The Role of Geophysics in Exploring Venus's Volcanic and Thermal Evolution

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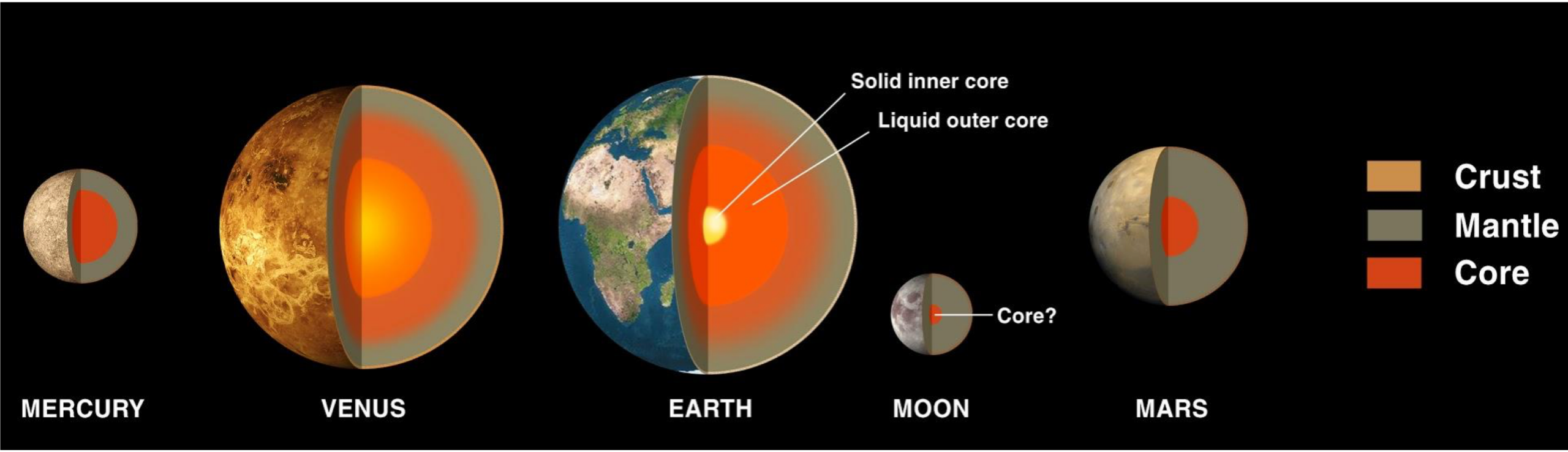
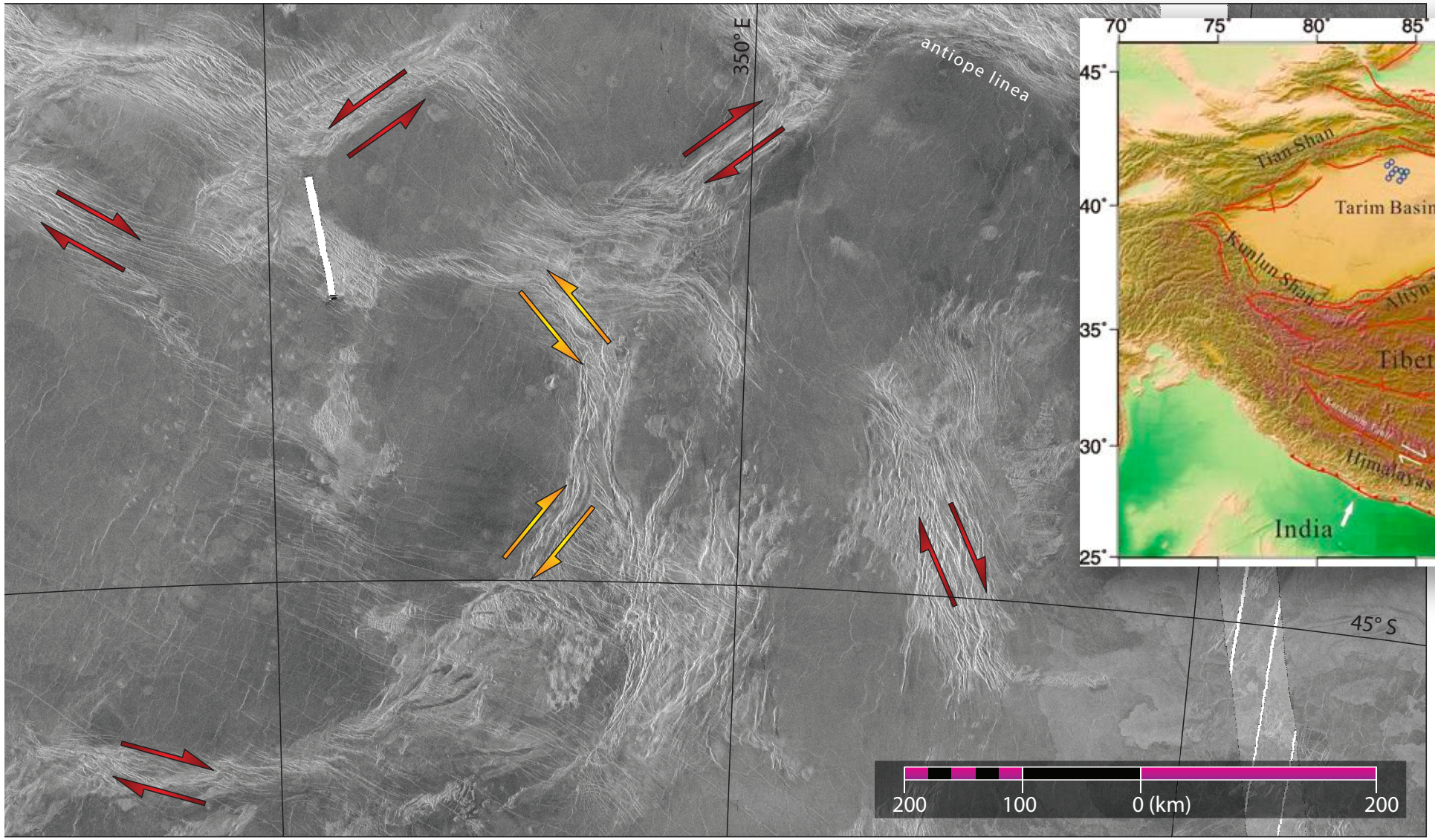
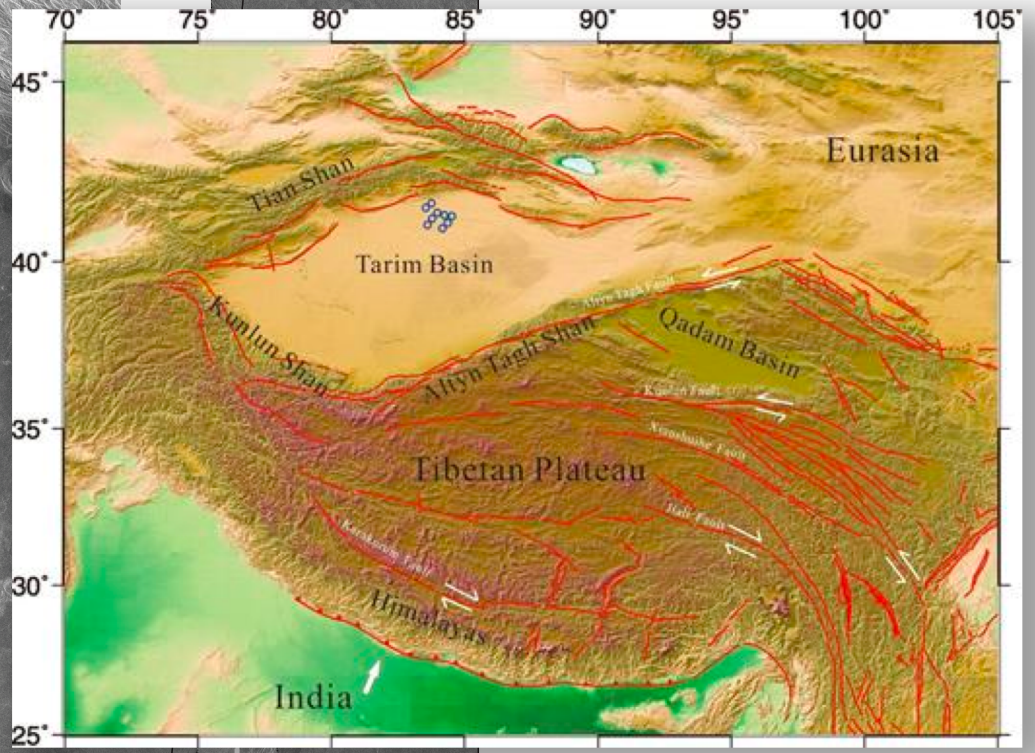
The divergent histories of Venus and Earth


Solid inner core
Liquid outer core
Core?
Crust
Mantle
Core
MERCURY
VENUS
EARTH
MOON
MARS

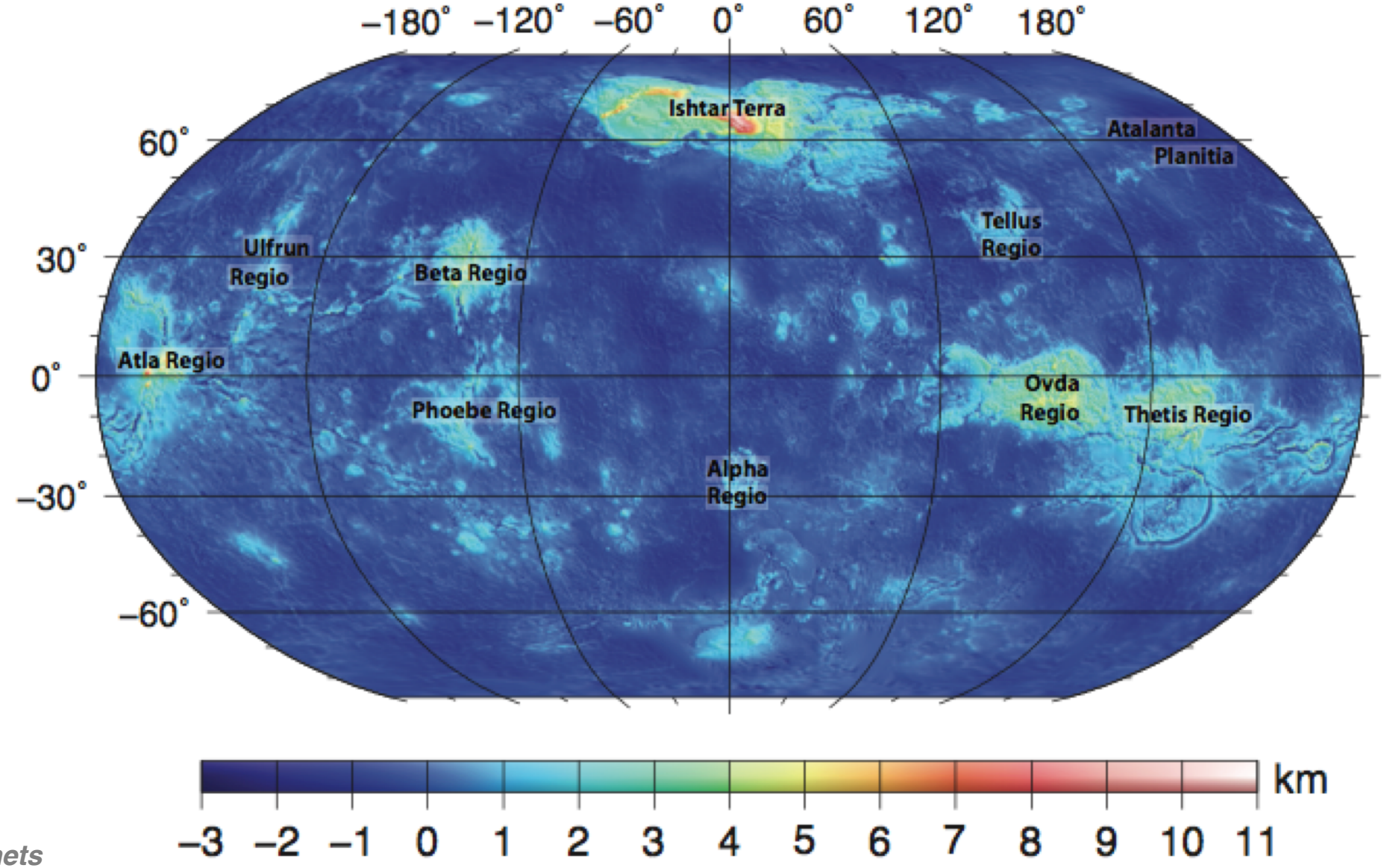




Liu et al., 2015

Byrne et al.* (2021), *PNAS

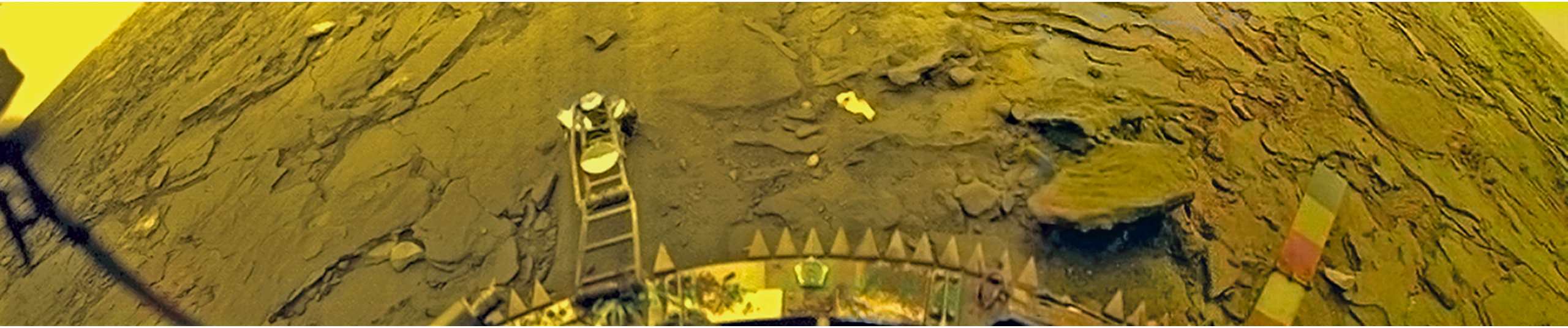
Magellan topography



James et al. (2013), *JGR-Planets*

The Venera and Vega landers revealed familiar geochemistry

- FeO/MnO ratio suggests a core size similar to Earth's — *Surkov et al.* (1986)
- Refractory elements are near CI-chondritic abundances — *Treiman* (2007)
- Venus's mantle has ~8% FeO, similar to Earth's mantle — *Treiman* (2007)

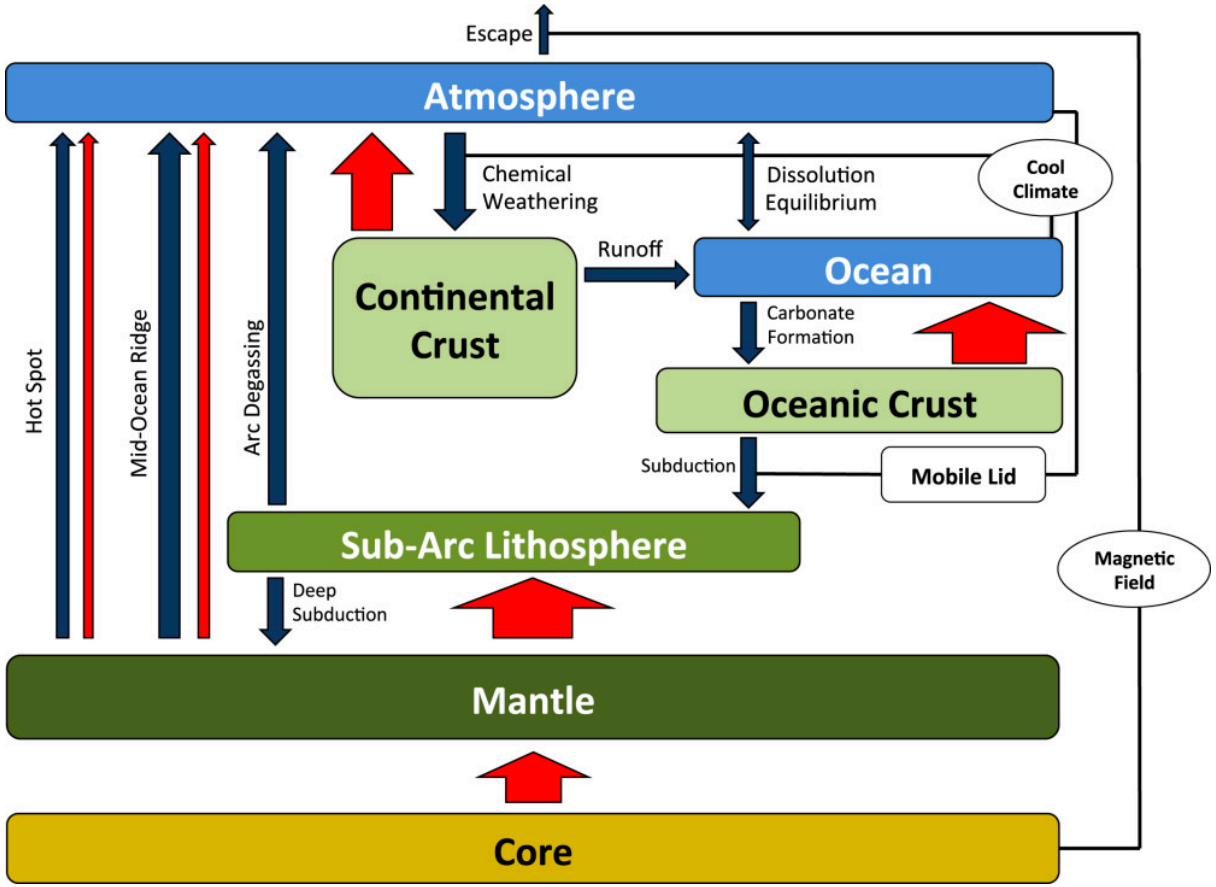


And yet, Venus is dramatically different from Earth:

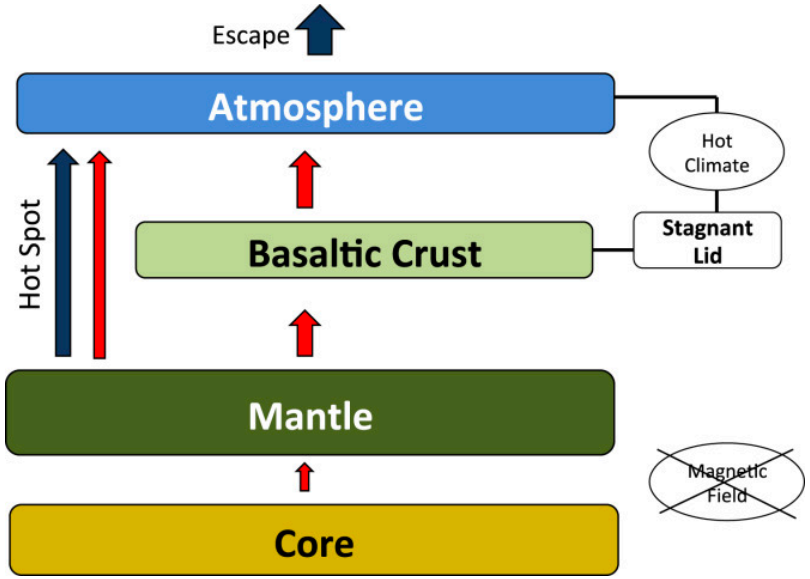
- 870ºF surface temperatures
- Atmospheric pressure is ninety times higher
- Sulfuric acid rain
- Very little water
- Super-rotating atmosphere
- No core dynamo or intrinsic magnetic field
- Quasi-stagnant lid instead of plate tectonics

"Earth's sister planet" – We have learned about Earth as a result of our investigation of other planets like Venus

Earth

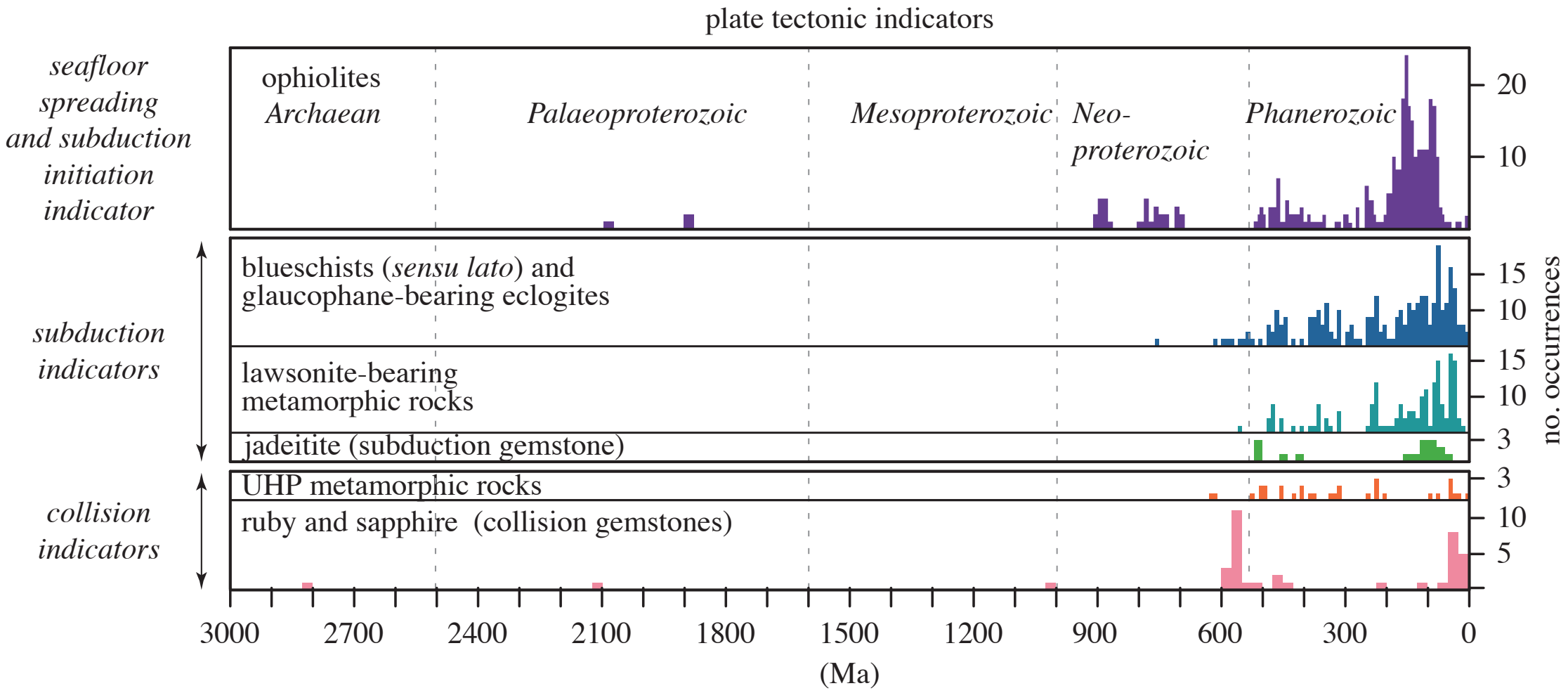


Venus

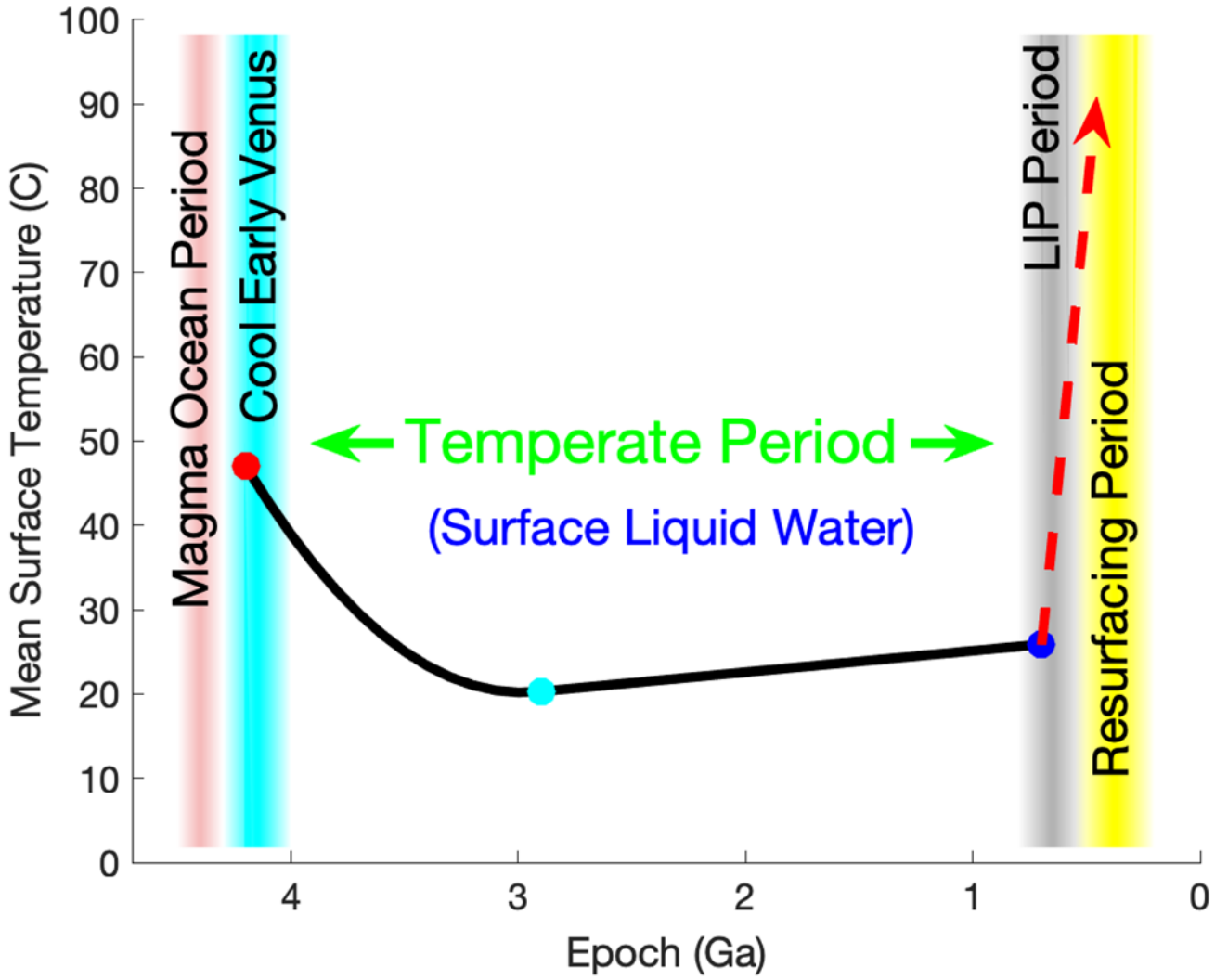


Blue: volatile flux
Red: heat flux

Foley & Driscoll (2016), *Geochemistry, Geophysics, Geosystems*



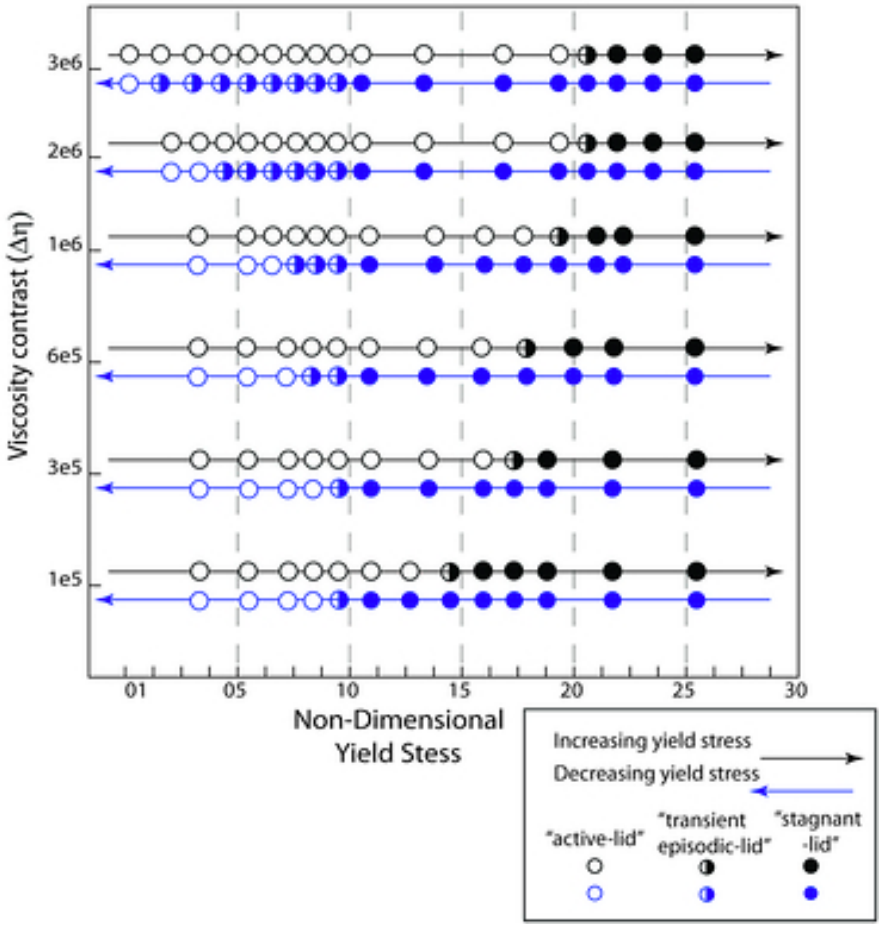
Stern (2018), *Phil. Trans. R. Soc.*



Way & Del Genio (2020), *JGR-Planets*

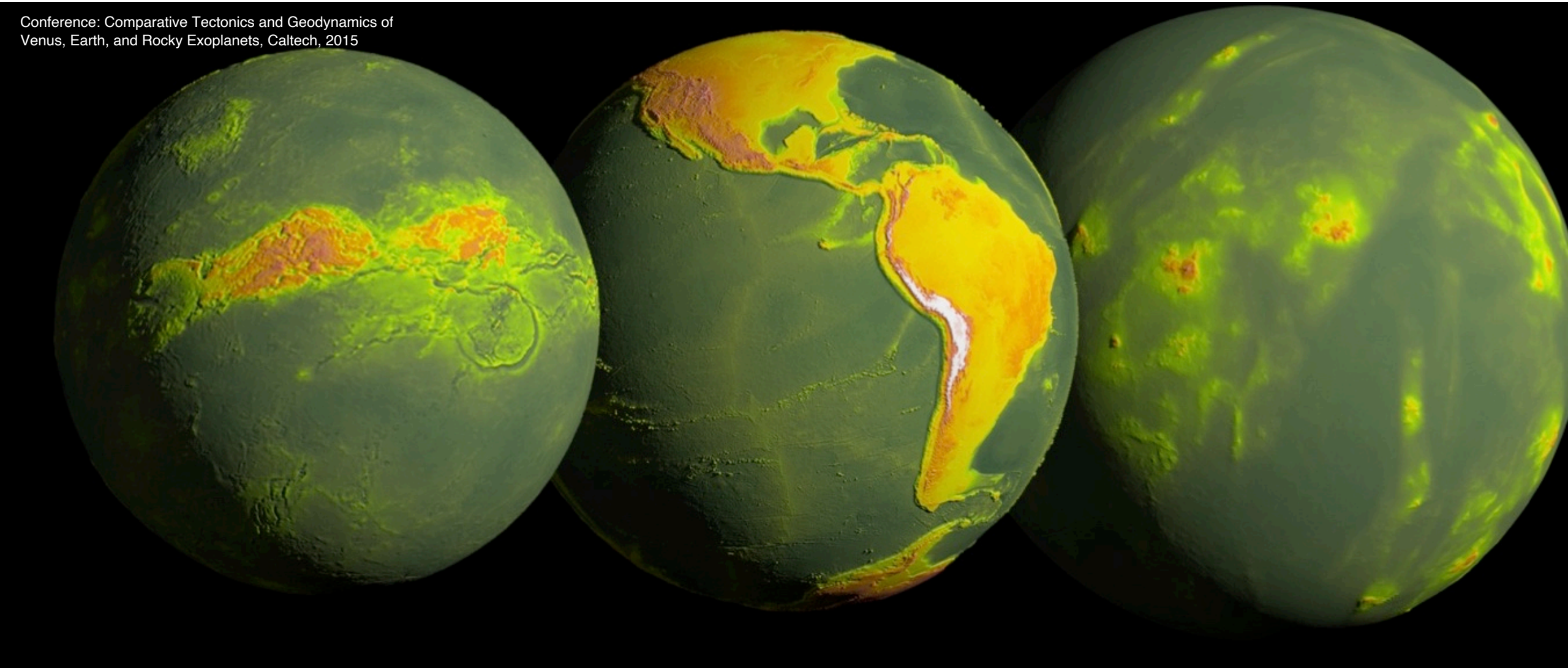
Hysteresis (the past history of deformation) partially determines a planet's tectonic regime.

Weller & Lenardic (2012), *GRL*



Wayfinding: "It's seeing where you're going by knowing where you've been".

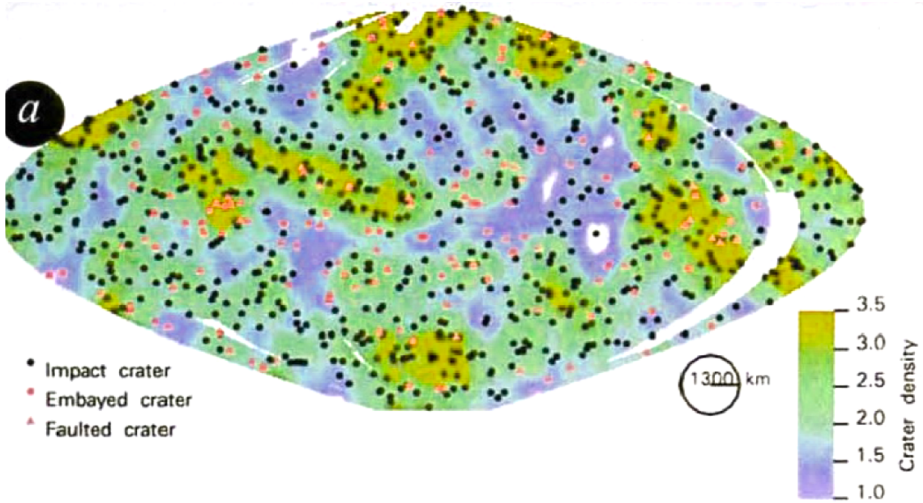
Disney


Conference: Comparative Tectonics and Geodynamics of
Venus, Earth, and Rocky Exoplanets, Caltech, 2015

Current state of knowledge (what we know)

Magellan observed a relatively low number of craters, which implies that the surface is young.

Moreover, the distribution of craters is statistically indistinguishable from a purely random distribution. This yielded two important conclusions in the early years of the Magellan mission:



Price & Suppe* (1994), *Nature

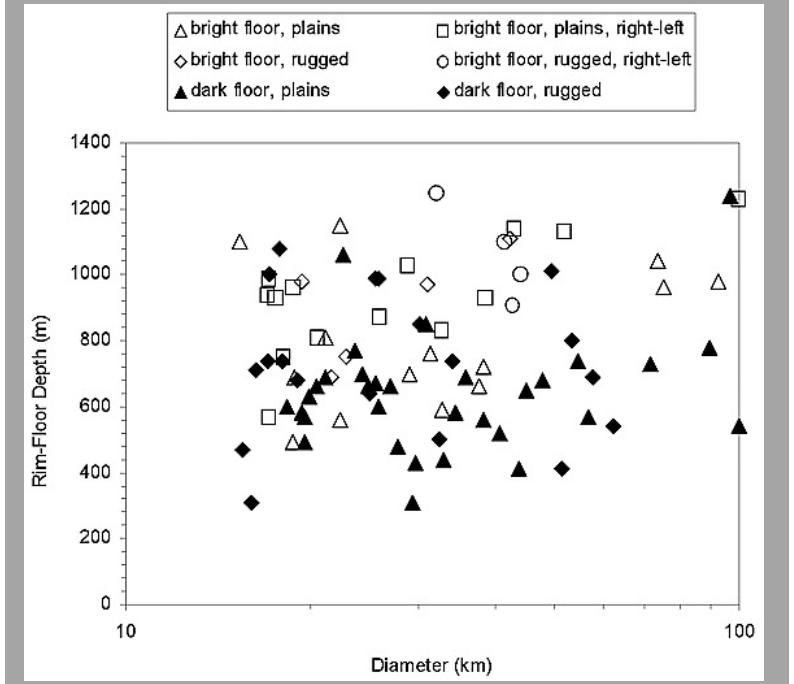
- ~~Venus was entirely resurfaced—perhaps catastrophically—several hundred million years ago.~~
- ~~Venus's lithosphere has remained stagnant and inactive since that resurfacing event.~~

Alternative theory: patchwork resurfacing

Randomly distributed regional resurfacing is equally capable of explaining the observed crater distribution. (***Hauck et al.*, 1998, *Icarus***)

The debate is far from settled, and there still is some indication of a period of elevated resurfacing. (***Kreslavsky et al.*, 2015, *Icarus***)

Stereo topography has shown that many craters are shallower than expected, indicating the presence of recent volcanic flooding on a local scale. (***RIGHT***)



80% of craters have dark floors. Are they volcanically flooded? Stereo topo suggests they are shallower, and thus infilled.

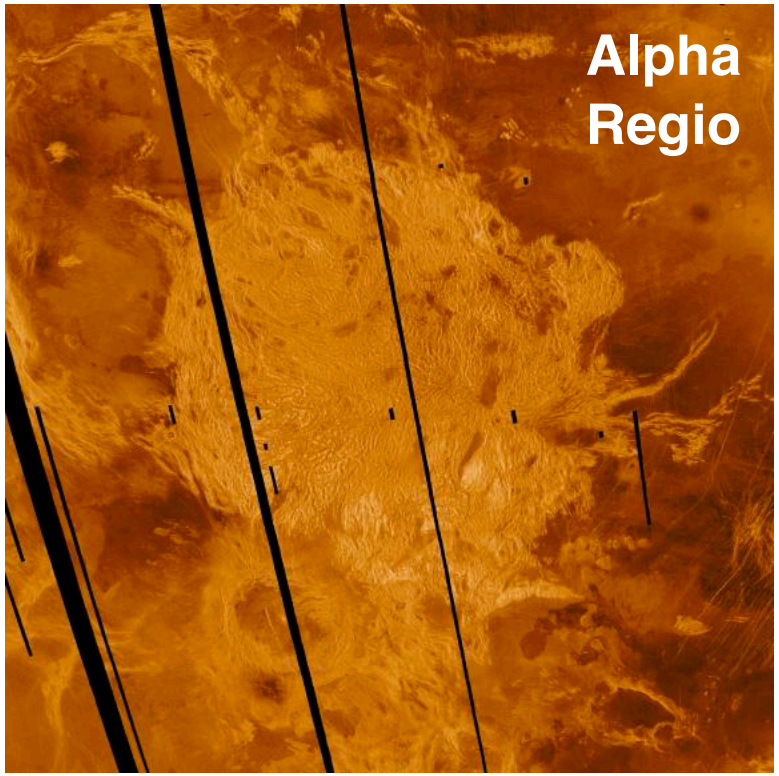
Herrick and Rumpf, 2011

Tesserae – the oldest terrains on Venus?

Venus's tessera terrains are highly deformed with multiple generations of tectonic activity, and this roughness contributes to the brightness of the terrains in radar imagery.

Tesserae are embayed by volcanic plains, which implies a relative age difference.

The origins of the tesserae are still in dispute. One of the crucial pieces of desired evidence is the mode of oldest tectonic deformation (**extension** versus **shortening**).



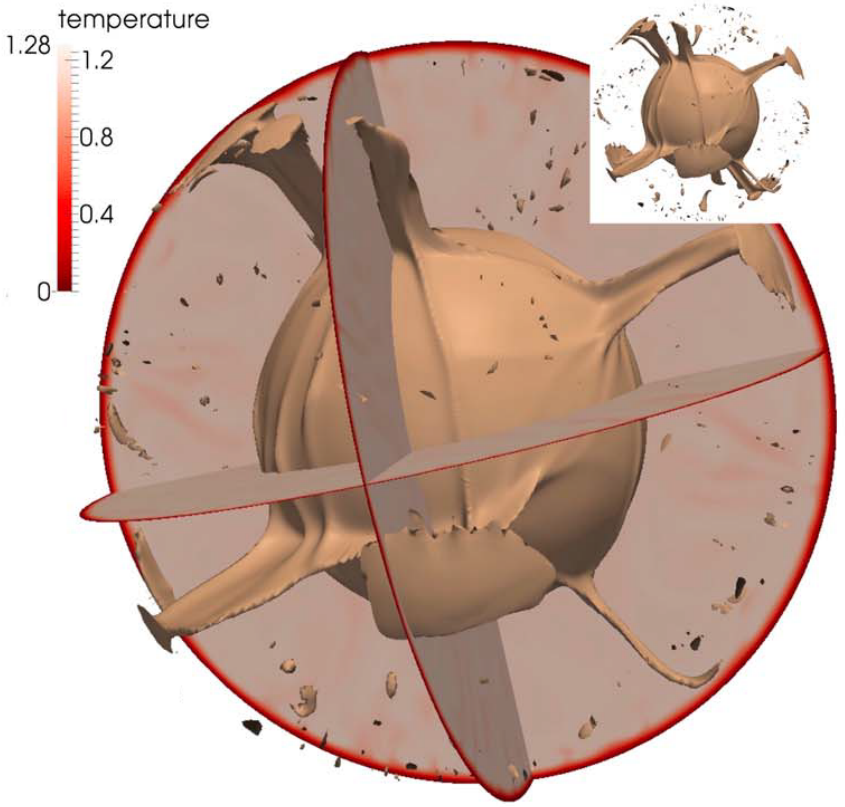
NASA JPL

What mantle convection models have to add

Venus has a relatively small Center-of-Mass / Center-of-Figure offset (280 meters). Catastrophic resurfacing would produce offsets ~4x larger, so the observed offset rules out a catastrophic resurfacing model.

Mantle plumes are remarkably stable over 100 Myr timescales. Since the effective rigidity of a viscoelastic lithosphere weakens over long timescales, it's reasonable to expect that small-scale plumes and drips could produce a discernable gravity signal.

(***King*, 2018, *JGR-Planets***)

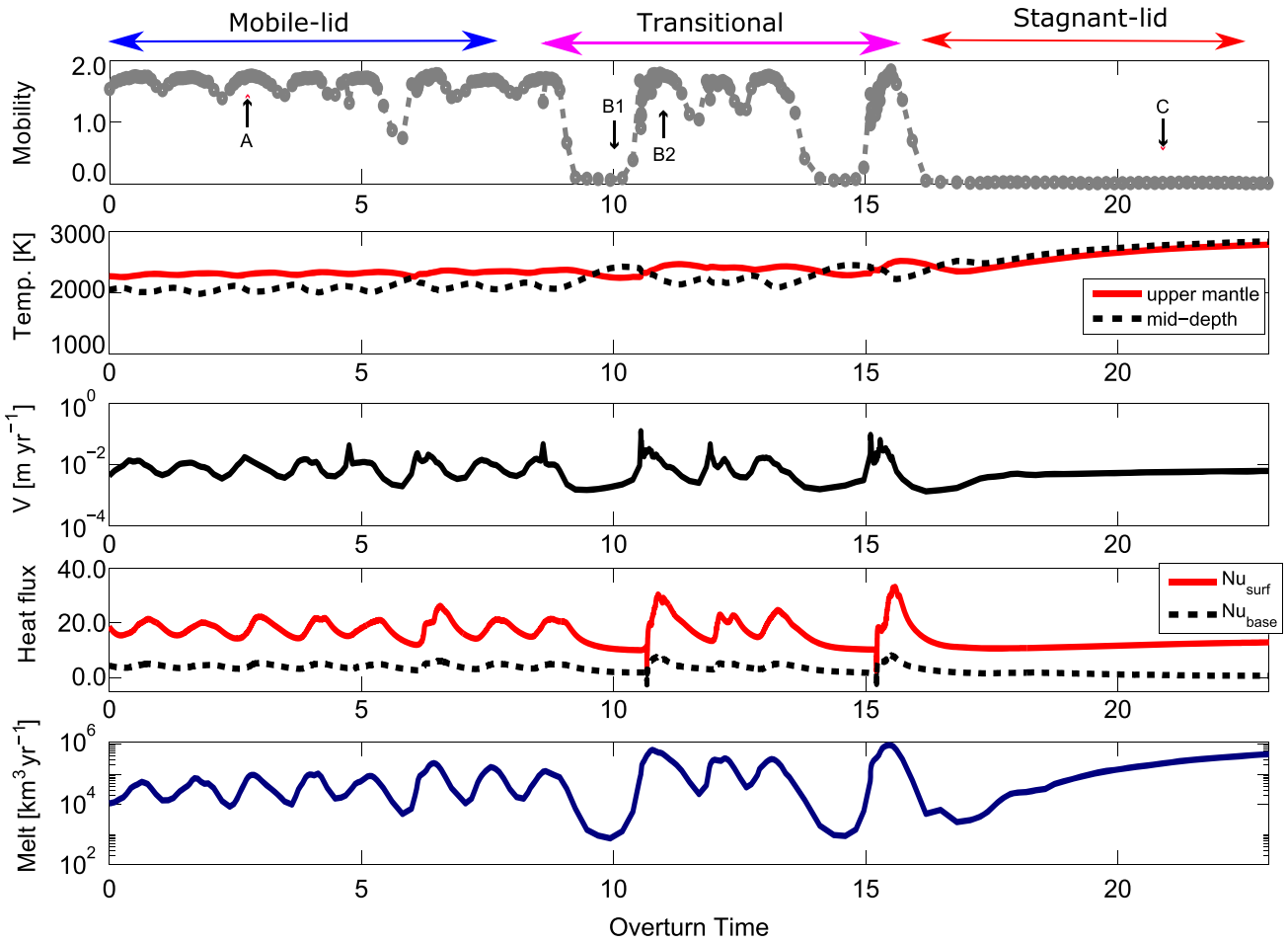


What mantle convection models have to add

Venus has likely transitioned from a mobile lid state (like Earth) to an episodic lid and/or a stagnant lid sometime in its history.

There should be remnants of Venus's mobile lid preserved today. Ishtar Terra may have been formed with thousands of kilometers of tectonic convergence.

(***Weller & Kiefer*, 2020, *JGR-Planets***)



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mobile lid
episodic
sometim

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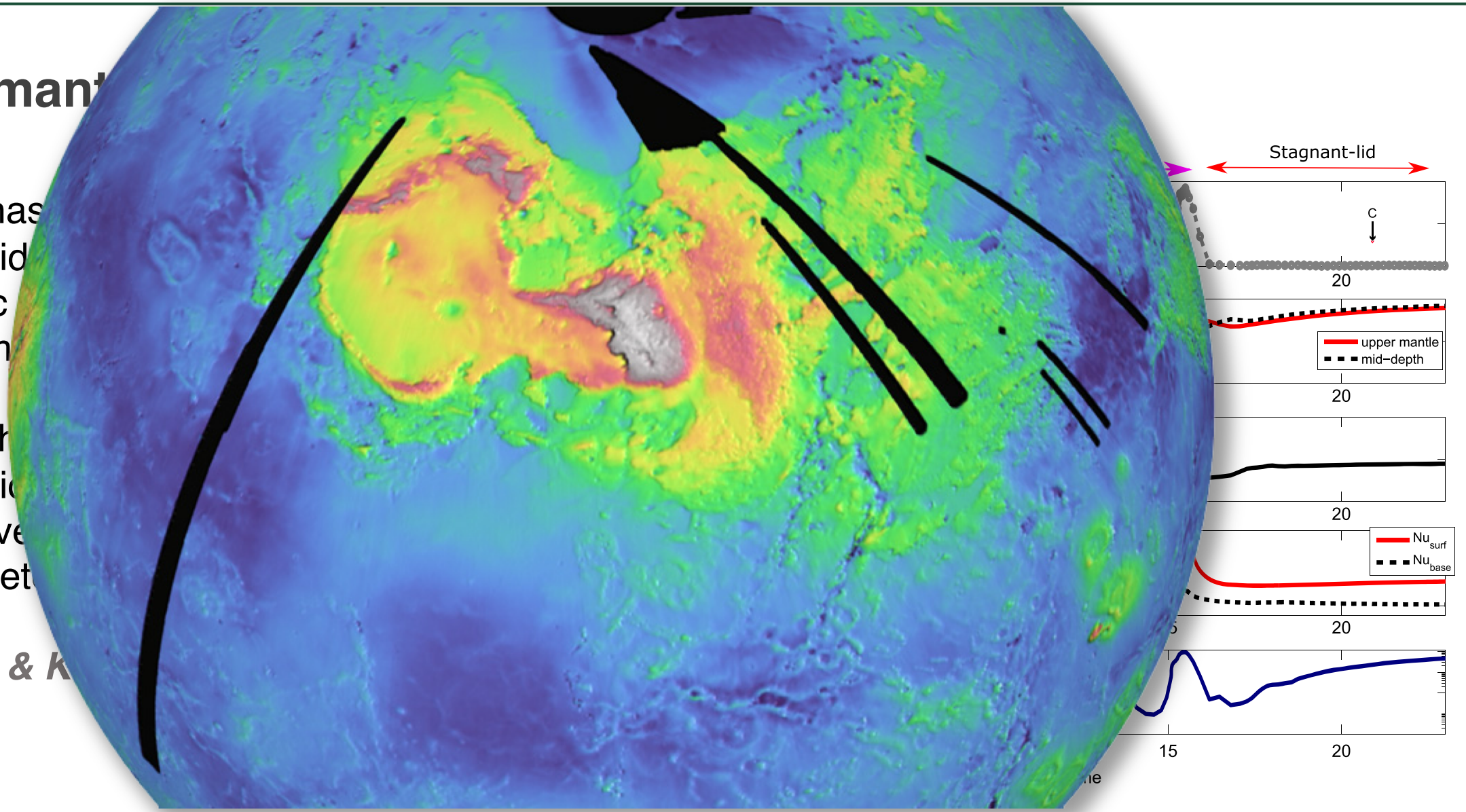
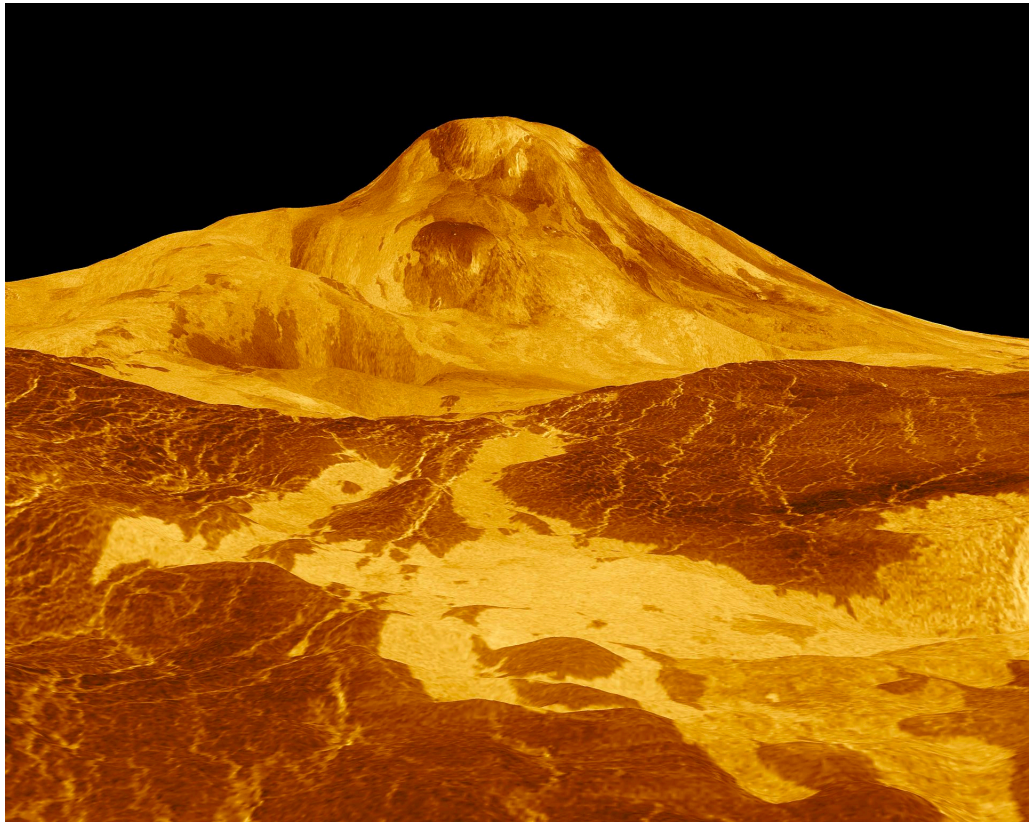
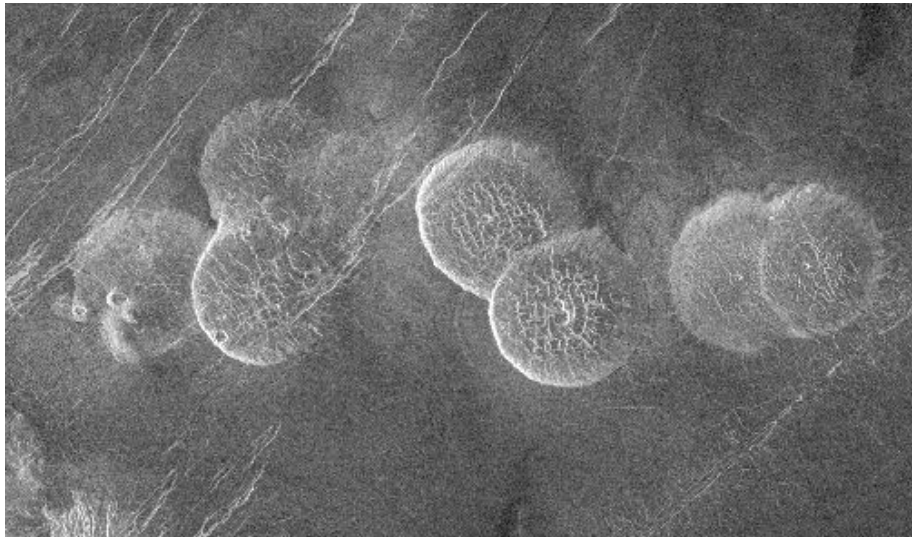
mobile li
may have
of kilomet

(*Weller & K*

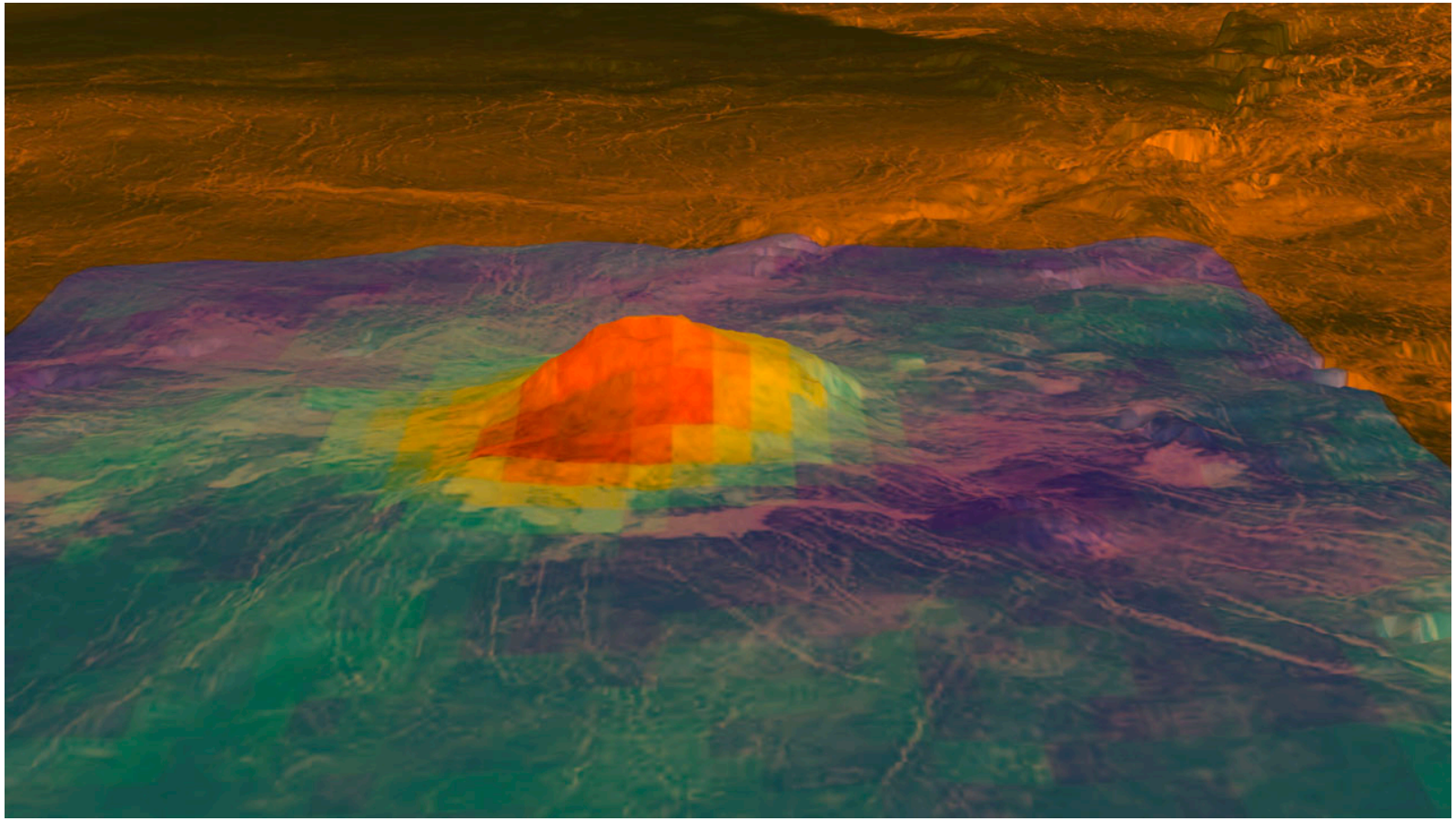


Volcanoes



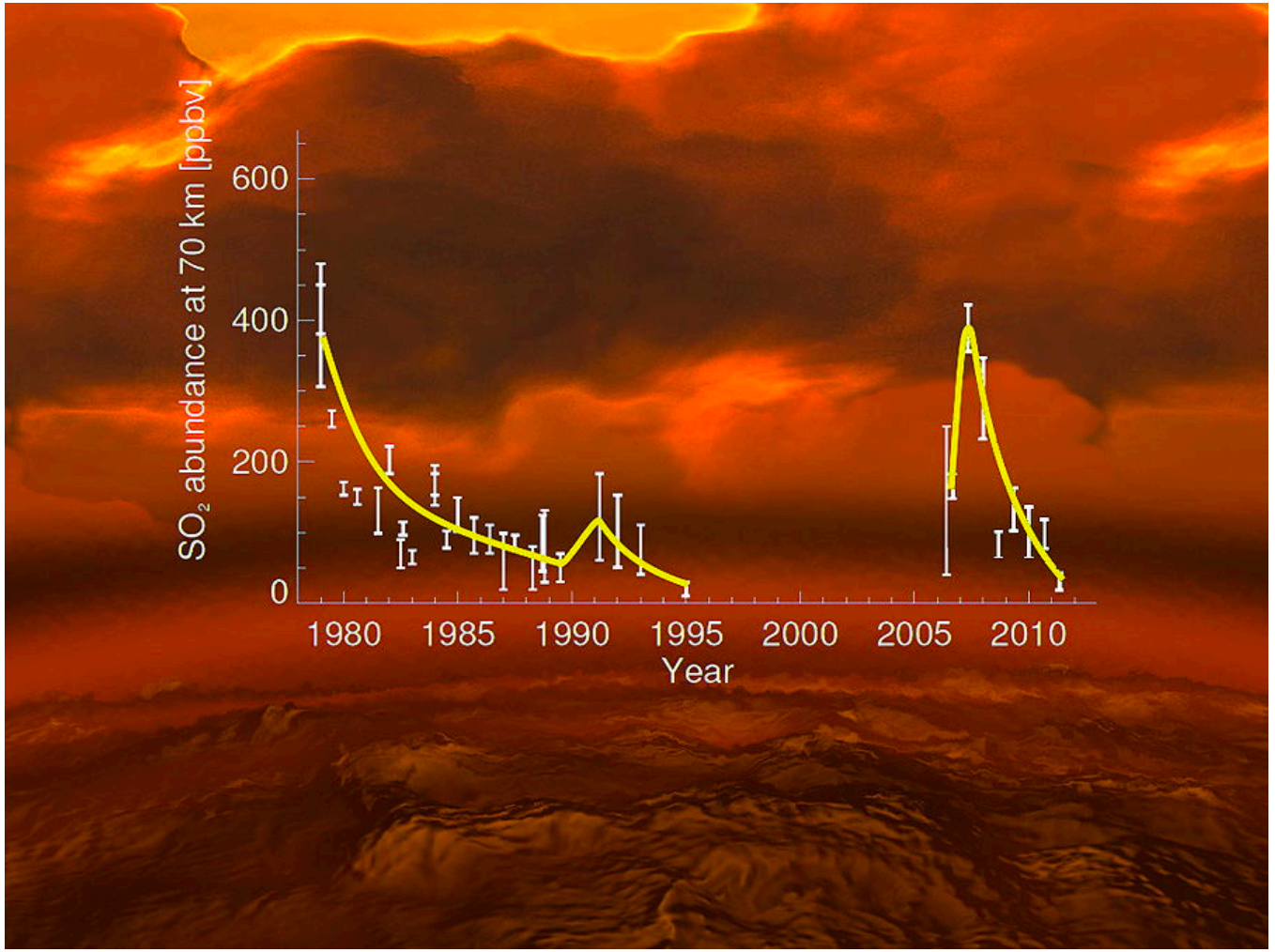


Volcanoes are active! (more recently than 100,000 years)



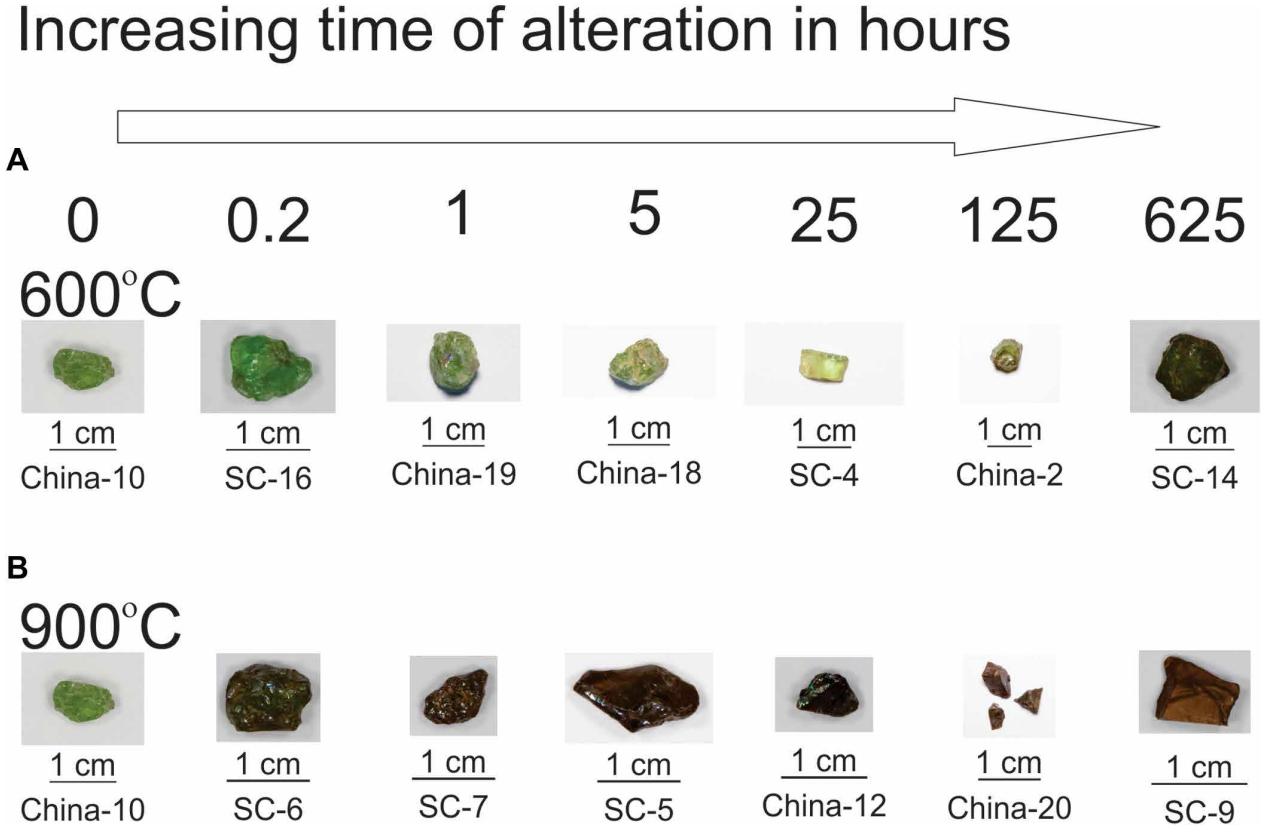
Smrekar et al. (2010), *Science*

Volcanoes are active! (in the past decade)



ESA

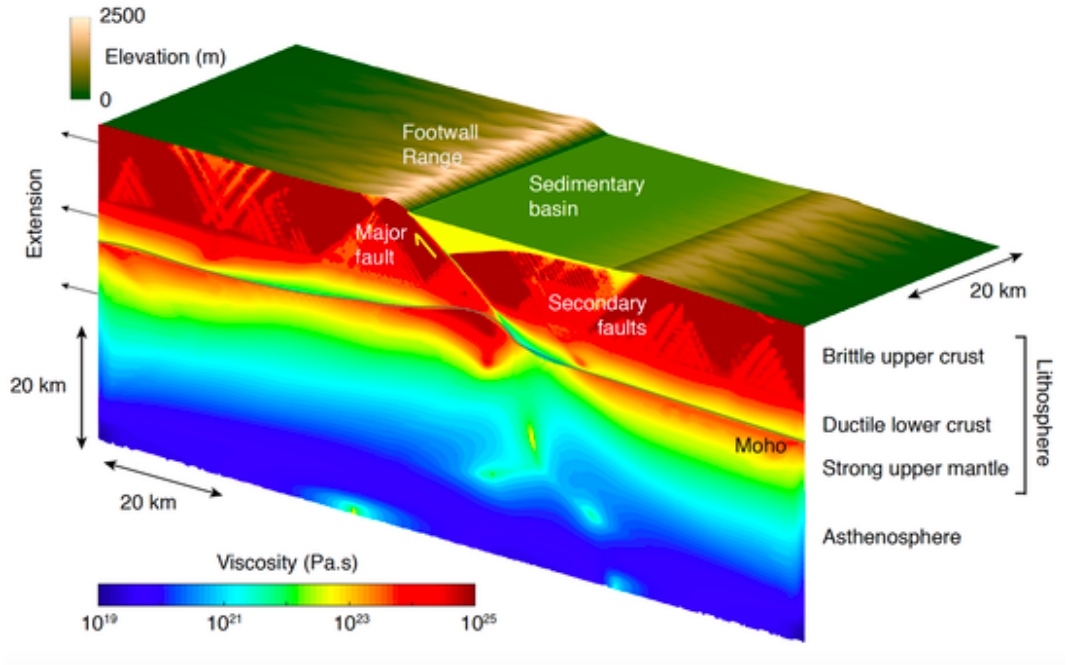
Volcanoes are active! (as we speak?)



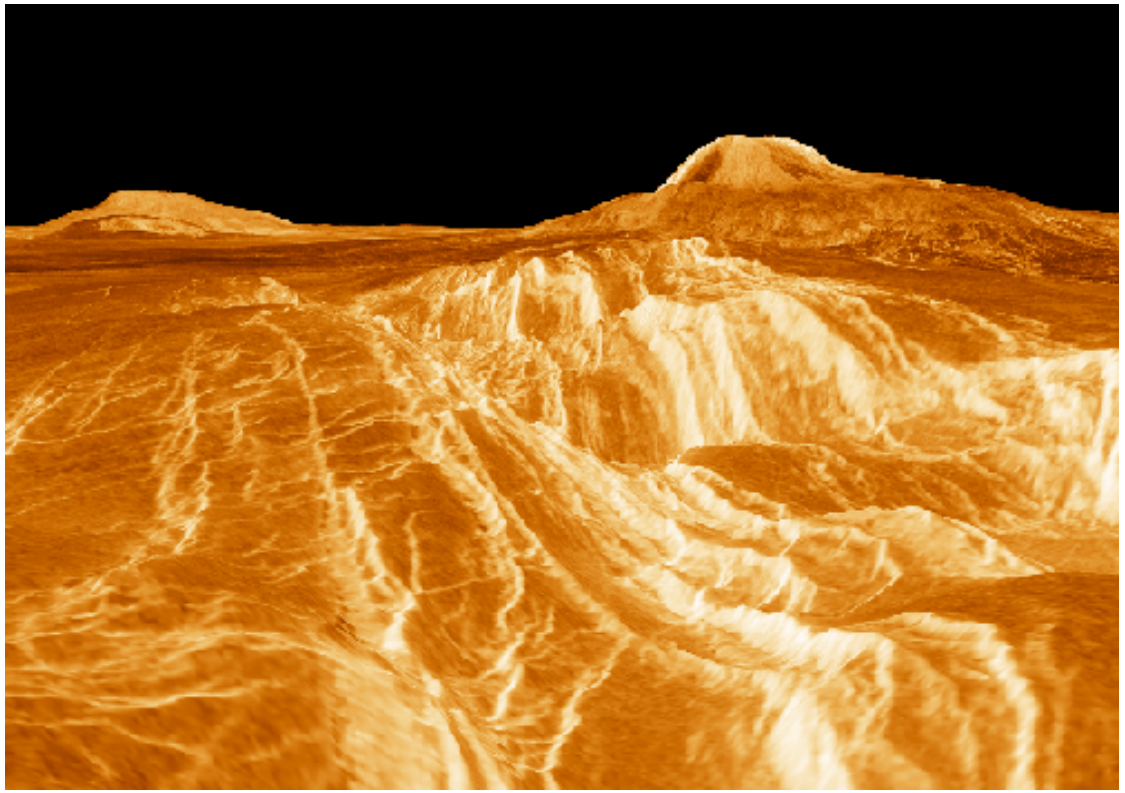
Filiberto et al. (2020), *Sci. Adv.*

Chasmata

Venus hosts pervasive chasma structures, which indicate tectonic spreading. Large chasmata have typical widths of ~200 km.



https://jaolive.weebly.com/research.html

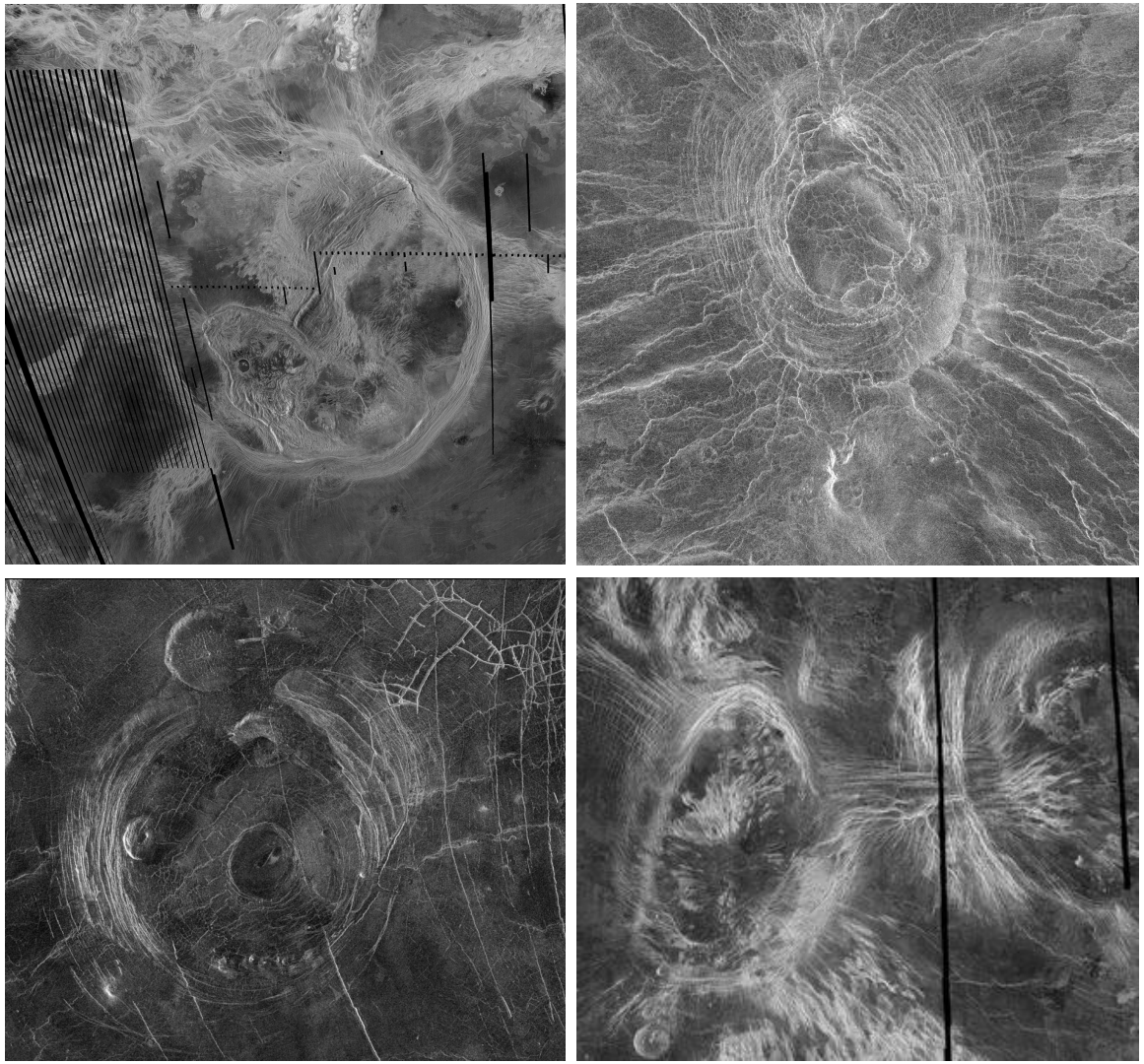


Chasma near Gula Mons – *NASA/JPL*

Coronae

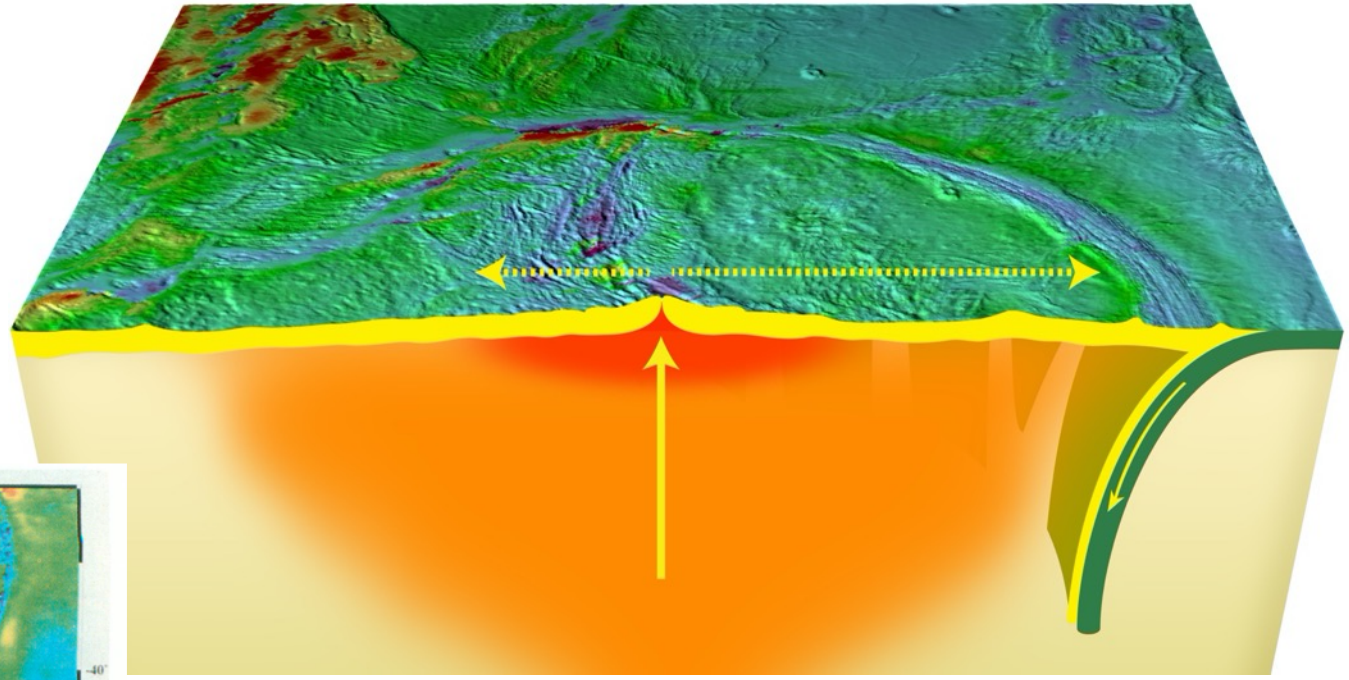
Corona structures are tectonic features characterized by a circular shape and likely formed by small-scale mantle upwellings.

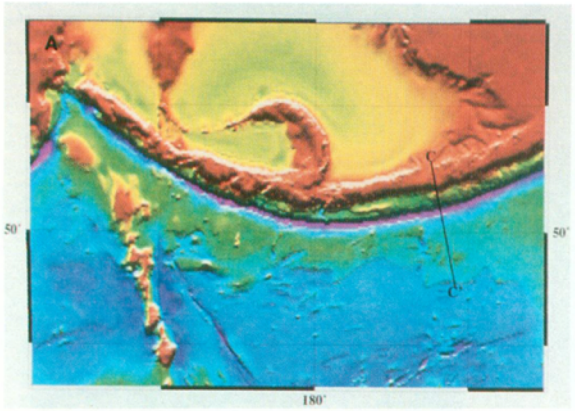
Venus is the only† known planet with coronae, but coronae may play a crucial role in the tectonic evolution of Earth-like planets.

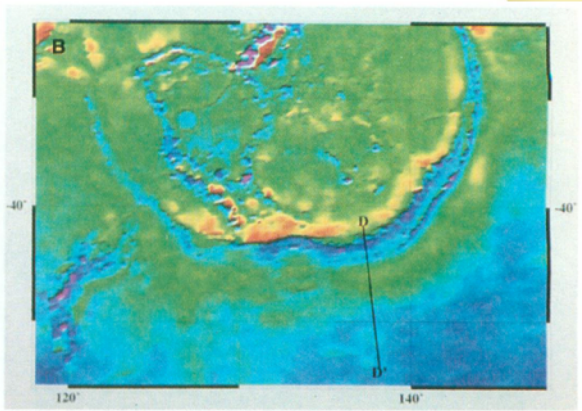


†Uranus's moon Miranda has circular features by the same name that are possibly associated with cryovolcanism.

Subduction on Venus

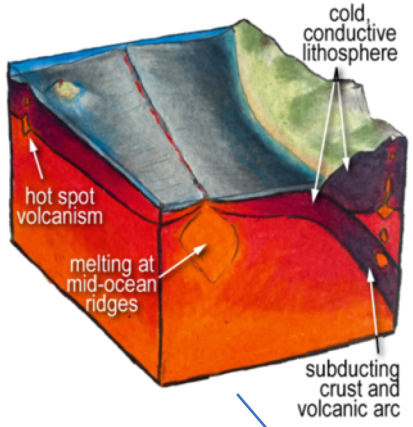






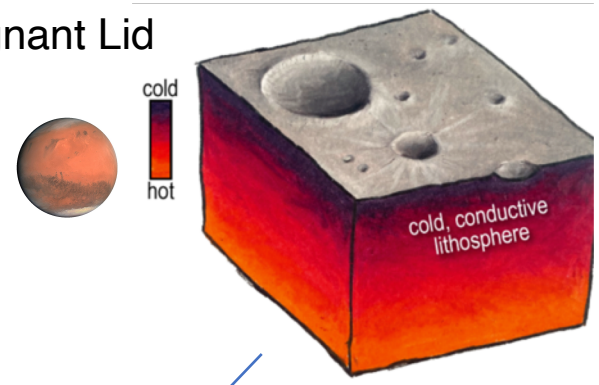
Subduction recycles volatiles that stabilize long-term climate.

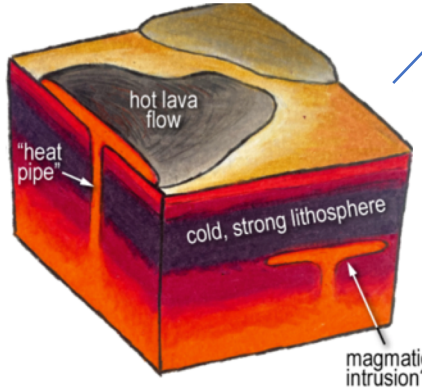
Is this how plate tectonics started on Earth?



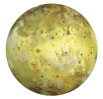
Mobile Lid
(Plate Tectonics)

Stagnant Lid



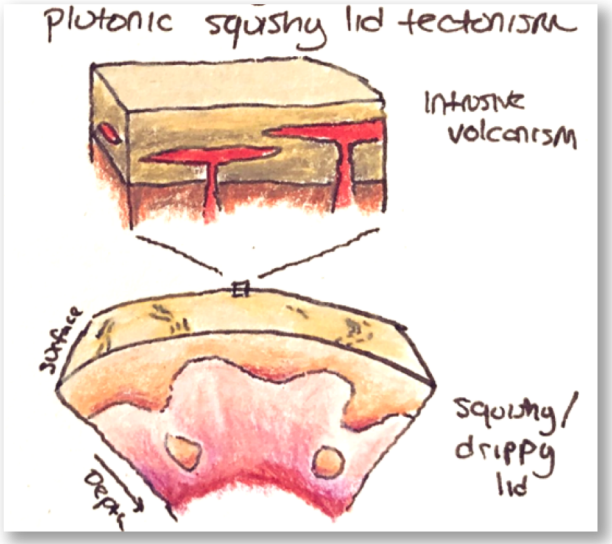


Heat pipe



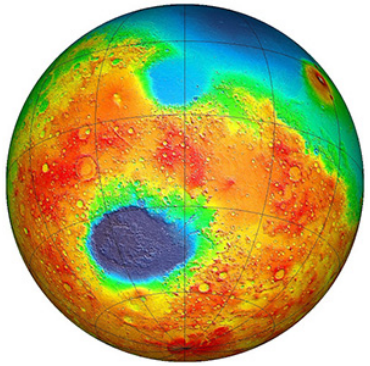
Cartoons: James Tuttle Keane, Io, Decadal Survey White Paper 2020

Diagram from Sue Smrekar, Decadal Survey 2021



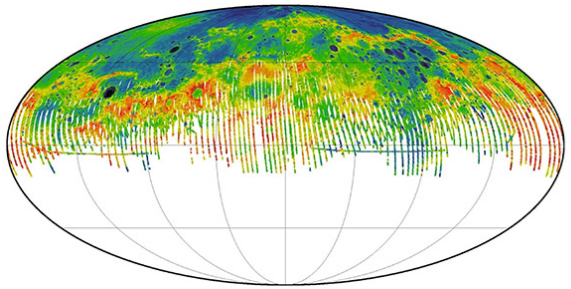
Lourenço et al. (2018), *Nature Geoscience*

Future insights into Venus' static structure



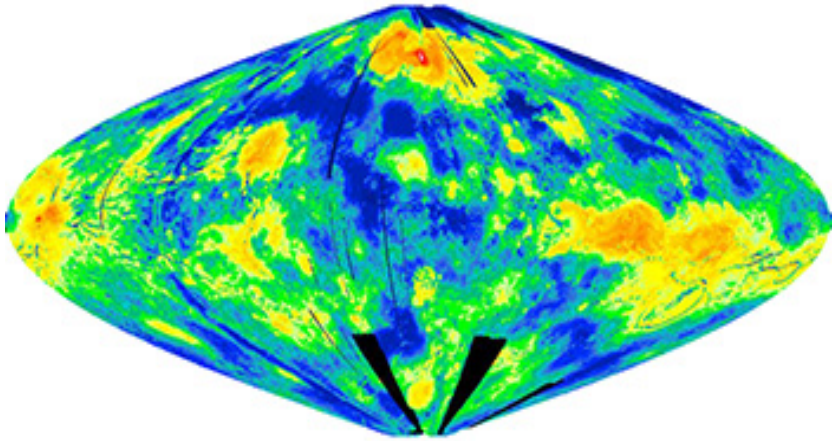
Mars
MOLA
Accuracy: 3 meters
Resolution: 1-2 km

Moon
LOLA
Accuracy: 1 meter
Resolution: 0.5 km



Mercury
MLA
Accuracy: 5 meters
Resolution: >2 km

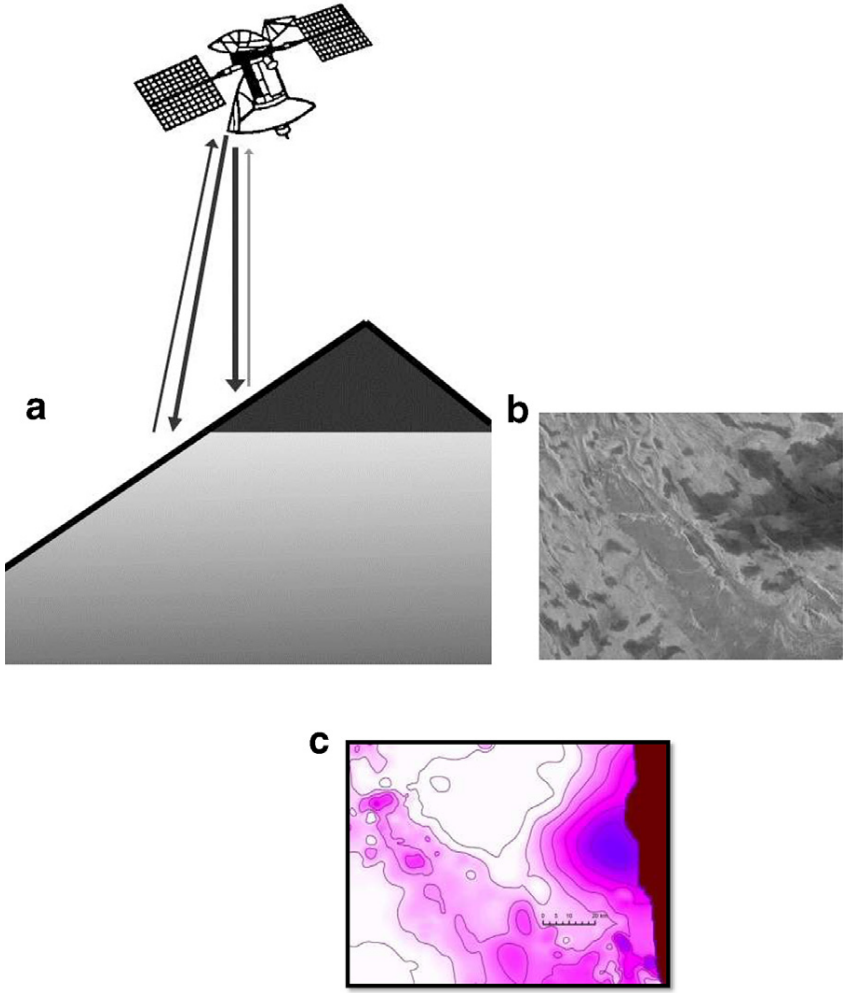
Earth
SRTM
Accuracy: 6 meters
Resolution: 1-2 km



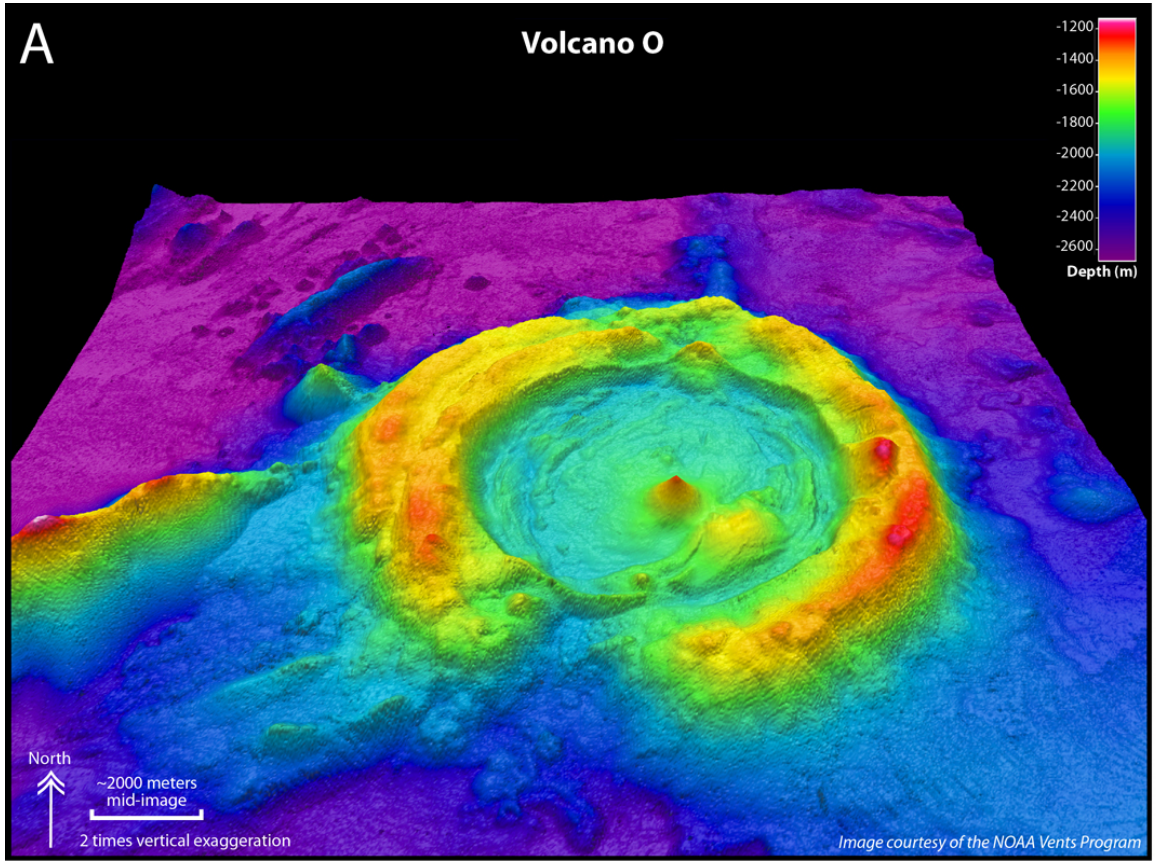
Venus
Magellan
Accuracy: 80 meters
Resolution: 20 km

Magellan radar topography

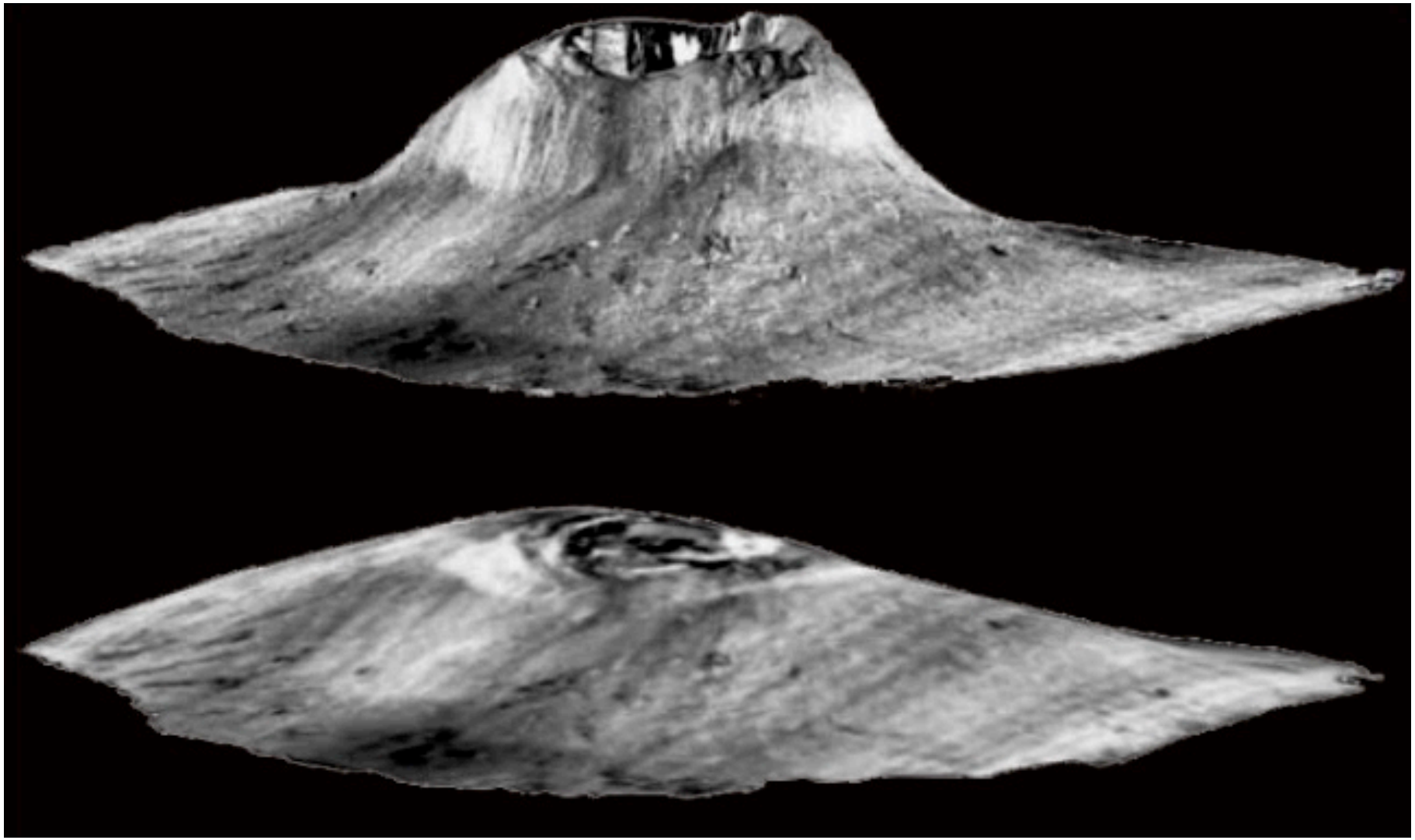
- Since Venus's atmosphere is opaque at visible wavelengths, Magellan used radar travel time to measure Venusian topography.
- The brightness of radar backscatter is dependent on the material properties (permittivity) and the surface roughness.
- The "darkest" regions can trigger an off-nadir detection, which can spoof a delayed arrival time, which can lead to an underestimation of elevation by multiple kilometers.



Treiman et al. (2016), *Icarus*

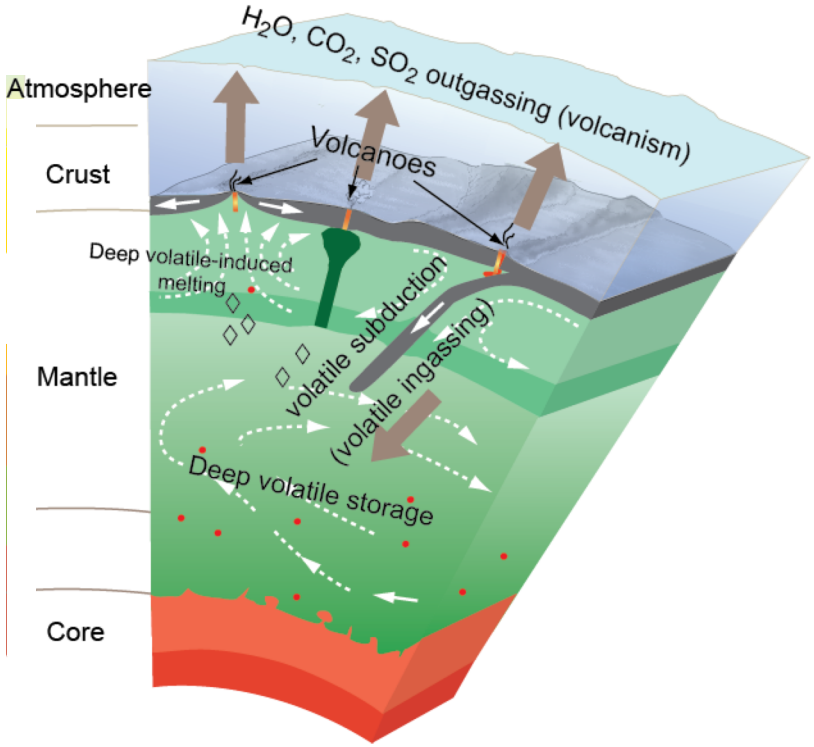

A
Volcano O
-1200
-1400
-1600
-1800
-2000
-2200
-2400
-2600
Depth (m)
North
~2000 meters
mid-image
2 times vertical exaggeration
Image courtesy of the NOAA Vents Program


B



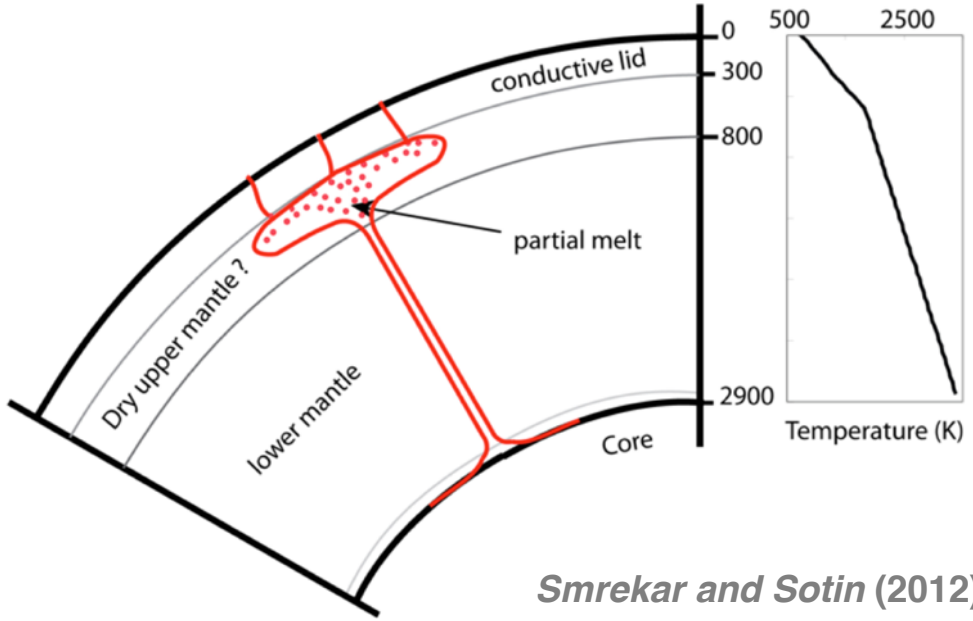
McGovern **(2021)**, ***White paper***

Volcanism/tectonism link the surface, atmosphere, and interior



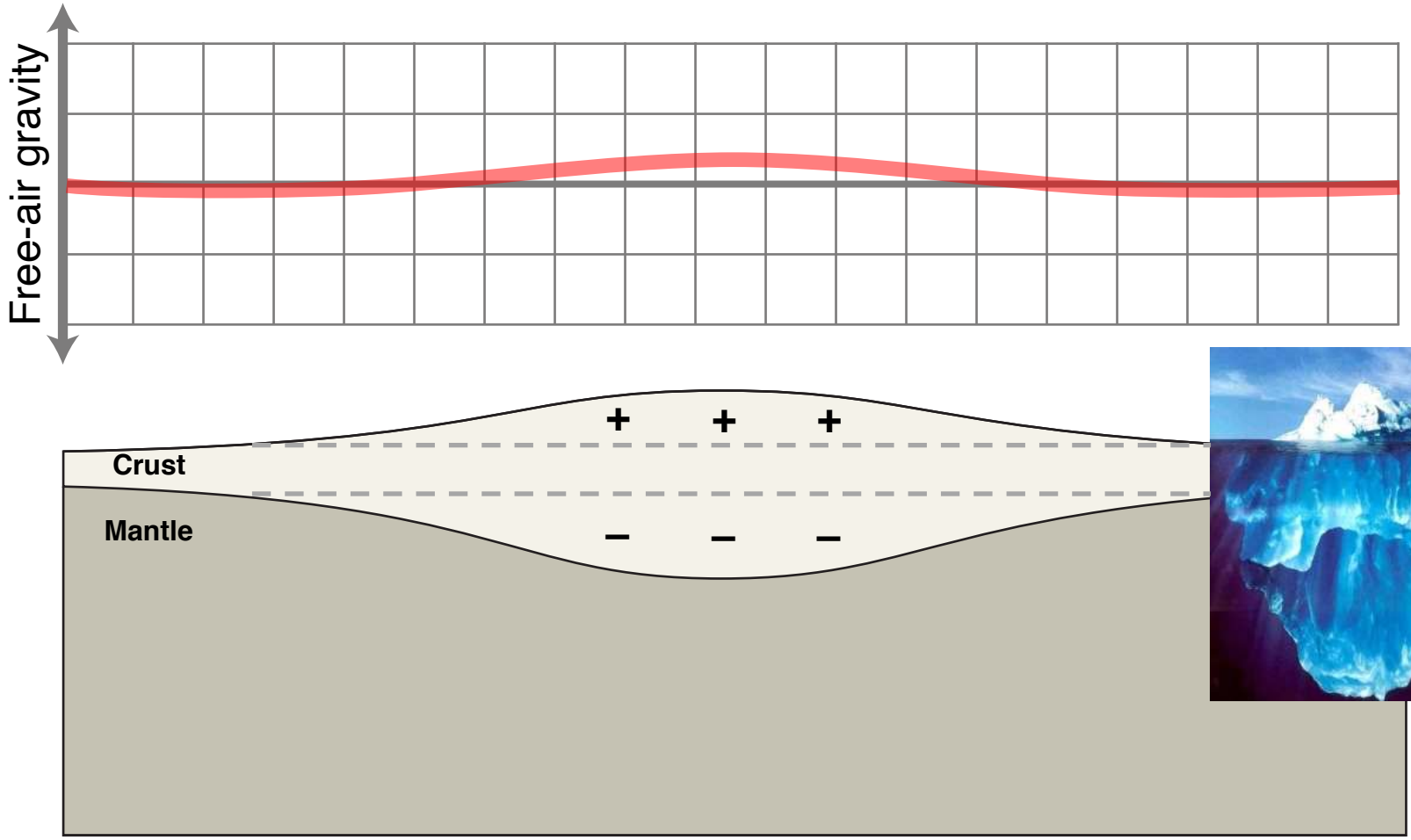
http://dasgupta.rice.edu/

- Does all recent volcanism due to pressure release melting come from deep mantle plumes?
- Is lower mantle water (or other volatiles) needed to enable melting? Is the upper mantle desiccated?

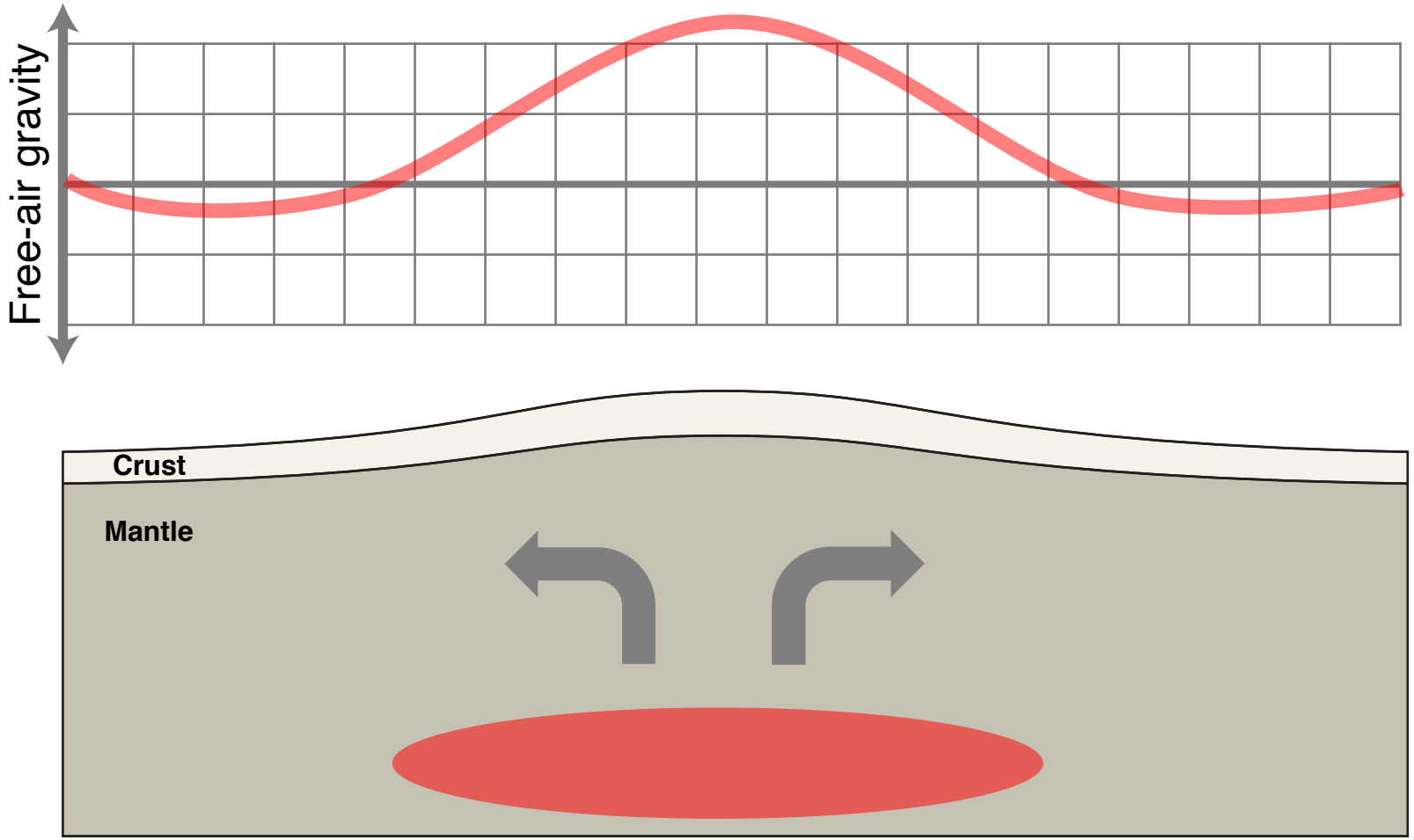


Smrekar and Sotin (2012), *Icarus*

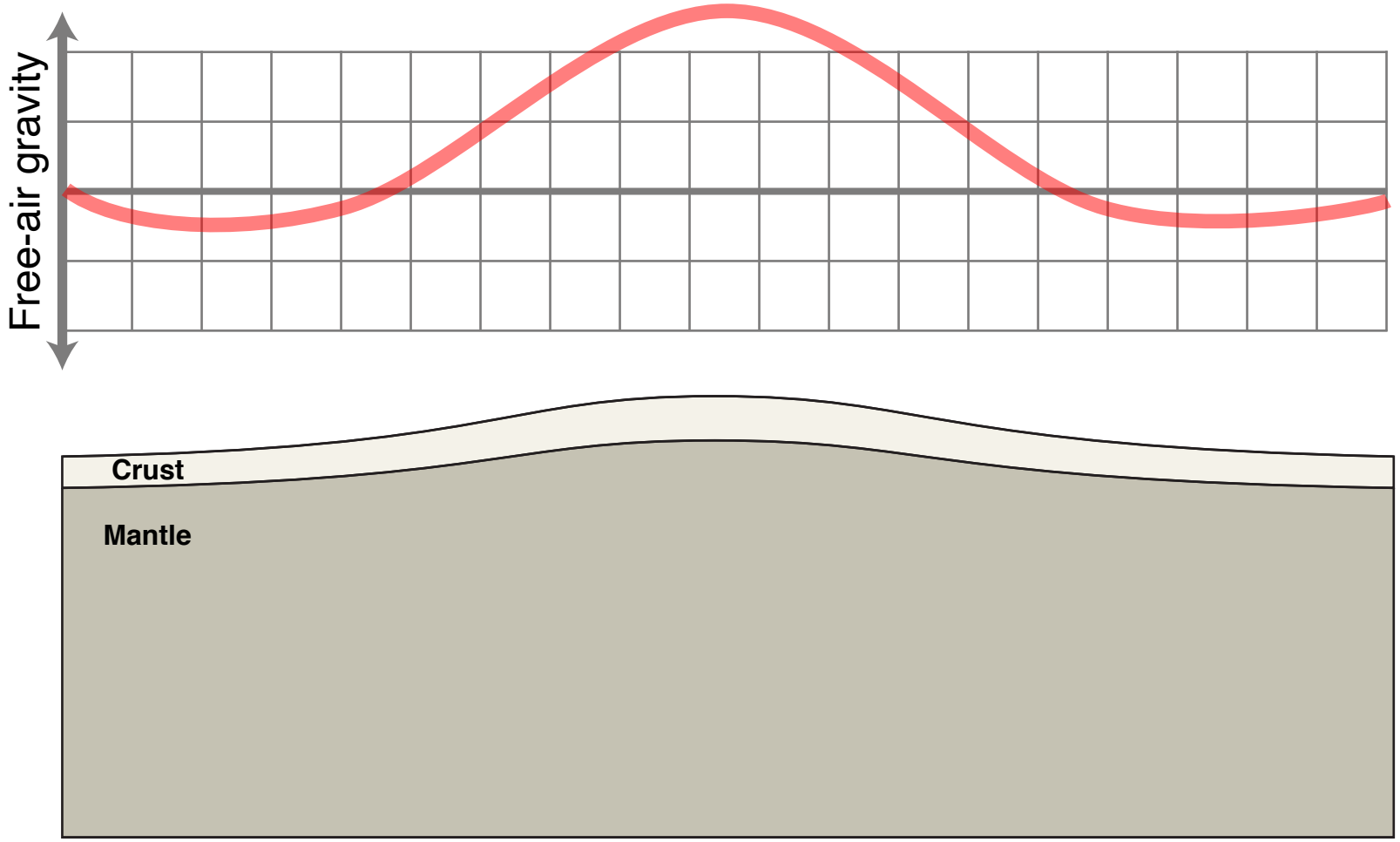
Gravity from a cross-section



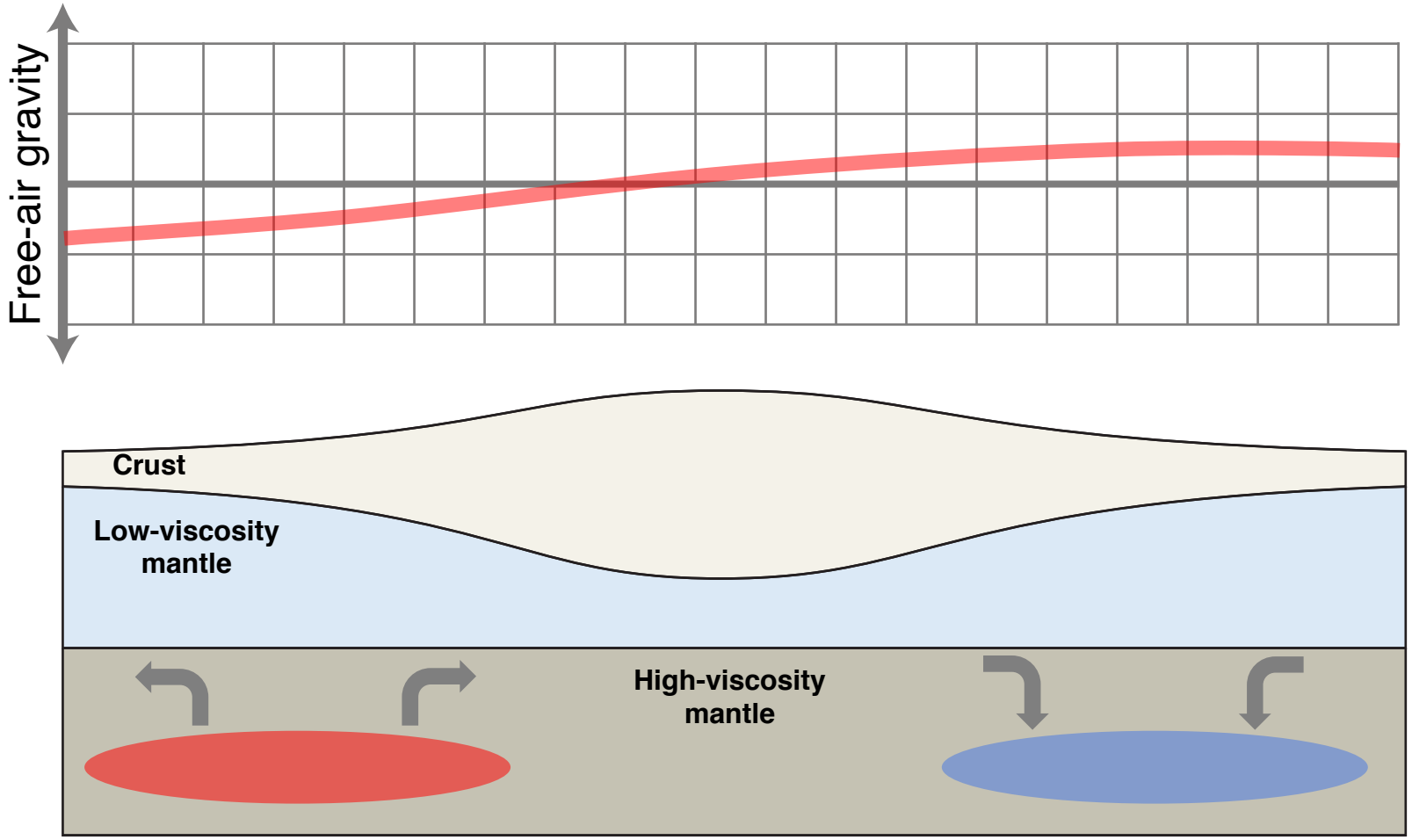
Gravity from a cross-section



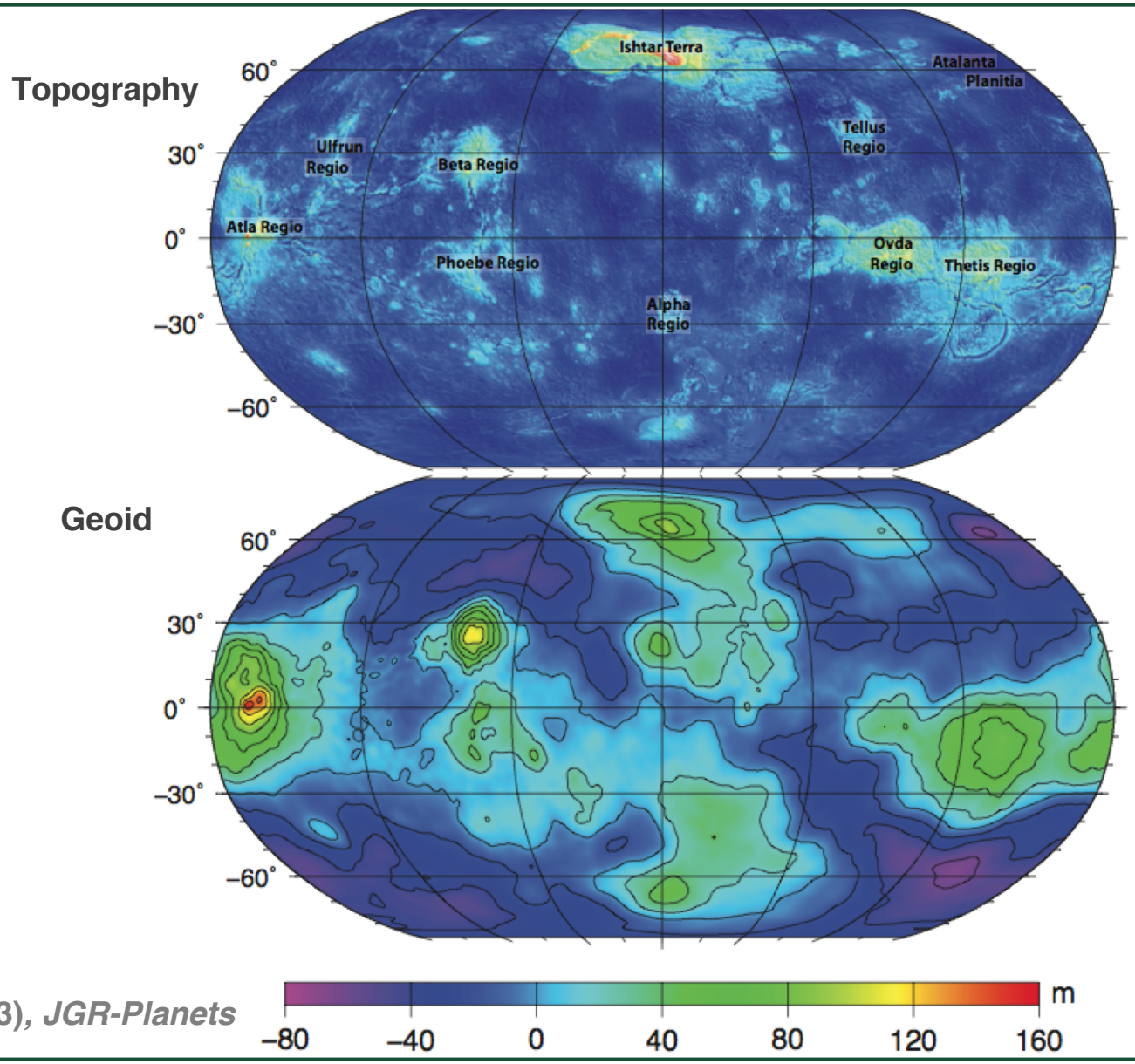
Gravity from a cross-section



Gravity from a cross-section

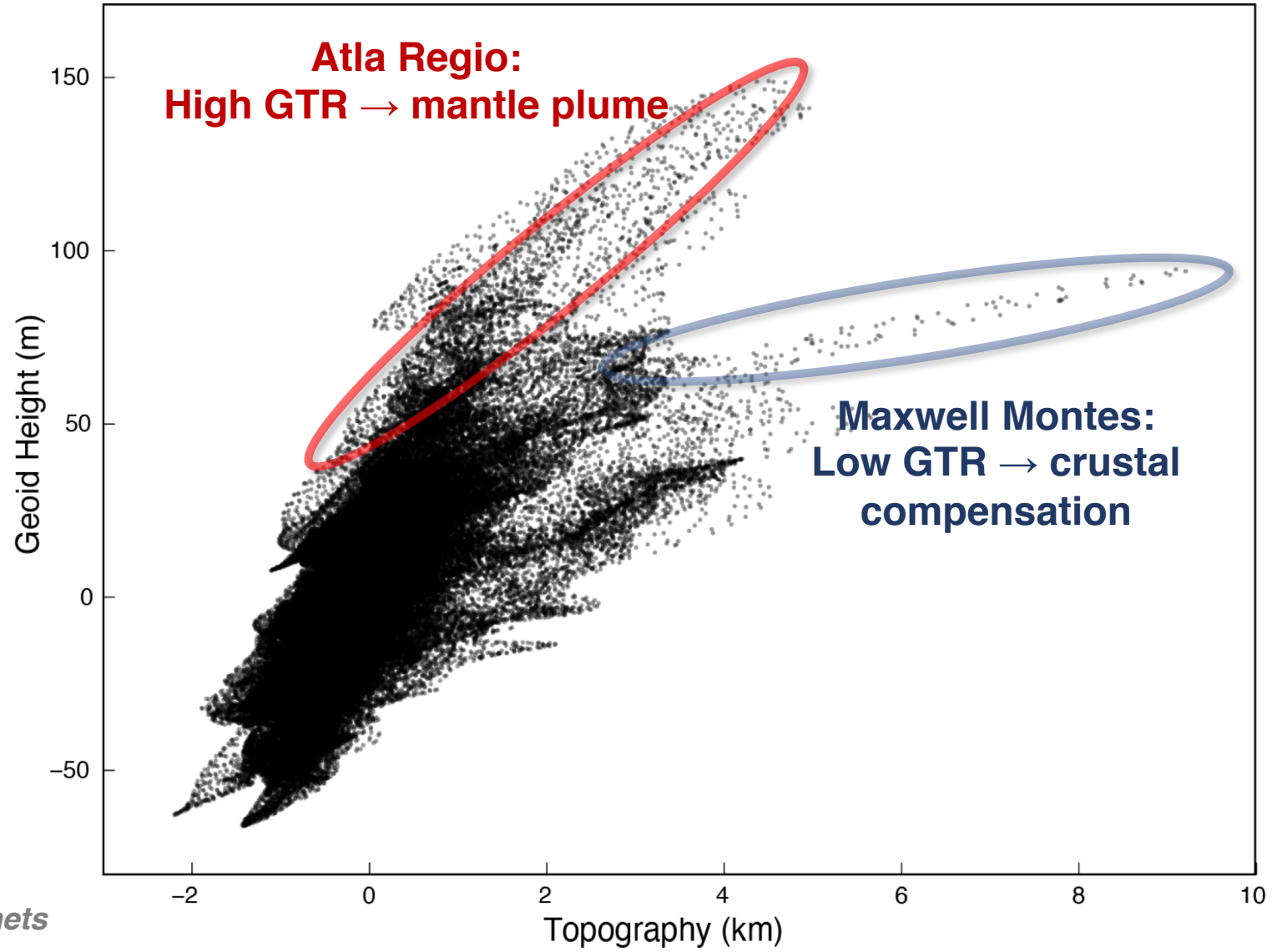


Venus's gravity and topography are highly correlated, even at long wavelengths.



James et al. (2013), *JGR-Planets*

Geoid/topography ratios (GTRs)

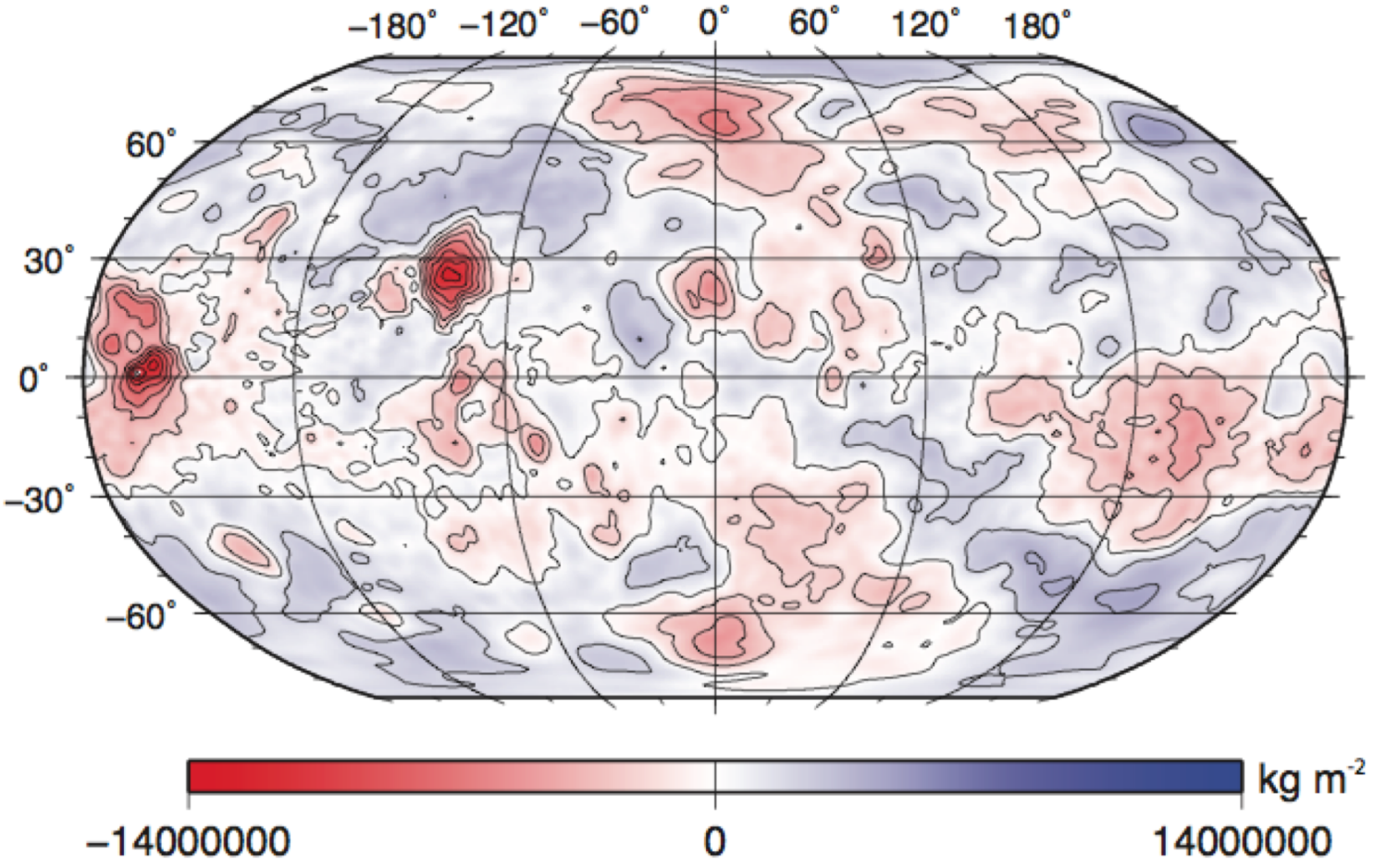


James et al. (2013), *JGR-Planets*

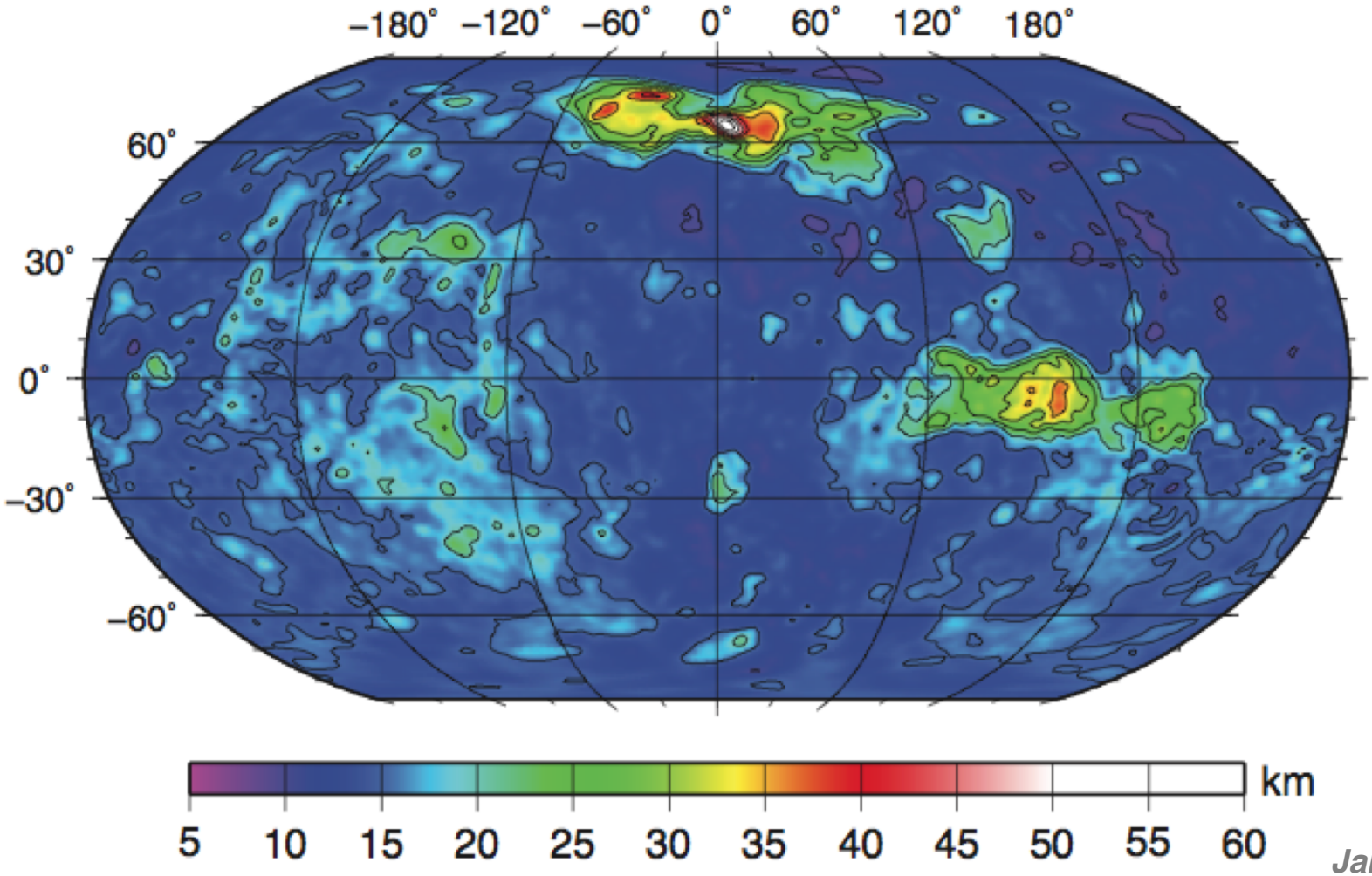
Two-layered models of internal structure

By assuming that non-isostatic stresses are minimized inside Venus, it is possible to isolate the portion of a gravity field arising from mass anomalies in the mantle.

- Banerdt et al. (1986)
- Herrick et al. (1992)
- James et al. (2013)

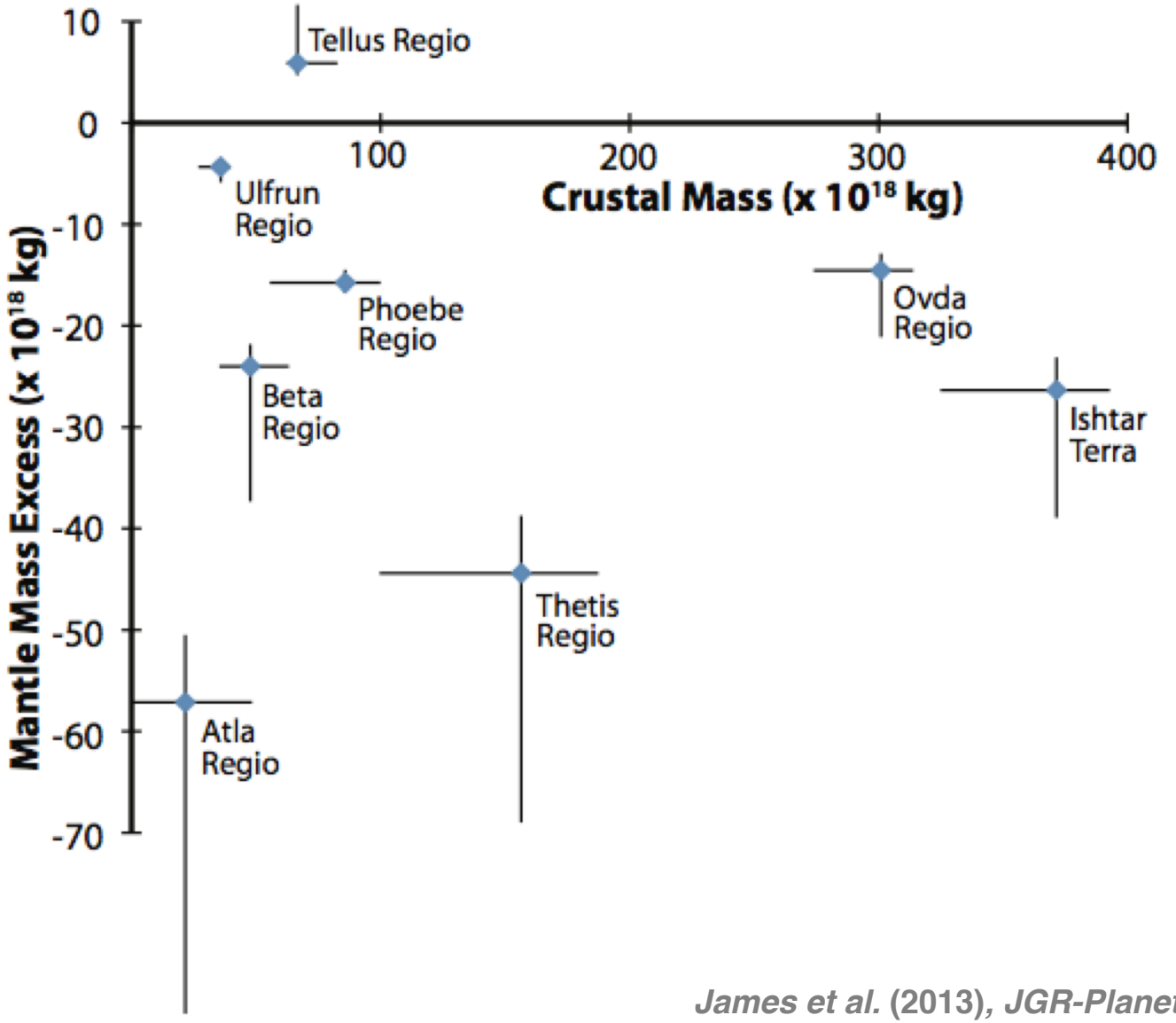


Crustal thickness maps

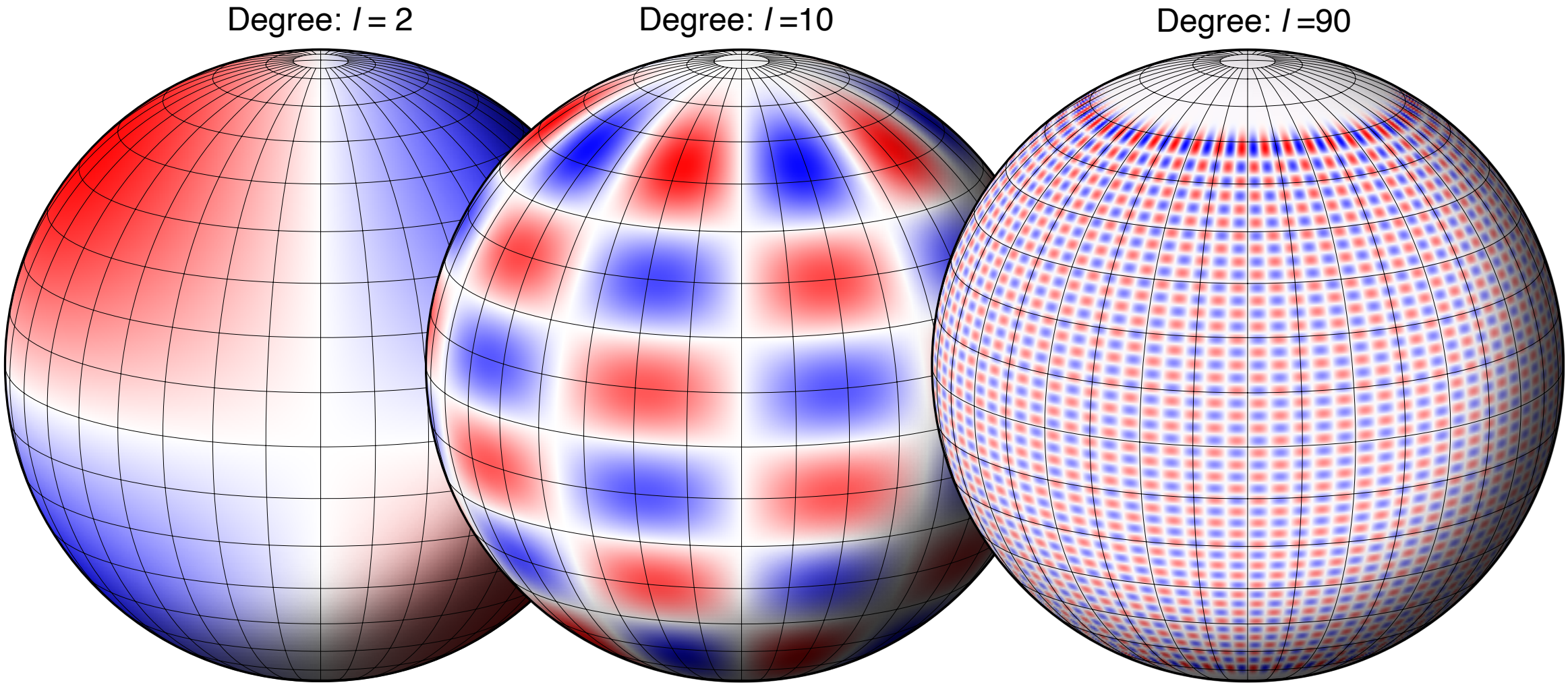


James et al. (2013), *JGR-Planets*

Mantle hot spots correlate with some surface features, including crustal thickness



James et al. (2013), *JGR-Planets*


Degree: l = 2
Degree: l =10
Degree: l =90

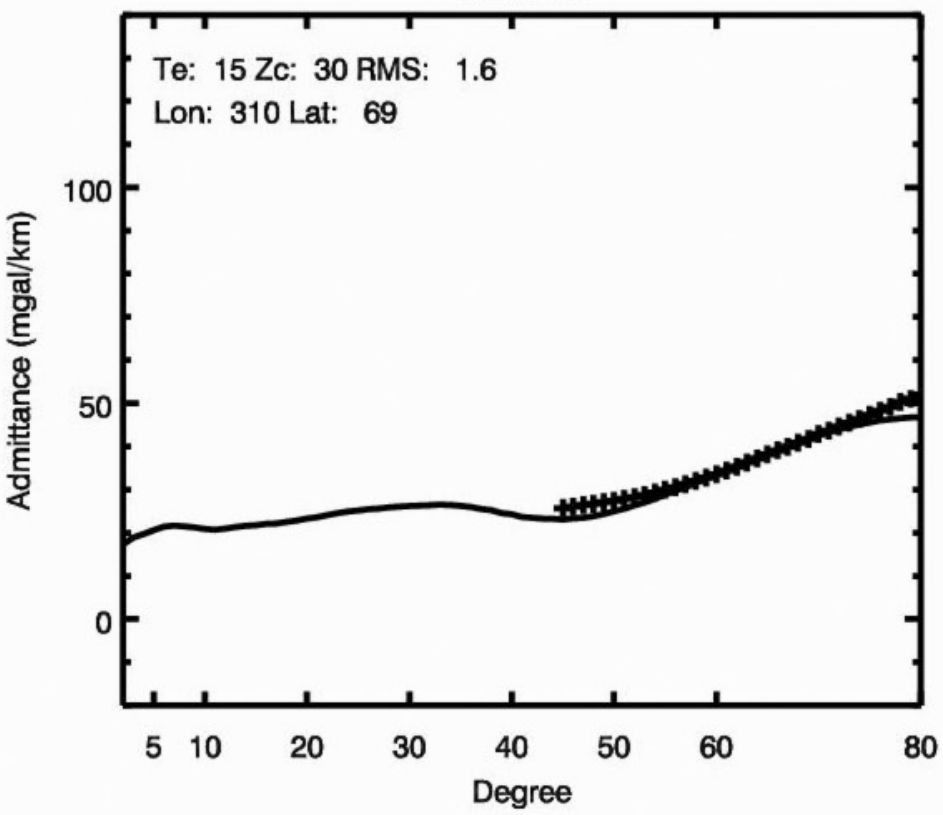
Depth sensitivity of gravity by spherical harmonic degree

The lowest spherical harmonic degrees are sensitive to the entire interior.

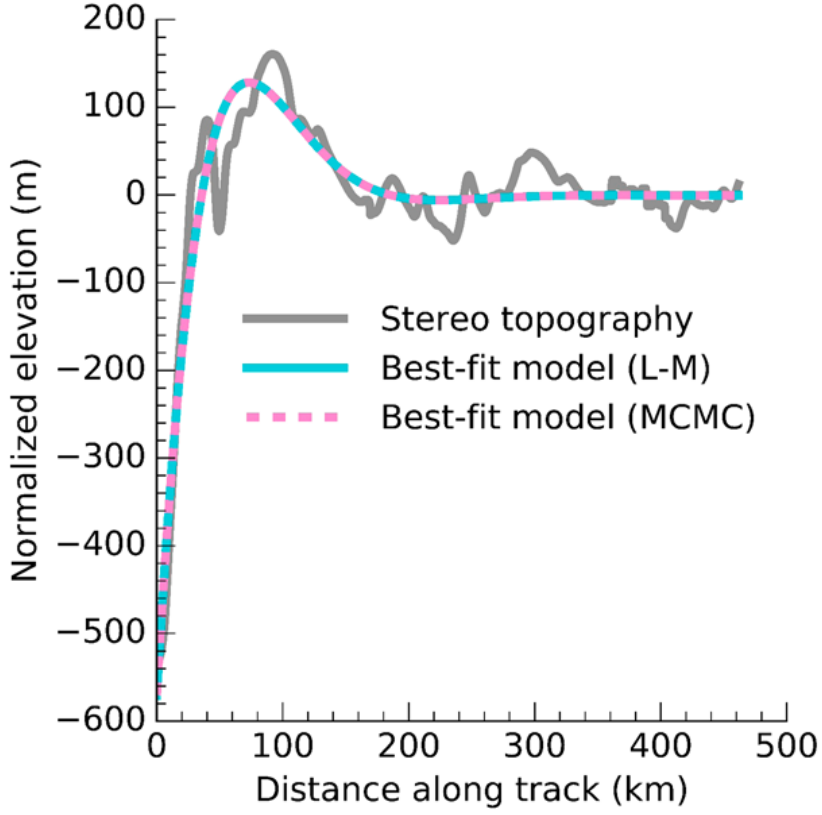
High spherical harmonic degrees are ***only*** sensitive to the shallow crust.

	Crust	Moho	Mantle	Core
$l \leq 2$	✓	✓	✓	✓
$2 < l \leq 30$	✓	✓	✓	
$30 < l \leq 90$	✓	✓		
$l > 90$	✓			

Elastic flexure and the thermal state of the lithosphere



Anderson and Smrekar (2006), *JGR*



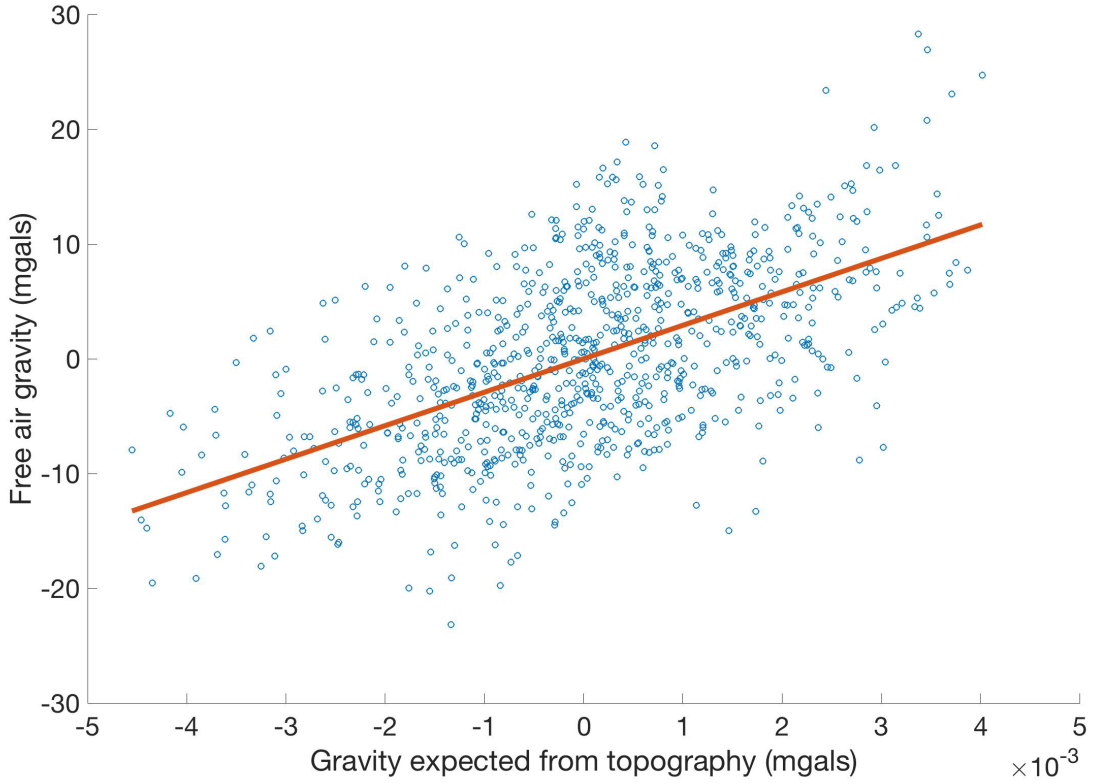
O'Rourke and Smrekar (2018), *JGR-Planets*

Nettleton method of bulk density estimation

Bulk density of Haastse-baad tessera: 2930 ± 800 kg/m^3

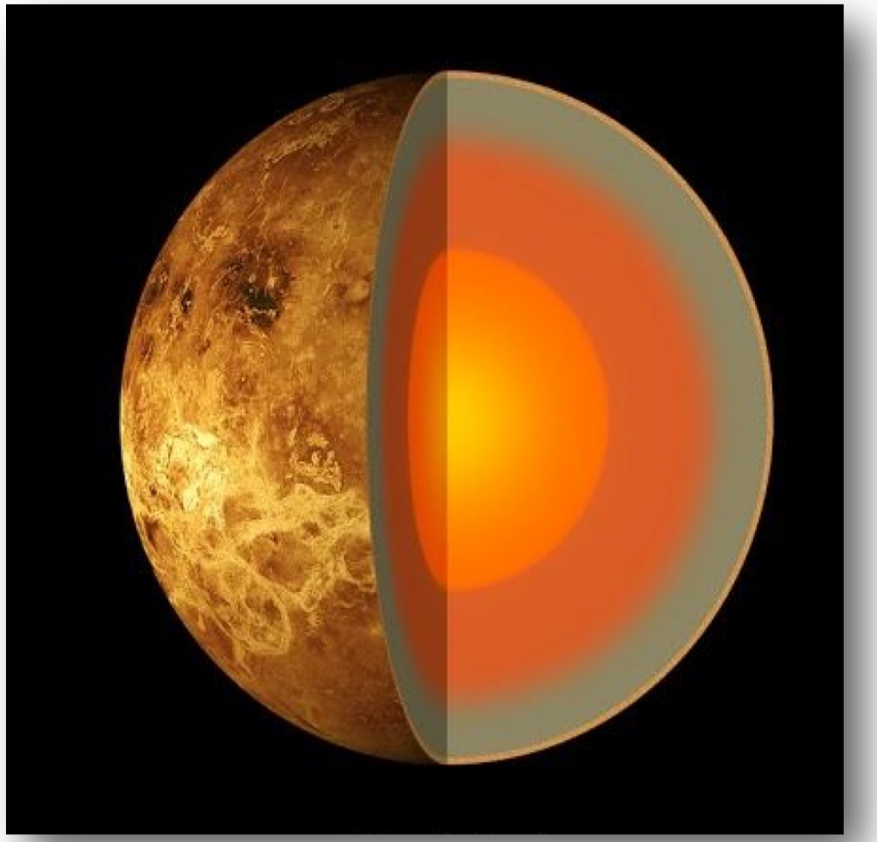
Science reward:

If it could be demonstrated that some tesserae have felsic densities, this would be evidence for a wetter time in Venus's history.



Dame and James (2020), *LPSC*

What is the size and state of the core?

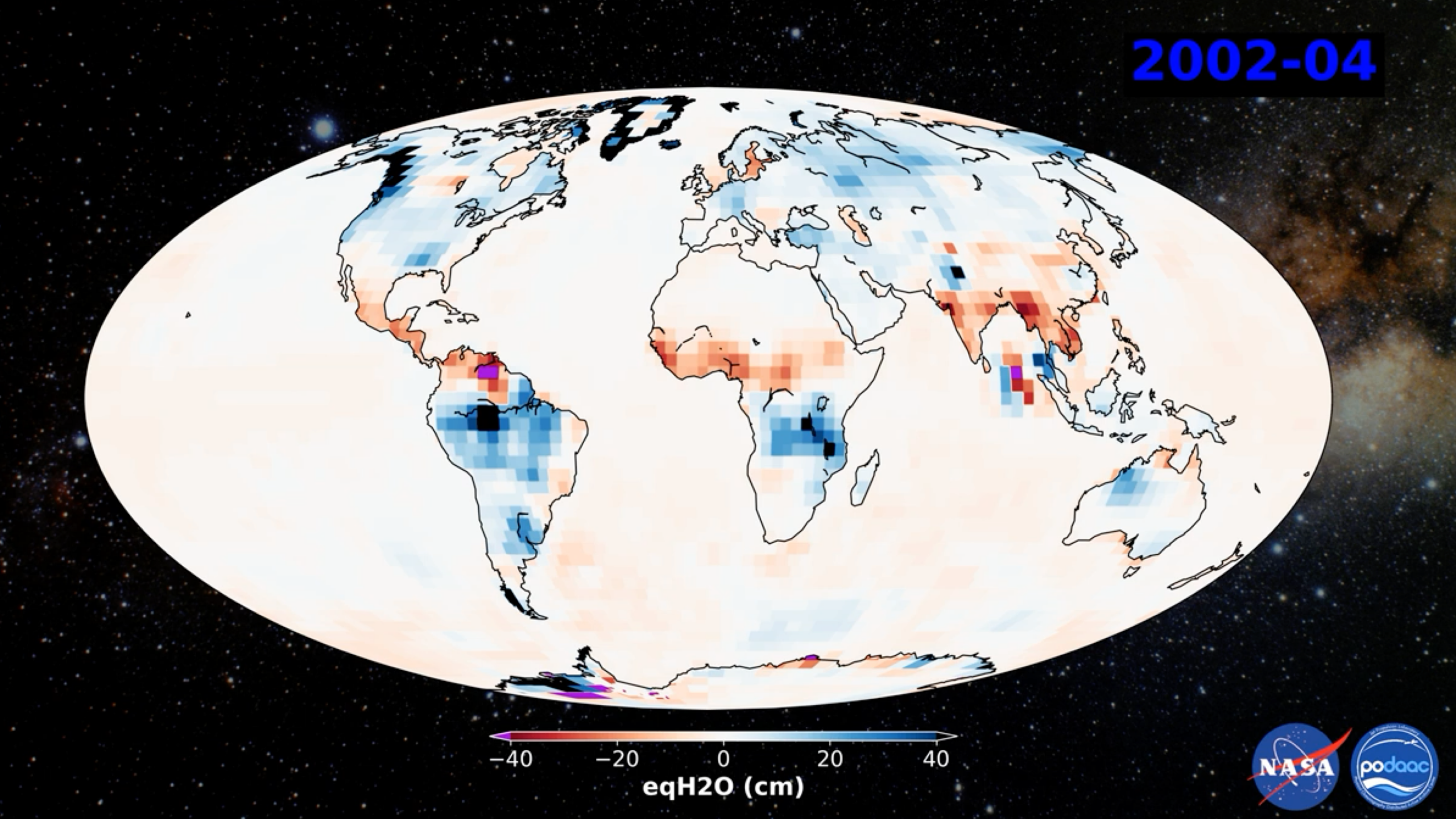


Why doesn't Venus have a dynamo?

Constraints on core size & state (and thus composition) and mantle viscosity can come from:

- High precision Moment of Inertia
- Love numbers
- Phase lag derived from a high resolution gravity field
- Librations (***Margot et al.,* 2021**)

Future insights into time-variable processes

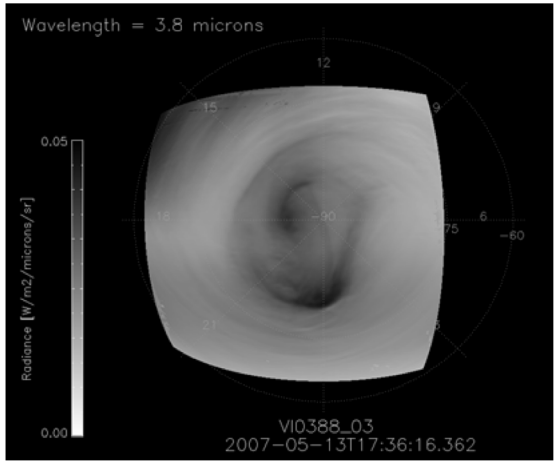

2002-04
−40
−20
0
20
40
eqH2O (cm)
NASA
podaac

Gravity anomalies from atmospheric pressure variations?

Pressure = (Total column mass) x (gravity acceleration)

Gravity anomaly = 2πG x (Total column mass)

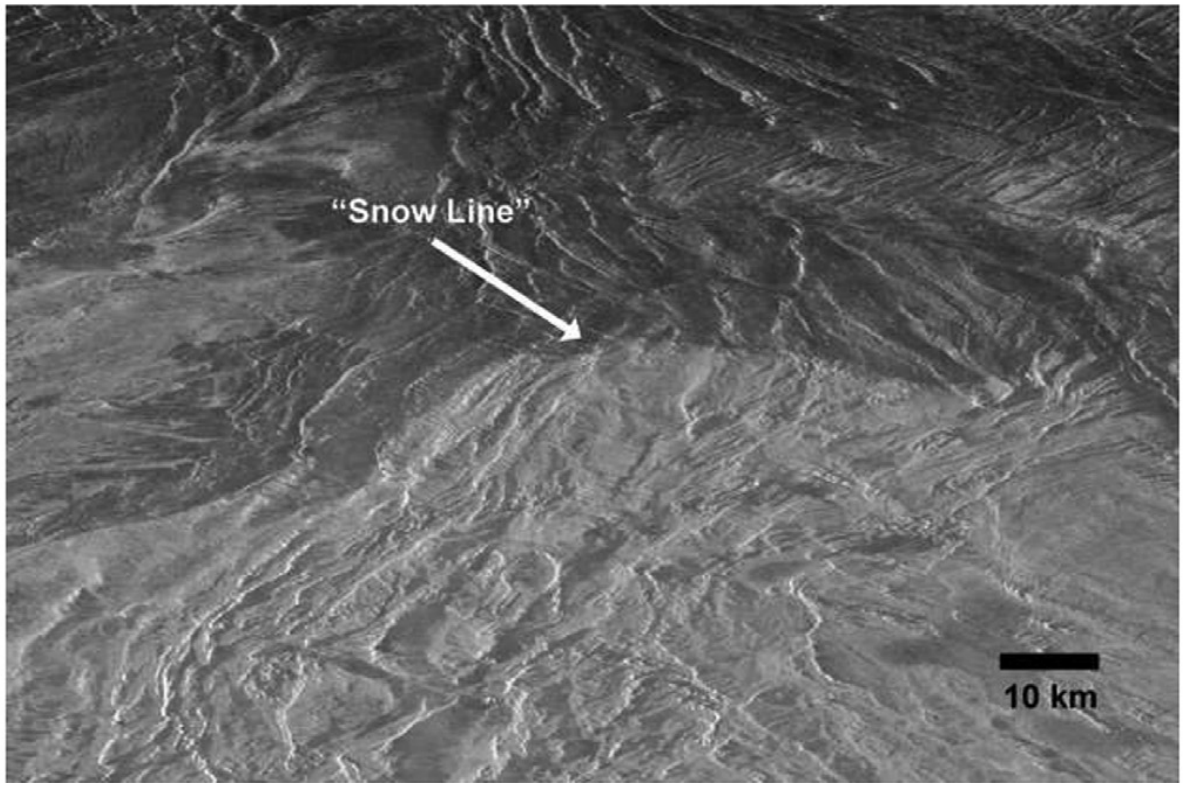
→ ±0.3 bar pressure anomaly = 280 μGal



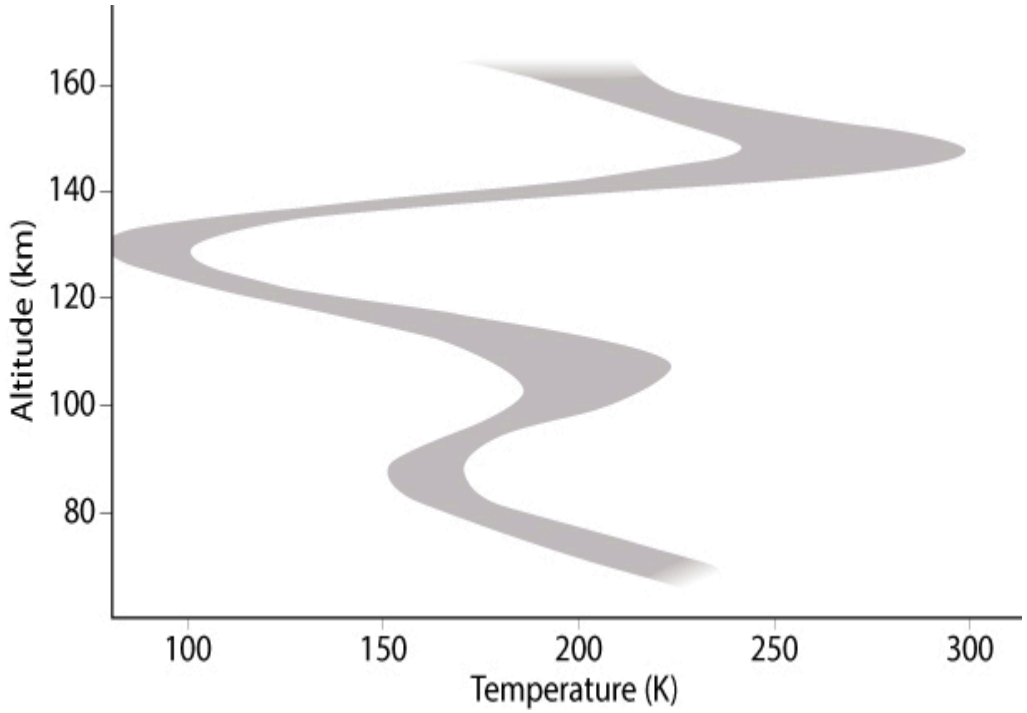
Venus Express VIRTIS

ESA/VIRTIS-VenusX/INAF-IASF/LESIA-Obs. de Paris

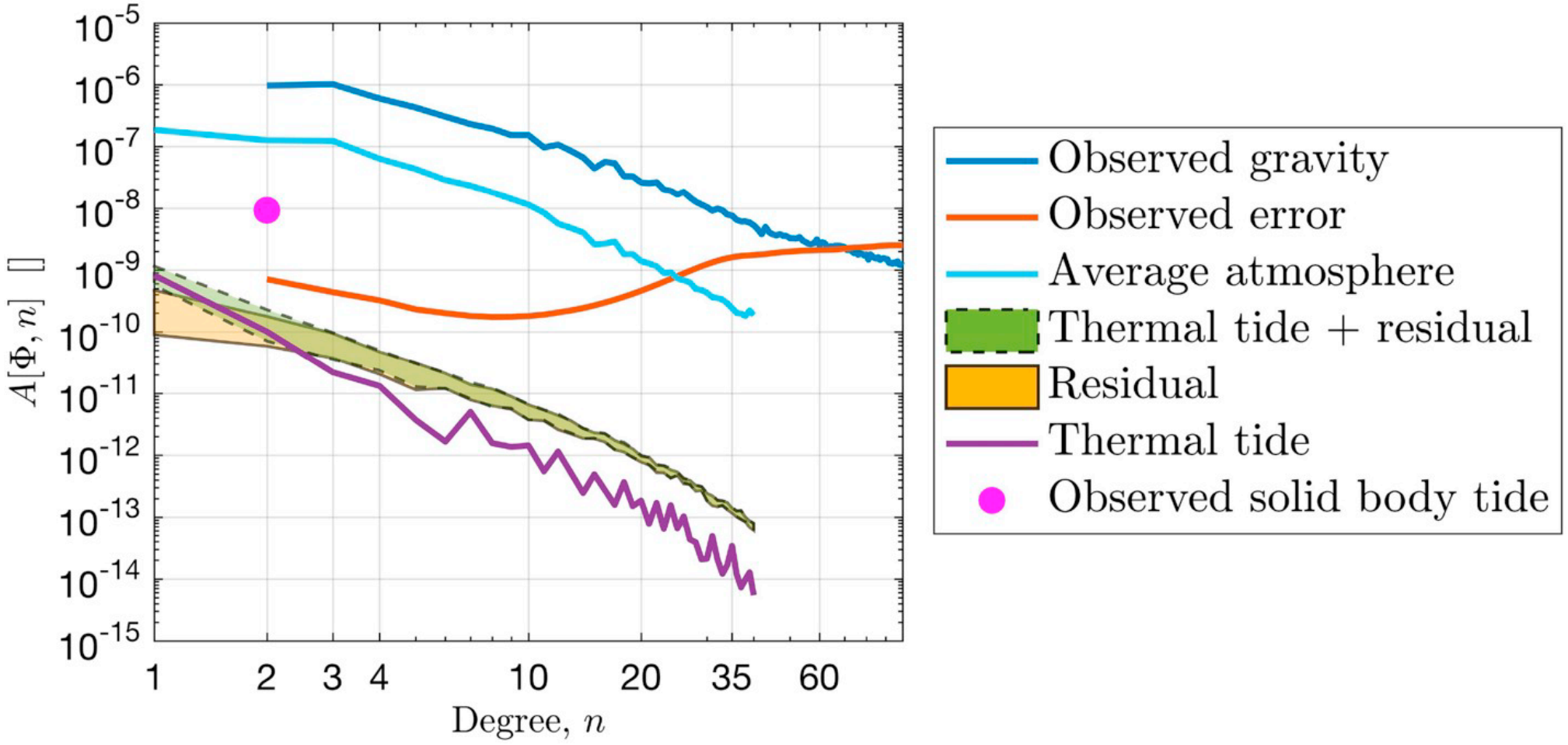
Exotic precipitation?



Treiman et al. (2016), *Icarus*

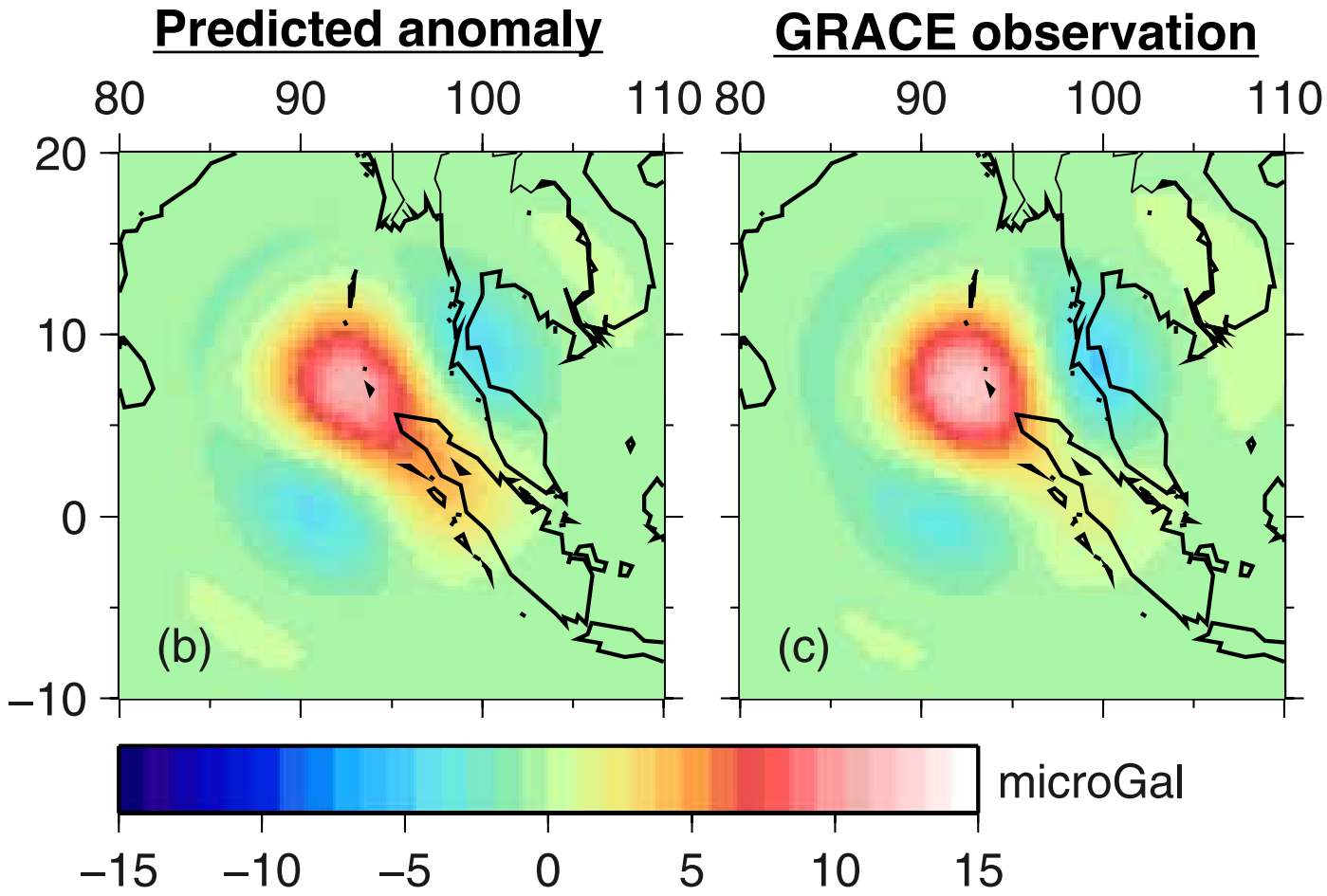


ESA/AOES



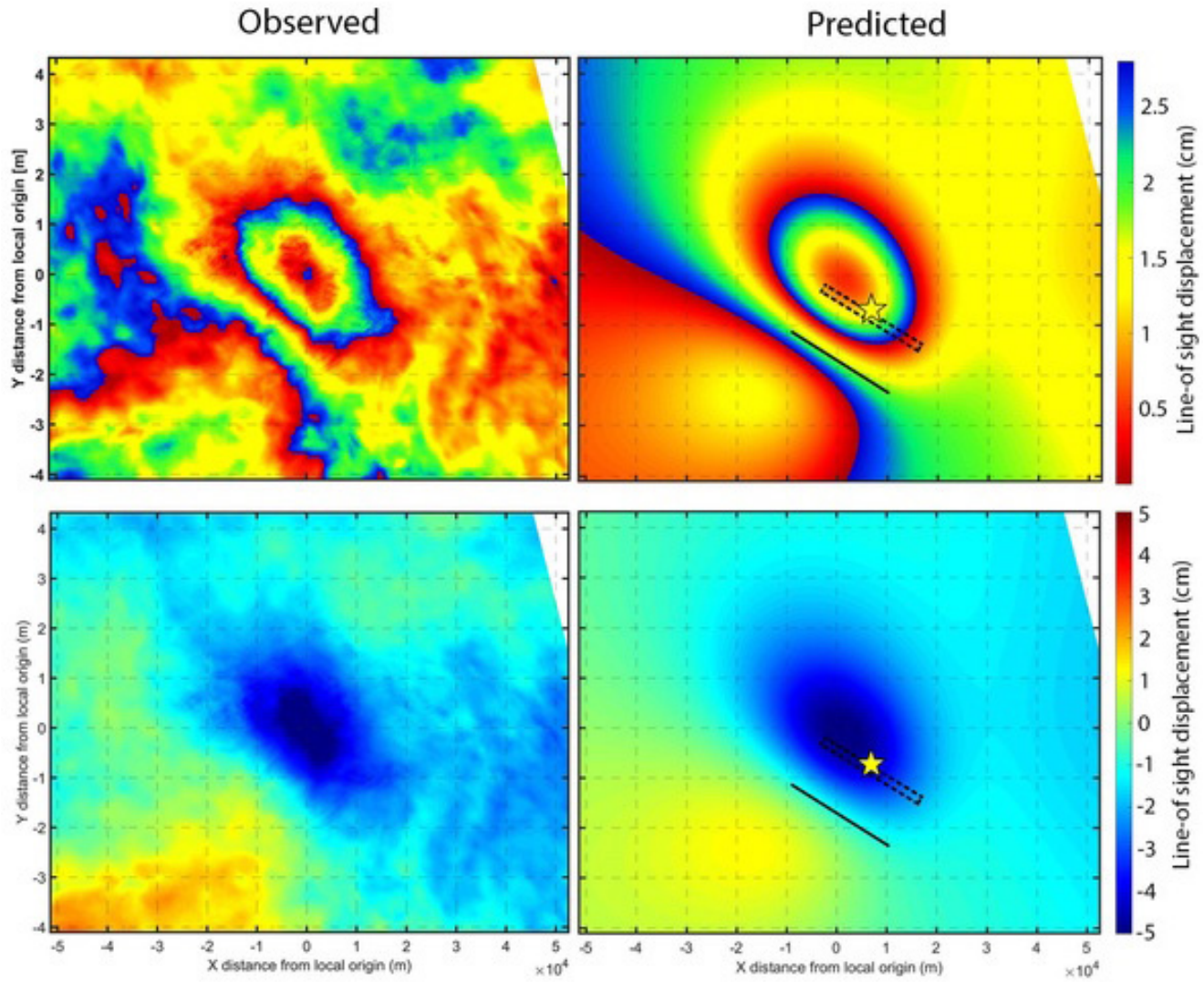
Bills et al. (2020), *Icarus*

Co-seismic gravity



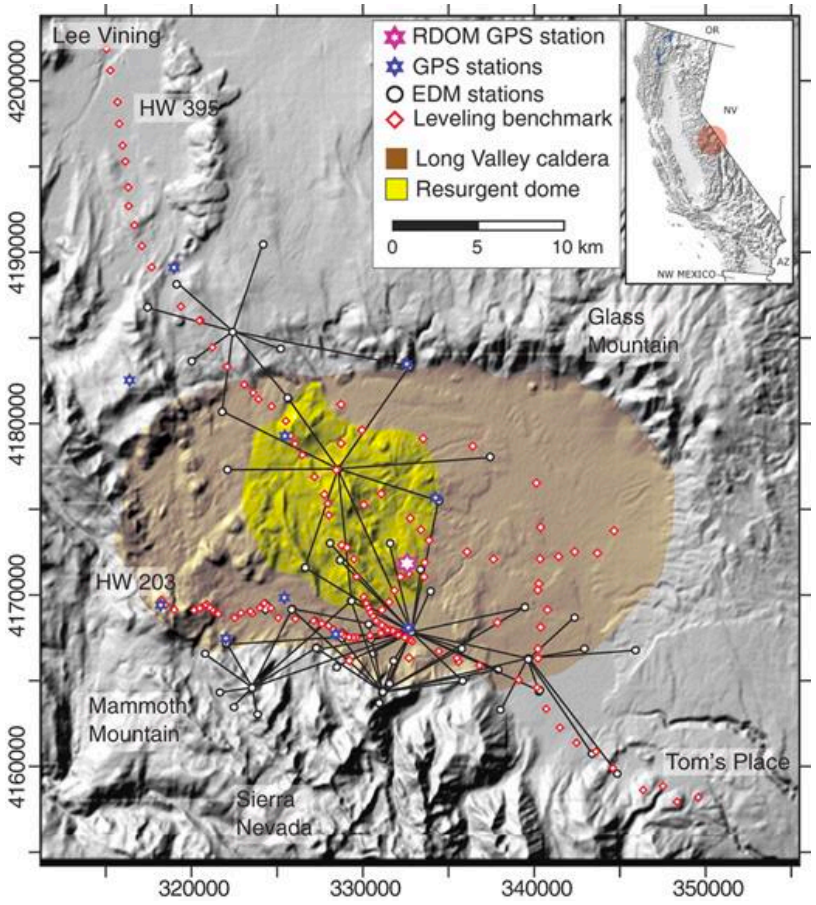
Han et al. (2006), *Journal of Geophysical Research*

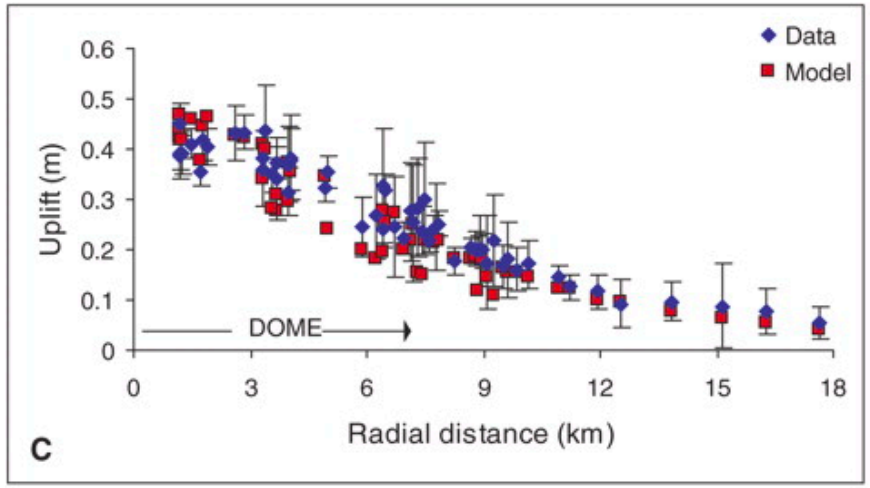
Co-seismic deformation

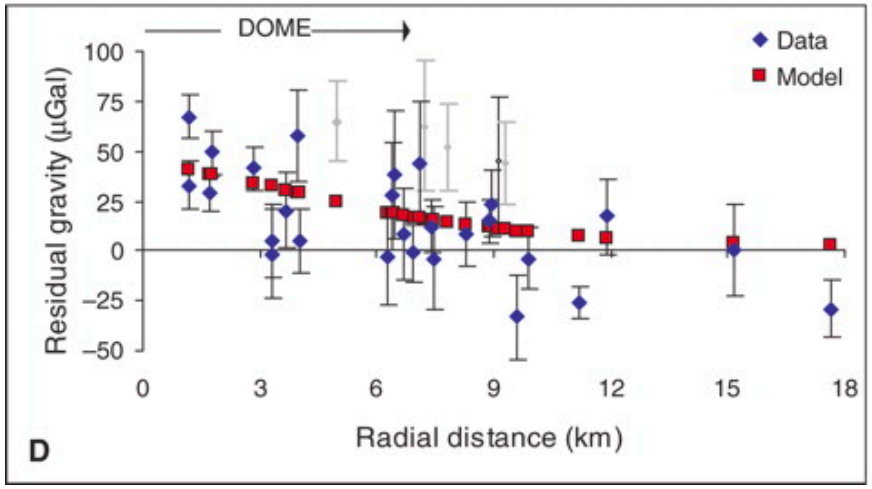


April 2017 Mw 6.5 Botswana earthquake – *Albano et al.* (2017), *Icarus*

Long Valley caldera inflation

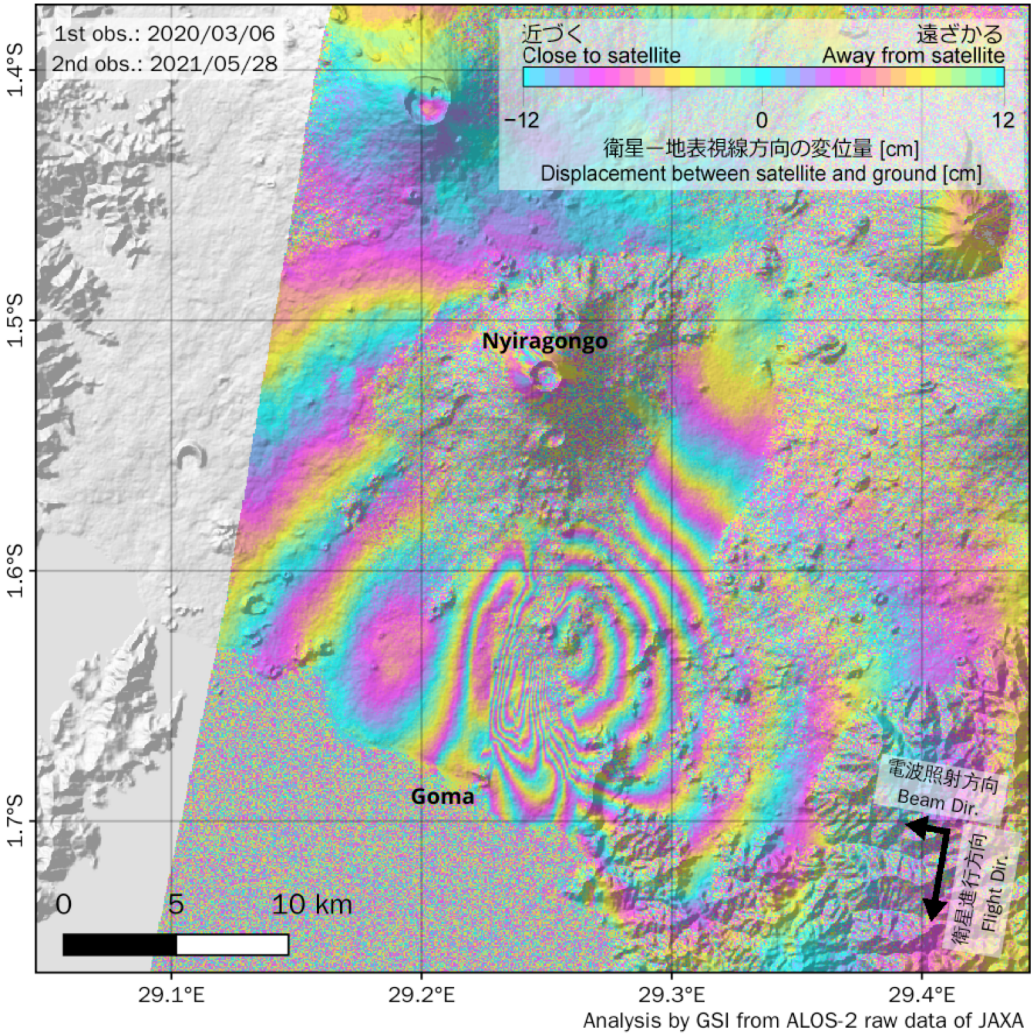


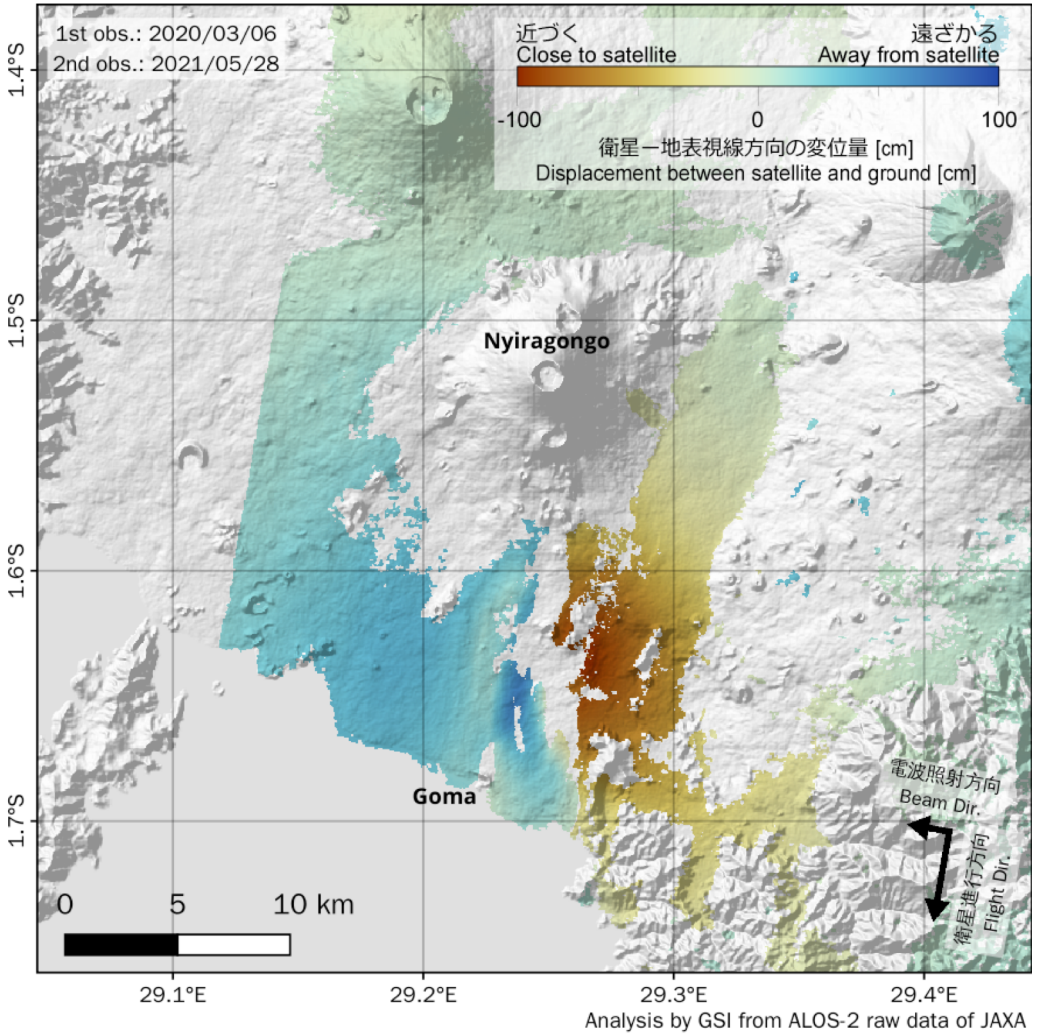




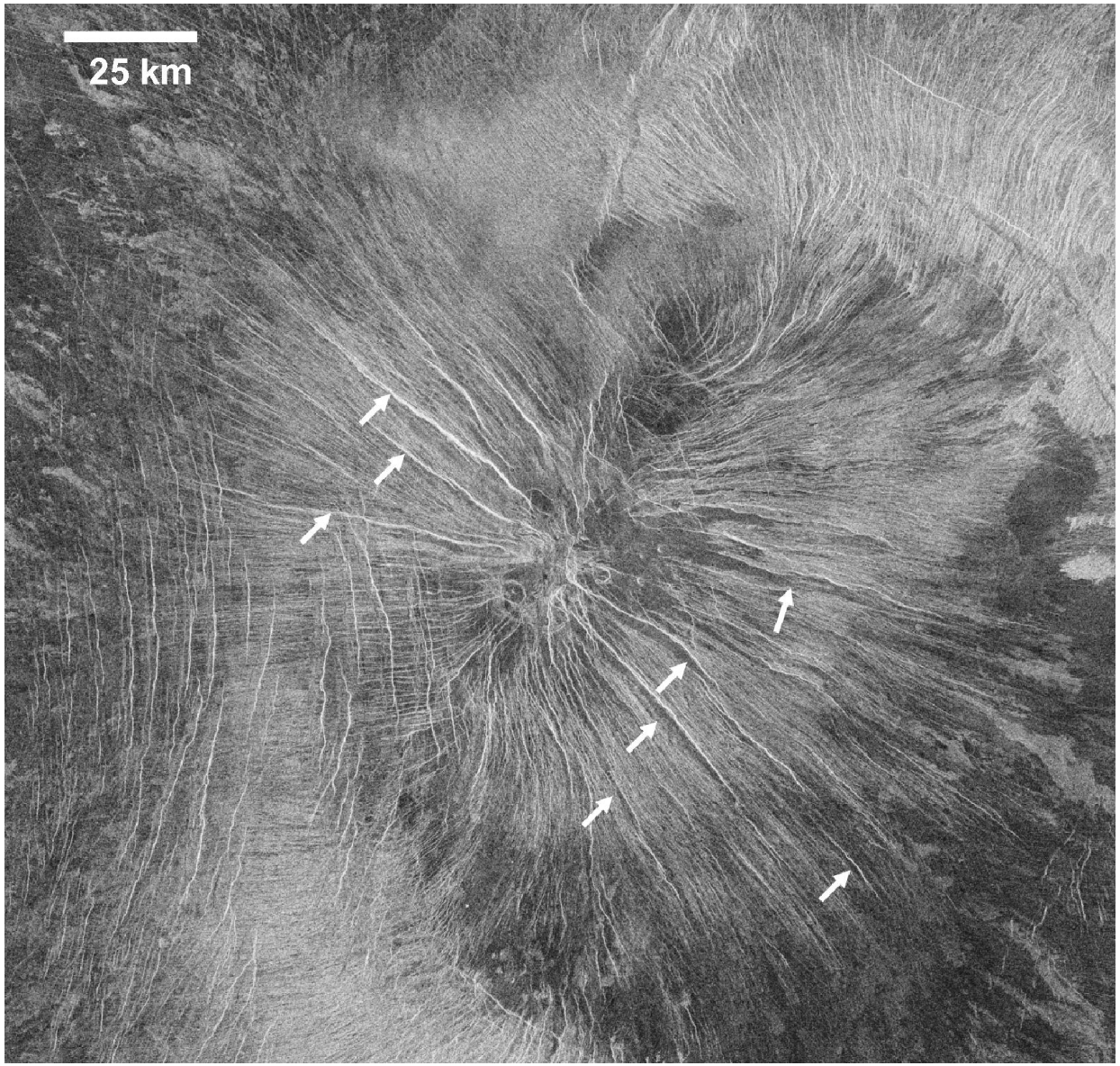
Tizzani et al. (2009), *Geology*

Dike inflation



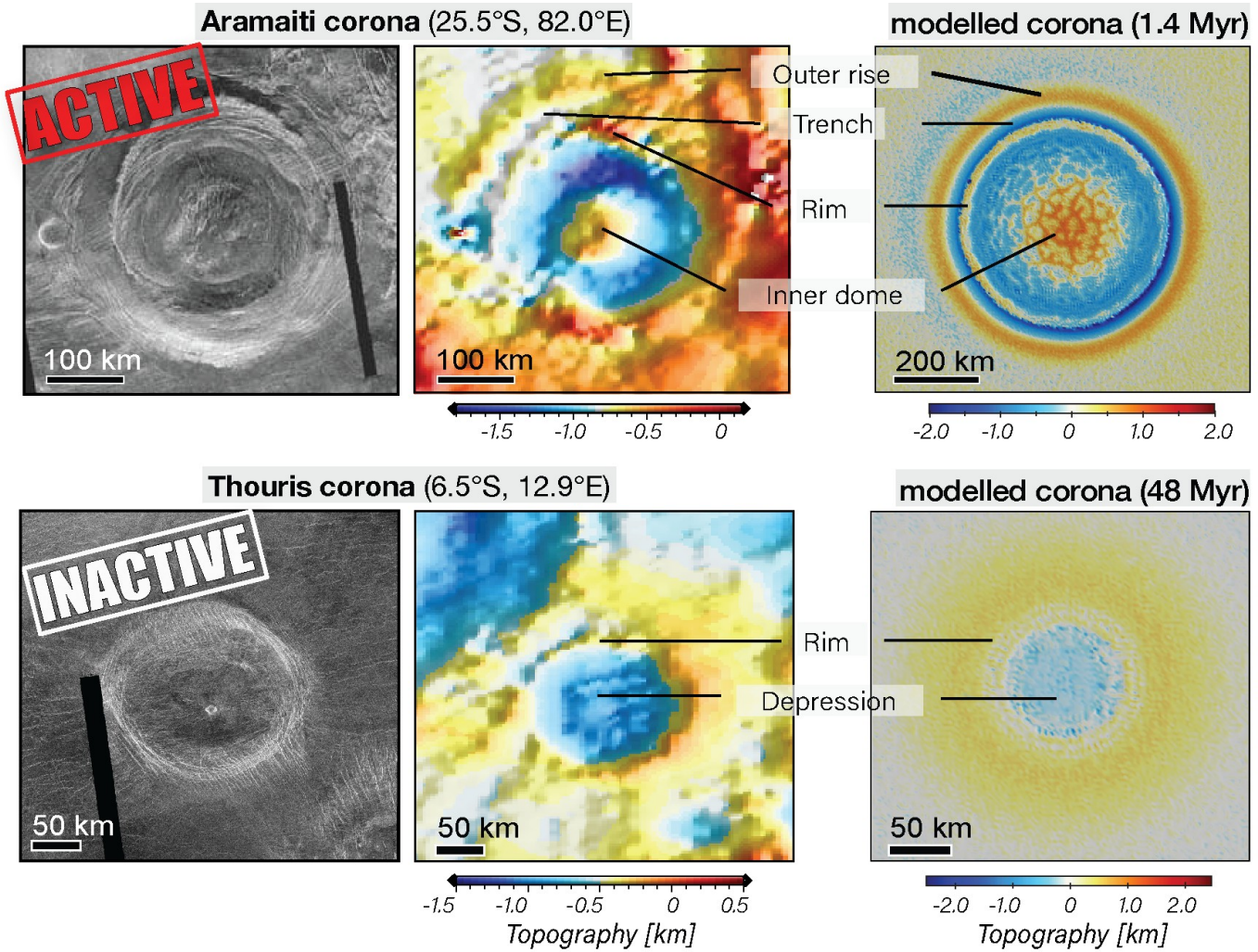


Dikes



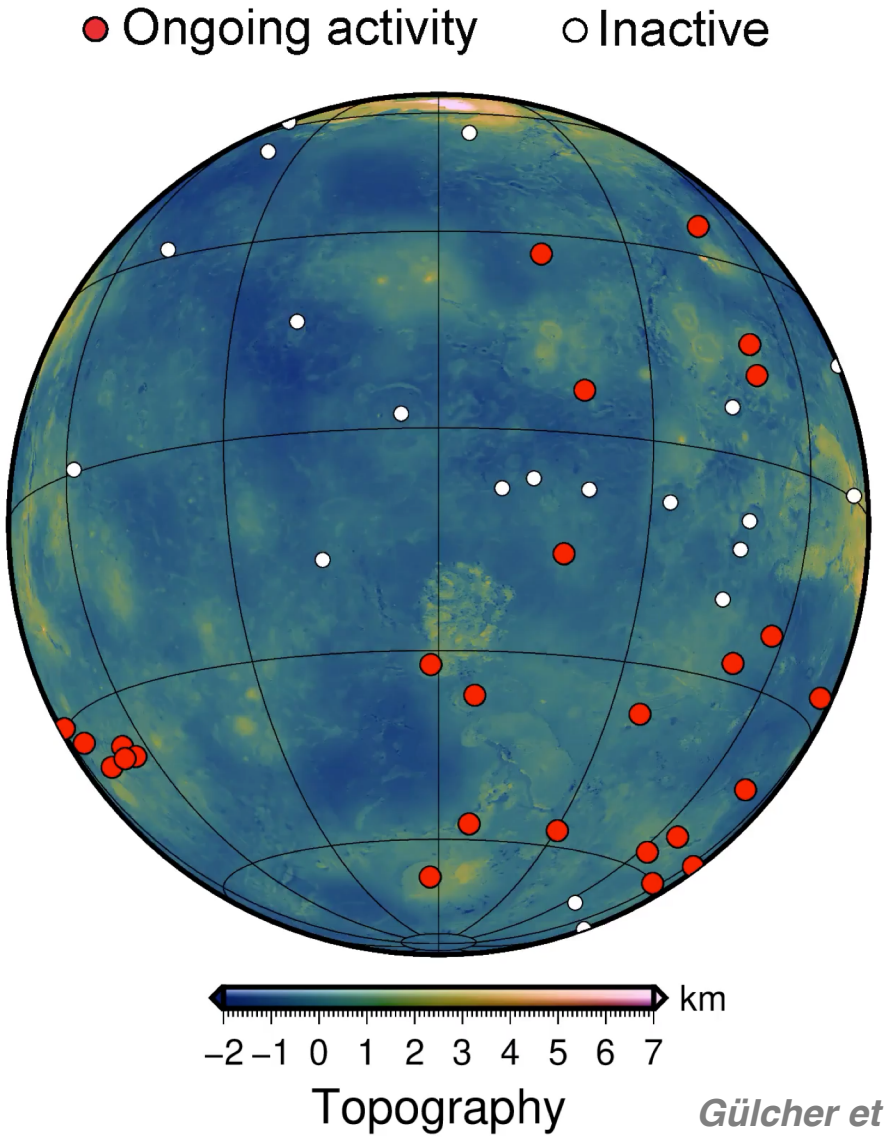
Galgana et al. (2013), *Icarus*

Active corona deformation



Gülcher et al. (2020), *Nature Geo.*

Active corona deformation



Gülcher et al. (2020), *Nature Geo.*

Summary

Existing gravity data has a typical spatial block size of ~270 km, which barely misses many compelling geologic structures:

- Coronae
- Volcanoes
- Chasmata

Improved resolution would also enable techniques for understanding Venus's geology:

- Bulk density estimation
- Elastic lithosphere characterization

Altimetry is difficult on Venus due to the thick atmosphere, and as a result, topographic accuracy and resolution are significantly poorer than those of other inner solar system bodies.

Venus's surface may plausibly experience topographic change at the scale of centimeters to meters, produced by magma chamber inflation, co-seismic deformation, and/or new lava flows.