Plutonic-squishy lid:
a new global tectonic regime generated by intrusive magmatism on Earth-like planets

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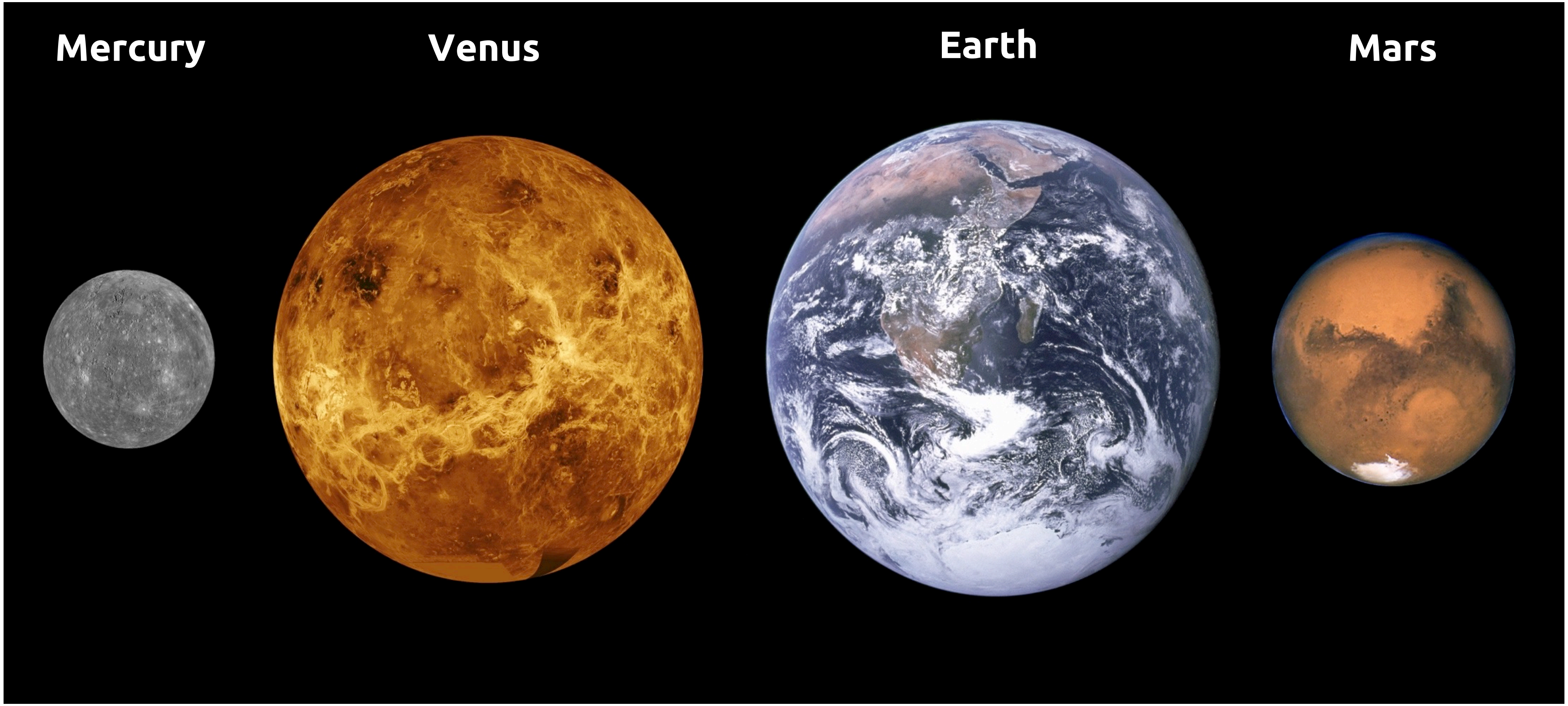
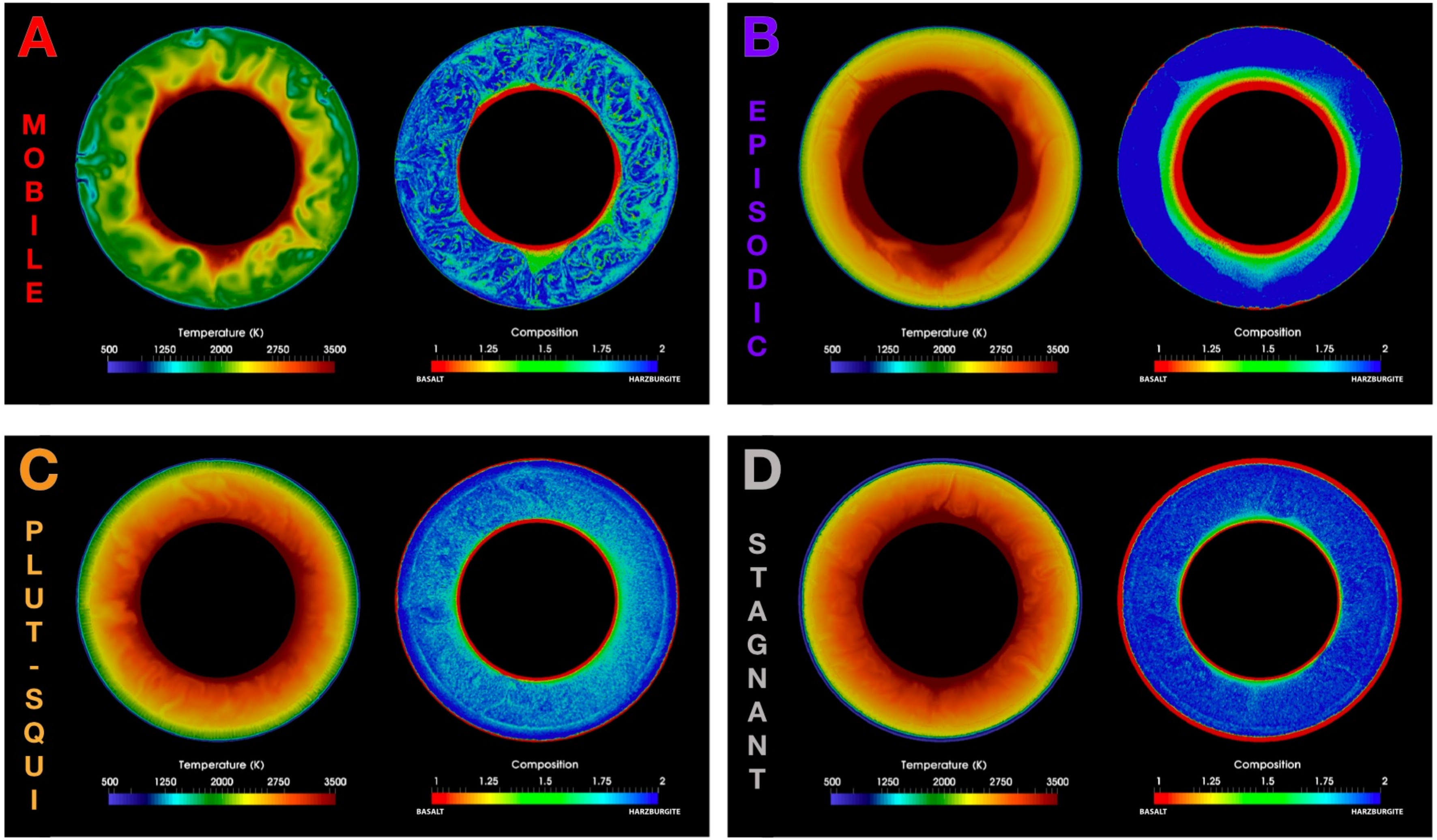
Introduction: Tectonic regimes on rocky planets

- The thermal and chemical evolution of rocky planets is controlled by their surface tectonics and magmatic processes.



Introduction: Tectonic regimes on rocky planets

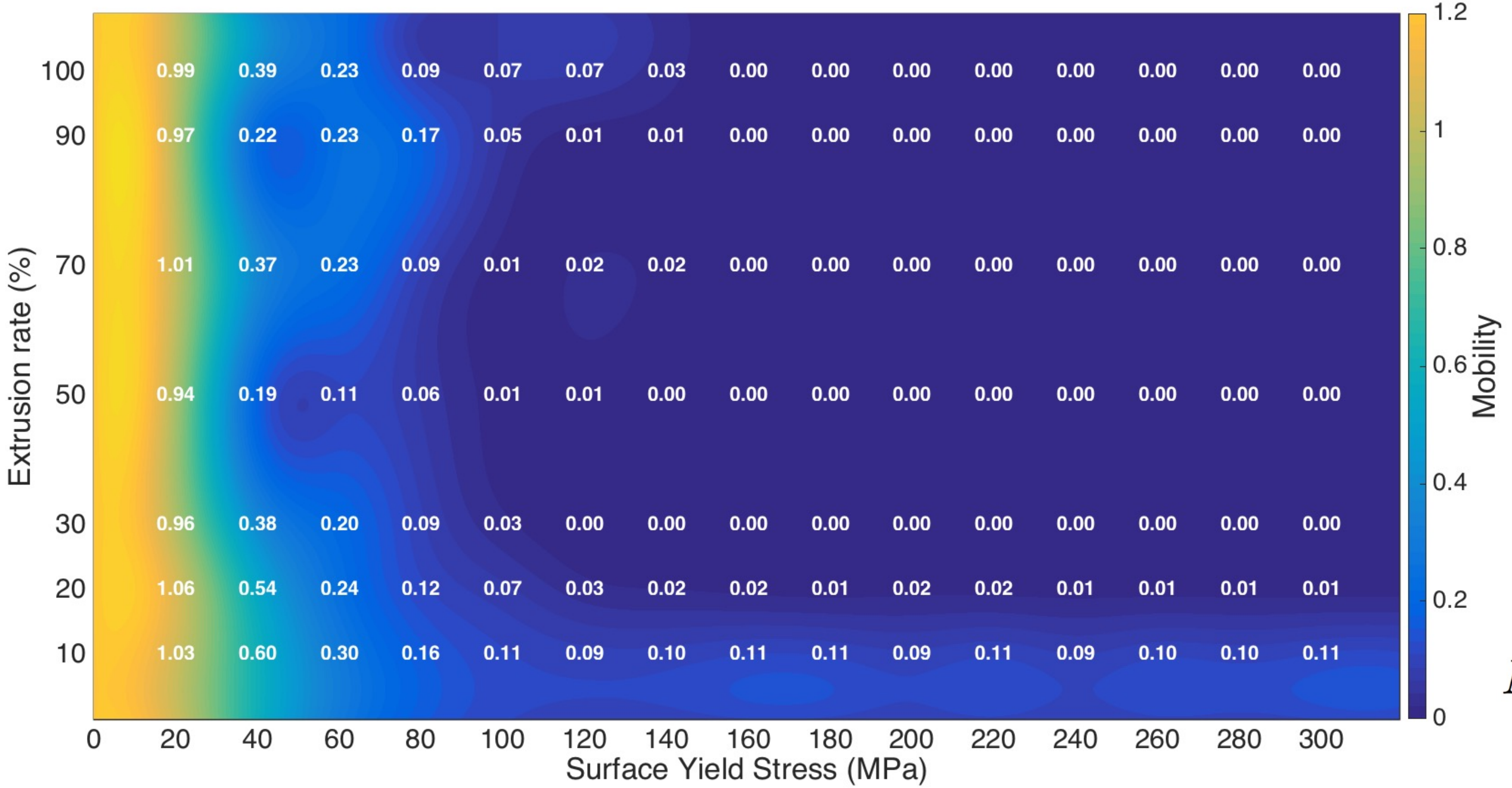
- On Earth, magmatism is dominated by plutonism/intrusion versus volcanism/extrusion.
- On Venus this is also likely to be the case.
- However, the role of plutonism on planetary tectonics and long-term evolution of rocky planets has not been systematically studied.



Temperature and composition state after 4.5 Gyrs of evolution

Results: mobility

- In this study, we use numerical simulations to systematically investigate the effect of plutonism combined with eruptive volcanism.



Mobility as a function of yield strength and eruption efficiency. The value represents the mobility averaged in time from 0 to 4.5 Gyr. Each number inside the diagrams represents one computation.

$$M = \frac{(\nu_{rms})_{surface}}{(\nu_{rms})_{whole}}$$

Results: mobility

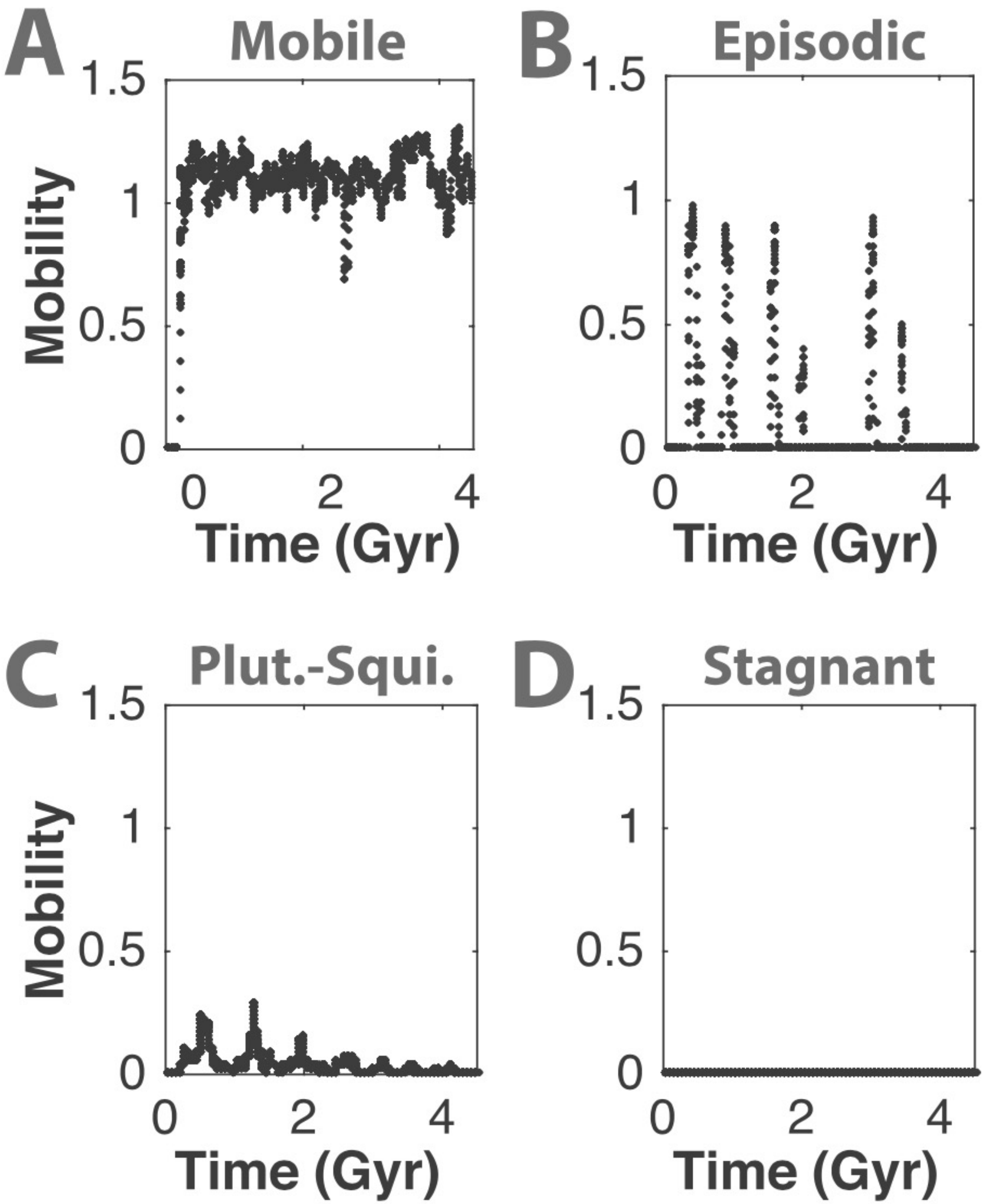
- Mobility (*M*) represents the extent to which the lithosphere can move in each time frame, when compared to the mantle
- When M~1surface velocities are similar to mantle velocities; when M~0 velocities at the surface are negligible

A. Mobile lid: surface yield stress (σ_{duct}) = 20 MPa, eruption efficiency (E)= 10%

B. Episodic lid: σ_{duct} = 100 MPa, E = 70%

C. Plutonic-squishy-lid: σ_{duct} = 300 MPa, E = 10%)

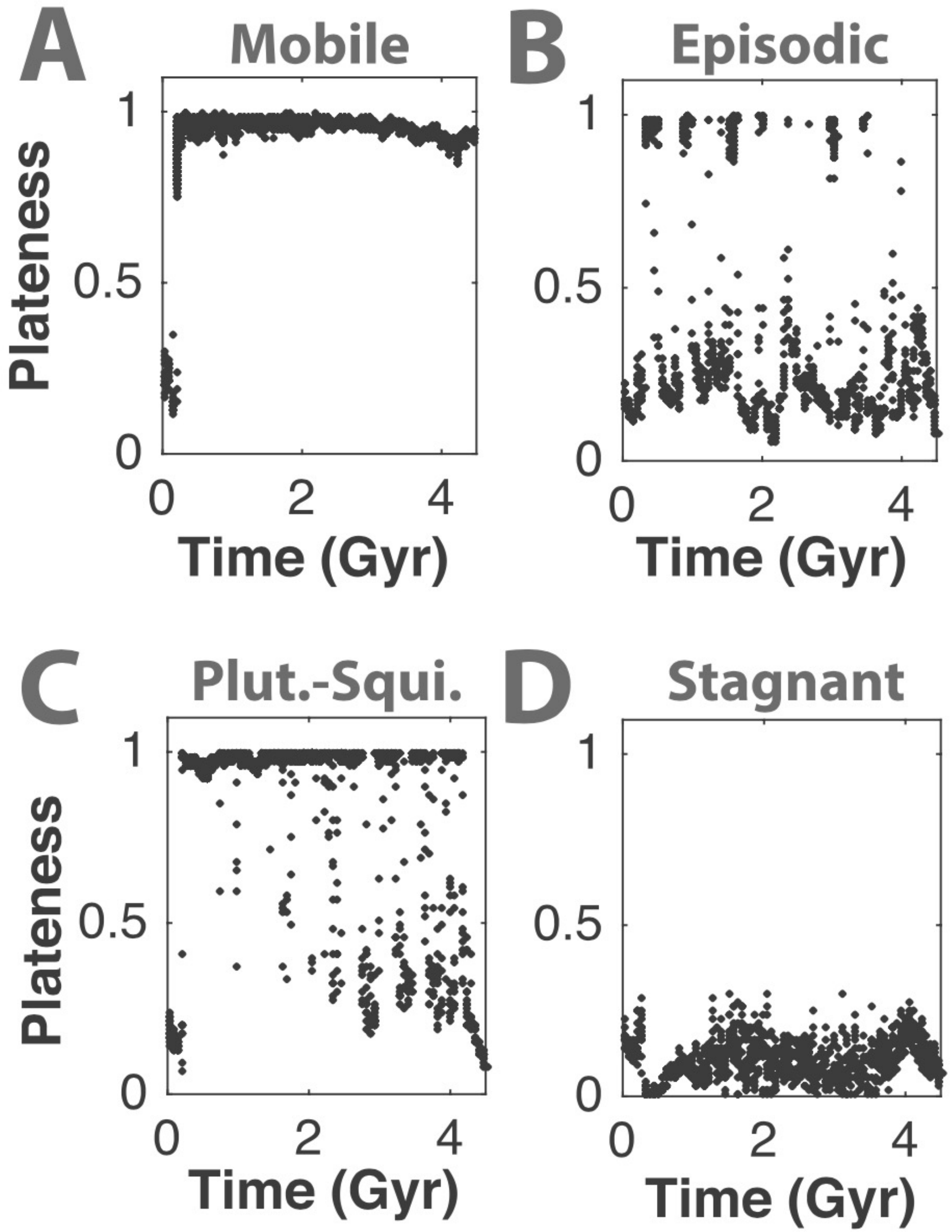
D. Stagnant lid: σ_{duct} = 300 MPa, E = 100%



Results: plateness

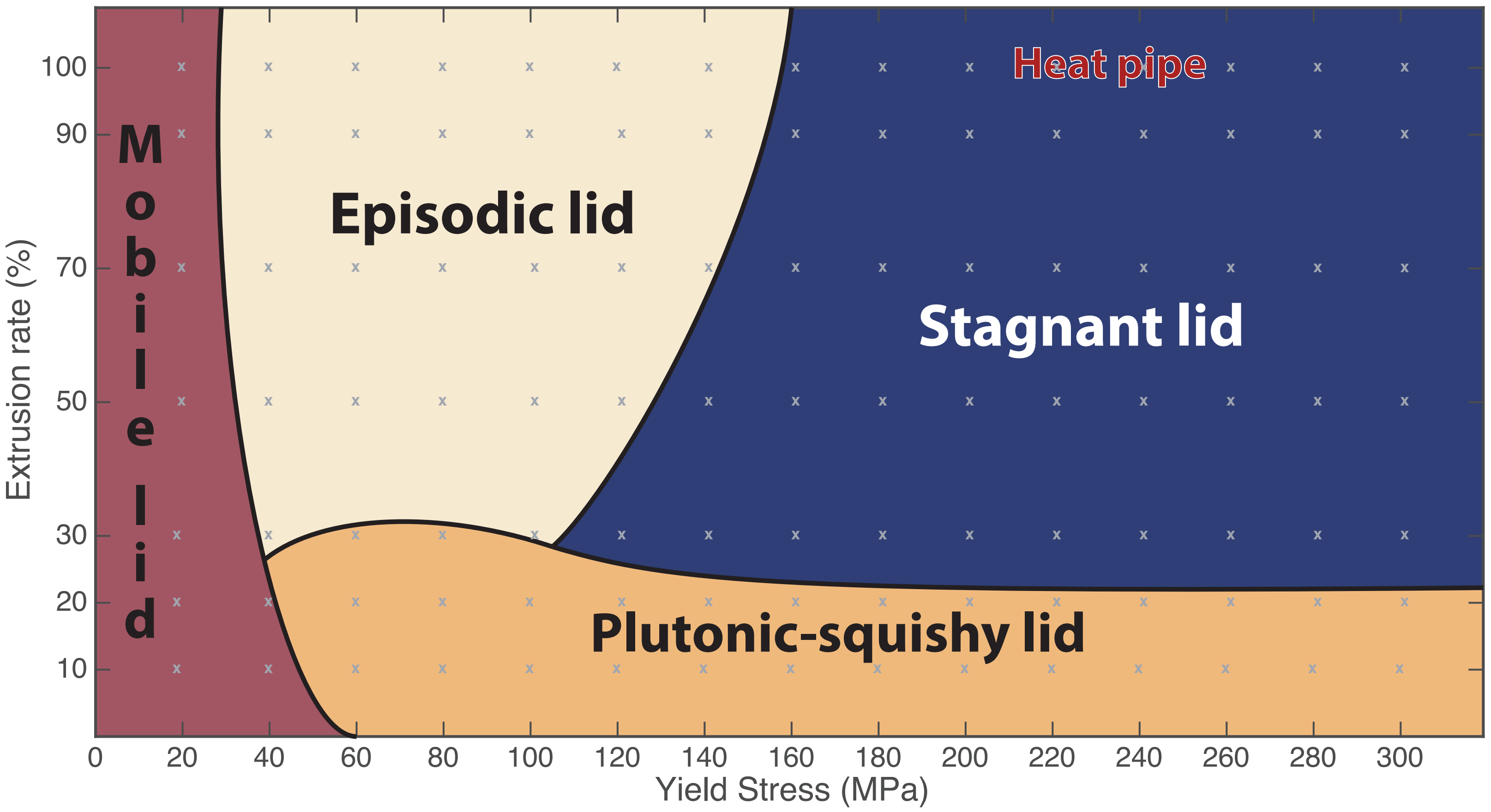
- <u>Fundamental characteristic of plate tectonics:</u> almost rigid plates separated by weak boundary regions in which most of the deformation occurs
- When M~1 plates exist
- From Weinstein and Olson (1992) and Tackley (2000):

$$P = 1 - \frac{f_{80}}{0.6}$$



Regime diagram

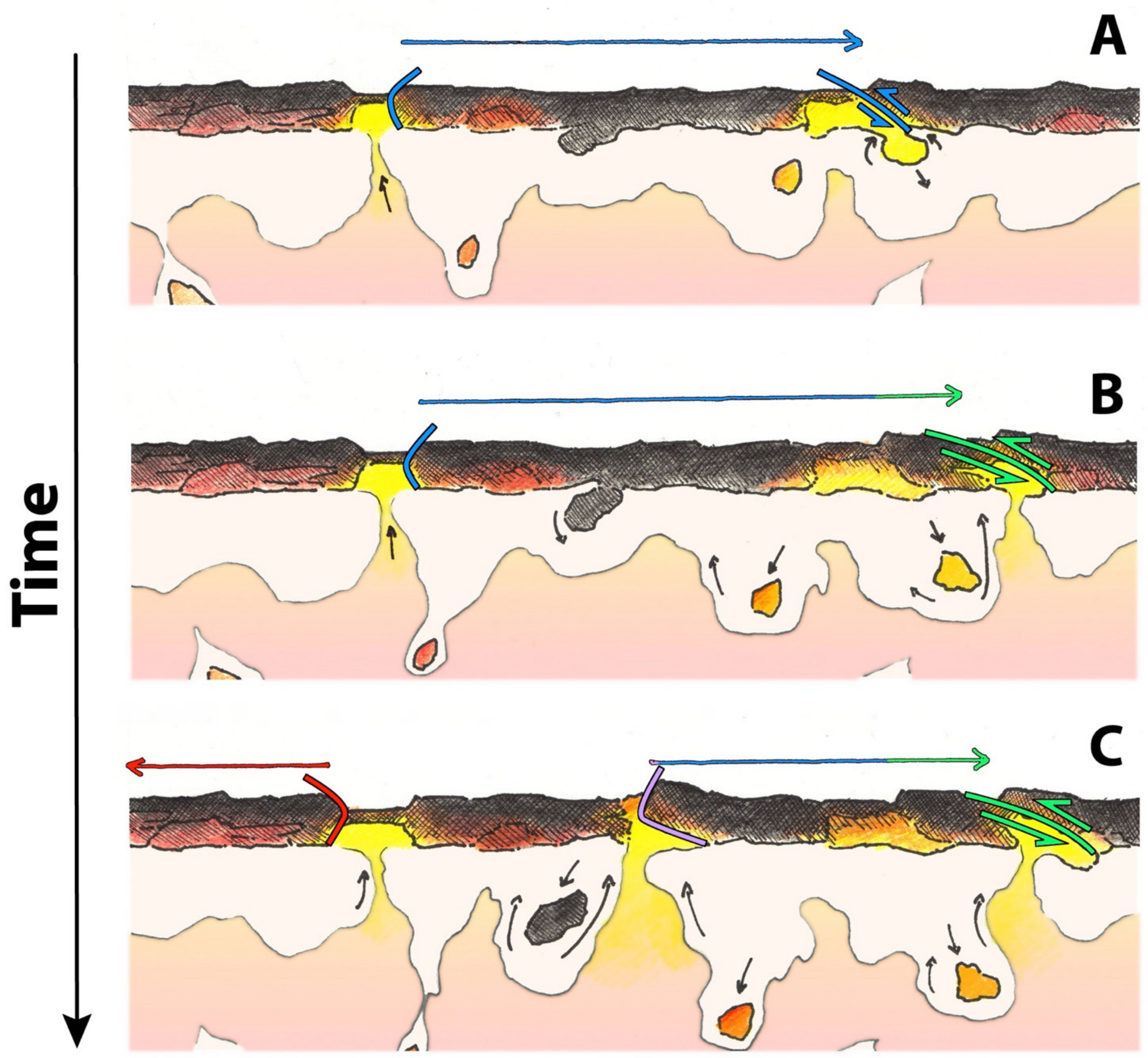
- At low-to-intermediate intrusion efficiencies, results reproduce the three common tectonic/convective regimes: stagnant-lid (a one-plate planet), episodic (where the lithosphere is usually stagnant and sometimes overturns into the mantle), and mobile-lid (similar to plate tectonics).
- At high intrusion efficiencies, we observe a new additional regime called "plutonic-squishy lid."



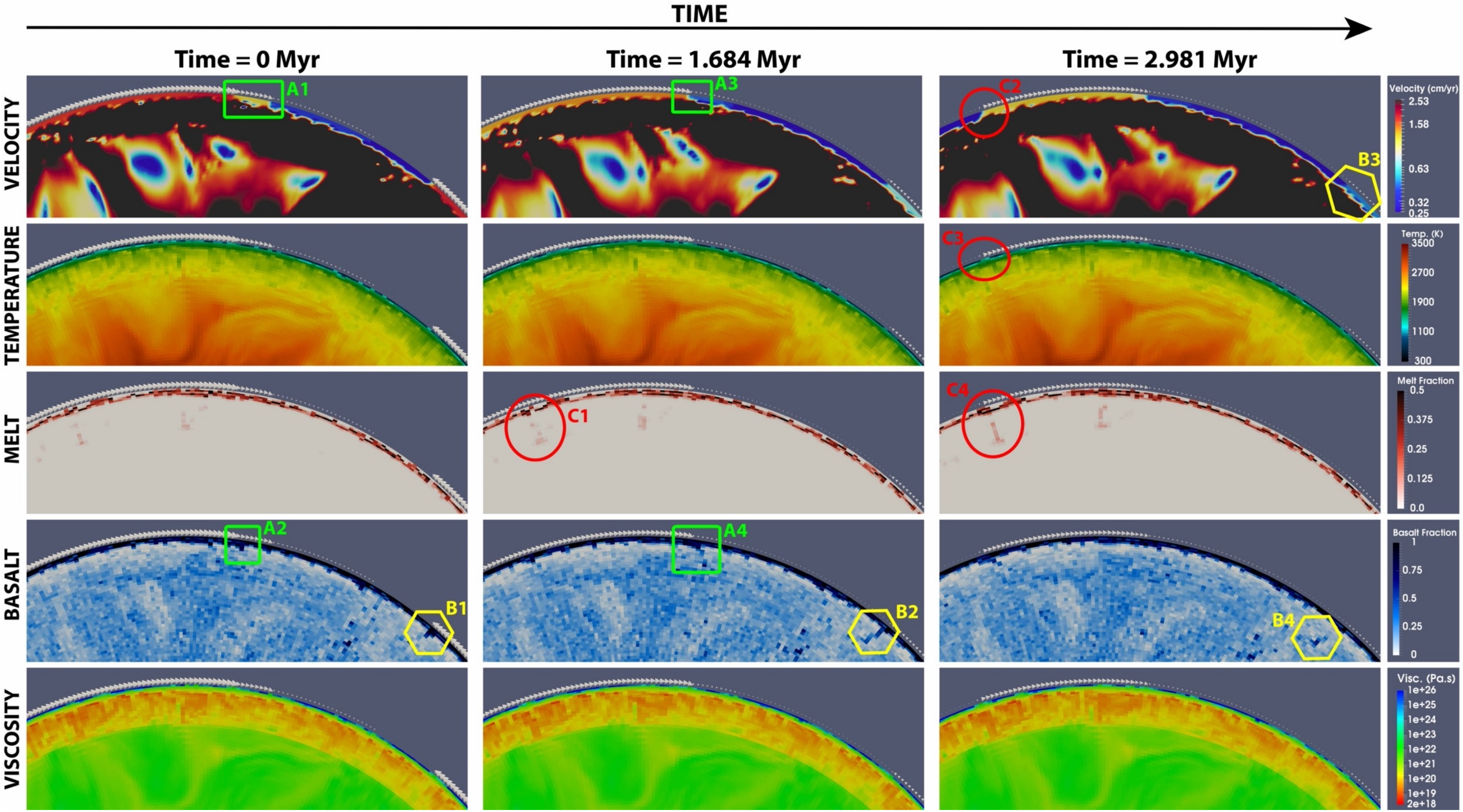
Dynamics and evolution of a plutonic-squishy lid

This regime is characterized by:

- a set of small, strong plates (or blocks) separated by warm and weak regions generated by plutonism
- eclogitic drippings and lithospheric delaminations often occur close to these weak regions, which leads to significant surface velocities toward the focus of delamination, even if subduction is not active
- the location of the plate boundaries is strongly time dependent and mainly occurs in regions of magma intrusion, leading to small, ephemeral plates.

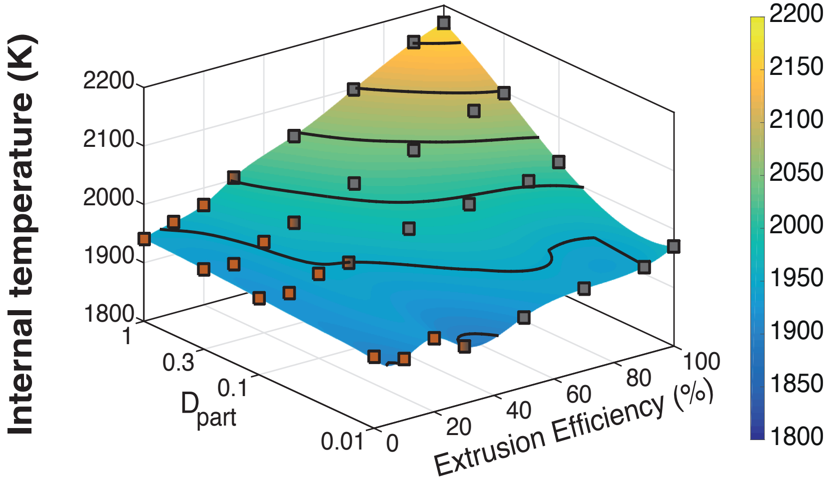


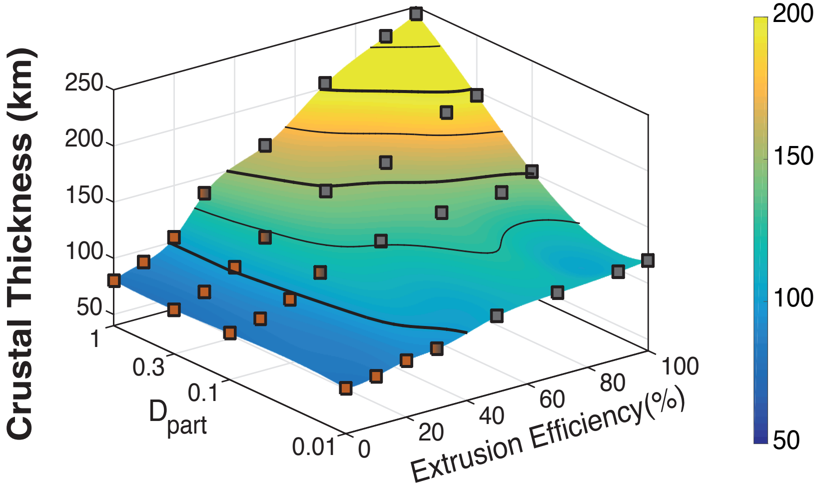
Dynamics and evolution of a plutonic-squishy lid

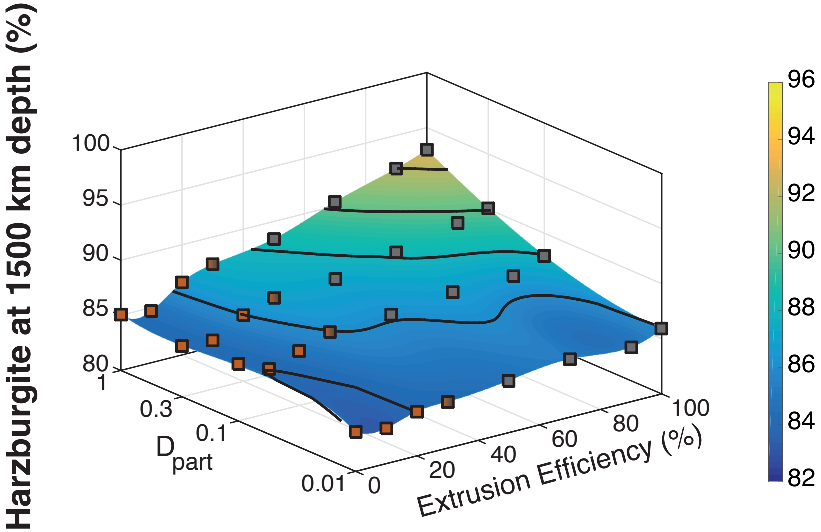


Dynamics and evolution of a plutonic-squishy lid

- The plutonic-squishy-lid regime is also distinctive from other regimes because it generates a thin lithosphere, which results in high conductive heat fluxes and lower internal mantle temperatures when compared to a stagnant lid.

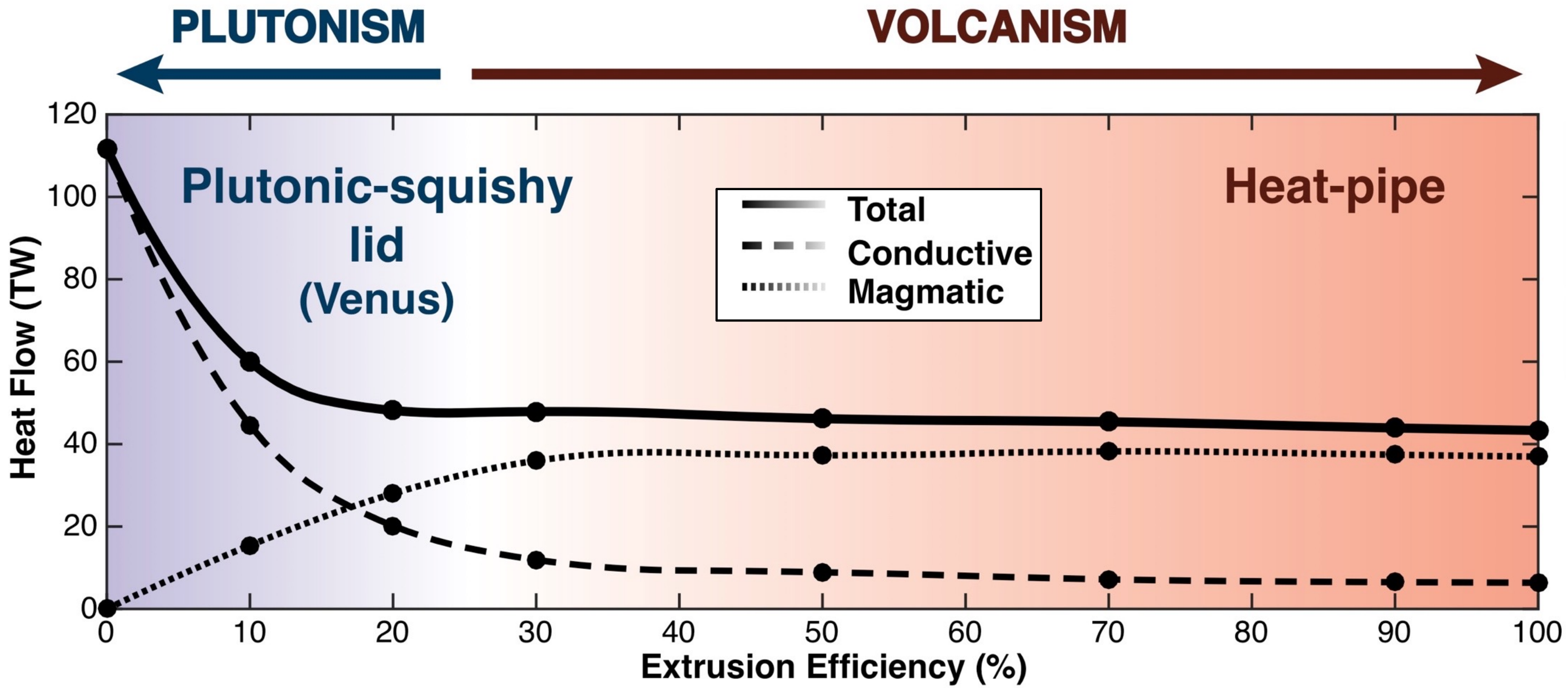






Dynamics and evolution of a plutonic-squishy lid

- Volcanic eruption or magma intrusion: which cools planets better?

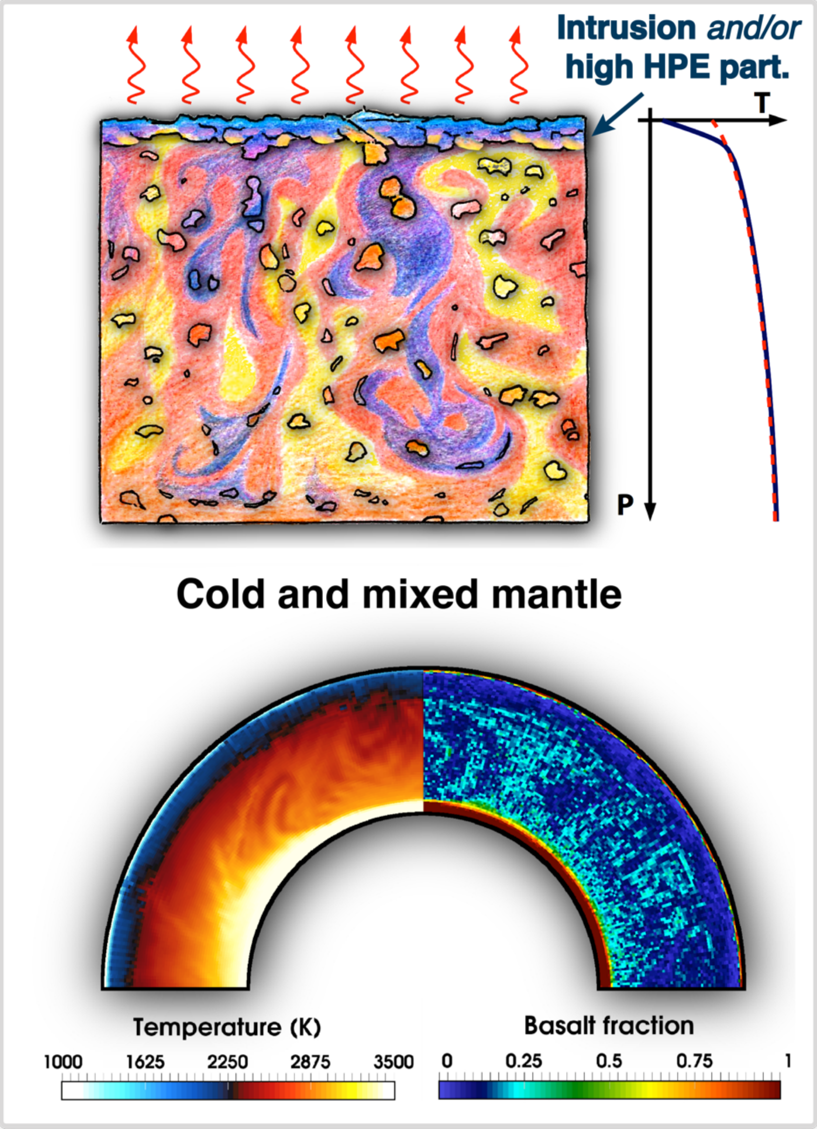


Conductive, magmatic and total surface heat flow as a function of the eruption efficiency

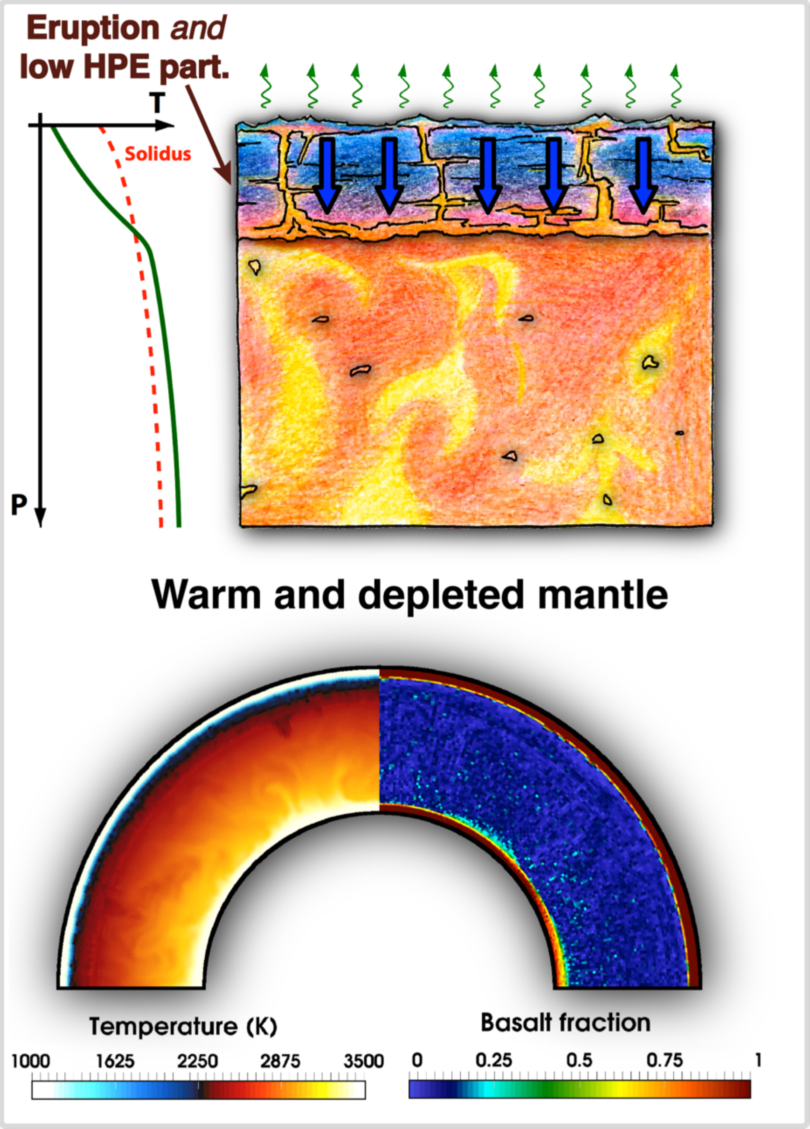
Dynamics and evolution of a plutonic-squishy lid

- Volcanic eruption or magma intrusion: which cools planets better?
- The plutonic-squishy-lid regime(high intrusion rates) is distinctive from other regimes because it generates a thin lithosphere, which results in high conductive heat fluxes and lower internal mantle temperatures when compared to a stagnant lid.

High intrusion rates

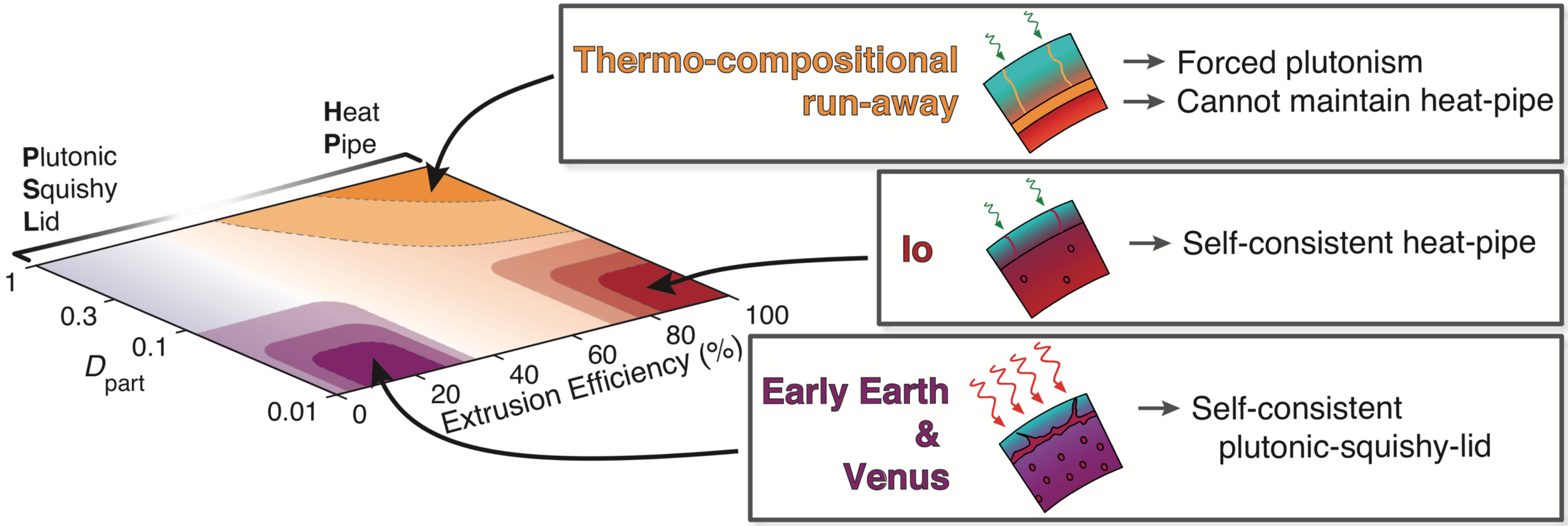


High extrusion rates



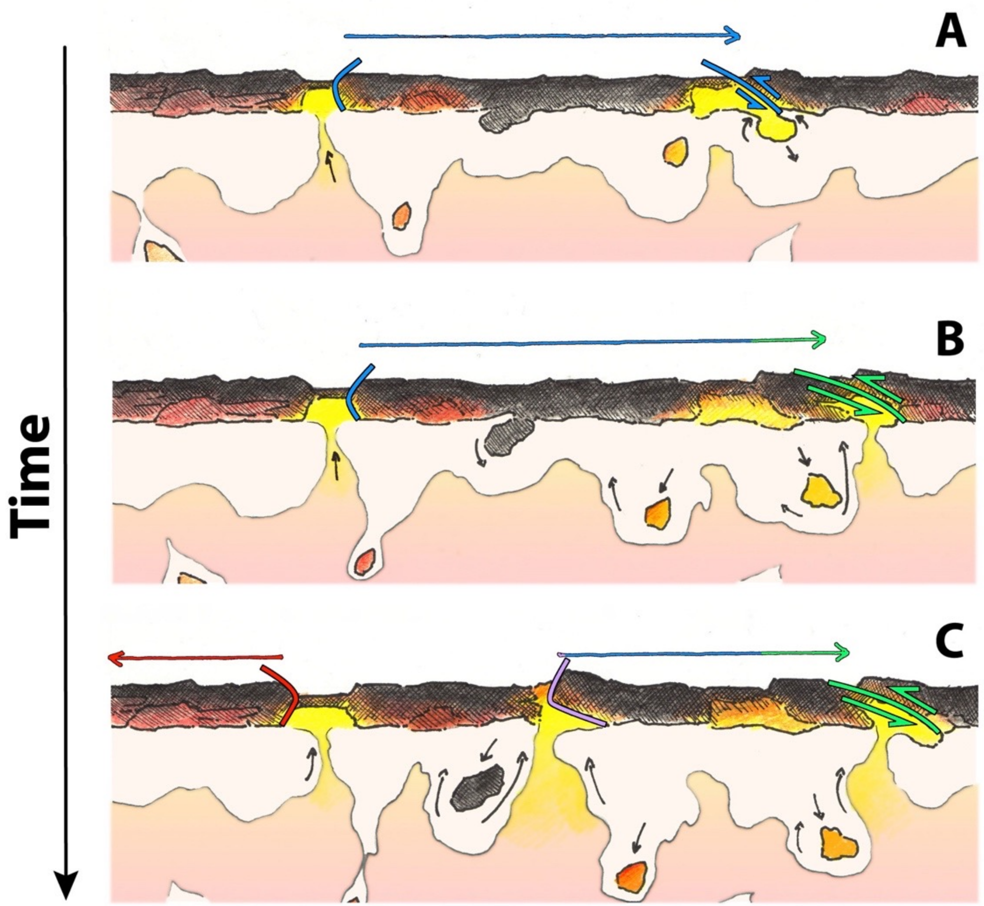
Possible applications: Venus and Early Earth

- The plutonic-squishy lid regime has the potential to be applicable to the Early Archean Earth as it combines elements of both protoplate tectonic and vertical tectonic models, and high intrusion efficiencies are required to form Earth's early continental crust (e.g., Rozel et al., *Nature* 2017)

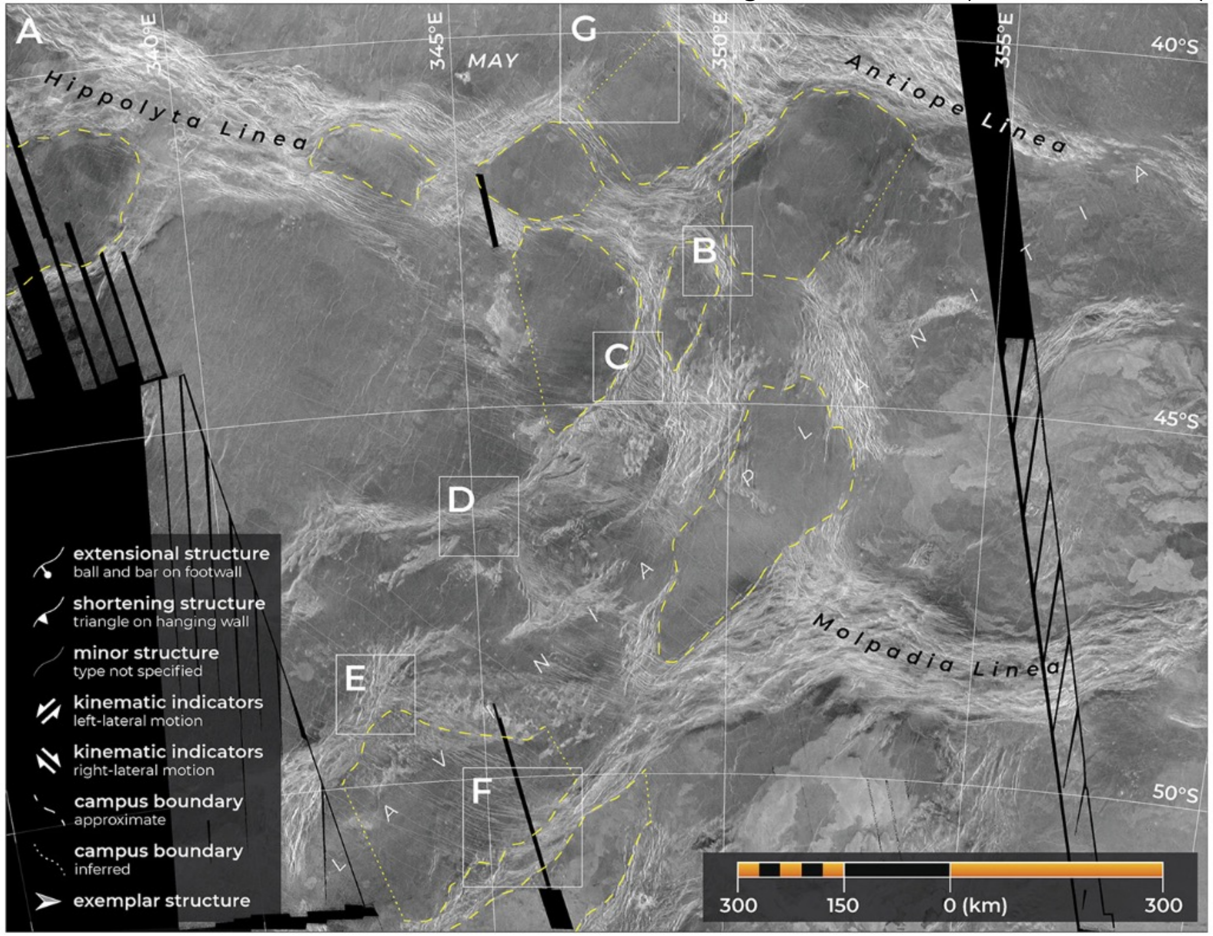


Possible applications: Venus

- The plutonic-squishy lid regime has the potential to be applicable to to present-day Venus, agreeing well with observations of a globally fragmented and mobile lithosphere on Venus (e.g., Byrne et al., *PNAS* 2021)



Byrne et al. (PNAS 2021)



Conclusions

- A new global tectonic regime is identified, characterized by:
    - Set of strong plates/blocks separated by weak regions
    - Significant lid velocities (without subduction)
    - Eclogitic drippings and lithospheric delaminations
- Intrusive magmatism is able to cool down the mantle more efficiently than eruptive processes
- The plutonic-squishy-lid regime can potentially apply to the Early Earth, Venus, and extra-solar bodies

Read more

- Lourenço D. L. et al. (2020) *Geochem. Geophys. Geosyst. 21*, e2019GC008756
- Lourenço D. L. et al. (2018) *Nat. Geosci. 11(5)*, 322-327