (see: *Himalaya*)

So what process allows continental material to be recycled?



Continental crust has an average life span of ~2.8 billion years – much longer than ocean crust

But if there is no net growth in continental crust, something is slowly destroying it

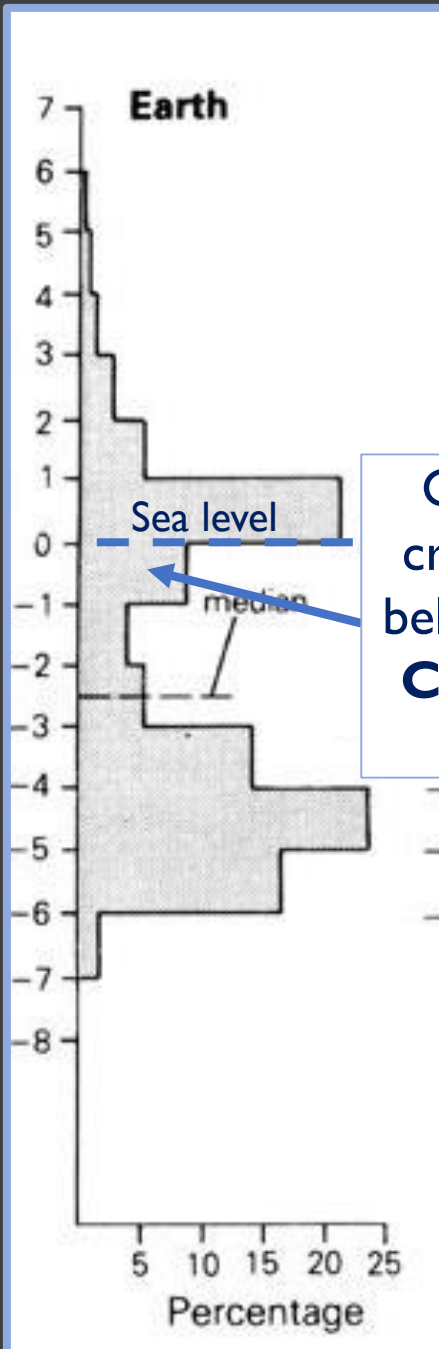
Continents are too light to be subducted (see: *Himalaya*)

So what process allows continental material to be recycled?



Erosion (a kind of progressive taxation that exacts the most from the loftiest) is a start, but not the whole story

Most eroded continental sediments end up on the **continental shelf** – still part of the continent, and not subductable

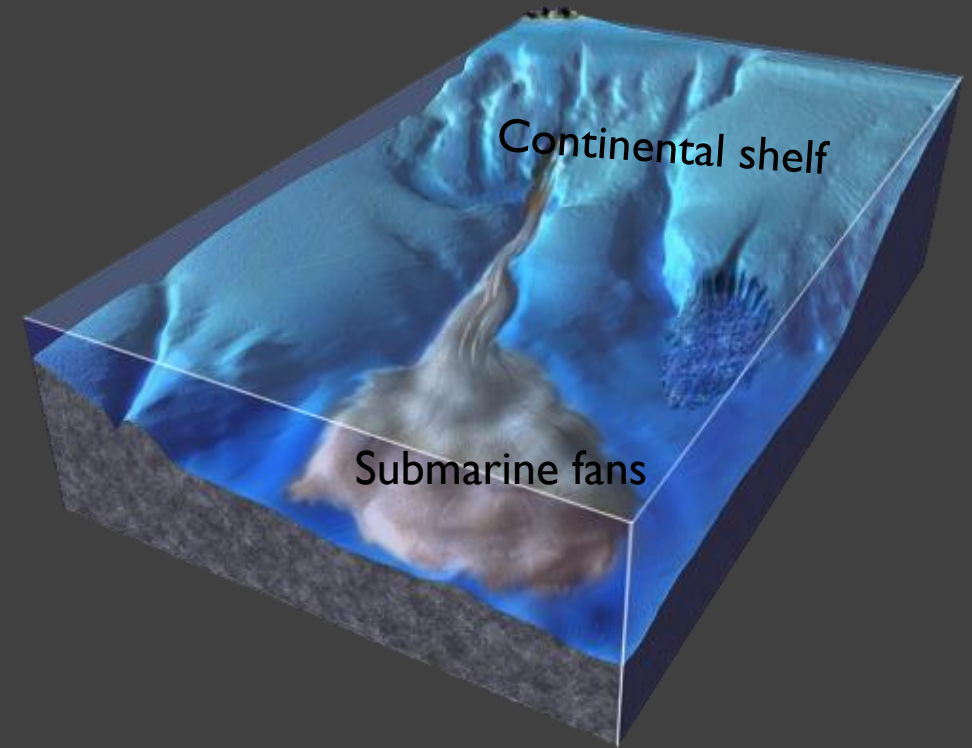


Continental crust that lies below sea level:  
**Continental shelves**



Continental shelf sediments host most of the world's oil and gas fields

Intermittent submarine landslides –  
**turbidity currents** – can carry  
continental sediment to the deep  
seafloor forming submarine fans that  
may one day be subducted



Strangely, this multi-stage process  
keeps pace with the creation of  
new continental material above  
subduction zones



The **continental shelves**, with their rich sedimentary and paleontological records, are **Earth's historical archives**

Not subject to erosion like exposed continental crust, and not subject to subduction like oceanic crust

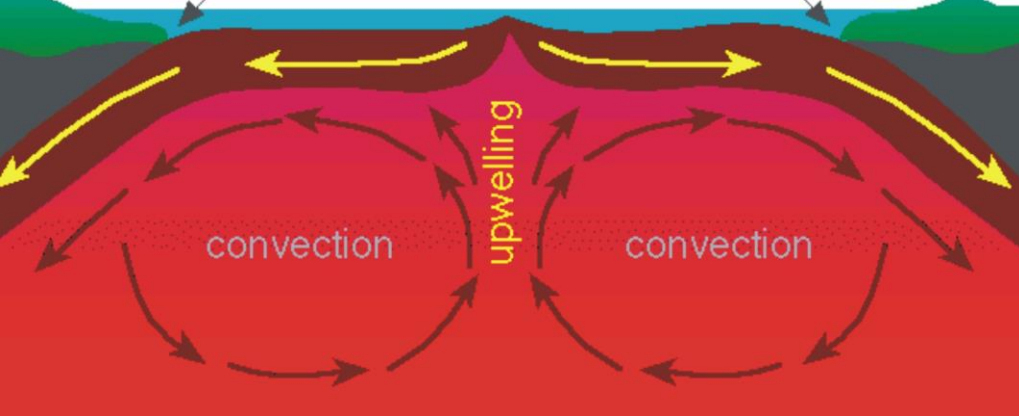


Most of what we know about life, climate and surface processes over time comes from recent or ancient continental shelf sediments (some conveniently tilted on edge in mountain belts)

The continental shelves -- these planetary archives -- are purely an accident of the relative volumes of surface water and oceanic vs. continental crust

The planet wouldn't have to be that way. It's almost as if it wants to be read.





And wants everyone  
to dance around  
endlessly in circles



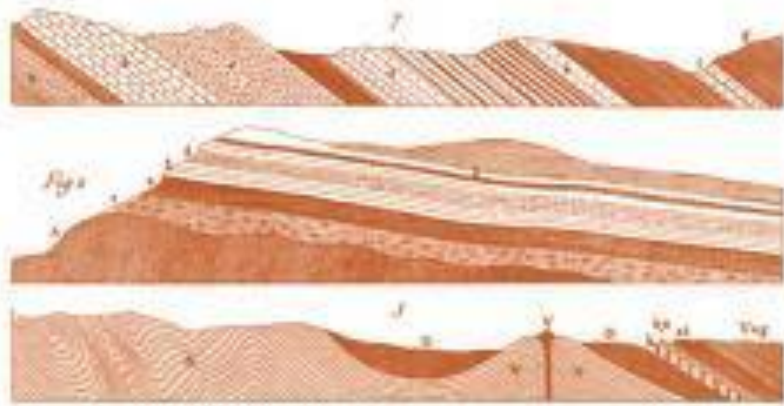
We're finally starting to  
understand the logic of  
the choreography



# Earth Sweet Earth

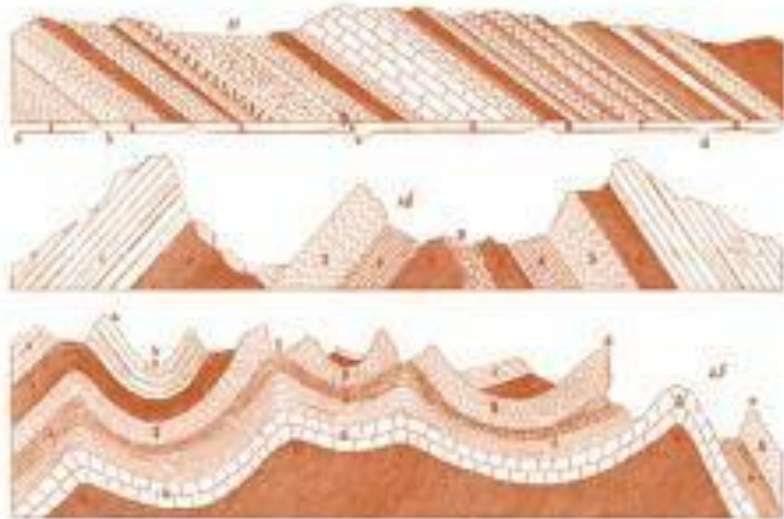
## The deep logic of the planet

Marcia Bjornerud  
Professor of Geosciences  
Lawrence University  
Appleton, Wisconsin



# TIMEFULNESS

HOW THINKING LIKE A GEOLOGIST  
CAN HELP SAVE THE WORLD



MARCIA BJORNERUD

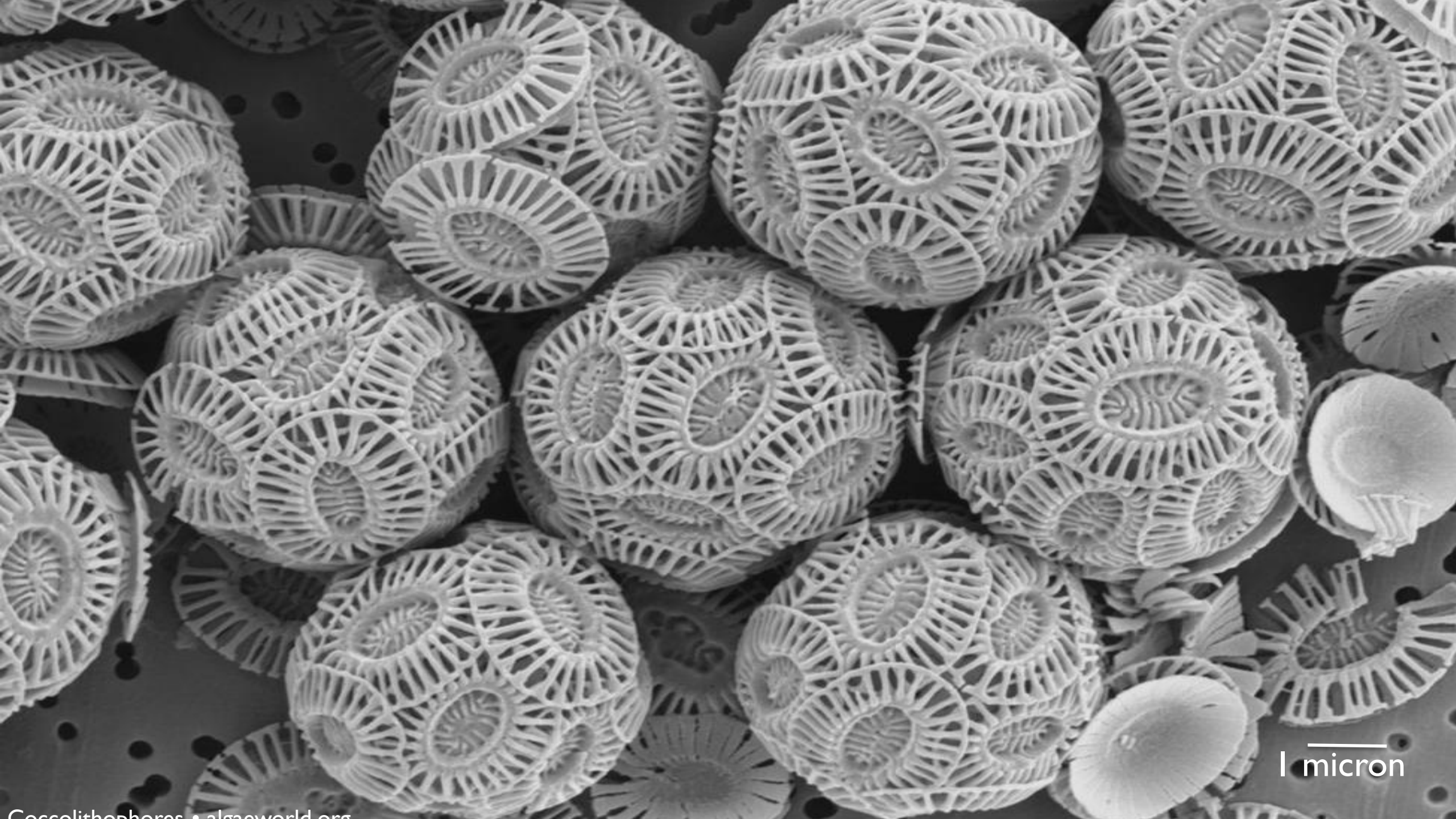
# READING THE ROCKS

The Autobiography  
of the Earth

"We certainly need popular science books like *Reading the Rocks* to help science fight back... Bjornerud has a rare talent for explaining scientific ideas clearly with intriguing and helpful analogies, similes, and metaphors." —*NATURE Magazine*

MARCIA BJORNERUD





1 micron

# APPENDIX III: Environmental Crises in Earth's History: Causes and Consequences

EVENT <sup>1</sup>	Extinction Severity <sup>2</sup>	C Cycle Perturbation: Volcanic/Tectonic	C Cycle Perturbation: Biogenic ( $\Delta\delta^{13}\text{C}$ ) <sup>3</sup>	Climate Change	Sea Level	Ocean Acidity	Ocean Anoxia	Ozone Destruction	Aftermath/Legacy
Snowball Earth 750–570 Ma	Unknown—likely severe	Initial cooling: C sequestration > volcanic emissions	Possibly ended by methane hydrate release ( $\Delta\delta^{13}\text{C} = -10$ ) <sup>4</sup>	Extreme cold, then extreme warmth	Very low to high				Ediacaran fauna, then Cambrian explosion
End-Ordovician extinction (#2) 440 Ma	57% of genera 86% of species	Probably some type of C cycle disturbances, but not well constrained		Abrupt ice age followed by rapid warming	High to low to high		Yes		Cambrian organisms (e.g., trilobites) decimated
Late Devonian extinction (#4) 365 Ma	35% of genera 75% of species		Biogenic C burial > decomposition ( $\Delta\delta^{13}\text{C} = \text{ca. } +4$ ) <sup>5</sup>	Abrupt cooling	High to low		Yes		Marine filter-feeders diversify
End-Permian extinction (#1) 250 Ma	56% of genera 95% of species	Siberian Traps (flood basalts)	Methane hydrates and/or burning coal seams ( $\Delta\delta^{13}\text{C} = -8$ ) <sup>6</sup>	Cold to extremely warm	Low to high	Yes	Yes	Yes—by volcanic gases	Permanent ecosystem reorganization; low $\text{O}_2$ for >1 million years
End-Triassic (#3) 200 Ma	47% of genera 80% of species	Central Atlantic	( $\Delta\delta^{13}\text{C} = -3$ ) <sup>7</sup>	Hot and dry		Yes			Dinosaurs diversify
End-Cretaceous (#4) 65 Ma	40% of genera 76% of species	Meteorite impact releases $\text{CO}_2$ from carbonates Deccan Traps	( $\Delta\delta^{13}\text{C} = -1$ )	Short cold spell (ash, $\text{SO}_2$ ), then long warm period ( $\text{CO}_2$ )		Yes		Maybe—chlorine from seawater vaporized in impact?	Dinosaurs vanish (except birds); mammals diversify
Paleocene-Eocene Thermal Max. 55 Ma	Deep-ocean foraminifera hit hard	North Atlantic flood basalts	Methane hydrates and/or burning coal seams ( $\Delta\delta^{13}\text{C} = -3$ ) <sup>8</sup>	Warming spike	Rapid rise	Yes			No ice; major land and deep-sea ecosystem changes
Anthropocene	Extinction rates 100–100X background		Fossil fuel combustion ( $\Delta\delta^{13}\text{C} = -2$ ) <sup>9</sup>	Rapid warming	Rapid rise	Yes	Yes	Yes	? ?