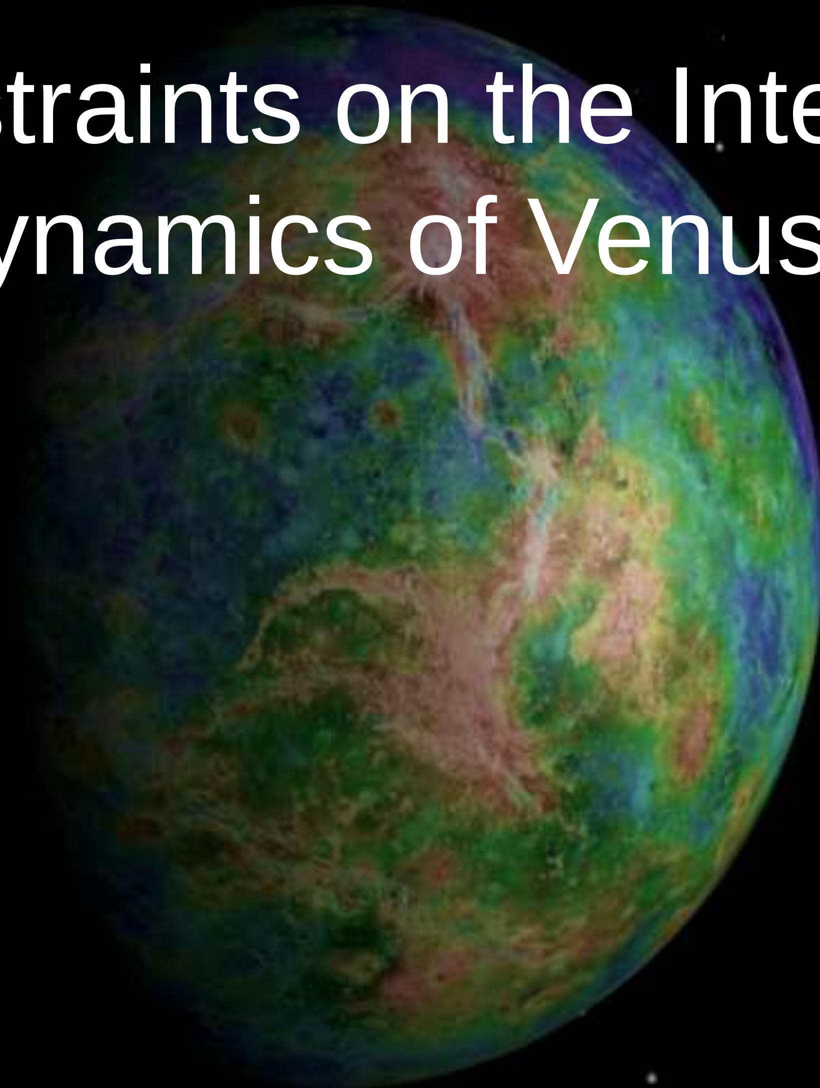
Constraints on the Interior Dynamics of Venus



Sue Smrekar
Jet Propulsion Laboratory

Venus: Earth's evil twin or distant cousin?

- Twin:
  - Diameter is 5% smaller
  - Same bulk composition
  - Once had an ocean's worth of water
  - Average surface age: 0.3-1 b.y
- Evil Twin:
  - Surface T ~460°C
  - Surface P ~90 bars
  - Atmosphere: CO_2 greenhouse
  - No magnetic field
- Distant Cousin:
  - No terrestial style plate tectonics

Outline

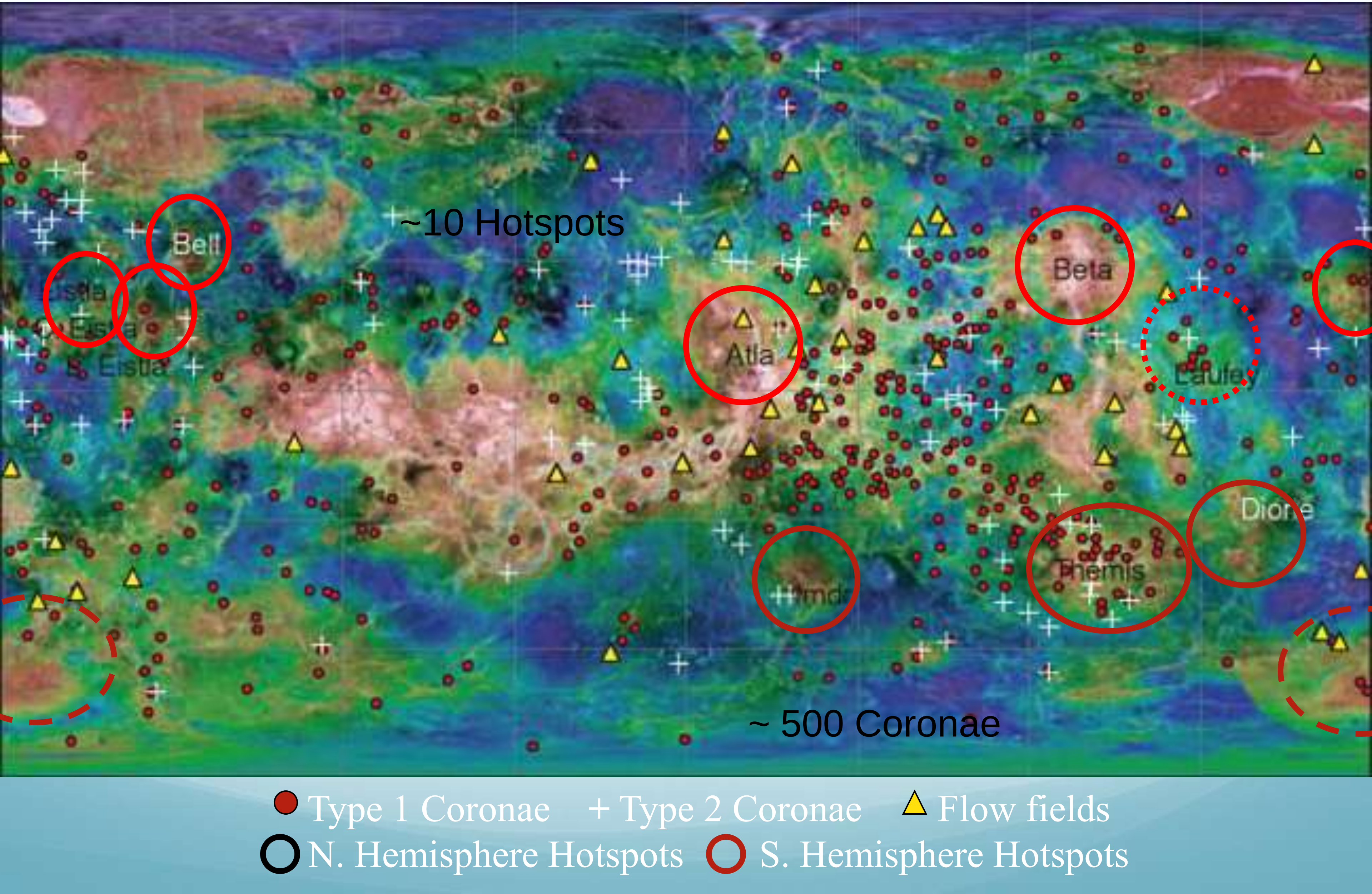
- Available constraints
  - Geologic overview
  - Composition
  - Topography, gravity
- Recent data
  - Evidence for “Continents”
  - Evidence for recent hotspot volcanism
  - Implications for the interior
- Inferences (myths?)
  - Catastrophic resurfacing
  - No evidence for plate tectonic *processes*
  - Venus interior is dry

Geologic Overview

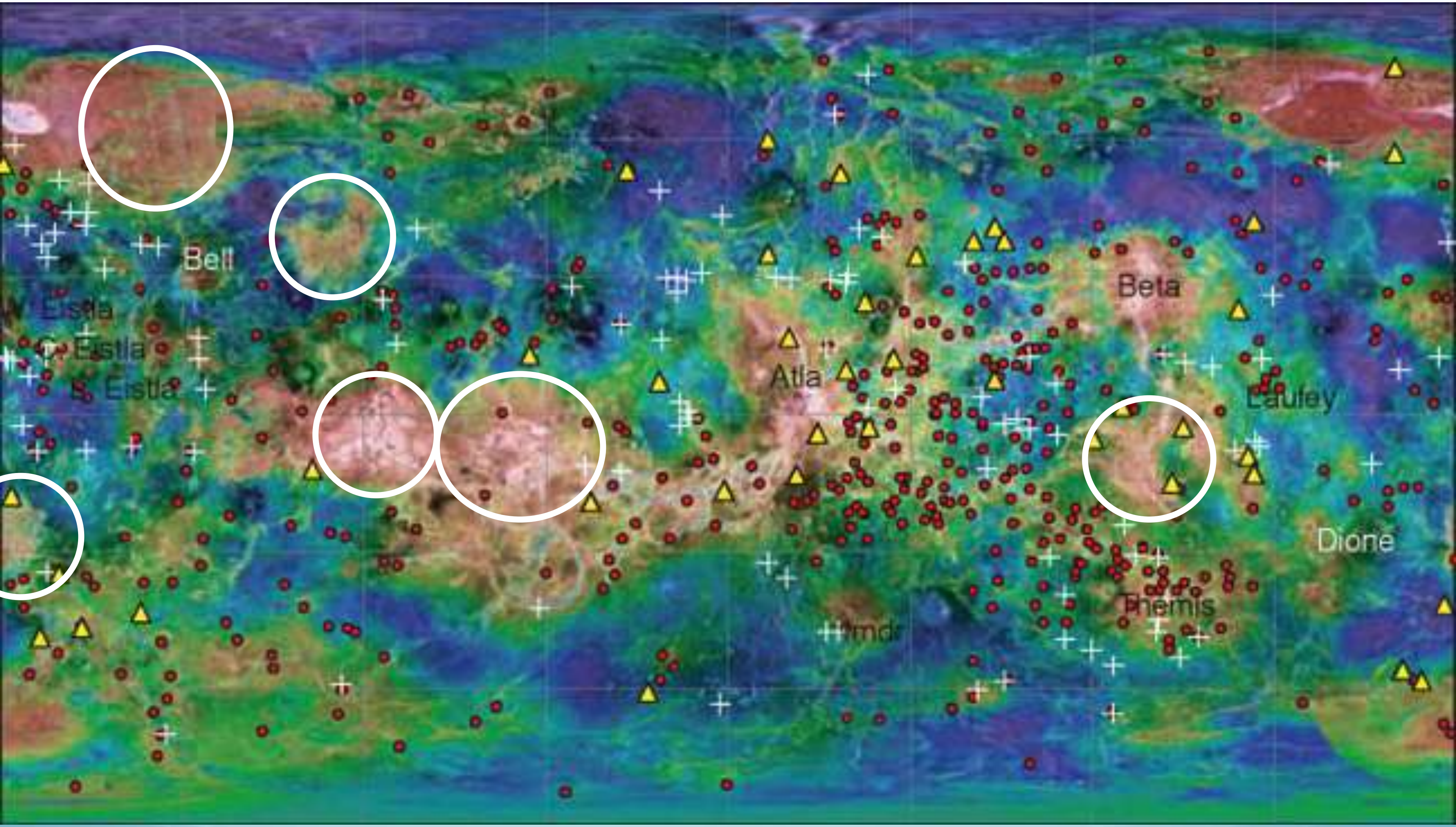
- Main Features
  - Hotspots (analogs to Hawaii, etc)
    - *Coronae (smaller scale upwelling, delamination, combo)*
  - Chasmata (Troughs with fractures)
    - Rifts (Chasmata w/graben)
    - Subduction? (analogs to ocean-ocean subduction)
  - *Tessera* Plateaus (highly deformed, isostatically compensated)
    - Analogs to continents?

- Data:
  - Magellan Mission: Early 1990s
    - Topo (12-25 km footprint)
    - Synthetic Apeture Radar Imaging (~125 m pixel)
    - Gravity (Deg. & Order 40-90, ~500-250 km)
  - Derived surface thermal emissivity from Venus Express

Hotspots, Coronae, Tessera, RIFTS



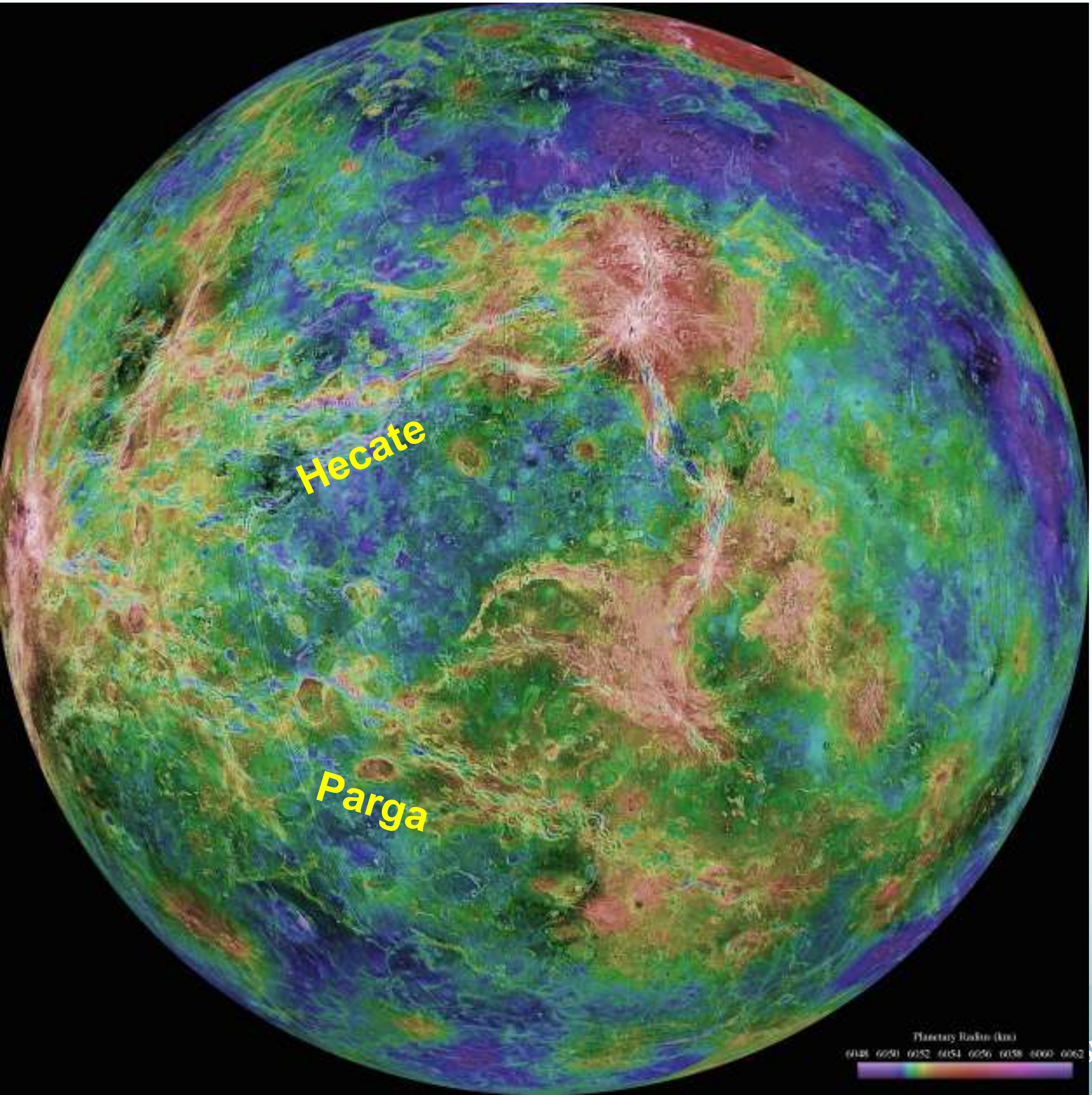
Hotspots, Coronae, Tessera, RIFTS



● Type 1 Coronae + Type 2 Coronae △ Flow fields

○ N. Hemisphere Hotspots ○ S. Hemisphere Hotspots

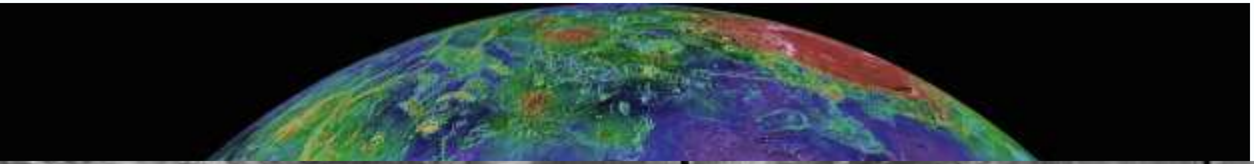
Hotspots, Coronae, Tessera, RIFTS

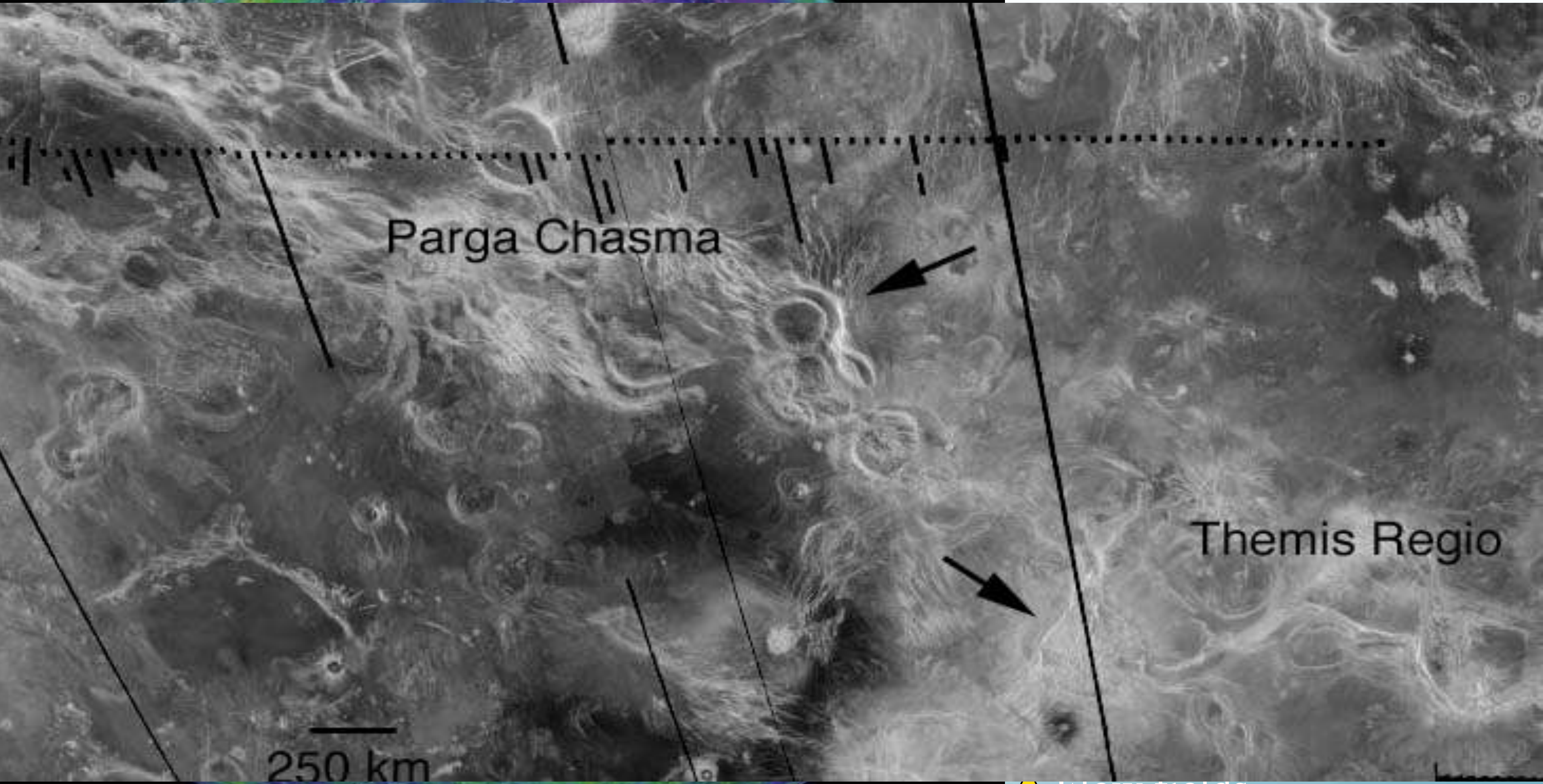


- Flow fields

sphere Hotspots

Hotspots, Coronae, Tessera, Rifts





- Flow fields

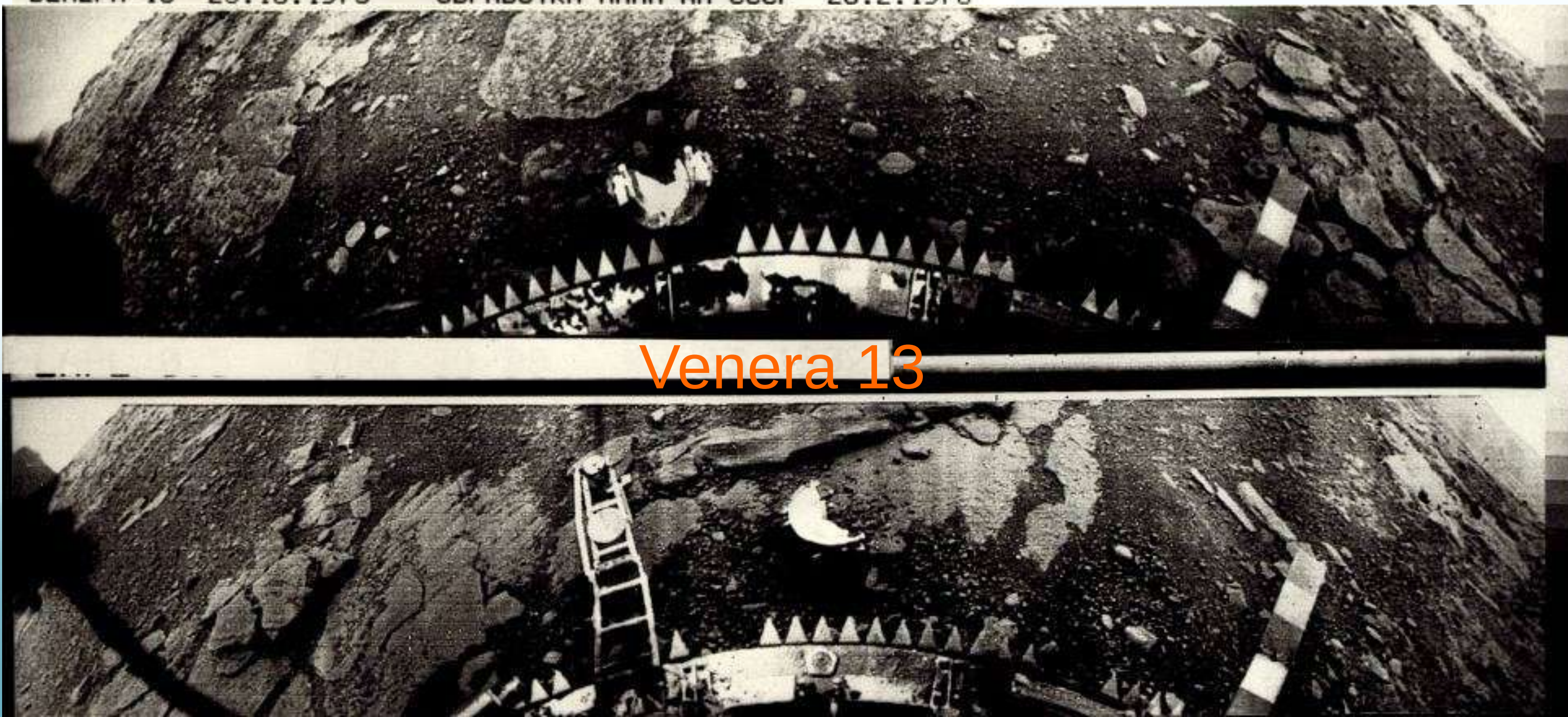
sphere Hotspots

Composition

Soviet landers (1970s) had x-ray fluorescence and gamma-ray spectrometers.

Compositions all found to be basalts to alkaline basalts.

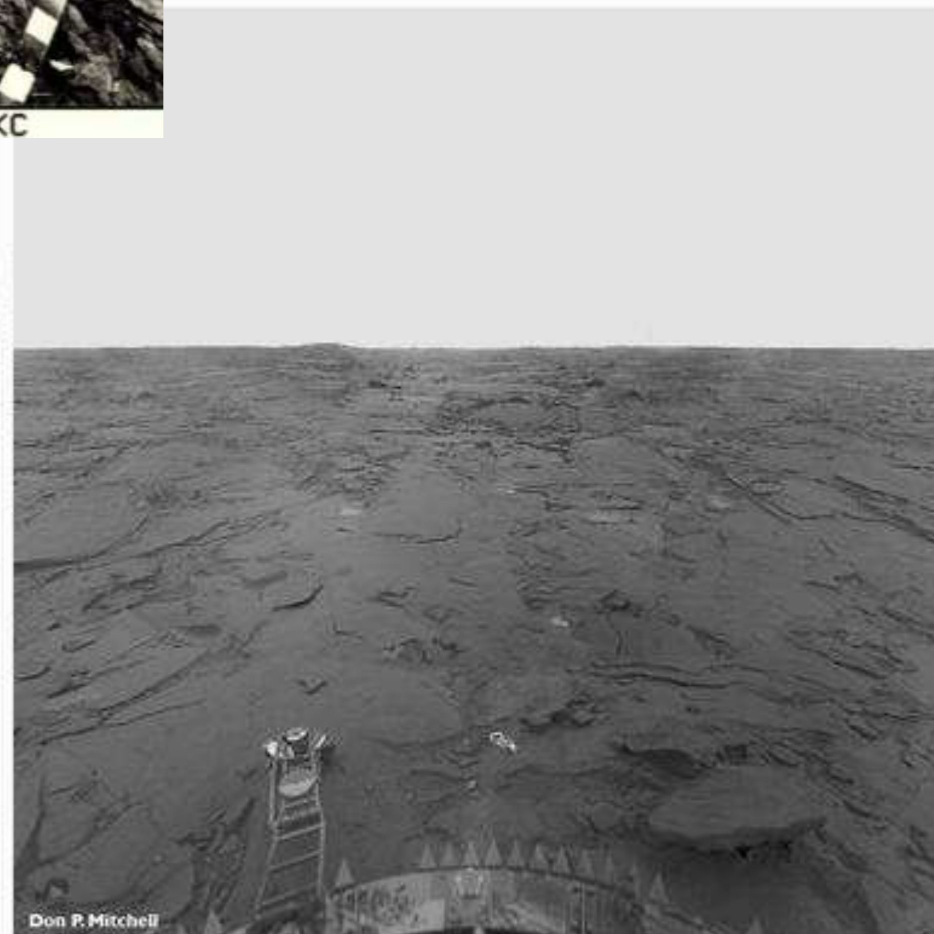
Layers: aeolian deposits?
Locally weathered horizons?
Platey lava flows?



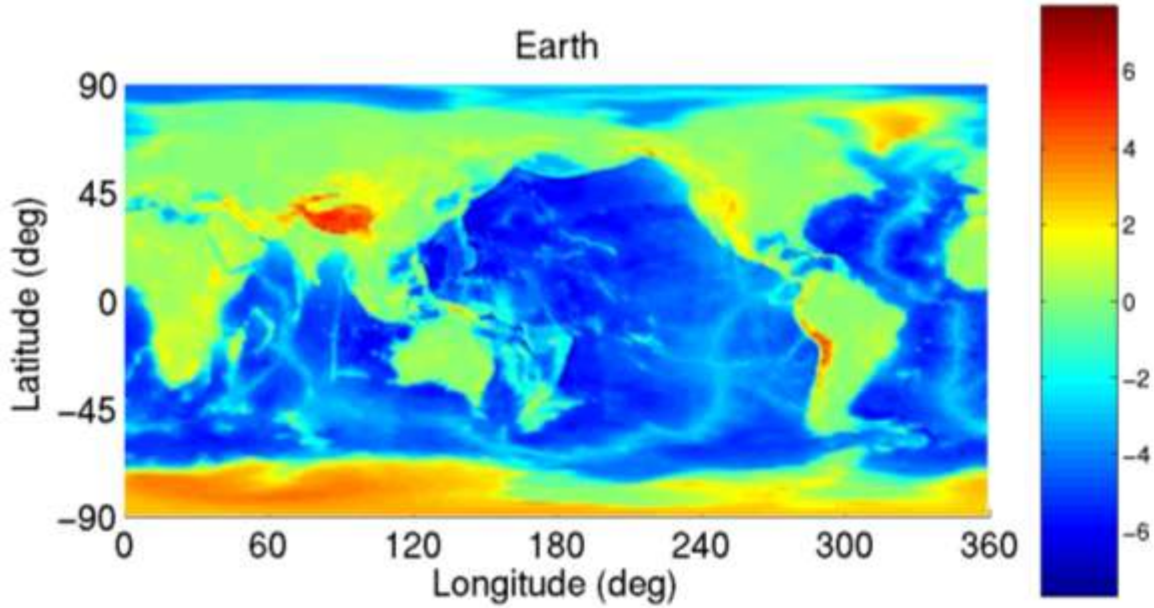
Venera 13

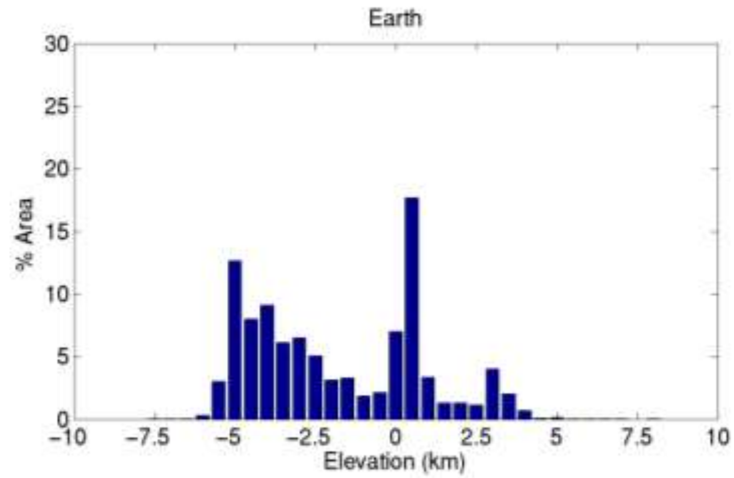
Venera 14,

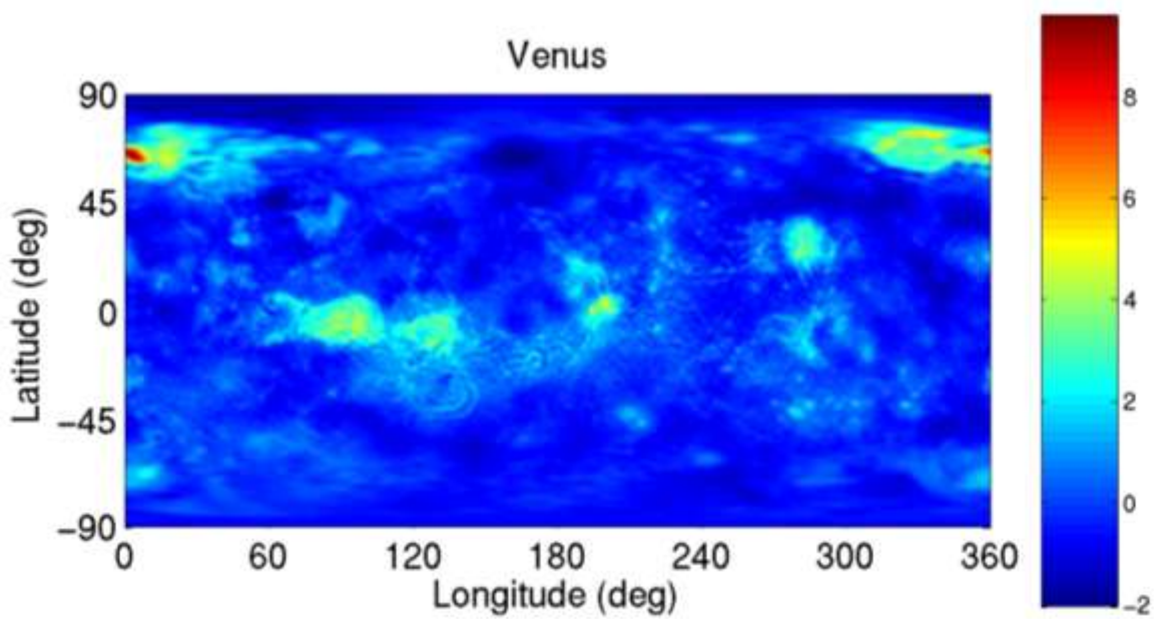
reprocessed by
Don Mitchell

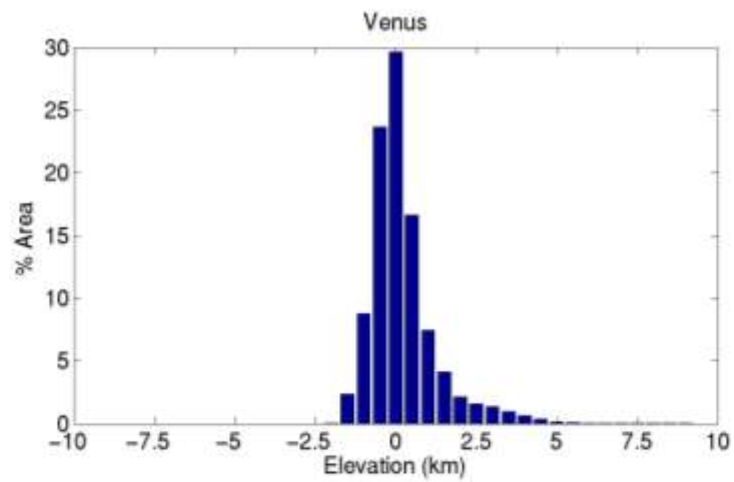


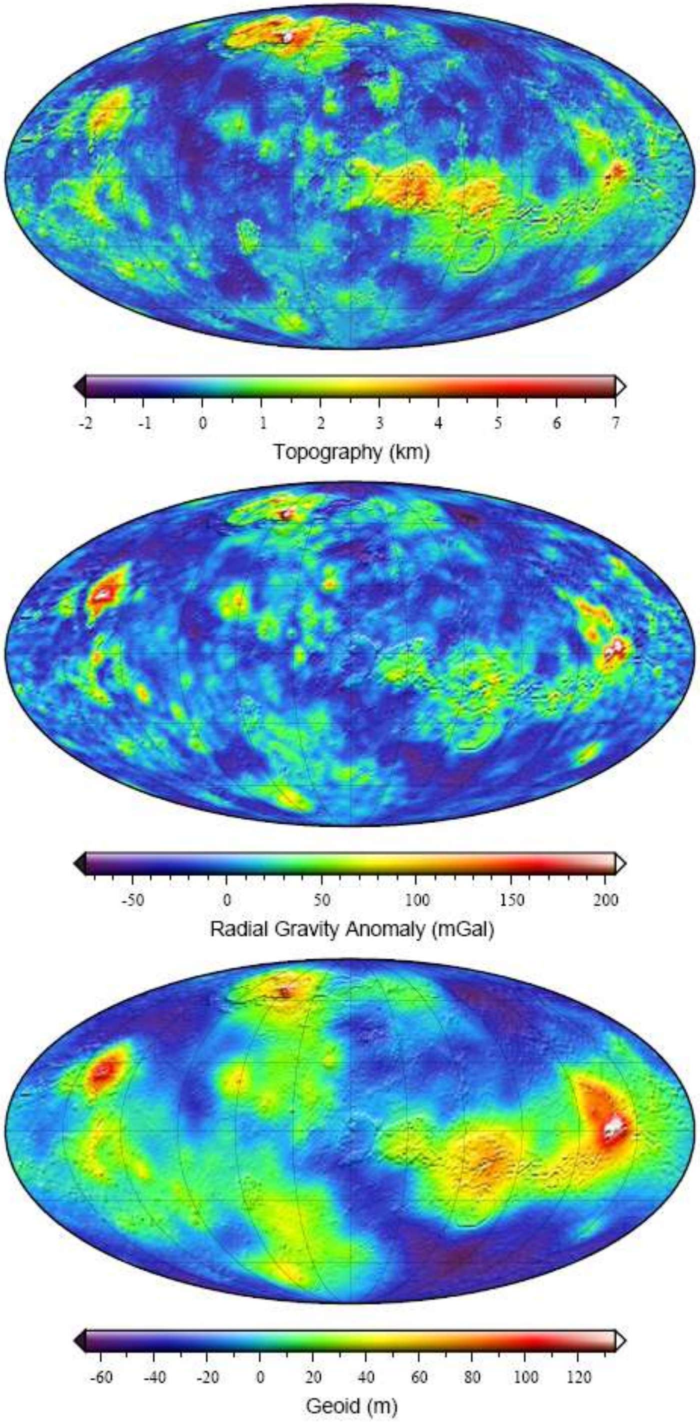
No Interconnected Plate Boundaries









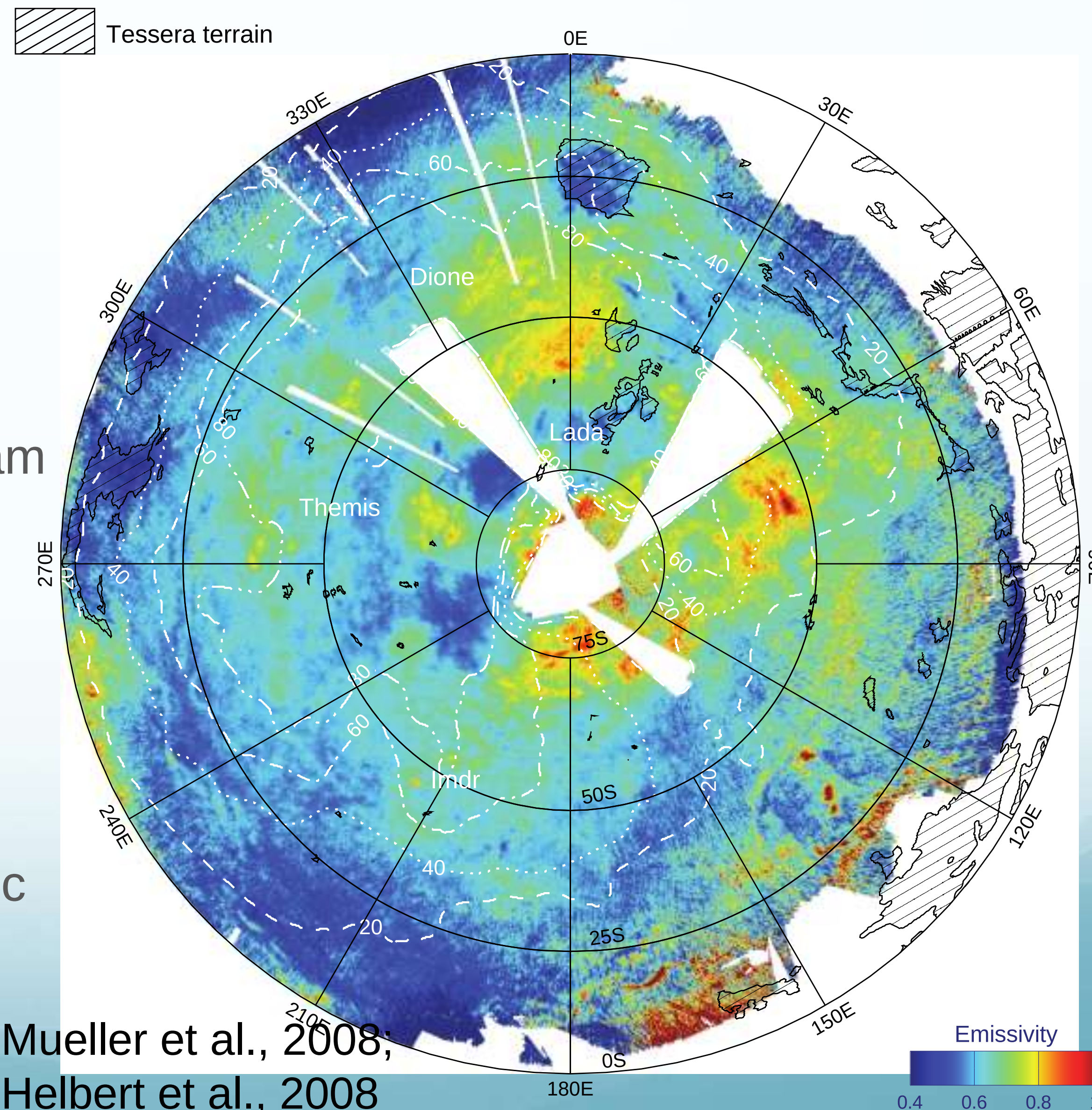


Venus - Gravity

- Gravity and topography are more highly correlated than on Earth (no erosion)
- Highlands:
  - Shallow compensation: isostatically compensated plateaus
  - Deep compensation: large volcanic rises or ‘hotspots’
- Range of elastic thickness values from 0-70 km
- Crustal thickness: mean ~30km, 10-70 km range
- Geoid to Topography ratios for hotspots are much larger than on Earth> No low viscosity zone
- Likely a liquid core

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
- Calculations use a two-stream approx. of radiative transfer with an atmos. reflectivity of 0.82 and a non-absorbing atmosphere.
- Correlations: low emissivity w/most tesserae; high emissivity with some volcanic flows.



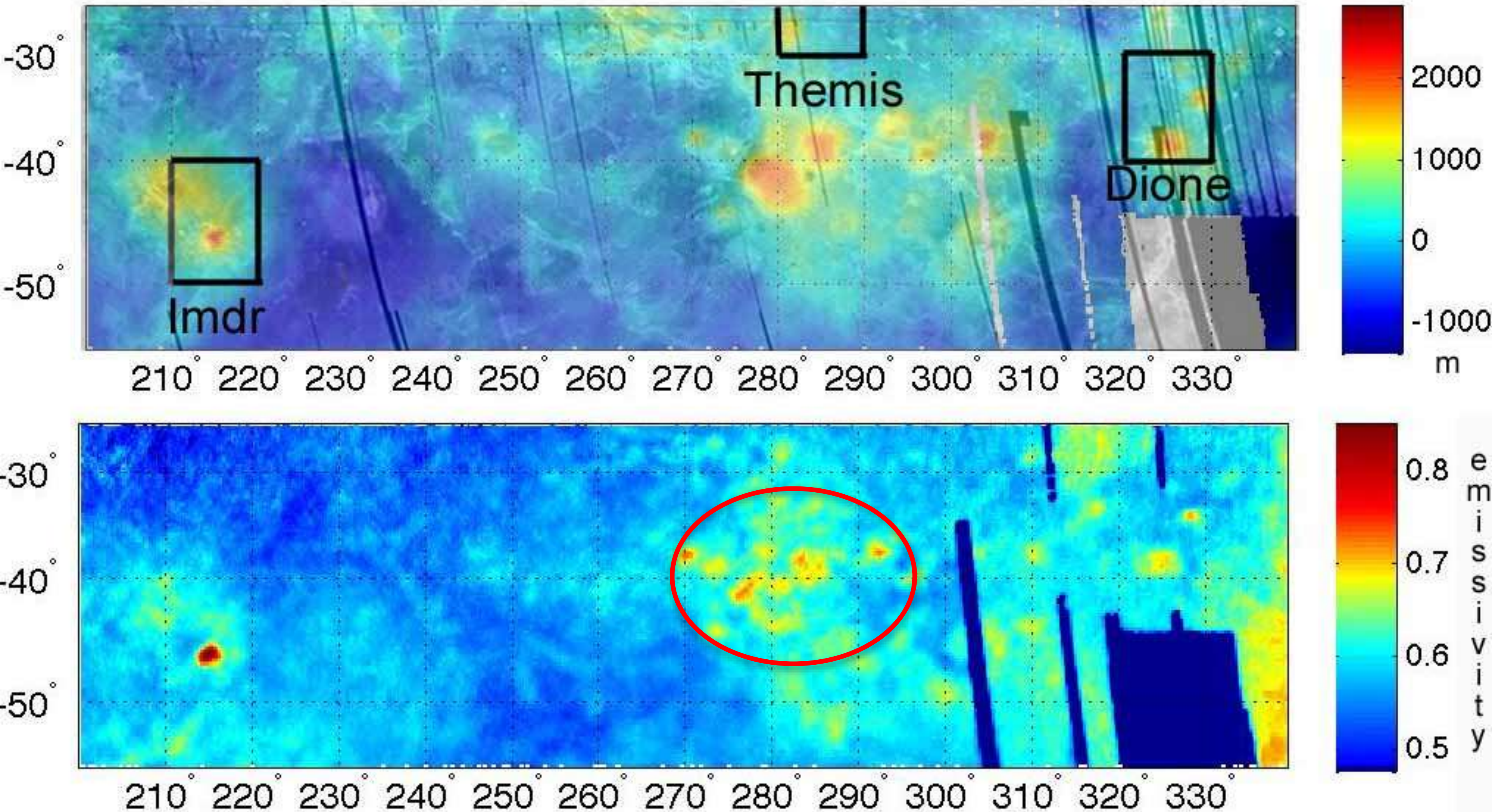
Mueller et al., 2008;
Helbert et al., 2008

Low Emissivity Anomalies (Continents on Venus?)

- 1μm coincides w/the FeO absorbtion band, so is a function of mafic mineral content (and grainsize)
- Low e means low FeO, possibly high Si
- Alpha Regio, the only tessera plateau in the S. Hemisphere, has low e.
- On Earth, continental crust is formed when basalt melts in the pressense of water.
- **Hypothesis: low e > high Si > evidence of past water!**
- Complication: Magellan altimetry in tesserae regions could have enough uncertainty to account for the anomaly…

Southern Hemisphere Hotspots

Topography + SAR



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

High Emissivity Anomalies (Recent volcanism on Venus?)

- 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**

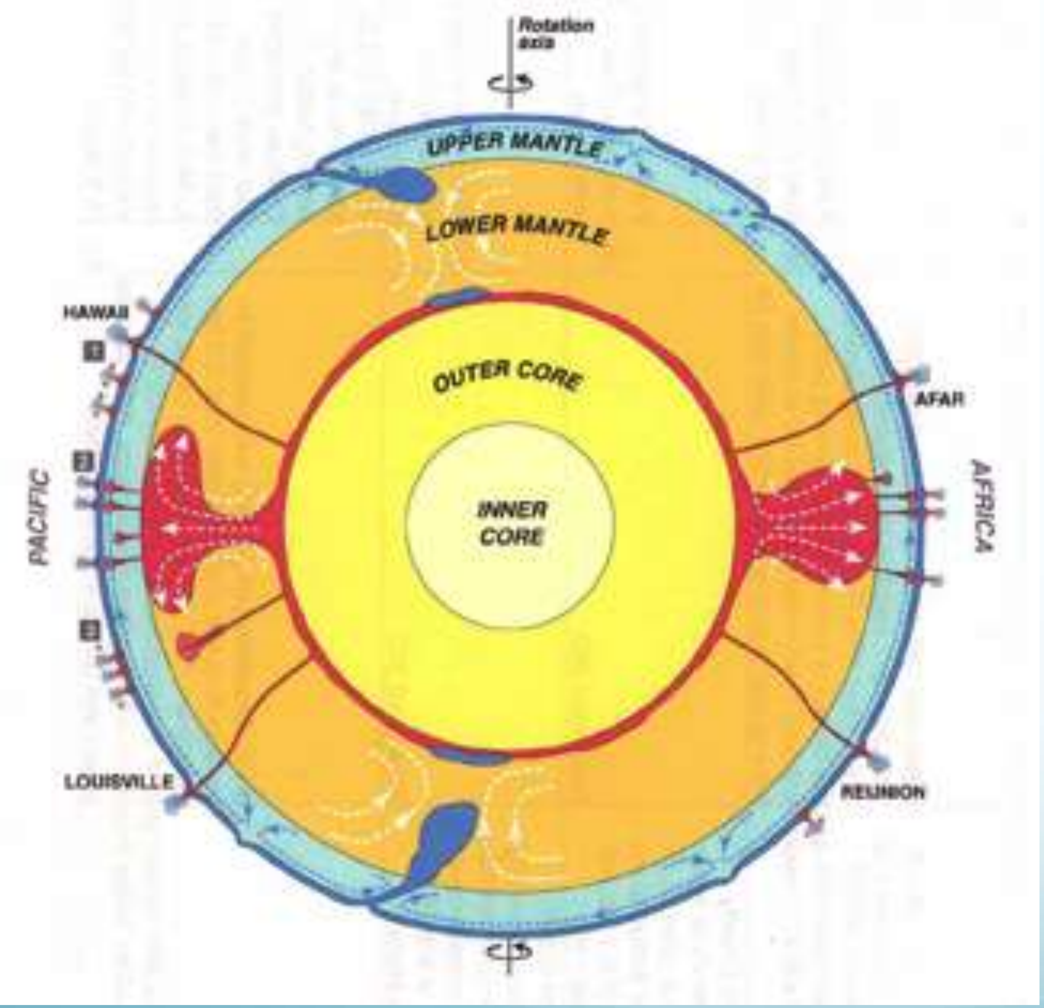
Supporting Evidence for Recent Volcanism

- Context:
  - All locations of high emissivity anomalies also have large positive gravity anomalies, interpreted as evidence of **mantle plumes**
  - Anomalies are associated with stratigraphically young flows
- Atmospheric SO_2 increased substantially over ~a decade, possibly due to new volcanic outgassing (Marcq et al. 2012)

Implications of Recent Volcanism

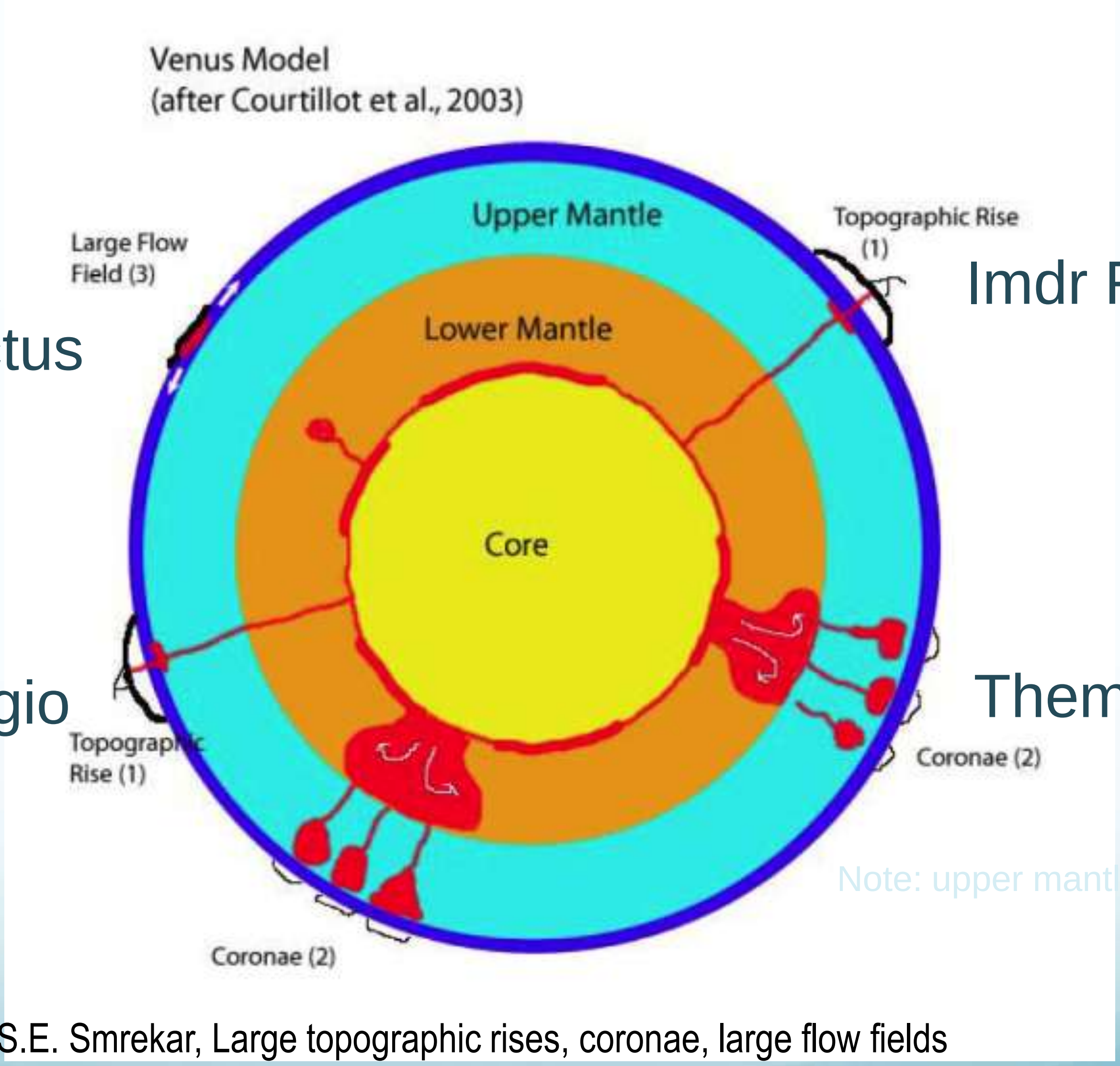
- All hotspots (N & S) presumed active, ~9
  - Plumes from the core-mantle-boundary
- No plains volcanism???
- How do plumes form in stagnant lid environment?
  - A hot enough mantle would thin or remove a hot thermal boundary layer at the CMB
  - Several recent studies of examined the implications for the amount of internal heating
  - What about the lack of a magnetic field?
- Themis Regio shows numerous volcanic sites active simultaneously
  - Two scales of plumes active …

The Terrestrial Plume Debate



- How many plumes are there? What is their role in producing volcanism? How much heat do they transport?
- 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 a la Courtillot



Mylitta Fluctus

Imdr Regio

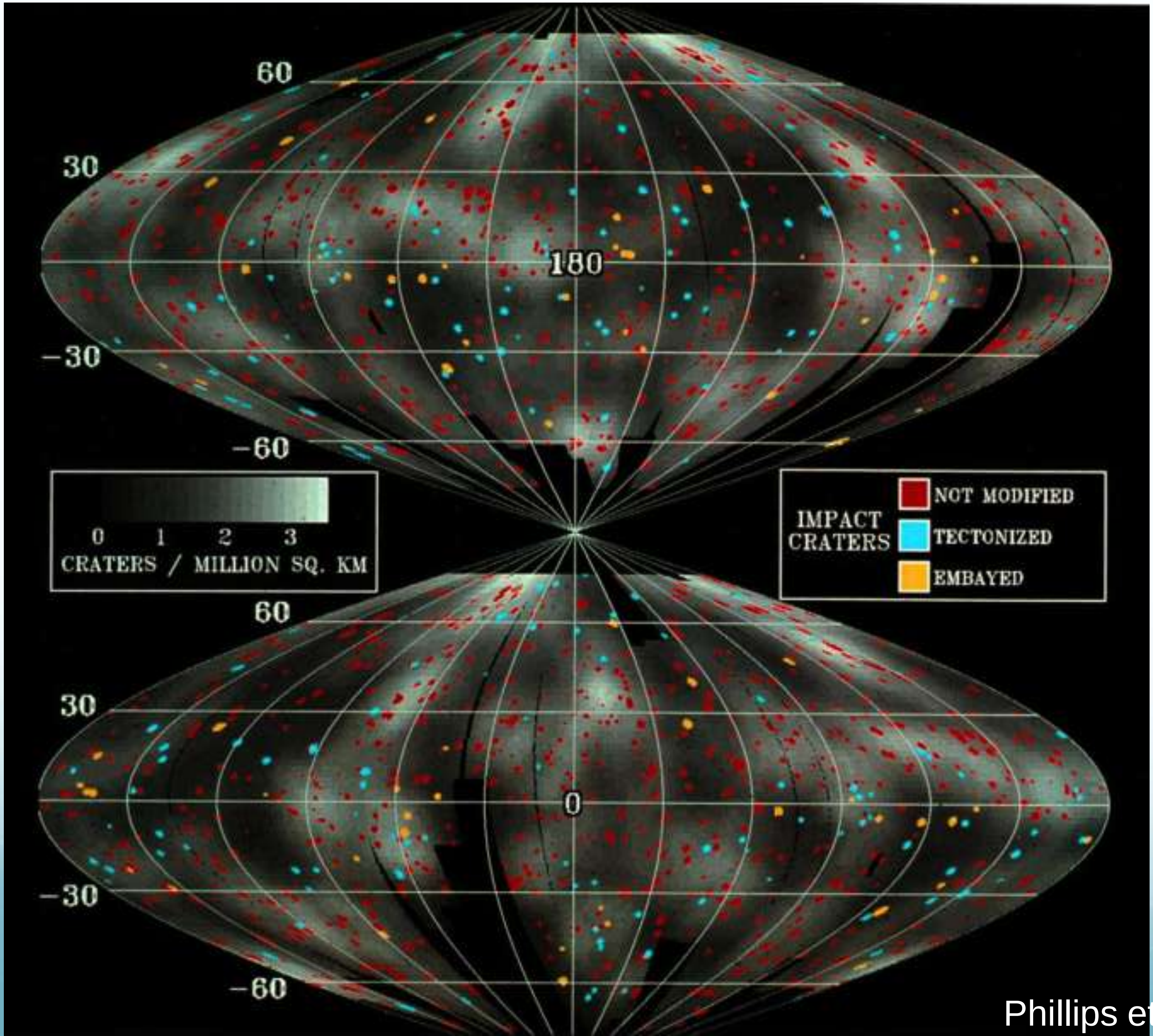
Dione Regio

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.

Geologic History &The Impact Cratering Record

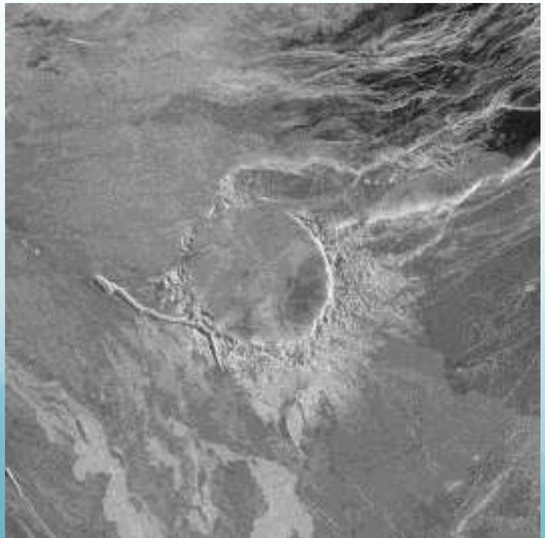


Surface age: 0.3-1 b.y.

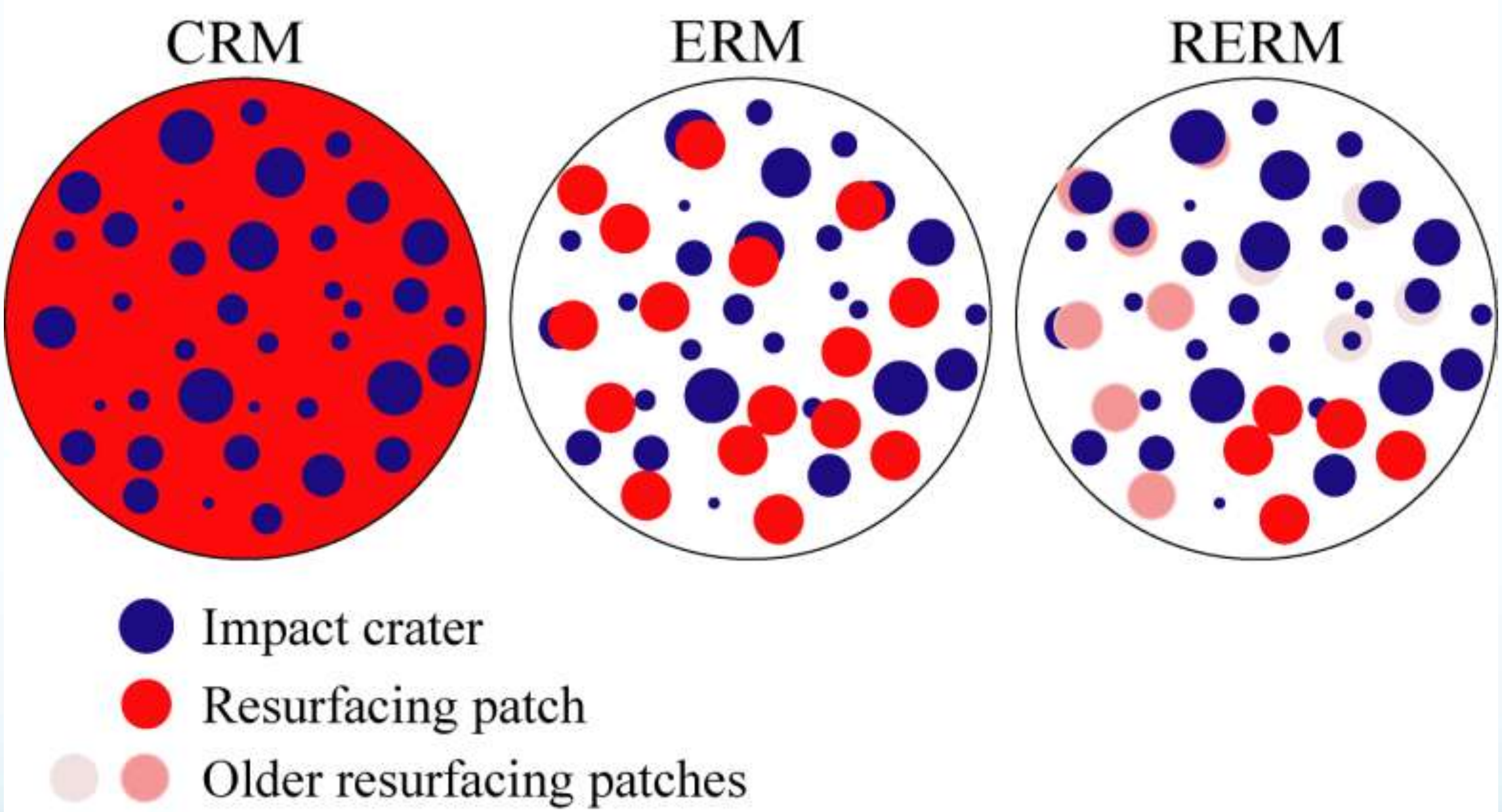
Phillips et al., 1992

“Myth” 1: Catastrophic Resurfacing Hypothesis

- Based on two observations
  - Distribution of ~1000 craters can not be distinguished from a random one
  - Very few craters modified
- Great for modelers:
  - Geodynamics hypotheses to explain young age & history of volcanism
    - Led to episodic convective models?
  - Climate: Massive volcanic outgassing could have led to surface temperature changes of several 100s of ° C



Some Resurfacing Models



•Catastrophic Resurfacing Model (CRM) [*Schaber et al.*, 1992, *Strom et al.*, 1994; *Phillips et al.*, 1992]

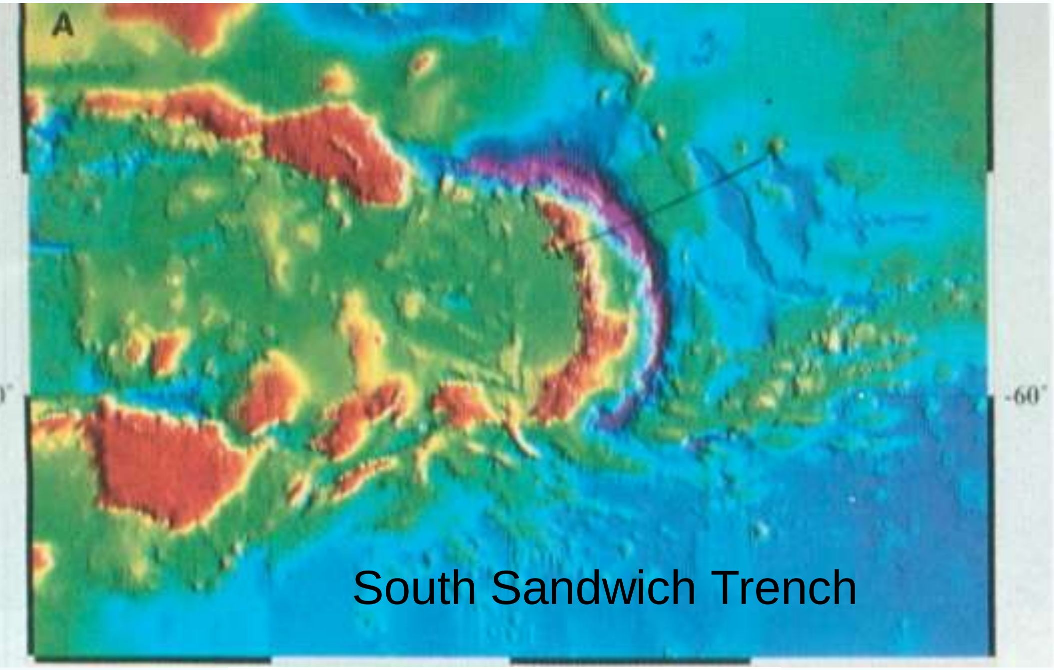
•Equilibrium Resurfacing Model (ERM) [*Phillips et al.*, 1992]

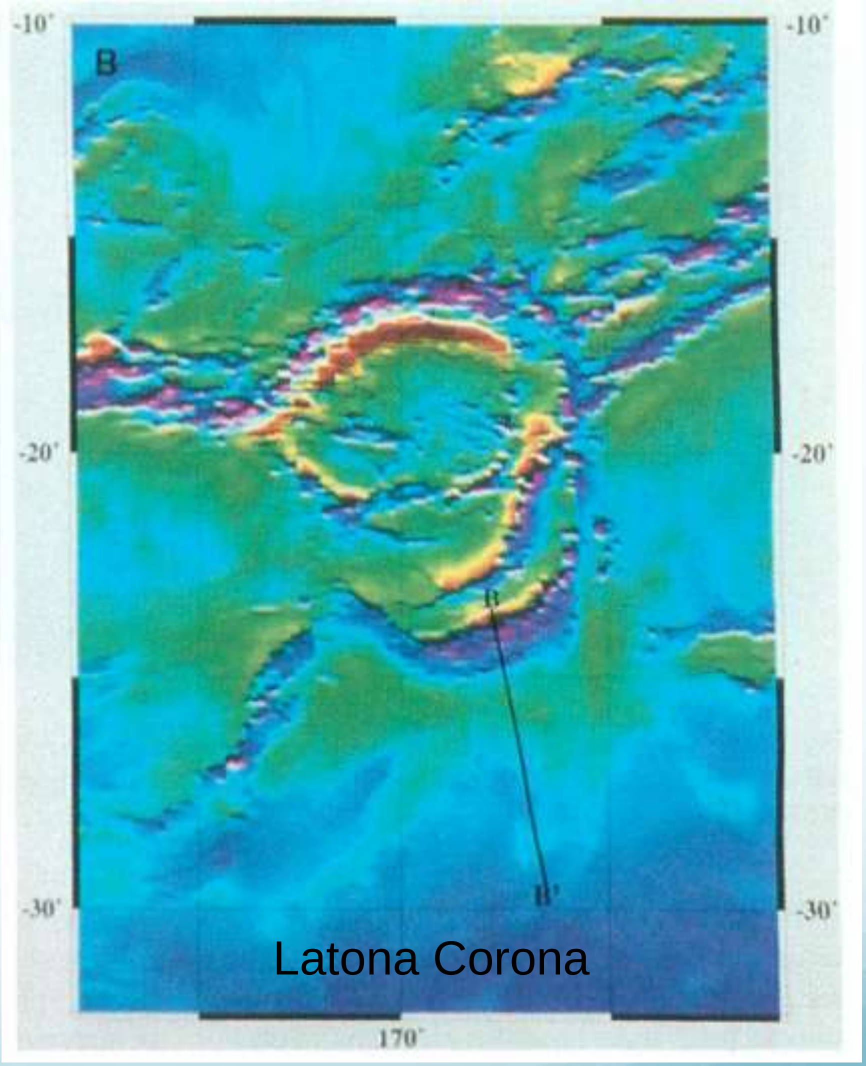
•Regional ERM (RERM) [*Phillips et al.*, 1992; *Hauck et al*., 1998; Romeo & Turcotte, 2010; Bjonnes et al., 2012]

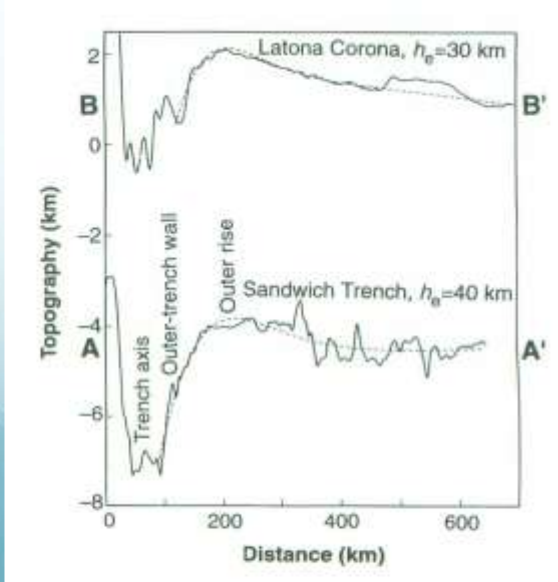
Resurfacing & Volcanism

- Herrick and Rumpf (2011) use stereo topography data available for a subset of craters to suggest that many more craters are flooded (up to 80%)
  - Implies the surface could be as young as 150 m.y.
- Models that take into account erosion of ‘halos’ find that equilibrium models are preferred (Phillips and Izenberg, 1995).
- More papers favor regional equilibrium resurfacing.
- **No geologic requirement for episodic plate tectonics.**
- **Tectonics prior to present surface unknown.**

Subduction: Latona Corona

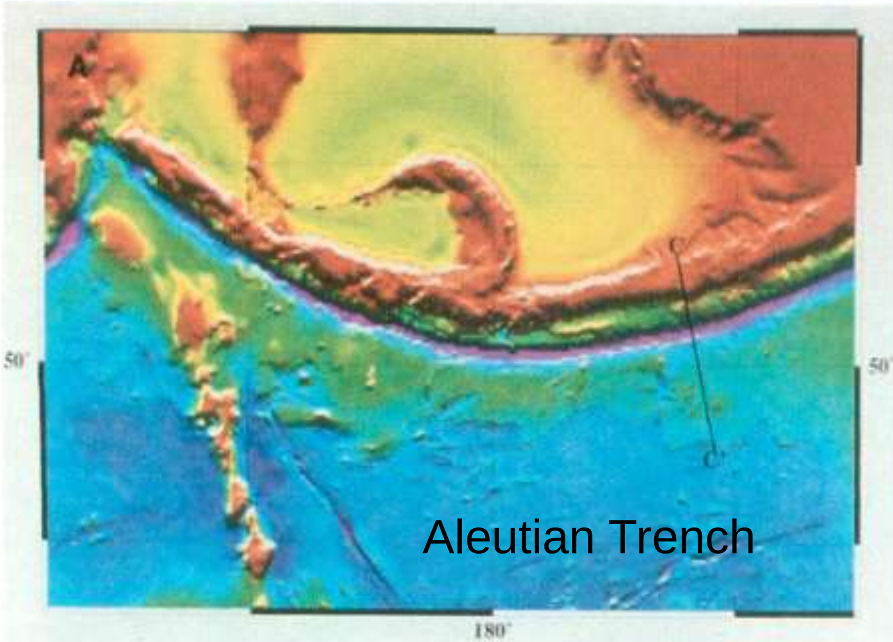


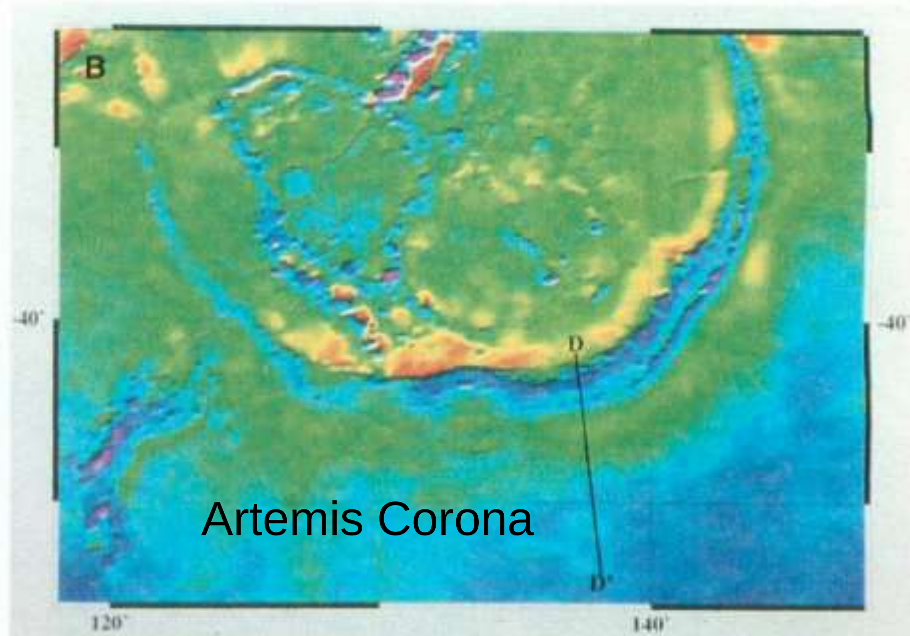


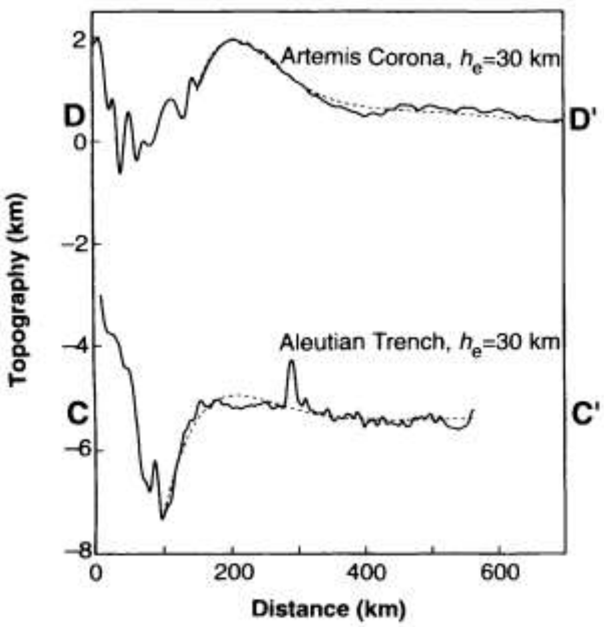


Sandwell and Schubert, 1992

Artemis Corona





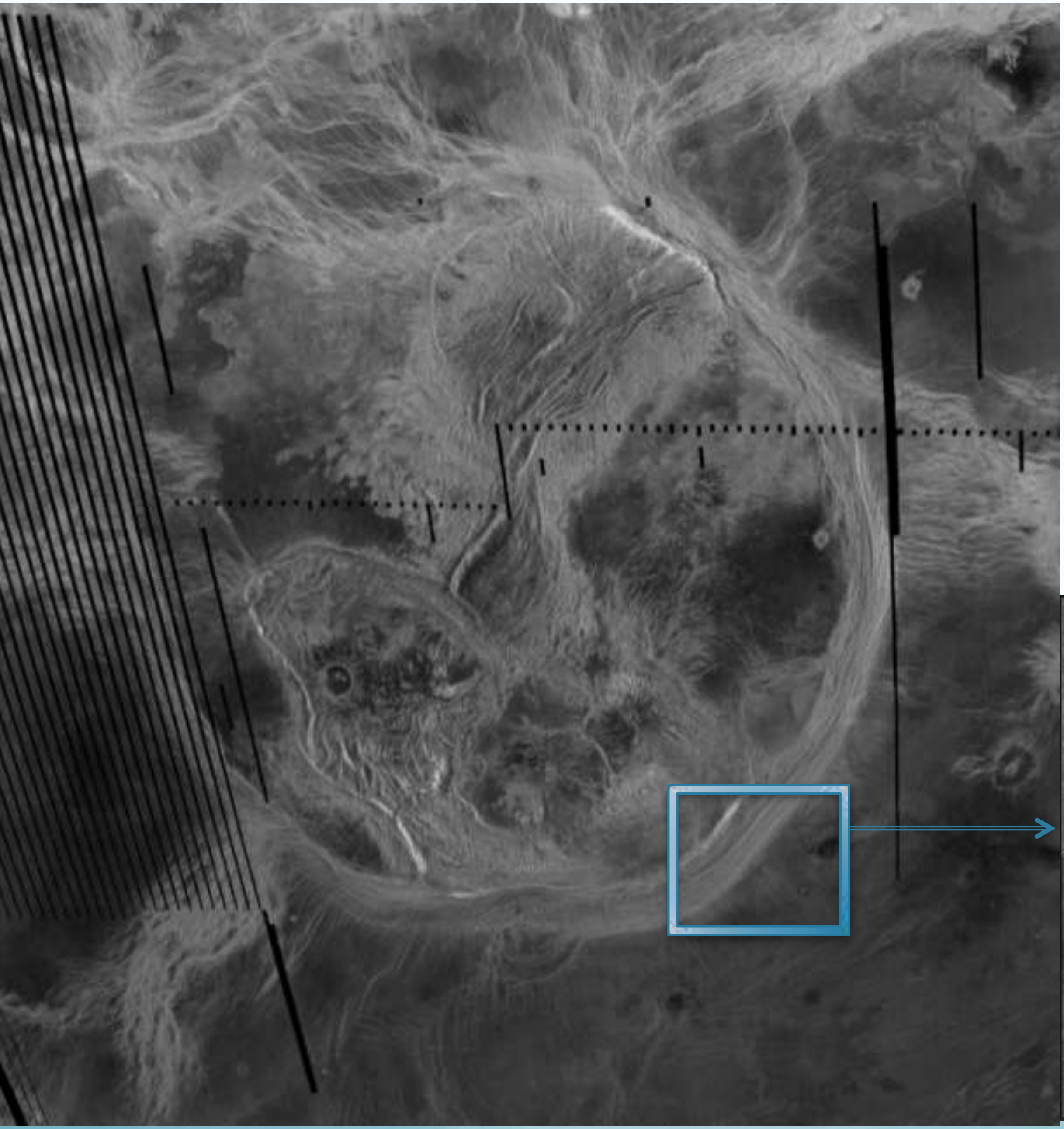


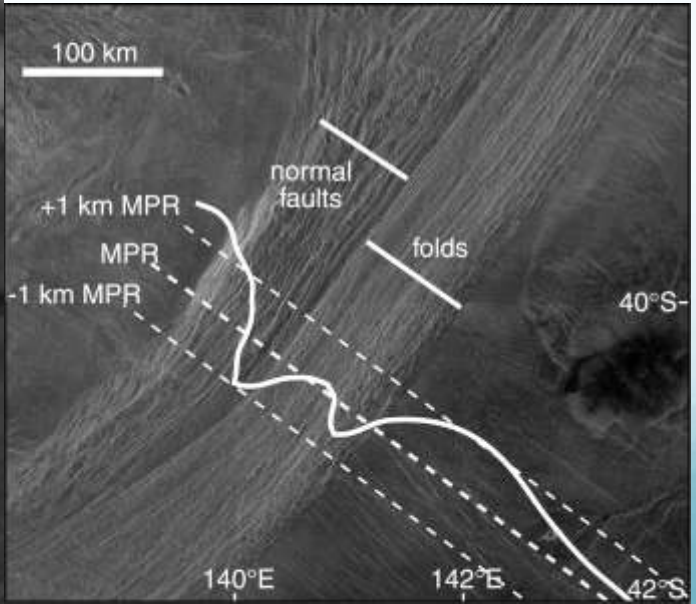
Pacific, Earth) showing a ep ocean trench (outside (East Aphrodite, Venus)

from Magellan altimetry (*5*) displayed at the same horizontal and vertical scale as the Aleutian trench (A) to emphasize the similarities between the two trenches.

Sandwell and Schubert, 1992

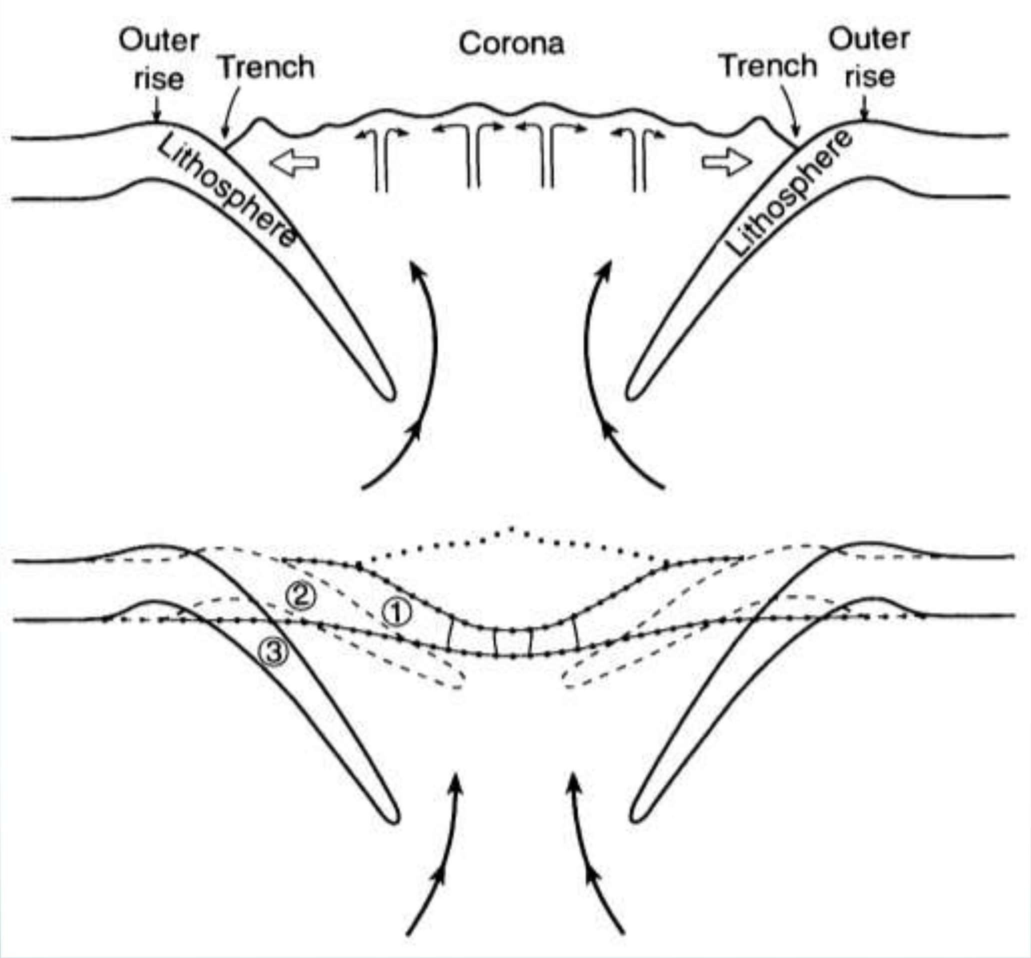
Artemis Chasma





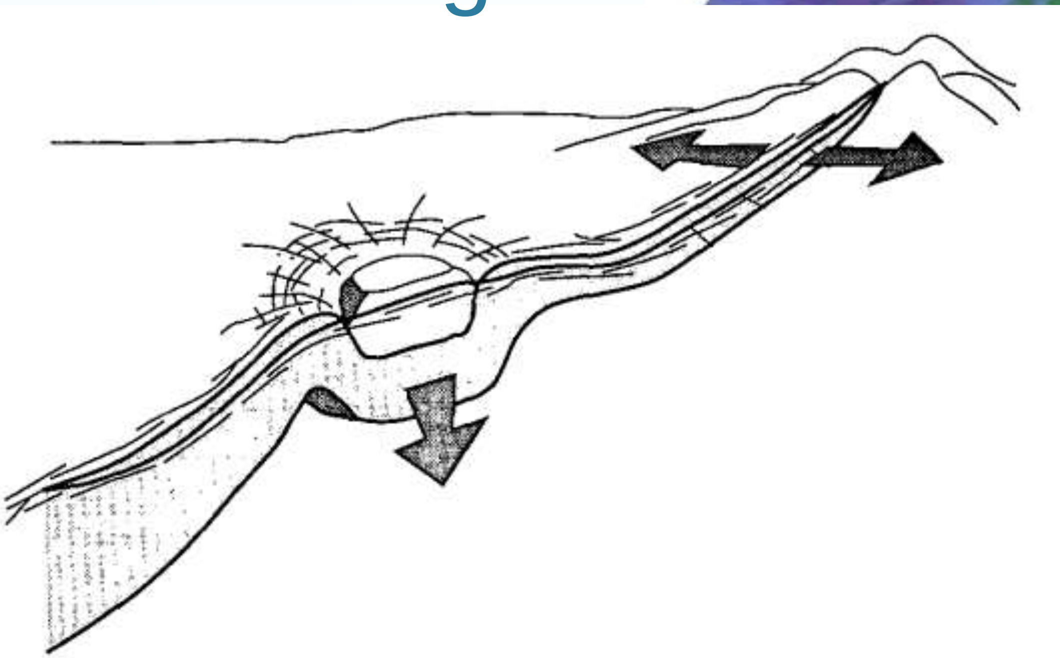
Artemis: Surface expression of a deep mantle plume on Venus, Hansan, 2002

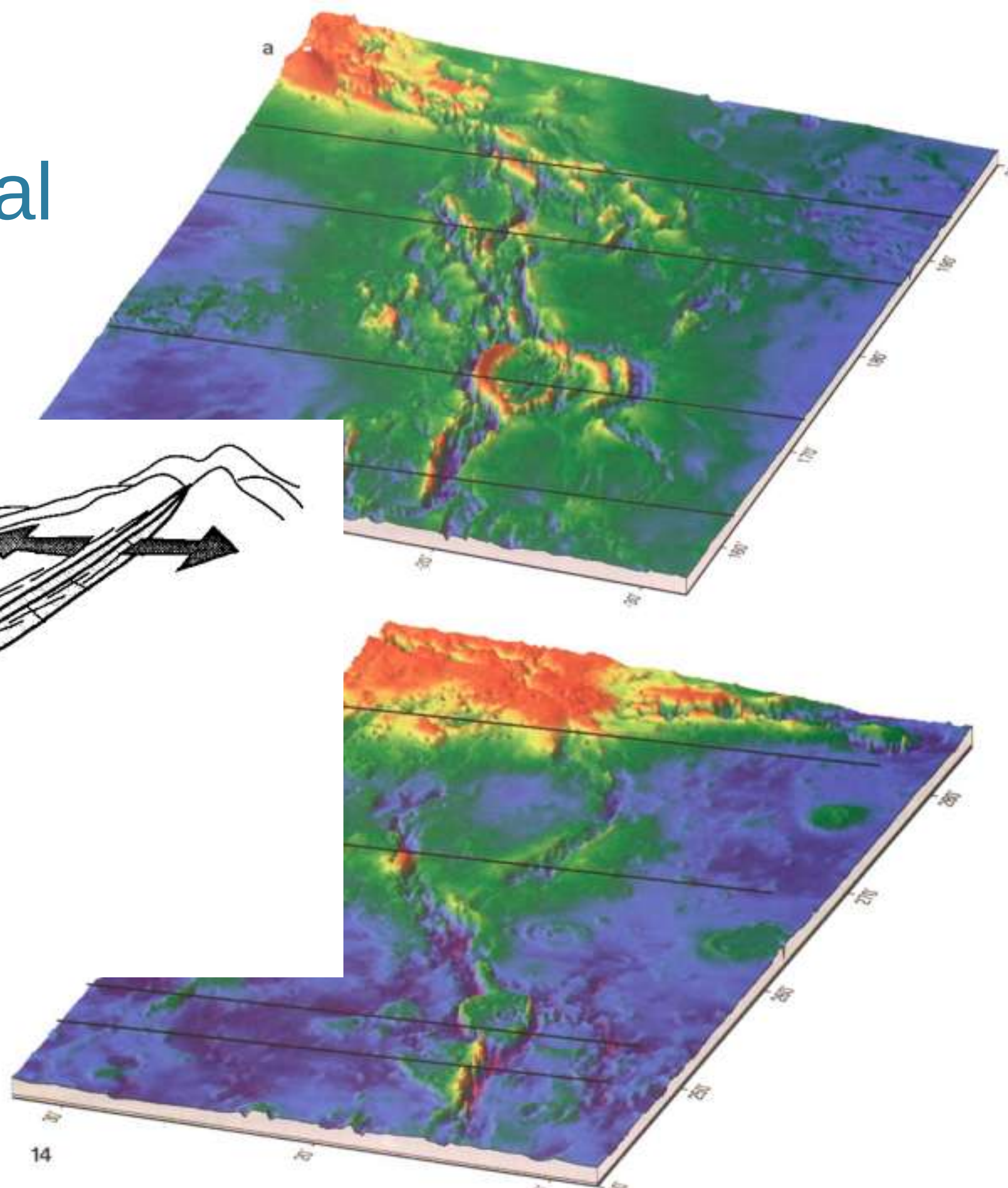
Model 1: ‘Foundering’



Sandwell and Schubert, 1992

del 2: Extensional Lithospheric Fracturing

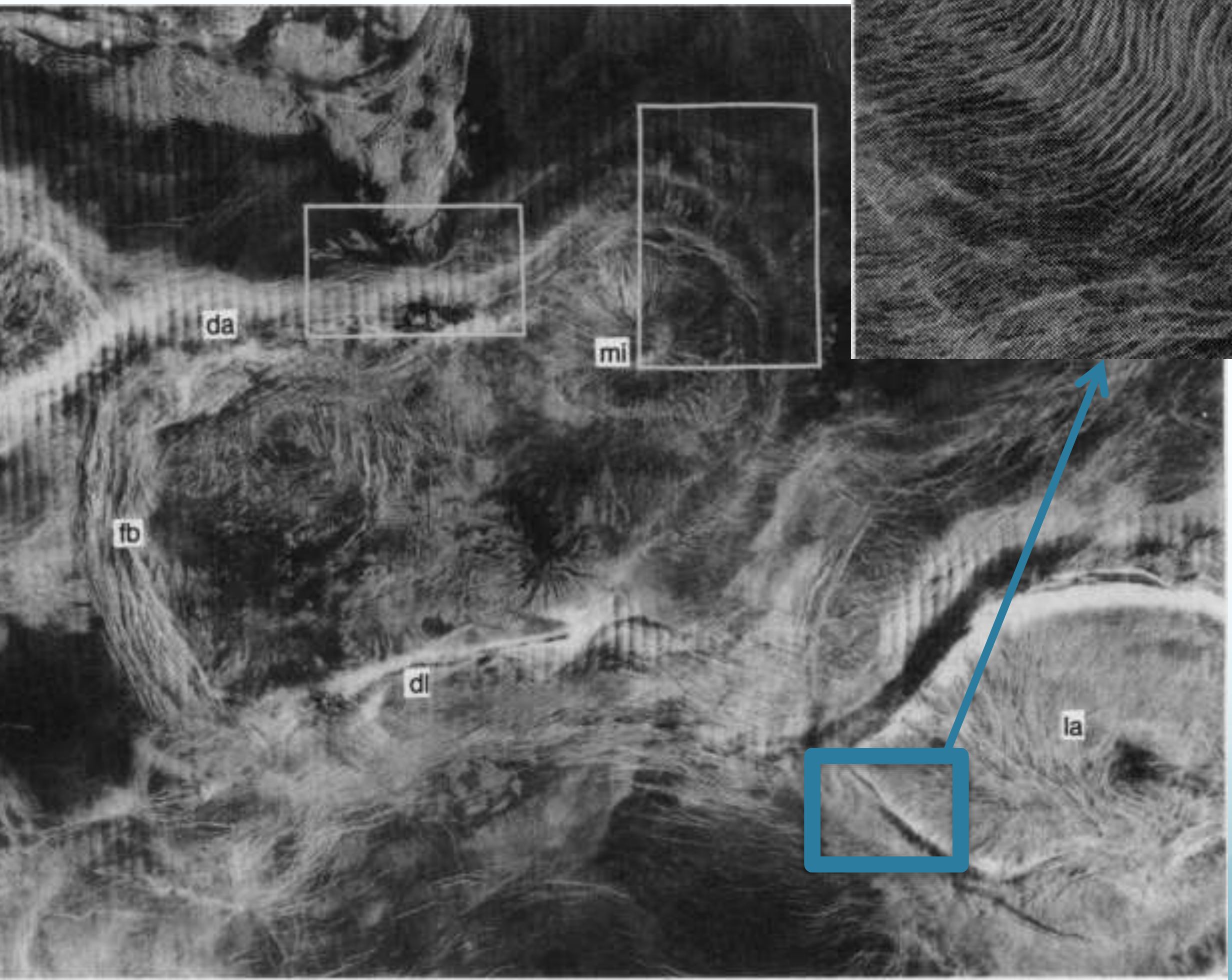




Schubert and Sandwell, 1995

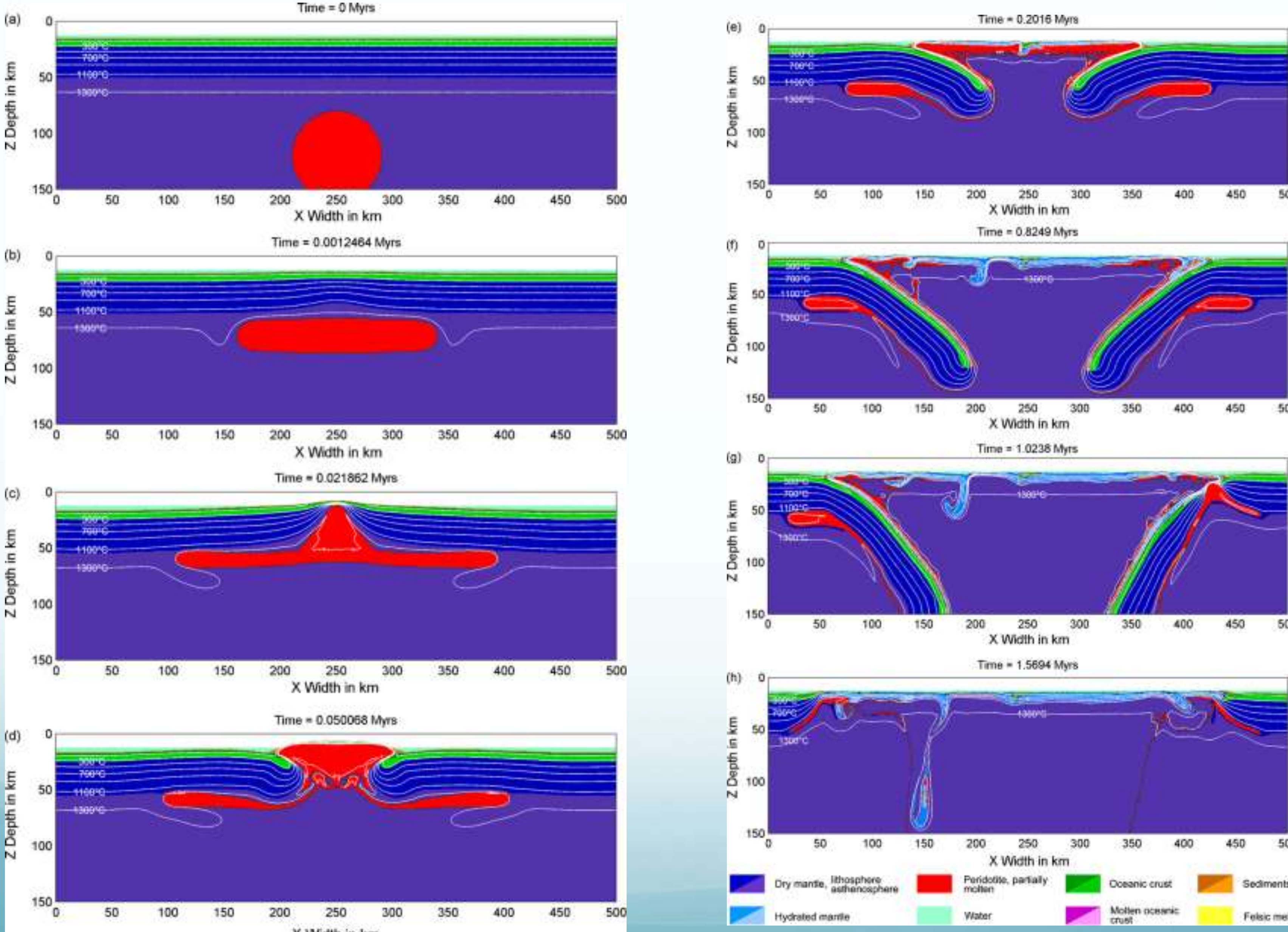
Subduction Issues…

Hansen and Phillips, Tectonics and Volcanism of Eastern Aphrodite Terra, Venus: No Subduction , No Spreading, 1993



Problems for subduction:
1. Radial fractures extend across trenches
2. Radial fractures are typically the oldest structures at coronae

Ueda et al., Subduction initiation by thermal–chemical plumes: Numerical studies, 2008

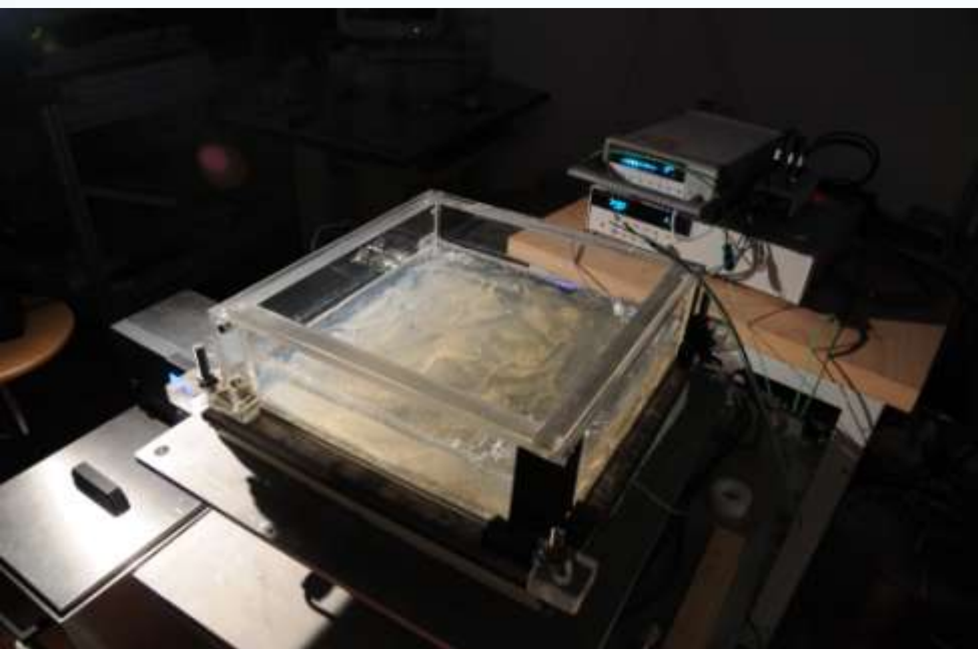


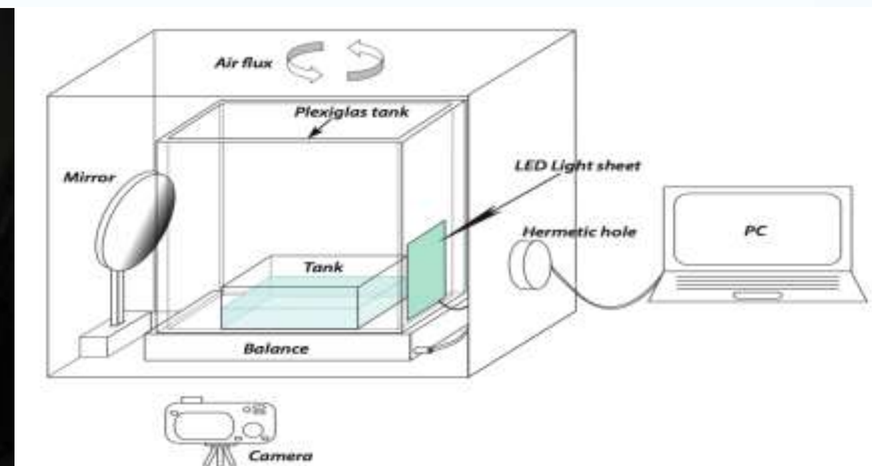
Lab simulations of convection-driven tectonic deformation

Experiments by Davaille and colleagues @ CNR/Univ. Paris Sud

Uses polymers, colloidal solutions

- Rheology and density depend on particle content
- Lid can deform via elastic, viscous, and plastic deformation
- Drying/Diffusion from above (analogous to cooling) + Heat from below



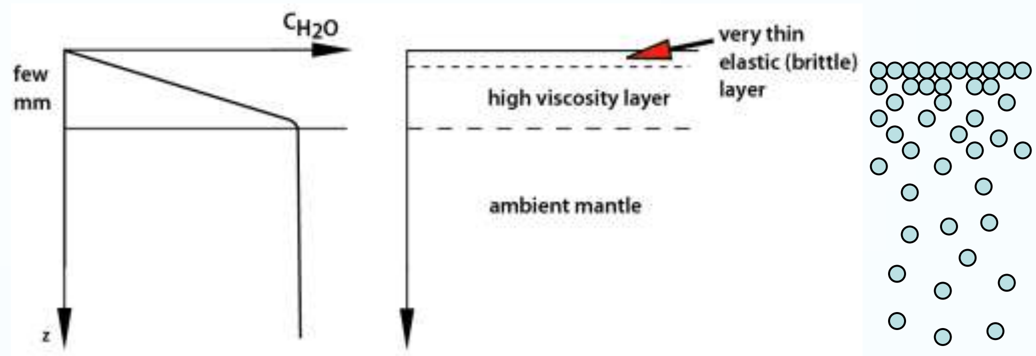


Rayleigh number (solutal)

$$Ra_{sol} = \frac{\Delta\rho g h^3}{D_x \eta} \approx 10^5 - 10^9$$

Simulates Lithospheric Deformation

As solvent evaporates, the rheology of the solution changes from ductile to brittle behavior. Drying of the crust mimics faulting throughout the lithosphere.



Silica
Particles

Aggregates

Shear bands

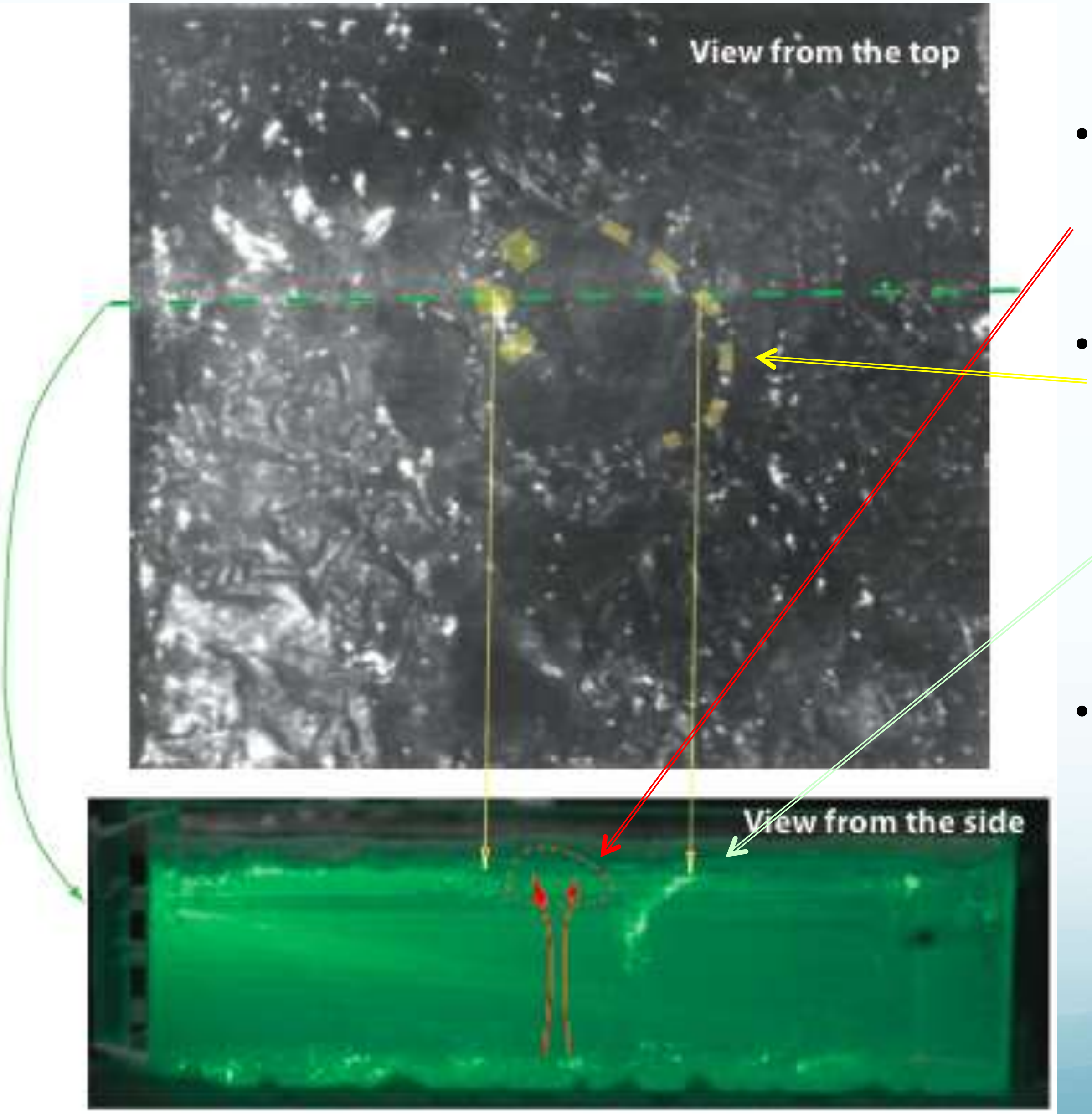
In 3D!

Drying of brittle layer
=> contraction cracks

Elasticity => folds

Buoyancy
=> convection

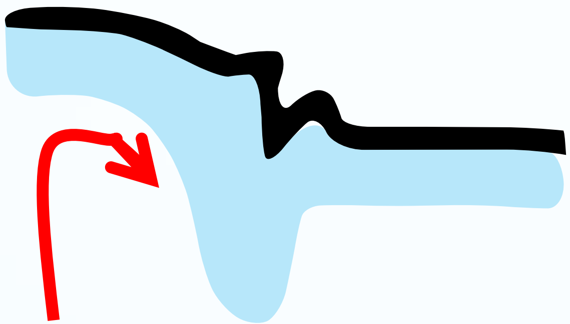
Plume-induced Subduction in the Lab



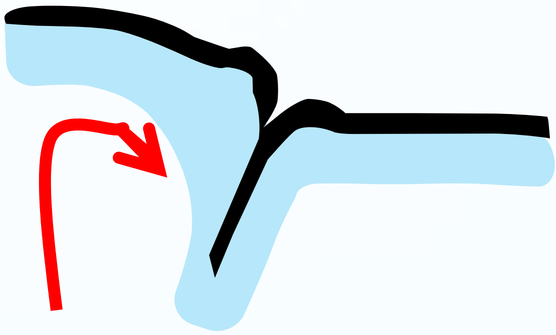
- Heating from below produces plumes (highlighted in red).
- Plume produces ridges (in yellow) at the surface and nascent subduction at depth where the lithosphere has broken and been pushed under.
- Subduction occurs in an arc, not a full circle.

Cartoon of Plume-induced Subduction

Laboratory experiments show:



Plume stresses cause delamination, and deformation at the surface, forming a double ridge forms'.



The entire lithosphere breaks.
The outer plate is pulled by its own weight and that of the overriding plate.

Depending on the lithospheric rheology, the nascent subducting slab can break off as the result of plate necking, or continue to sink smoothly.

Explains both observed plume-like and subduction-like characteristics!

Convection in the lab

- Laboratory experiments produce stagnant, sluggish and plate tectonic regimes.
  - Regimes can transition from one to another.
  - The strength of the lithosphere increases from sluggish to plate tectonic to stagnant.
- The regime that produces many of the features seen on Venus (subduction at plumes, shear zones, etc.) has a weaker lithosphere than for the plate tectonic regime.

Why does Venus lack Plate Tectonics?

- Dry interior offered as an explanation for lack of plate tectonics: no LVZ, strong plates
  - What do we know about the interior?
- Planets may be hard to dry out..
  - They probably form wet
    - Though large impacts or magma ocean processes could affect volatiles
  - More evidence for water & volatiles through out the solar system, including Earth

Is Venus' Interior Wet or Dry?

- No Low Viscosity Zone > dry ?
- Topographic relaxation – assumed to imply dry, but no real constraint
- Atmospheric water ~30 ppm
- Does outgassing continue? Water, sulfur have to be resupplied
- Ar Isotopes – indicates Venus is about 25% degassed > wet (Earth more like 50% degassed)

Could high T prevent plate tectonics?

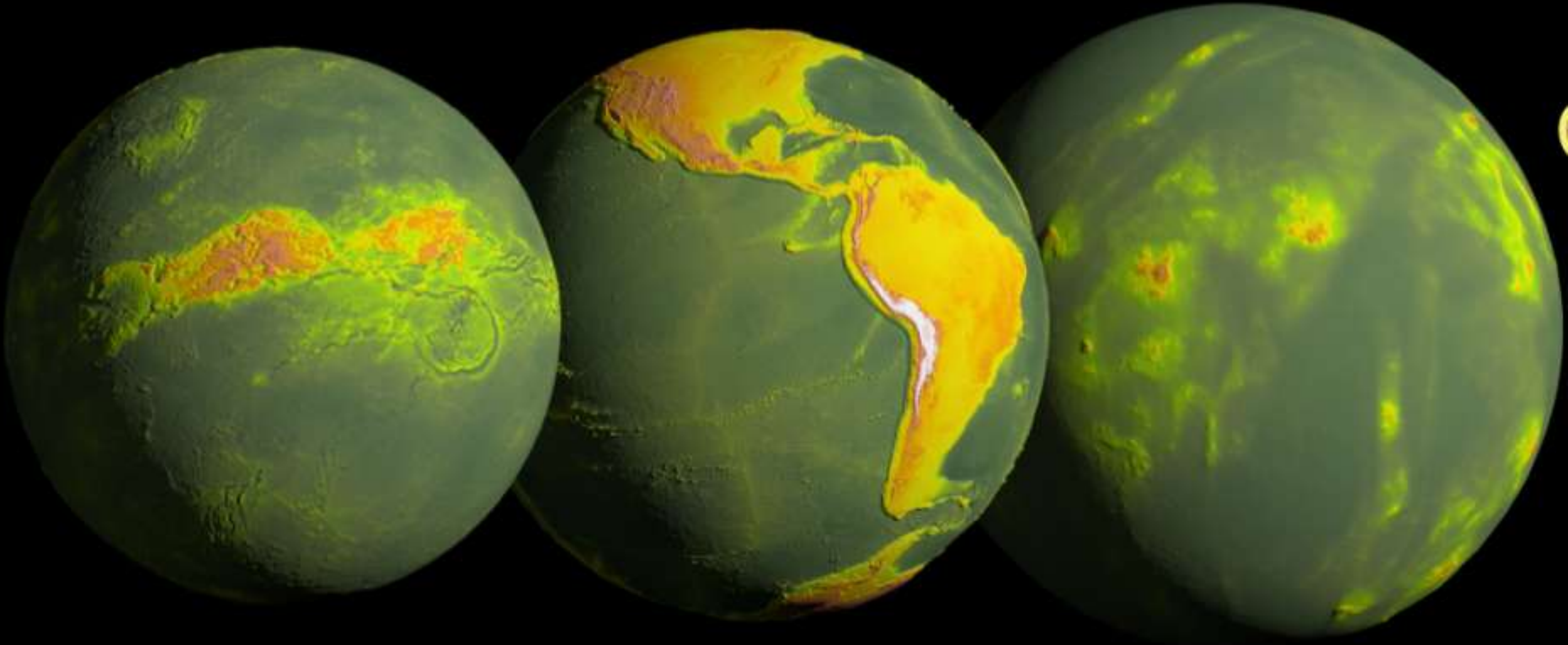
- Series of papers (e.g. Bercovici and Ricard, 2012) on the role of damage theory on the initiation of plate tectonics. The ability of a hotter lithosphere to ‘heal’ faults more rapidly could prevent plate tectonics.

Venus Tectonics & Dynamics

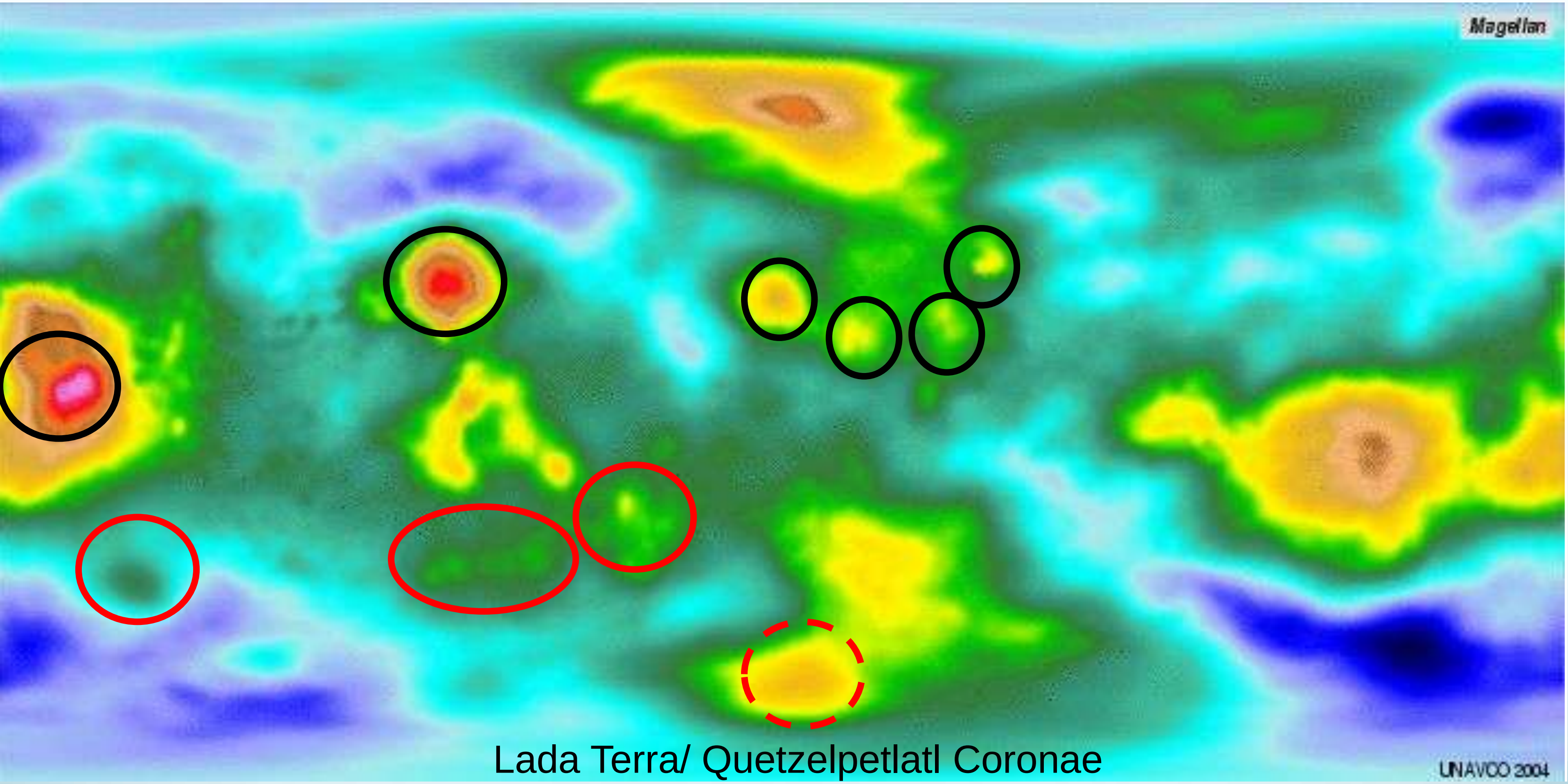
- No terrestrial style plate tectonics, but could have (plume-driven) subduction
- No geologic requirement for episodic tectonics, but heat still must be lost
- No low viscosity zone?
- "Active" volcanism, mantle plumes – 2 scales
- No magnetic field
- Lessons for early Earth, exoplanets? T matters?

Comparative Tectonics and Geodynamics of Venus, Earth, and Rocky Exoplanets

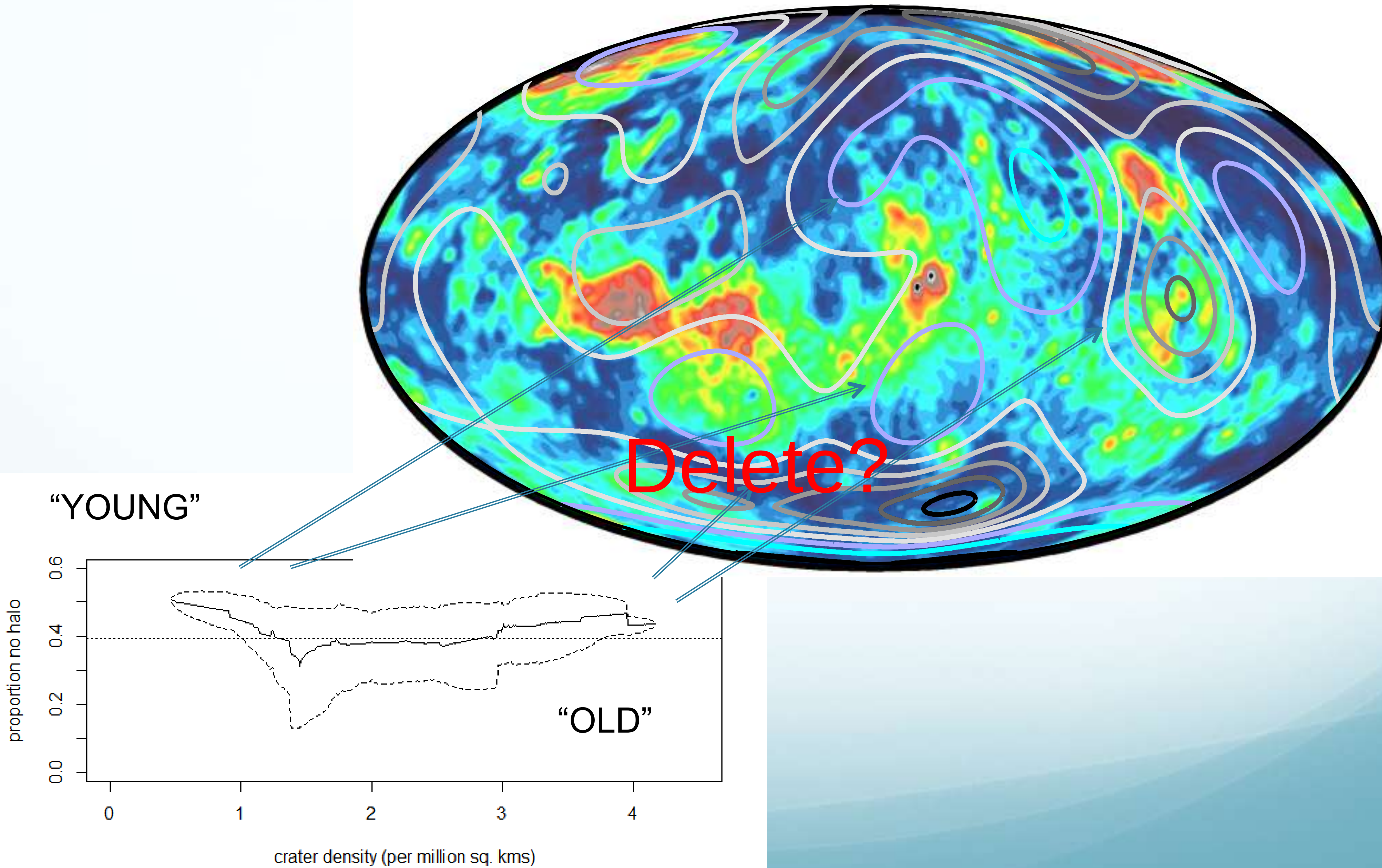
May 4-6, 2015
Pasadena, CA



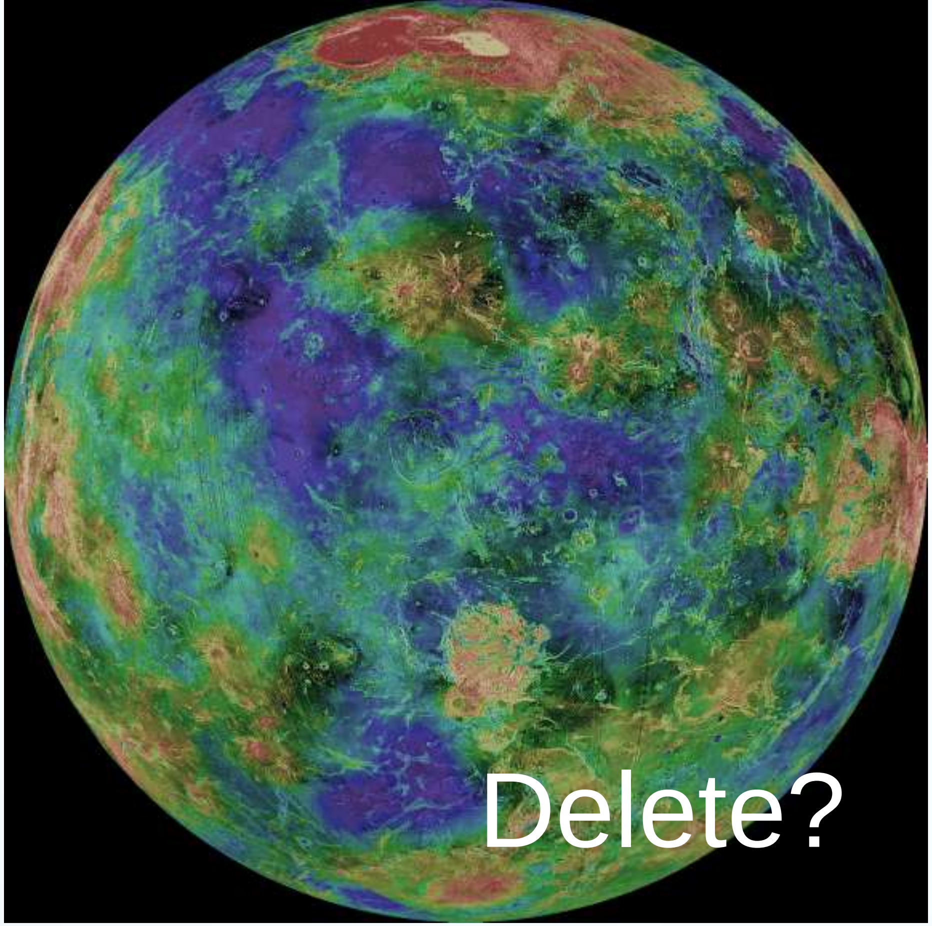
Geoid Anomalies over ‘Hotspots’

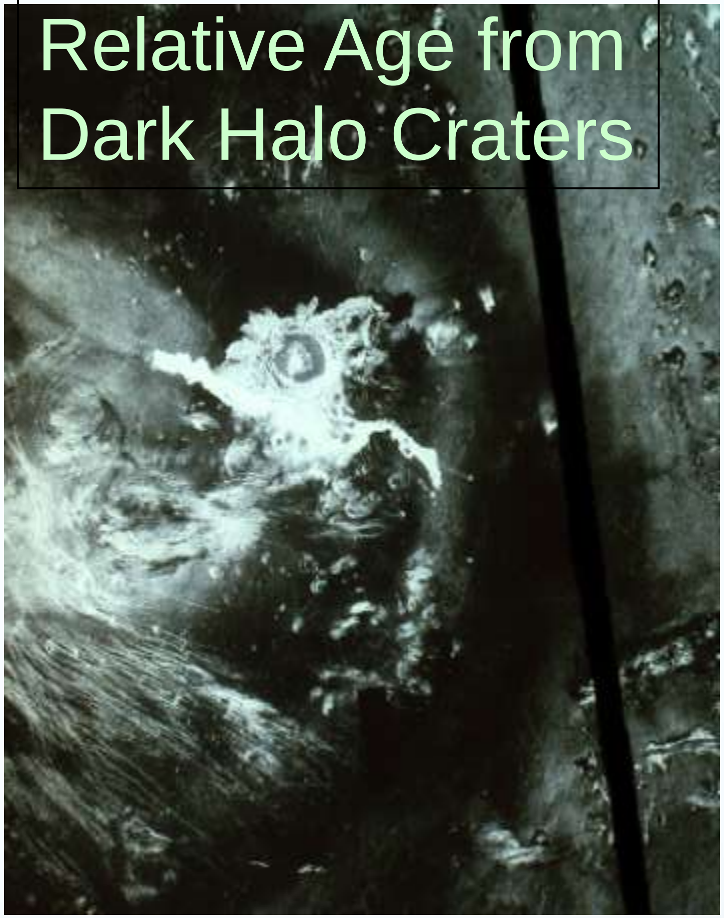


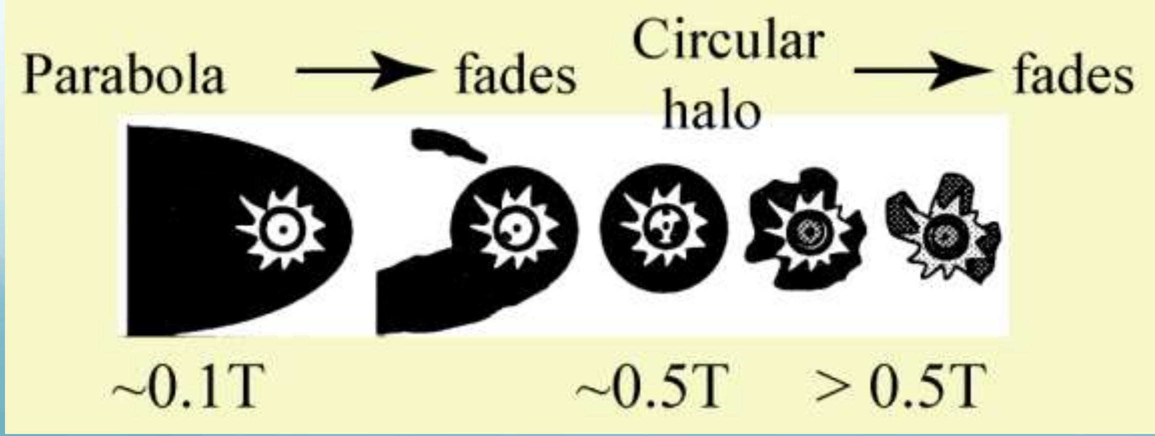
Relative Age:
Halo Erosion + Crater Density



Relative Age from Dark Halo Craters







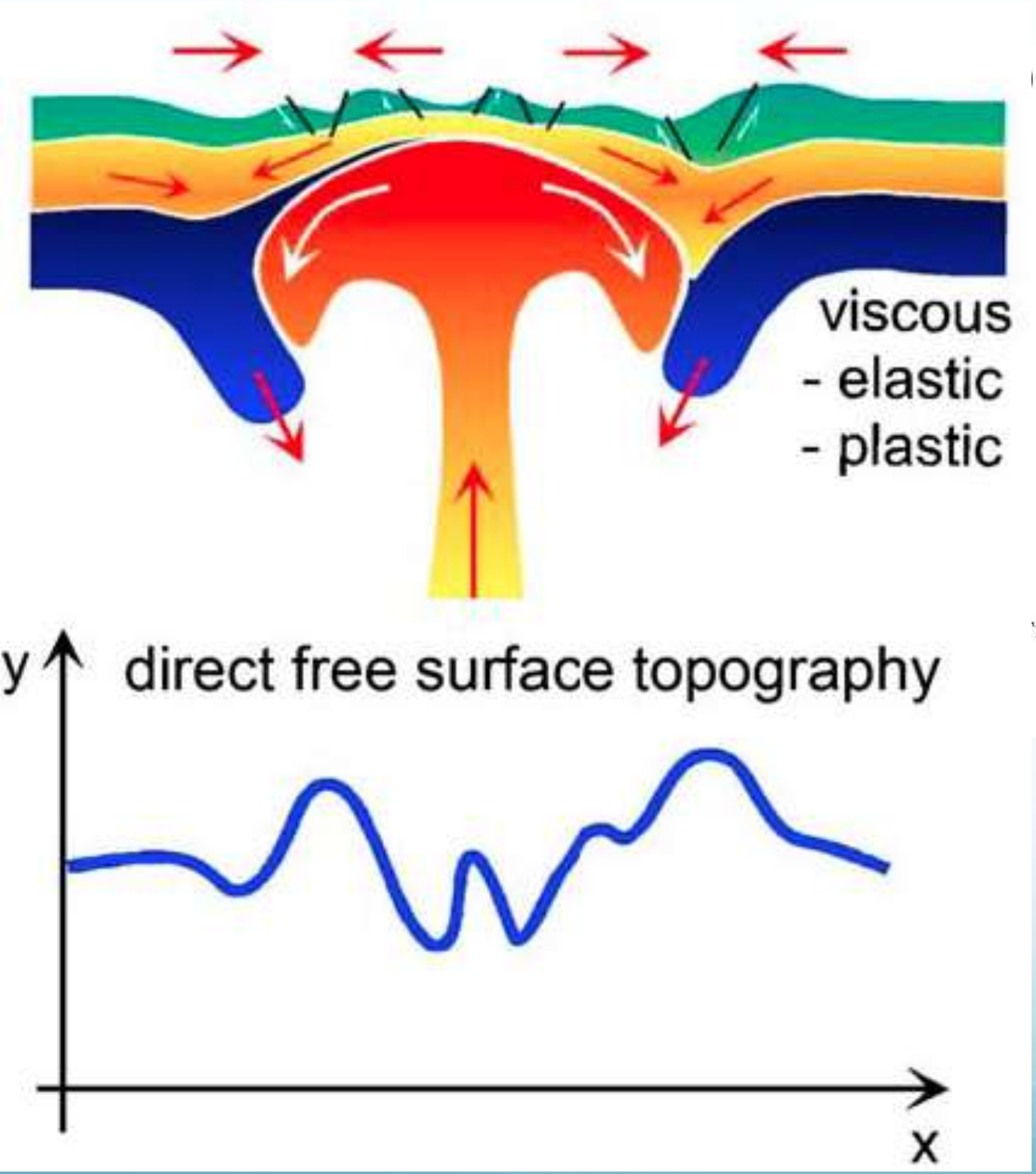
Izenberg, Arvidson & Phillips [1994]

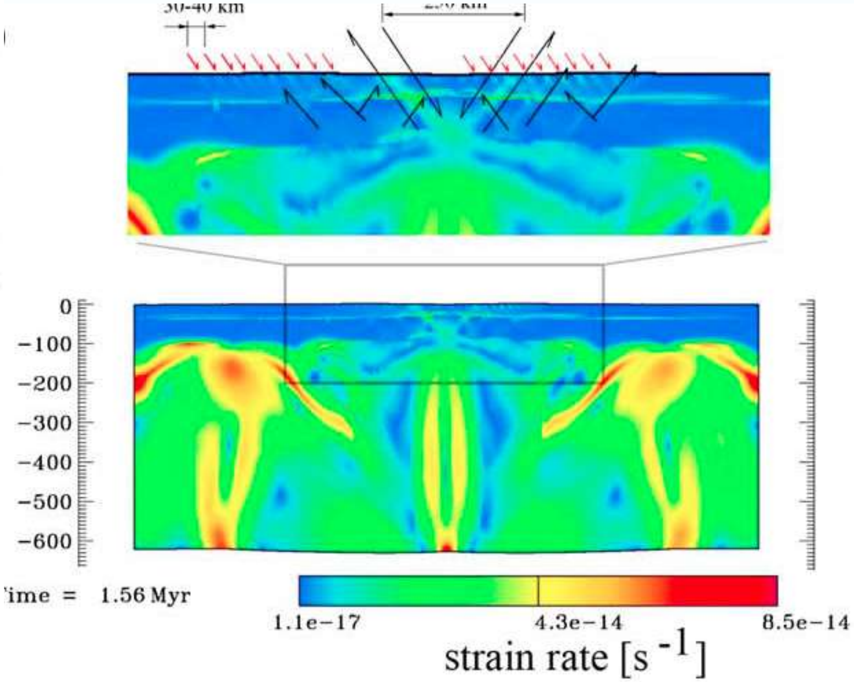
Recent Papers: Plumes & Convection

New modeling papers inspired at least in part by evidence of current volcanism above mantle plumes (hotspots):

- Armann and Tackley (2012) Simulating the thermochemical magmatic and tectonic evolution of Venus' mantle and lithosphere: Two-dimensional models, JGR
- Noack, Breuer, Spohn (2012) Coupling the Atmosphere with the Interior Dynamics: Implications for the Resurfacing of Venus, Icarus
- Smrekar, S.E. and Sotin, C. (2012) Constraints on mantle plumes on Venus: Implications for volcanism and volatile history, Icarus
- Huang, Yang, and Zhong (2013) Constraints of the topography, gravity and volcanism on Venusian mantle dynamics and generation of plate tectonics, EPSL

(Earth) Plumes, subduction, and tectonics





Burov and Cloetingh, 2010