The evolution of Venus, a global perspective — from exogenic to endogenic over time

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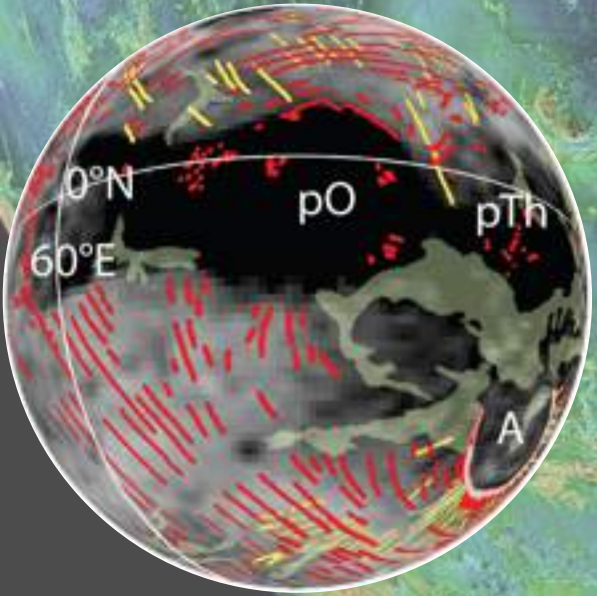
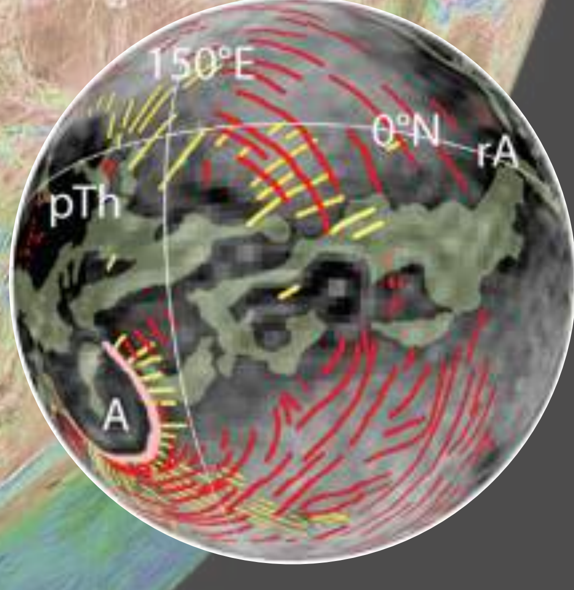
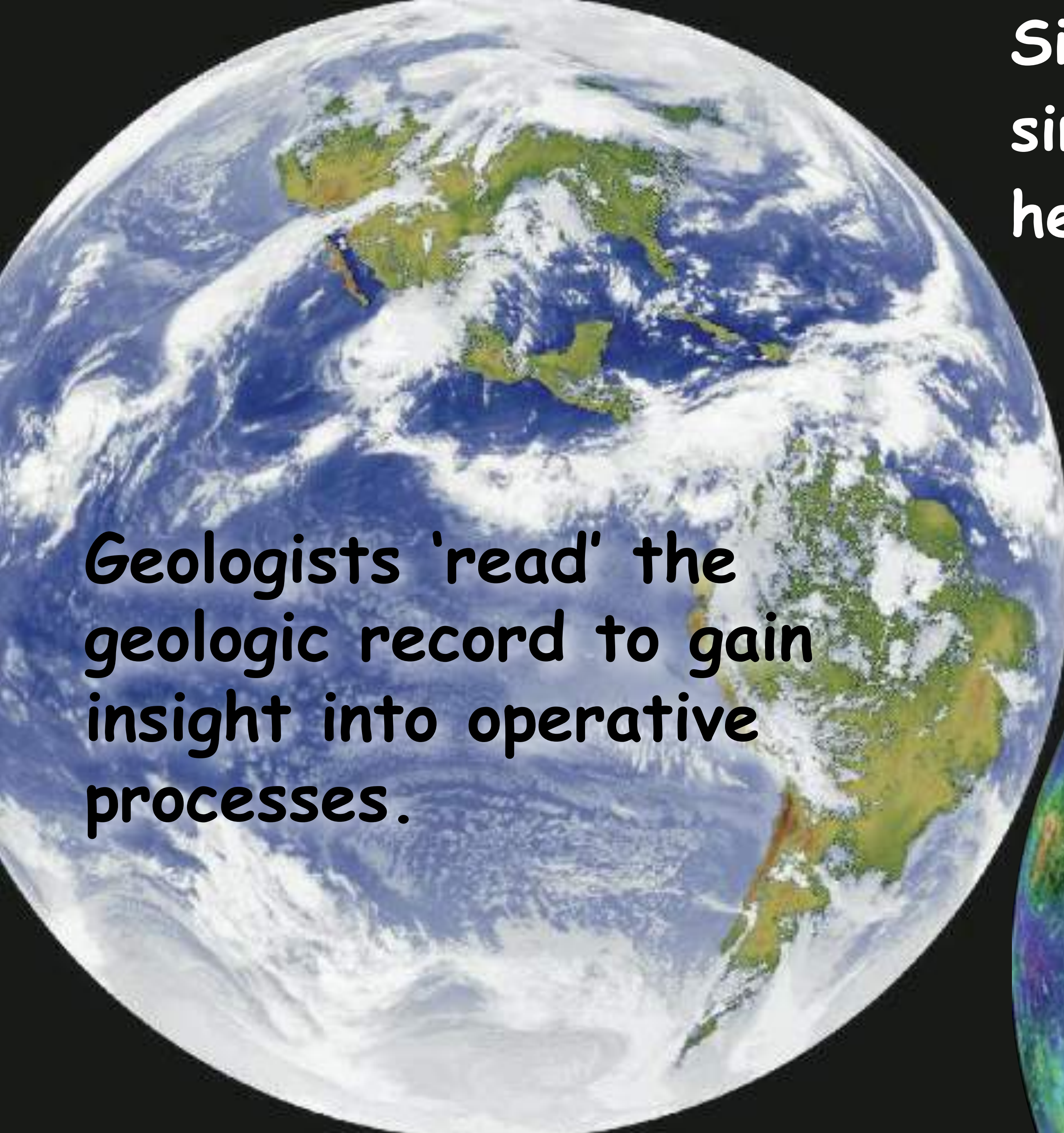


Thanks to: NASA PGG, NASA PGGURP, NASA PDAP, McKnight Foundation, and U.S. citizens and taxpayers!



Sister planets:
similar: size, density, composition, heat budget, solar location...



Geologists 'read' the geologic record to gain insight into operative processes.

What is the geologic history, and hence evolution of Venus, that we can glean from study of the surface geology?

Similar (but not the same) at birth—
How different (or similar) have their evolutionary paths been?
Clues for Venus from Earth?
Clues about early Earth from Venus?

VENUS DATA:

NASA global Magellan mapping Mission (1989-1994)

- *SAR (Synthetic Aperture Radar)
- *Altimetry (topography)
- *Gravity
  - [*Emissivity]

THE SETTING:

T ~475 °C; 750 K; ~900 °F

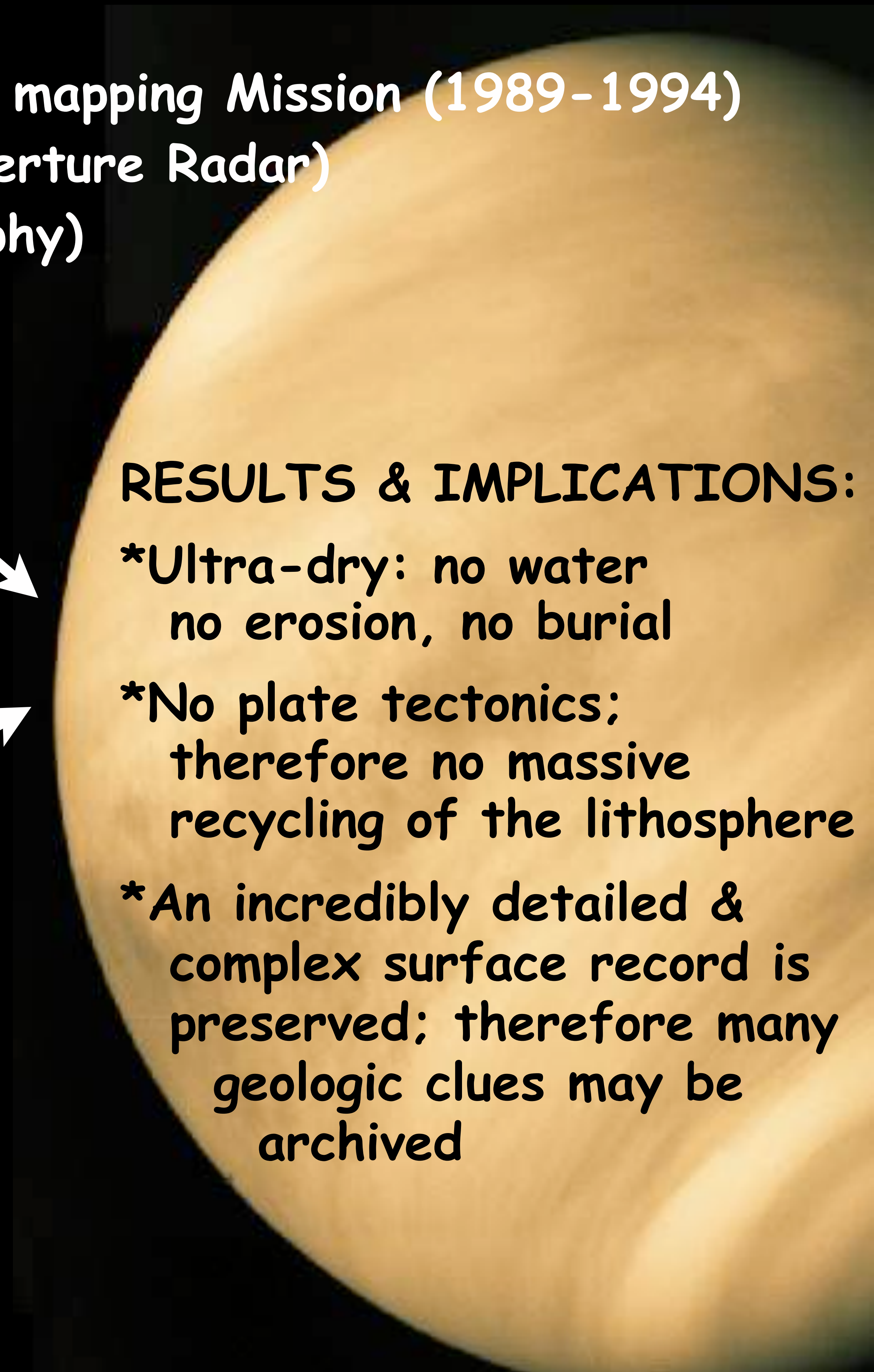
P ~100 bars (similar to Early Earth?)

Dry!

Atm: 96.5% CO_2; 3.5% N_2, H_2O, SO_2, Ar, CO, Ne, HCl, HF

Atmosphere is supercritical CO_2

Surface: basalt



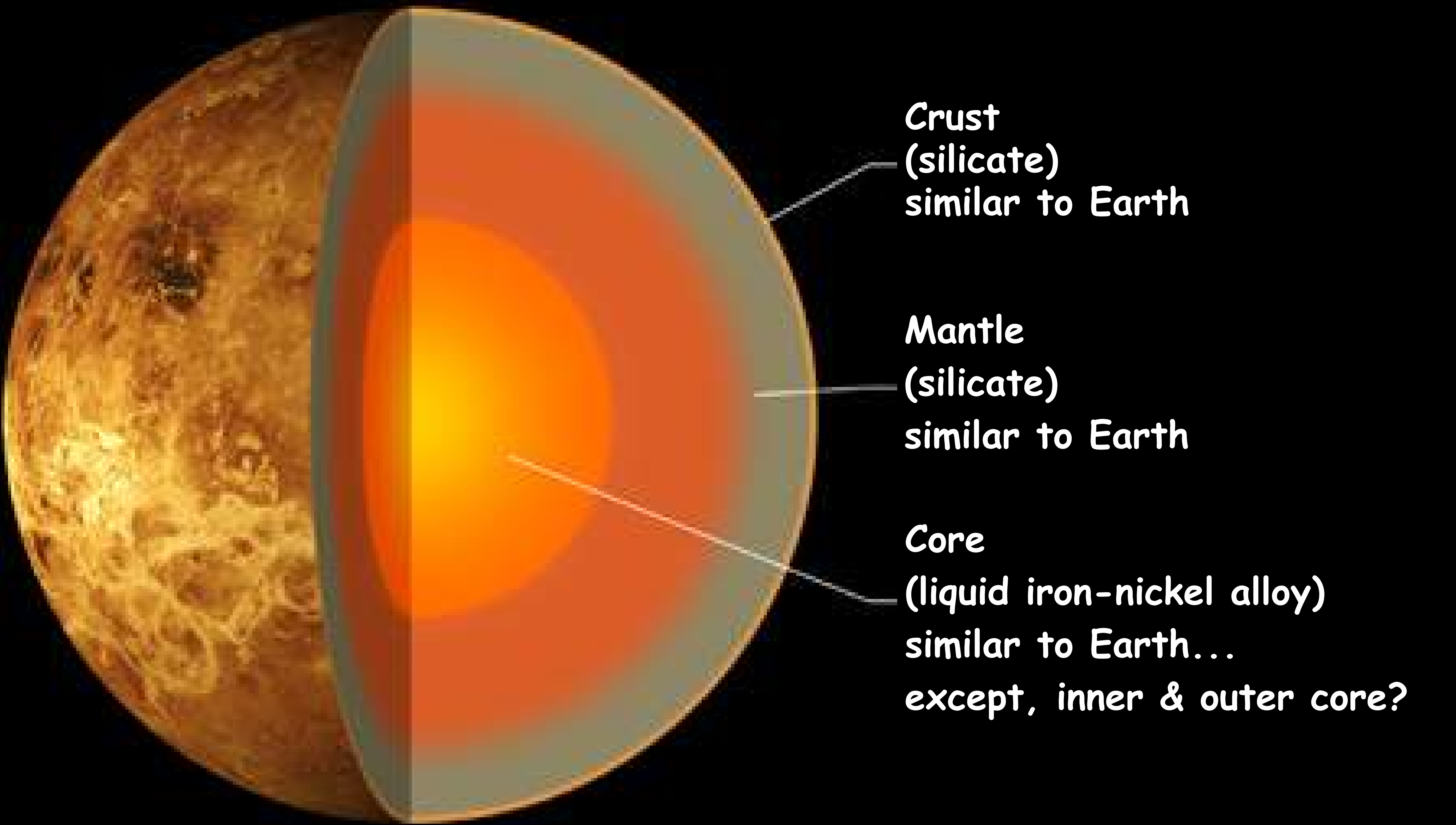
RESULTS & IMPLICATIONS:

*Ultra-dry: no water
no erosion, no burial

*No plate tectonics;
therefore no massive recycling of the lithosphere

*An incredibly detailed & complex surface record is preserved; therefore many geologic clues may be archived

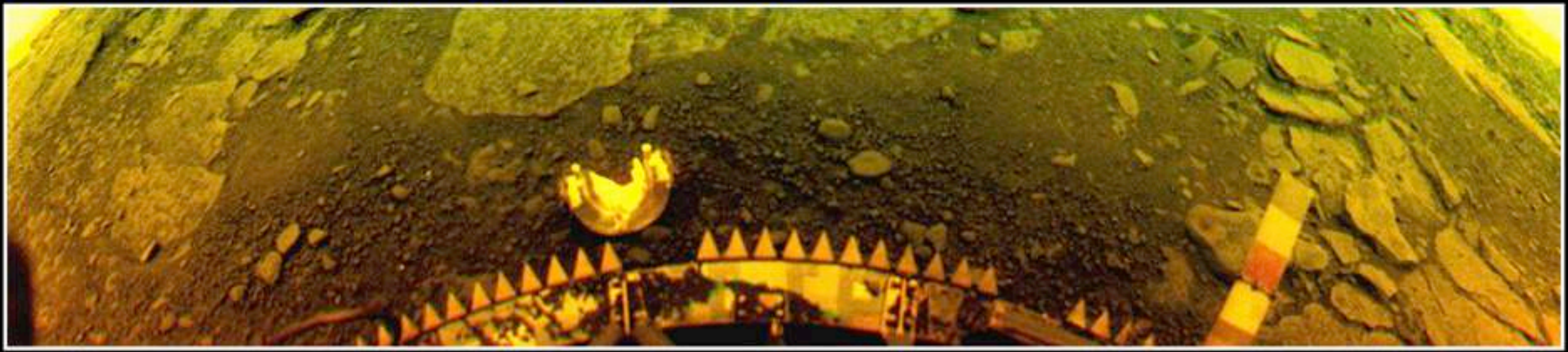
Venus below the skin—similar to Earth?



Venus, composition of the skin — similar to average Earth

Soviet Venera Mission landers returned pictures and bulk chemical analyses of the surface

Color as seen on the surface of Venus

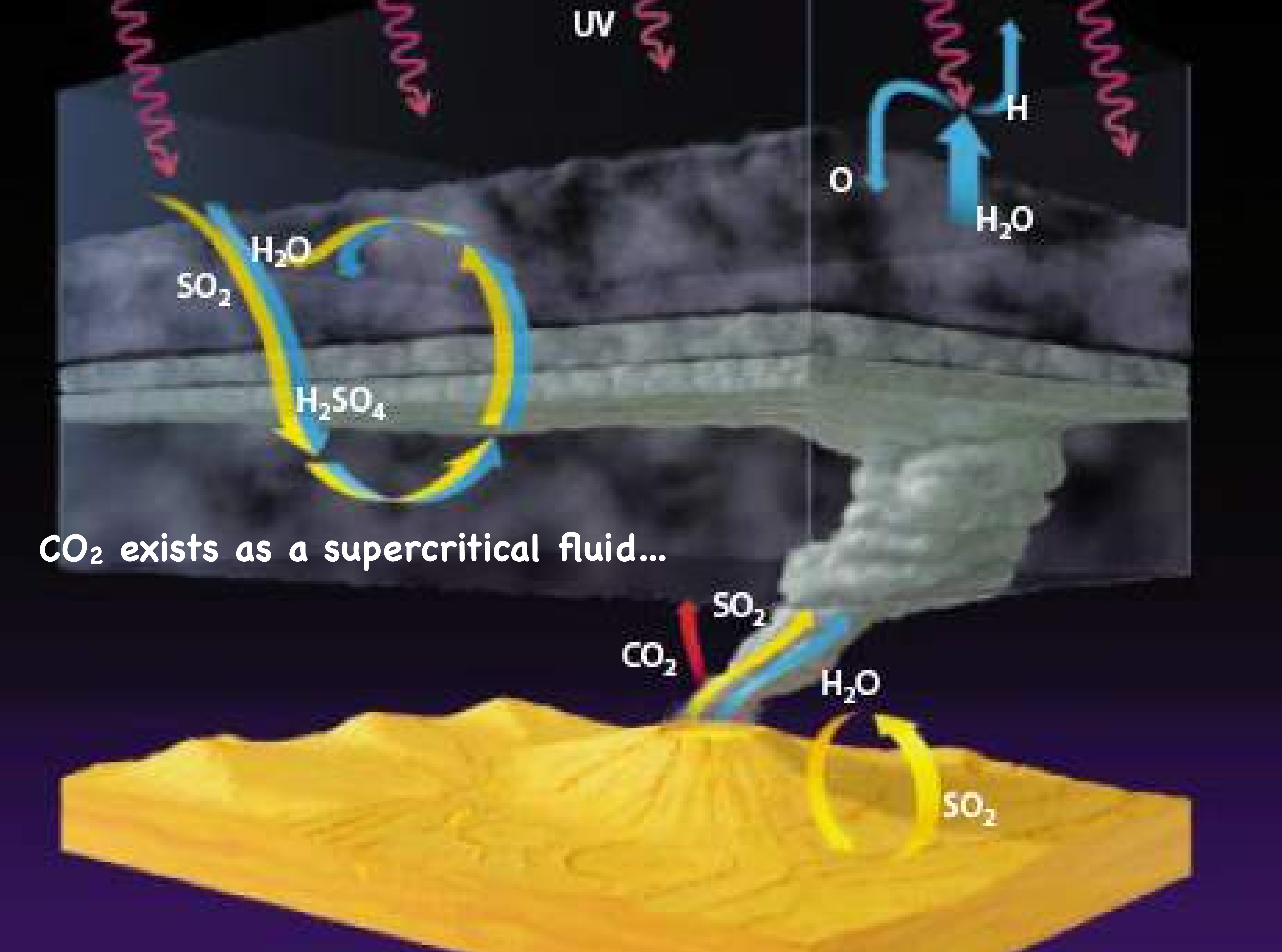


Color with atmospheric effects removed

VENERA 13

Venus' surface is interpreted as dominated by basalt — common on Earth

Above the skin—Venus' run away greenhouse effect



CO_2 exists as a supercritical fluid…

Combined Magellan SAR & altimetry data

Regional scale Geomorphic Features

Unique features:
Artemis
Ishtar Terra

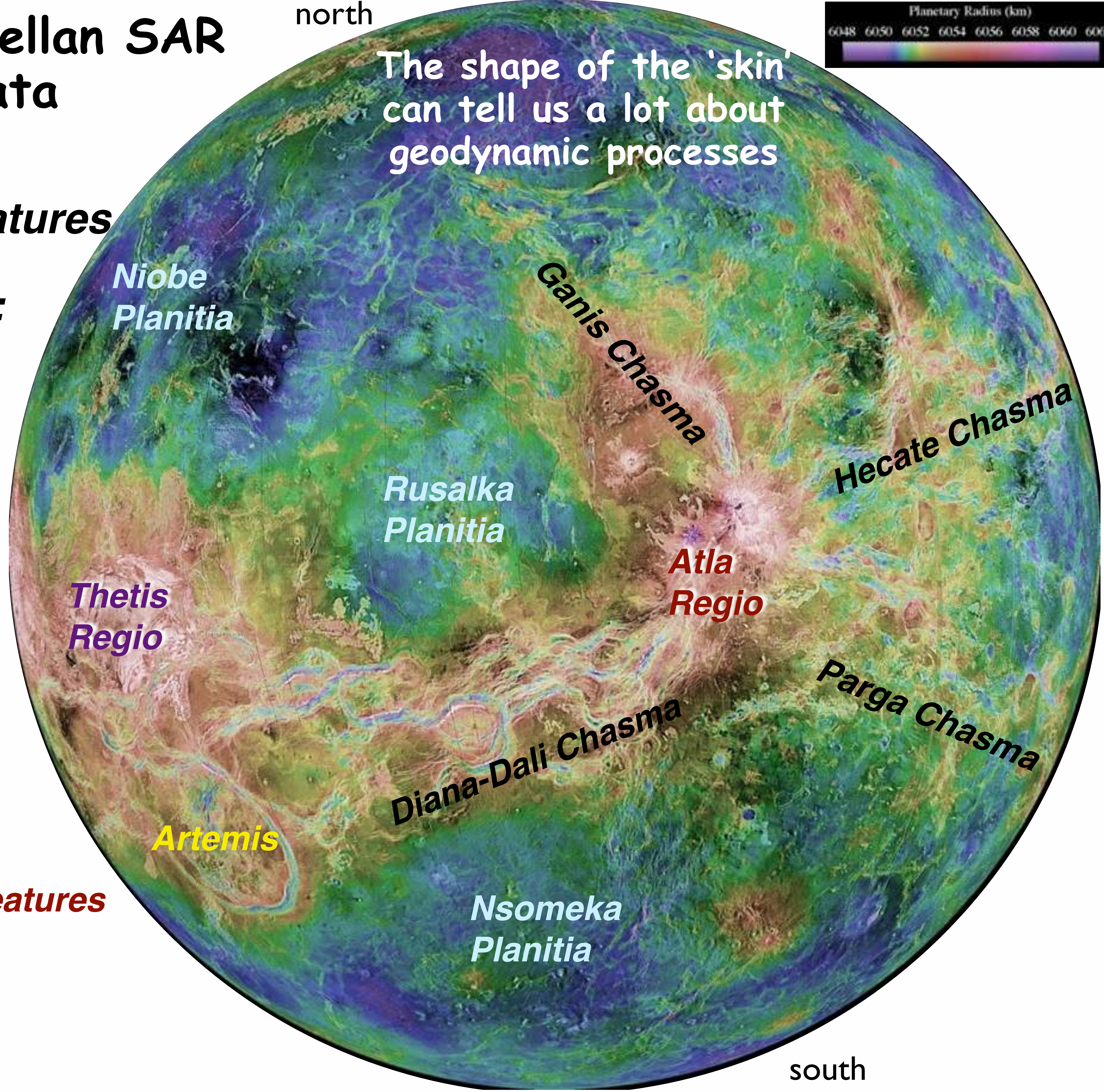
Lowlands
Planitia

Mesolands
Corona & Chasma chains

Highlands

Volcanic Rises
Contemporary features

Crustal Plateaus
Ancient features



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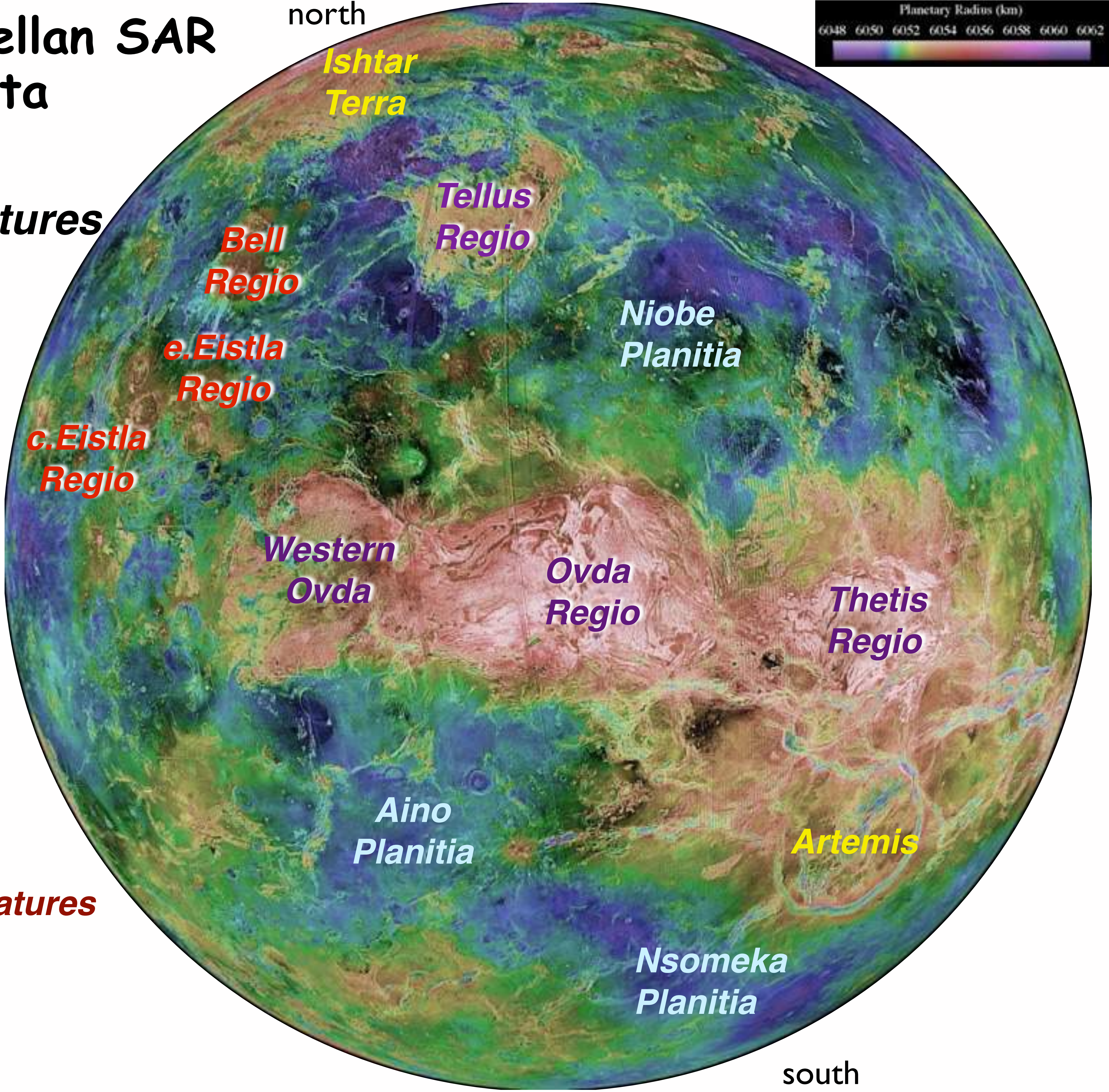


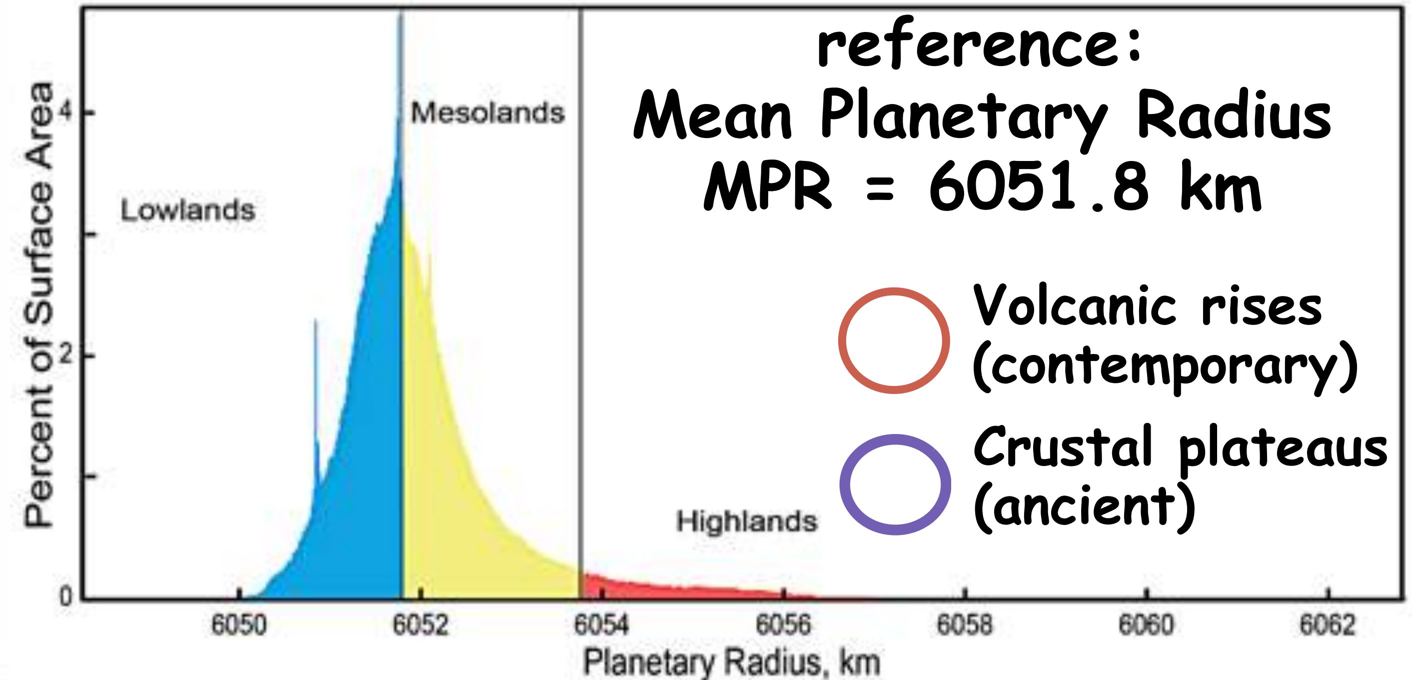
Focus here: Shape of the skin...

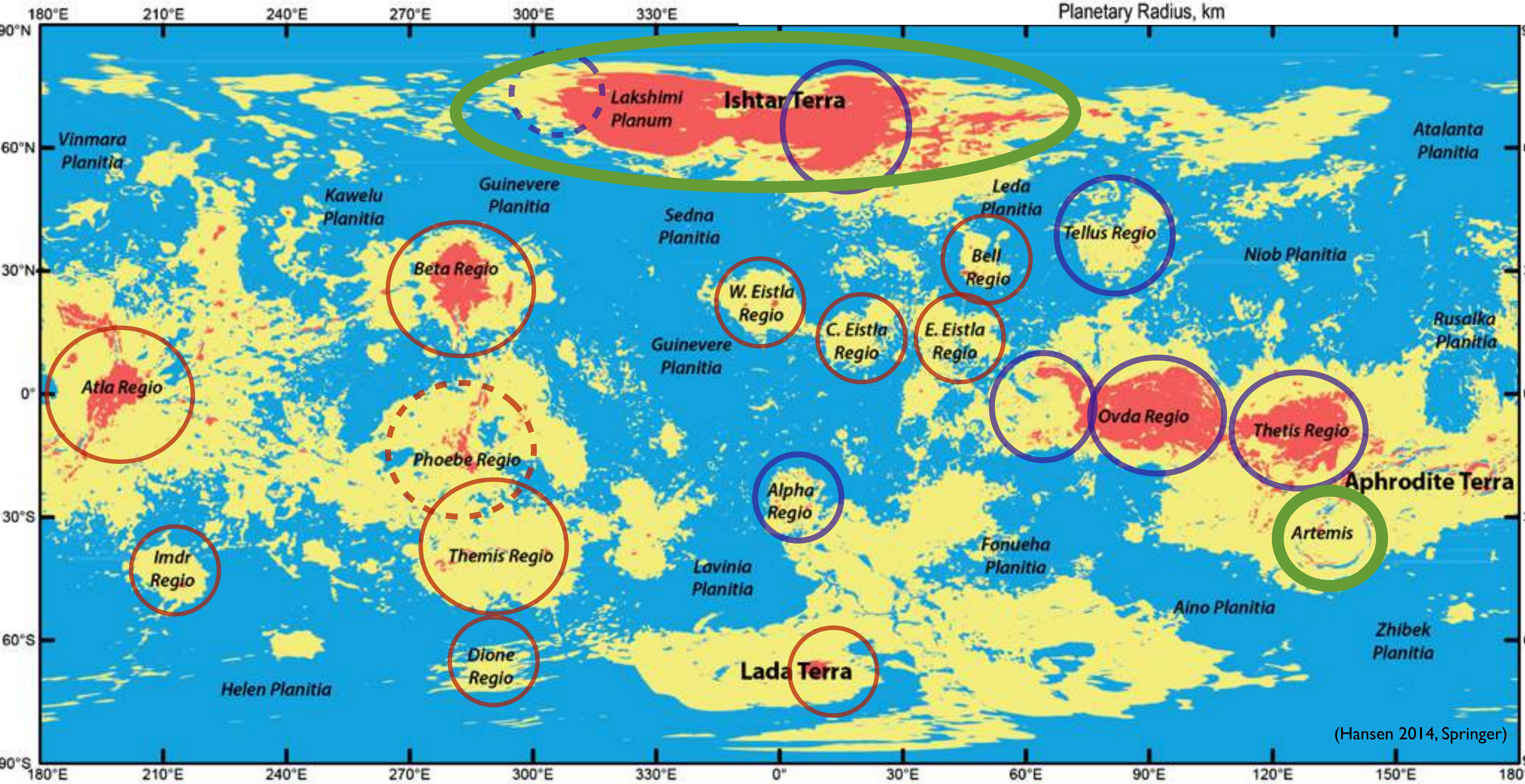
Unlike Earth....

Venus' topography is **unimodal**

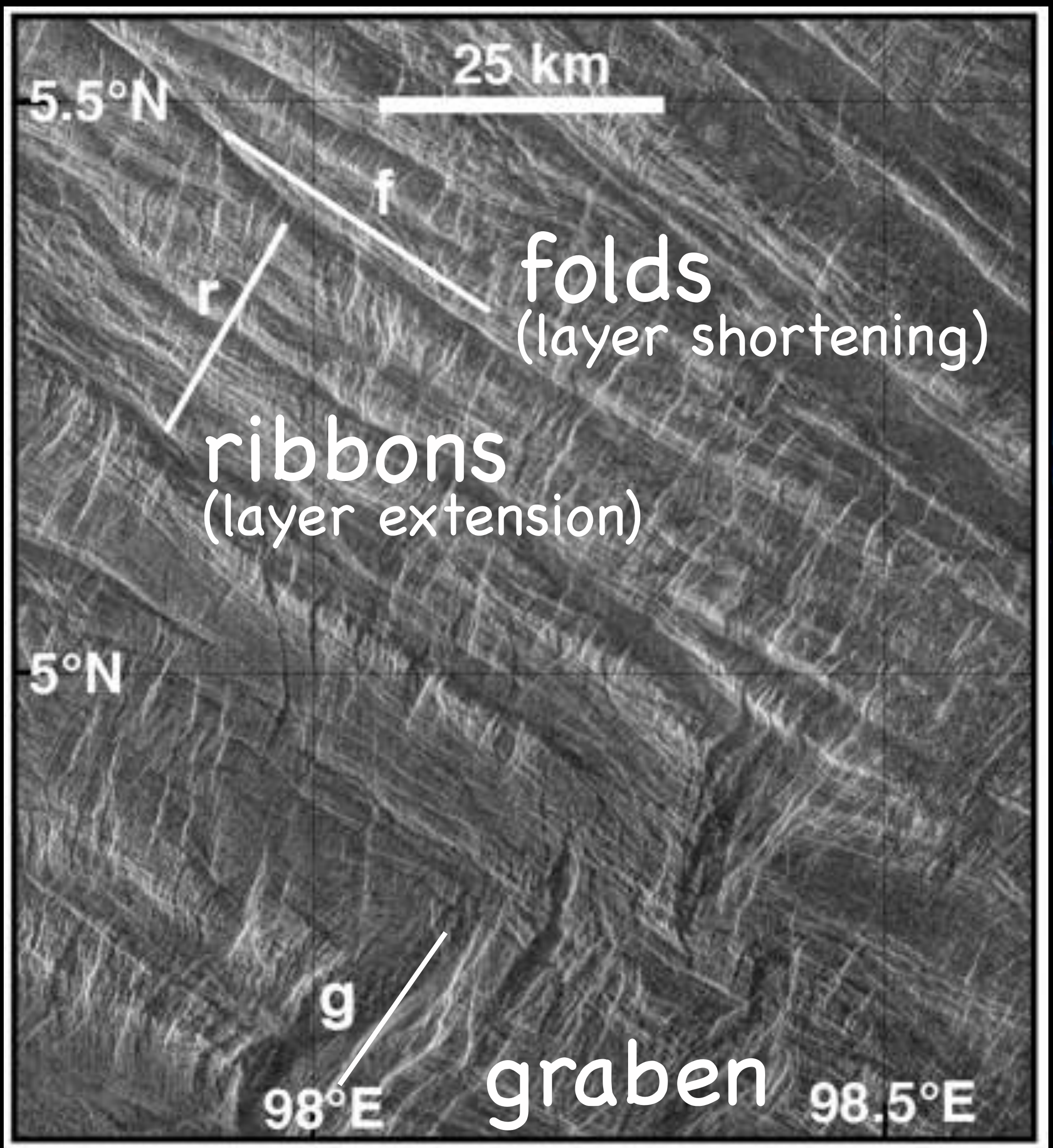
- Highlands
- Mesolands
- Lowlands

unique features: Ishtar Terra & Artemis



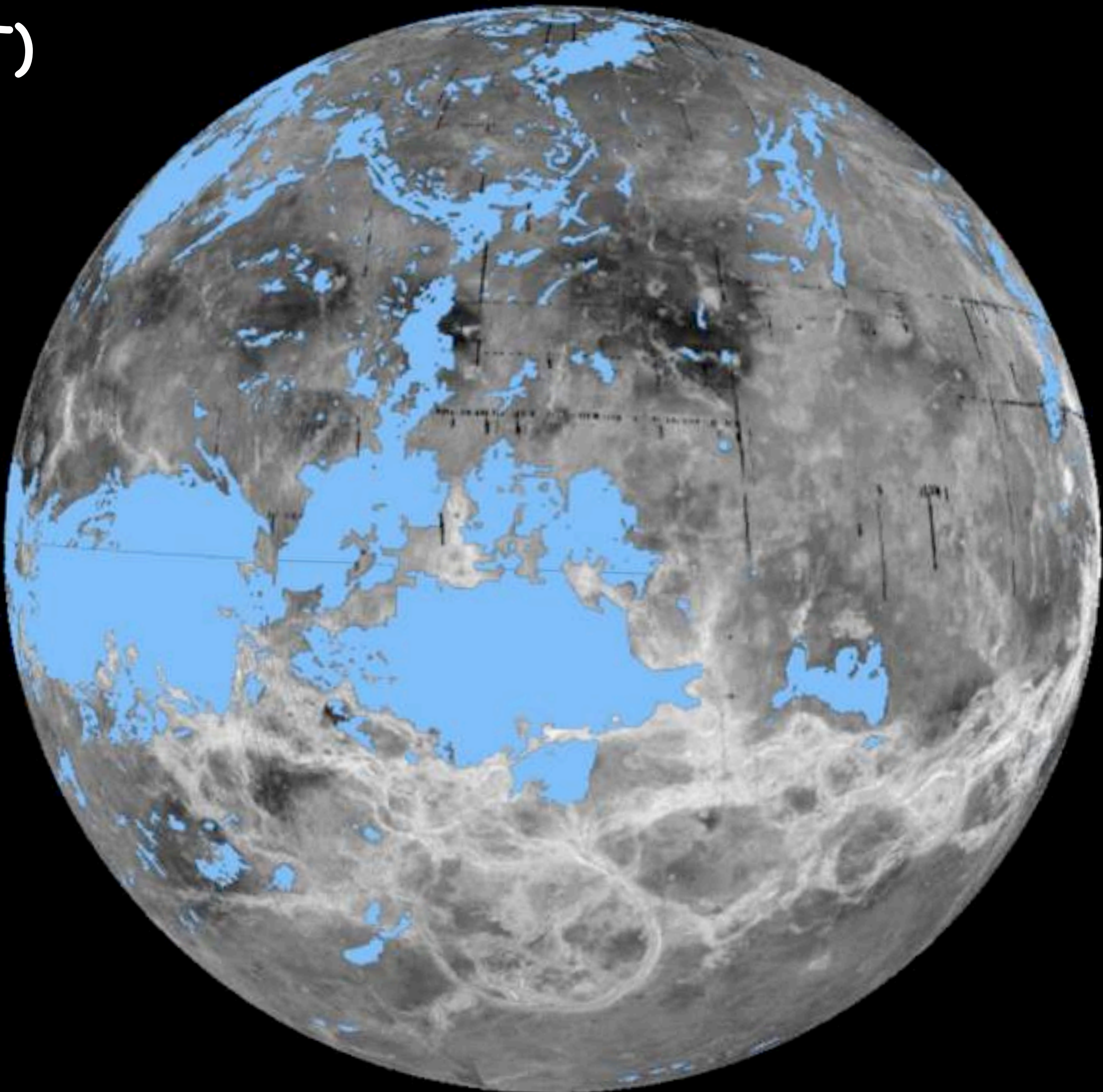


Ribbon tessera terrain (RTT) global distribution

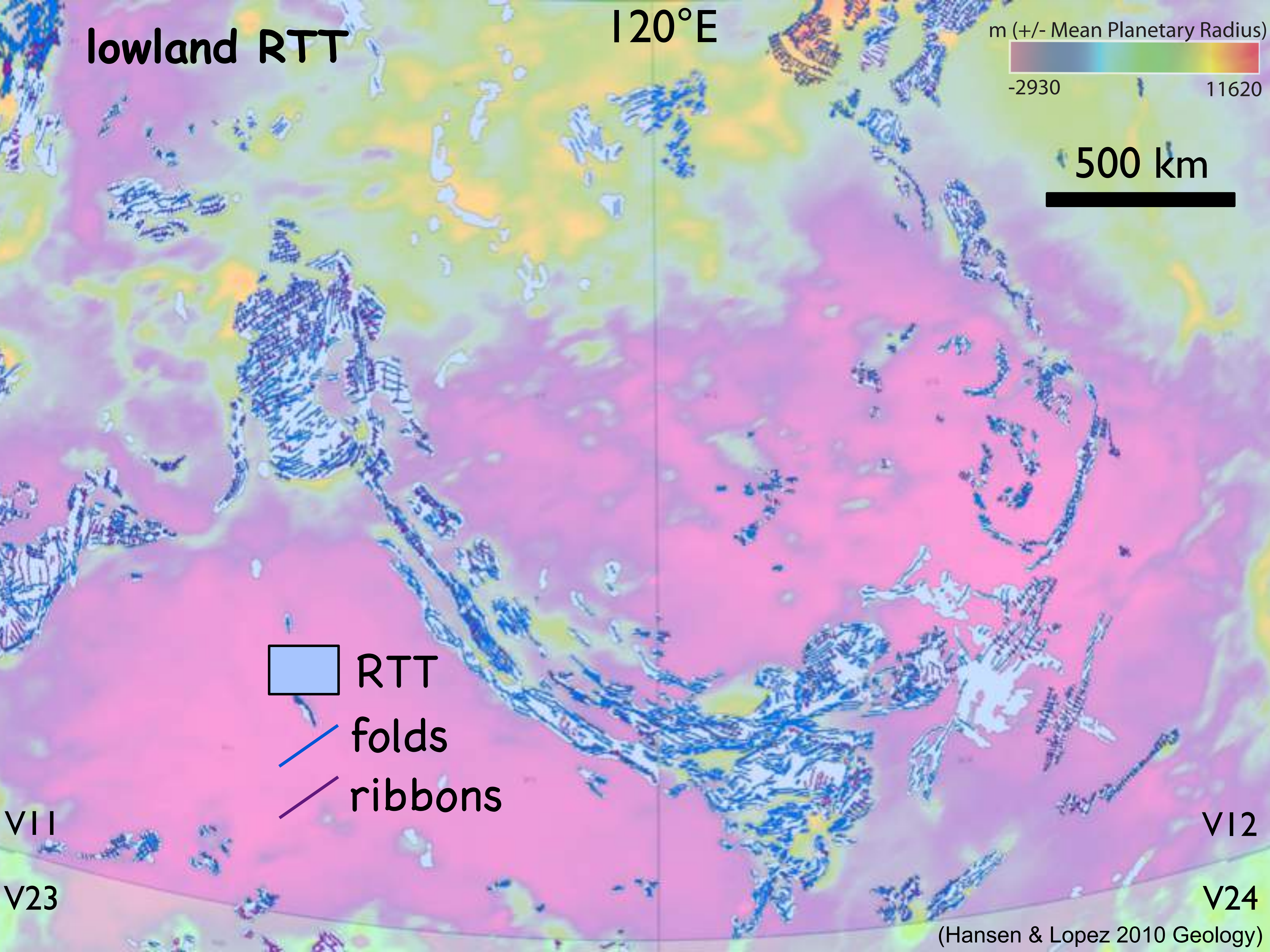


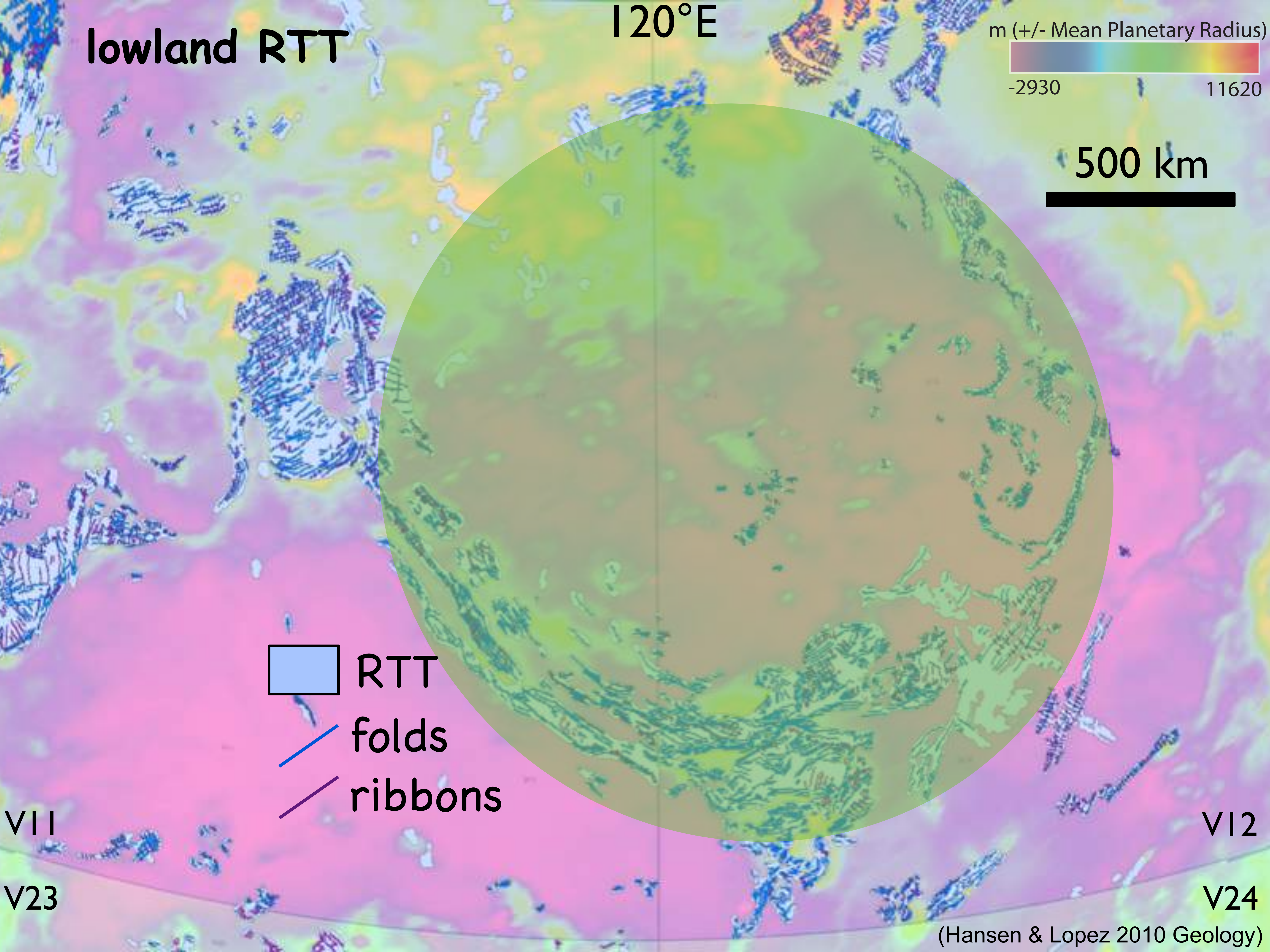
SAR image

(Phillips & Hansen 1998 Science)



RTT defines high-standing crustal plateaus
RTT occurs in tracts across the lowlands
RTT records processes of an ancient era


lowland RTT
120°E
m (+/- Mean Planetary Radius)
-2930
11620
500 km
RTT
folds
ribbons
V11
V12
V23
V24
(Hansen & Lopez 2010 Geology)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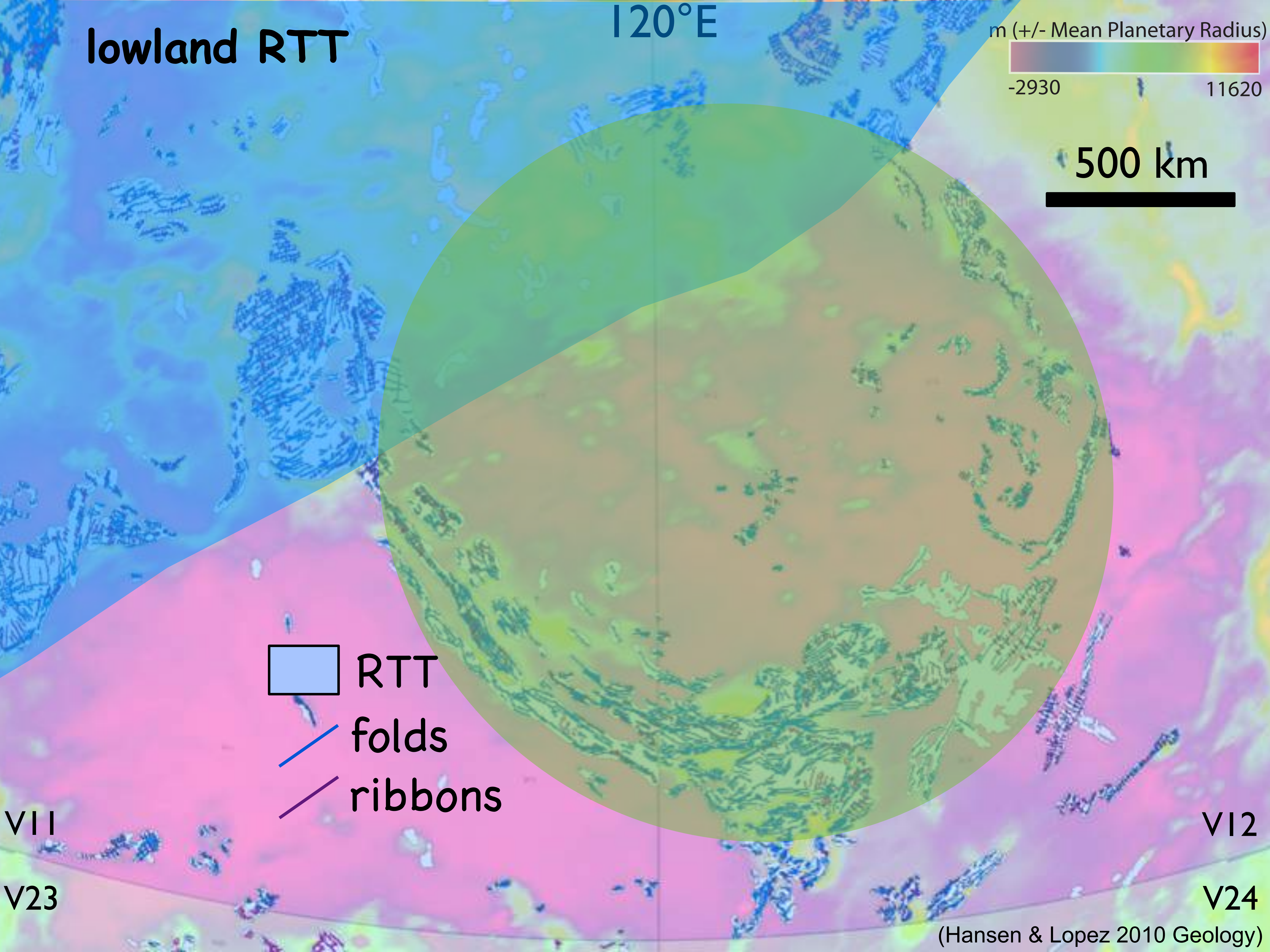
lowland RTT
120°E
m (+/- Mean Planetary Radius)
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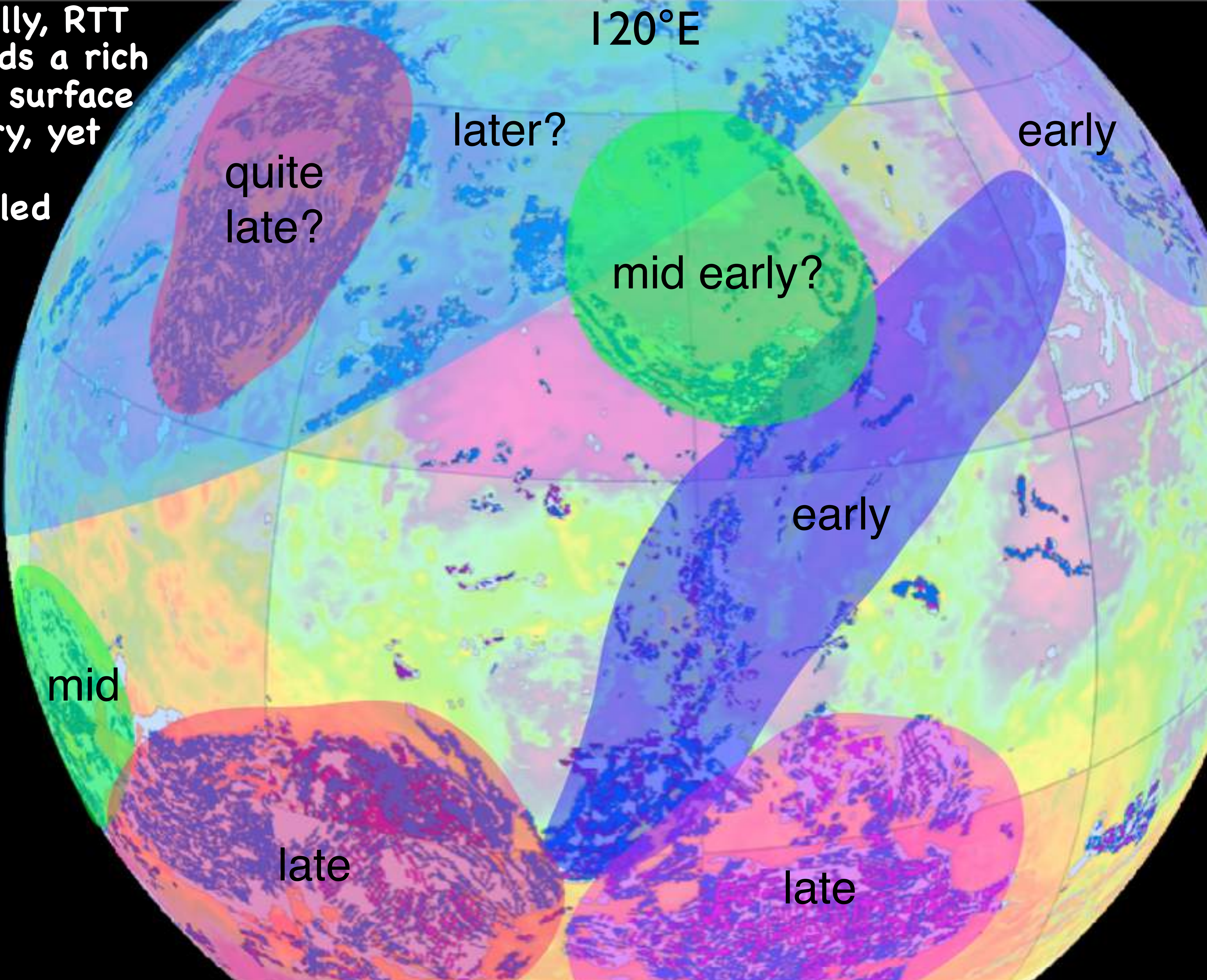
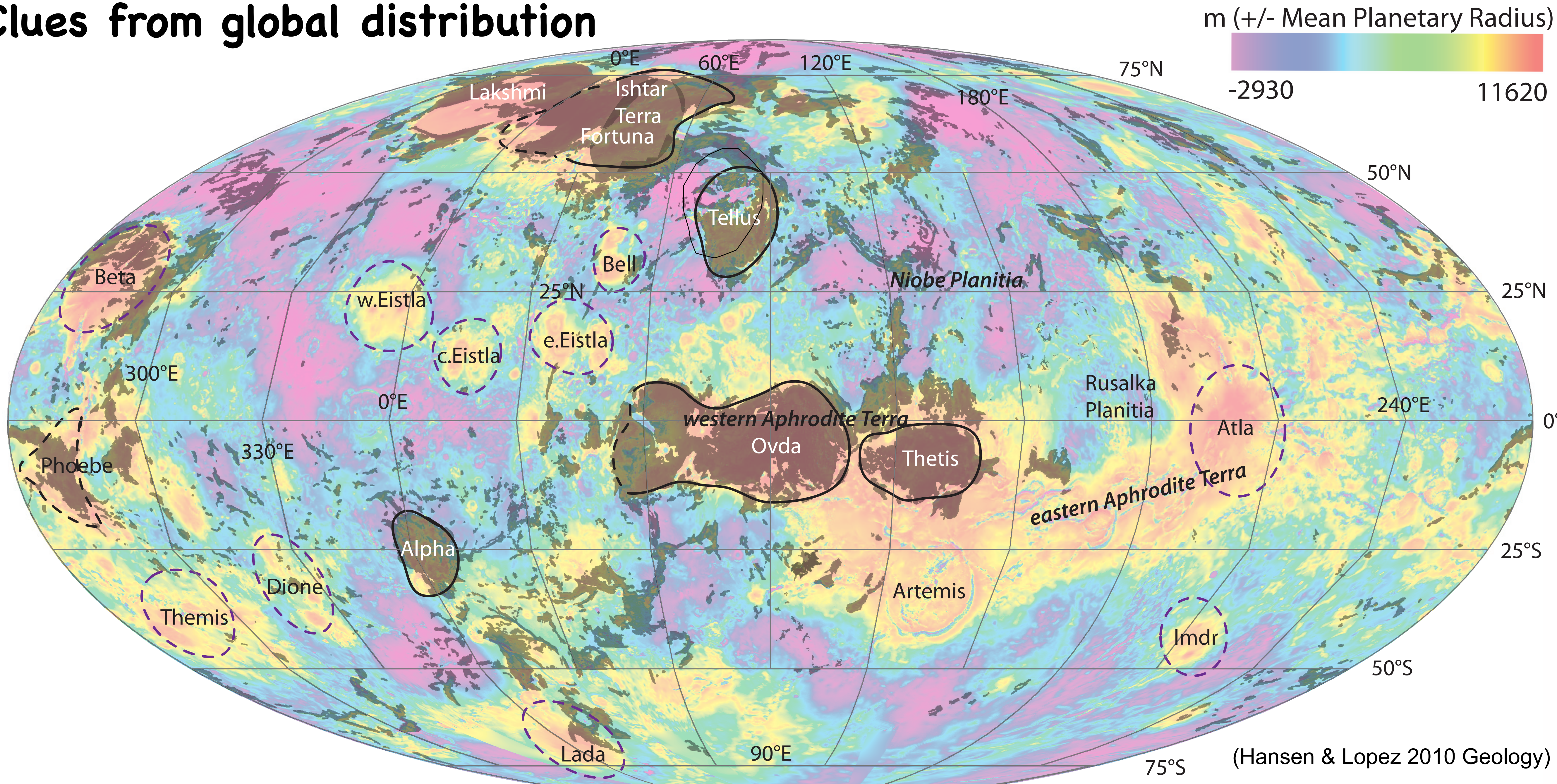
11620
500 km
RTT
folds
ribbons
V11
V12
V23
V24
(Hansen & Lopez 2010 Geology)

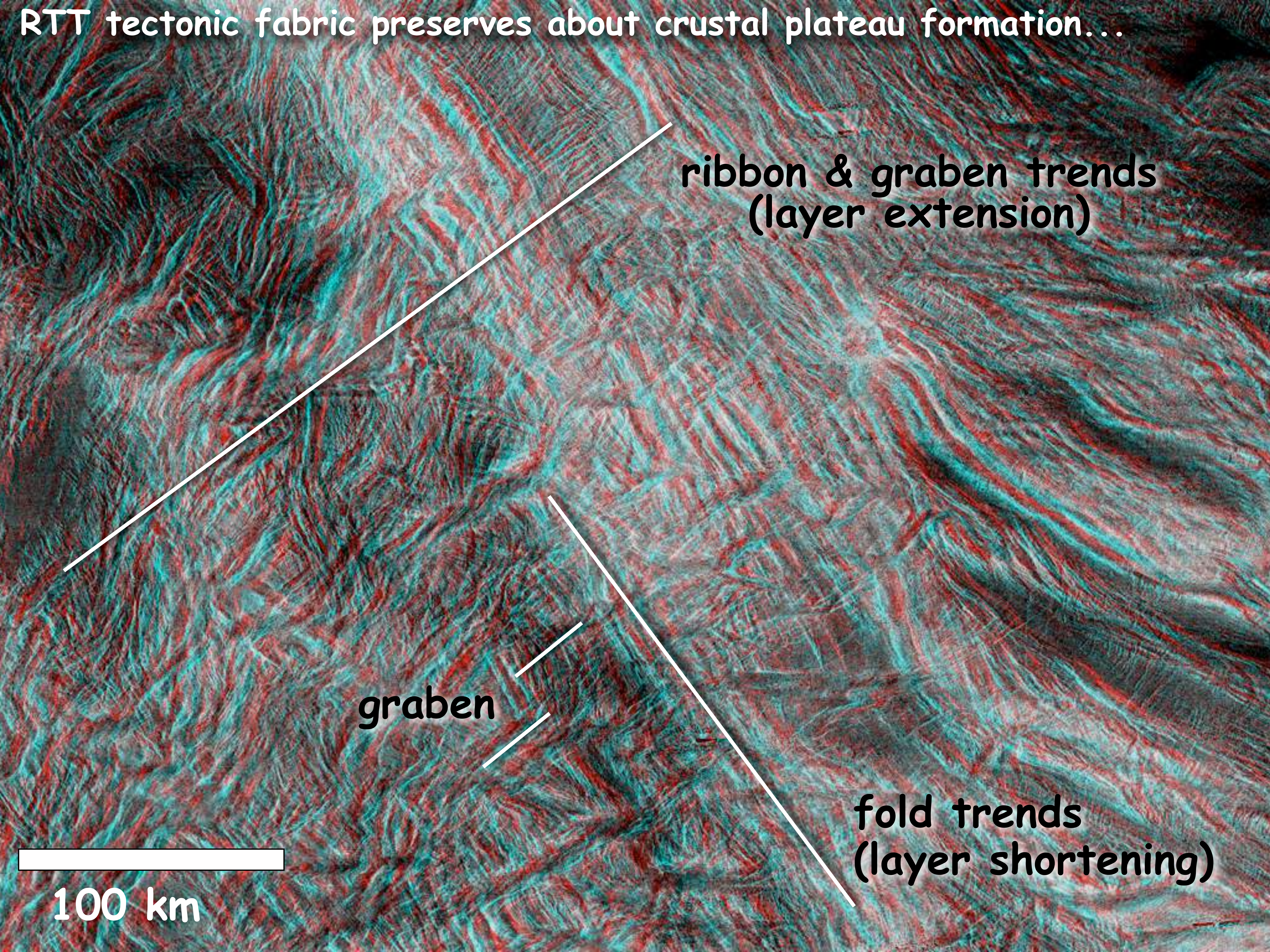
Globally, RTT records a rich early surface history, yet to be revealed

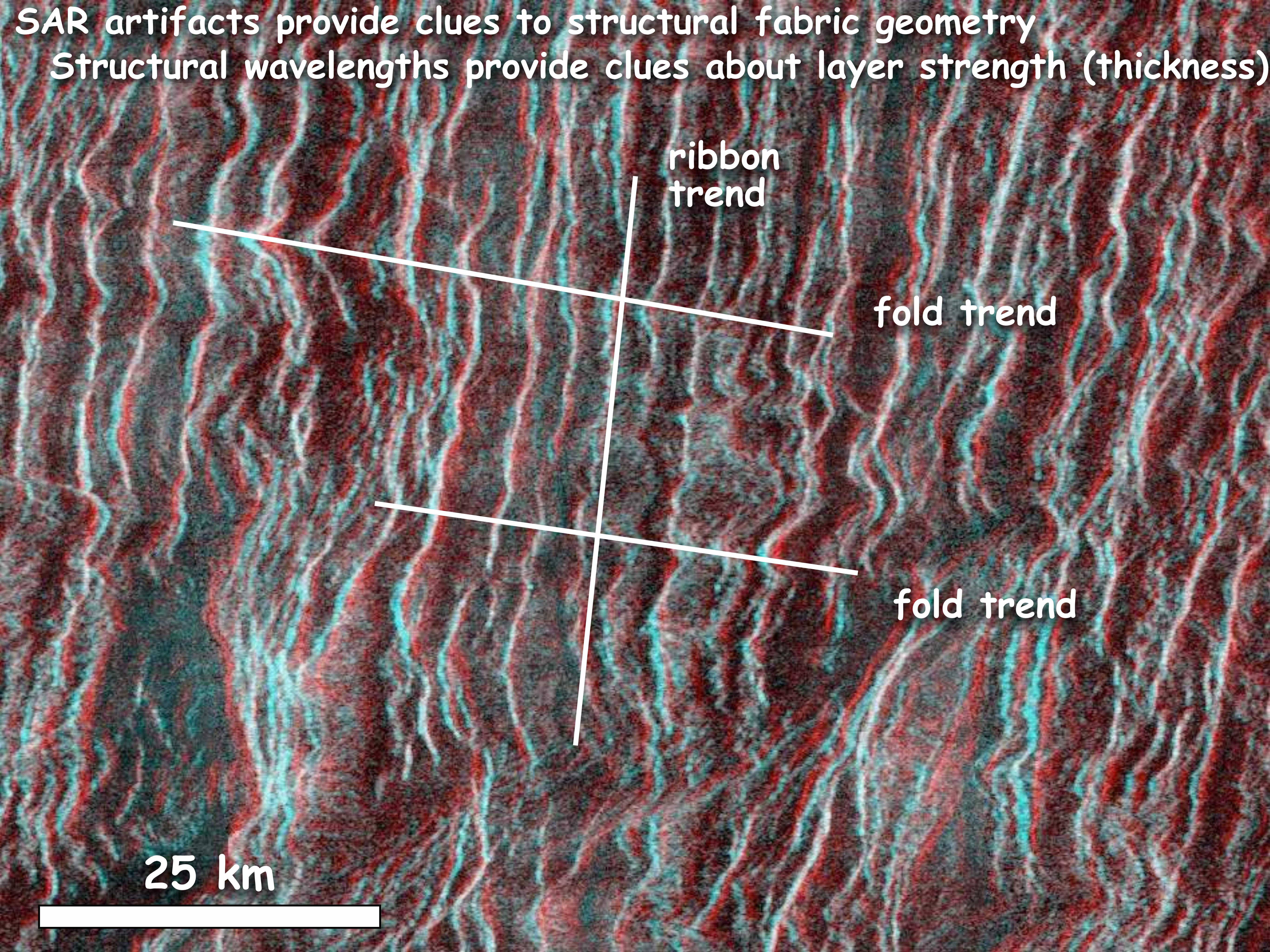


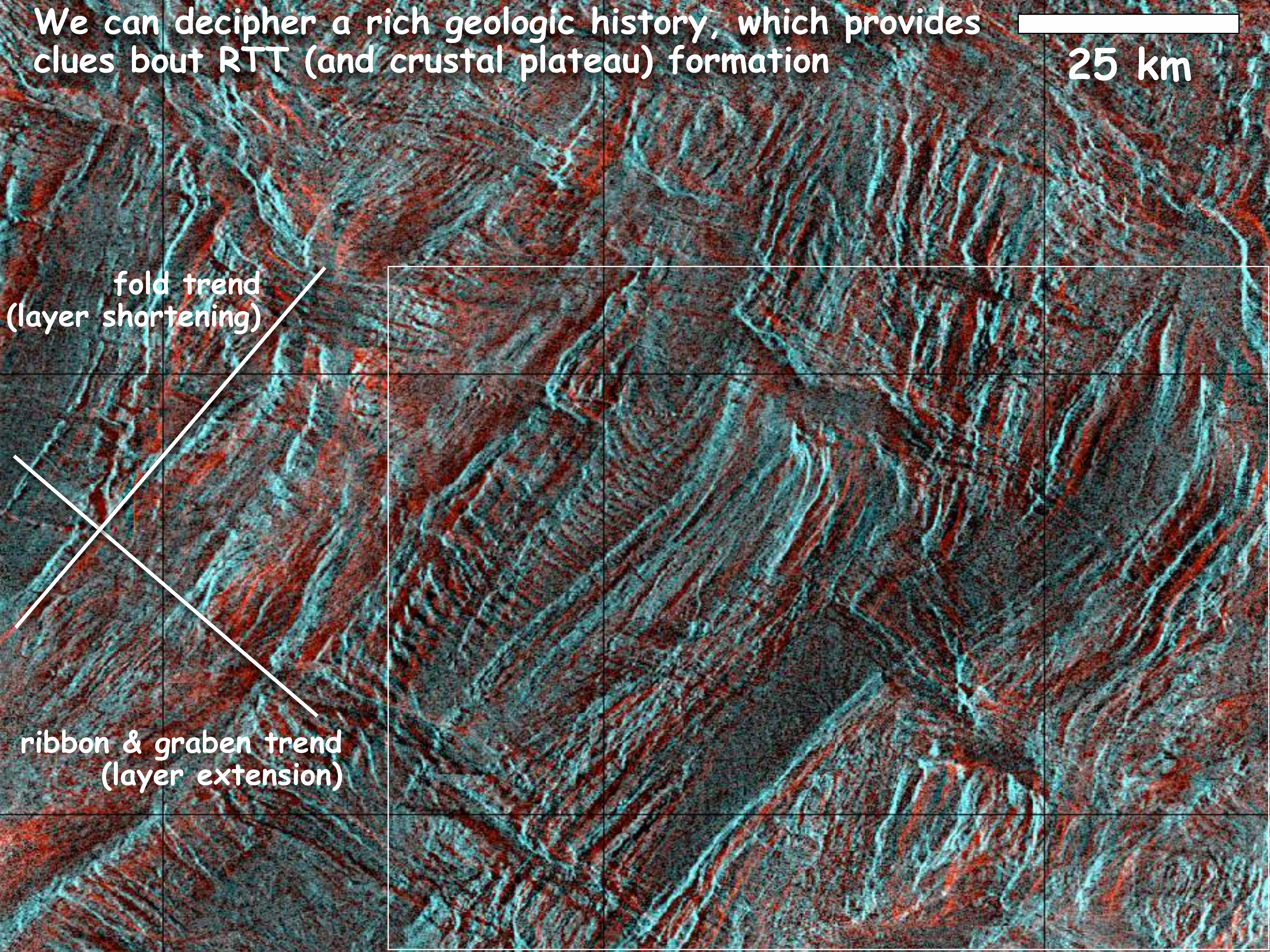
Clues from global distribution



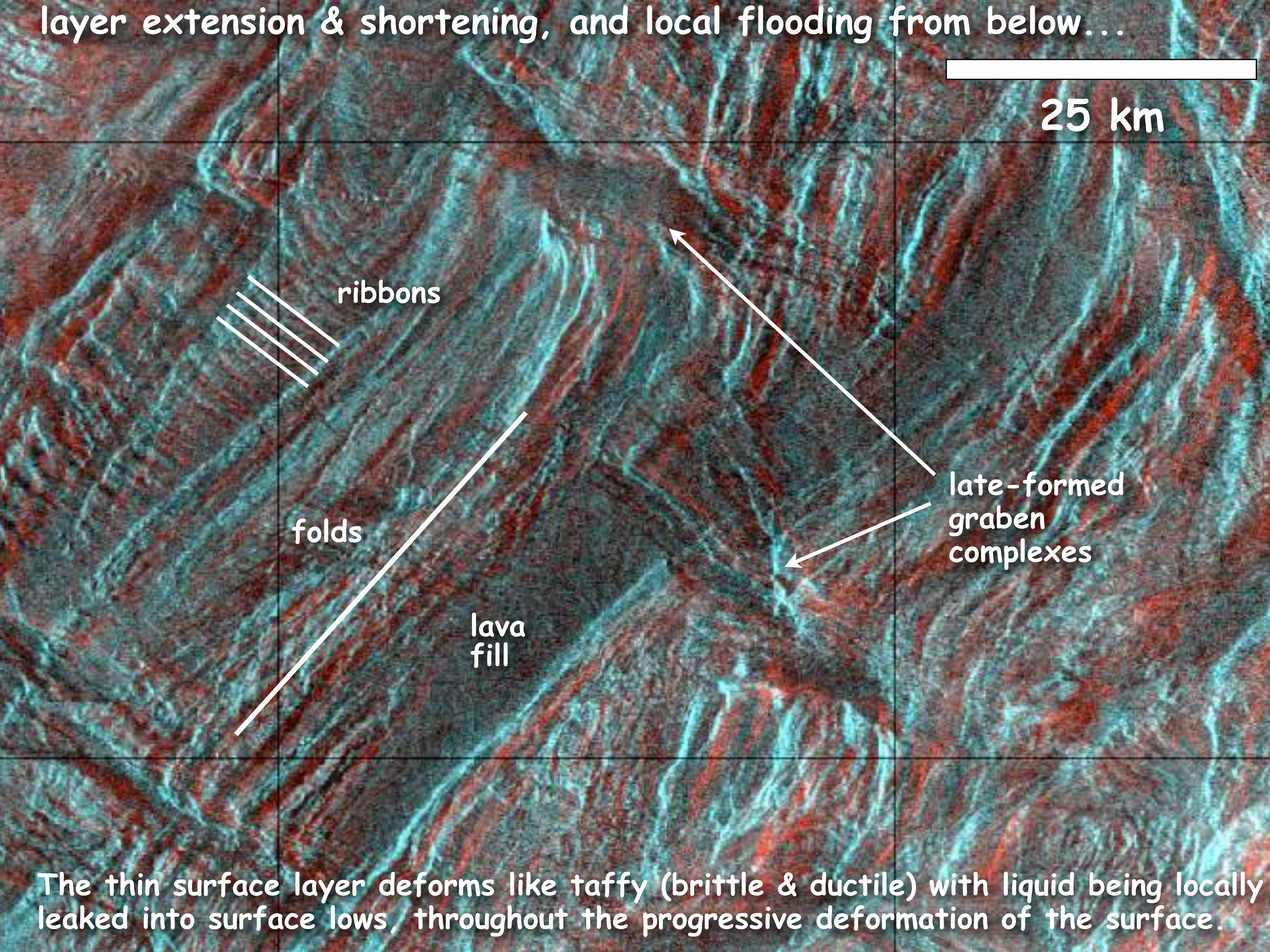
1. RTT occurs across much of the surface, despite much more recent burial
2. RTT (~12%) & shallowly-buried RTT occur across >35% of the surface
3. RTT occurs in some of the deepest lowland basins
4. Observations 1-3 (#3 in particular) are inconsistent with global catastrophic resurfacing hypotheses
5. RTT's rich global surface history is difficult to reconcile with Venus ever having hosted plate tectonics


RTT tectonic fabric preserves about crustal plateau formation...
ribbon & graben trends
(layer extension)
graben
fold trends
(layer shortening)
100 km


SAR artifacts provide clues to structural fabric geometry
Structural wavelengths provide clues about layer strength (thickness)
ribbon
trend
fold trend
fold trend
25 km


We can decipher a rich geologic history, which provides clues bout RTT (and crustal plateau) formation
25 km
fold trend
(layer shortening)
ribbon & graben trend
(layer extension)

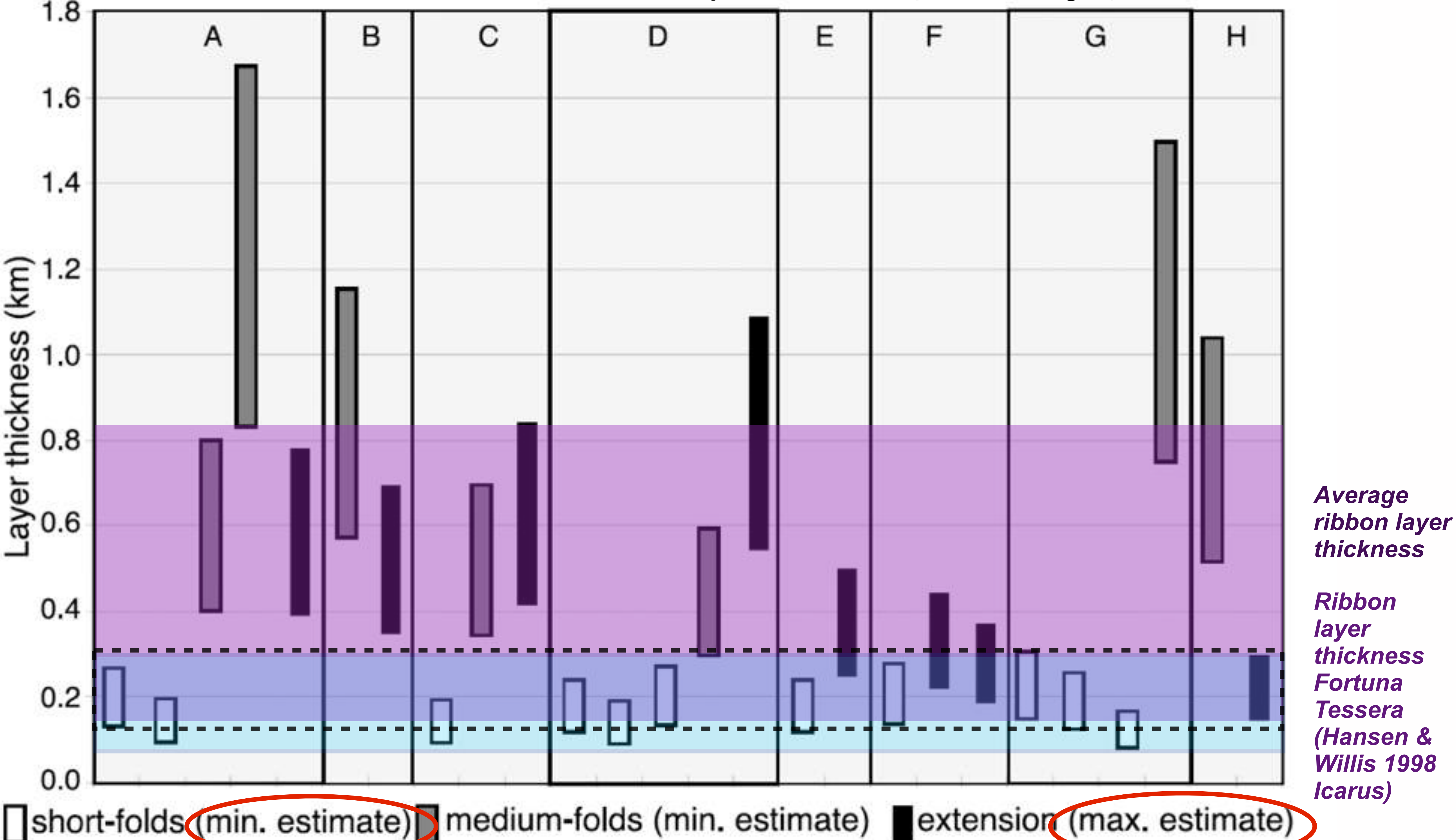
layer extension & shortening, and local flooding from below...



The thin surface layer deforms like taffy (brittle & ductile) with liquid being locally leaked into surface lows, throughout the progressive deformation of the surface.

Short-λ folds & ribbons formed broadly synchronously, deforming a layer <<1 km thick

data from transects/study areas A-H (Ovda Regio)



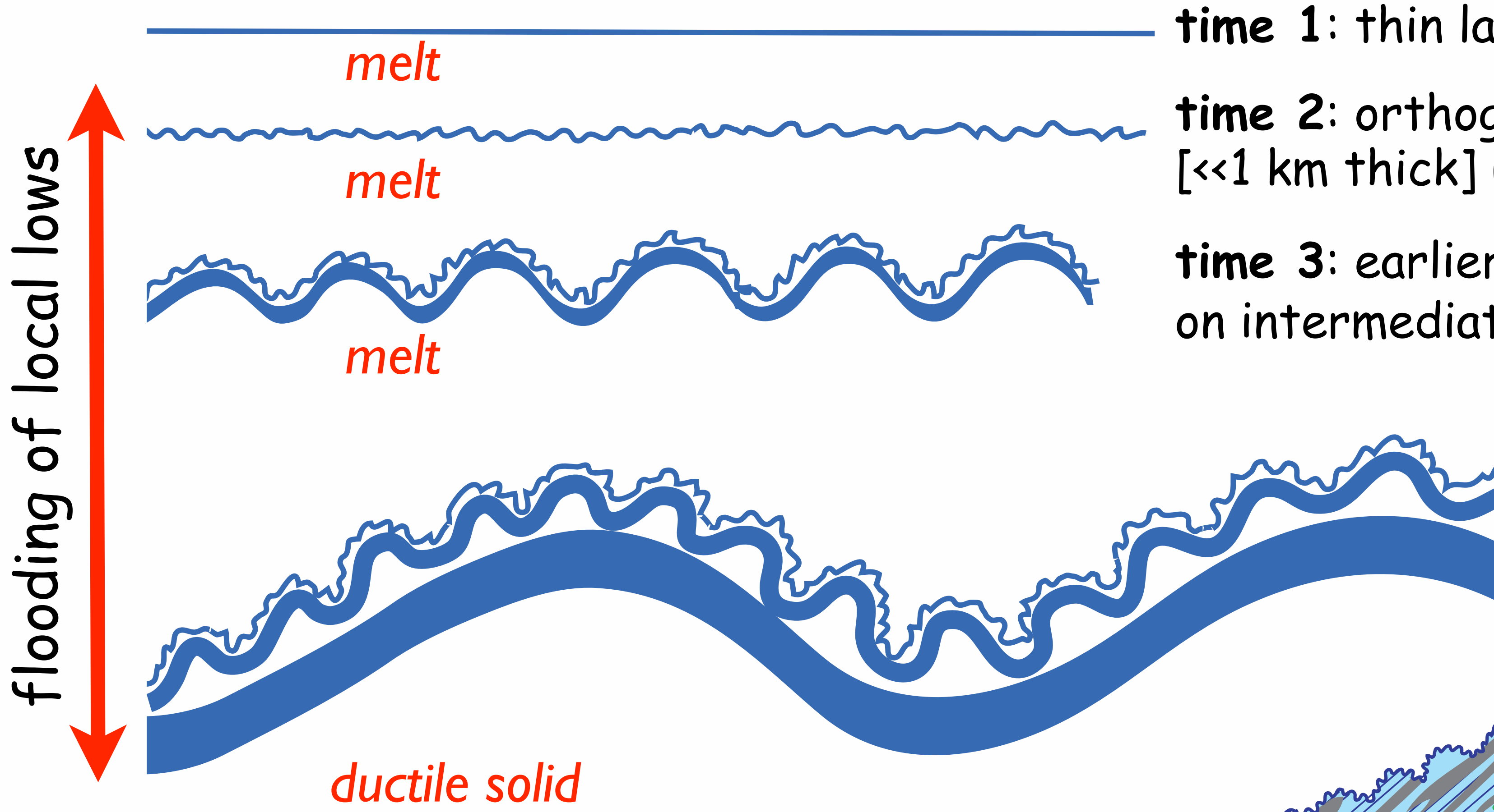
layer shortening

layer extension

average layer thickness

(Hansen 2006 JGR)

RTT history derived from wavelength analysis and X-cutting relations, with clues from experimental & theoretical modeling



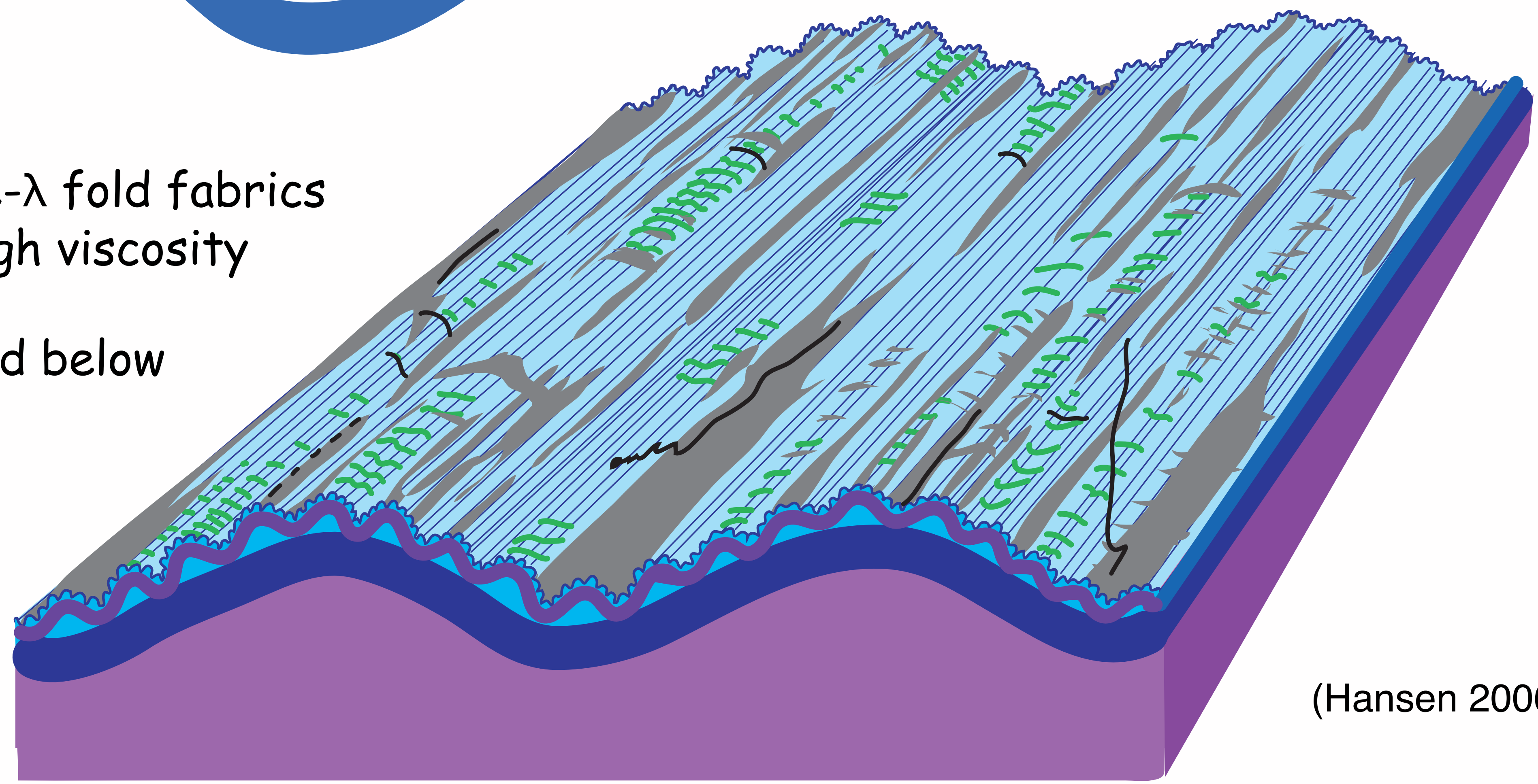
time 1: thin layer (solid above melt)

time 2: orthogonal folding & extension of thin layer [<<1 km thick] (formed short-λ folds & ribbons)

time 3: earlier-formed fabrics carried piggy-back on intermediate-λ folds

time 4: earlier-formed fabrics were carried piggy-back on long-λ folds (with late extension along graben complexes)

- short-λ & intermediate-λ fold fabrics require an extremely high viscosity contrast — i.e., solid above and liquid below
- long-λ folds (actually warps) formed by uplift of crust with strong-weak-strong layer rheology



(Hansen 2006 JGR)

RTT is basically a rocky 'scum' formed on <u>huge</u> 'ponds' of lava

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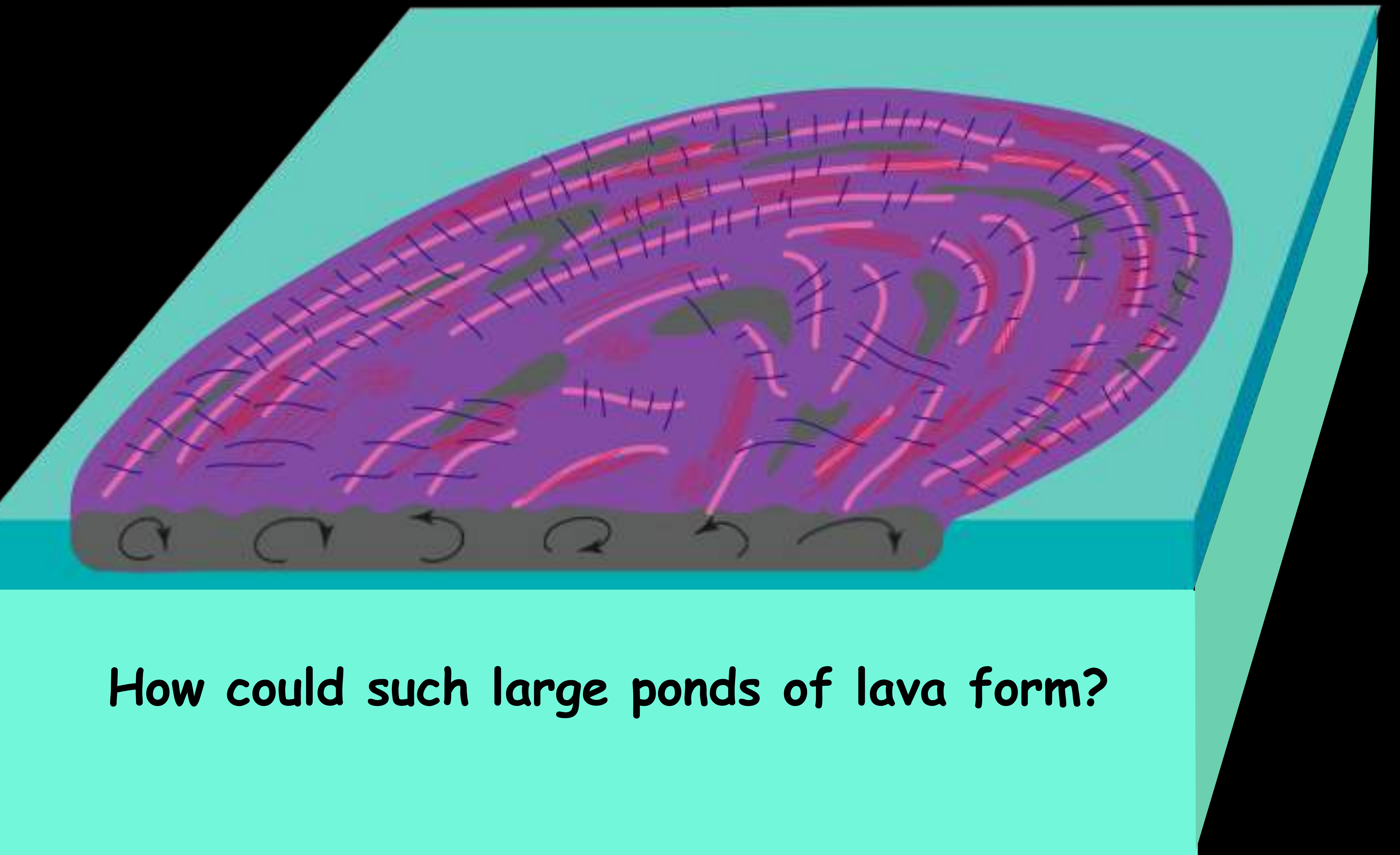
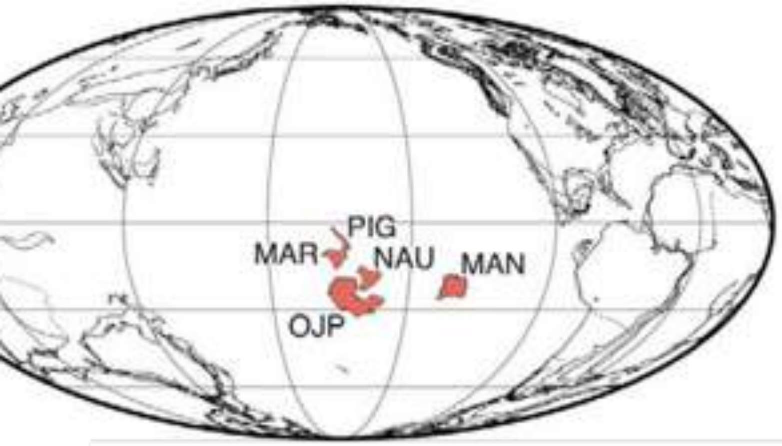


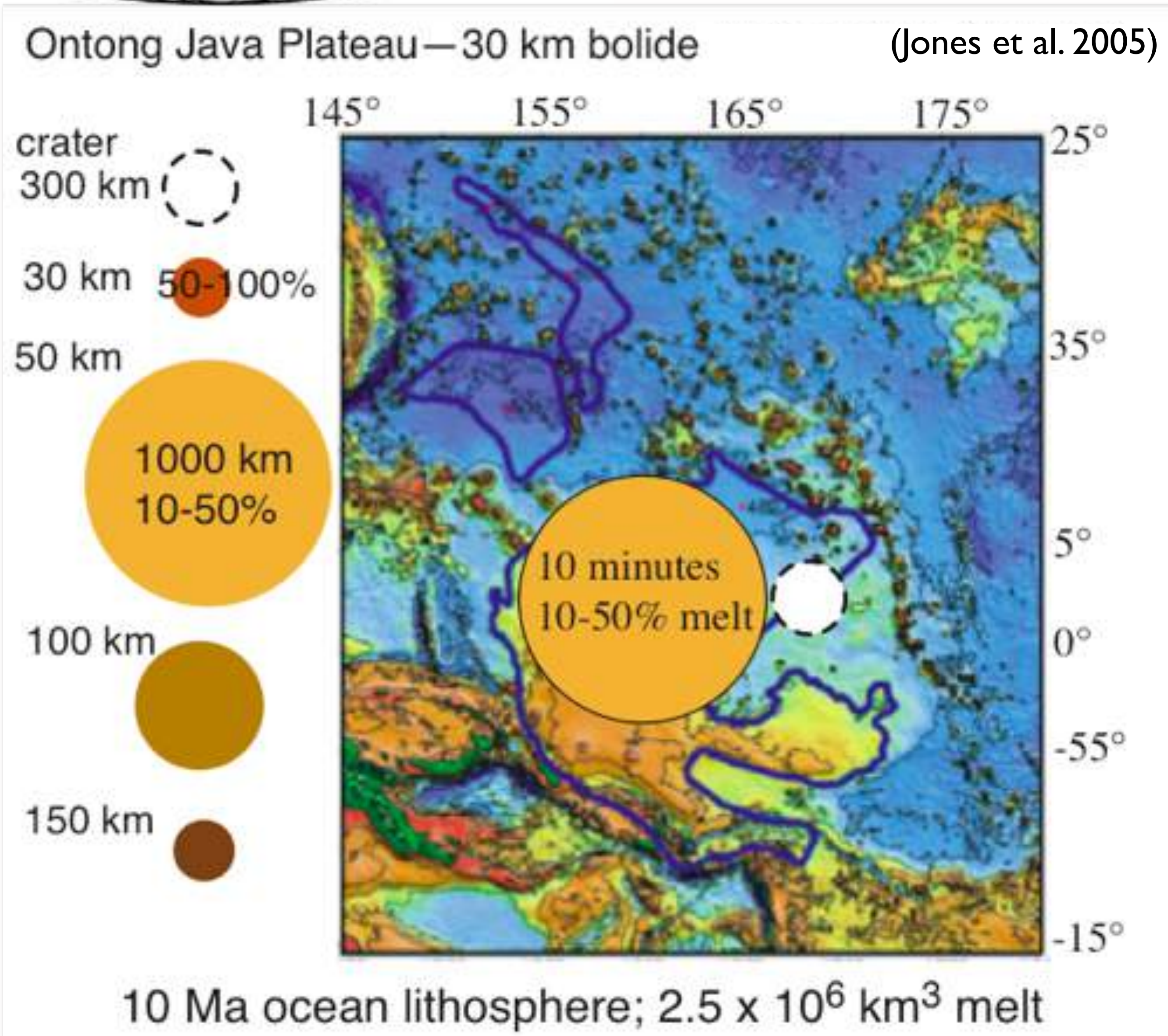
How could such large ponds of lava form?

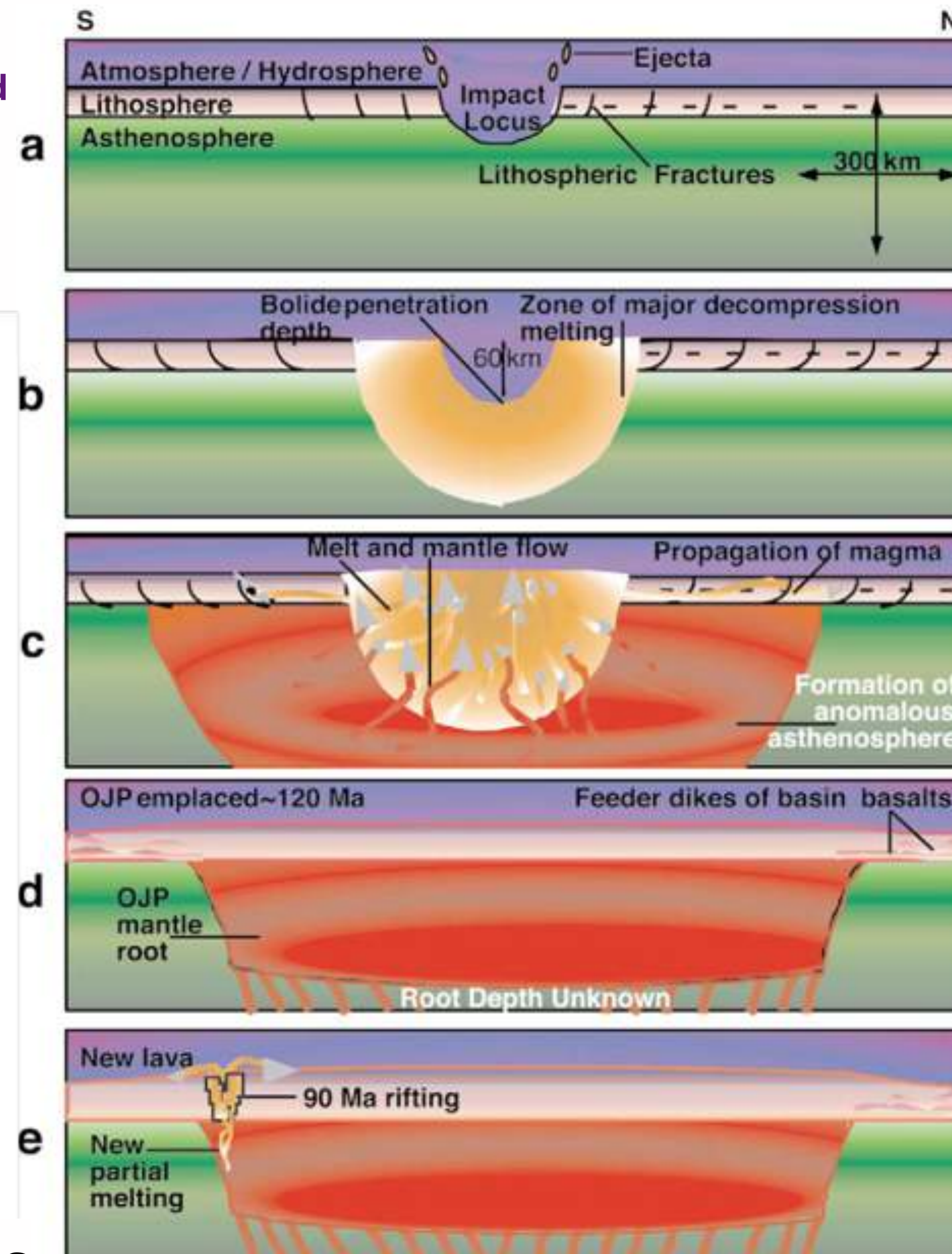
Re(turn) to Earth for possible mechanism...

Ingle & Coffin (2002, 2004) proposed that the Ontong Java Plateau formed by bolide impact; Ontong Java Plateau is similar in size to a Venus crustal plateau



Modeling indicates the viability of huge lava pond formation in this manner (e.g., Jones et al. 2002, 2005; Elkins-Tanton & Hager 2005)



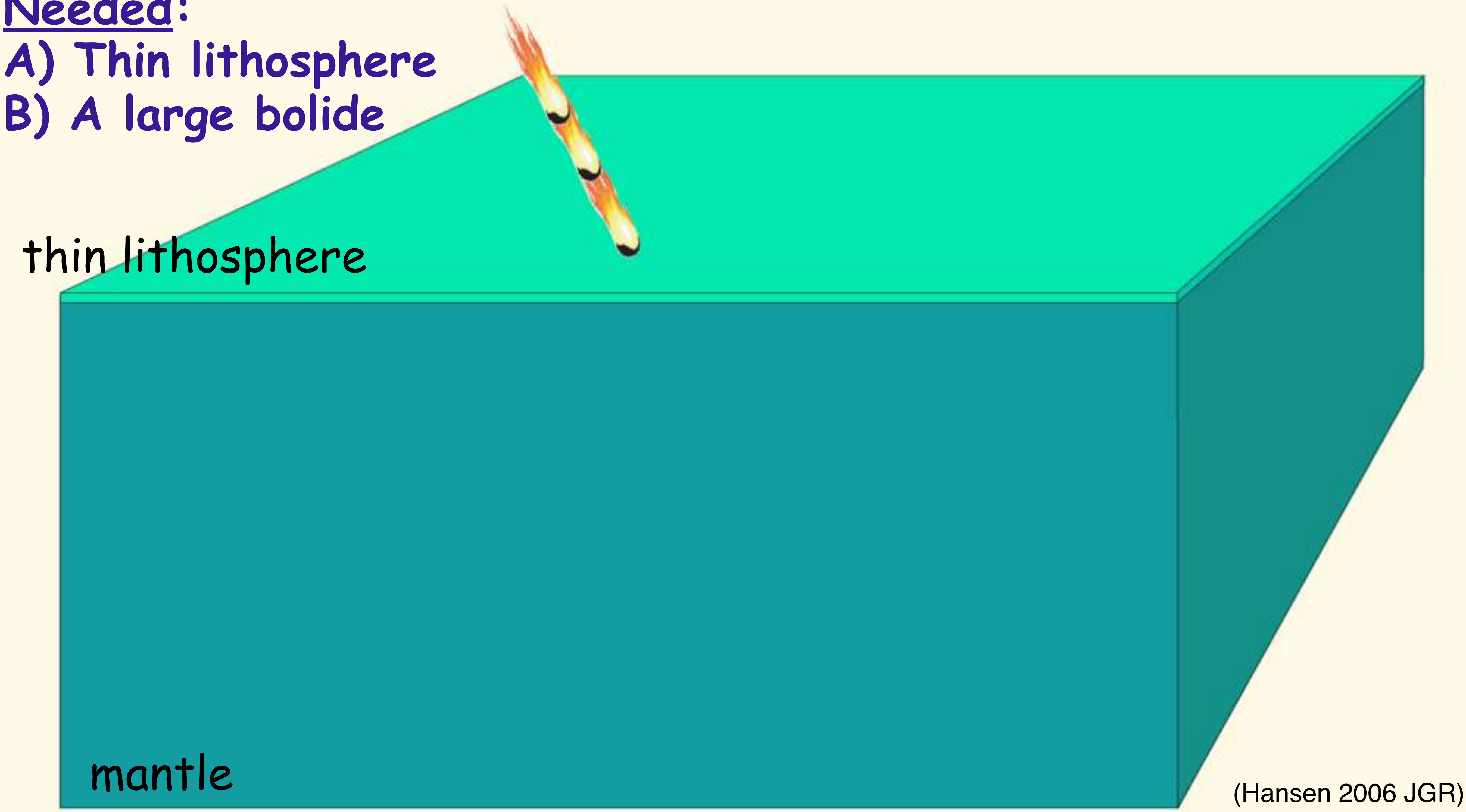


need: thin lithosphere & large bolide

Ingle & Coffin (2004 EPSL)

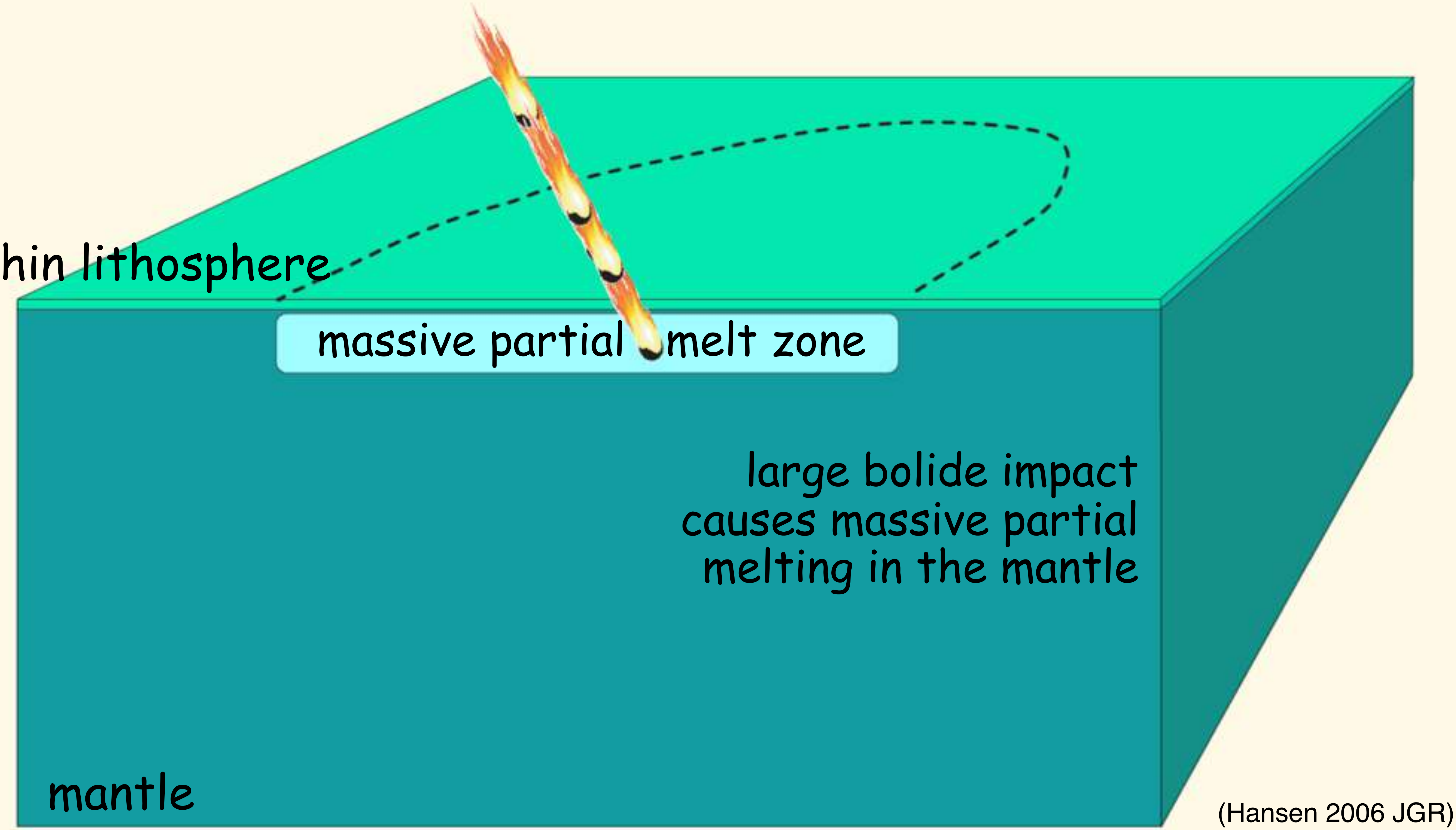
So let's form a huge pond of lava...

Needed:
A) Thin lithosphere
B) A large bolide

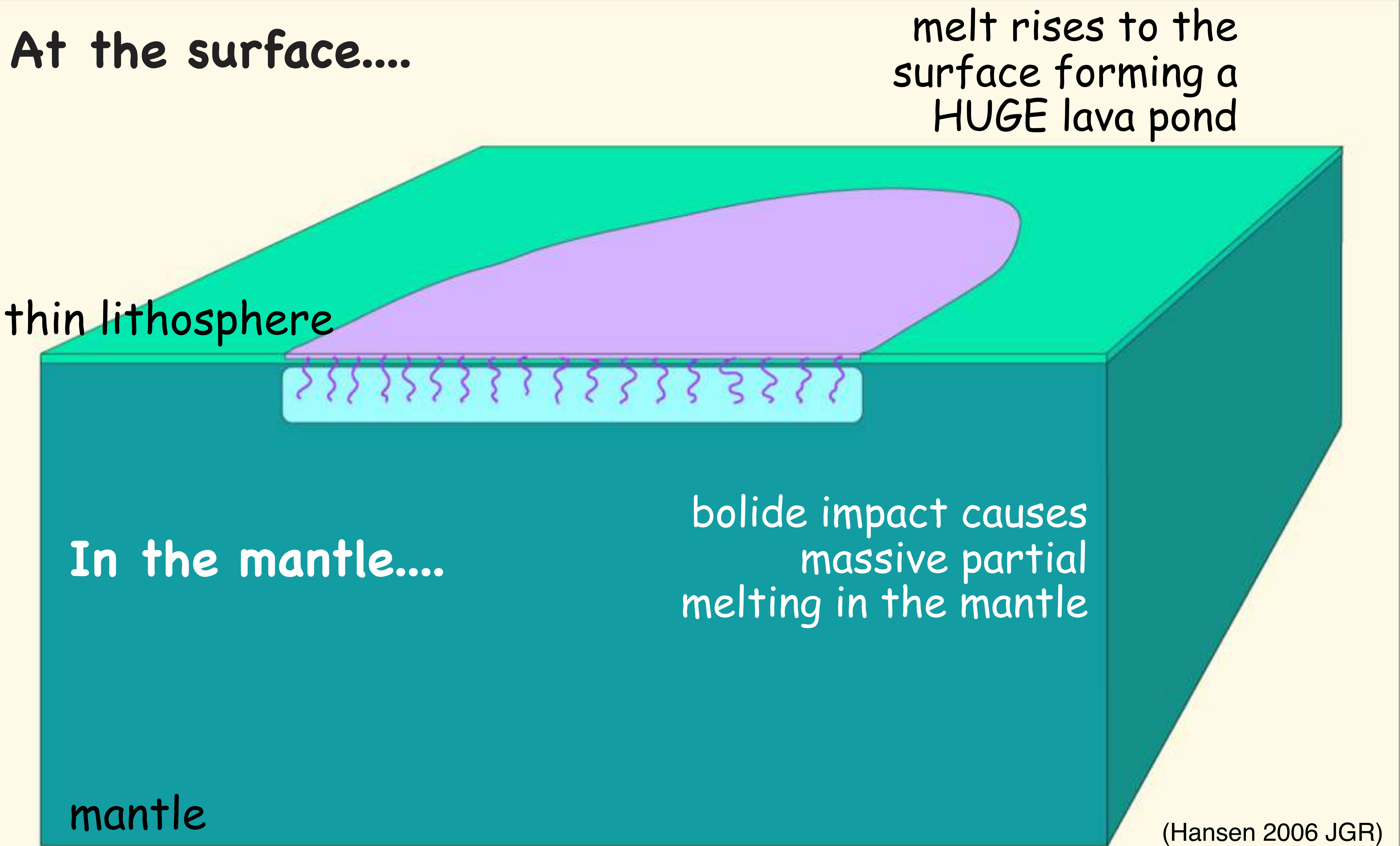


Cartoon illustrating formation of ribbon tessera & crustal plateaus

So let's form a huge pond of lava...



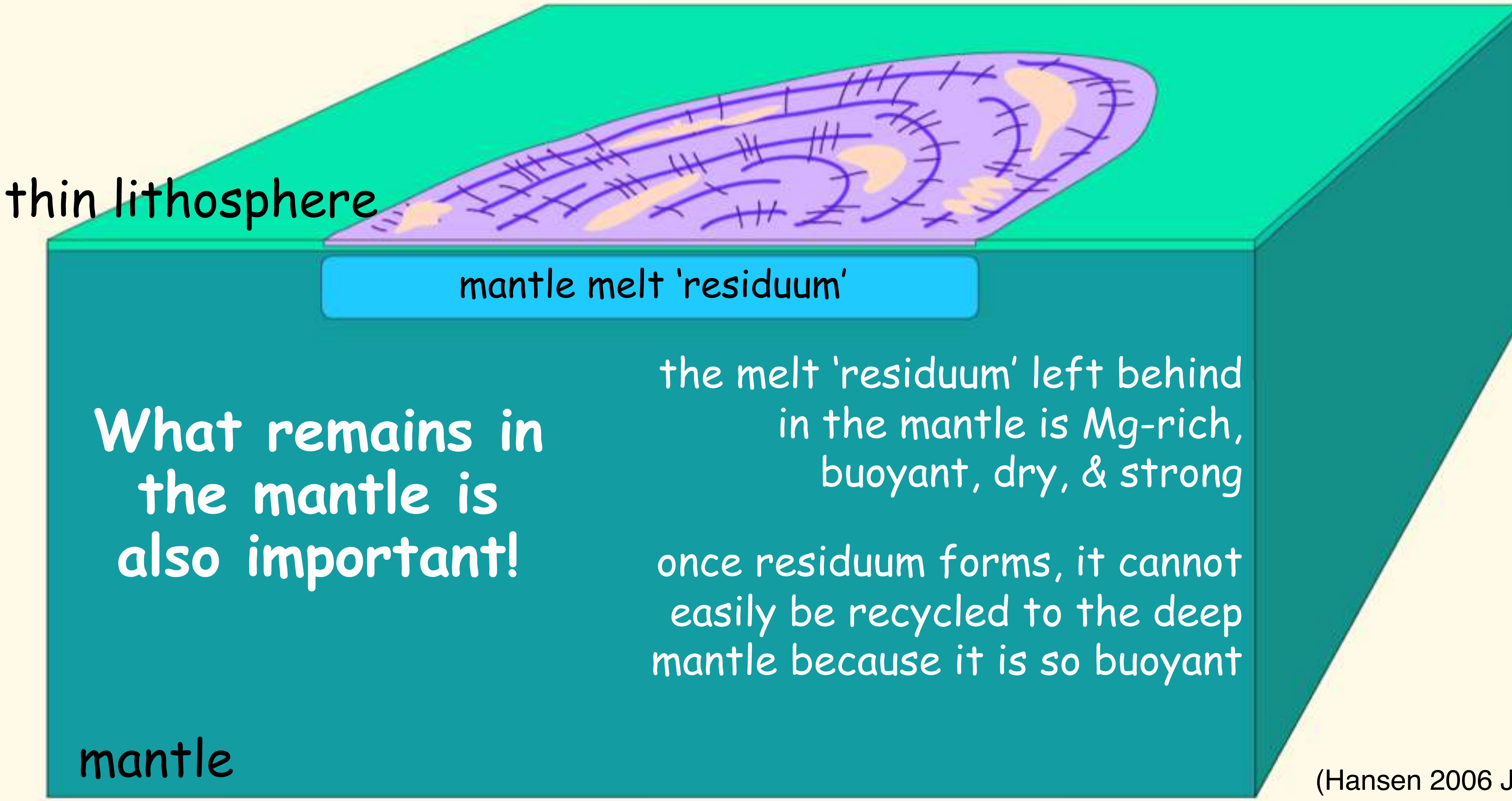
Cartoon illustrating formation of ribbon tessera & crustal plateaus



Cartoon illustrating formation of ribbon tessera & crustal plateaus

At the surface....

solidification (freezing) of the lava pond forms RTT fabric as 'pond scum', driven by pond melt convection; lava leaks to the surface filling local topographic lows

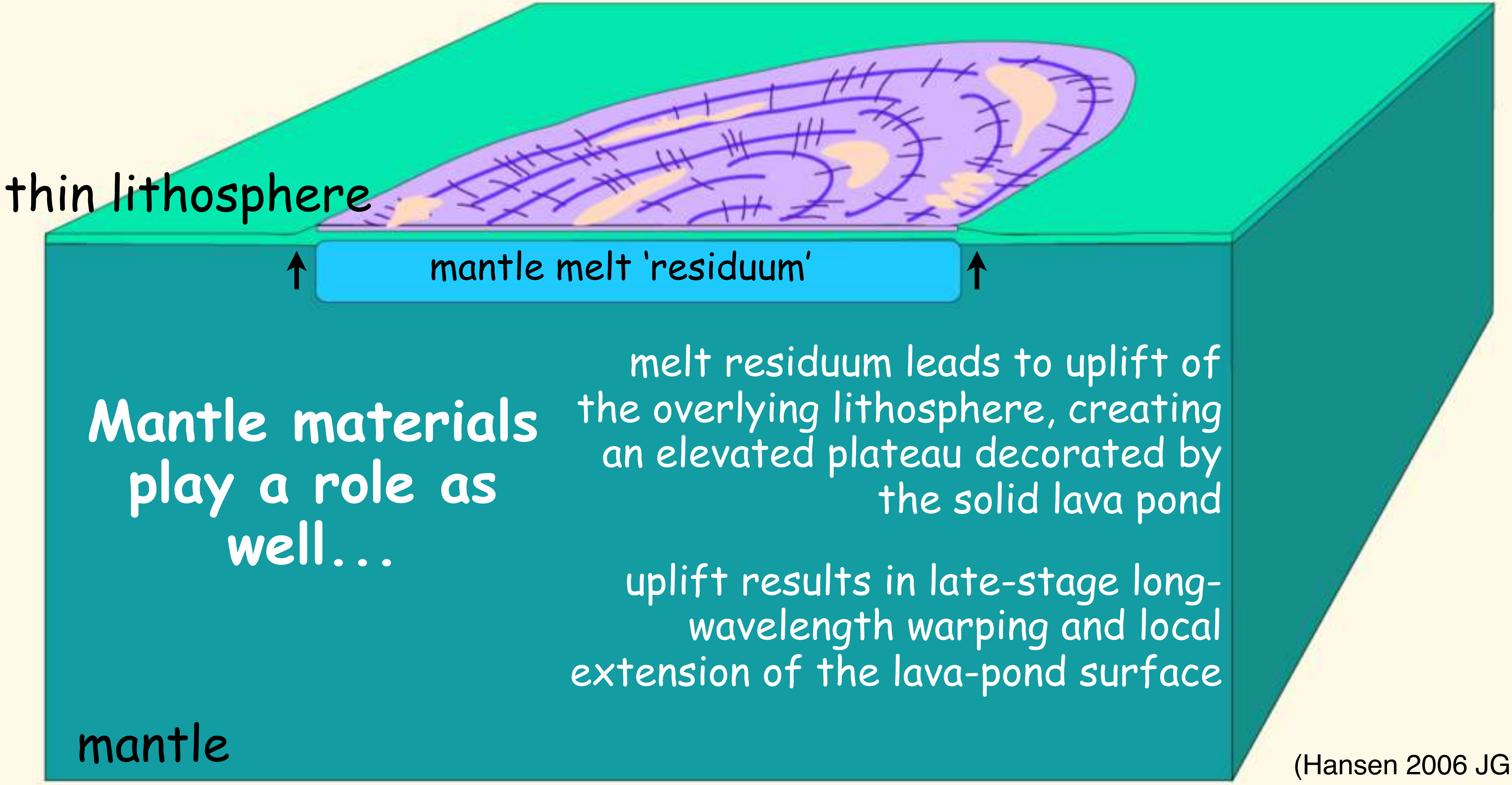


(Hansen 2006 JGR)

Cartoon illustrating formation of ribbon tessera & crustal plateaus

At the surface....

the solidified lava pond (RTT) becomes elevated, forming a crustal plateau

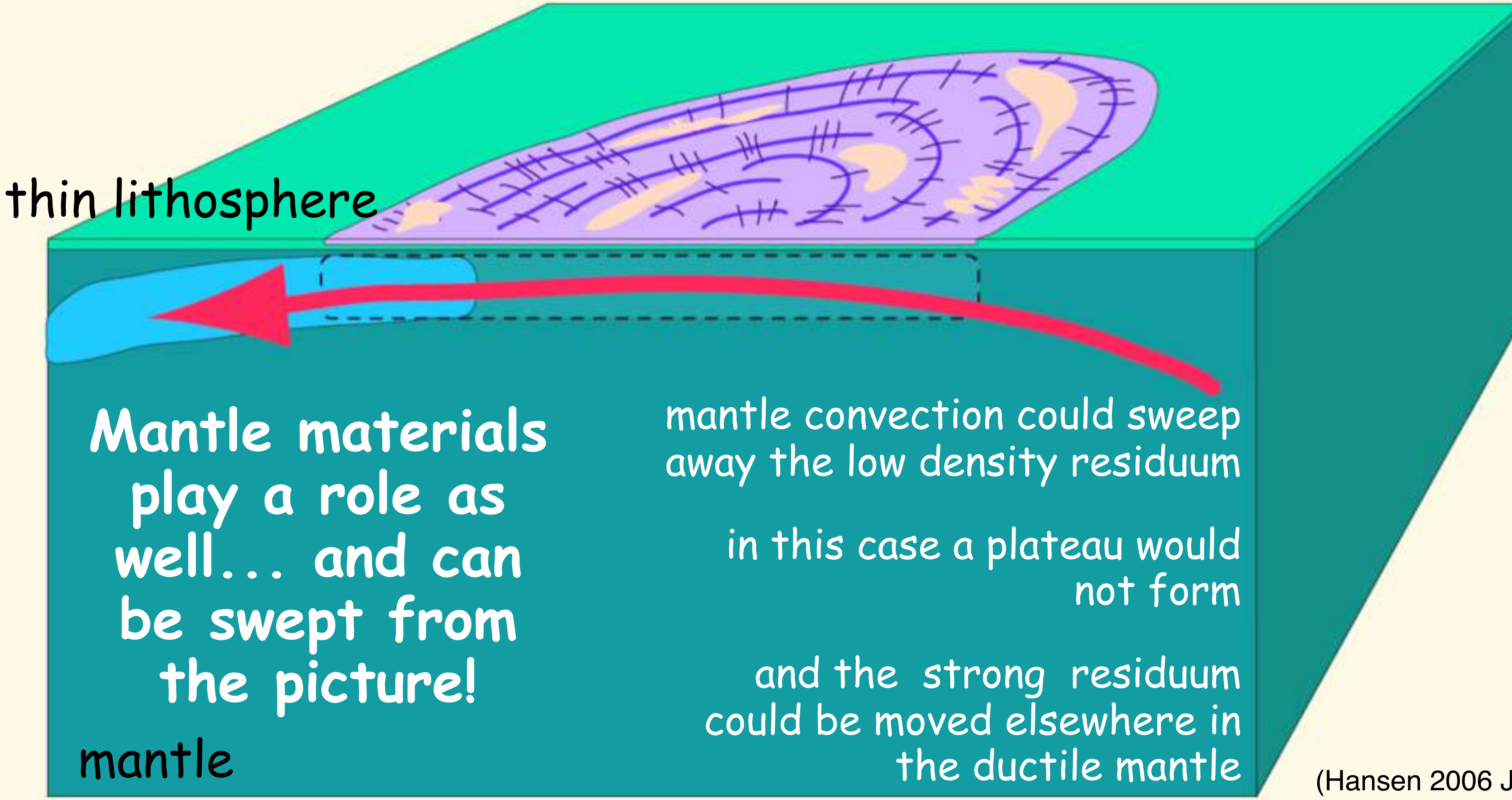


(Hansen 2006 JGR)

Cartoon illustrating formation of ribbon tessera & crustal plateaus

At the surface...

the solidified lava pond (RTT) is lowered (or never raised to plateau status) — forming lowland RTT inliers

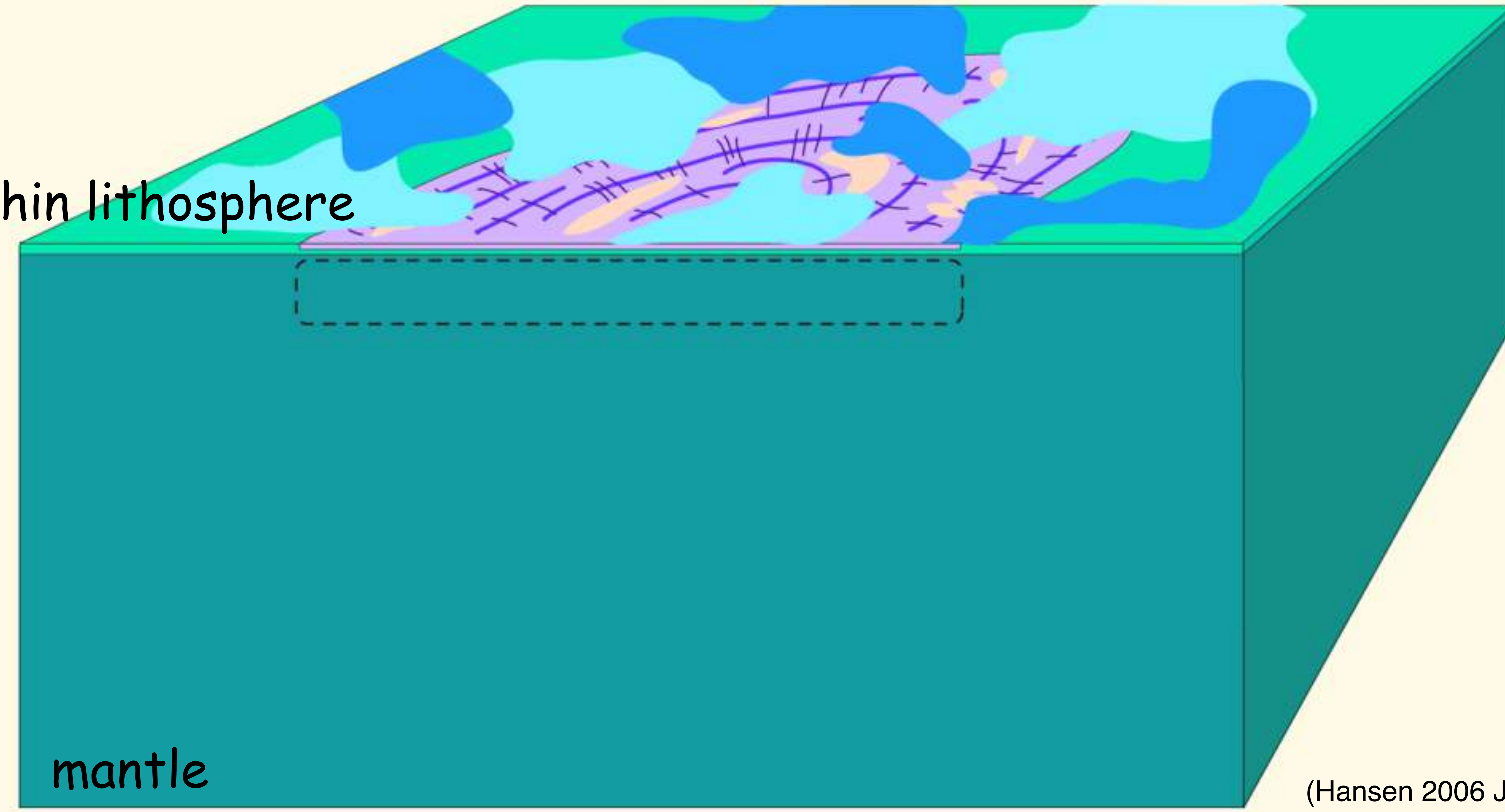


(Hansen 2006 JGR)

Cartoon illustrating formation of ribbon tessera & crustal plateaus

At the surface....

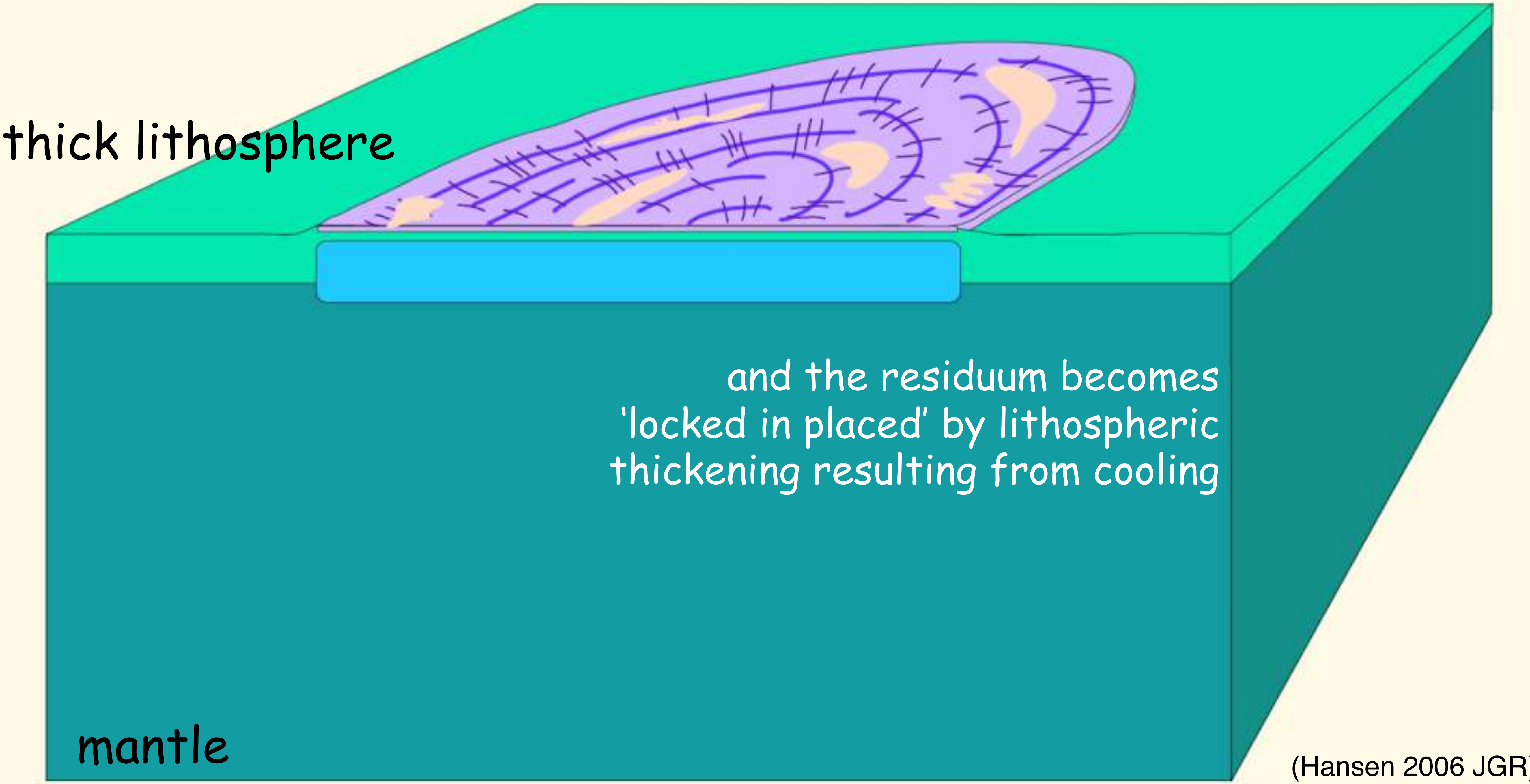
the frozen lava pond (RTT) is subject to burial by younger deposits



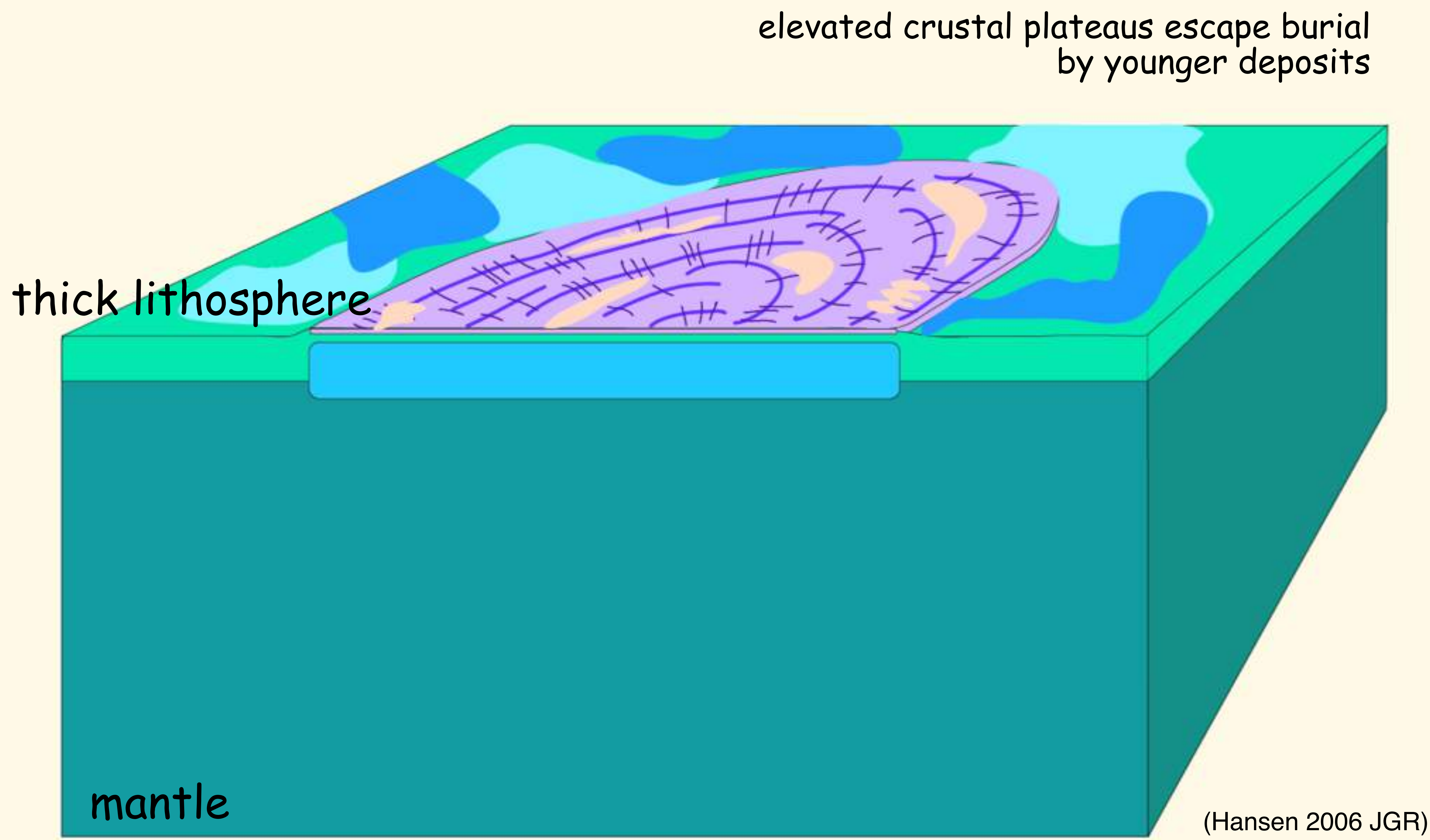
(Hansen 2006 JGR)

Cartoon illustrating formation of ribbon tessera & crustal plateaus

OR, residuum can remain in place... and a crustal plateau survives as the lithosphere thickens due to cooling

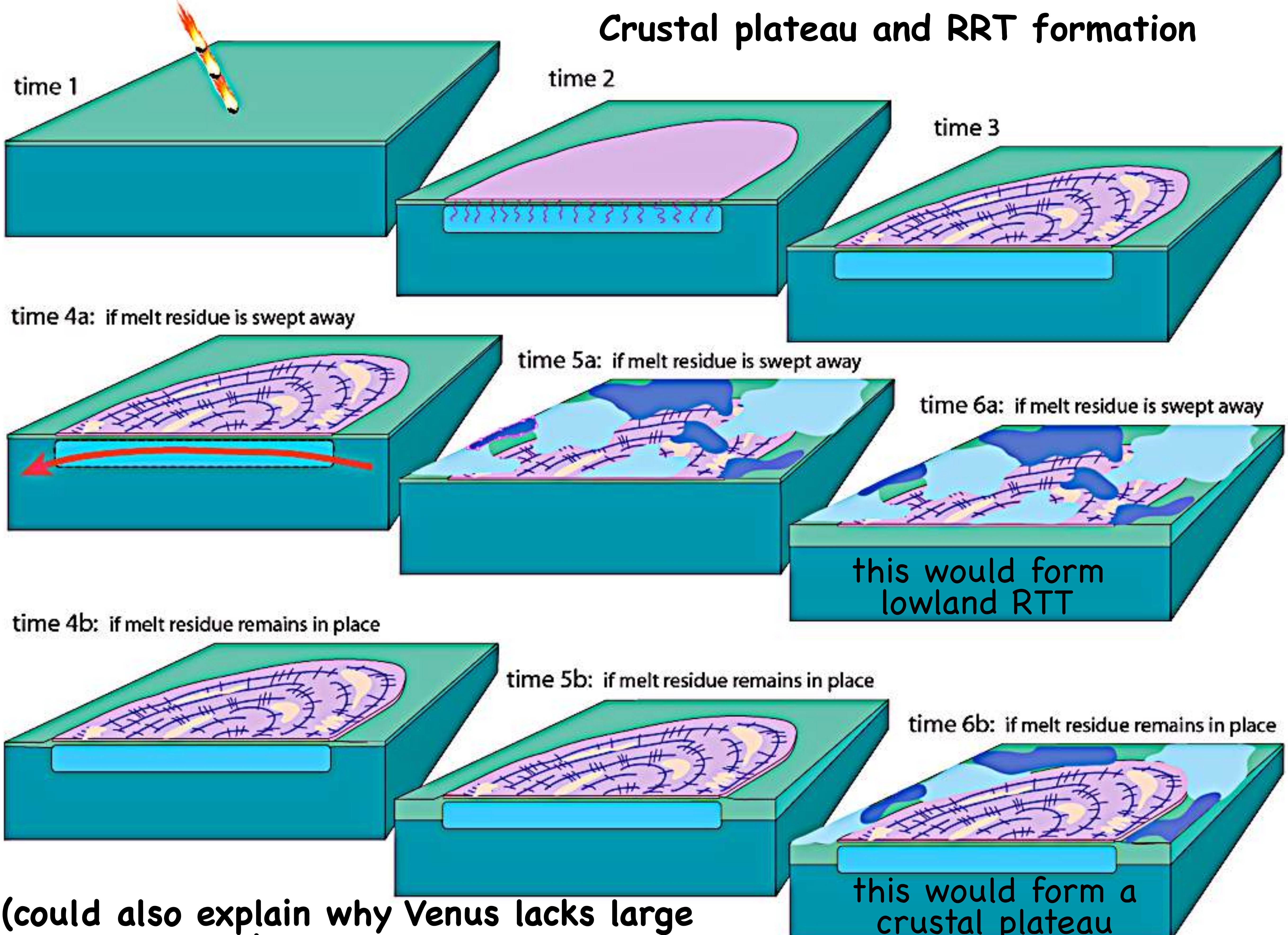


Cartoon illustrating formation of ribbon tessera & crustal plateaus



Cartoon illustrating formation of ribbon tessera & crustal plateaus

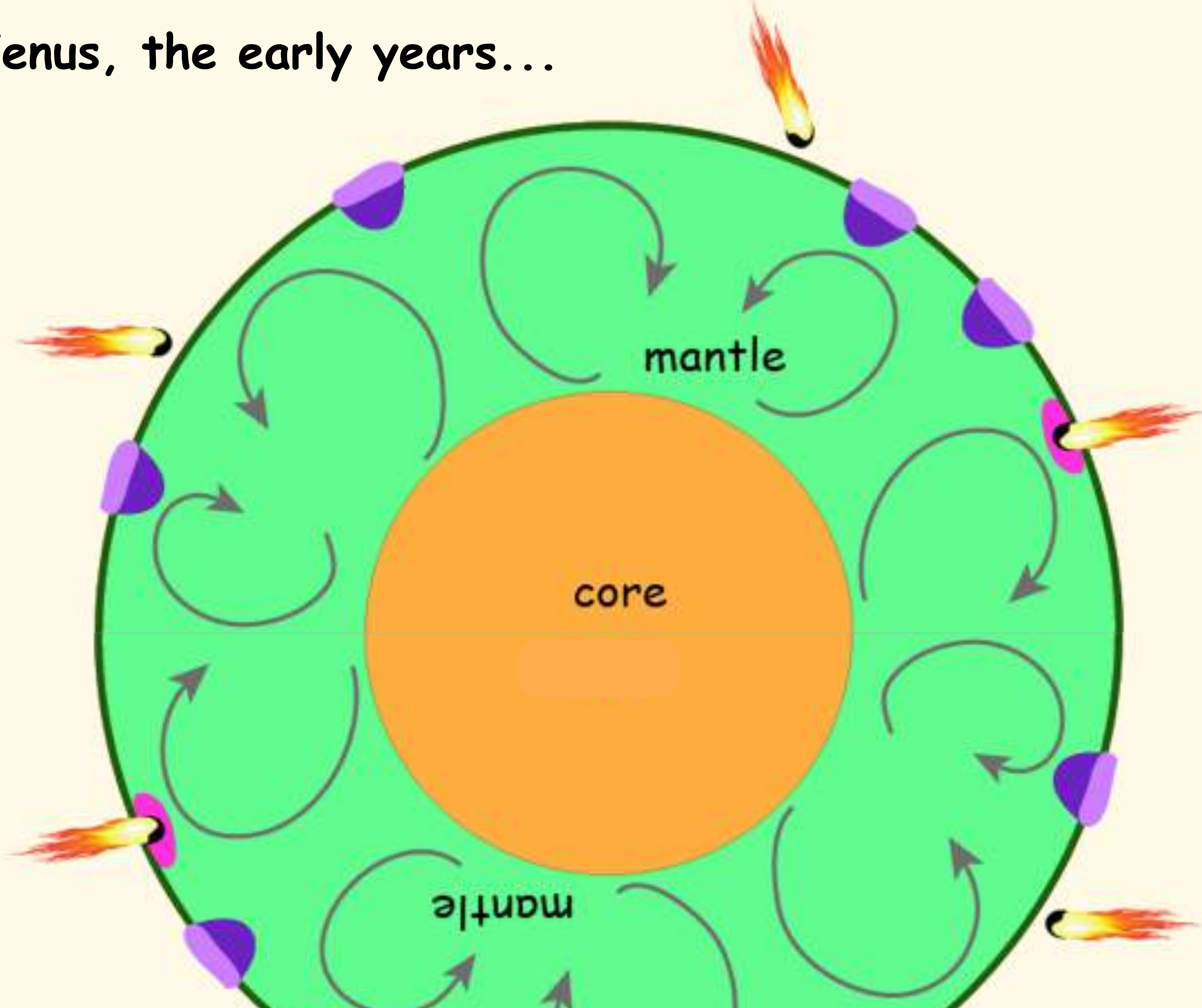
Crustal plateau and RRT formation



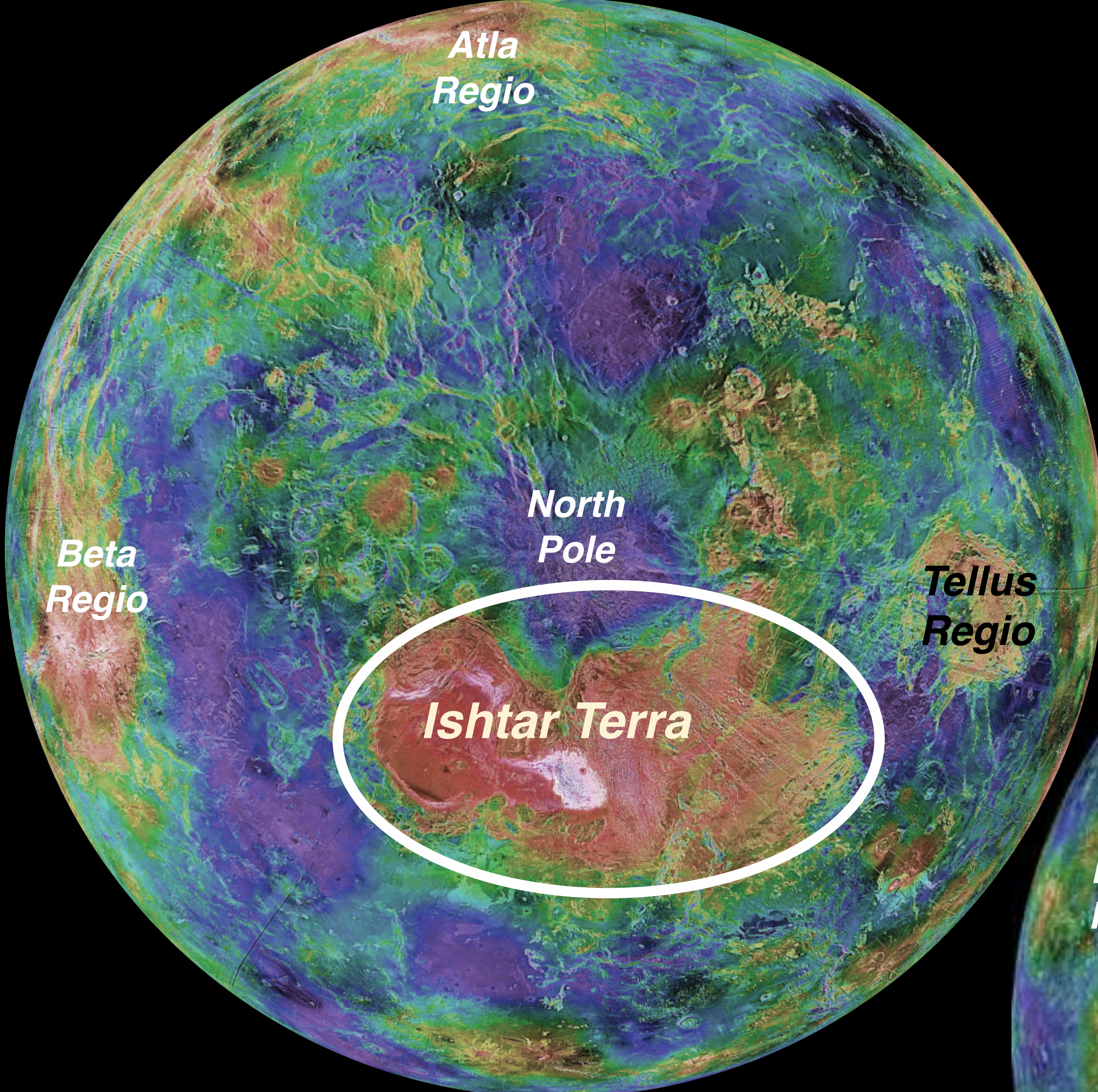
(could also explain why Venus lacks large impact basins...)

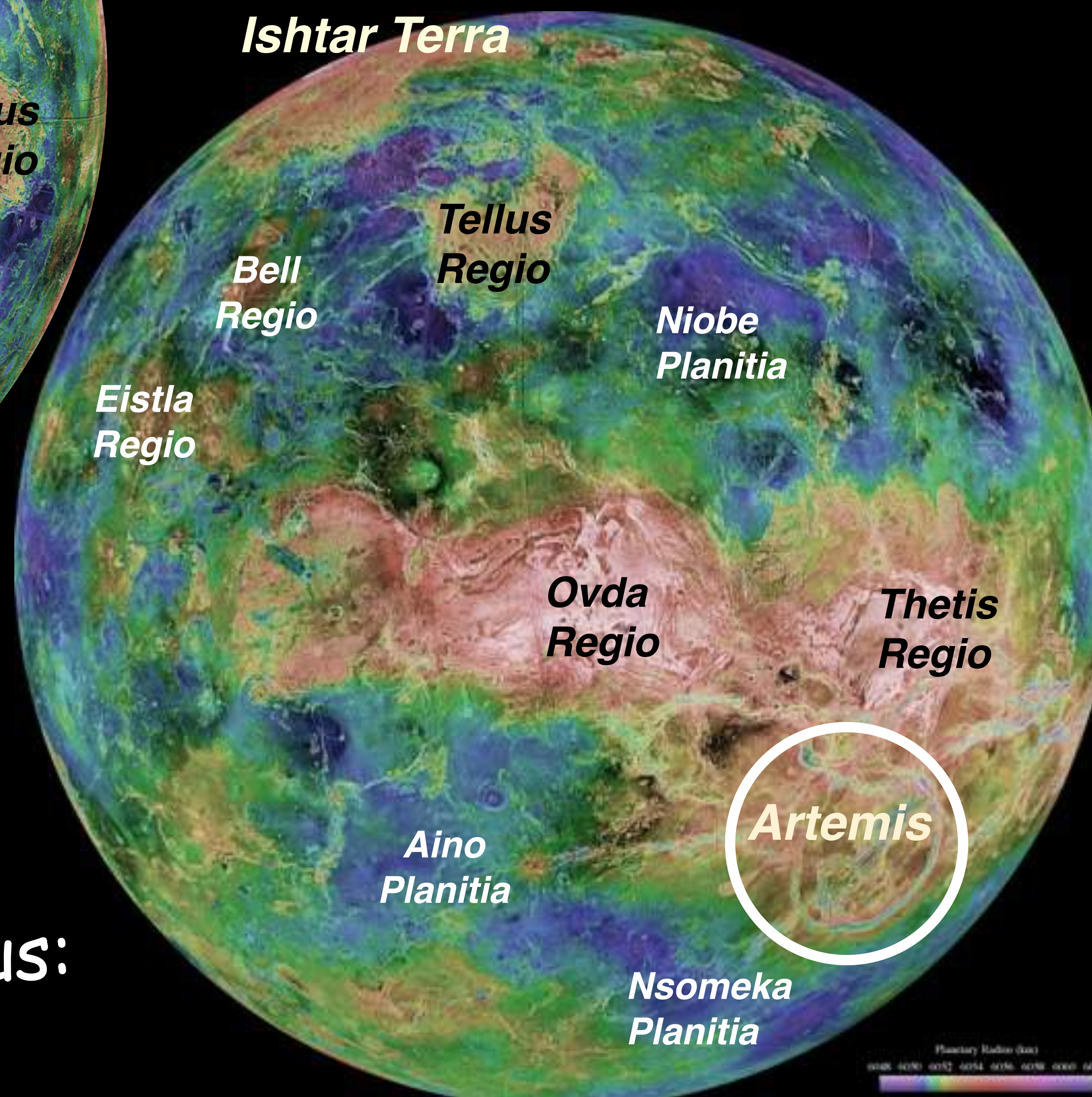
(Hansen 2006 JGR, 2015 Lithosphere)

Venus, the early years...



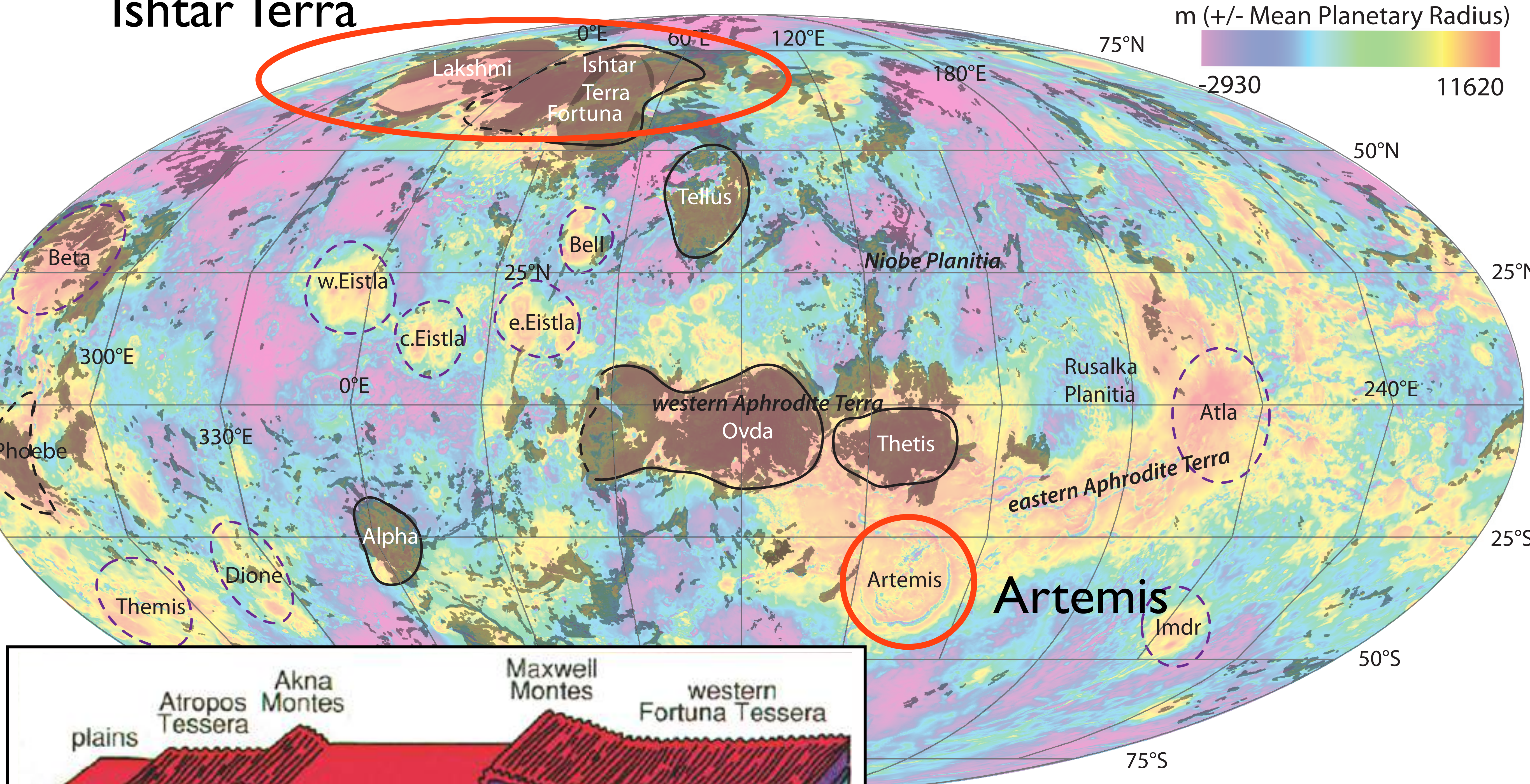
From thin lithosphere and large bolide impact to the dawn of a new **era**...



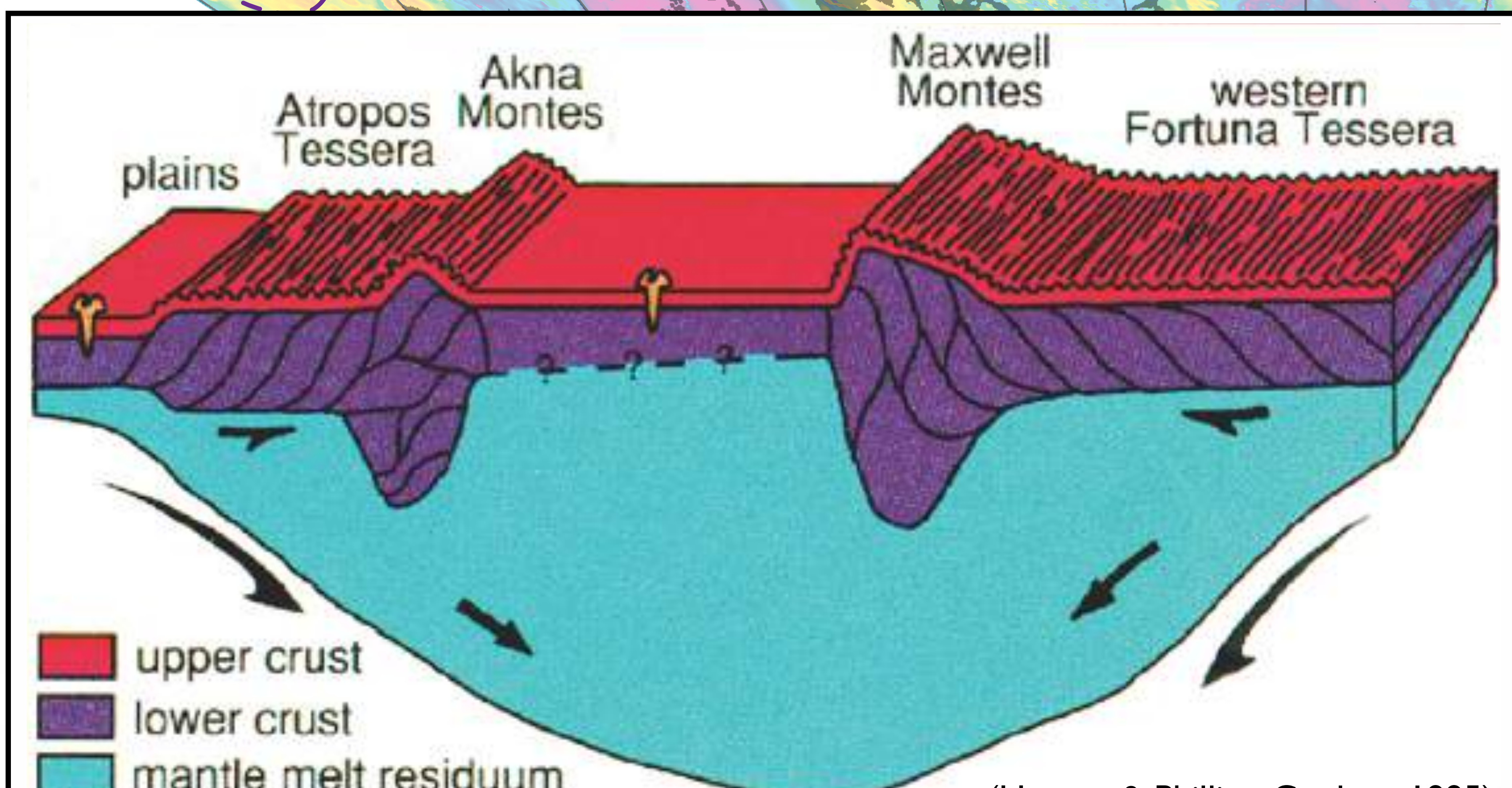


Two unique features on Venus:
Artemis and Ishtar Terra

Ishtar Terra



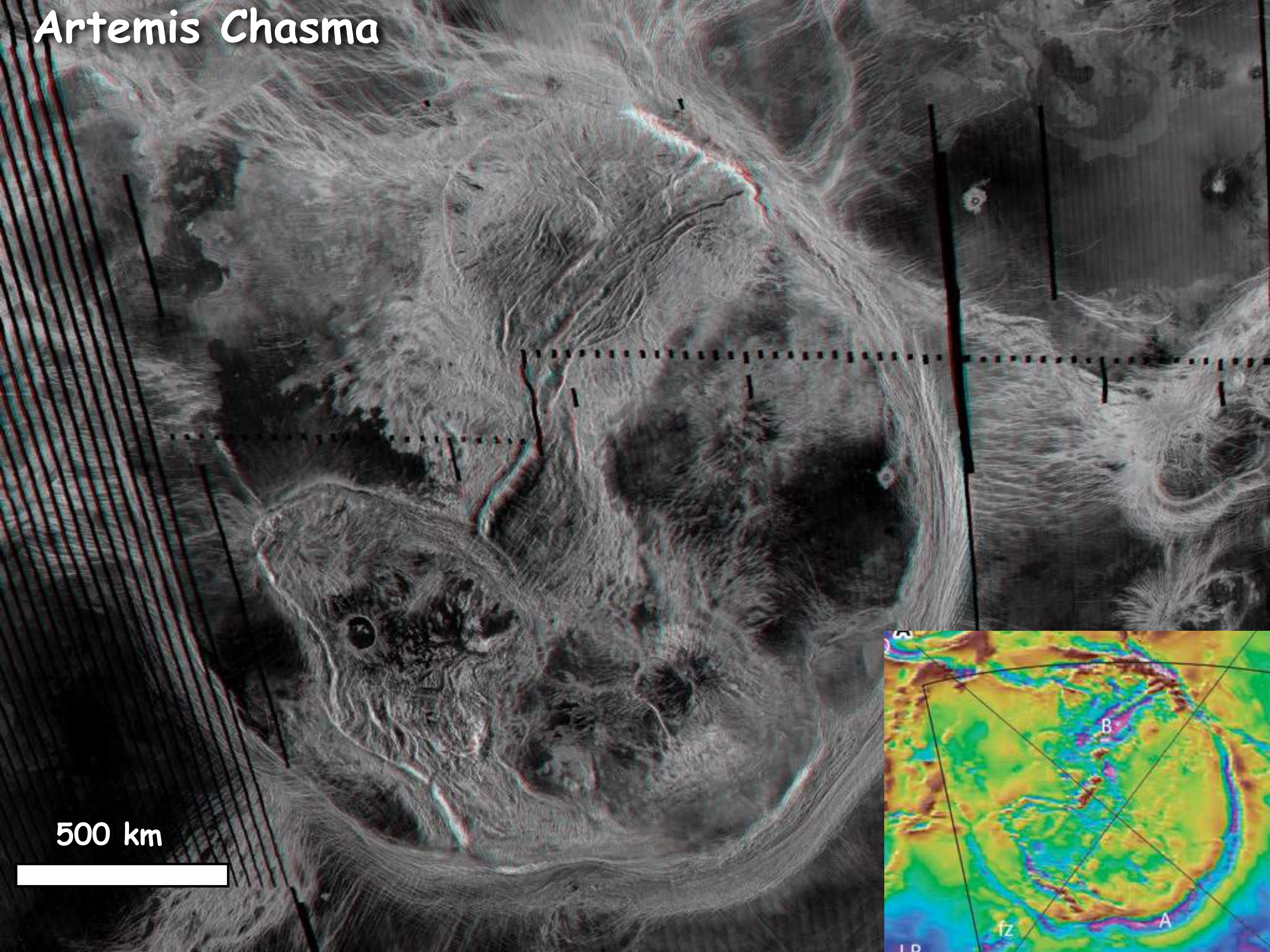
Artemis

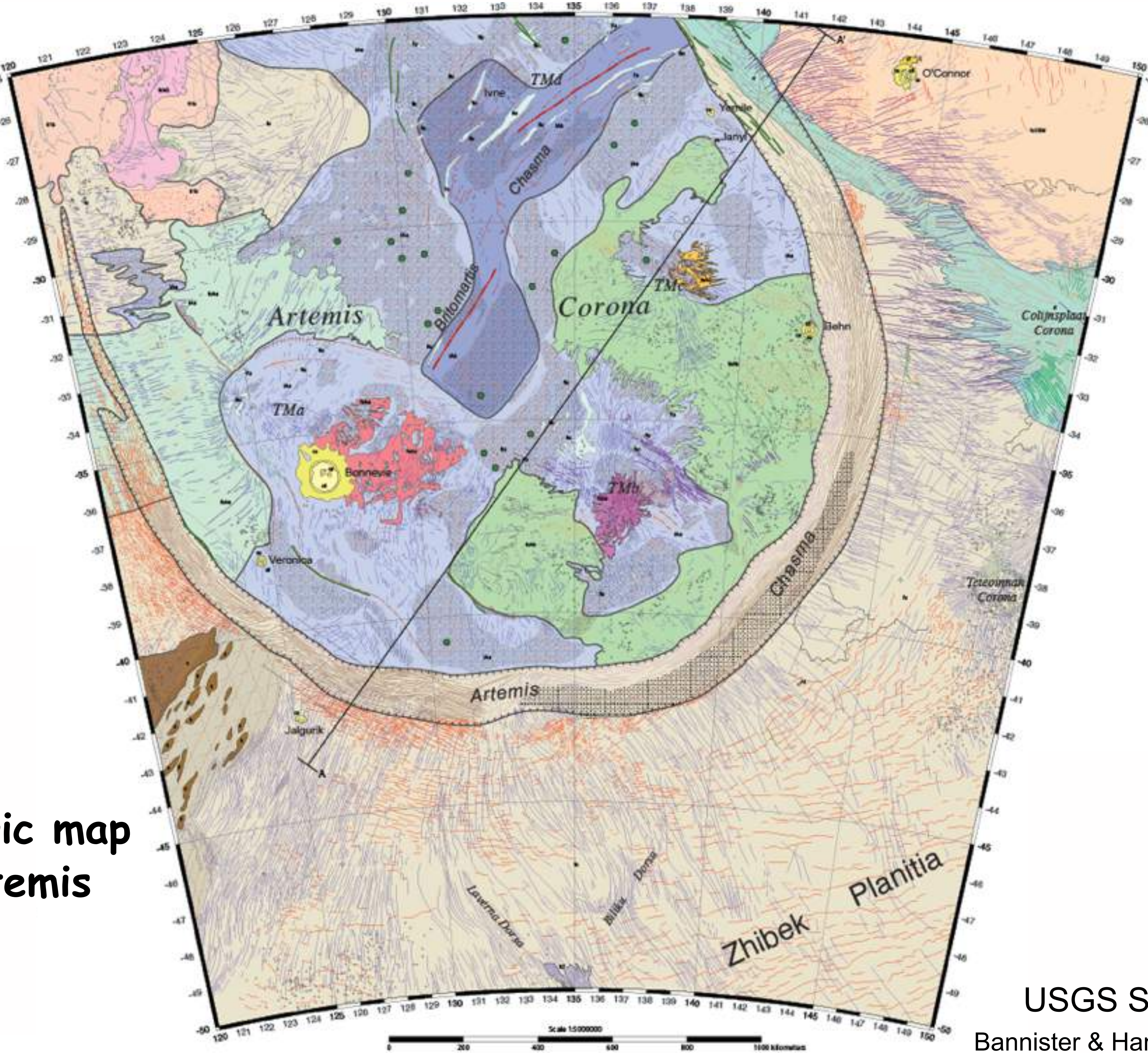


(Hansen & Phillips, Geology 1995)

Ishtar Terra, unique on Venus, is proposed to be supported by massive ponding of mantle melt residuum (based on analysis of gravity & topography data, and surface structural geologic relations interpreted from SAR data).

Artemis Chasma





Geologic map of Artemis

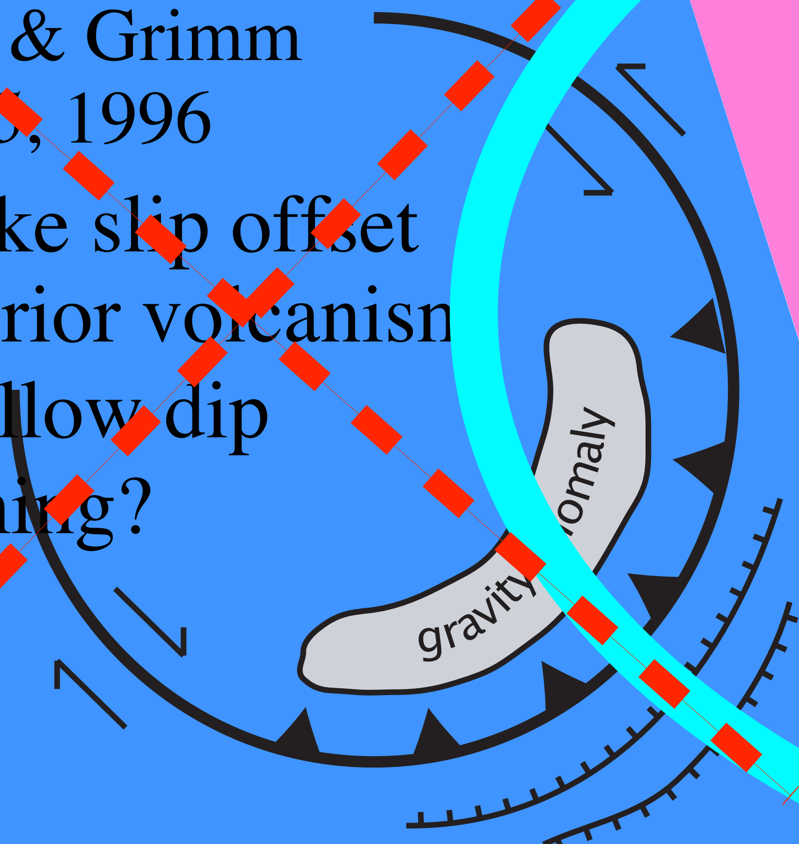
V-48
Artemis
USGS SIM-3099
Bannister & Hansen (2010)

Artemis Hypotheses

I. Subduction

Brown & Grimm
1995, 1996

1. Strike slip offset
2. Interior volcanism
3. Shallow dip
4. Timing?



IV. Mantle Plume

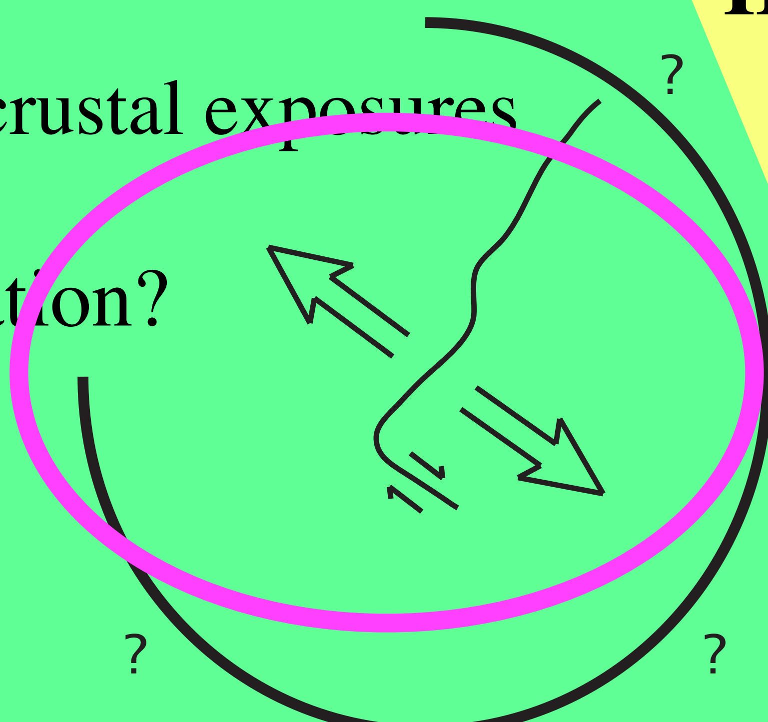
Griffiths & Campbell, 1991
Koch & Manga, 1996
Smerkar & Stofan, 1997
Hansen, 2002

1. Strike slip offset
2. Outward trough movement
3. Temporal relations
4. Thin lithosphere

II. Metamorphic Core Complex

Spencer, 2001

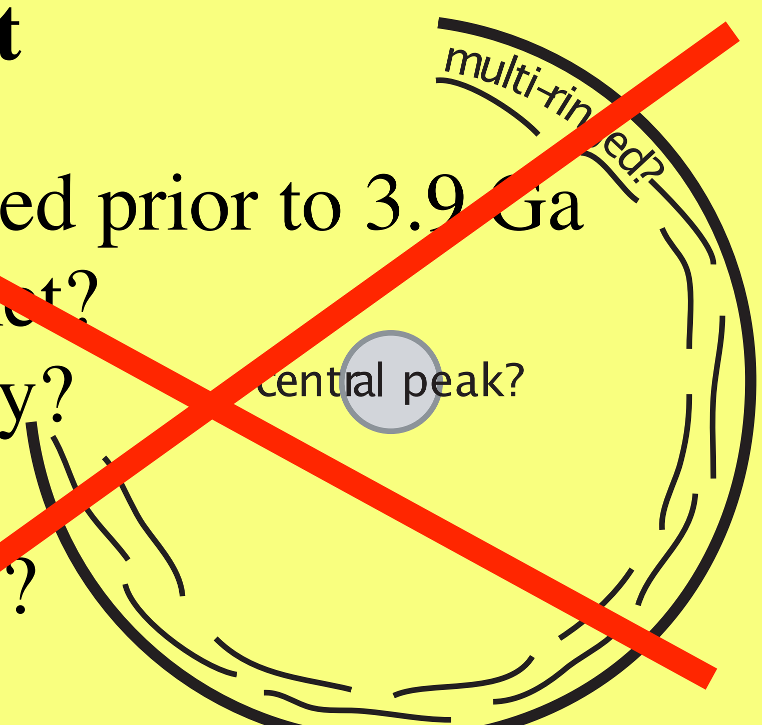
1. Interior deep-crustal exposures
2. Mechanism?
3. Trough formation?

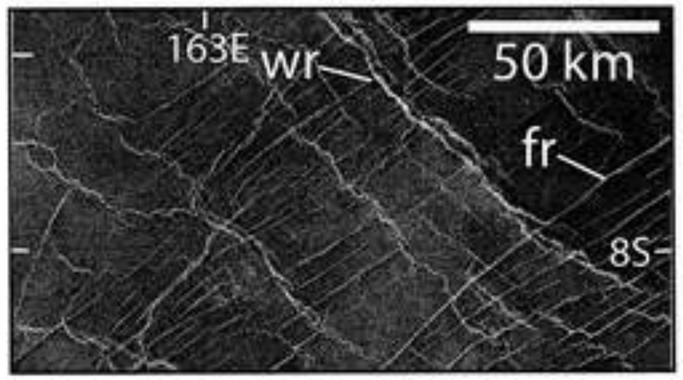


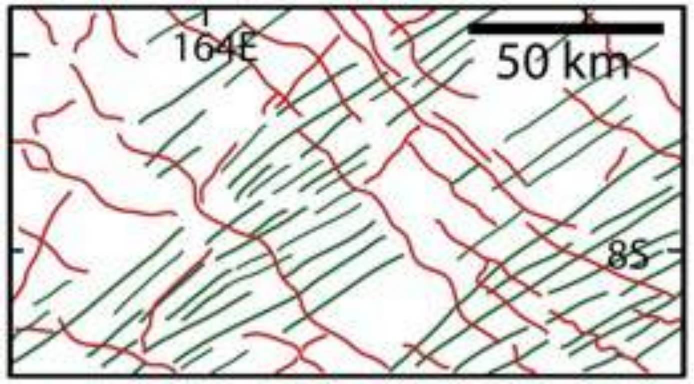
III. Bolide Impact

Hamilton, 2005

1. Artemis formed prior to 3.9 Ga
2. Ejecta blanket?
3. Topography?
4. Interior formation?

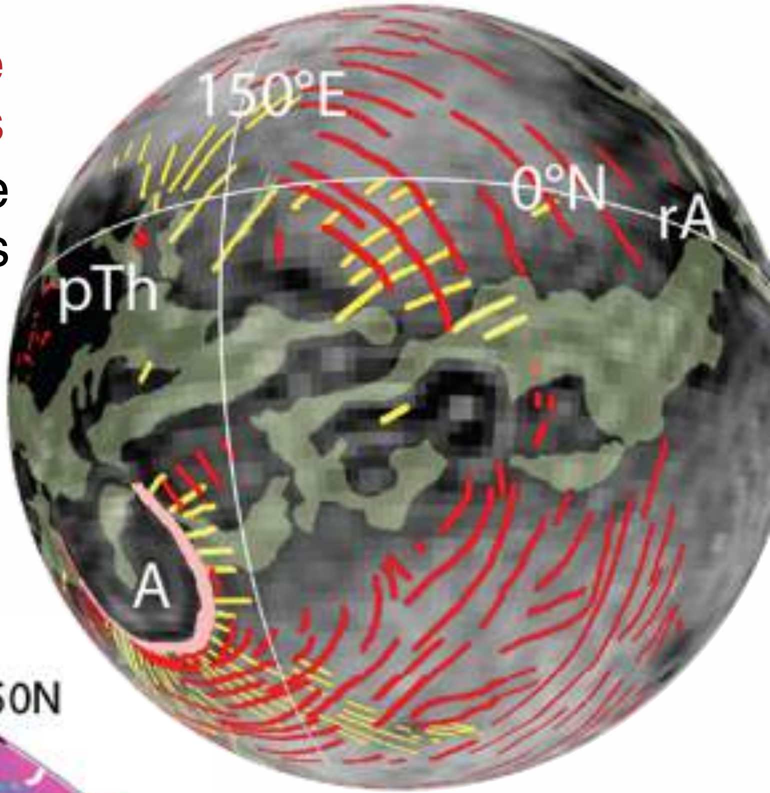




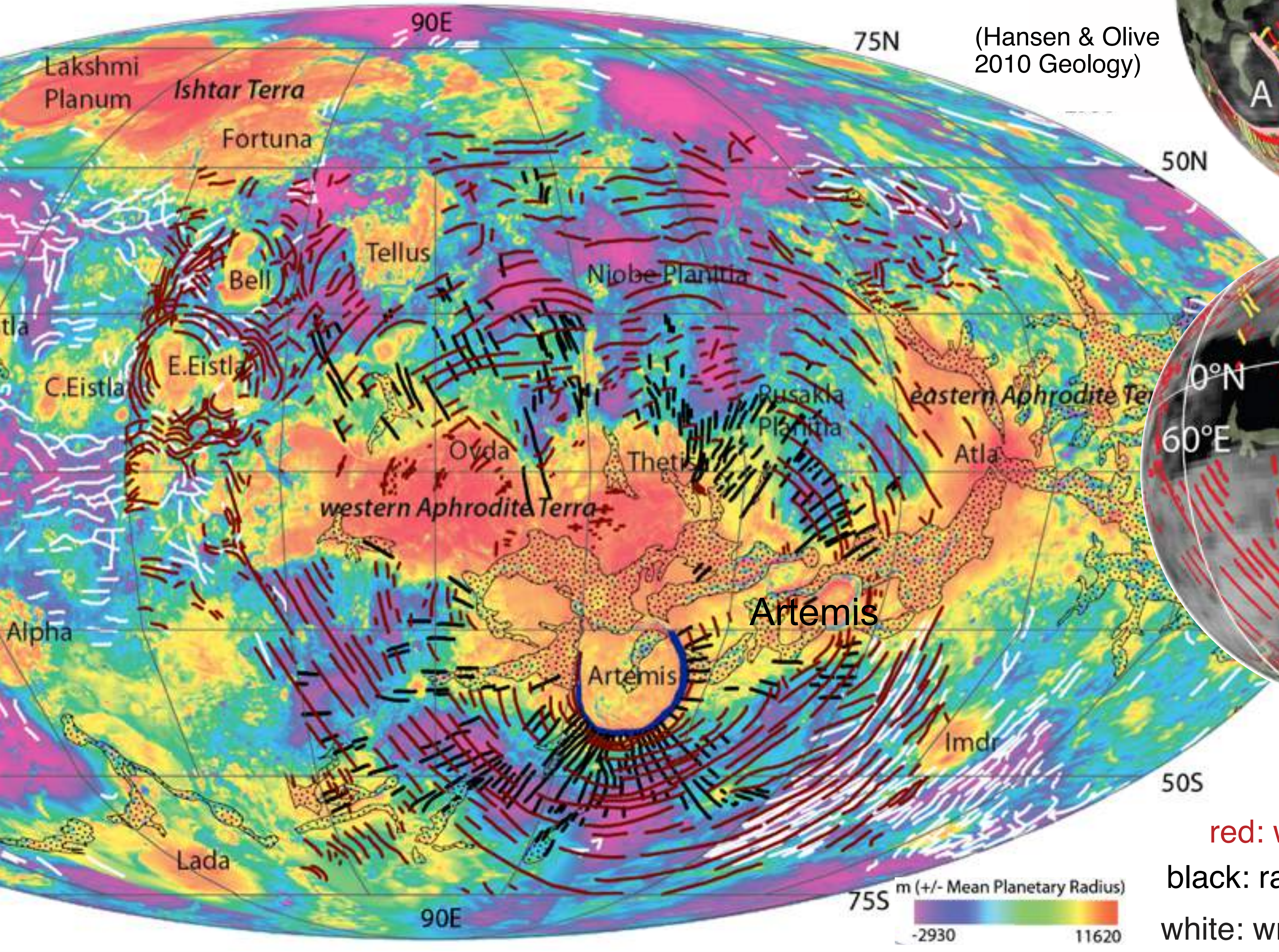


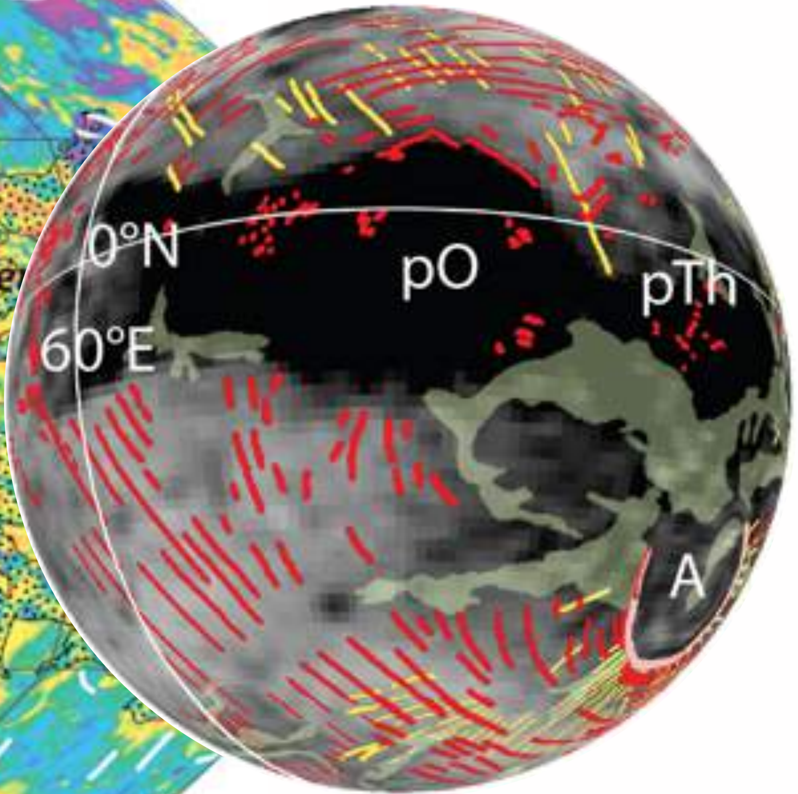
red: wrinkle ridge trajectories

yellow: radial fracture trajectories



(Hansen & Olive 2010 Geology)

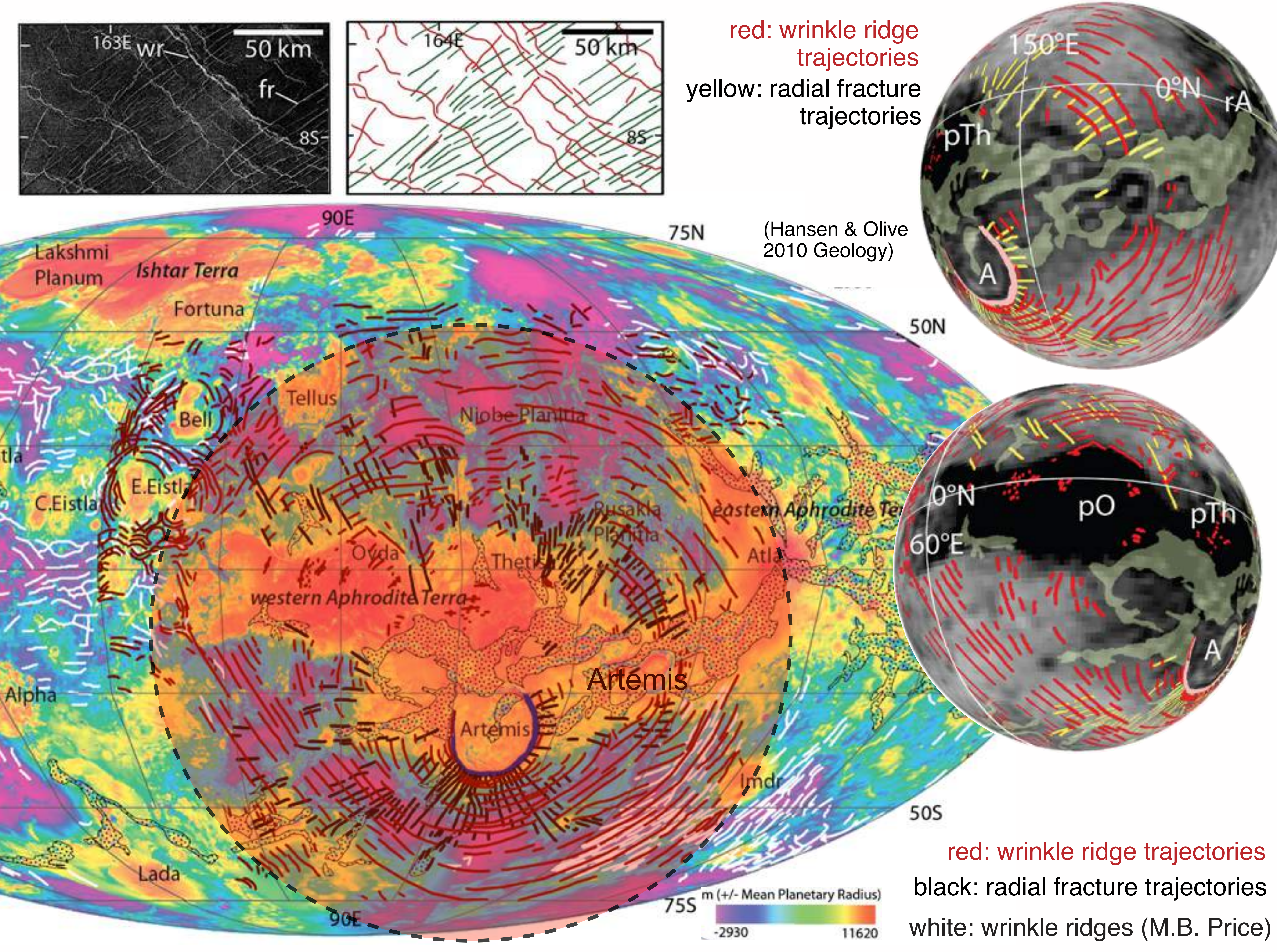




red: wrinkle ridge trajectories

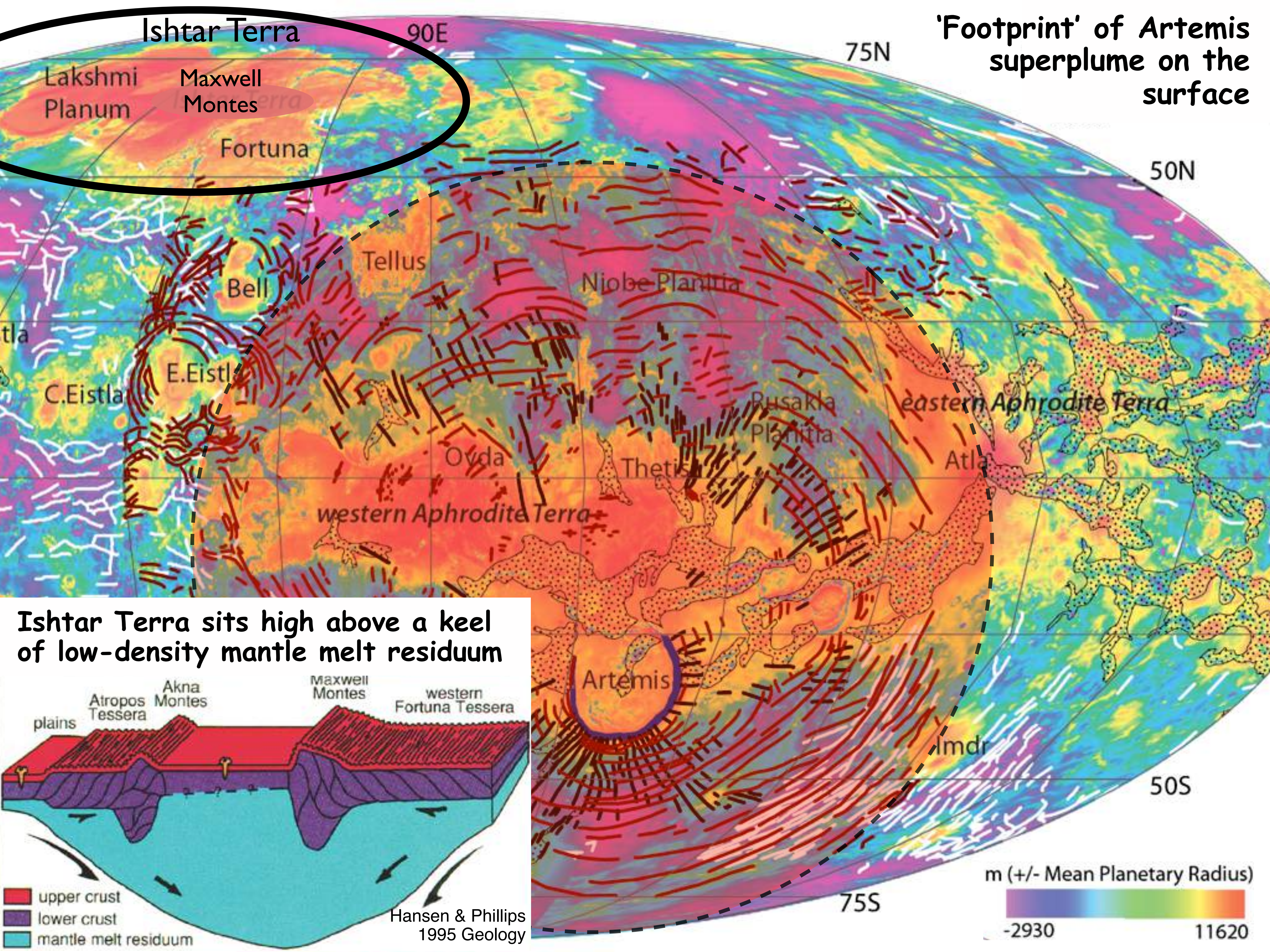
black: radial fracture trajectories

white: wrinkle ridges (M.B. Price)



163E
wr
50 km
fr
8S
164E
50 km
8S
red: wrinkle ridge trajectories
yellow: radial fracture trajectories
150°E
0°N
rA
pTh
A
(Hansen & Olive 2010 Geology)
90E
75N
Lakshmi Planum
Ishtar Terra
Fortuna
50N
Tellus
Bell
Niobe Planitia
E.Eistla
C.Eistla
Rusalka Planitia
eastern Aphrodite Terra
Ovda
Thetis
Atla
western Aphrodite Terra
Artemis
Artemis
Alpha
Imdr
Lada
50S
75S
90E
m (+/- Mean Planetary Radius)
-2930
11620
0°N
60°E
pO
pTh
A
red: wrinkle ridge trajectories
black: radial fracture trajectories
white: wrinkle ridges (M.B. Price)

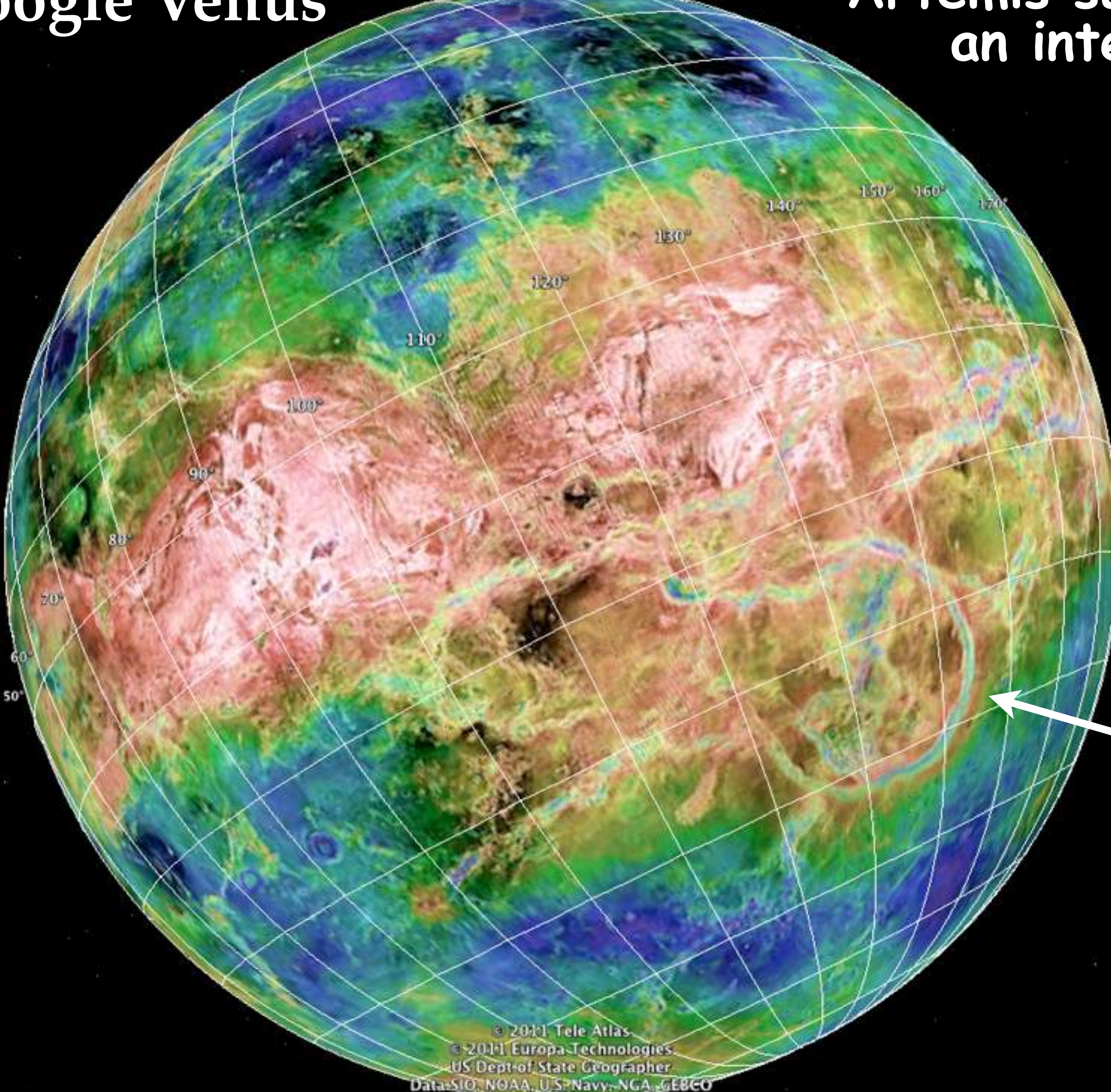
'Footprint' of Artemis superplume on the surface



Ishtar Terra sits high above a keel of low-density mantle melt residuum

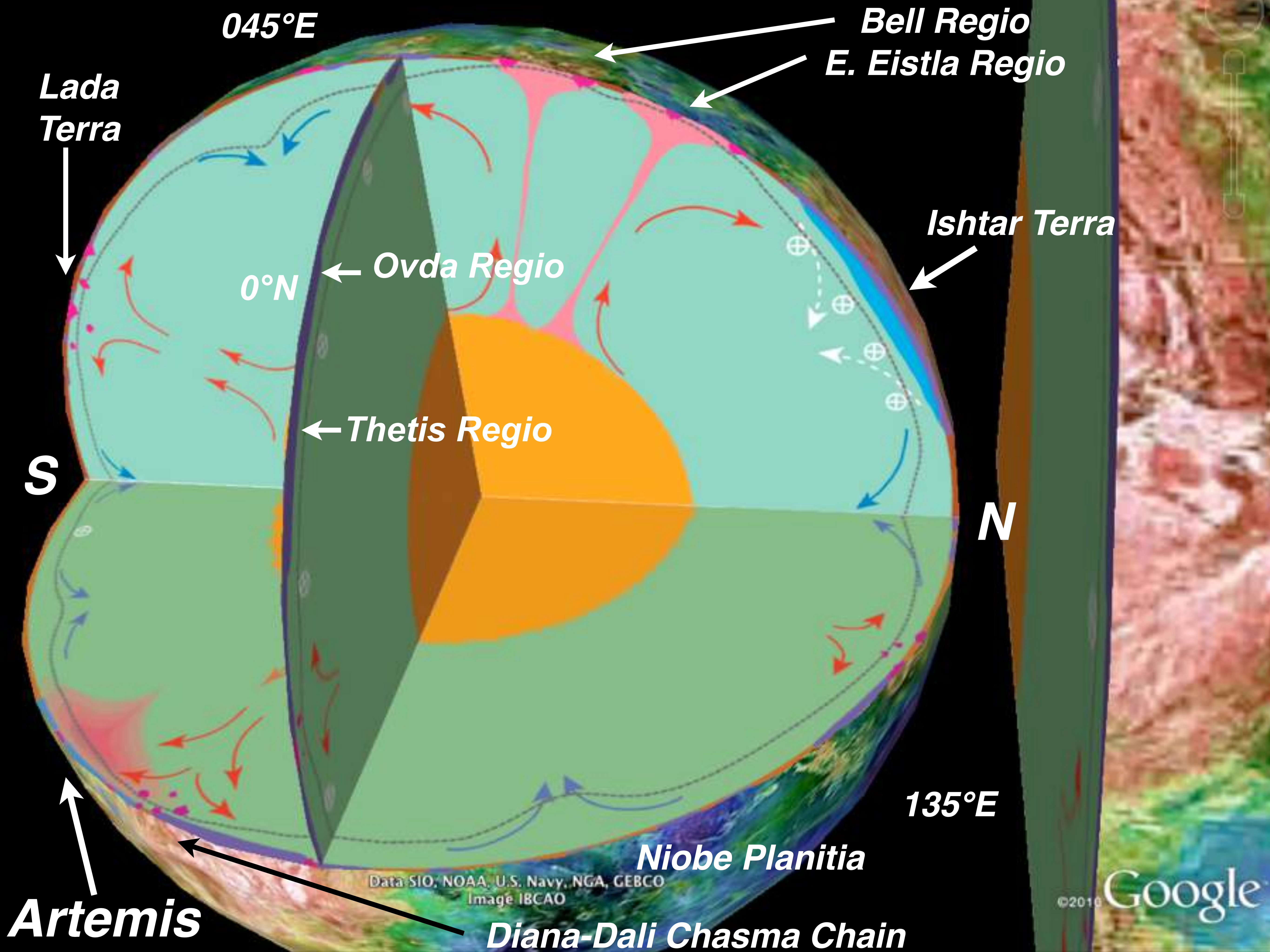
Google Venus

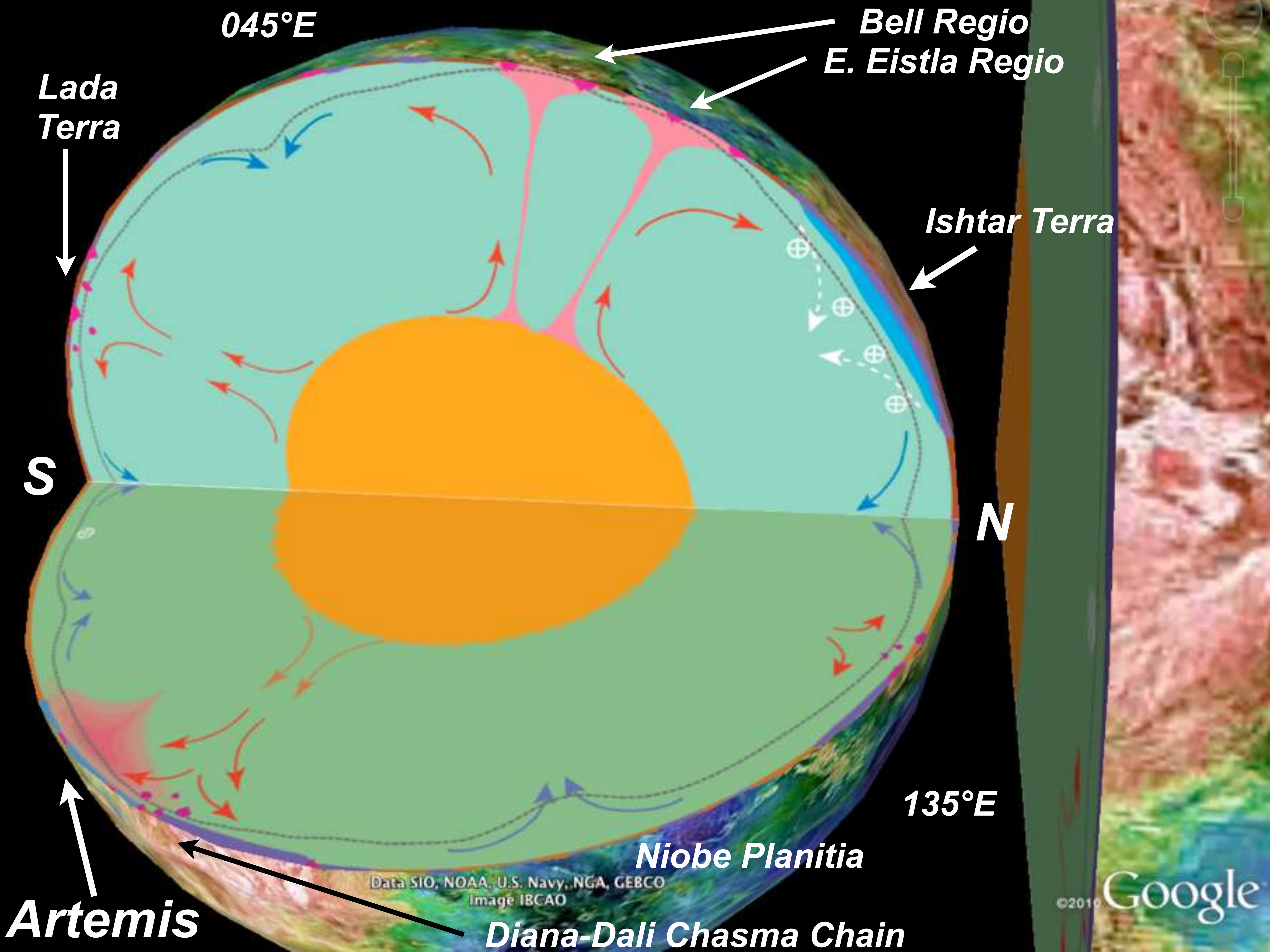
Artemis superplume — an interior view...

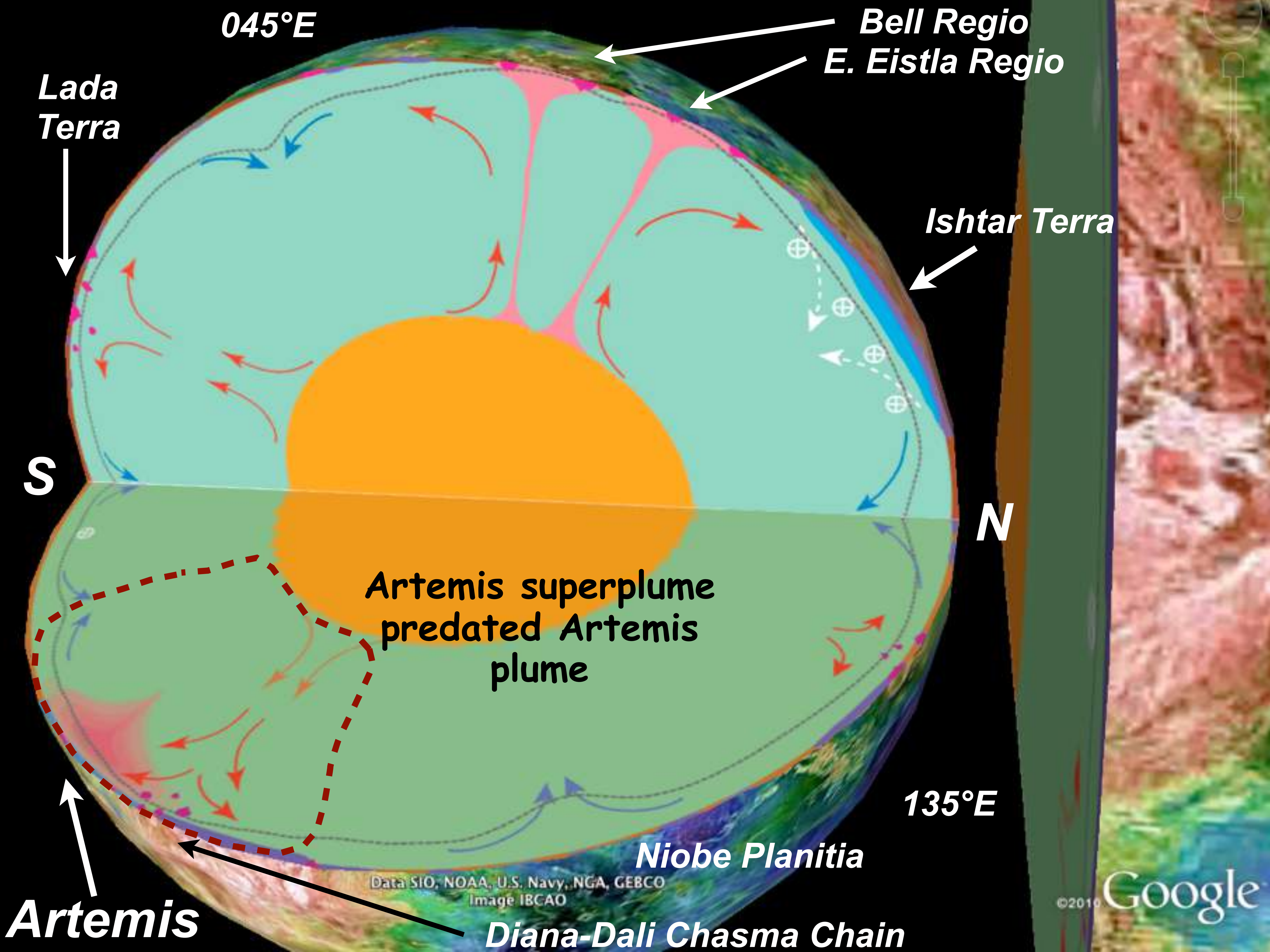


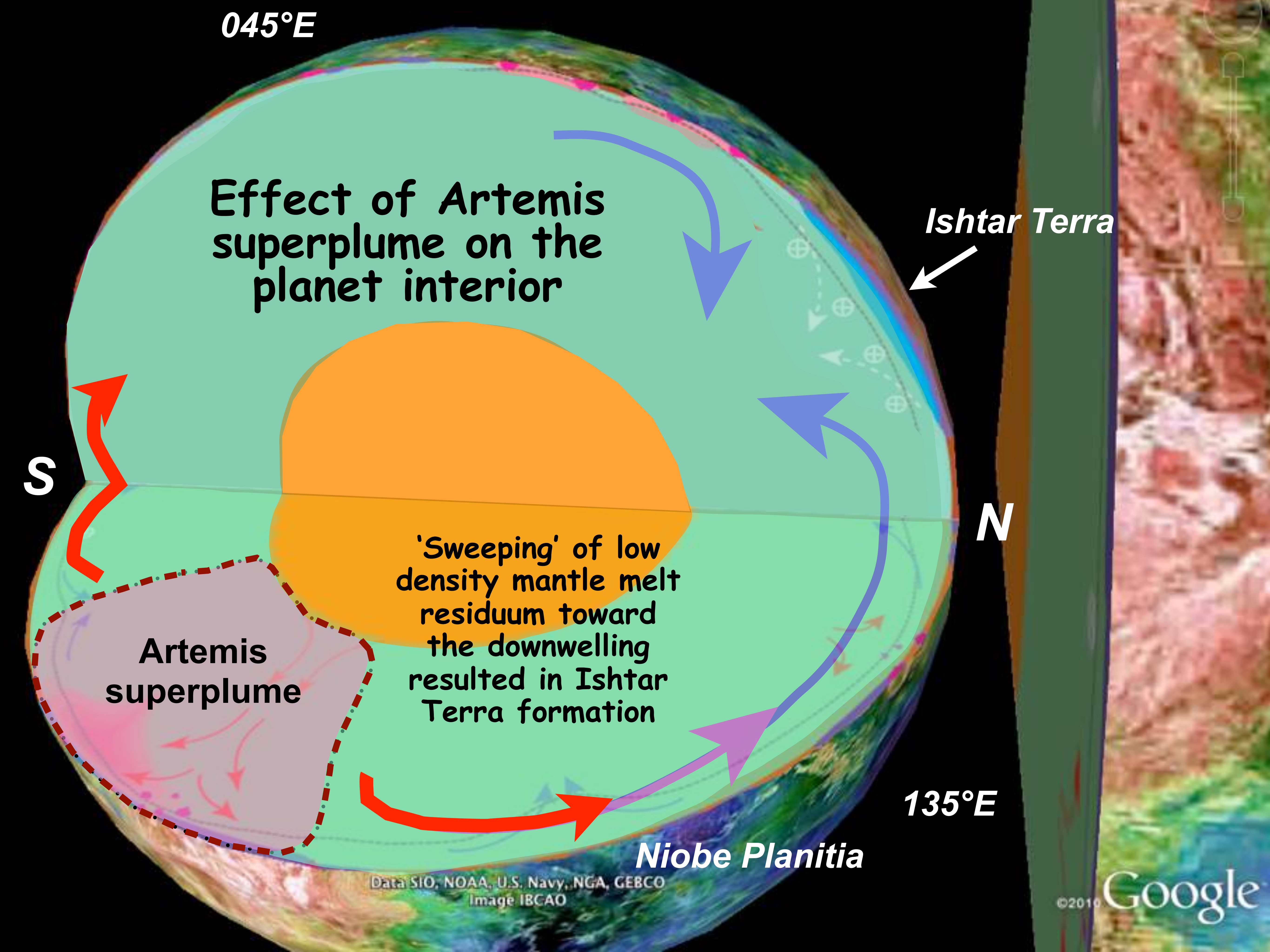
Artemis

Created by:
Declan De Paor
Mladen Dordevic
Vicki Hansen
(2012)

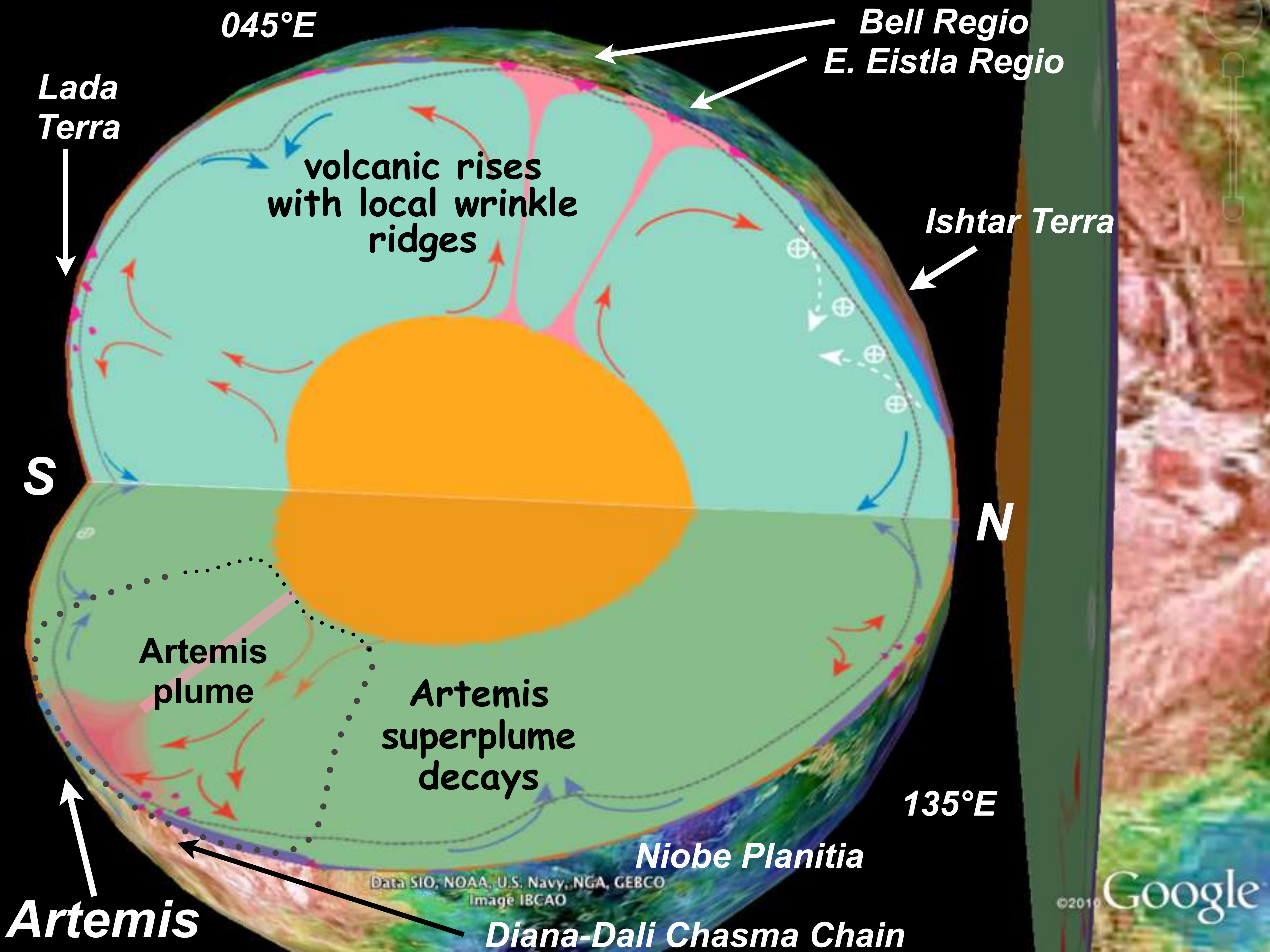

045°E
Bell Regio
E. Eistla Regio
Lada Terra
Ishtar Terra
Ovda Regio
0°N
Thetis Regio
S
N
135°E
Niobe Planitia
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image IBCAO
Artemis
Diana-Dali Chasma Chain
Google


045°E
Bell Regio
E. Eistla Regio
Lada
Terra
Ishtar Terra
S
N
135°E
Niobe Planitia
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image IBCAO
©2010
Google
Artemis
Diana-Dali Chasma Chain

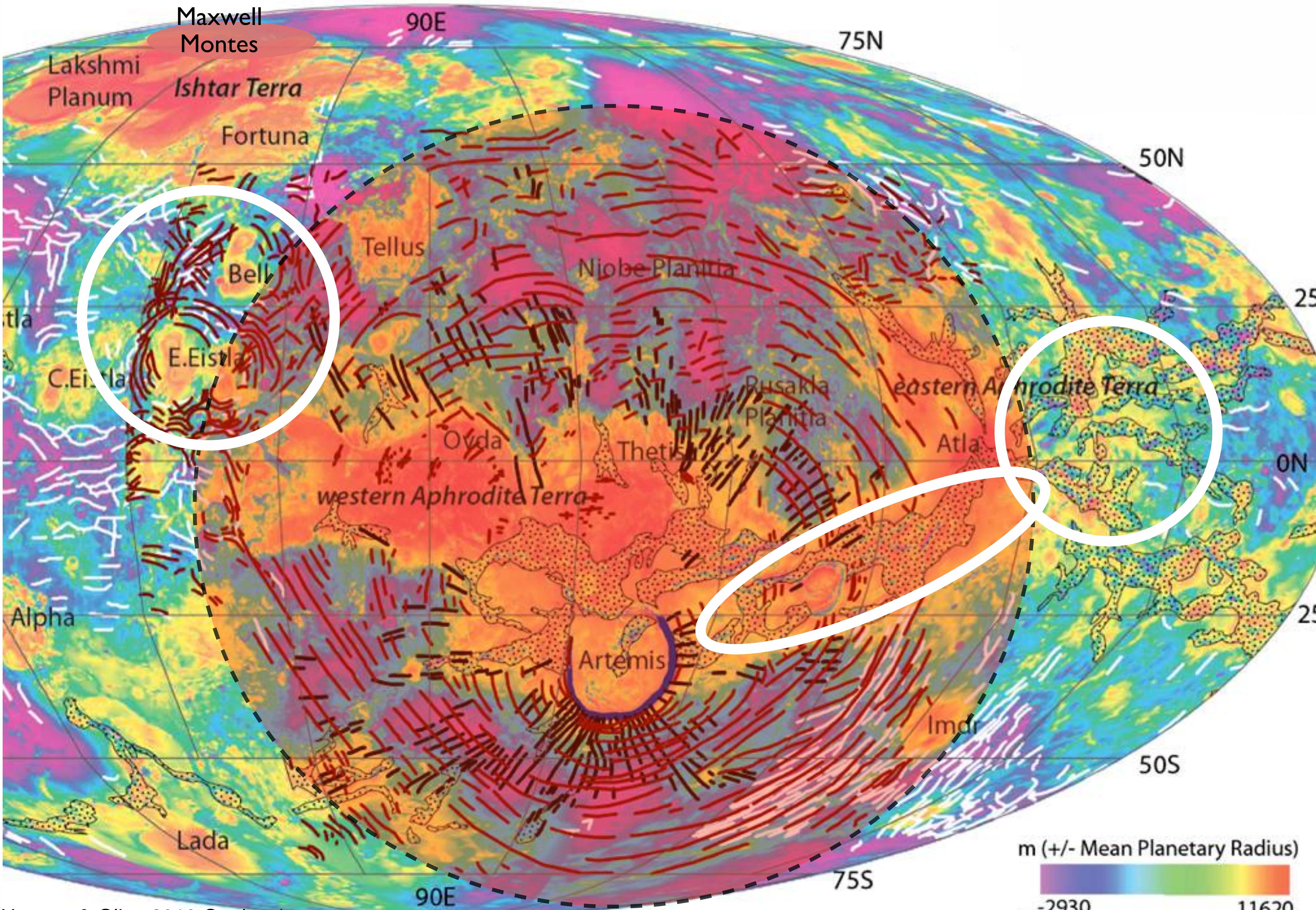

045°E
Bell Regio
E. Eistla Regio
Lada
Terra
Ishtar Terra
S
N
Artemis superplume
predated Artemis
plume
135°E
Niobe Planitia
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image IBCAO
©2010 Google
Artemis
Diana-Dali Chasma Chain



045°E
Effect of Artemis superplume on the planet interior
Ishtar Terra
S
N
'Sweeping' of low density mantle melt residuum toward the downwelling resulted in Ishtar Terra formation
Artemis superplume
135°E
Niobe Planitia
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image IBCAO
©2010 Google

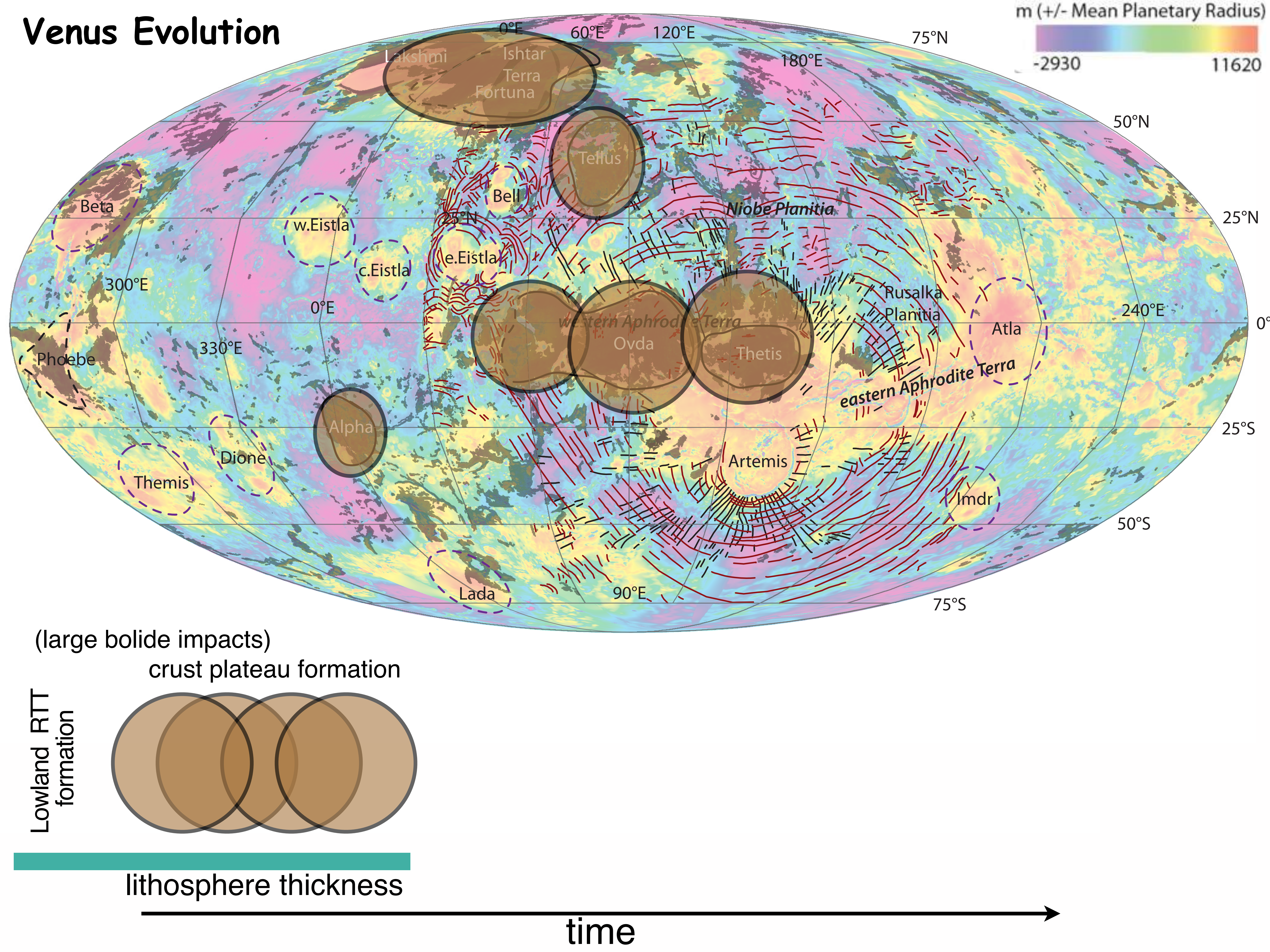

045°E
Bell Regio
E. Eistla Regio
Lada Terra
volcanic rises with local wrinkle ridges
Ishtar Terra
S
N
Artemis plume
Artemis superplume decays
135°E
Niobe Planitia
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image IBCAO
©2010 Google
Artemis
Diana-Dali Chasma Chain

Artemis superplume 'footprint' provides a 'near global' time marker

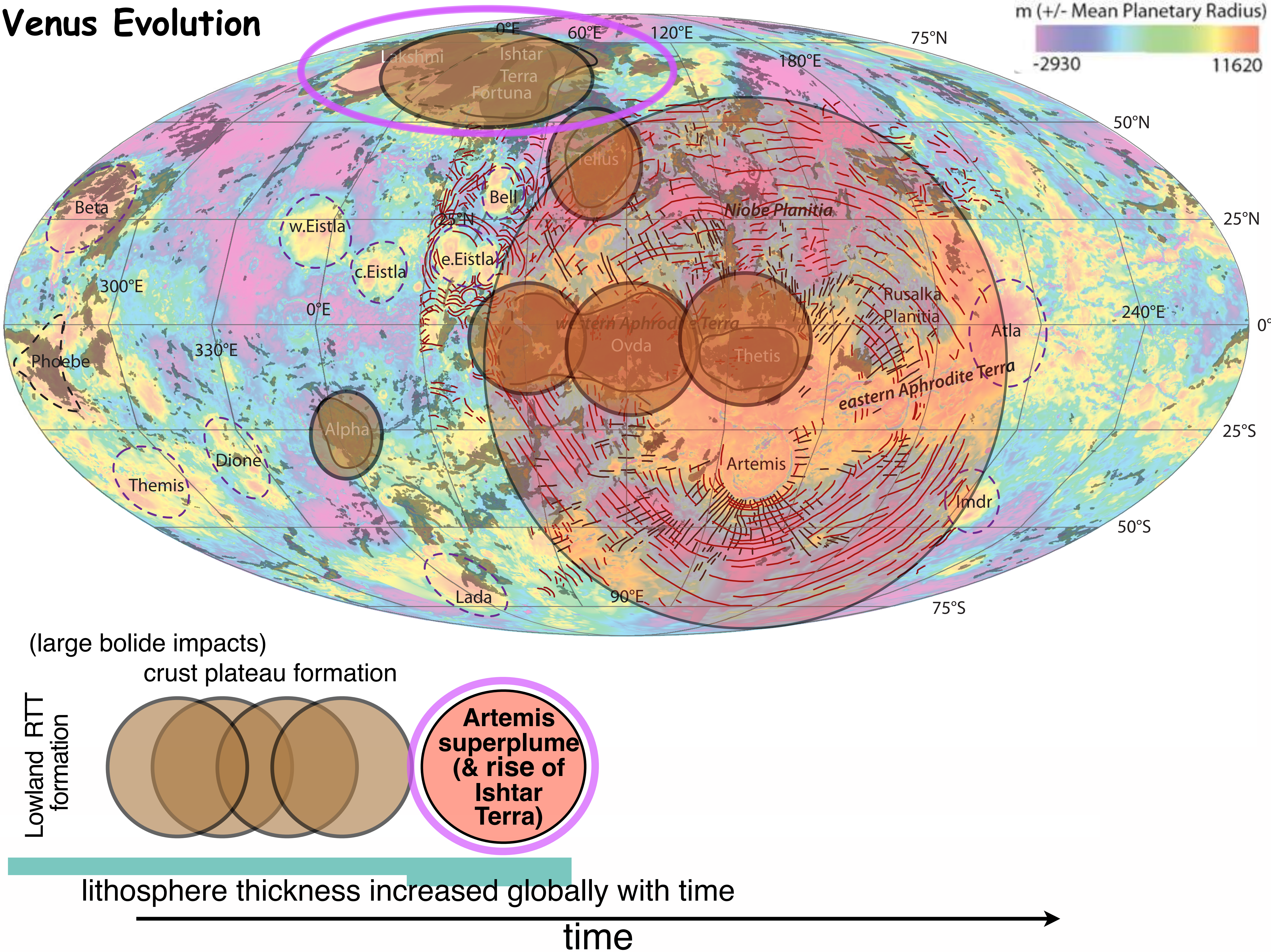


(Hansen & Olive 2010 Geology)

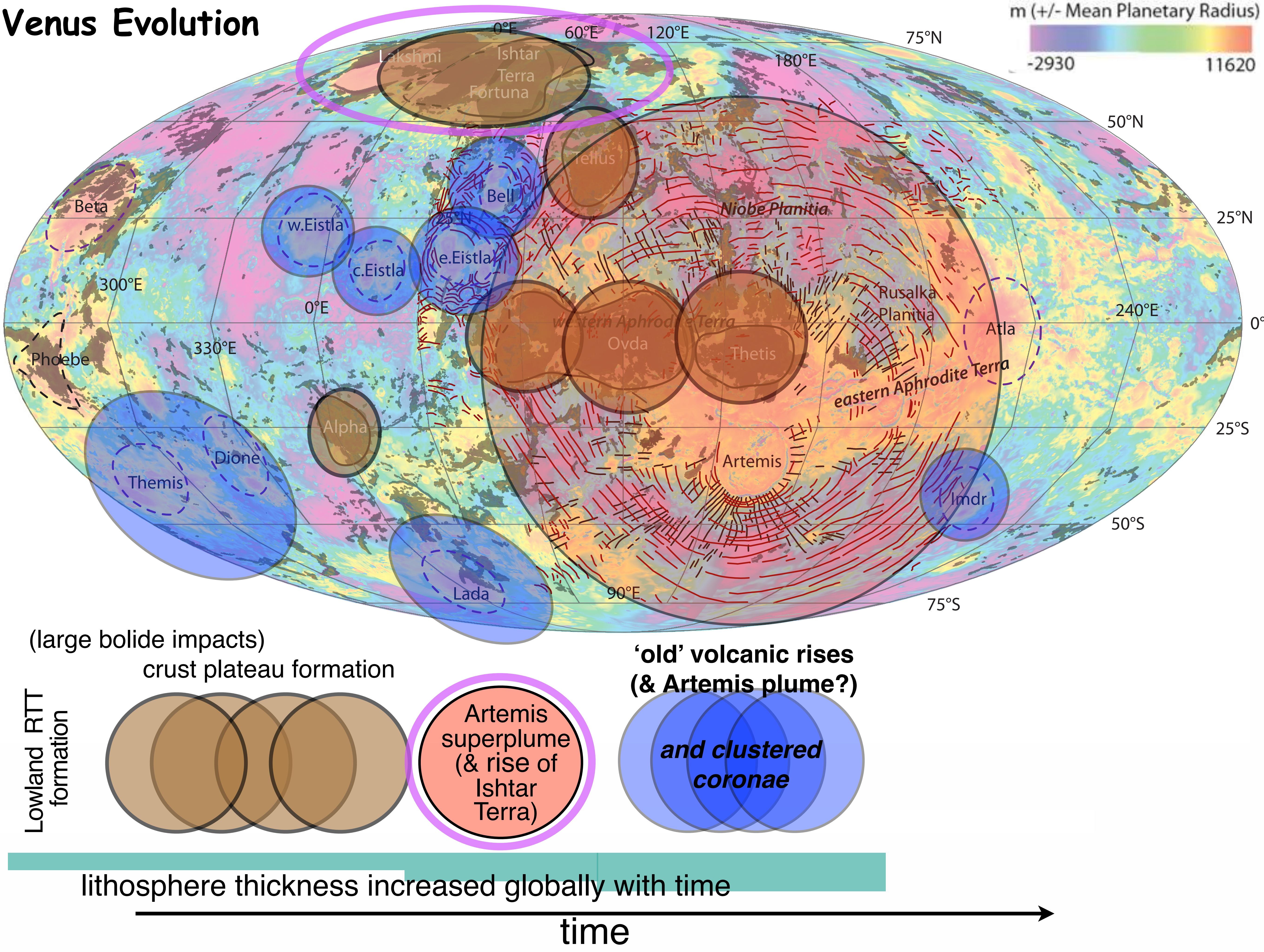
Venus Evolution



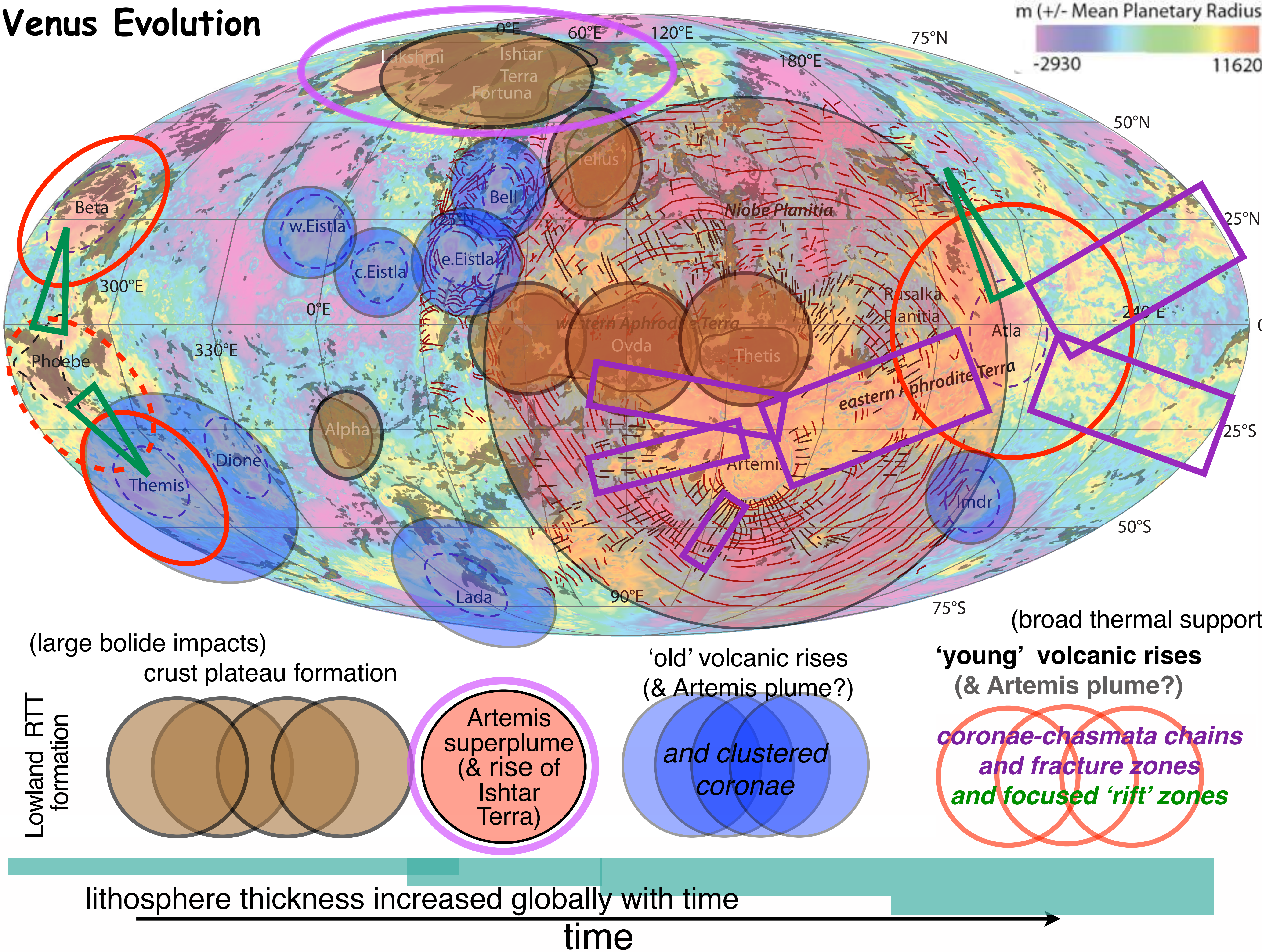
Venus Evolution



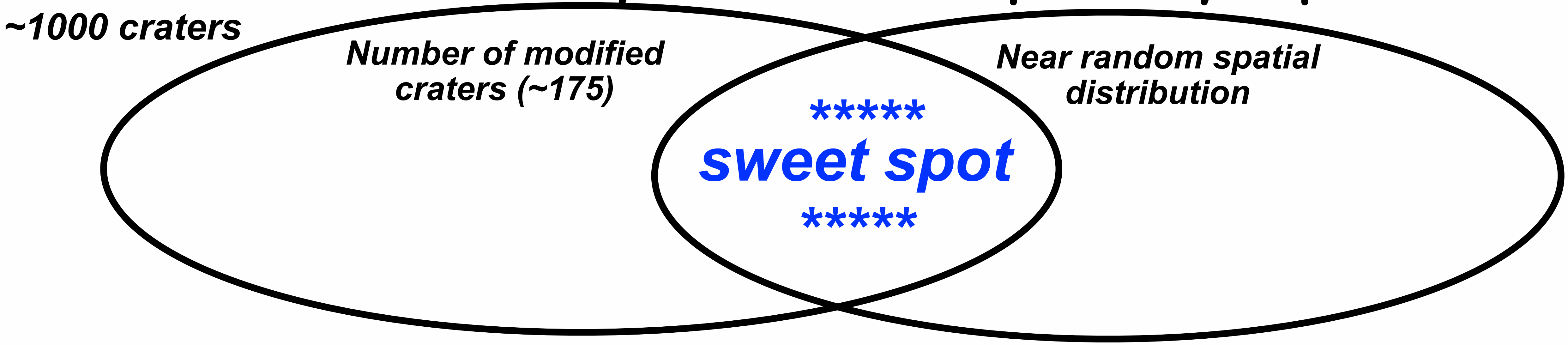
Venus Evolution



Venus Evolution



Venus surface history constraints imposed by impact craters



'catastrophic resurfacing'
short-duration events across a large spatial areas occur in random locations with large time intervals between events.

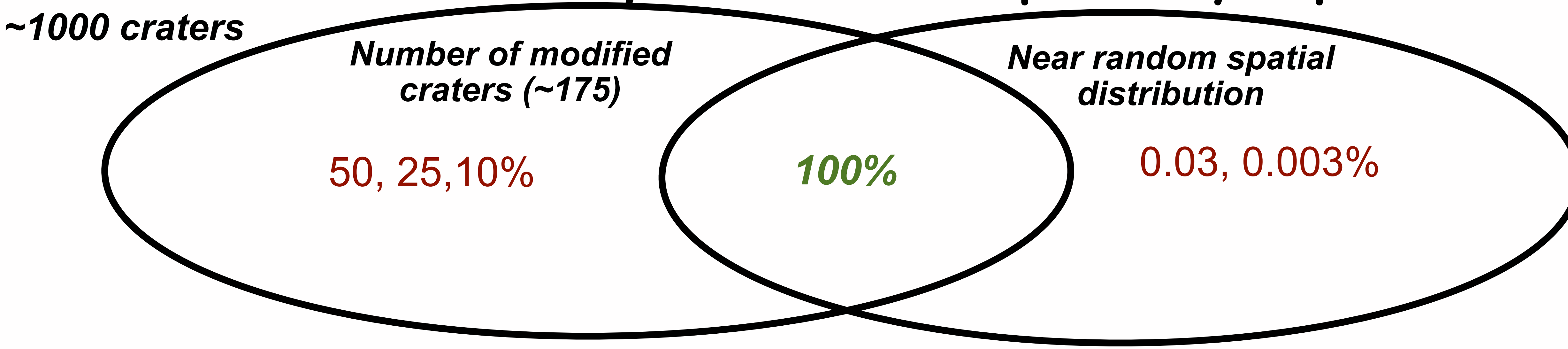
Requires: craters occur at the top of stratigraphic piles; that is craters are the youngest geologic event.

'equilibrium resurfacing'
frequently occurring, randomly distributed resurfacing events across small spatial areas.

'steady-state resurfacing'

'uniformitarian resurfacing'

Venus surface history constraints imposed by impact craters



Monte Carlo model results:
'catastrophic resurfacing required'
(Strom et al. 1994 JGR)

However, Monte Carlo studies can only test if specify models are viable, they cannot comment on histories not modeled...

And there are various potential problems with this analysis...

1. Additional geological constraints emerged from further study of crater morphology and density, and study of detailed crater topography.

2. Note huge 'jump' in resurfacing parameter space explored — **from 10% to 0.03%.**

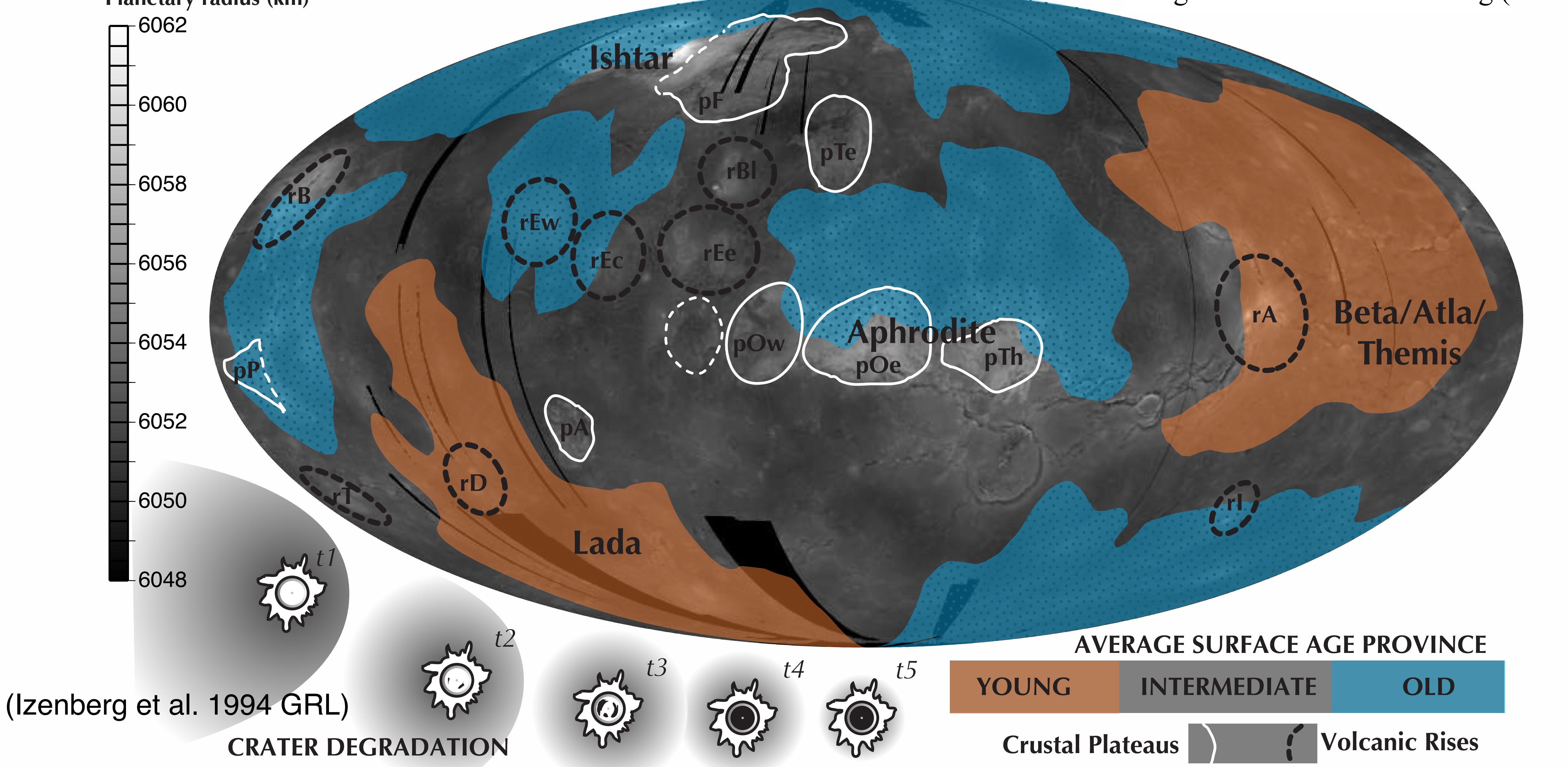
3. Bond & Warner (2006 LPSC) showed that histories with ***changes in resurfacing rate*** can also accommodate the statistical crater constraints...

Additional geological data impose different/new/additional constraints...

Average Model Surface Ages (AMSA) based on crater density & morphology

data from Phillips & Izenberg (1995) and Herrick et al. (1997)

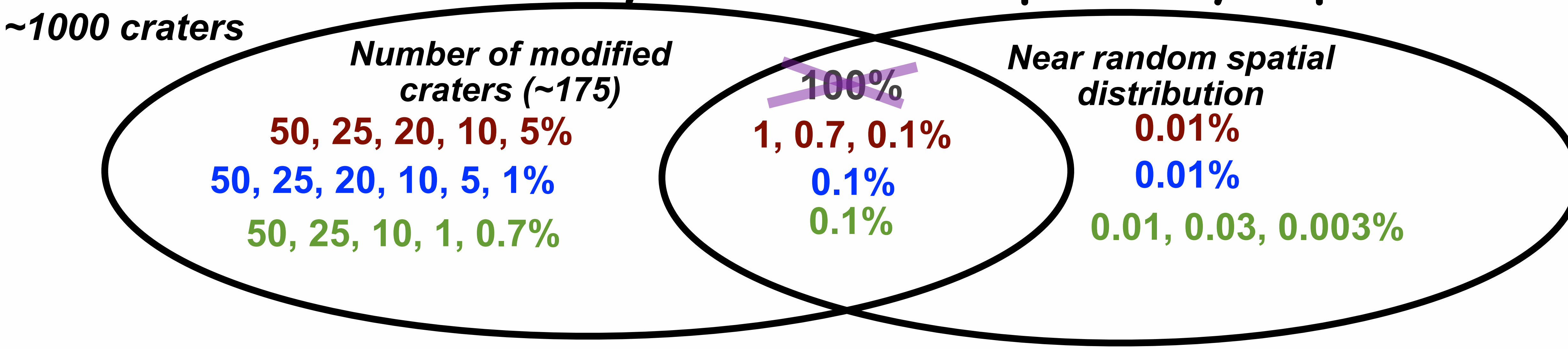
figure after Hansen & Young (2007)



- **Venus' surface preserves 3 different relative AMSA provinces (not just one)**
- **Mapping of craters (using high-resolution DEMs)** shows that the number of modified craters is significantly higher than previously recognized; and **many craters are not at the top of the stratigraphic pile** (Herrick & Rumpf 2011)

These results are inconsistent with catastrophic resurfacing hypotheses

Venus surface history constraints imposed by impact craters

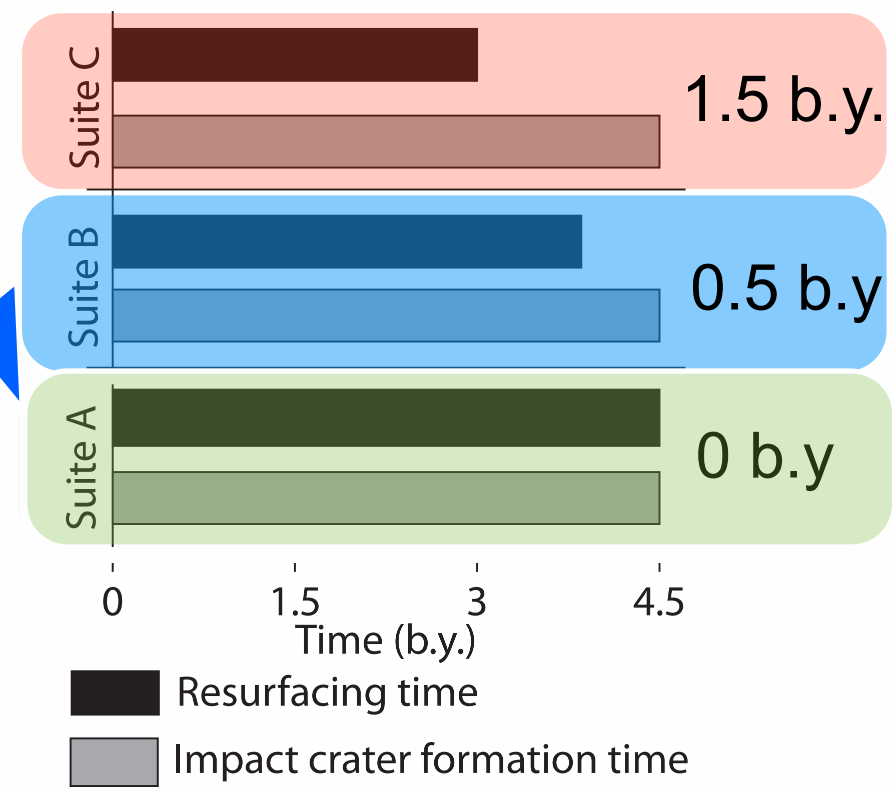


Geologic constraints from crater morphology & density indicate that Venus is divisible into 3 AMSA provinces, and many craters are not at the top of the stratigraphic pile; therefore 100% resurfacing-a.k.a. 'catastrophic resurfacing' is not valid.

Monte Carlo modeling with changes in resurfacing rate can accommodate the statistical crater constraints (Bond & Warner 2006)

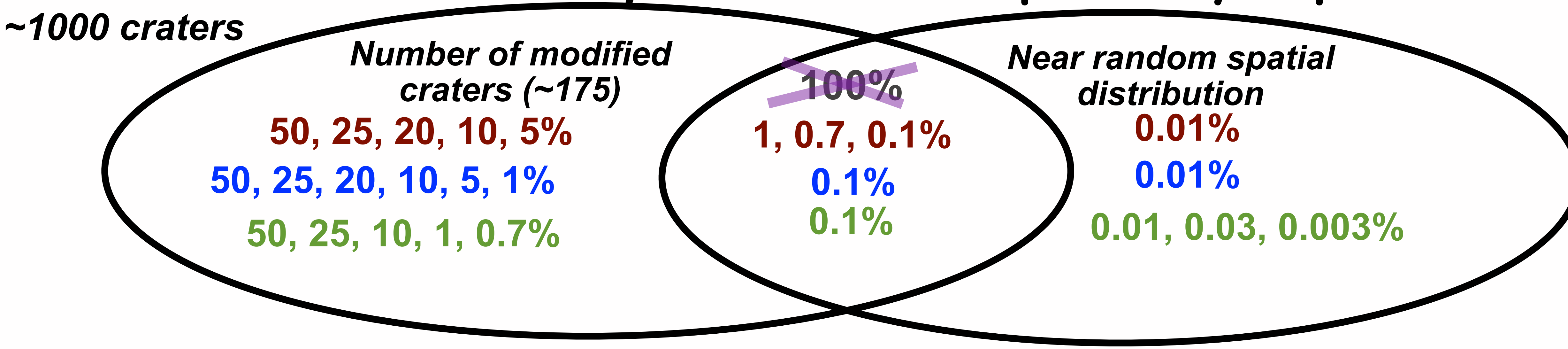
***Monte Carlo modeling of different histories of 'steady-state resurfacing*'** shows catastrophic resurfacing is not required (Bjonnes et al. 2012); varied resurfacing rates, and addressed missing parameter space

Monte Carlo modeling of two types of volcanic resurfacing shows catastrophic resurfacing is not required (O'Rouke et al. 2014)



(Bjonnes et al. Icarus 2012)

Venus surface history constraints imposed by impact craters



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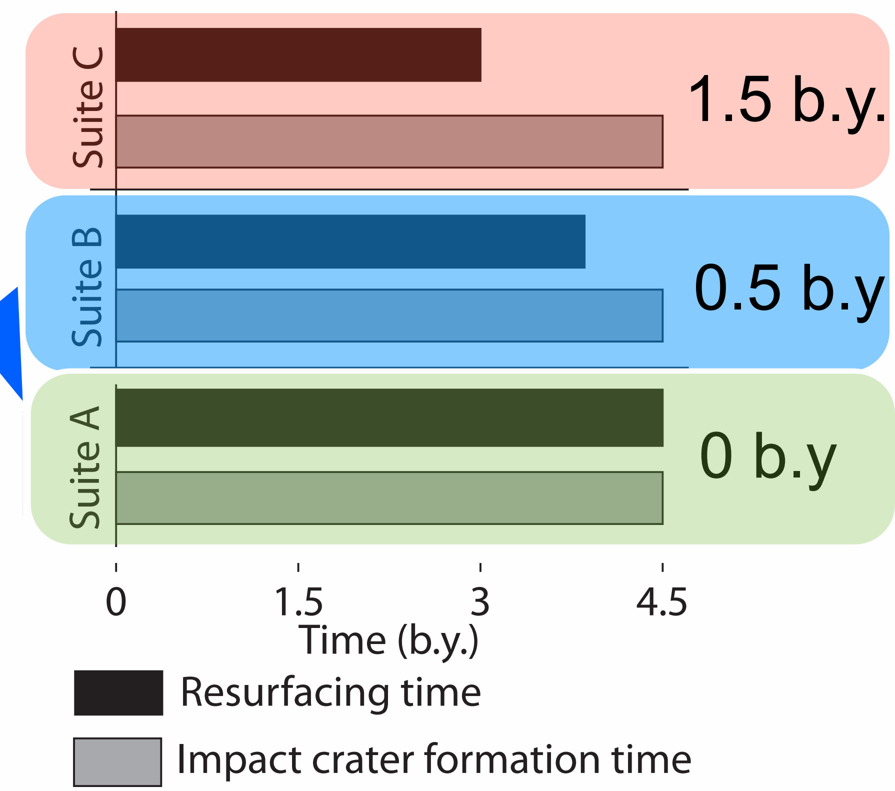


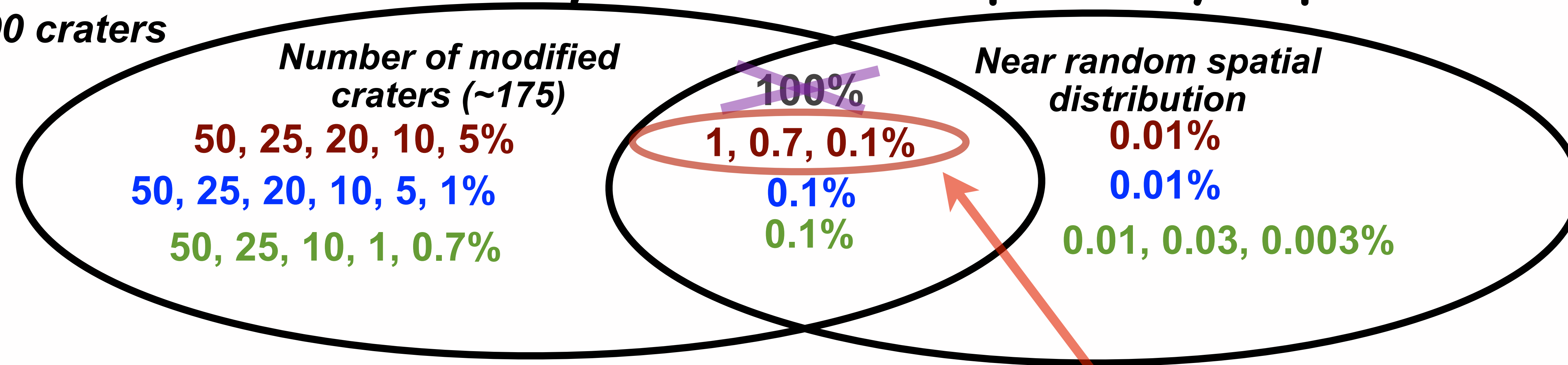
(Bjonnes et al. Icarus 2012)

Several geologic histories can accommodate constraints imposed by the impact crater population...

What clues might geologic relations provide?’

Venus surface history constraints imposed by impact craters

~1000 craters



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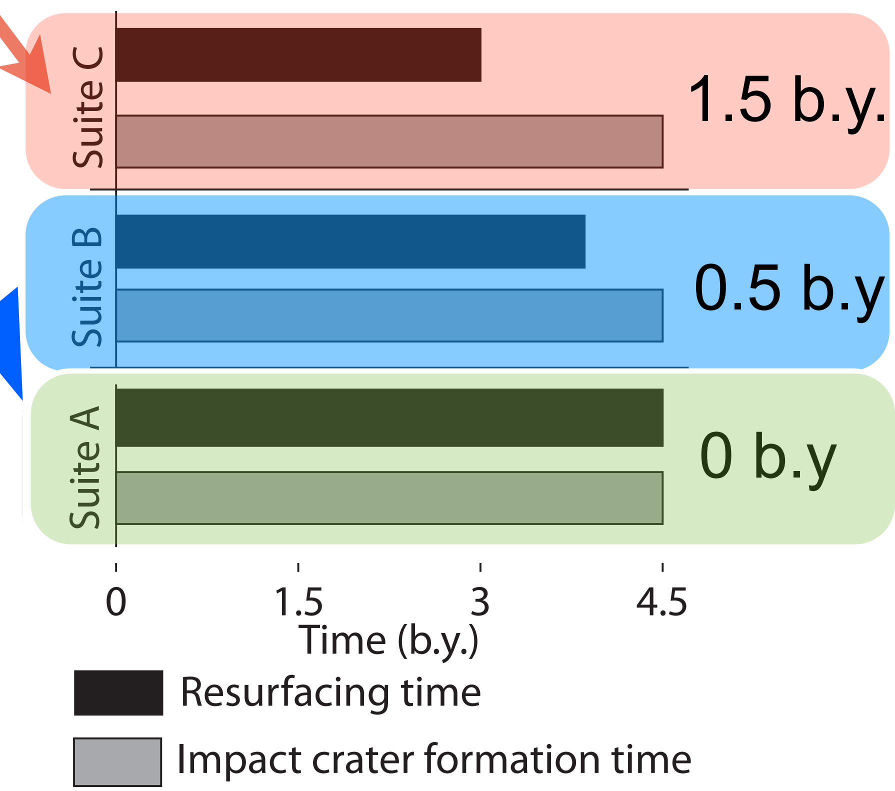
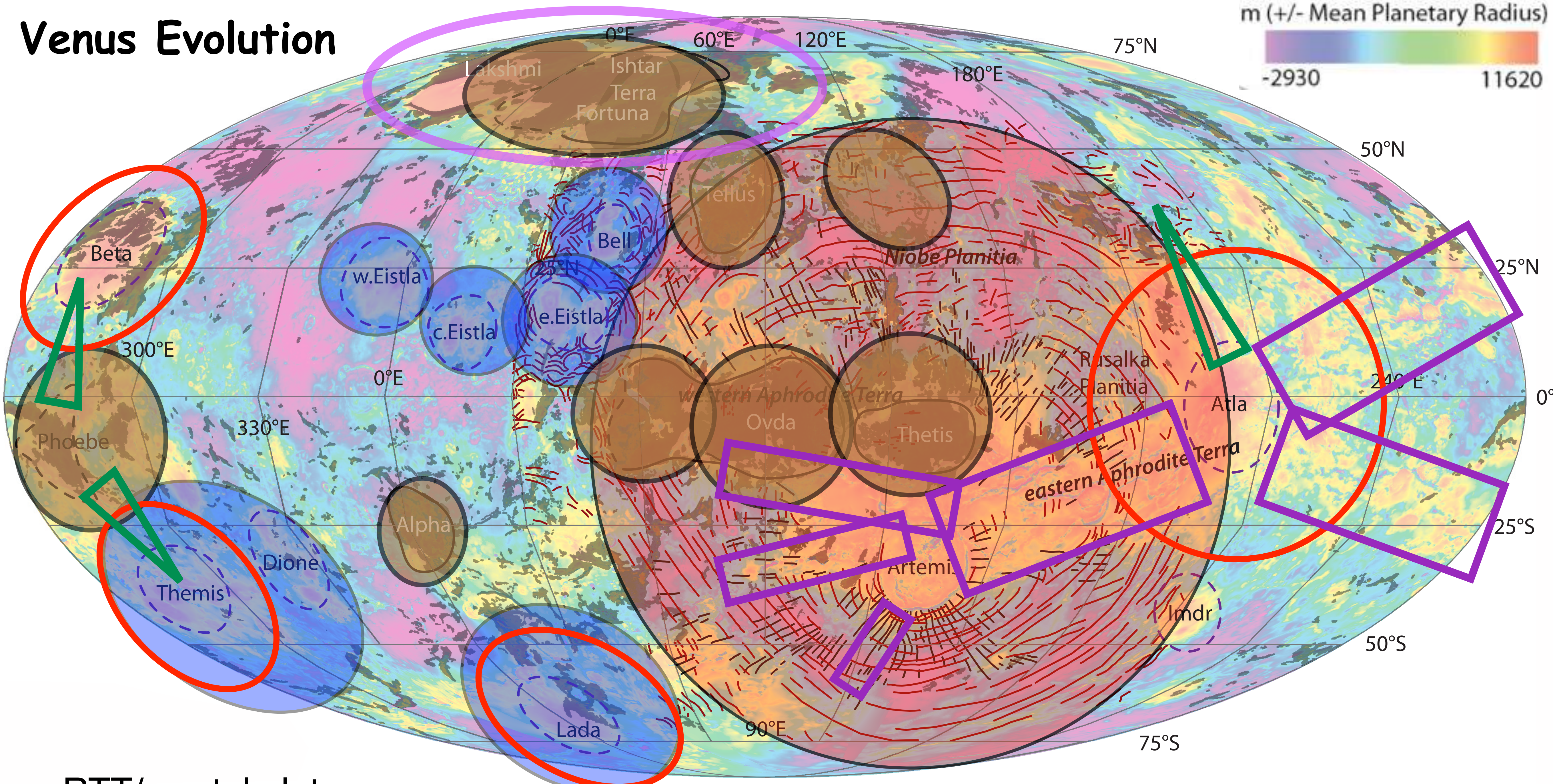


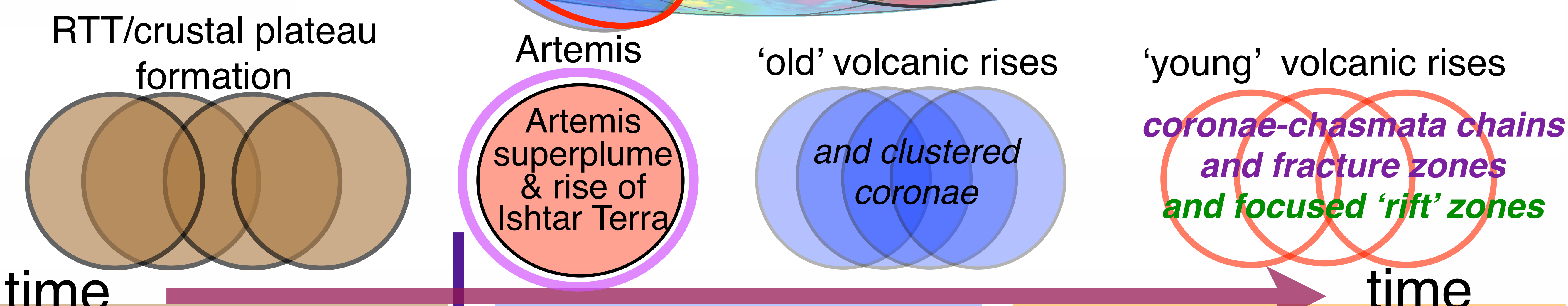
(Bjonnes et al. Icarus 2012)

Individual crustal plateaus formed early in Venus' history; these features completely destroyed pre-existing craters in their local areas; and they cover individual areas of ~2-5 million km^2, or, ~1 to 0.4% of the surface

Early steady-state resurfacing: thin lithosphere & large bolides

Venus Evolution



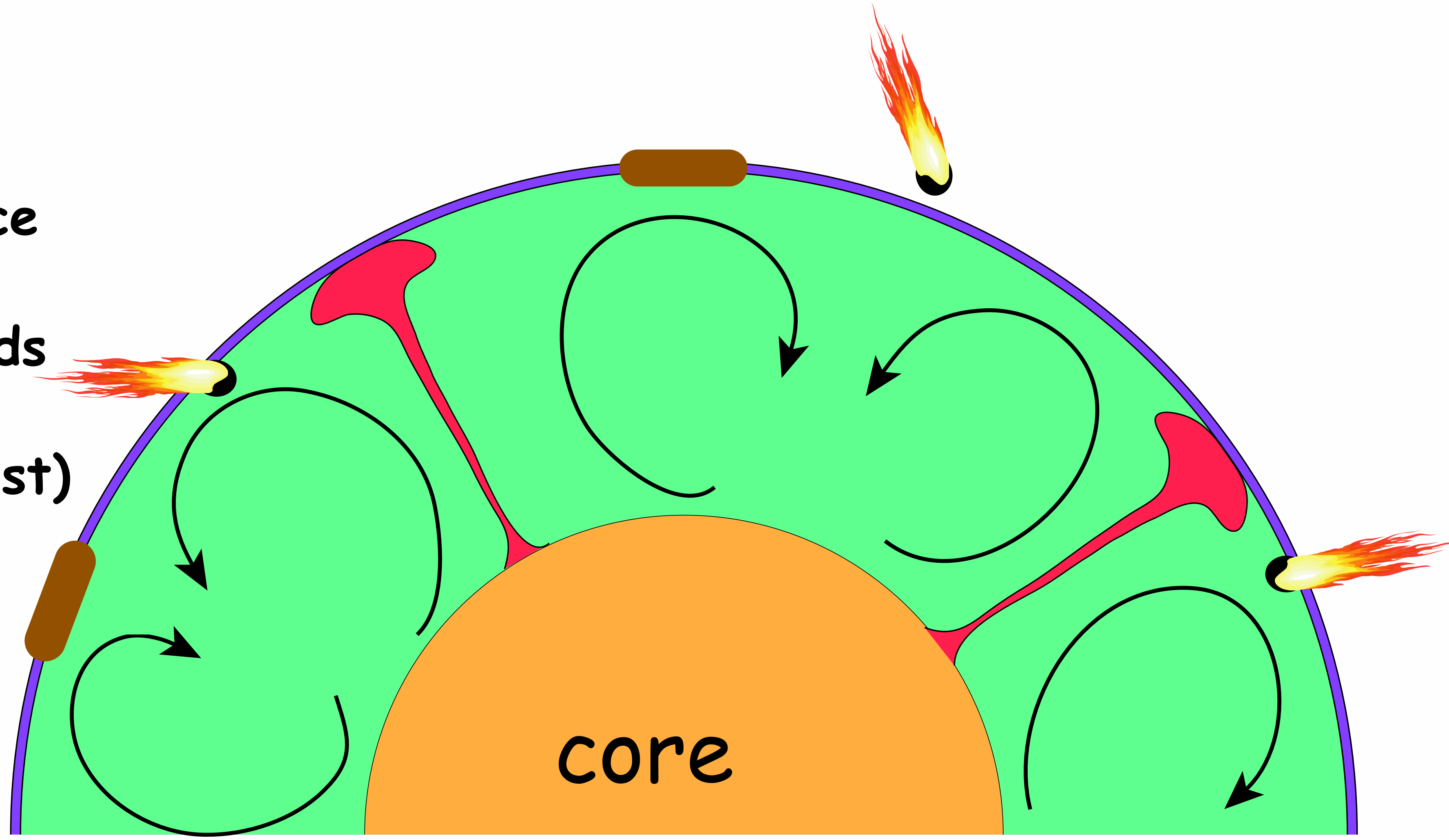


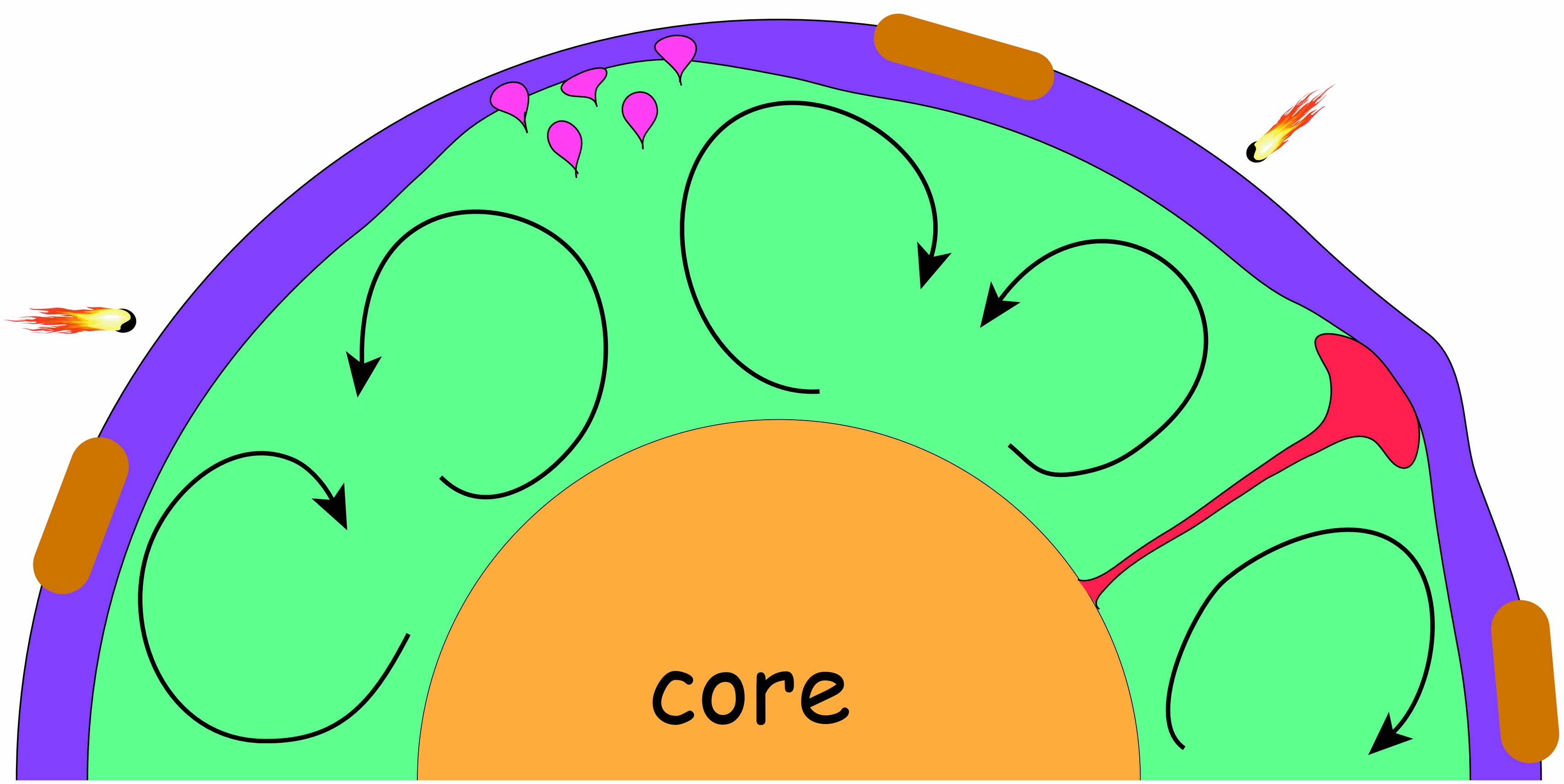
Steady-State resurfacing; many craters destroyed

Craters accumulate, but can locally fill

Craters preferentially buried in the BAT & Lada Provinces

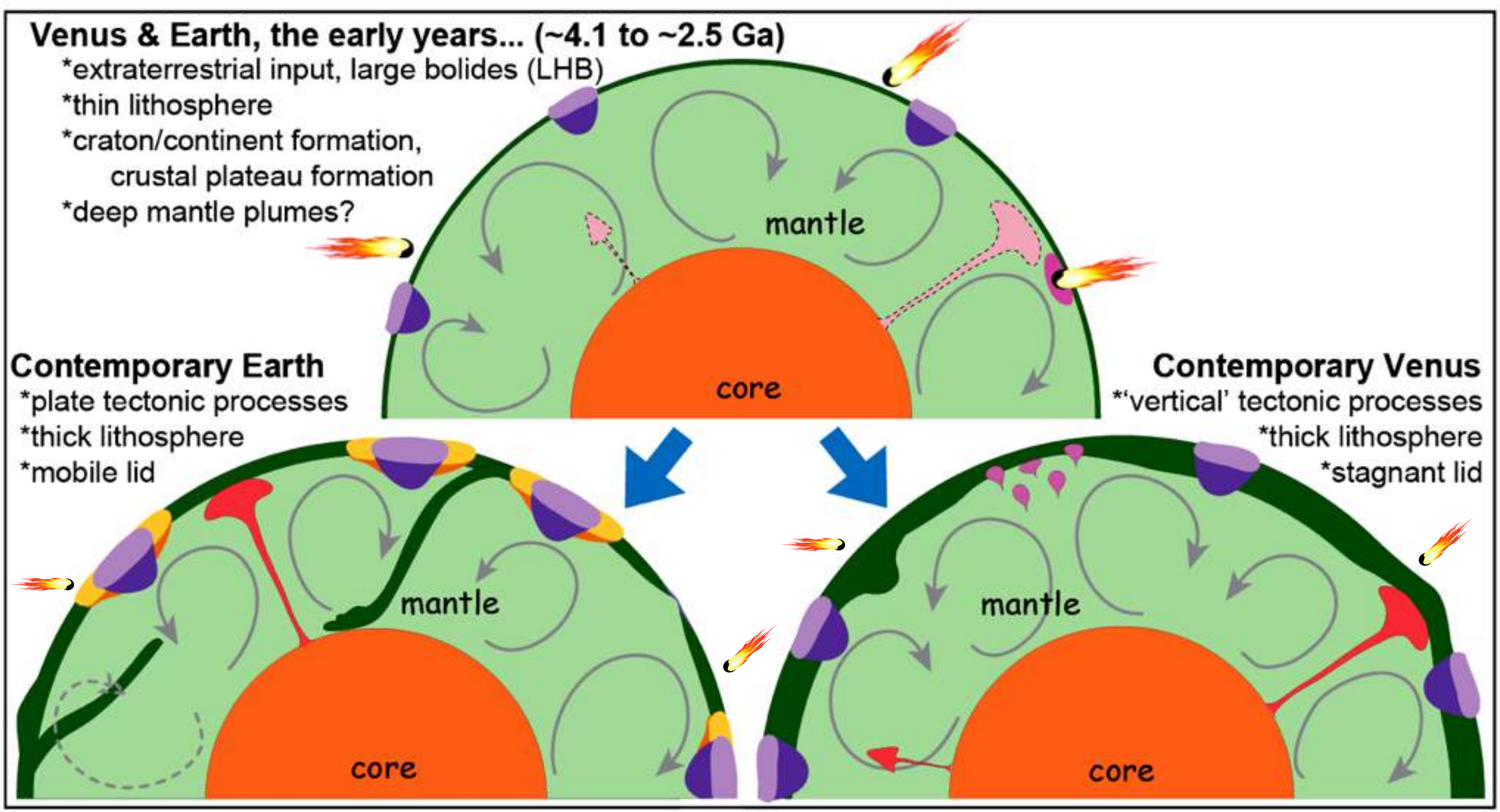
Ancient Venus:
*thin lithosphere
*large heat budget
*cooling across entire surface
(efficient conduction)
*crustal plateaus & lava ponds
formed by large bolides
(that penetrated the crust)
*steady-state resurfacing





Venus Today:
*thicker lithosphere
*depleted heat budget
*bolides form impact craters
*craters accumulate (and are
locally buried)
*slow cooling across the surface
(slow conduction)
*cooling focused along coronae-
chasma chains/fracture zones
& volcanic rises

Just as we can learn about individuals by knowing their siblings—Earth has clues about sister Venus, and sister Venus preserves many clues about Earth—for the early years, in particular, Venus' 'baby book' is perhaps more complete than Earth's



(Hansen 2015 Lithosphere)

Cited References

Bannister, R.A., Hansen,V.L., 2010, Geologic map of the Artemis quadrangle (V-48),Venus: U.S. Geological Survey SIM 3099, 1:5,000,000 scale, pamphlet [map and text].

Bjonnes, E.E., Hansen V.L., James, B., Swenson, J.B., 2012, Equilibrium resurfacing of Venus: Results from new Monte Carlo modeling and implications for Venus surface histories: Icarus, v. 217, p. 451-461; doi:10.1016/j.icarus.2011.03.033

Bond,T.M.,Warner, M.R., 2006. Dating Venus: Statistical models of magmatic activity and impact cratering. Proc. Lunar Sci. Conf. 37 (1957.pdf).

Brown, C.D., Grimm, R.E., 1995, Tectonics of Artemis Chasma: A Venusian "plate" boundary: Icarus, v. 117, p. 219–249.

Brown, C.D., Grimm, R.E., 1996, Lithospheric rheology and flexure at Artemis Chasma, Venus: JGR, v. 101, p. 12697–12708.

De Paor, D.G., Hansen,V.L., Dordevic, M.M., 2012. "Google Venus." in: Whitmeyer, S.J., Bailey, J., De Paor, D.G., and Ornduff, T. (Eds.) "Google Earth and Virtual Visualization in Geoscience Education and Research. GSA Special Paper 492, p. 367-382, doi:10.1130/2012.2492(27)

Elkins-Tanton, L., Hager, B., 2005, Giant meteoroid impacts can cause volcanism: EPSL, v. 239, p. 219–232, doi:10.1016/j.epsl .2005 .07.029.

Griffiths, R.W., and Campbell, I.H., 1991, Interaction of mantle plume heads with the Earth's surface and onset of small-scale convection: JGR, v. 96, p. 18295–18310.

Hamilton, W.B., 2005, Plumeless Venus has ancient impact-accretionary surface, *in* Foulger, G.R., Natland, J.H., Presnall, D.C., Anderson, D.L., eds., Plates, Plumes, and Paradigms: GSA Special Paper, 781–814.

Hansen,V.L., 2015, Impact origin for Archean cratons; Lithosphere; doi:10.1130/L371.1

Hansen,V.L., 2014, Topographic domains (Venus), in Encyclopedia of Planetary Landforms (H. Hargitai, Á. Kereszturi, eds.), Springer Reference, 2014.

Hansen,V.L., 2006, Geologic constraints on crustal plateau surface histories, Venus: The lava pond and bolide impact hypotheses: JGR, v.111, E1 1010, doi: 10.1029/2006JE002714

Hansen,V.L., 2002, Artemis: signature of a deep venusian mantle plume: GSA Bulletin, v. 114, no. 7, p. 839-848.

Hansen,V. L., López, I., 2010, Venus records a rich early history: Geology, v. 38; no. 4; p. 311-314; doi: 10.1130/G30587.1

Hansen,V. L., Olive, A., 2010, Artemis, Venus, the largest tectonomagmatic feature in the solar system?: Geology, v. 38, no. 5; p. 467-470; doi: 10.1130/G30643.1

Hansen,V.L., Young, D.A., 2007, Venus evolution: A synthesis, in: Convergent Margin Terranes and Associated Regions: A Tribute to W.G. Ernst; (eds.) M. Cloos, W.D. Carlson, M.C. Gilbert, J.G. Liou, S.S. Sorenson; GSA Special Paper 419, p. 255-273.

Hansen,V.L., Phillips, R.J., 1995, Formation of Ishtar Terra, Venus: surface and gravity constraints: Geology, v. 23, p. 292-296.

Herrick, R.R., Rumpf, M.E., 2011. Post-impact modification by volcanic or tectonic processes as the rule, not the exception, for venusian craters. JGR, 116, E02004. doi: 10.1029/2010JE003722.

Herrick, R.R., Sharpton, V.L., Malin, M.C., Lyons, S.N., Feely, K., 1997, Morphology and morphometry of impact craters, *in* Bouger, S.W., Hunten, D.M., Phillips, R.J., eds., Venus II, Tucson, University of Arizona Press, p. 1,015–1,046.

Ingle, S., Coffin, M.F., 2004, Impact origin for the greater Ontong Java Plateau?: EPSL, v. 218, p. 123–134, doi:10.1016/S0012 -821X (03)00629-0.

Izenberg, N.R., Arvidson, R.E., Phillips, R.J., 1994, Impact crater degradation on Venusian plains: GRL, v. 21, p. 289–292.

Jones, A.P., Price, G.D., Price, N.J., DeCarli, P.S., Clegg, R.A., 2002, Impact induced melting and the development of large igneous provinces: EPSL, v. 202, p. 551–561, doi: 10.1016/S0012-821X (02) 00824-5.

Jones, A.P., Wunemann, K., Price, D., 2005, Impact volcanism as a possible origin for the Ontong Java Plateau (OJP), in Foulger, G.R., Natland, J.H., Presnall, D.C., Anderson, D.L., eds., Plates, Plumes, and Paradigms: GSA Special Paper 388, 711–720, doi:10.1130/0-8137-2388-4.711.

Koch, D.M., Manga, M., 1996, Neutrally buoyant diapirs: A model for Venus coronae: GRL, v. 23, p. 225–228.

O'Rourke, J.G. Wolf, A.S. & Ehlmann, B., 2014, Venus: Interpreting the spatial distribution of volcanically modified craters, GRL, v. 41, p. 8252-8260.

Phillips, R.J., Izenberg, N.R., 1995, Ejecta correlations with spatial crater density and Venus resurfacing history: GRL, v. 22, no. 12, p. 1,517–1,520.

Phillips, R.J. & Hansen,V.L., 1998, Geological Evolution of Venus: Rises, Plains, Plumes, and Plateaus: *Science*, v. 279, p. 1492-1497.

Smrekar, S.E., Stofan, E.R., 1997, Corona formation and heat loss on Venus by coupled upwelling and delamination: Science, v. 277, p. 1289–1294.

Spencer, J., 2001, Possible giant metamorphic core complex at the center of Artemis Corona, Venus: GSA Bulletin, v. 113, p. 333–345.

Strom, R.G., Schaber, G.G., Dawson, D.D., 1994. The global resurfacing of Venus. JGR, v. 99, p. 10899–10926.