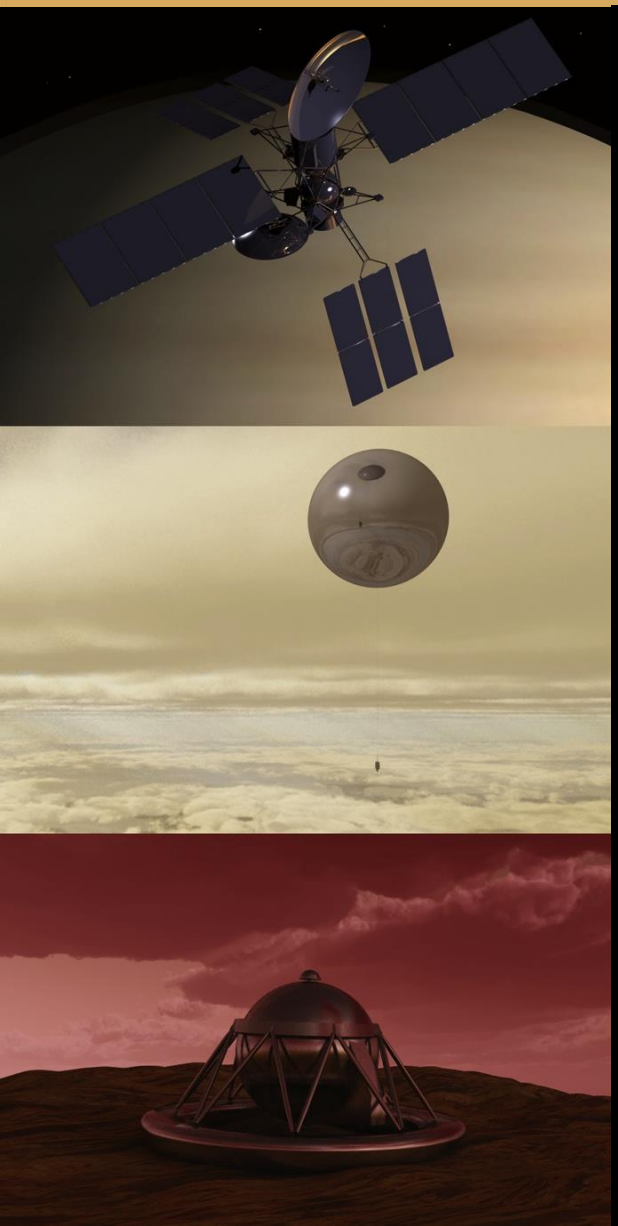
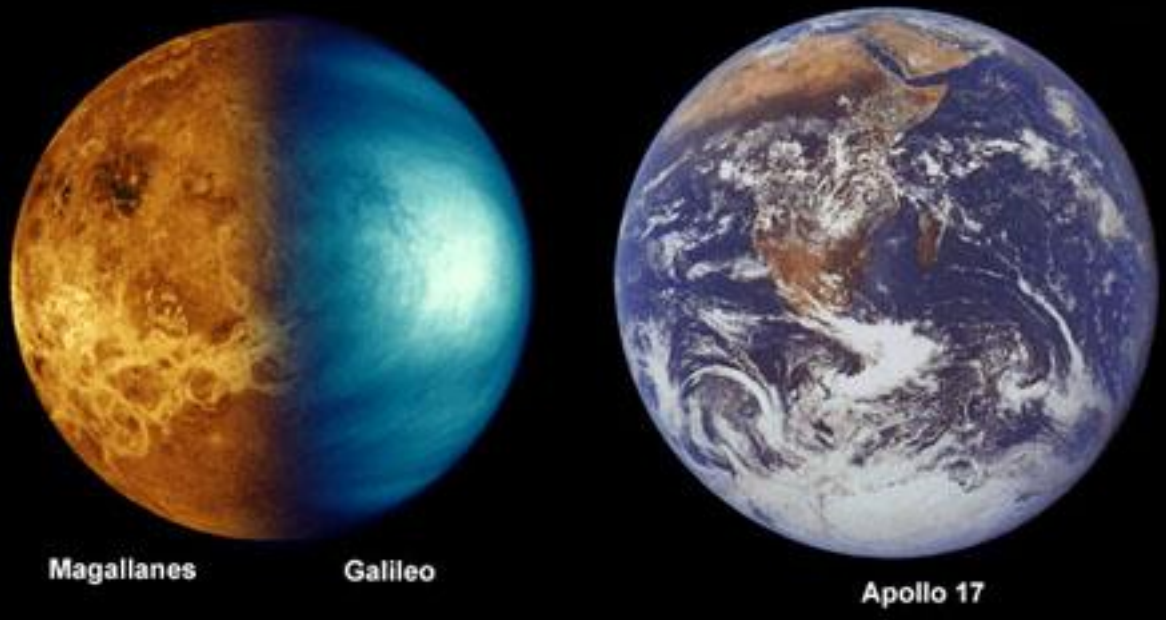


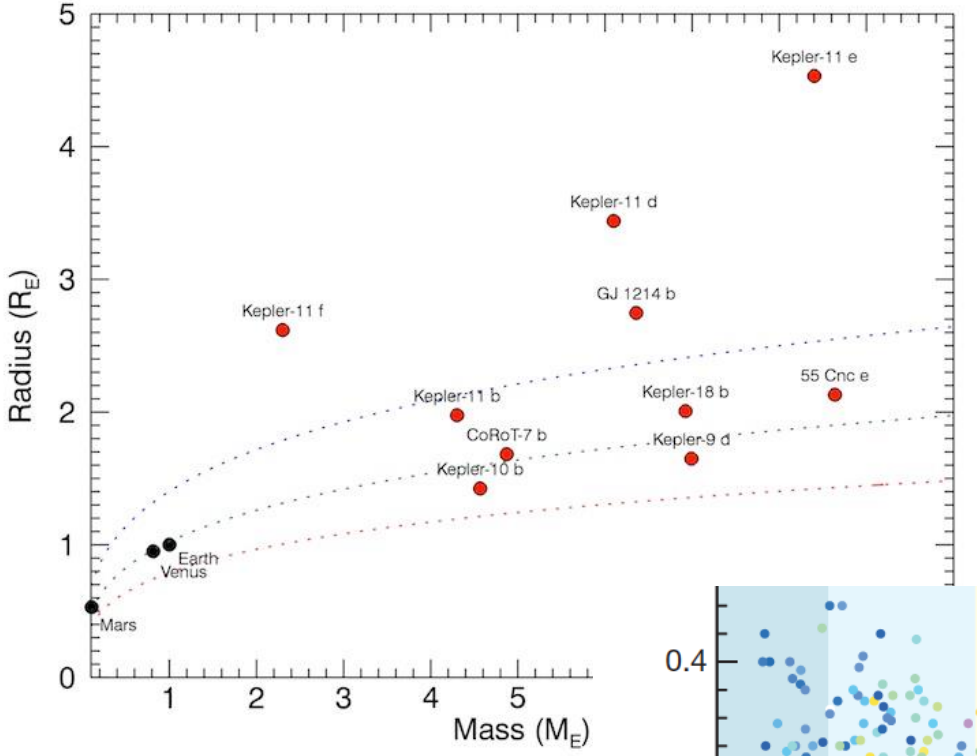
KISS Workshop Venus Seismology Short Course

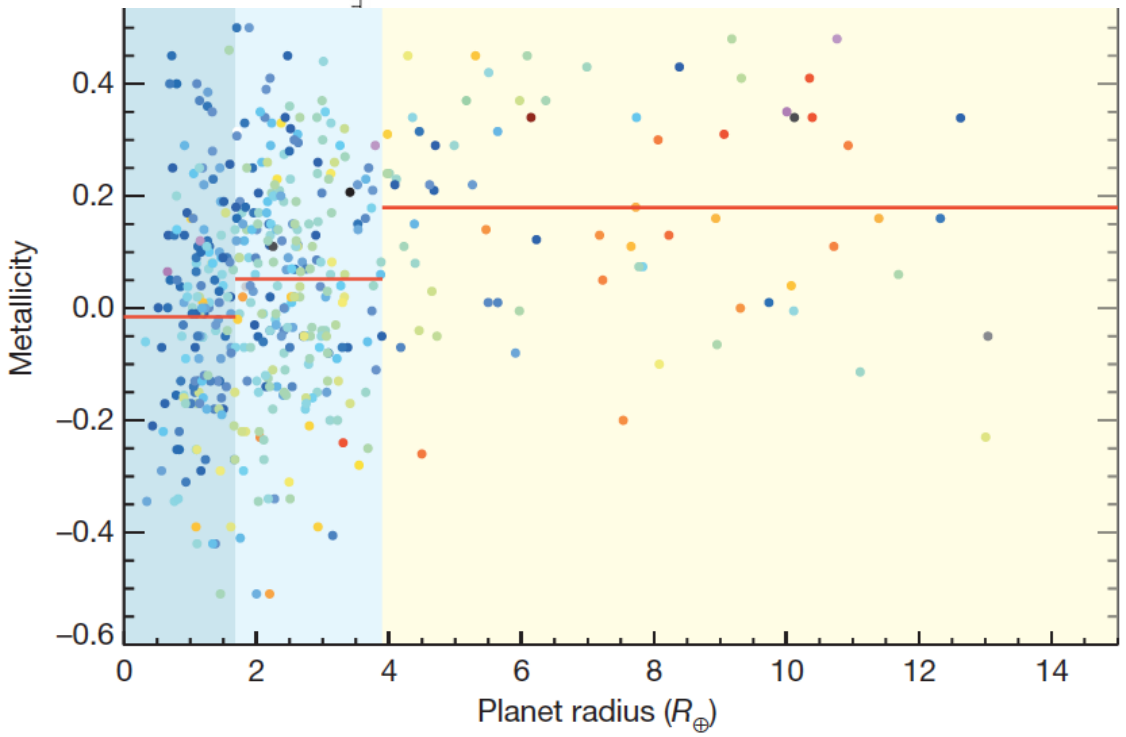
Venus: Major Science Questions

Dave Stevenson, Caltech

Monday June, 2nd, 2014


Magallanes
Galileo
Apollo 17





Buchhave et al, 2014

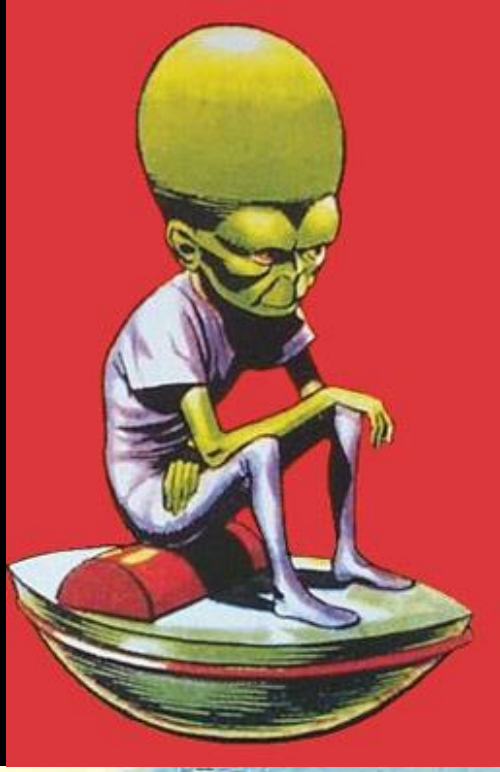
Q. Why do we know so little about Venus?

A. Because it is a hard place to get to know.

Q. Why do we want to know about Venus?

A. Because it is as important as Earth in understanding the formation, evolution and nature of terrestrial planets.


THE FIRST VENUS SERIES
DAN DARE - VOLUME 1
(14 April 1950 - 28th September 1951)

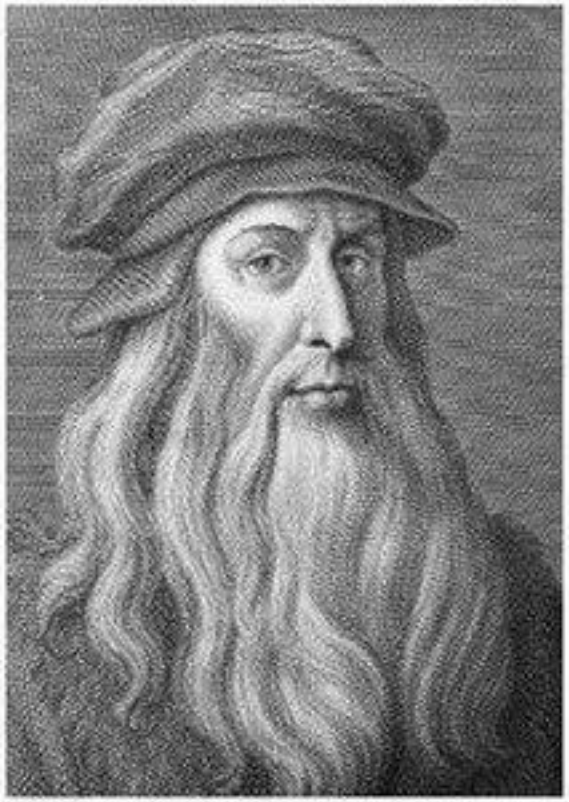


Buyer's Guide

Bad Good Worst

Earth	Venus
6400 km radius	6050 km radius
5.53 g/cc mean density	5.24 g/cc
Basaltic volcanism	Surface consistent with basaltic crust; volcanic constructs
Large Fe-rich Core	Large Fe Core inferred
~100 bars equivalent of CO_2	100 bars of CO_2

Earth	Venus
Thin atmosphere& water ocean	Thick atmosphere and much less water(?)
Plate tectonics	Stagnant lid (but previously mobile?)
24 hr day	243 day rotation period (retrograde)
Large Moon	No moon (requires explanation?)
Dynamo	No intrinsic magnetic field

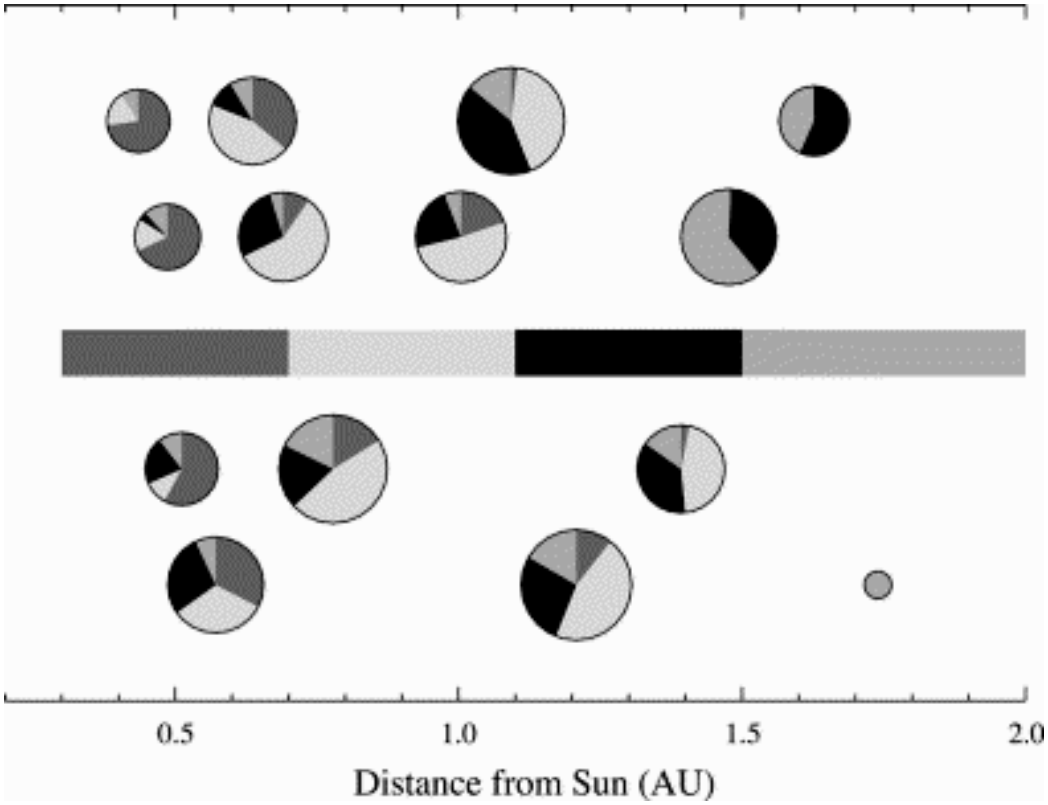


To develop a complete mind:
Study the science of art;
Study the art of science.
Learn how to see.
Realize that everything connects to everything else.

– leonardo da vinci

In current terrestrial accretion models, the material that goes into making Earth or Venus comes from many different regions…

It is **very unlikely** that the Venus is substantially different from Earth but it is **very likely** that Venus started out somewhat different from Earth ***by chance***



Results from Chambers, 2003
(Similar results from Morbidelli)

What do Planet Formation Stories tell us about Venus-Earth differences?

- It is not difficult to make models where Earth ~Venus in mass & composition
- It is difficult to make models where Earth is different from Venus in bulk composition
- It is difficult to make models where Venus receives much less water than Earth
- Isotopic differences are diagnostic
  - Oxygen isotopic difference, if any, would be of interest

Subject: stone
Date: Sat, 10 May 2014 15:40:11 +0400
From: сергей шлабович
<s.t.shlabovich@mail.ru>
Reply-To: сергей шлабович
<s.t.shlabovich@mail.ru>
To: djs@gps.caltech.edu

Dear Mr.Stevenson,

Perhaps you are interested in rock from Venus? This turbidit with andesitic composition. I can offer you the results of isotopic analysis for oxygen.
Stone, of course, is a meteorite.

Sergei Shlabovich.

Why Venus has no Moon?

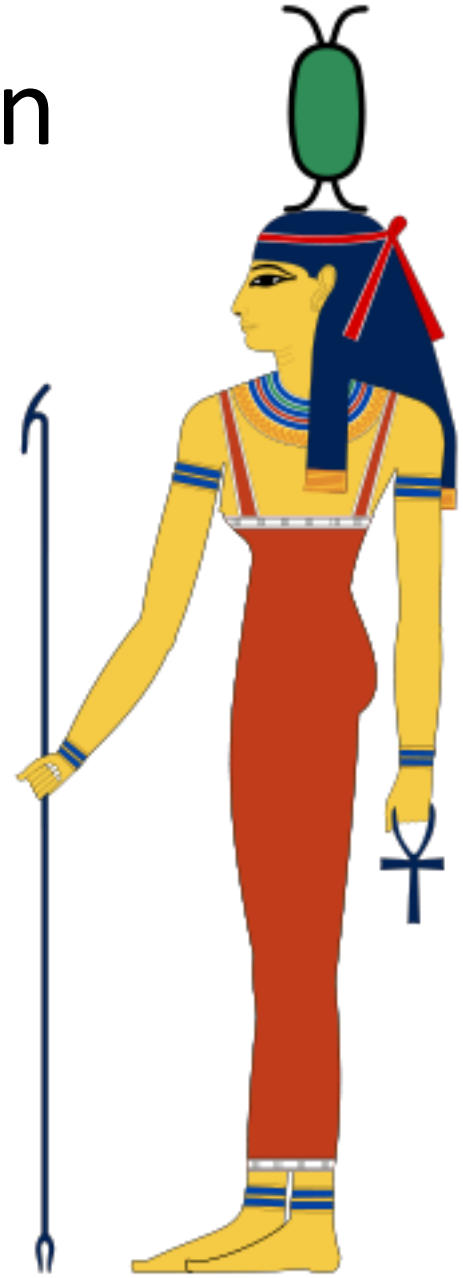
- Never had one (certainly a possibility)
  - BUT why then does Venus have such low spin?
  - Standard story for this is questionable
- Had one and lost it early on
  - Escaped & subsequently crashed
  - Spiraled in & crashed
- WORKING HYPOTHESIS:
  - Giant impacts that make moons are common
  - Earth-Moon differs from Venus-Neith in that it was the last major event in the terrestrial zone. This is suggested by isotopic evidence

Neith - Venus' Moon

- "Discovered" by Cassini in 1672
- "Confirmed" by Lagrange in 1761
- Named after Egyptian goddess
- Consistent with philosophy of the time wherein other planets should have Earthly attributes

The Moon that Wasn't

Helge Kragh (2008)



Letter from d'Alembert to Voltaire in 1761

"I do not know what has happened to the lackey* of Venus. I am afraid it cannot be a hired lackey which has ceased to stay with it a long time, but rather that the said lackey has declined to follow his mistress during her passage over the Sun."

*valet in French

What would happen if you placed Earth-Moon at Venus orbit (4.5Ga ago)?

- Moon stays well within Hill sphere of Venus –escape does not seem likely in any unperturbed story
- Moon+Sun do not despin Venus to orbit period=spin period (unless tidal Q is Earthlike, which is very unlikely)
  - It must be conceded , however, that our ignorance about tidal Q's is very large! (In general, not just in this case!)
- But if you increase moon mass by factor of 2 (or decrease initial angular momentum budget by factor of 2) then moon would end up absorbed by Venus.. Incompatible with observed low spin; might also leave a signature on surface

A Story to Consider

- Giant impact led to Neith. This impact occurred earlier than the Earth-Moon event (perhaps only ~10 Ma after solar system formation)
- Moon evolves out quickly to 10 or 20 Venus radii.
- This reduces the spin of Venus
- Large impactors (~Mars mass) still present; one will eventually impact Venus (without making another Moon?)
- But close encounters are much more common than impacts… what are the consequences? Can further reduce the spin or eject the moon.

Rotation State of Venus

- Slow rotation more significant than retrograde rotation
- Balance of solar solid body and thermal tides
- Plausible but not firmly established; would in any event imply small changes with time that we should seek to measure
- Length of Day (LOD) variations can be diagnostic of atmospheric-interior coupling
- True Polar Wander (TPW) should be fast… geodetically detectable?

Origin of the Atmosphere

- Presumably (as with Earth) part of primary accretion
  - "late veneer" is a minor component for Earth; of interest to establish its presence for Venus
  - Comets also minor?
- Ingassing of solar nebula of interest (e.g., Ne isotopes)
- History of outgassing related to volcanism ; expressed in noble gases

Where has All the Water Gone?

Long time passing…

- Delivery seems likely
- Surface & crust are dry
- “Runaway “ greenhouse likely but not assured
  - More correct to say that Earth “healed” and Venus did not?
  - 2D models needed? LeConte et al , 2013.
- What about the interior?
- Loss from the atmosphere
  - Water photolysis and hydrogen loss affected by presence of CO_2 (e.g., Wordsworth &PierreHumbert, 2013)
  - Magnetic field may matter? (Did early Venus have a dynamo?)

Thermal Evolution

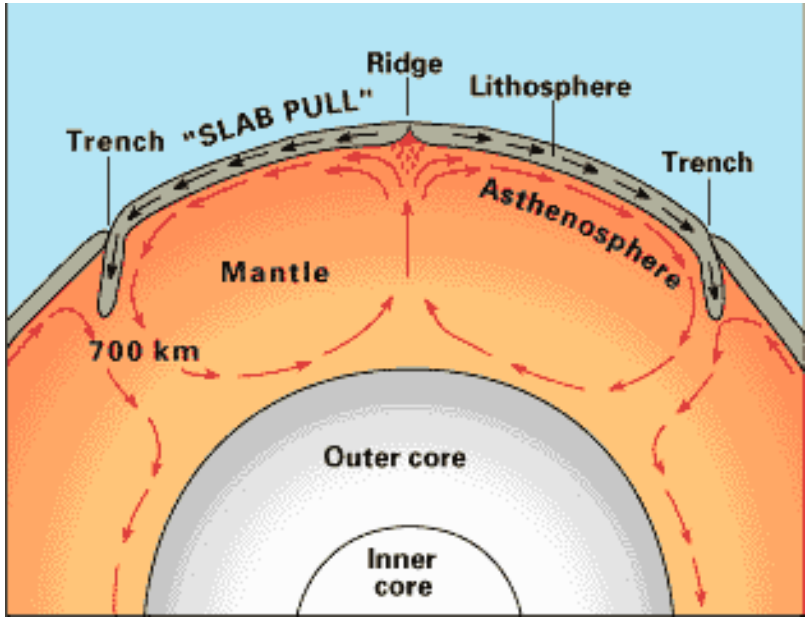
- Mantle Convection is obligatory
- Differentiation and Liquid core is assured (theory)
  - No observational evidence!
- Igneous activity assured
  - Style of volcanism is unclear though plume-like activity is popular in modeling
- Surface mobility is not assured
  - No plate tectonics
  - Stagnant Lid is likely

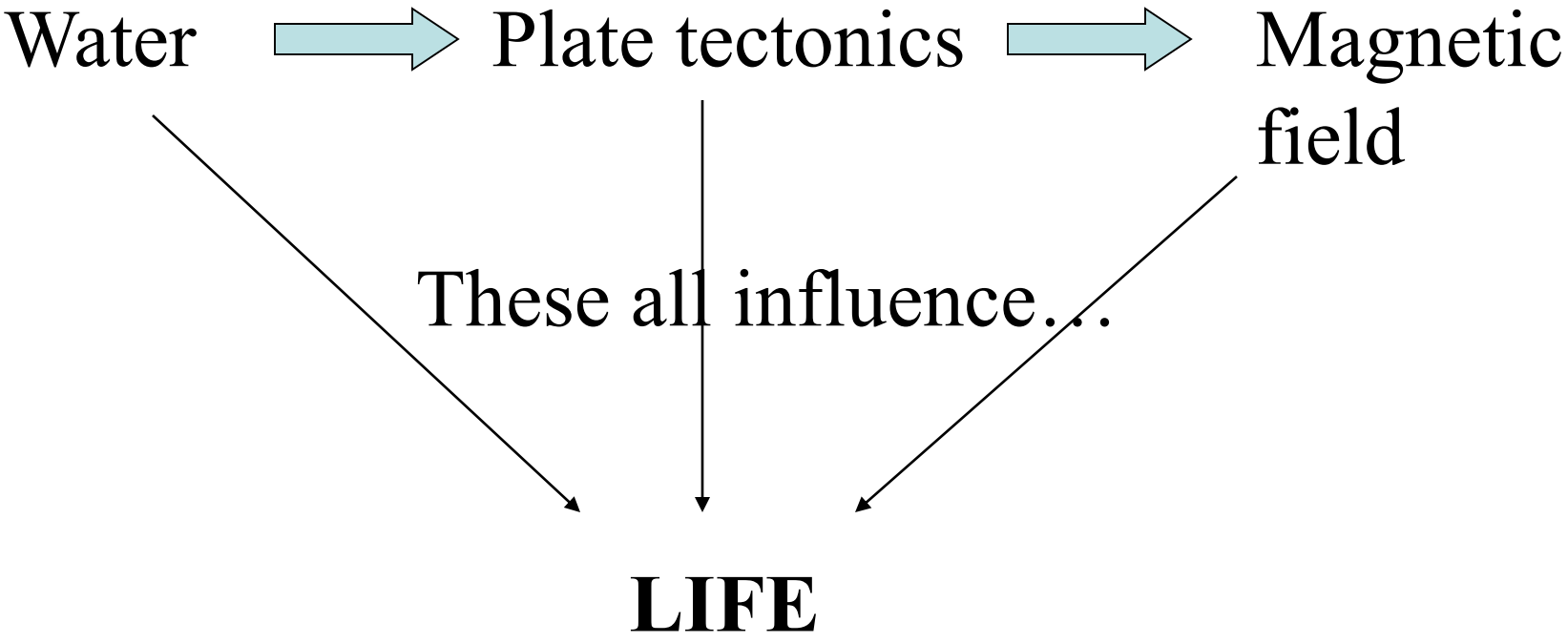
Stagnant lid vs. Plate Tectonics

- We do not know why Earth has plate tectonics
  - Water, melting, continents may all play a role
- Stagnant lid is the “natural” form for convection when you have a very high viscosity near surface region
  - Venus has this despite the high surface temperature
- Other things being equal, stagnant id planets run hotter and have greater capability for magmatism
  - But pressure release melting dominates on Earth

Plate Tectonics & the Role of Water (Earth Perspective)

- Water lubricates the asthenosphere
- Water ***defines*** the plates
- Maintenance of water in the mantle depends on subduction; this may not have persisted except on Earth
- Plate tectonics helps the dynamo by promoting core cooling

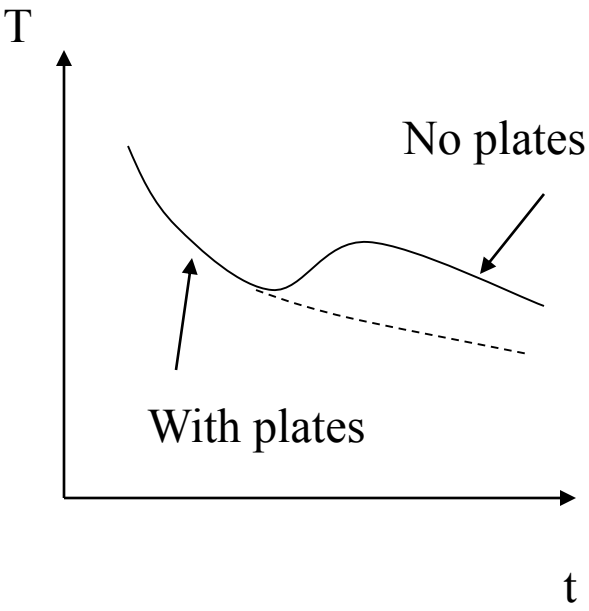



Water
Plate tectonics
Magnetic field
These all influence…
LIFE

Did Venus undergo a Change in Convective Style over Geologic Time?

- Catastrophic resurfacing at 500Ma to 1Ga ago? Compatible with but not required by the surface age deduced from cratering record (e.g. McKinnon, Zahnle).
- Convection models are permissive (i.e can be tuned) ;sometimes show episodic behavior (e.g. ,Armann & Tackley, 2012)
- May connect to evidence for a current thick lithosphere (possible low heat flow) compared to earth
  - Most of Earth's heat flow is secular cooling, not radiogenic at present (Urey number problem)

Changes in Convective Style (existence or extent of plate tectonics) can have big effects on Thermal History



"With plates" means any convective style that involves recycling of the surface layer

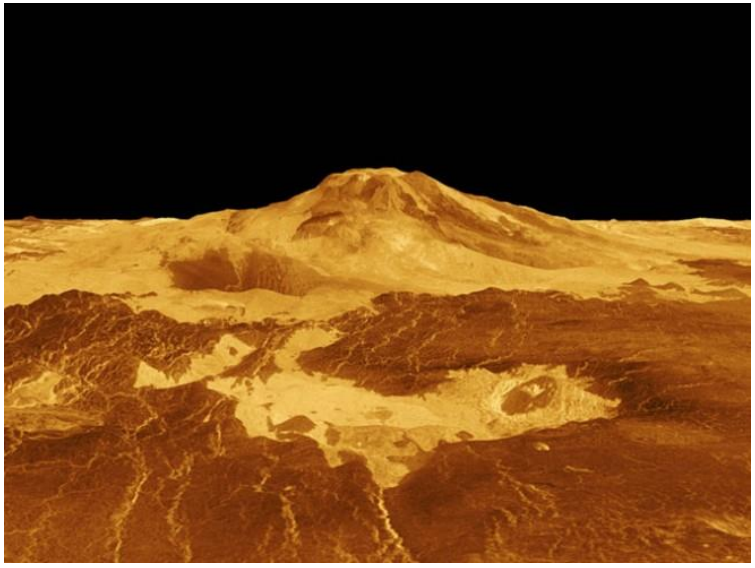
Mantle T does not have to decrease monotonically. This can also affect core cooling and the presence of plumes or extent of igneous activity

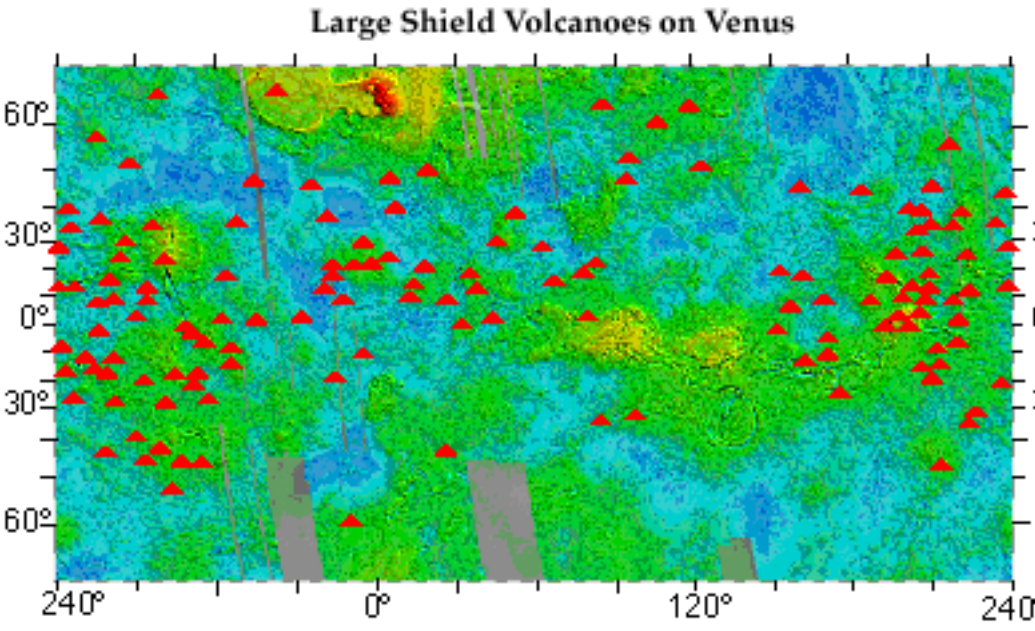
State of the Core: Why no Dynamo?

- Liquid because the minimal freezing point is below plausible mantle operating temperatures
- Slow rotation is NOT slow for core fluid motions of interest (i.e. $Ro = v/\Omega L \ll 1$). Might even favor the dynamo!
- Core convection must be absent
  - Core unable to cool efficiently?
  - Core is stably stratified?
  - No inner core?

Volcanism: Shield Volcanoes

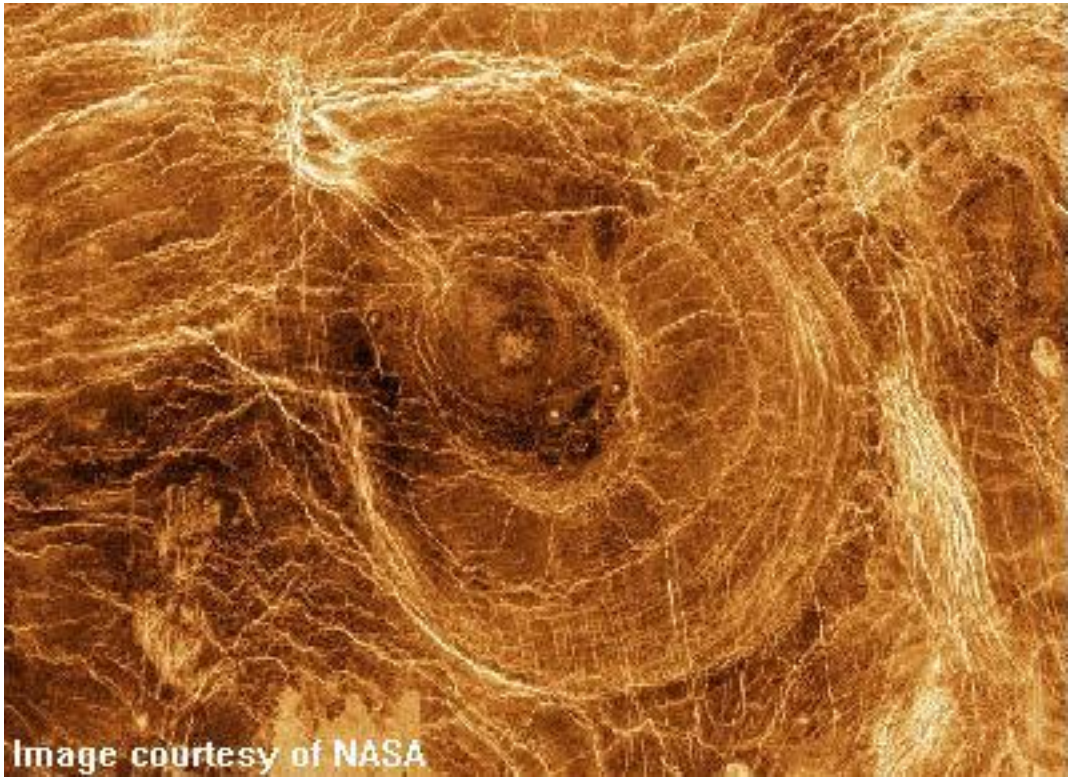
- Plume volcanism is a popular framework in which to describe Venus
  - Not clear why Venus would have plume volcanism! (In the sense of deep seated plumes as on Earth)

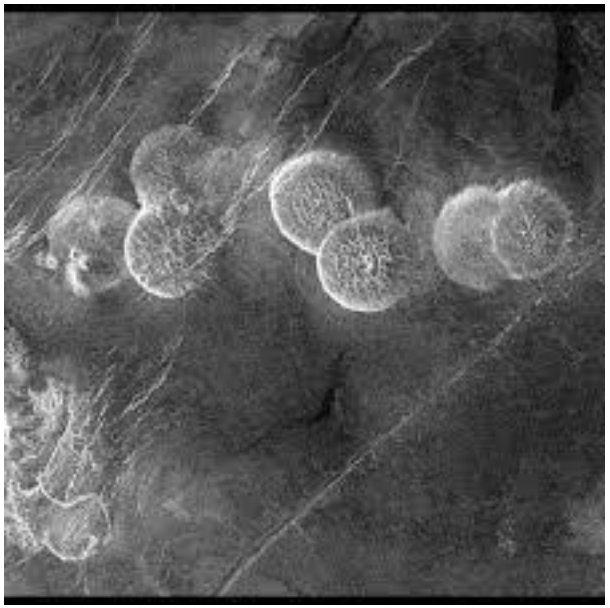


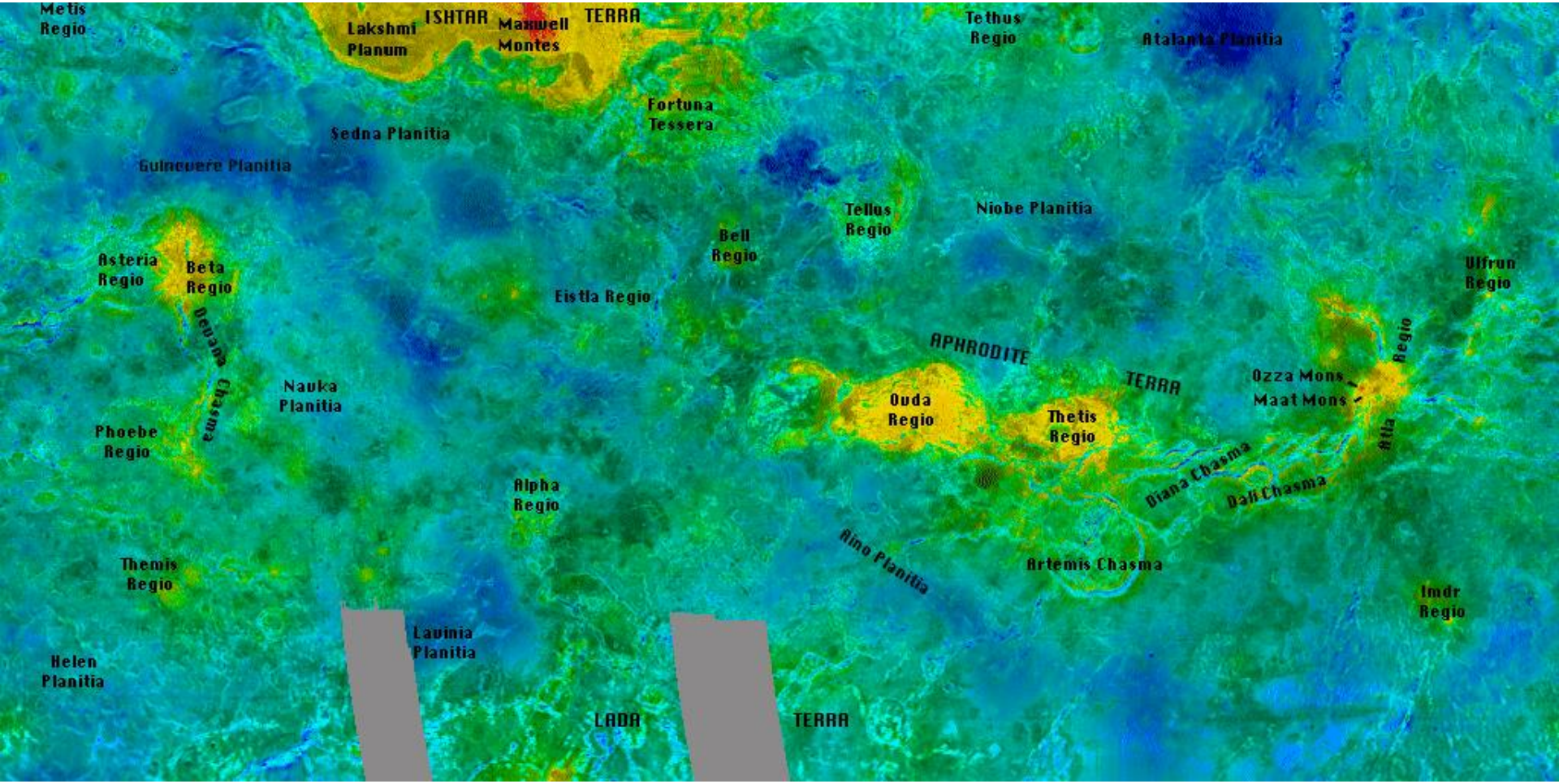


Volcanism: Coronae & Domes

- Smaller than shield volcanoes
- Many hundreds in a limited size range
- Pancake Domes






Metis Regio
Lakshmi Planum
ISHTAR TERRA
Maxwell Montes
Tethus Regio
Atalanta Planitia
Fortuna Tessera
Sedna Planitia
Guinevere Planitia
Tellus Regio
Niobe Planitia
Bell Regio
Asteria Regio
Beta Regio
Devana Chasma
Eistla Regio
Ulfrun Regio
APHRODITE TERRA
Ozza Mons
Maat Mons
Ouda Regio
Thetis Regio
Nauka Planitia
Phoebe Regio
Alpha Regio
Diana Chasma
Dali Chasma
Rino Planitia
Artemis Chasma
Themis Regio
Imdr Regio
Lavinia Planitia
Helen Planitia
LADA TERRA

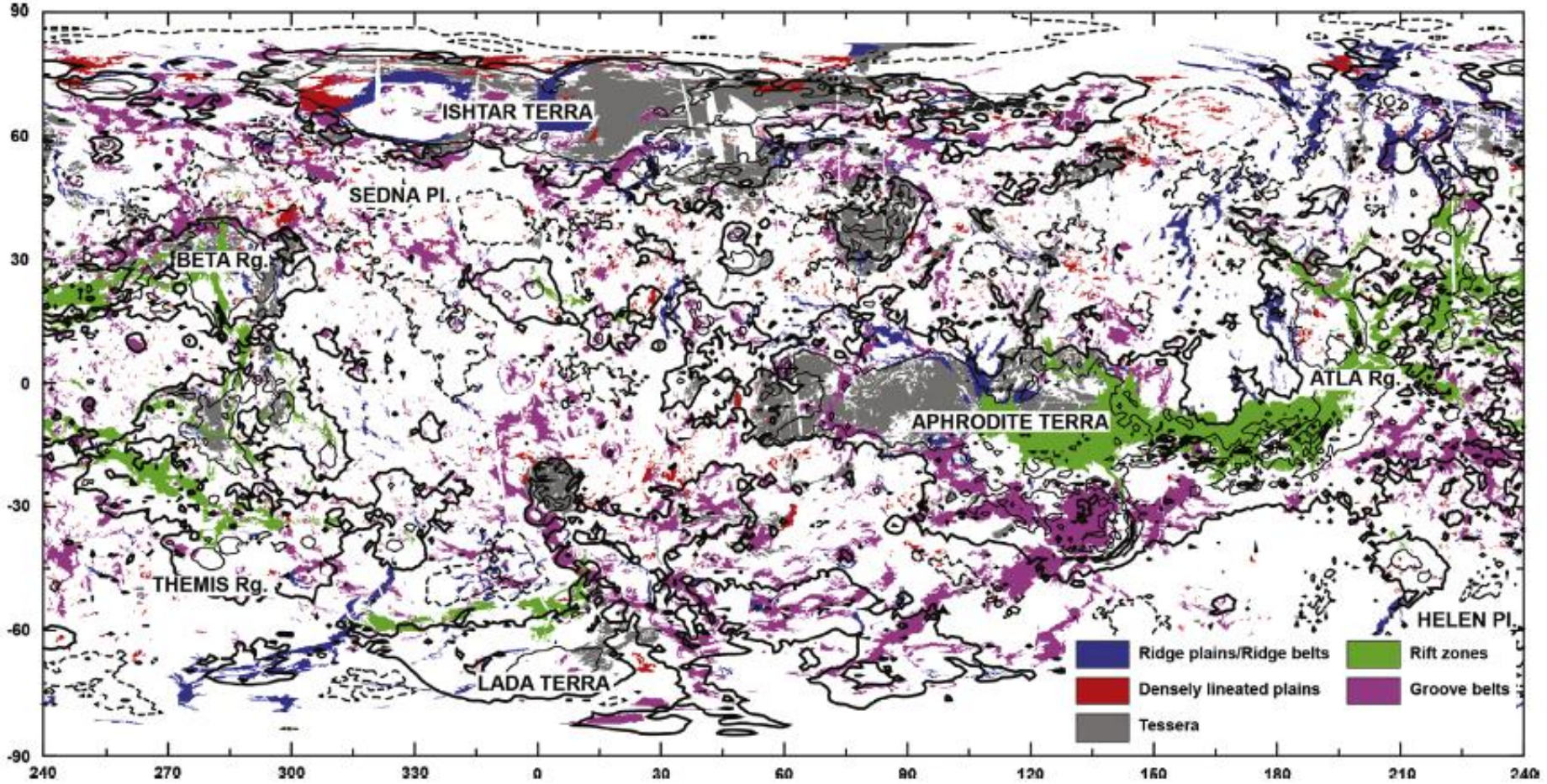
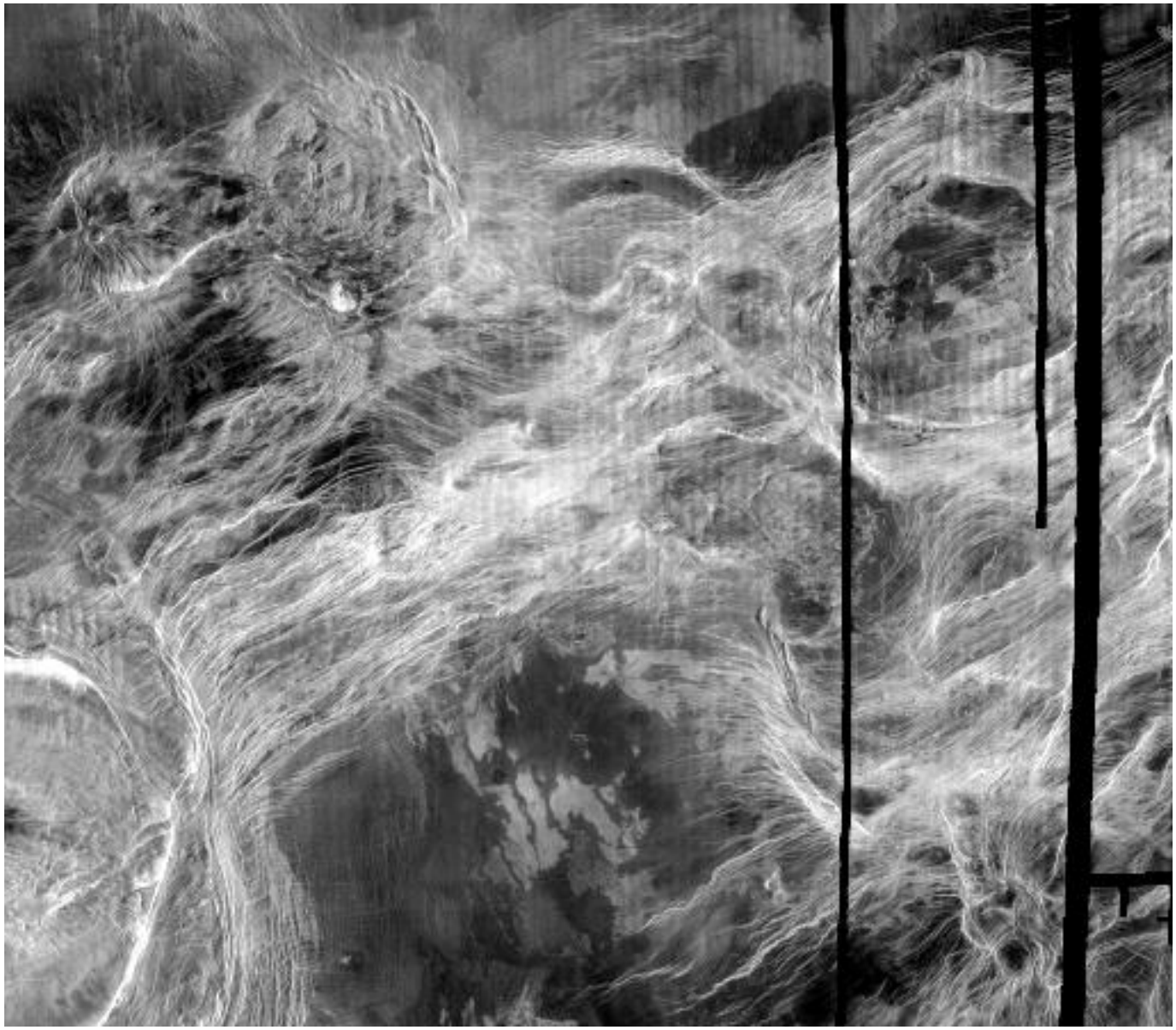


Fig. 21. The spatial distribution of tectonized units on Venus. Rift zones are organized into a few compact zones and are not as pervasive as the older tectonized units. White spots (except for obvious data gaps) show the major occurrences of the main volcanic units. Thick black line represents the 0 km contour line, the thinner lines indicate elevation −1 km (dashed line) and +1 km (solid line). The map is in simple cylindrical projection.

Ivanov & Head,
2013



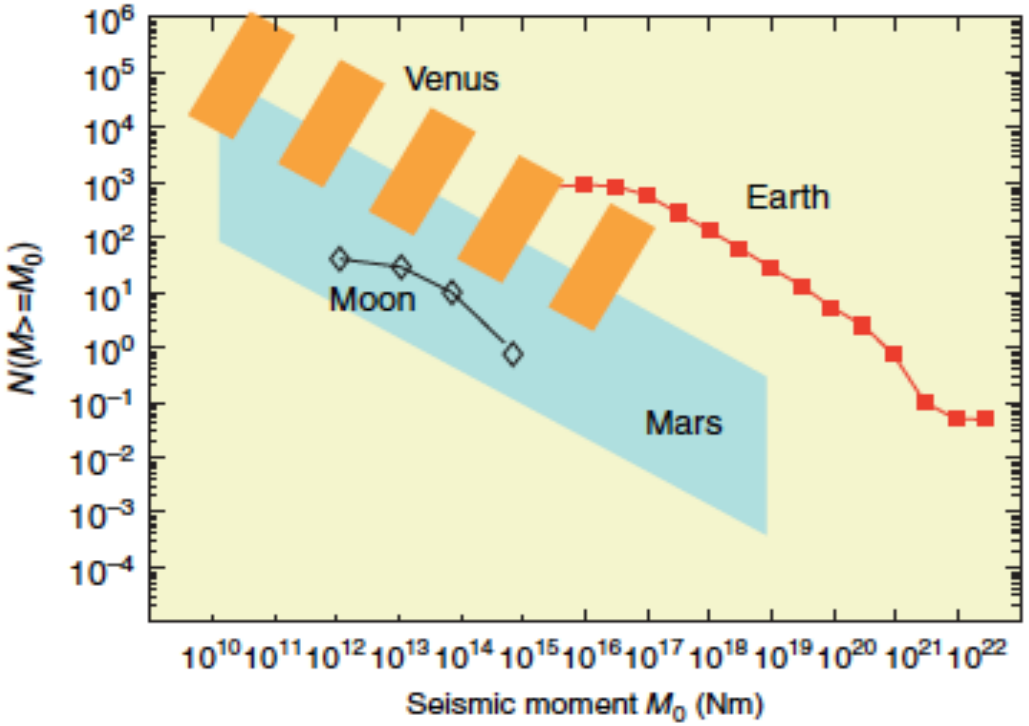
An example of Venus tesserae (folded mountain belts)

Seismic Activity?

- Thermal stresses due to secular planetary cooling (Phillips; Solomon)
  - But are we sure Venus is cooling?!
- Mantle Convection: Total energy release is bounded above by work done
  - But in practice this is not a useful bound
  - Tectonic deformation likely (but could be aseismic)
- Volcanic construction (current level is not known)
- Landslides, etc…nothing plausible

Guiding Principles

- No good reason to doubt Gutenberg-Richter
  - Even though it is imperfectly understood!
- But the upper cut-off is not known and might be important
  - Most energy release is in the largest quakes
  - On Earth these are subduction zone quakes
- Using identified or guessed faults , estimates of strain and lithospheric thickness , one can come up with (highly uncertain) numbers



Lognonné & Johnson, Treatise on Geophysics, 2007)

Figure 12 Seismic activity of the telluric bodies. The figure shows the number of events per year larger than a given seismic moment. For the Moon, the estimate is obtained from Oberst (1987) and is only for the shallow moonquakes. For Mars and Venus, the activity is estimated from various published models, based on the thermoelastic cooling of the lithosphere. The terrestrial activity is the mean activity in the period 1984–2004. Adapted from Knapmeyer M, Oberst J, Hauber E, Wählisch M, Deuchler C, and Wagner R (2006) Implications of the Martian surface fault distribution and lithospheric cooling for seismicity: A working model. *Journal of Geophysical Research* 111: E11006 (doi:10.1029/2006JE002708).

Things We Don't know (I wish we did!)

- ***Seismic activity & structure*** Essential for understanding interior .
- ***Isotopes (oxygen, Hf/W)*** Crucial or placing Venus in context. Not just for chronology!
- ***Rotation & Geodesy*** Essential dynamical constraints. Can be done partly from earth.
- ***Atmospheric origin and evolution***
- ***True Water content*** Mantle water not known.
- ***Magnetism*** Even small effects (paleo or present) would be of great interest.
  - Electromagnetic induction
- ***Heat flow*** Most difficult of all. (But indirect constraints exist).
- ***Igneous Activity,Volcanism***
- ***Gravity & Topography*** beyond Magellan