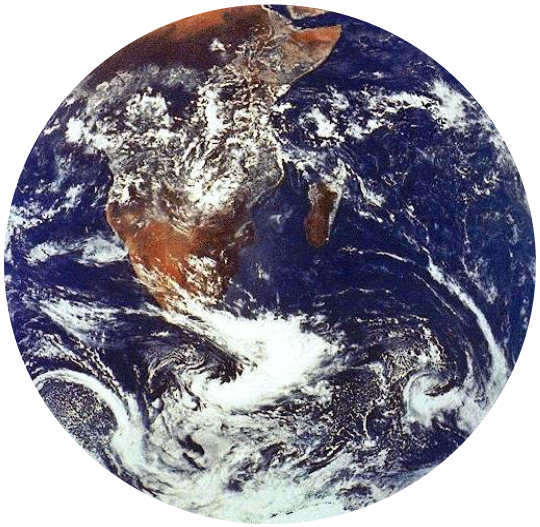
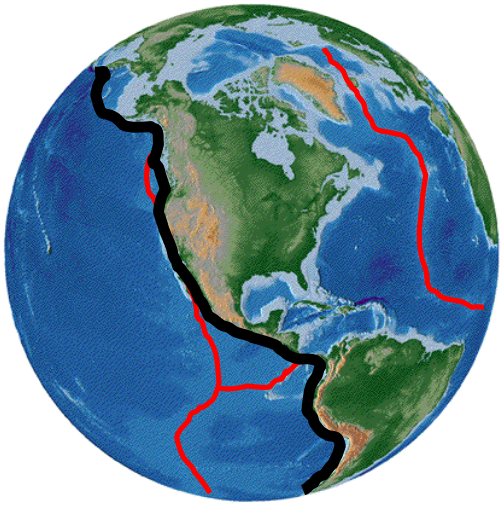
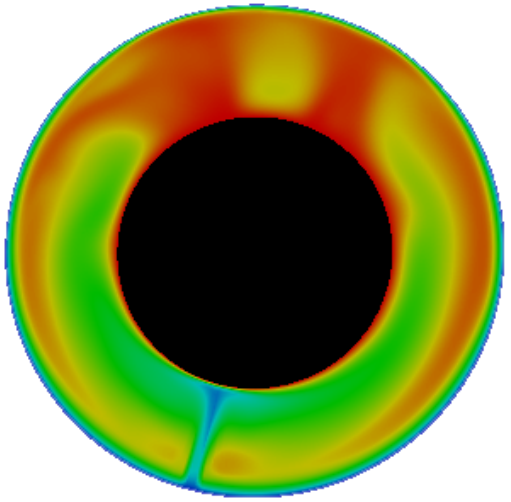
Tectonic Regimes of Terrestrial Planets & Exoclimes

atmo/hydrosphere ⟷ *surface* ⟷ *interior*

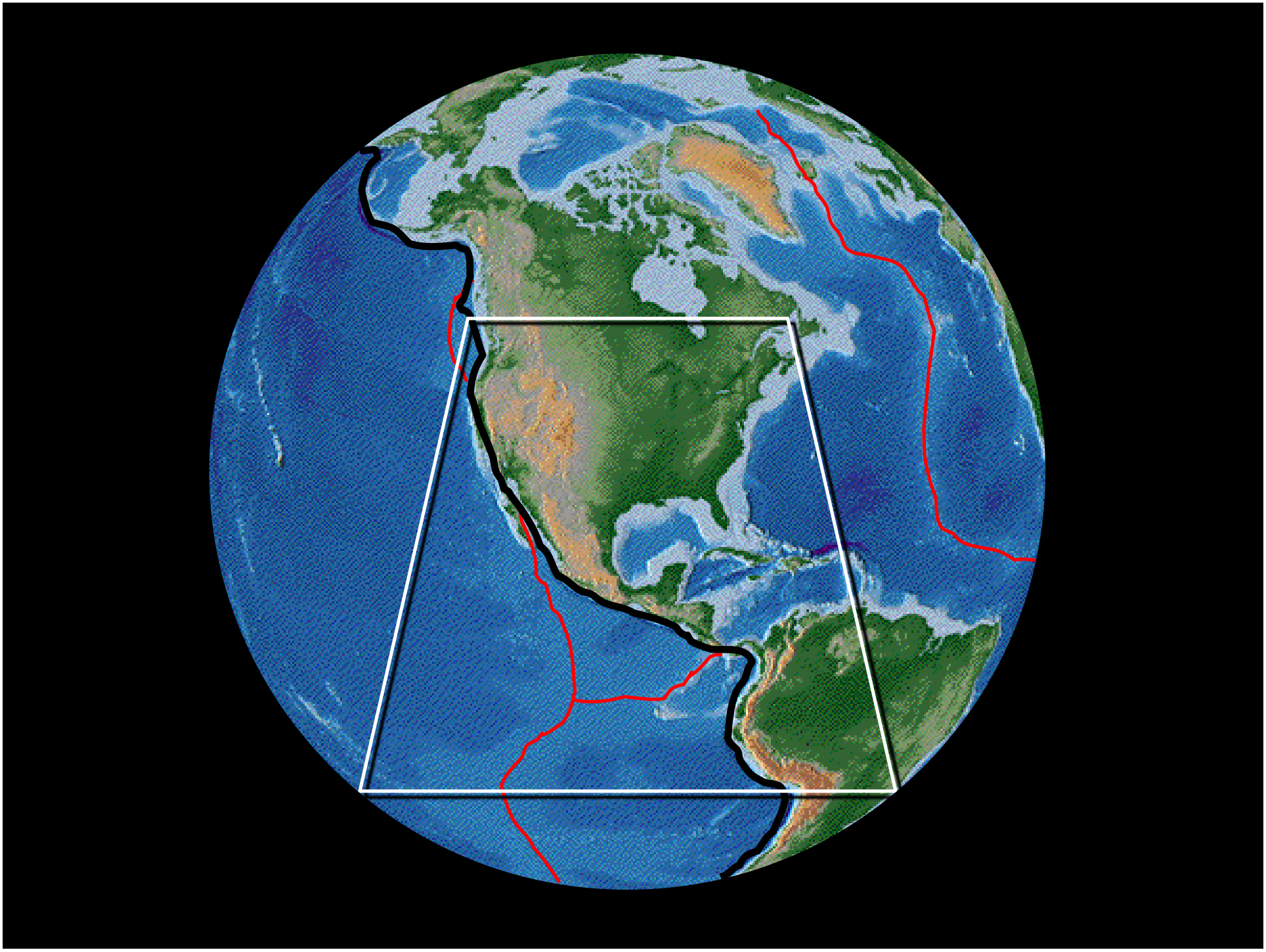
A. Lenardic, T. Höink, C. Sandu, M. Weller - Rice U

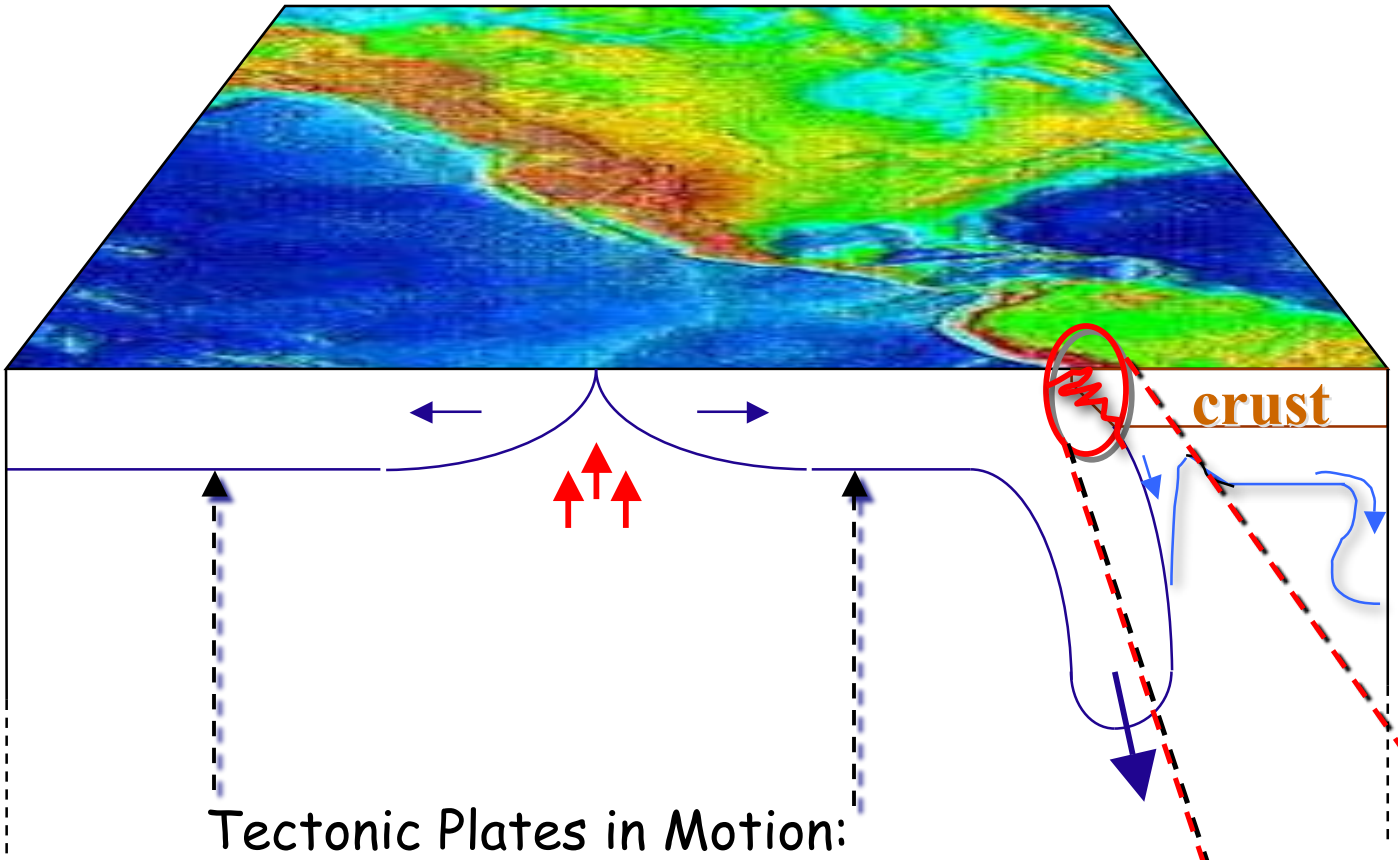
C. O'Neill - Macquarie U

A.M. Jellinek - UBC

L. Moresi - Monash U

P. McGovern - LPI

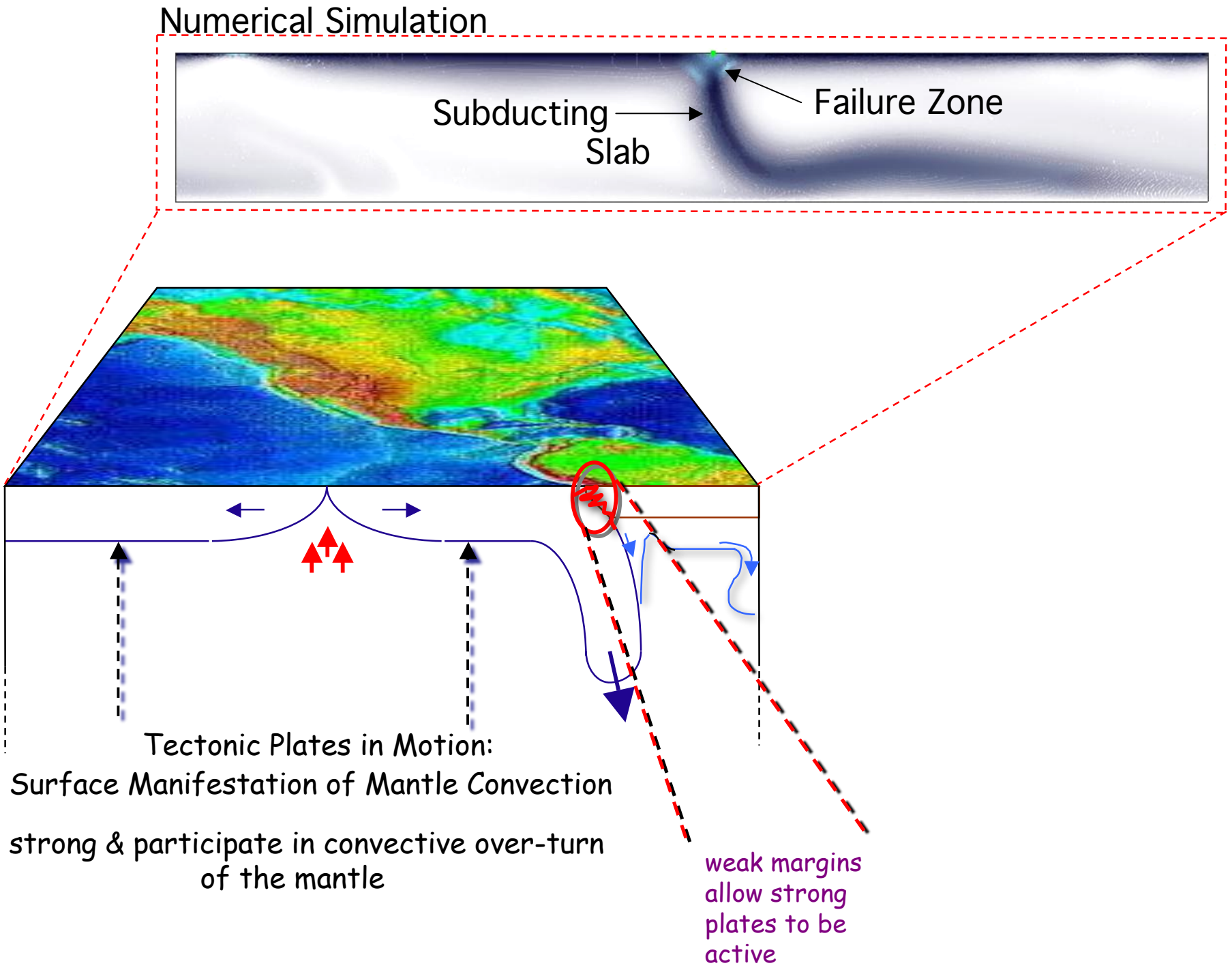




Tectonic Plates in Motion:
Surface Manifestation of Mantle Convection

strong & participate in convective over-turn of the mantle

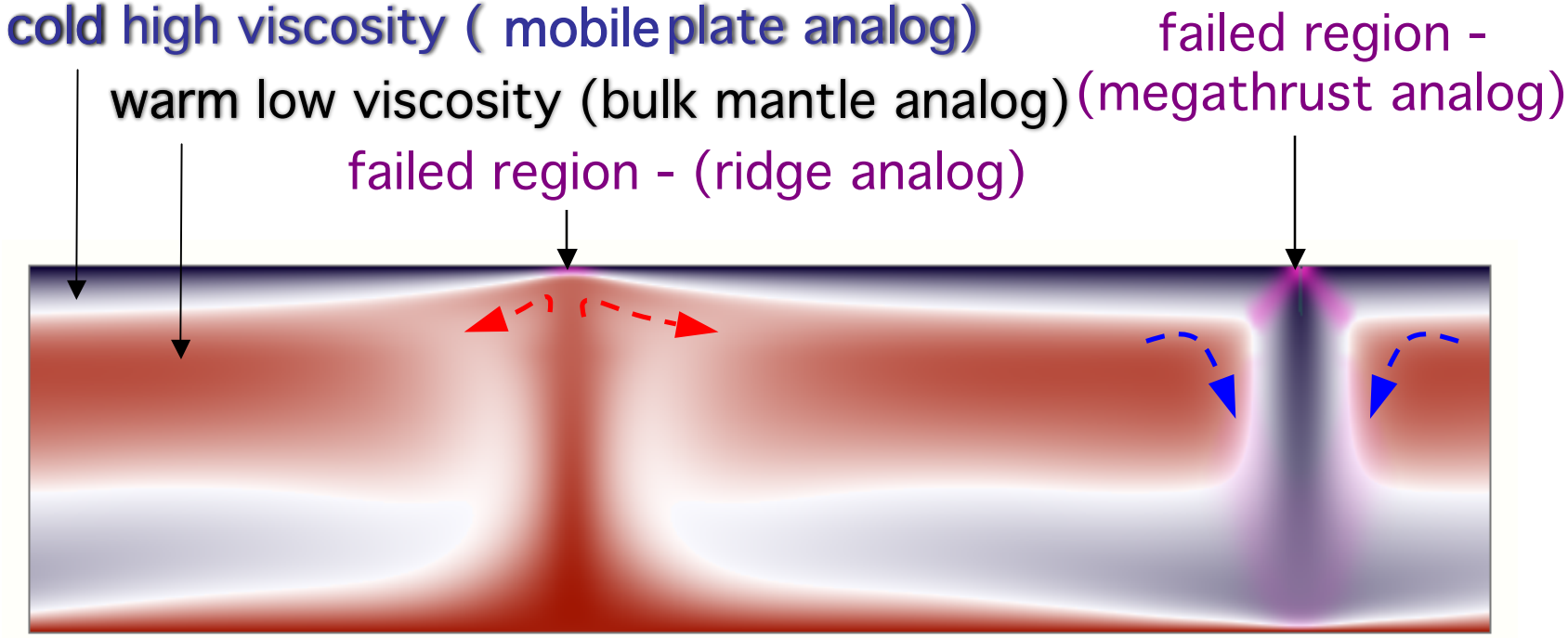
weak margins allow strong plates to be active


Numerical Simulation
Subducting Slab
Failure Zone
Tectonic Plates in Motion:
Surface Manifestation of Mantle Convection
strong & participate in convective over-turn of the mantle
weak margins allow strong plates to be active

Mantle Convection Simulation
With **Temperature-** and **Yield Stress-**Dependent Rheology

Stress Below Yield: Temperature Dependent Viscosity

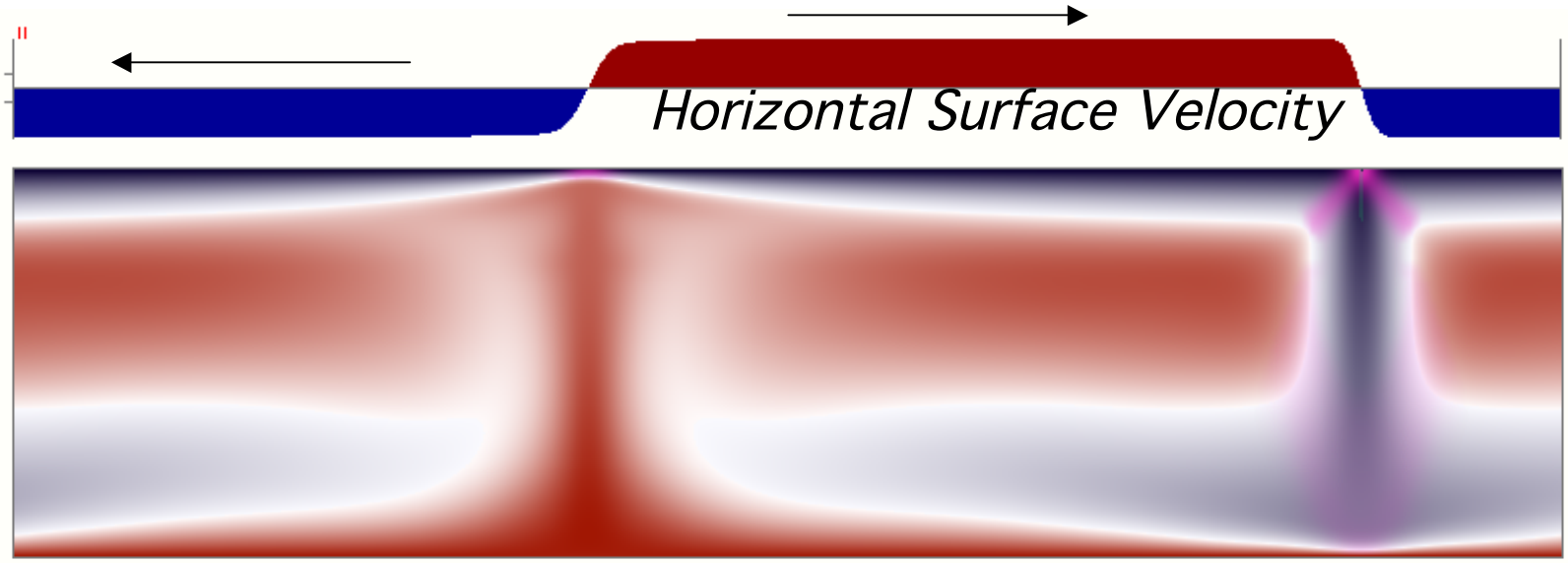
Stress At Yield: Plastic Rheology that generates
Ductile Shear Zones (weak plate margins)



Cooled from Above & Heated From Within by Decay of Radiogenics
And From Below by Core Heat Flux

If Convective Stress < Lithosphere Yield Then Upper Layer Stagnates

Single Plate Planet (e.g., Present Day Venus and Mars)



For Mobile Plate Regime: Convective Stress > Lithosphere Yield

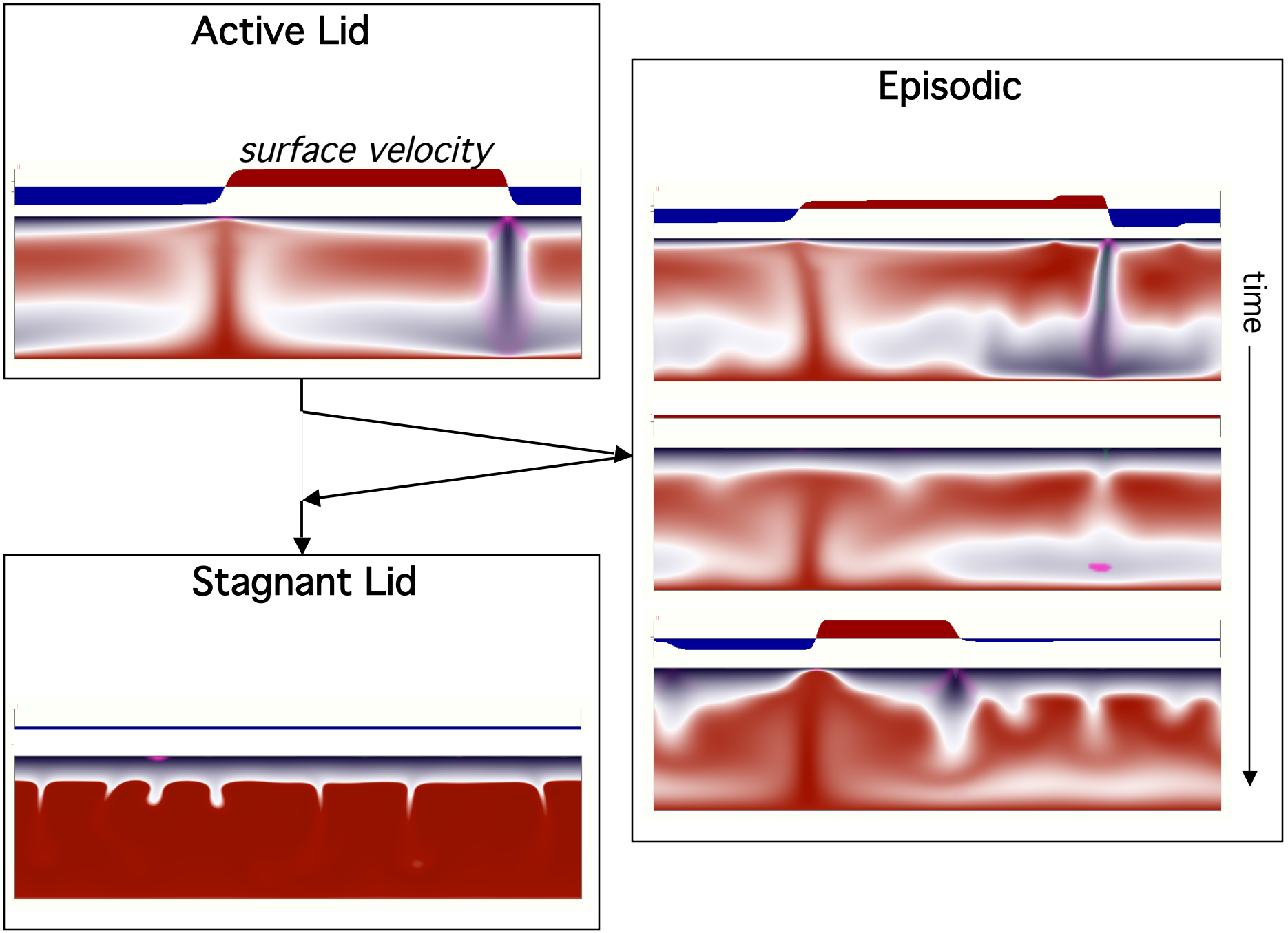
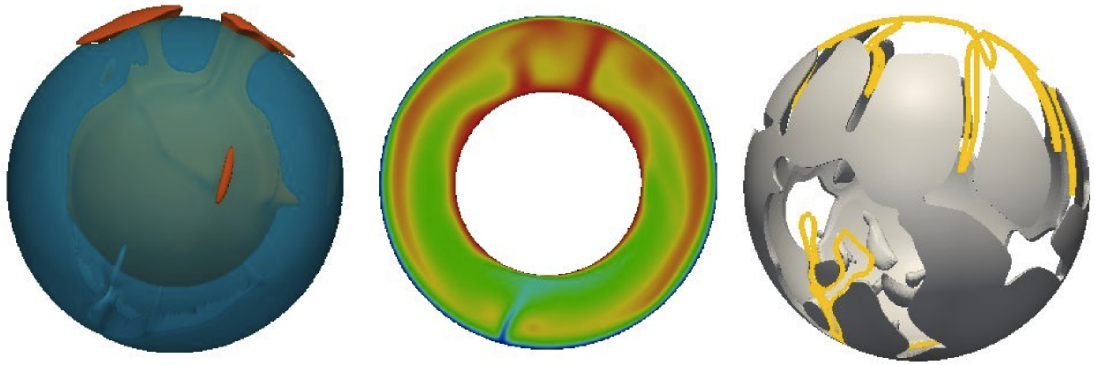
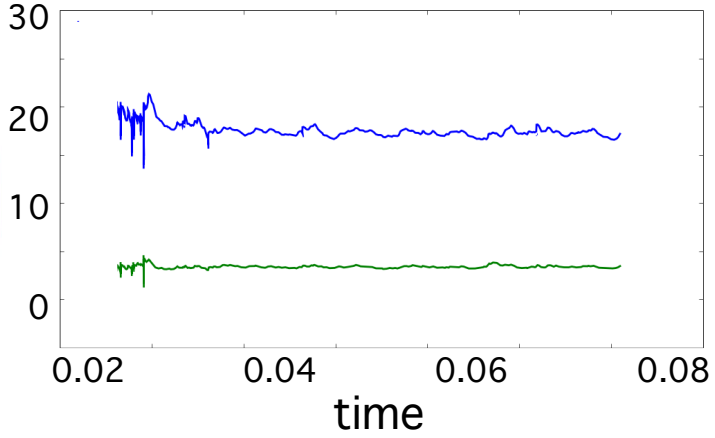
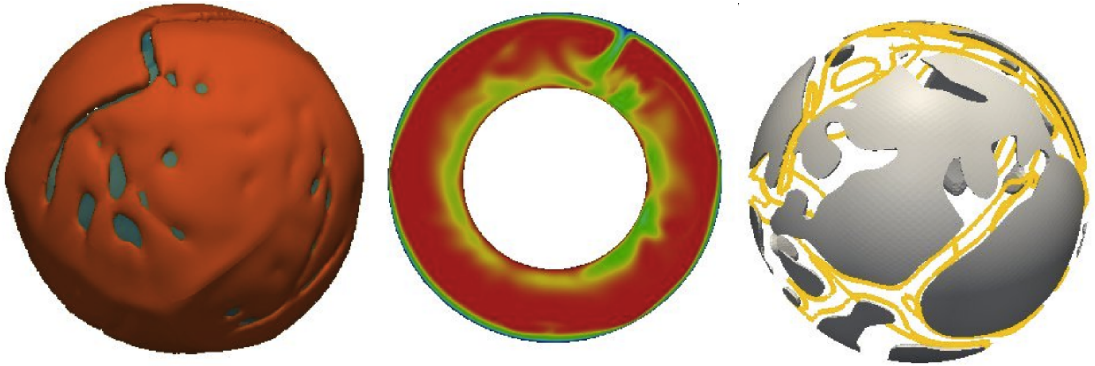

Active Lid
surface velocity
Episodic
time
Stagnant Lid

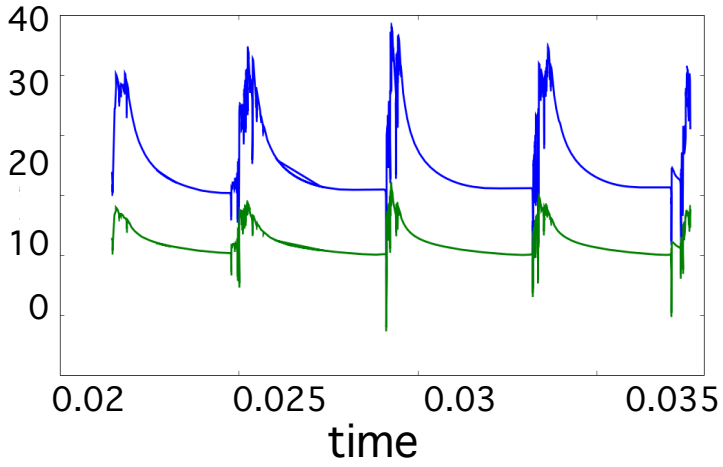
Plate Tectonic (mobile lid) Regime



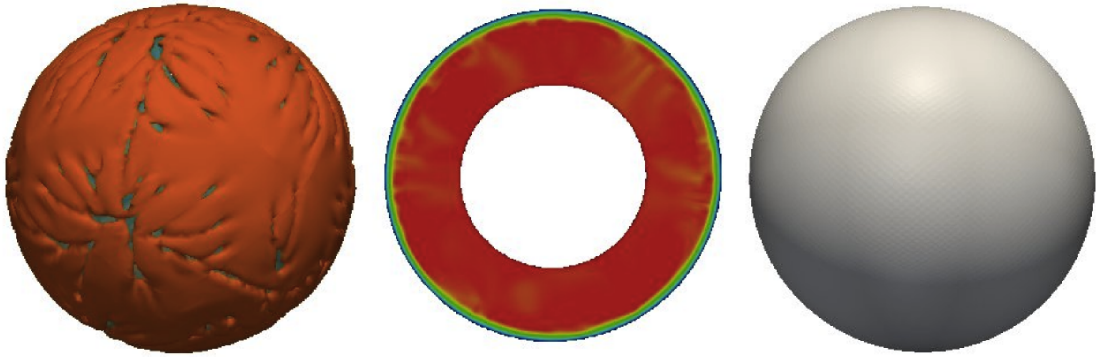


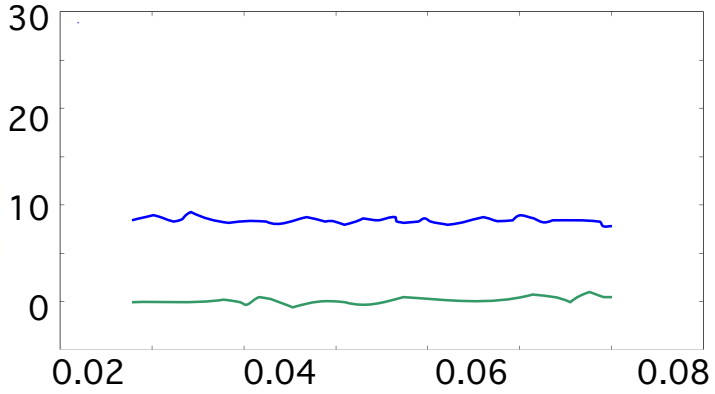
Episodic Regime

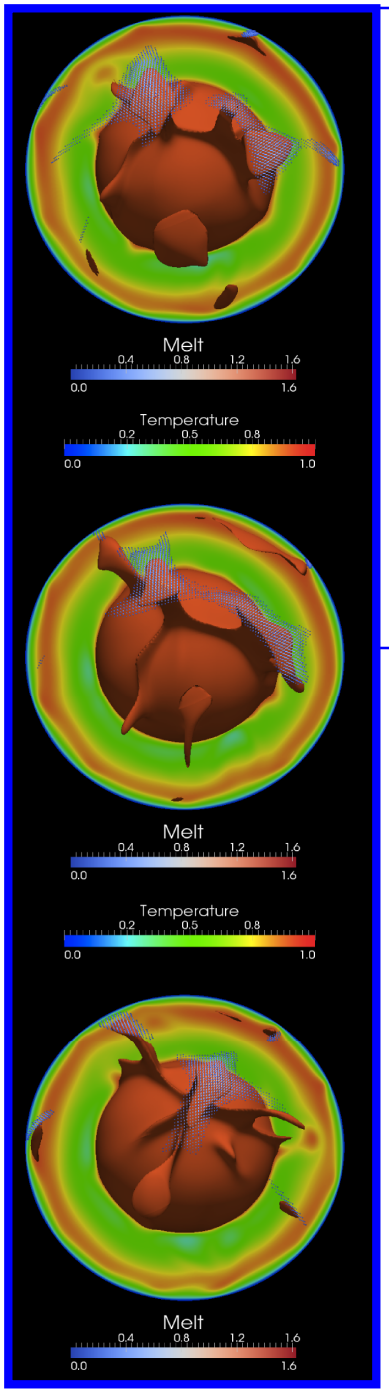


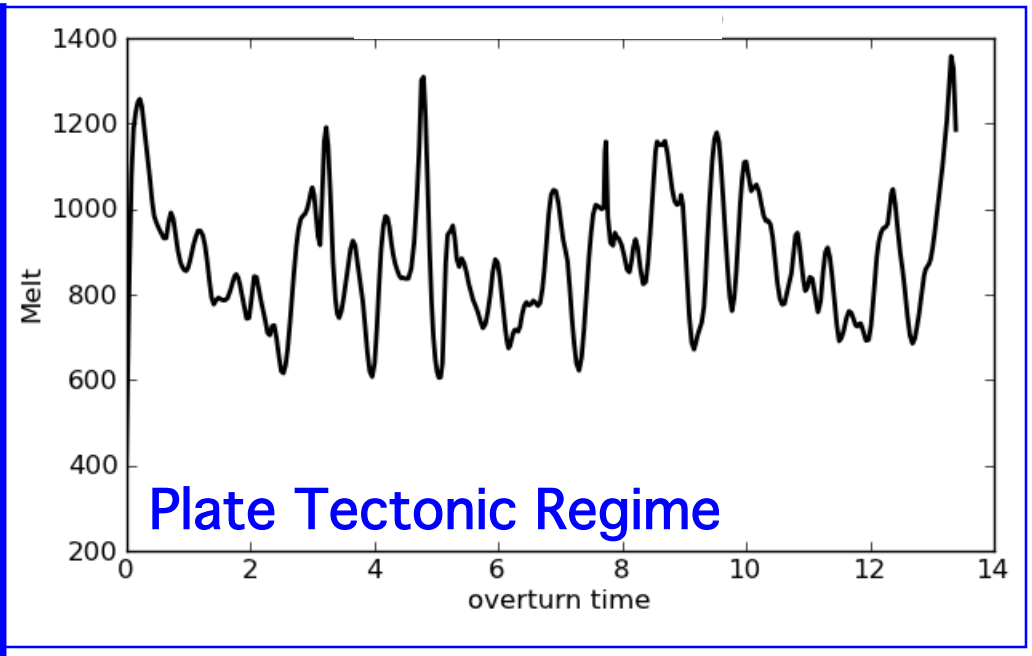


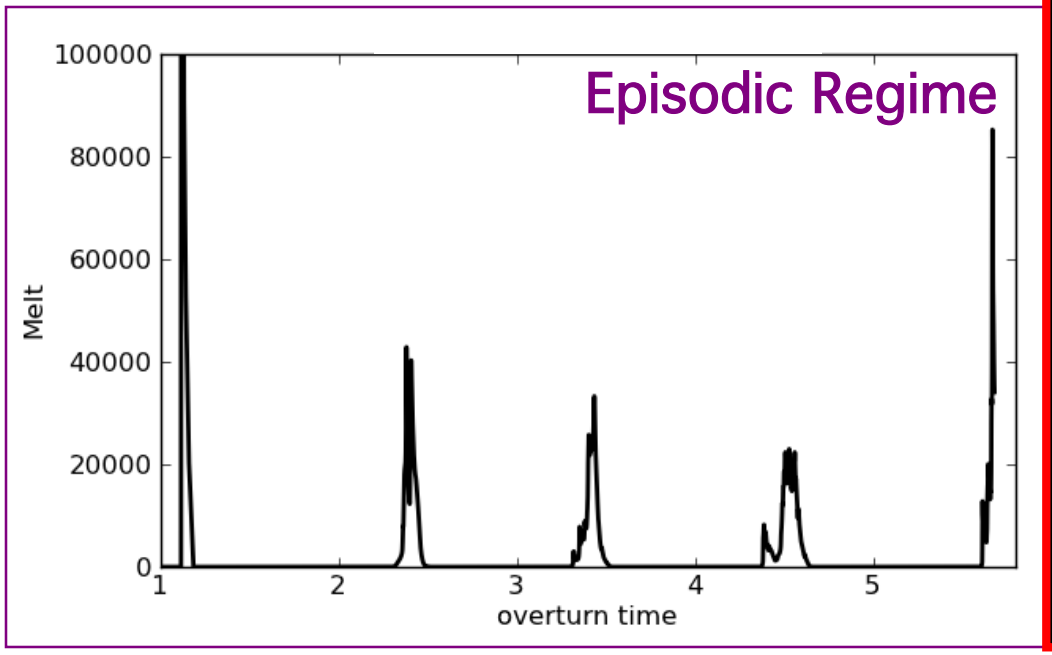
Stagnant Lid Regime

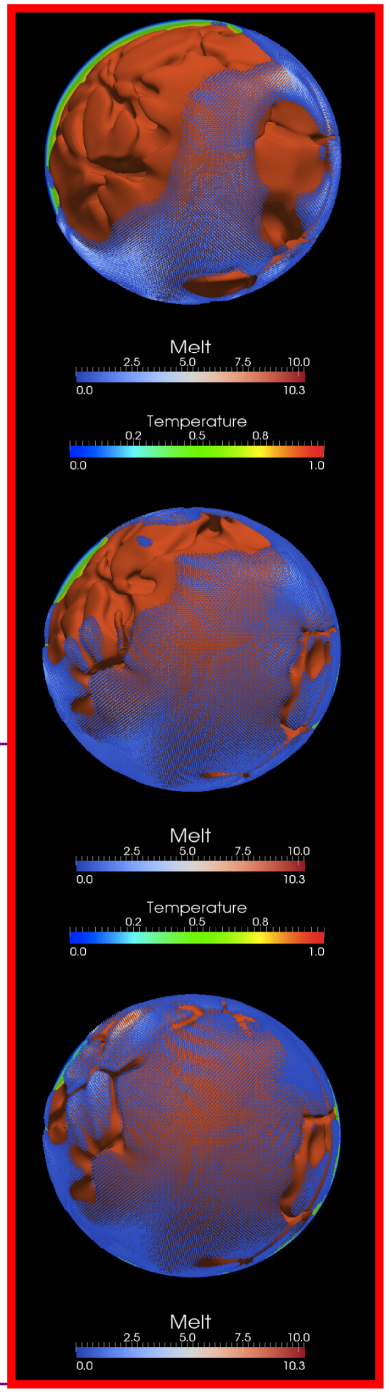





Melt
0.0 0.4 0.8 1.2 1.6
Temperature
0.0 0.2 0.5 0.8 1.0


Melt
overturn time
Plate Tectonic Regime


Melt
overturn time
Episodic Regime


Melt
0.0 2.5 5.0 7.5 10.0 10.3
Temperature
0.0 0.2 0.5 0.8 1.0

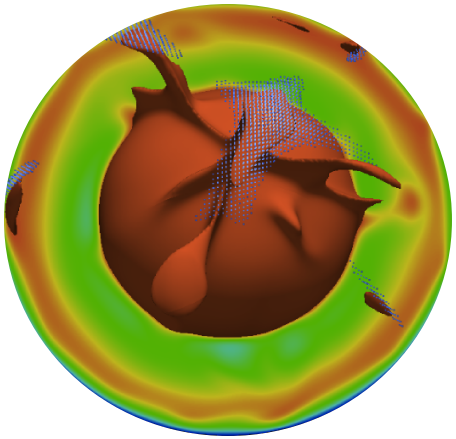
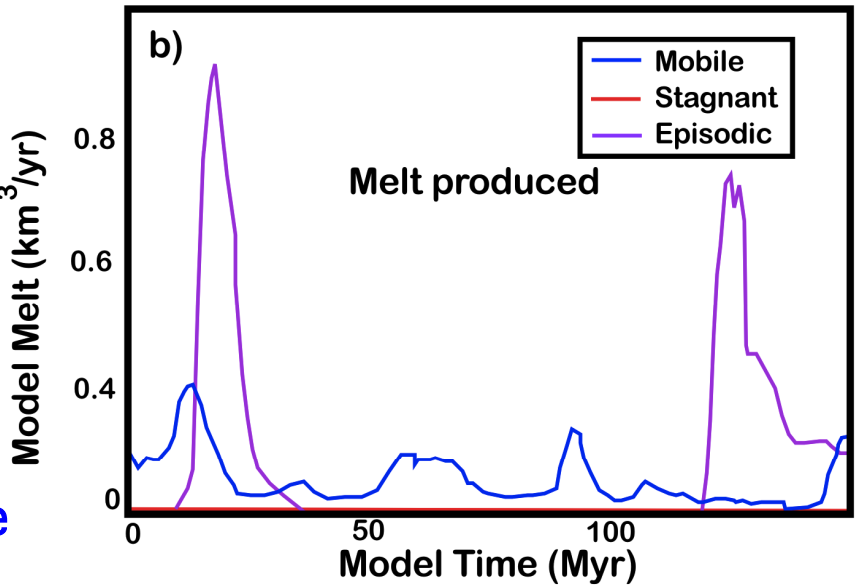
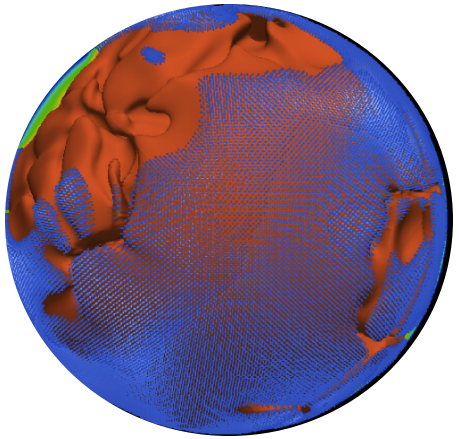


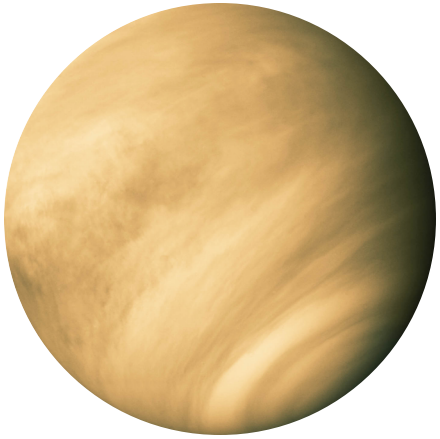
Plate Tectonic Regime



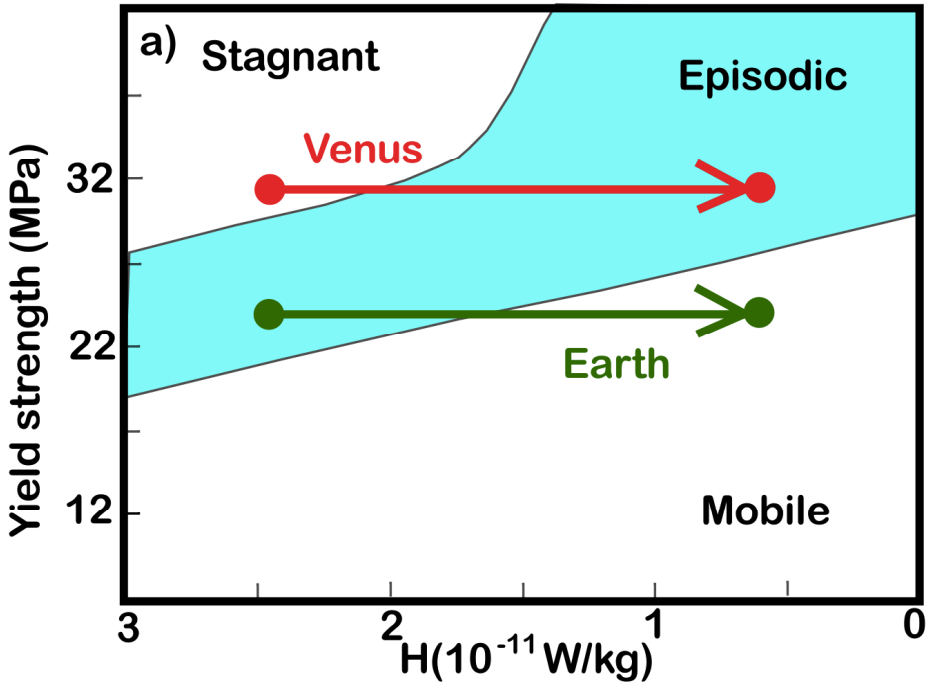


Episodic Regime

Earth

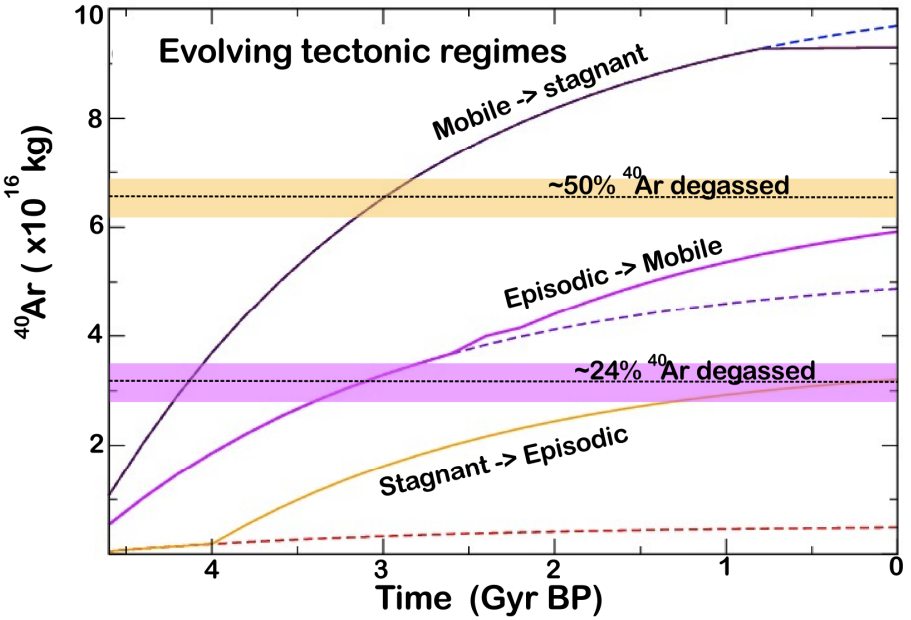


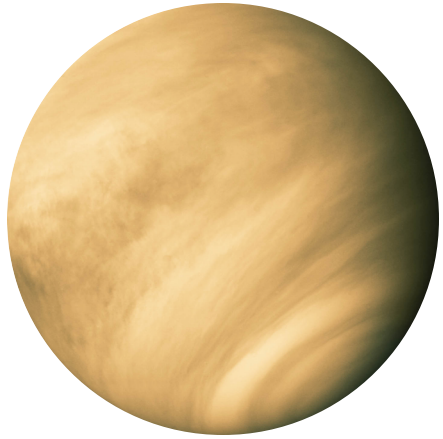
Venus



Changing Tectonic Regimes over Time Match ^{40}Ar Constraints

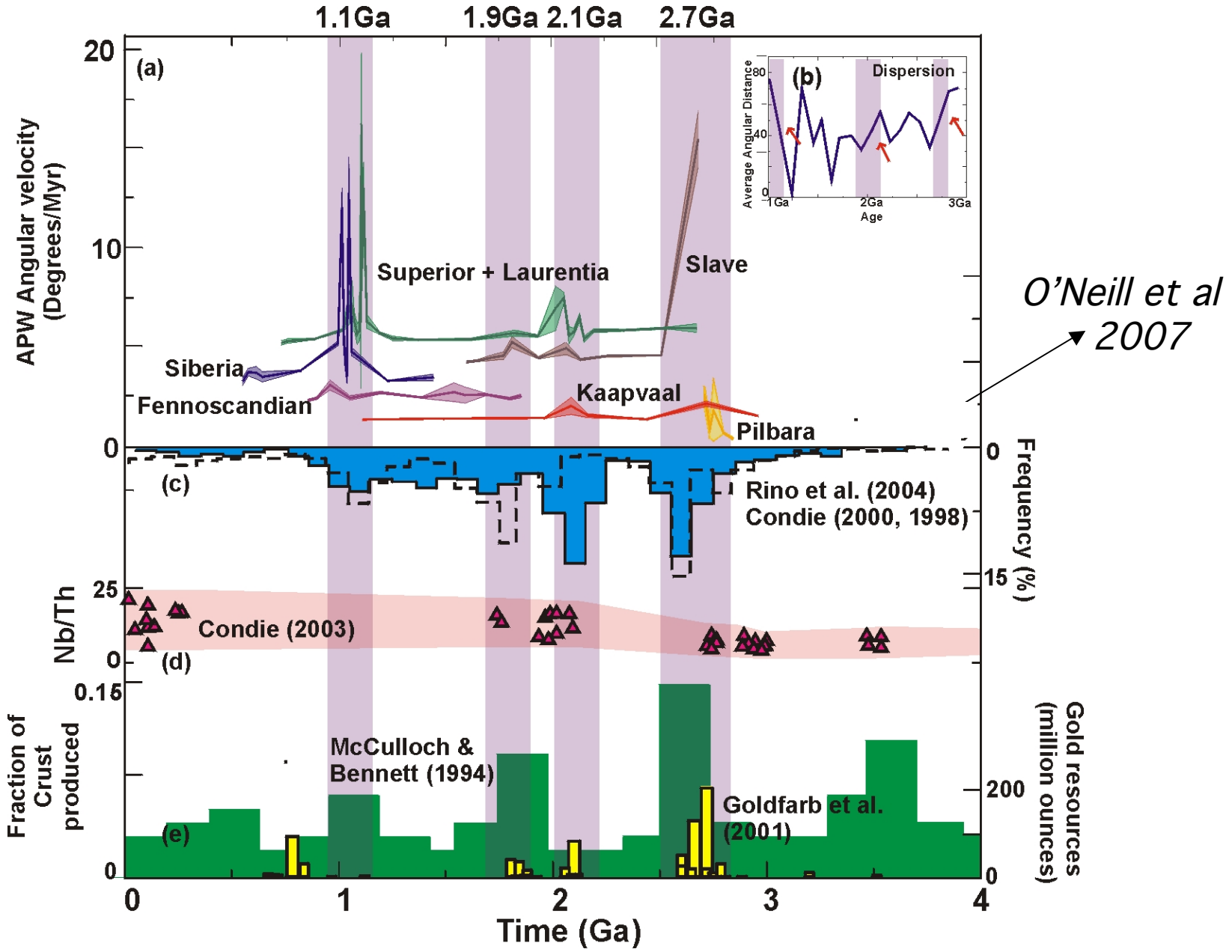
Earth





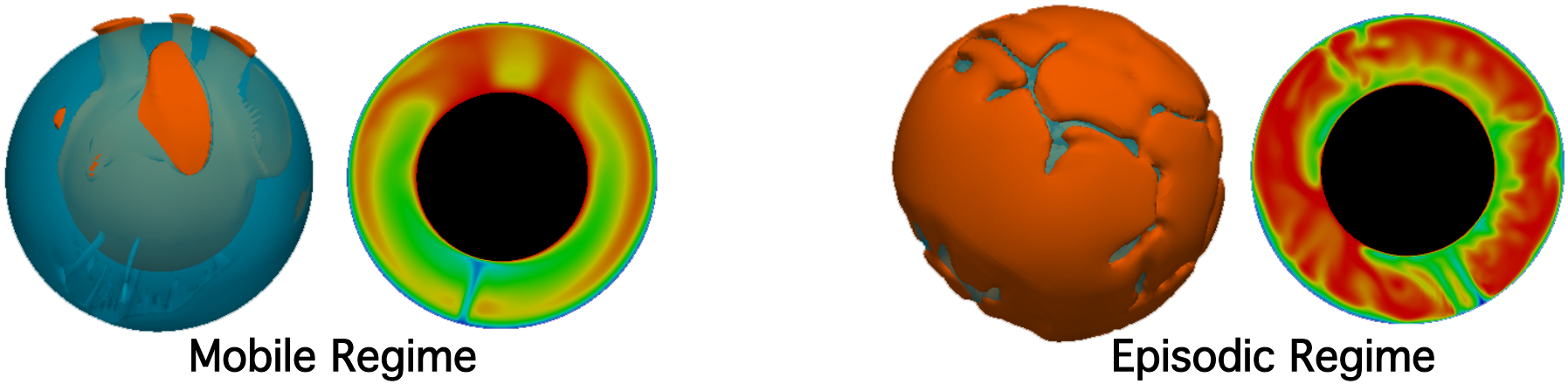
Venus

Changing Tectonic Regimes over Time



Atmospheric Signature of Tectonic Regimes

Changing Tectonic Regimes over Planets Life



Mobile Regime

Episodic Regime

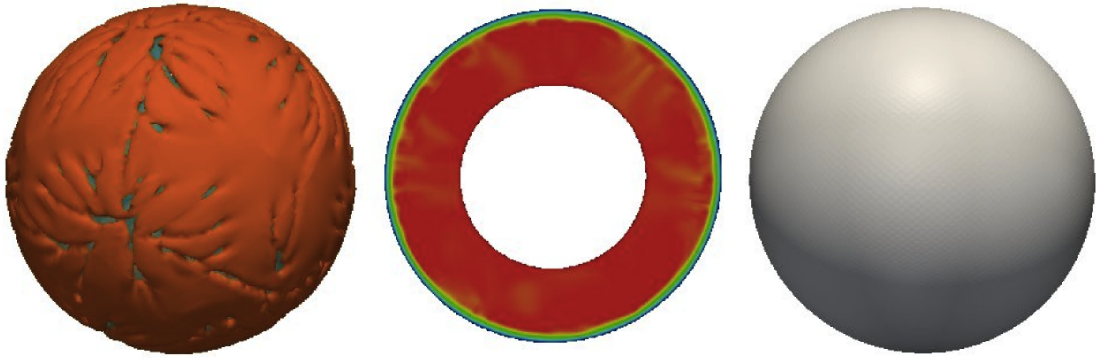
MANTLE TEMPERATURE

RADIOGENIC HEAT PRODUCTION

EVOLUTION IN TIME

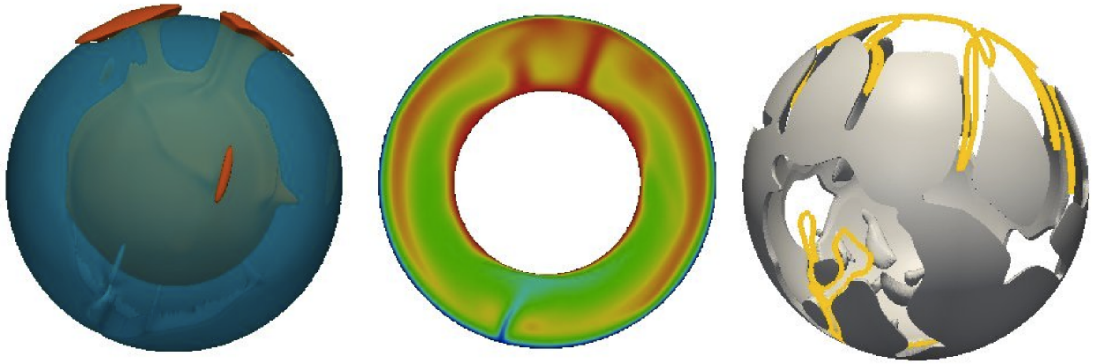
Will Super Sized Earths Have Plate Tectonics or Not ?

Will Super Sized Earths Have Plate Tectonics or Not ?



If Convective Stress < Lithosphere Yield Then Upper Layer Stagnates

Single Plate Planet (e.g., Present Day Venus and Mars)



For Mobile Plate Regime: Convective Stress > Lithosphere Yield

Will Super Sized Earths Have Plate Tectonics or Not ?

Super Sizing Leads To:

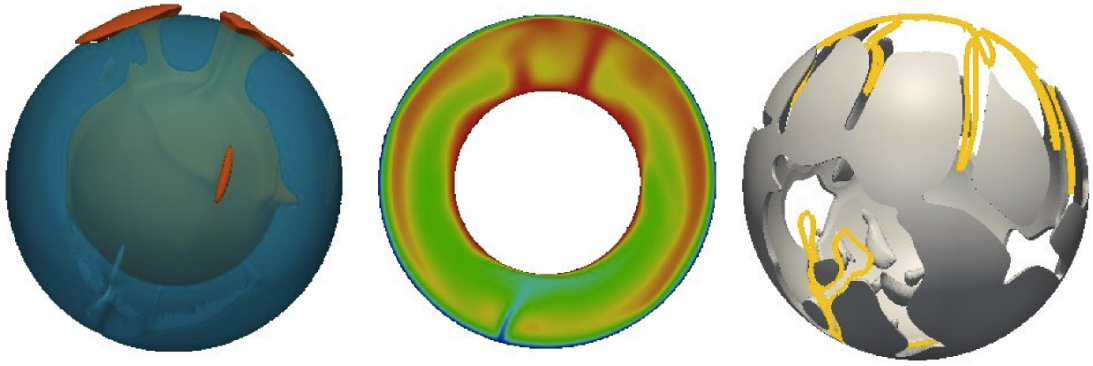
Greater Radiogenic Content in Mantle

Greater Convective Velocity - Increases Convective Stress

Hotter - Lower Viscosity - Decreases Convective Stress

Greater Gravitational Acceleration

Greater Fault Normal Stress - Increases Yield Stress



For Mobile Plate Regime: Convective Stress > Lithosphere Yield


Super Earths will not have plate tectonics (2)
(2) many groups
Super Earths will have plate tectonics (1)
(1) many groups

Super Earths will not have plate tectonics (2)

(2) many groups

Super Earths will have plate tectonics (1)

(1) many groups

2 Groups get 2 Different Answers to Same Question

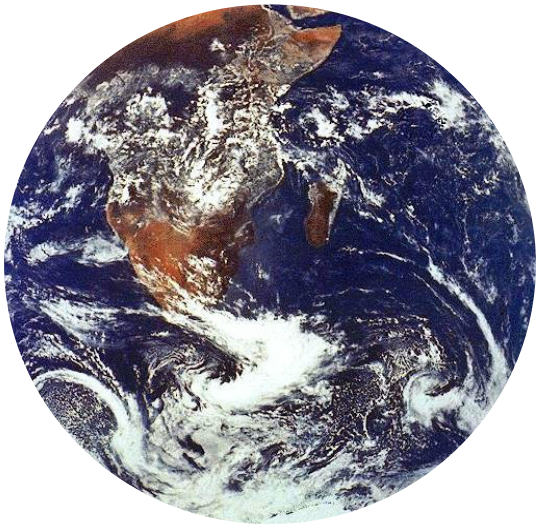
You Can:

Assume one group right & see where that takes you (provides two options)

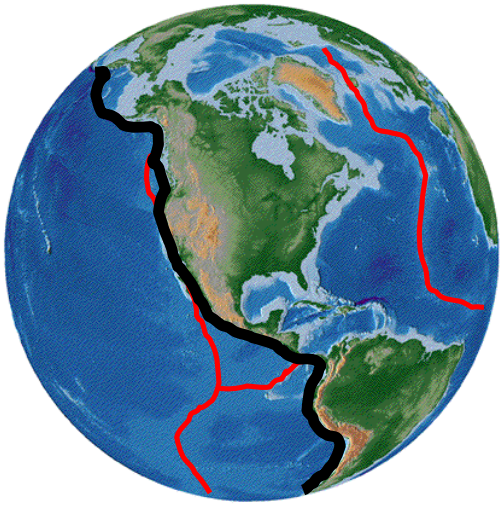
Assume both are right & see where that takes you (provides third option)

"If there are two courses of action, you should always take the third"

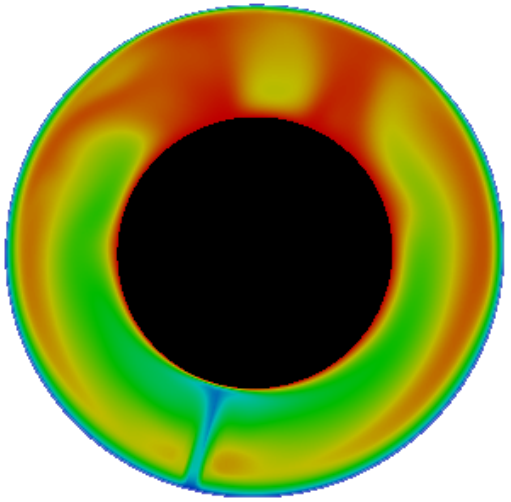
Tectonic Regimes of Terrestrial Planets & Exoclimes



atmosphere



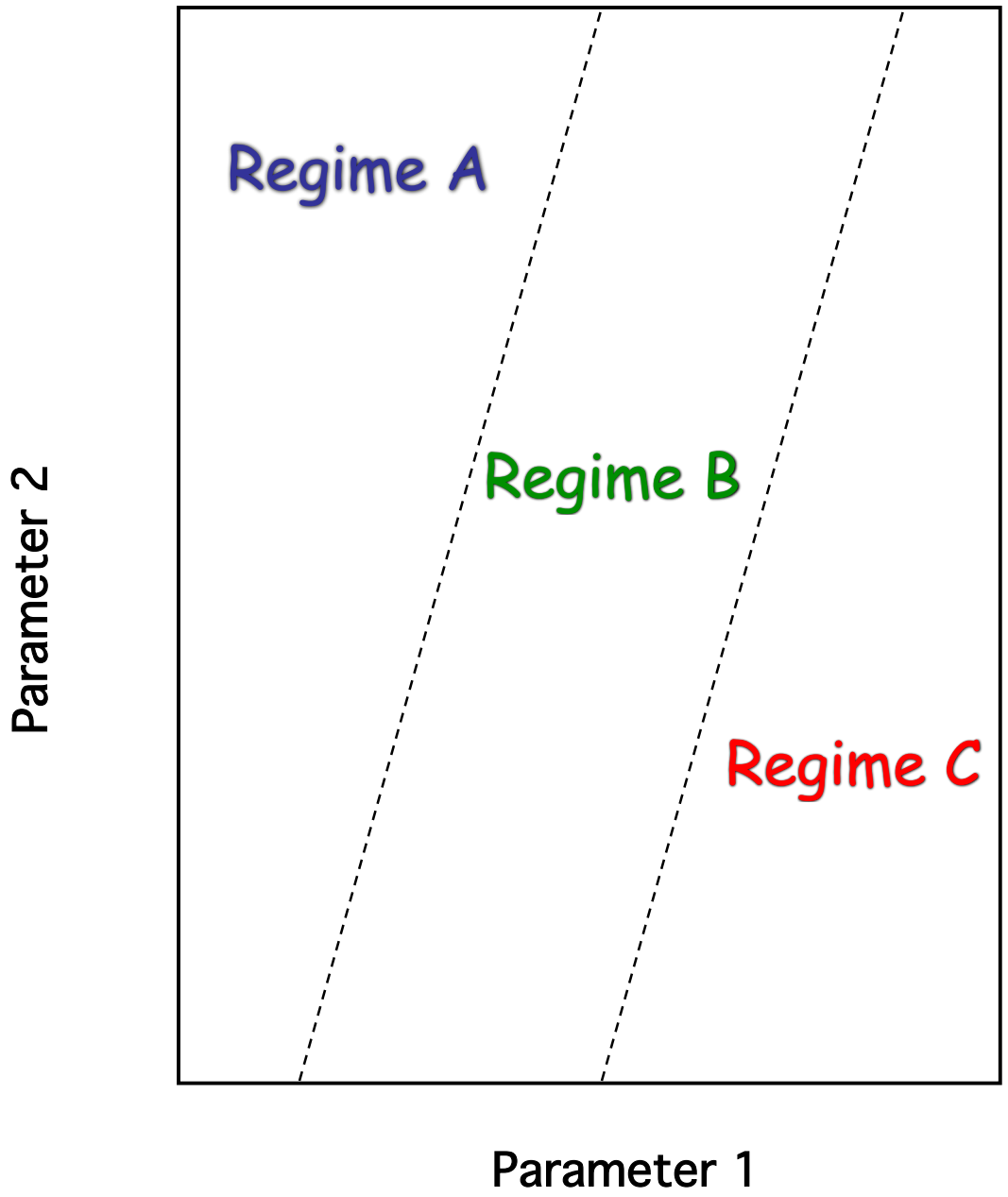
surface

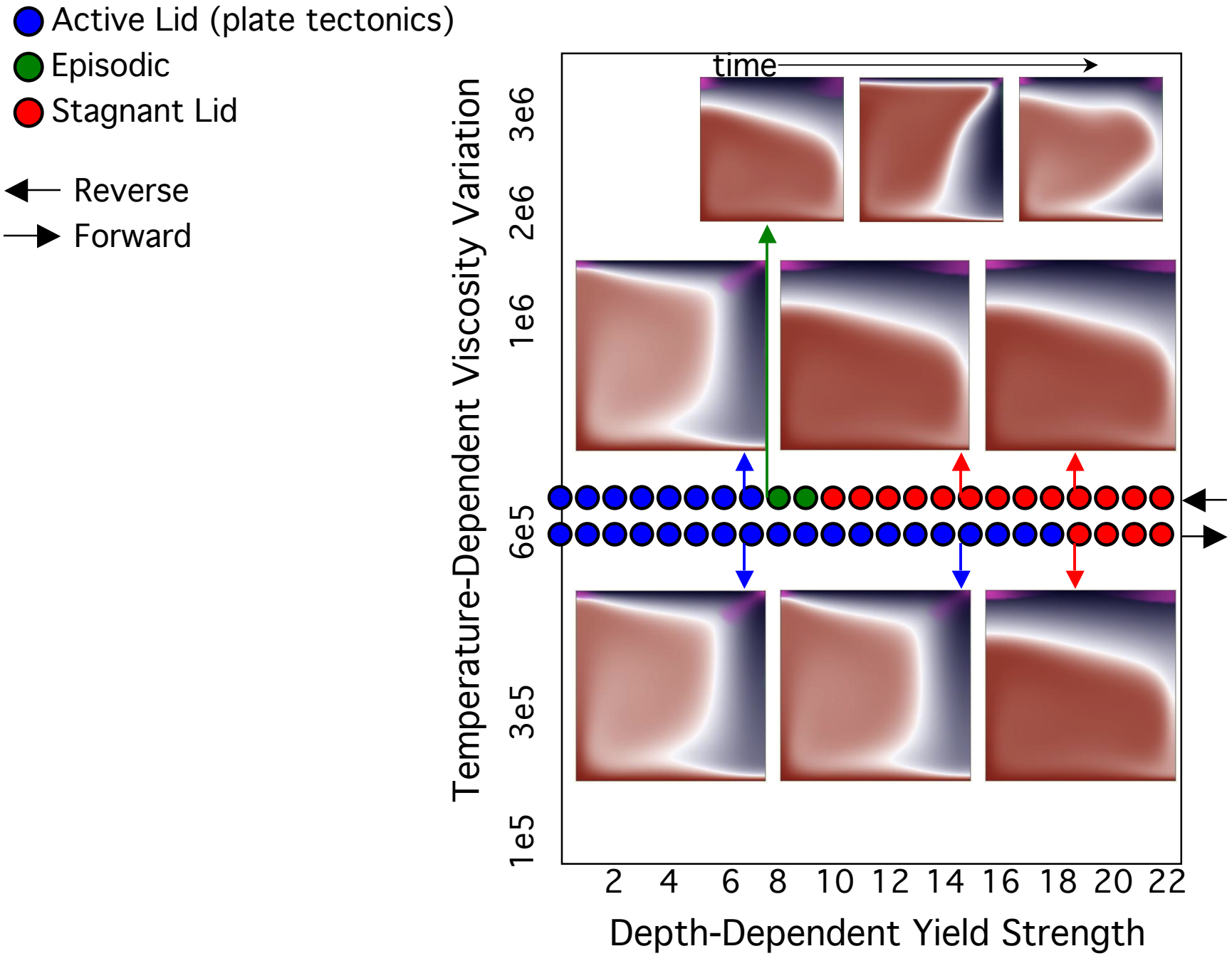


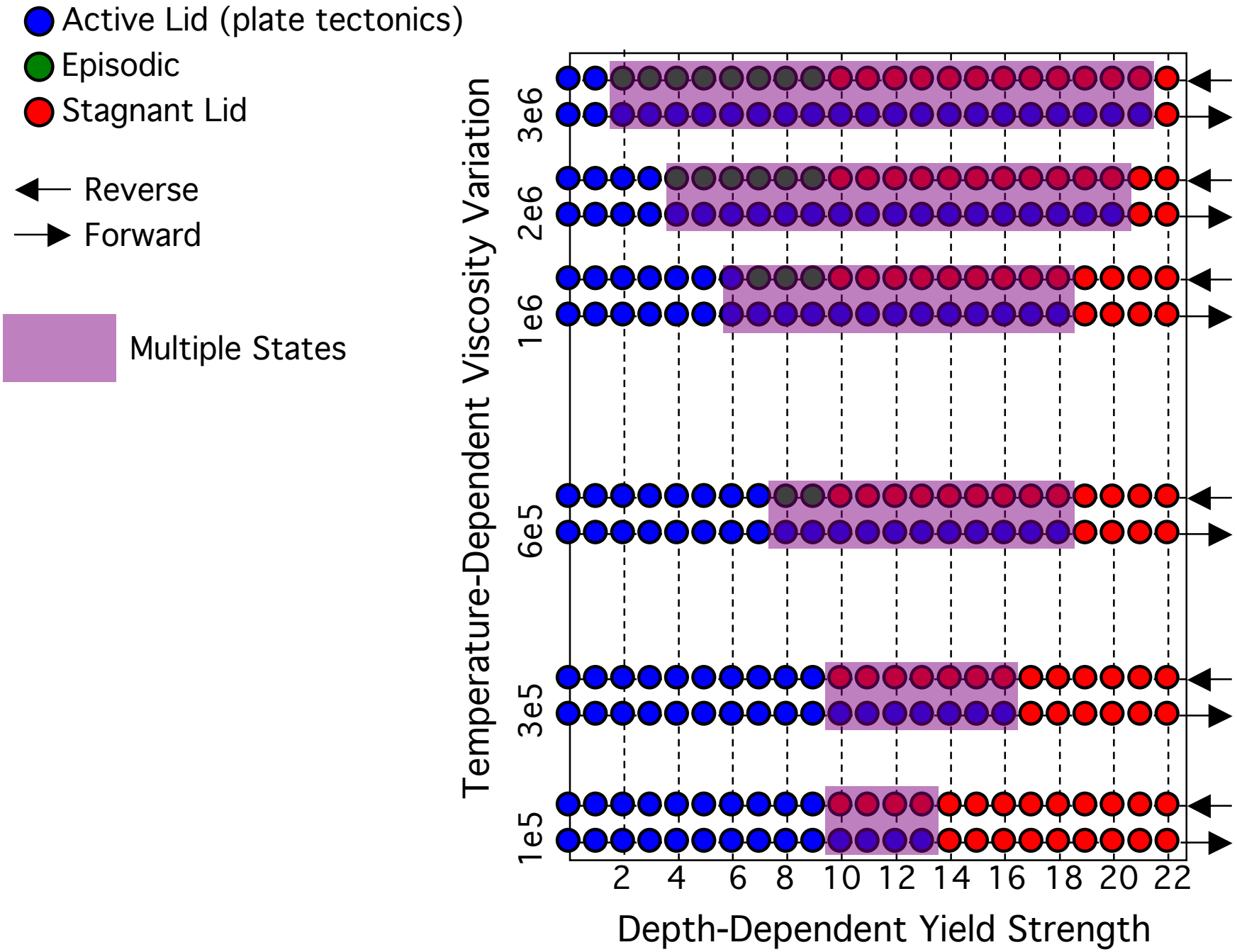
interior

On the Notion of Well Defined Tectonic Regimes for Terrestrial Planets in this Solar System and in Other Solar Systems

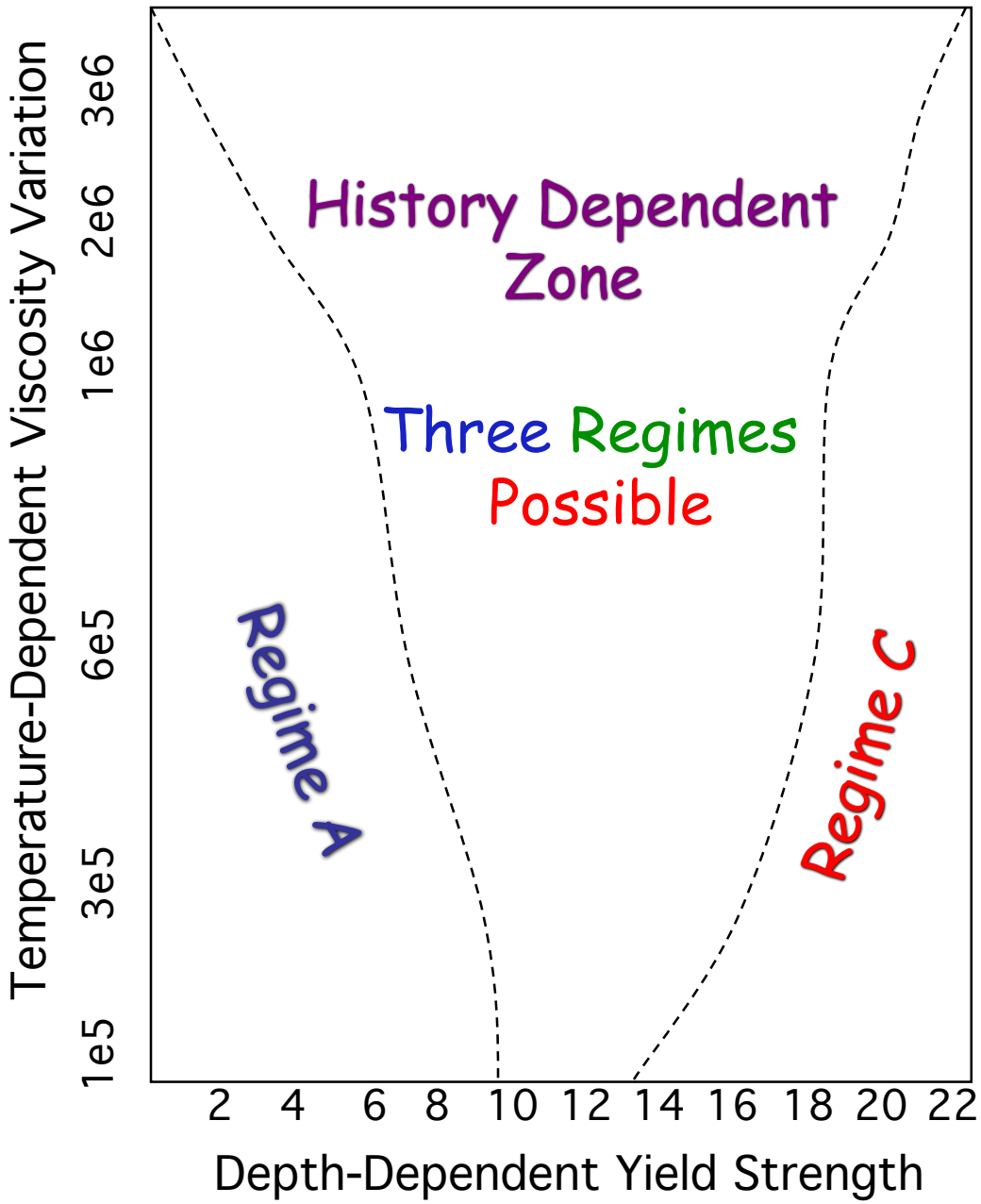
The Notion of Well Defined Tectonic Regimes

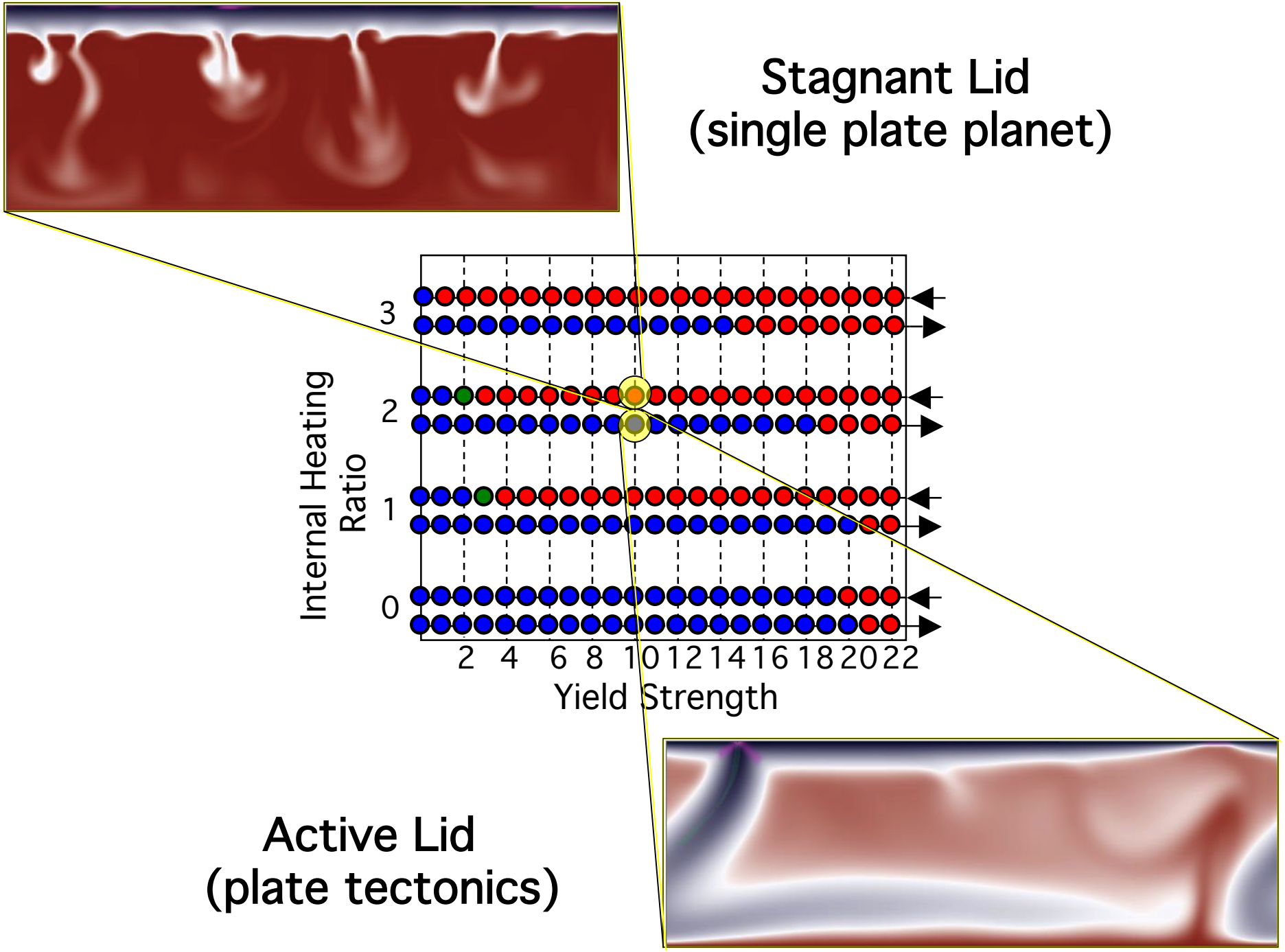



Active Lid (plate tectonics)
Episodic
Stagnant Lid
Reverse
Forward
time
Temperature-Dependent Viscosity Variation
3e6
2e6
1e6
6e5
3e5
1e5
2
4
6
8
10
12
14
16
18
20
22
Depth-Dependent Yield Strength


Active Lid (plate tectonics)
Episodic
Stagnant Lid
Reverse
Forward
Multiple States
Temperature-Dependent Viscosity Variation
3e6
2e6
1e6
6e5
3e5
1e5
2
4
6
8
10
12
14
16
18
20
22
Depth-Dependent Yield Strength

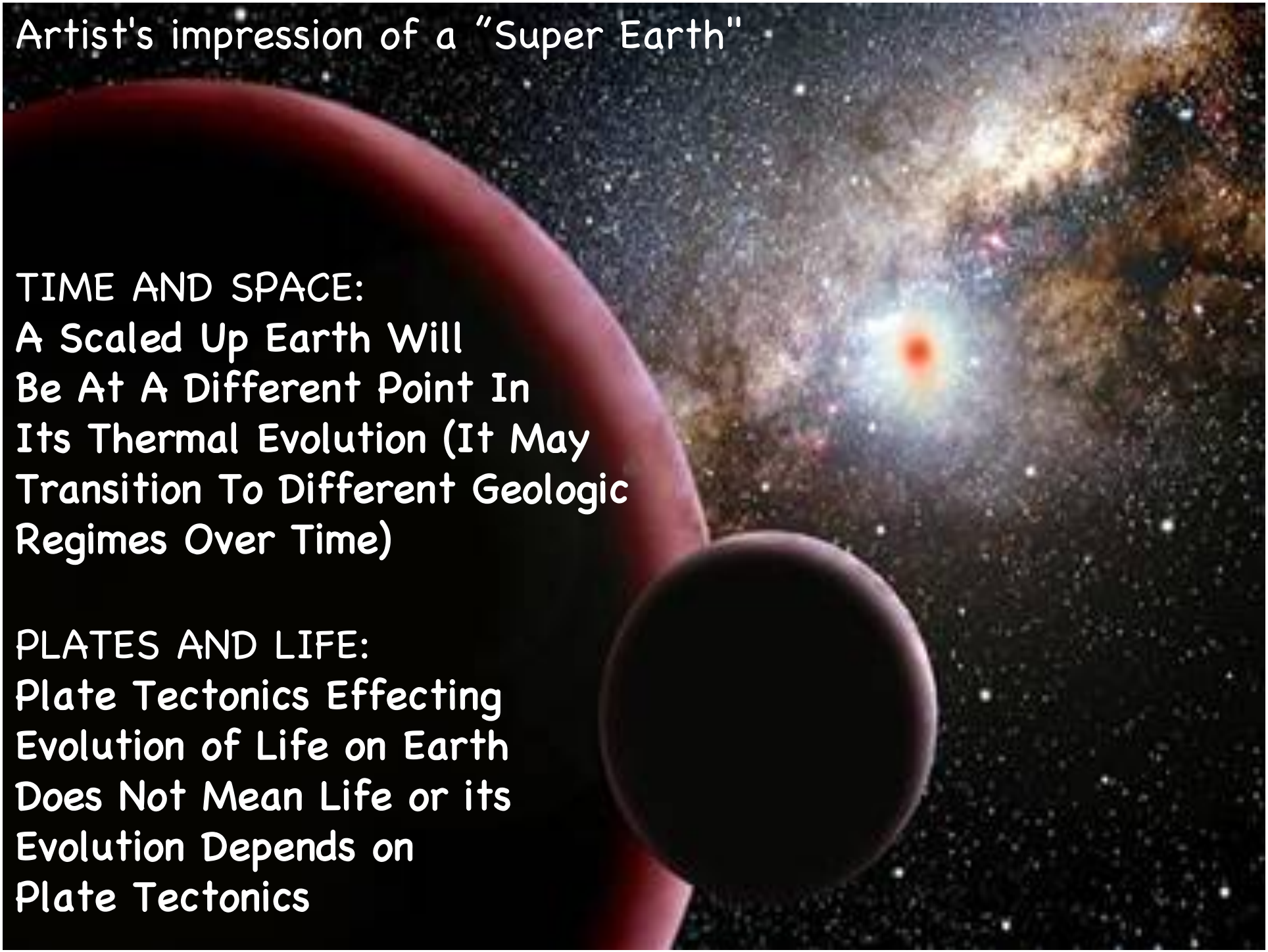
The Notion of Well Defined Tectonic Regimes




Stagnant Lid
(single plate planet)
Internal Heating
Ratio
3
2
1
0
2 4 6 8 10 12 14 16 18 20 22
Yield Strength
Active Lid
(plate tectonics)

Super Plate Tectonics is Not Clear Cut

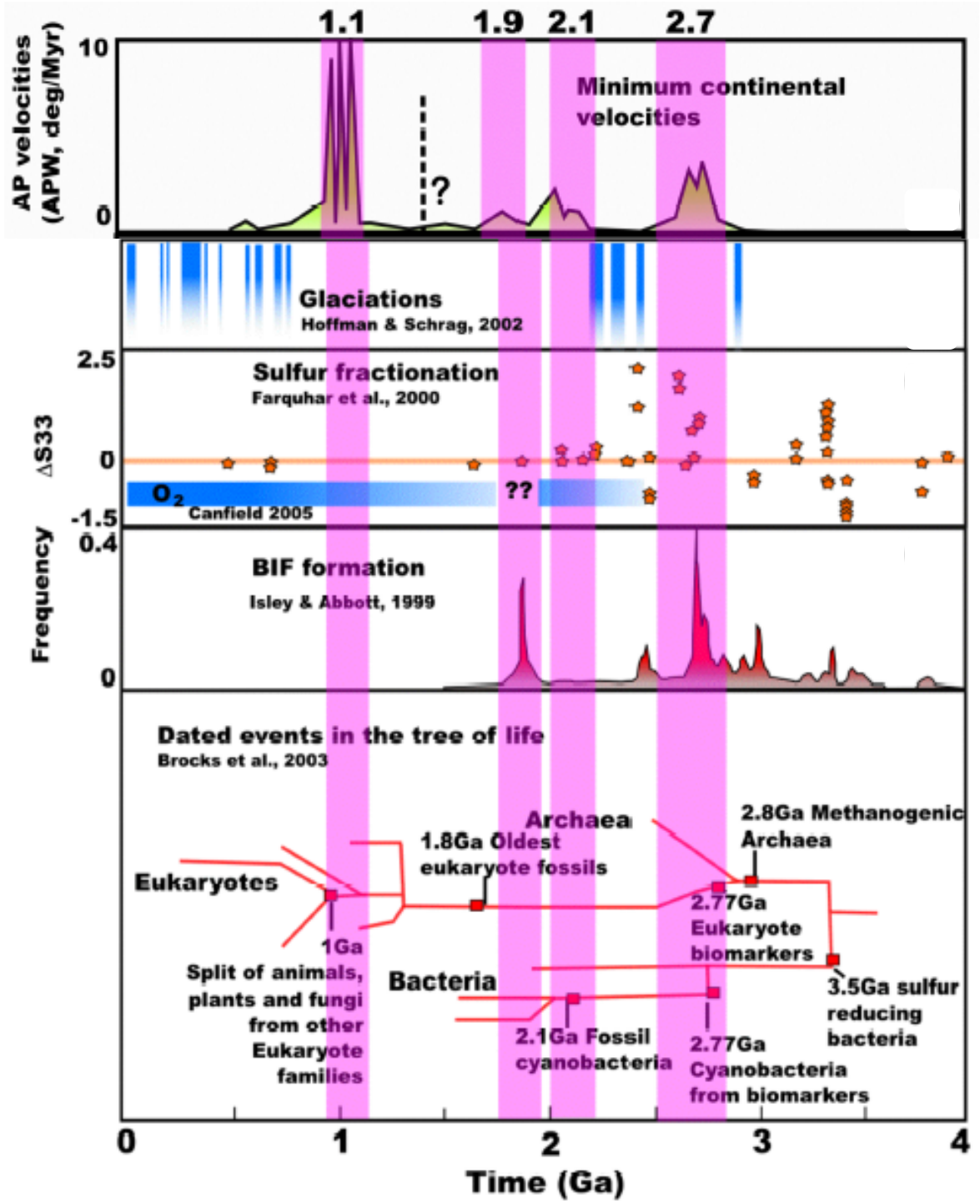
"So You Guys Are Just Being Bummers
to the Astro-Biologists, Isn't That Right ?"



TIME AND SPACE:
A Scaled Up Earth Will Be At A Different Point In Its Thermal Evolution (It May Transition To Different Geologic Regimes Over Time)

PLATES AND LIFE:
Plate Tectonics Effecting Evolution of Life on Earth Does Not Mean Life or its Evolution Depends on Plate Tectonics

MAYBE THERE IS SUCH A THING AS TOO MUCH OF A SMOOTH THING

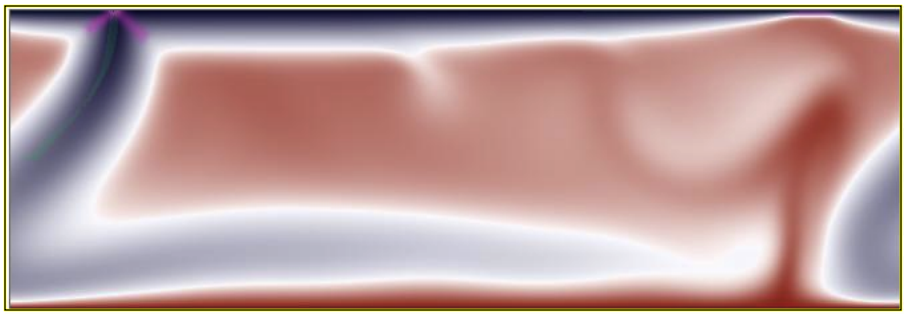

1.1
1.9
2.1
2.7
AP velocities (APW, deg/Myr)
10
0
Minimum continental velocities
?
Glaciations
Hoffman & Schrag, 2002
2.5
Sulfur fractionation
Farquhar et al., 2000
ΔS33
0
-1.5
O2
Canfield 2005
??
Frequency
0.4
BIF formation
Isley & Abbott, 1999
0
Dated events in the tree of life
Brocks et al., 2003
Archaea
2.8Ga Methanogenic Archaea
1.8Ga Oldest eukaryote fossils
Eukaryotes
2.77Ga Eukaryote biomarkers
1Ga
Split of animals, plants and fungi from other Eukaryote families
Bacteria
3.5Ga sulfur reducing bacteria
2.1Ga Fossil cyanobacteria
2.77Ga Cyanobacteria from biomarkers
0
1
2
3
4
Time (Ga)

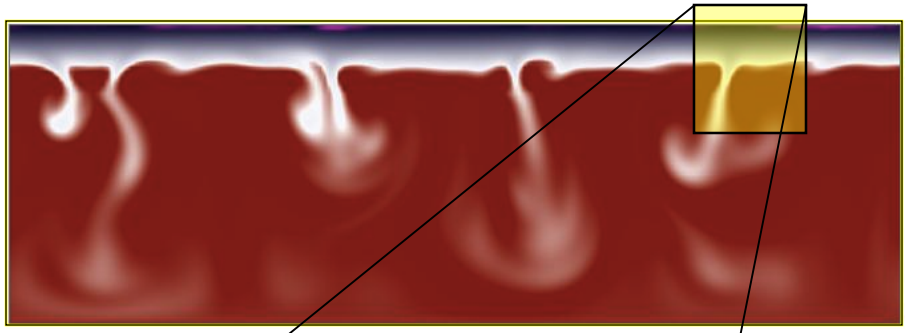
Notion of Plate Tectonics Being Key to Habitability

Is Not Tied to "Laws of Plate Tectonics"
(e.g., rigid plate interiors, narrow boundaries, Euler poles, ...)

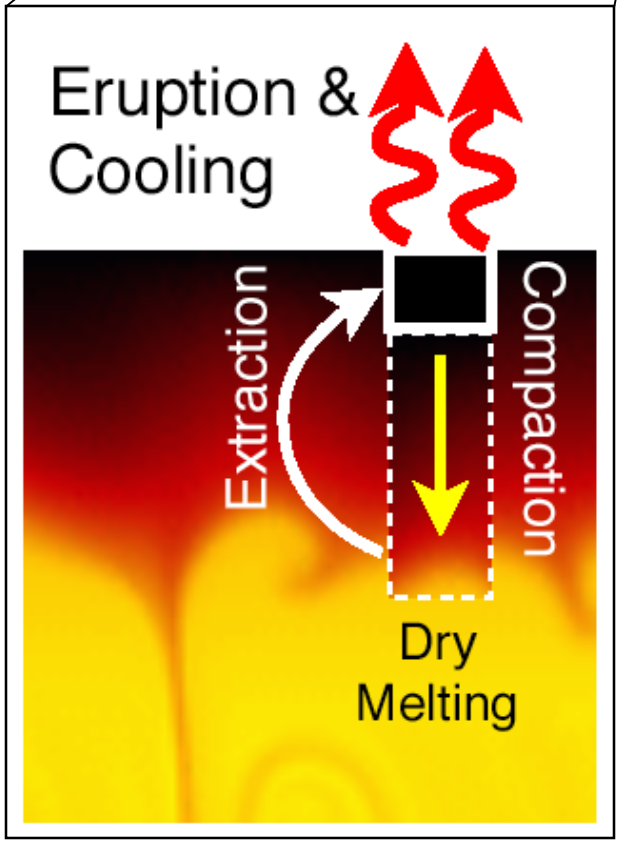
It's Principally Tied to Volatile Cycling
(Climate Stability: Volcanism-Weathering, Oceans-Deep Water Cycle)

Active Lid
(plate tectonics)



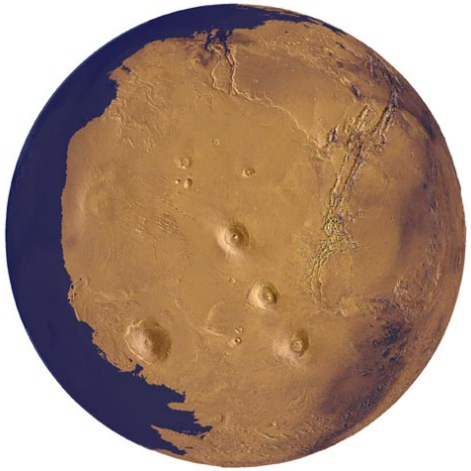


Volatile Cycling Possible



from *Moore 2012*

Stagnant Lid
(single plate planet)



Melt produced & extracted to surface.
Region below compacts downward.
Conveyor-belt that moves material downward as it moves heat upward.

+ Crustal Entrainment Recycling
+ Phase Change Driven Recycling

Atmospheric Signature of Tectonic Regimes

Changing Tectonic Regimes over Planets Life

Will Super Earths Have Plate Tectonics?
- Undeterminable
- Multiples States are Allowable

Does it Matter for Habitability?
- Worth Considering Volatile Cycling w/o Plate Tectonics