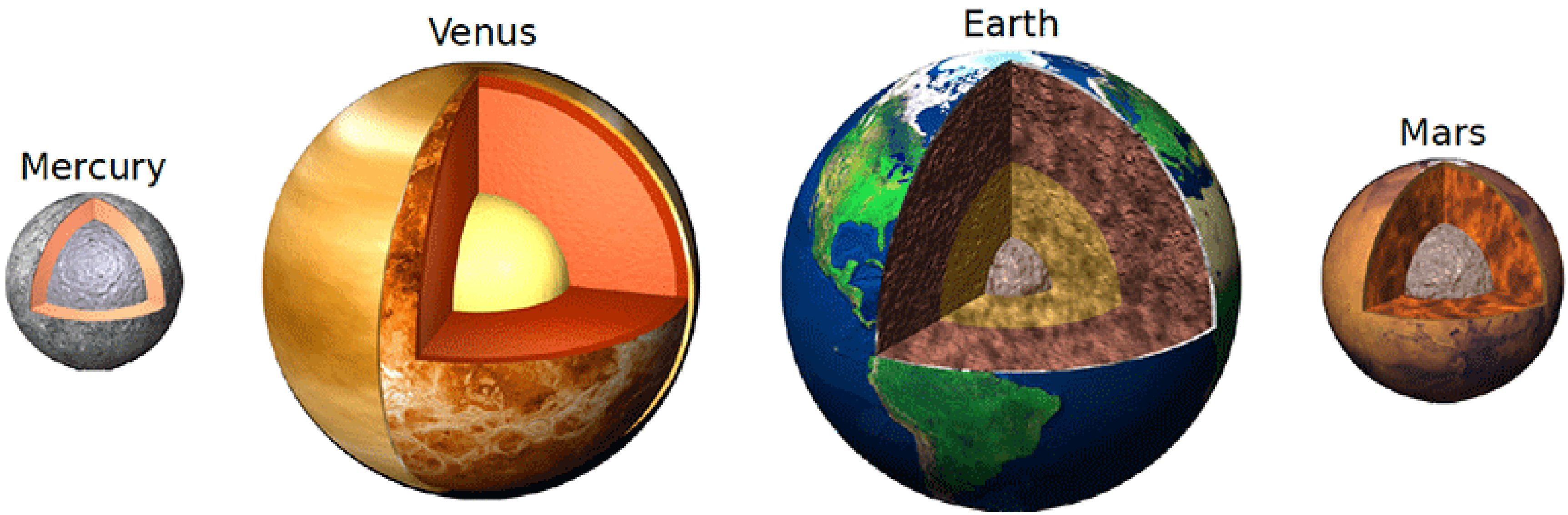
Venus

Convection on the other rocky terrestrial planets



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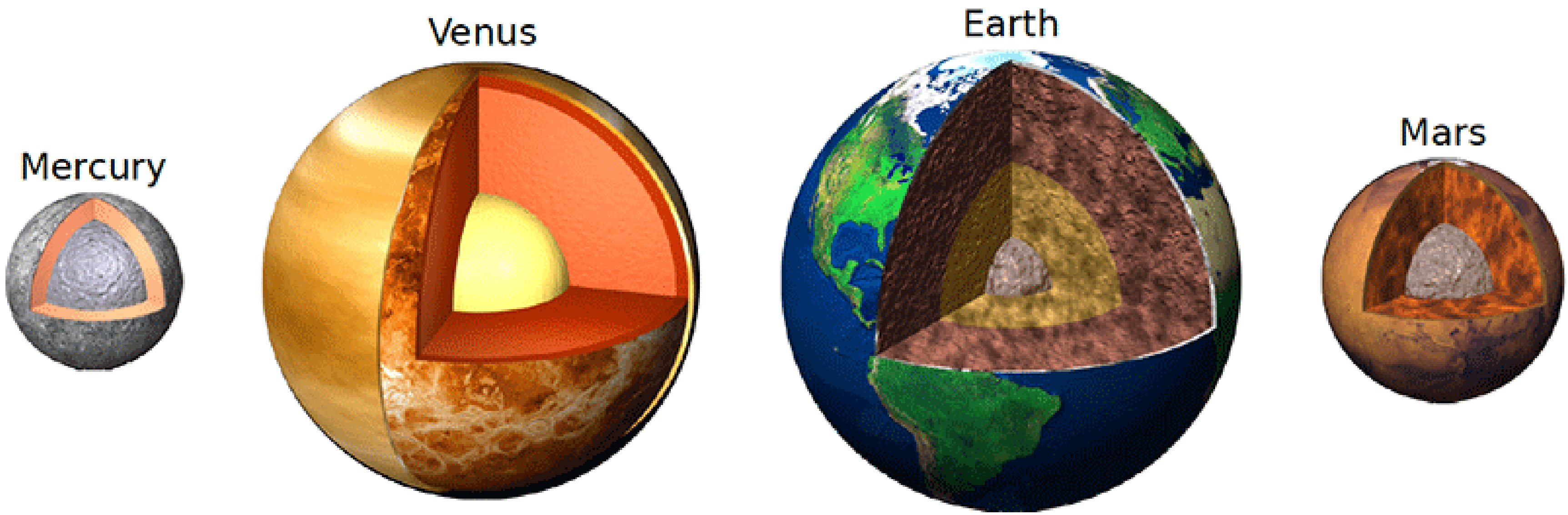
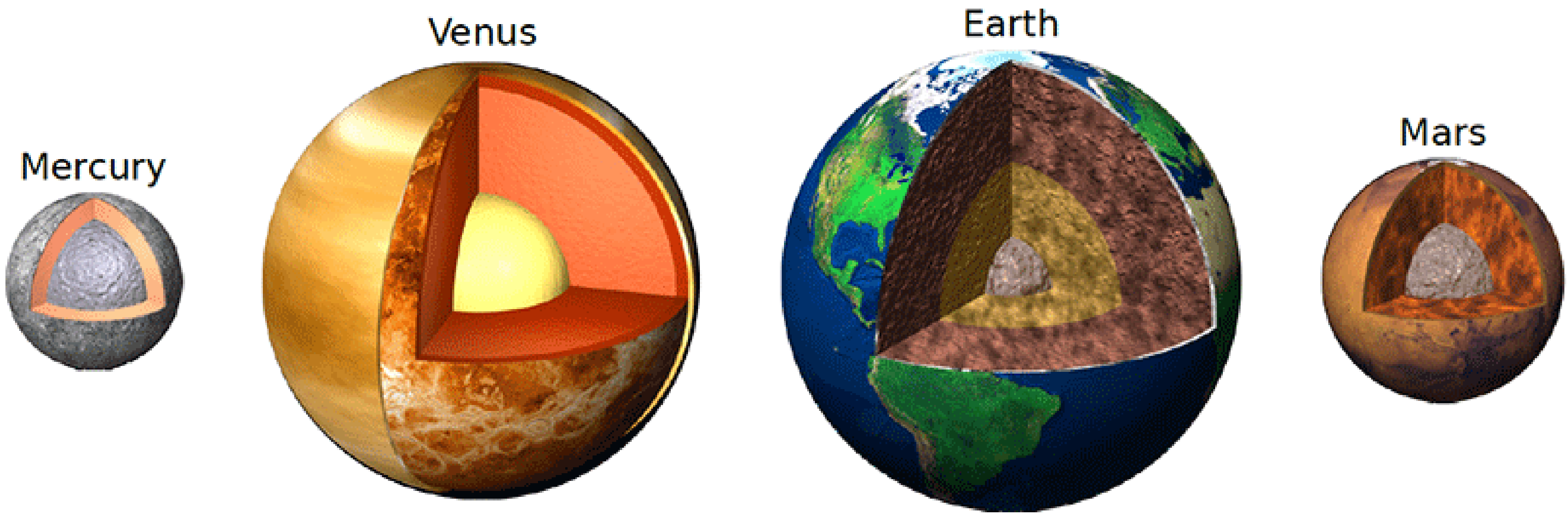


Property	Mercury[1]	Venus[2]	Earth[3]	Mars[4]
Density [kg m^{-3}]	3,500	4,000	4,000	3,500
Surface Temperature [K]	440	730	285	220
CMB Temperature [K]	3,000	3,500	3,500	3,000
Mantle Thickness [km]	400	2,900	2,900	2,000
Gravity [ms^{-2}]	3.7	10	10	3.5

Mulyukova and Bercovici, 2020

Convection on the other rocky terrestrial planets



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Mulyukova and Bercovici, 2020

$$Ra_{Earth} \sim 10^7$$

Assuming Earth material properties:

$$Ra_{Mercury} \sim 10^4$$

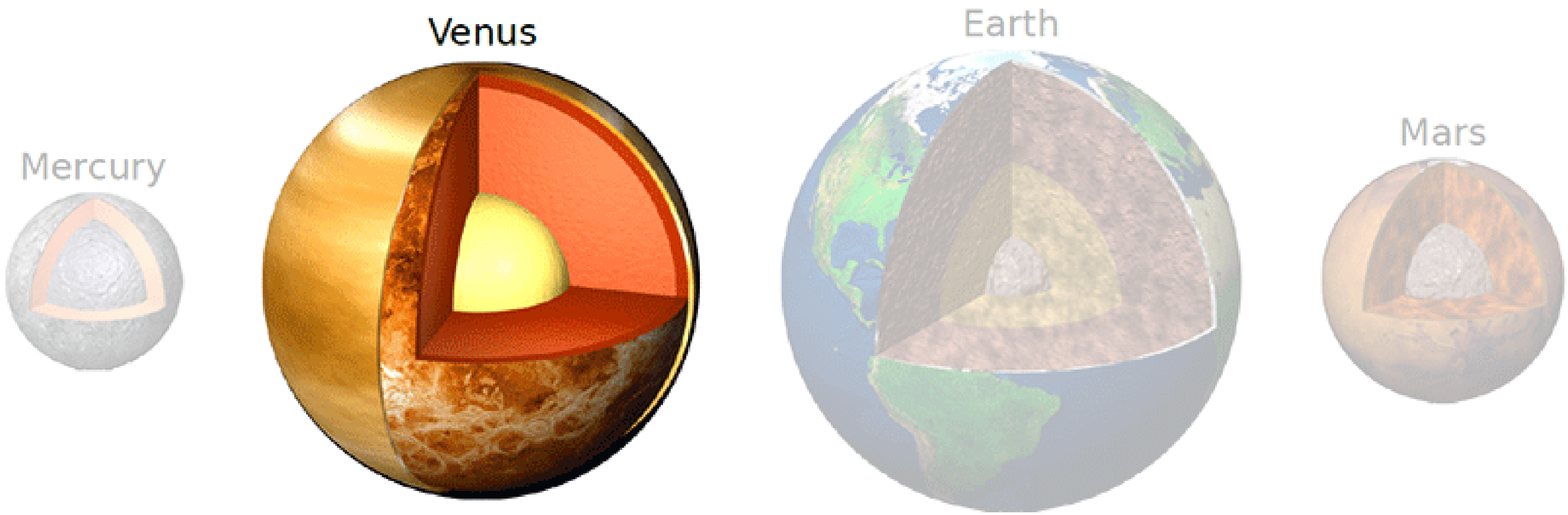
$$Ra_{Venus} \sim 10^7$$

$$Ra_{Mars} \sim 10^6$$

CONVECTION DOMINANT!

(Because $Ra_{critical} \sim 10^3$)

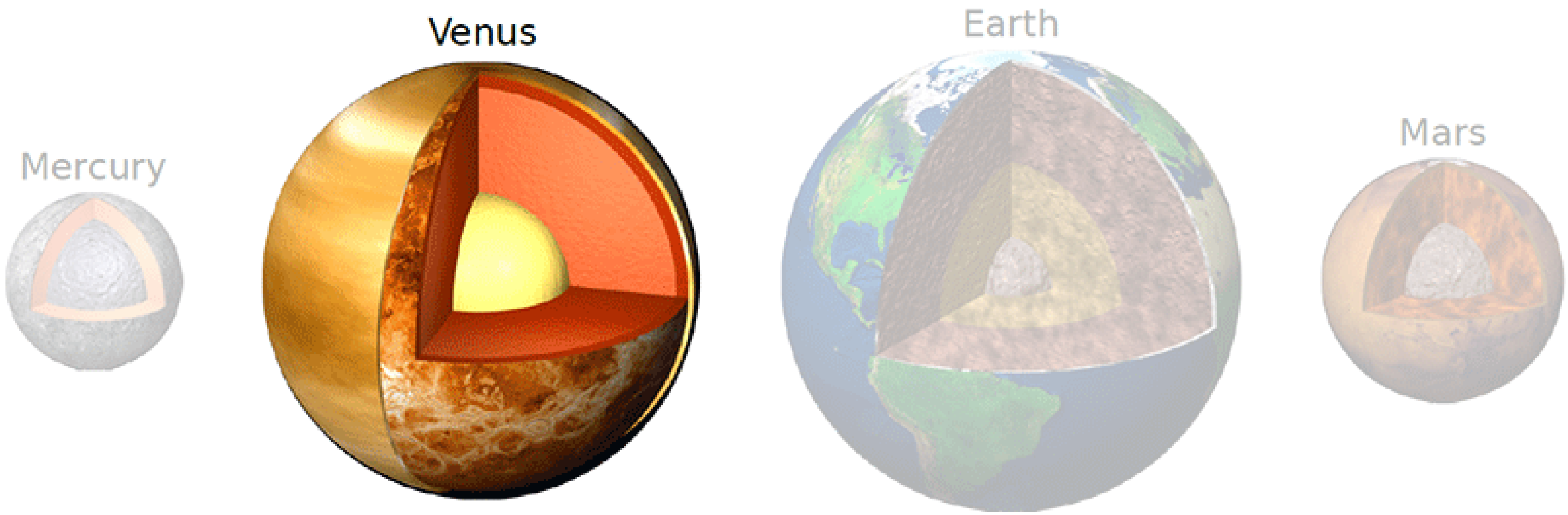
Convection on the other rocky terrestrial planets



Venus:

- Most like Earth in terms of size, density/internal structure, distance from Sun.
- 460 °C surface, mantle hotter than Earth (by ~200 °C). Analog for early Earth?
- No internally generated magnetic field (or "geodynamo").
- Crust is young (< 500 Ma). Global resurfacing event?

Convection on the other rocky terrestrial planets



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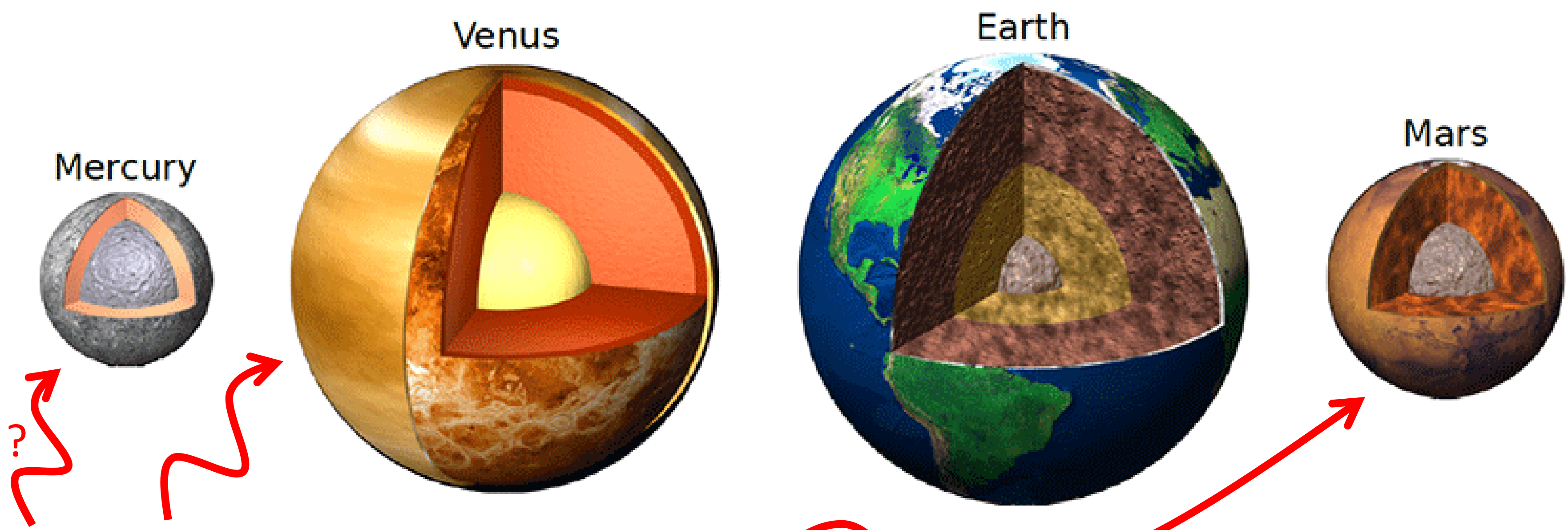
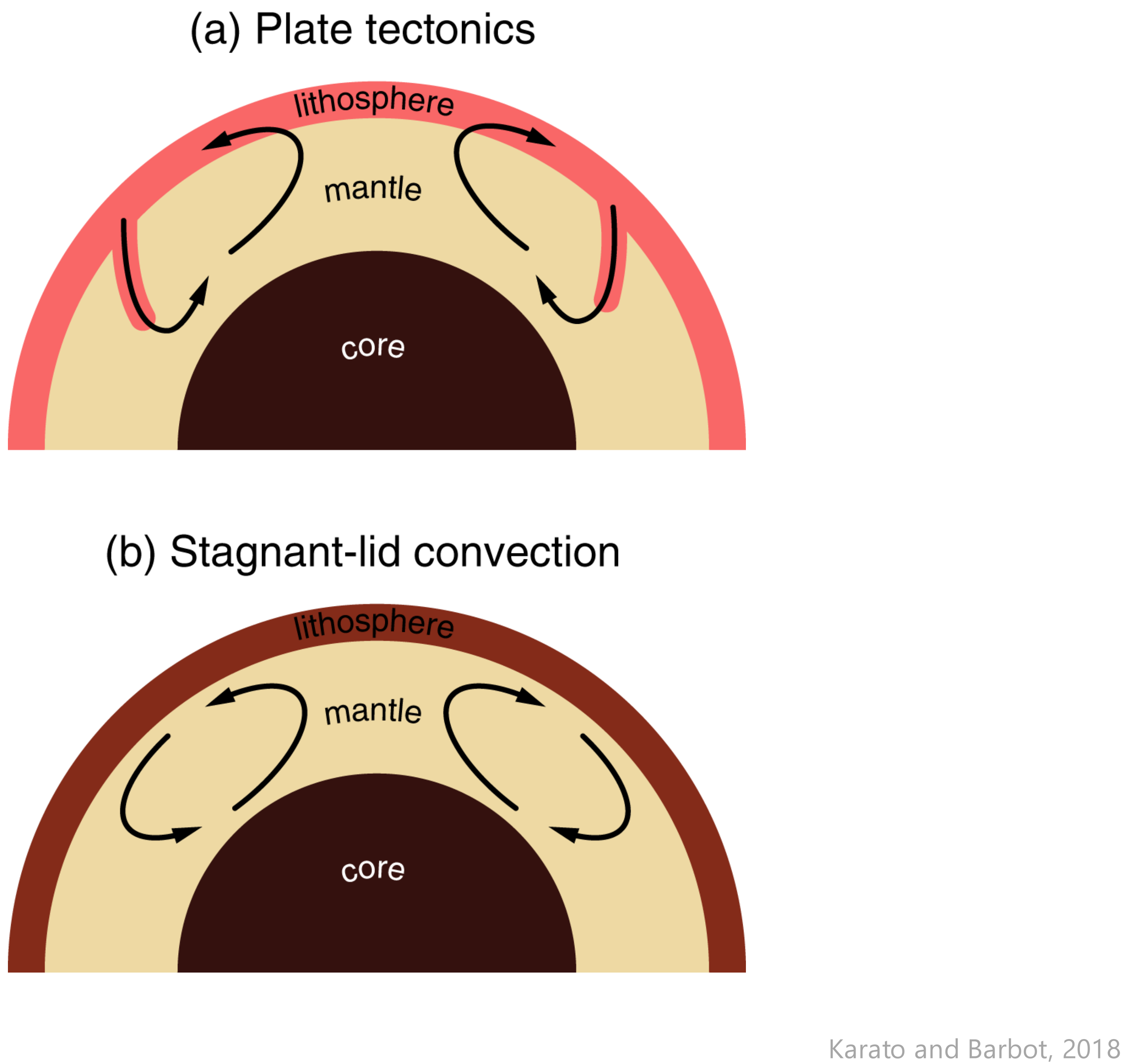
- No internally generated magnetic field (or "geodynamo").
- Crust is young (< 500 Ma). Global resurfacing event?
- Why no plate tectonics? (At least near-present day…)
  - *Hotter mantle so lower (relative) negative buoyancy of lithosphere?*
  - *Hotter surface limits the grain damage that can produce weak zones? Lack of water in mantle and lithosphere?*
  - *No weak asthenosphere: Produces lower convective stresses?*

Convection on the other rocky terrestrial planets



<u>Stagnant lid convection!</u>

On most terrestrial planets (except Earth), mantle convection occurs beneath the surface; while the surface may get deformed and have volcanic lavas emplaced on top of it, it remains in place for periods much longer than the characteristic timescale of mantle overturn. This mode of convection is "**<u>stagnant lid convection</u>**," with the lid being the portion of the thermal boundary layer that does not participate in convective flow.


(a) Plate tectonics
lithosphere
mantle
core
(b) Stagnant-lid convection
lithosphere
mantle
core
Karato and Barbot, 2018

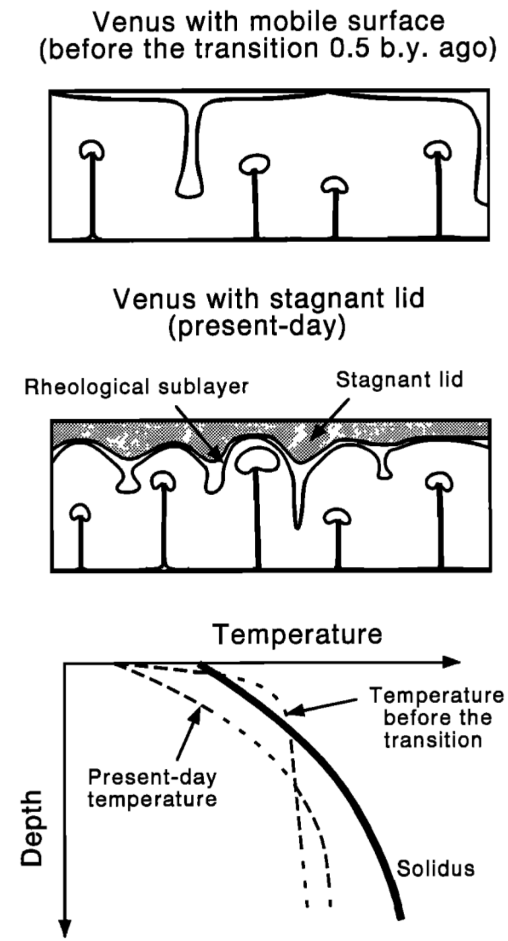
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 101, NO. E2, PAGES 4737–4753, FEBRUARY 25, 1996

Stagnant lid convection on Venus

V. S. Solomatov and L.-N. Moresi

Seismological Laboratory, California Institute of Technology, Pasadena

Abstract. The effect of strongly temperature-dependent viscosity on convection in the interior of Venus is studied systematically with the help of finite element numerical models. For viscosity contrasts satisfying experimental constraints on the rheology of rocks, Venus is likely to be in the regime of stagnant lid convection. This regime is characterized by the formation of a slowly creeping, very viscous lid on top of the mantle–Venusian lithosphere and is in agreement with the tectonic style observed on Venus. Stagnant lid convection explains large geoid to topography ratios on Venus by the thermal thinning of a thick lithosphere. The thickness of the lithosphere can be as large as 400–550 km for Beta Regio and 200–400 km on average. Geoid and topography data and experimental data on the rheology of rocks provide constraints on the viscosity of the mantle, 10^{20}–10^{21} Pa s; the convective stresses in the interior, 0.2–0.5 MPa; the stresses in the lid, 100–200 MPa; the velocity in the interior, 0.5–3 cm yr^{-1}; and the heat flux beneath the lithosphere, 8–16 mW m^{-2}. Parameterized convection calculations of thermal history of Venus are difficult to reconcile with a thick present-day lithosphere. However, a sufficiently thick lithosphere can be formed if a convective regime with mobile plates was replaced by stagnant lid convection around 0.5 b.y. ago. One of the possible explanations for the cessation of Venusian plate tectonics is that during the evolution of Venus, stresses in the lid dropped below the yield strength of the lithosphere. This model predicts a drastic drop in the heat flux, thickening of the lithosphere, and suppression of melting and is consistent with the hypothesis of cessation of resurfacing on Venus around 0.5 b.y. ago.



2-D finite element models confirm/predict that Venus is in the stagnant lid regime. Mantle viscosities explored (that satisfy geoid/topography). Reduction in lithosphere stress at ~500 Myr ago?

Geophys. J. Int. (1998) **133,** 669–682

Mantle convection with a brittle lithosphere: thoughts on the global tectonic styles of the Earth and Venus

Louis Moresi[1,2] and Viatcheslav Solomatov[3]

[1] *Research School of Earth Sciences, Australian National University, Canberra* ACT 0200, *Australia*
[2] *Australian Geodynamics Cooperative Research Centre, CSIRO Exploration & Mining,* PO Box 437, *Nedlands,* 6009 *Western Australia.*
E-mail: louis@ned.dem.csiro.au
[3] *Department of Physics, New Mexico State University, Las Cruces* NM 88003-8001, *USA. E-mail: slava@nmsu.edu*

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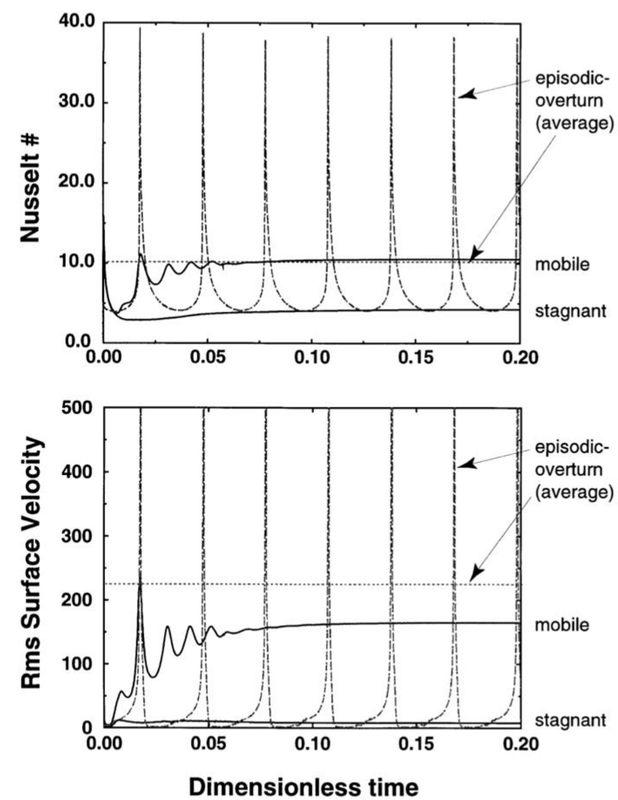
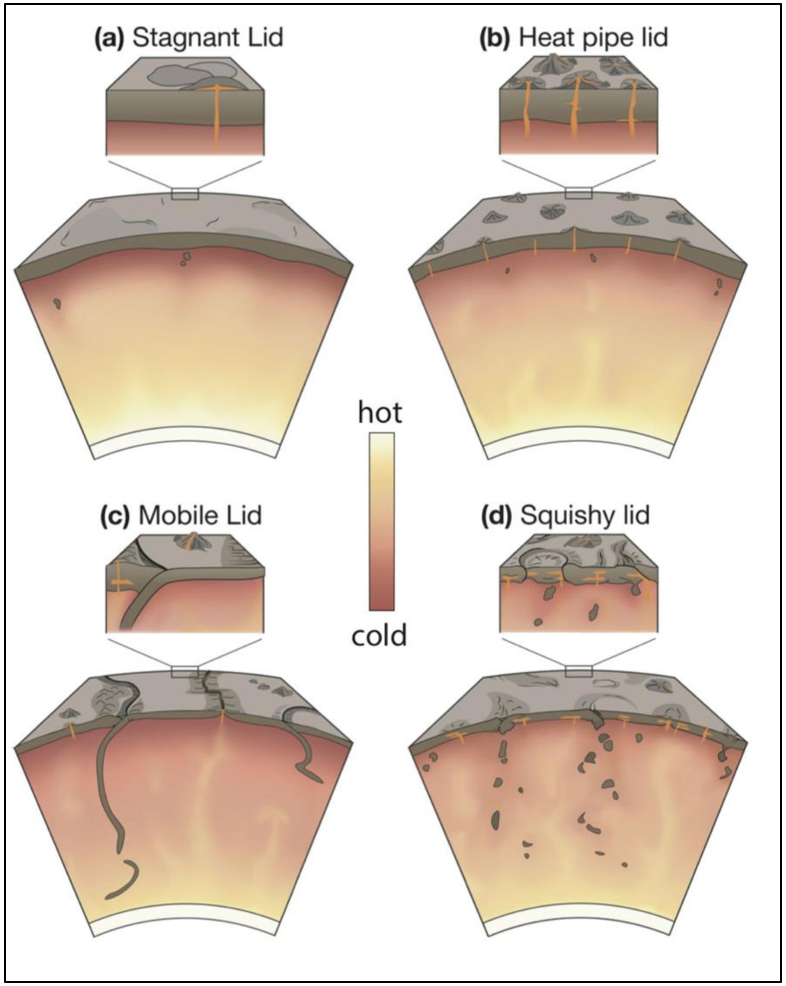
E-mail: louis@ned.dem.csiro.au
[3] *Department of Physics, New Mexico State University, Las Cruces* NM 88003-8001, *USA. E-mail: slava@nmsu.edu*

- Implemented (Byerlee) yield stresses.
- Showed that you can get stagnant, mobile lid, and overturning (Venus resurfacing analog?) for variable yield stresses.
- Suggested that Venus' friction coefficient may be high due to the dry conditions in the lithosphere (hence only stagnant lid and episodic overturn possible).



Lots of more recent work on Venus' convective regime!

E.g., see review of Rolf et al., 2022



Potentially relevant geodynamic regimes (note heat pipe: heat loss primarily through magmatic ascent).

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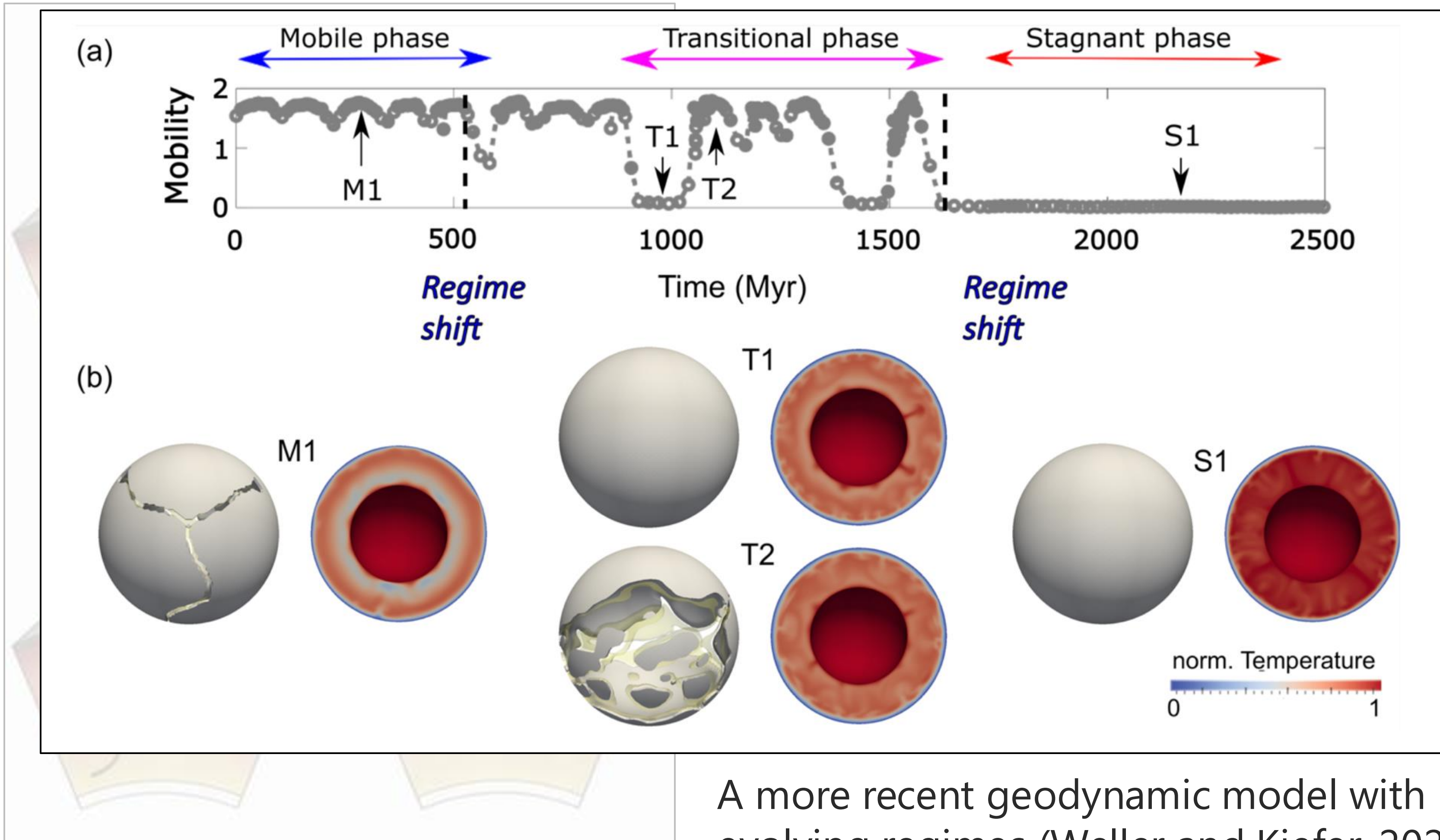
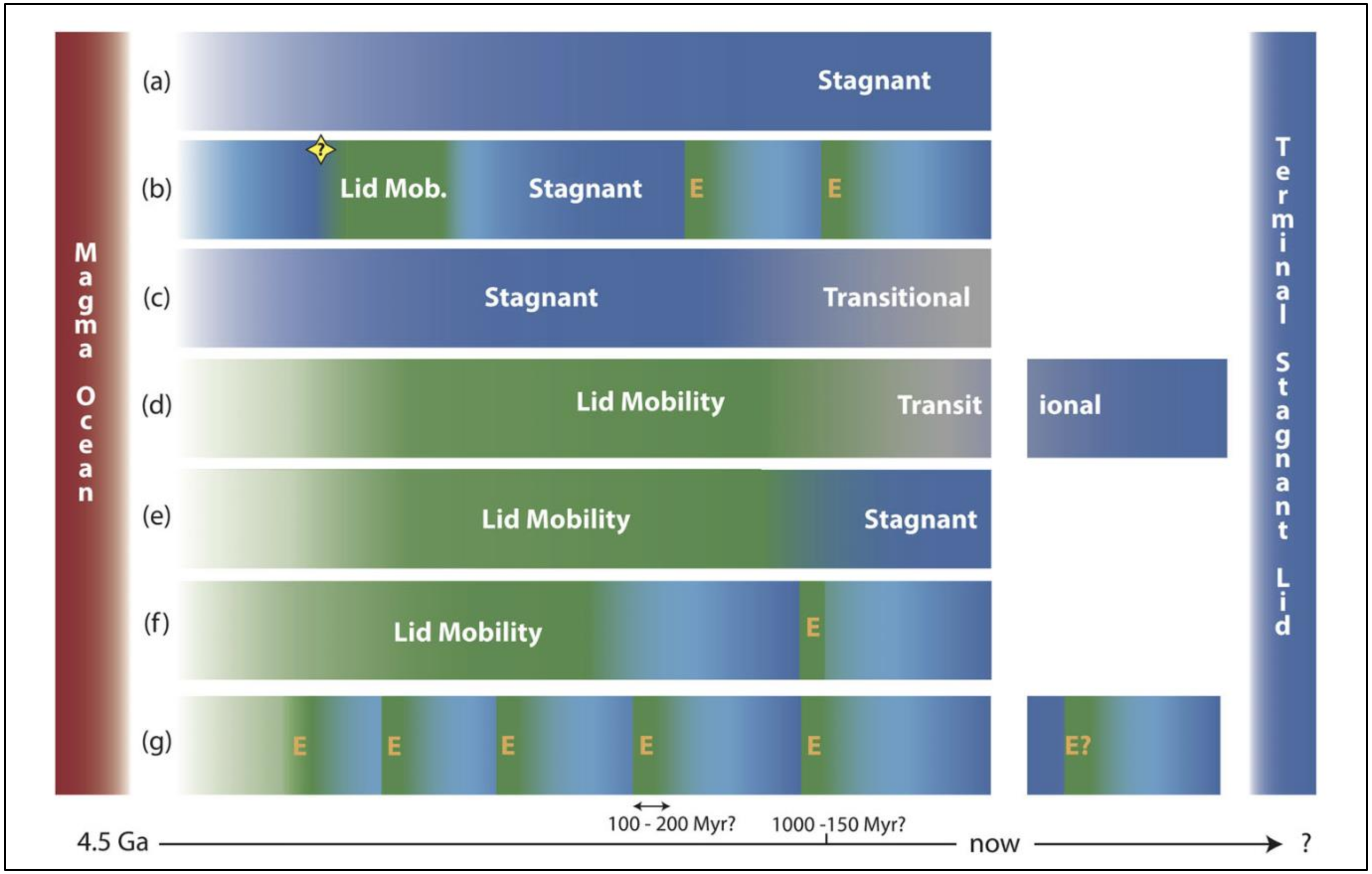


Potentially relevant geodynamic regimes (note heat pipe: heat loss primarily through magmatic ascent).

A more recent geodynamic model with evolving regimes (Weller and Kiefer, 2020), with imposed increasing yield strength. Recent authors also note a path-dependence of the regime (i.e., a hysteresis)

Lots of more recent work on Venus' convective regime!

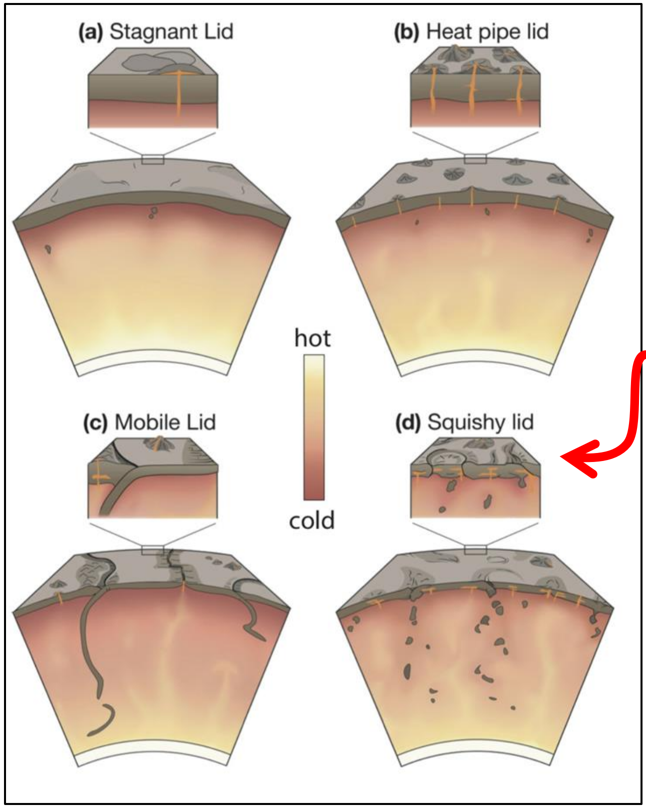


Lots of uncertainty about the mantle evolution

(Compilation from Rolf et al's review)

Existing studies propose a wide range of possibilities of Venus' present and past interior dynamics. These options are only converging in the sense that Venus' lithosphere does not feature large-scale coherent horizontal motion in contrast to Earth. Some works suggest that Venus is in the stagnant lid regime, but upon closer inspection this regime is likely different from that of the classical stagnant-lid bodies, such as the Moon or Mercury. The current tectonic state may be transient, with Venus in transition between a past mobile state and a future stagnant state

Lots of more recent work on Venus' convective regime!



Something like subduction?

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It has long been speculated based on surface features

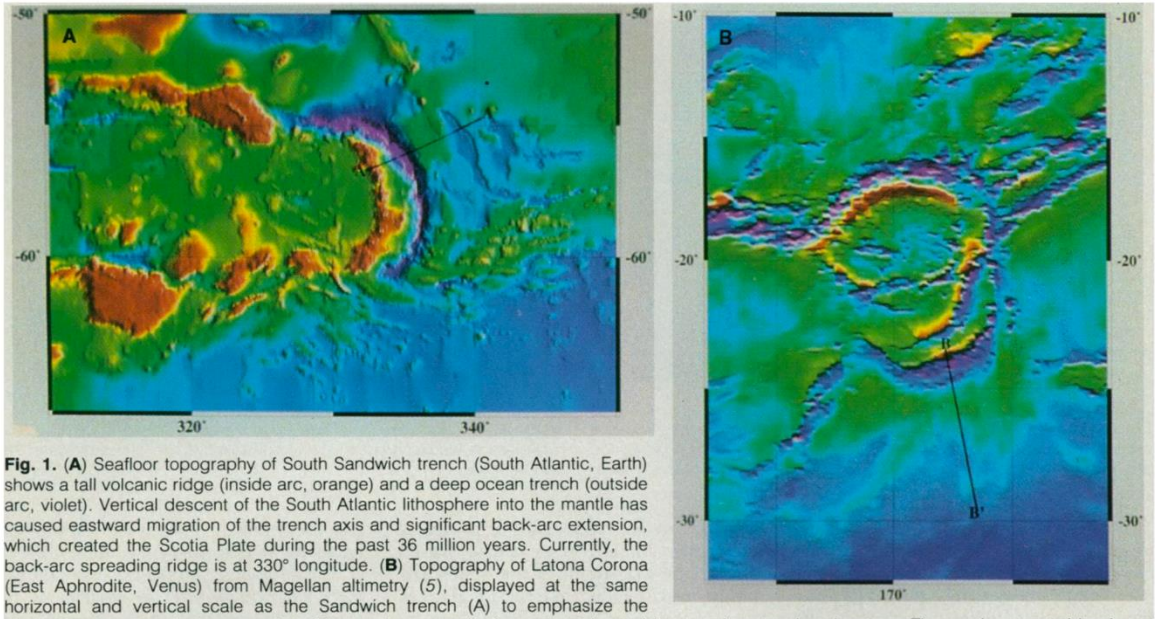

Fig. 1. (**A**) Seafloor topography of South Sandwich trench (South Atlantic, Earth) shows a tall volcanic ridge (inside arc, orange) and a deep ocean trench (outside arc, violet). Vertical descent of the South Atlantic lithosphere into the mantle has caused eastward migration of the trench axis and significant back-arc extension, which created the Scotia Plate during the past 36 million years. Currently, the back-arc spreading ridge is at 330° longitude. (**B**) Topography of Latona Corona (East Aphrodite, Venus) from Magellan altimetry (*5*), displayed at the same horizontal and vertical scale as the Sandwich trench (A) to emphasize the similarities between the two trenches. The southern arc displays a prominent ridge-trench–outer rise signature. The southernmost ridge is not massive enough to maintain the bending moment of the trench–outer rise flexure. Additional bending moment can be supplied by a subducted slab or by the second interior ridge.

Sandwell & Schubert, 1992, *Science*

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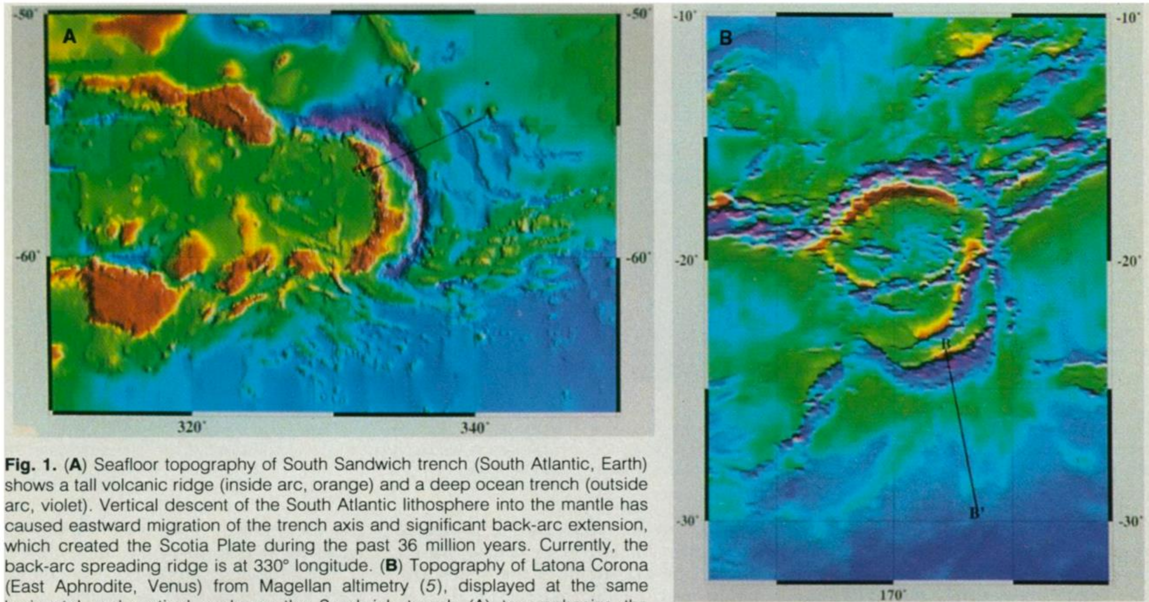

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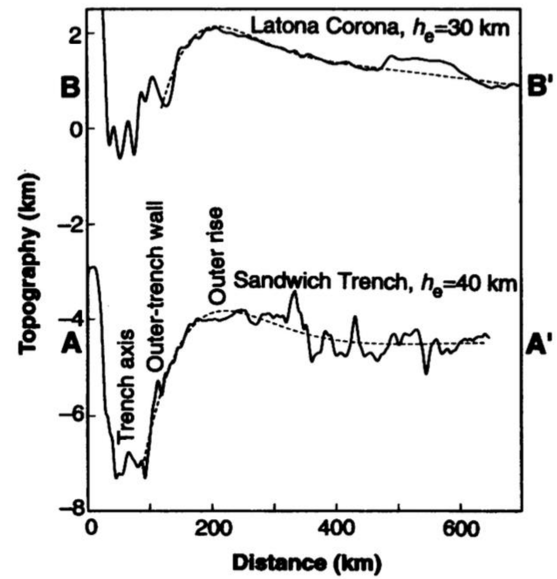
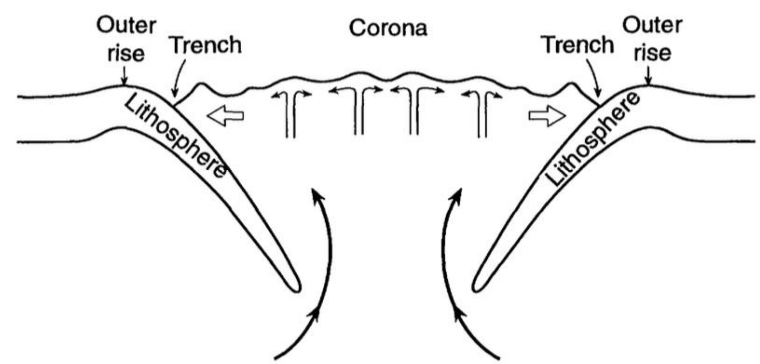


- As on Earth, trench and outer rise-like features are modeled as the flexural response of a thin elastic lithosphere to the bending moment of the subducted slab.
- Proposes retrograde lithospheric subduction is occurring on the margins of the large Venus coronae with compensating back-arc extension is in the expanding coronae interiors.



Also see Schubert & Sandwell (1995) for their more extensive follow-up

It has long been speculated based on surface features

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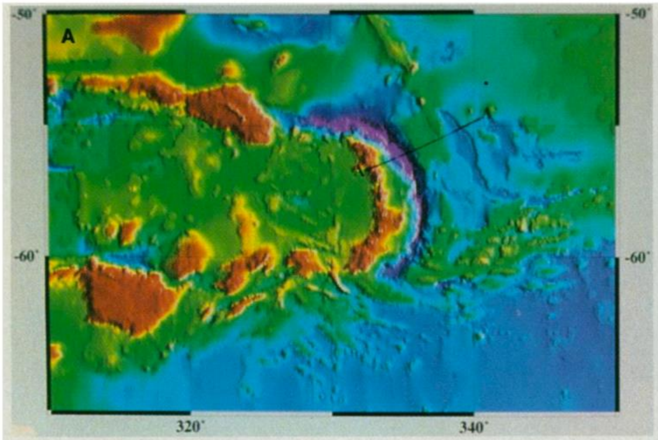

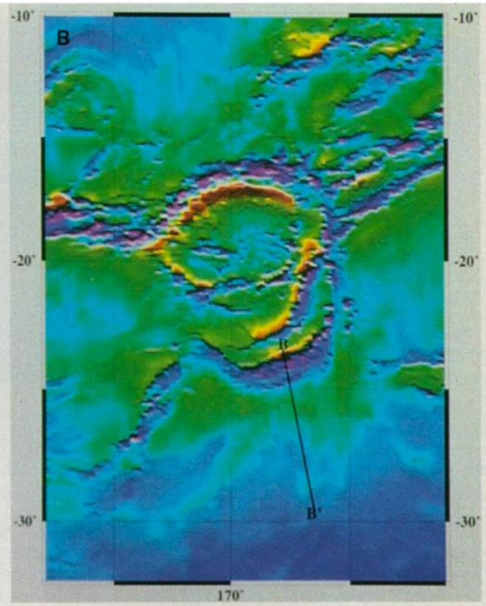

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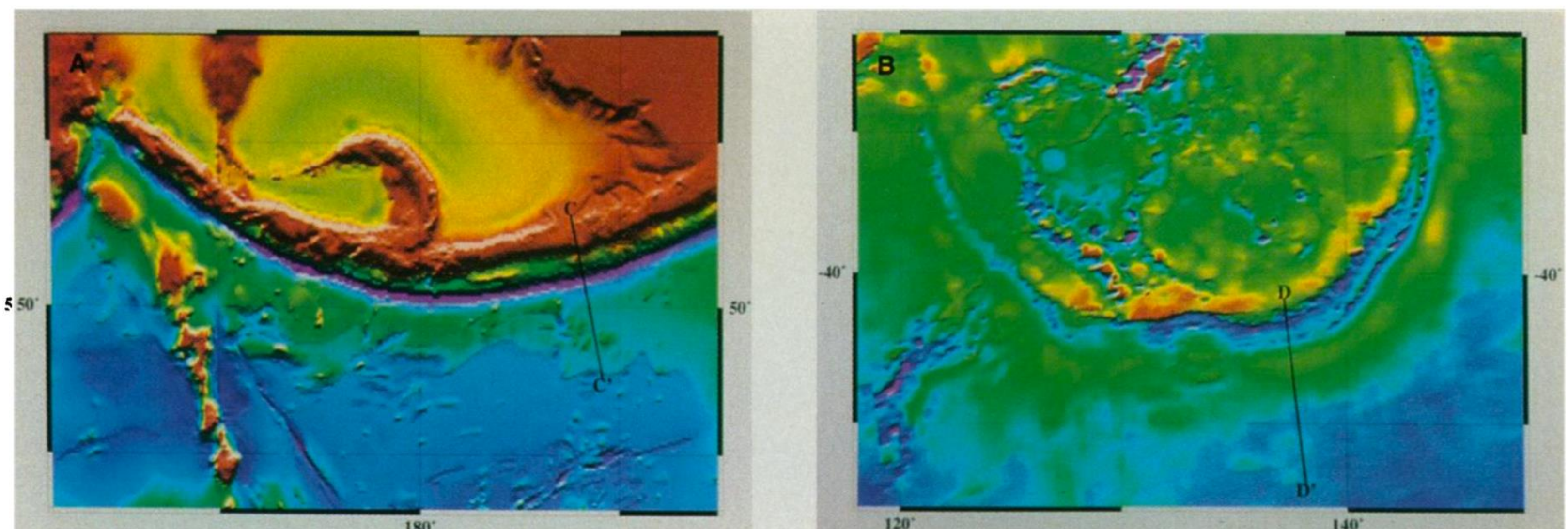
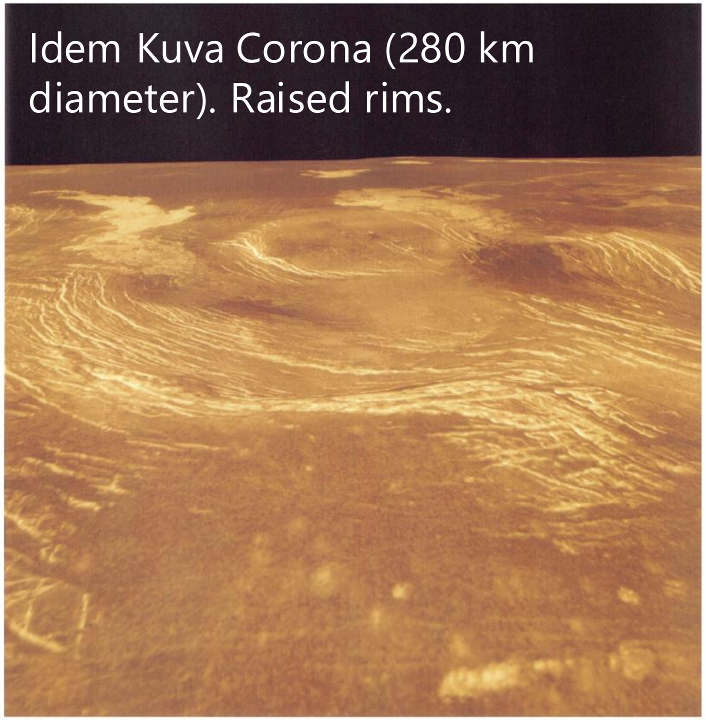
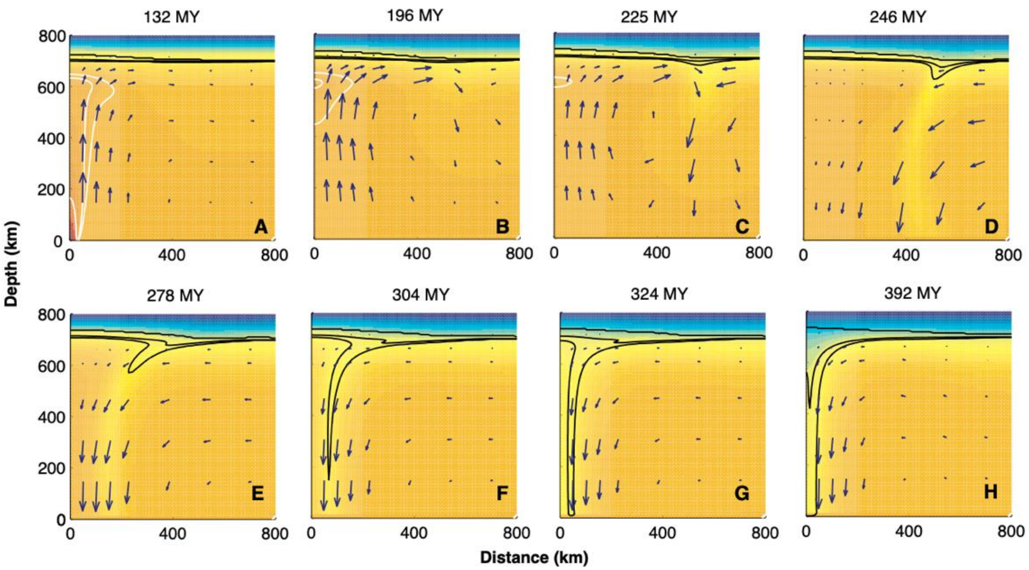
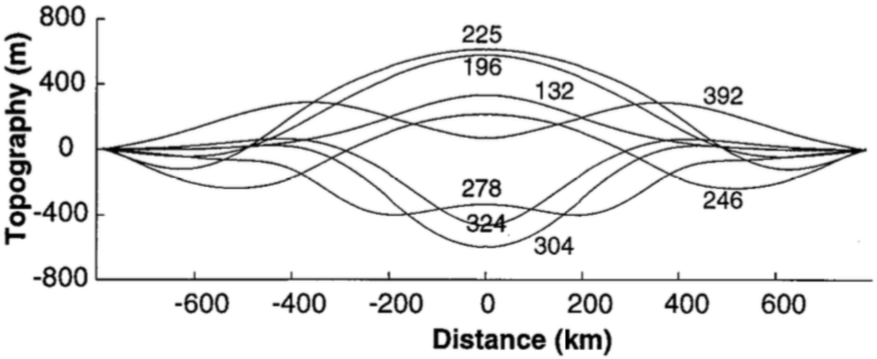
Artemis Corona – the largest one (2600 km diam), with a central rift



Coronae formation





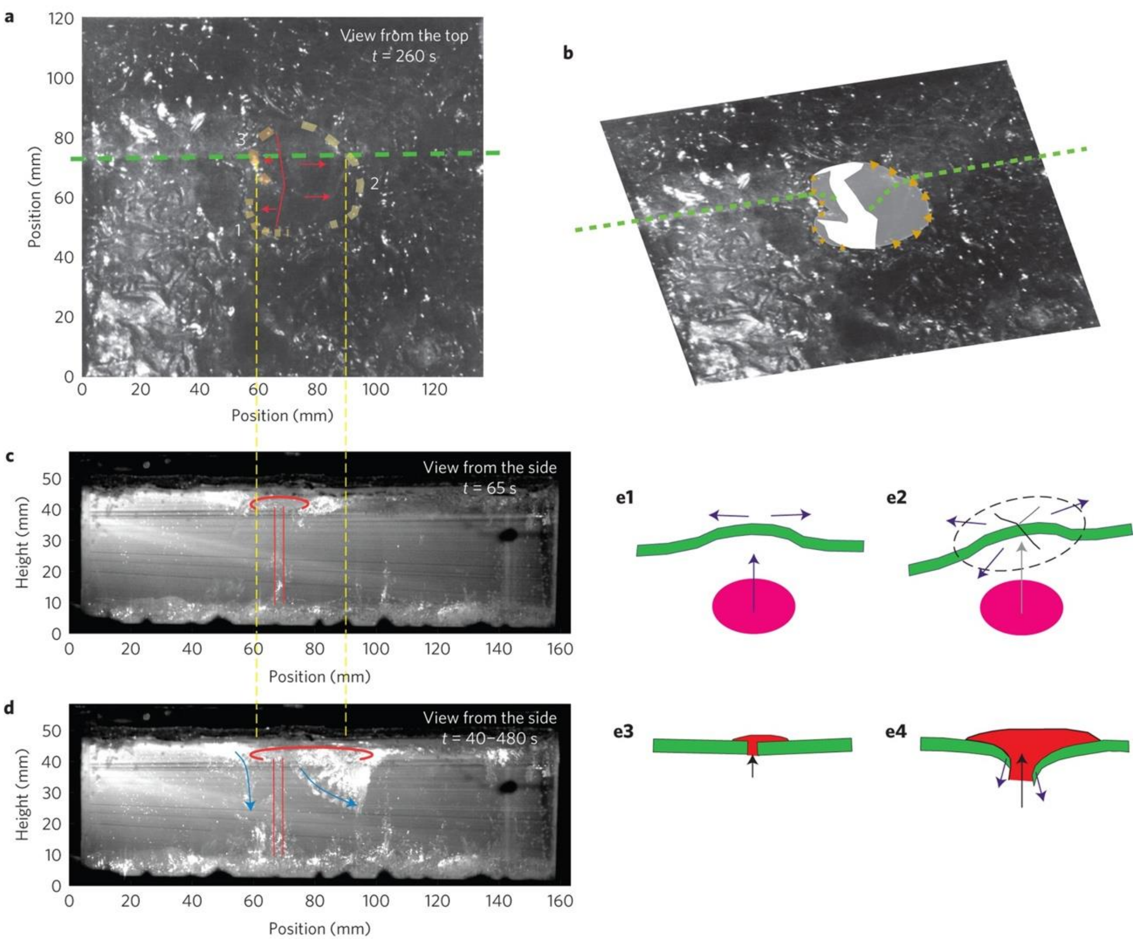


Smrekar & Stofan (1997) suggest that upwelling in the center and relatively minor delamination at the edge produces the full range of corona topographies.

Circular planform shape indeed suggests some kind of plume-like activity.

Plume-induced subduction?

Davaille et al. (2017) experiments using colloidal aqueous dispersions of silica nanoparticles (simulate visco-elasto-plastic deformation):



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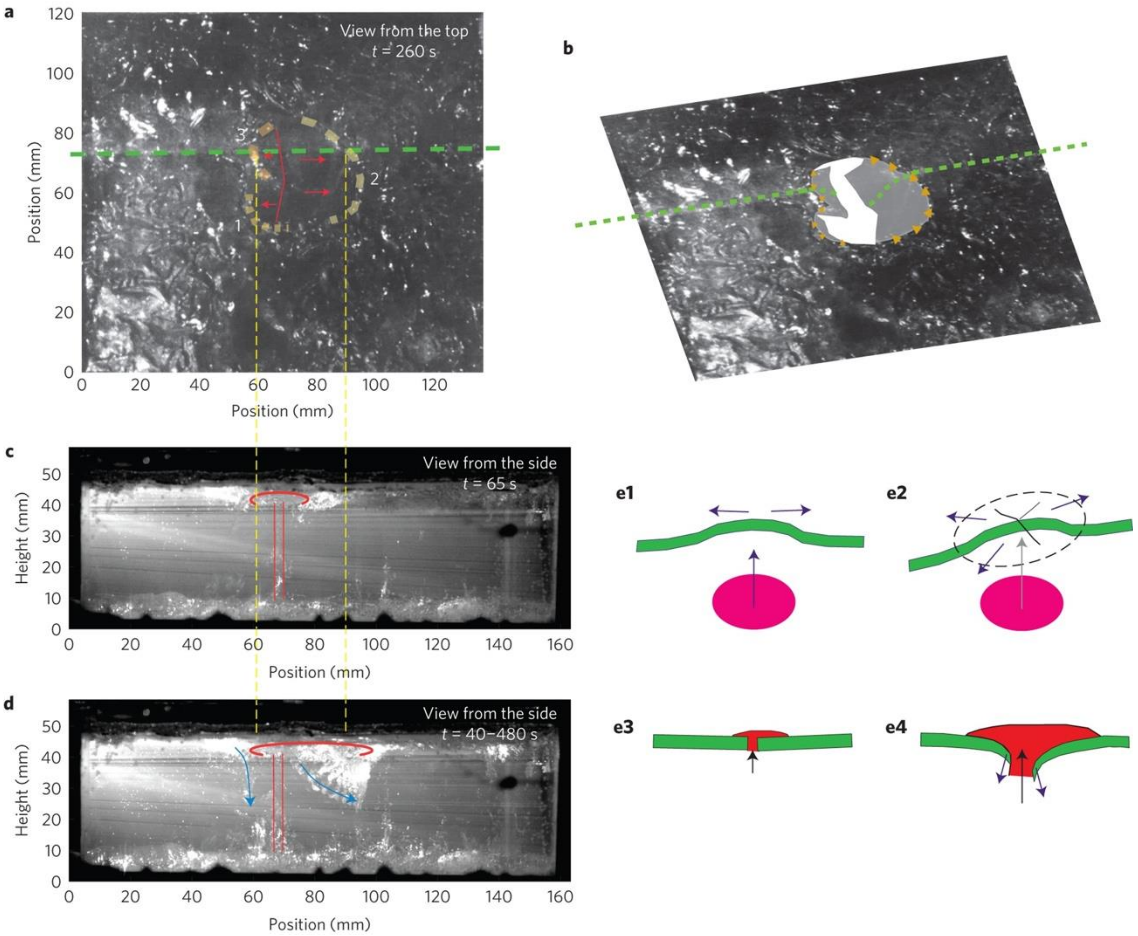
- Skin (lithosphere) flexes above rising plume.
- Skin breaks in radial fractures and rifts.
- Plume material percolates through the fracture, creating new lithosphere and loading the system.
- Non-continuous slab segments (weighed down by the surface plume) produced along sections of the circular rim.



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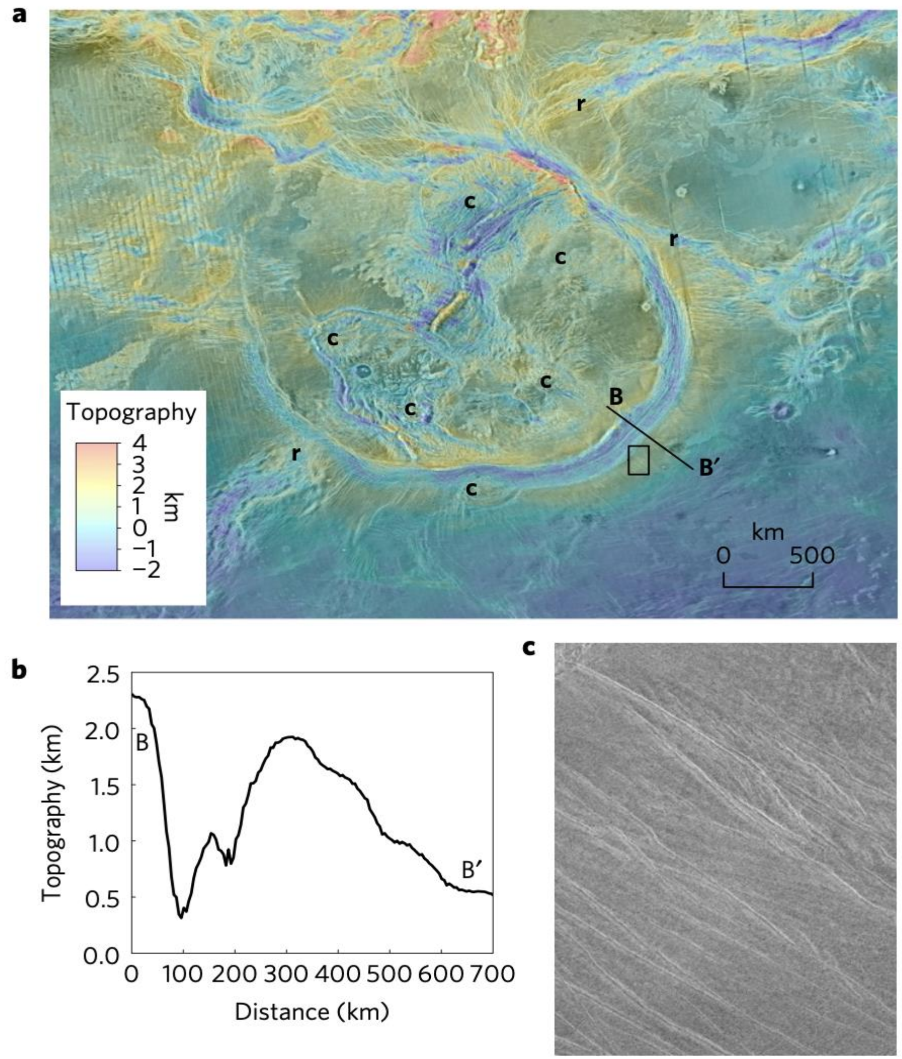
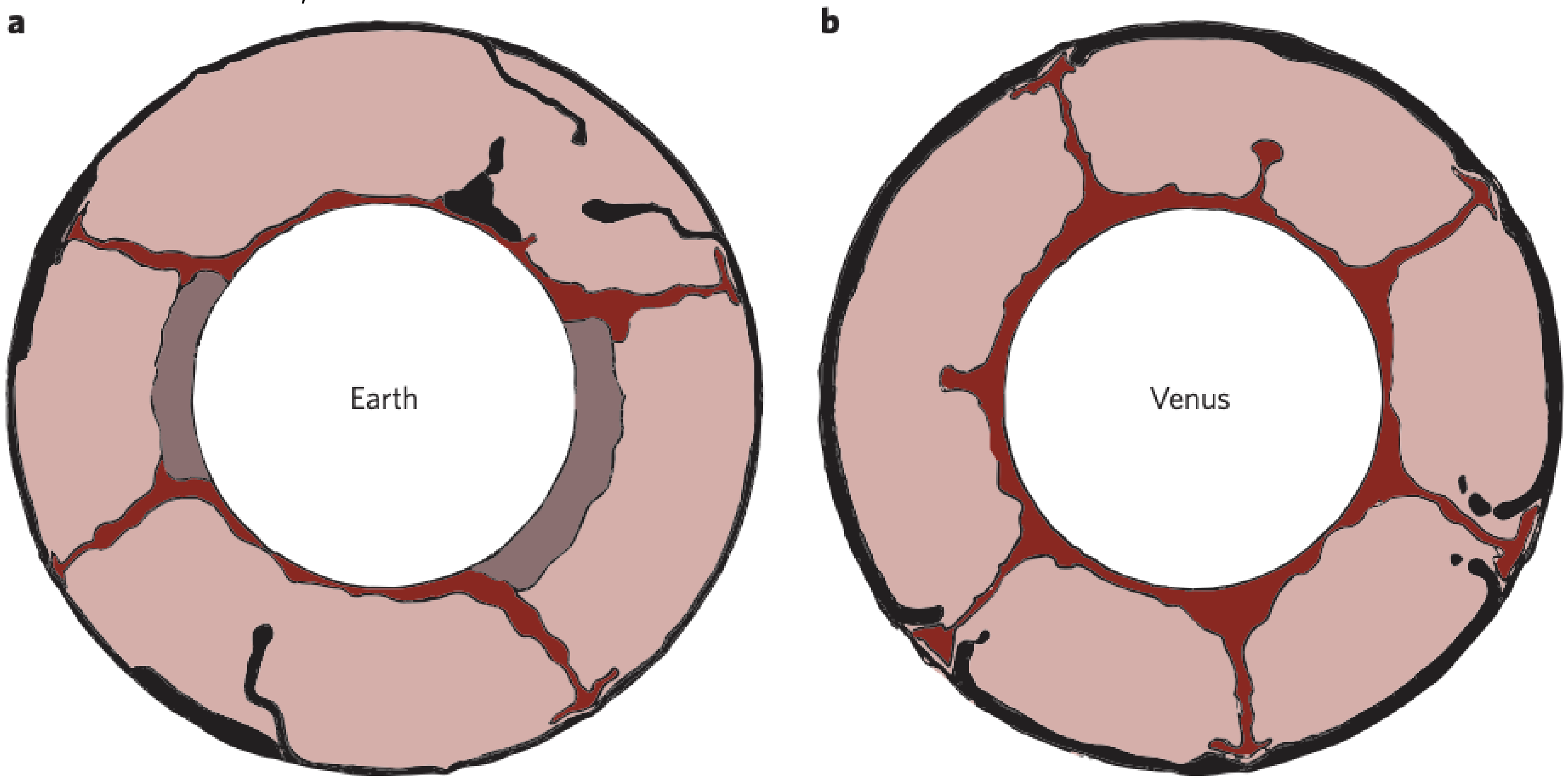


Appears compatible with the observed topography, gravity, and volcanism at, e.g., the **Artemis** and Quetzalpetlatl coronae.

Plume-induced subduction?

Crameri, News and Views



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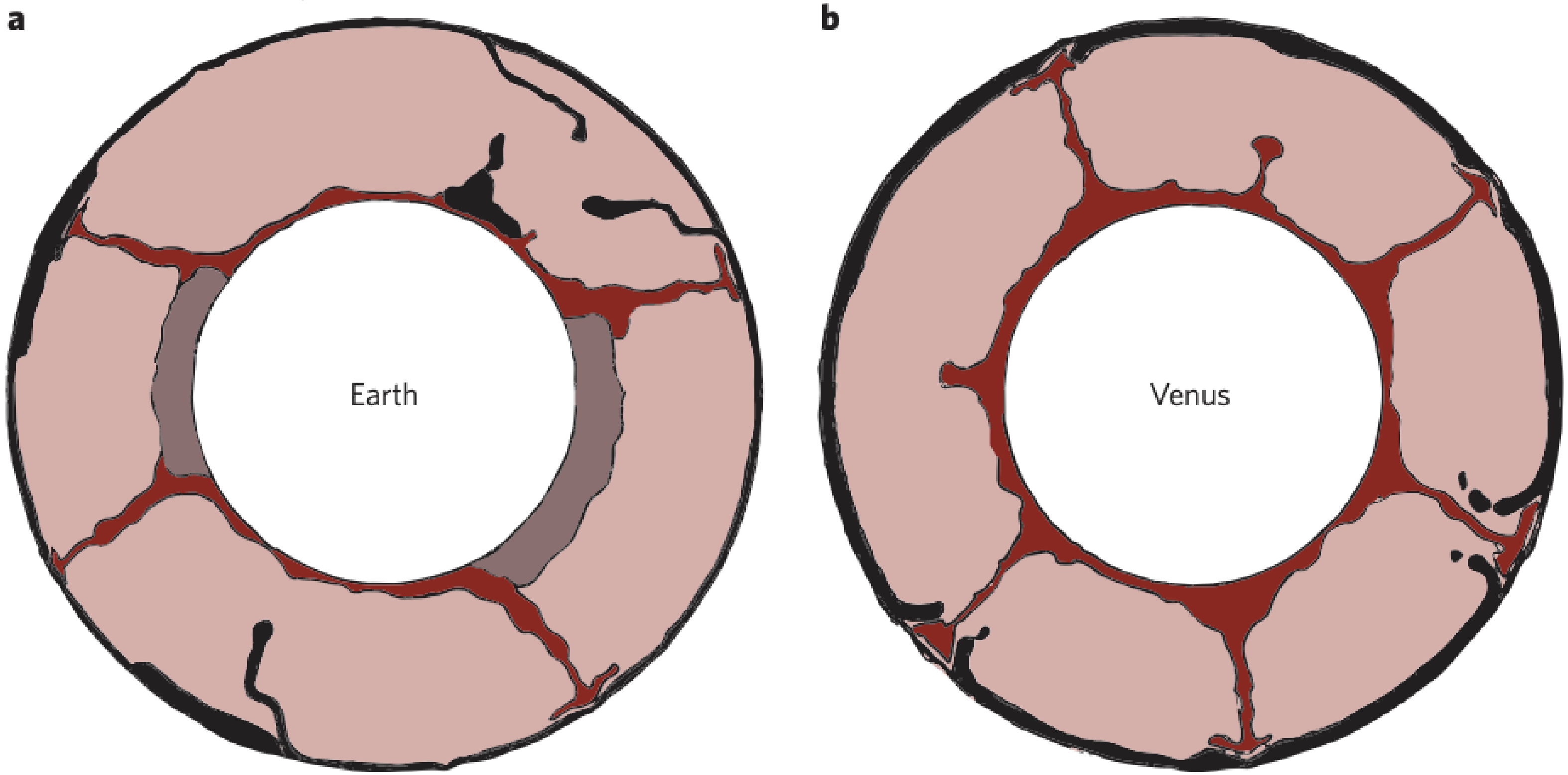
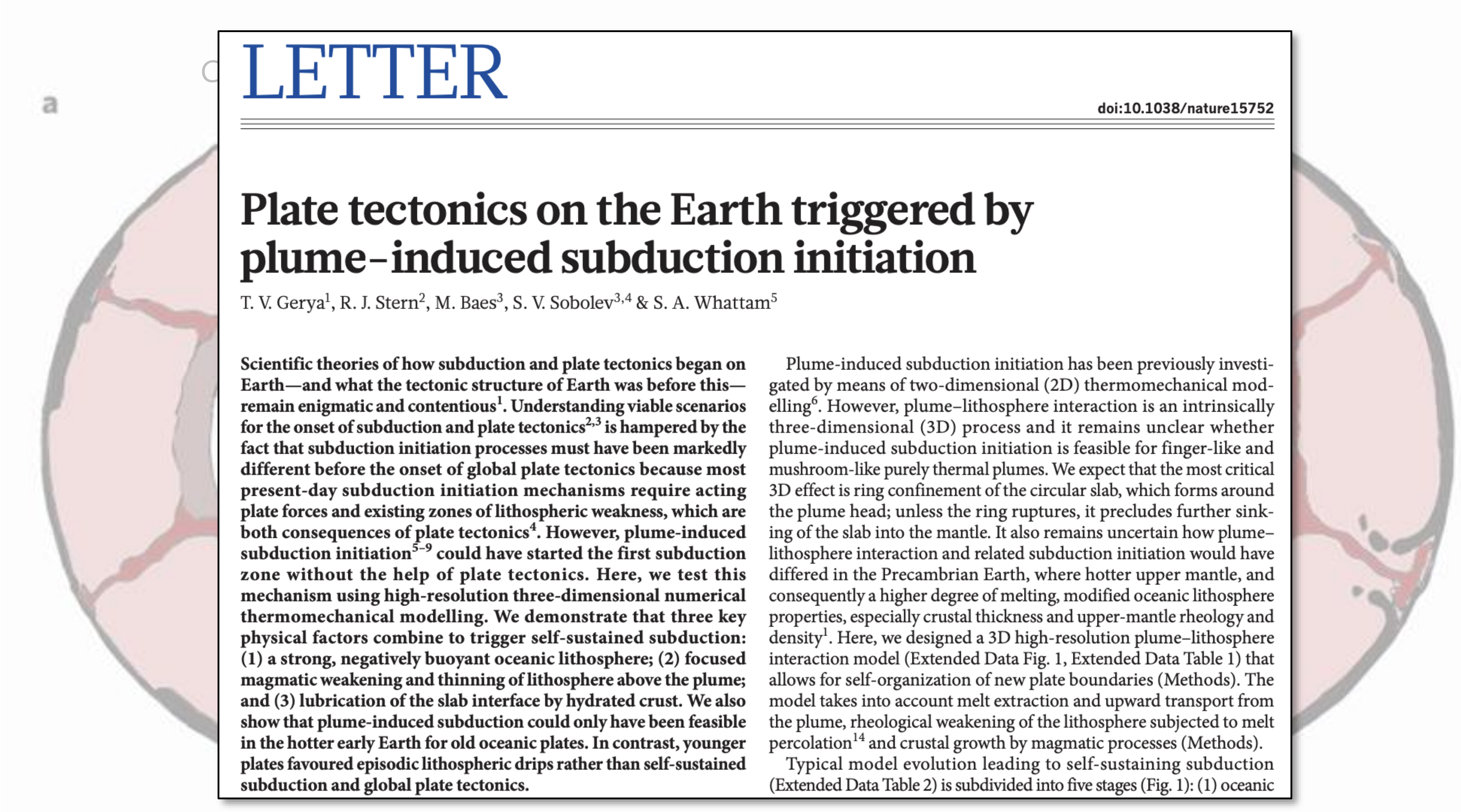


- Why limited plume-induced subduction on Earth?
  - Lithosphere too strong/thick. Early Earth analog?
- Why no globally-spanning subduction zones on Venus?
  - Slabs not negatively buoyant enough?

Plume-induced subduction?



LETTER

doi:10.1038/nature15752

Plate tectonics on the Earth triggered by plume-induced subduction initiation

T. V. Gerya[1], R. J. Stern[2], M. Baes[3], S. V. Sobolev[3,4] & S. A. Whattam[5]

Scientific theories of how subduction and plate tectonics began on Earth—and what the tectonic structure of Earth was before this—remain enigmatic and contentious[1]. Understanding viable scenarios for the onset of subduction and plate tectonics[2,3] is hampered by the fact that subduction initiation processes must have been markedly different before the onset of global plate tectonics because most present-day subduction initiation mechanisms require acting plate forces and existing zones of lithospheric weakness, which are both consequences of plate tectonics[4]. However, plume-induced subduction initiation[5–9] could have started the first subduction zone without the help of plate tectonics. Here, we test this mechanism using high-resolution three-dimensional numerical thermomechanical modelling. We demonstrate that three key physical factors combine to trigger self-sustained subduction: (1) a strong, negatively buoyant oceanic lithosphere; (2) focused magmatic weakening and thinning of lithosphere above the plume; and (3) lubrication of the slab interface by hydrated crust. We also show that plume-induced subduction could only have been feasible in the hotter early Earth for old oceanic plates. In contrast, younger plates favoured episodic lithospheric drips rather than self-sustained subduction and global plate tectonics.

Plume-induced subduction initiation has been previously investigated by means of two-dimensional (2D) thermomechanical modelling[6]. However, plume–lithosphere interaction is an intrinsically three-dimensional (3D) process and it remains unclear whether plume-induced subduction initiation is feasible for finger-like and mushroom-like purely thermal plumes. We expect that the most critical 3D effect is ring confinement of the circular slab, which forms around the plume head; unless the ring ruptures, it precludes further sinking of the slab into the mantle. It also remains uncertain how plume–lithosphere interaction and related subduction initiation would have differed in the Precambrian Earth, where hotter upper mantle, and consequently a higher degree of melting, modified oceanic lithosphere properties, especially crustal thickness and upper-mantle rheology and density[1]. Here, we designed a 3D high-resolution plume–lithosphere interaction model (Extended Data Fig. 1, Extended Data Table 1) that allows for self-organization of new plate boundaries (Methods). The model takes into account melt extraction and upward transport from the plume, rheological weakening of the lithosphere subjected to melt percolation[14] and crustal growth by magmatic processes (Methods).

Typical model evolution leading to self-sustaining subduction (Extended Data Table 2) is subdivided into five stages (Fig. 1): (1) oceanic

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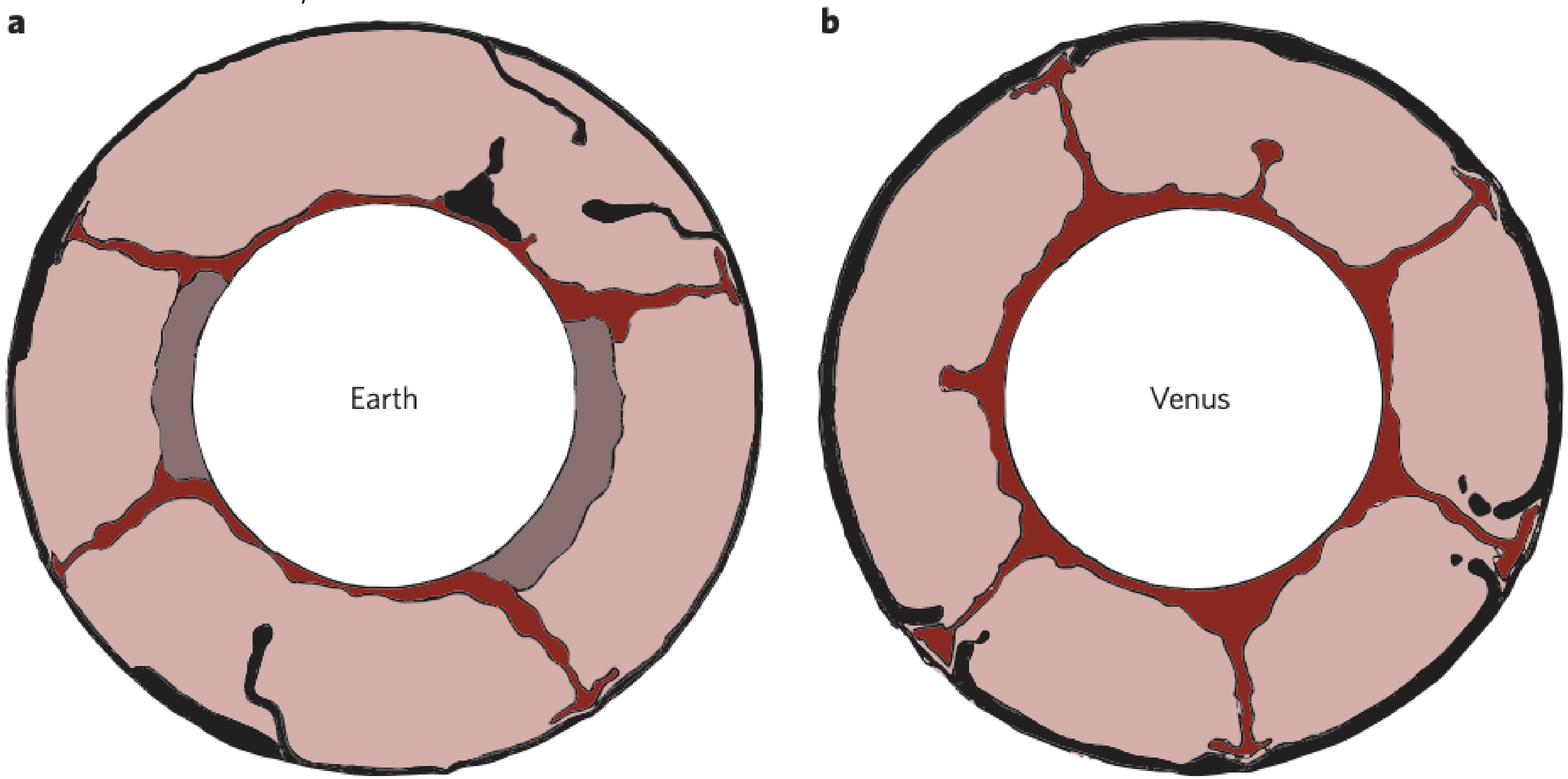
Plume-induced subduction?

Crameri, News and Views



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nature communications

Article

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Venus' light slab hinders its development of planetary-scale subduction

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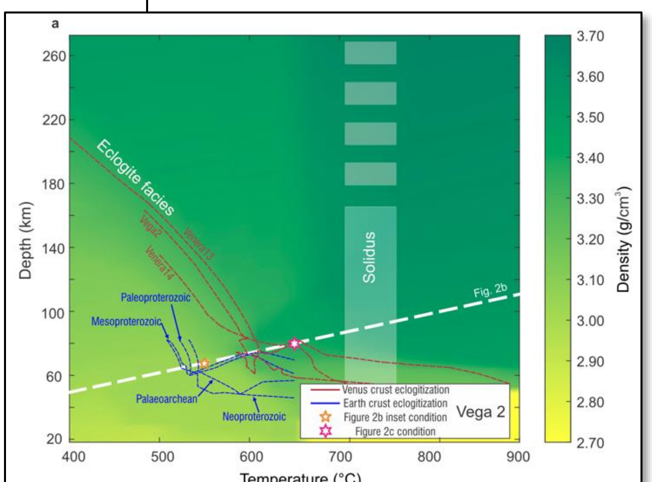
Published online: 10 December 2022

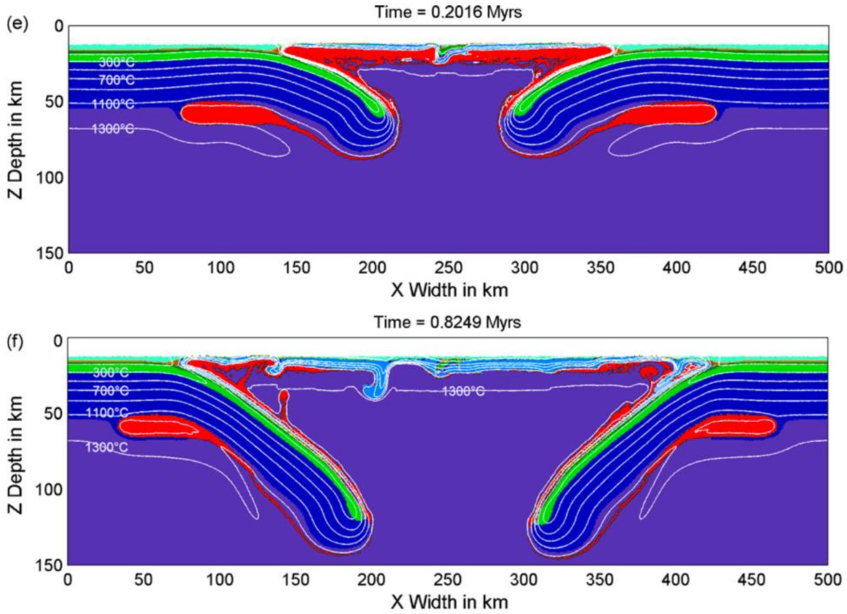
Check for updates

Junxing Chen [1], Hehe Jiang [1,2], Ming Tang [3], Jihua Hao [4], Meng Tian [5] & Xu Chu [1]

Terrestrial planet Venus has a similar size, mass, and bulk composition to Earth. Previous studies proposed that local plume-induced subduction existed on both early Earth and Venus, and this prototype subduction might initiate plate tectonics on Earth but not on Venus. In this study, we simulate the buoyancy of submerged slabs in a hypothesized 2-D thermo-metamorphic model. We analyze the thermal state of the slab, which is then used for calculating density in response to thermal and phase changes. The buoyancy of slab mantle lithosphere is primarily controlled by the temperatures and the buoyancy of slab crust is dominated by metamorphic phase changes. Difference in the eclogitization process contributes most to the slab buoyancy difference between Earth and Venus, which makes the subducted Venus' slab consistently less dense than Earth's. The greater chemical buoyancy on Venus, acting as a resistance to subduction, may have impeded the transition into self-sustained subduction and led to a different tectonic regime on Venus. This hypothesis may be further tested as more petrological data of Venus become available, which will further help to assess the impact of petro-tectonics on the planet's habitability.

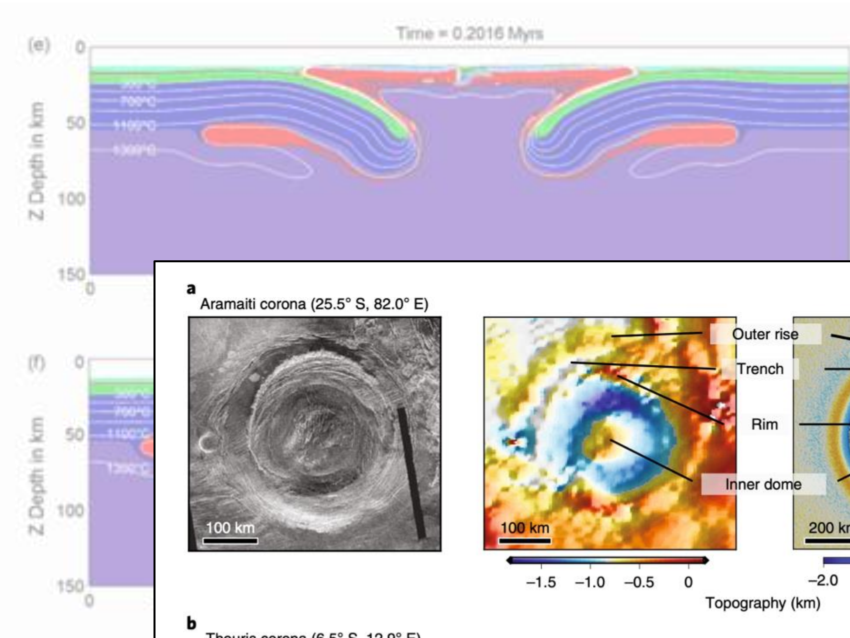


Plume-induced subduction: Numerical modeling



Ueda et al. (2008): Feasible providing the overriding lithosphere can weaken significantly (e.g., contains lots of fluids).

Plume-induced subduction: Numerical modeling



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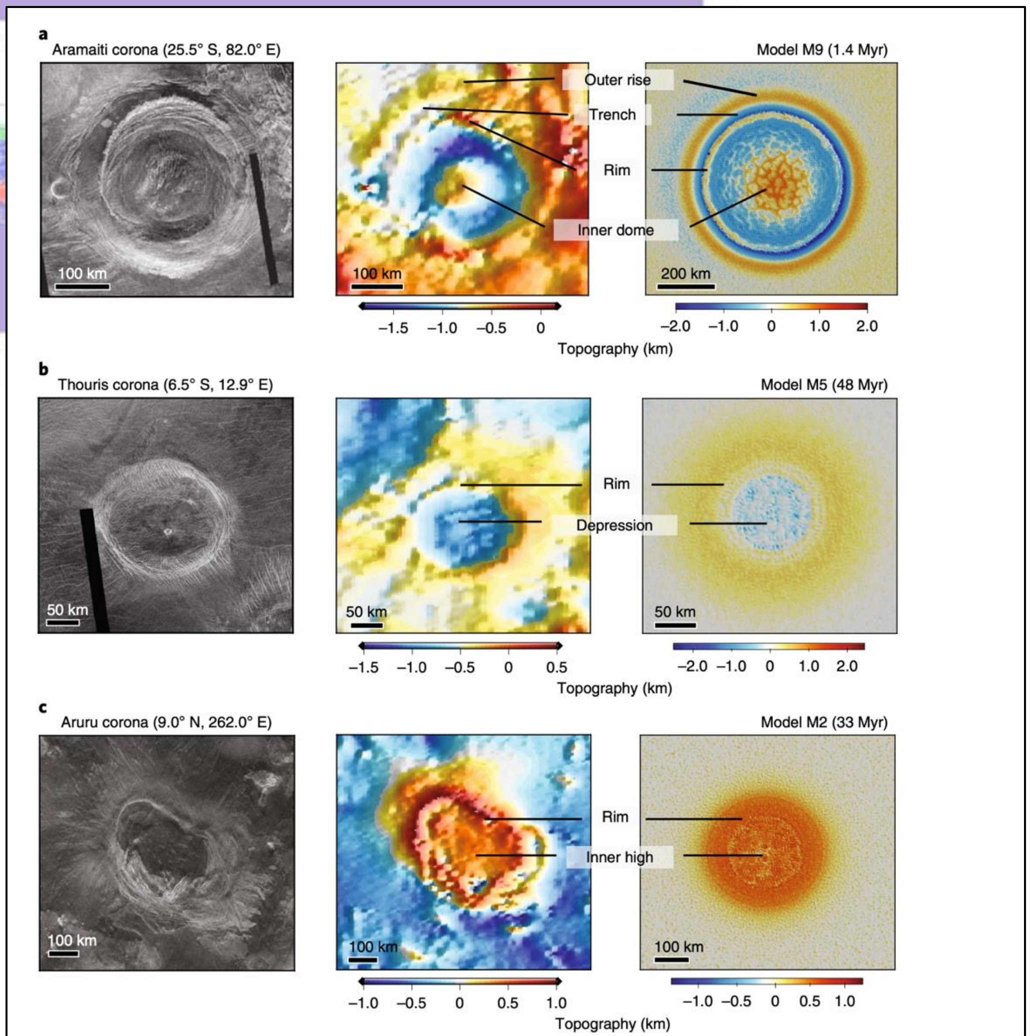


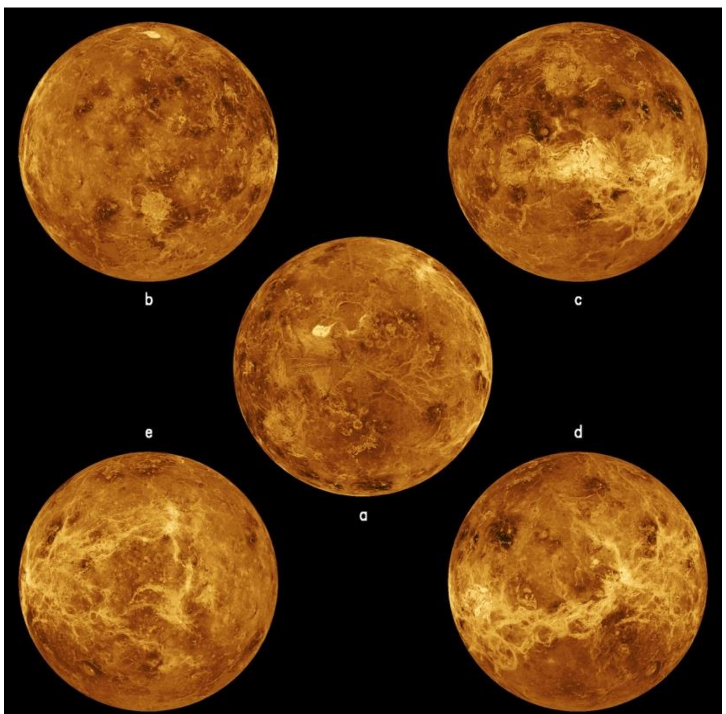
Gulcher et al (2020, 2023): Broader parameter exploration. Apparently able to reproduce the wide range of corona topographies/morphologies.

More details on Friday!

Venus missions

MAGELLAN (NASA): 1989-1994. Permitted the first global geological understanding of Venus.

- First global topography maps (98% coverage, 100m res.)
- First global gravity maps.
    - *> 85% of the surface covered with volcanic flows.*
    - *Few impact craters. Surface age < 800 Myrs.*
    - *No global plate tectonic network*



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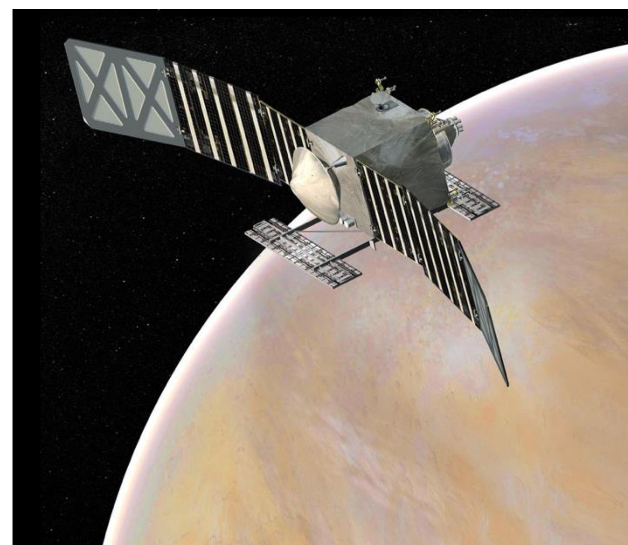
VERITAS (NASA): ~2031 - *Venus Emissivity, Radio Science, InSAR, Topography and Spectroscopy*



Goals:

- Create the first global, high-resolution topographic and radar images of Venus.
- Make the first maps of regions where geologic processes are actively changing the surface of Venus.
- Produce the first near-global map of surface rock composition.
- Make the first determination of core composition and whether it is solid or liquid.