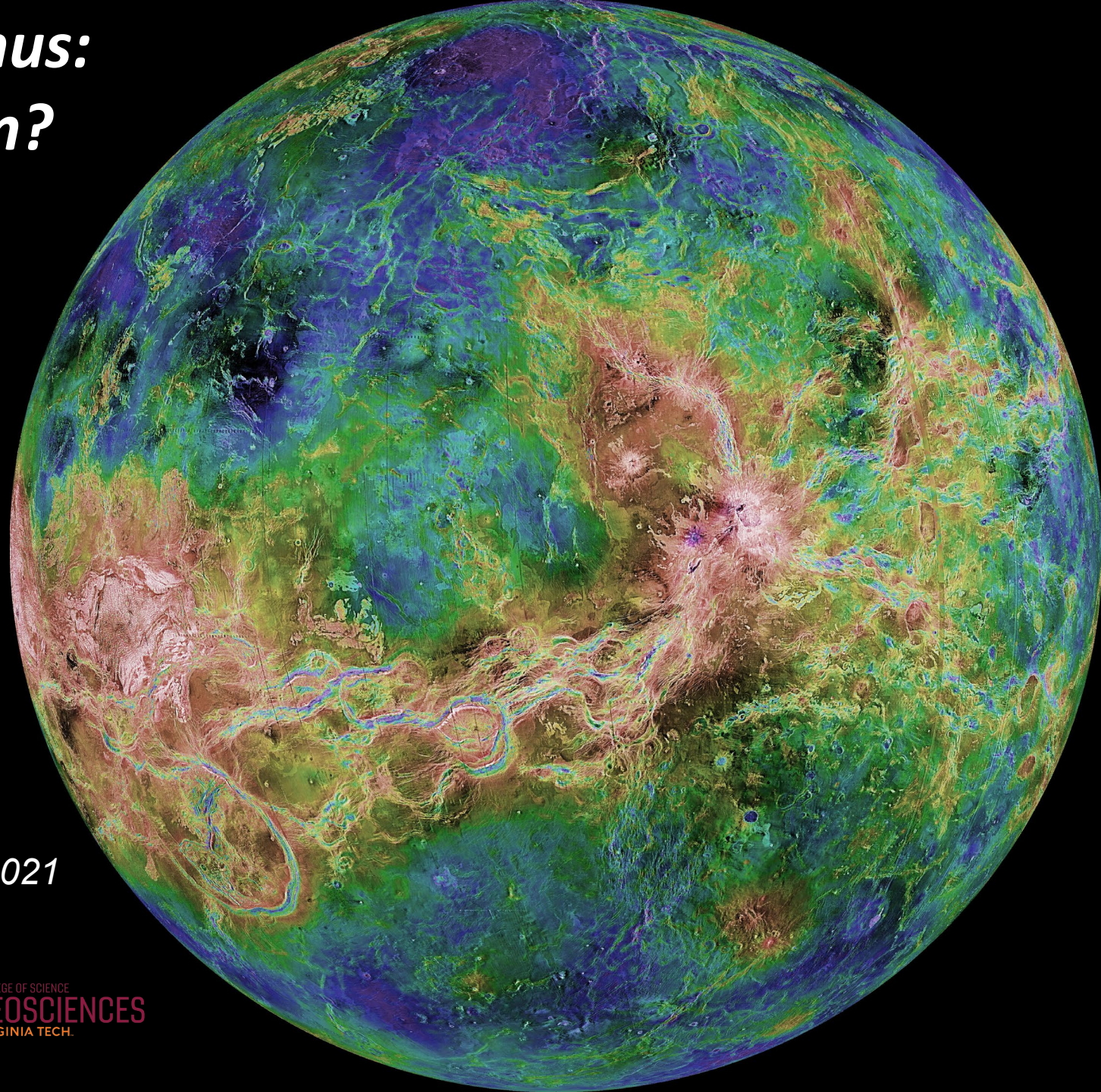
Tectonic Evolution of Venus: A Planet in Transition?



Matthew B. Weller[1]

Special Guest Contributors
Walter S. Kiefer[2] and Megan S. Duncan[3]

[1] Brown University
[2] Lunar and Planetary Institute
[3] Virginia Tech.

Decadal Survey Venus Panel |
Venus Geodynamics session
March 24th 2021

BROWN

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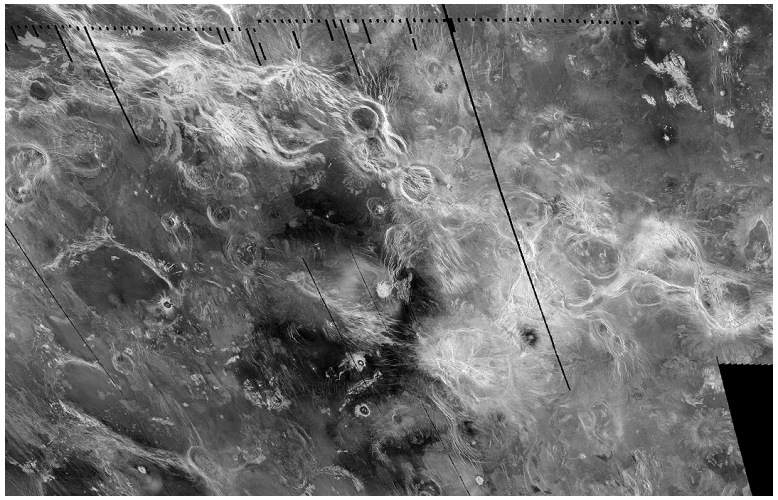
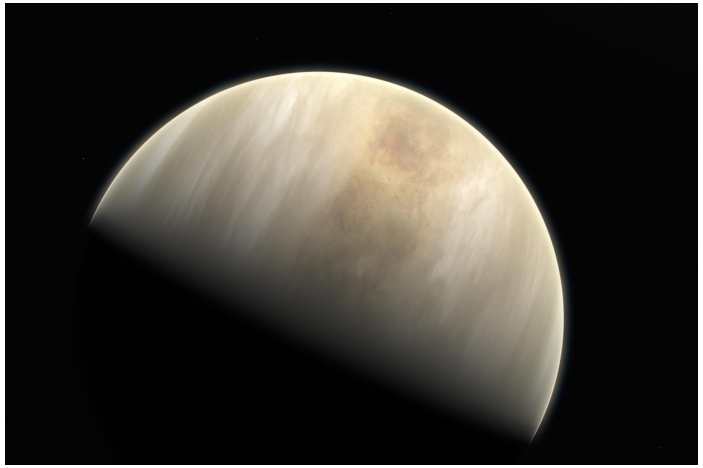
- Current Venus
  - Thick atmosphere; high surface temperatures
    - Before? Argued… *[e.g., Way + 2016; Gillmann + 2020]*
    - Ambiguous degassing (*more/less* Earth)
      [e.g., O'Neill et al., 2013; O'Rourke & Korenaga, 2015; Pioneer Venus Large Probe; Halliday 2013]
  - no clear evidence of current plate tectonics
    - Evidence of **convergence/mobility** plume-surface interactions (*subduction?*)
      [e.g., Solomon + 1992; Schubert + 1997; Kiefer 2013; Davaille + 2017; Gülcher + 2020]





- Observations of vast volcanic plains
  - **young**; emplaced in the last 500 – 1,100 Myr
  - ~ 80% of the planets surface
  - Current Volcanic rates **0.5 – 4 km³/yr**; ~ 1 – 20 % Earth rate
    [e.g., Schaber + 1992; McKinnon + 1997; Basilevsky & Head 1998; Herrick & Rumpf, 2011; Stofan + 2005]

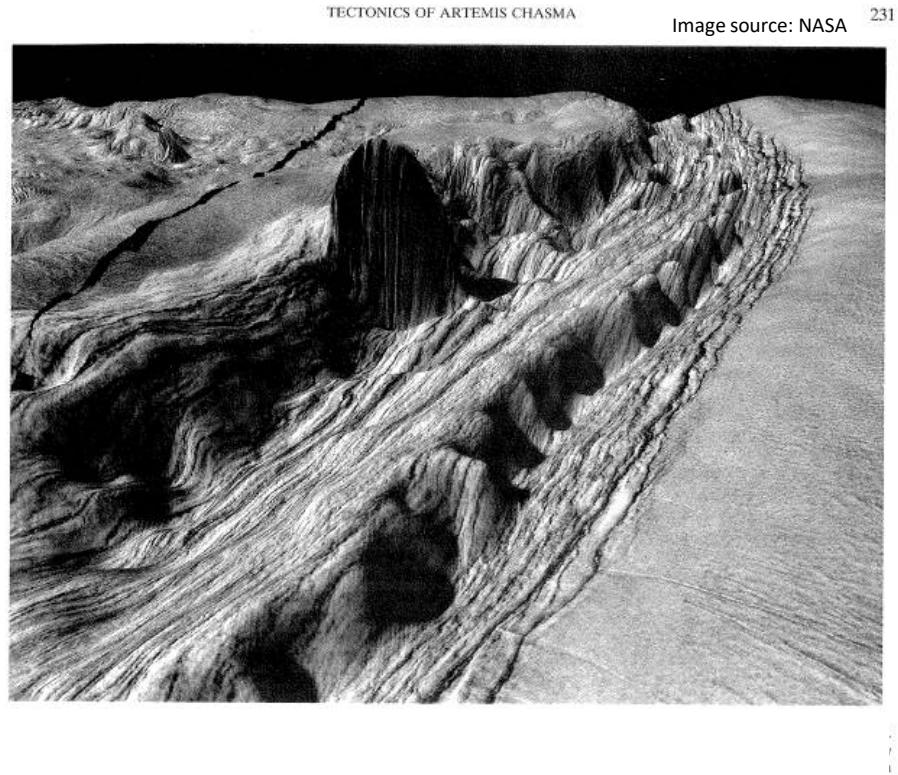


Image source: NASA

- The current and past tectonic states of Venus are hotly debated
  - "Catastrophic'' (*Episodic lid*)
    [e.g., Turcotte 1993; Moresi & Solomatov, 1998]
  - Single Plate (*Stagnant lid*)
    [e.g., Guest & Stofan 1999; O'Rourke & Korenaga, 2015]
  - Plate Tectonic-like (*Mobile lid*)
    [e.g., Phillips + 1981; Weller & Kiefer, 2020; Noack + 2012]

Contenders Based on current observations

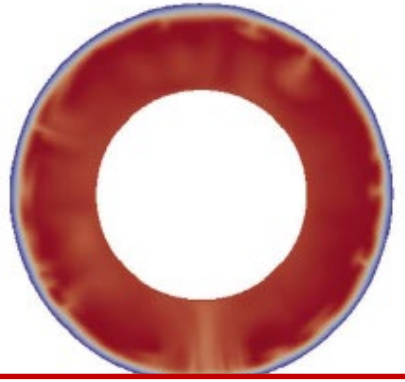
Venus in a nutshell (*more shell, less nut*)

- Endmember 1: *Stagnant lid* model
  - High early rates of volcanism, likely Heat-pipe *[e.g., Moore and Webb, 2013]*
  - Monotonically decreasing
    - **Volcanism, Outgassing, and Resurfacing rates**
    - Implies Venus' Atmosphere is old/relict
  - Can explain: **Volcanic history** *[e.g., O'Rourke & Korenaga. 2015]*
  - Problems
    - Evidence of large-scale convergence; Ishtar Terra
      - 2000-3000 km of crustal convergence *[e.g., Kiefer 2013]*
    - Physics of convection and thermal evolution
      *[e.g., **Weller et al., 2016; Weller & Lenardic 2016, 2018**]*

- Endmember 2: 'Catastrophic' model
  - Periodic large scale
    - **Volcanism, Outgassing and Resurfacing rates**
    - Implies Venus' Atmosphere evolved overtime/changed
  - Can explain: Volcanic history and **Convergence** *[e.g., Kiefer 2013]*
  - Problems
    - Ad-hoc/'instantaneous' (Physics of Convection)
      *[e.g., **Weller et al., 2016; Weller & Lenardic 2016, 2018**]*

Warm colors = high T

Steady



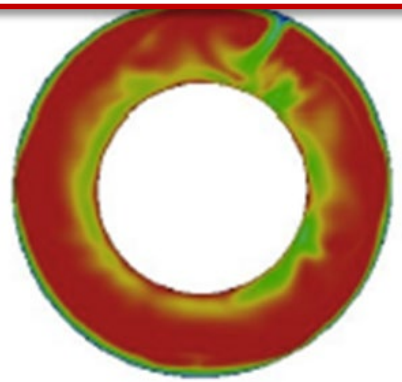
Low strain rate gray
Surface yielding

Understanding of convective ***physics has advanced***

[Weller & Kiefer, 2020; Weller & Kiefer in prep]

Are these ***endmembers robust****, or are they* ***pieces*** *of a* ***larger puzzle?***

'Catastrophic'



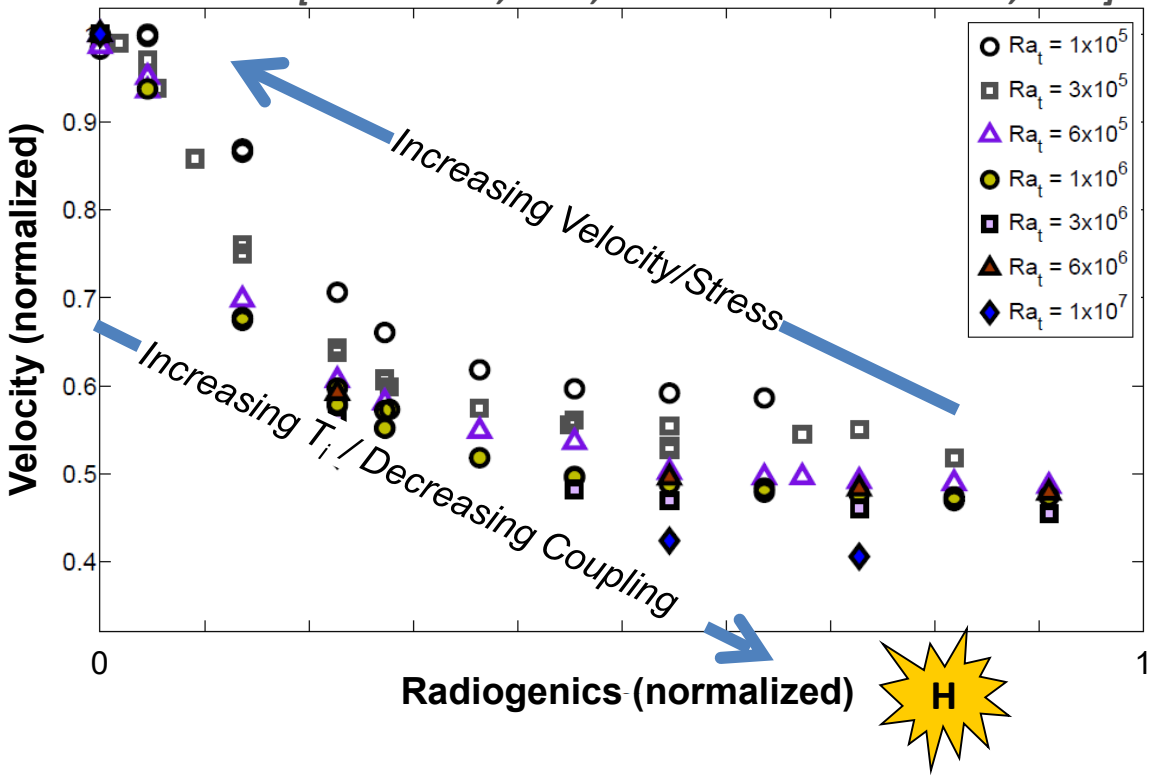
Canonical (***Static***) View of Global Tectonics

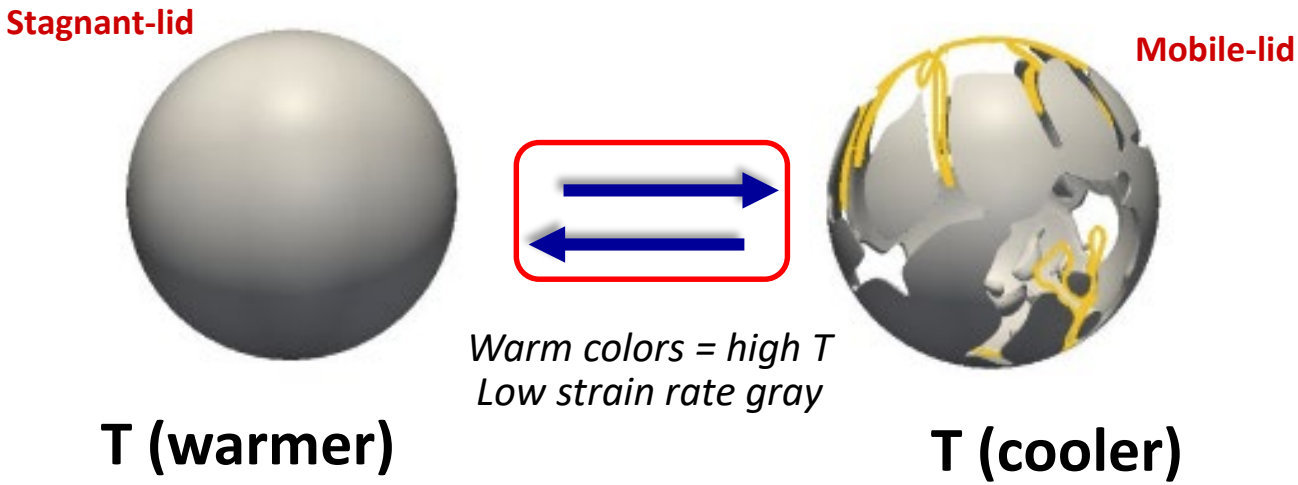
- ‘Recent’ Advances in Convective Physics
  - Higher internal heating favors *surface immobility*
  - Decreasing internal heating favors *surface mobility*
    - –Ability of the system to do work
      - – ***Velocity stress scale***
    - –Viscous coupling of mantle and lithosphere
      - – ***Temperature induced***

      *[Stein et al., 2013, **Weller et al., 2015**]*
  - Higher surface temperatures favor *immobility*

    *[e.g. Lenardic et al., 2008; Foley et al. 2012; **Weller et al., 2015**]*

[Weller et al., 2016; Weller and Lenardic 2016, 2018]





*Complex **feedback** in mantle convection **leads to** **instabilities** and changes*

Physics:

Tectonics can change

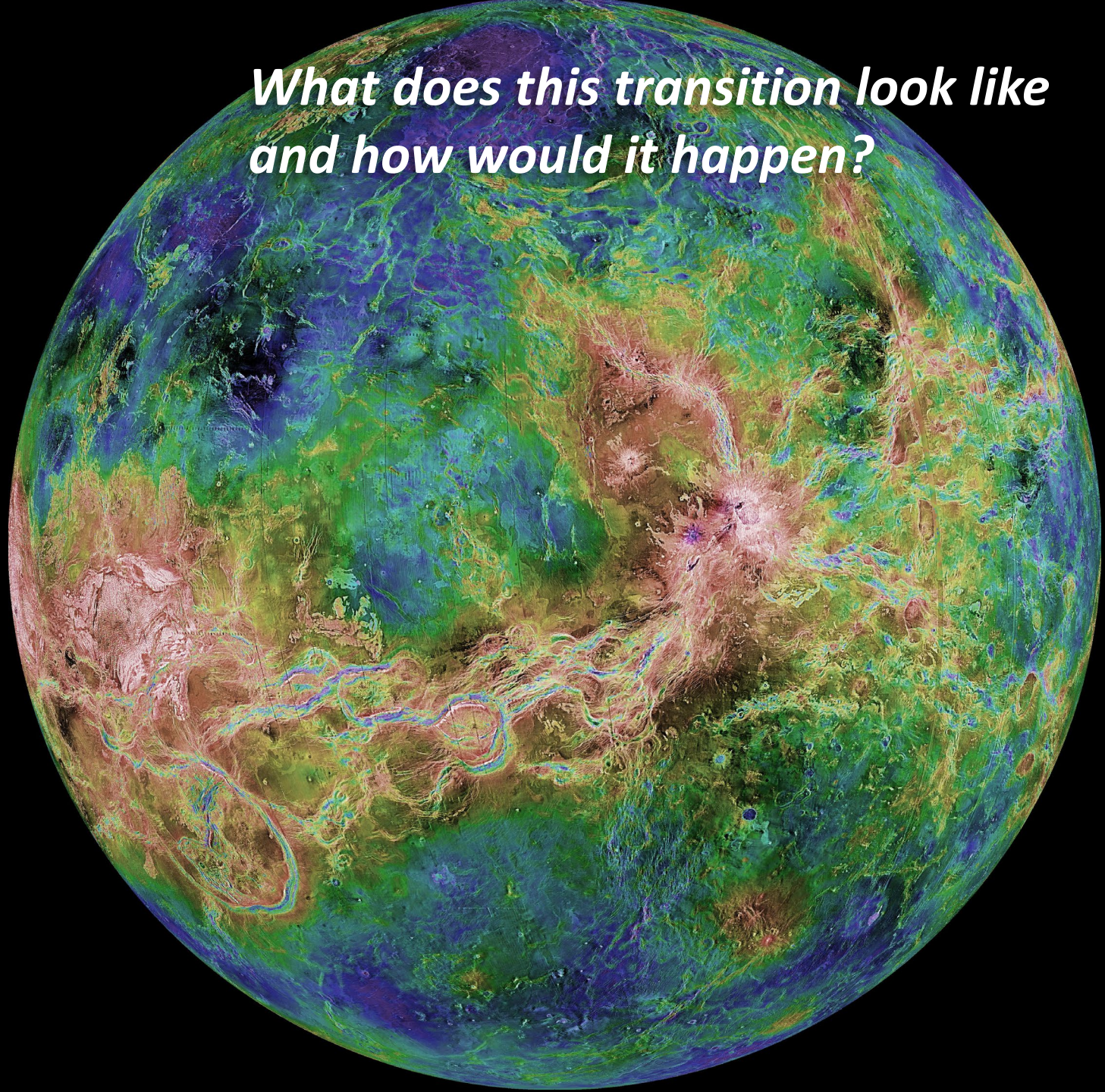
Observations:

Suggestions of mobility

Surface temperatures

Inference:

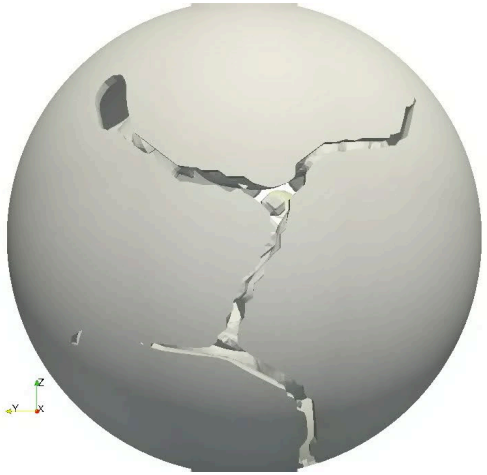
Venus may have transitioned tectonic states

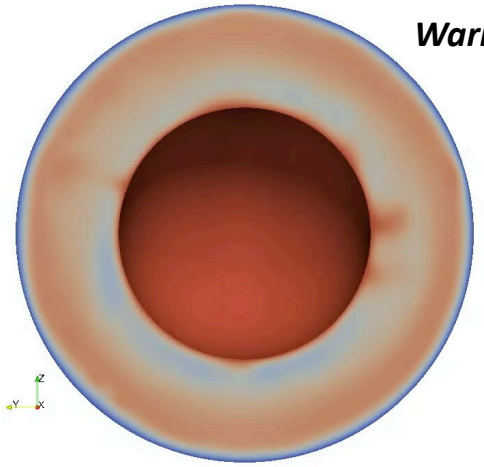


What does this transition look like and how would it happen?

Change in Regimes

A Continuum of States





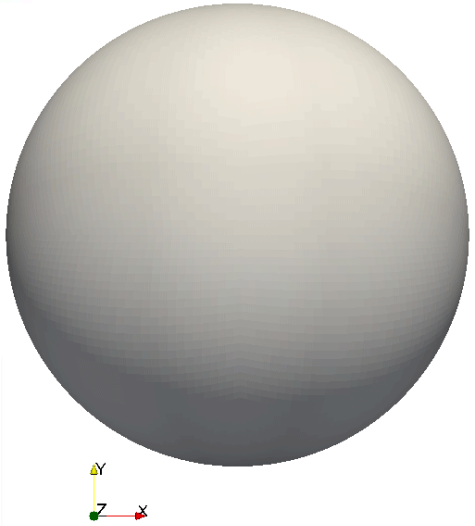
Warm colors = high T

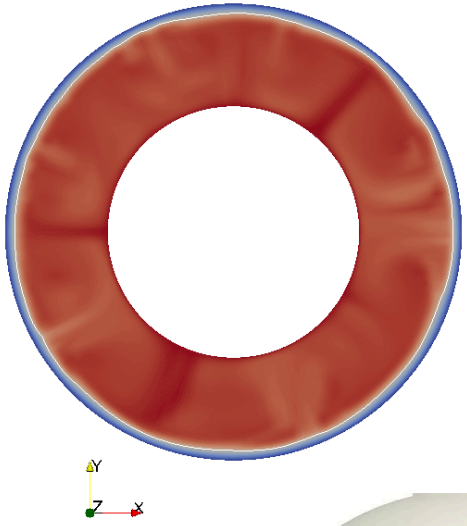
Surface yielding

Low strain rate gray

Early Mobile State

stable



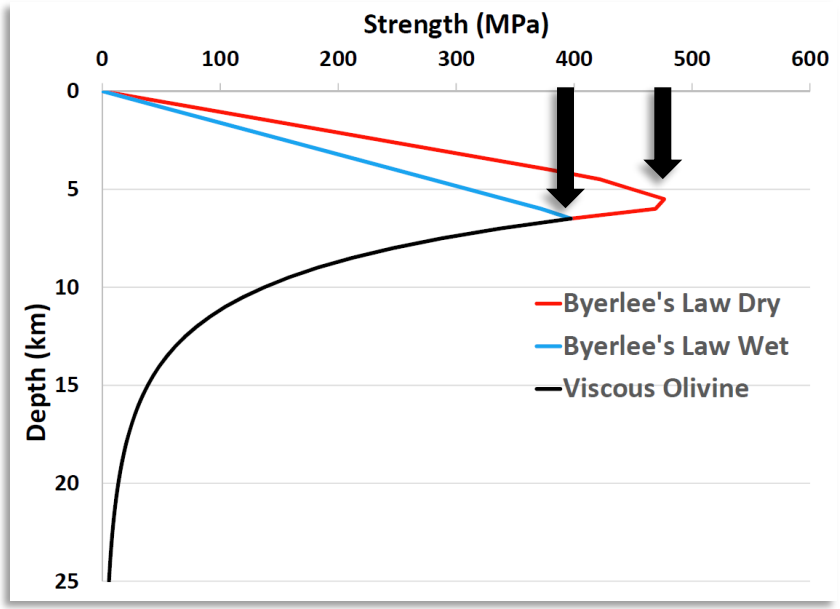


What?

Episodic/Transitional

unstable

How?



Loss of pore fluids

30% increase in yield strength

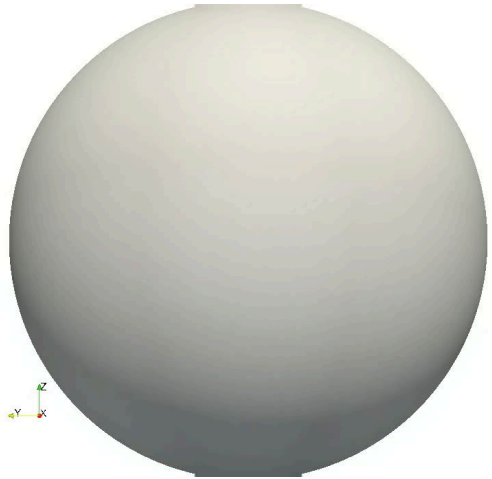
Implies similar effects

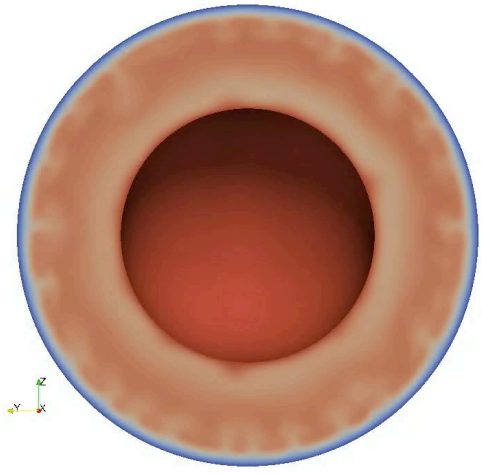
reduction in buoyancy force

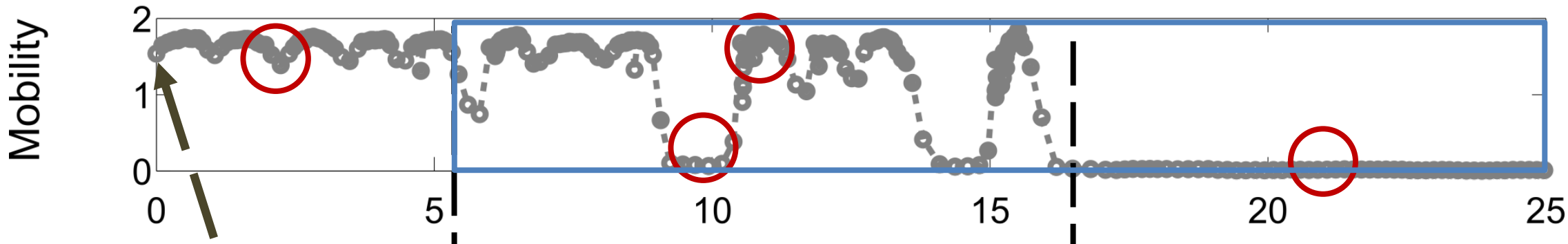
increase in T_s

Single Plate

stable

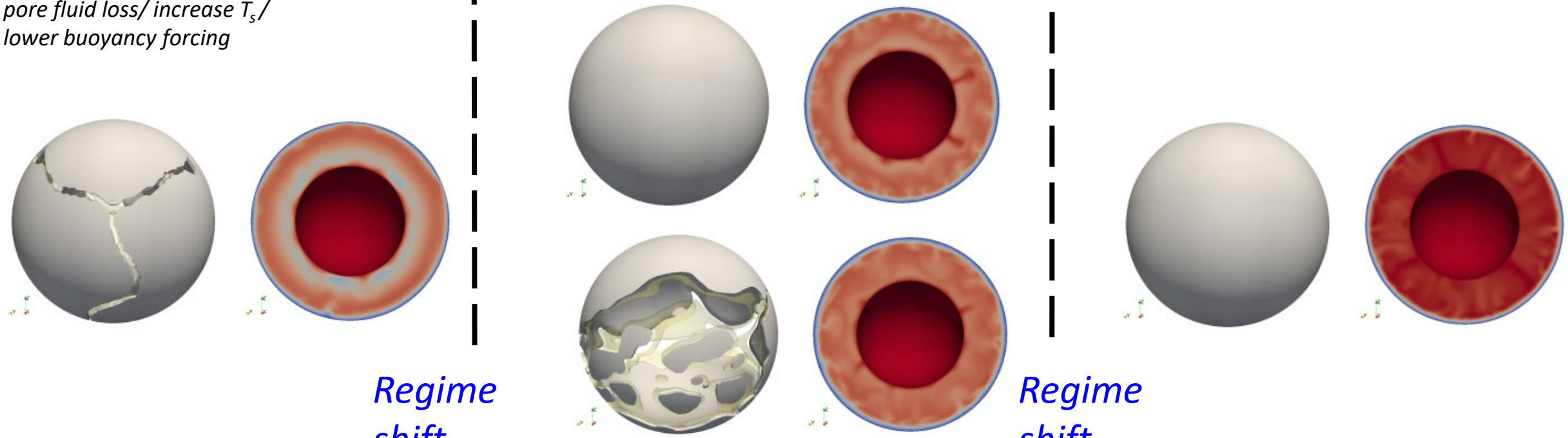






Initial steady state

*yield **increase** 8% (~9 MPa)*
pore fluid loss/ increase T_s/
lower buoyancy forcing



Regime shift

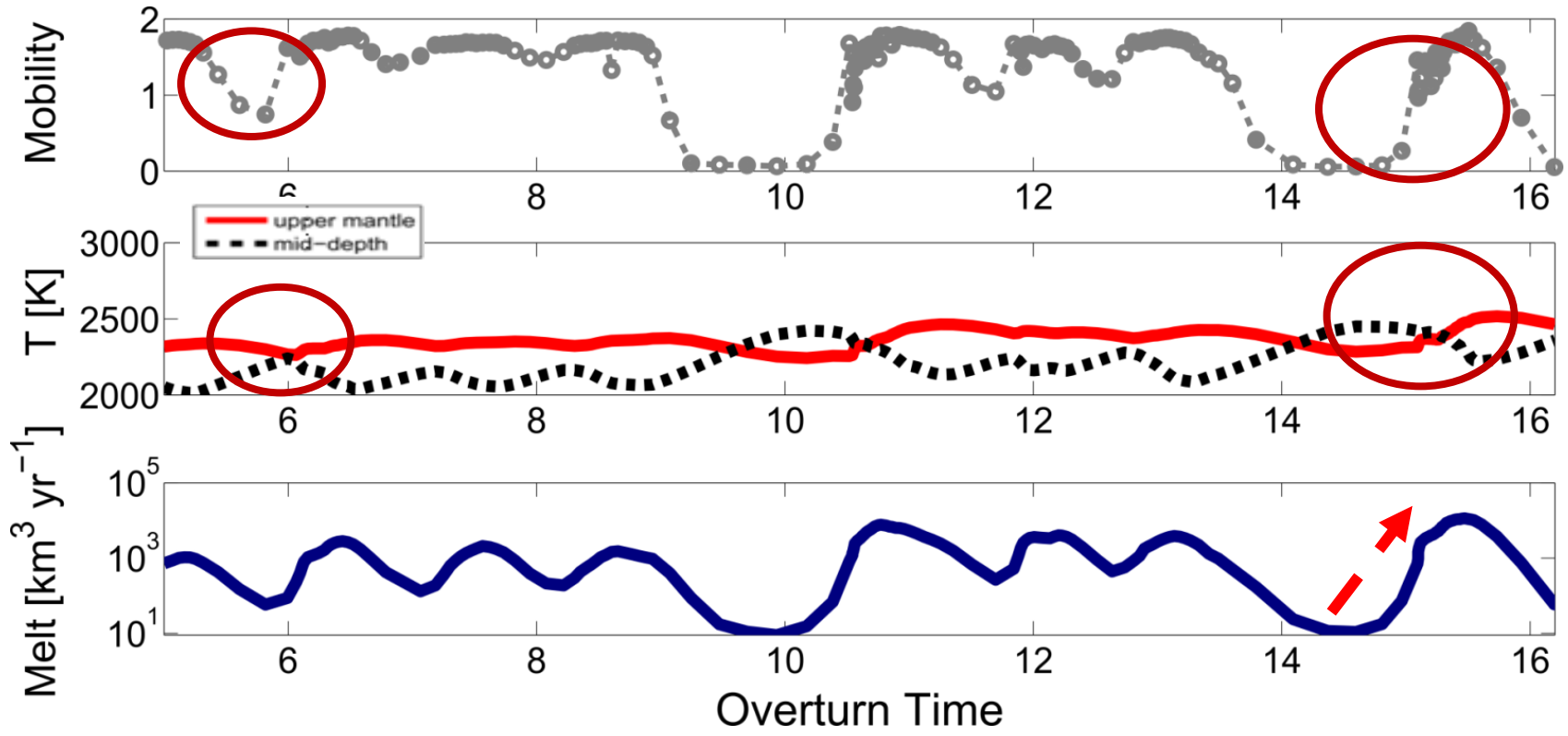
Regime shift

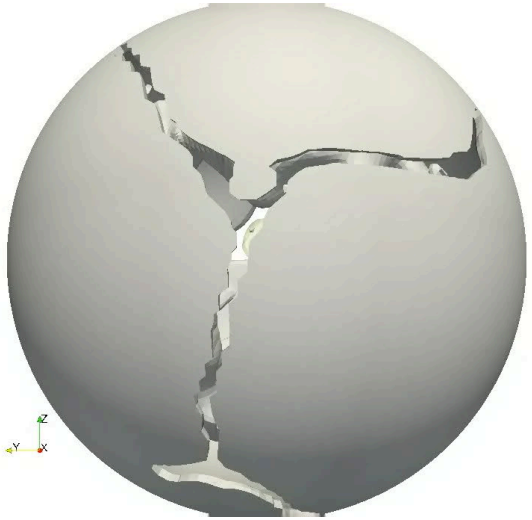
Mobility = surface/bulk velocity

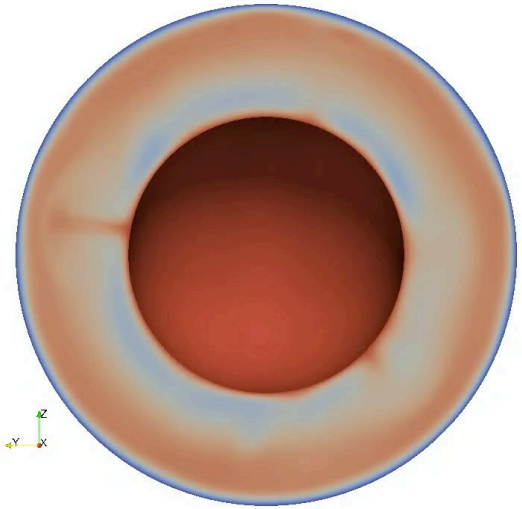
[Weller & Kiefer, 2020]

Overturn time = parcel to traverse mantle

One case of a Global Transition in Tectonics







[Weller & Kiefer, 2020]

Unstable

Active → Quiescent

O(10) Myr

Warming, inversions, and plumes

ΔT ~ 200 K

O(100) Myr

Melt Variation

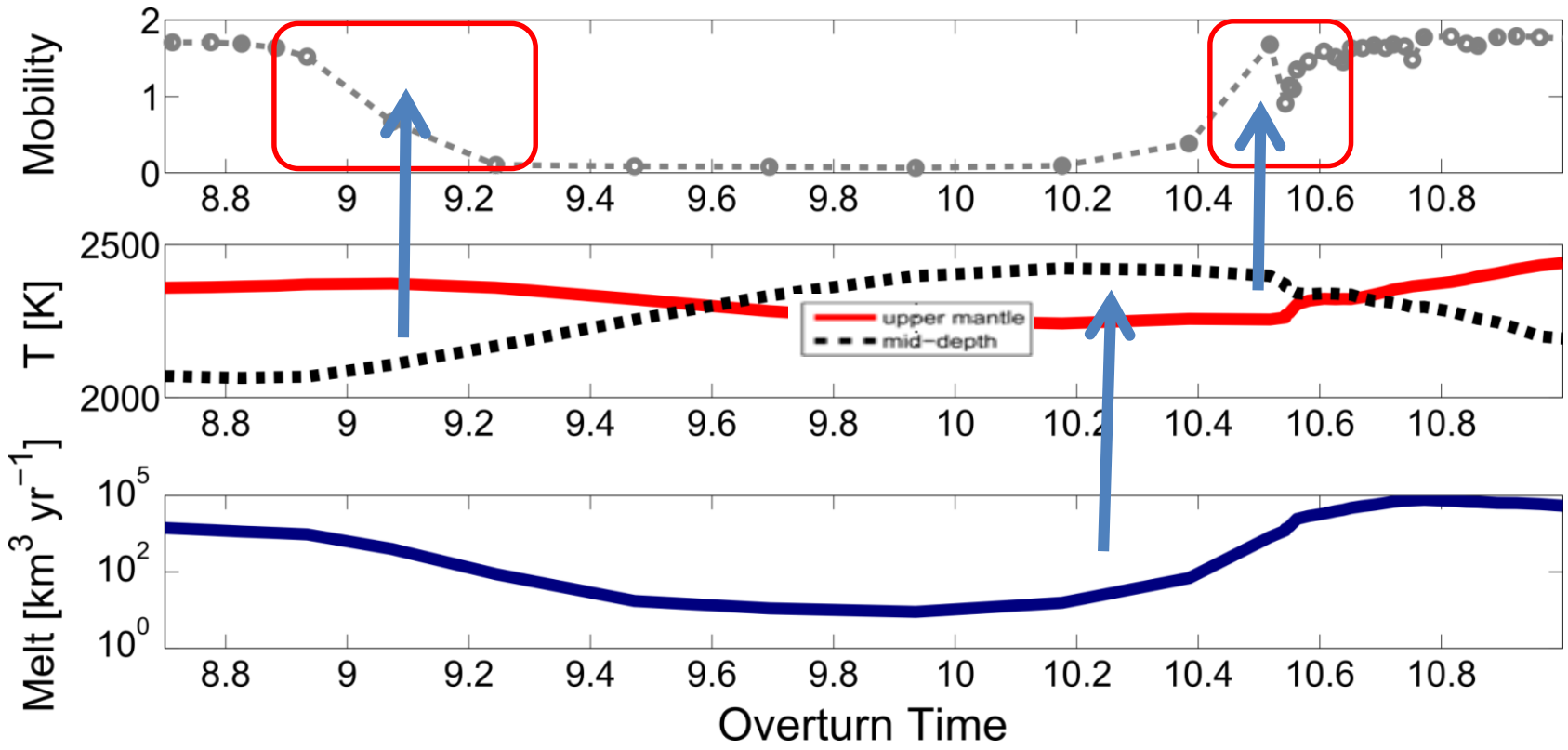
Extreme O(1e4)

→ minimal O(1e0-1e1)

t ~ 40 - 100 Myr

Time scale O(1-2) Gyr

Transitional Episodic lid



[Weller & Kiefer, 2020]

Shut down, startup

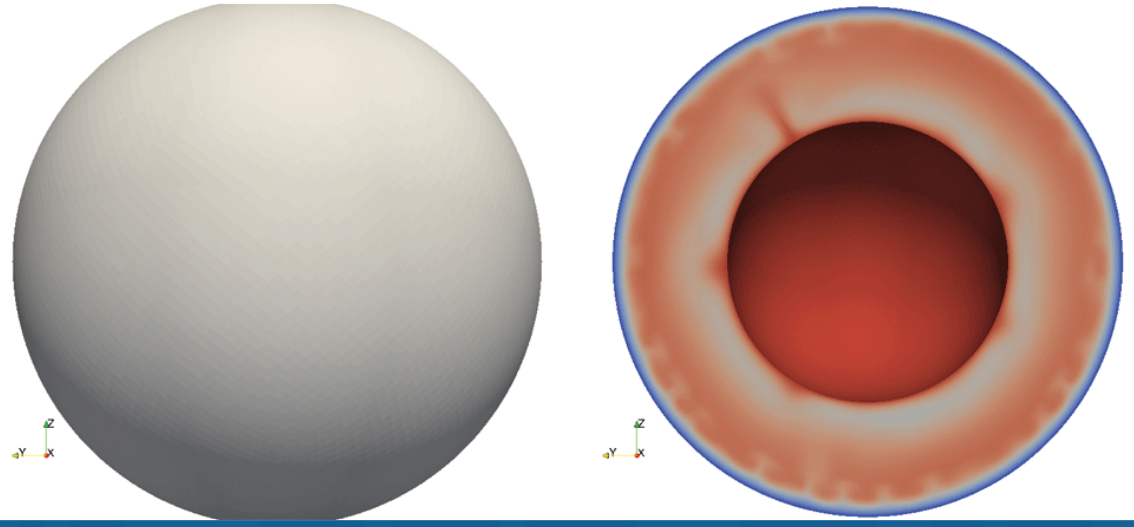
O(10) Myr

Lags with Shutdown

thickening boundary layers; ***O(100 Myr)***

Melt suppressed

Plume generation and destabilization



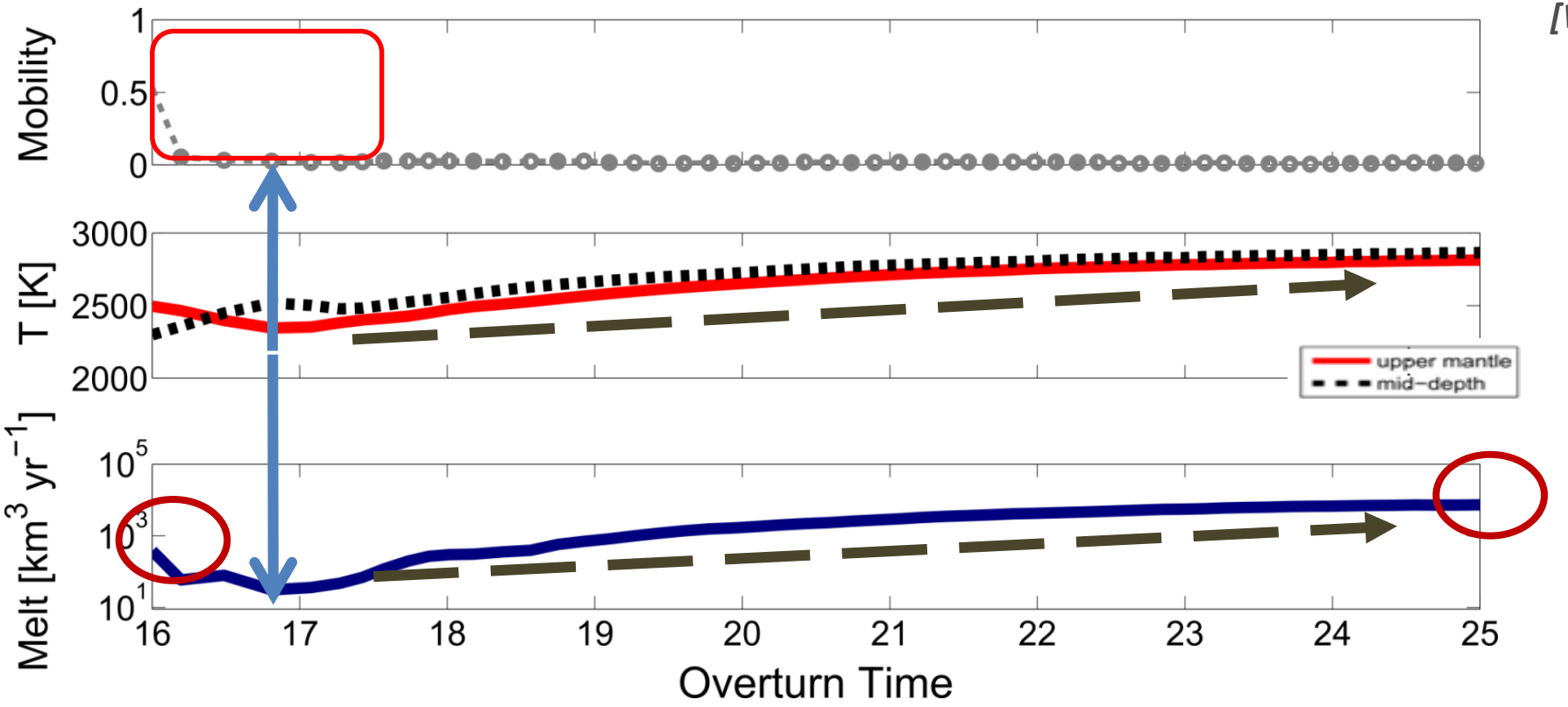
Not "Catastrophic", Stochastic

- Thermal equilibration
- Reorganization
- ***Lithosphere Preservation***

Time scale 200 – 400 Myr

Transitional Development (Redux)

[Weller & Kiefer, 2020]



Final cessation

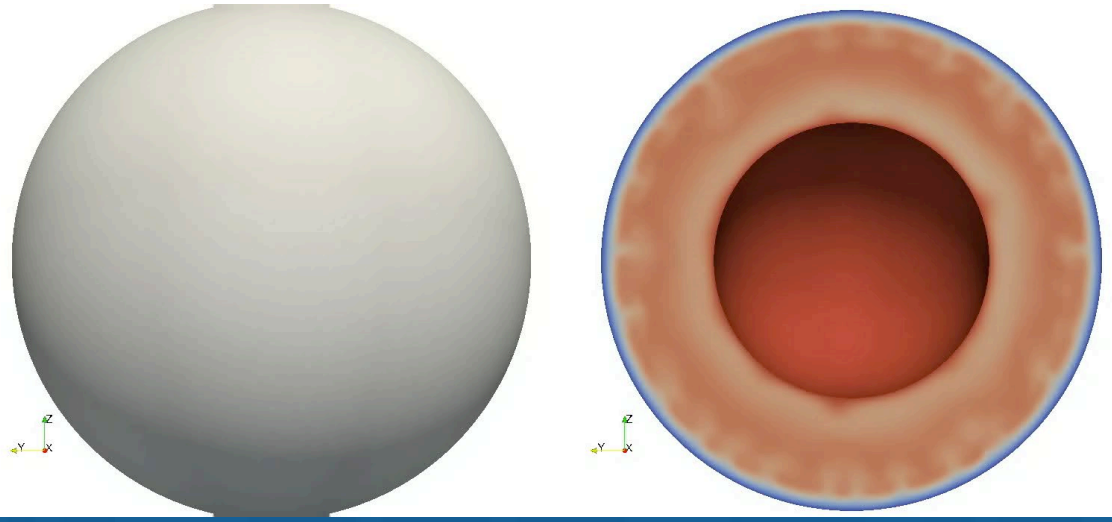
Quiescence

Warming/ inversion

ΔT ~ 300 K;

Minima, increase

decompression melt ceases, temperature effects



Compared with earlier states

- Melt increases ~7x
  - Diffuse; Global; Steady state
- Mantle T_p increases

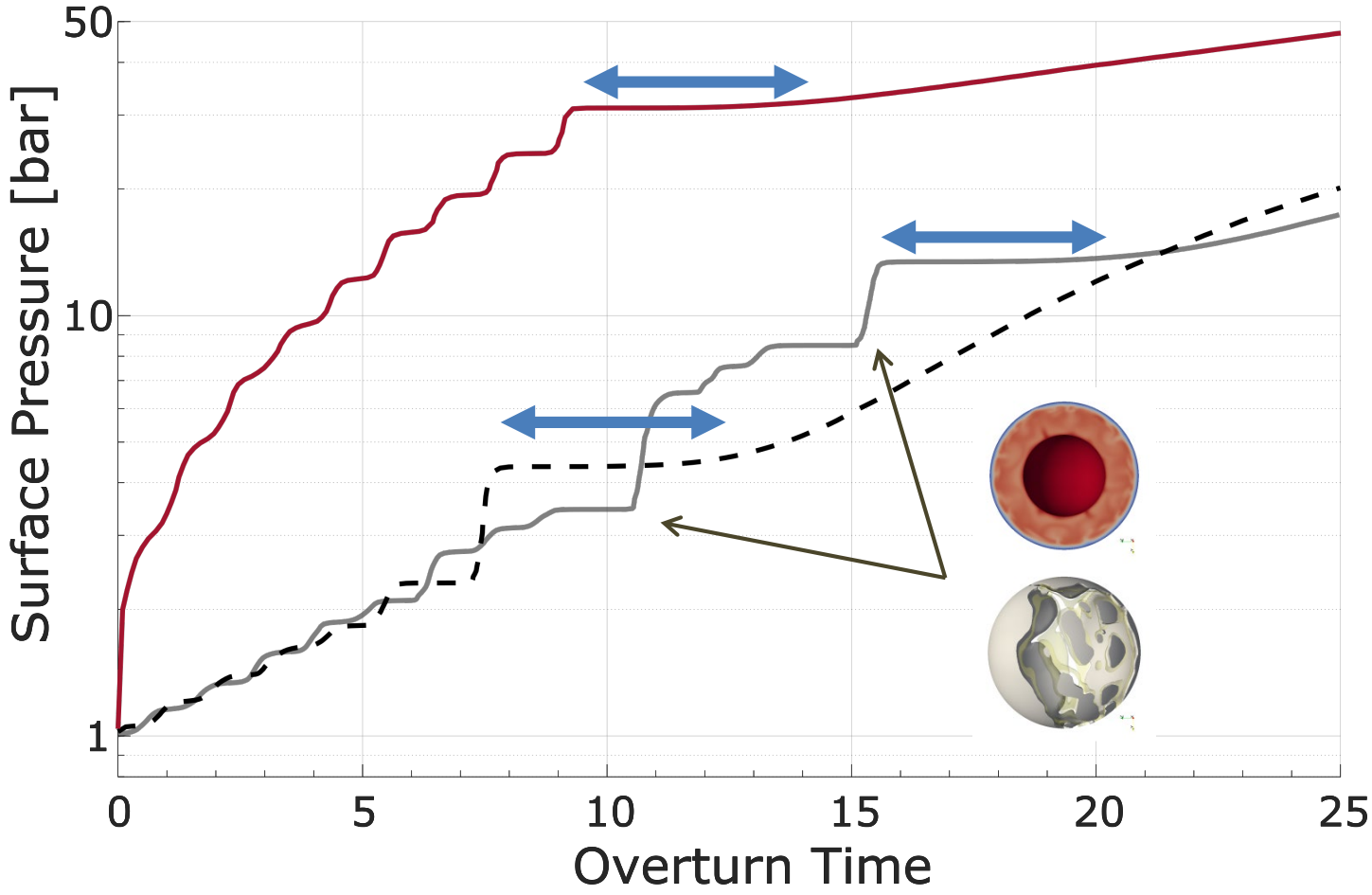
Time scale O(1-2) Gyr

Stagnant (*Arrested*) Development

— σ_y = 108 MPa

- Outgassing
  - Overturn phase
    - –**punctuated atmosphere** generation events
    - – increases **3 – 5 Bar over ~60 Myr**
  - Post Overturn phase
    - – melt and atmosphere generation is **subdued for ~ 1 Gyr**
  - All cases
    - – Qualitatively similar
    - – Generate **significant atmospheres**

The transition is a stochastic process



[Weller & Kiefer, in prep]

Critical Points & Implications

Consequences of a transitioning planet

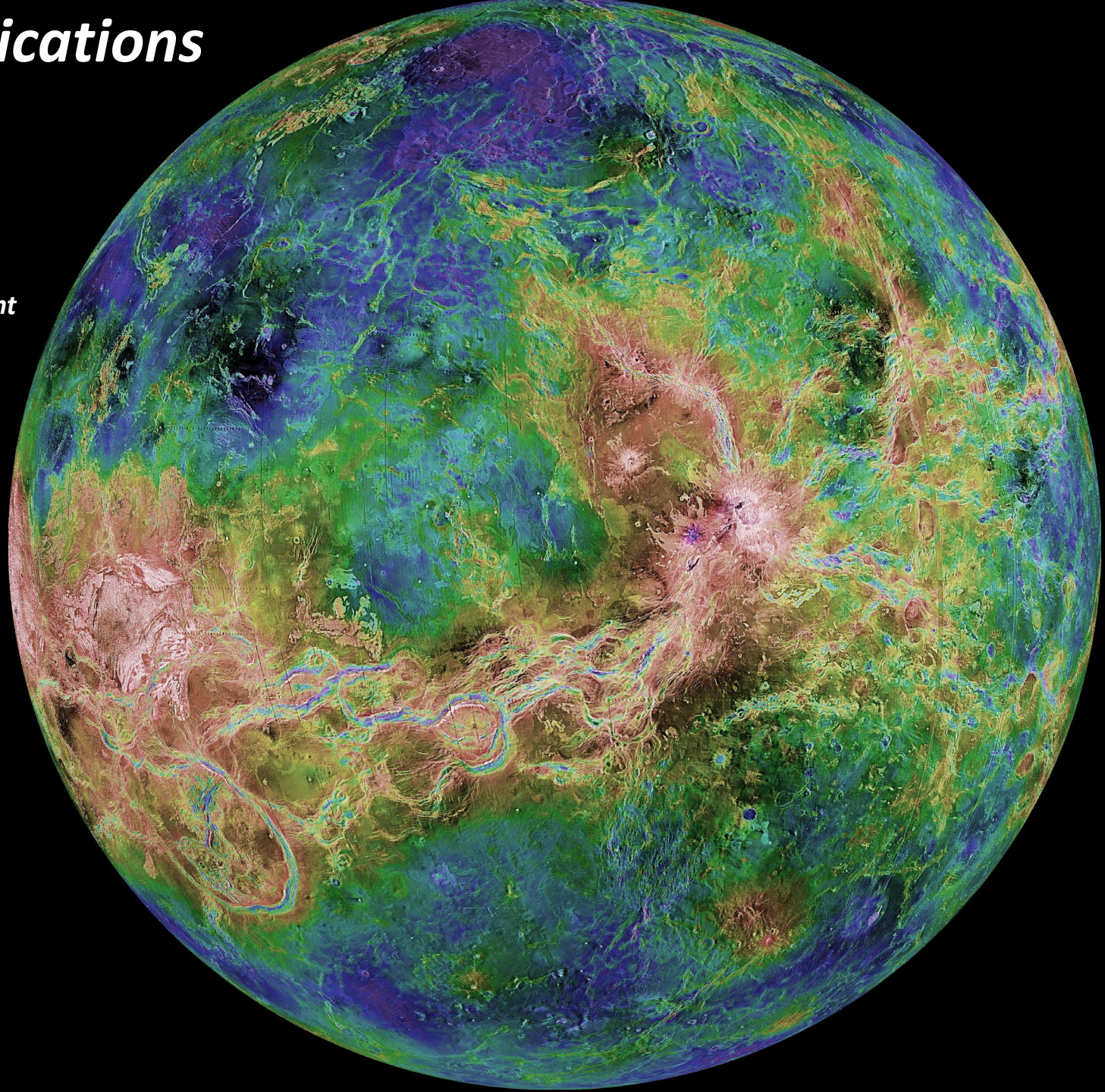
- *Extensive and stochastic resurfacing events*
  - ***Caveat: observations may only record last event***
- *Generation of thick outgassed atmospheres*
  - ***Caveat: Time integrated, may not reflect most recent event***

Quiescence after overturn

- *Volcanism negligible for ~1 Gyr*
  - ***Caveat: Observations cannot distinguish between a transition to stagnant phase and continuing overturns***

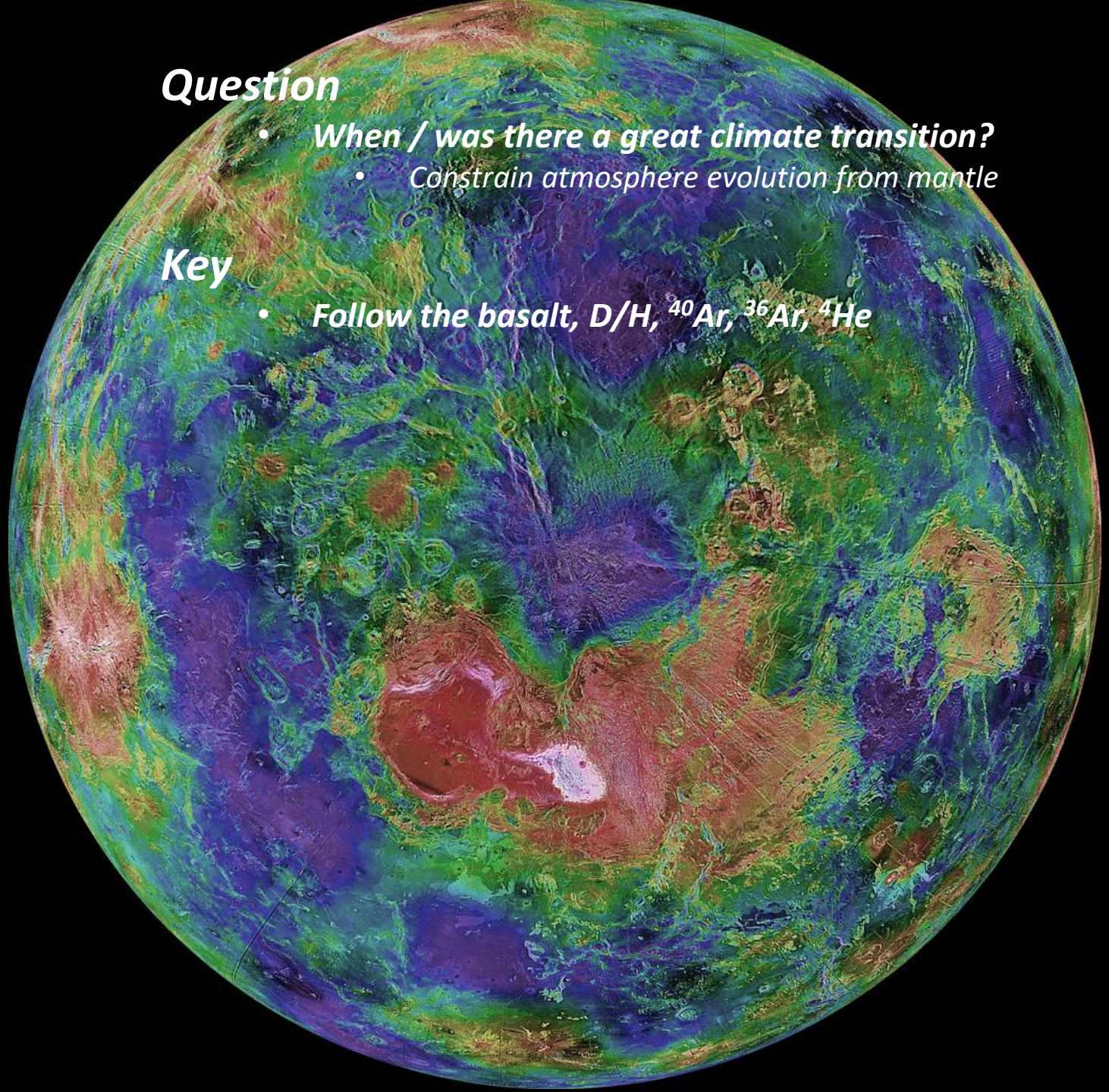
Tectonic Transitions occur over Gyr's

- *Venus could still be transitioning*



Decadal Survey

- ***Mantle temperatures and mineralogy (Fe/Mg) change with time and tectonics***
  - *Calculate Mantle T_p over time (following Earth, Mars, and Mercury)*
- ***We need more than three (Vega 2, Venera 13/14) high error measurements***
  - *Alpha Particle X-Ray Spectrometer (APXS)*
- ***Tessera are important targets, but we need the basaltic plains***
  - *Context and records the 'background' Venus state*



Question

- ***When / was there a great climate transition?***
  - *Constrain atmosphere evolution from mantle*

Key

- ***Follow the basalt, D/H, ^{40}Ar, ^{36}Ar, ^{4}He***