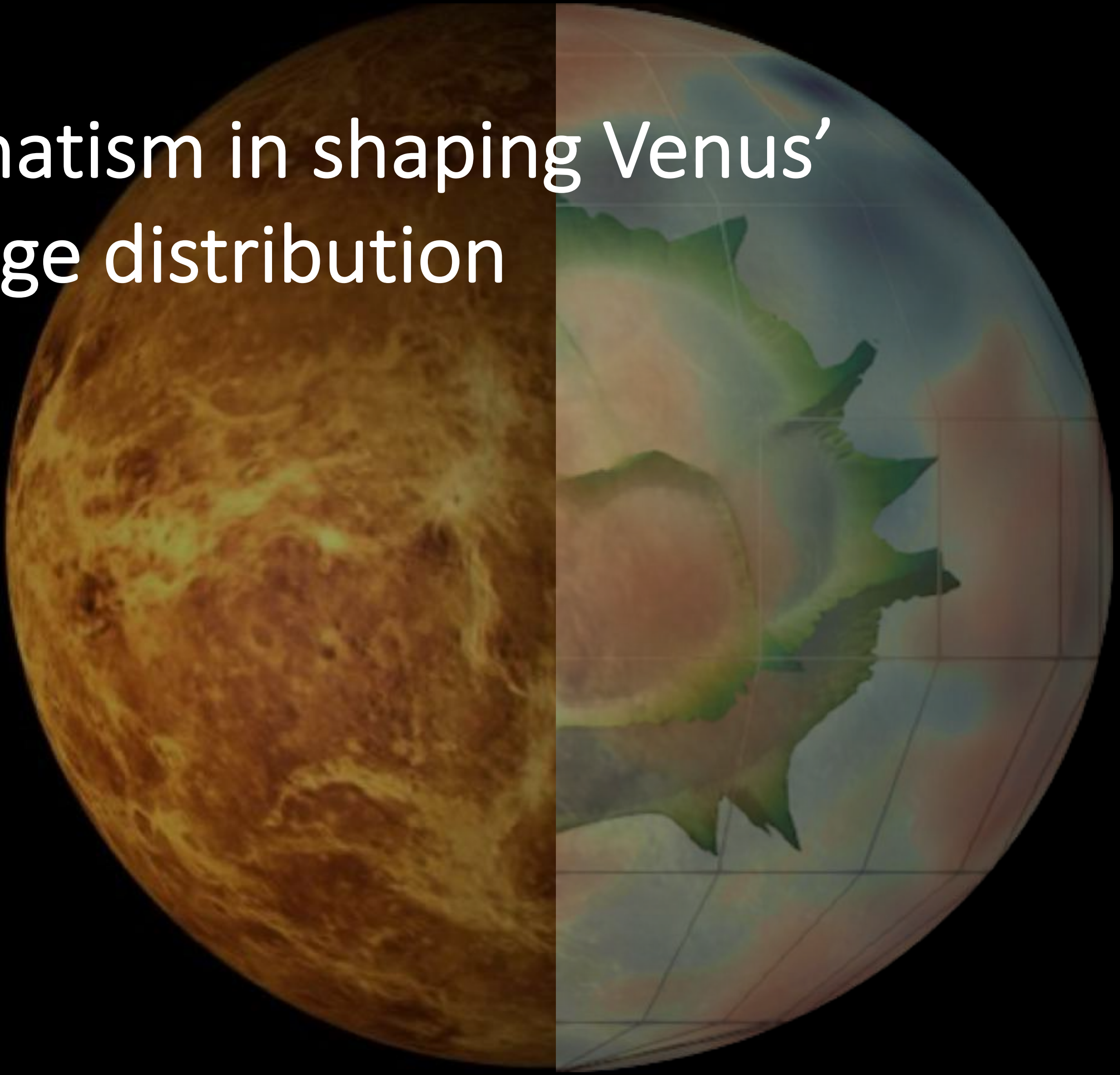
The role of intrusive magmatism in shaping Venus' present-day crust and its age distribution



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Venus Open questions

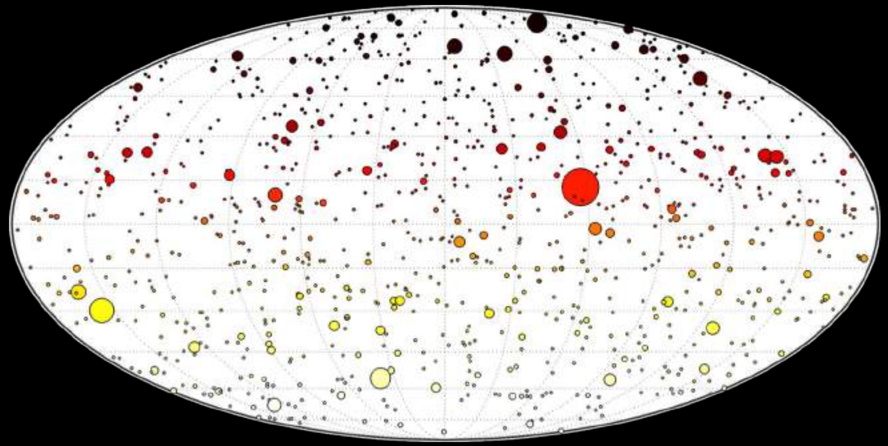
EARTH and VENUS: sister planets?

Grand scheme: Why is Venus so different from Earth?

→ How thick is Venus’ crust? How much magmatic/volcanic activity at present?

→ How old is Venus’ surface, compared to e.g. the Moon, Mars, Mercury?

→ Is the surface age uniform or are there substantial lateral variations?



Crater distribution on Venus (color by latitude, symbol size is scaled with diameter but does not relate to actual area on the map): the small number (<1000) and ~random distribution indicates a young surface with possibly ~uniform age.

What can models of Venus’ interior thermo-magmatic evolution tell us about these?

Venus Evolution model

StagYY [Tackley, 2008] in 2D spherical annullus geometry

- → Strongly temperature-dependent viscosity, no plasticity: **stagnant lid**
- → Evolution from early on (4.4 Ga) until present-day with evolving internal heating and core cooling
- → Magmatism and extrusive volcanism: immediate extraction of magma and placement as basaltic crust on surface

For details: see Armann & Tackley (2012), Rolf et al. (2018)

Now: Intrusive magmatism [see Lourenco et al. (2018,2020)]

With intrusions, not all melt is extracted and placed on surface:

- → Melt pockets with high melt fraction can exist at shallow depth
- → Would cause very low viscosity, effective thermal conductivity needed to parametrise heat flux:

$$k_h = \exp\left(\frac{k_{max}}{2}\left[1 + \tanh\left(\frac{f - f_c}{df}\right)\right]\right) - 1 \longrightarrow$$

$k_h(f \ll f_C) \rightarrow 0$
$k_h(f \sim f_C) \rightarrow$ rapid increase
$k_h(f \gg f_C) \rightarrow 10^5$

f_C = 35% = critical melt fraction
k_{max} = 10^5= max conductivity

Model Magmatism

→ Partial melting occurs where the temperature exceeds the solidus

→ Melting dominantly in upper mantle (< 300 km)

Extrusion:

→ Immediate extraction of hot melt to surface (with probability f_E)

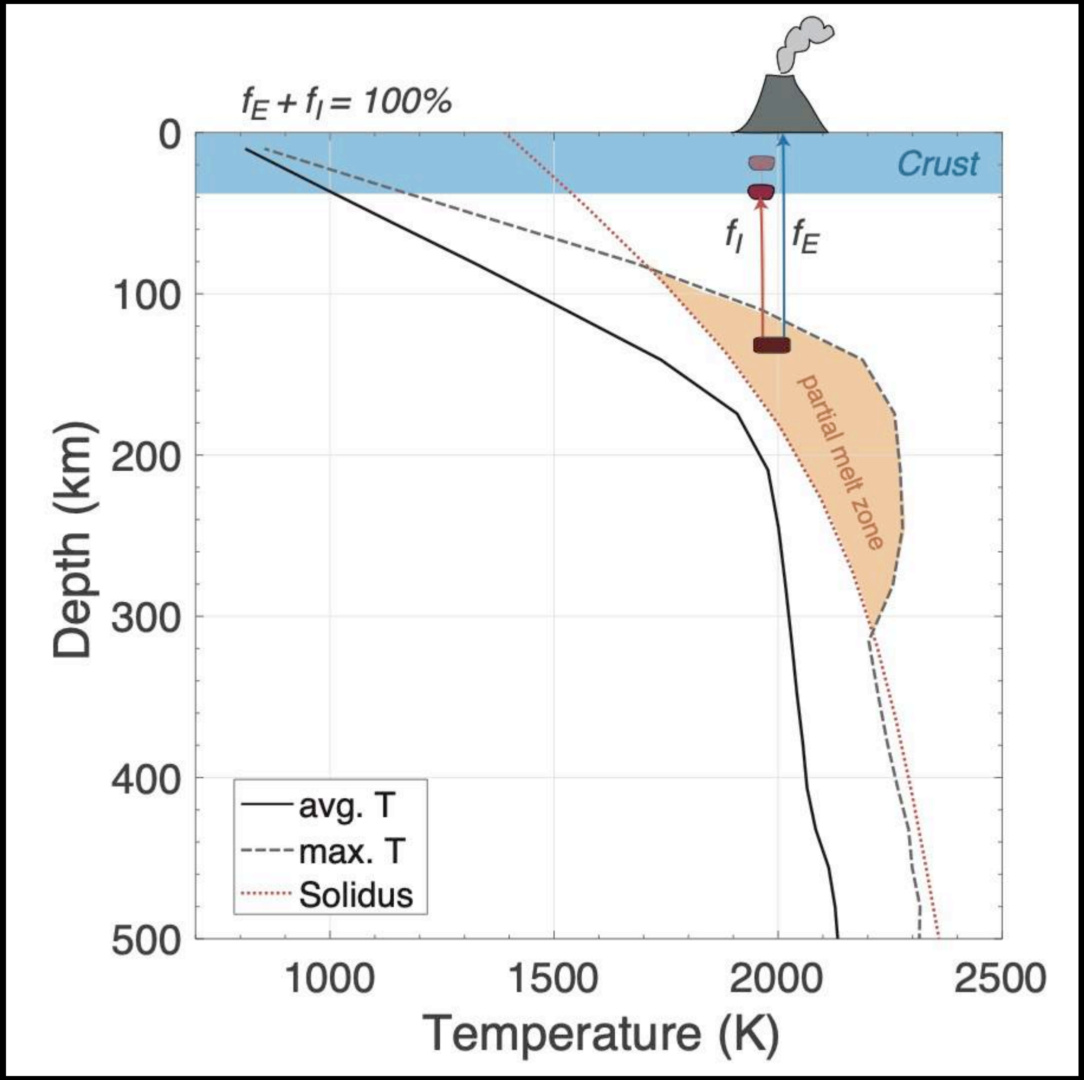
→ **Leads to volcanism and surface renewal**

Intrusion:

→ Emplacement at existing crustal base (with probability f_I=100%-f_E)

→ Melt stays within model domain and affects heat transport (← previous slide)

→ **Weakening of crust, but no direct surface renewal**



Conceptual illustration of the magmatic/volcanic processes implemented in the mantle evolution model.

Results

Present-day state (after 4.4 Gyr evolution)

Temperature

760 K 3240 K

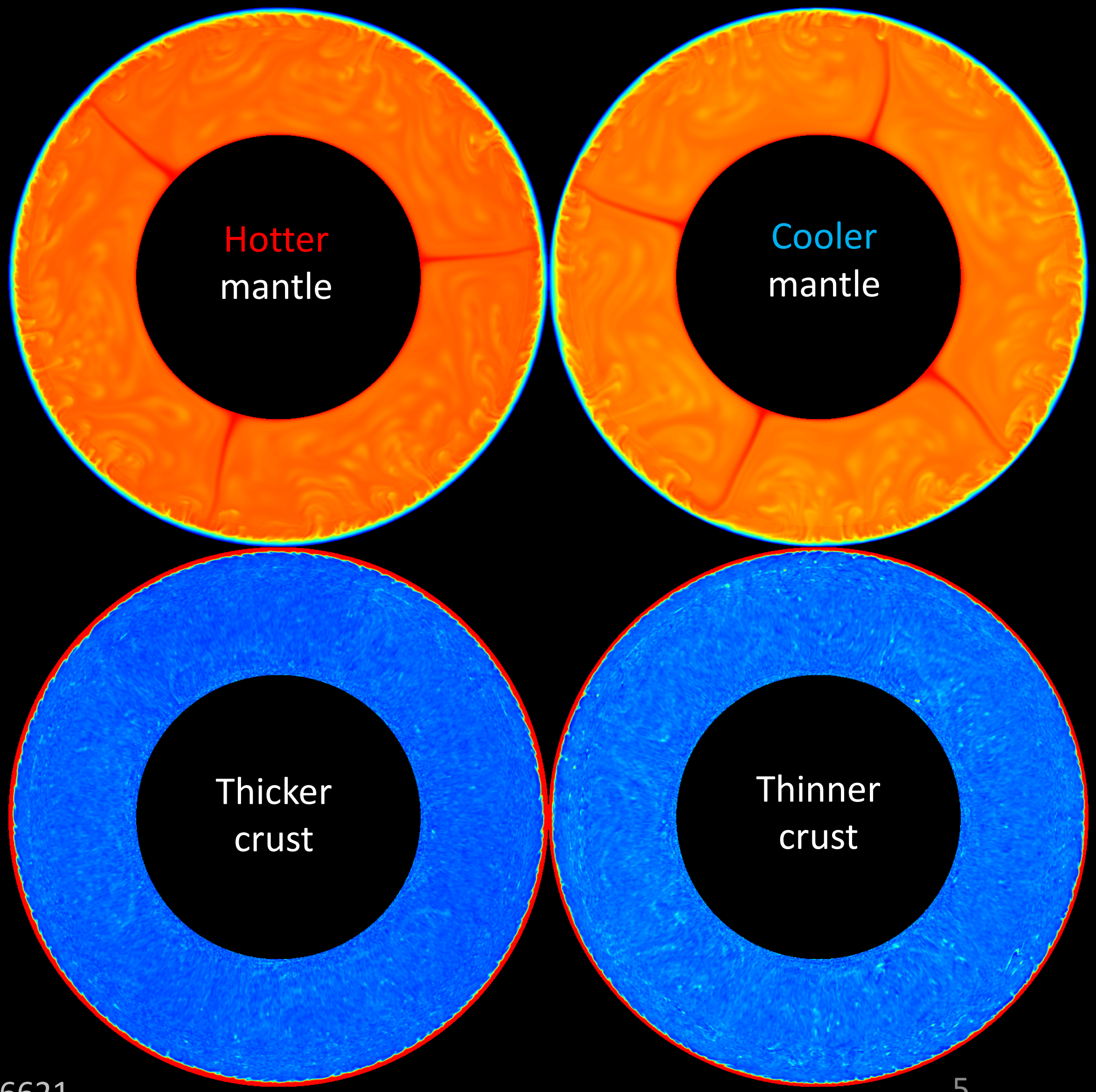
Considering intrusive magmatism has effects on:

- → Mantle temperature (reduced)
- → Mantle flow pattern (here, more plumes)
- → Crustal thickness (here, thinner crust)

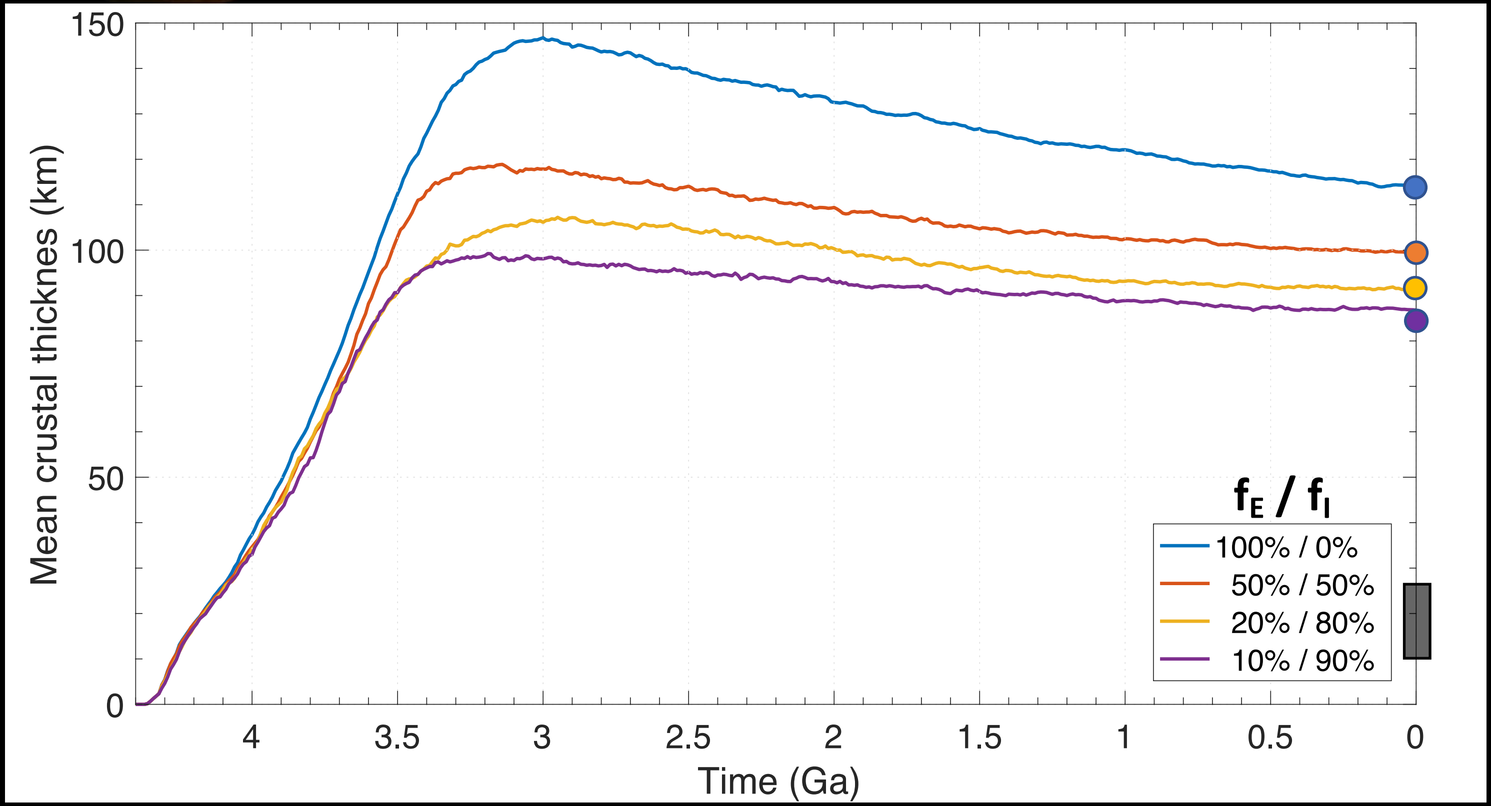
Composition

Harzburgite Basalt (Crust)

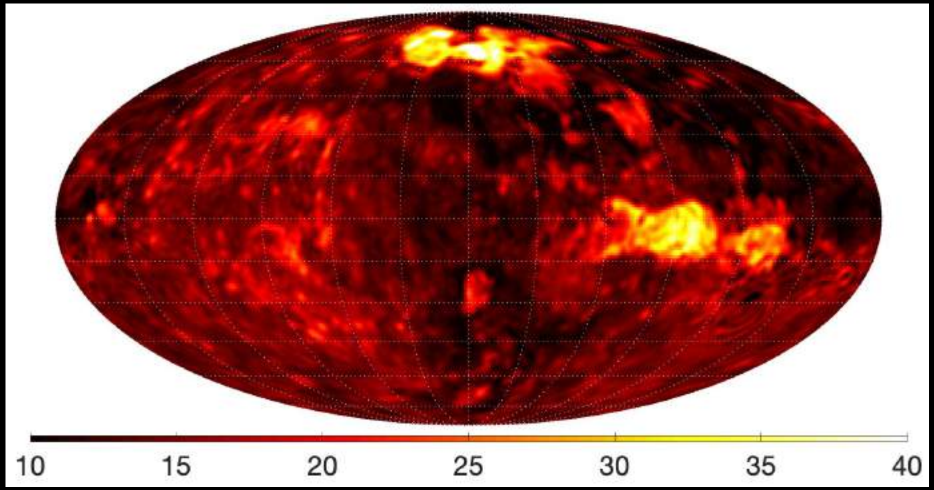
Purely extrusive $f_E=100\%, f_I=0\%$ | Dominantly intrusive $f_E=10\%, f_I=90\%$



Results Crustal thickness evolution



Evolution of mean crustal thickness for different extrusion and intrusion probabilities.



Present-day estimate (no actual data) of Venus' crustal thickness in km based on James et al., 2013

With higher intrusion probability mean thickness is reduced:

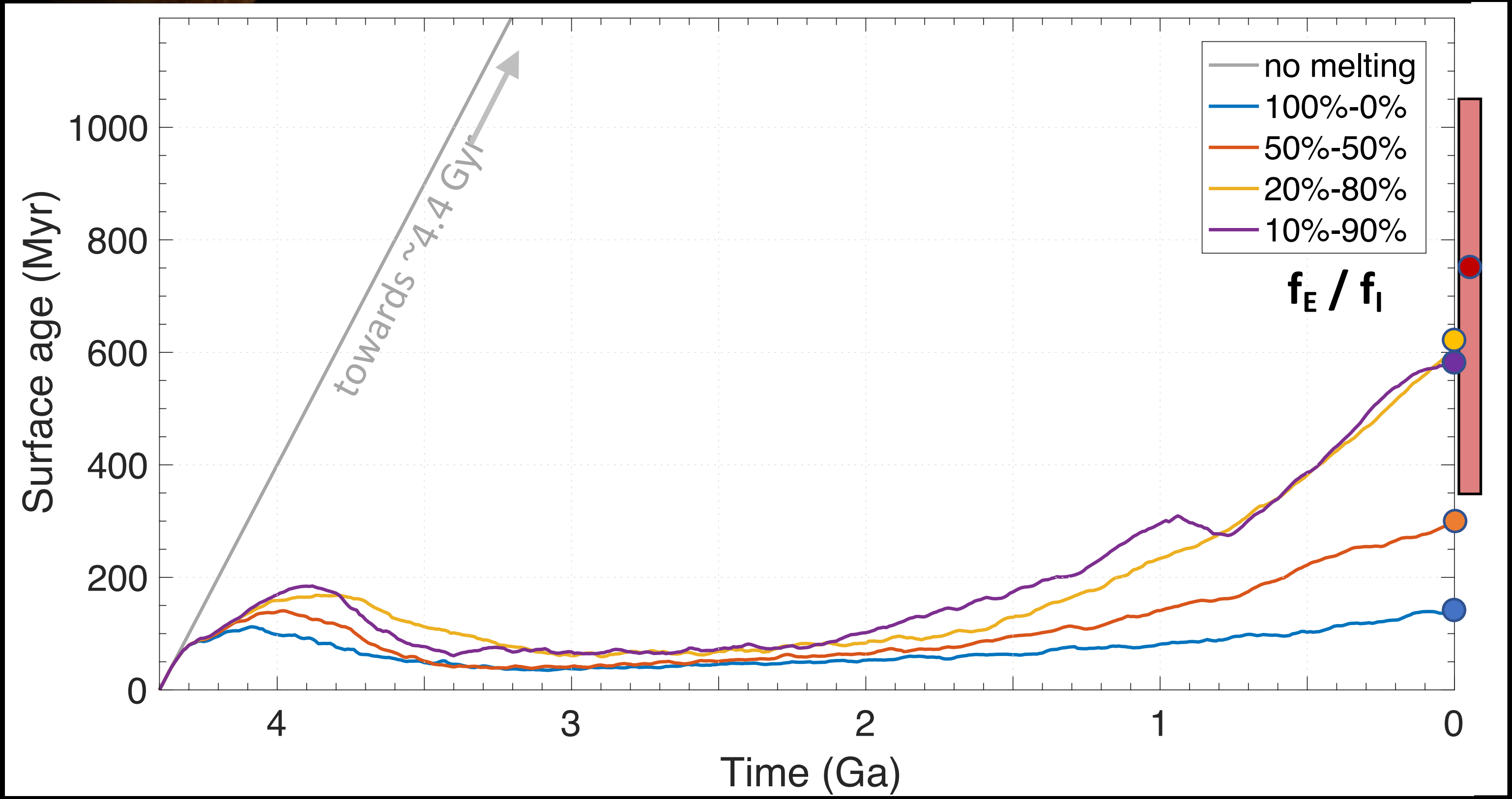
112 km
100 km
91 km
87 km

20-25% thinner crust with dominantly intrusive magmatism

But model estimates are still larger than other estimates
(typically a few 10s of km)

Results Mean surface age

Surface age := residence time of tracer particles (initially 90/cell) in surface grid layer (top ~20 km)



Time evolution of mean surface age for different extrusion and intrusion probabilities (f_E, f_I). The grey curve displays an endmember scenario without melting present.

With higher intrusion probability mean age increases:

140/ 300/600 /570 Myr
for f_I = 0/ 50/ 80/ 90 %

This happens because less lava reaches the surface to renew it.

However, absolute age estimates for Venus are uncertain:

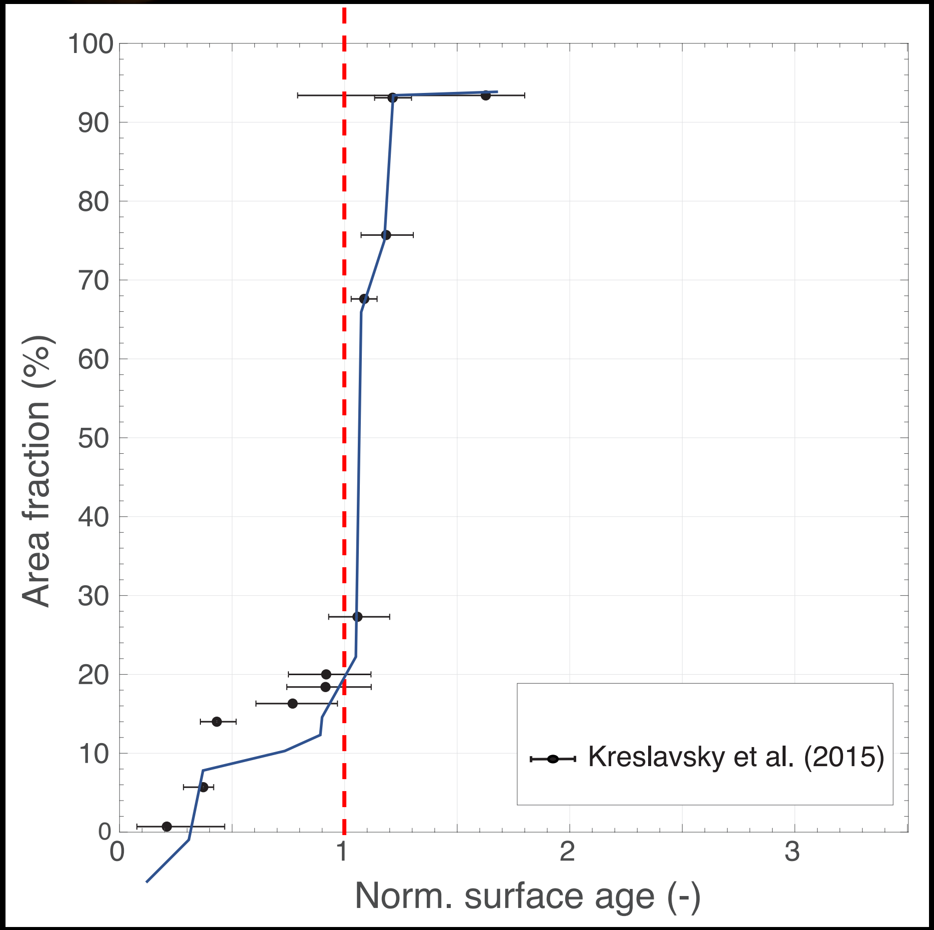
$750^{+47\%}_{-53\%}$ Myr McKinnon et al. (1997)

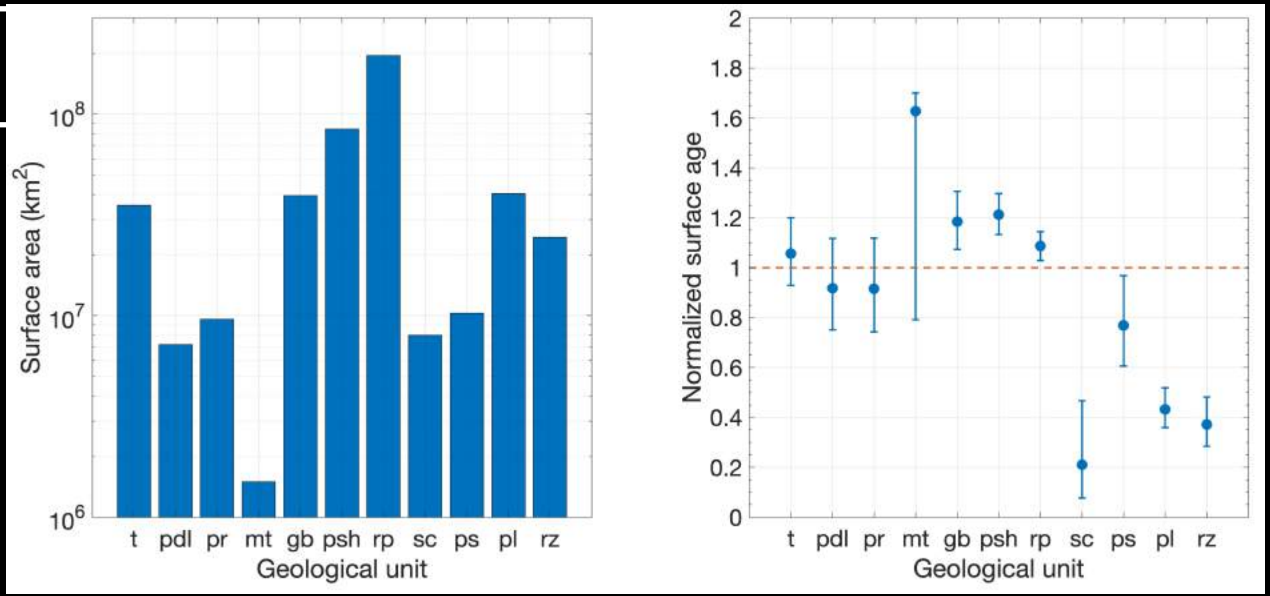
< 200 Myr Bottke et al. (2016)

Results Lateral age variations

Area and relative age estimate of the 11 categorized geological units on Venus as mapped by Ivanov & Head (2011). The red horizontal line denotes the mean surface age, after Kreslavsky et al., 2015.

Mean age



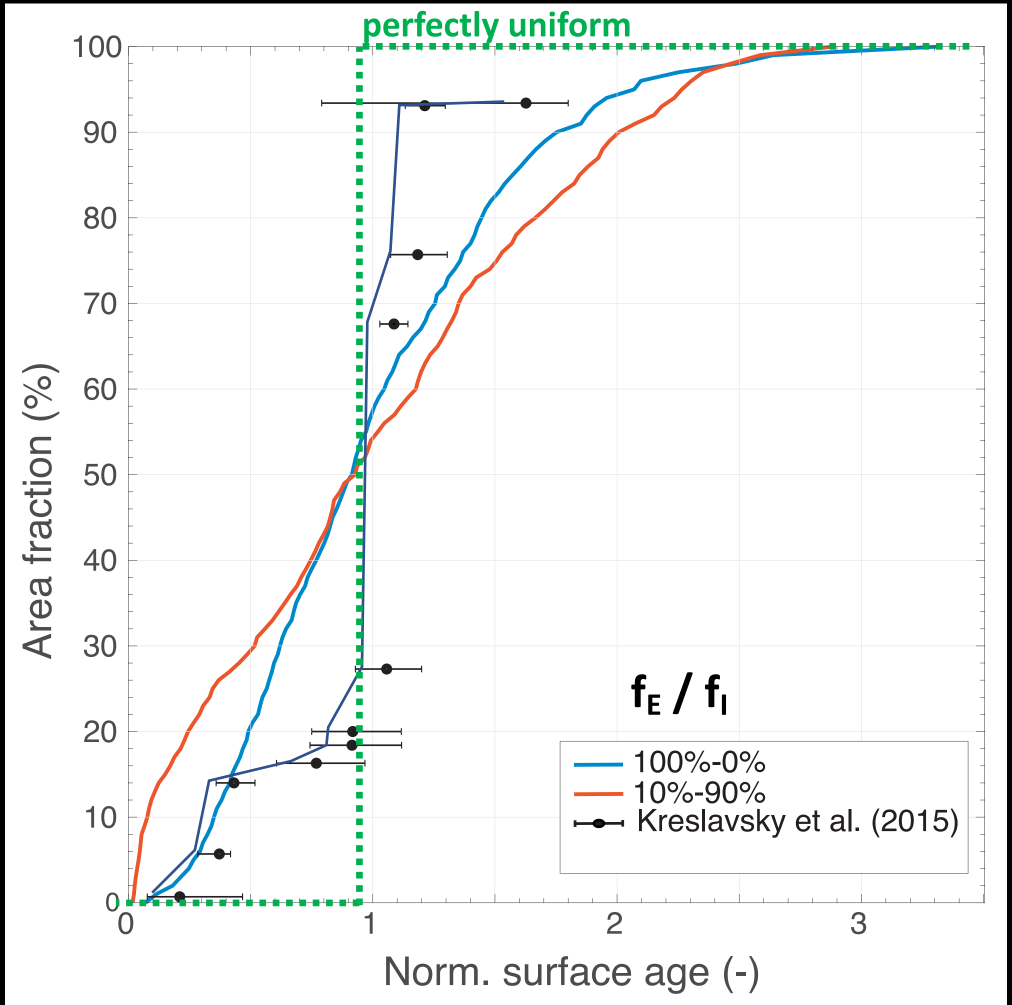


Geological units are [Ivanov & Head, 2011]: (t) tesserae, (pdl) densely lineated plains, (pr) ridged plains, (mt) mountain belts, (gb) groove belts, (psh) shield plains, (rp) regional plains, (sc) shield clusters, (ps) smooth plains, (pl) lobate plains, (rz) rift zones).

Cumulative distribution of normalized (or relative!) surface age using the observed area and age estimates.

Results Lateral age variations

- → Venus' surface age is not completely uniform, ~15% seem younger
- → Purely extrusive model predictions are less uniform than inferred from geology and crater statistics
- → Age uniformity is worse with dominantly intrusive magmatism



Cumulative distribution of normalized surface age using the observed area and age estimates (dots + error bars).

The blue and red lines indicate results for two cases with different partitioning of extrusive (f_E) and intrusive (f_I) volcanism/magmatism.

The green dotted line denotes a perfectly uniform distribution.

Results Parameters

Mantle viscosity determines convective vigor and thus heat transport, mantle internal temperature and the amount of partial melting.

Reducing mantle viscosity leads to

1.) reduced mean crustal thickness

thinner thermal boundary layer

more efficient erosion of crustal base

2.) increased mean surface age (absolute)

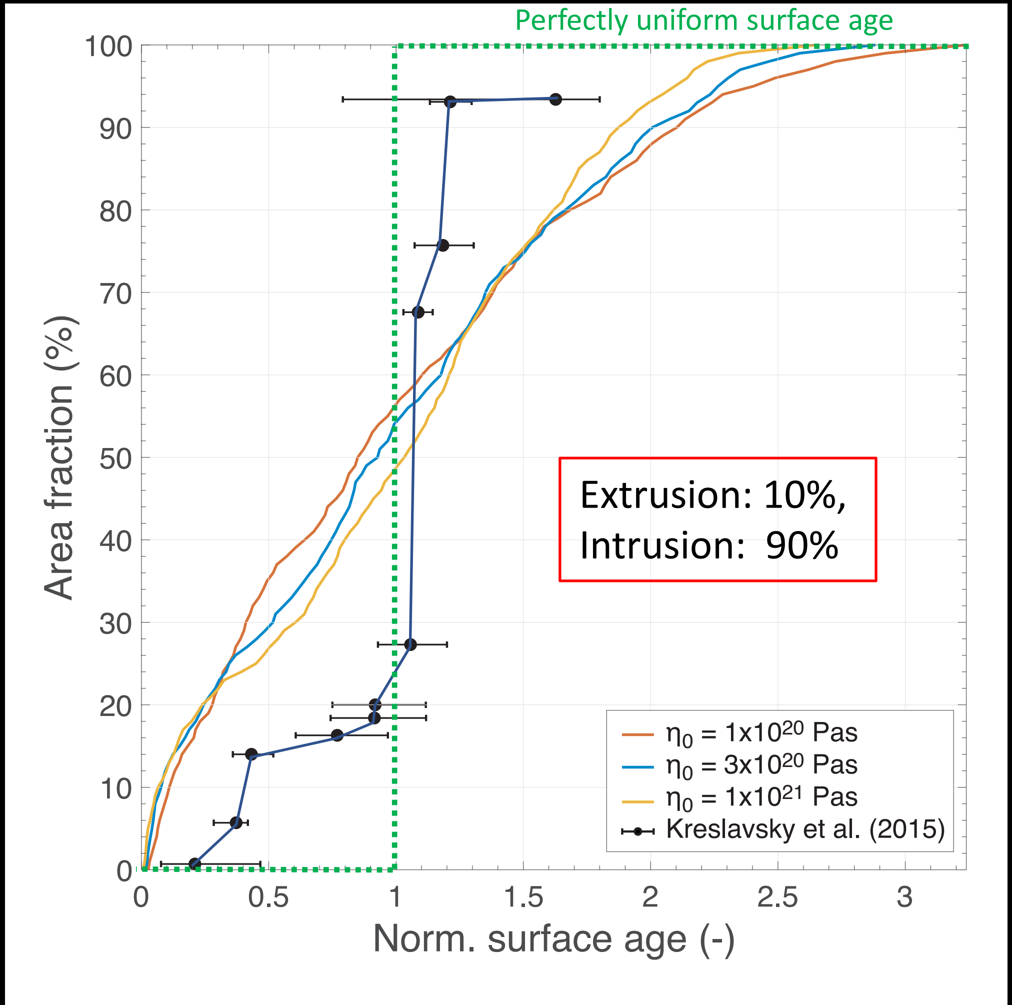
more efficient heat loss

→ mantle cools faster

3.) increased lateral age variations (relative)

magmatism/volcanism begins to cease in colder, but not in hotter parts of the upper mantle

→ **More parameter exploration is needed**



Cumulative distribution of relative surface age for different mantle reference viscosities (defined at temperature 1613 K and 0 Pa pressure).

Summary

1.) Interior evolution models predict Venus' global resurfacing history, now considering both **<u>extrusive and intrusive magmatic</u>** processes.

2.) Intrusive magmatism reduces resurfacing rates in the stagnant lid regime. Mean crustal thickness is reduced, mean surface age is higher (right tendency to match other independent estimates for Venus)

3.) Strong intrusive magmatism enhances lateral age contrasts. Yet, no model predicts a surface crust with both a mean age matching crater statistics estimates and high degree of uniformity

Perspectives

→ **<u>Episodic overturns</u>**: Mantle cools quicker with time, earlier cessation of volcanic activity is feasible. Surface is expected to be older (absolute), but relative variations will depend on duration and lateral extent of the overturn events (regional vs. global)

→ **<u>3D models</u>**: Detailed comparison to Venus' surface characteristics requires 3D geometry