

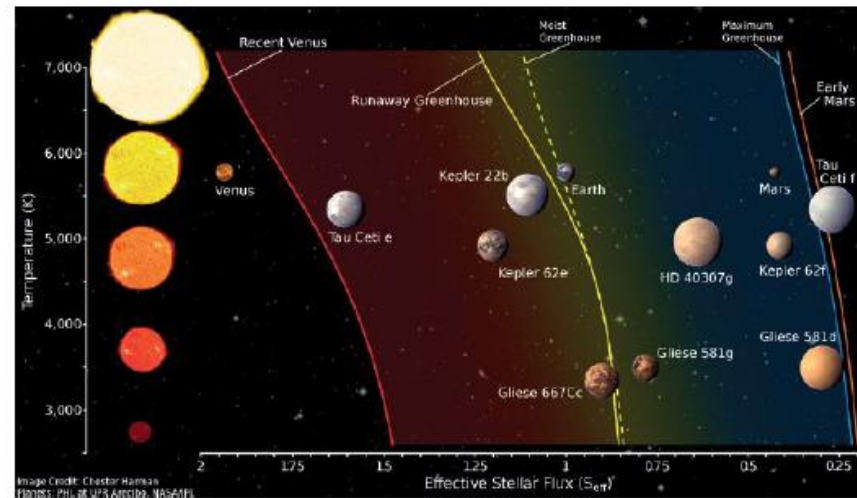
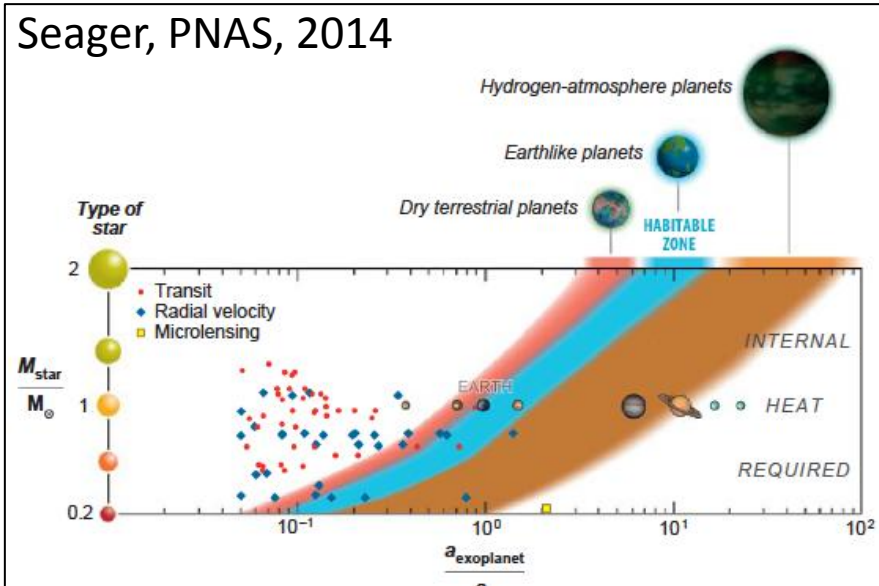
Links between the age, tectonic regime and climates of terrestrial planets:
How truly weird is Earth?

Jan 29, 2015

Mark Jellinek, UBC

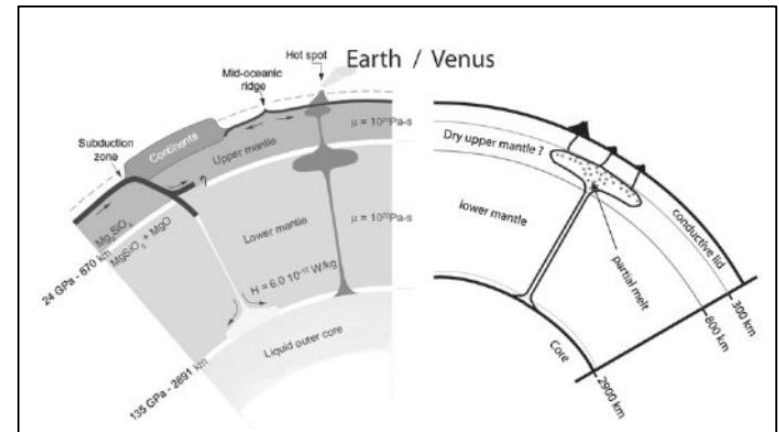
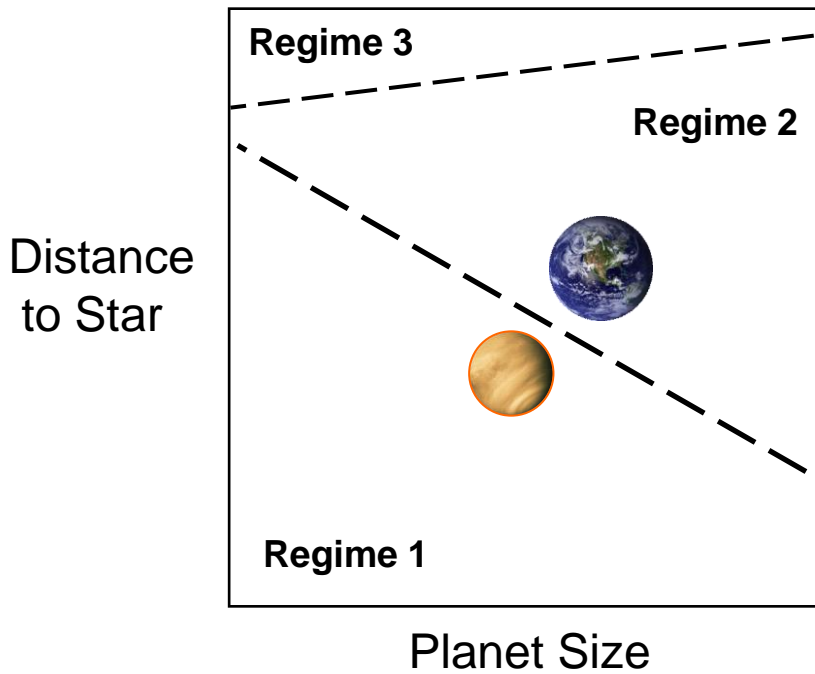
KITP EvoPlanets15

Reliable Dynamical “Regime Diagrams”?



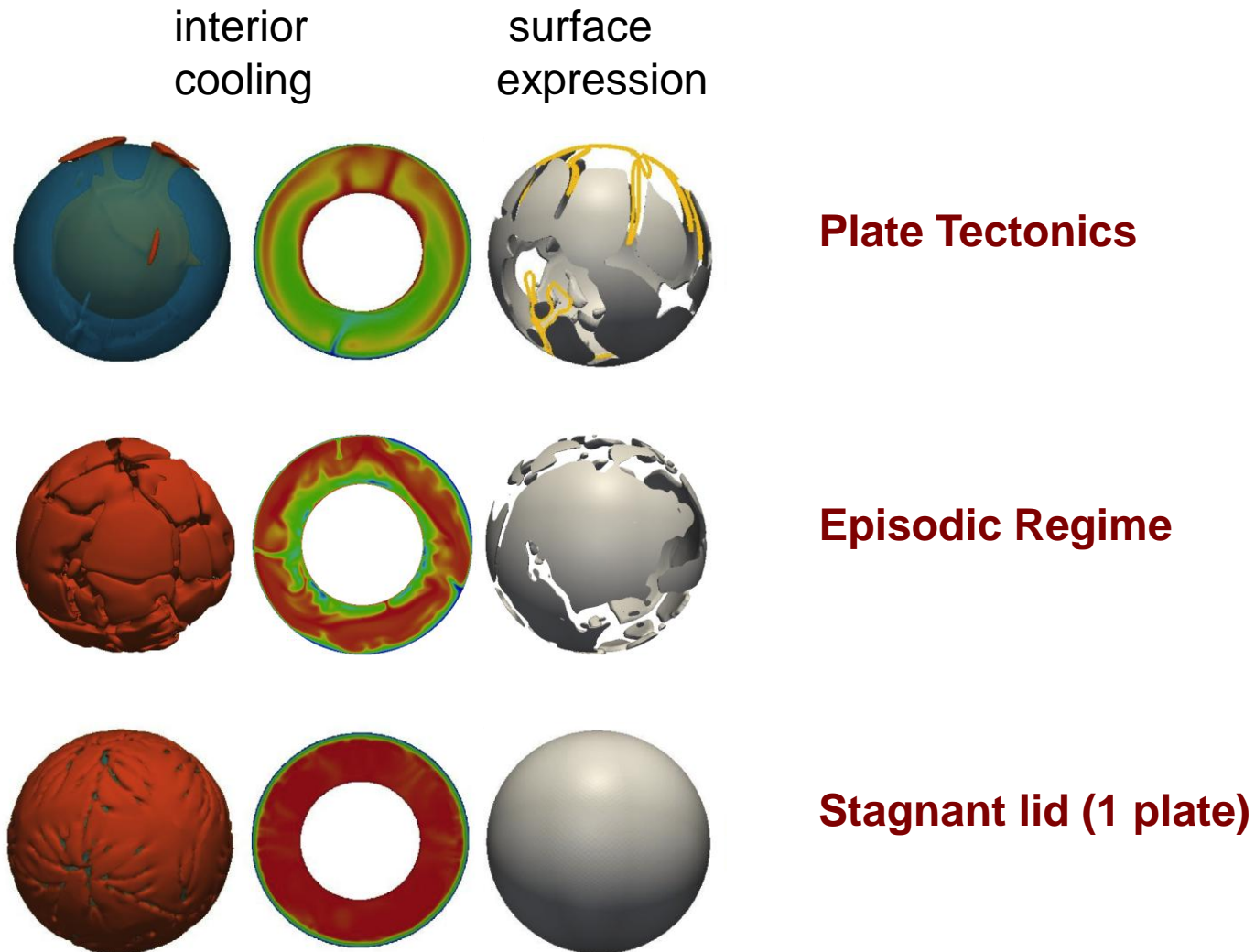
Kasting, PNAS, 2014

This “regime diagram” picture is popular

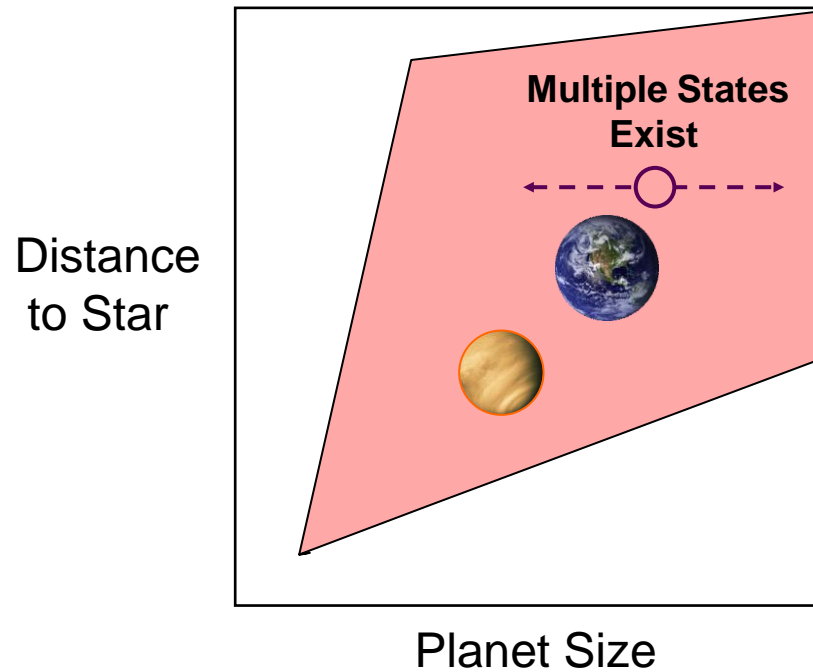


Spiegel et al. 2014 PNAS

Distinct dynamical regimes are identified (and understood)



A picture like this is, however, more likely

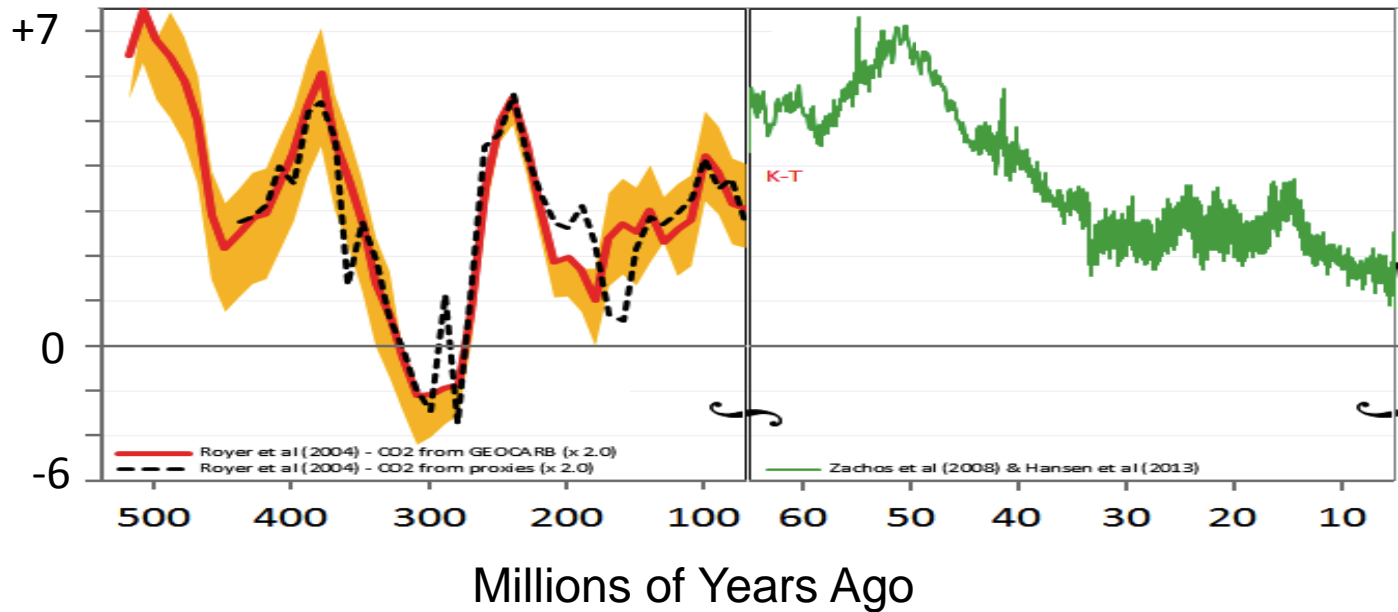


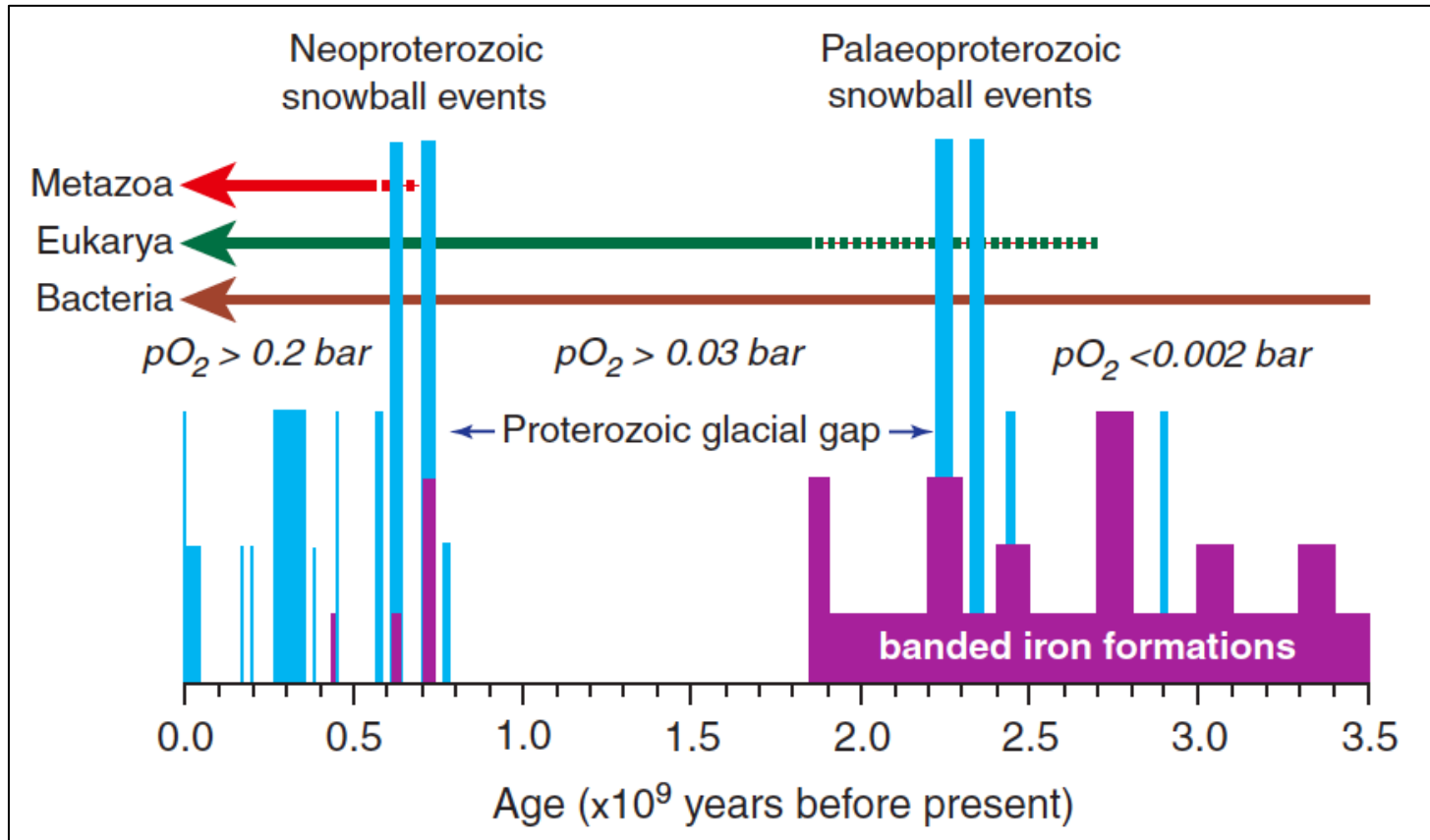
“...understanding its atmosphere is a necessary condition for understanding not only the planet itself, but also its formation, evolution, and (where relevant) habitability, and this goal is far from being realized”

Burrows, PNAS 2014

Earth's "stable climate"?

Temperature
Relative to
1960-1990
average C





Hoffman,

....A Basic Mantle-Climate Coupling Experiment...

A climate model over long time scales: 3 questions

1. How much C is in the ocean-atmosphere system?

[Rate of change] = [In – Out]

$$\frac{d}{dt}C_T = \underline{\Sigma F_{in}(t)} - \underline{k_{eff}(t)}C_T \quad [\text{mols/yr}]$$

Volcanic Outgassing,...

Silicate Weathering
Organic Burial

A basic climate model over long time scales: 3 questions

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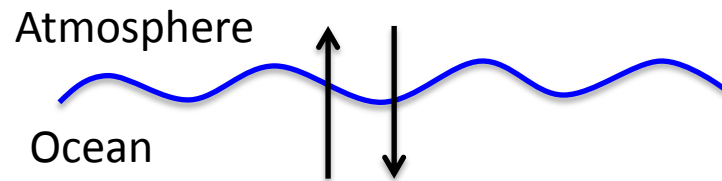
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Volcanic Outgassing,...

Silicate Weathering
Organic Burial

2. How much CO₂ is in the atmosphere (given ocean T, alkalinity, biology....)?



A basic climate model over long time scales: 3 questions

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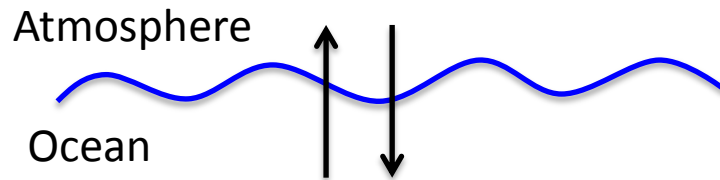
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Volcanic Outgassing,...

Silicate Weathering
Organic Burial

2. How much CO₂ is in the atmosphere (given T, Alk, biology....)?



3. What is the mean surface T (i.e. climate)?

$$OLR(T, H_2O, pCO_2) = L/4(1 - \alpha) \quad [\text{W/m}^2]$$

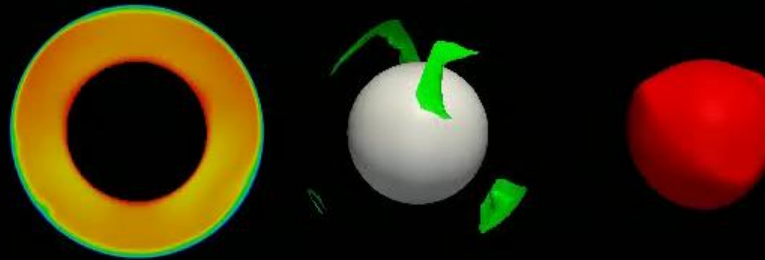
Volcanic Forcing:
Mantle stirring, resurfacing, volatile exchange

Insulating continents, “supercontinents”, plate tectonics, mantle stirring, melting and outgassing...

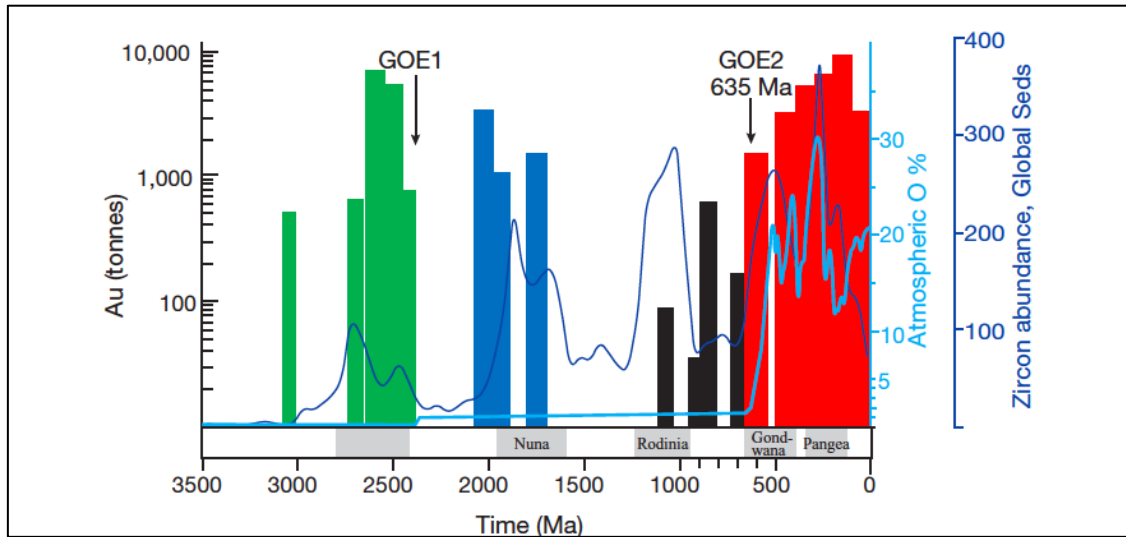
Continents =>



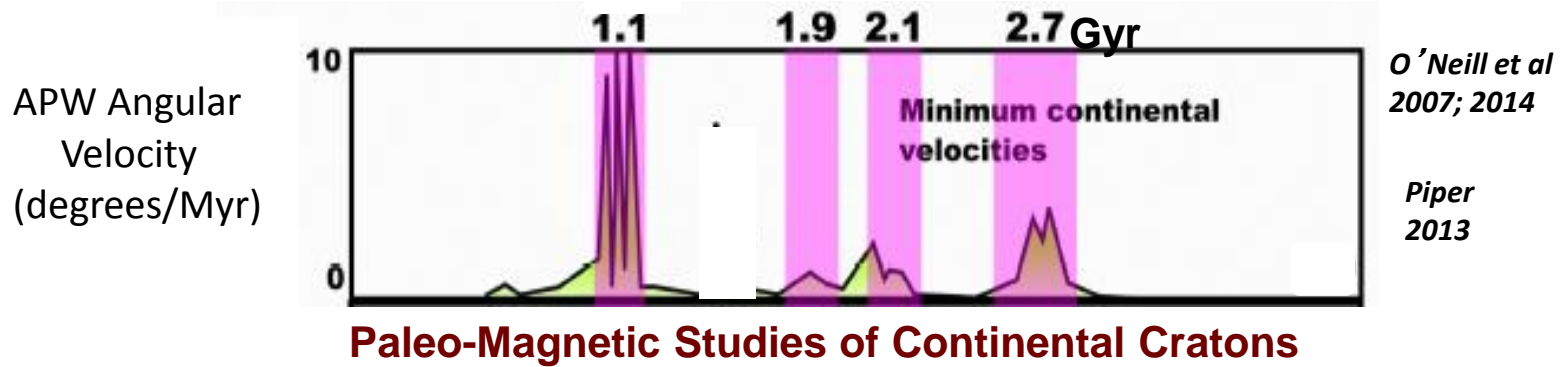
T, Plates, Plumes =>



Hints about the time-dependent nature of mantle stirring?



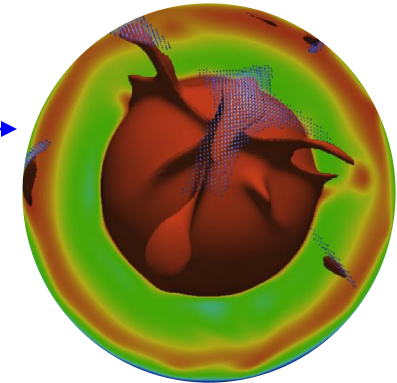
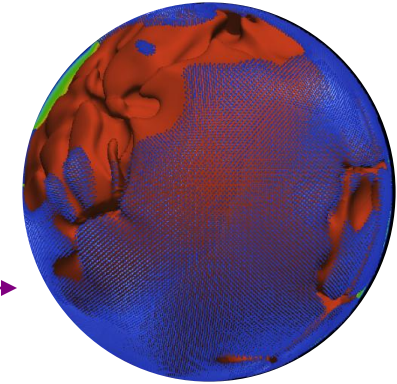
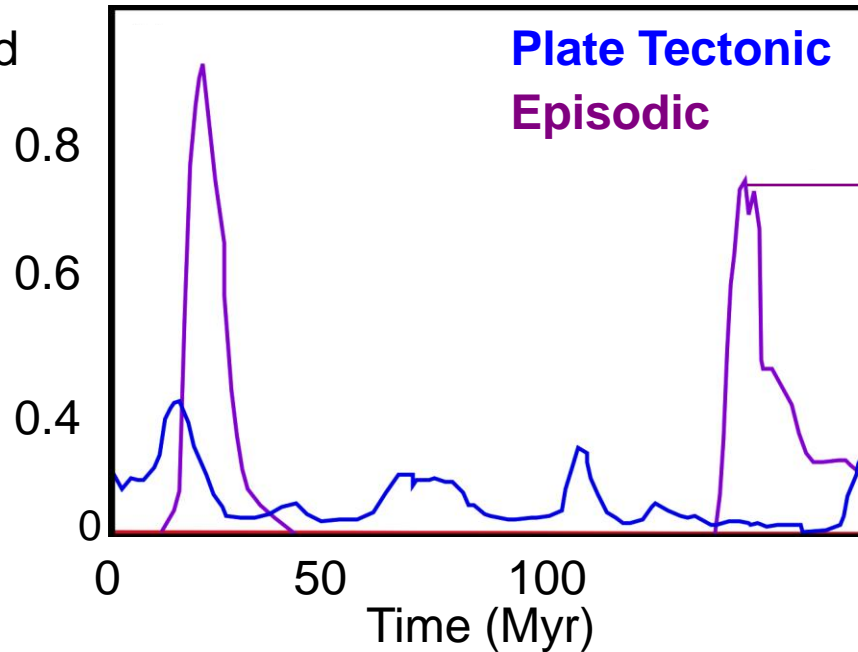
Tomkins, 2012



Paleo-Magnetic Studies of Continental Cratons

Basic Melt Production=> GH forcing

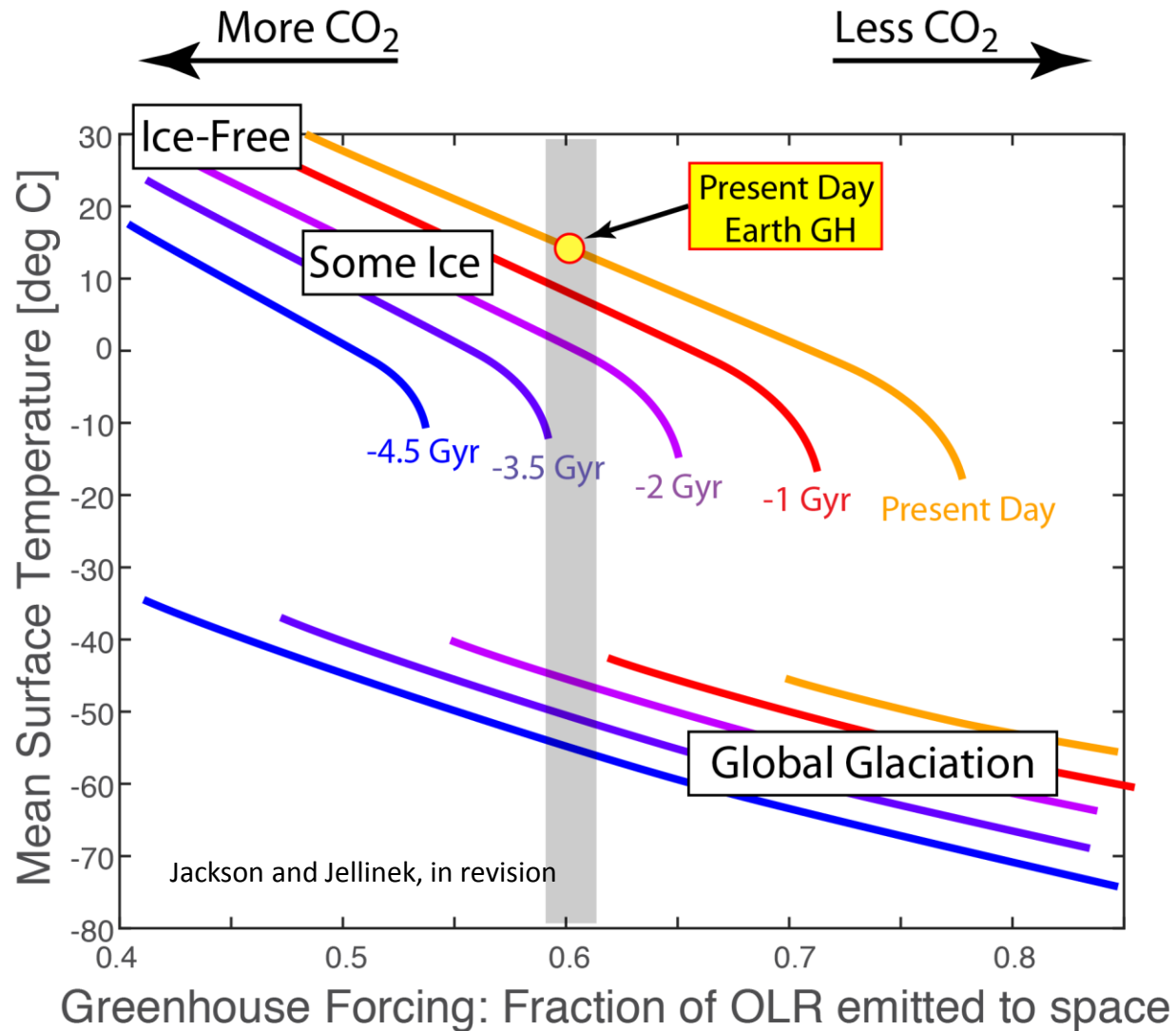
Melt Produced
km³yr



What is the climate response
of an episodic mode?

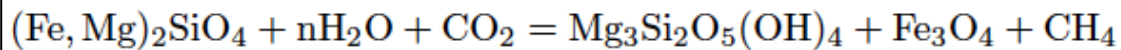
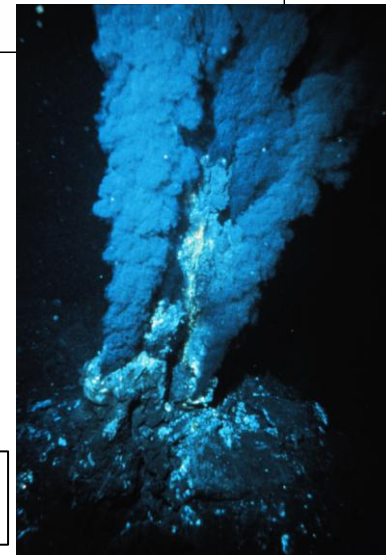
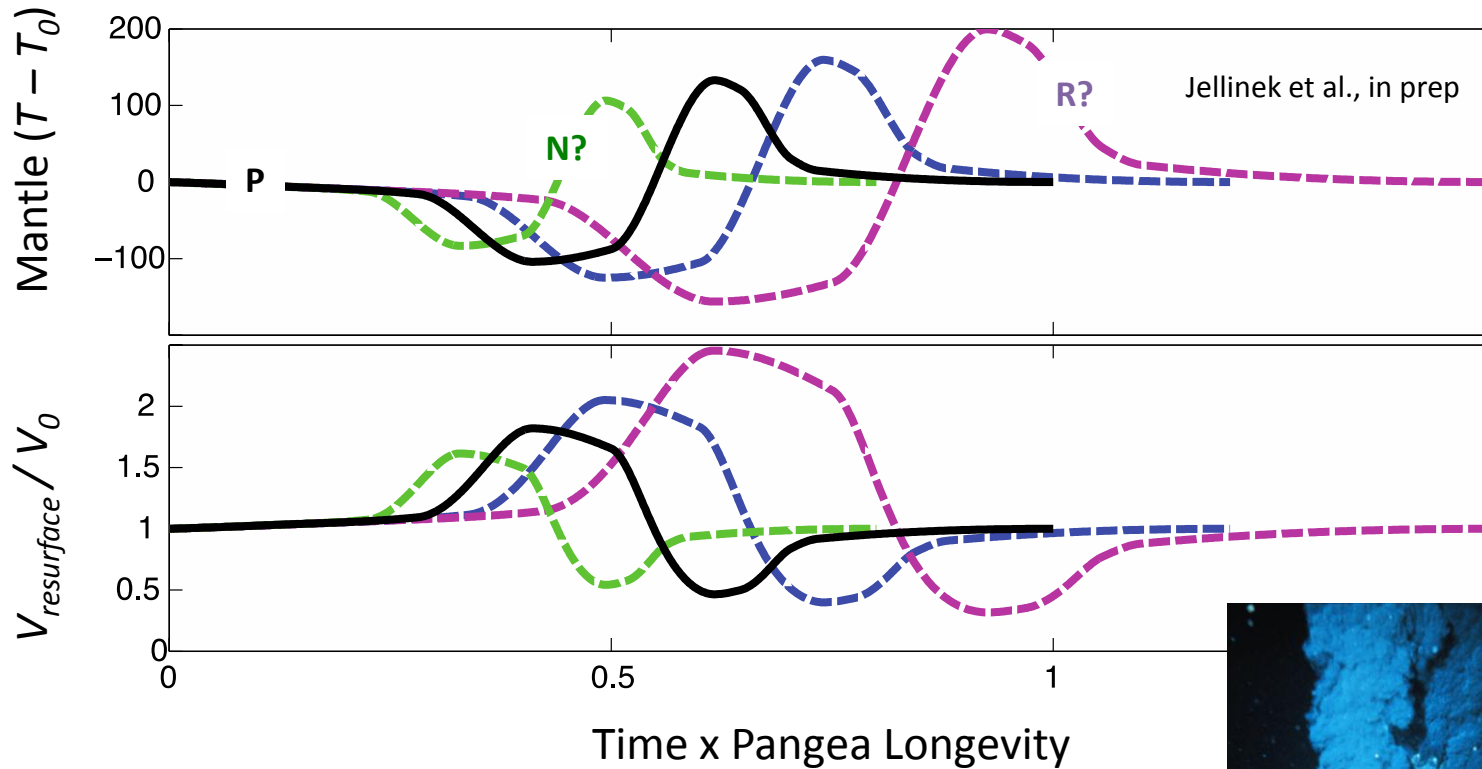
Climate responses to mantle forcing

Given volcanic forcing: What sort of climate might we have?

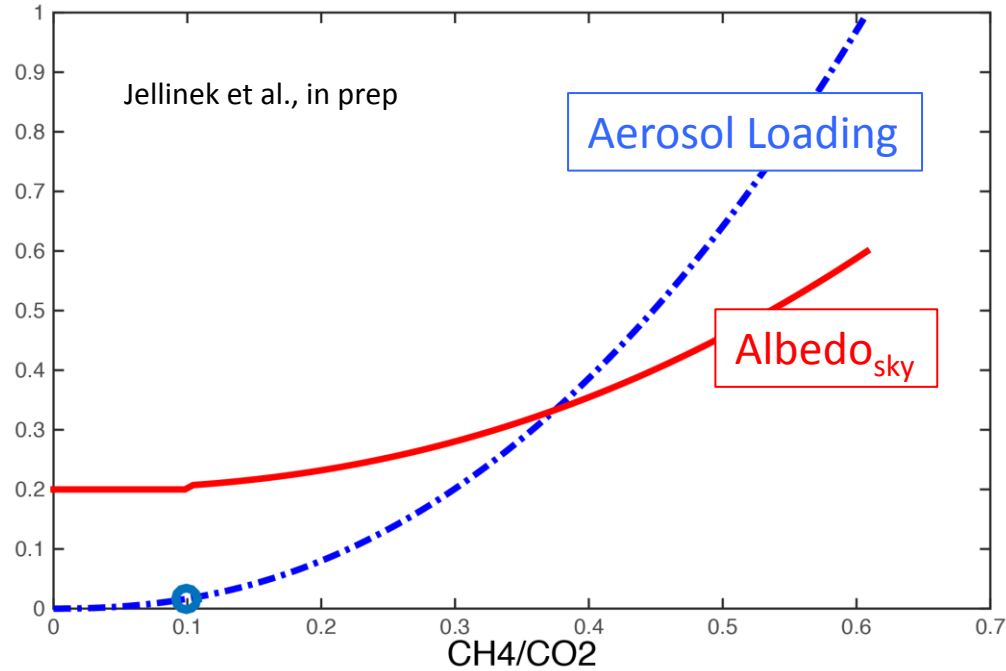


“Supercontinents” and Lateral Temperature Variations

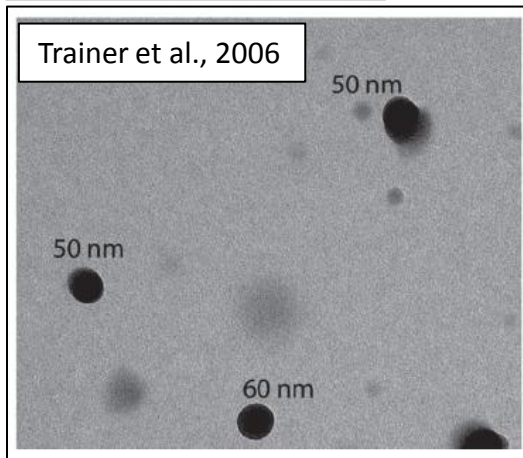
Methane Production at MORs in a low O₂ world



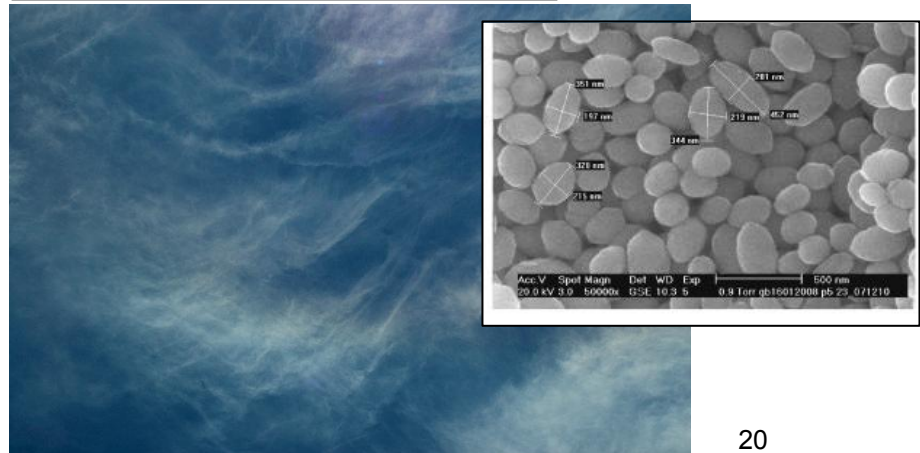
Methane Production and Organic Hazes: New photochemistry



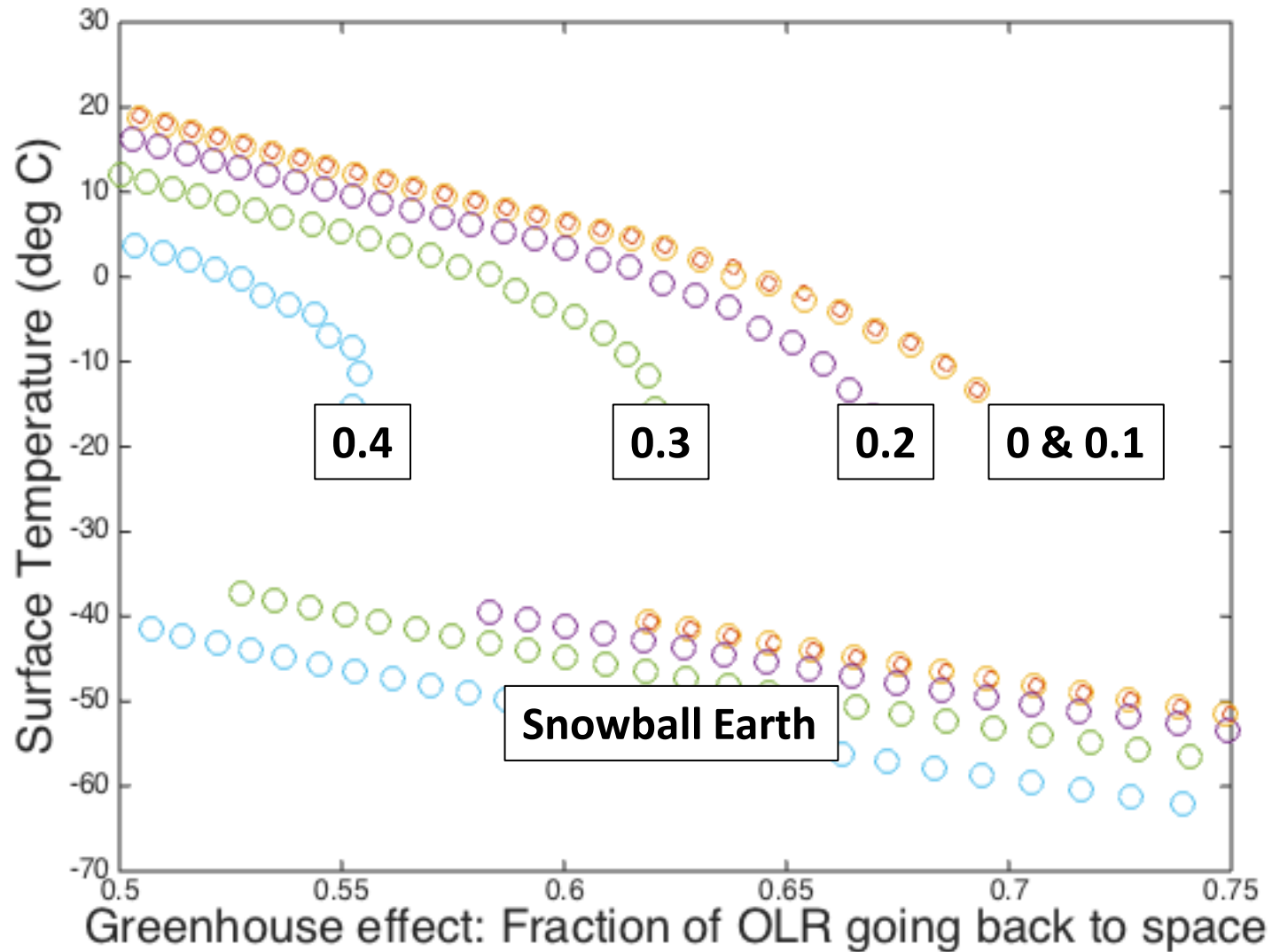
Methane Aerosol



Sulfate Aerosol ~ Nitrate?



$$\frac{S_0}{4} (1 - \alpha) (1 - \alpha_{sky}(CH_4/CO_2)) = OLR(T, pCO_2, H_2O, \text{etc.})$$



Climate-driven tectonic changes?

Venus: Climate-driven

Climate Model

Dynamic:

- 1D radiative/convective
- Cloud chem/microphysics

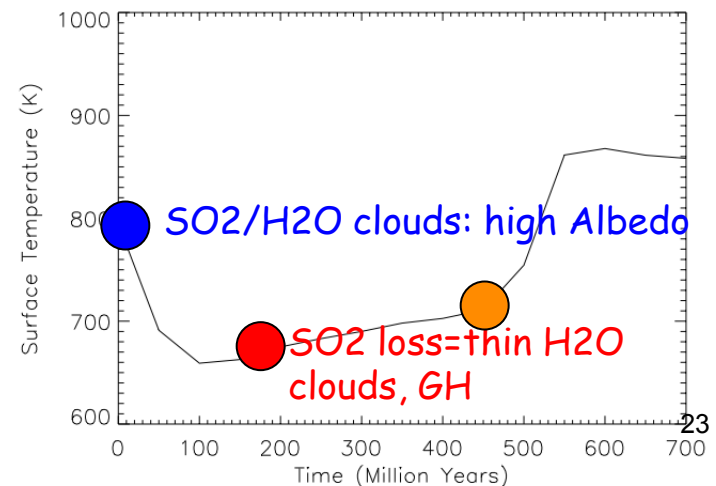
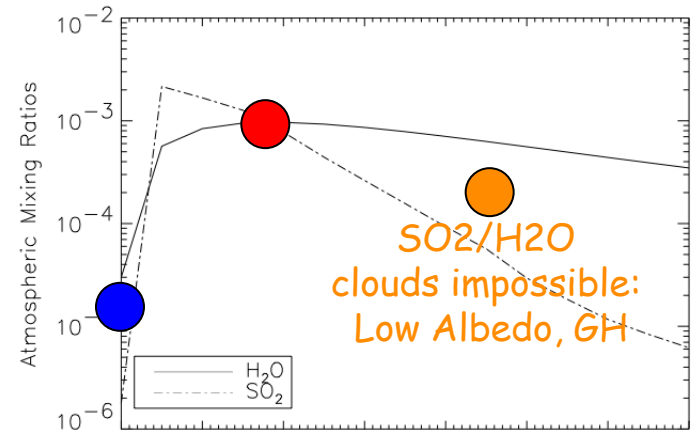
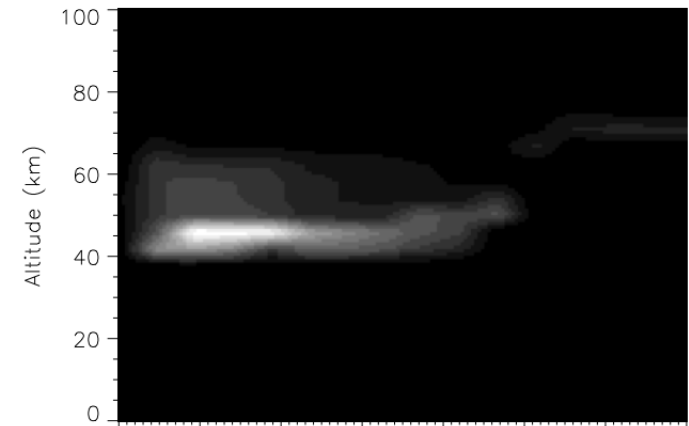
Fluxes

IN:

SO₂ and H₂O gas flux =
 $12\text{Gt/yr}(t=0) * \exp(-\lambda t)$;
 $\lambda = 1/10^8 \text{ yrs}$

OUT:

- SO₂ to surface by
 $\text{SO}_2 + \text{CaCO}_3 = \text{CaSO}_4 + \text{CO}$
 e-fold time $\sim 20\text{-}50 \text{ Myr}$
- H to exosphere
 e-fold time H₂O $\sim 160 \text{ Myr}$

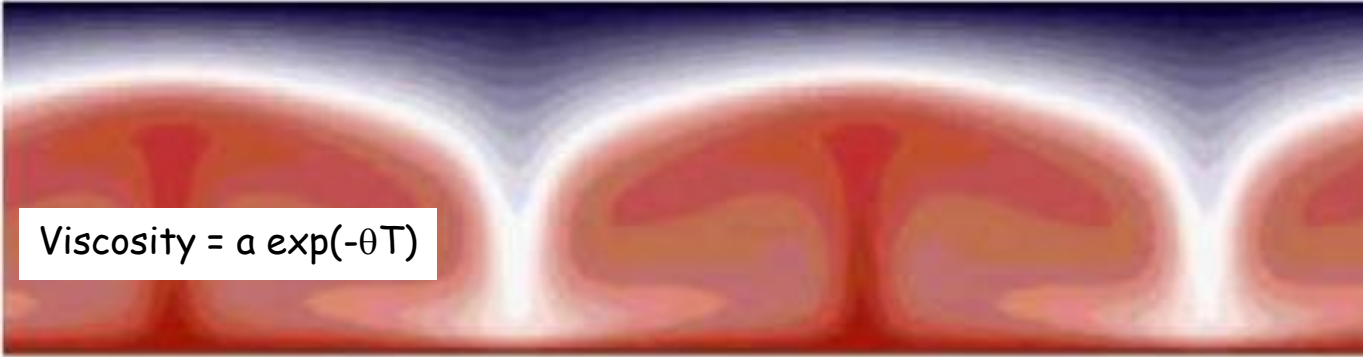


Making and breaking plates: A primer

Convective stresses and yield stresses:

Stagnant- vs. Mobile-lid regimes

Stagnant Lid Convection: One plate planet



Can flow into the drip break the lid?

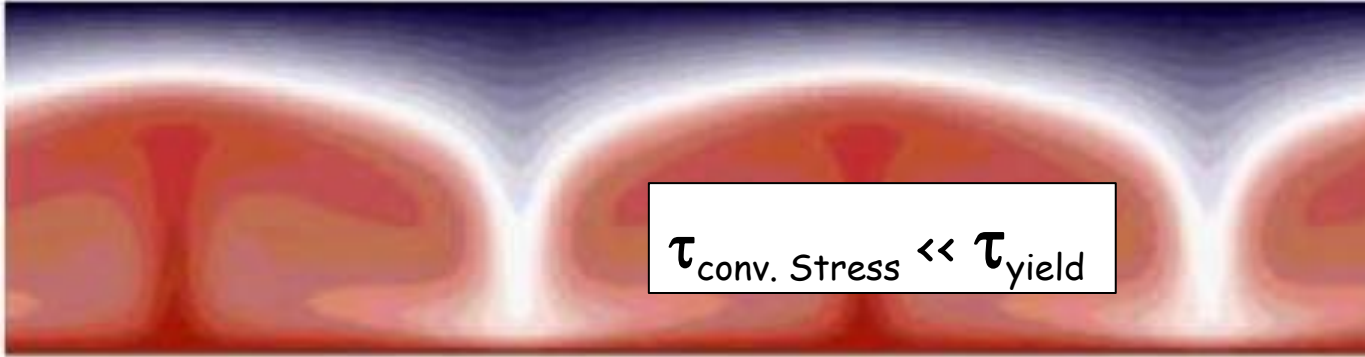
Convective Stress Increases w/
Viscosity and flow speed

Yield Stress Increases w/
Depth, dehydration, gravity

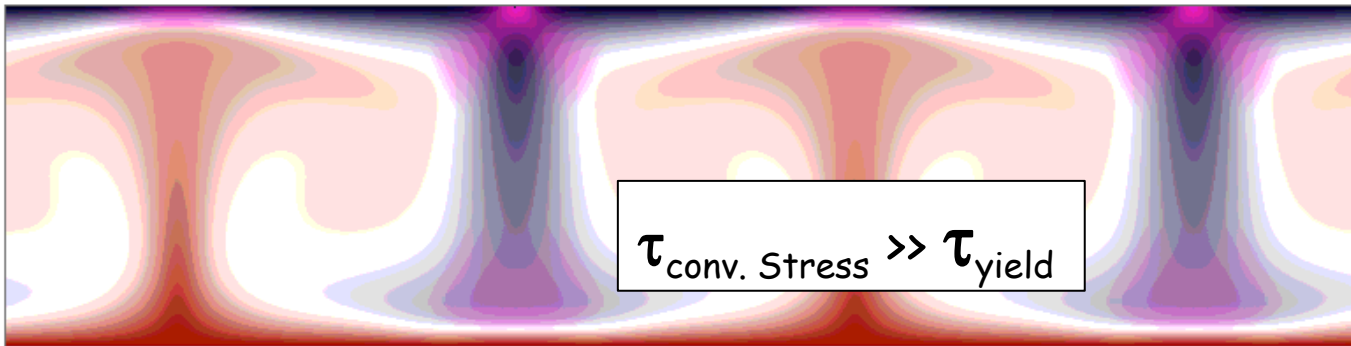
Convective stresses and yield stresses:

Breaking the lid to define two regimes

Stagnant Lid Convection: One plate planet

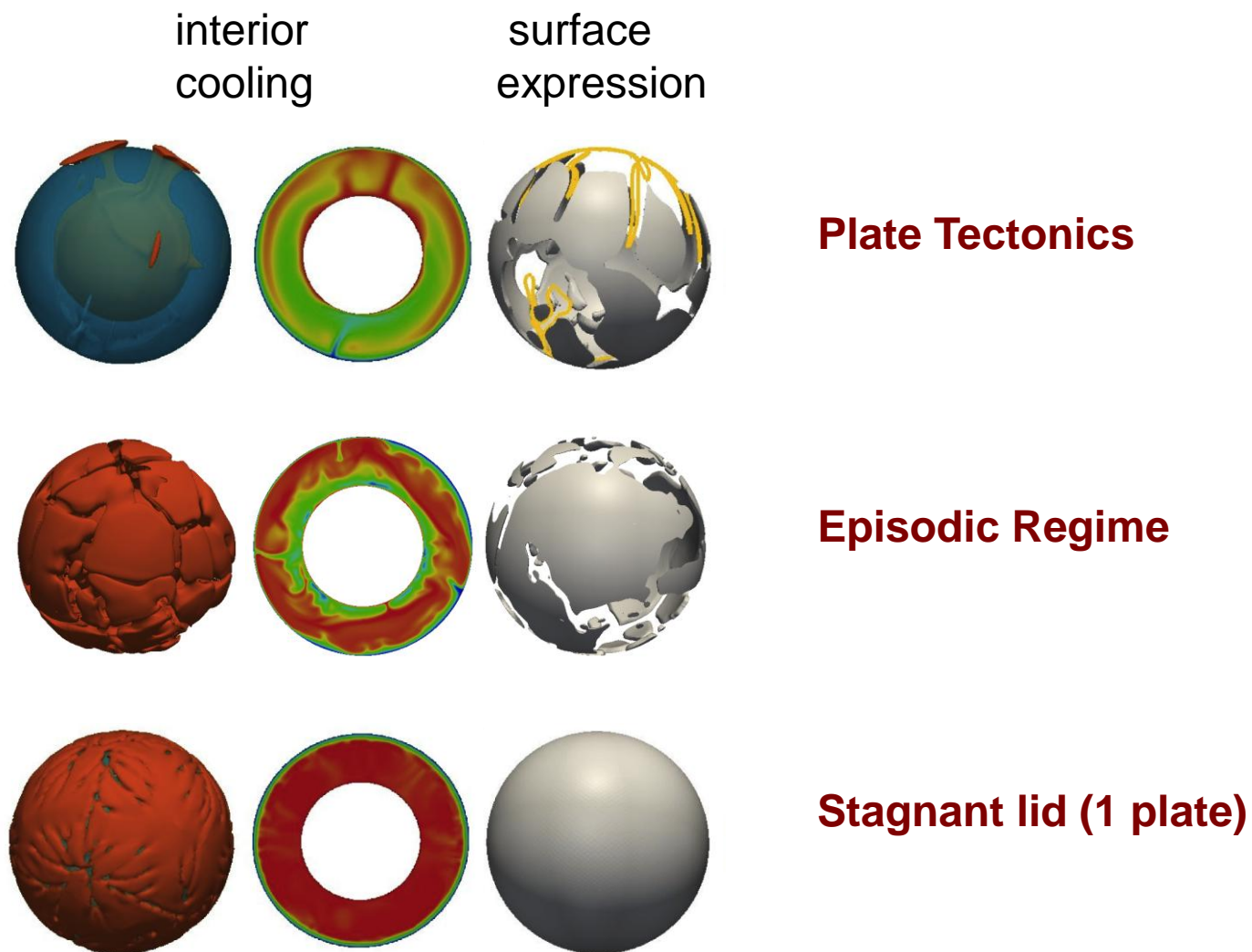


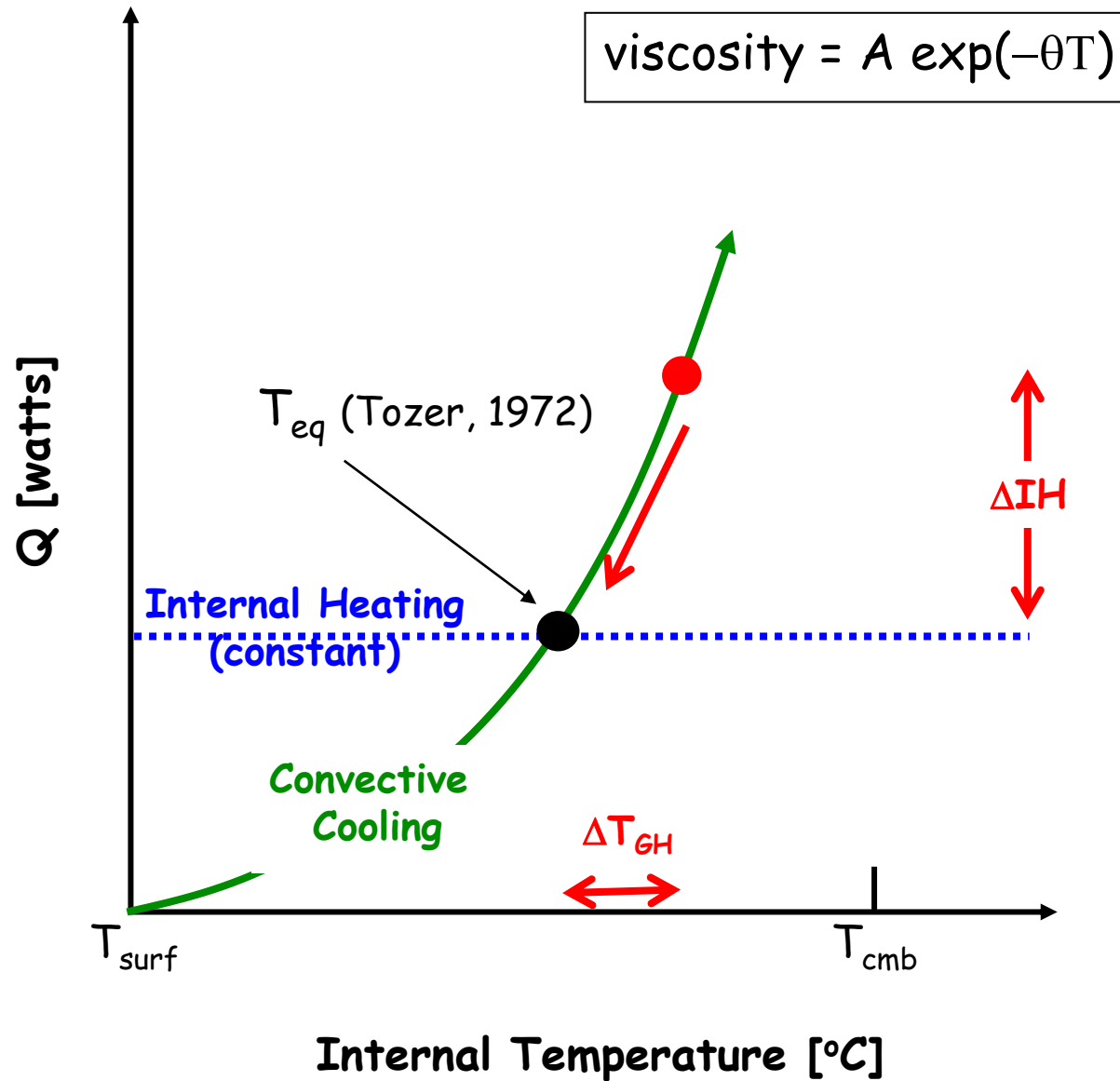
"Mobile Lid" Convection: Plates

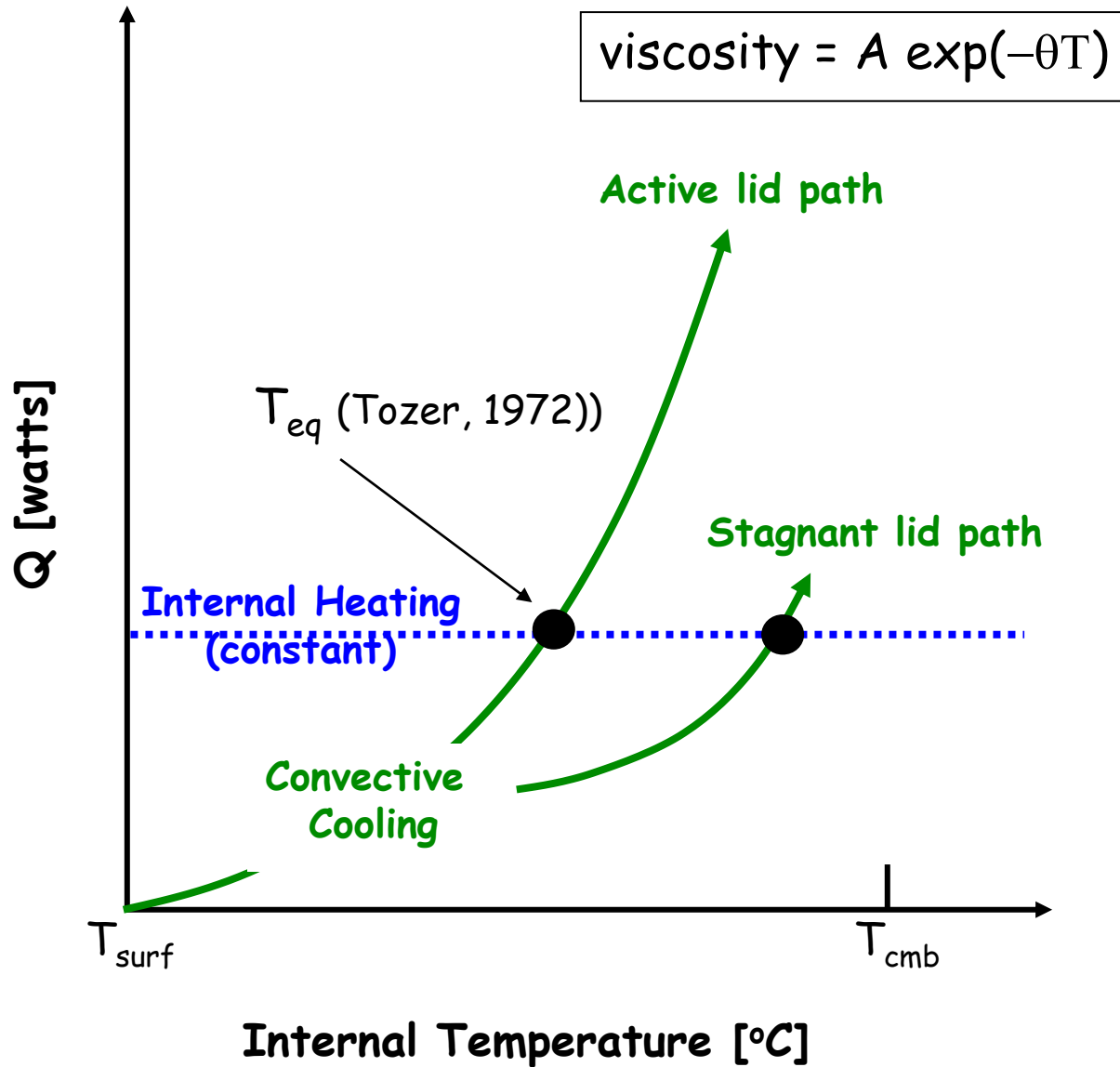


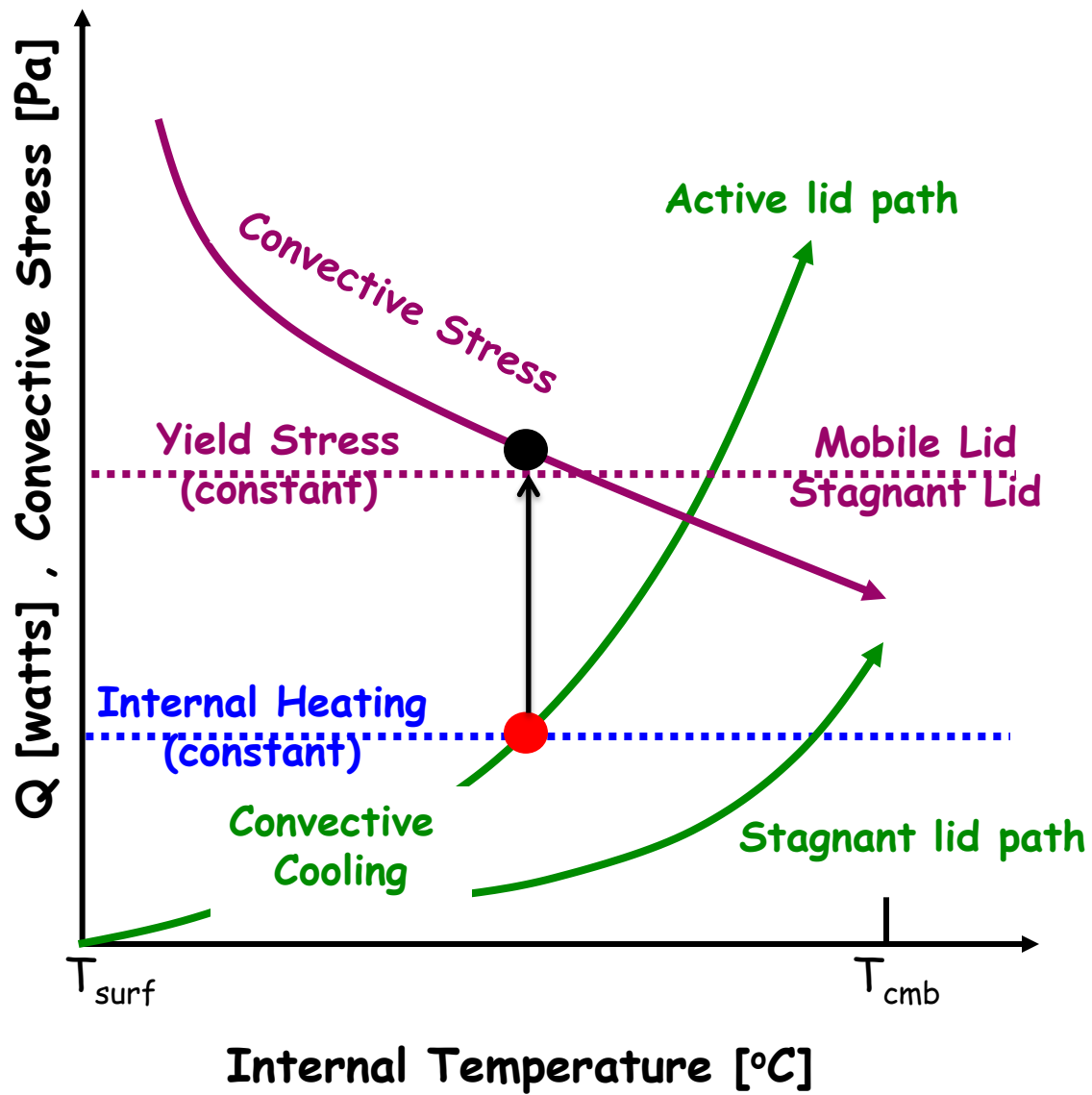
Mantle Temperature, Tectonic Regimes & Their Sensitivity to Radiogenic and GH Forcing

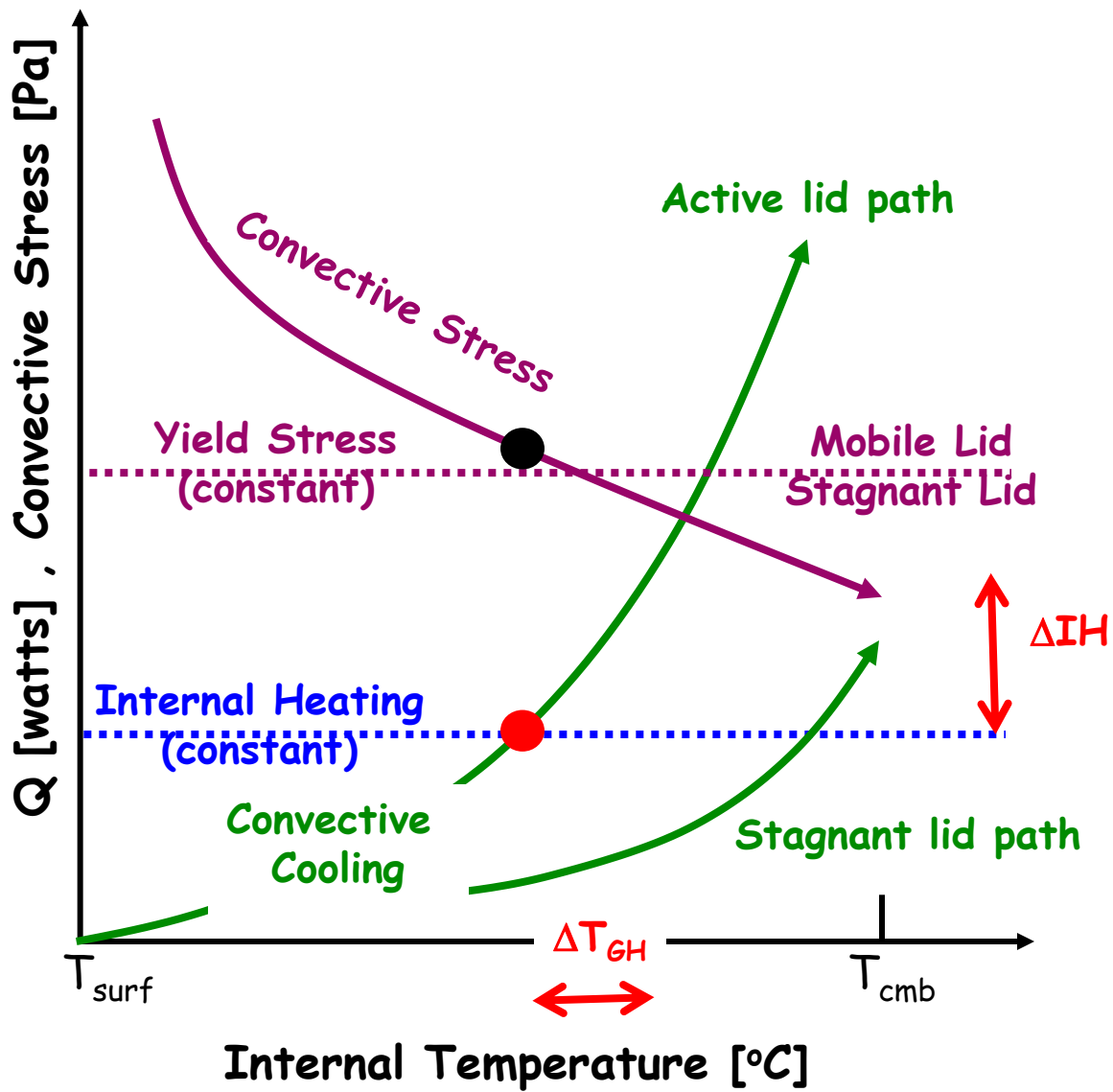
Distinct dynamical regimes are identified (and understood)

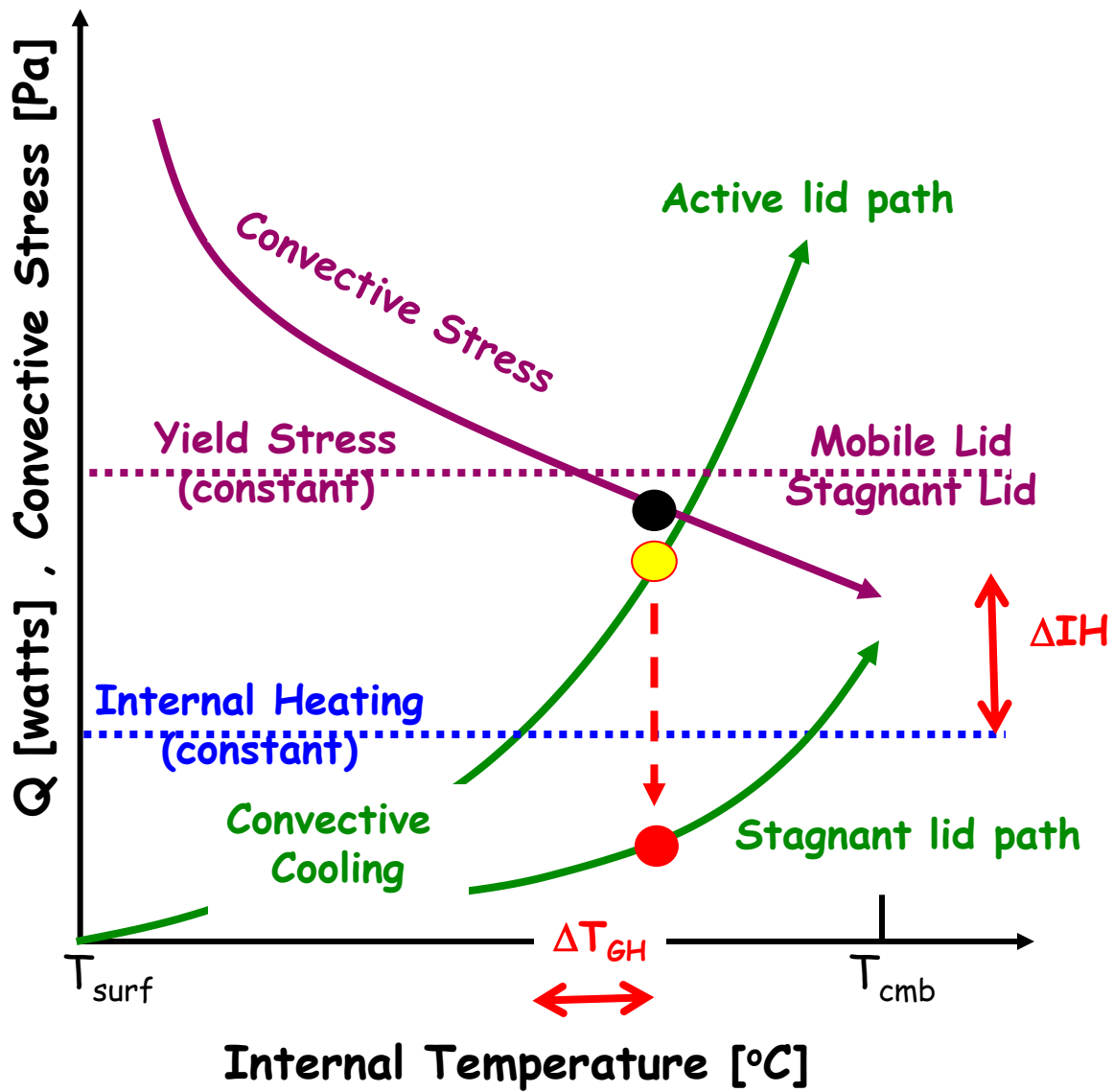




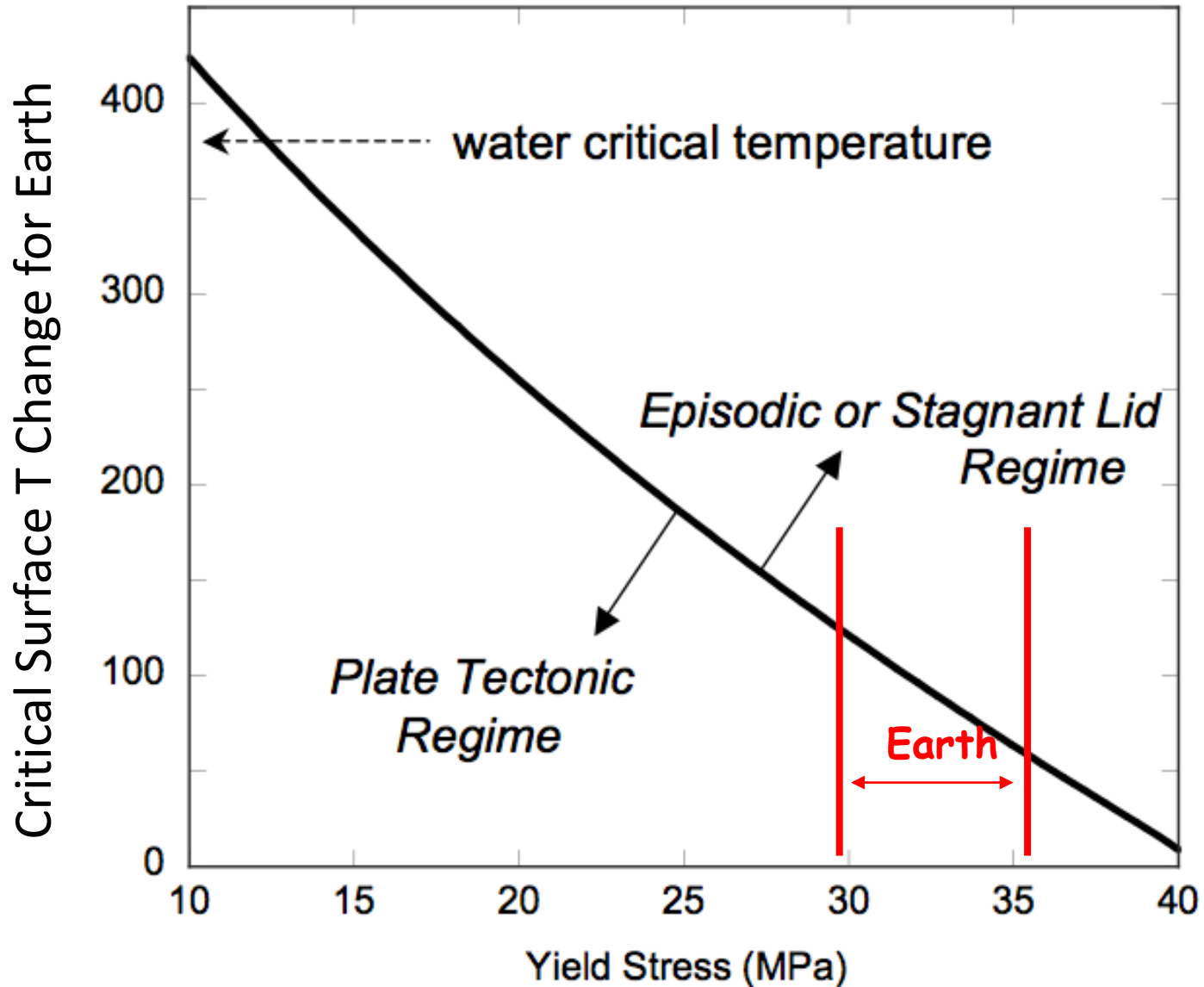




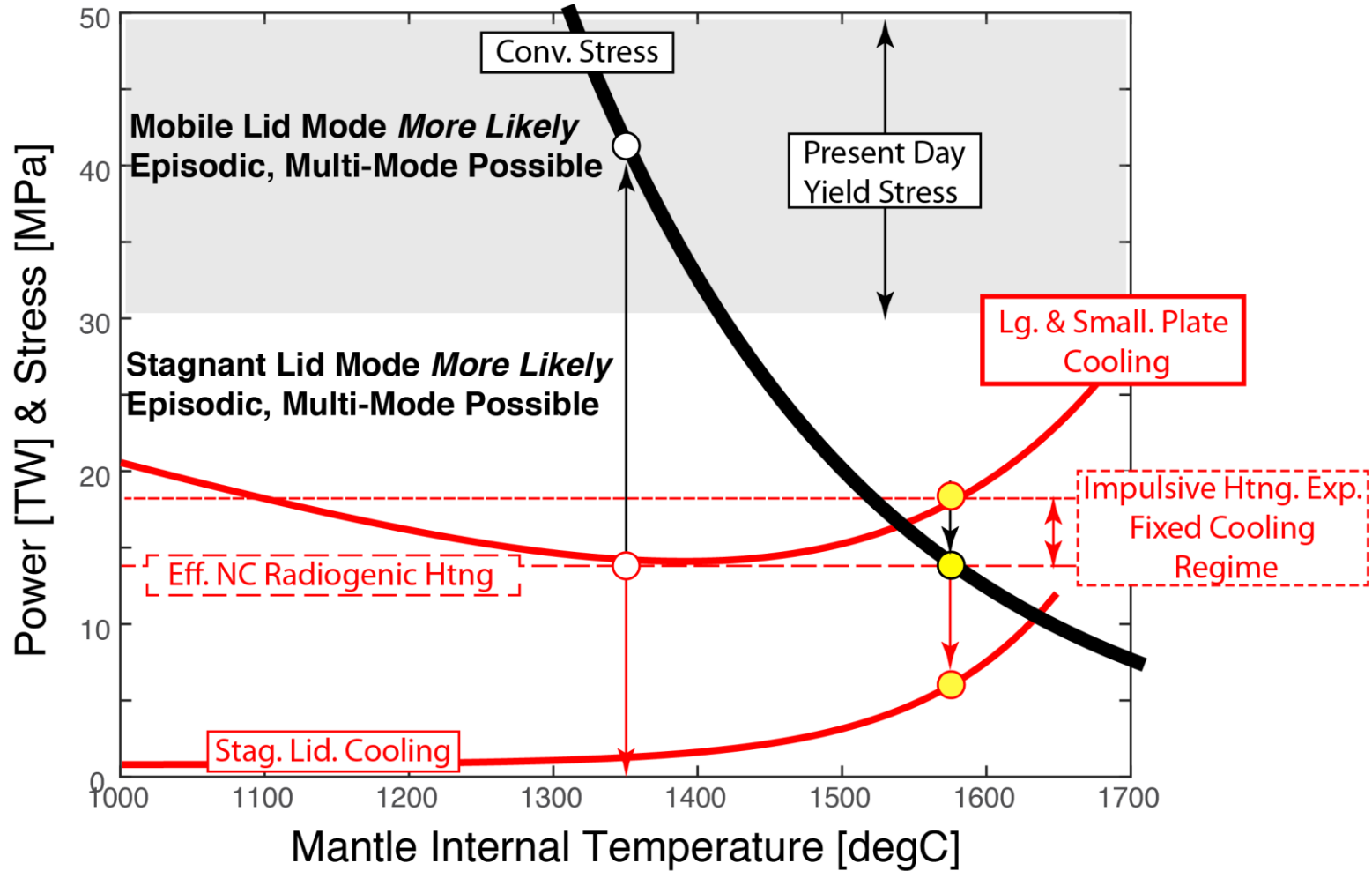


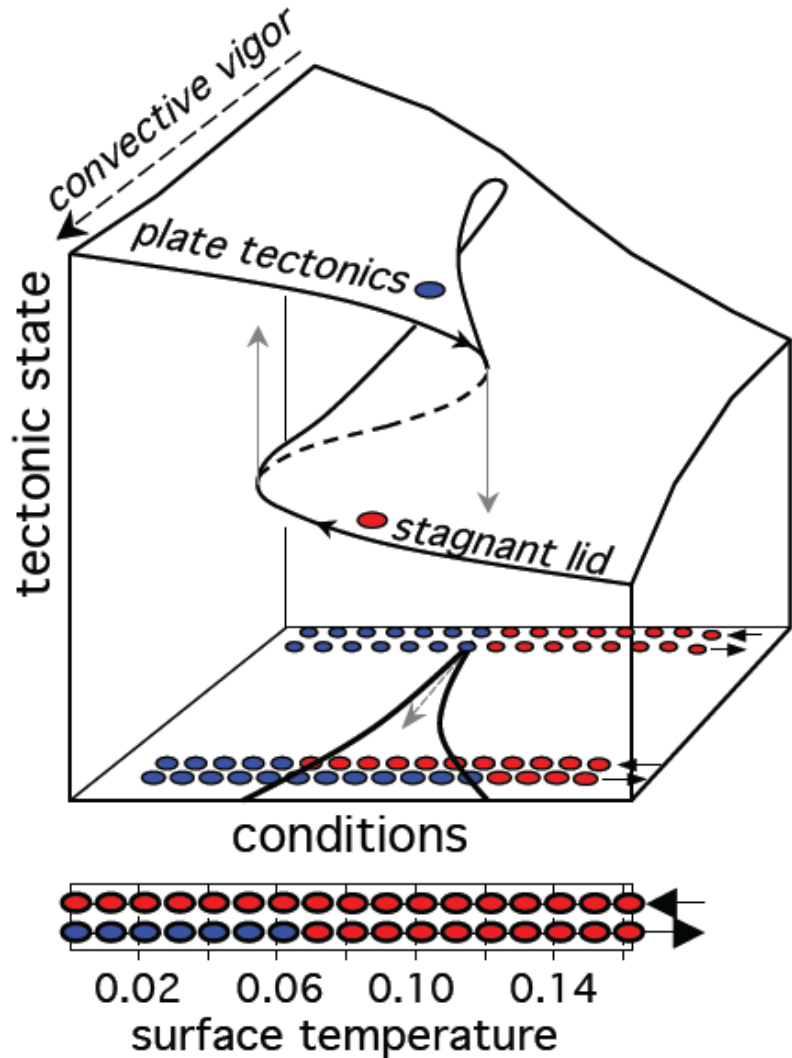


Greenhouse forcing can kill plate tectonics Will anti-greenhouse turn plate tectonics on?



A more realistic thermal picture and a probabilistic view of tectonic outcomes





Terrestrial planet evolution depends on a lot of things:

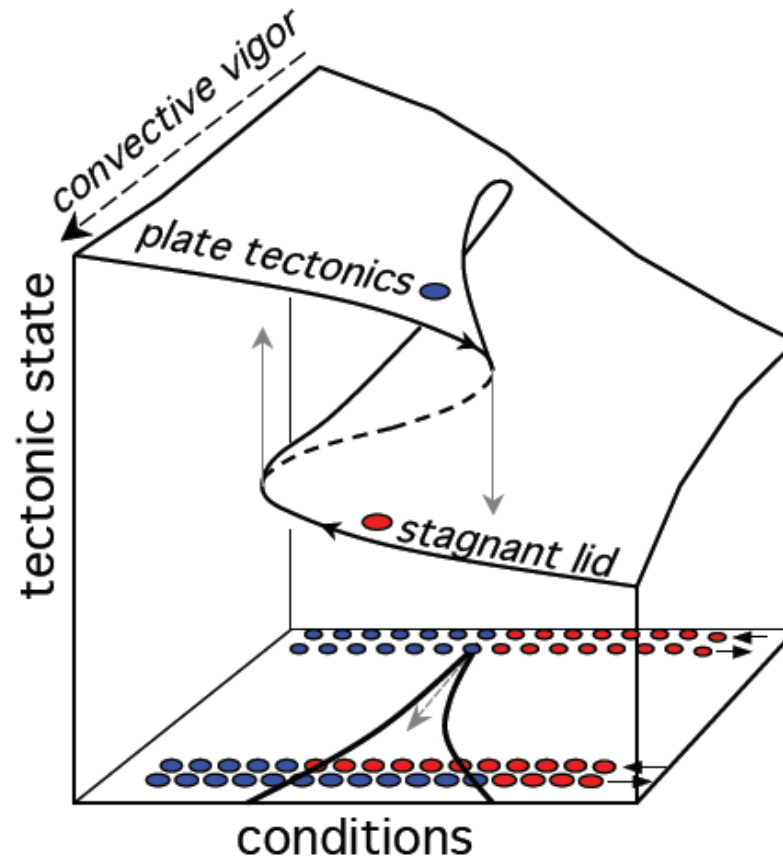
- *Long-term climate change*
- *Internal heating*
- *Plate strength*
- *History*

Lenardic, Crowley and Jellinek, in flight

Multiple solutions for terrestrial planet evolution:

Can we exploit the growing richness of the XO planet “taxonomy” to explore tectonic/climate/atmosphere connections probabilistically?

If we admit to “dynamic habitability” how does this enhance the search for “habitable worlds”?

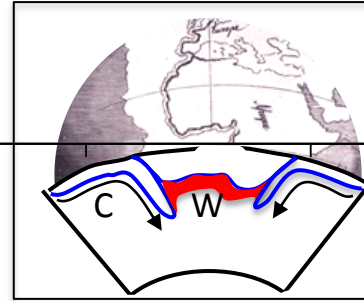


Extra

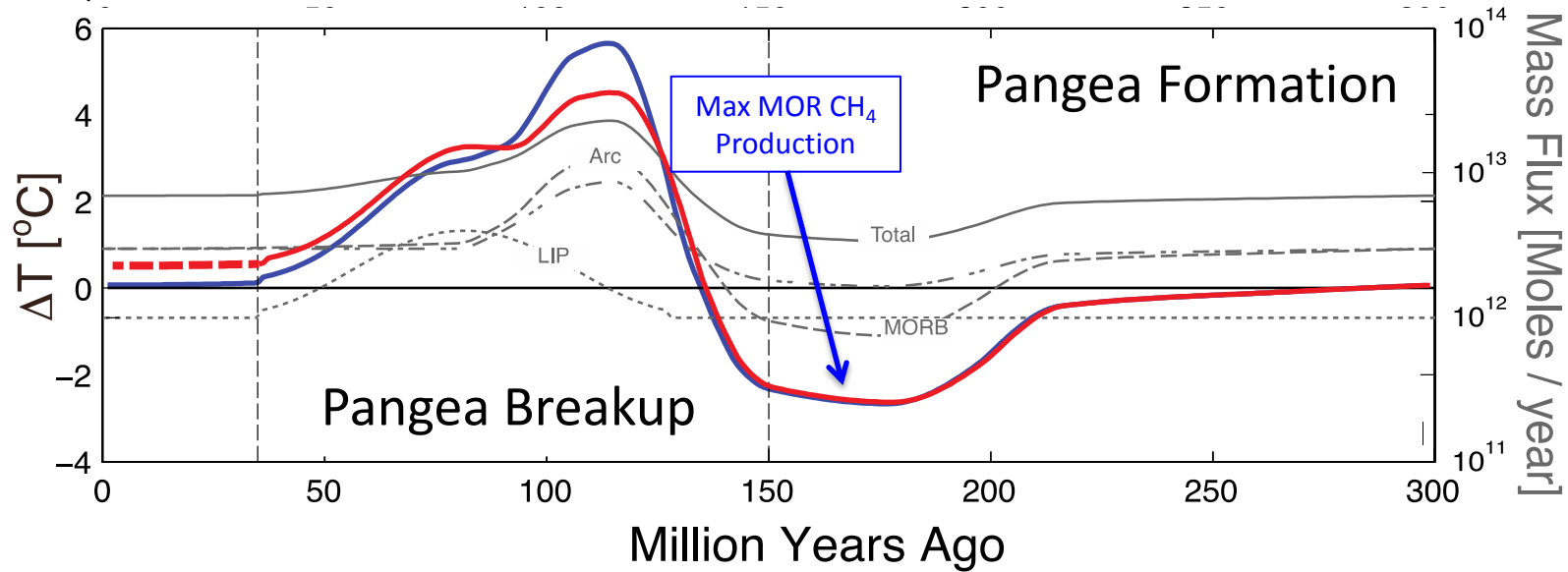
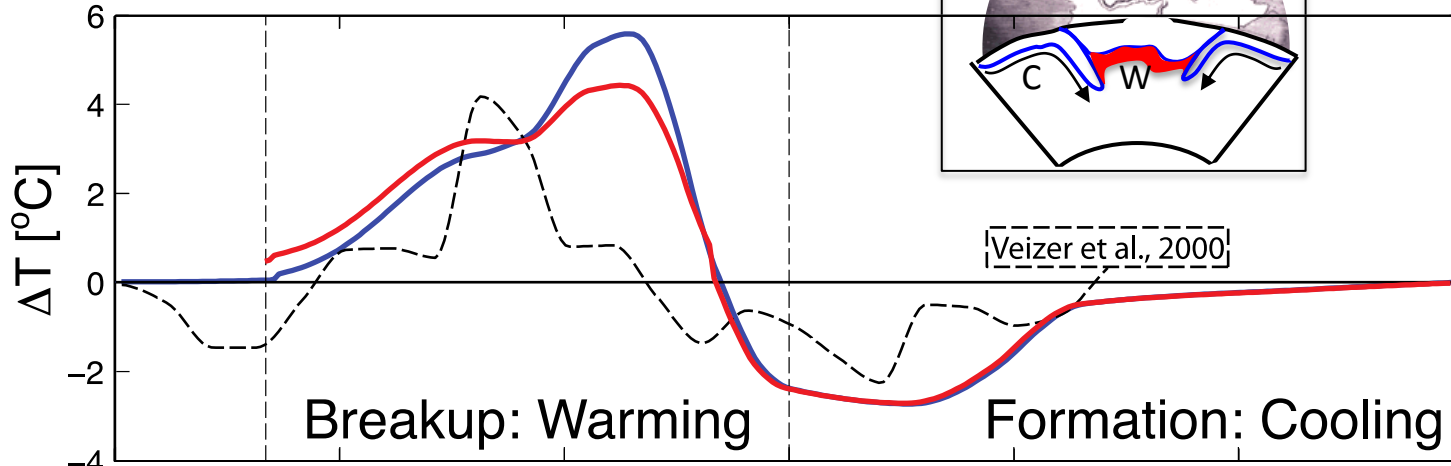
SC Subduction and thermal Mixing

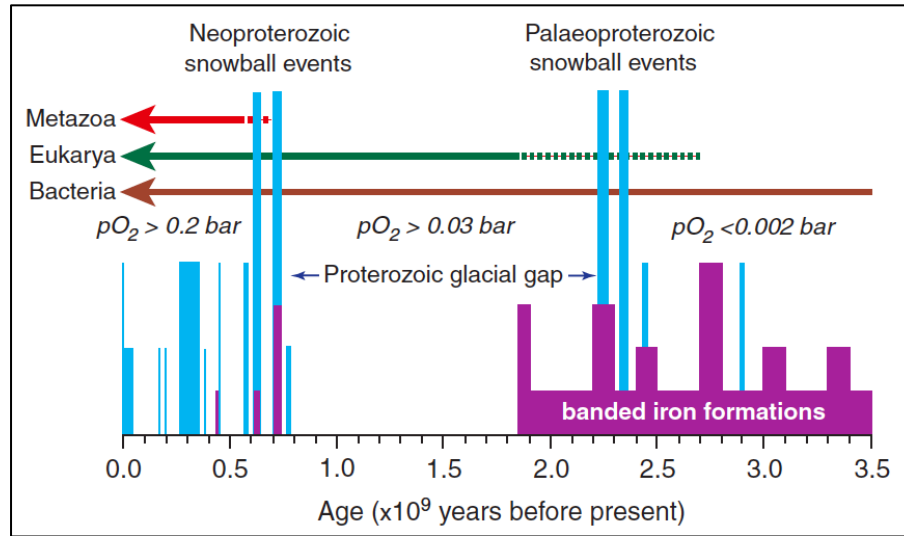
$$\frac{d}{dt}C_T = \Sigma F_{in}(t) - k_{eff}(t)C_T$$

$$\frac{pCO_2}{pCO_2_0} \sim \left(\frac{F_{in}(t)}{k_{eff}(t)}\right)^2 \left(\frac{k_{ref}}{F_0}\right)^2 \left(\frac{K_0}{K}\right)$$

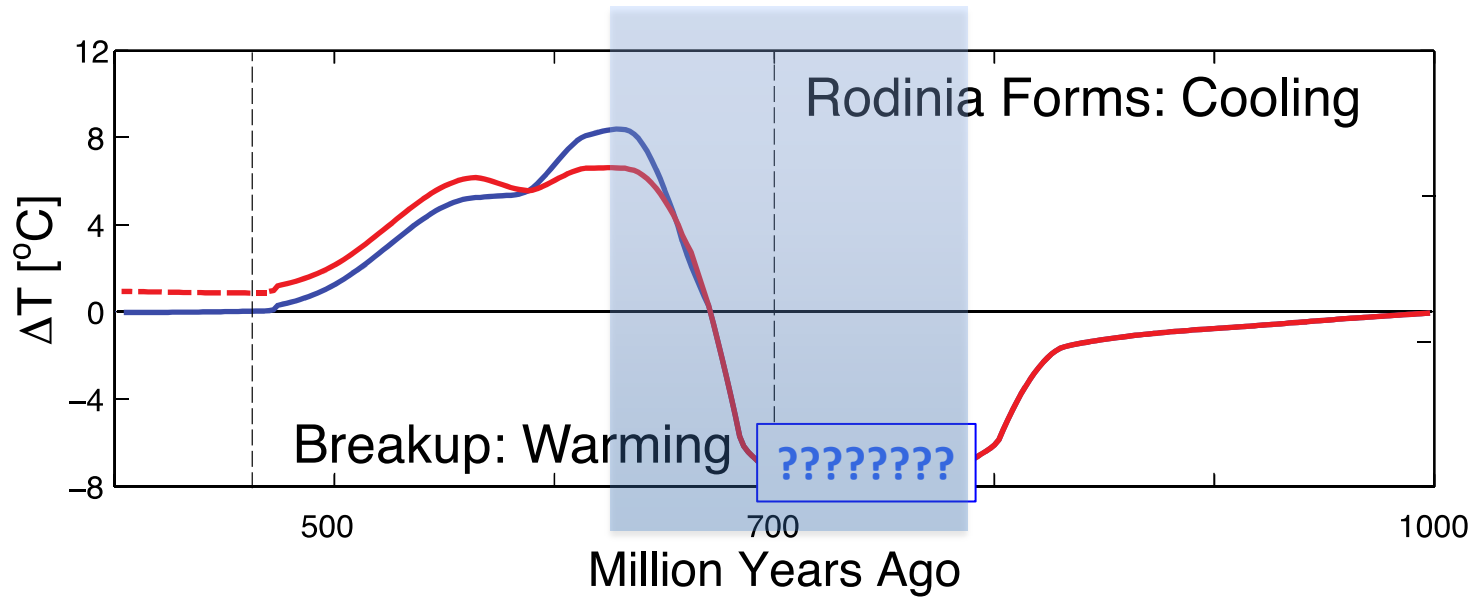


[Veizer et al., 2000]





Snowball Earth



Climate Model

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- 1D radiative/convective
- Cloud chem/microphysics

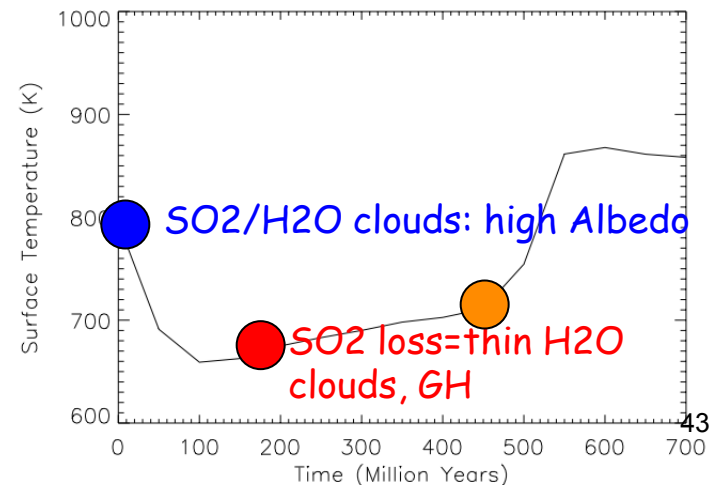
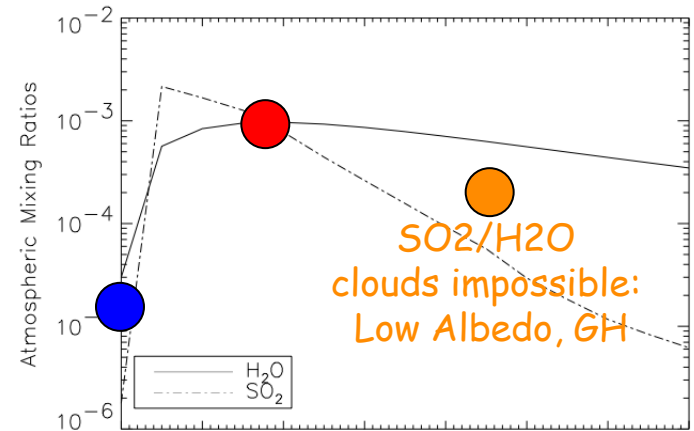
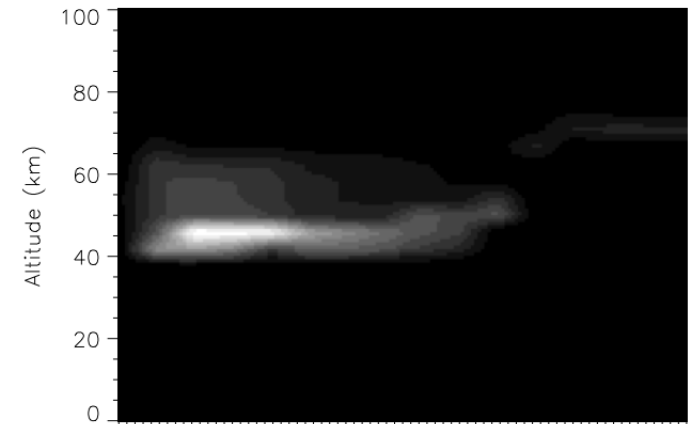
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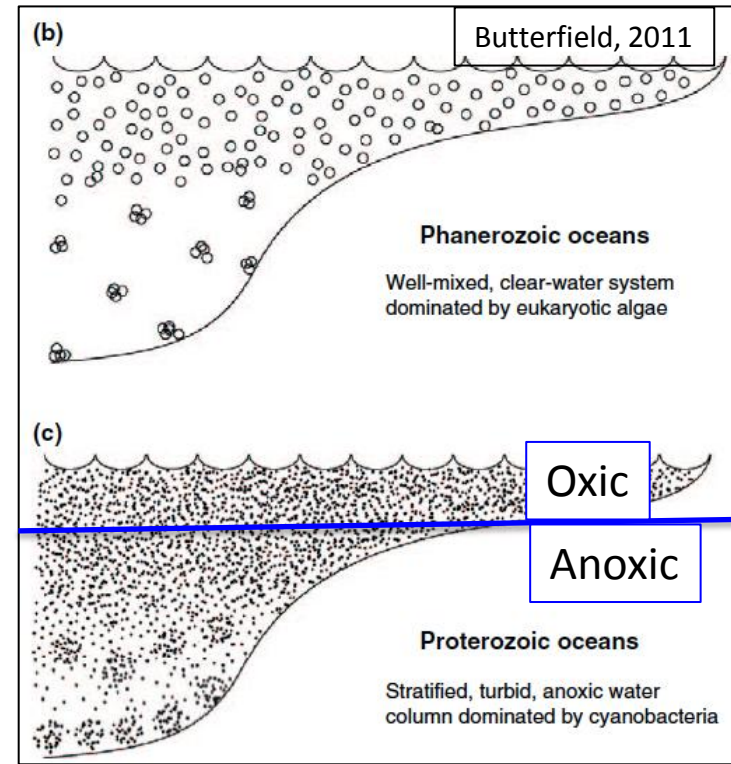
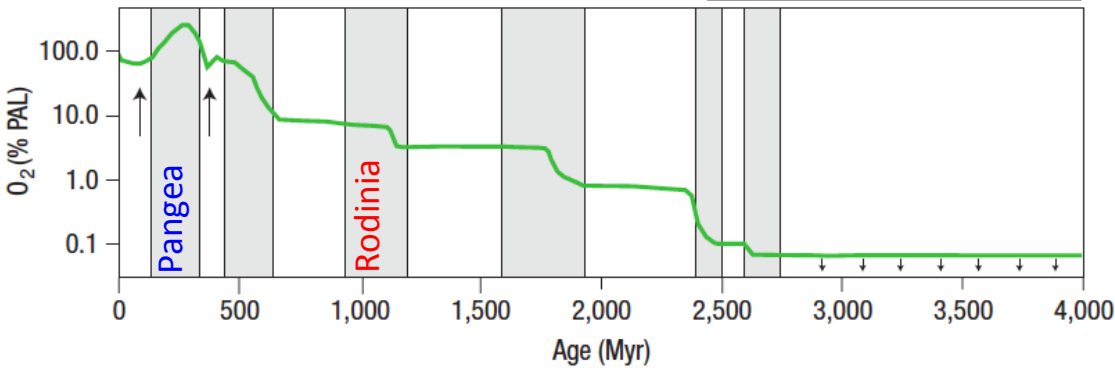


10 seconds devoted to the ocean
(20 more seconds in a little bit)

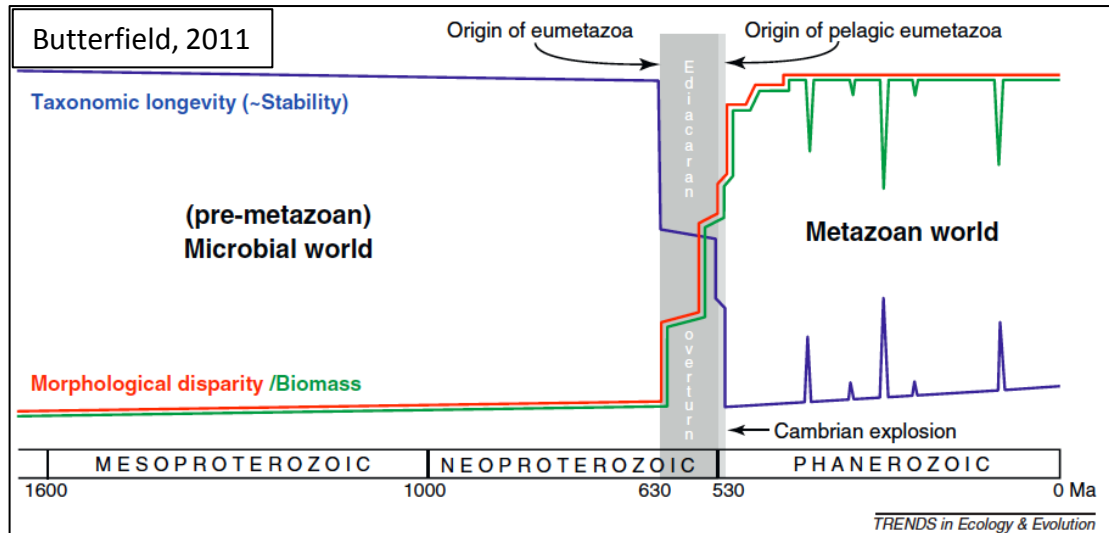
“Experimental conditions” vary:

Link between mantle forcing and climate response of Earth system is complex

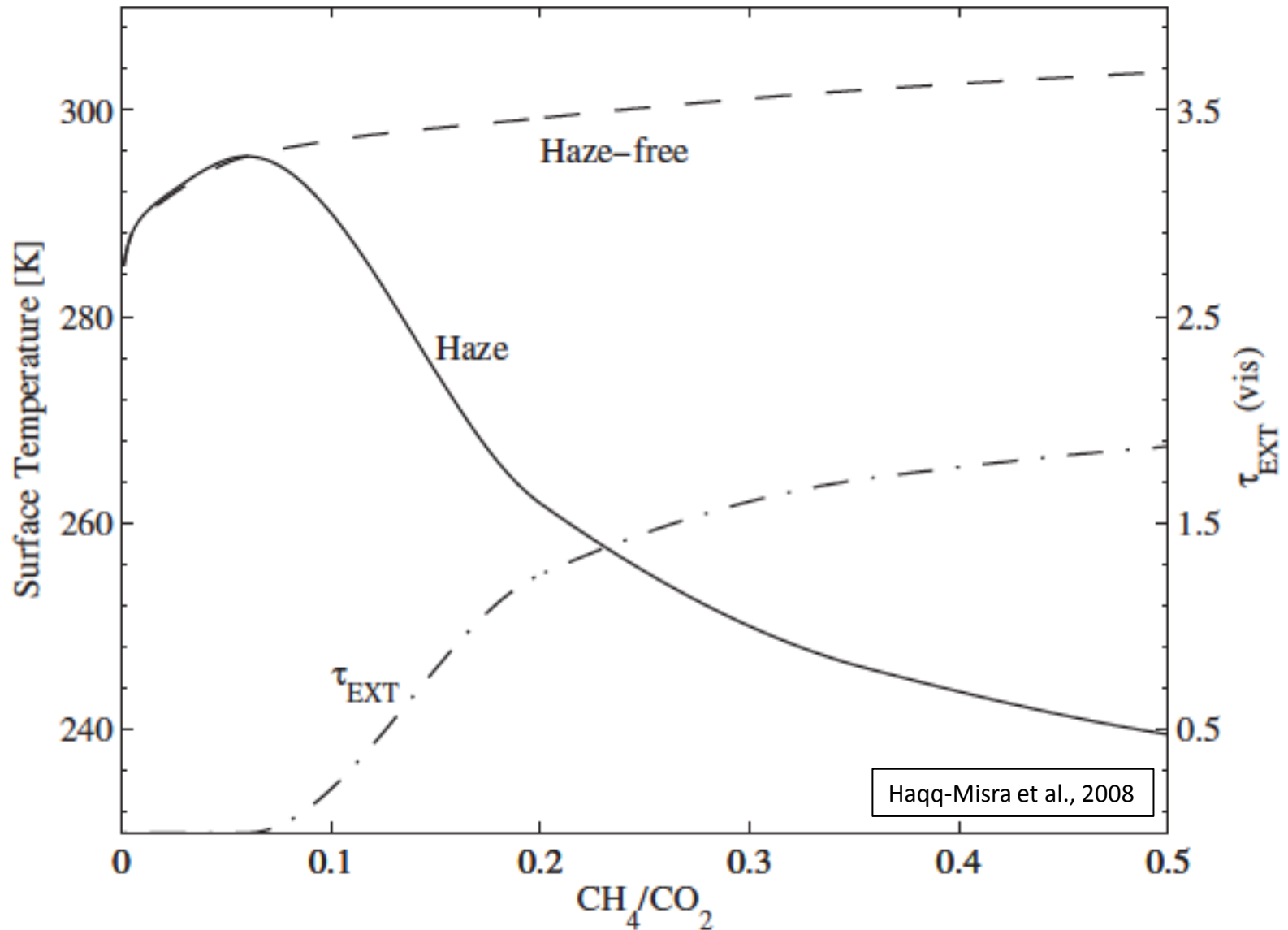
Campbell and Allen, 2010

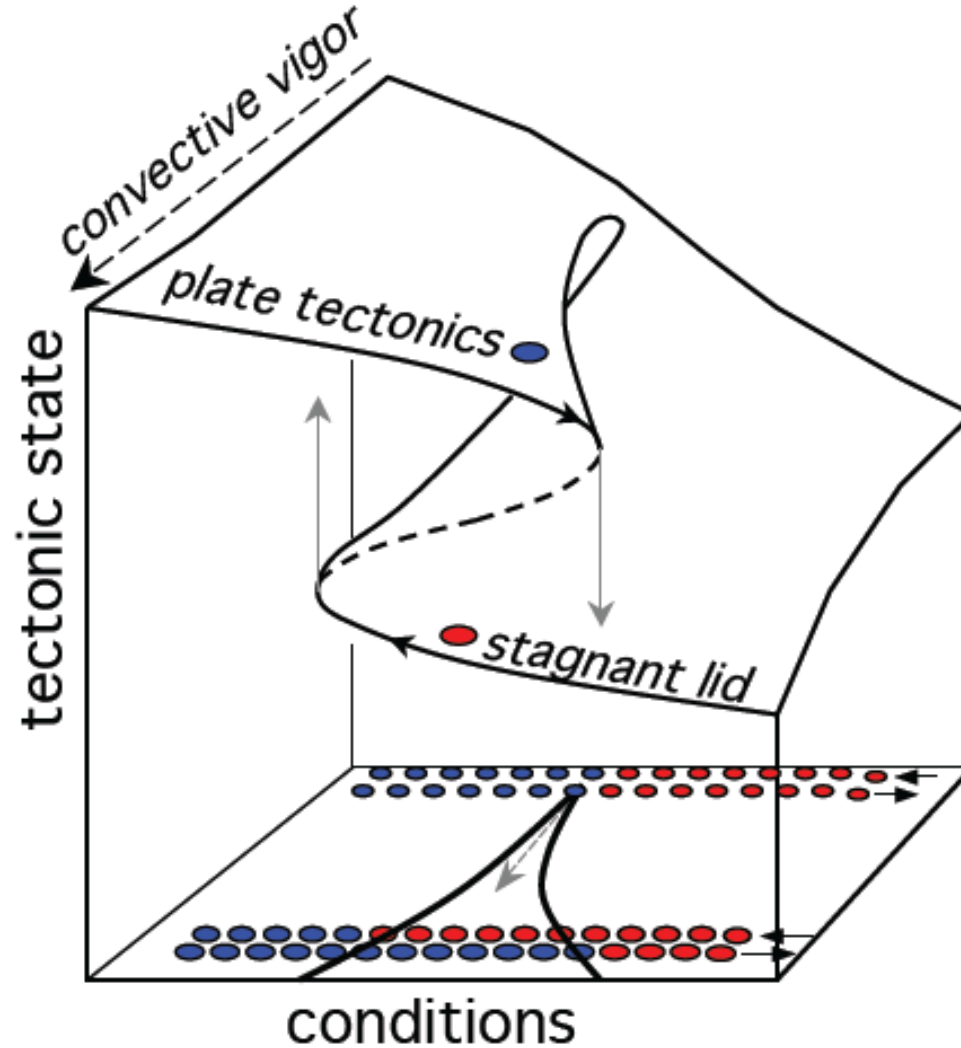


Butterfield, 2011

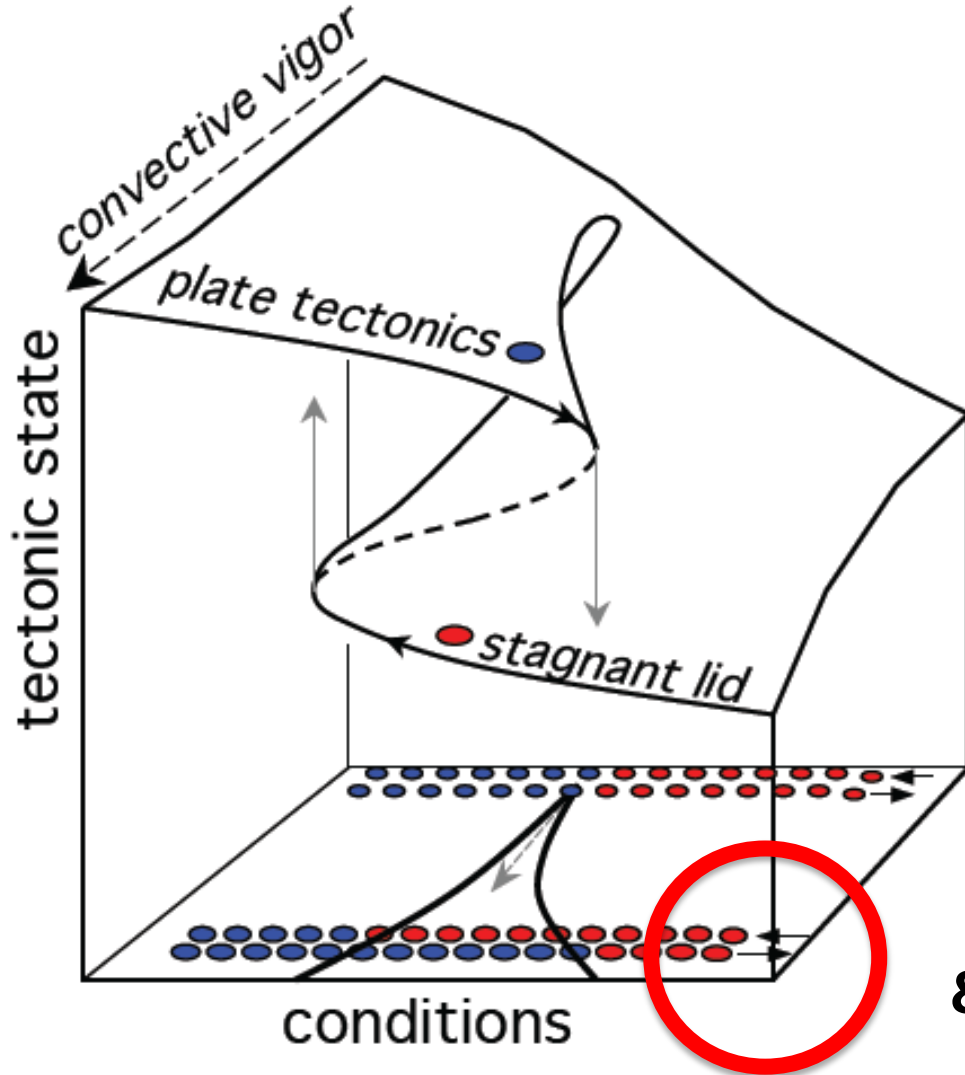


Organic Hazes and Radiative Forcing with no O₂ or N₂





Terrestrial planet evolution depends on a lot of things:
*Long-term climate change (i.e., surface temperature),
 Internal heating, Plate strength*



& History Matters!

Terrestrial planet evolution depends on a lot of things:
Long-term climate change (i.e., surface temperature),
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