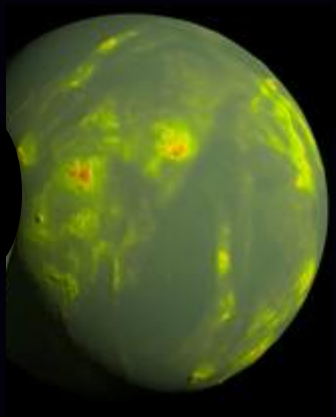
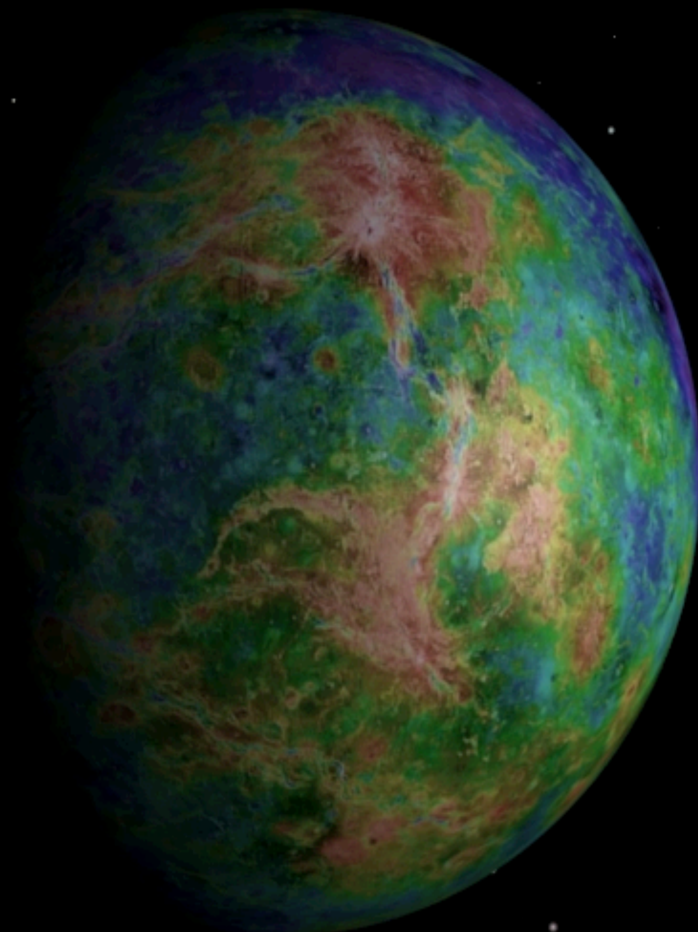
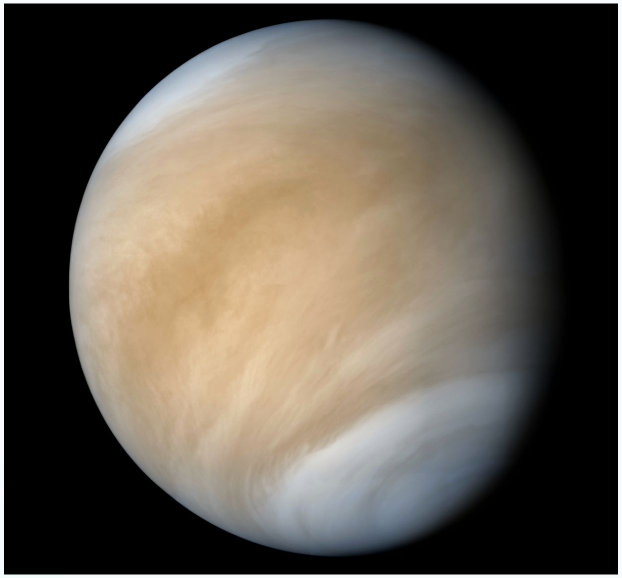
Overview and Observational Constraints on Venus' Geodynamics and Tectonics





Sue Smrekar
Jet Propulsion Laboratory/Caltech

Venus: Earth's evil twin or distant cousin?



- Twin:
  - Diameter is 5% smaller
  - Same bulk composition
  - Once had a shallow ocean's worth of water
- Evil Twin:
  - Surface T ~460°C
  - Surface P ~90 bars
  - Atmosphere: CO_2 greenhouse
  - No magnetic field
- Distant Cousin:
  - No terrestrial style plate tectonics
  - Little measurable water (3 ppm in atm.)
  - Young, diverse tectonics

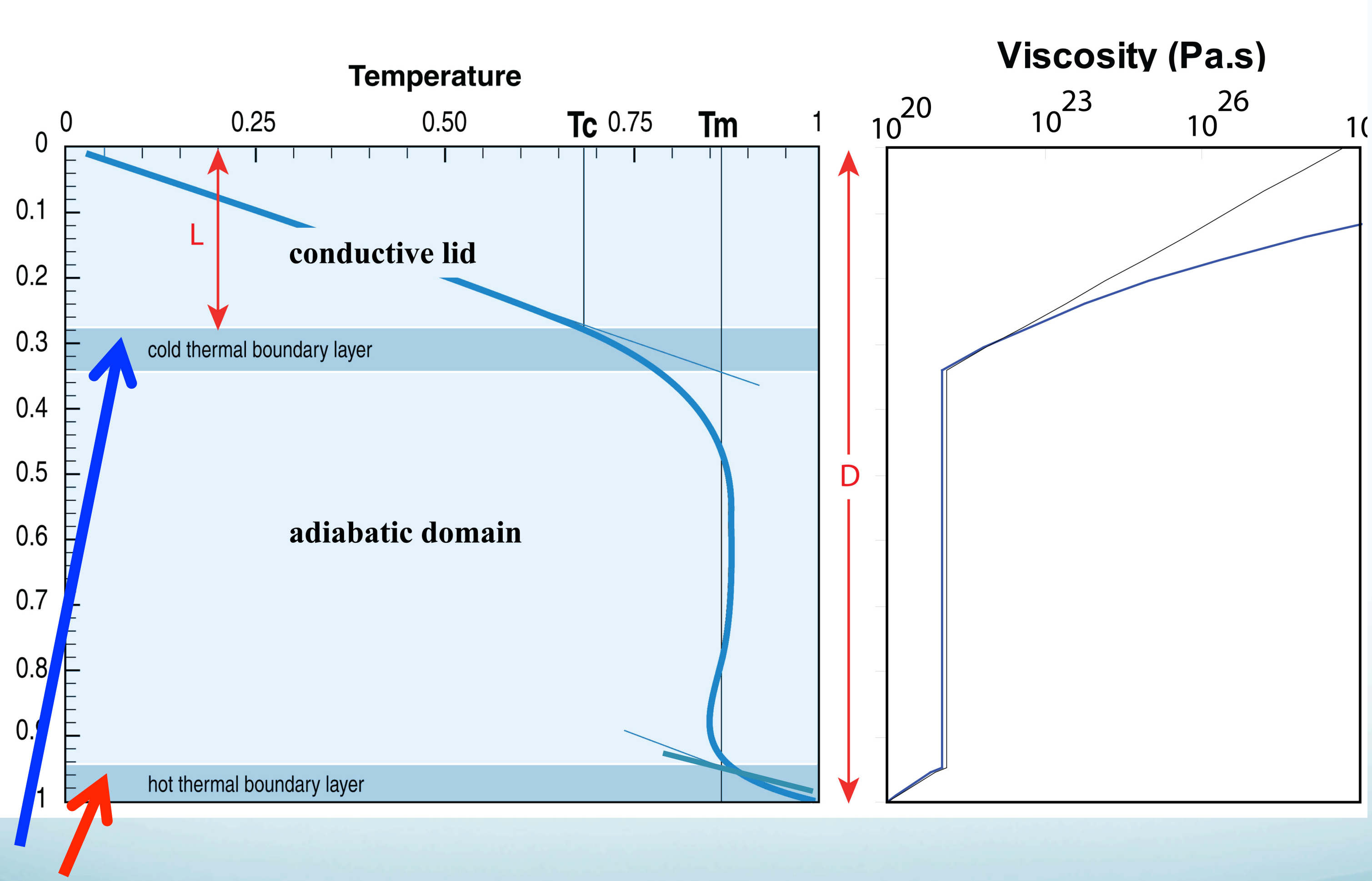
Why Venus?

- **How Venus and Earth diverged is one of the essential questions in understanding planetary habitability.**
  - Geology (volcanism and tectonics, not comets) – releases volatiles into the atmosphere.
  - Plate tectonics cycles volatiles between the interior and atmosphere, and thus may be needed for extended habitability.
  - Why does Venus lack terrestrial-style plate tectonics?
- **SURFACE AGE**: Only rocky planet (besides Earth) with a young surface (< 1 b.y.); Geologic processes on Mars, the Moon, Mercury were largely confined to the 1st b.y.
  - Venus is likely active today (more on this later)
- **TECTONICS**: Venus has major tectonic features, and perhaps even elements of plate tectonics
  - Rifts up to 10,000 km long
  - Mechanisms for initiation of subduction? (see poster)
  - 'Hotspots'
- **HIGH T**: provides an analog to early Earth?
  - Lithosphere is hot
  - Mantle is likely hot as well

Focus: Why doesn't Venus have Plate Tectonics?

- Plate tectonics occurs when the mantle convects vigorously enough to break the lithosphere
  - What is the rheology of the lithosphere? How vigorous is conection?
    - Composition, Volatiles, Strain rate, Heat flow, Viscosity
- "Venus lacks plate tectonics because it is too dry"
  - Lithosphere too strong to break
  - Mantle lacks a low viscosity zone
- But, what do we know and how do we know it?
    - "Knowns", Unknowns

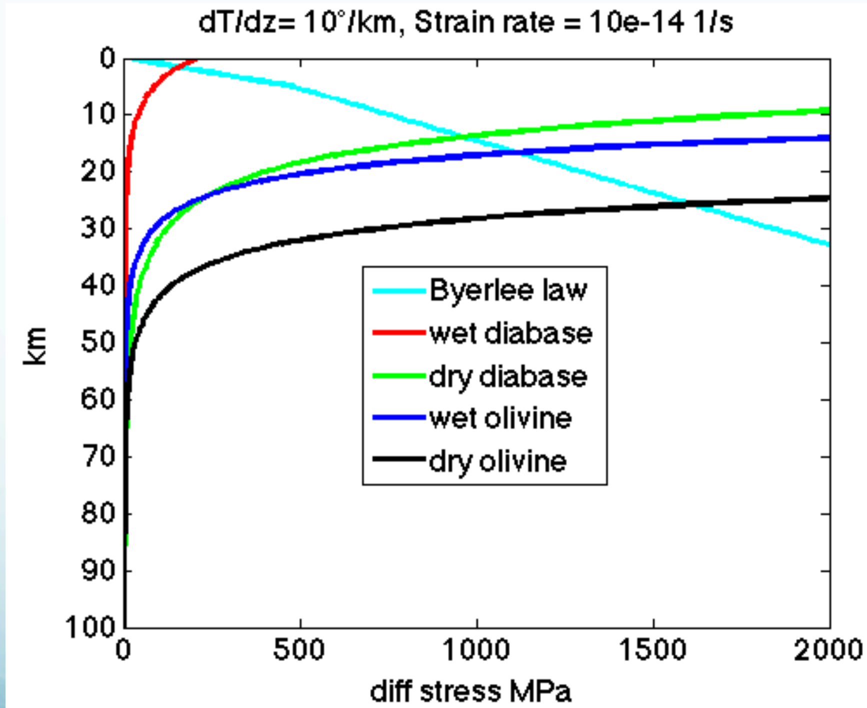
Convection Schematic

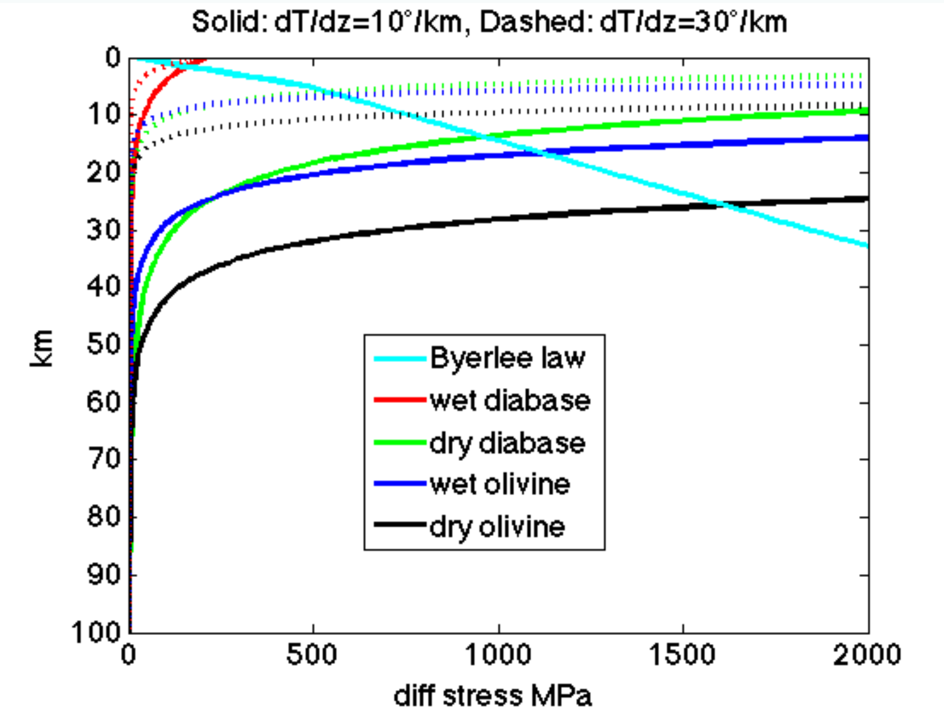


(Thermal) plumes require a thermal boundary layer

The Elastic (Brittle) Lithosphere

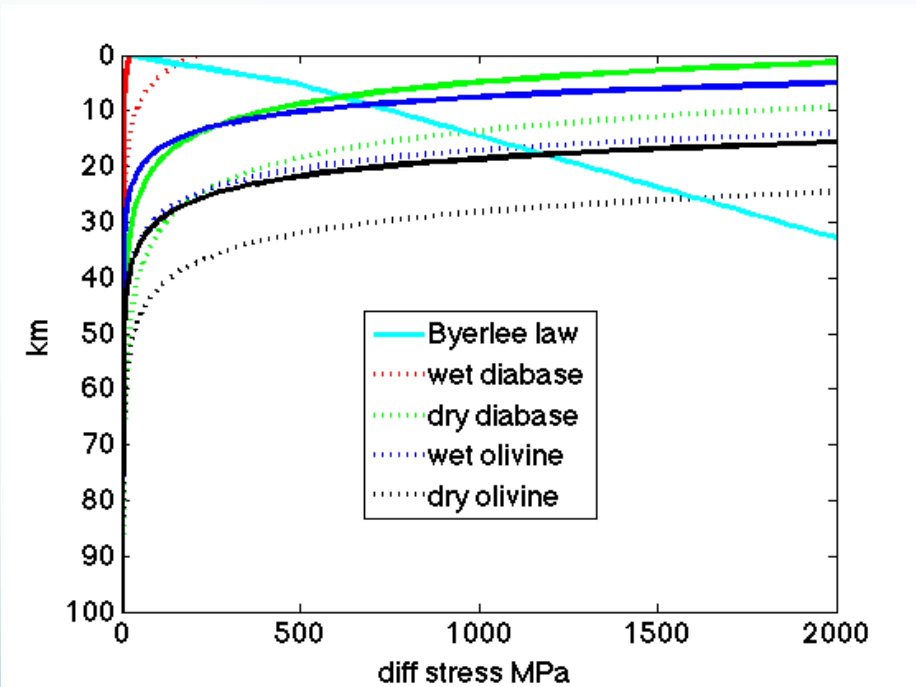
Deformation is a function of composition, volatile content, temperature, and strain rate



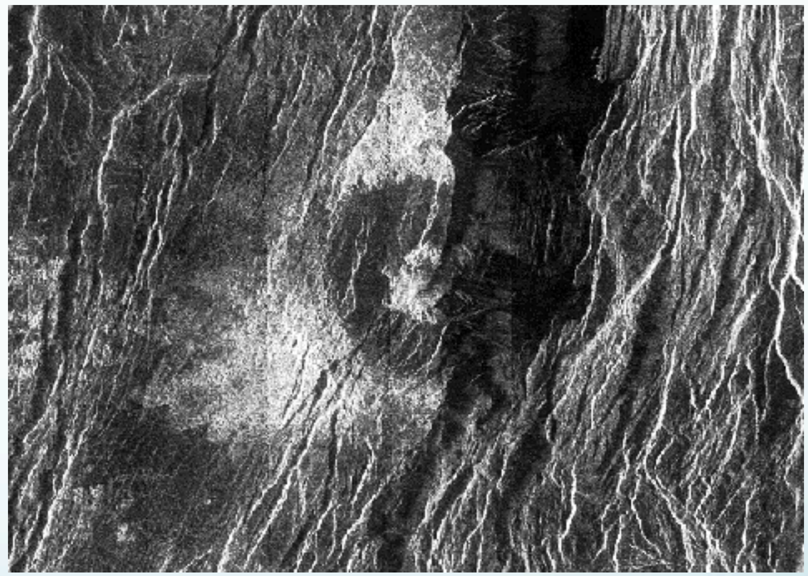


The Elastic (Brittle) Lithosphere

Stain rate effect similar to T, volatiles



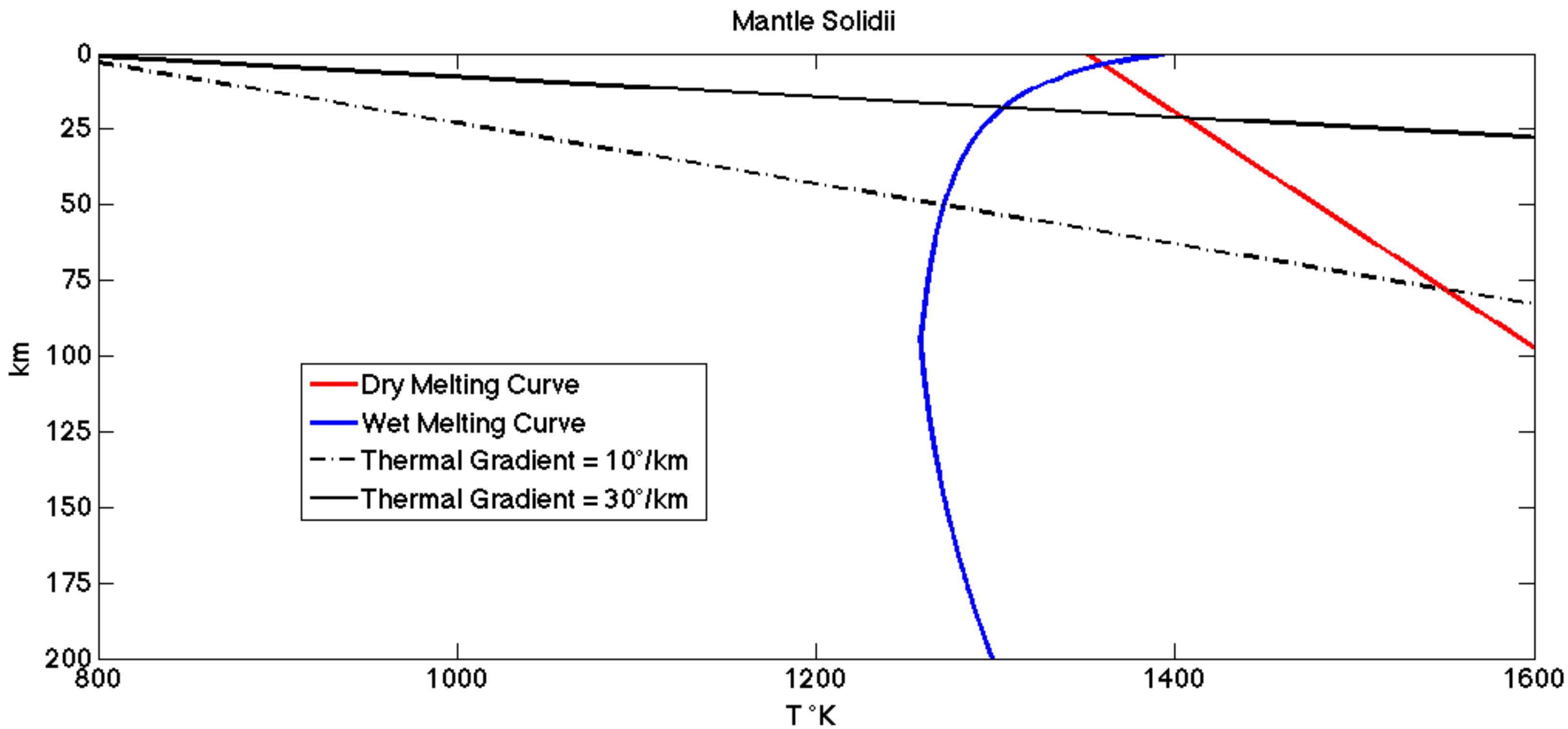
Little constraint on strain rate



Somerville Crater, 37 km diam

Thermal Lithosphere

Volcanism is a function of T and volatile content



Data & Geologic Overview

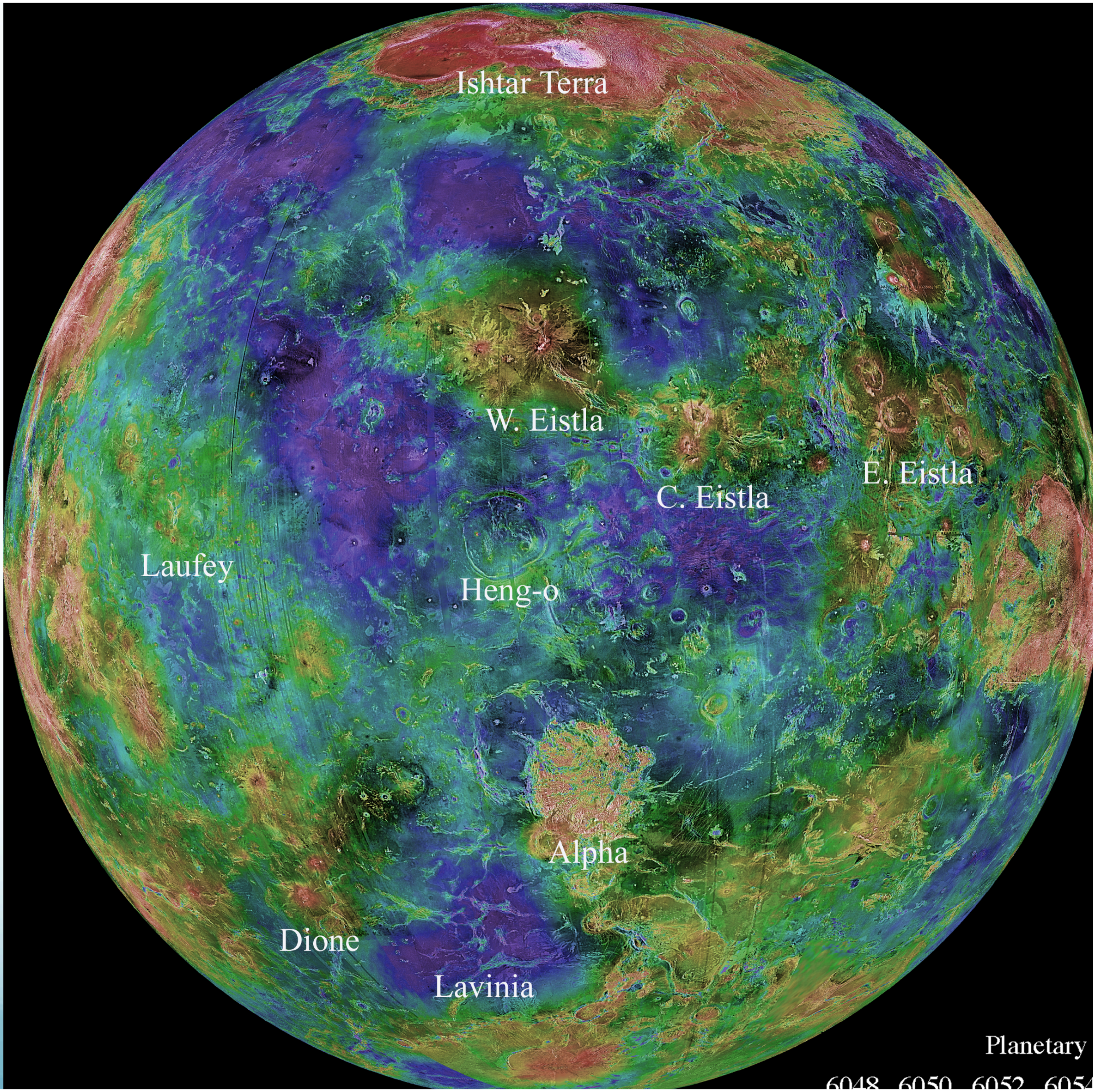
Data:

- Magellan Mission: Early 1990s
  - Topo (12-25 km footprint, 10-1000+ m vertical accuracy)
  - Synthetic Aperture Radar Imaging (~125 m pixel)
  - Gravity (Deg. & Order 40-90, ~500-250 km)
- Venus Express: 2005-2015
  - Surface emissivity, derived from surface brightness

Main Geologic Features

- *Tessera* Plateaus (highly deformed, isostatically compensated)
  - Analogs to continents? – see Gilmore
- Chasmata (Troughs with fractures), Ridge belts
  - Rifts– see Herrick
- Volcanism
  - ~80% of surface volcanic plains – see Mouginis-Mark
- Hotspots (analogs to Hawaii, etc)
- *Coronae (smaller scale upwelling, delamination, combo)*
- Subduction? (analogs to ocean-ocean subduction – see poster)

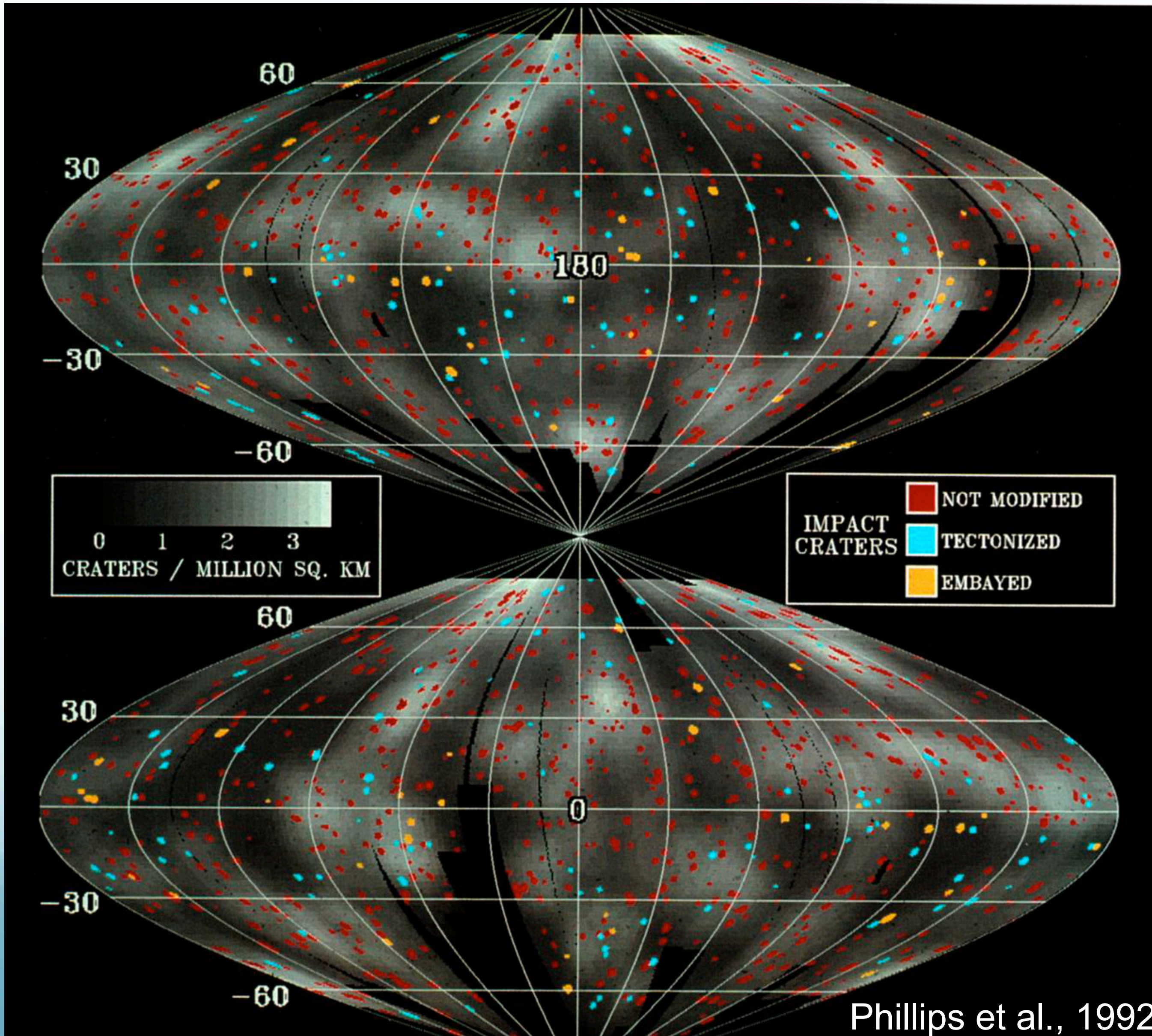
- (Rifts)
- Tessera Plateaus
- Hotspots
- *Coronae*



“Knowns”

1. Avg. resurfacing age is 0.3-1.0 b.y.
2. No ‘terrestrial style” plate tectonics
3. Crust is dominantly basaltic, avg. thickness ~ 10-50 km
4. Earthlike elastic thicknesses: 5-45 km where measured
5. There is little surface erosion
6. Core may be liquid, diam. ~3120 km (Konopliv & Yoder, 1996)
7. *There are ~10 active mantle plumes*

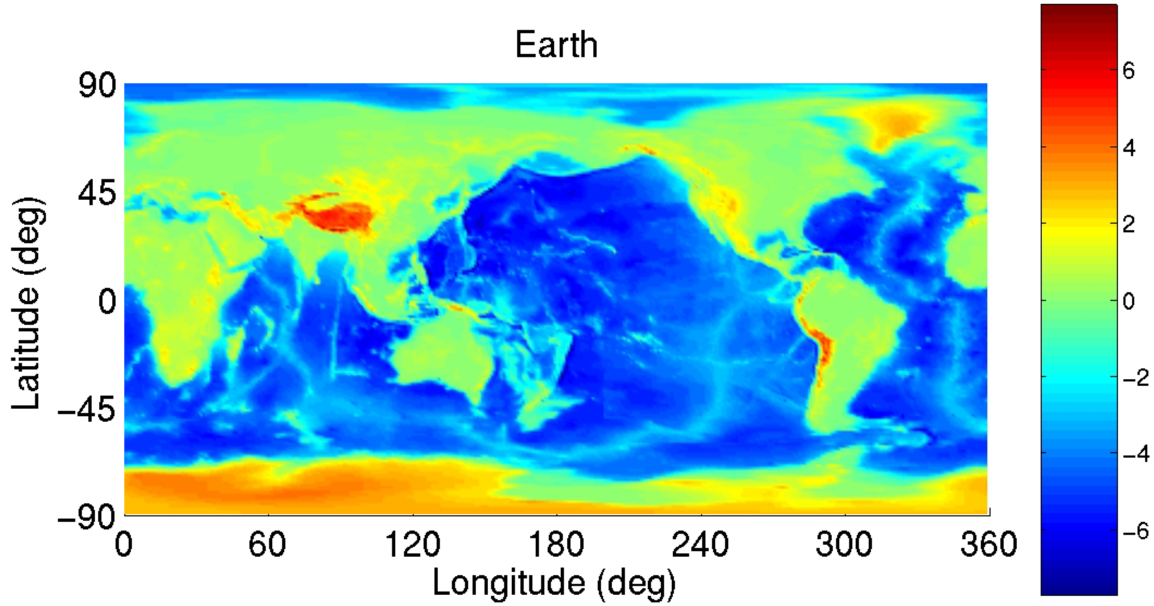
K1. Average resurfacing age is 0.3-1.0 b.y.

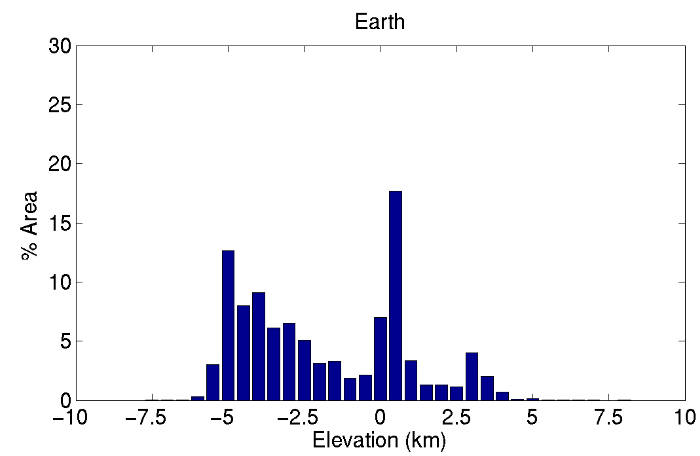


- Distribution of craters cannot be distinguished from a random one
- Apparently few craters modified

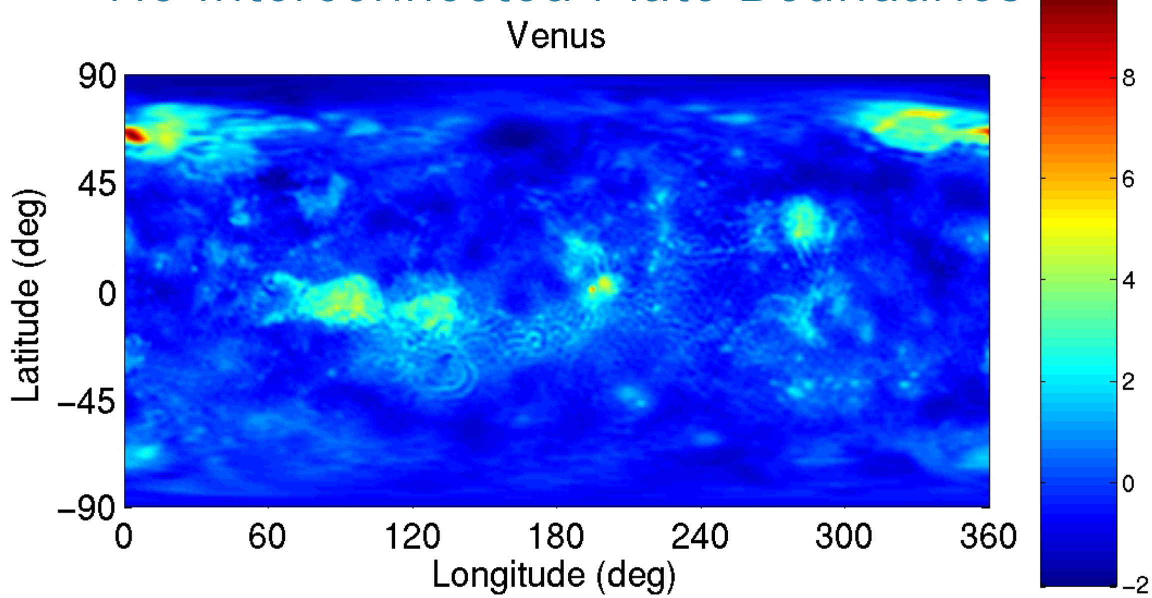
- (A majority of studies finds no compelling evidence for catastrophic resurfacing..)

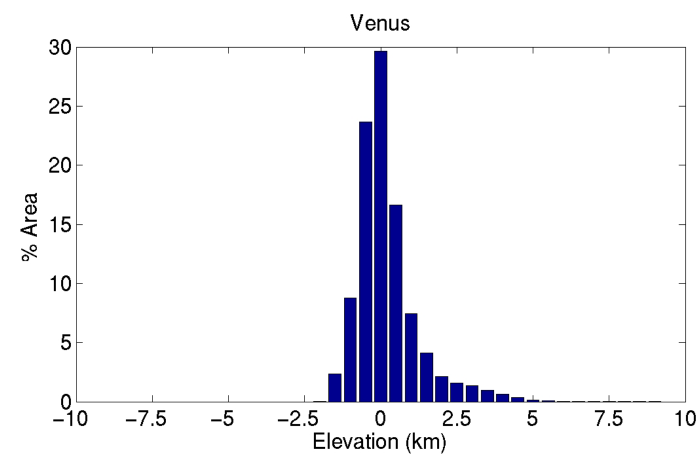
K2: No 'terrestrial style" plate tectonics





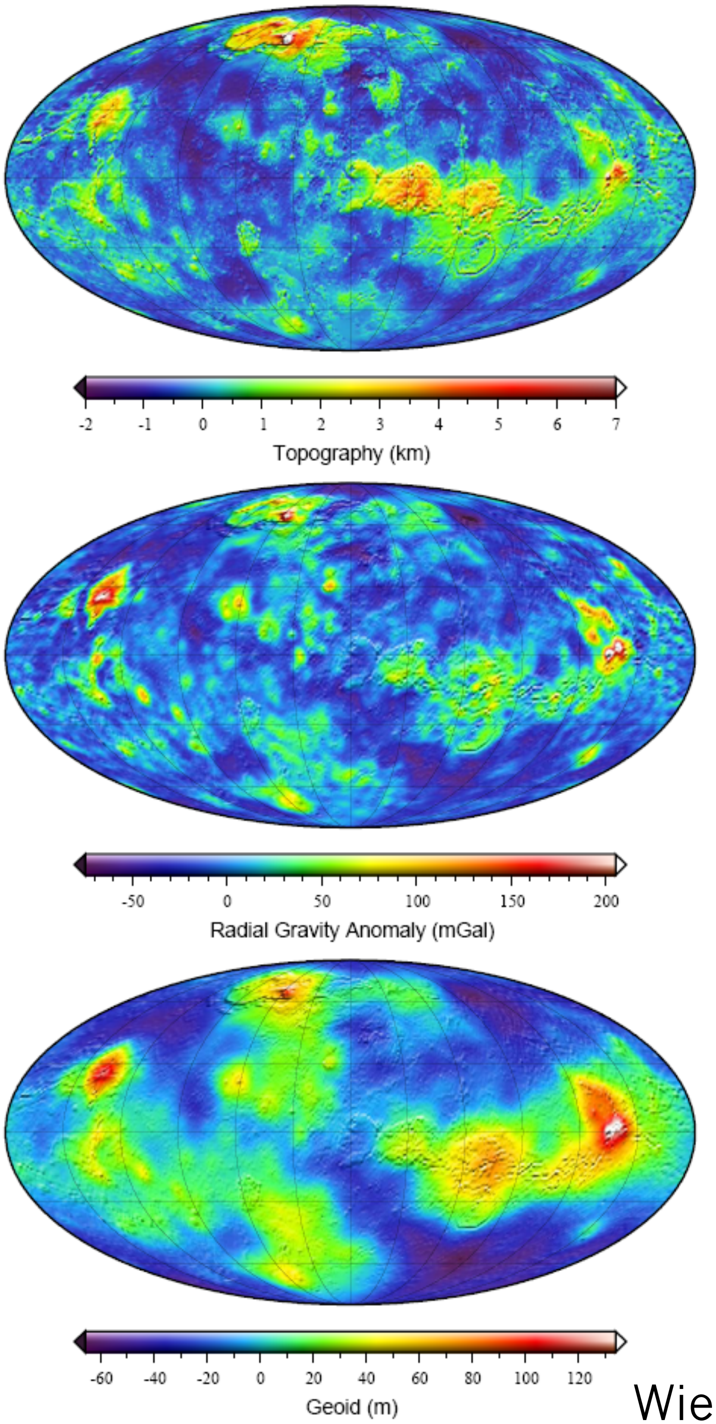
No Interconnected Plate Boundaries





K3. Crust is dominantly basaltic..

- Soviet landers (1970s) had x-ray fluorescence and gamma-ray spectrometers.
- Basalts to alkaline basalts identified in 7 locations.
- Layers in most sites: aeolian deposits? Weathering horizons? Platey lava flows?

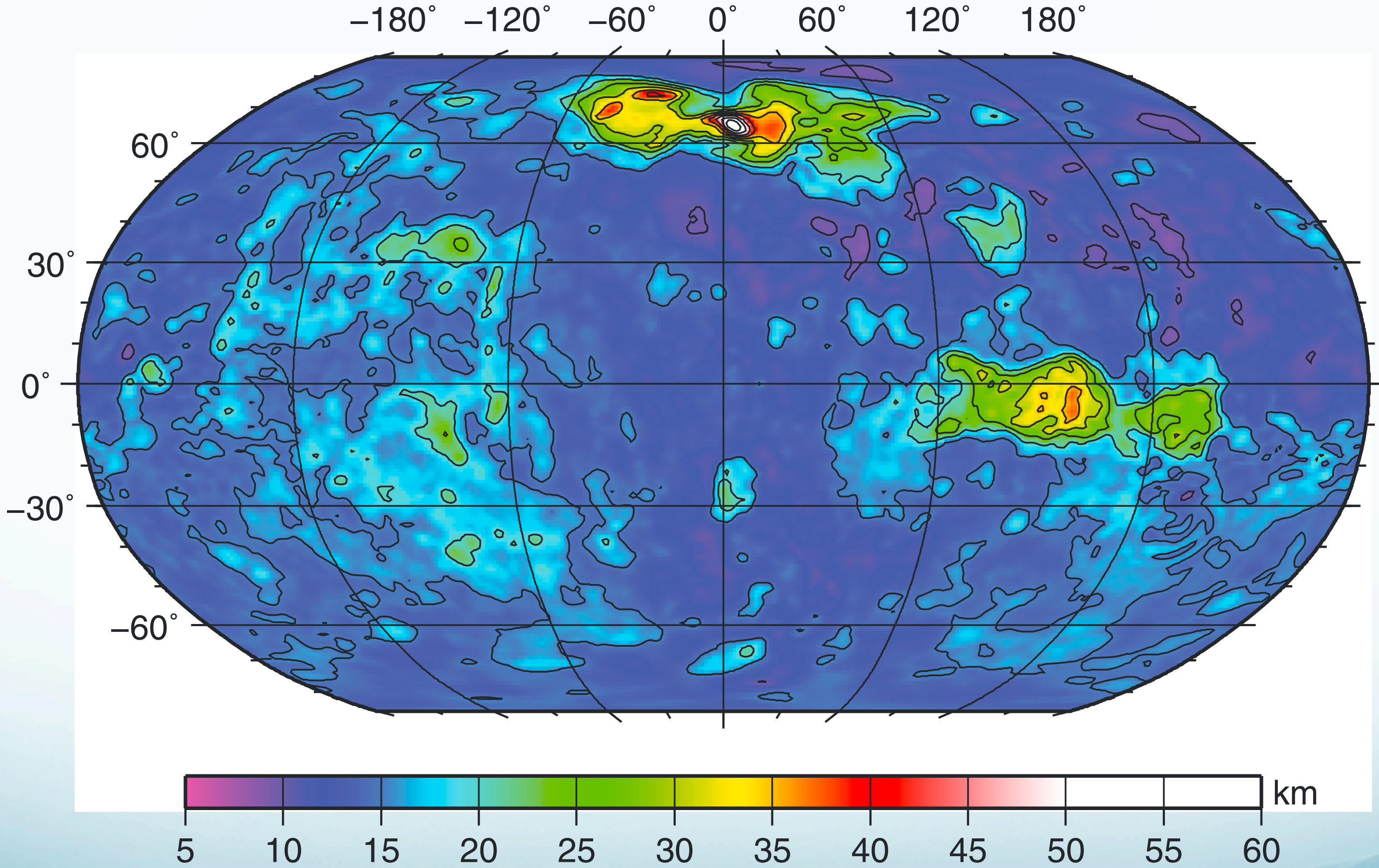


Wieczorek 2007

Venus - Gravity

- Gravity and topography are more highly correlated than on Earth
- Highlands:
  - Shallow compensation: isostatically compensated plateaus
  - Deep compensation: large volcanic rises or 'hotspots'
- Geoid to Topography ratios for hotspots are much larger than on Earth> No low viscosity zone

K3 Avg. crustal thickness: 10-50 km



From gravity and topography modeling- James et al., 2013

Deep Compensation

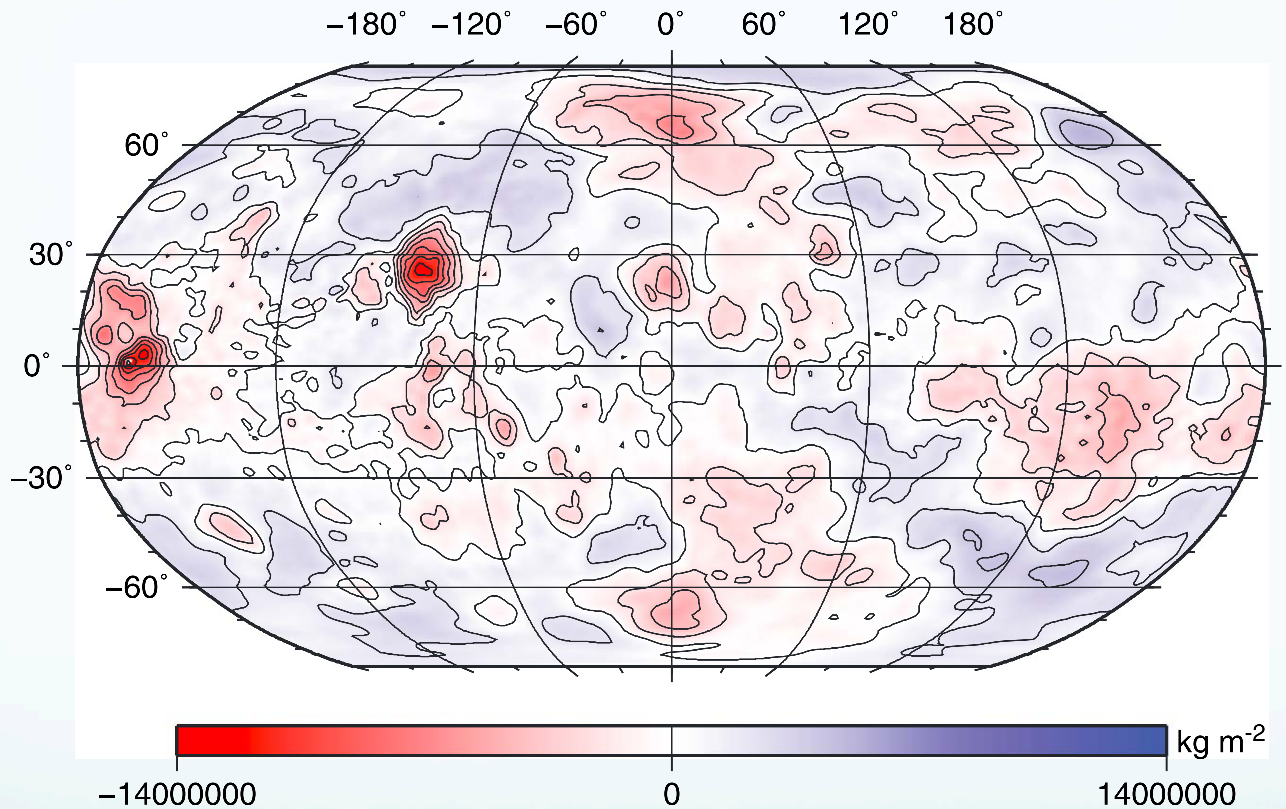
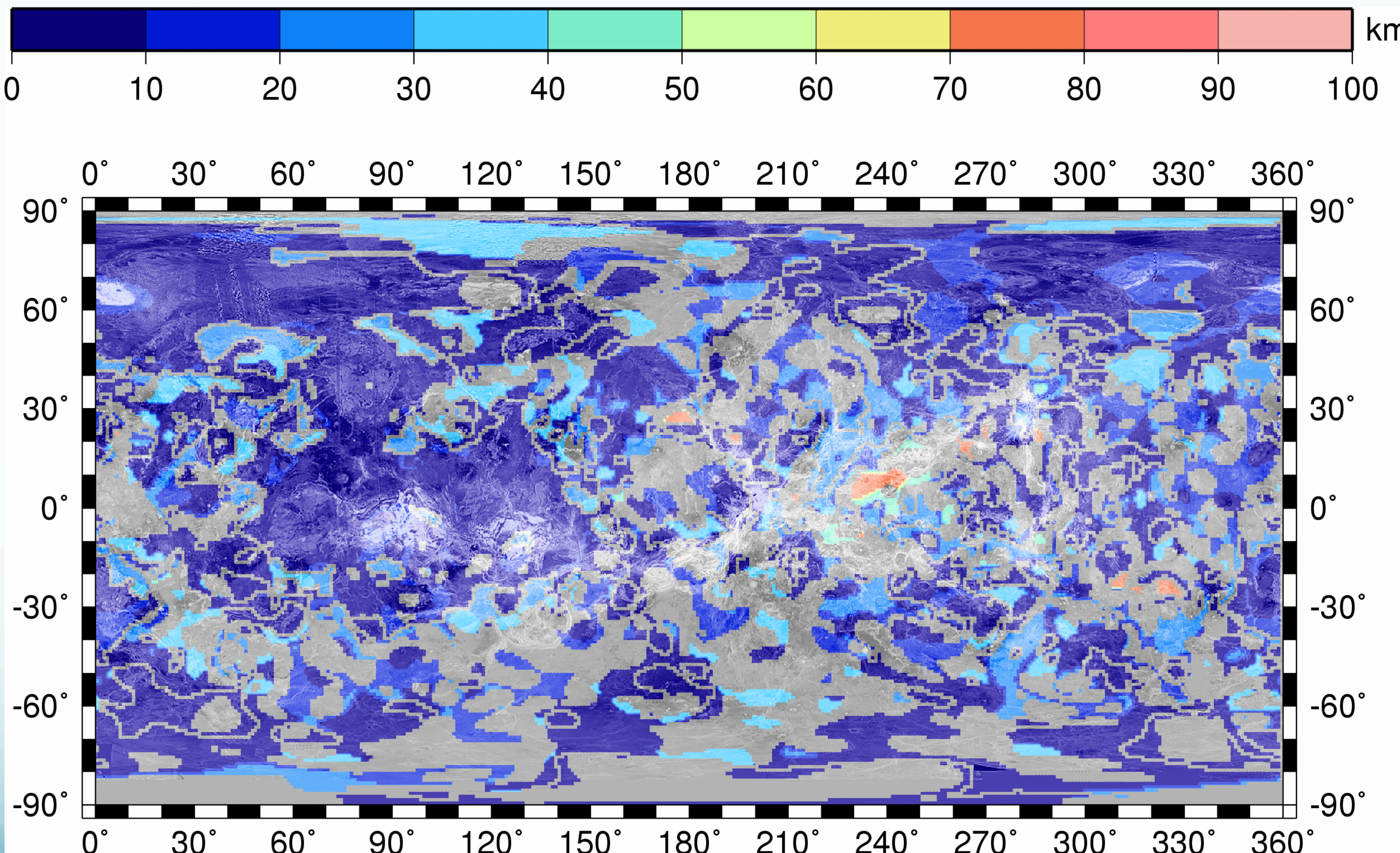


Figure 11. Mantle load distribution (in units of kg m^{-3}) for a mean crustal thickness of 15 km and a mantle load depth of 250 km. Warm colors indicate a mass deficit in the mantle and positive buoyancy; cool colors indicate mass excess and negative buoyancy. Contour spacing is 2×10^6 kg m^{-2}.

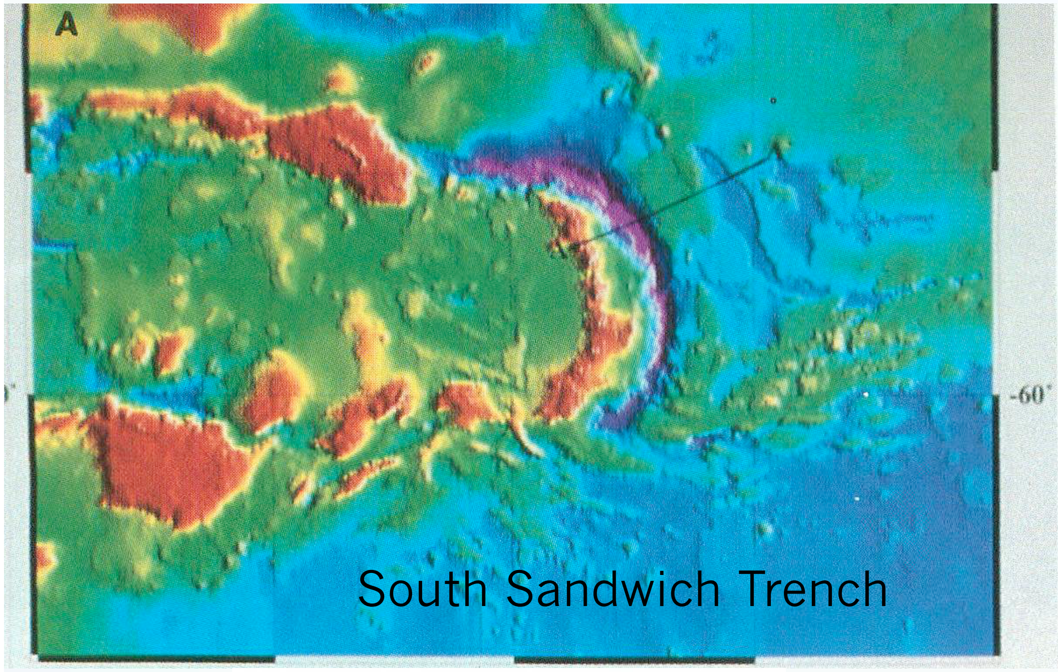
From gravity and topography modeling- James et al., 2013

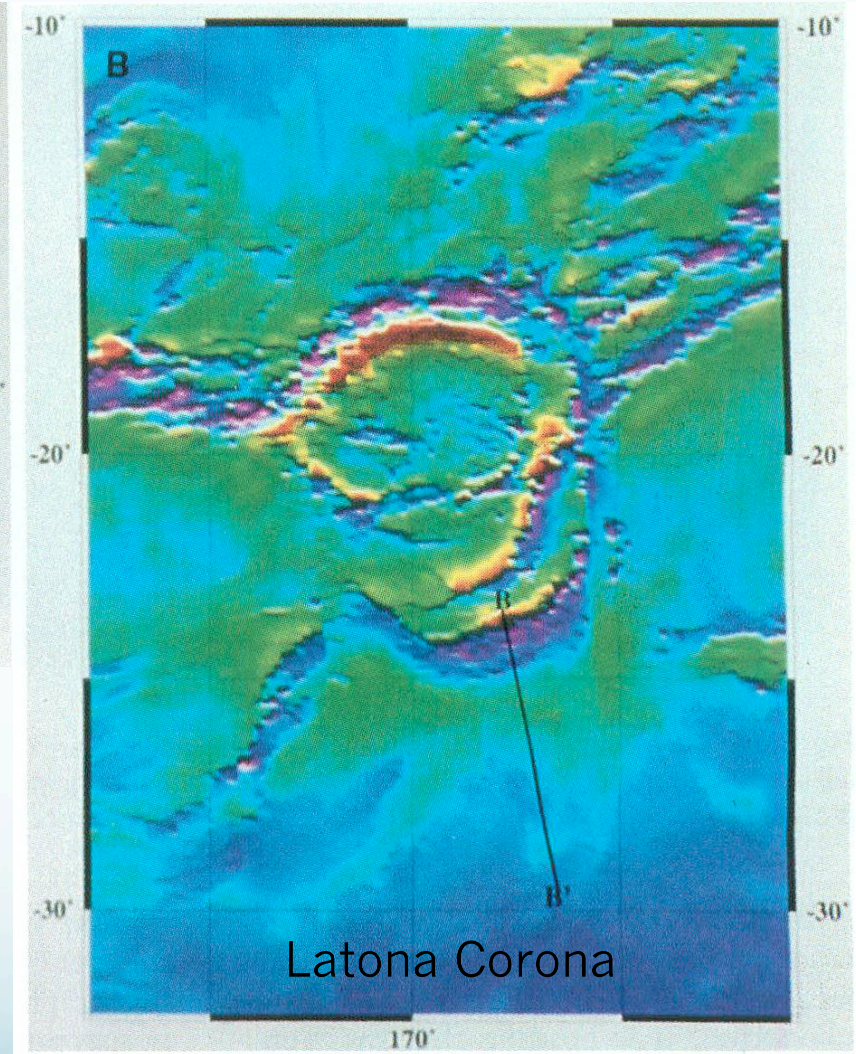
K4: Elastic thicknesses: 5-45 km

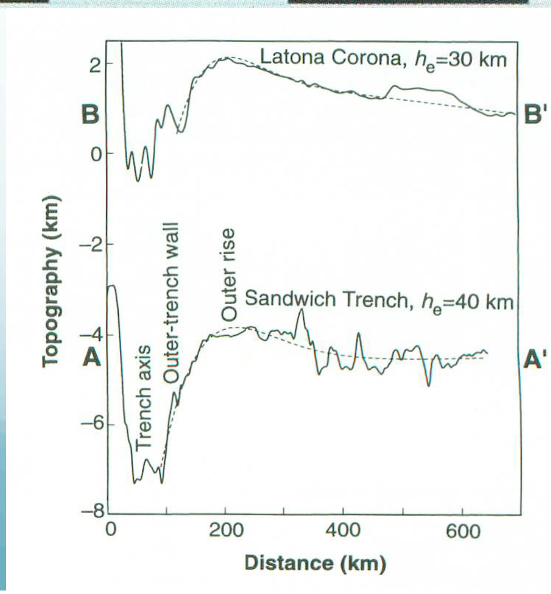


From gravity and topography modeling- Anderson and Smrekar, 2006

Flexural bending provides estimates of elastic thickness in numerous environments



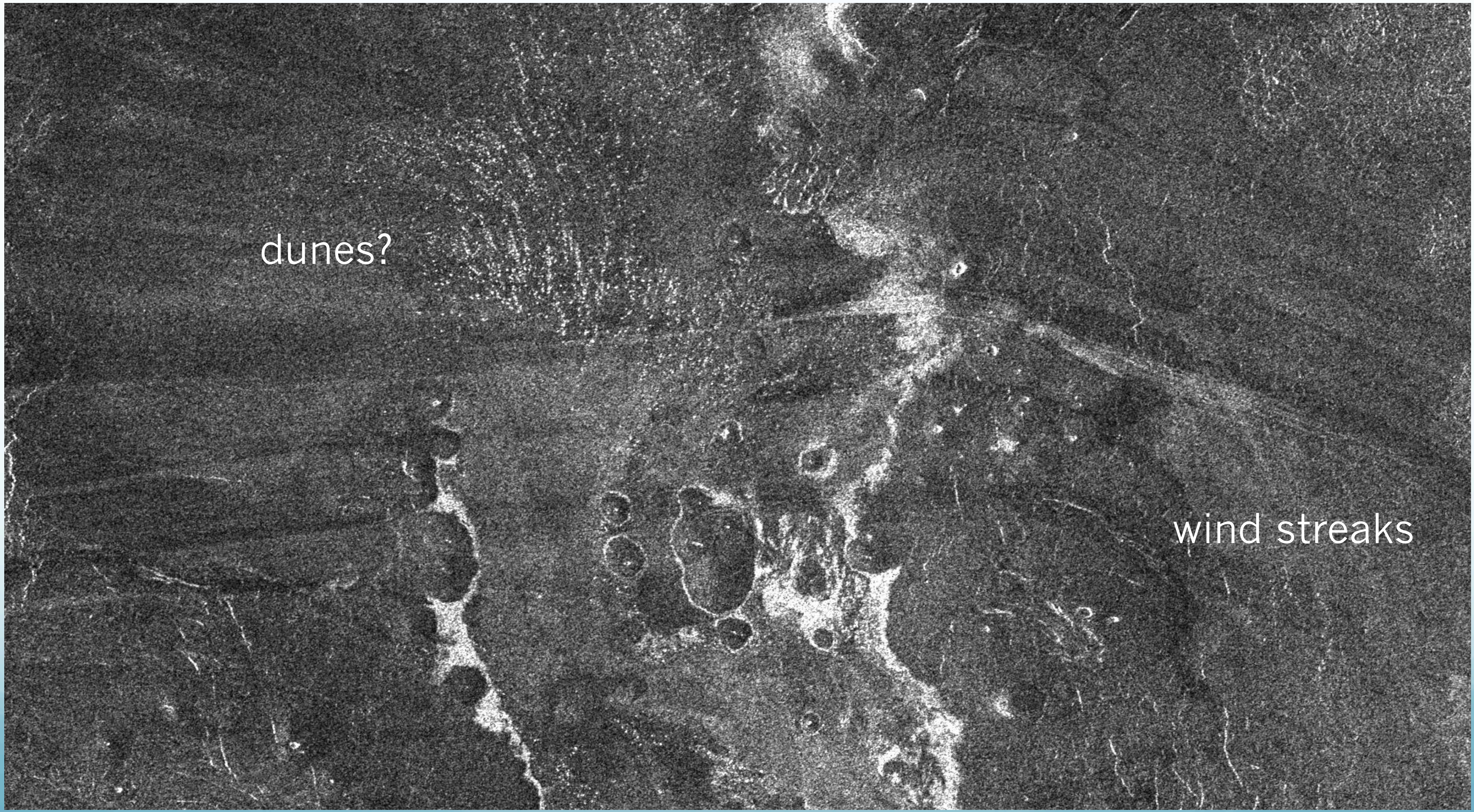




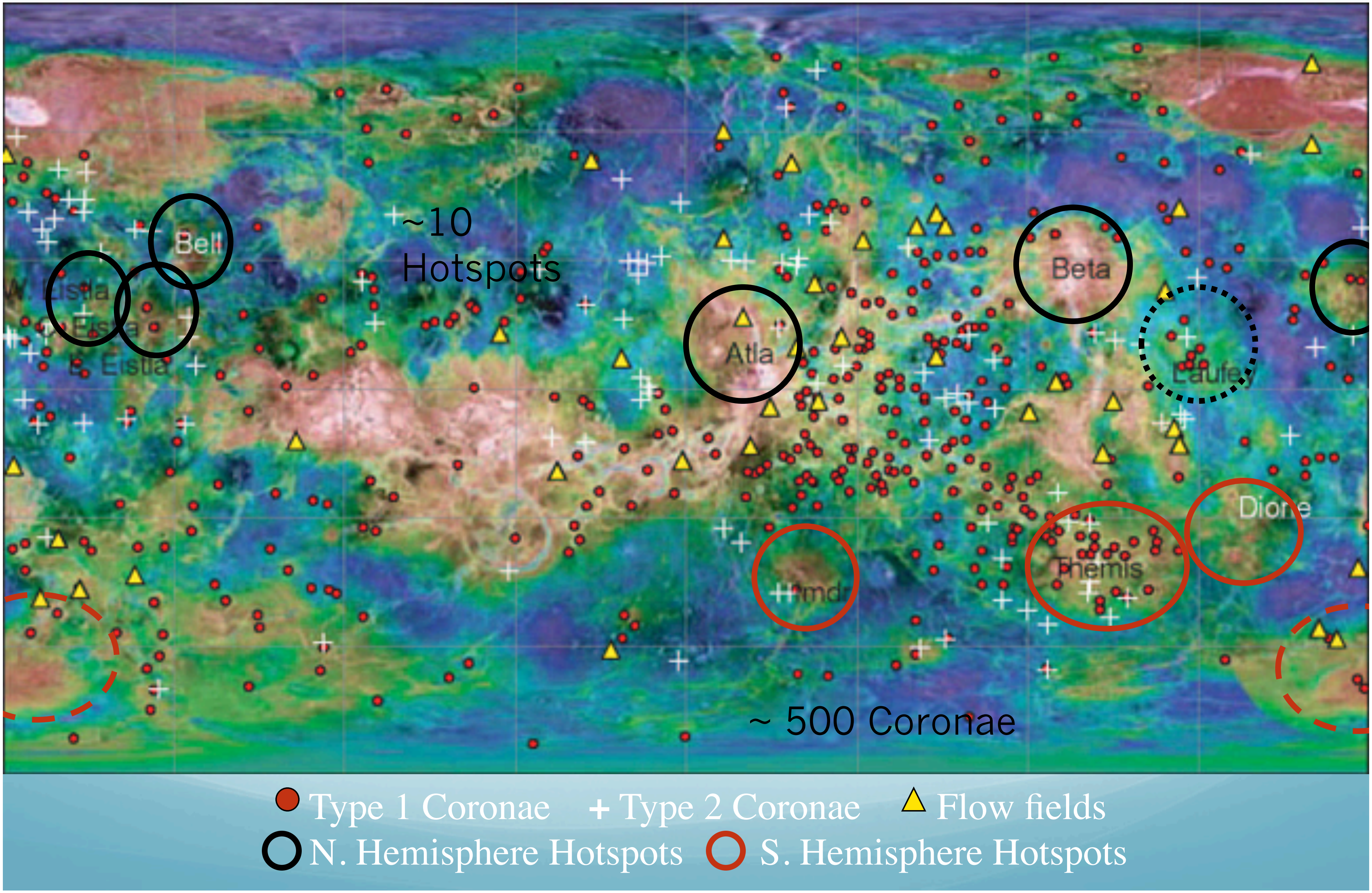
Sandwell and Schubert, 1992

K5. There is little surface erosion

- Dunes and wind streaks are rare..

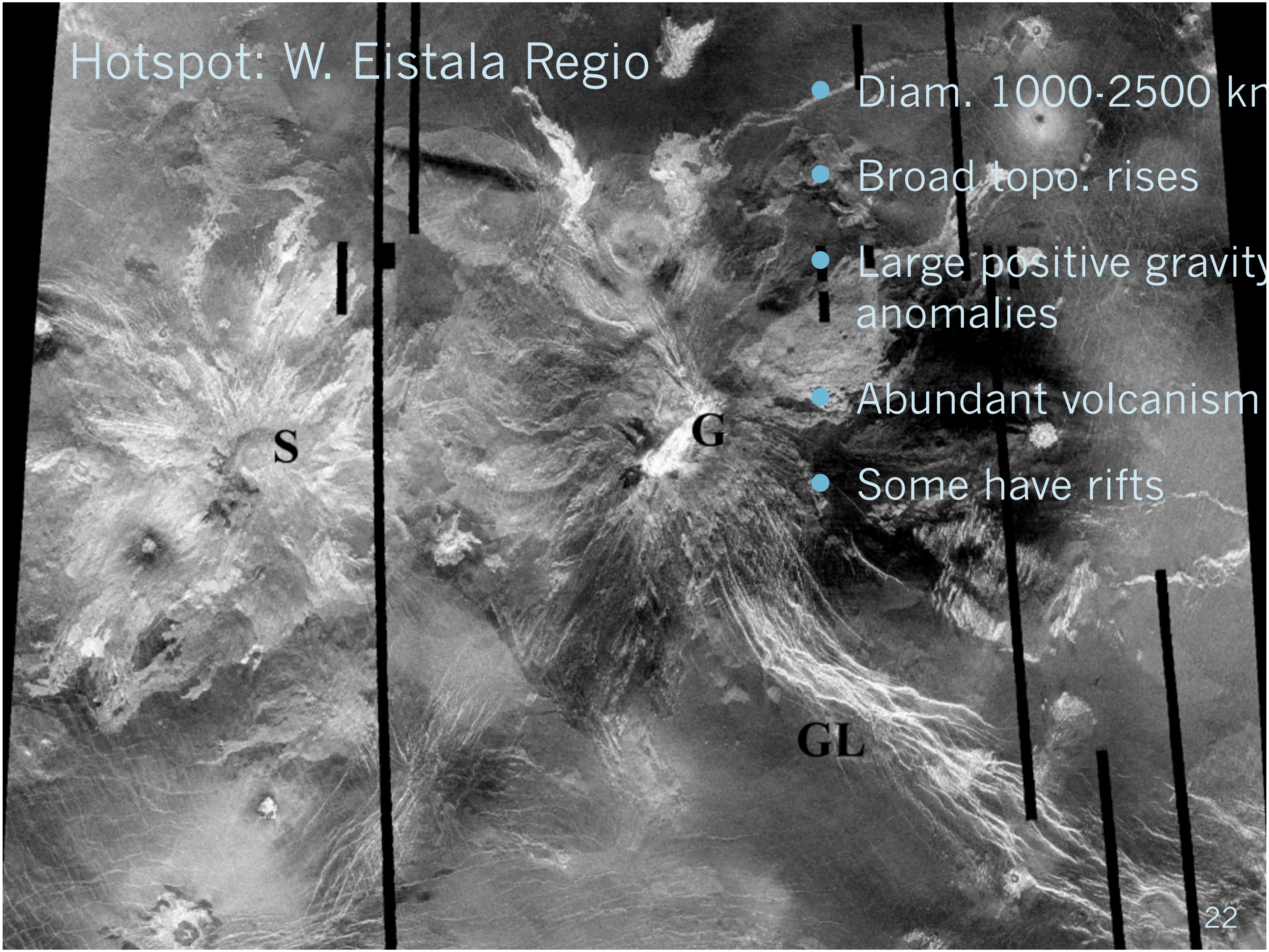


K7. There are ~10 active mantle plumes



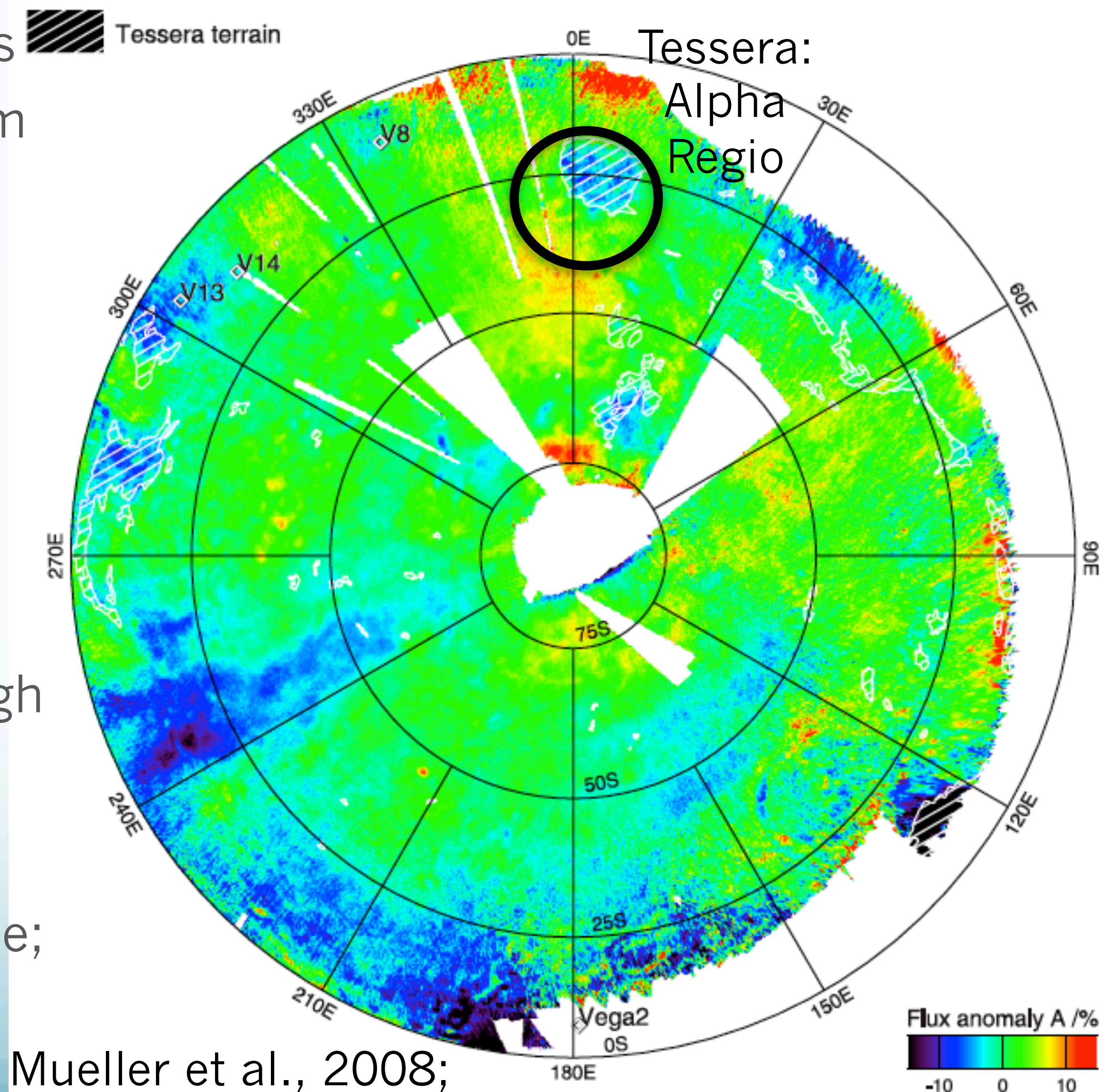
Hotspot: W. Eistala Regio

- Diam. 1000-2500 km
- Broad topo. rises
- Large positive gravity anomalies
- Abundant volcanism
- Some have rifts



New Data: Surface Emissivity (1.02 μm)

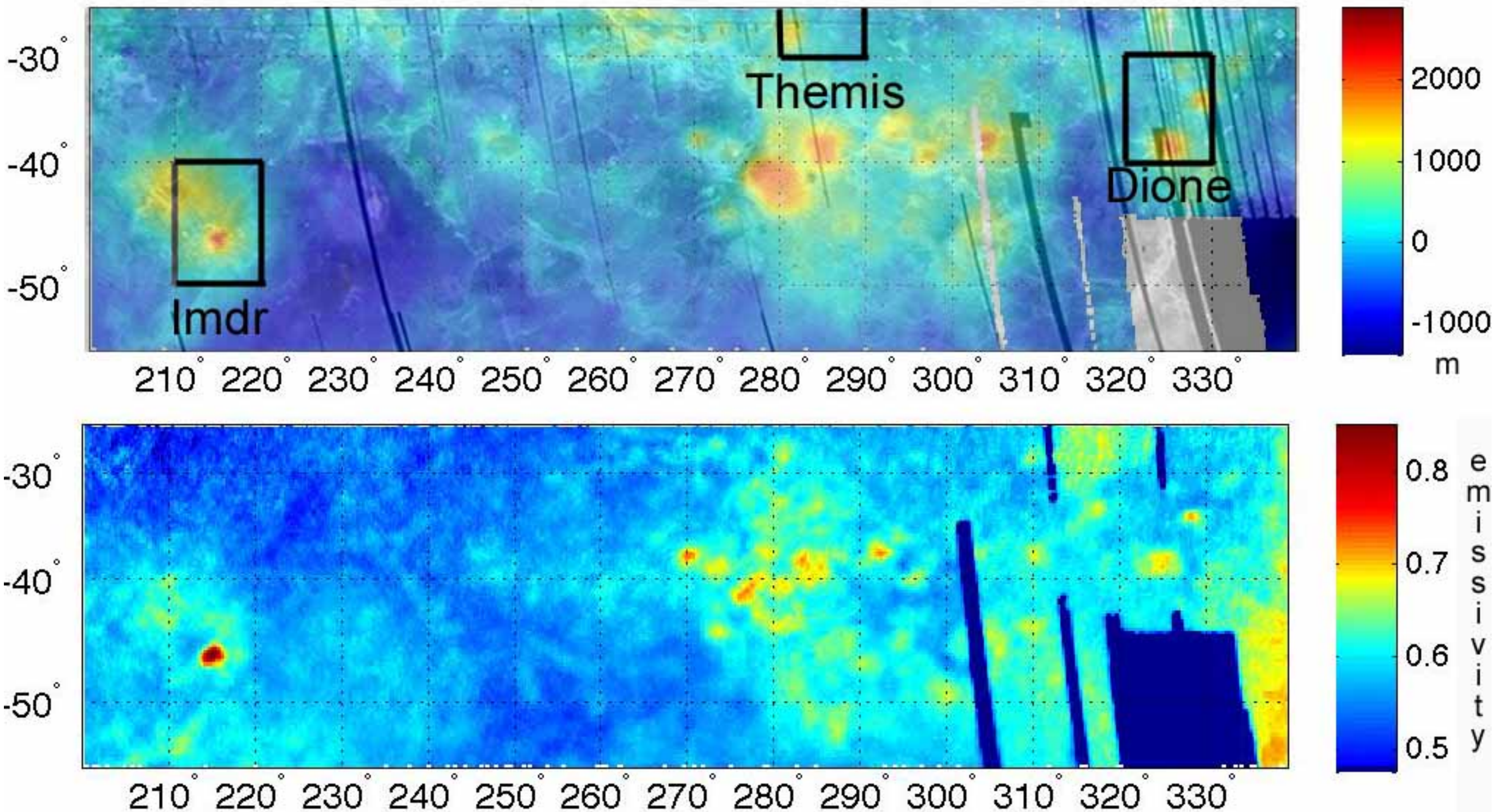
- Derived from VIRTIS spectrometer observations
- Emissivity is retrieved from surface brightness by correcting for stray light, viewing geometry, cloud opacity, and elevation
- 1μm coincides w/the FeO absorbtion band, and is a function of mafic mineral content (and grainsize)
- Low/high e means low/high FeO
- Geologic correlations: low emissivity w/most tesserae; high emissivity with some volcanic flows.



Mueller et al., 2008;
Helbert et al., 2008

High Emissivity Anomalies

Topography & Radar



Emissivity (topo from Rappaport et al., 1999; mean emissivity set to 0.58)

Evidence for Recent Volcanism

- Δe due to primary compositional differences, or differential weathering?
  - Compositional differences requires very high Mg, Ti, or Fe. Possible, but would still weather..
  - **Preferred interpretation: Weathered (avg. e) vs. unweathered basalt (high e)**
    - Predicted weathering products include calcite, quartz, dolomite, hematite and anhydrite, all with lower emissivity relative to mafic minerals in basalt.
- Note: Δe due to active flows is highly unlikely due to averaging of data over 1.5 years.
- Using estimated volumes of volcanism, the range of available estimates of resurfacing gives an age range of 2.5-2500 k.y.
  - **Laboratory experiments suggest they are very recent**

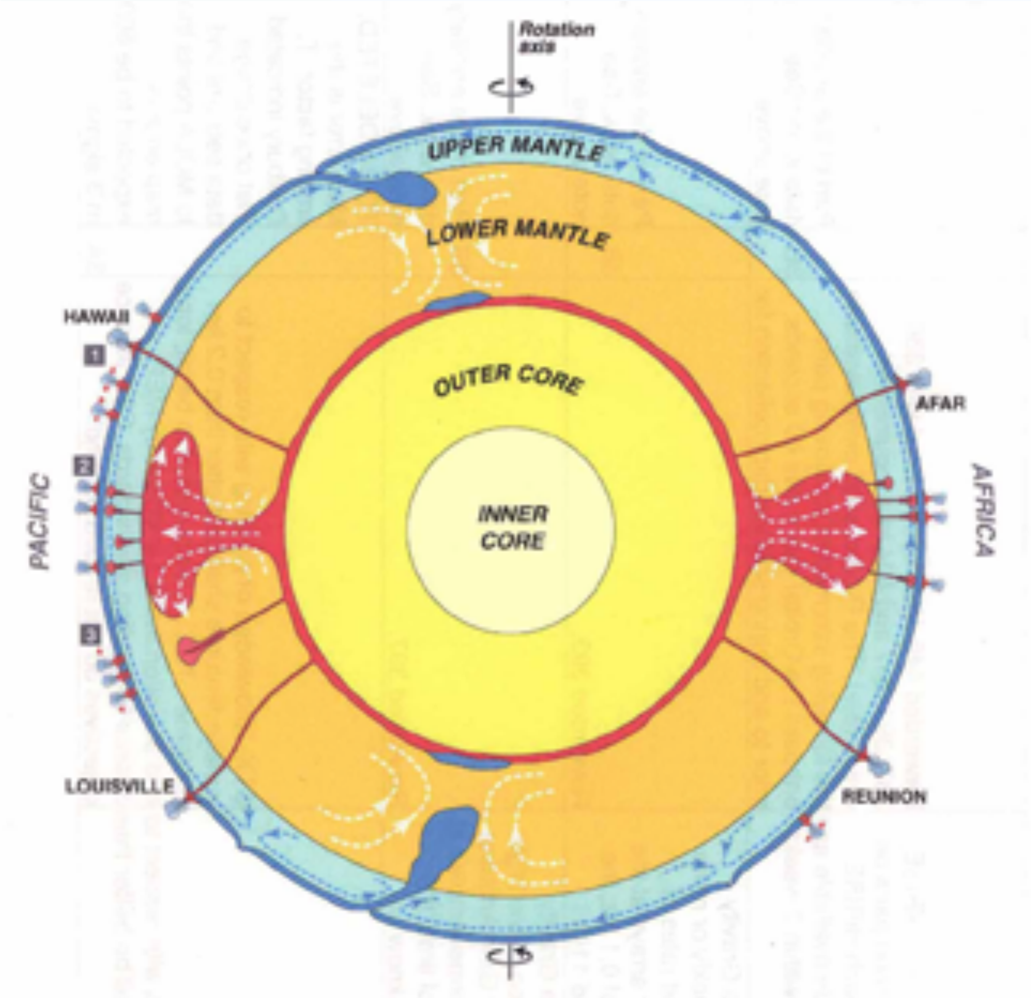
Supporting Evidence

- Context:
  - Gravity data implies mantle plumes
  - Anomalies are associated with stratigraphically young flows
- Atmospheric sulfur increased substantially during the Venus Express mission (Marq et al. 2012)
  - Interpreted as volcanic or climatic
- Sulfuric acid/water clouds require outgassing of S in the last 20-50 m.y. (Bullock and Grinspoon, 2001)

Implications of Recent Volcanism -1

- All hotspots (N & S) presumed active
- Presumed to come from the core-mantle-boundary
  - Implies thermal boundary layer and heat loss from core
  - So.. Why no magnetic field?
  - Contradicts theories that require subduction to produce upwelling from the core
- Multiple scales of upwellings.. Implications for the interior?

The Terrestrial Plume Debate

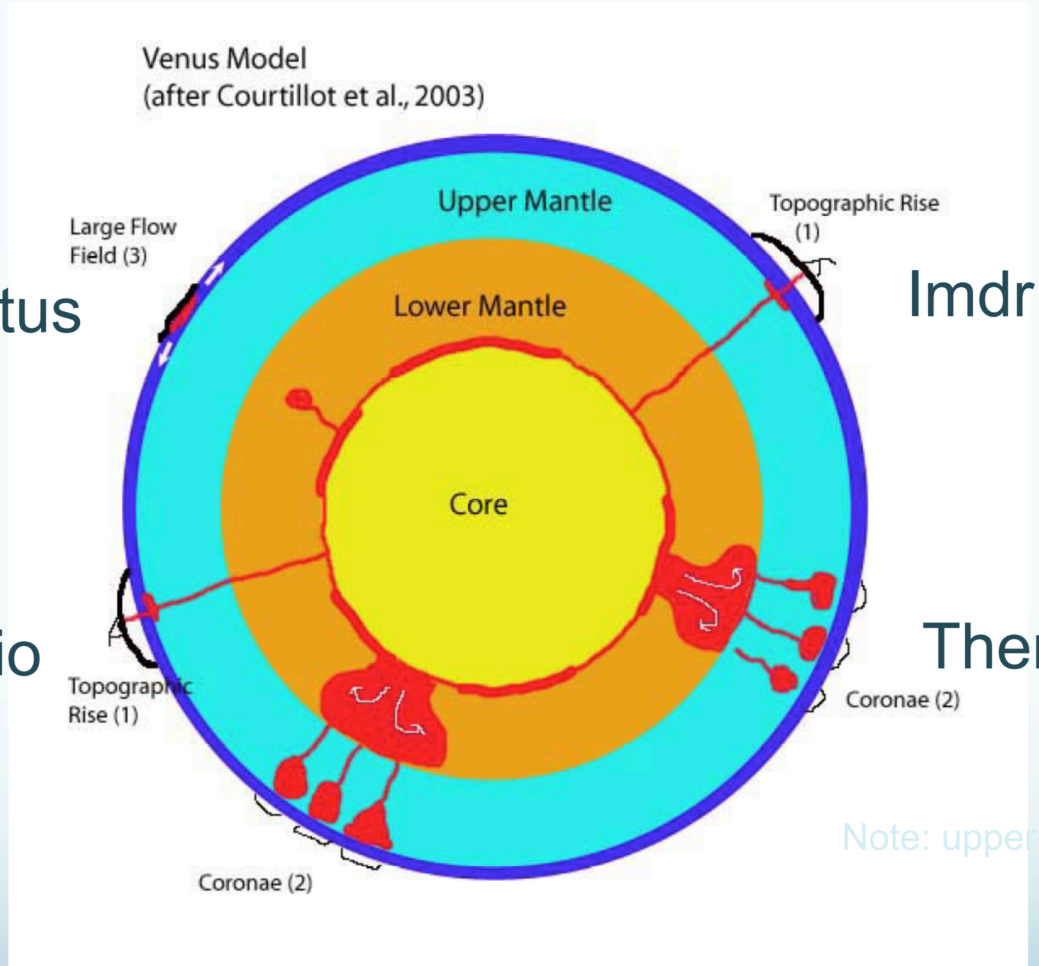


- The study of plumes has undergone a paradigm shift in the last ~15 yr, from all volcanism related to plumes to no plumes at all…
- Courtillot et al. (2003) suggested a model with three depths of plume origin:
  - Deep or core-mantle boundary plumes (~10)
  - Intermediate or secondary plumes that originate at the base of the upper mantle
  - Shallow or tertiary plumes that originate in the lithosphere.

Venus à la Courtillot

Mylitta Fluctus

Imdr Regio



Dione Regio

Themis Regio

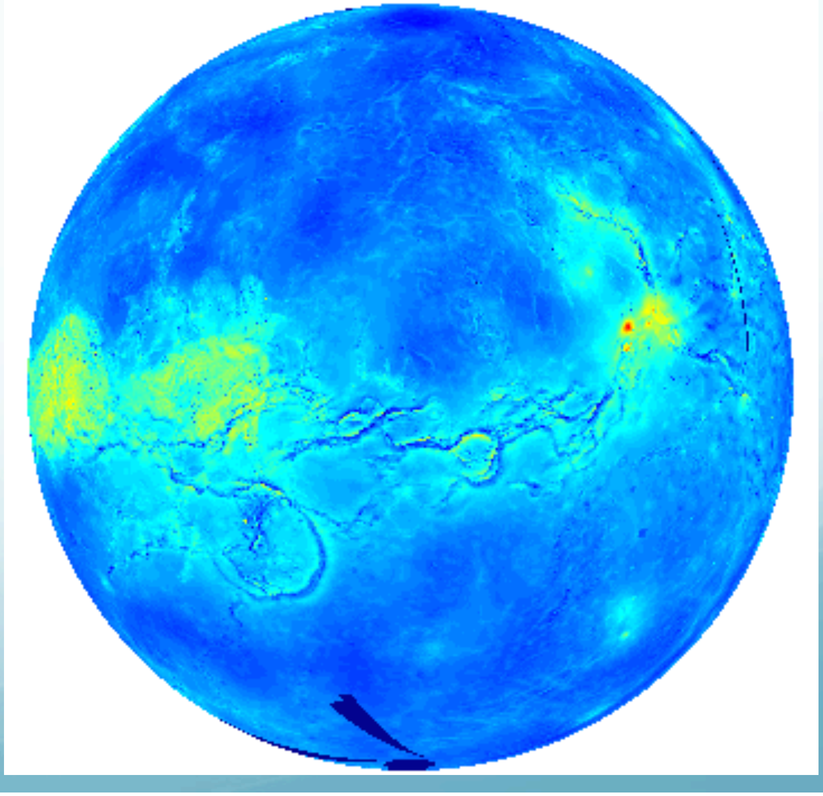
Note: upper mantle not to scale

Stofan, E.R., and S.E. Smrekar, Large topographic rises, coronae, large flow fields and large volcanoes on Venus: Evidence for mantle plumes? In *Plates, Plumes, and Paradigms,* eds. G.R. Foulger, J.H. Natland, D.C. Presnall, and D.L. Anderson, Geol. Soc. Am. Special Vol. 388, pp. 861, 2005.

“Unknowns”

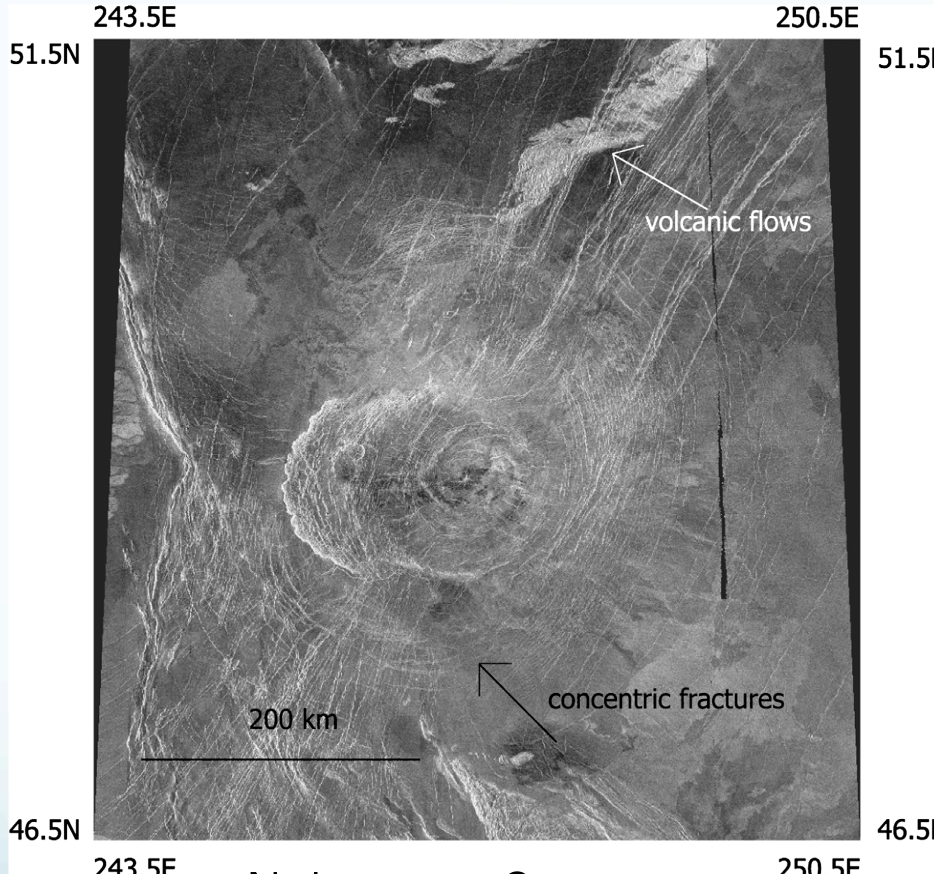
- Is there evolved (Si-rich) crust? Are the tesserae “continents”?
  - Implications for planetary evolution & habitability
- Was there a global resurfacing event? Was there past or episodic plate tectonics?
  - Motivation for episodic plate tectonic models
- How is the interior coupled to the lithosphere
  - Formation mechanisms for key tectonic features (tesserae, rifts)
- What is the interior volatile content?

U1. Coupling of convection & lithosphere?



Coronae: Volcano-Tectonic Features

- Circular to semi-circular fracture annulae, some w/ radial fractures
- All have volcanism
- Highly variable topographic shape
- ~500 globally, 1/3 at rifts
- Majority occur in association with rifts
- Diam: ~75-2600 km; Mean: ~250 km
- Formation: small upwelling plumes? Downwelling?

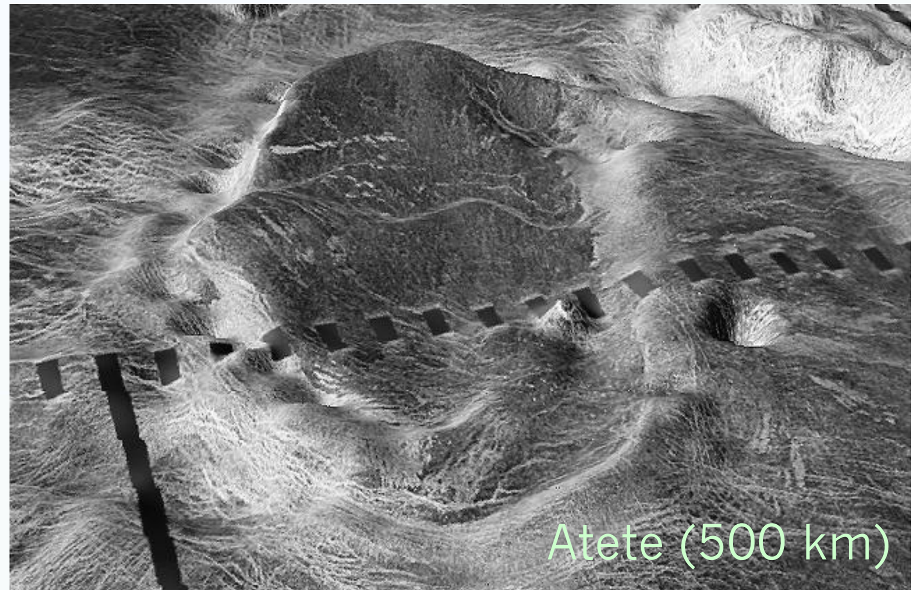


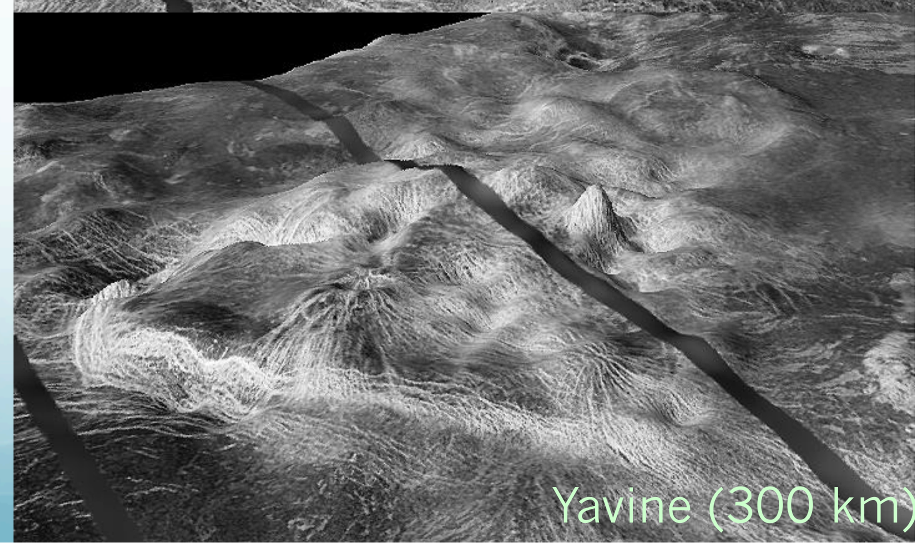
Nalwomga Corona
Diam. 380 km
Concentric fractures
Topographic depression

Coronae Topographic Classifications

Group	Topographic profile	Description	% of coronae
1		Dome	10
2		Plateau	10
3a		Rim surrounding interior high	21 (a+b)
3b		Rim surrounding interior dome	
4		Rim surrounding depression	25
5		Outer rise, trough, rim, inner high	5
6		Outer rise, trough, rim, inner low	1
7		Rim only	7
8		Depression	7
9		No discernible signature	14

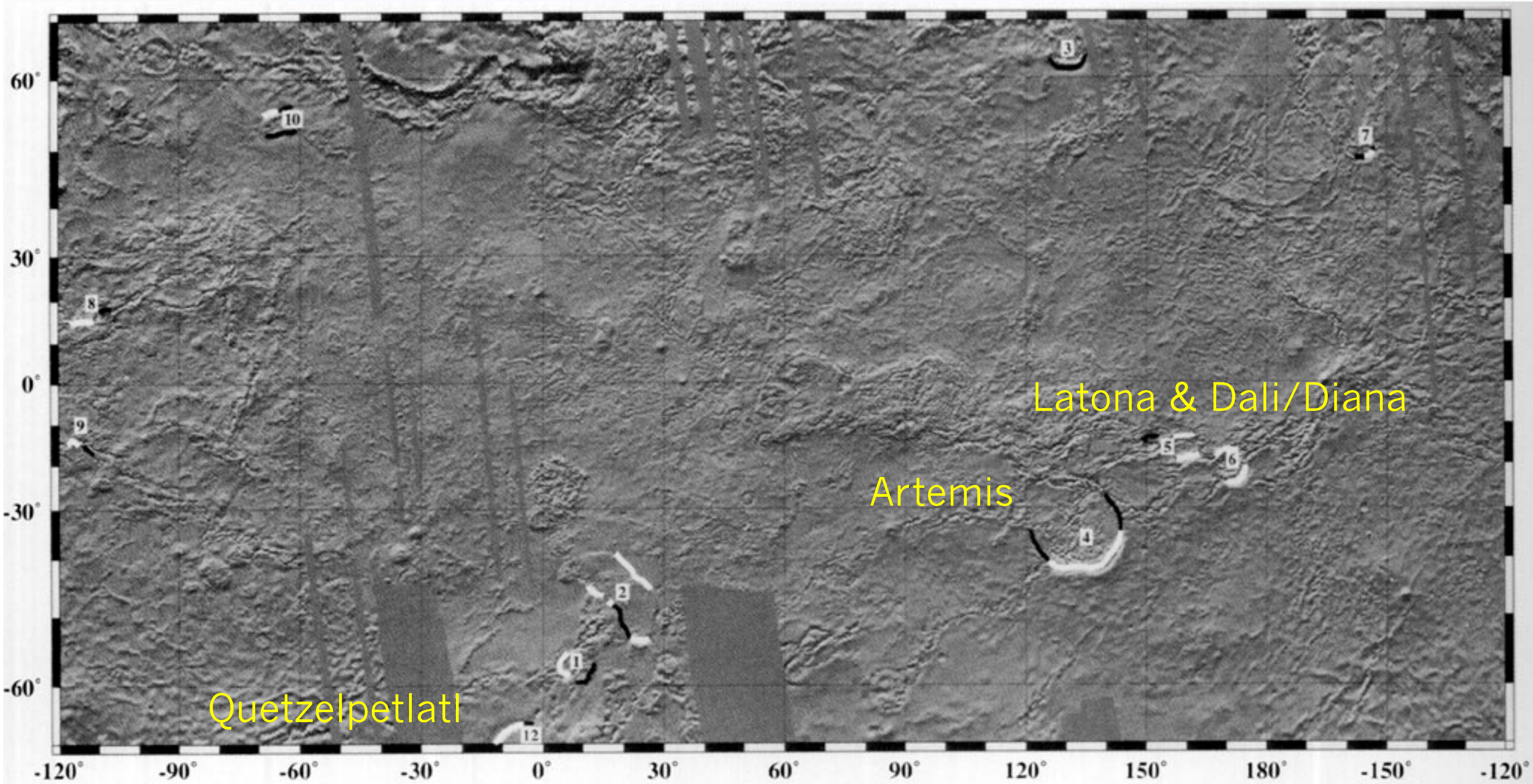
Smrekar and Stofan, 1997





Subduction Zones on Venus?

- Many large coronae proposed to be subduction sites.
- Delamination proposed to form some coronae.



Sandwell and Schubert, 1995

U2. Is Venus' Interior Wet or Dry?

- Atmospheric water ~30 ppm
  - Does outgassing continue? Water, sulfur have to be resupplied, but at poorly constrained rates
- Tectonic deformation studies yield Earthlike Te
  - Could imply: low strain rate, thin crust, or dry interior
- No Low Viscosity Zone > dry ?
  - Inferred from very large Geoid-to-Topography Ratios at hotspots…
- Ar Isotopes – indicates Venus is about 25% degassed > wet (Earth more like 50% degassed) –see O'Rourke
  - Contradicts the dry Venus idea..?

Comparison to Earth

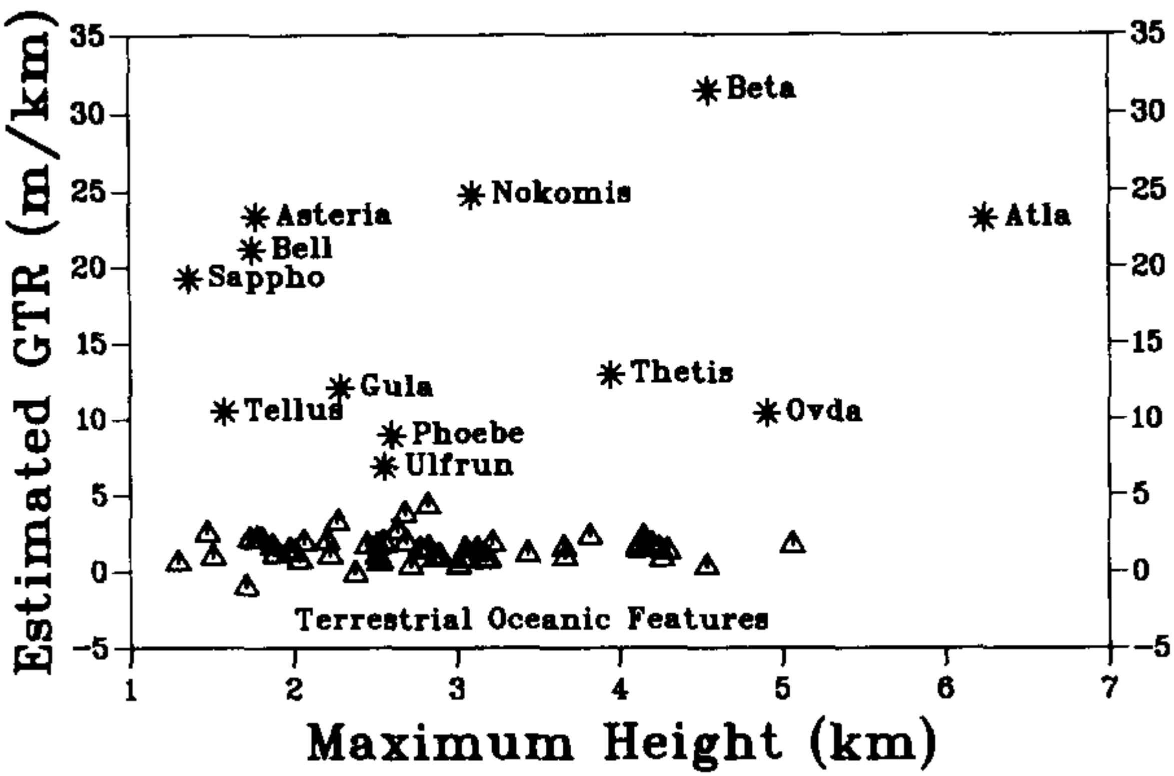


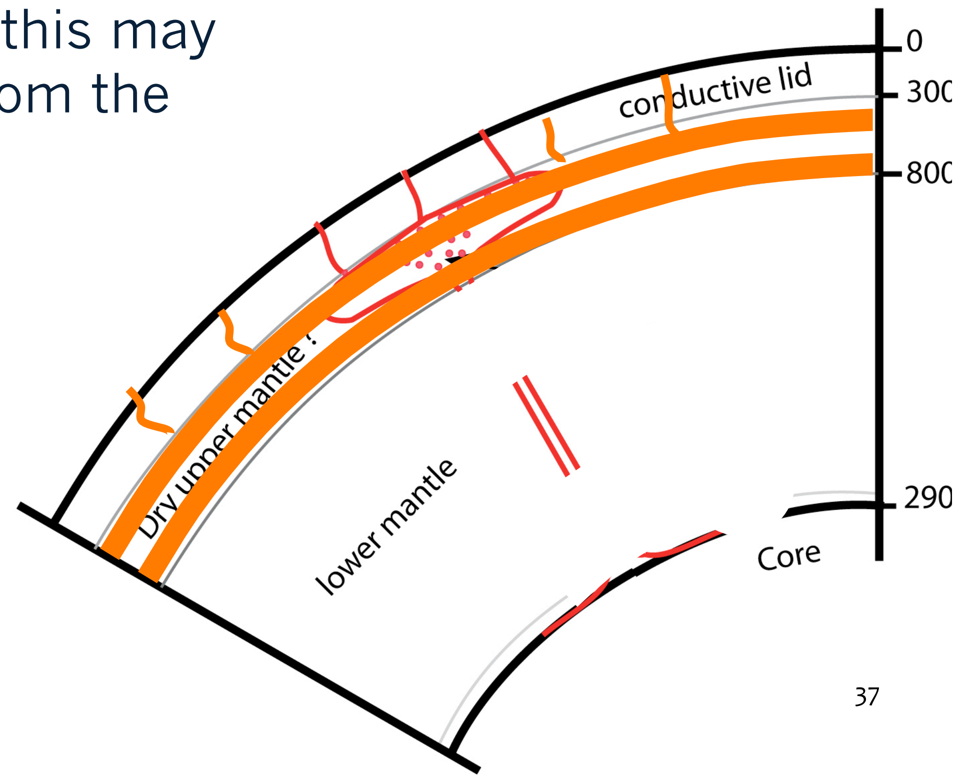
Fig. 4. Estimated GTR versus maximum topographic height. Asterisks indicate Venusian highland features; triangles indicate terrestrial oceanic swells, hot spots and plateaus [9].

- Low Viscosity Zone under oceanic crust decouples the lithosphere from the plume, reducing dynamic uplift
- But is this the right comparison?
  - No moving plates, so as melt products build up, a LVZ could be displaced

Smrekar and Phillips, EPSL, 1991

Implications for Volatiles in the Interior

- Currently volcanism ,appears> to occur primarily at hotspots
- Did pervasive melting create the plains and dry the upper mantle?
  - The upper mantle is ~25% of the mantle volume, equal to the amount of Ar lost
- If the upper mantle is degassed, this may require somewhat wet material from the lower mantle to produce melting



Questions for Venus?

Tectonics:

- **How do key tectonic features (tesserae, rifts) form?**
- **Are there elements of plate tectonics?**
  - **Subduction, spreading centers, strike-slip zones?**
- **Did Venus have plate tectonics, is it episodic?**
- **What are the key parameters that permit plate tectonics initiation and perpetuation? Volatiles, temp., strain rate?**

Interior:

- **How vigorous is convection? How does it couple to the surface?**
- **How wet is the interior?**
- **What is the role of other key variables (phase transitions, heat producing elements, heat flow from the core, plumes)?**