The Origin of Asymmetrical Coronae on Venus:

Insights from topography data and 3D thermomechanical modelling

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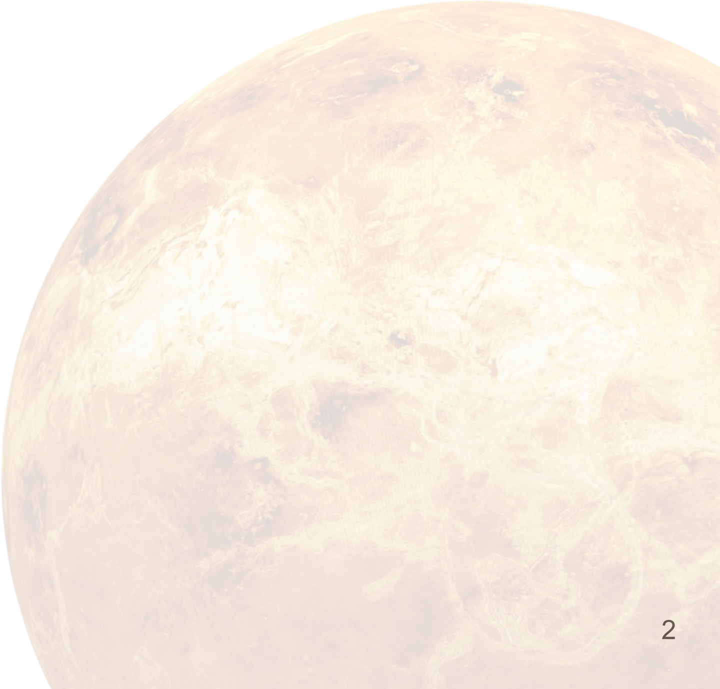
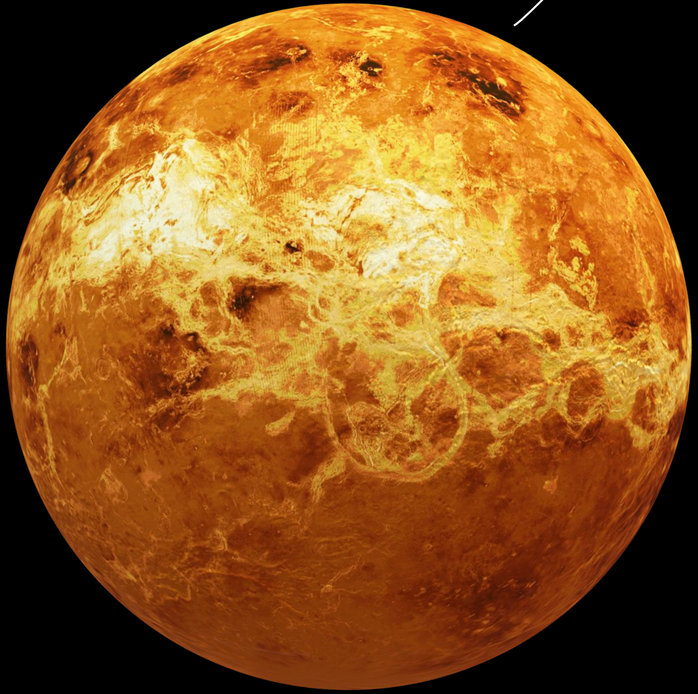
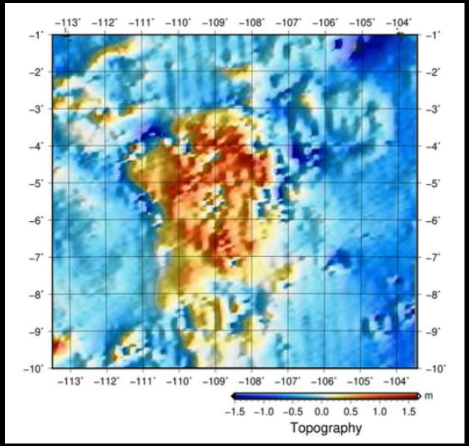
Talk Outline

1. Introduction
    - **Venus and coronae structure**
2. Research Methods and Results
    - **Part 1: Coronae classification**
    - **Part 2: Numerical Modeling**
3. Conclusion



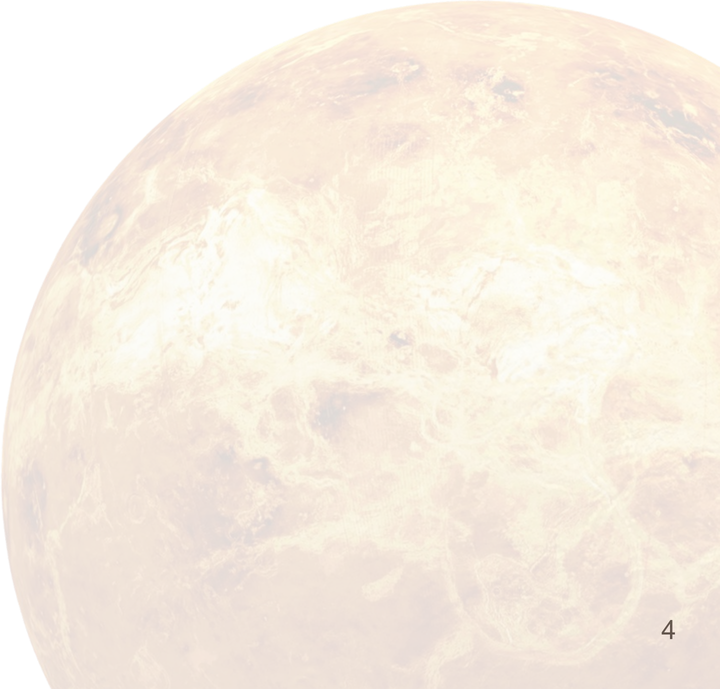
Venus and coronae structure





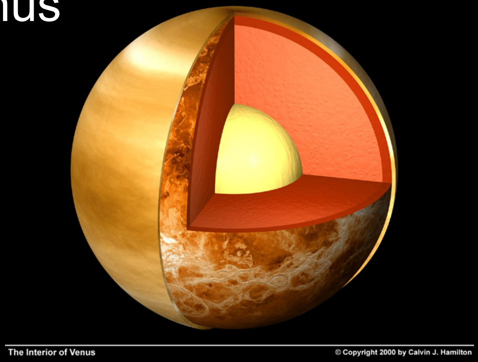
Quick Outline for **Venus and coronae structure**

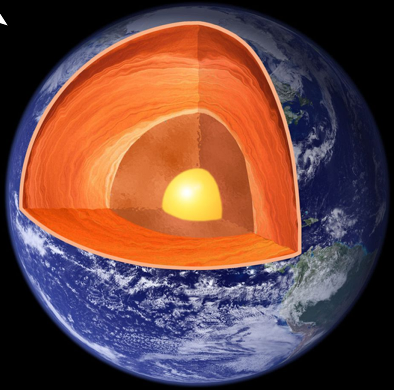
1. Motivation
   - Earth vs Venus
   - Coronae
2. Research Question



Motivation | Earth vs Venus

Venus

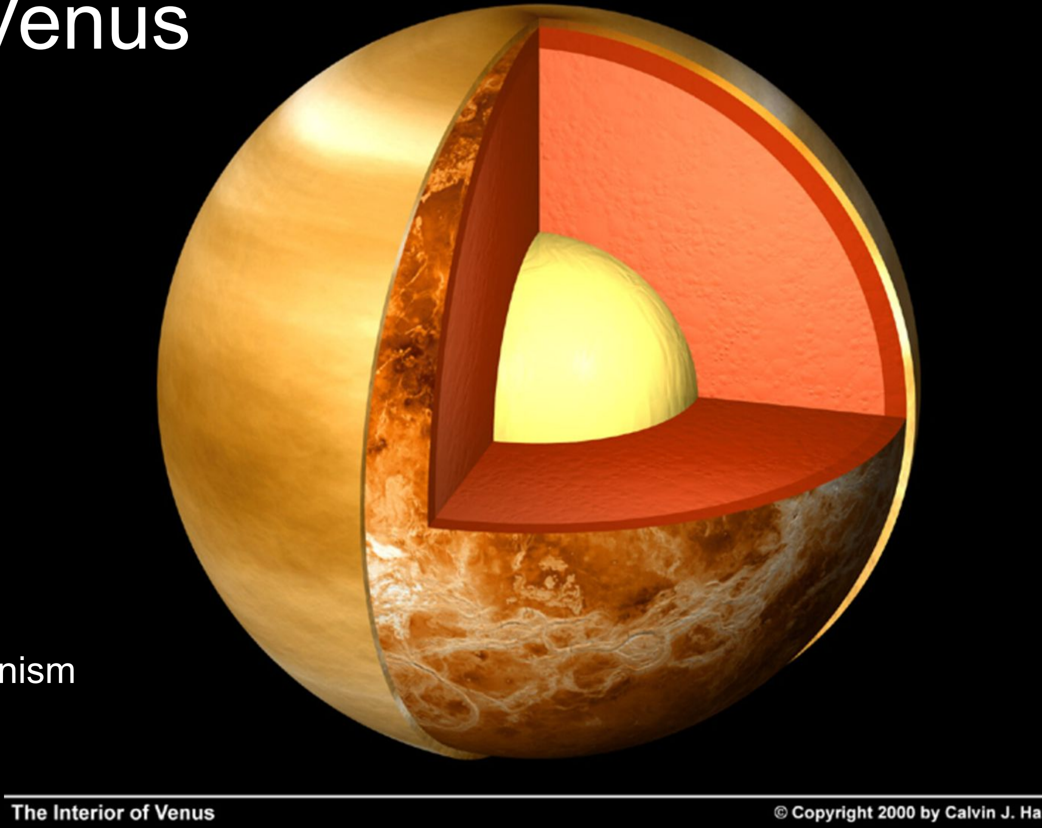




Earth

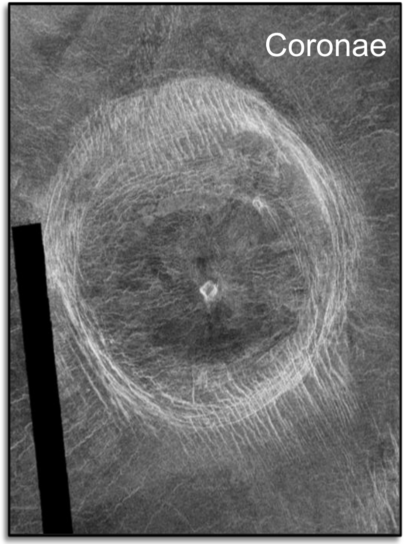
Motivation | Earth vs Venus

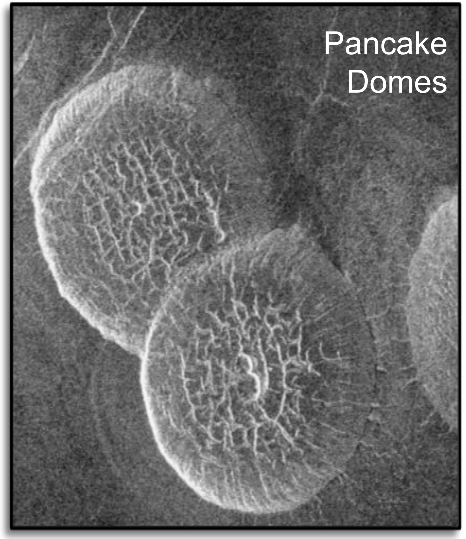
- The Twin Planet of Earth
  - Similar size, mass, bulk composition, internal structure and gravity
- Different interior dynamics
  - No plate tectonics
  - Resurfacing
    - Upwelling mental result in volcanism *(Nimmo and McKenzie, 1998)*

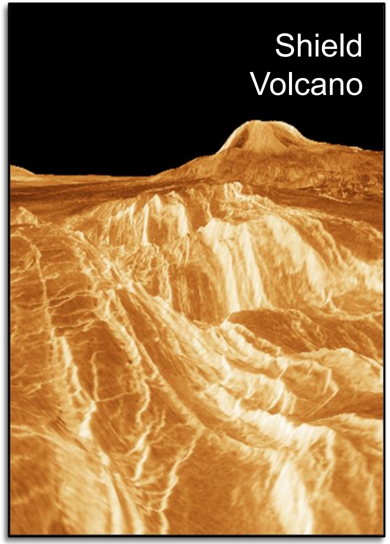


Motivation | Venus Surface

- ➢ Basaltic crust
- ➢ Active volcanism reflecting interior dynamics
    - ○ "Pyroclastic flow deposits on Venus as indicators of renewed magmatic activity" (Campbell et al., 2017)
    - ○ "Present-day volcanism on Venus as evidenced from weathering rates of olivine" (Filiberto, 2020)

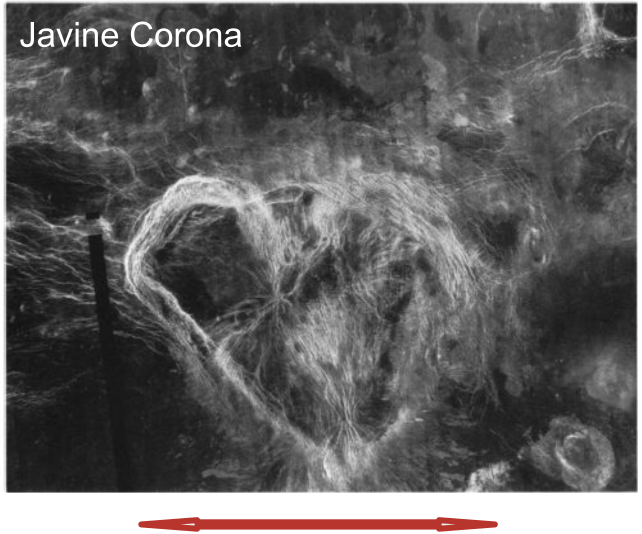


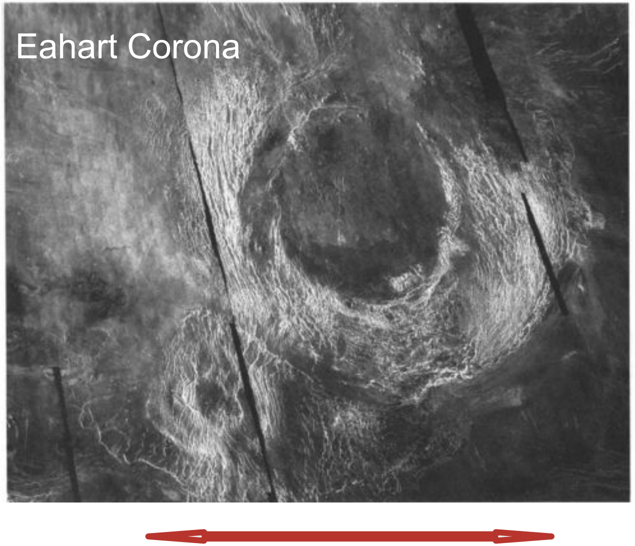




Motivation | Coronae

- Large, circular to elongated tectonics structures
  - Diameter ranges from 60 ~ 1000km
- Various morphologies & shapes





Motivation | Coronae

- ➢ Large, circular to elongated tectonics structures
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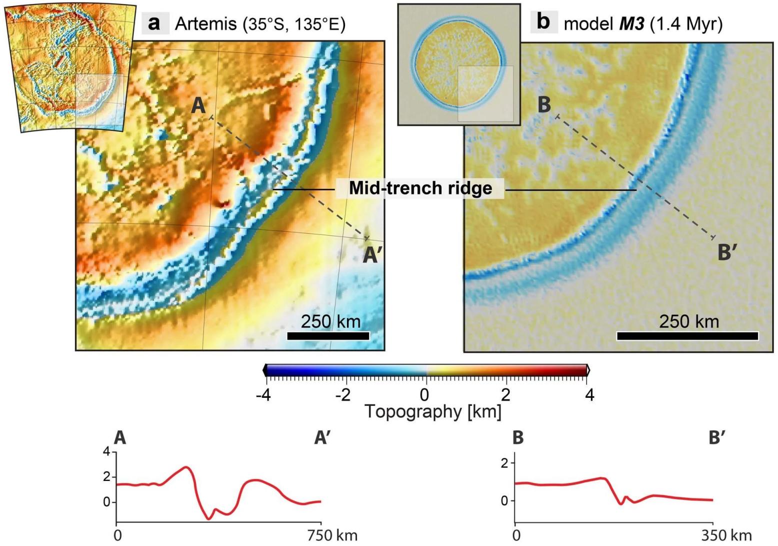
- ➢ Various morphologies & shapes

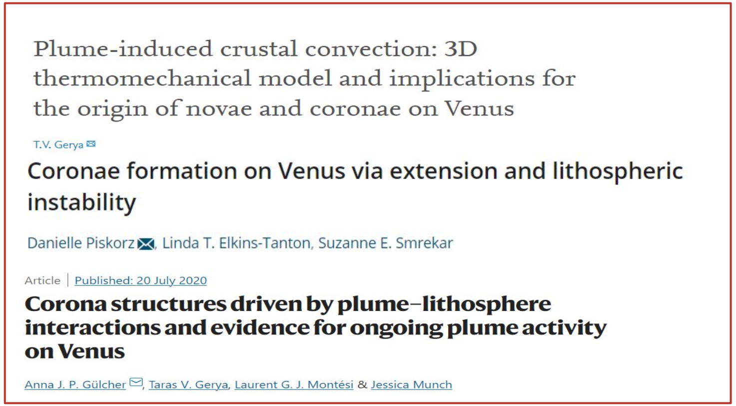
Gülcher et al., 2021



Smrekar and Stofan, 1997

Topographic profile	Description	% of coronae
	Dome	10
	Plateau	10
	Rim surroundig interior high	21
	Rim surrounding interior dome	
	Rim surrounding depression	25
	Outer rise, trough, rim, inner high	5
	Outer rise, trough, rim, inner low	1
	Rim only	7
	Depression	7
	No discernible signature	14

Motivation | Coronae


Plume-induced crustal convection: 3D thermomechanical model and implications for the origin of novae and coronae on Venus

T.V. Gerya

Coronae formation on Venus via extension and lithospheric instability

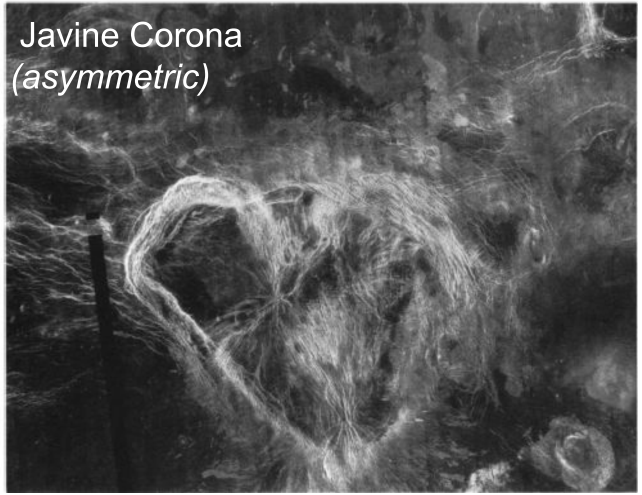
Danielle Piskorz, Linda T. Elkins-Tanton, Suzanne E. Smrekar

Article | Published: 20 July 2020

Corona structures driven by plume–lithosphere interactions and evidence for ongoing plume activity on Venus

Anna J. P. Gülcher, Taras V. Gerya, Laurent G. J. Montési & Jessica Munch

- ➢ Large, circular to elongated tectonics structures
  - Diameter ranges from 60 ~ 1000km
- ➢ Various morphologies & shapes



500km

370km

Motivation | Coronae

- ➢ Large, circular to elongated tectonics structures
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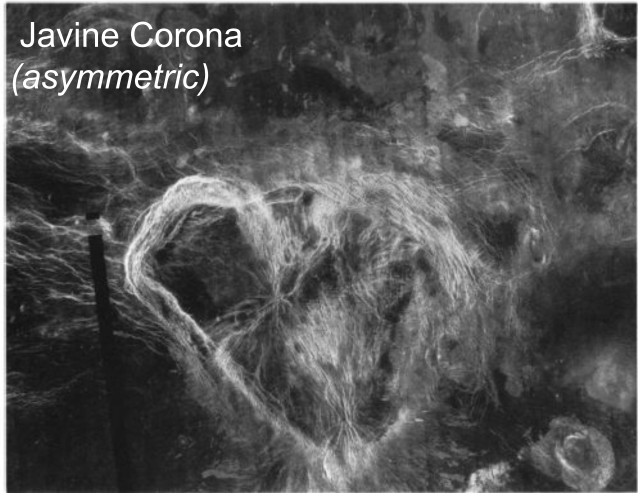
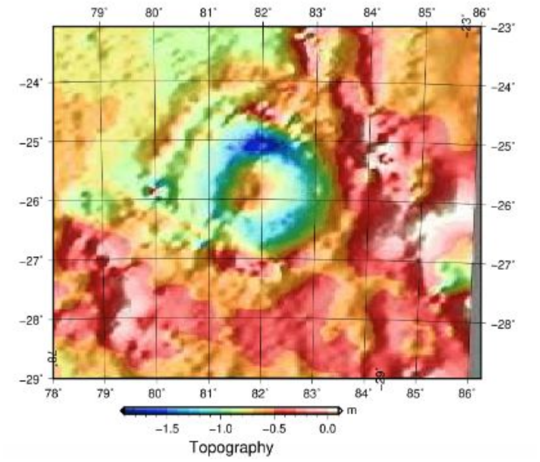


500km

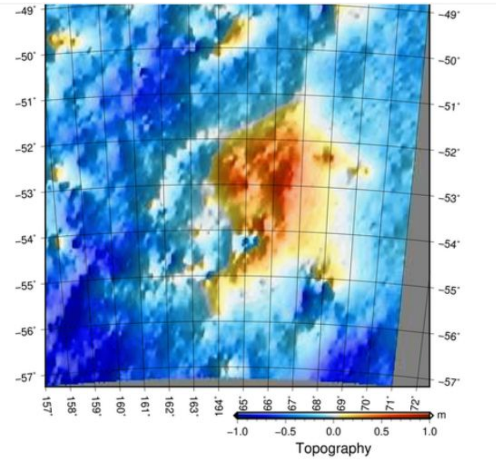
370km

Motivation | Coronae

➢ Coronae might be the key to **understanding Venus' tectonics** and surface evolution



Aramaiti Coronae, located at [-26°, 82°],
an example of asymmetrical coronae

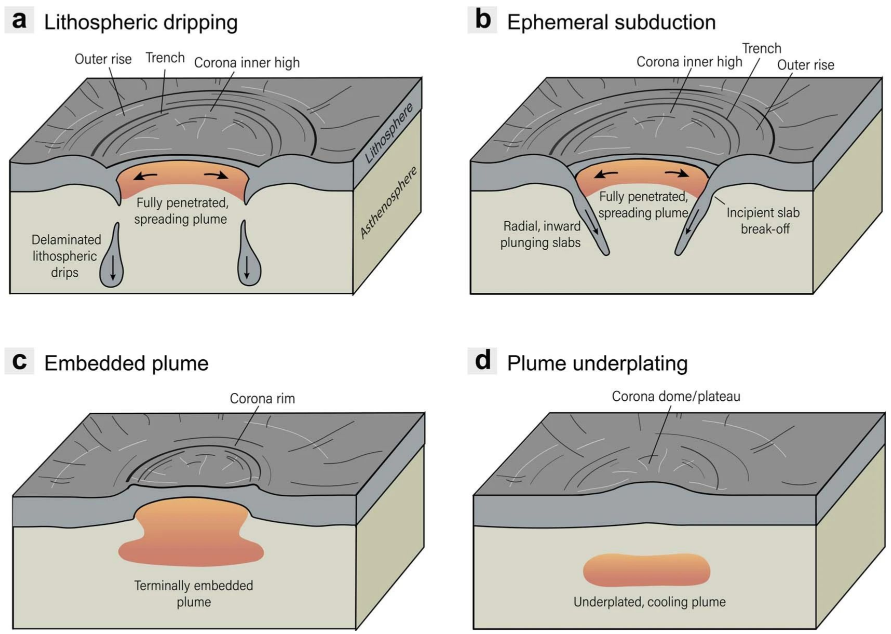


Tonatzin Coronae, located at [-53°, 164°],
an example of asymmetrical coronae

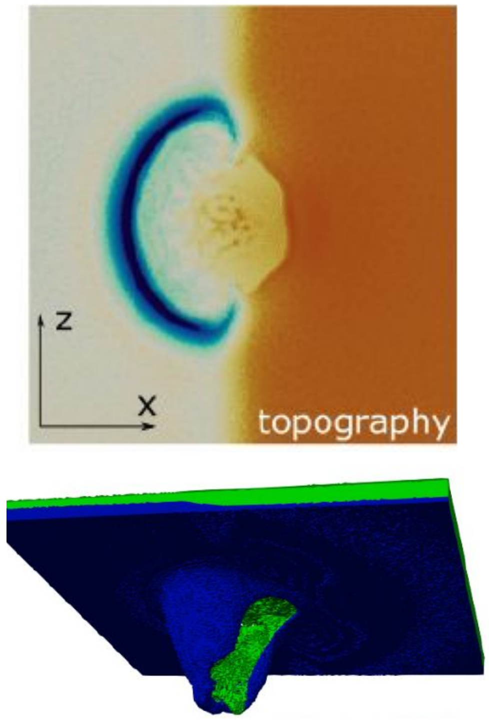
Motivation | Coronae Formation

Previous researches show strong correlation between **coronae asymmetry** & its **local topography** and **geodynamics**

(Gülcher et al., 2021; Stadler D et al., 2019.)



The four geodynamic regimes identified in numerical models. "*Corona structures driven by plume–lithosphere interactions and evidence for ongoing plume activity on Venus*" *(Gülcher et al., 2021)*



2D & 3D topography plots of crustal heterogeneous model. *"The origin of asymmetrical coronae on Venus: insights from 3D thermomechanical Modelling" by Stadler D et al., 2019.*

Motivation | Coronae Formation

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BACHELOR THESIS

The origin of asymmetrical coronae on Venus: insights from 3D thermomechanical modelling

Research Questions

1. What are the **common geological features** observed among asymmetry coronae?

    → Perform coronae data analysis

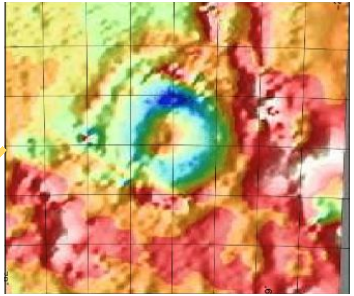
2. What is the **geodynamics** of asymmetry coronae formation?

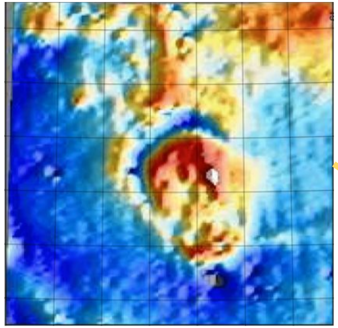
3. What factors control the **degree of coronae asymmetry**?

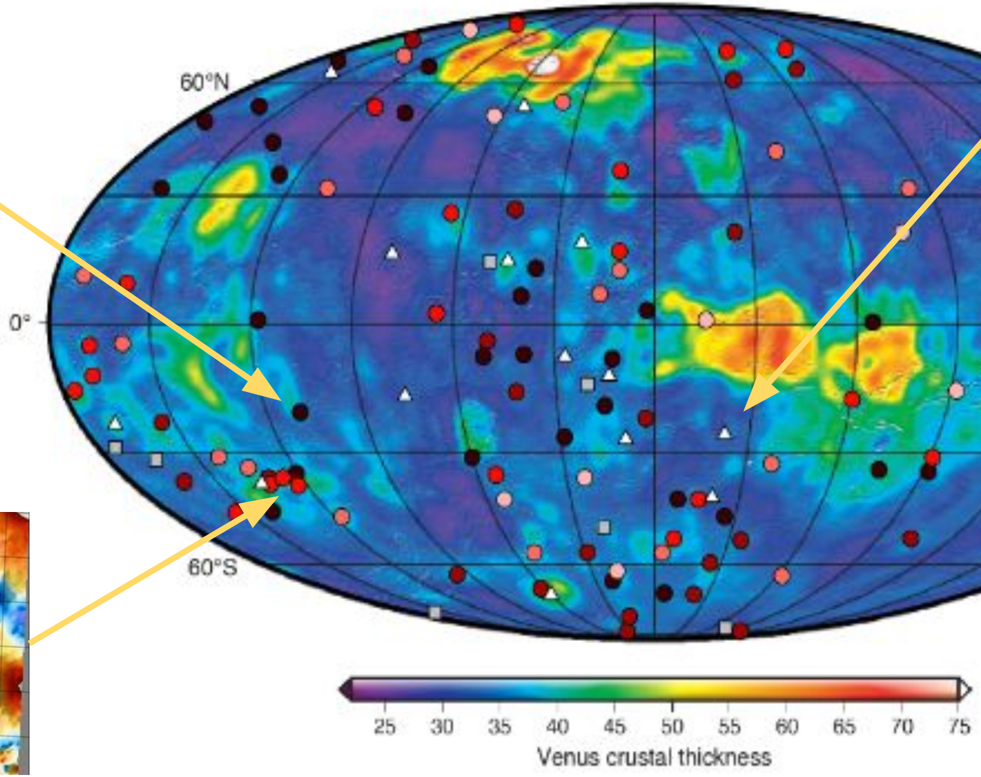
    → Numerical Modeling Experiments

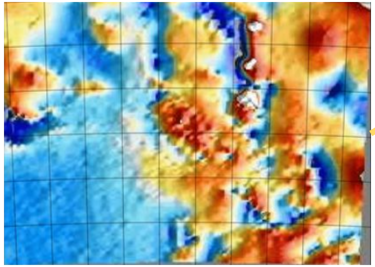
Part 1: Coronae Data Analysis

Part 1: Coronae Data Analysis









Quick Outline for Coronae Data Analysis

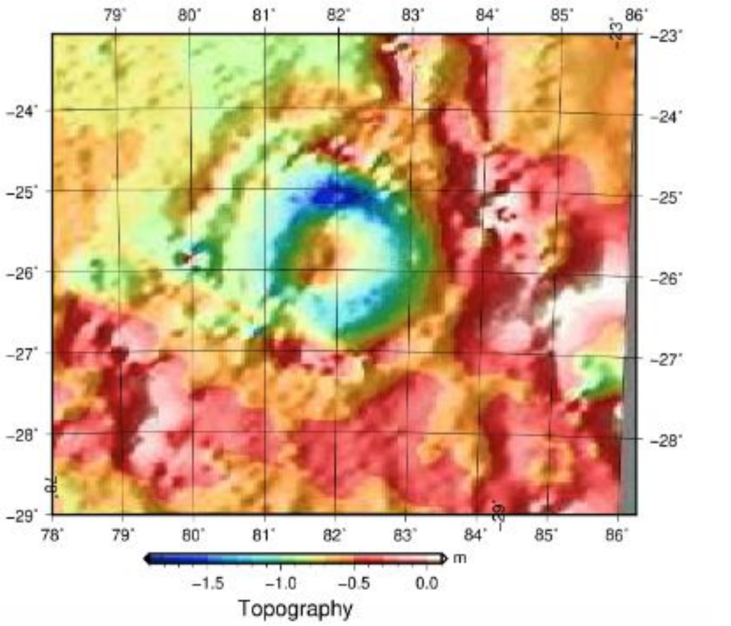
1. Methods
   - Coronae Data Analysis
2. Results
   - Coronae Classification
   - Coronae Global Distribution

Methods | Coronae Data Analysis

Finding coronae's common geological feature:

- Utilizing coronae data from the coronae databases[1~ 4] (mainly from USGS)
  - Total of ~130 coronae

- Investigated the factors that affect coronae's asymmetry:
  - Local **topography**
  - **Locations** (relative to other tectonic structures)



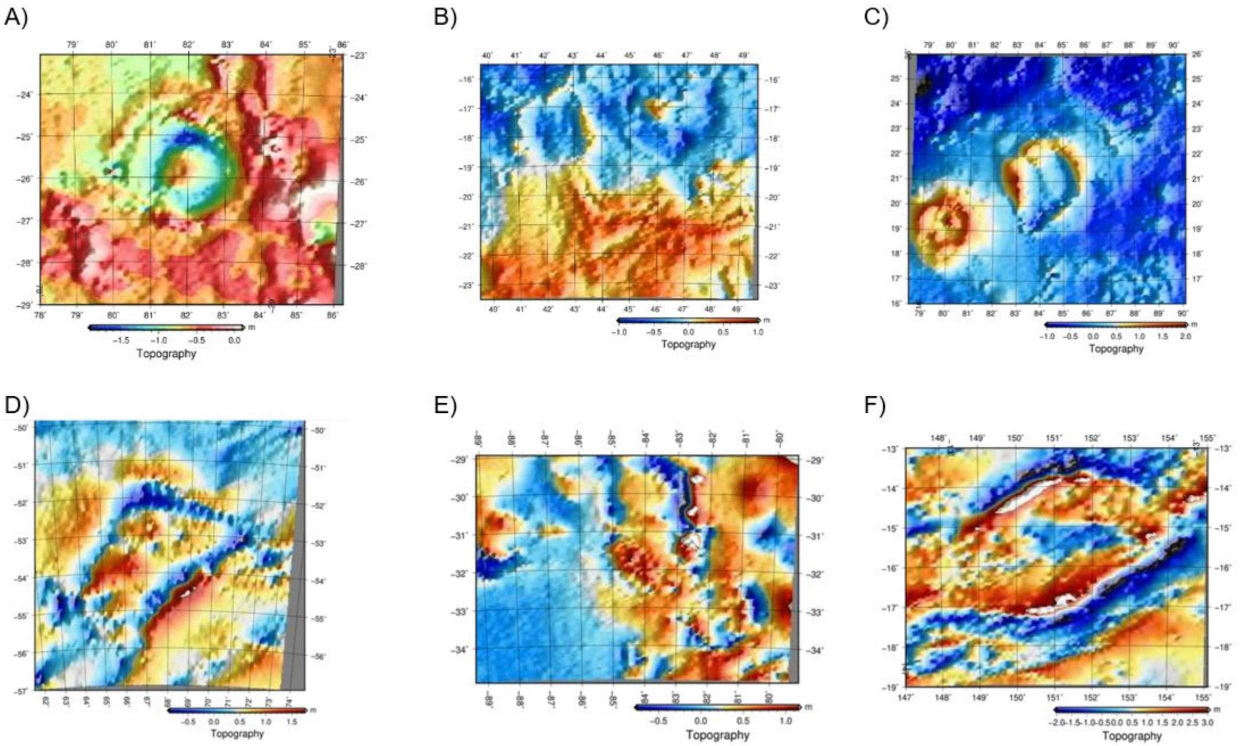
Example of a coronae topography plot. Aramaiti Coronae located at [-26°, 82°], an example of asymmetrical coronae

1. Lang, N.P. and López, I. (2015). The magmatic evolution of three Venusian coronae. From: Platz, T., Massironi, M., Byrne, P. K. & Hiesinger, H. (eds) 2015. Volcanism and Tectonism across the Inner Solar System. Geological Society London, Special Publications, 401, 77-95.
2. Smrekar, S. E., & Stofan, E. R. (1999). Origin of Corona-Dominated Topographic Rises on Venus. Icarus, 139(1), 100115. https://doi.org/10.1006/icar.1999.6090
3. USGS Astrogeologicy Science Centre, Gazeteer for Planetary Nomenclature https://planetarynames.wr.usgs.gov/SearchResults?target=VENUS&featureType=Corona,%20coronae
4. Gülcher, A. J., Gerya, T. V., Montési, L. G., & Munch, J. (2021). Corona structures driven by plume–lithosphere interactions and evidence for ongoing plume activity on Venus. Nature Geoscience, 13(8), 547-554.

Results | Coronae Classification

Six Categories of Coronae:

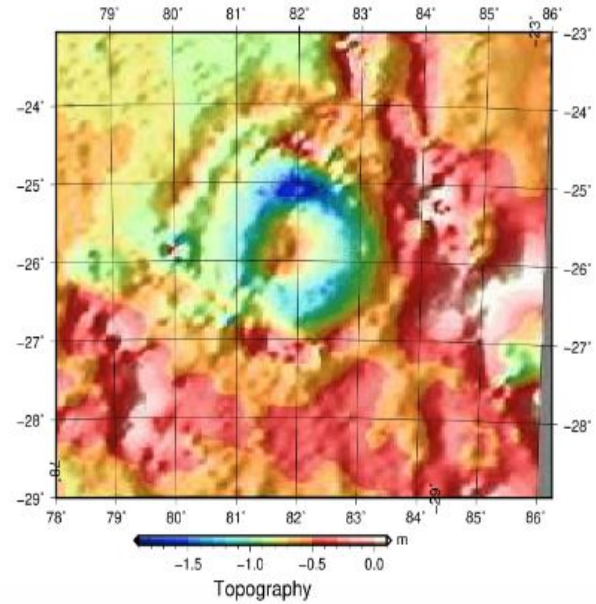
- A) **Symmetric**
- Asymmetric
    - B) **Margin**
    - C) **Intrinsic**
    - D) **Angular**
    - E) **Cluster**
    - F) **Elongated**



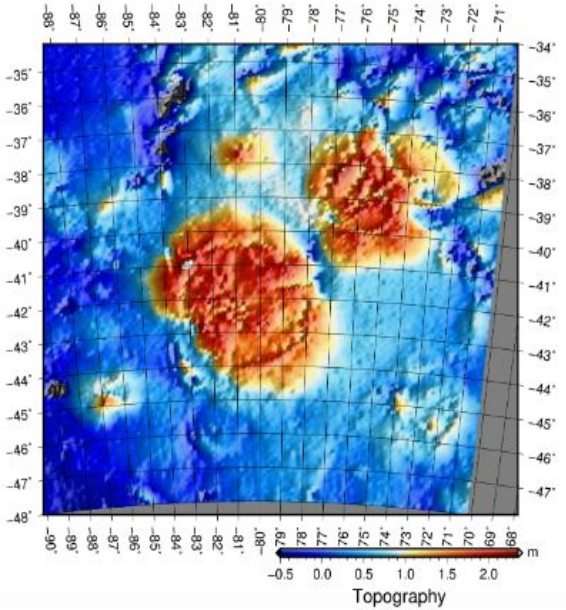
Examples of a coronae topography plot from each category

Results | Coronae Classification

A) Symmetrical Coronae: Coronae with circular, symmetrical shape



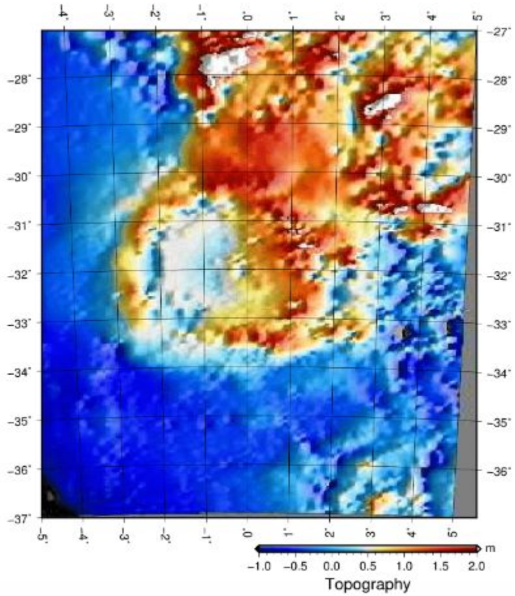
Aramaiti Coronae, located at [-26°, 82°],
an example of asymmetrical coronae



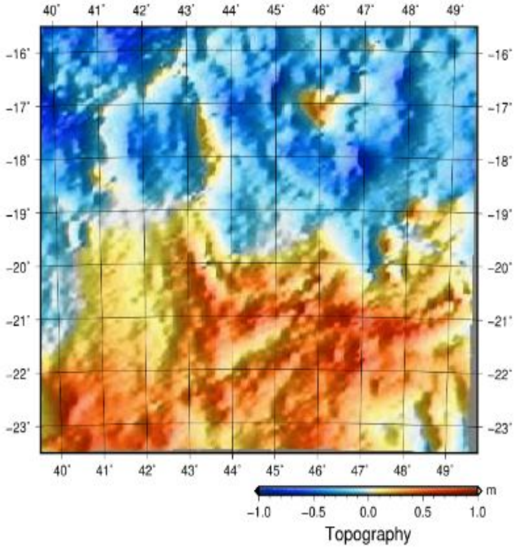
Shiwanokia Coronae, located at [-42°, 80°],
an example of asymmetrical coronae

Results | Coronae Classification

B) Margin Coronae: *Asymmetrical* coronae attached to a plate with higher topography



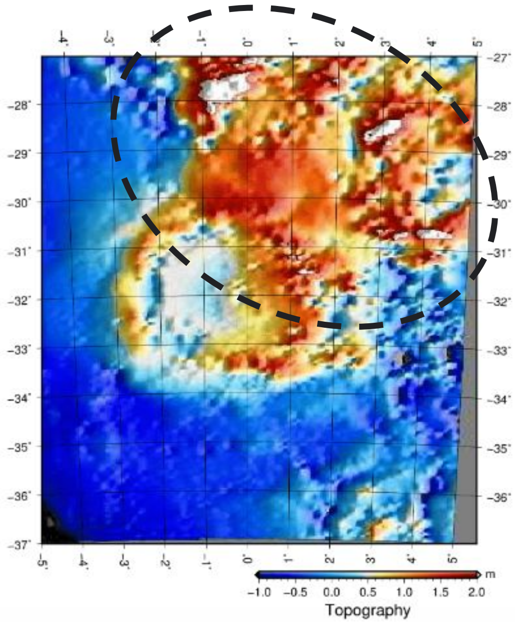
Eve Coronae, located at [-32°, 0.2°], an example of margin coronae



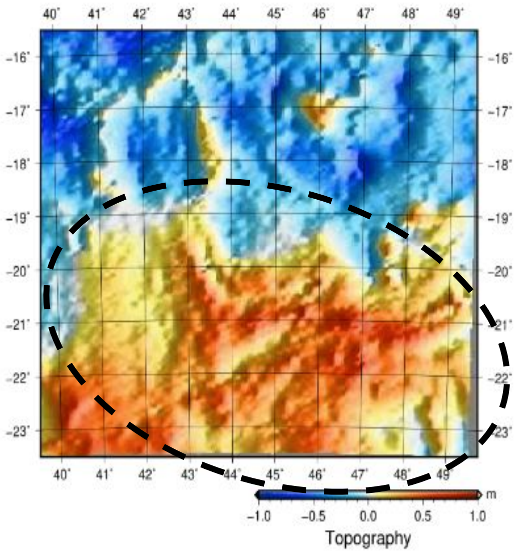
May-Enensi Coronae, located at [-42°, 68°], an example of margin coronae

Results | Coronae Classification

B) Margin Coronae: *Asymmetrical* coronae attached to a plate with higher topography



Eve Coronae, located at [-32°, 0.2°], an example of margin coronae

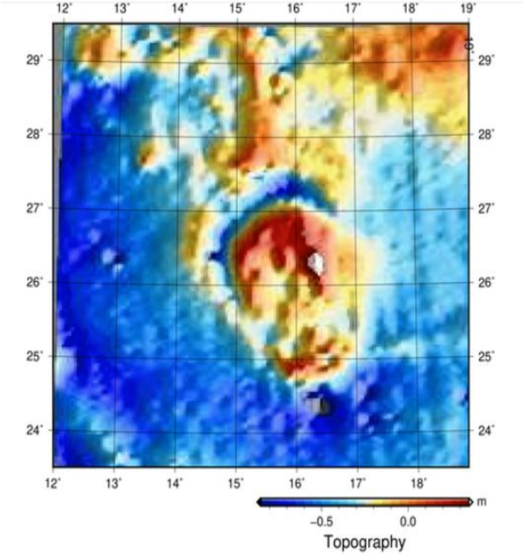


May-Enensi Coronae, located at [-42°, 68°], an example of margin coronae

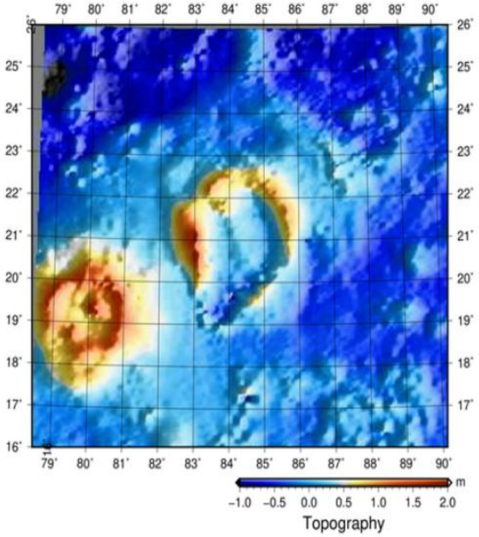
Results | Coronae Classification

C) Intrinsic Coronae: *Asymmetrical* coronae located on a plate with uniform topography

(Indicating the *asymmetry is intrinsically caused* during coronae formation)



Beyla Coronae, located at [-26°, 15°], an example of intrinsic coronae.

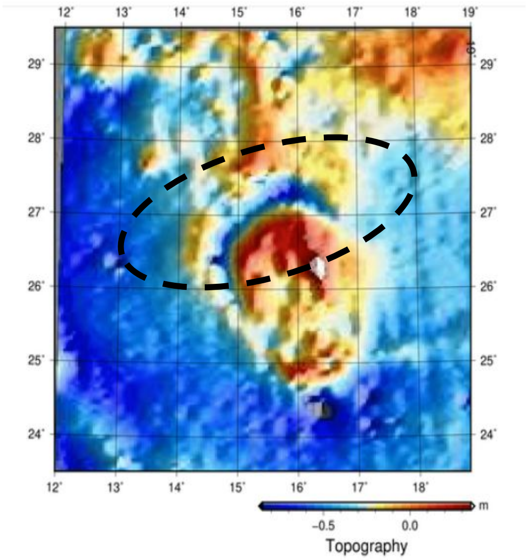


Ereshkigal Coronae, located at [21°, 84°], an example of intrinsic coronae.

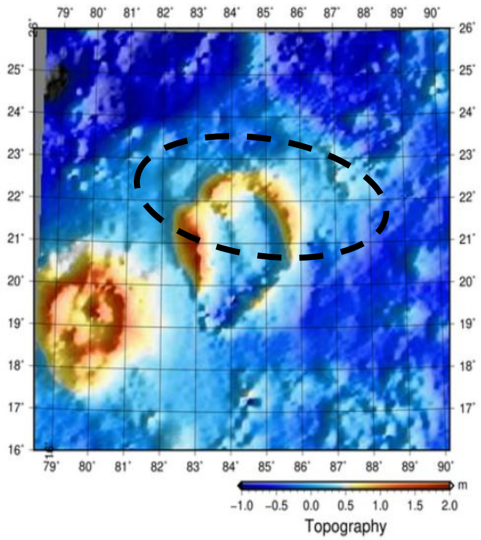
Results | Coronae Classification

C) Intrinsic Coronae: *Asymmetrical* coronae located on a plate with uniform topography

(Indicating the *asymmetry is intrinsically caused* during coronae formation)



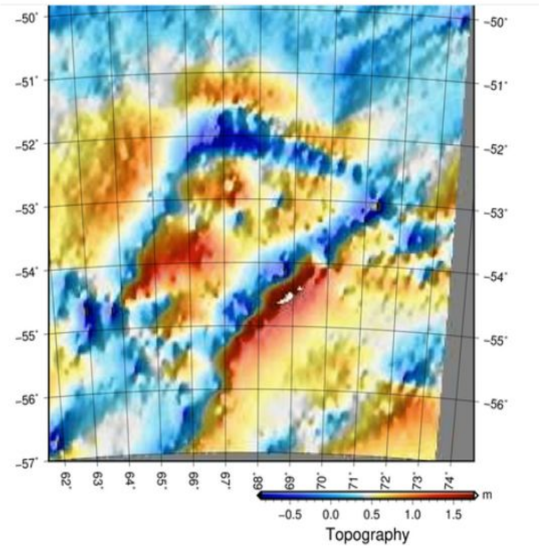
Beyla Coronae, located at [-26°, 15°], an example of intrinsic coronae.



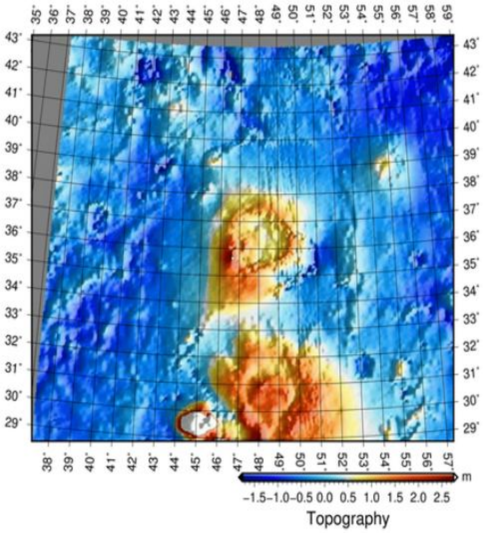
Ereshkigal Coronae, located at [21°, 84°], an example of intrinsic coronae.

Results | Coronae Classification

D) Angular Coronae: *Asymmetrical* coronae in *angular shapes* such as triangles, quadrangles, or any shape with a sharp angled rim



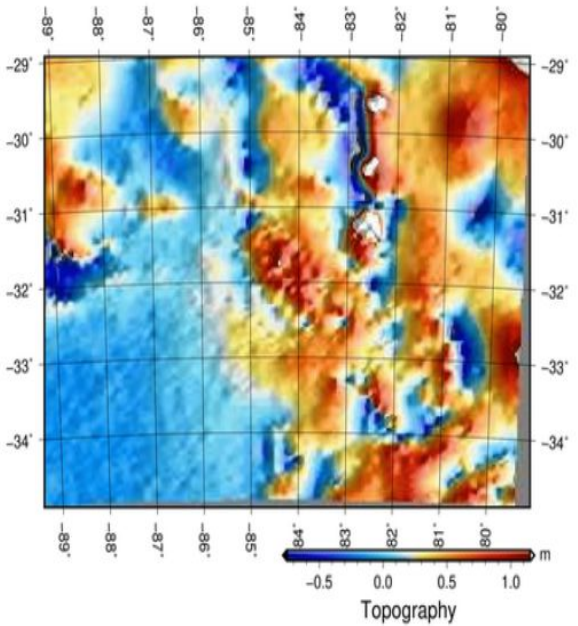
Marzyana Coronae, located at [-53°, 67°], an example of angular coronae.



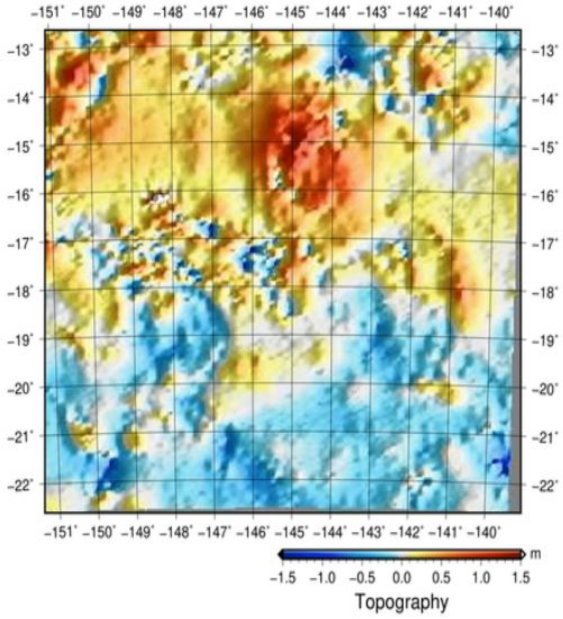
Nefertiti Coronae, located at [36°, 48°], an example of angular coronae.

Results | Coronae Classification

E) Cluster Coronae: Multiple *Asymmetrical* coronae *clustering* in the same region



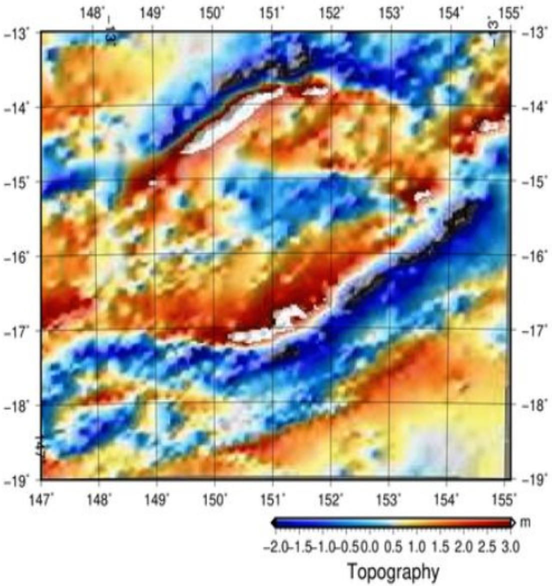
Obiemi Coronae, located at [-32°, -83°], an example of angular coronae.



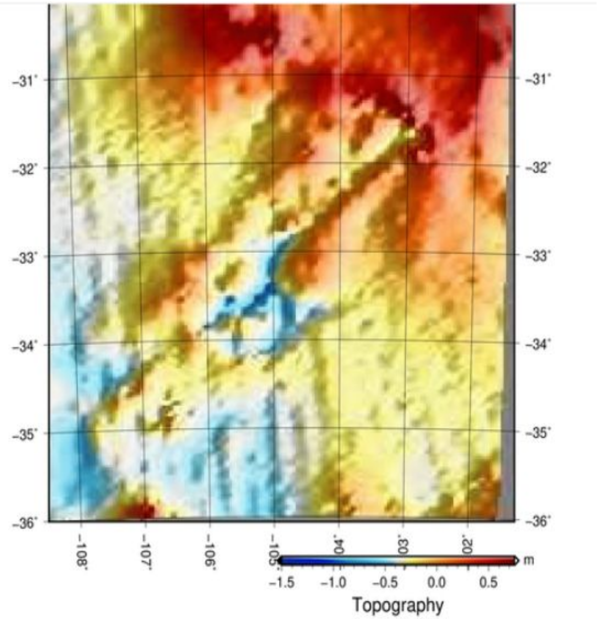
Rzhanitsa Coronae, located at [-18°, -145°], an example of angular coronae.

Results | Coronae Classification

F) Elongated Coronae: *Asymmetrical* coronae in *elliptical, elongated shape*



Ceres Coronae, located at [-16°, 151°], an example of angular coronae.

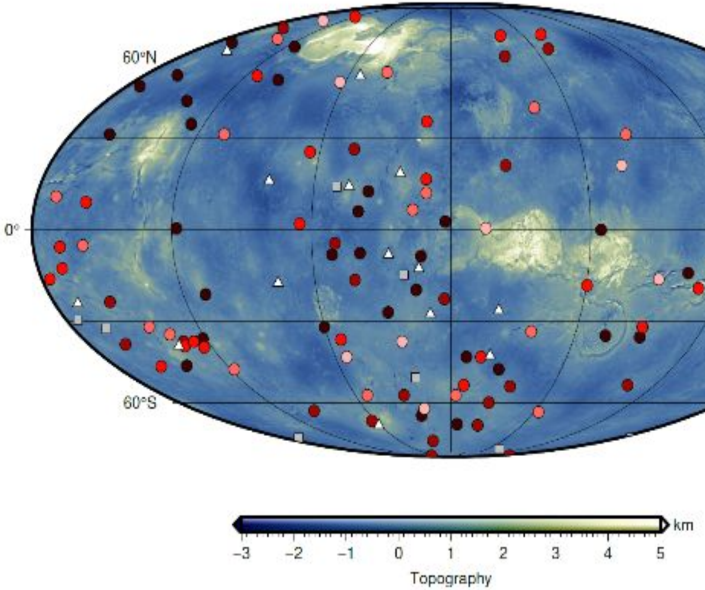


Oanuavae Coronae, located at [-32°, -104°], an example of angular coronae.

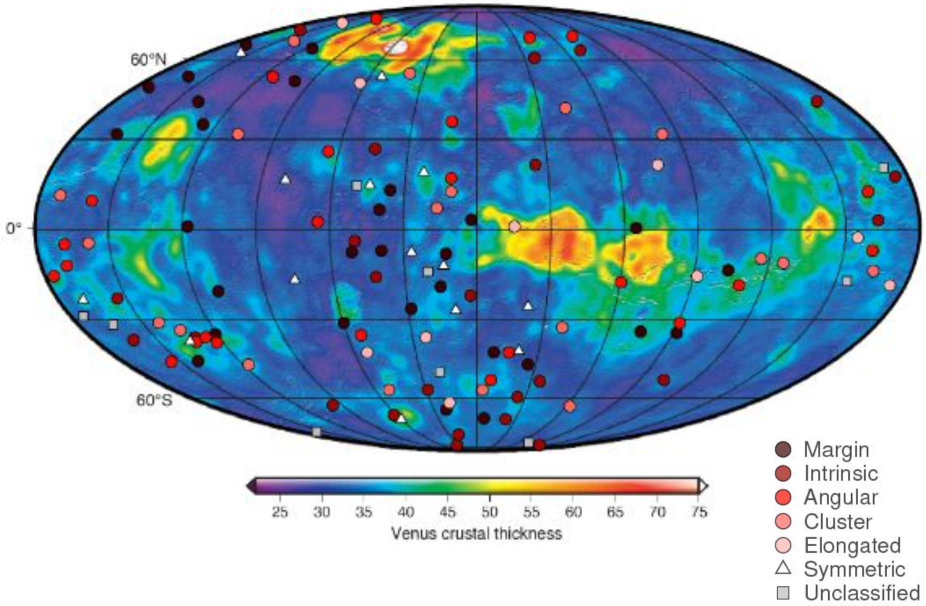
Results | Coronae Global Distribution

** Plotting tool: PyGMT*

(A)



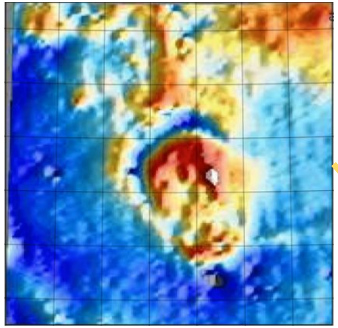
(B)

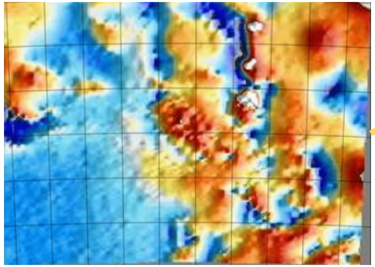


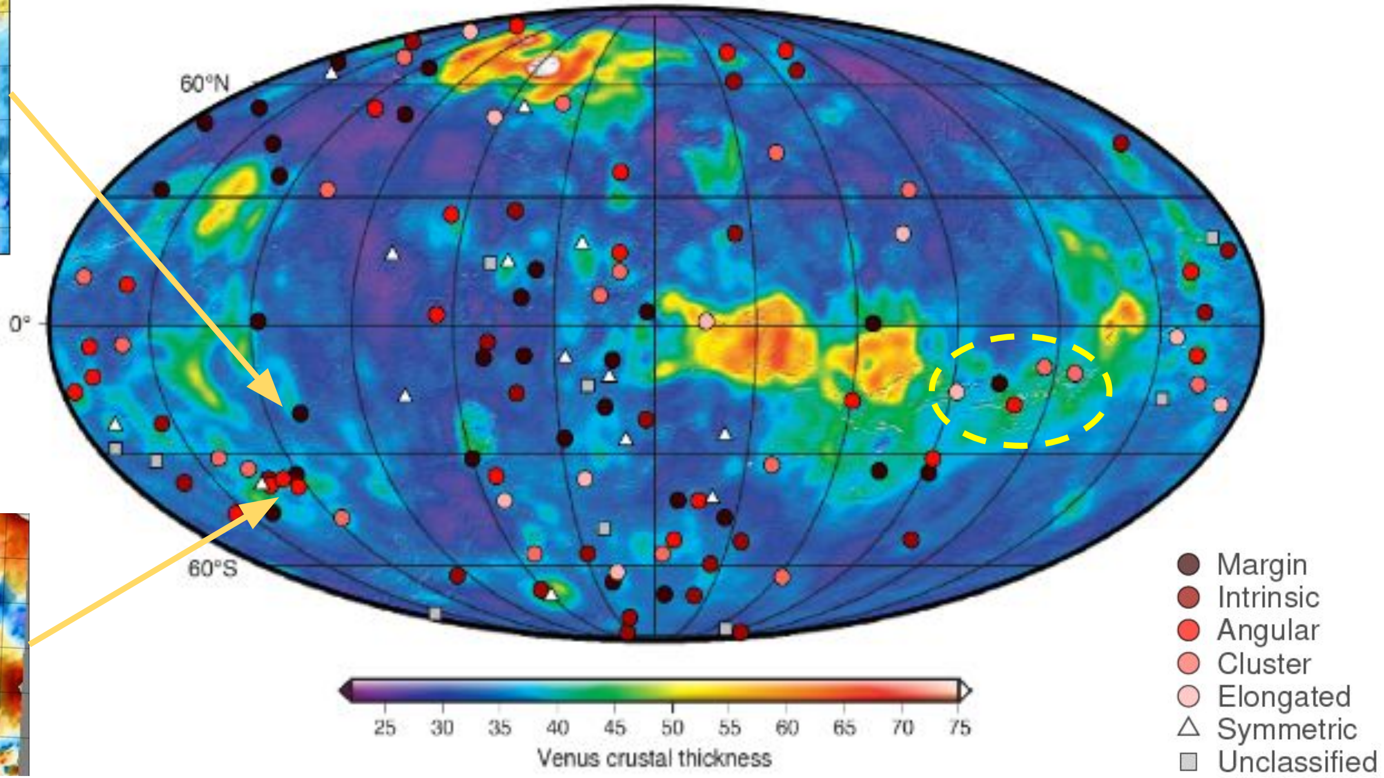
(A) Global distribution of coronae identified as symmetric or asymmetric subclasses plotted on **the global topography** relative to 6051.877 km (Sandwell, 2015; Gülcher, 2020)

(B) Global distribution of coronae identified as symmetric or asymmetric subclasses plotted on **the Venus crustal thickness** (Weiczorek, 2015).

- ➢ Most coronae are located at where topography drastically change







Part 2: Numerical Modeling

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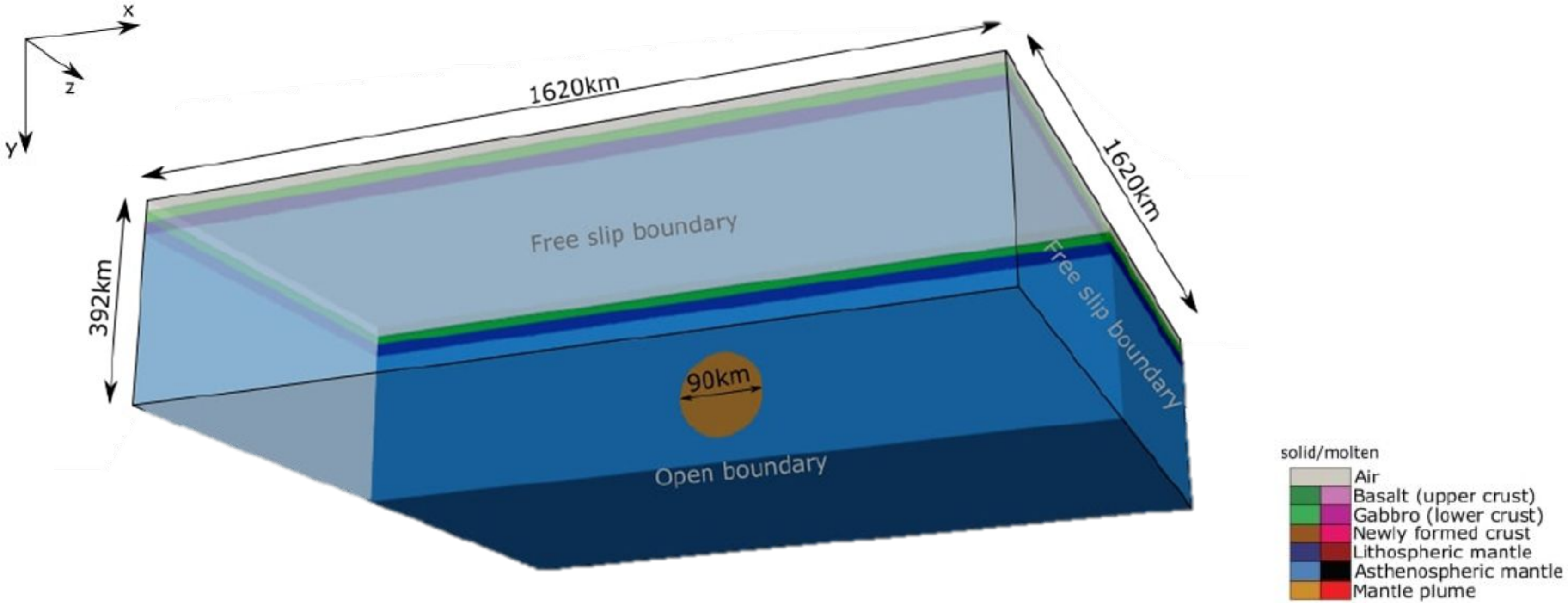


3D View with composition of initial set-up for the reference model. (Fig. 2 from the *Bachelor Thesis "The origin of asymmetrical coronae on Venus: insights from 3D thermomechanical Modelling" by Stadler D et al., 2019.*)

Quick Outline for Numerical Modeling

1. Methods
   - I3ELVIS
   - Model Setup
2. Results
   - Geodynamics Regime
   - Observational evidence of asymmetric coronae formation from each variation

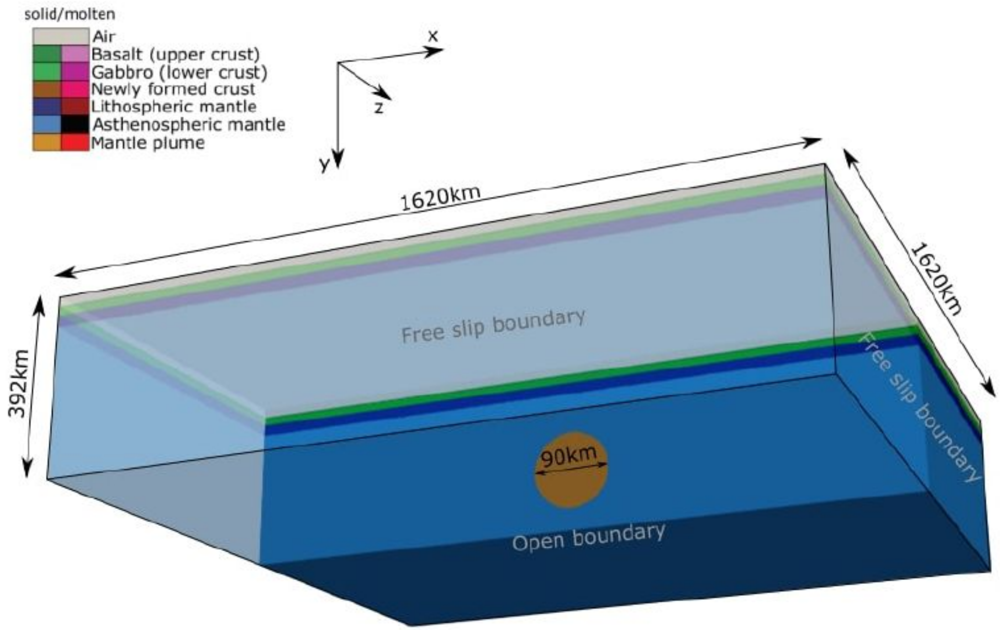
Methods | I3ELVIS (Gerya, 2010)

- ➢ Computer language C
- ➢ Finite-difference method
- ➢ Marker-in-cell techniques
- ➢ Using staggered Eulerian grid to obtain a velocity field
- ➢ Solving mass, momentum, and energy conservation equations
- ➢ Adapted to Venusian conditions while accounting for
  - Visco-plastic rheologies
  - Magmatic weakening of crustal material
  - Melting
  - Relevant phase changes (i.e. eclogitization)

See Gülcher et al. (2021) for details

Methods | I3ELVIS model setup

- ➢ Box dimension: 1620x392x1620km
- ➢ Resolution: 4x2x4km
- ➢ A spherical mantle plume
  - ○ 90km diameter
  - ○ 230km below the surface



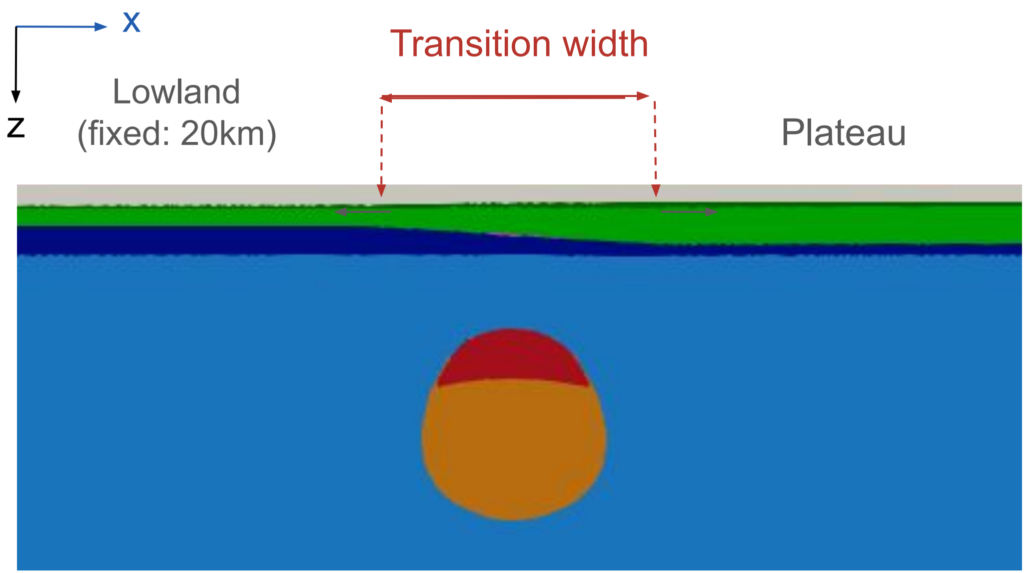
3D View with composition of initial set-up for the reference model. (Fig. 2 from the *Bachelor Thesis "The origin of asymmetrical coronae on Venus: insights from 3D thermomechanical Modelling"* by *Stadler D et al., 2019.*)

(using the exact same model as Stadler D. et al., 2019)

Methods | Numerical Modeling

18 Numerical Models varying:

- **Crustal thickness heterogeneity**
    - Plateau: 40, 33, 27 km
- **Transition width**
    - 100, 200, 300 km
- **Thermal heterogeneity**
    - ON / OFF

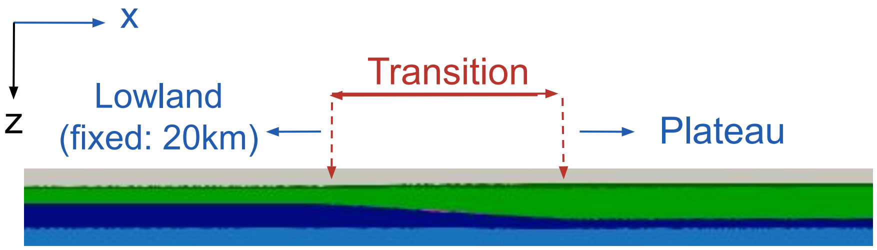


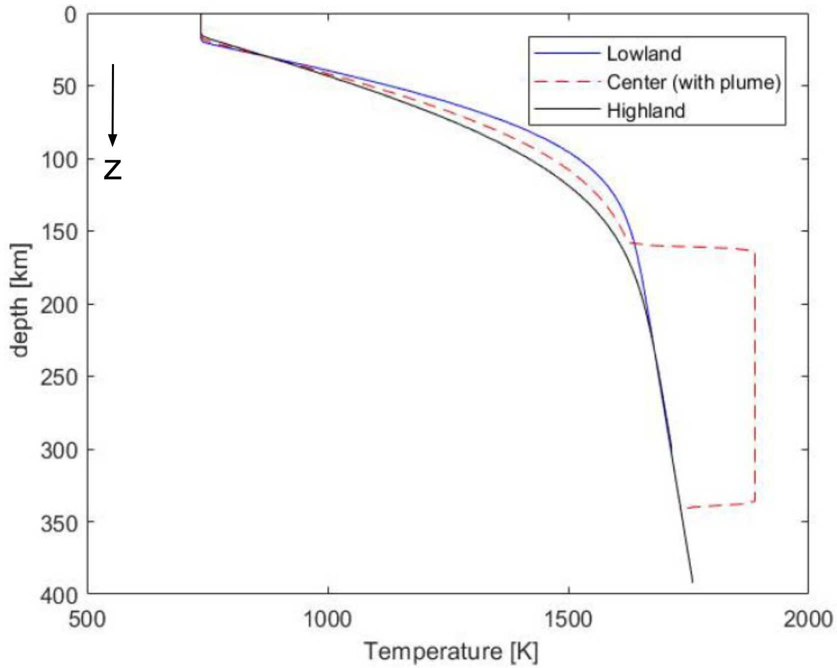
The front section of the 3D model box. All numerical models are two plate with different crustal thickness connected by a transition zone as shown in the image.

Method | Thermal heterogeneity

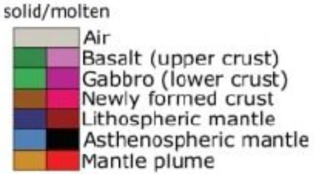
What is **Thermal Heterogeneity:**

➢ Different thermal profiles are taken from different places in x-direction
(Stadler D et al., 2019.)





Thermal prole through the model lth2040m. (Fig. 3 from the *Bachelor Thesis "The origin of asymmetrical coronae on Venus: insights from 3D thermomechanical Modelling" by Stadler D et al., 2019*.)



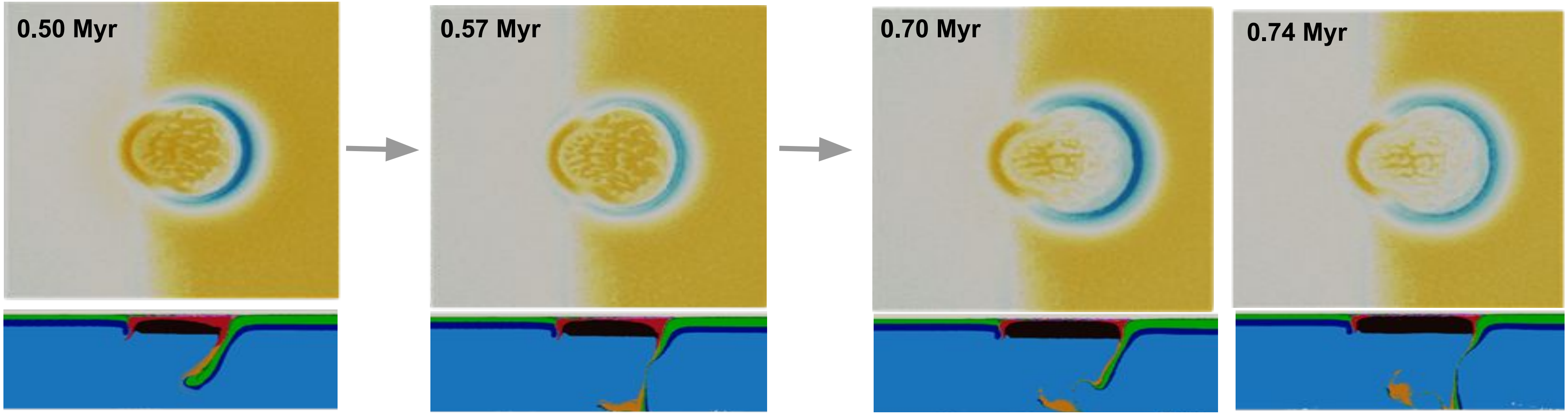
Results | Geodynamics Regime

1. **Dripping Regime:** All Thermal Heterogeneous models

Crustal materials accumulate into a "drip"

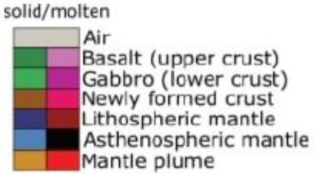
Drip fall off into mantle

Repeat the previous dripping sequence



*Model specs: Thermal heterogeneous model, 40km thick plateau, 200km transition

Results | Geodynamics Regime



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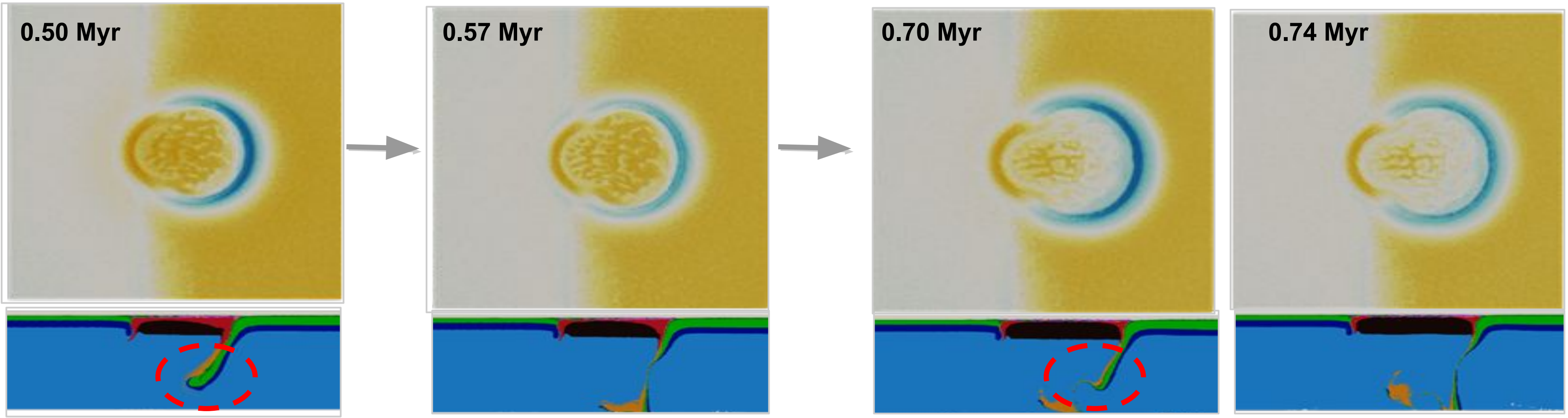
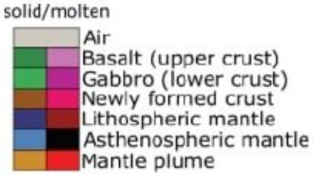


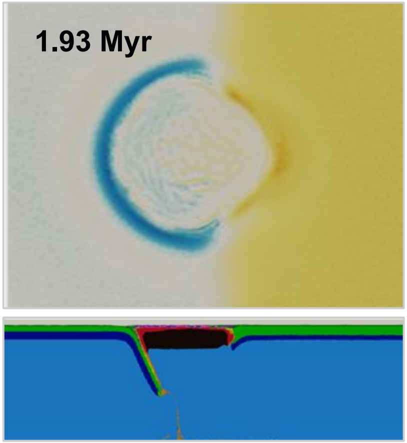
*Model specs: Thermal heterogeneous model, 40km thick plateau, 200km transition

Results | Geodynamics Regime

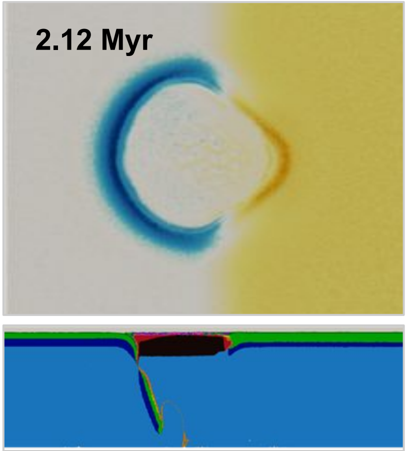


2. Subduction Regime: Models ONLY with crustal thickness heterogeneity

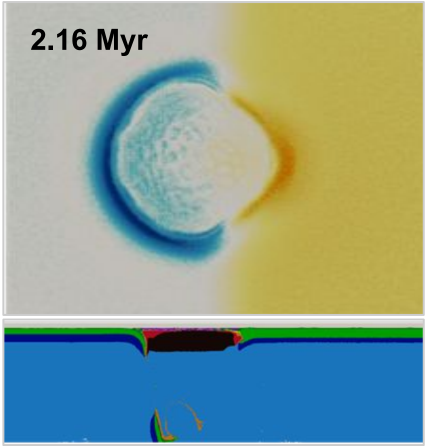
A subducted slab is formed

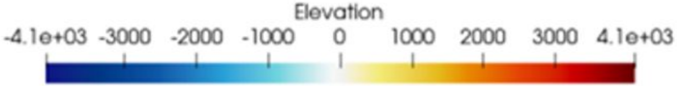


Lithospheric materials accumulate more



Slab falls into mantle



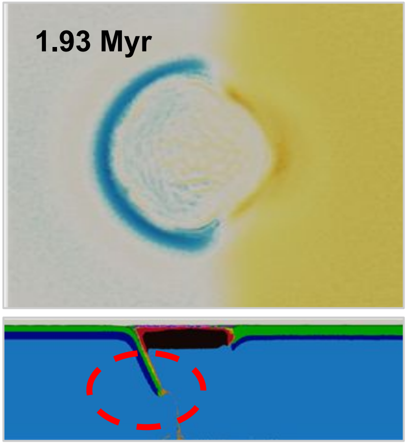


*No thermal heterogeneity, 33km plateau & 100km transition

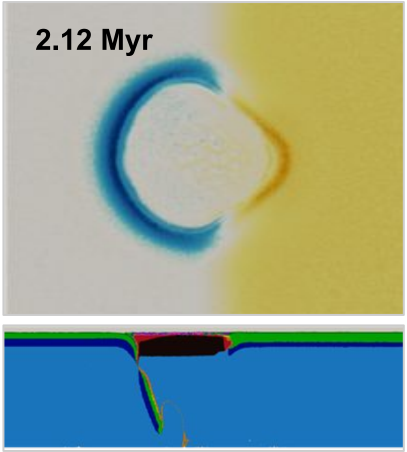
Results | Geodynamics Regime

2. Subduction Regime: Models ONLY with crustal thickness heterogeneity

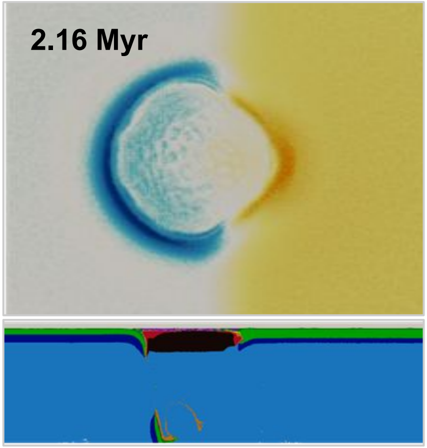
A subducted slab is formed

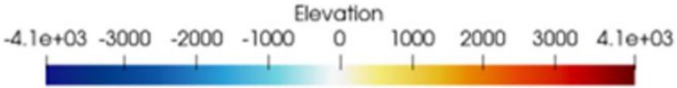


Lithospheric materials accumulate more

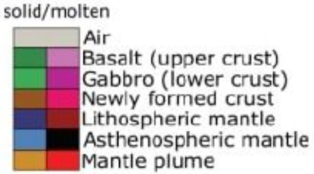


Slab falls into mantle





*No thermal heterogeneity, 33km plateau & 100km transition

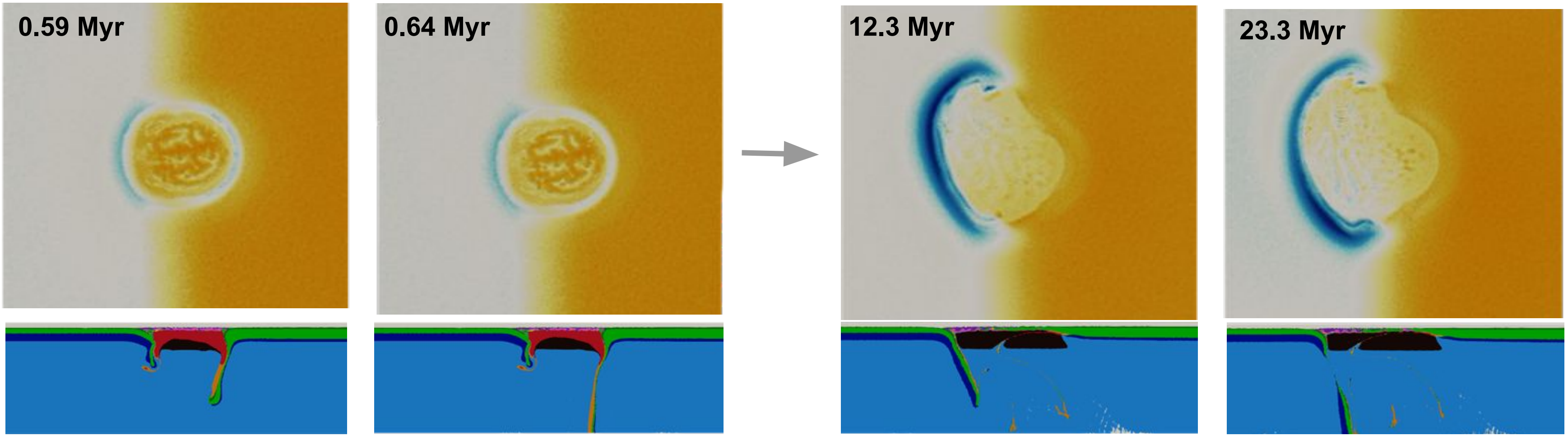


Results | Geodynamics Regime

3. Combination of regimes: Models with 40km plateau and transition width of 200 or 300 km

Dripping Regime

Subduction Regime



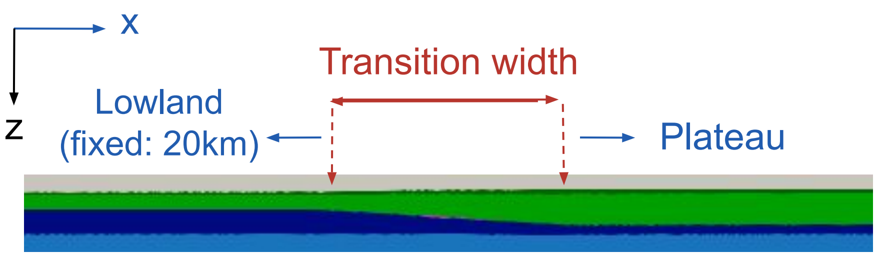
*Model specs: No thermal heterogeneity, 40km plateau and 200km transition

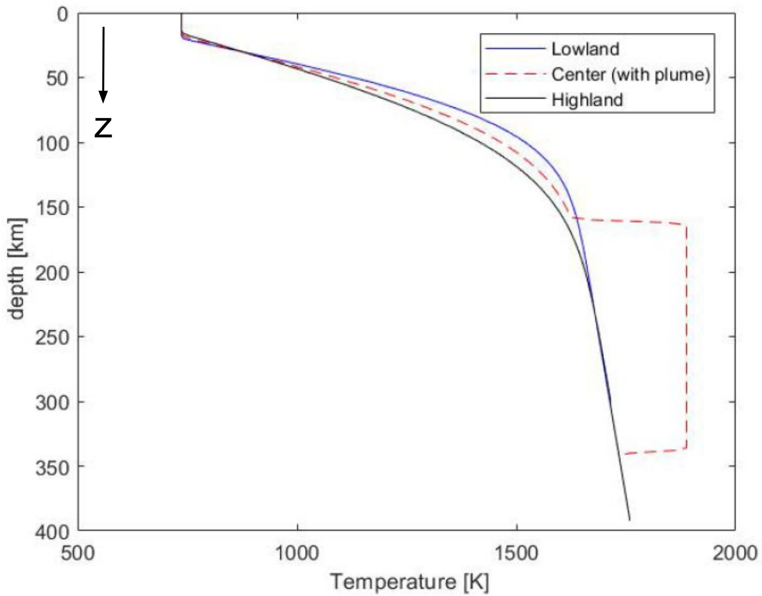
Results | Thermal heterogeneity

What is **Thermal Heterogeneity:**

➢ Different thermal profiles are taken from different places in x-direction

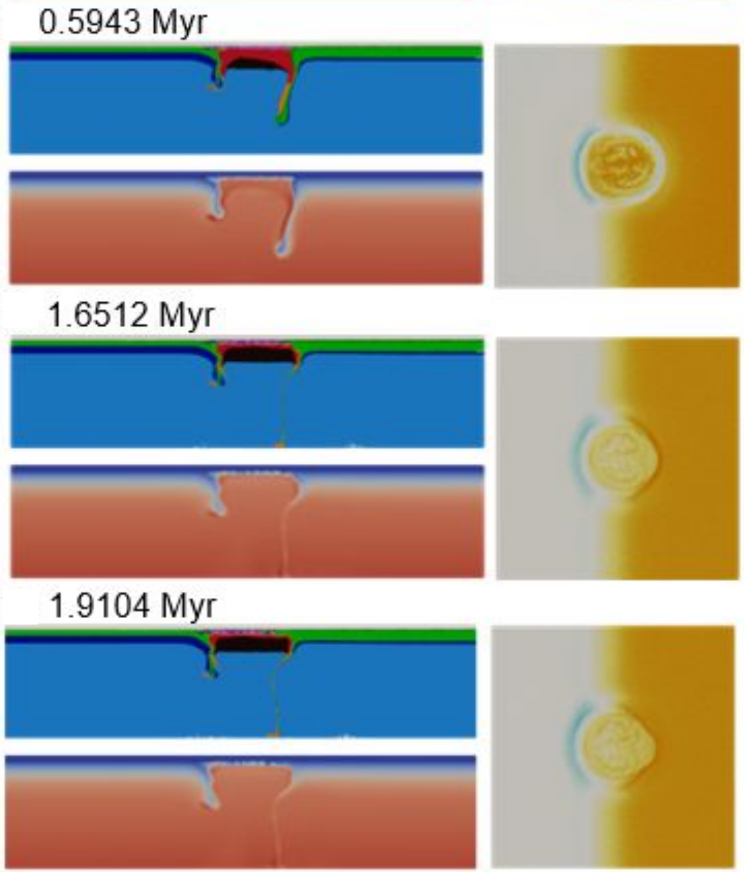
{ lowland, center(transition), highland(plateau) }



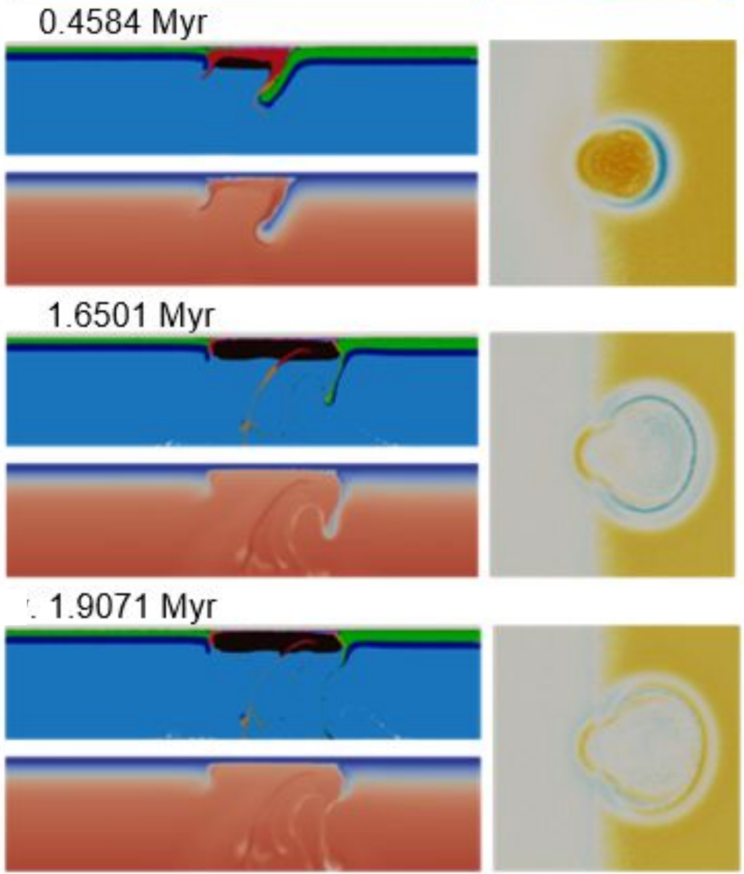


Thermal prole through the model lth2040m. (Fig. 3 from the *Bachelor Thesis "The origin of asymmetrical coronae on Venus: insights from 3D thermomechanical Modelling" by Stadler D et al., 2019.*)

Without Thermal Heterogeneity

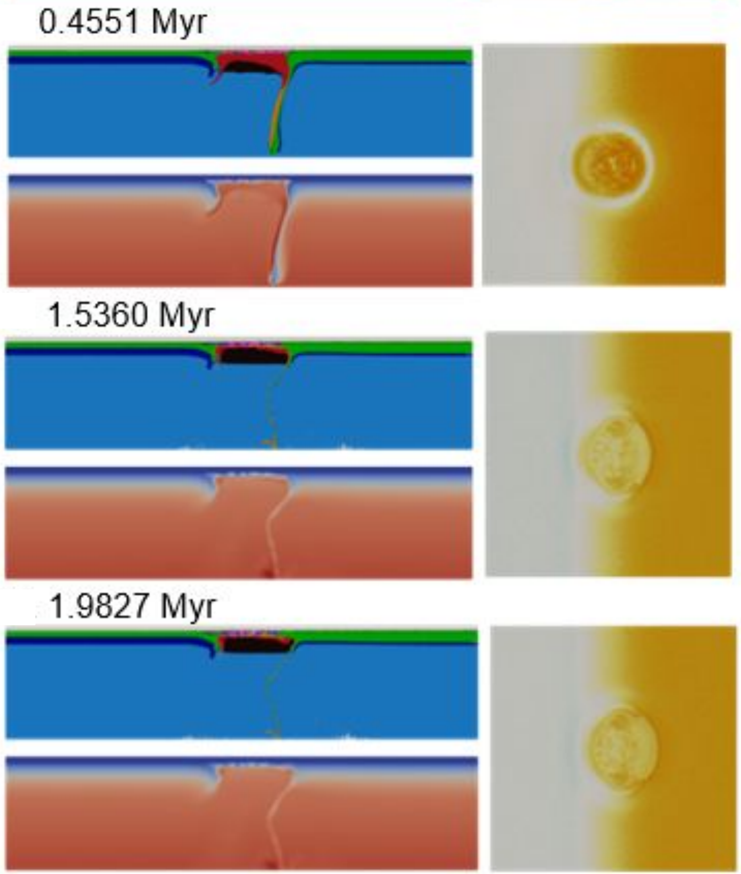


With Thermal Heterogeneity

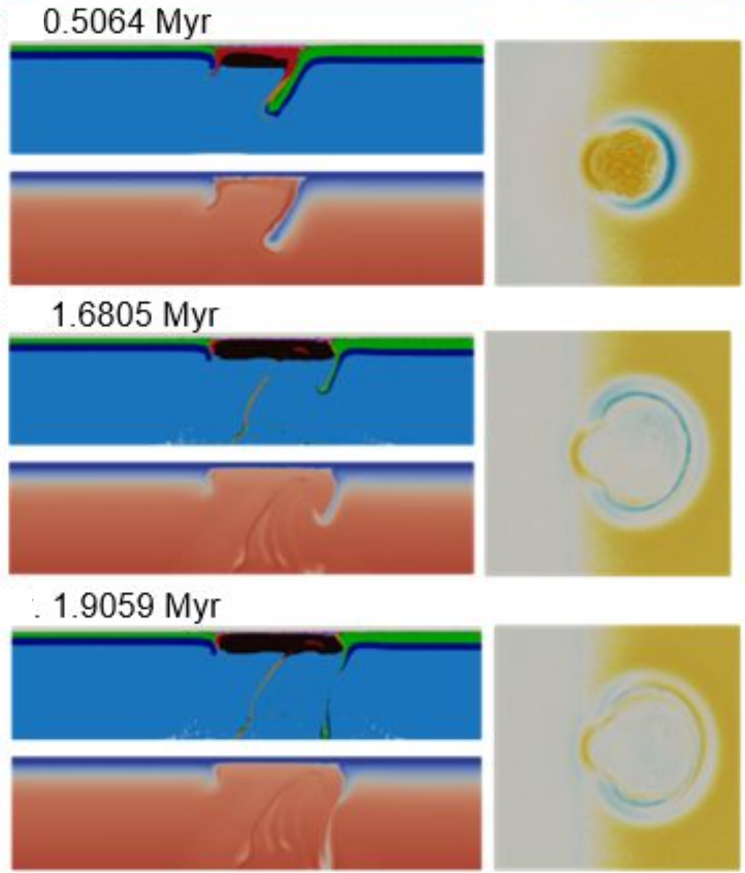


* Both model have 40km plateau thickness & Transition Length 100km

Without Thermal Heterogeneity

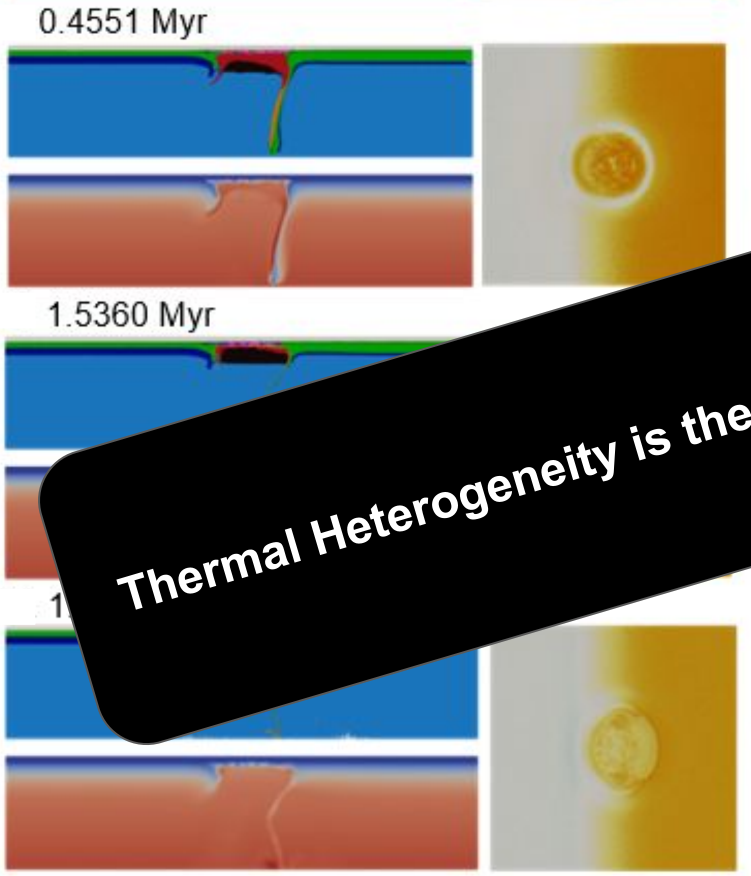


With Thermal Heterogeneity

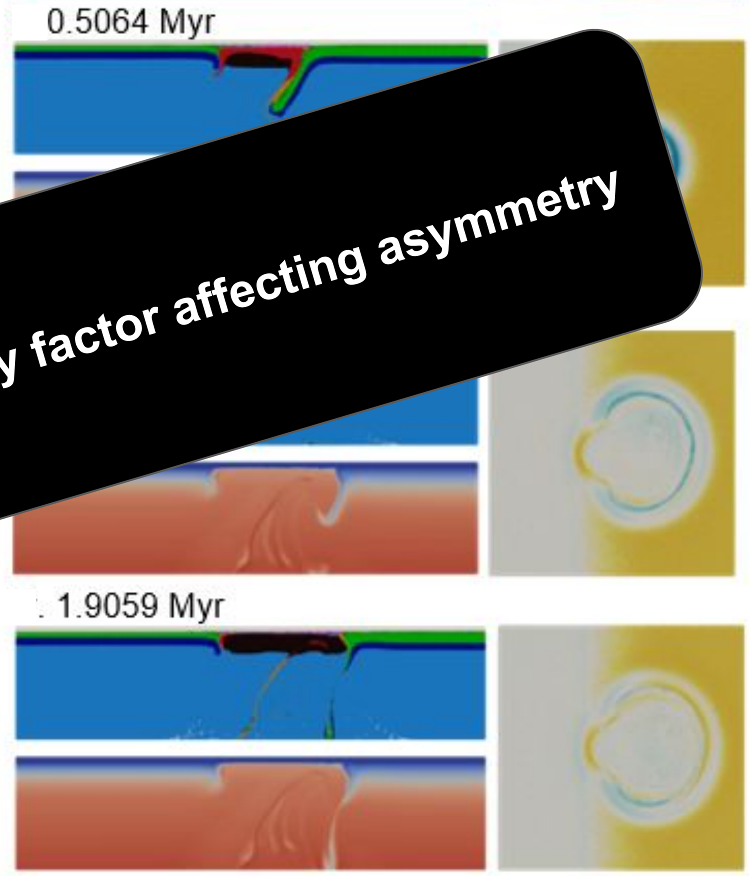


* Both model have 40km plateau thickness & Transition Length 200km

Without Thermal Heterogeneity

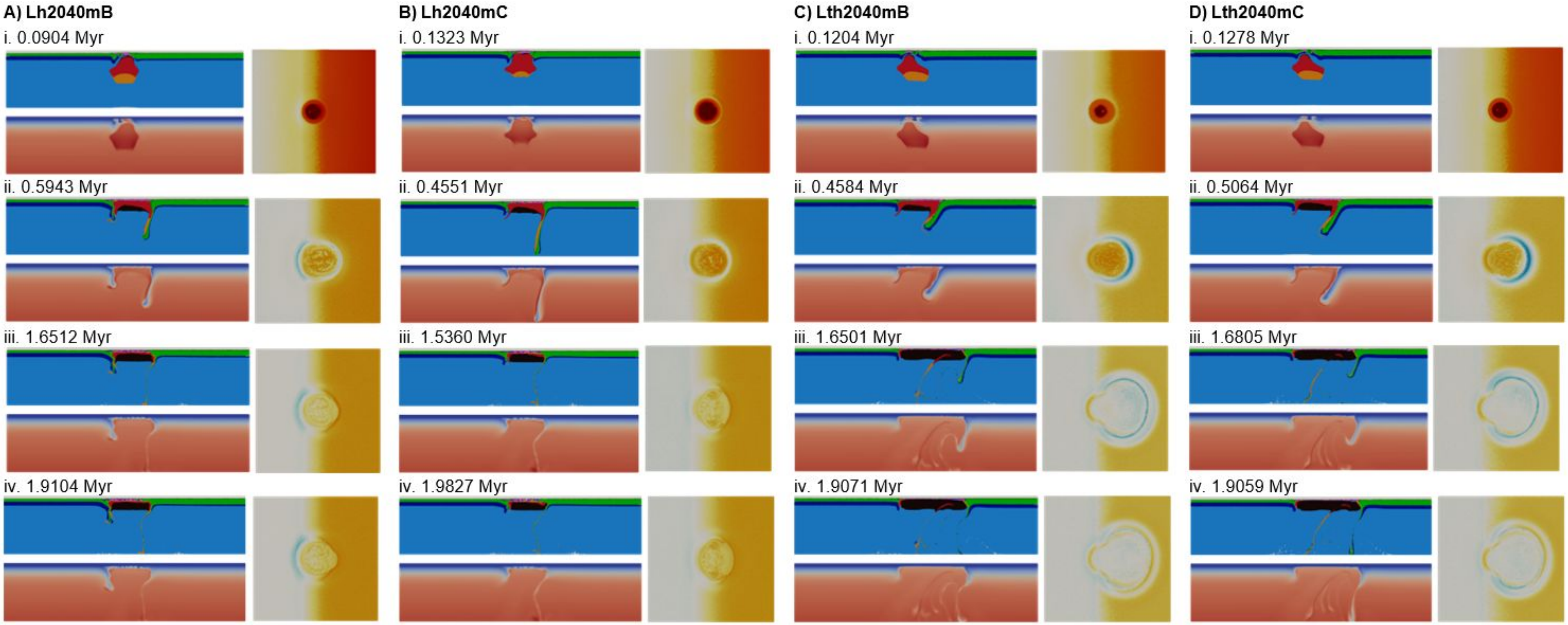


With Thermal Heterogeneity

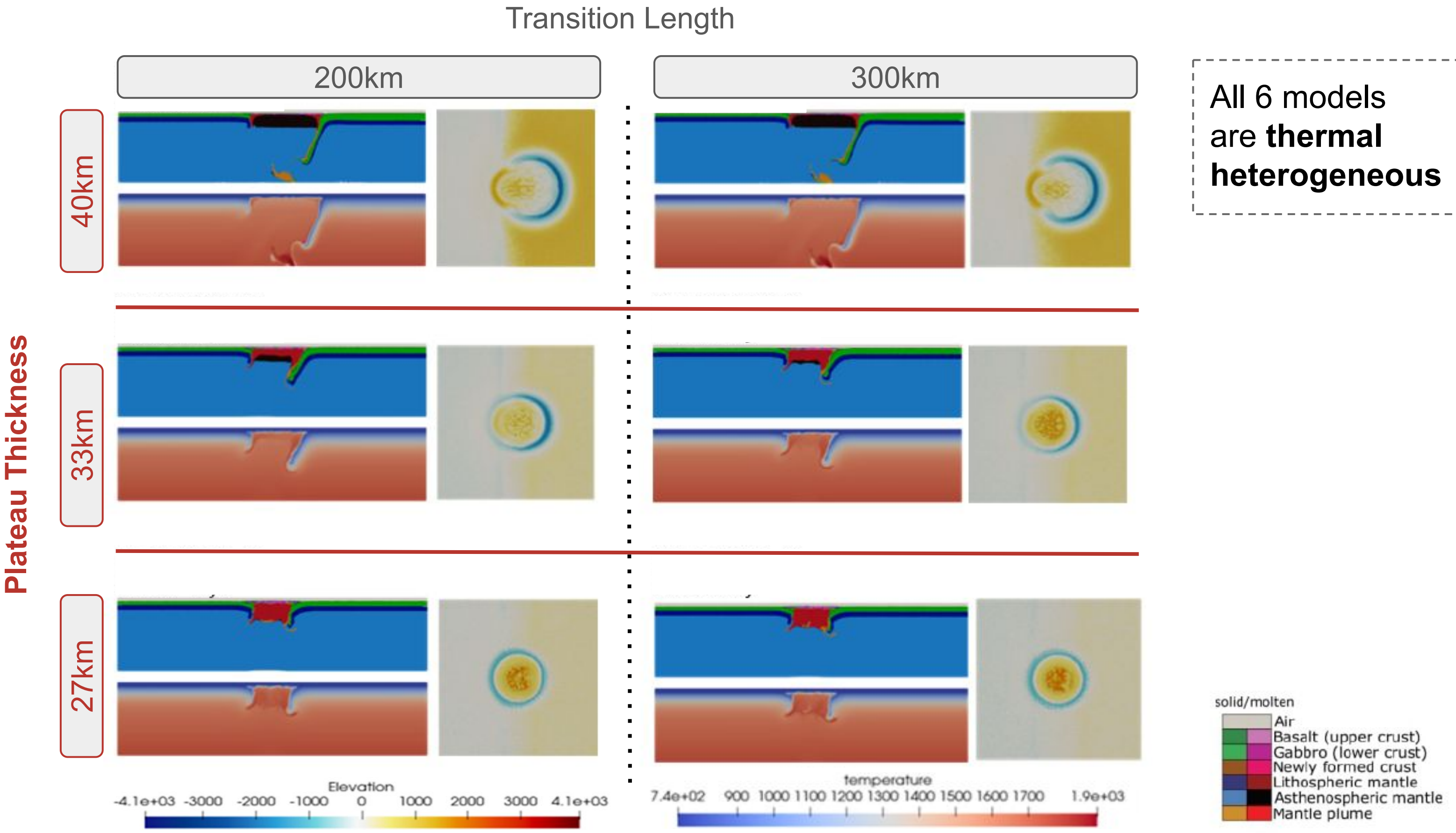


Thermal Heterogeneity is the primary factor affecting asymmetry

* Both model have 40km plateau thickness & Transition Length 200km

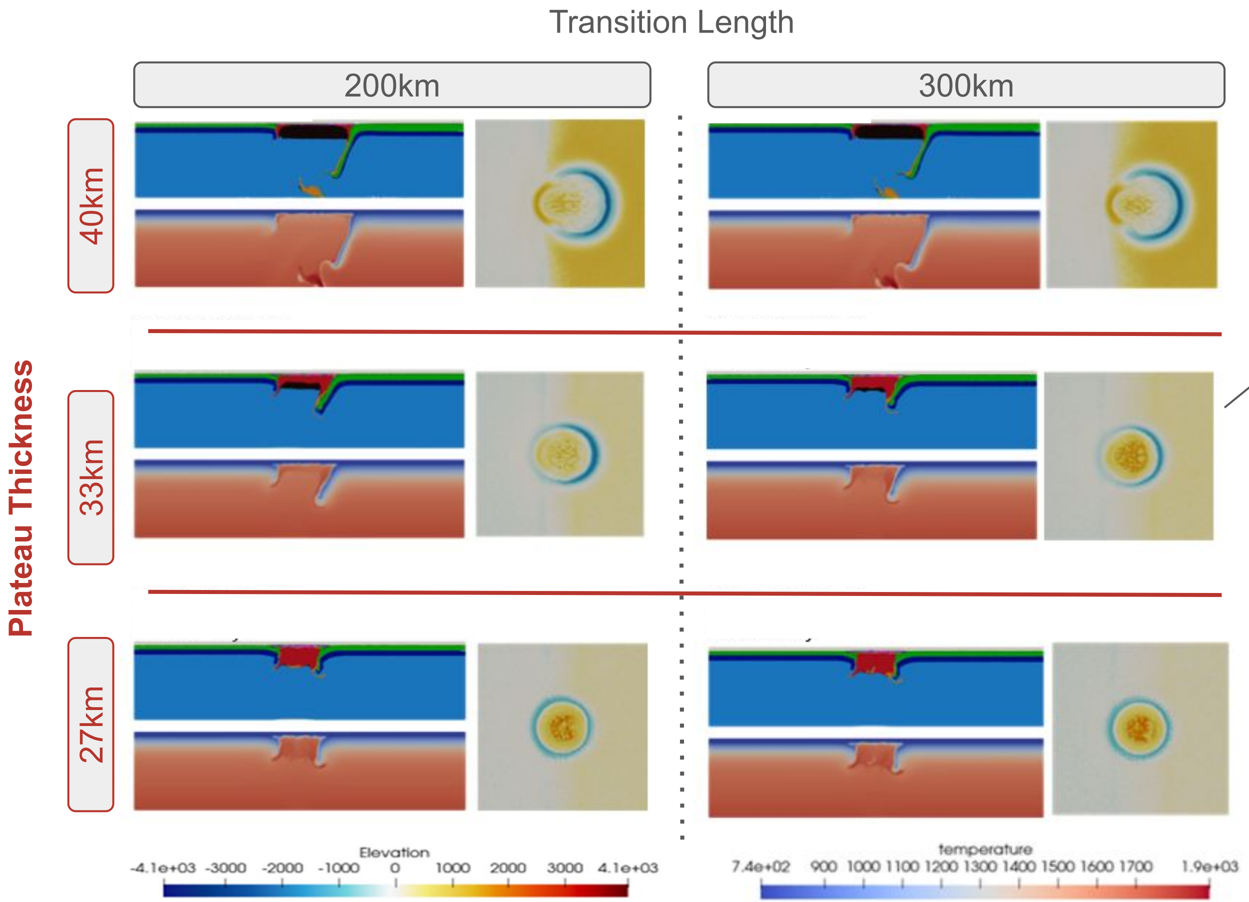

A) Lh2040mB
i. 0.0904 Myr
ii. 0.5943 Myr
iii. 1.6512 Myr
iv. 1.9104 Myr
B) Lh2040mC
i. 0.1323 Myr
ii. 0.4551 Myr
iii. 1.5360 Myr
iv. 1.9827 Myr
C) Lth2040mB
i. 0.1204 Myr
ii. 0.4584 Myr
iii. 1.6501 Myr
iv. 1.9071 Myr
D) Lth2040mC
i. 0.1278 Myr
ii. 0.5064 Myr
iii. 1.6805 Myr
iv. 1.9059 Myr

Results | Crustal Thicknesses Heterogeneity



All 6 models are **thermal heterogeneous**

Results | Crustal Thicknesses Heterogeneity

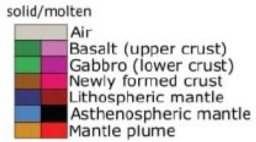


1. Crustal thickness difference ↑

   → Asymmetry ↑

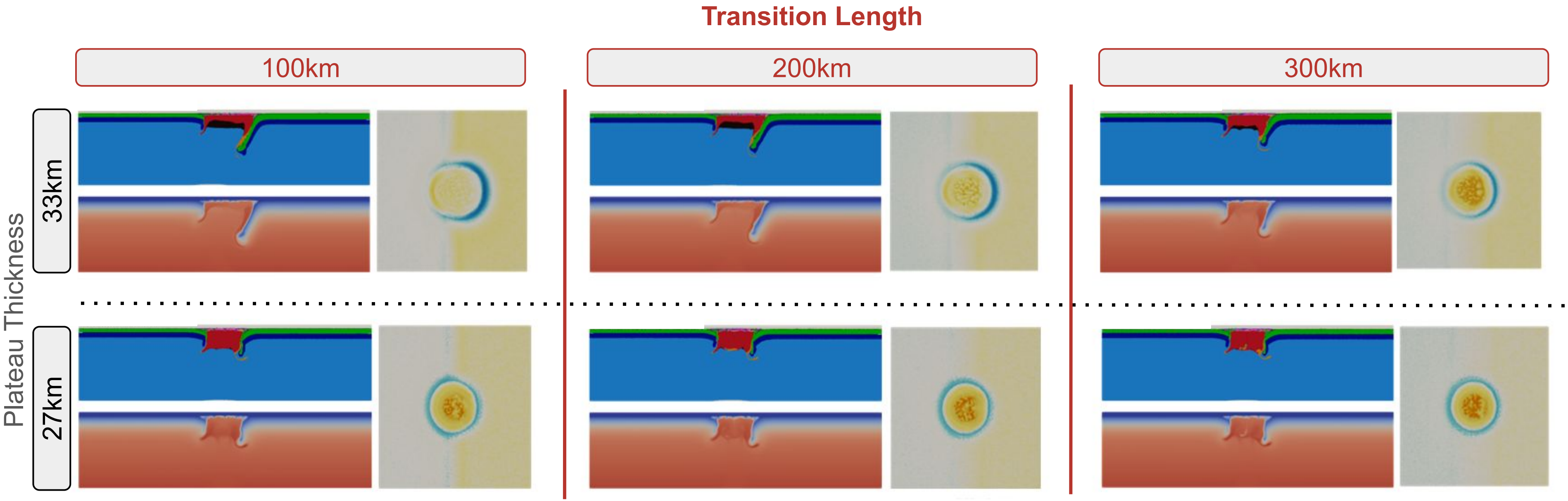
2. Thickness difference affect

   coronae formation speed



Results | Transition Section dimensions

1. Larger transition section → less gradient in crustal thickness → less asymmetric
2. All models are thermal heterogeneous models



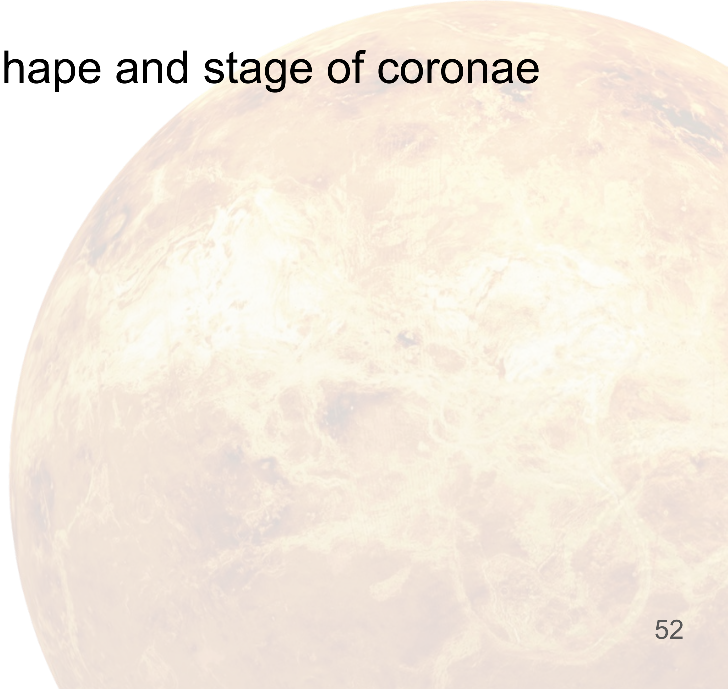
Conclusions

- ➢ From **Coronae Data Analysis**
  - Asymmetry coronae are more likely located at places where there are local variations in crustal thickness

- ➢ From **Numerical Models**
  - Geodynamics Regime:
    - Plateau-sided dripping regime (thermal heterogeneity models)
    - Lowland-sided subduction regime (models with only crustal heterogeneity)
    - Alternating from dripping to subduction regime
      (models with 40km plateau and a transition length > 100km)
  - Parameters of Variation:
    - Dominating factor: **Thermal Heterogeneity**
    - **Larger gradient** in thickness (buoyancy affects) induces **greater asymmetry**

Future Outlook

- Quantify the results of numerical modelings with the gradient of crustal thickness
- 3D composition visualization of models
- Investigate the relationship between asymmetric shape and stage of coronae formation



Acknowledgement

- I am very grateful to my supervisor Dr. Taras Gerya providing me an opportunity to work on this very interesting project and your advice as well as support through the project.

- I would also like to thank Anna Gülcher for all your guidance through the project as well as your patience, constructive advice, and many helpful discussions.

- Lastly, thanks to everyone who I met at ETH Zurich and all your help during my stay!

References

- Crane, L. (2021). NASA plans two Venus missions. New Scientiest.
- Koptev, A., Calais, E., Burov, E., Leroy, S., and Gerya, T. (2015). Dual continental rift systems generated by plume-lithosphere interaction. Nature Geoscience, 8(5):388-392.
- Nimmo, F. and McKenzie, D. (1998). Volcanism and Tectonics on Venus. Annual Review of Earth and Planetary Sciences, 26(1):23-51.
- Phillips, R. J. (1990). Convection-Driven Tectonics on Venus Free-air Dk4 + Psgo), where Ps is the density contrast at the surface and go is gravitational acceleration . At short wave-. 95:1301-1316.
- Piskorz, D., Elkins-Tanton, L. T., and Smrekar, S. E. (2014). Coronae formation on Venus via extension and lithospheric instability. Journal of Geophysical Research: Planets, 119(12):2568-2582.
- Schmeling, H. et al. A benchmark comparison of spontaneous subduction models—towards a free surface. Phys. Earth Planet. Inter. 171, 198–223 (2008).
- Smrekar, S. E. and Stofan, E. R. (1997). Corona Formation and Heat Loss on Venus by Coupled Upwelling and Delamination. Science, 277(5330):1289-1294.
- Solomon, S. C., Head, J. W., and Solomon, Sean C. ; Head, J. W. (1982). Mechanisms for Lithospheric Heat Transport on Venus: Implications for Tectonic Style and Volcanism. Journal of Geophysical Research, 87(B11):9236-9246.
- Stadler, D., Gerya, T., and Gülcher,A (2019). The origin of asymmetrical coronae on Venus: insights from 3D thermomechanical modelling. Bachelor Thesis presented to the Earth Science Department of ETH Zürich Institute of Geophysics.
- Stofan, E. R., Bindschadler, D. L., Head, J. W., and Parmentier, E. M. (1991). Corona Structures on Venus: Models of Origin. Journal of Geophysical Research, 96946(25):920-933.
- Gerya and Yuen (2007). Robust characteristics method for modelling multiphase visco-elasto-plastic thermo-mechanical problems. Physics of the Earth and Planetary Interiors, 163(1-4):83-105.
- Gerya, T. V. (2014). Plume-induced crustal convection: 3D thermomechanical model and implications for the origin of novae and coronae on Venus. Earth and Planetary Science Letters, 391:183-192.
- Gerya, T. V., Stern, R. J., Baes, M., Sobolev, S. V., and Whattam, S. A. (2015). Plate tectonics on the Earth triggered by plume-induced subduction initiation. Nature, 527(7577):221-225.
- Gülcher, A. J., Gerya, T. V., Montési, L. G., & Munch, J. (2021). Corona structures driven by plume–lithosphere interactions and evidence for ongoing plume activity on Venus. Nature Geoscience, 13(8), 547-554.
- Wieczorek, M.A. (2015). Gravity and Topography of the Terrestrial Planets.

Thank you for your attention