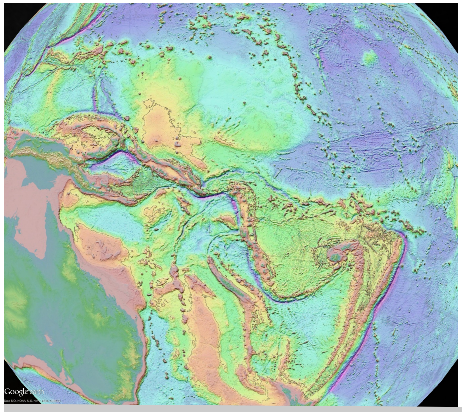
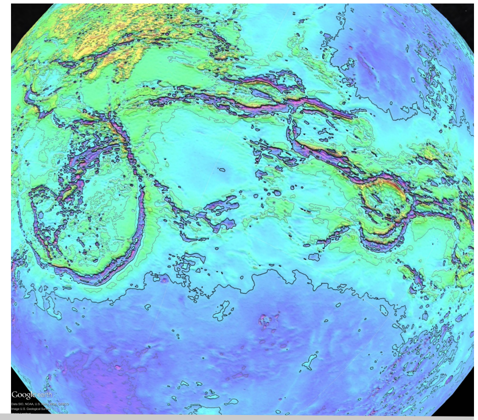


Lithospheric Subduction on Earth and **Venus**?



David Sandwell

IGPP, April 15, 2016

- Venus vs. Earth – Heat Loss Mechanisms
- Subduction Zones on Earth
- Magellan Findings
- Subduction on Venus?
- Episodic Tectonics
- Recent Progress in Our Lab
- NASA Mission - VERITAS

Lithospheric Subduction on Earth and Venus: Publications

1977	Compositional and density stratification in oceanic lithosphere - causes and consequences	Oxburgh, E. R. Parmentier, E. M.
1982	Mechanismsfor Lithospheric Heat Transport on Venus: Implications for Tectonic Style and Volcanism	Solomon, S. C. Head, J. W.
1990	Lithospheric flexure beneath the Freyja Montes foredeep, venus: Constraints on lithospheric thermal gradient and heat flow	Solomon, S. C. Head, J. W.
1991	Corona Structures on Venus: Models of Origin	Stofan et al.
1991	Fundamental Issues in the Geology and Geophysics of Venus	Solomon, S. C. Head, J. W.
1992	Thermal buoyancy on Venus: Underthrusting vs subduction	Burt, J. D. Head, J. W.
1992	Features on Venus Generated by Plate Boundary Processes	McKenzie et al.
1992a	Flexural Ridges,Trenches, and Outer Rises Around Coronae on Venus	Sandwell, D. T. Schubert, G.
1992b	Evidence for Retrograde Subduction on Venus	Sandwell, D. T. Schubert, G.
1993	Tectonics and Volcanism of Eastern Aphrodite Terra, Venus: No Subduction, No Spreading	Hansen, V. L. Phillips, R. J.
1993	Subduction on the margins o f coronae on Venus: Evidence from radiothermal emissivity measurements.	Robinson, C. A.
1994	Lithospheric flexure on Venus	Johnson, C. L. Sandwell, D. T.
1994	Gravity over Coronae and Chasmata on Venus	Schubert et al.
1995	How does Venus lose heat?	Turcotte, D. L.
1995	A Global Survey of Possible Subduction Sites on Venus	Schubert, G. Sandwell, D. T.
1996	Lithospheric rheology and flexure at Artemis Chasma, Venus	Brown, C. D. Grimm, R. E.
1996	A mechanism for episodic subduction on Venus	Fowler, A. C. O’Brien, S. B. G.
1998	Mantle convection with a brittle lithosphere: Thoughts on the global tectonic styles of the Earth and Venus	Moresi, L. Solomatov, V.
1997	Lithospheric Mechanics and Dynamics of Venus	Phillips et al.
1997	Corona Formation and Heat Loss on Venus by Coupled Upwelling and Delamination	Smrekar, S. E. Stofan, E. R.
1998	Driving Forces for Limited Tectonics on Venus	Sandwell et al.
1999	Catastrophic Resurfacing and Episodic Subduction on Venus	Turcotte et al.
2002	Artemis: Surface expression of a deep mantle plume on Venus	Hansen, V. L.
2002	Lithospheric failure on Venus	Fowler, A. C. O’Brien, S. B. G.
2012	Simulating the thermochemical magmatic and tectonic evolution of Venus’s mantle and lithosphere: Two-dimensional models	Armann, M. Tackley, P. J.
2007	A magmatic loading model for coronae on Venus	Dombard et al.
2010	Artemis, Venus: The largest tectonomagmatic feature in the solar system?	Hansen, V. L. Olive, A.
2016	Plume-Induced Subduction on Venus	Smrekar et al., 2016

Heat Loss Mechanisms

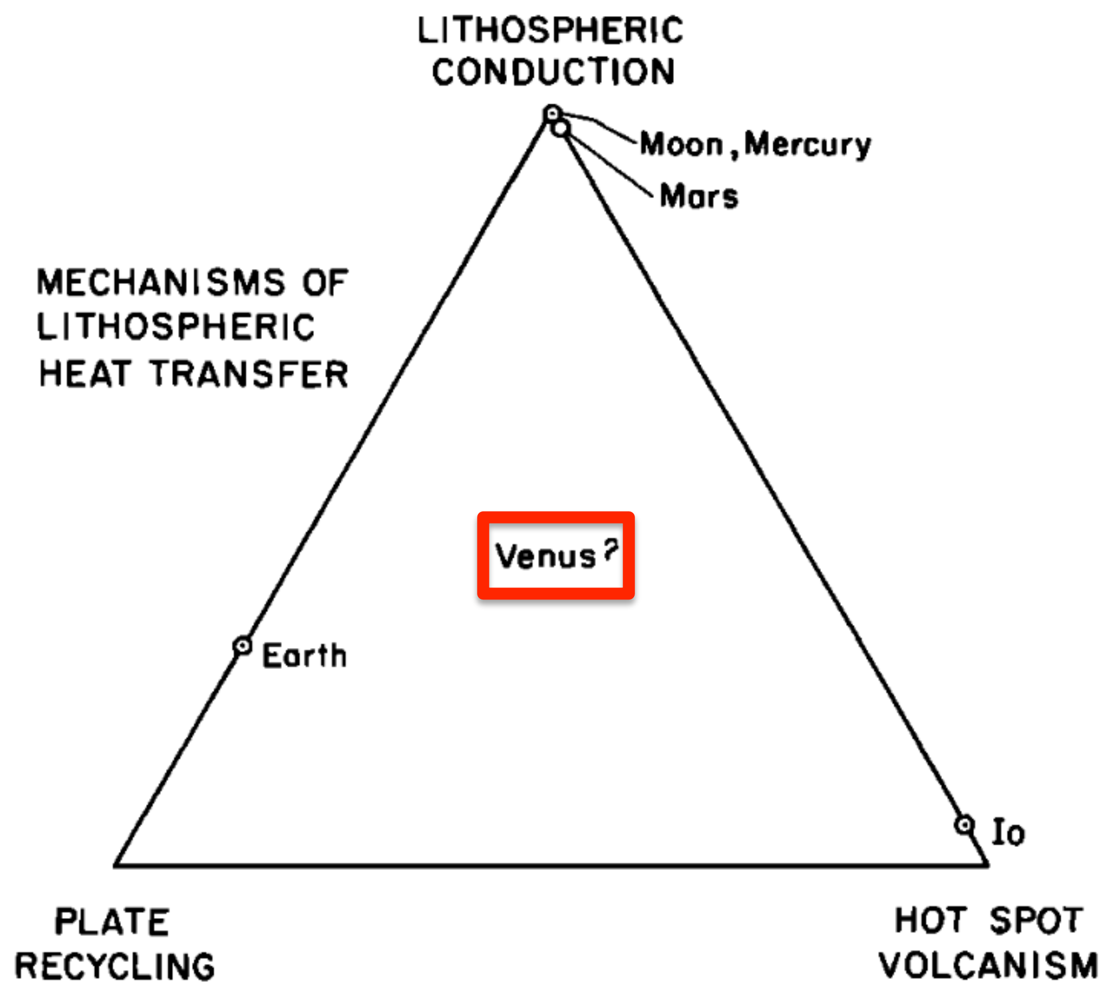
Assume Venus and Earth
have similar global heat output.

How does this heat escape?

1) plate recycling – predicts rapid spreading and **subduction zones**

2) lithospheric conduction – predicts **thin elastic lithosphere** (< 10 km)

3) hot spot volcanism – predicts that 10000 Hawaii-sized volcanoes **are active today.** generates 1 km thickness of new volcanic material every 2 Ma.



[Solomon and Head, JGR 1982]

Lithospheric Conduction

Assume Venus and Earth
have similar global heat output.

Conduction predicts:

1) high geothermal gradient 24 ˚K/km

2) thin elastic lithosphere < 10 km

How can 13 km or relief be supported
by such a thin lithosphere?

Plate recycling cannot be ruled out.

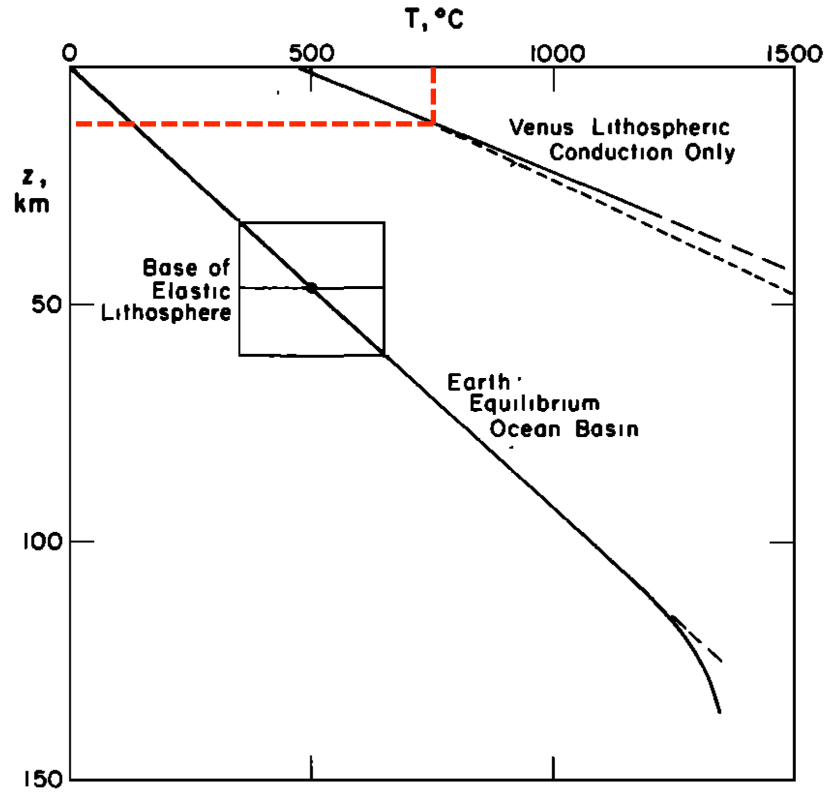


Fig. 3. Average lithospheric geotherms on Venus assuming that conduction is the only mode of lithospheric heat transfer. The solid line shows the case when all of the heat loss from Venus is generated below the lithosphere; the short-dashed curve indicates the case when 15% of the Venus heat loss is generated by radioactivity distributed uniformly in a crust 30 km thick. Also shown are the terrestrial geotherm for an old ocean basin in thermal equilibrium [*Parsons and Sclater*, 1977; *Sclater et al.*, 1980] and the range of isotherms inferred to define the base of the elastic lithosphere in ocean basins [*Watts et al.*, 1980].

[Solomon and Head, JGR 1982]

Lithospheric Buoyancy

(Oxburgh and Parmentier, 1977; Burt and Head; 1992; Schubert and Sandwell, 1995)

$$\delta = \int_0^\infty \left[\frac{\rho_m - \rho(z)}{\rho_m} \right] dz$$

δ - density defect thickness
> 0 no subduction
< 0 subduction possible

$\rho(z)$ - lithospheric density

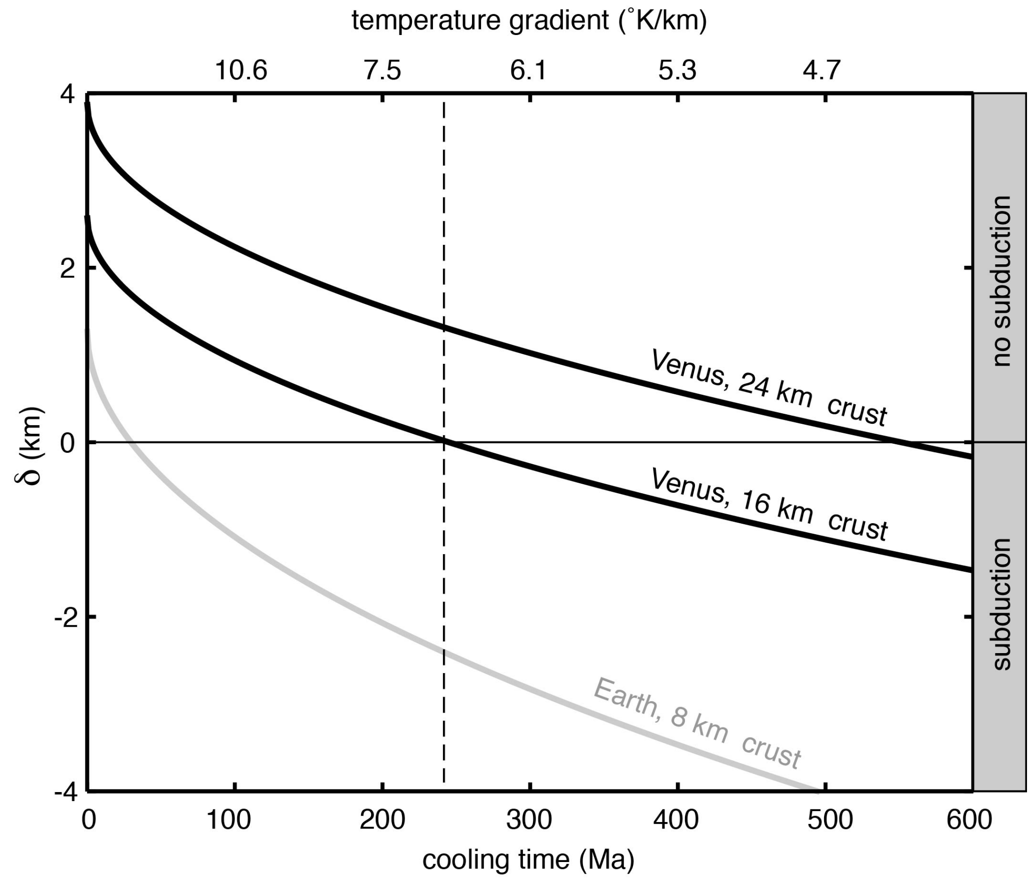
ρ_m - undepleted mantle density

$$\delta_{total} = \delta_{comp} + \delta_{thermal}$$

$$\delta_{total} = \text{light crust + depleted mantle}$$

$$\delta_{thermal} = -2\alpha(T_m - T_o)\sqrt{\frac{\kappa t}{\pi}}$$

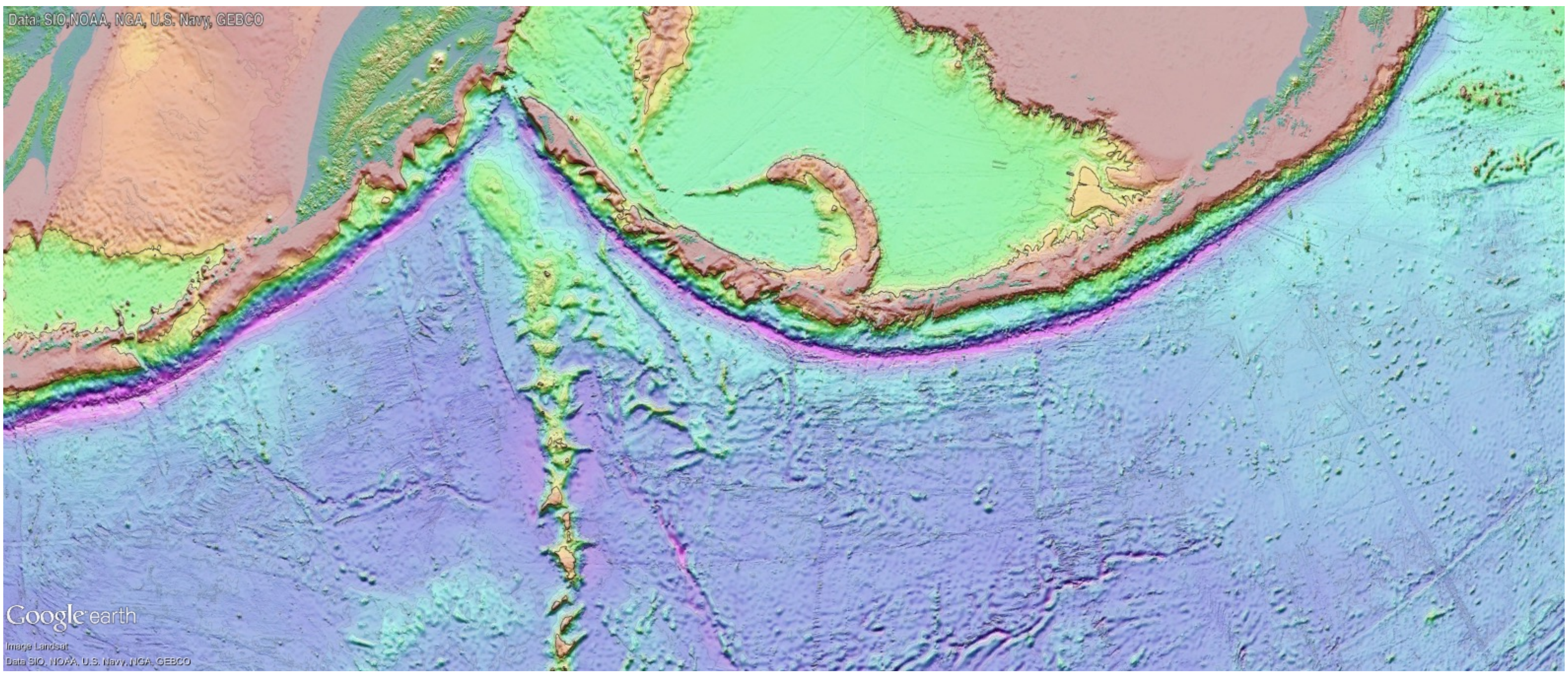
	Earth	Venus
δ_{comp}	1.3 km	?
T_o	0°C	455°C
T_m	1300°C	1400°C
α	3.1×10^{-5} C^{-1}	3.1×10^{-5} C^{-1}
κ	8.0×10^{-7} $m^2 s^{-1}$	8.0×10^{-7} $m^2 s^{-1}$



No subduction for temperature gradient greater than ~7 ˚K/km

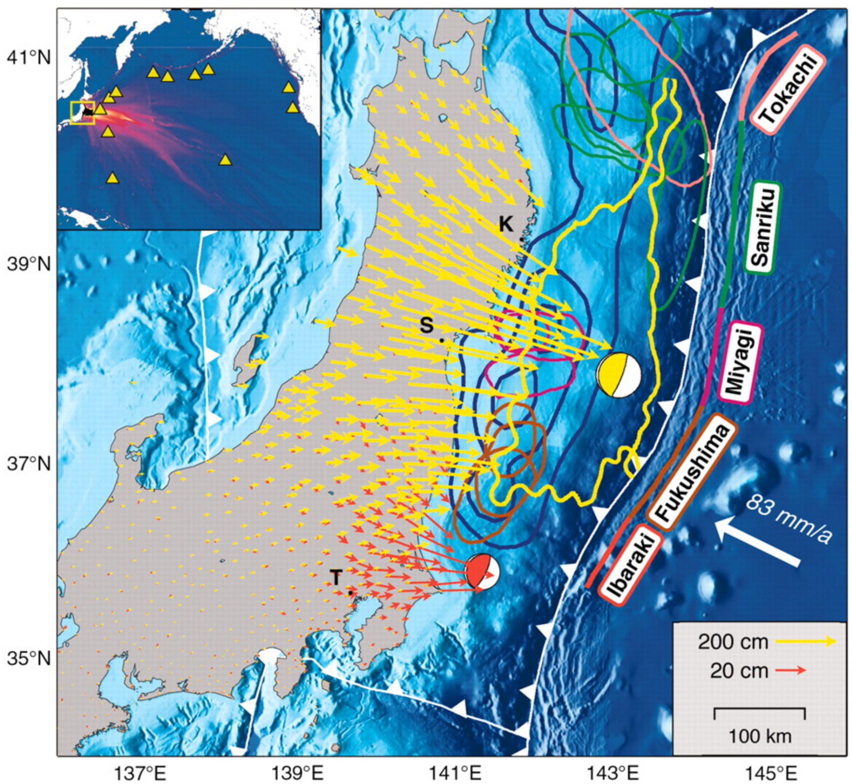
Characteristics of Subduction

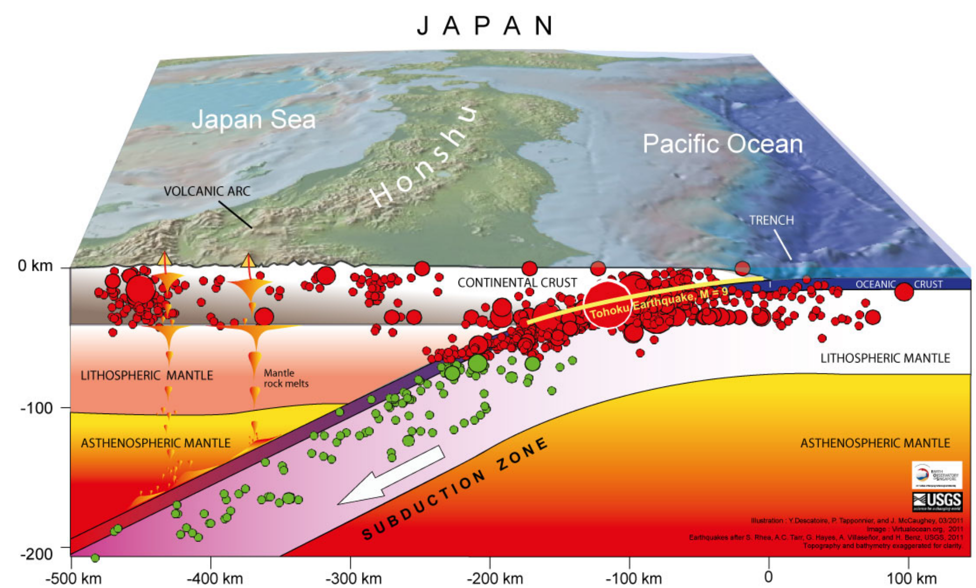
asymmetric trench outer rise topography
arcuate planform
large outer trench wall curvature
outer trench wall fractures



Characteristics of Subduction

megathrust earthquakes and tsunami
Benioff zone down to 700 km
geodetic measured plate motions across trench boundaries
interseismic locking between 10 and 40 km deep
co-seismic and postseismic displacements





[Simons et al., 2011]

Characteristics of Subduction

asymmetric trench outer rise topography

arcuate planform

large outer trench wall curvature

outer trench wall fractures

Would you believe in subduction if these observations were not available?

back arc volcanoes

megathrust earthquakes and tsunami

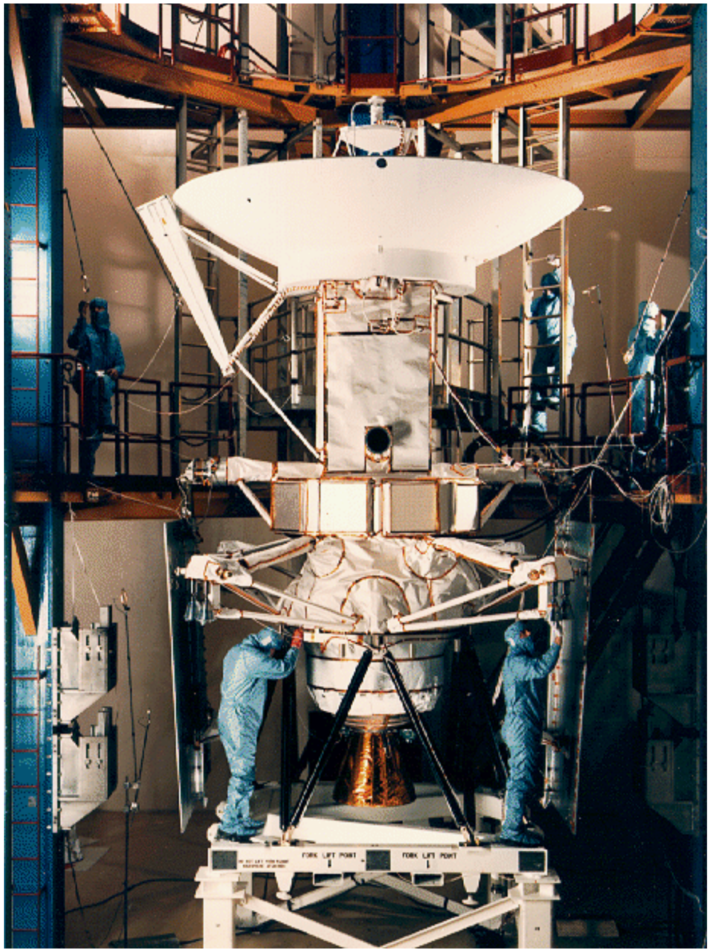
Benioff zone down to 700 km

geodetic measured plate motions across trench boundaries

interseismic locking between 10 and 40 km deep

co-seismic and postseismic displacements

Magellan Fact Sheet



Major Mission Characteristics

```
Interplanetary Cruise: May 4, 1989, to August 10, 1990
First Mapping Cycle: September 15, 1990 to September 15, 1991
Orbit Period: 3.25 hours
Orbit Inclination: 86 degrees
Radar Mapping Per Orbit: 37.2 minutes
Planetary Coverage: 98%
Extended Mission: September 15, 1991
Cycle 2: Image the south pole region and gaps from Cycle 1
Cycle 3: Fill remaining gaps and collect stereo imagery
Cycle 4: Measure Venus' gravitational field
Cycle 5: Aerobraking to circular orbit and global gravity measurements
Cycle 6: Global gravity measurements
Windmill experiment
End of Mission - atmospheric entry 12-13 Oct 1994
```

Mission Objectives

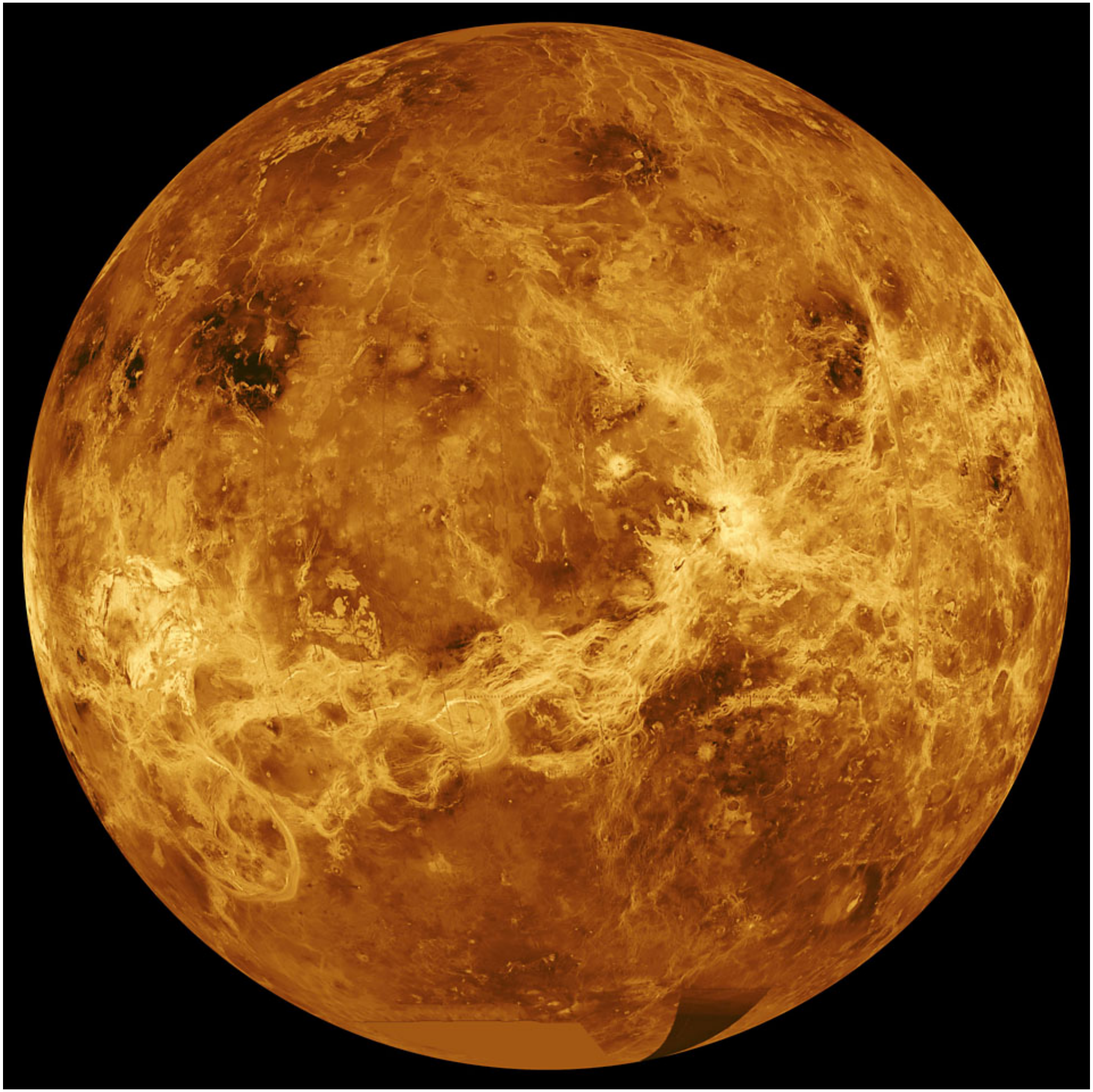
- Obtain near-global radar images of Venus' surface, with resolution equivalent to optical imaging of 1 km per line pair.
- Obtain a near-global topographic map with 50km spatial and 100m vertical resolution.
- Obtain near-global gravity field data with 700km resolution and 2-3 milligals accuracy.
- Develop an understanding of the geological structure of the planet, including its density distribution and dynamics.

http://www2.jpl.nasa.gov/magellan/

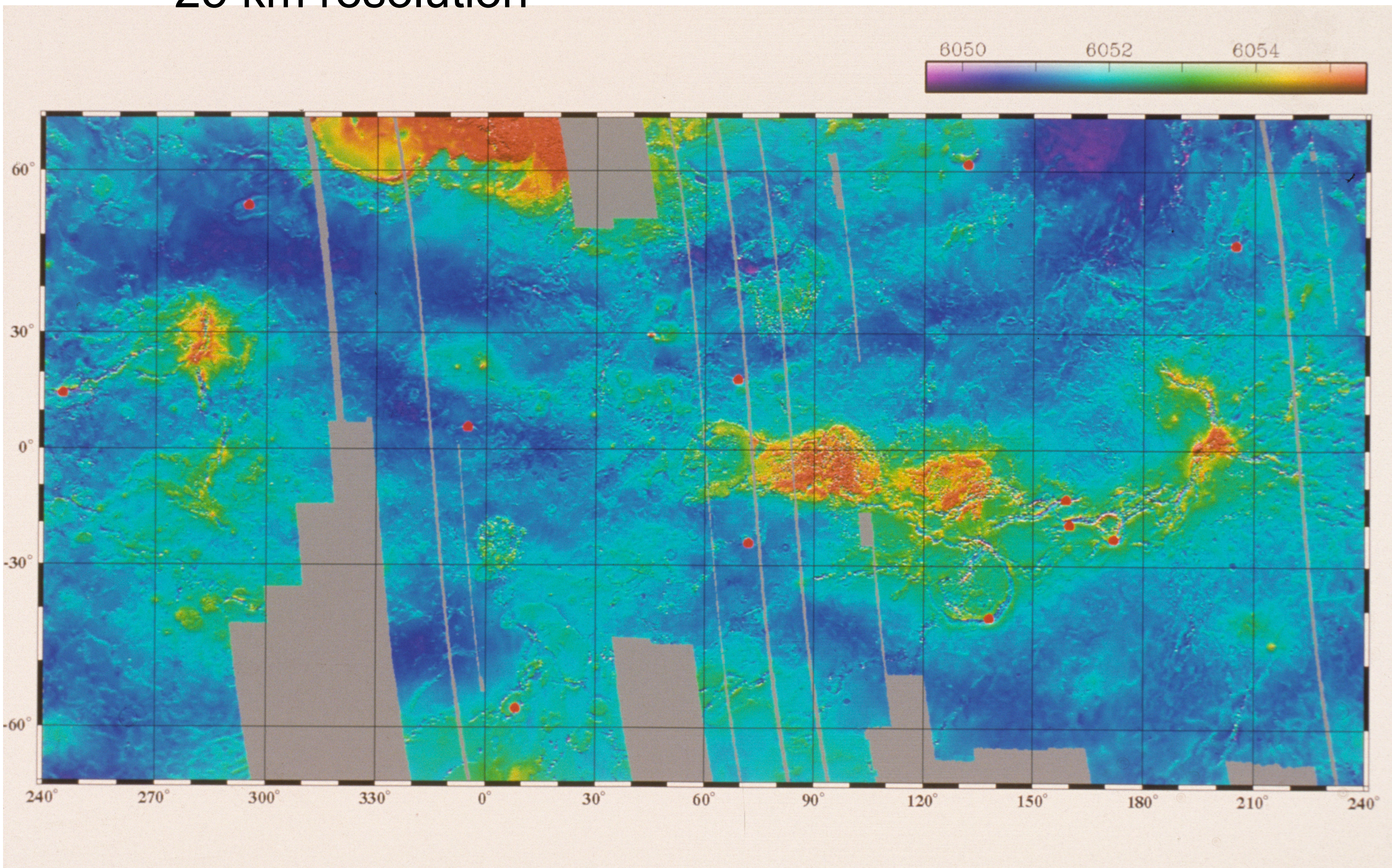
Magellan Science Team, 1991

Global SAR Mosaic

NASA - JPL



Global Topography of Venus from Radar Altimetry
25 km resolution

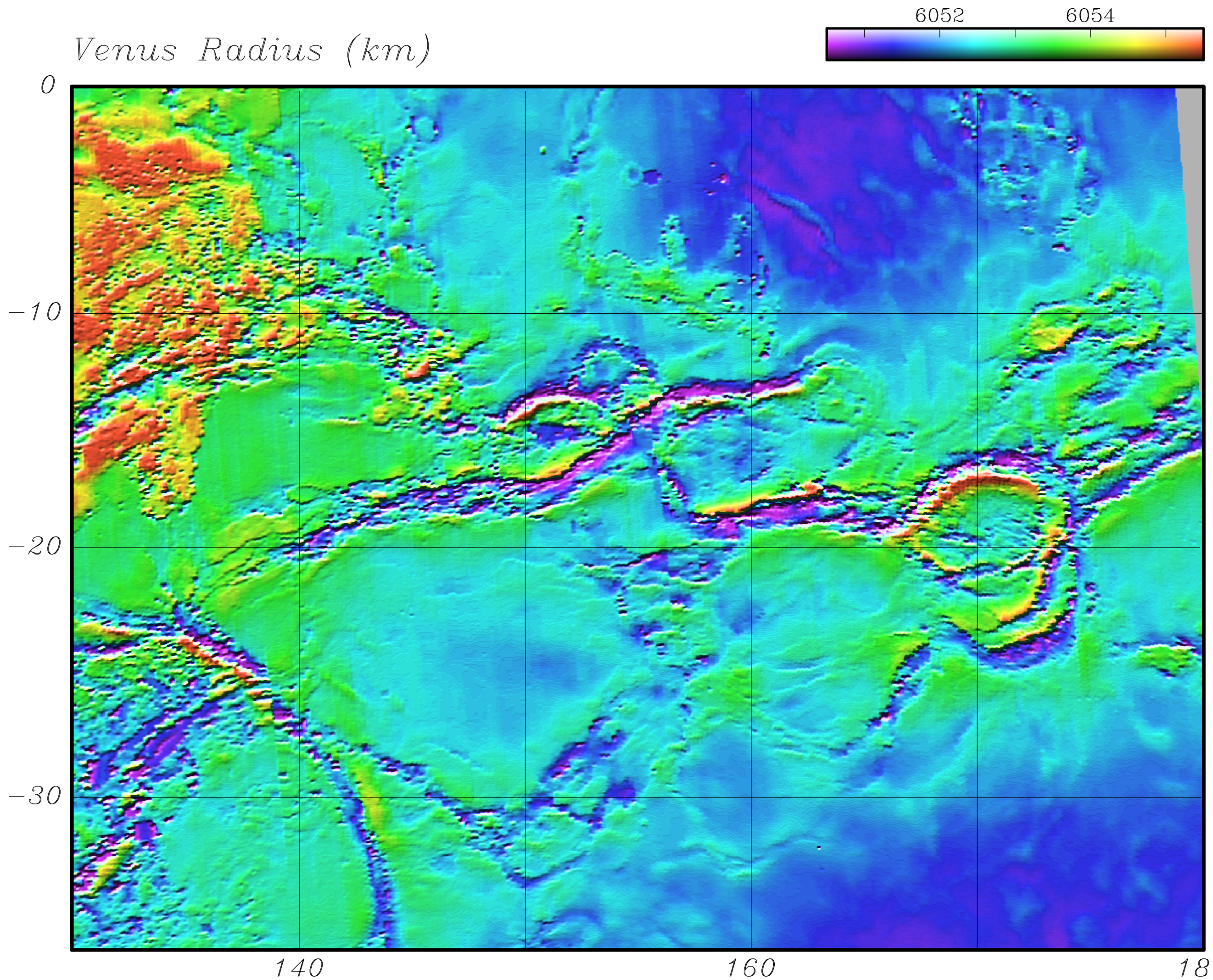


Ford and Pettengill, 1992

Venus Topography from Magellan

[McKenzie et al., JGR 1992]

"Structures that resemble trenches are widespread on Venus and show the same curvature and asymmetry as they do on Earth."

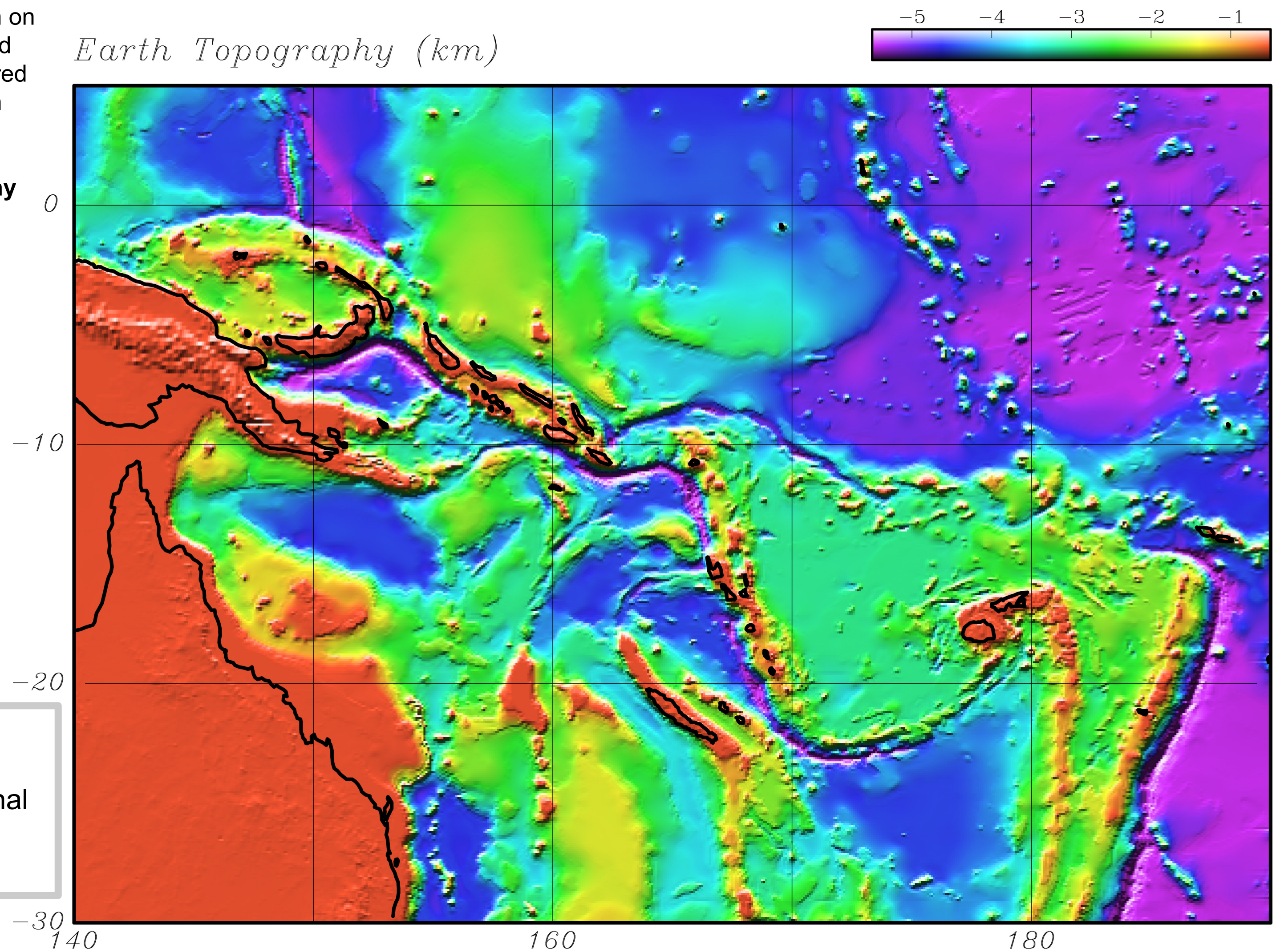


(Note Dan McKenzie was on sabbatical at SIO when he did this research. These are original postscript files made with Parker's HyperMap.)

Venus Topography from Magellan

[McKenzie et al., JGR 1992]

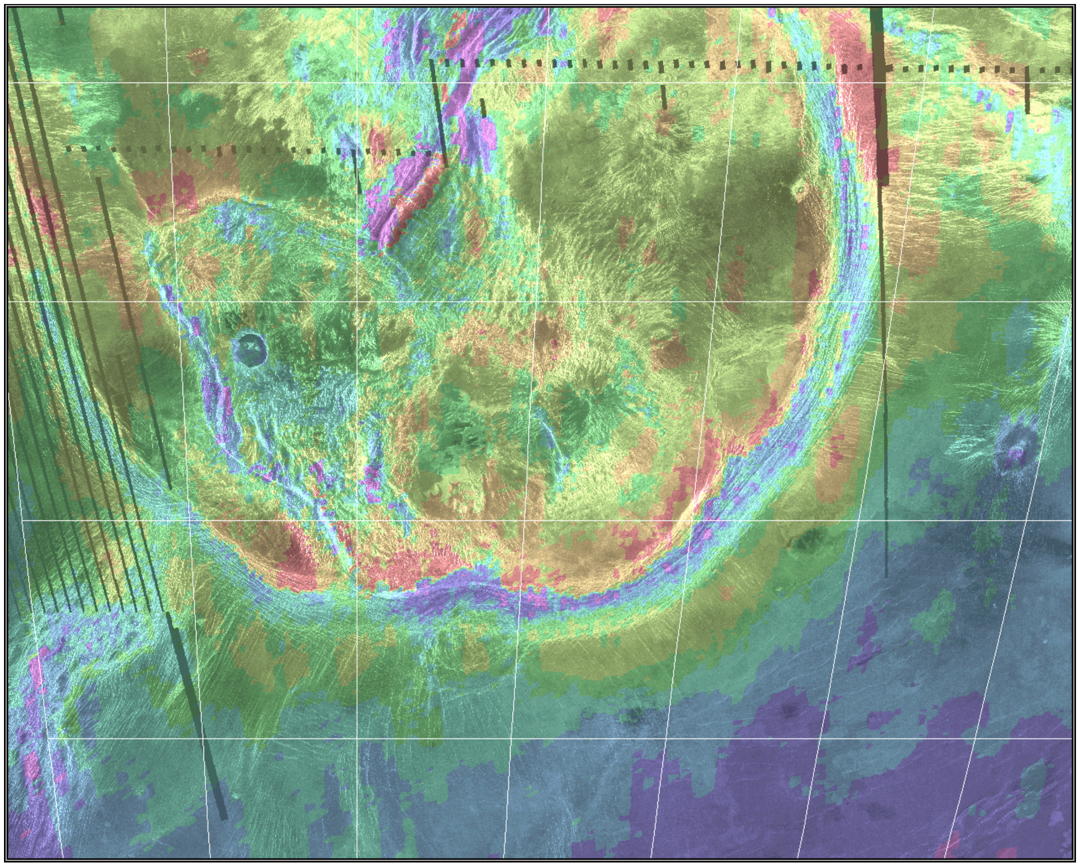
"Ridges and transform faults appear to be much less common on Venus than they are on Earth and for this reason were not discovered until most of the planet had been imaged. Trenches, however, are widespread, and **detailed comparison of their topography with those on Earth should provide constraints on the the rheology of the Venusian lithosphere.**
"

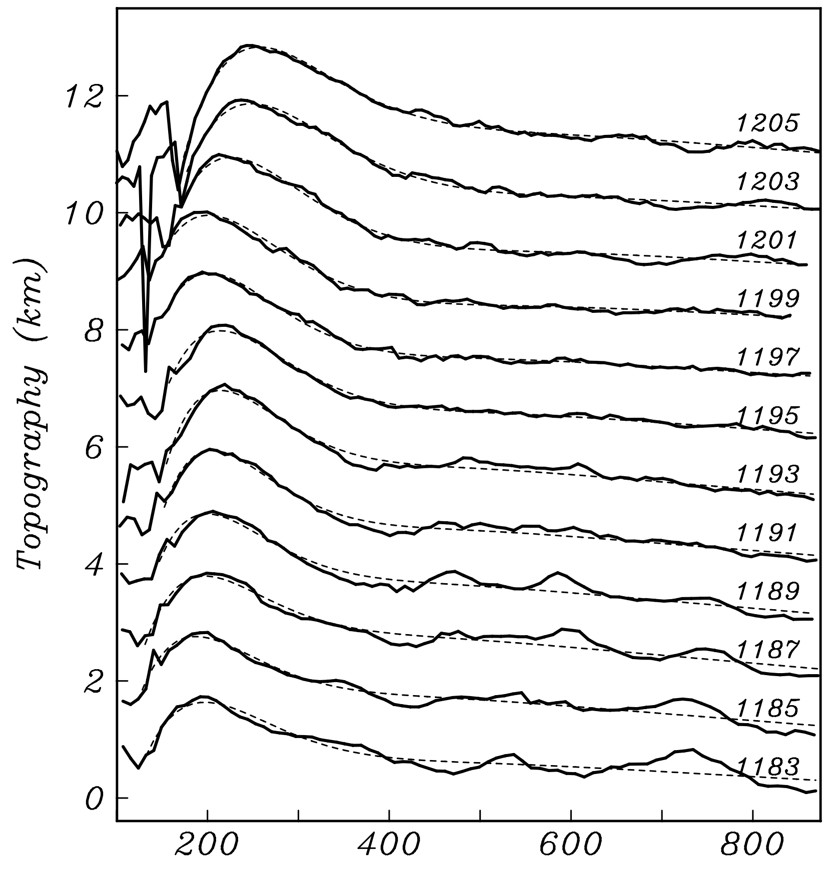


(Note Dan McKenzie was on sabbatical at SIO when he did this research. These are original postscript files made with Parker's HyperMap.)

Elastic Thickness from Flexure

Artemis

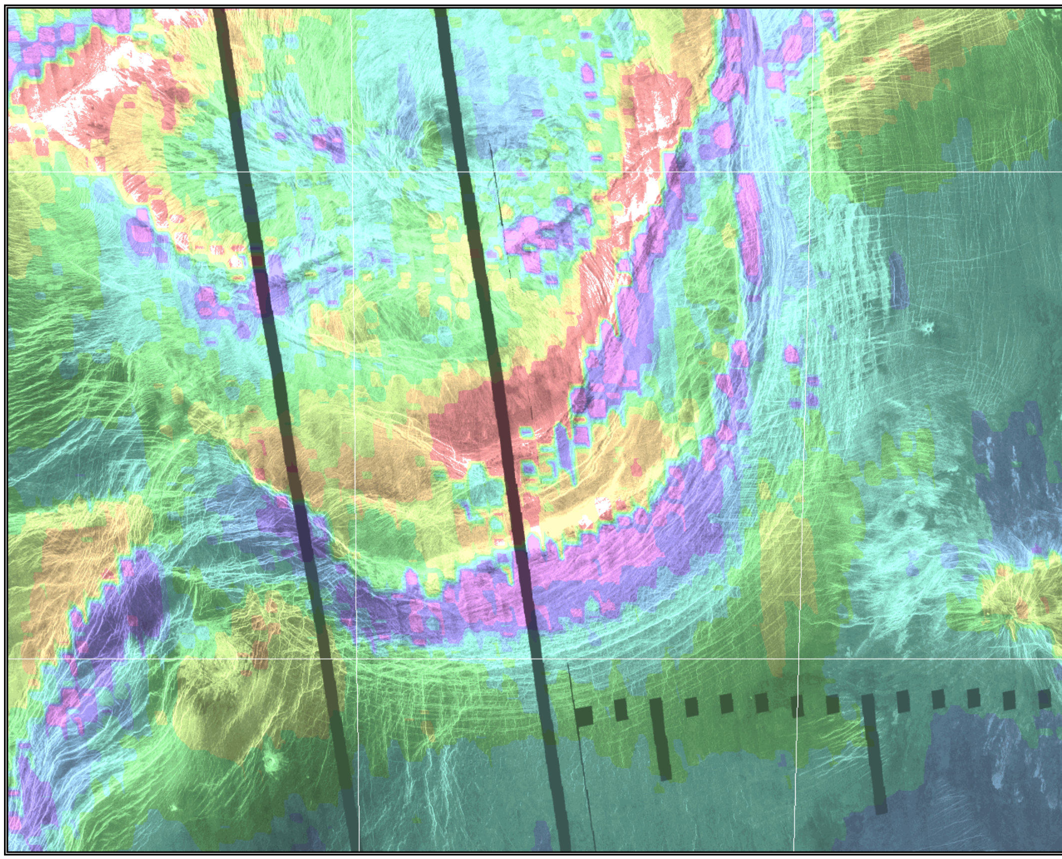


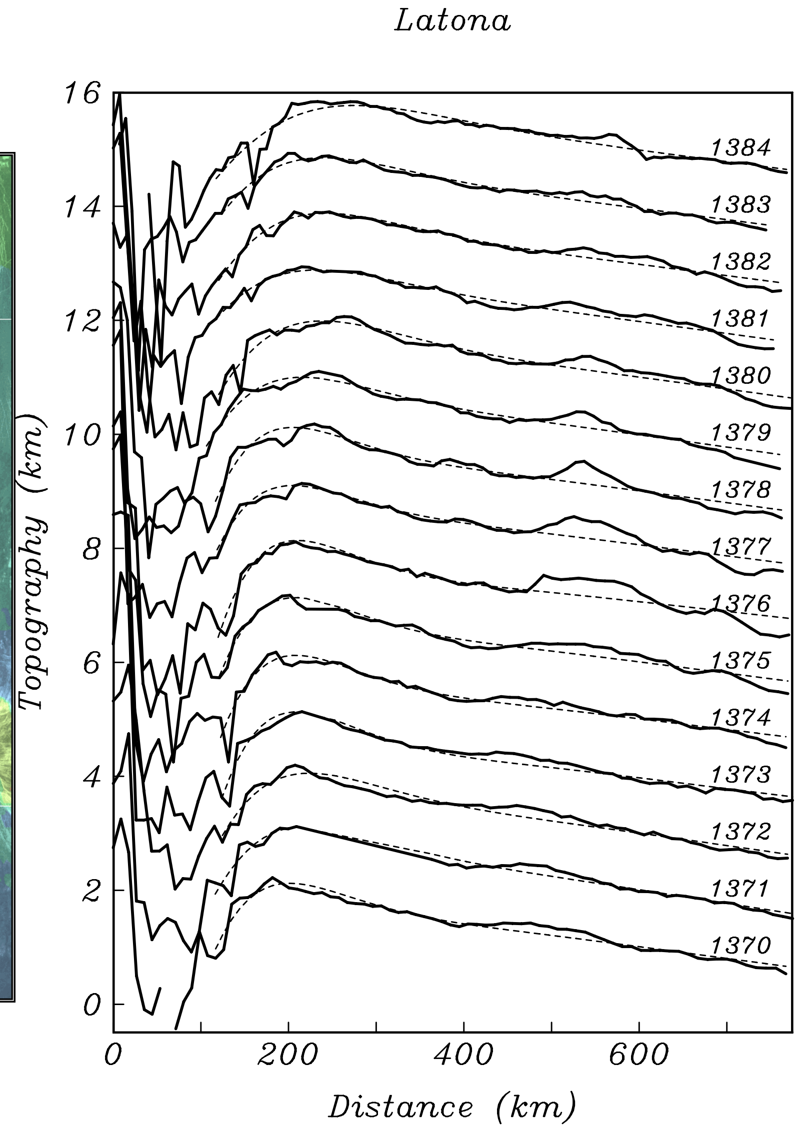


[Sandwell and Schubert, 1992]

Elastic Thickness from Flexure

Latona





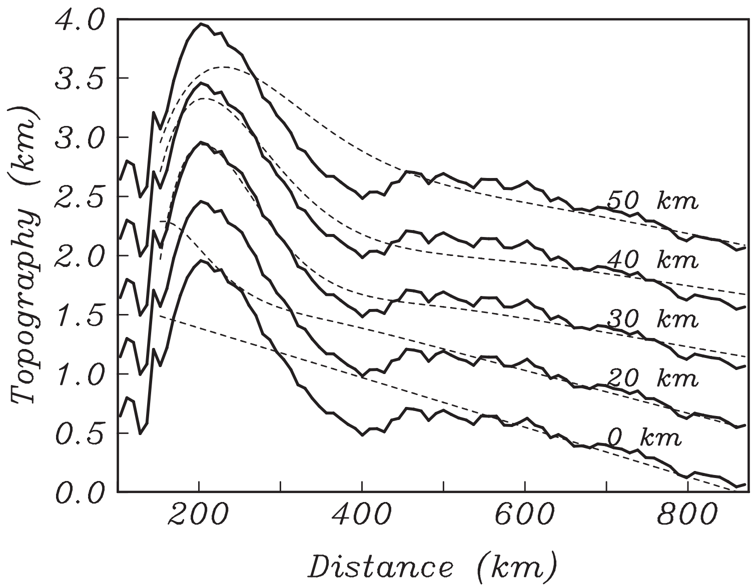
[Sandwell and Schubert, 1992]

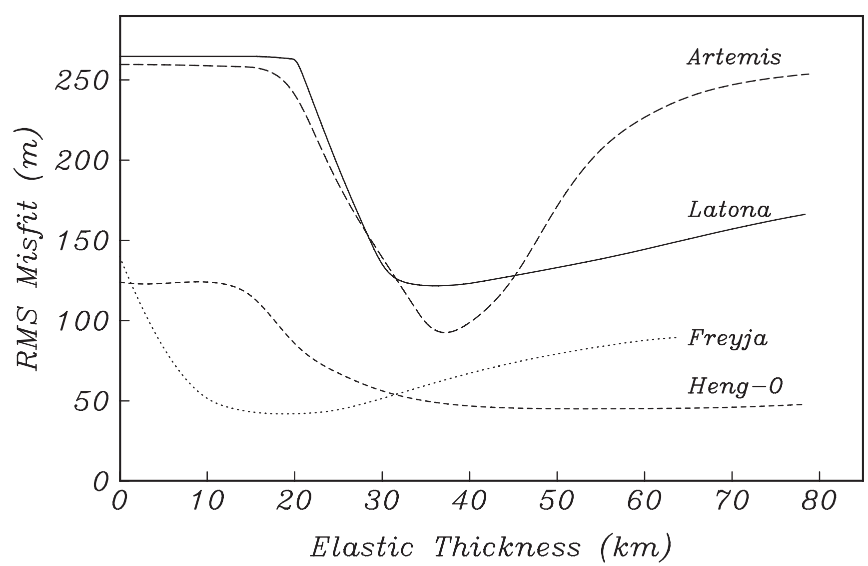
Elastic Thickness from Flexure

TABLE 3. Lithospheric Thickness and Temperature Gradient

	Elastic Thickness, km	Curvature, 10^{-8} m^{-1}	Mechanical Thickness,* km	Temperature Gradient,+ K km^{-1}
Freyja#	11 - 18	15	12 - 21	24 - 14
Freyja	10 - 25	13	11 - 30	26 - 9.5
Eithinoha	10 - 30	29	12 - 42	24 - 6.8
Heng-O	30 - 45	3	32 - 49	8.9 - 5.8
Artemis	30 - 45	103	60 - 90	4.8 - 3.2
Latona	27 - 60	29	37 - 82	7.7 - 3.5

*Mechanical thickness derived from Figure 4. of *Solomon and Head* [1990].
+Temperature gradient based on 1013 K (740°C) temperature at base of elastic layer.
Published results, *Solomon and Head* [1990].





[Sandwell and Schubert, 1992]

Elastic Thickness from Flexure

Table 3. Inelastic Flexure Model Results

Parameter	Weak Rheology*	Strong Rheology†
	Full Outer Rise Width Range‡	
dT/dz, K km^{-1}	3.4–5.4	3.8–6.4
	Mean Outer Rise Width	
dT/dz, K km^{-1}	2.8–4.0	3.8–4.4
N, N m^{-1}	$-(3.0–15) \times 10^{13}$	$-(9.3–14) \times 10^{13}$
M, N	$-(3.5–15) \times 10^{17}$	$-(4.9–10) \times 10^{17}$

* Two constraints: outer rise height and width.
† Three constraints: outer rise height and width and no surface failure.
‡ Upper bounds to geotherm over range of outer rise widths.

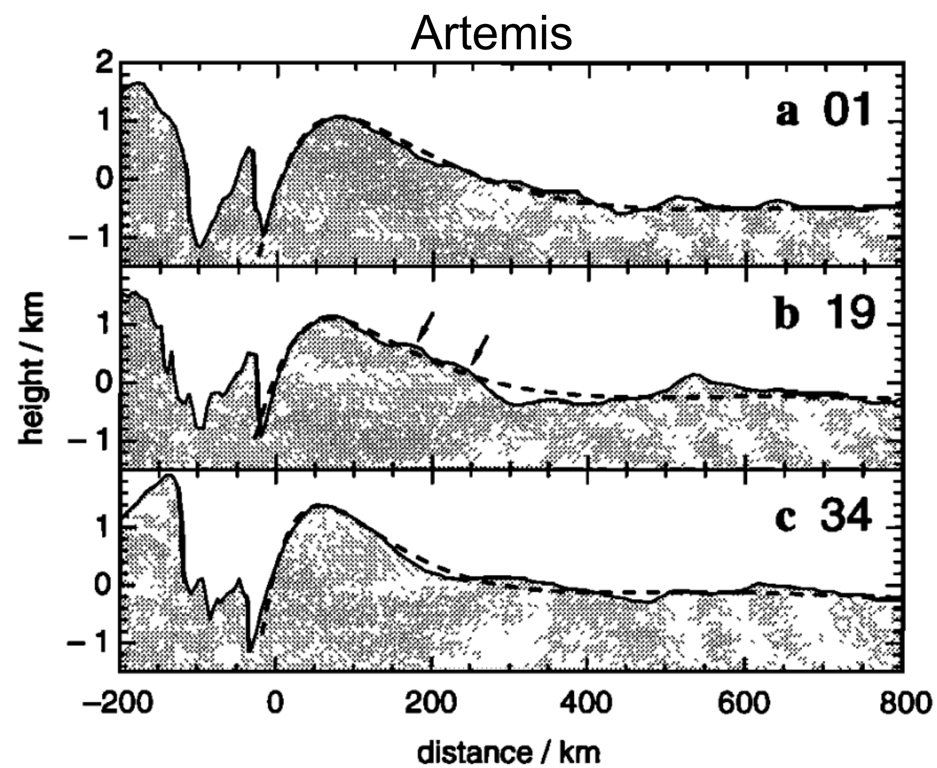


Figure 7. Inelastic model fits to three topographic profiles indicated in Figure 1, vertically exaggerated by a factor of 73. **(a)** Strong rheology, $dT/dz = 5$ K km^{-1}, $N = -8.5 \times 10^{13}$ N m^{-1}, $M = -7.2 \times 10^{17}$ N. **(b)** This profile is similar in shape to the average profile (Figure 5). Weak rheology, $dT/dz = 3.6$ K km^{-1}, $N = -1.0 \times 10^{14}$ N m^{-1}, $M = -3.5 \times 10^{17}$ N. The arrows mark a ridge that may be unrelated to the flexural topography, and which therefore exaggerates the outer rise width. **(c)** Strong rheology, $dT/dz = 7.3$ K km^{-1}, $N = -4.1 \times 10^{13}$ N m^{-1}, $M = -3.6 \times 10^{17}$ N.

[Brown and Grimm, 1996]

Lithospheric Buoyancy

(Oxburgh and Parmentier, 1977; Burt and Head; 1992; Schubert and Sandwell, 1995)

$$\delta = \int_0^\infty \left[\frac{\rho_m - \rho(z)}{\rho_m} \right] dz$$

δ - density defect thickness
> 0 no subduction
< 0 subduction possible

$\rho(z)$ - lithospheric density

ρ_m - undepleted mantle density

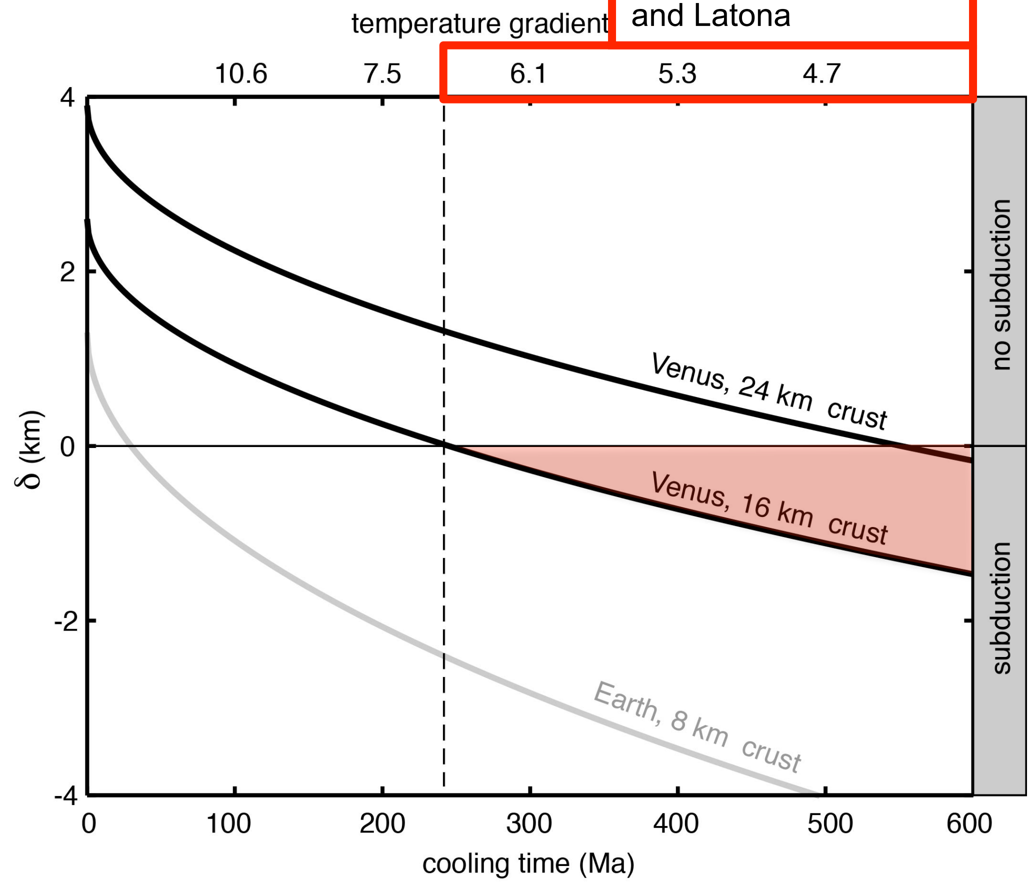
$$\delta_{total} = \delta_{comp} + \delta_{thermal}$$

$$\delta_{total} = \text{light crust} + \text{depleted mantle}$$

$$\delta_{thermal} = -2\alpha (T_m - T_o)\sqrt{\frac{\kappa t}{\pi}}$$

	Earth	Venus
δ_{comp}	1.3 km	?
T_o	0°C	455°C
T_m	1300°C	1400°C
α	3.1×10^{-5} C^{-1}	3.1×10^{-5} C^{-1}
κ	8.0×10^{-7} $m^2 s^{-1}$	8.0×10^{-7} $m^2 s^{-1}$

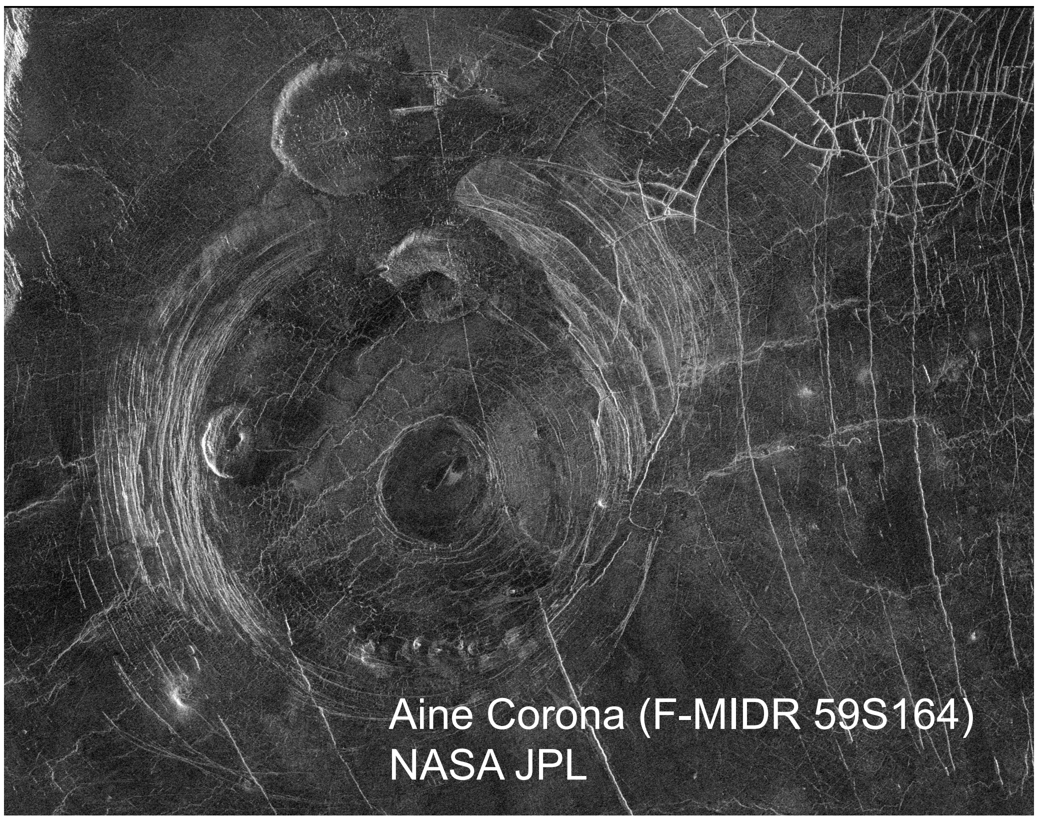
estimated temperature gradients at Artemis and Latona



No subduction for temperature gradient greater than ~7 ˚C/km

What about Corona

"Corona on Venus are circular to elongate structures with maximum widths of 150-1000 km characterized by an annulus of concentric ridges surrounding complex interiors. The features have raised topography relative to the surroundings, they are associated with volcanic activity, and most are partially surrounded by a peripheral trough." [Stofan et al., 1991]



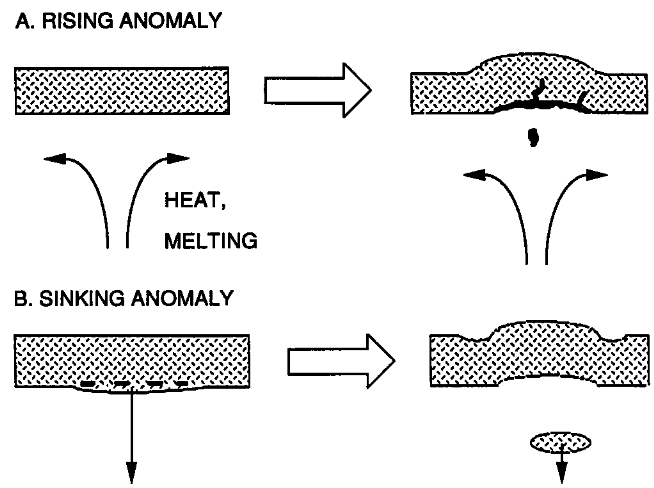


Fig. 5. (*a*) Idealized rising anomaly model of corona origin. A thermal anomaly or hotspot results in partial melting, with lighter buoyant material rising causing uplift and volcanism at the surface. (*b*) Idealized sinking anomaly model of corona origin. A sinking diapir may form due to a phase change produced by thickening of the lithosphere below a critical depth or cooling instabilities at the base of the lithosphere

What about Corona

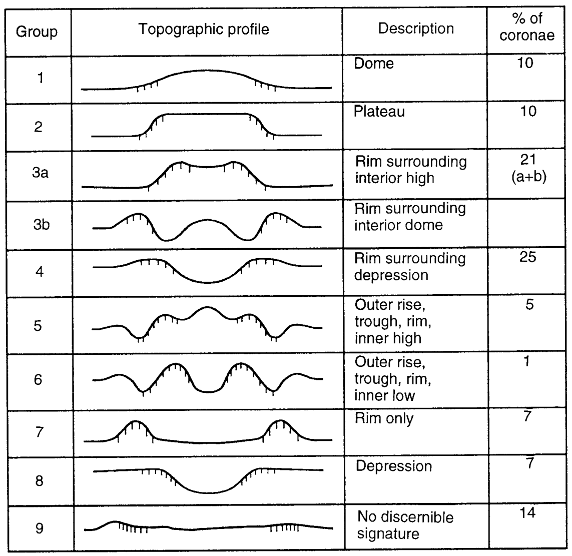
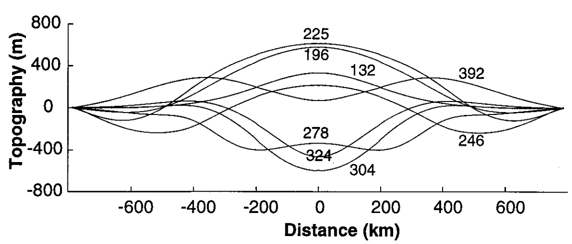


Table 1. Topographic groups. Vertical tick marks on topographic profiles indicate the typical location of annuli for each group.

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]

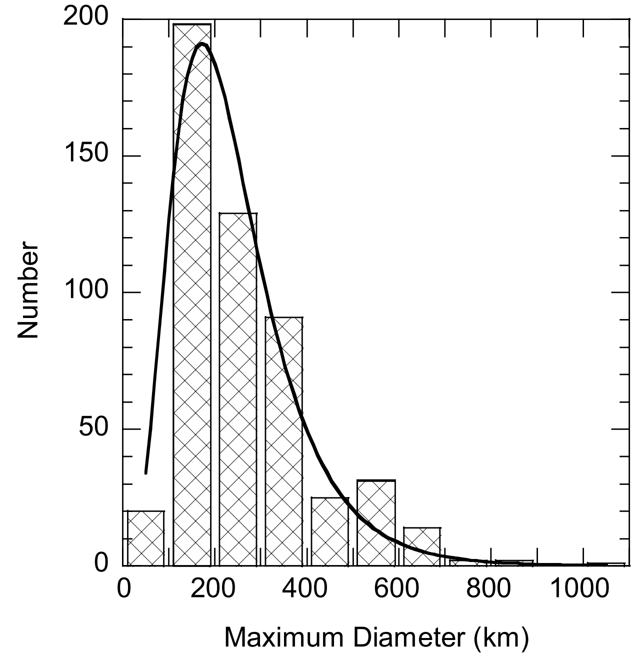


Figure 2. Histogram of maximum diameters for both Type 1 and Type 2 coronae (data from *Stofan et al.* [2001] and *Glaze et al.* [2002]), binned every 100 km. A fit of a lognormal distribution is also shown, with geometric and arithmetic means of ∼217 km and ∼243 km, respectively.

[Dombard et al., 2007]

Artemis, Latona, and other large trench-like structures are dissimilar to the typical corona.

Subduction Model

Corona Model

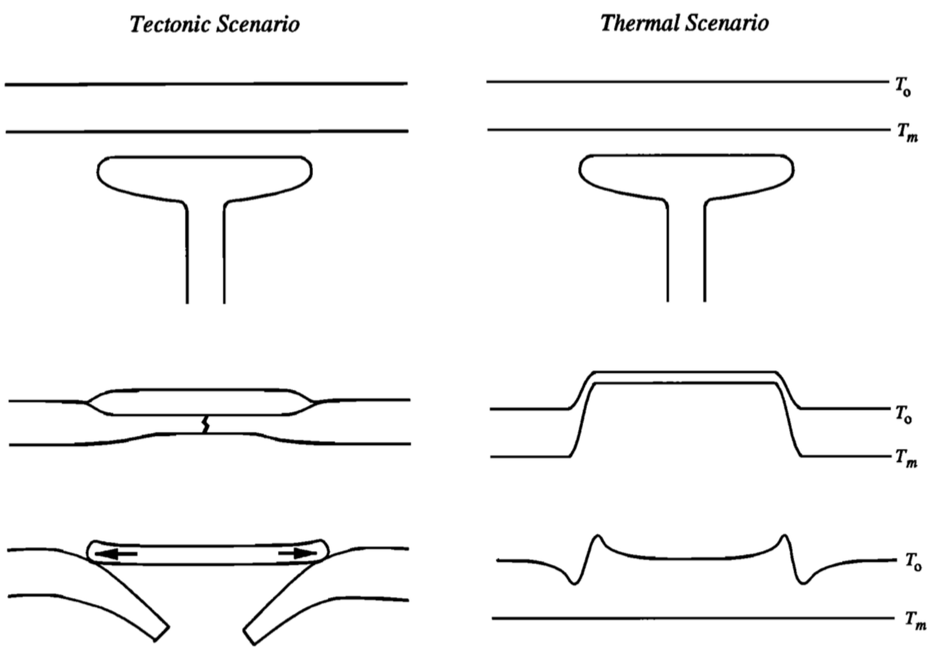
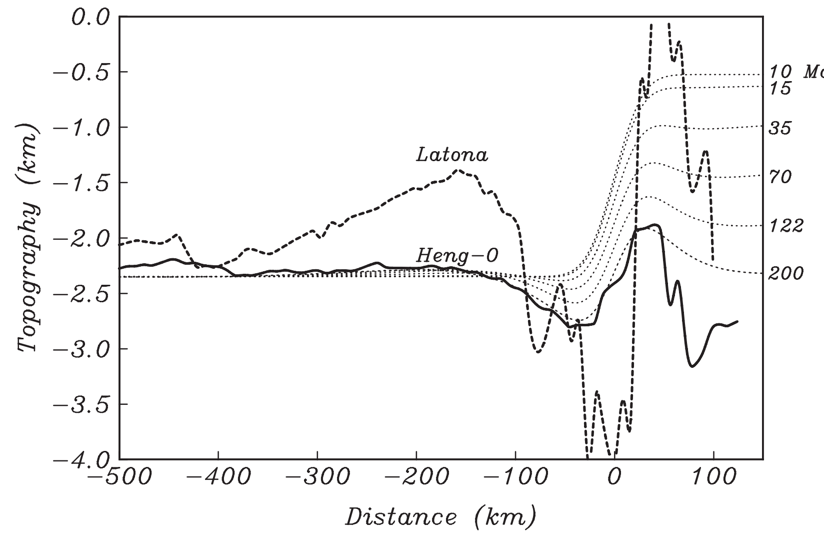


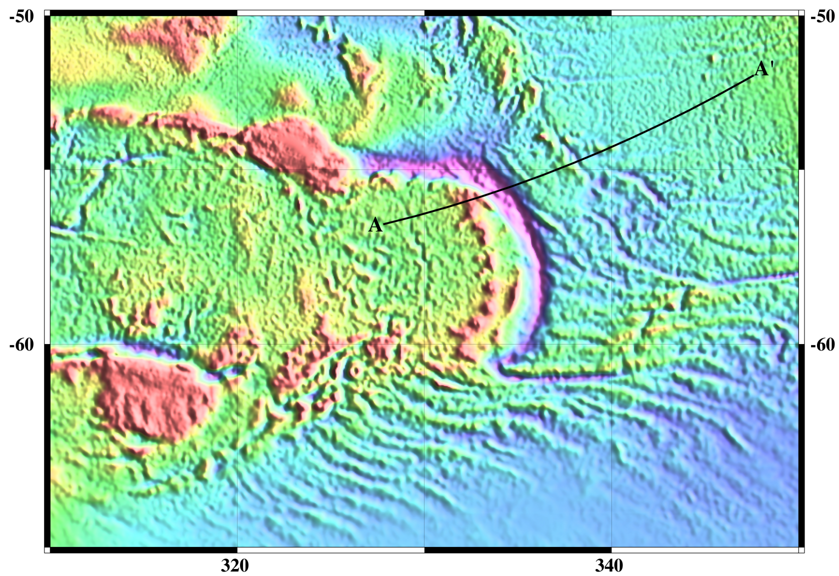
Fig. 14. (Left) Tectonic scenario: plume head approaches the lithosphere and spreads radially, causing it to thin and weaken; melt and hot mantle material pond on the surface of the lithosphere causing it to fail under the load; the old and dense lithosphere sinks into the mantle forming a circular subduction zone that increases in radius with time; the interior spreads radially to fill the growing void; a prominent trench and outer rise develop. (Right) Thermal scenario: plume head approaches the lithosphere and spreads radially; thermal conduction and/or advection thins the lower lithosphere in a circular area with sharp edges; the hot interior cools and subsides relative to the cool exterior forming ridge, trench, and outer rise topography.

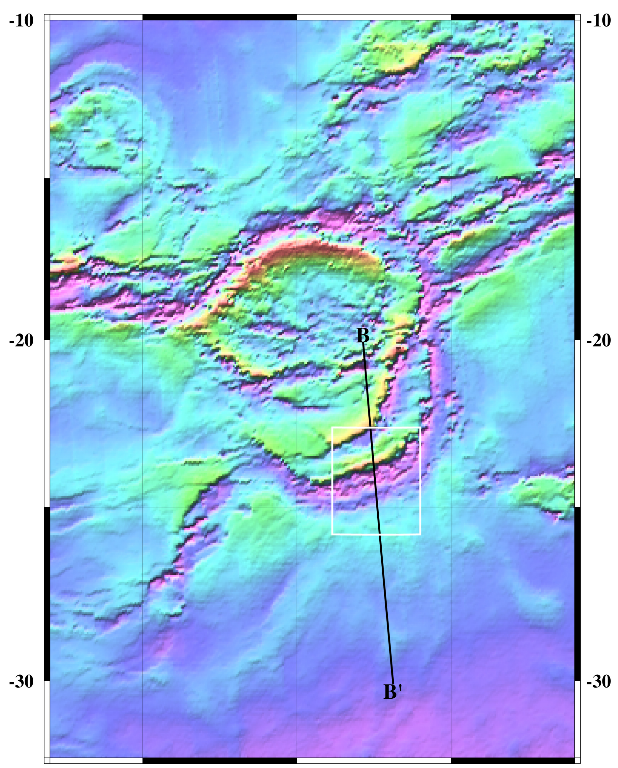


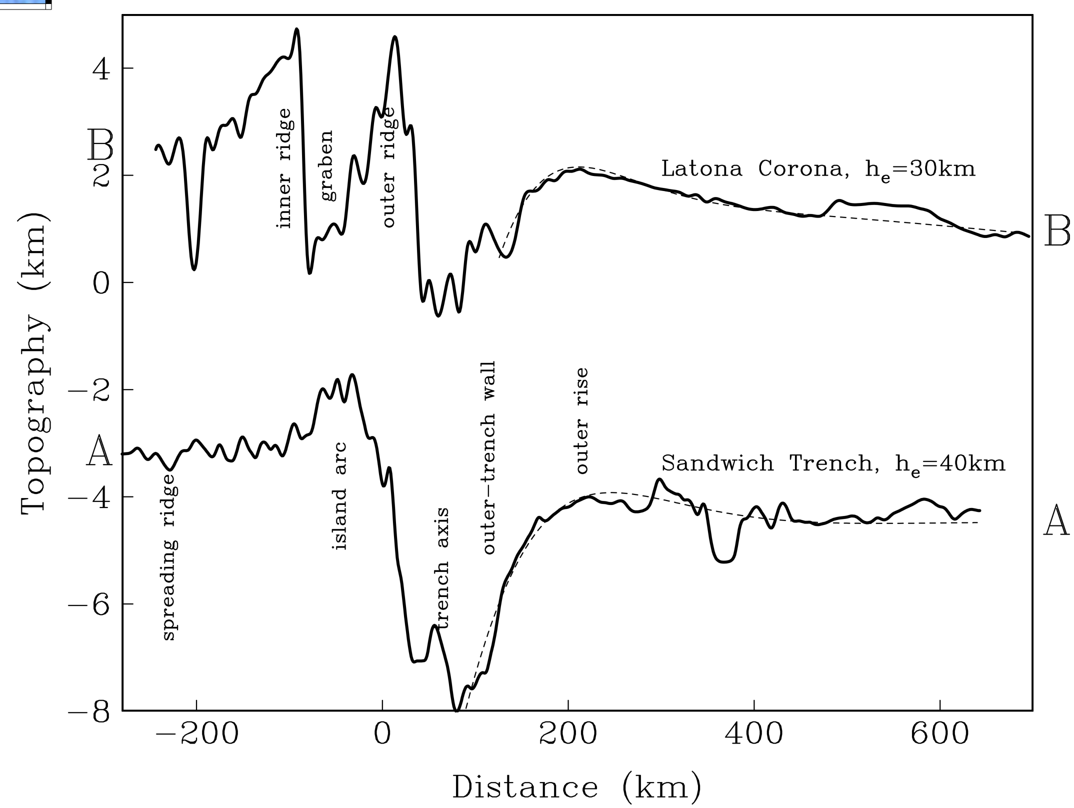
Thermal scenario fails to predict trench amplitude at Latona.

[Sandwell and Schubert, 1992]

Earth and Venus

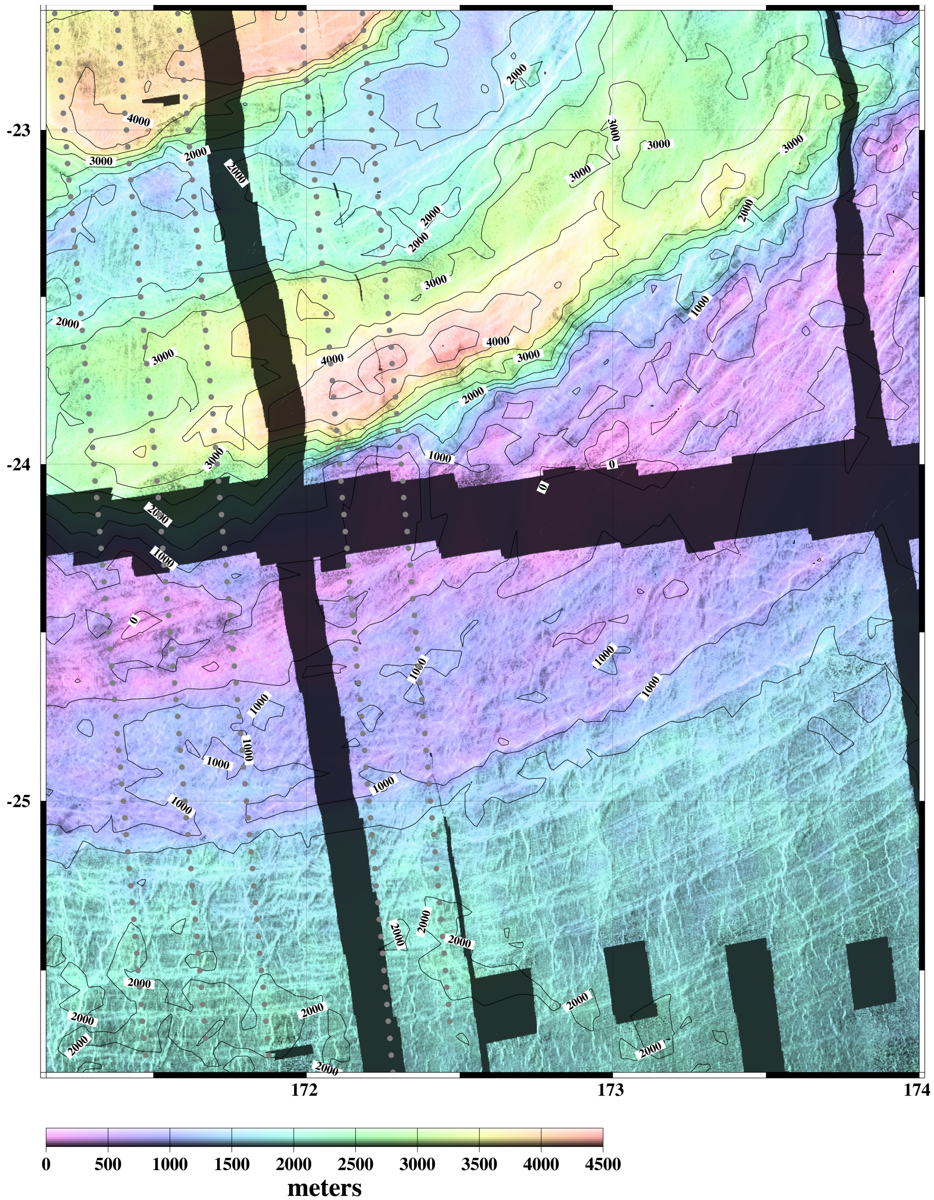




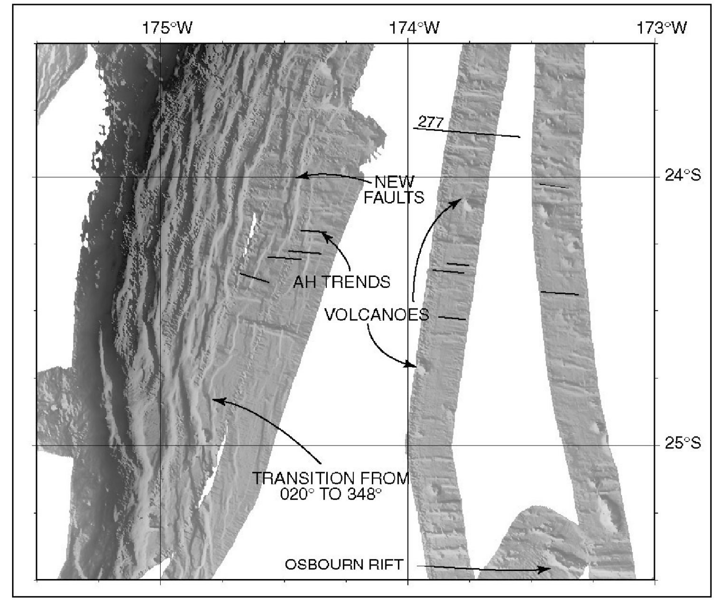


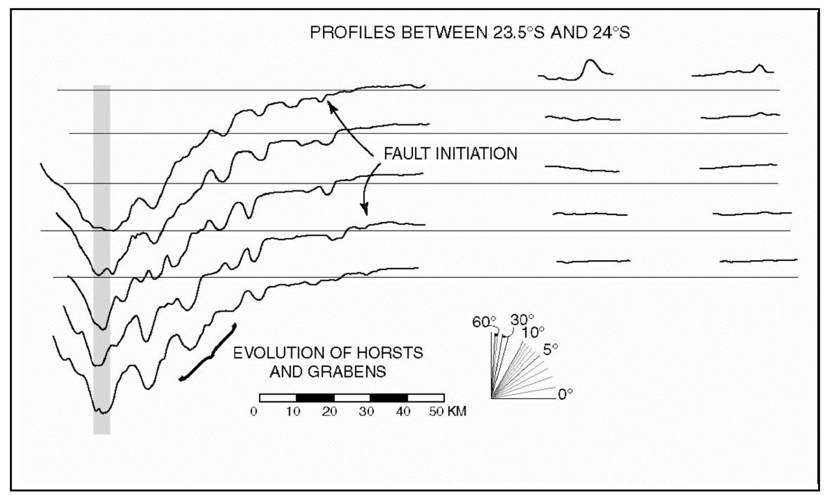
[Sandwell and Schubert, 1992b]

Latona Corona
Venus



Southern Tonga Trench [Massell, 2002]



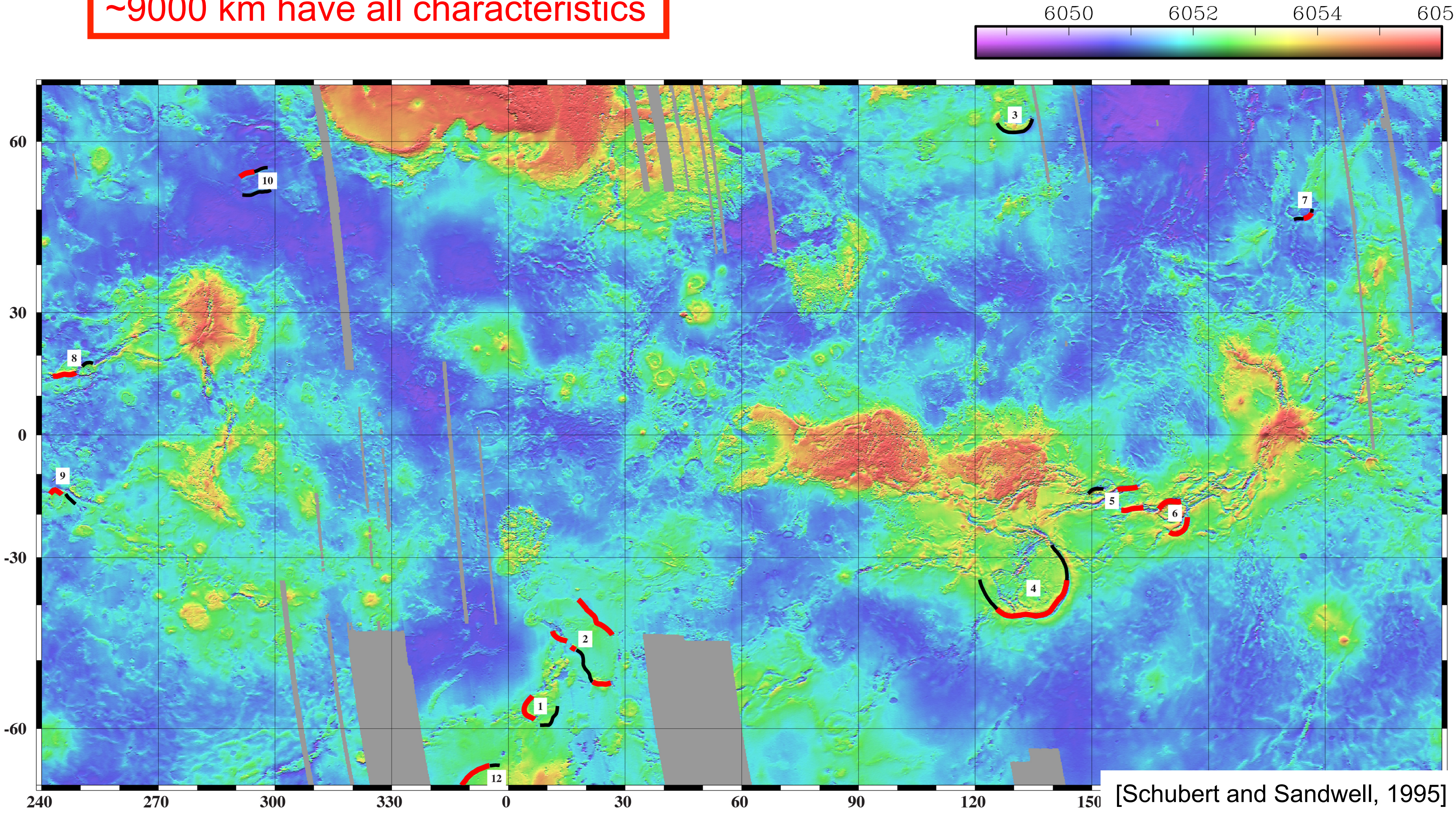


[Schubert and Sandwell, 1995]

What is the total length of possible subduction sites on Venus?

~9000 km have all characteristics

asymmetric trench outer rise topography;
arcuate planform
large outer trench wall curvature
outer trench wall fractures



[Schubert and Sandwell, 1995]

Could subduction on Venus account for Earth-like heat loss?

There are ~9000 km of Venus trenches having all 4 characteristics. Earth has 37,000 km of subduction zones.

The relatively uniform density of impacts is inconsistent with large areas of plate recycling so Venus **trenches are probably not active today**.

Elastic thickness estimates suggest very low thermal gradients in many areas < 7 ˚K/km. **Conductive heat loss is at least 5 times smaller than on the Earth**.

Venus lithosphere is negatively buoyant if the crustal thickness < ~20 km.

Possible subduction sites have **not removed a significant amount of heat** over the past ~500 Ma.

NO - How does Venus lose heat?

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 100, NO. E8, PAGES 16,931–16,940, AUGUST 25, 1995

How does Venus lose heat?

Donald L. Turcotte
Department of Geological Sciences, Cornell University, Ithaca, New York

Three mechanisms considered:

1) Steady heat loss like Earth from: conduction, tectonics and volcanics – NO
2) Strong upward concentration of heat producing elements – UNLIKELY
3) Episodic global subduction events followed by long periods of surface quiescence.

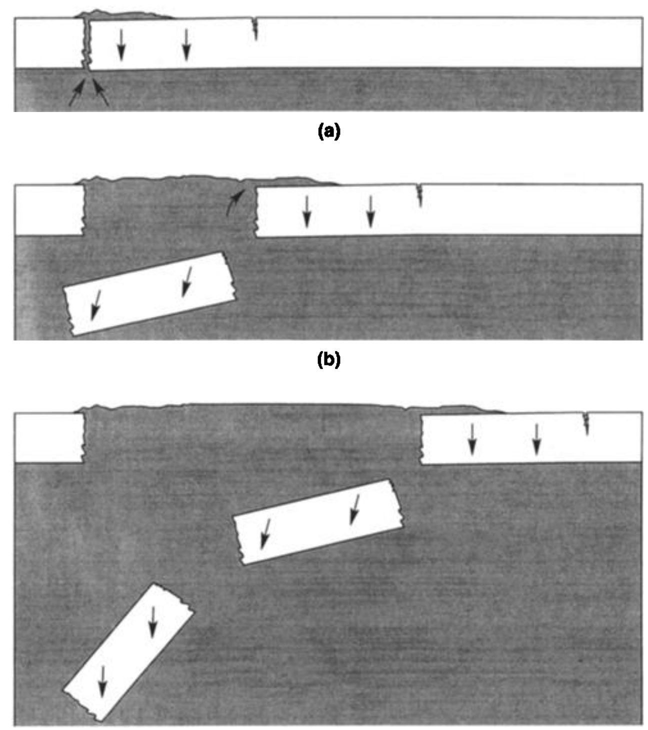


Figure 4. Schematic illustration of an episodic subduction event. The process described for a Hawaiian lava lake is the model, but the process may also be applicable to Venus.

More studies on non-steady tectonics - 1

Fowler and O'Brien, JGR 1996 – *A mechanism for episodic subduction on Venus*

- Developed a numerical model of Turcotte's conceptual episodic model.

Moresi and Solomatov, GJI 1998 - *Mantle convection with a brittle lithosphere: thoughts on the global tectonic styles of the Earth and Venus*

- Investigate the style of thermal convection for Venus and the Earth using a realistic Byerlee's law for the strength of the upper brittle lithosphere.
- They find that when the coefficient of friction is low (0.03-0.13) on the plate boundaries one gets mobile plates.
- When the coefficient of friction is larger (0.6) one gets stagnant lid convection.
- They find that the stagnant lid convection can "collapse" into a runaway mode.

Turcotte et al., Icarus 1999 - *Catastrophic Resurfacing and Episodic Subduction on Venus*

- Develop a thermal model of the episodic resurfacing hypothesis and find if the interval is 500-700 My the events can only transport 15-25% of the radiogenic heat.
- Propose that the remainder of the heat is lost during periods of vigorous tectonic activity following the overturn.

More studies on non-steady tectonics- 2

Fowler and O'Brien, Proc. R. Soc. Lond. 2002 – *LIthospheric failure on Venus*

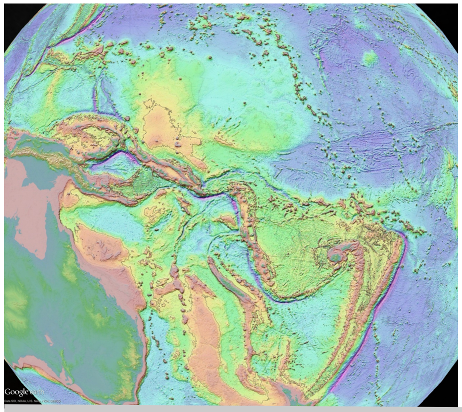
- Explore mechanisms for subduction zone initiation involving a rising plume.
- Perimeter of thermal swell collapses into transient trenches.

Armann and Tackley, JGR 2012 - *Simulating the thermochemical magmatic and tectonic evolution of Venus's mantle and lithosphere: Two-dimensional models*

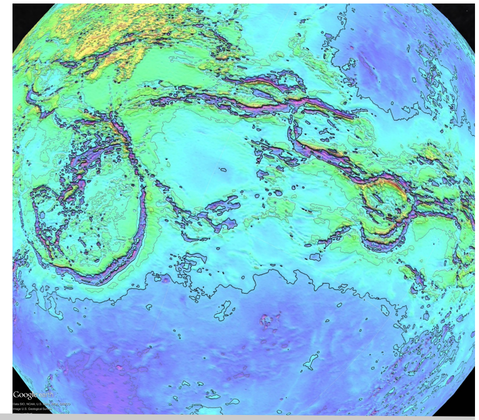
- Episodic lid overturn interspersed by periods of quiescence effectively loses Venus's heat while giving lower rates of volcanism and a thinner crust.
- Calculations predict 5–8 overturn events over Venus's history, each lasting ~150 Myr, initiating in one place and then spreading globally.

Smrekar et al., in revision, 2016 - *Plume-Induced Subduction on Venus*

- Most of the proposed subduction sites on Venus have both characteristics of mantle plumes and subduction zones, leading to debate over their origin.
- Fluid mechanics laboratory experiments provide new insights into surface deformation above a mantle plume that can develop into subduction
- Evidence for geologically recent volcanism at Quetzelpetlatl suggests that subduction may still be active.



Lithospheric Subduction on Earth and **Venus**?



David Sandwell

IGPP, April 15, 2016

- Venus vs. Earth – Heat Loss Mechanisms
- Subduction Zones on Earth
- Magellan Findings
- Subduction on Venus?
- Episodic Tectonics
- **Recent Progress in Our Lab**
- NASA Mission - VERITAS

Google Venus

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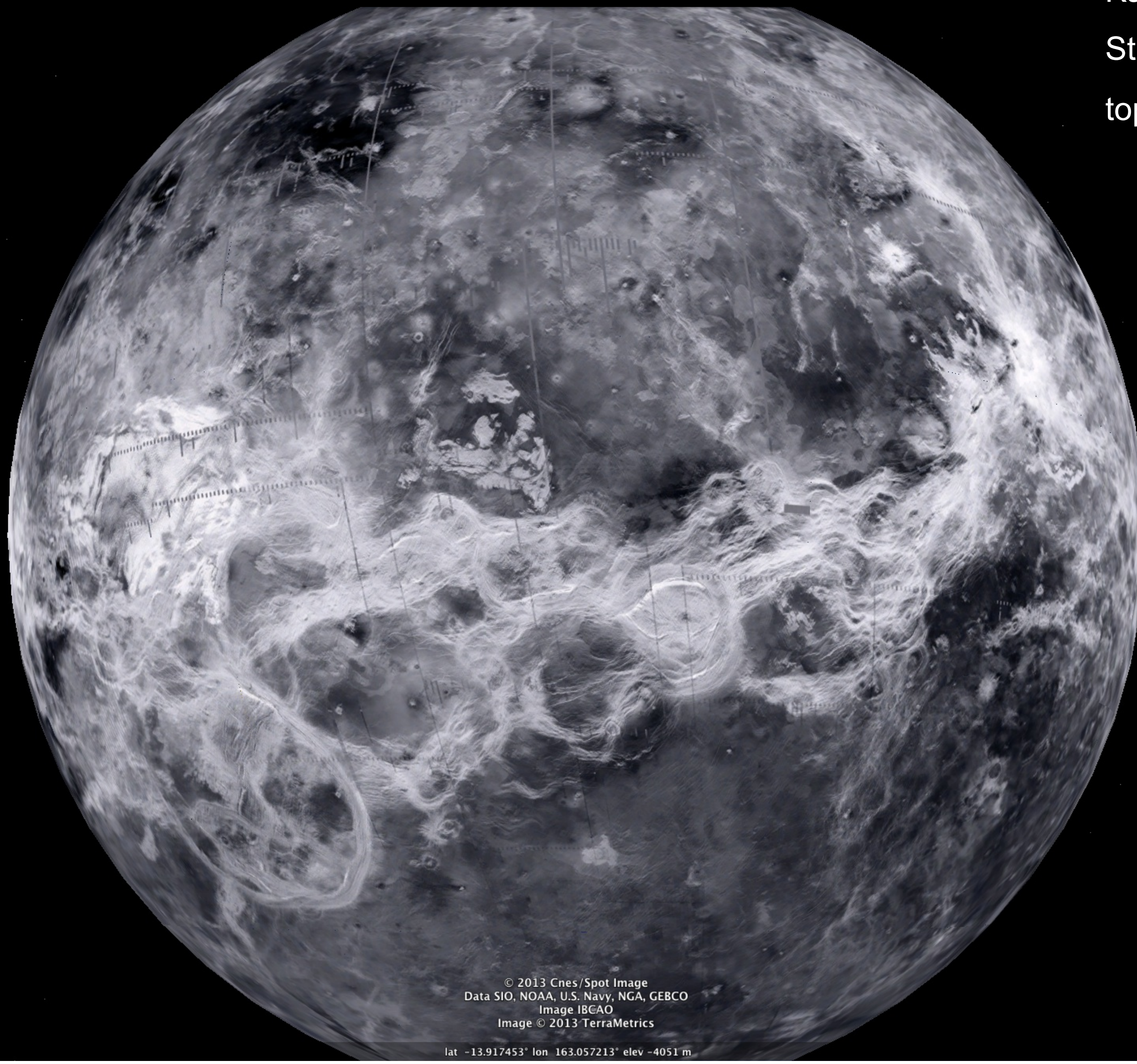
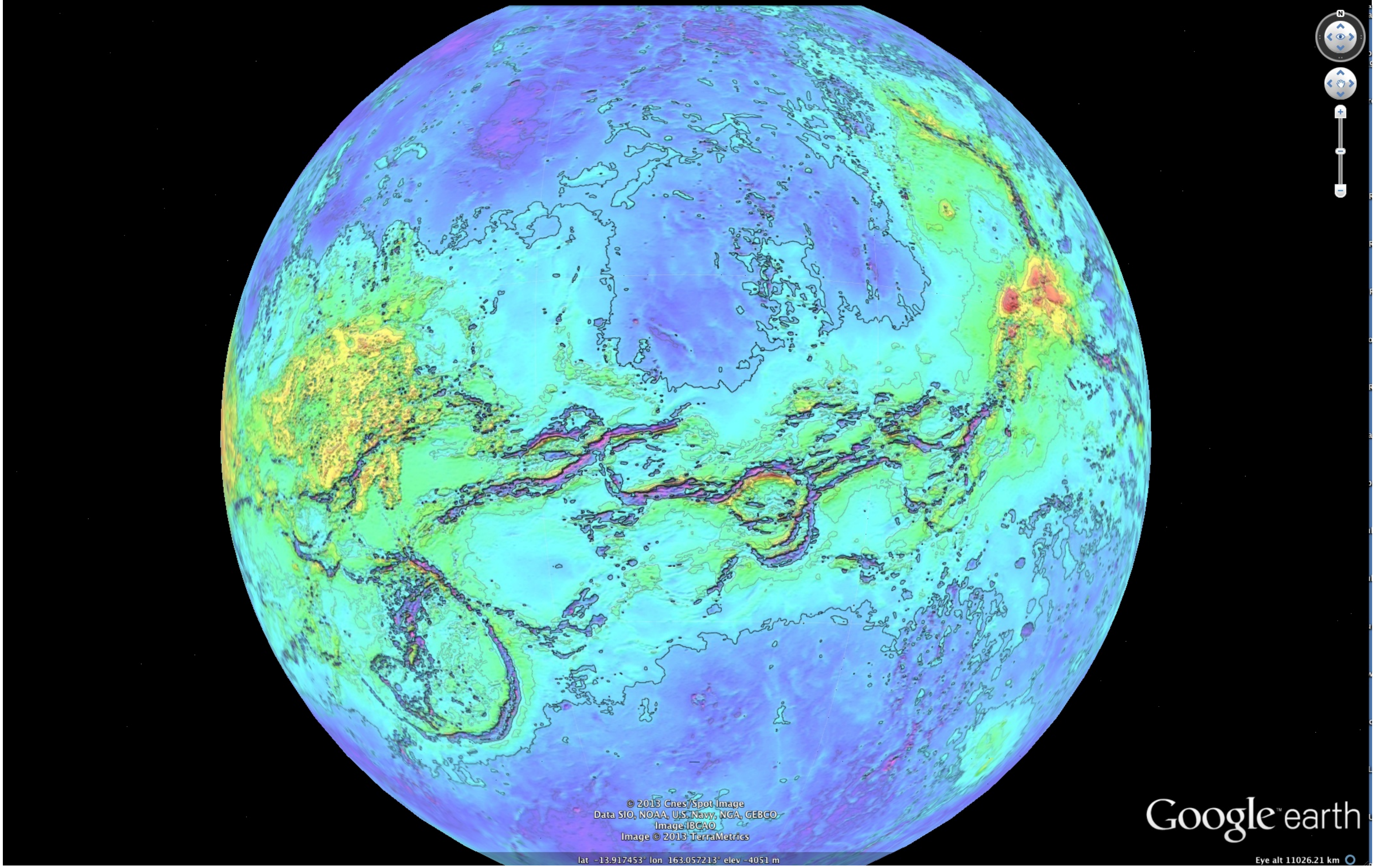


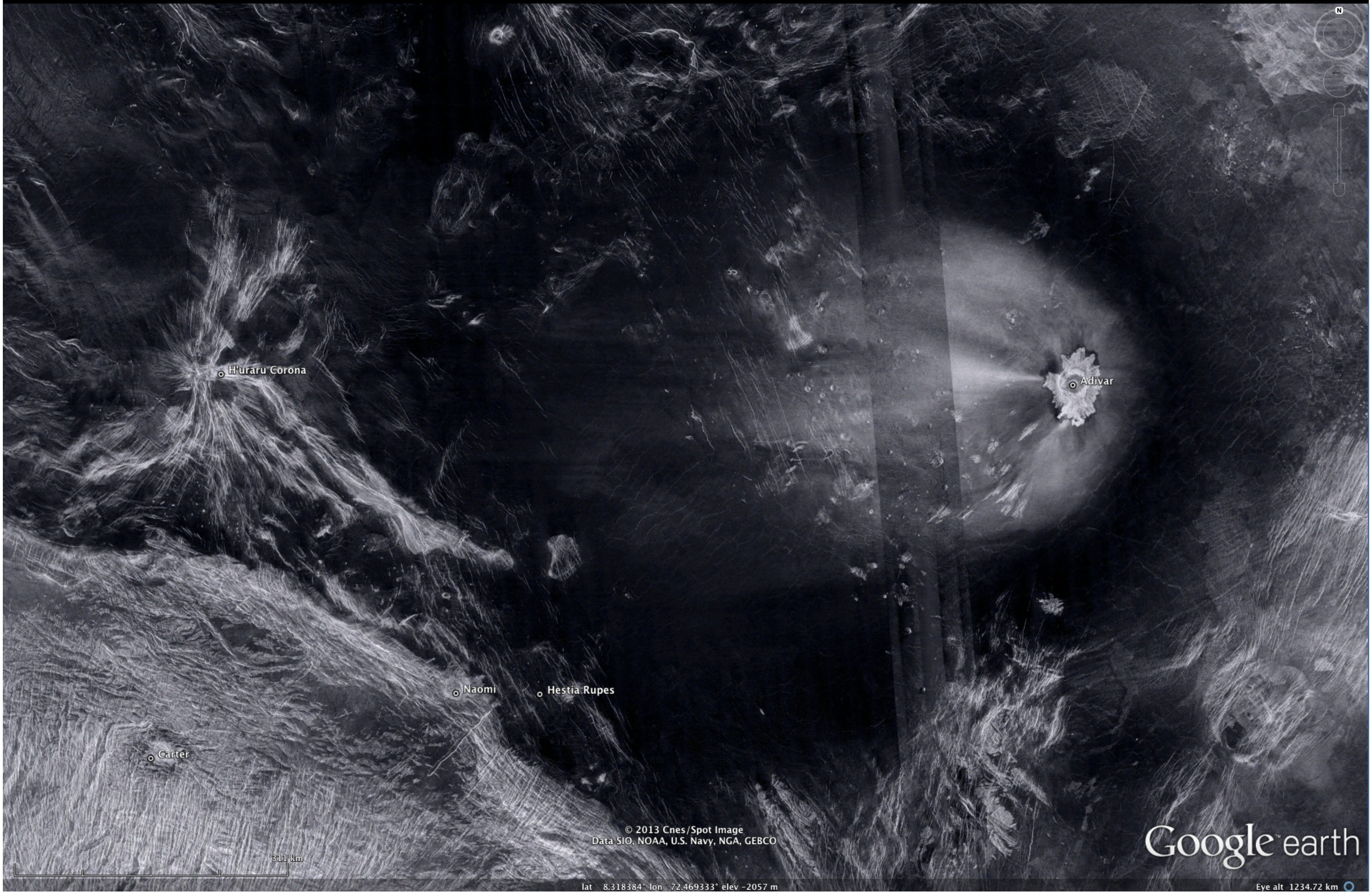
Google earth

Eye alt 11026.21 km

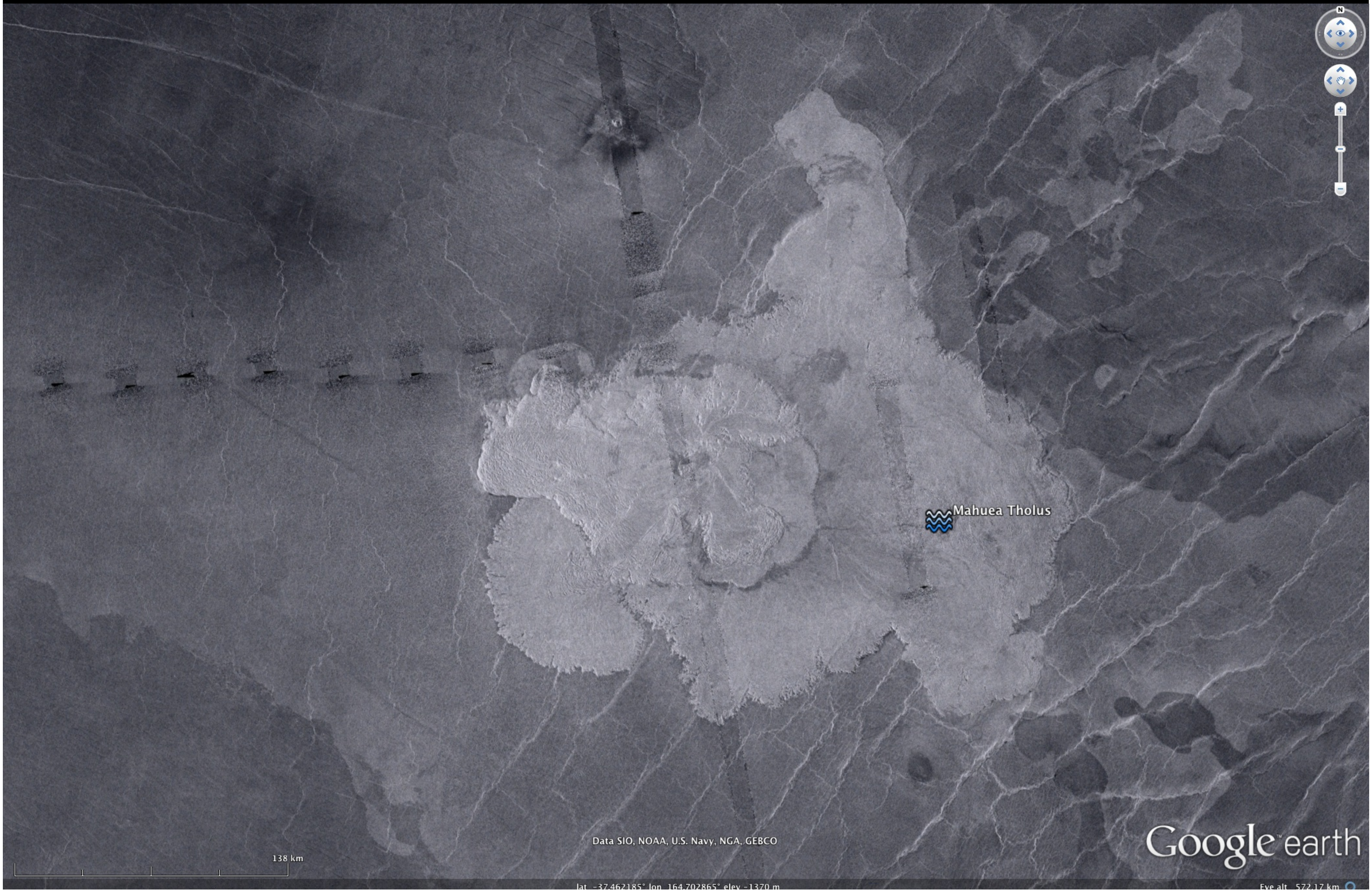
Google Venus



Google Venus

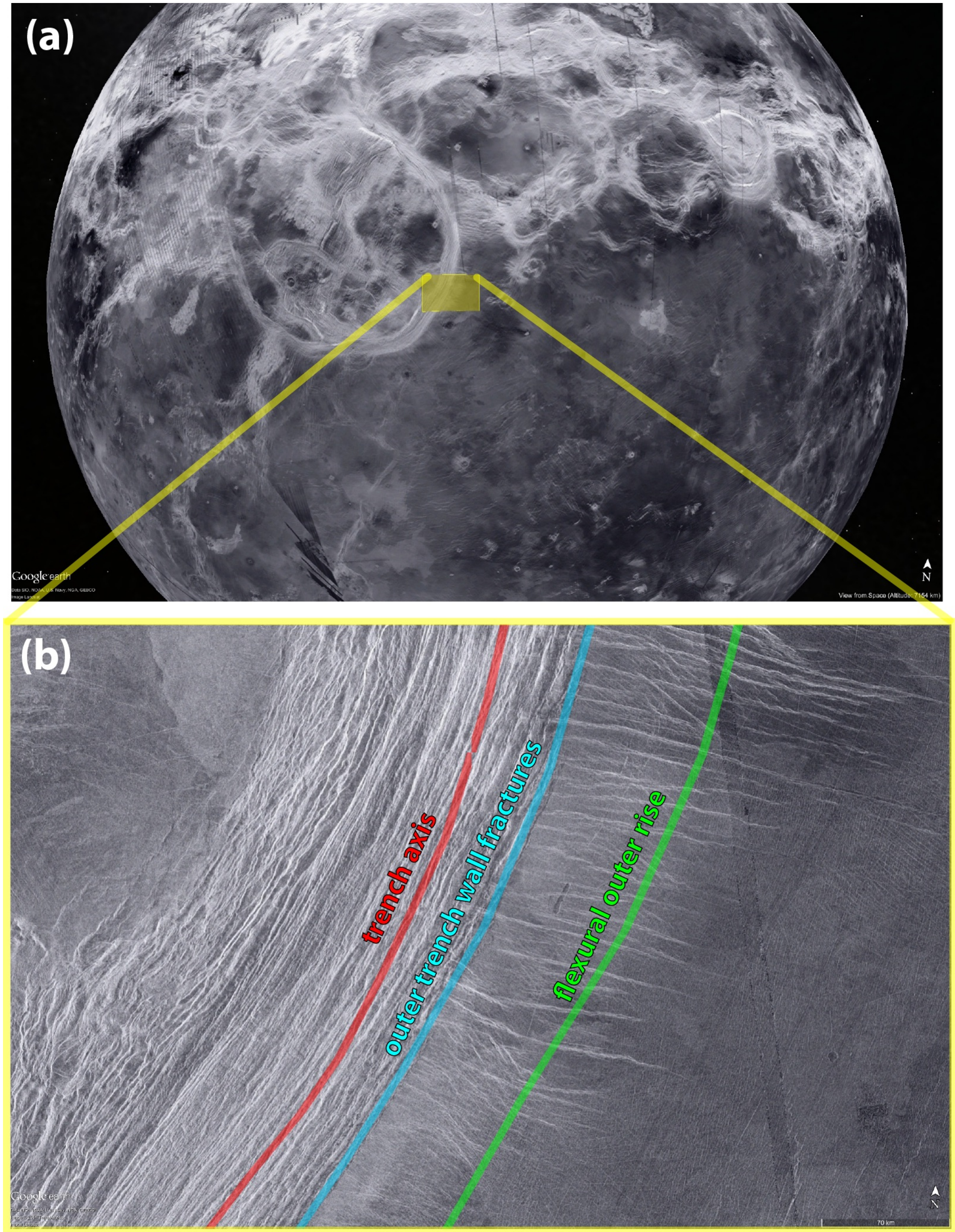


Google Venus

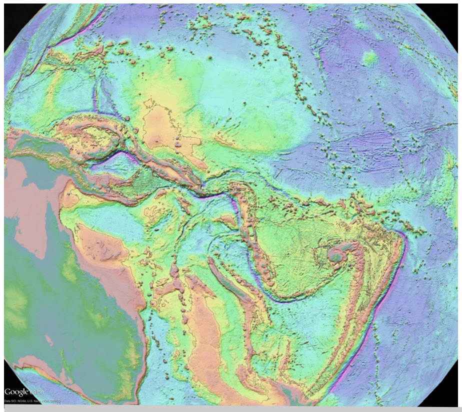


The Face of Venus
by
Roth and Wall in
Google Venus

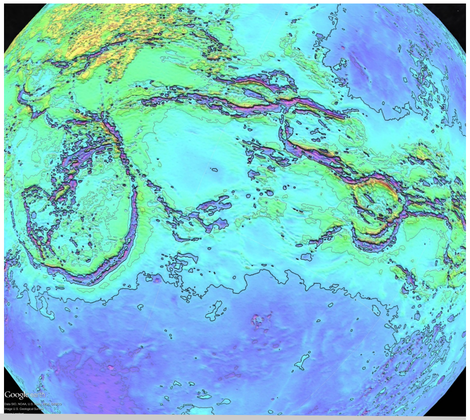
Google Venus



(a)
(b)
trench axis
outer trench wall fractures
flexural outer rise



What additional information is needed to confirm or reject the subduction hypothesis?



Crustal thickness at in plains – buoyancy estimate

Seismology for possible Venus quakes – active plate boundaries?

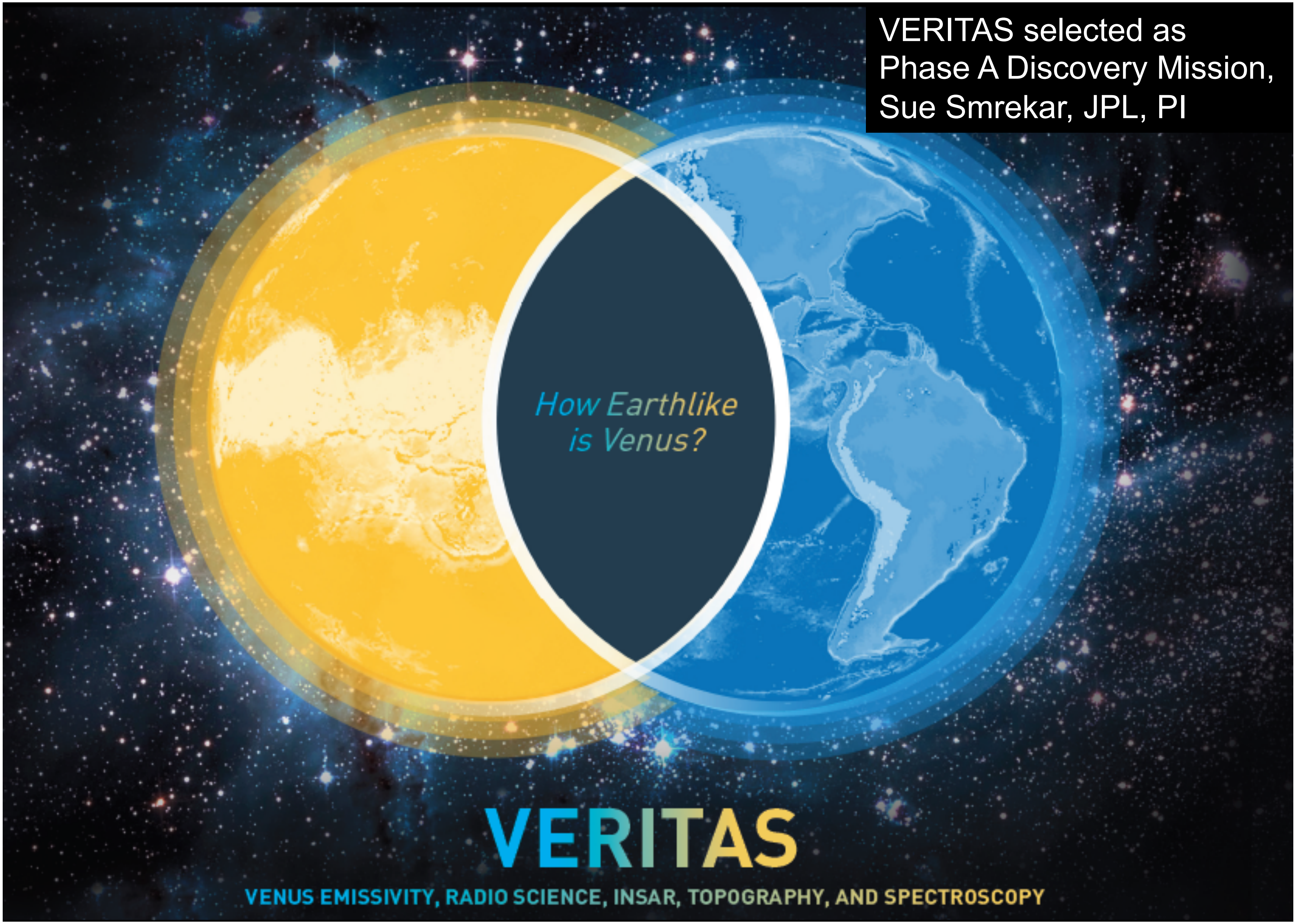
InSAR or GPS for crustal deformation – active today?

High resolution topography – trench depth and outer rise fractures.

Gravity at < 200 km resolution – resolve flexurally-compensated features

InSAR correlation – map active volcanic flows

Need a new mission(s) to Venus

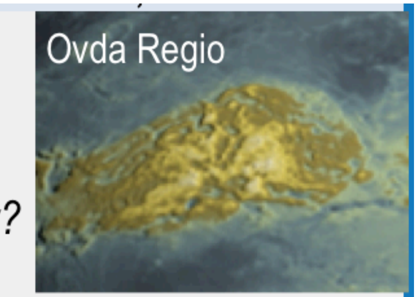

VERITAS selected as Phase A Discovery Mission, Sue Smrekar, JPL, PI
How Earthlike is Venus?
VERITAS
VENUS EMISSIVITY, RADIO SCIENCE, INSAR, TOPOGRAPHY, AND SPECTROSCOPY

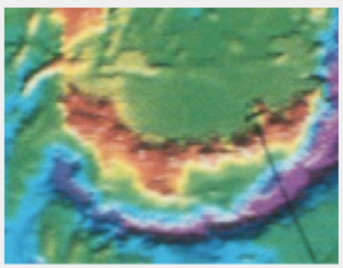
How Earthlike *is* Venus?

VERITAS will answer this fundamental question by revealing Venus' geologic history, determining how active it is today, and searching for the fingerprints of past and present water.

Earth's continents, formed when basalt melted in the presence of water, hold the record of several billion years of tectonic evolution.

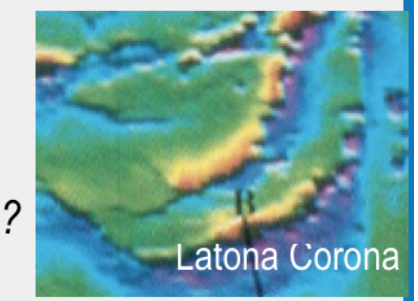
Did Venus' large plateaus form the same way?





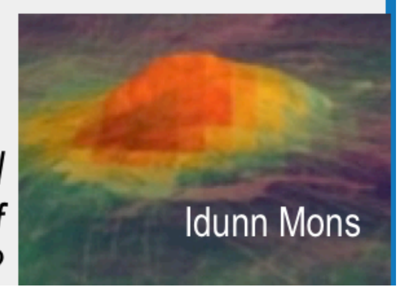
Earth's defining geologic feature, plate tectonics, may contribute to its habitability. Subduction is necessary to initiate plate tectonics.

Does subduction occur on Venus?



Volcanism shapes atmospheric composition and provides a window into interior processes.

Is Venus volcanically active? Is water still outgassing? Does this imply the presence of significant subsurface water?



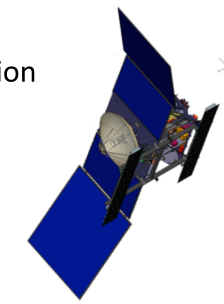
This is essential in predicting whether Earth-sized planets in habitable zones are more likely to resemble Earth or Venus.

The VERITAS Payload Suite

VISAR

(Venus Interferometric Synthetic Aperture RADAR)

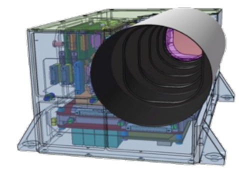
- Science Investigation:
  - Global tectonic and volcanic processes
  - Stratigraphy, relative age & current geologic activity
- Science Measurements:
  - Global DEM, at 250m hor, 5m vert resolution
  - Global SAR Imaging, 30 m resolution
  - Targeted imaging at 15 m resolution
  - Repeat pass I/F for surface deformation
- Joint Development: JPL and ASI



VEM

(Venus Emissivity Mapper)

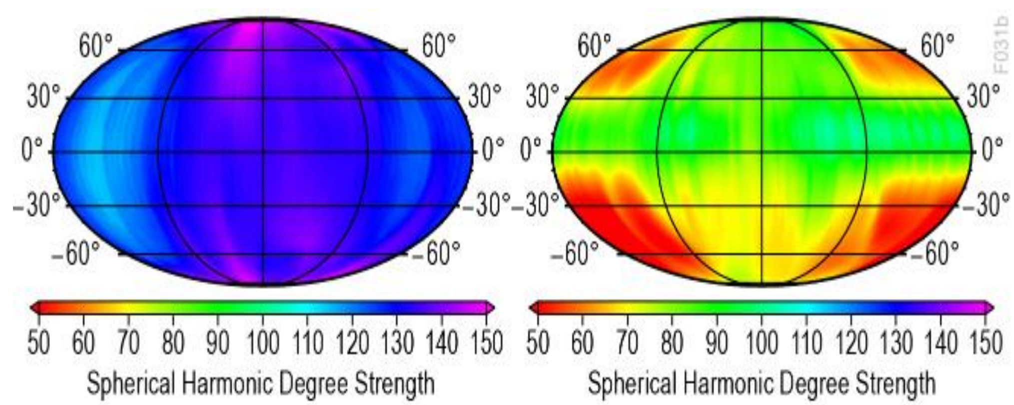
- Science Investigation:
  - Crustal composition and weathering processes
  - Detection of recent (or active) volcanism
- Science Measurements:
  - Global coverage of surface in 6 bands, SNR > 1000 and 8 atmospheric bands including calibration
- Provided by DLR
- PI: Joern Helbert

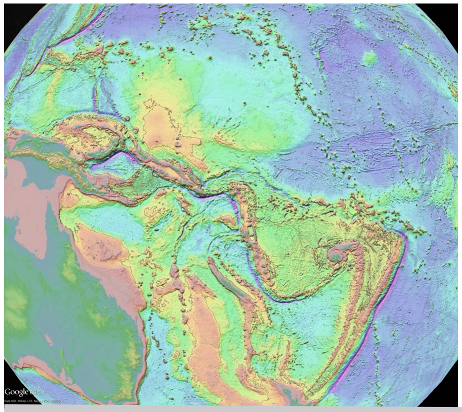


Gravity Science

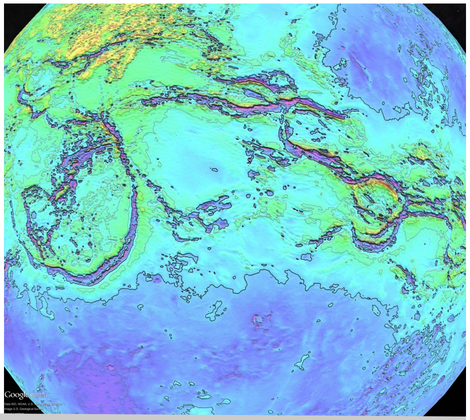
, (KaX-IDST)

- Science Investigation:
  - Lithospheric and crustal thickness and subsurface density variations
- Science Measurements:
  - Gravity field to d&o 140 (145 km), 3 mgal precision over lon 90-270 deg
  - Radio Science > 400 occultations
- Ka-band/X-band Integrated Deep Space





Conclusions



Venus has a thick lithosphere despite the high surface temperature.

Conduction is not an important heat loss mechanism.

Old lithosphere can be negatively buoyant if crustal thickness <~ 20 km.

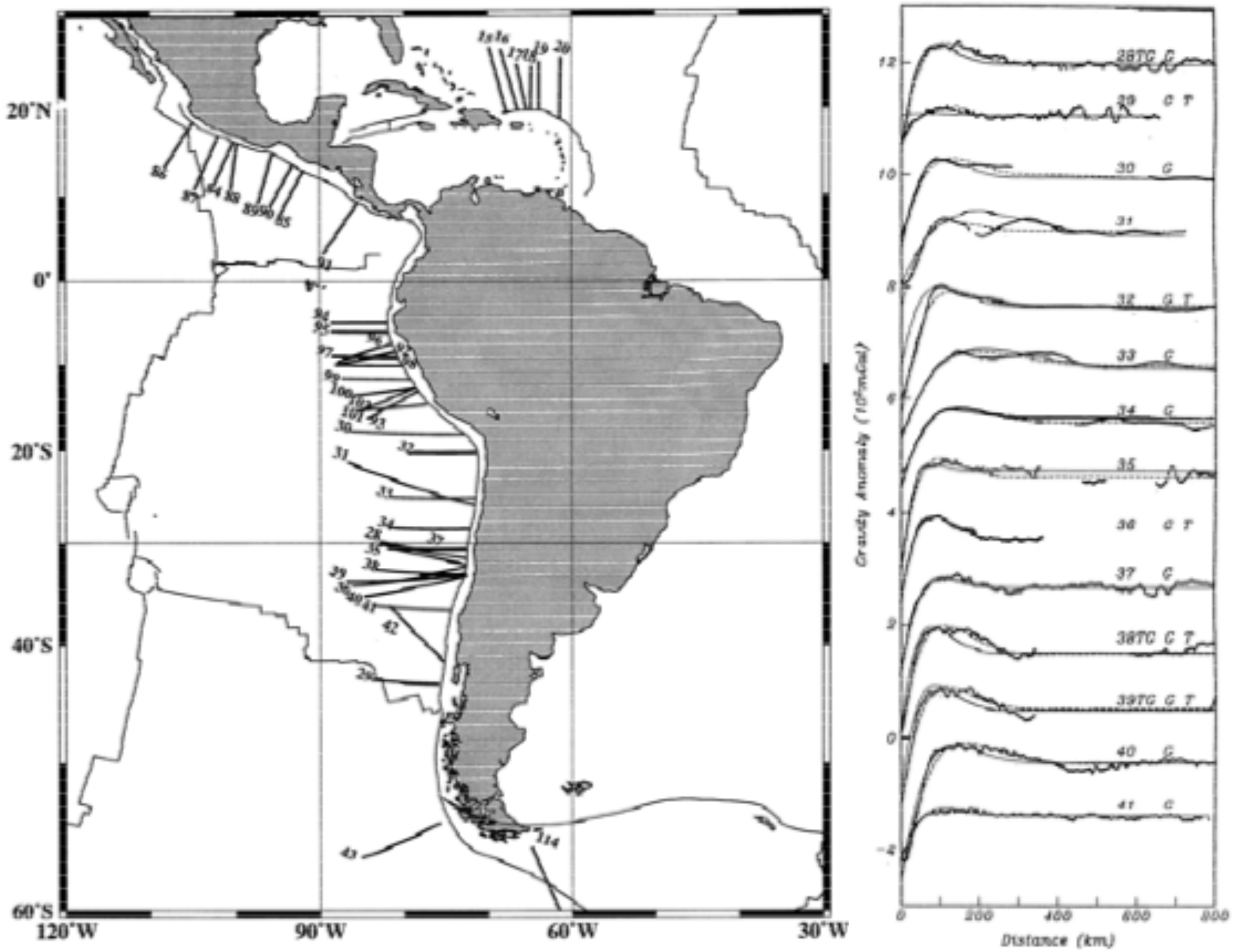
There are ~9000 km of trenches that have characteristics of subduction zones.

The near random distribution of impact craters is inconsistent with large area resurfacing from subduction or volcanism.

Episodic tectonics is a viable mechanism for keeping Venus cool but it is a largely untestable hypothesis.

VERITAS will measure global topography at 250 m horizontal resolution to better define trench depth and outer wall structure. Repeat-pass InSAR will map out areas of active volcanic flows. Gravity will confirm flexure.

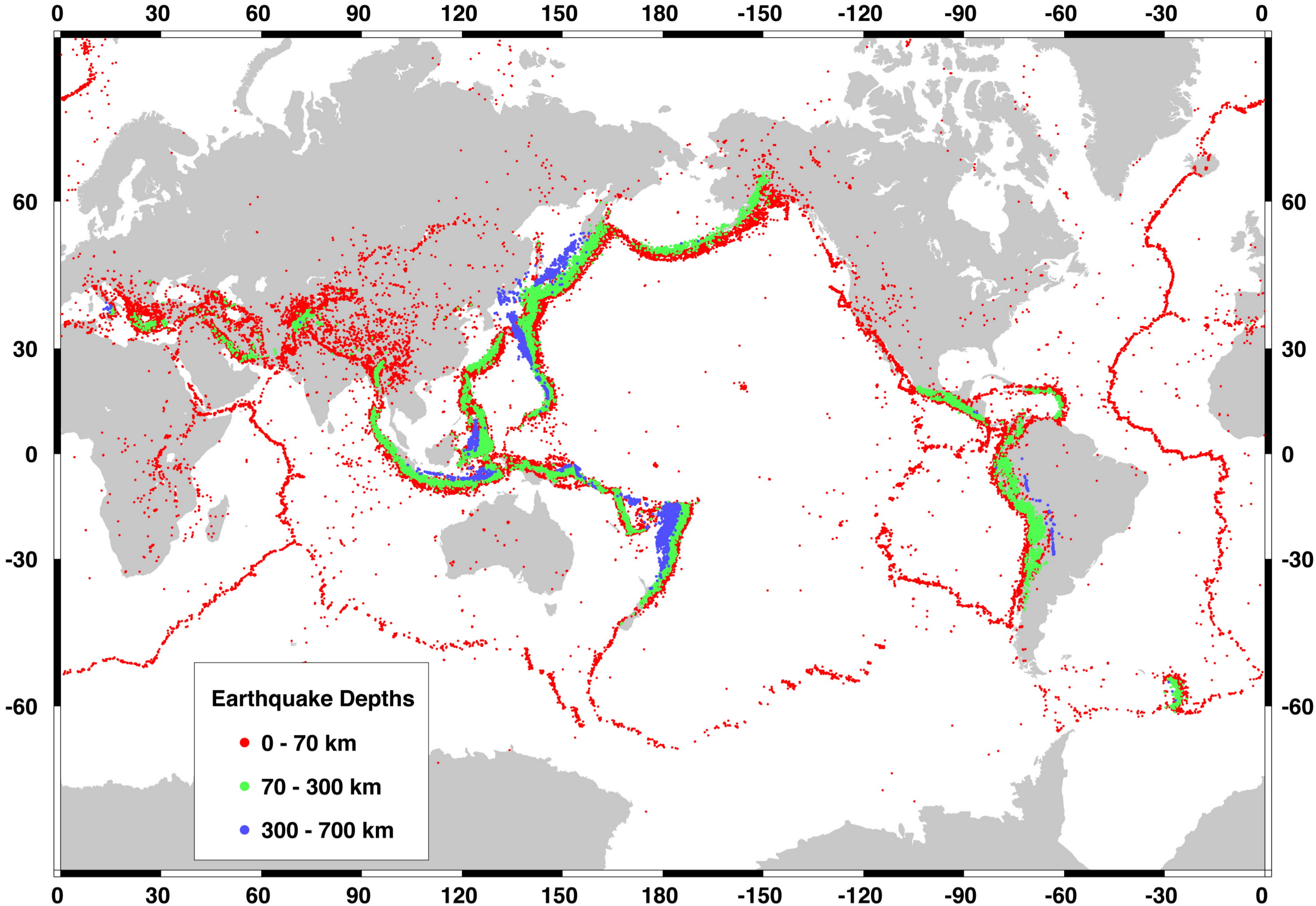
Observing Flexure in Marine Gravity Data



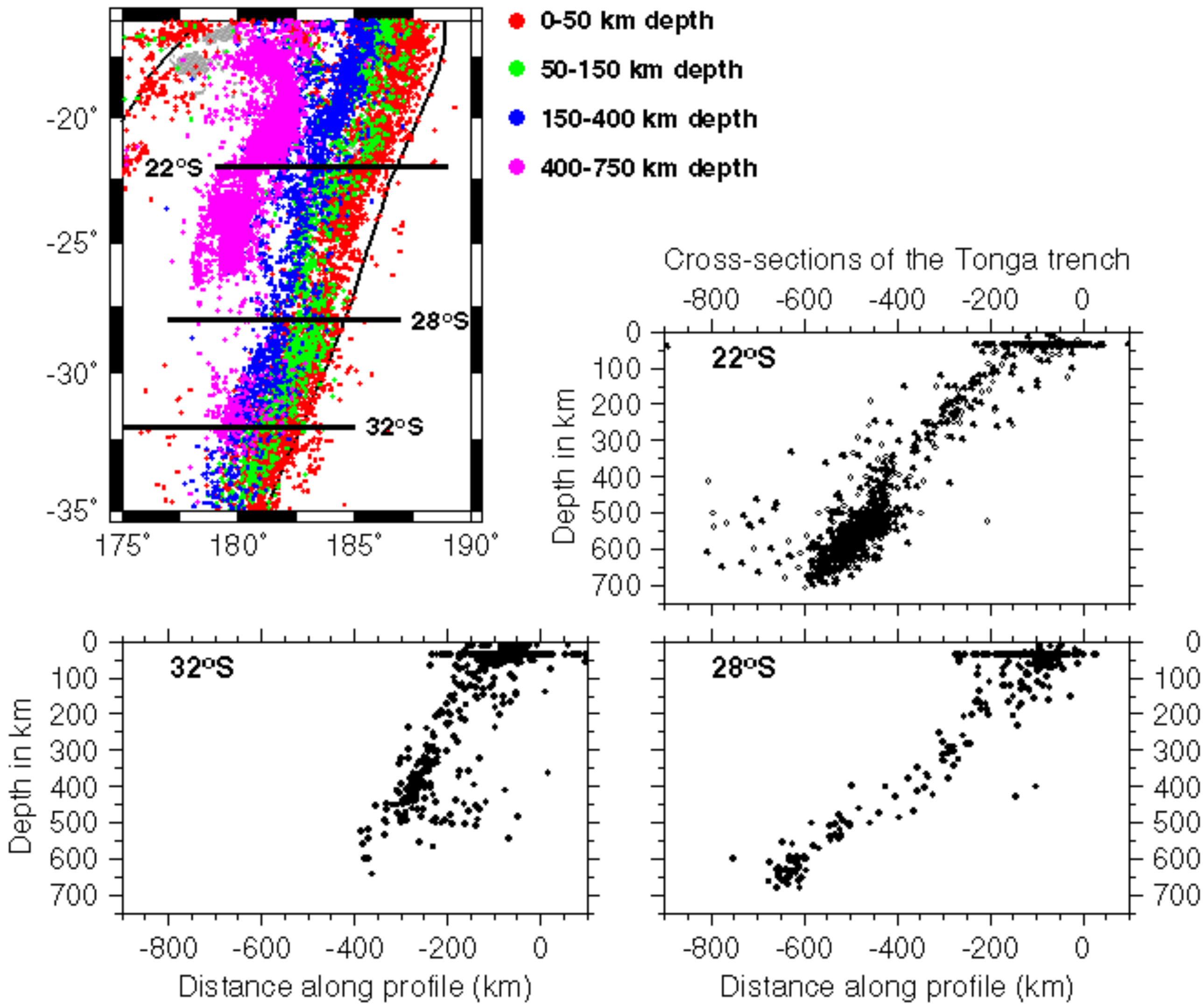
1-D Profiles of Gravity Data can be fit with thin elastic beam models

(*Levitt & Sandwell,* 1995)

global seismicity



Tonga Benioff zone



Kurile Subduction Zone

[Ammon, Kanamori & Lay *Nature* 2008)]

Why are there both thrust and normal fault mechanisms at a subduction zone?