

A recipe for continental fragment formation: big data analysis of rift models

Alan Yu, Erkan Gun, Ken Mccaffrey, Phil Heron

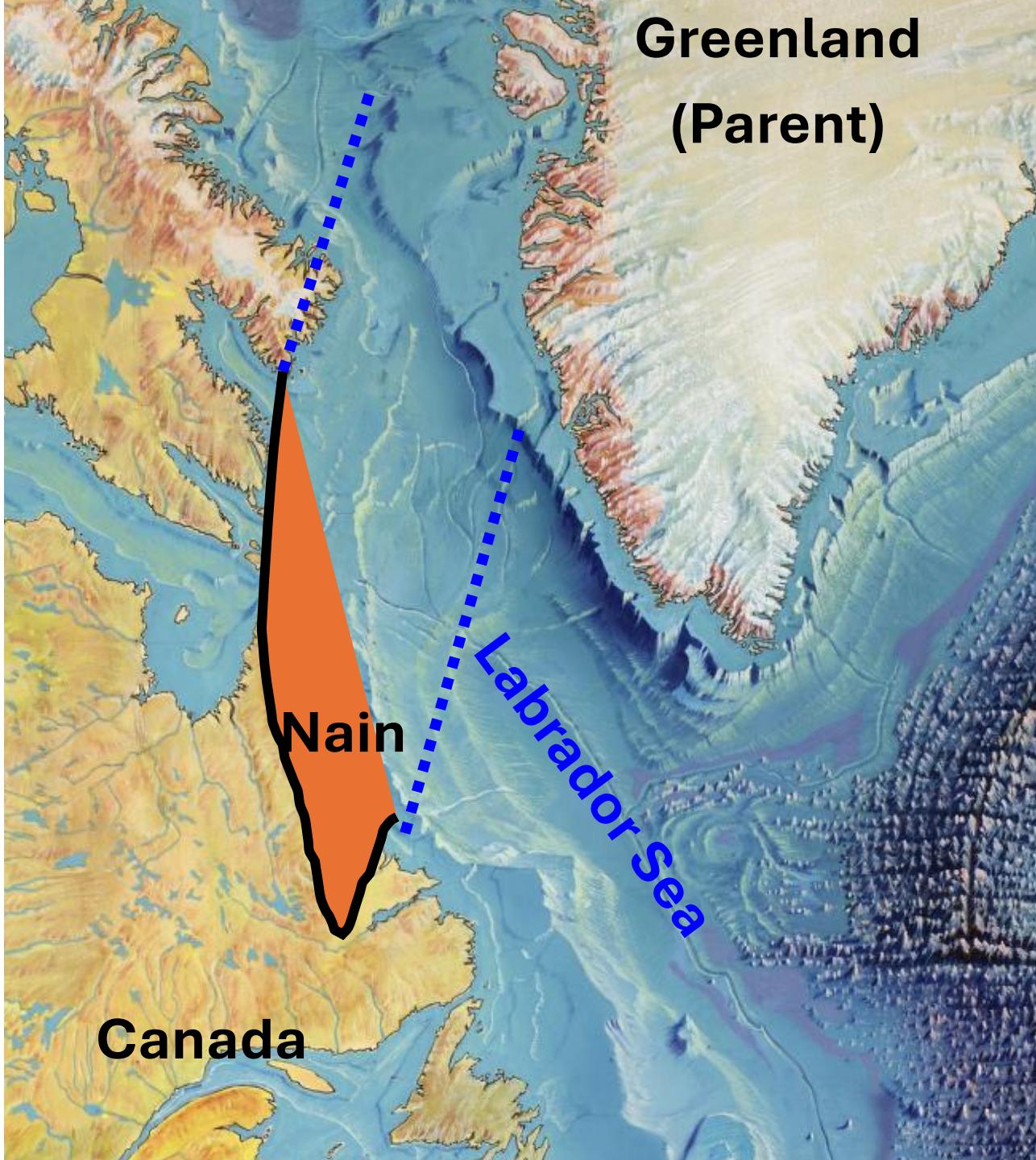


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Introduction

Continental fragment

- A small piece of continent separated from its parent plate.
- E.g., Canada's Nain Province, separated from Greenland
- Shares a similar geological signature to its parent.



Geological examples

North Atlantic Ocean:

- Nain Province
- Lewisian Complex

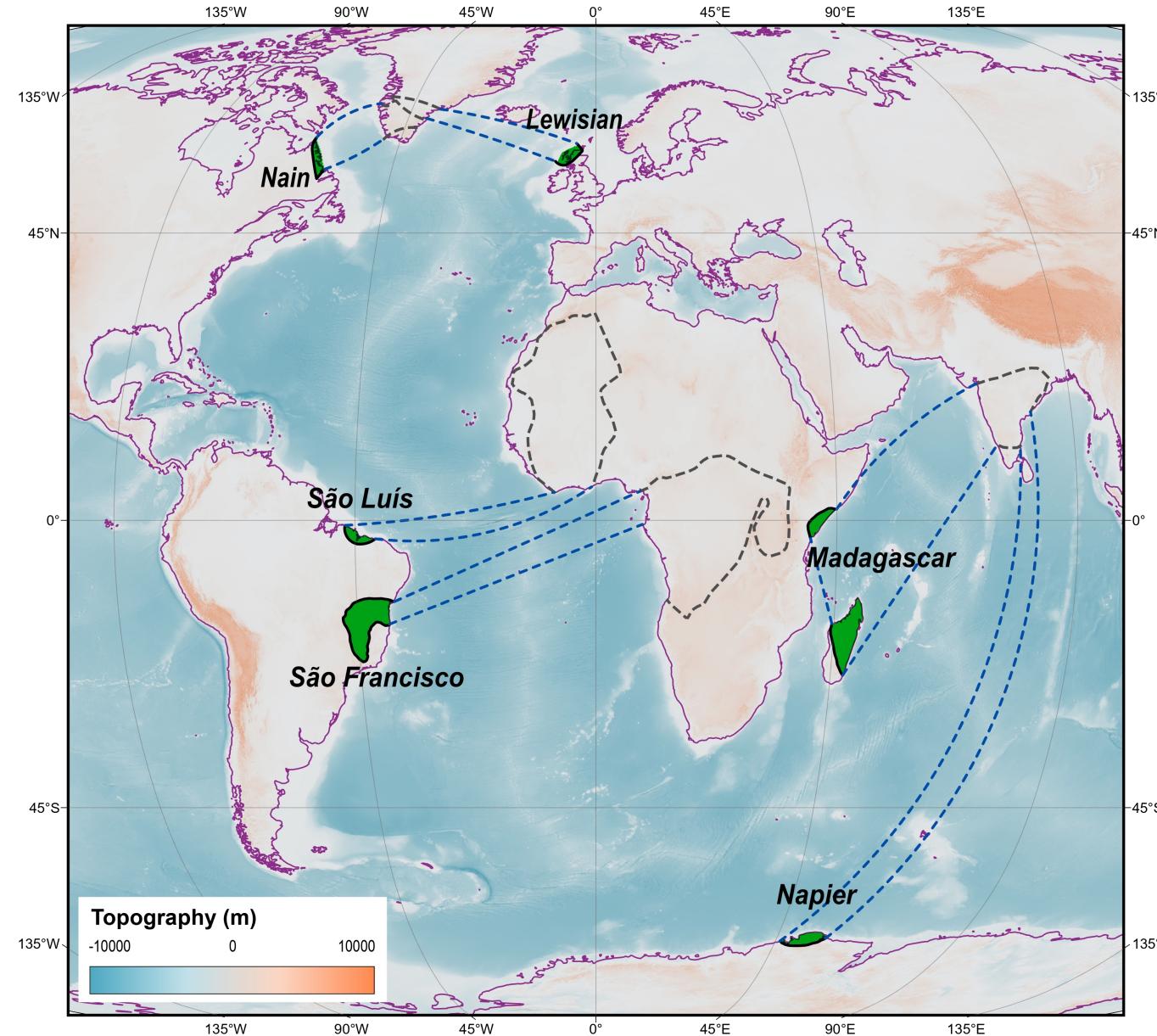
South Atlantic Ocean:

- São Luís Craton
- São Francisco Craton

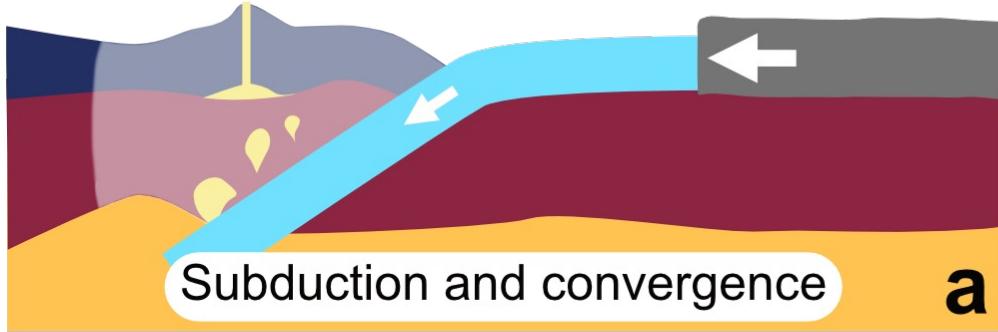
Indian Ocean:

- Madagascar
- Napier Complex

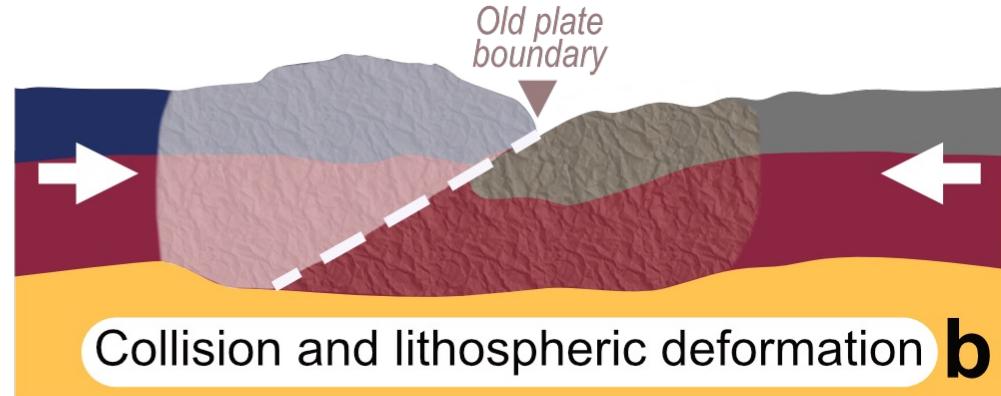
How did they form?



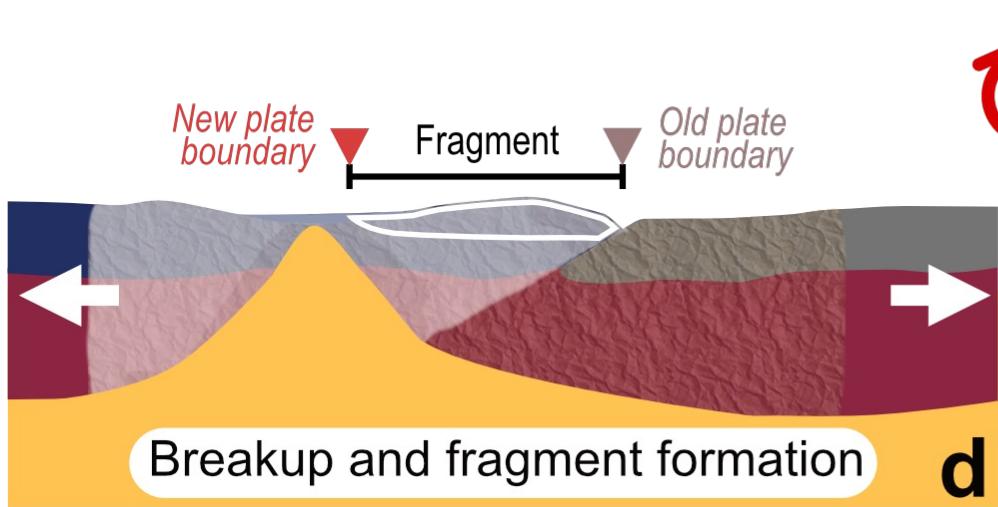
Wilson Cycle



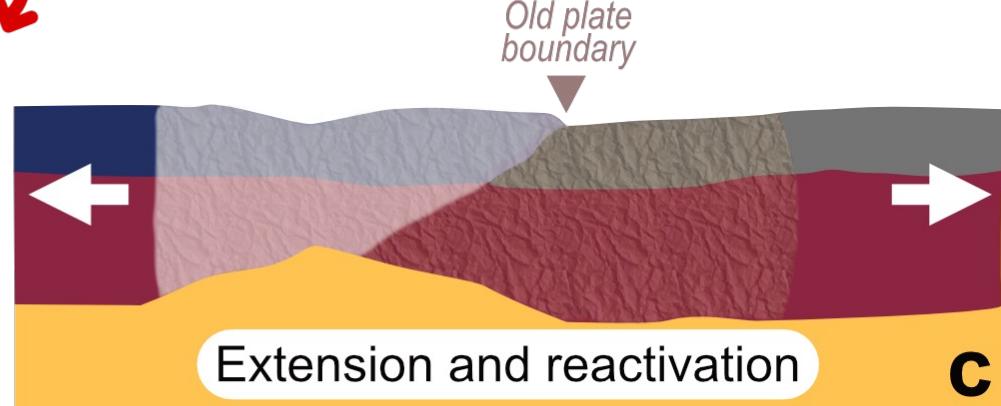
a



b



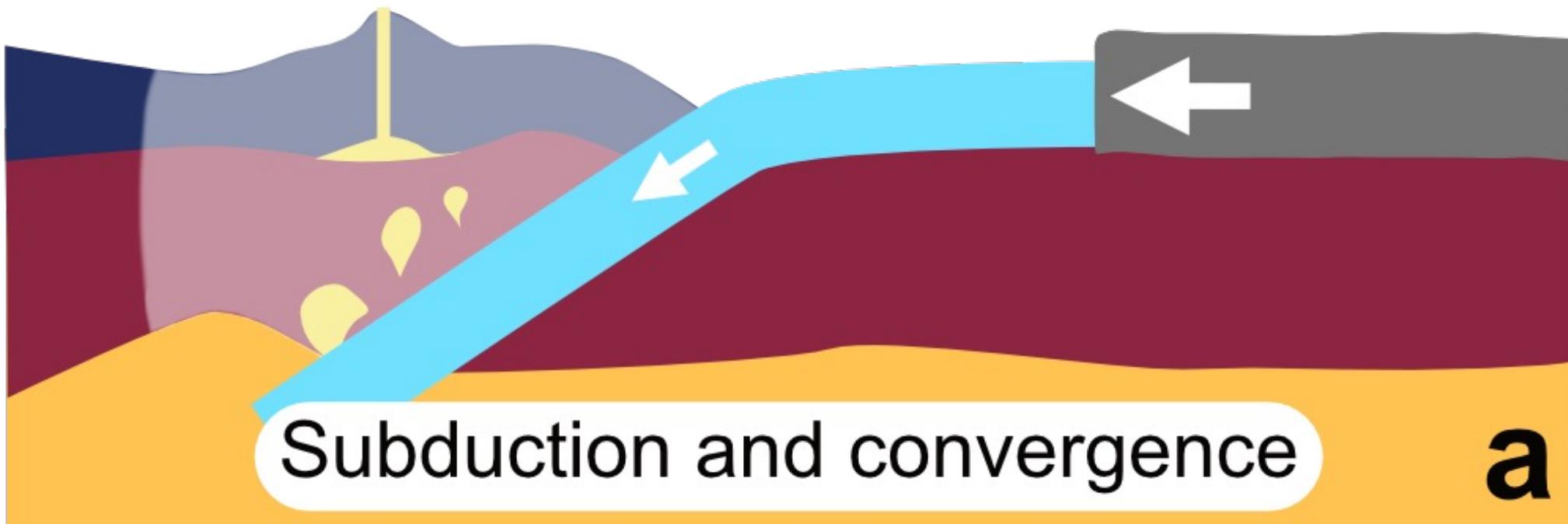
d



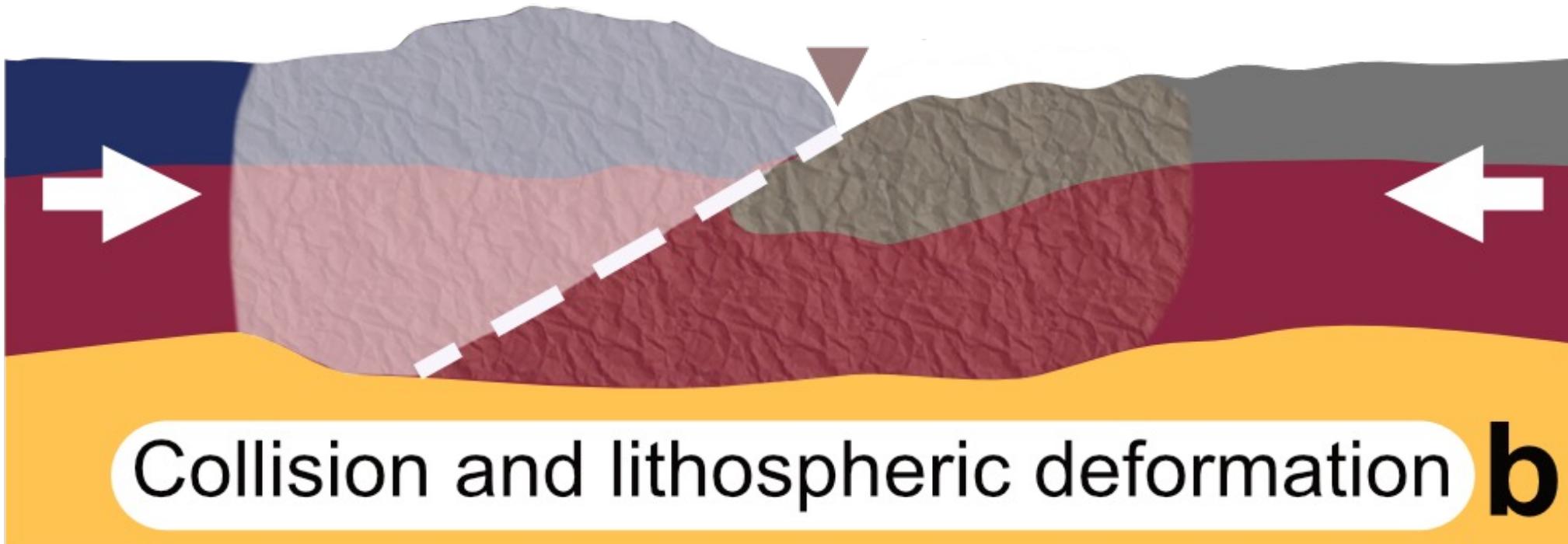
c



Convergence



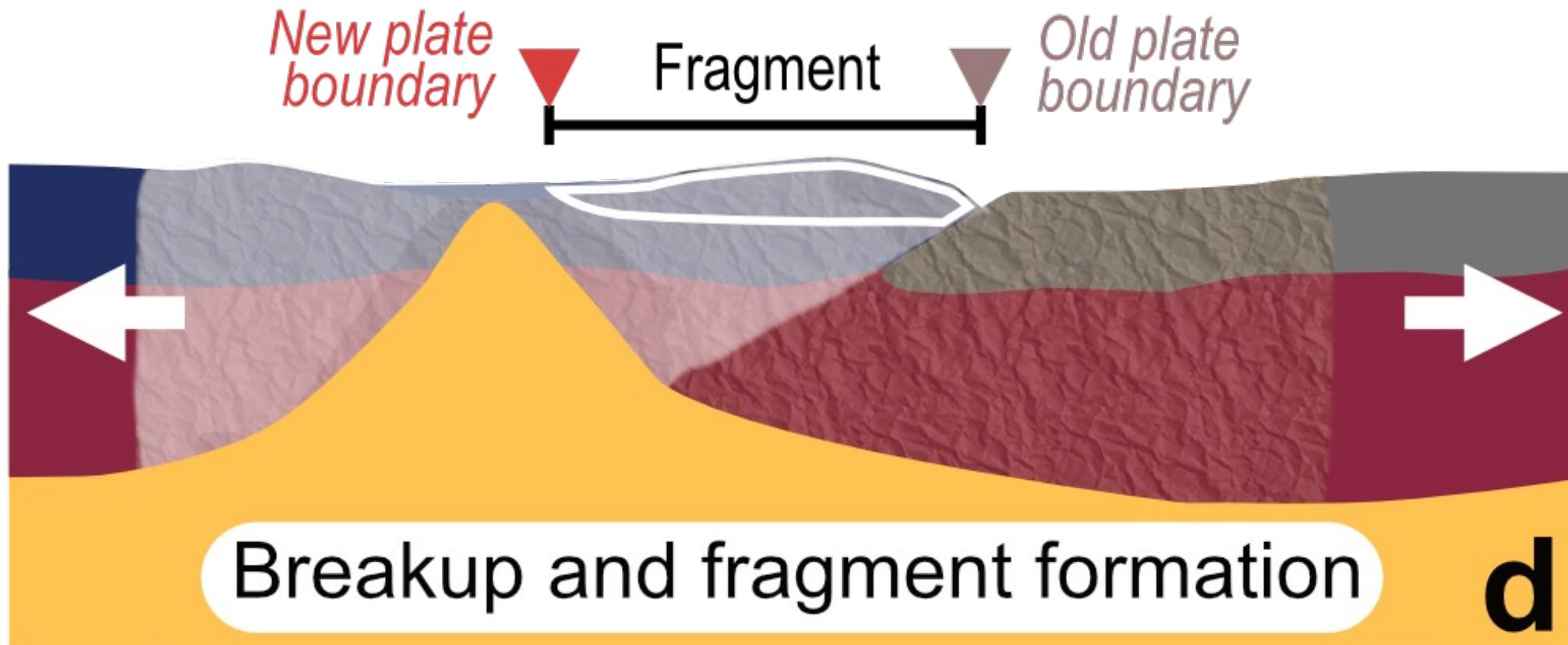
Convergence



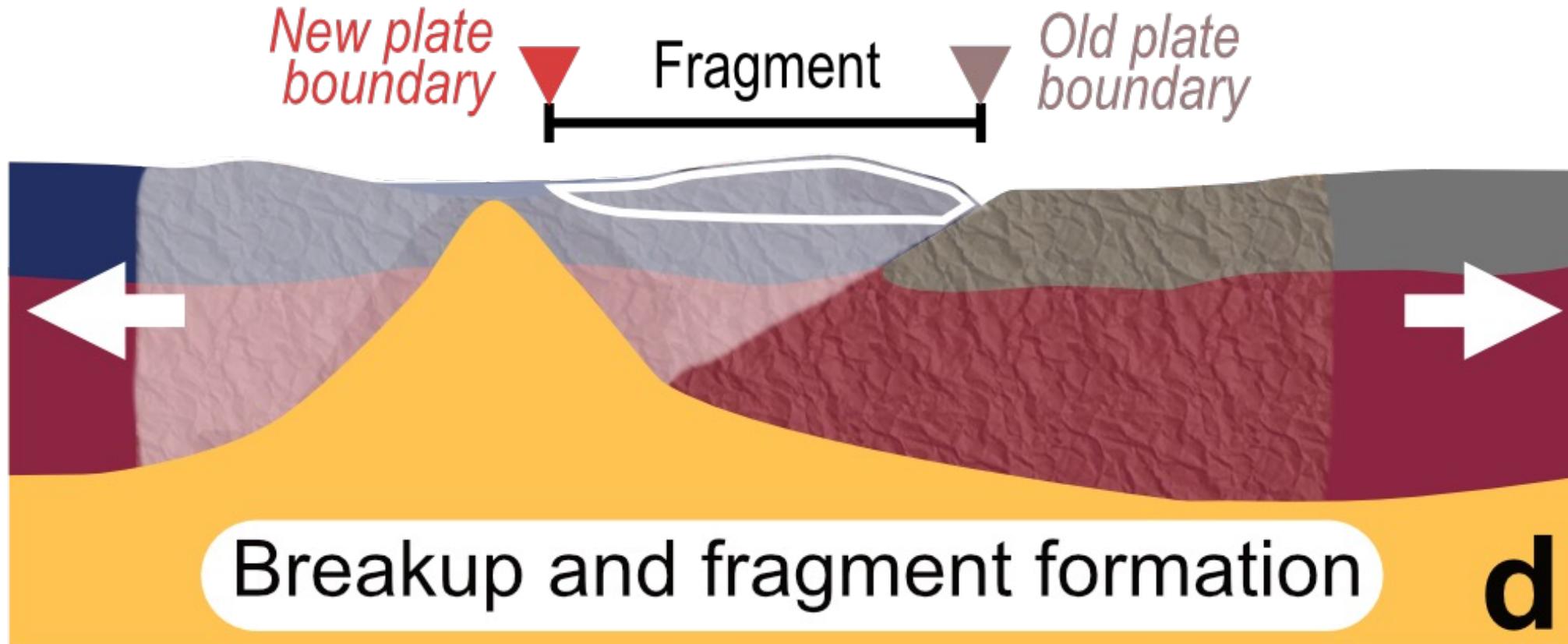
Divergence



Divergence



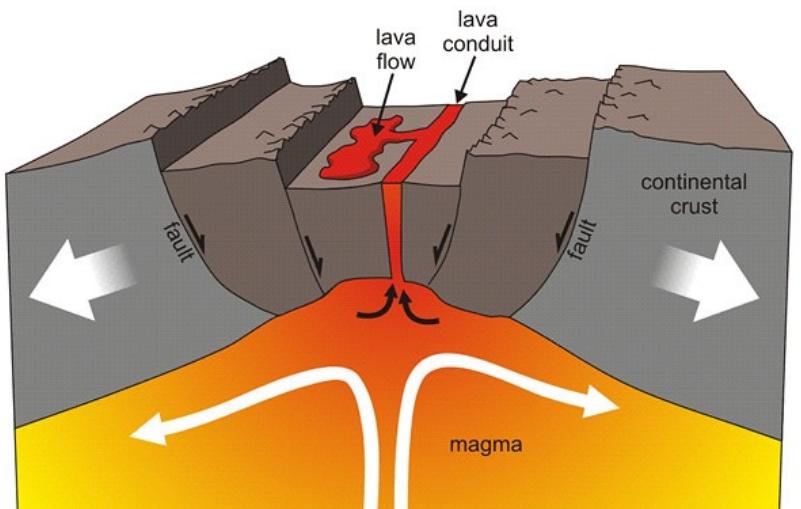
Objectives



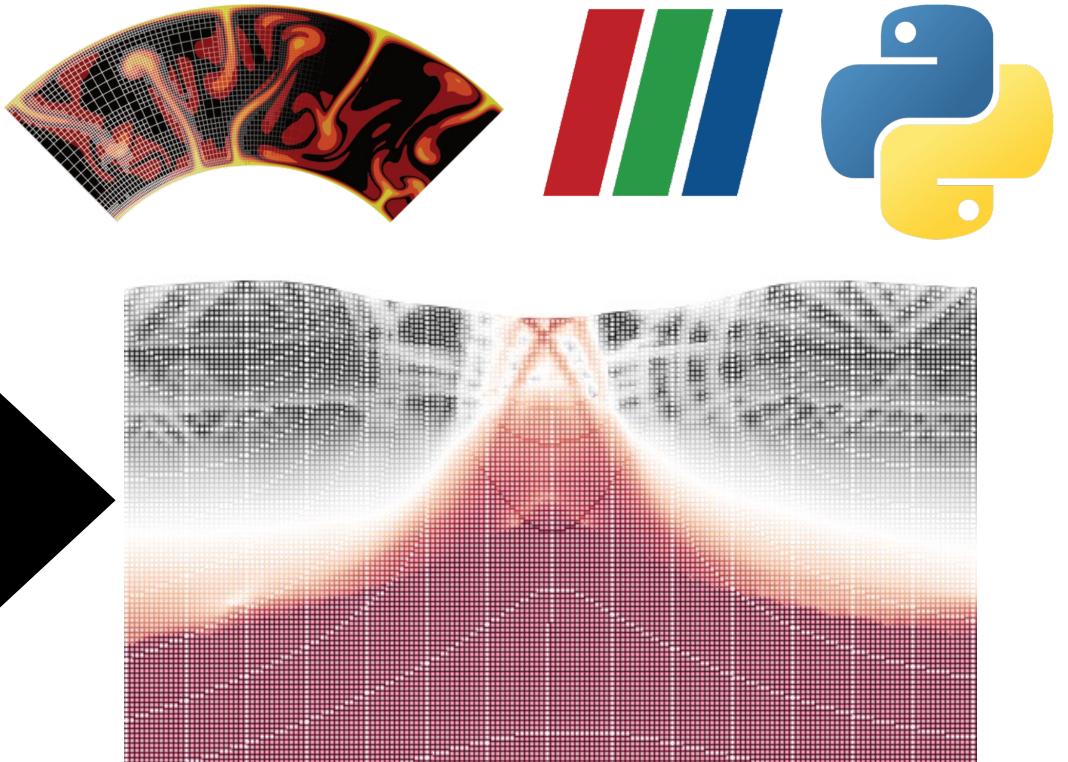
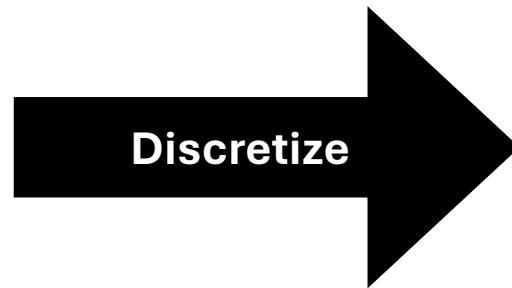
- We quantify the influence of different forms of inherited structures in fragment formation.

Methods

Numerical modelling



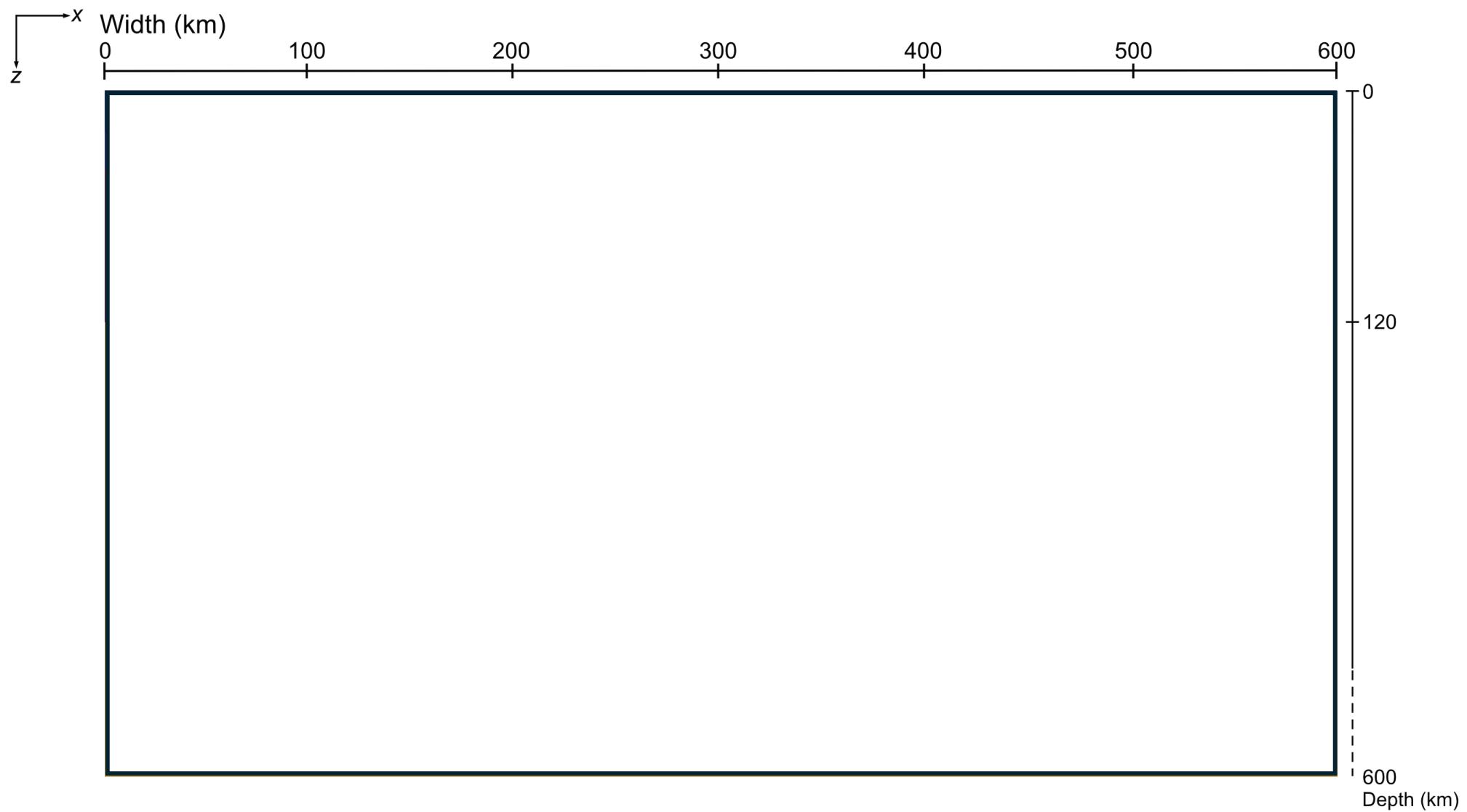
Tectonic process



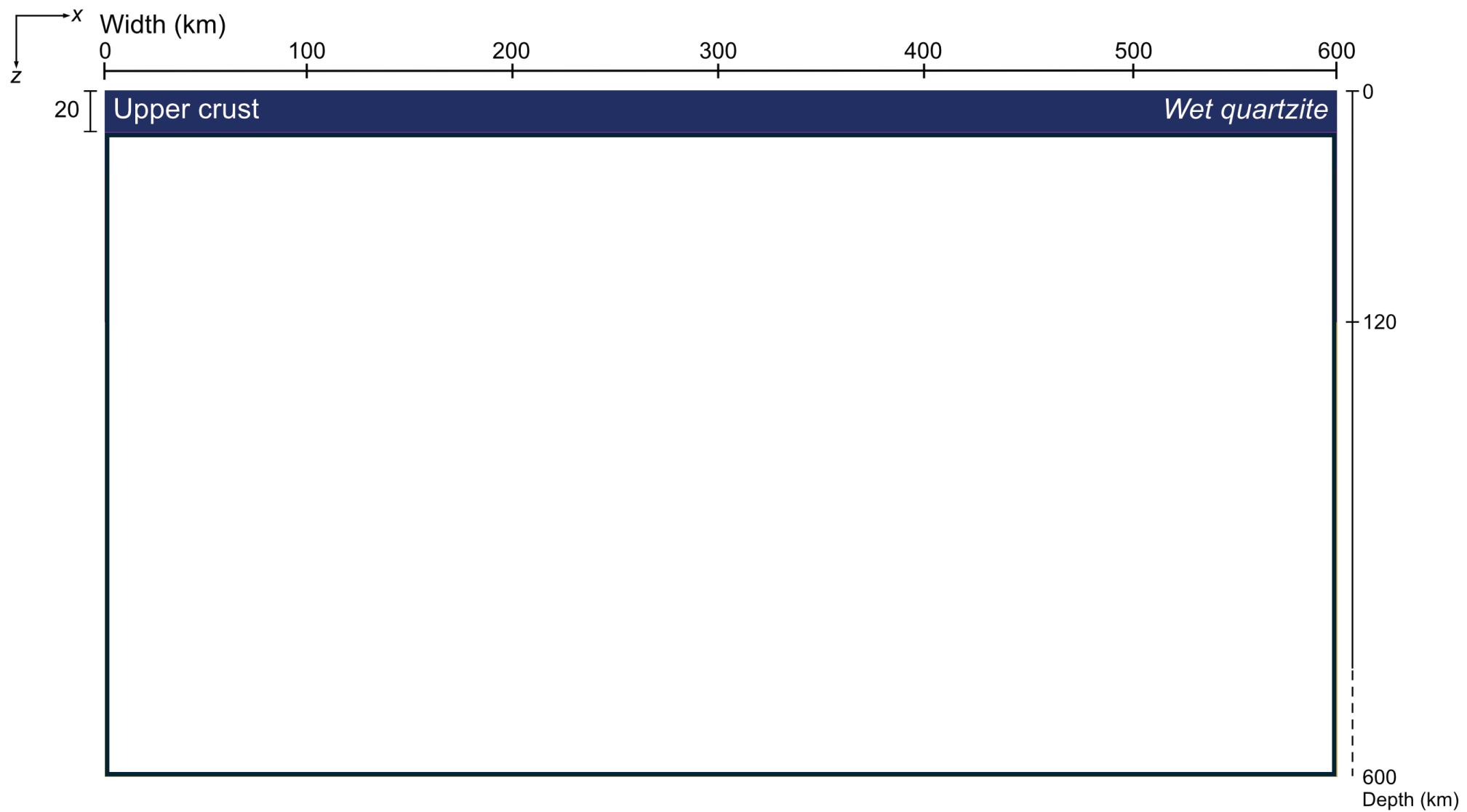
Numerical models



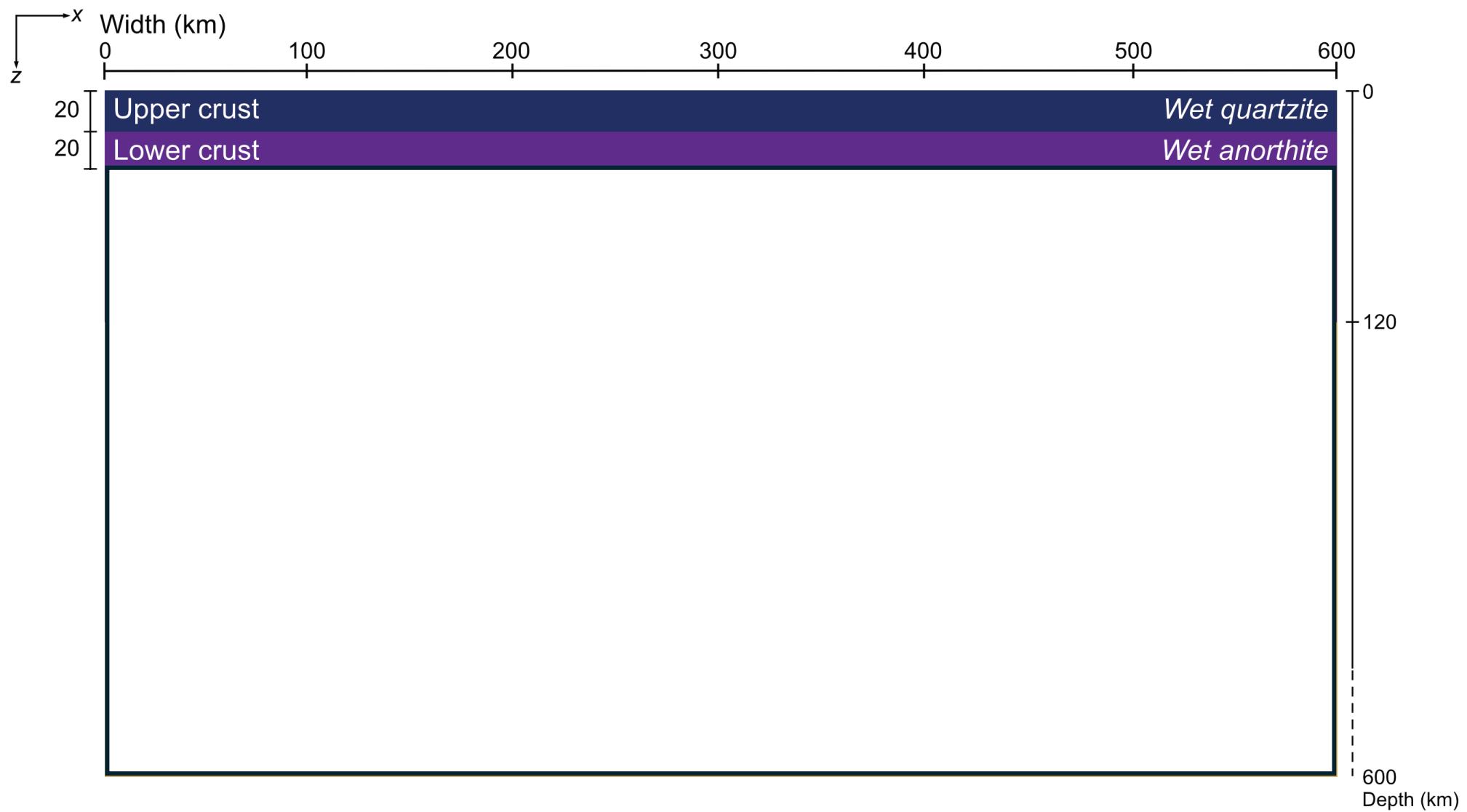
Model setup



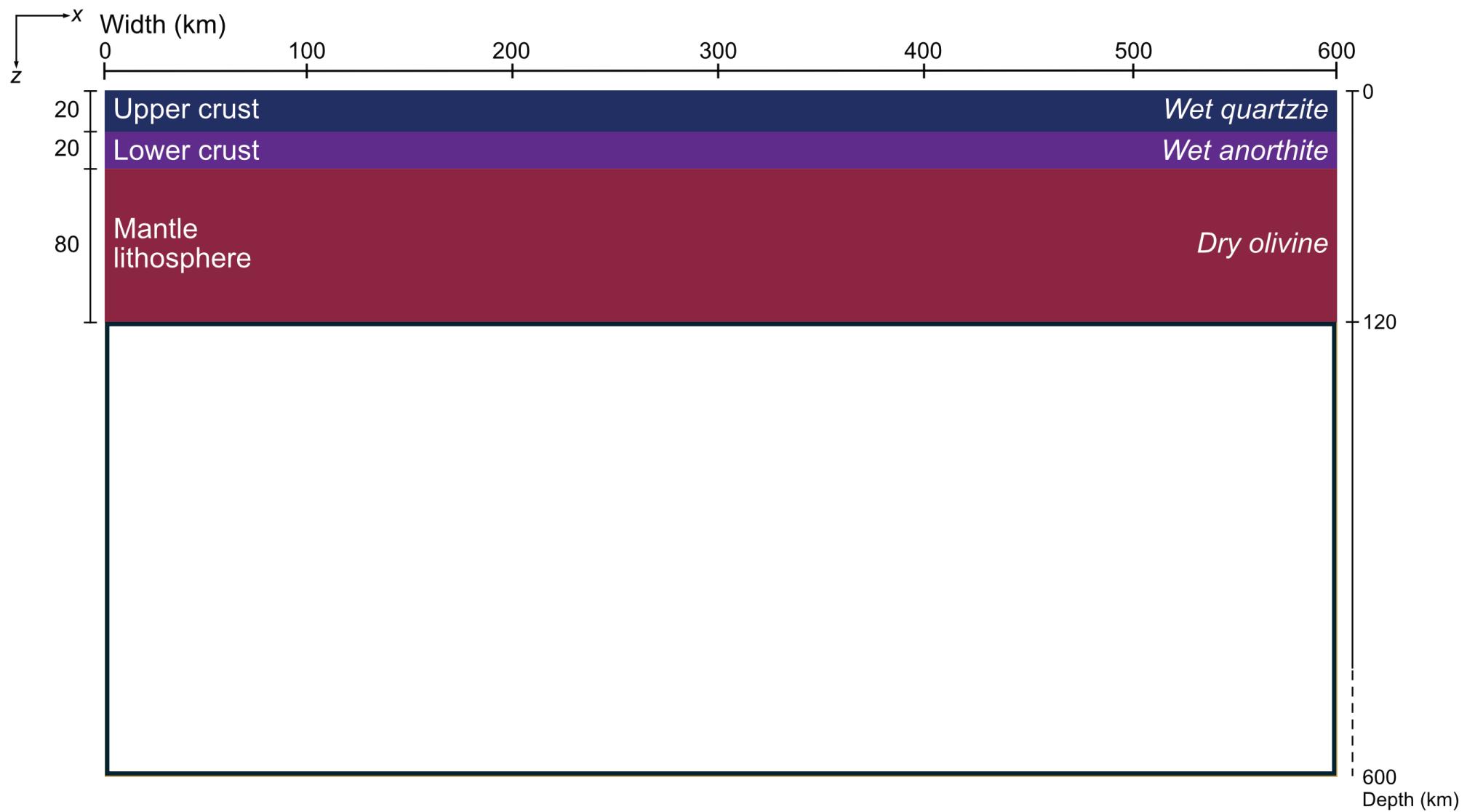
Model setup



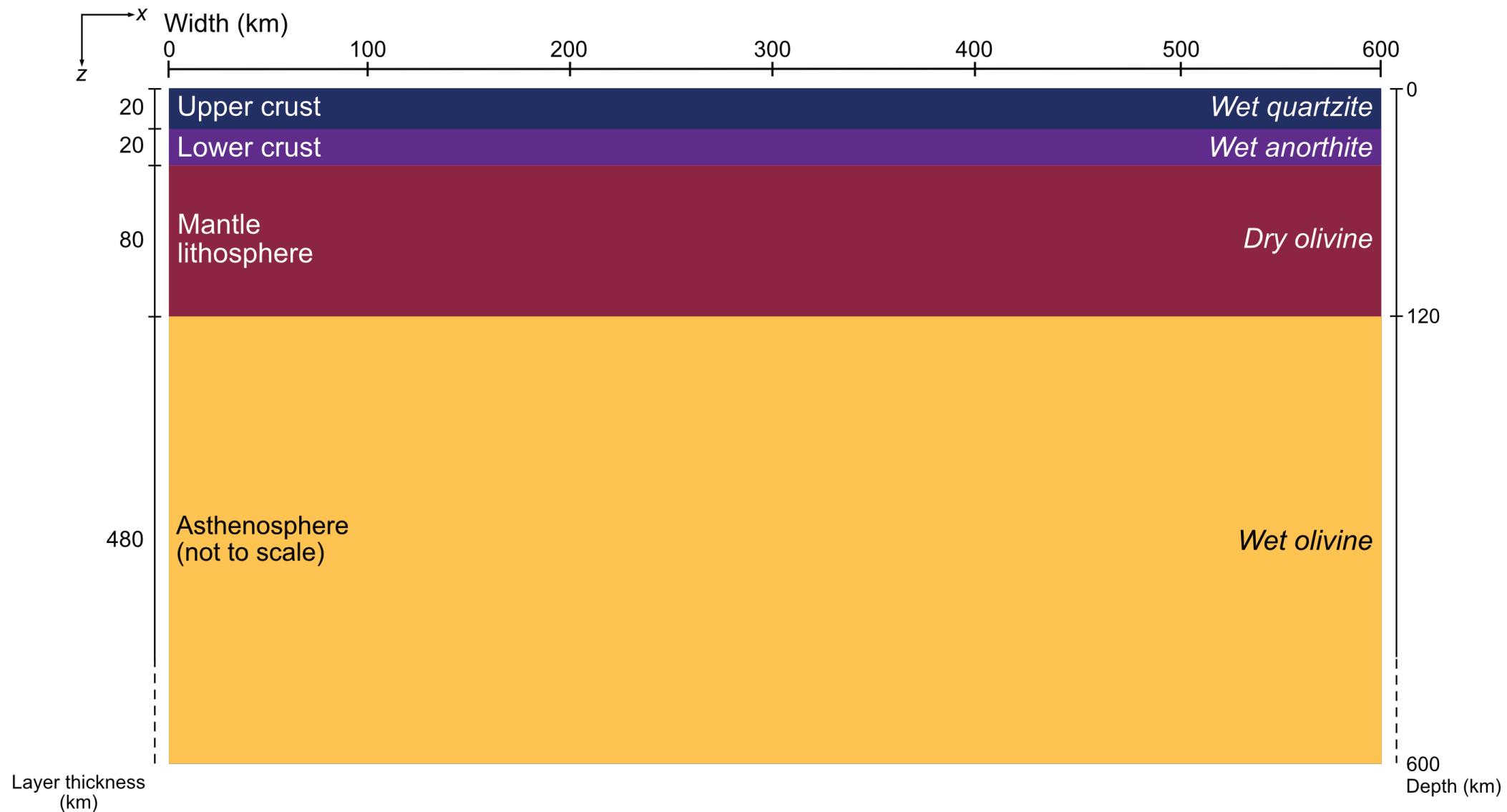
Model setup



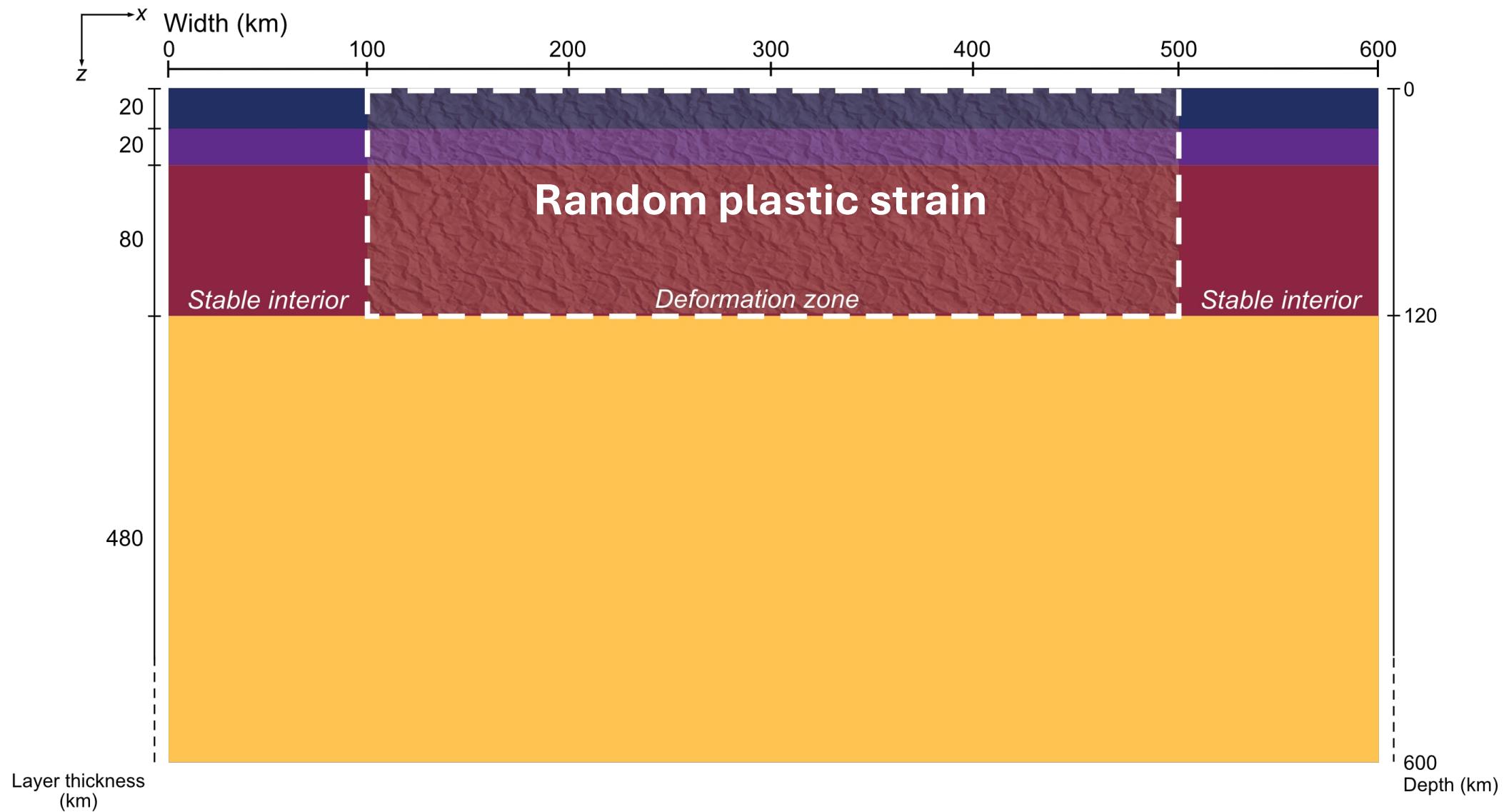
Model setup



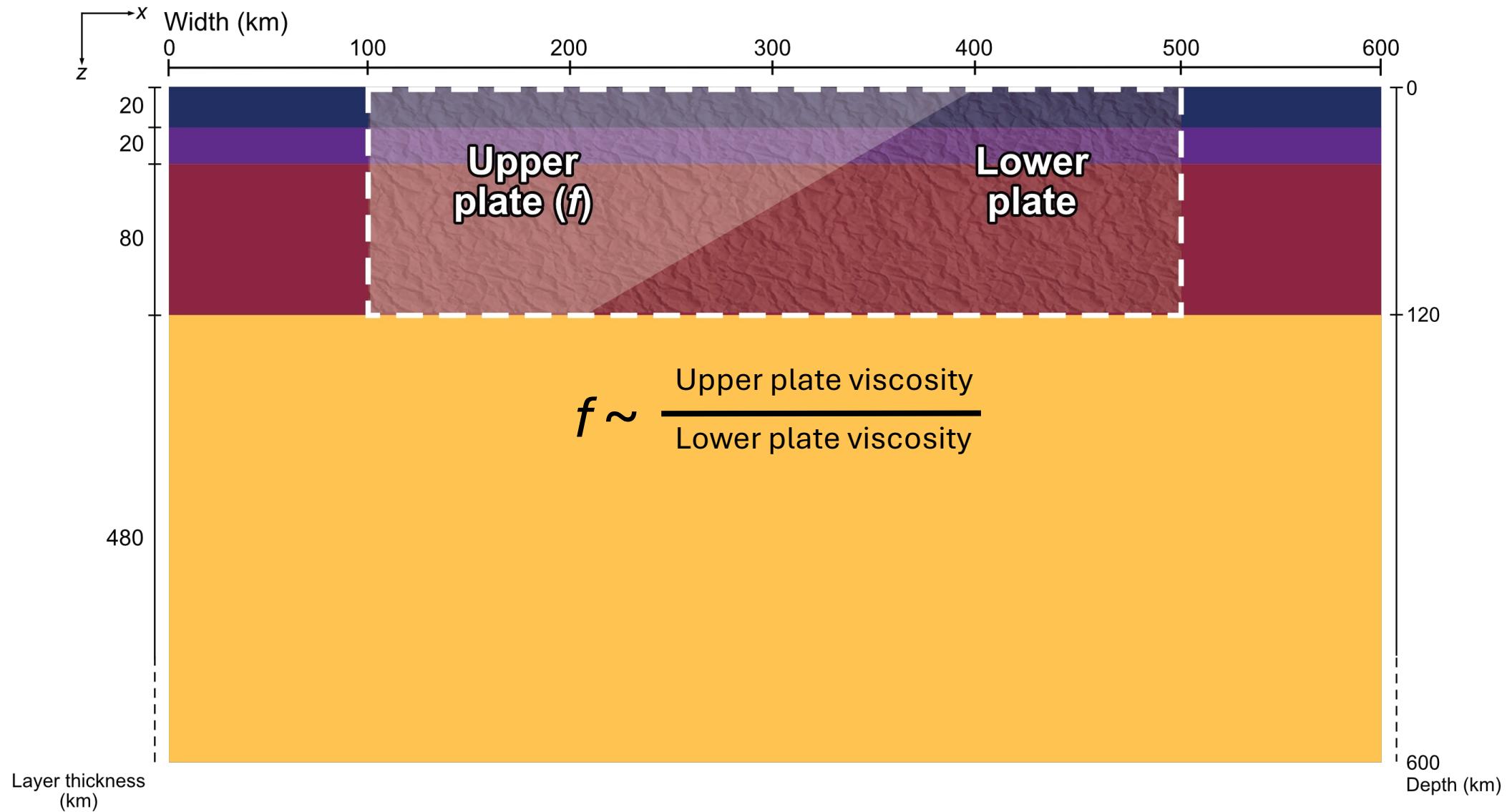
Model setup



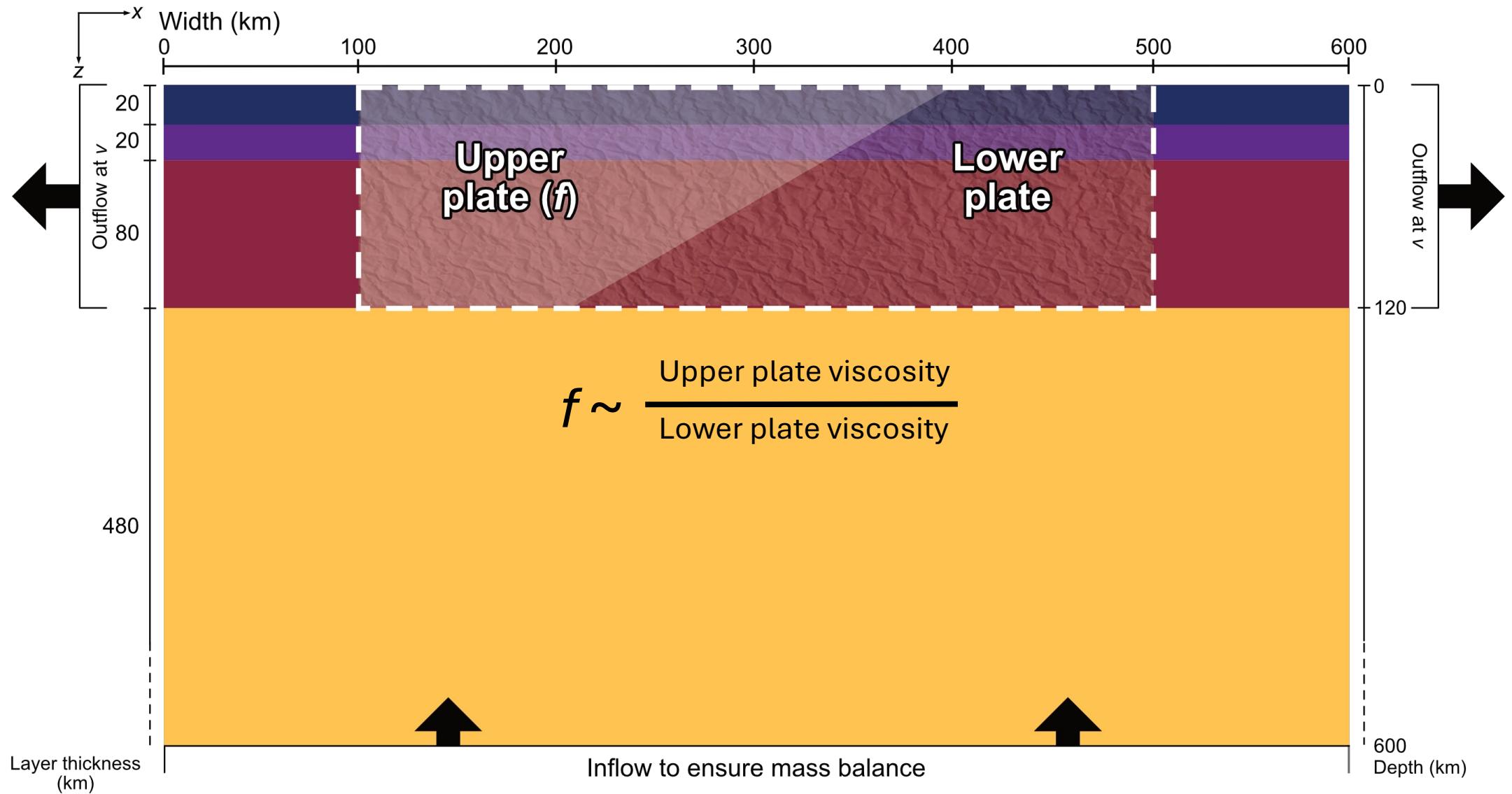
Model setup



Model setup

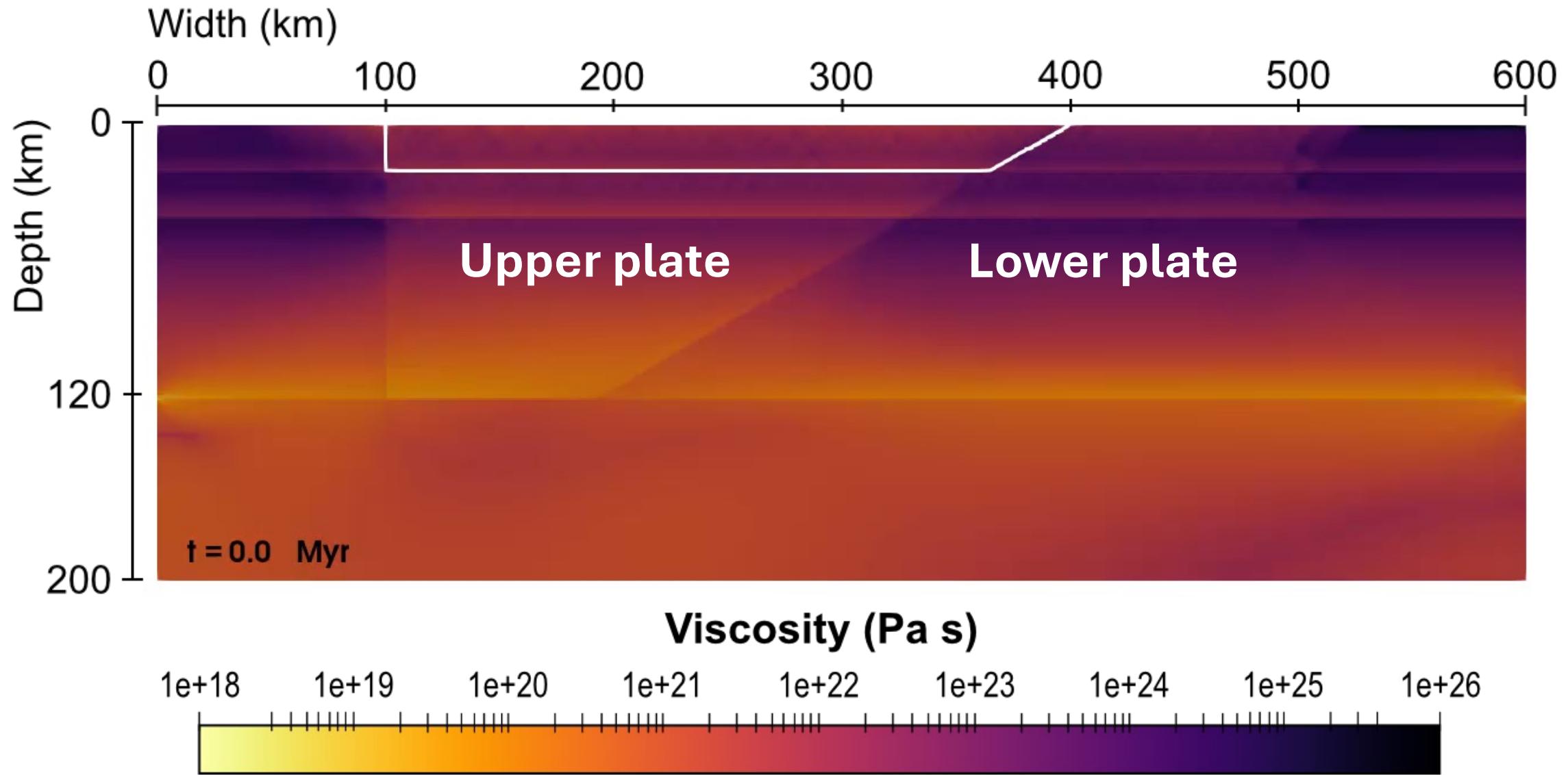


Model setup



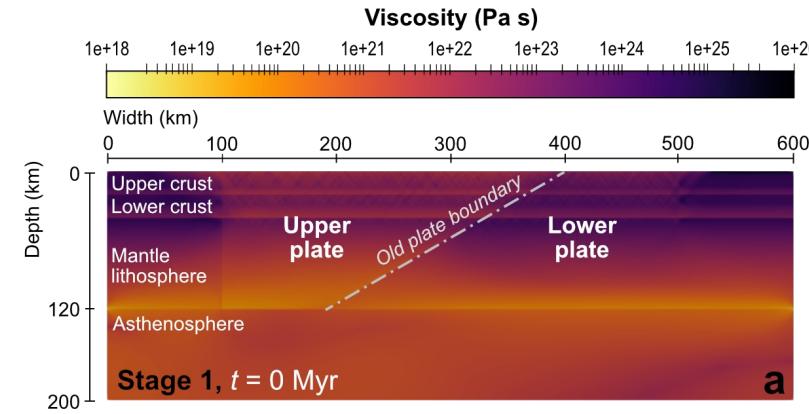
Results

Reference model



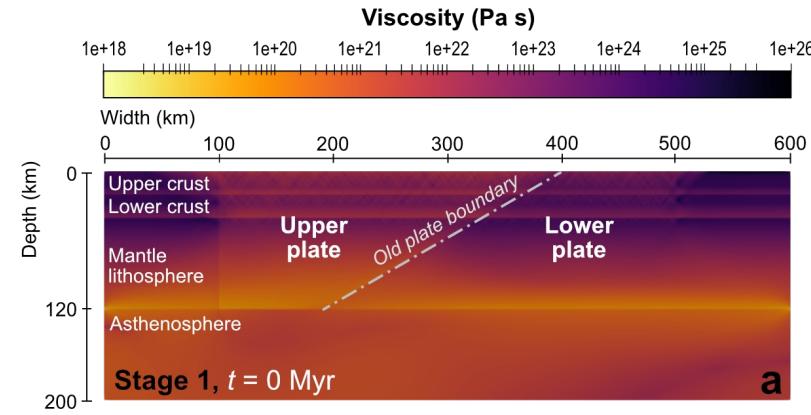
Reference model

Stage 1: widespread faulting

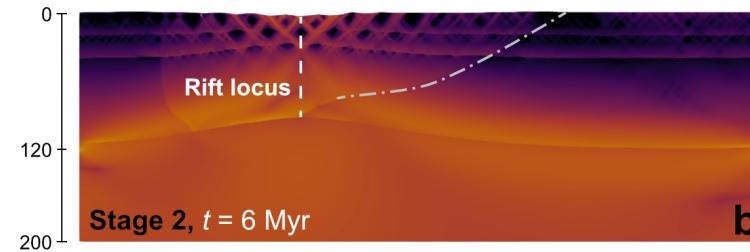


Reference model

Stage 1: widespread faulting

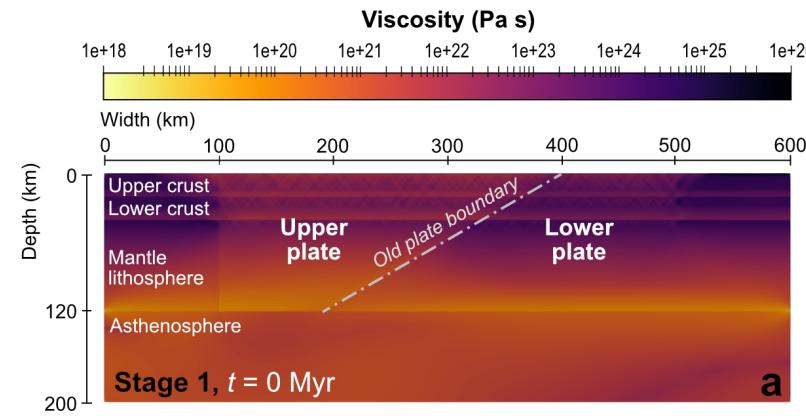


Stage 2: strain localization

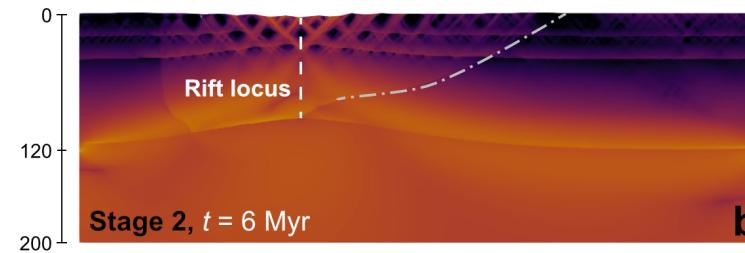


Reference model

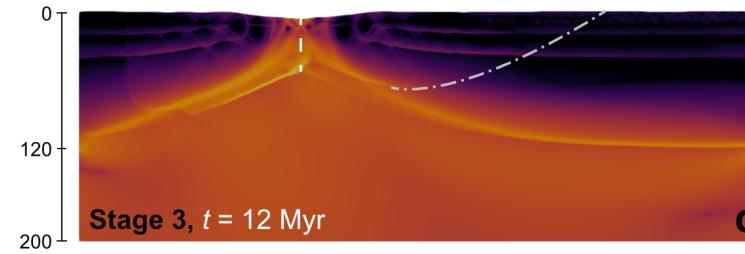
Stage 1: widespread faulting



Stage 2: strain localization

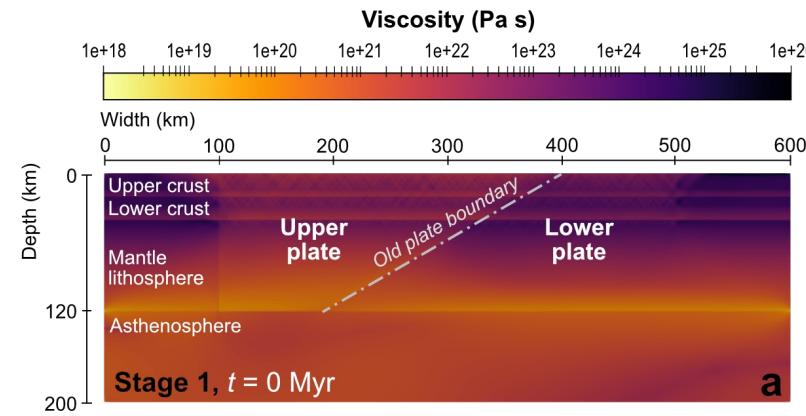


Stage 3: lithospheric thinning

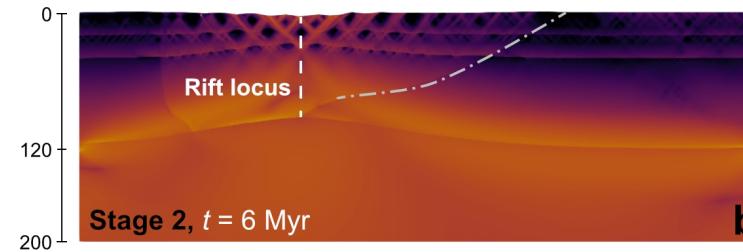


Reference model

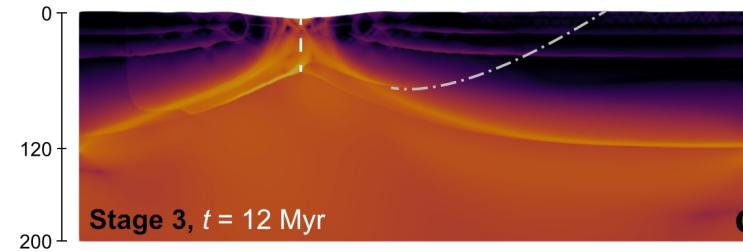
Stage 1: widespread faulting



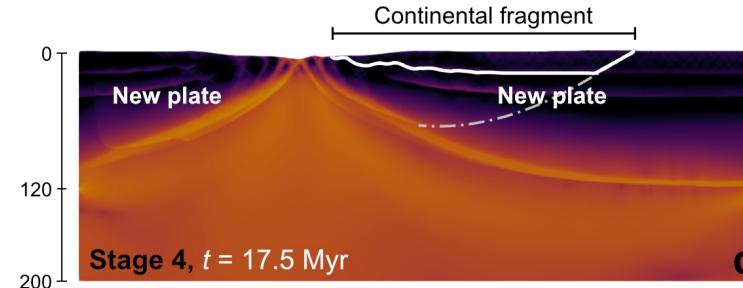
Stage 2: strain localization



Stage 3: lithospheric thinning

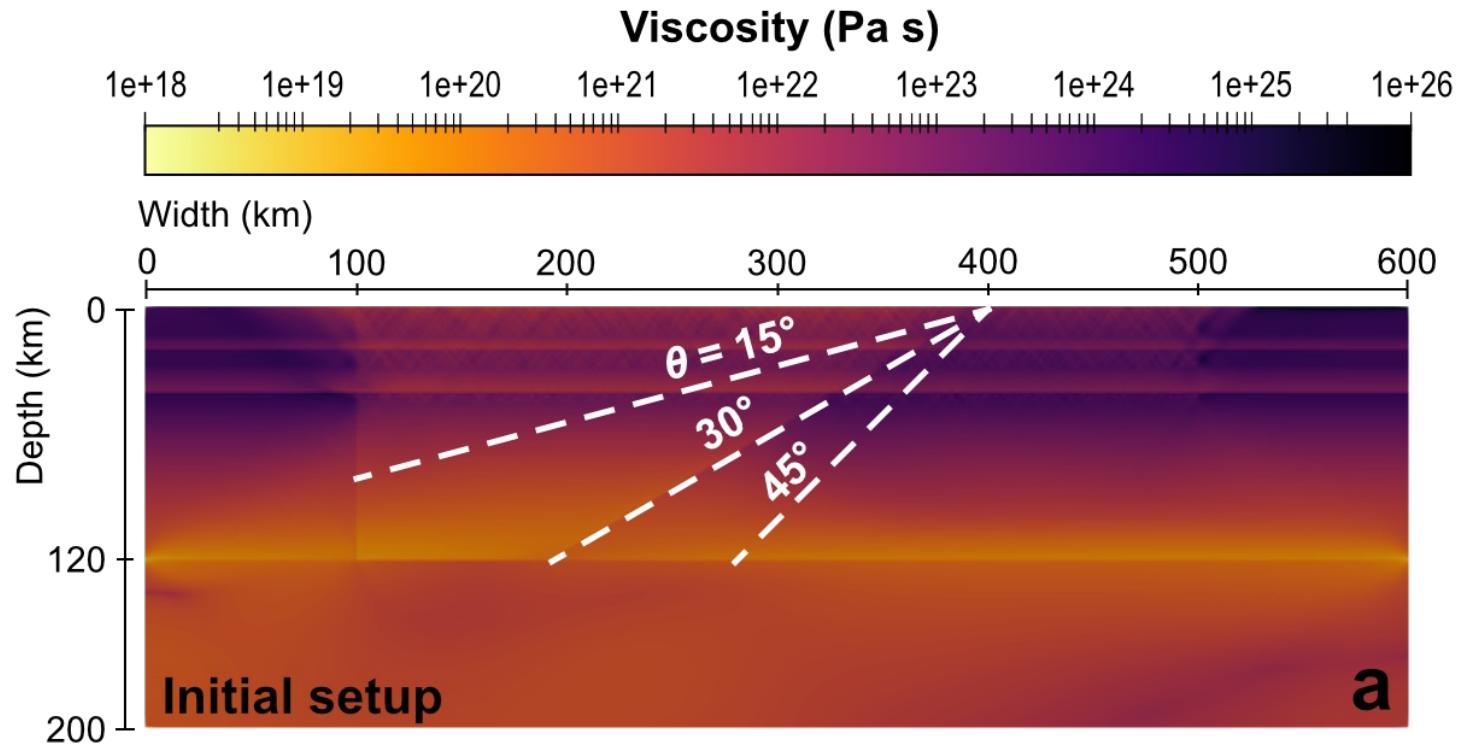


Stage 4: continental breakup



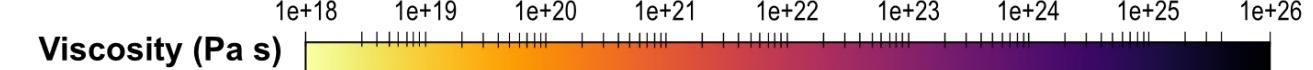
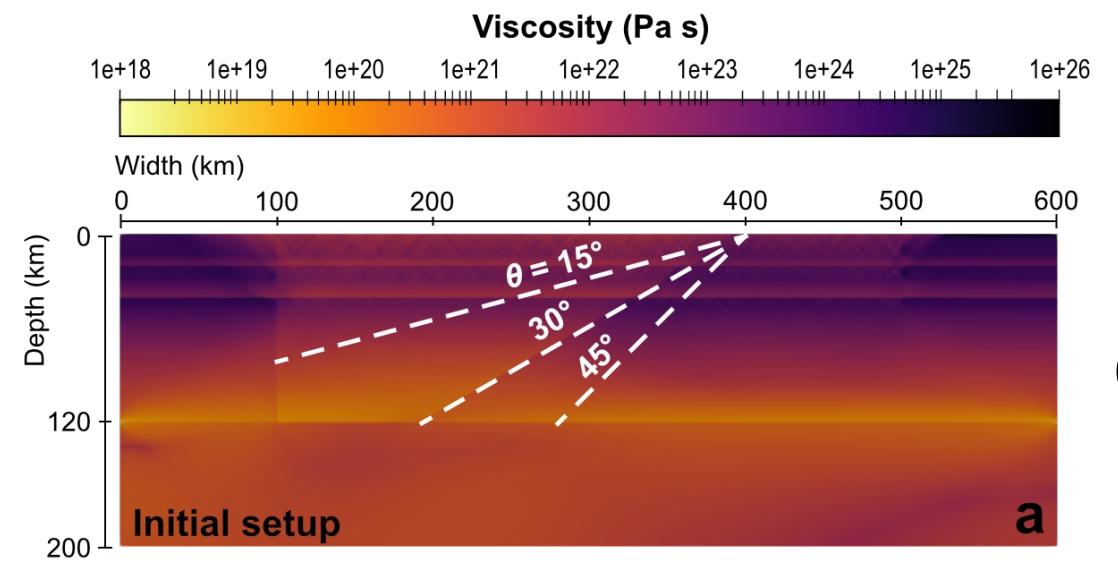
Parameter testing

Parameter testing – dip angle

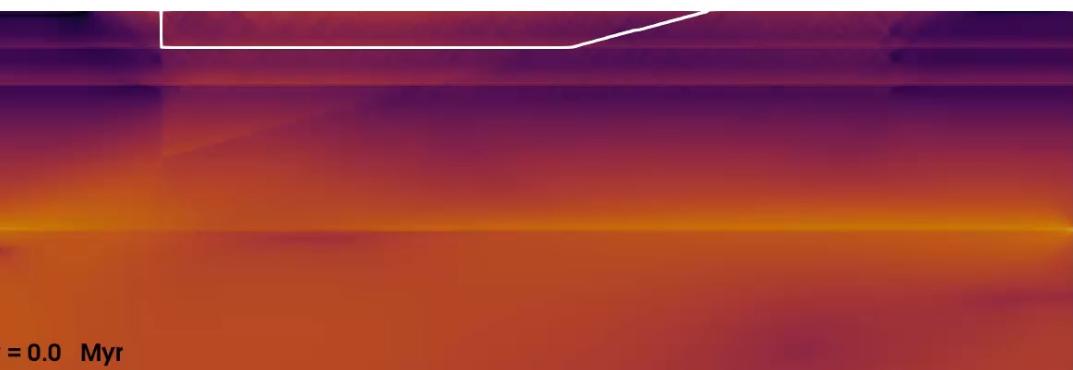


We adjusted the **dip angle between the upper and lower plate**.

Dip angle



$\theta = 15^\circ$



$\theta = 30^\circ$ (ref)

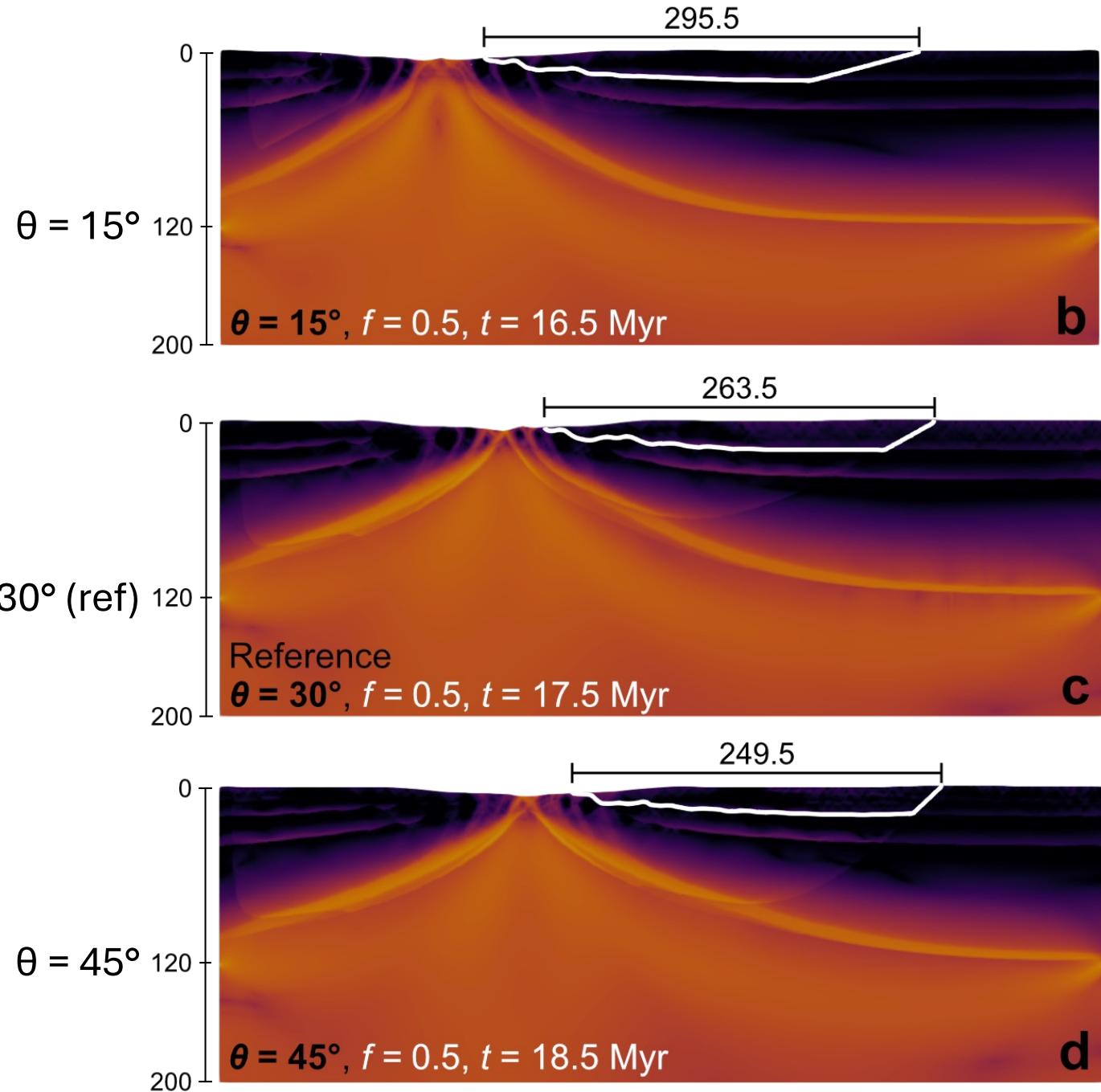


$\theta = 45^\circ$



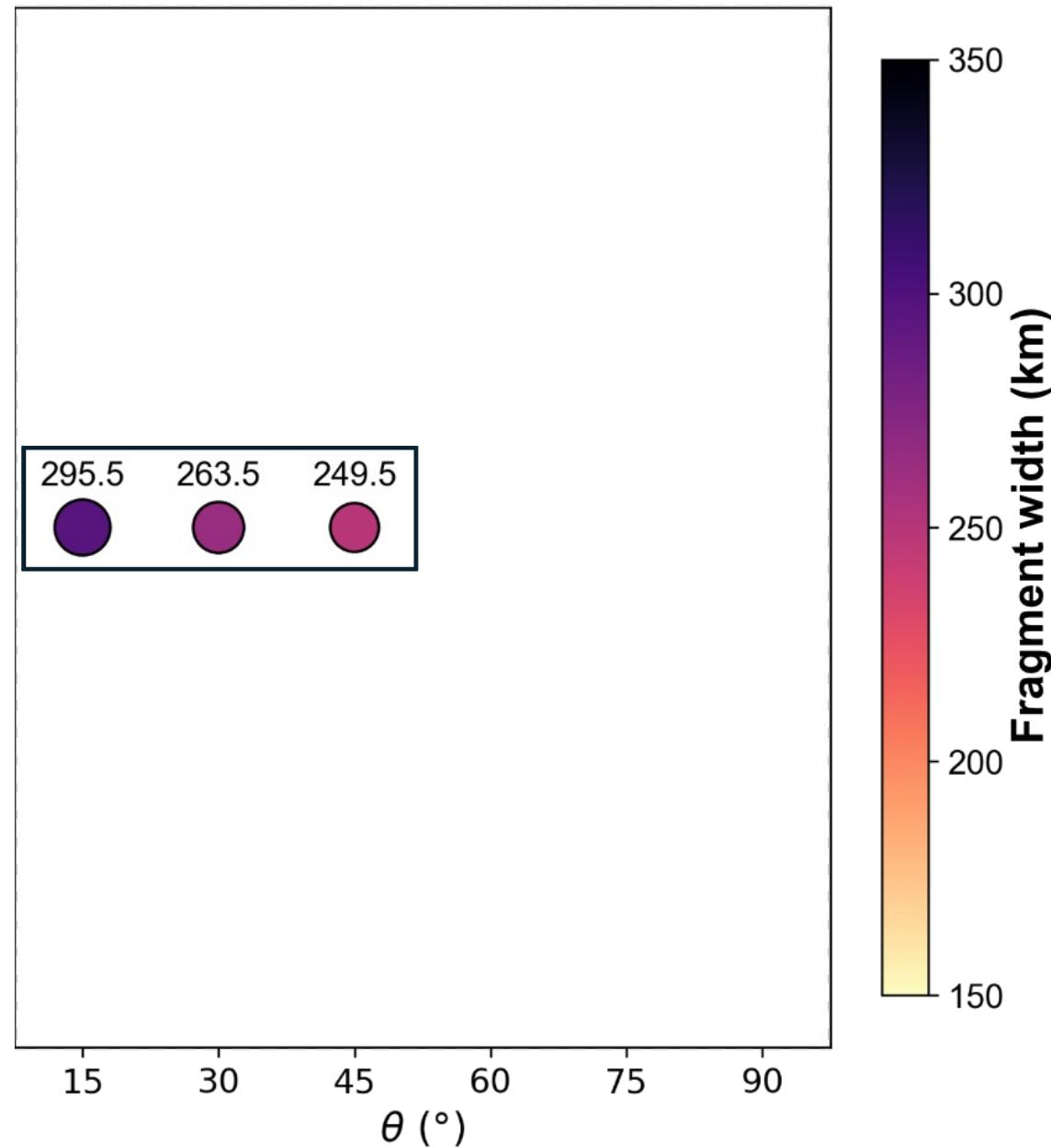
Dip angle

- Between $\theta = 15^\circ$ and 45° , a larger dip angle creates a smaller fragment.



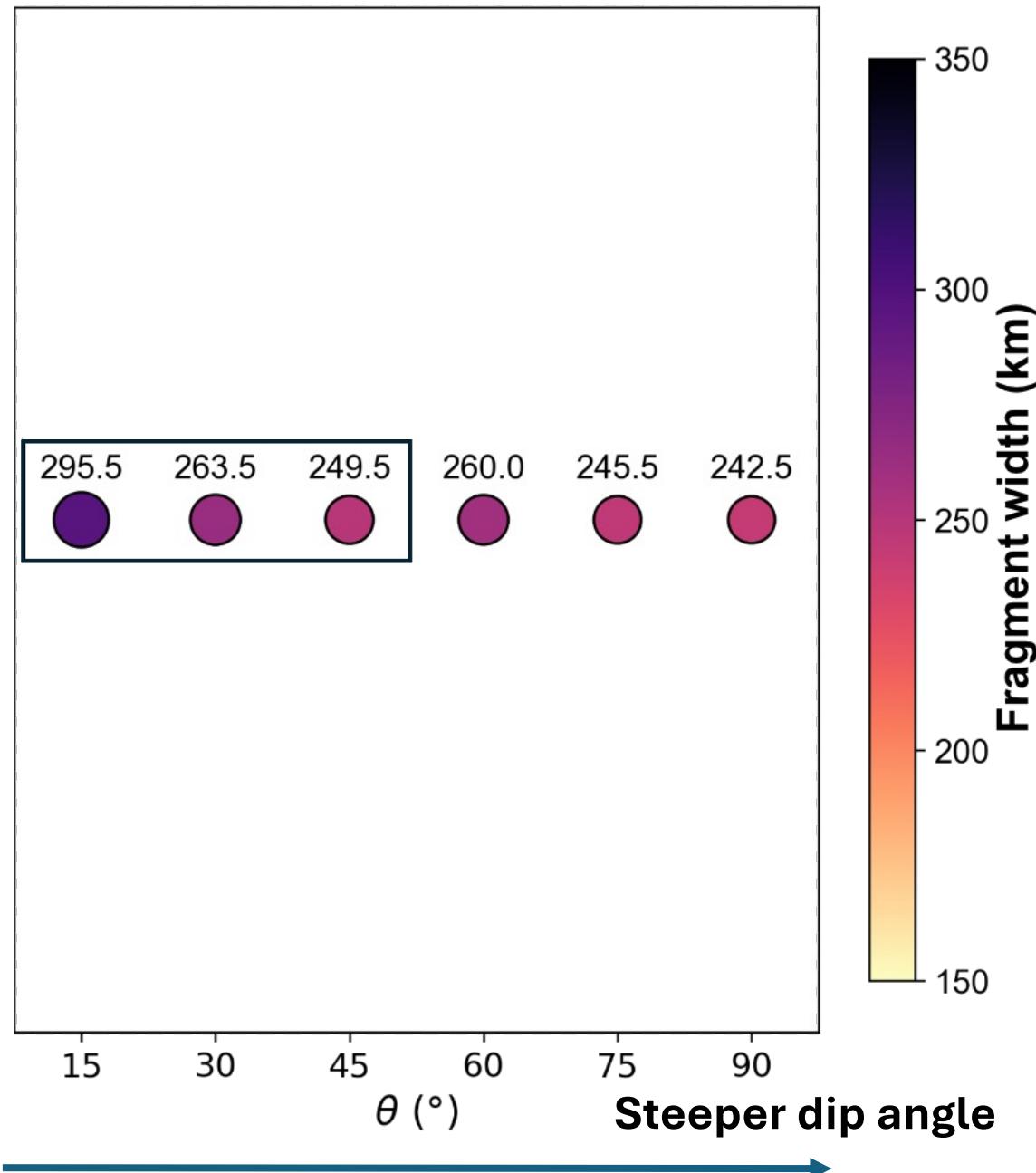
Dip angle

- Between $\theta = 15^\circ$ and 45° , a larger dip angle creates a smaller fragment.



Dip angle

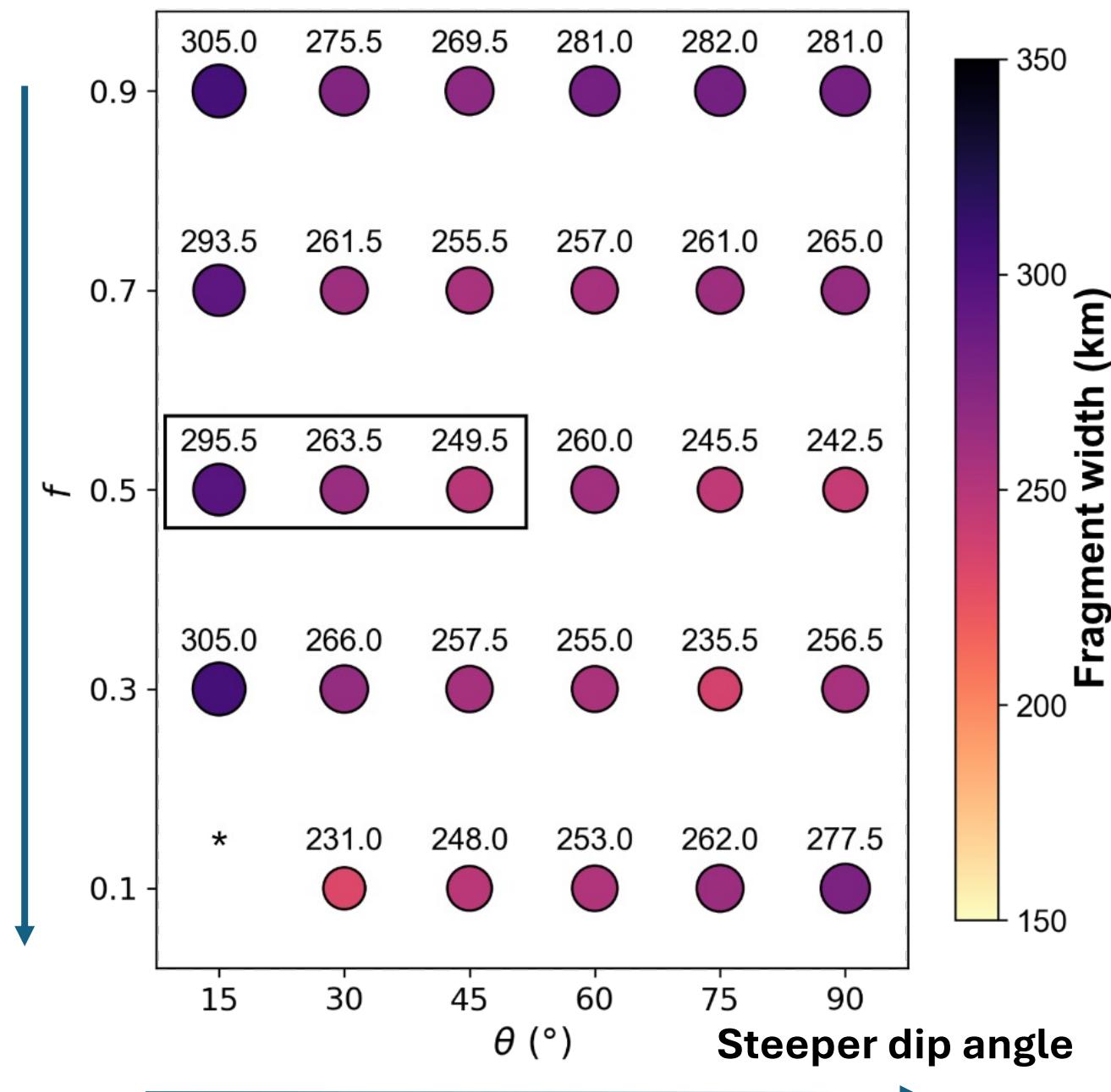
- Between $\theta = 15^\circ$ and 45° , a larger dip angle creates a smaller fragment.



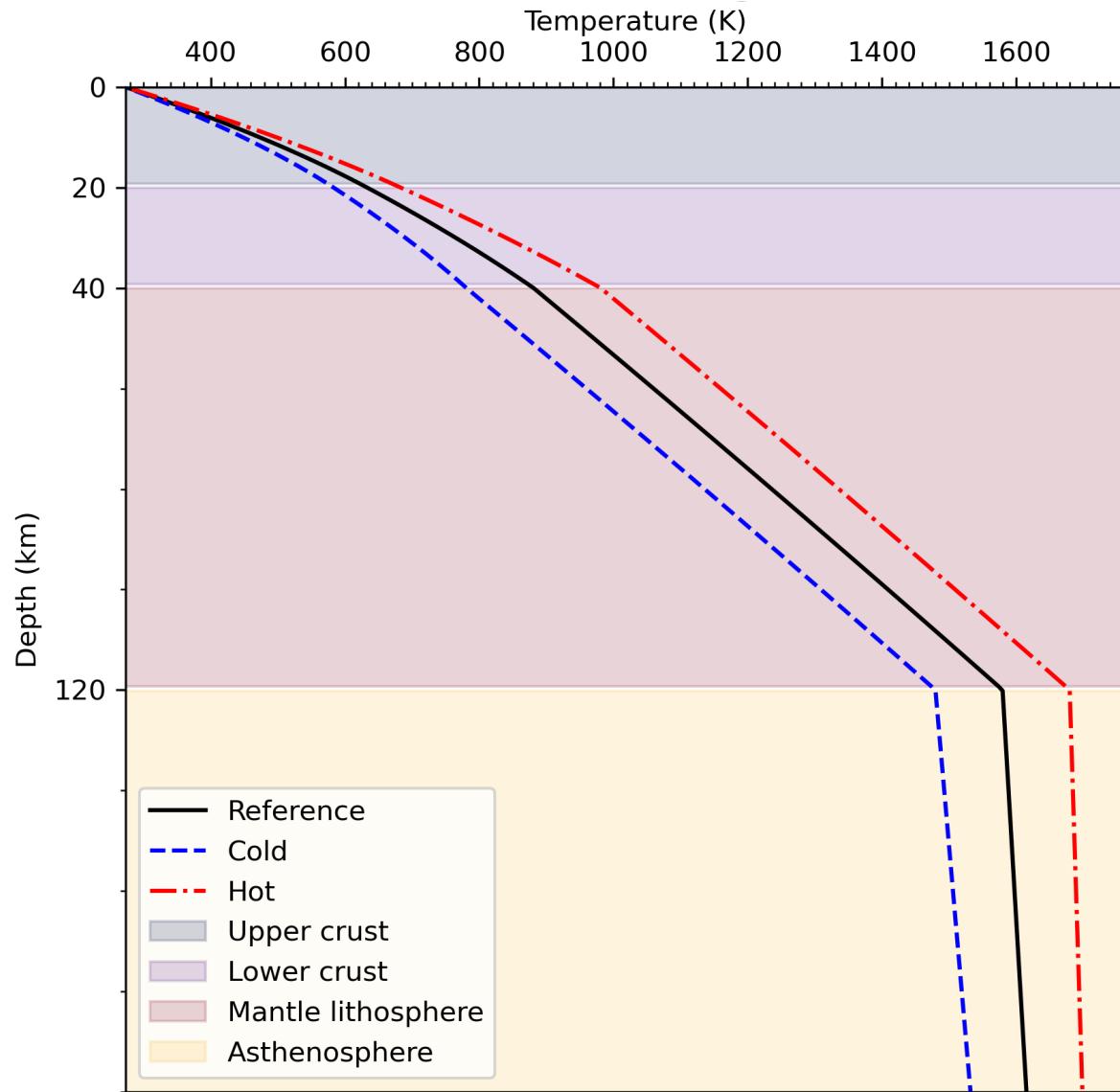
Dip angle

- Between $\theta = 15^\circ$ and 45° , a larger dip angle creates a smaller fragment.
- Between $\theta = 60^\circ$ and 90° , more random variations in fragment widths are observed.

Weaker upper plate

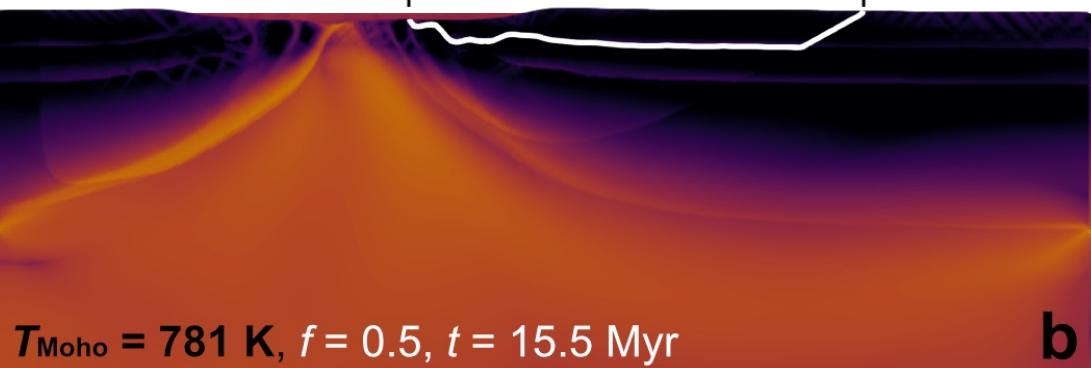


Parameter testing – initial geotherm

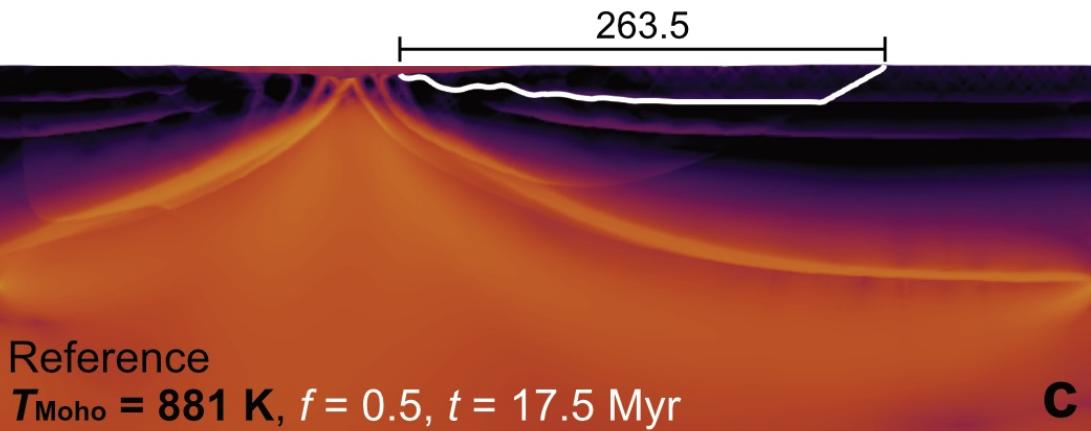


Initial geotherm

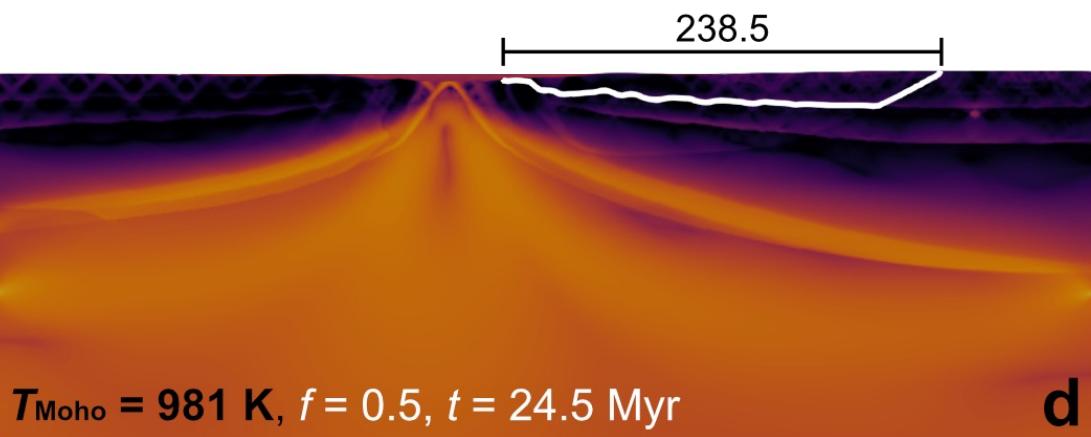
Viscosity (Pa s) 
1e+18 1e+19 1e+20 1e+21 1e+22 1e+23 1e+24 1e+25 1e+26



Reference



Hot

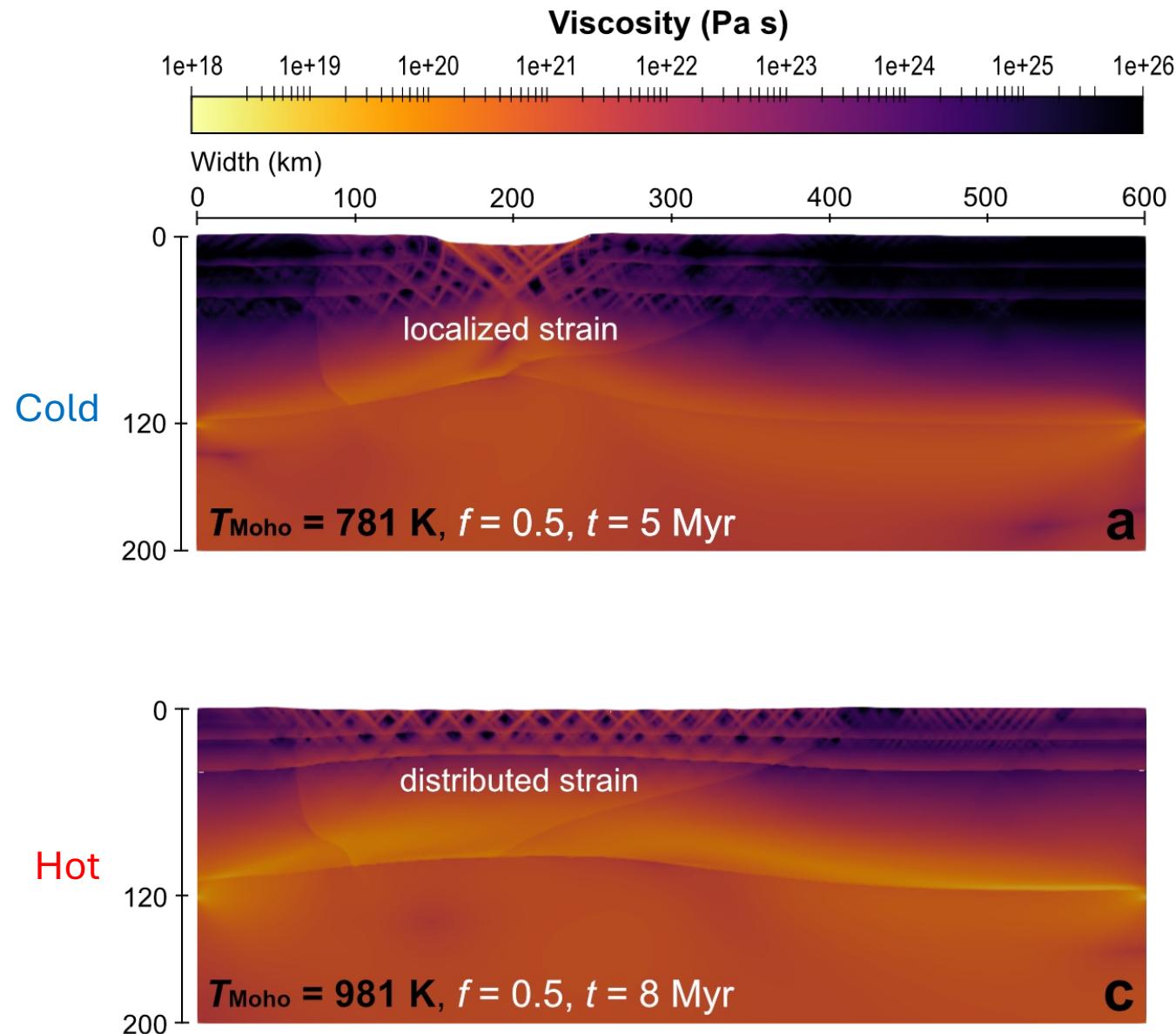


263.5

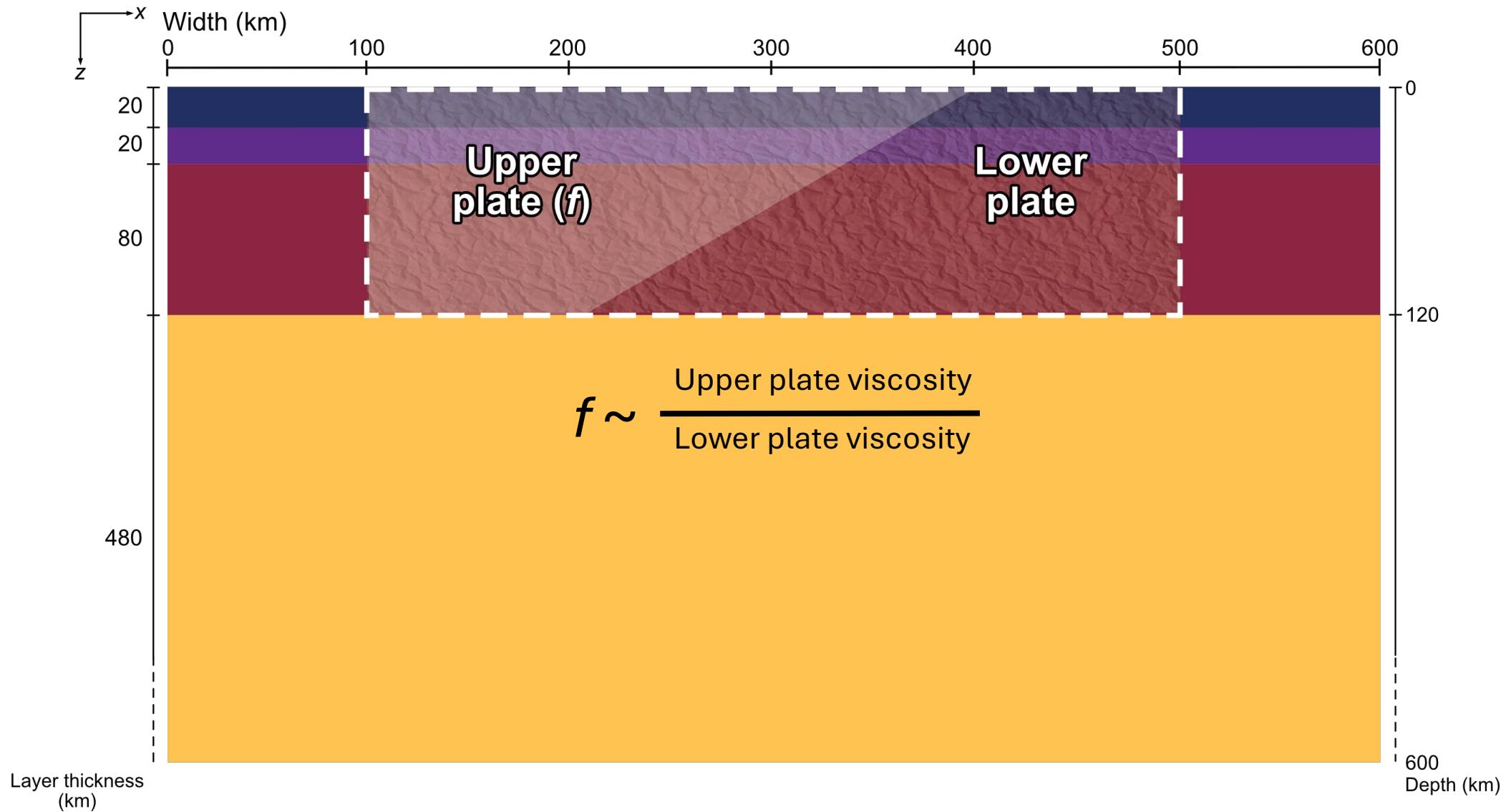
238.5

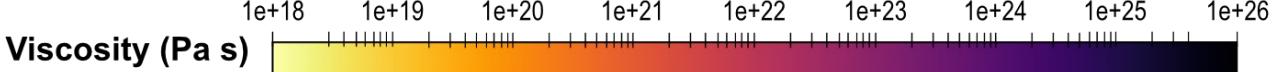
Initial geotherm

- A **colder** lithosphere creates a **narrower** rift.
- A **hotter** lithosphere creates a **wider** rift.



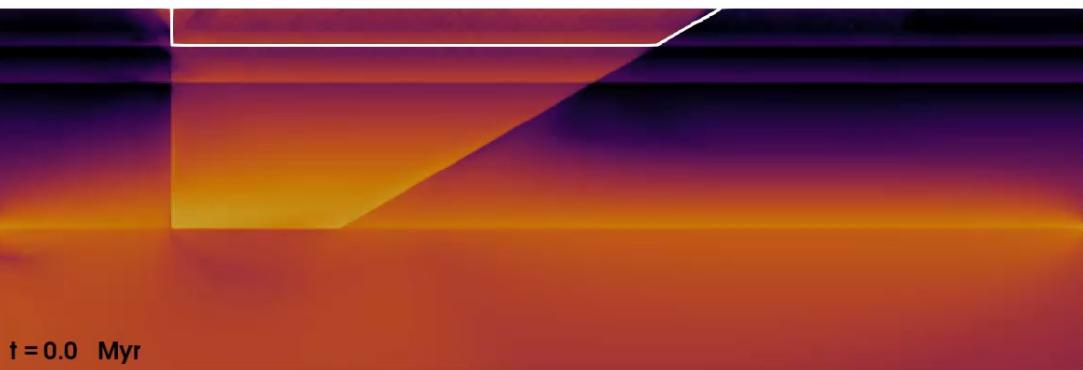
Parameter testing – upper plate strength





Upper plate strength

$f = 0.1$



$f = 0.5 \text{ (ref)}$

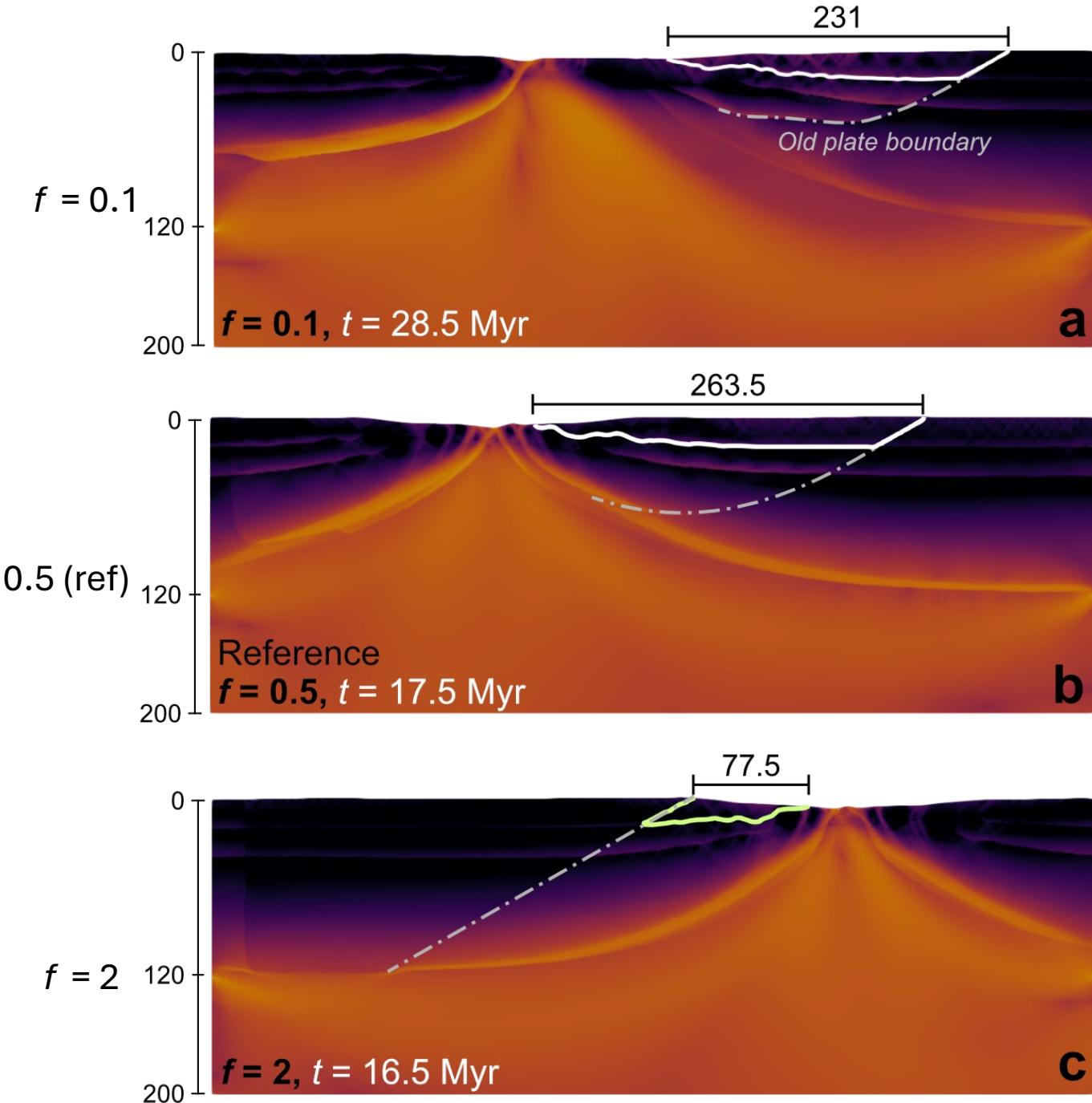


$f = 2$



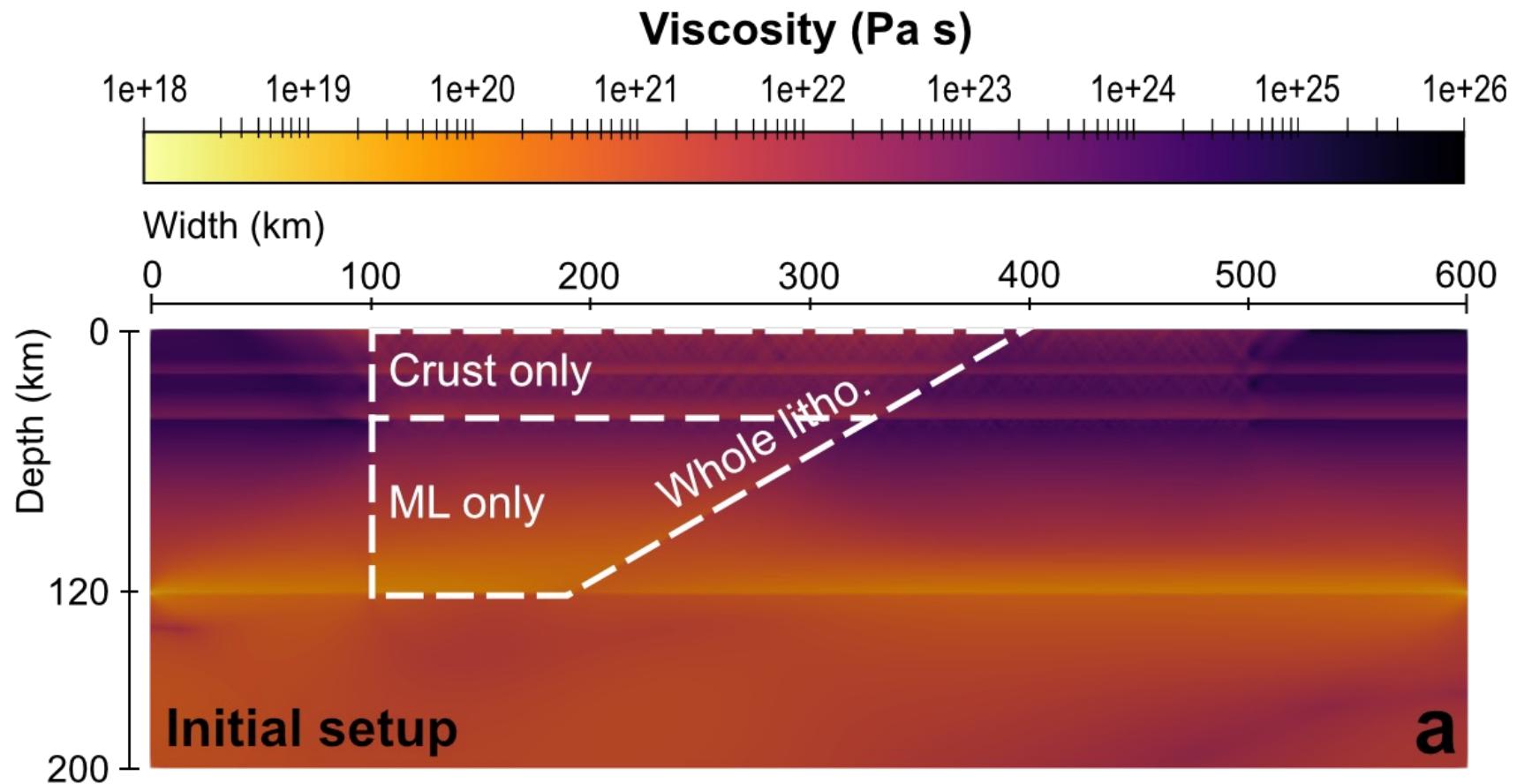
Upper plate strength

- When $f = 0.1$, delocalized thinning and longer breakup.
- When $f > 1$, the fragment formed in the lower plate.

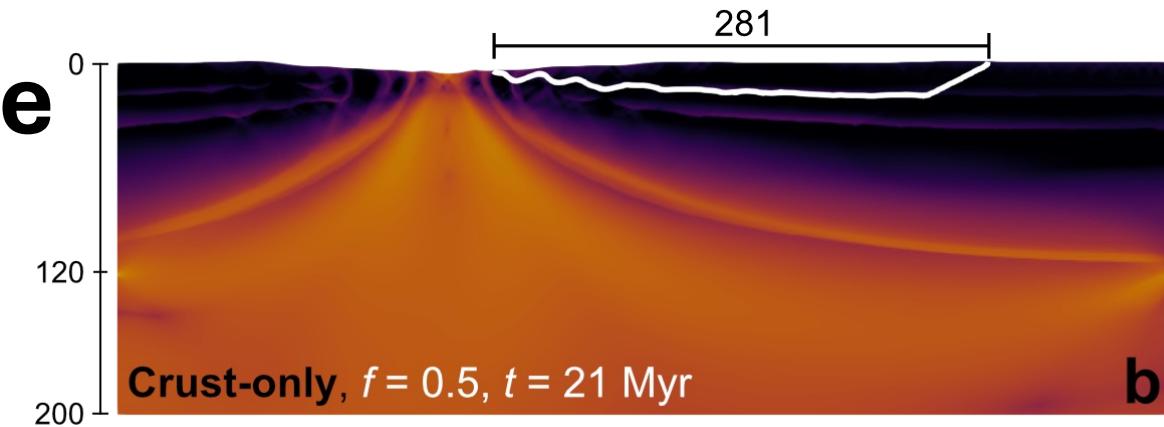
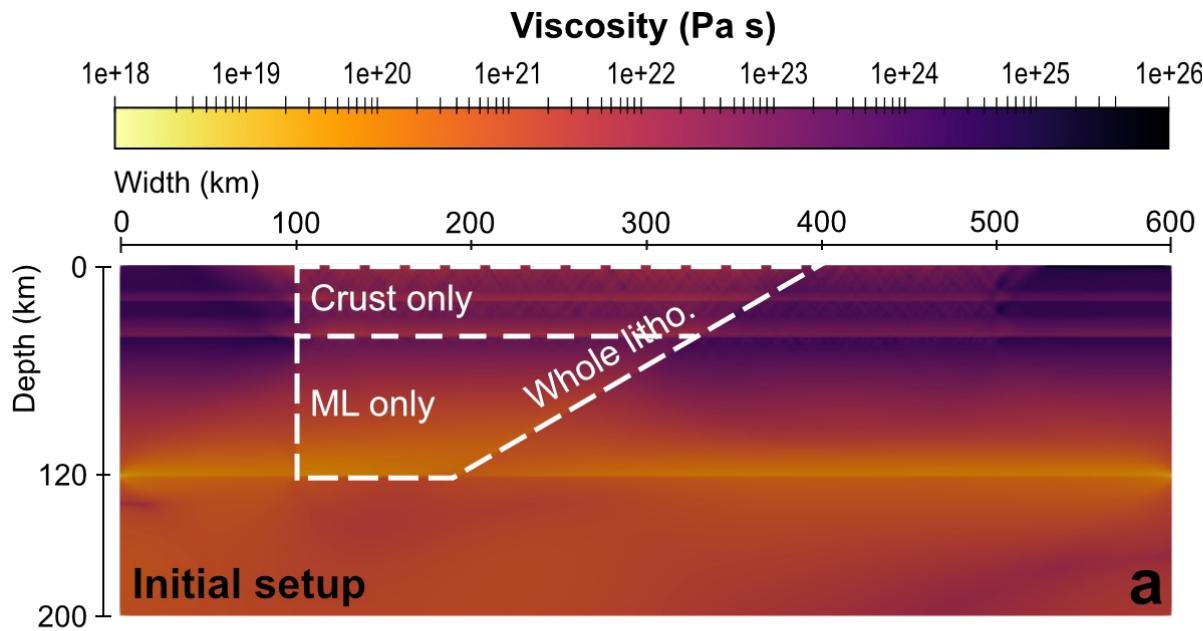


Crustal v. mantle lithospheric inheritance

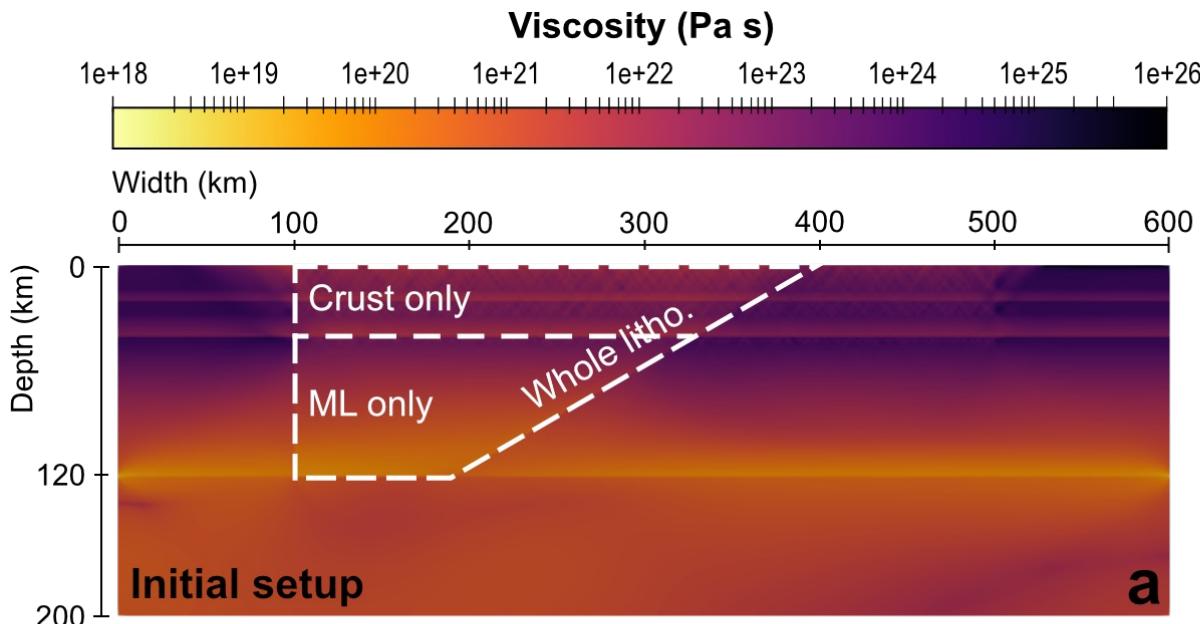
- Where f is applied to:



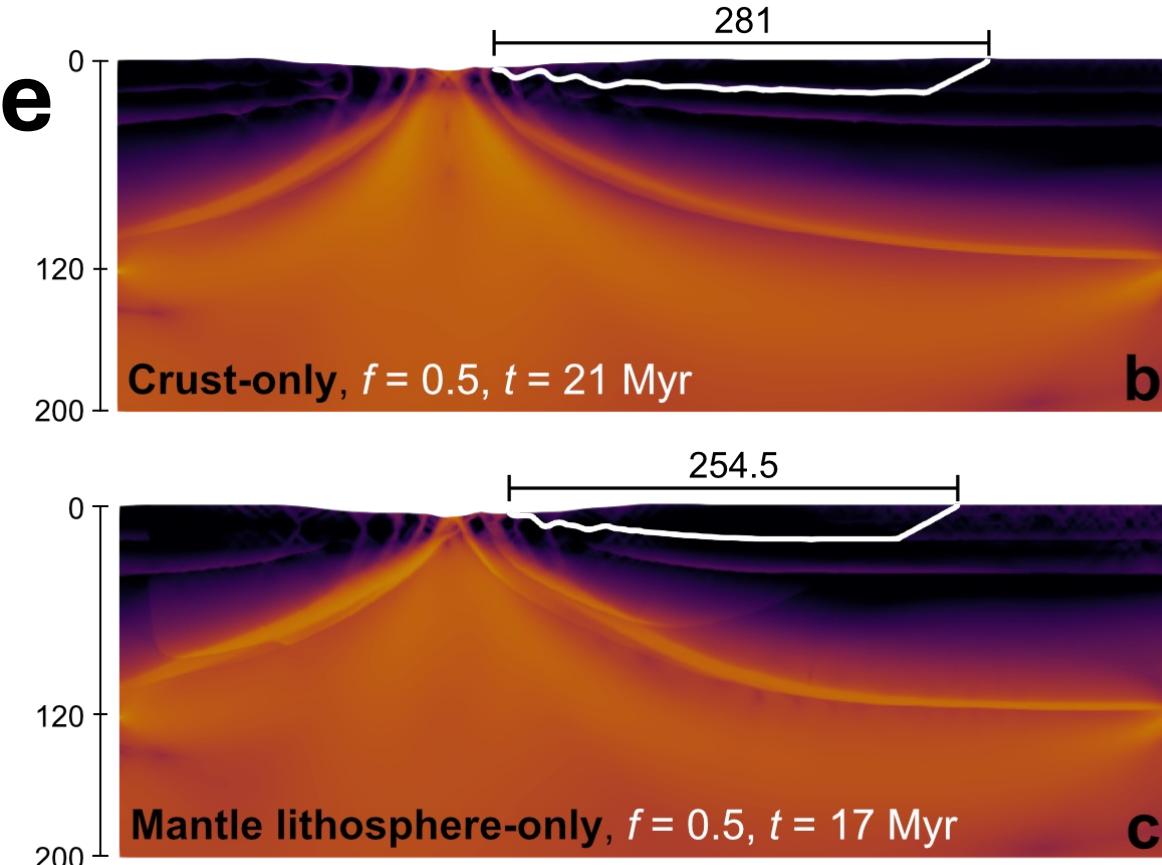
Crustal v. mantle inheritance



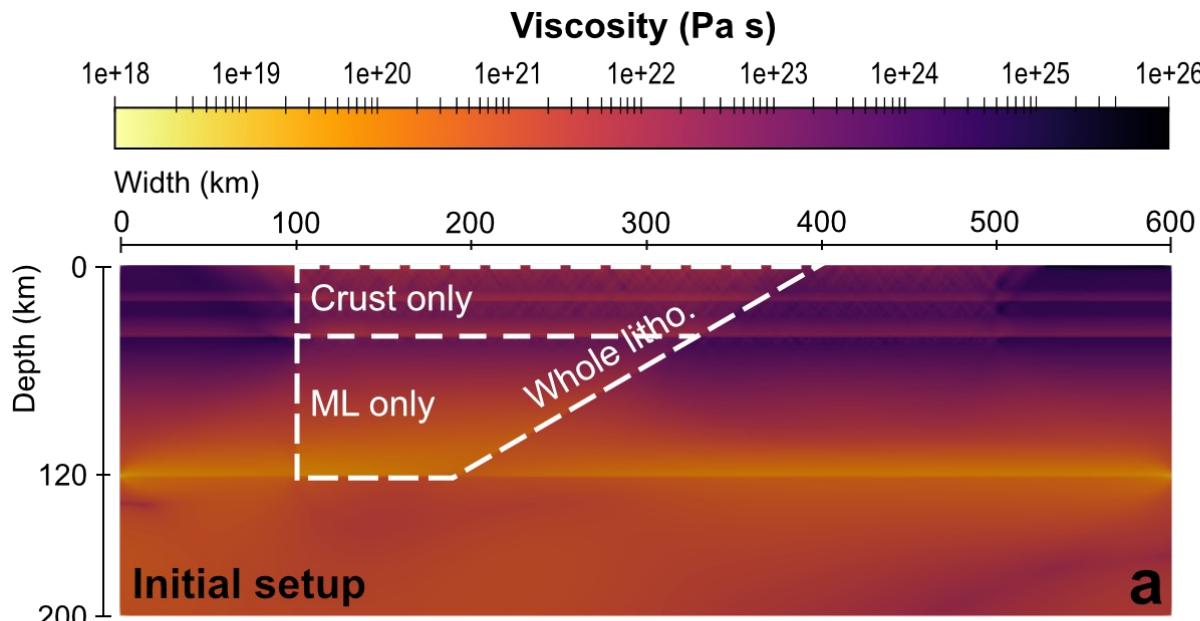
Crustal v. mantle inheritance



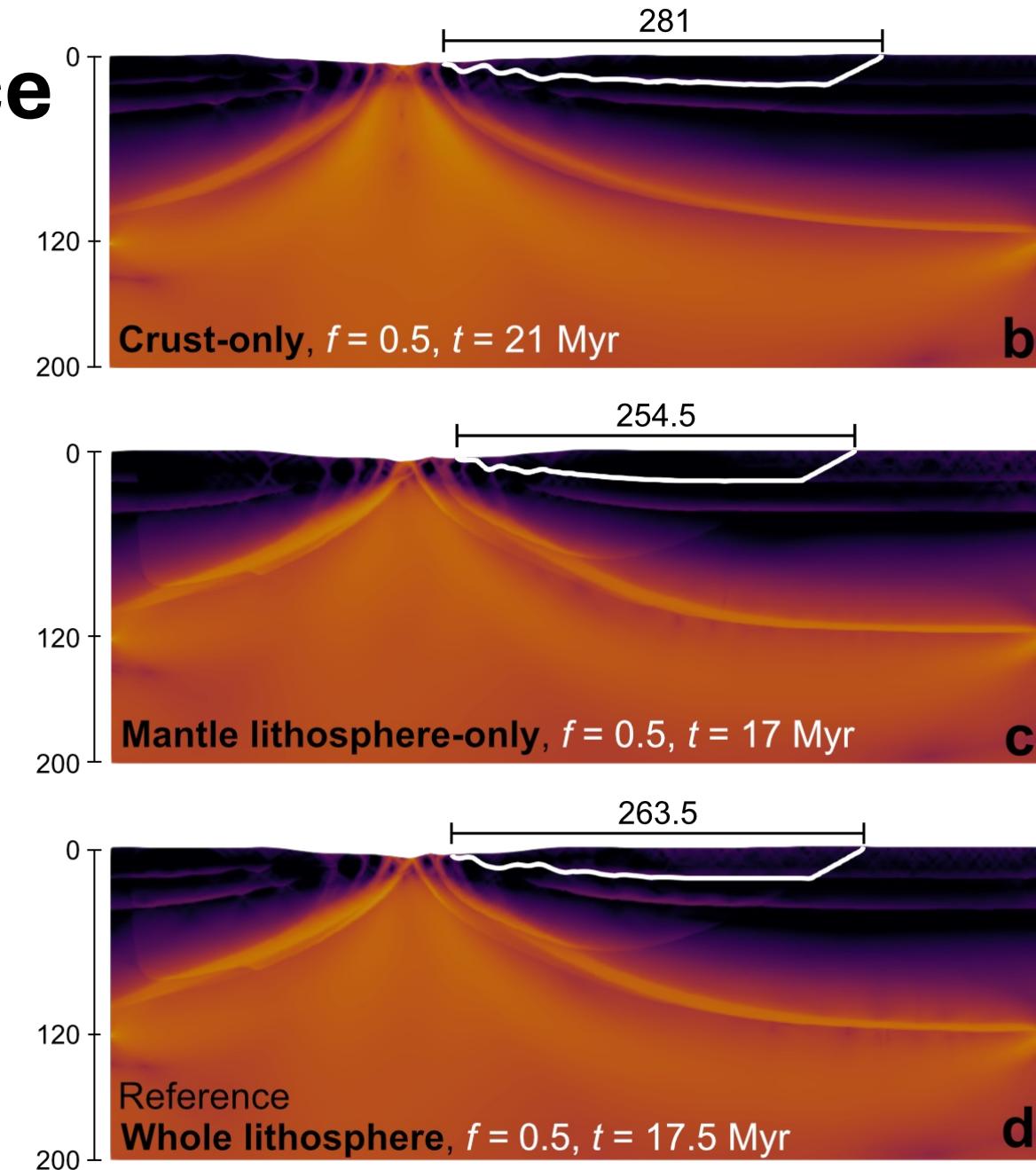
- Both **crustal** and **mantle lithospheric** inheritances are viable in fragment generation.



Crustal v. mantle inheritance

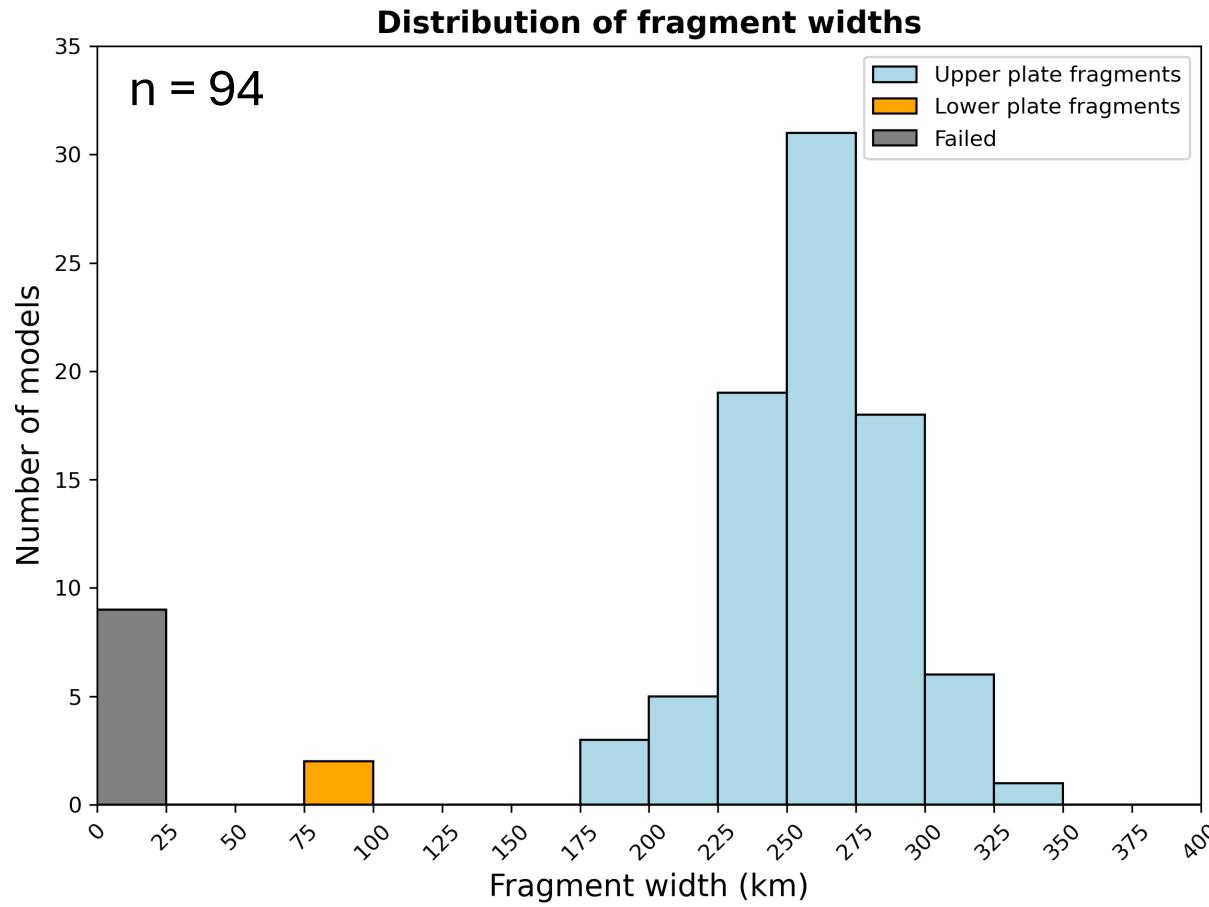


- Both **crustal** and **mantle lithospheric** inheritances are viable in fragment generation.
- Both **crustal** and **mantle lithospheric** inheritances exert tectonic control in the whole lithosphere model.



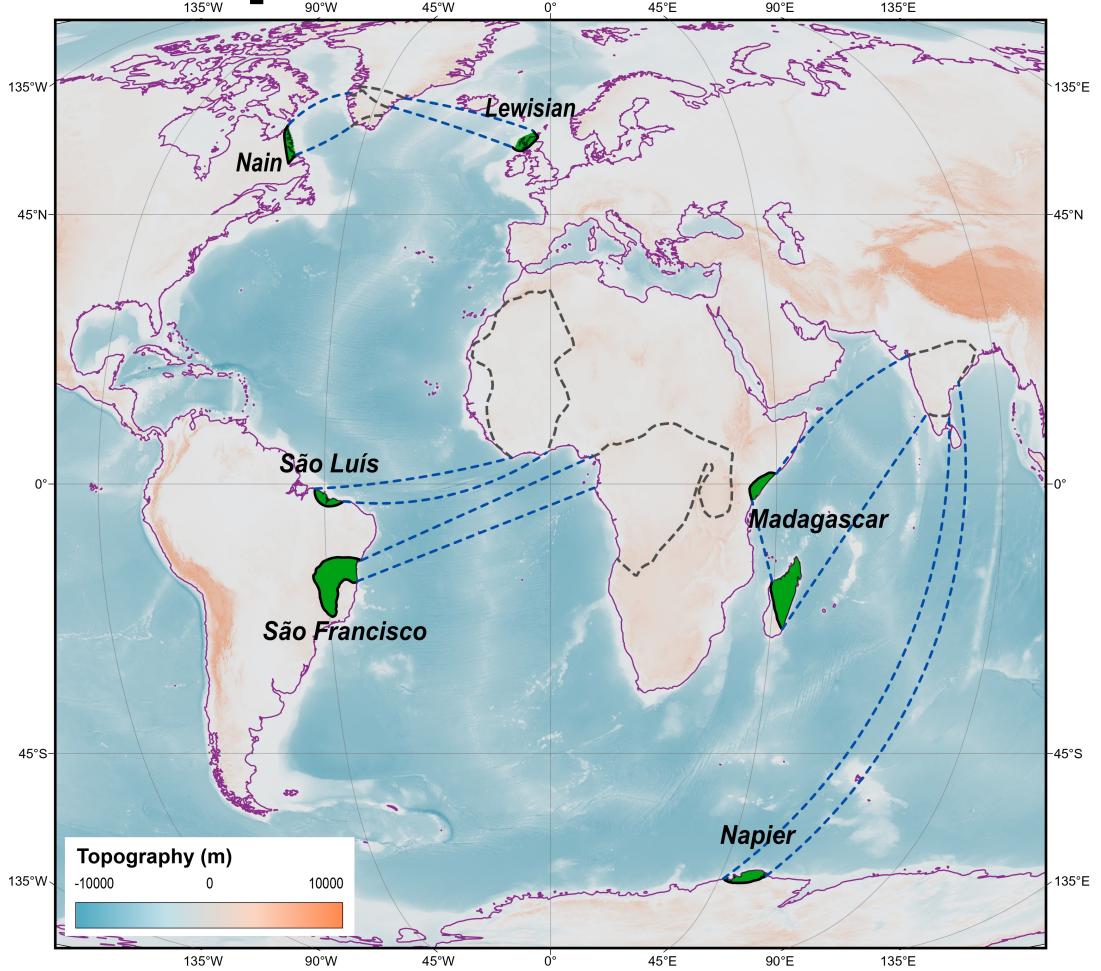
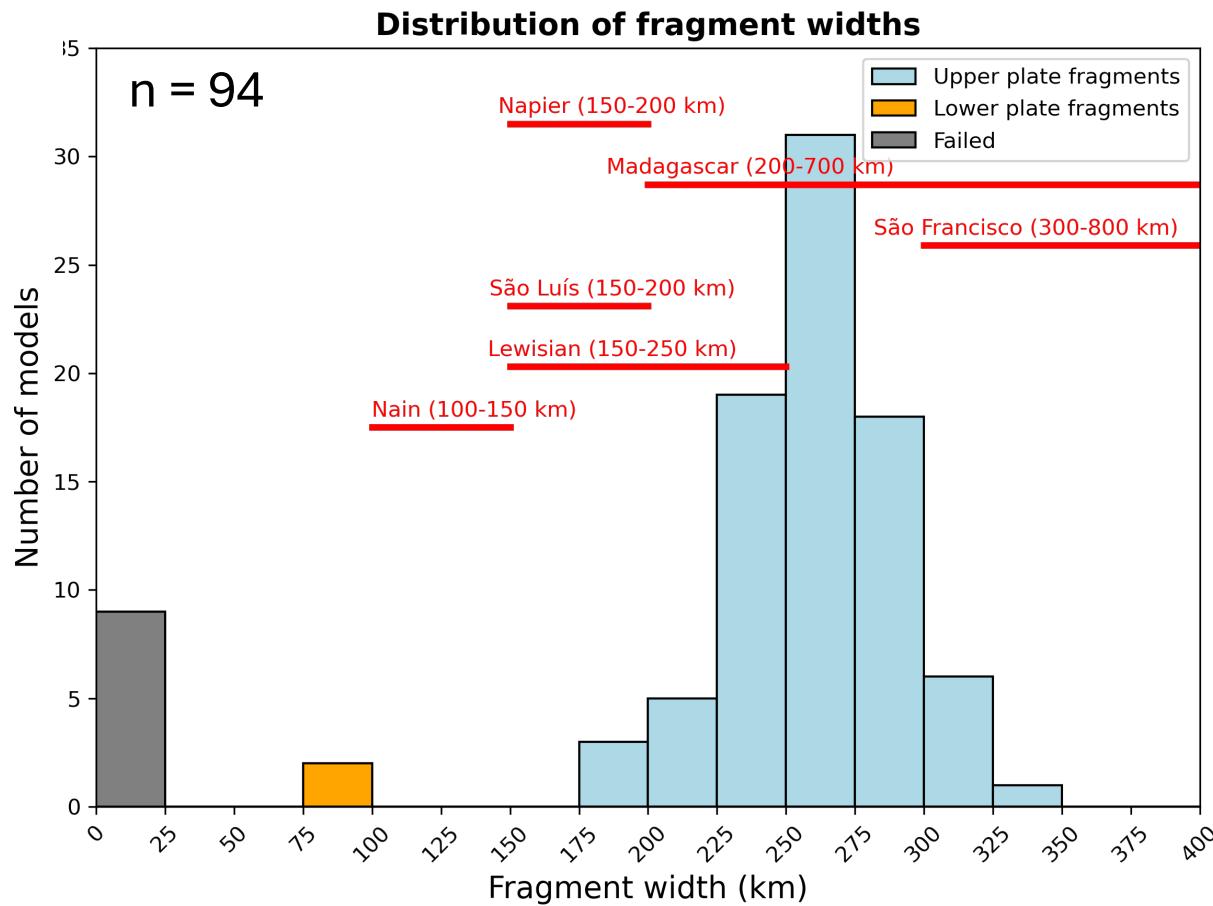
Summary

Fragment widths



- We produce fragments in widths of **~175–350 km** over **~15–35 Myr.**

Comparison with geological examples



- We produce fragments in widths of $\sim 175\text{--}350$ km over $\sim 15\text{--}35$ Myr.
- The modelled fragment widths align with many real-world examples.

Future work



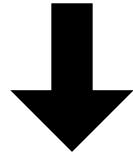
- Future work could focus on the formation of one specific fragment using 3-D models.

Conclusions

- We quantify the influence of structural inheritance in fragment formation.
- We ran 94 models, testing 8 parameters
- The geometry of inherited structures controls the fragment width.
- Our generated fragments align with real-world examples.
- We provide a tectonic recipe for future regional models.

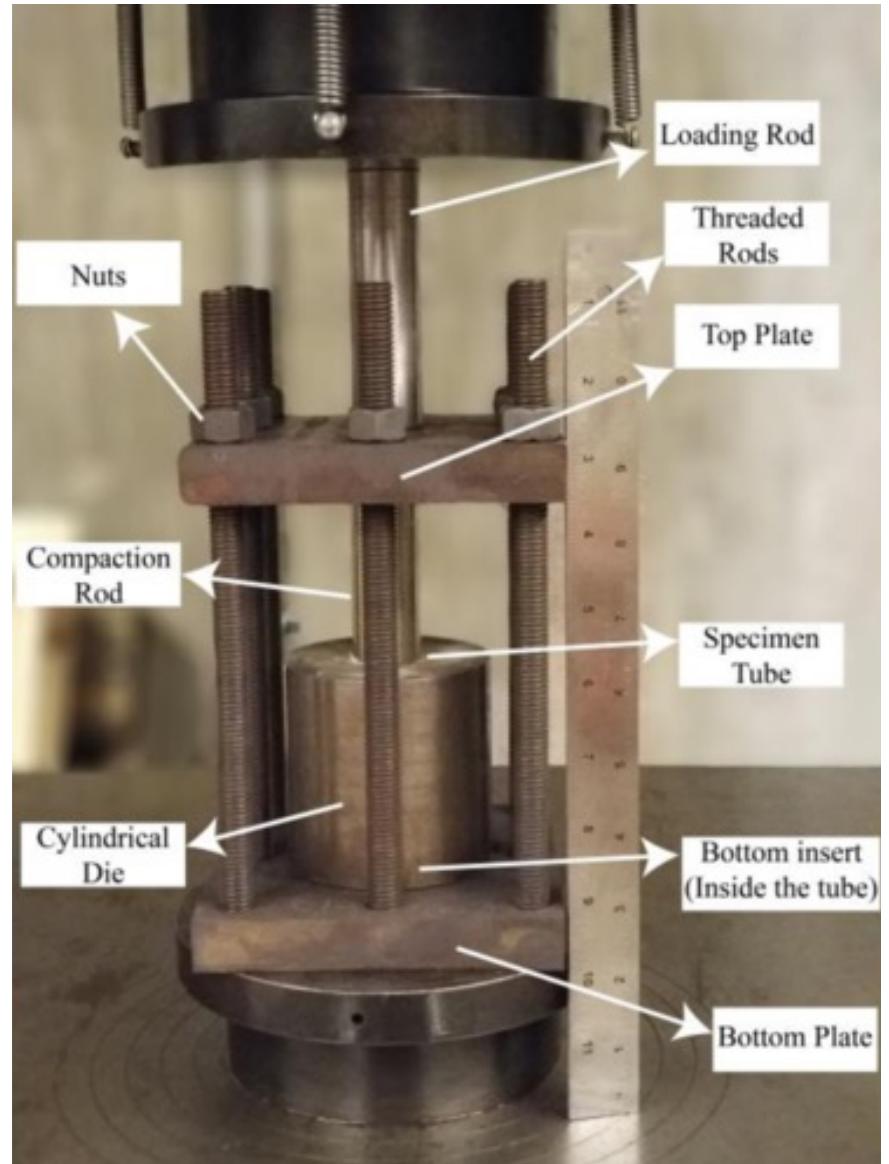
Thank you!

Access to setup, code, and data



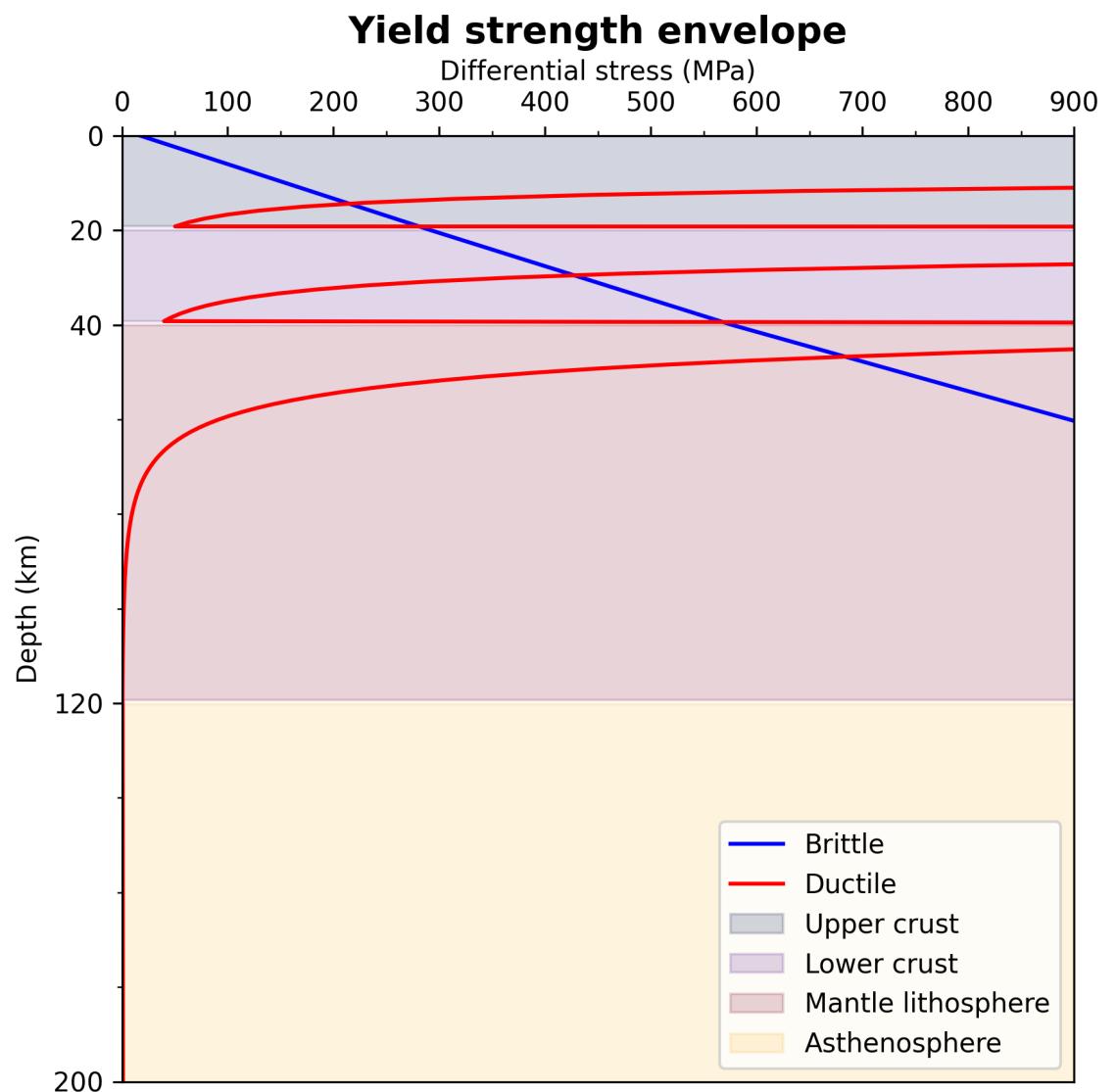
Rheology and flow laws

- Rheology describes the deformation of material.
- Most rocks are brittle at room temperature and atmosphere.
- However, they transition to a ductile state under mantle-like pressure and temperature.
- The ductile strength of rocks are measured in laboratory experiments (i.e., flow laws).



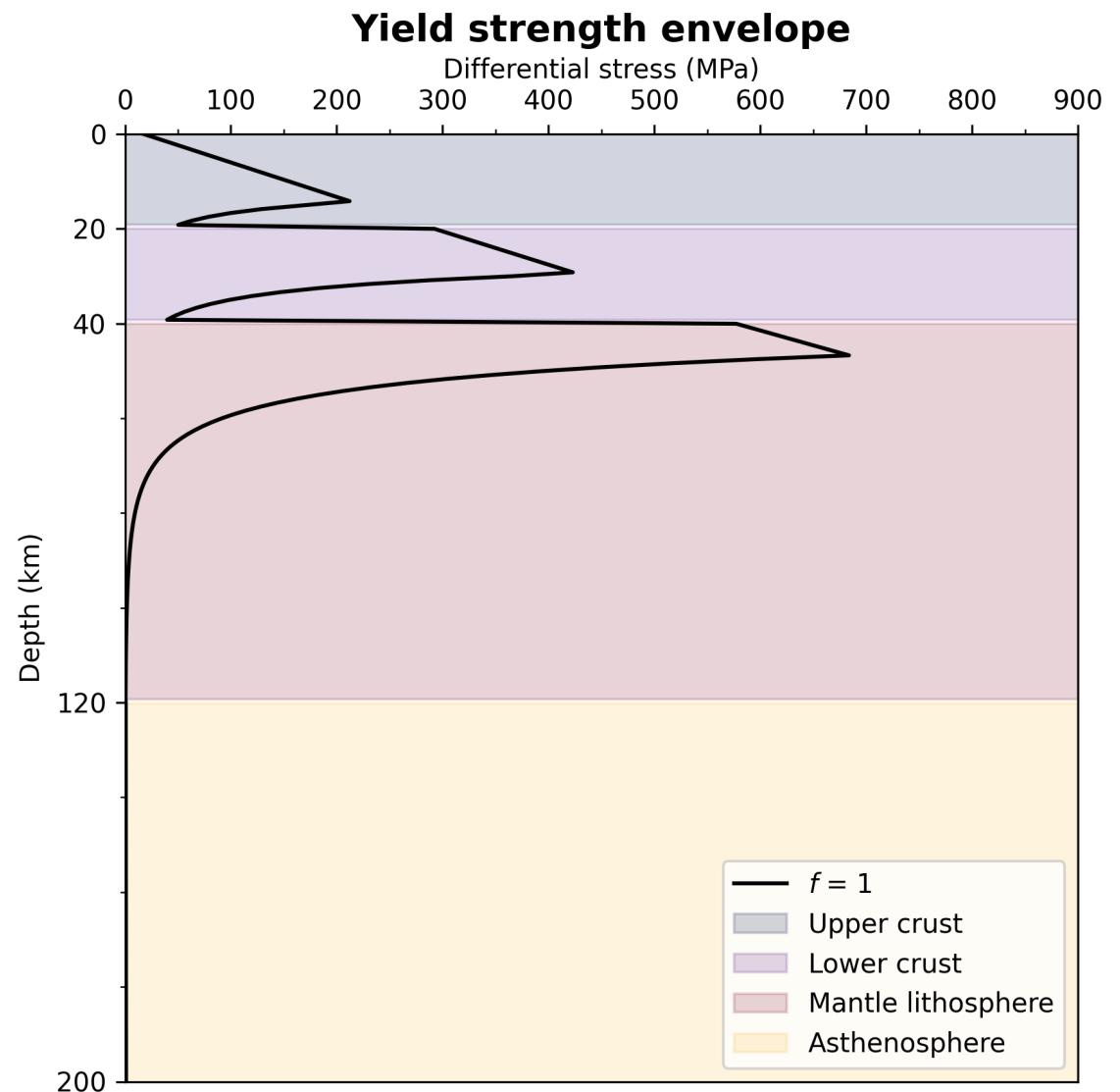
Rheology and flow laws

- ASPECT can simulate both **brittle** and **ductile** deformation.



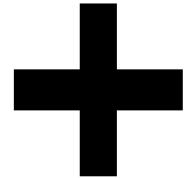
Rheology and flow laws

- ASPECT can simulate both brittle and ductile deformation.
- The lithospheric strength is determined by the minimum differential stress required to deform the rock.

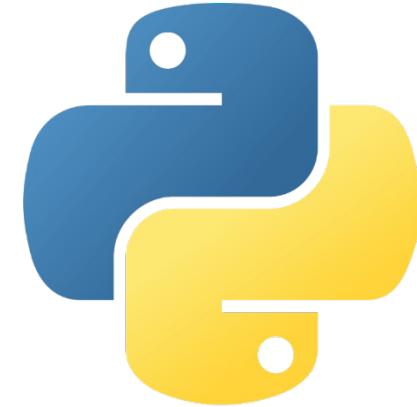


Big data analysis

Paraview



Python



- Good for analyzing one model.
- Can record analytical procedures in Python.
- Code base of Paraview.
- Good for automation (using *for* loops)

Big data analysis

Model solution files:

solution-00000.0000.vtu

solution-00000.pvtu

solution-00001.0000.vtu

solution-00001.pvtu

solution-00002.0000.vtu

solution-00002.pvtu

solution-00002.0000.vtu

solution-00003.pvtu

solution-00003.0000.vtu

solution-00004.pvtu

solution-00004.0000.vtu

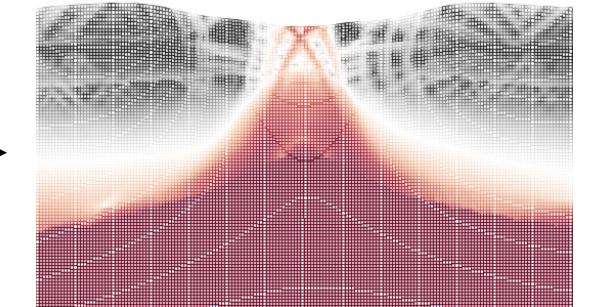
...

Solution at
timestep 0

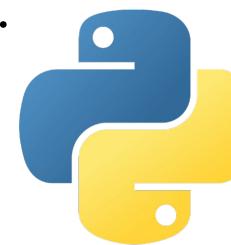
0.00E+00	0.00E+00	0.00E+00	1.10E-09	-2.8E-09	0	0	10	971	1.00E-19	3.00E-05	2.8E+02	1.00E+03
1.00E+03	8.00E+10	0.00E+00	0	0	0	0	41	1002	1.00E+19	3.00E-05	2.8E+02	1.00E+03
2.00E+03	8.00E+10	0.00E+00	0	0	0	0	72	1031	1.00E+19	3.00E-05	2.8E+02	1.00E+03
3.00E+03	8.00E+10	0.00E+00	0	0	0	0	103	1064	1.00E+19	3.00E-05	2.8E+02	1.00E+03
4.00E+03	8.00E+10	0.00E+00	0	0	0	0	134	1096	1.00E+19	3.00E-05	2.8E+02	1.00E+03
5.00E+03	8.00E+10	0.00E+00	0	0	0	0	165	1129	1.00E+19	3.00E-05	2.8E+02	1.00E+03
6.00E+03	8.00E+10	0.00E+00	0	0	0	0	196	1162	1.00E+19	3.00E-05	2.8E+02	1.00E+03
7.00E+03	8.00E+10	0.00E+00	0	0	0	0	227	1195	1.00E+19	3.00E-05	2.8E+02	1.00E+03
8.00E+03	8.00E+10	0.00E+00	0	0	0	0	258	1228	1.00E+19	3.00E-05	2.8E+02	1.00E+03
9.00E+03	8.00E+10	0.00E+00	0	0	0	0	289	1261	1.00E+19	3.00E-05	2.8E+02	1.00E+03
1.00E+04	8.00E+10	0.00E+00	0	0	0	0	320	1294	1.00E+19	3.00E-05	2.8E+02	1.00E+03
1.10E+04	8.00E+10	0.00E+00	0	0	0	0	351	1327	1.00E+19	3.00E-05	2.8E+02	1.00E+03
1.20E+04	8.00E+10	0.00E+00	0	0	0	0	382	1360	1.00E+19	3.00E-05	2.8E+02	1.00E+03
1.30E+04	8.00E+10	0.00E+00	0	0	0	0	413	1393	1.00E+19	3.00E-05	2.8E+02	1.00E+03
1.40E+04	8.00E+10	0.00E+00	0	0	0	0	444	1426	1.00E+19	3.00E-05	2.8E+02	1.00E+03
1.50E+04	8.00E+10	0.00E+00	0	0	0	0	475	1459	1.00E+19	3.00E-05	2.8E+02	1.00E+03
1.60E+04	8.00E+10	0.00E+00	0	0	0	0	506	1492	1.00E+19	3.00E-05	2.8E+02	1.00E+03
1.70E+04	8.00E+10	0.00E+00	0	0	0	0	537	1525	1.00E+19	3.00E-05	2.8E+02	1.00E+03
1.80E+04	8.00E+10	0.00E+00	0	0	0	0	568	1558	1.00E+19	3.00E-05	2.8E+02	1.00E+03
1.90E+04	8.00E+10	0.00E+00	0	0	0	0	600	1591	1.00E+19	3.00E-05	2.8E+02	1.00E+03
2.00E+04	8.00E+10	0.00E+00	0	0	0	0	631	1624	1.00E+19	3.00E-05	2.8E+02	1.00E+03
2.10E+04	8.00E+10	0.00E+00	0	0	0	0	662	1657	1.00E+19	3.00E-05	2.8E+02	1.00E+03
2.20E+04	8.00E+10	0.00E+00	0	0	0	0	693	1690	1.00E+19	3.00E-05	2.8E+02	1.00E+03
2.30E+04	8.00E+10	0.00E+00	0	0	0	0	724	1723	1.00E+19	3.00E-05	2.8E+02	1.00E+03
2.40E+04	8.00E+10	0.00E+00	0	0	0	0	755	1756	1.00E+19	3.00E-05	2.8E+02	1.00E+03
2.50E+04	8.00E+10	0.00E+00	0	0	0	0	786	1789	1.00E+19	3.00E-05	2.8E+02	1.00E+03
2.60E+04	8.00E+10	0.00E+00	0	0	0	0	817	1822	1.00E+19	3.00E-05	2.8E+02	1.00E+03
2.70E+04	8.00E+10	0.00E+00	0	0	0	0	847	1855	1.00E+19	3.00E-05	2.8E+02	1.00E+03
2.80E+04	8.00E+10	0.00E+00	0	0	0	0	878	1888	1.00E+19	3.00E-05	2.8E+02	1.00E+03
2.90E+04	8.00E+10	0.00E+00	0	0	0	0	909	1921	1.00E+19	3.00E-05	2.8E+02	1.00E+03
3.00E+04	8.00E+10	0.00E+00	0	0	0	0	940	1954	1.00E+19	3.00E-05	2.8E+02	1.00E+03
3.10E+04	8.00E+10	0.00E+00	0	0	0	0	971	1987	1.00E+19	3.00E-05	2.8E+02	1.00E+03
3.20E+04	8.00E+10	0.00E+00	0	0	0	0	1002	2020	1.00E+19	3.00E-05	2.8E+02	1.00E+03
3.30E+04	8.00E+10	0.00E+00	0	0	0	0	1033	2053	1.00E+19	3.00E-05	2.8E+02	1.00E+03
3.40E+04	8.00E+10	0.00E+00	0	0	0	0	1064	2086	1.00E+19	3.00E-05	2.8E+02	1.00E+03
3.50E+04	8.00E+10	0.00E+00	0	0	0	0	1095	2119	1.00E+19	3.00E-05	2.8E+02	1.00E+03
3.60E+04	8.00E+10	0.00E+00	0	0	0	0	1126	2152	1.00E+19	3.00E-05	2.8E+02	1.00E+03
3.70E+04	8.00E+10	0.00E+00	0	0	0	0	1157	2185	1.00E+19	3.00E-05	2.8E+02	1.00E+03
3.80E+04	8.00E+10	0.00E+00	0	0	0	0	1188	2218	1.00E+19	3.00E-05	2.8E+02	1.00E+03

Typical numerical model!
Analyze this!
Unsensored!

Paraview can **visualize** and
analyze ASPECT output results.



Paraview can record analytical
procedures in **Python**.

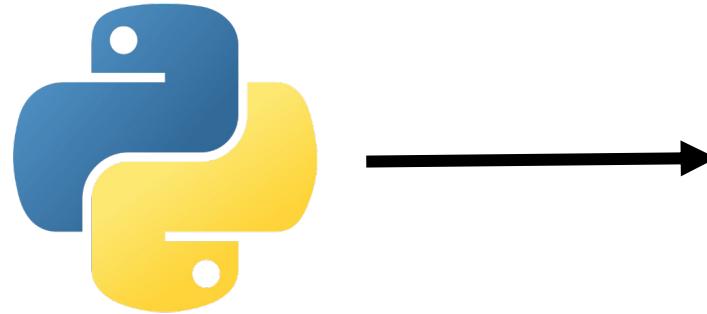


Big data analysis

Model solution files:

solution-00000.0000.vtu
solution-00000.pvtu
solution-00001.0000.vtu
solution-00001.pvtu
solution-00002.0000.vtu
solution-00002.pvtu
solution-00002.0000.vtu
solution-00003.pvtu
solution-00003.0000.vtu
solution-00004.pvtu
solution-00004.0000.vtu
...

the power of *for loops*



Quantify model observation (e.g., continental fragment width)

Numerical modelling

$$\nabla \cdot \mathbf{u} = 0$$

Mass

$$-\nabla \cdot \mu \dot{\varepsilon}(\mathbf{u}) + \nabla P = \rho \mathbf{g}$$

Linear momentum

$$\rho C_p \left(\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) - \nabla \cdot k \nabla T = \rho H$$

Energy

$$\rho = \rho_0 (1 - \alpha (T' - T_0'))$$

Equation of state

Boussinesq Approximation

- The compressional Navier-Stokes equations are highly non-linear and can be unstable.
- $\frac{\Delta\rho}{\rho} \ll 1$, density variation not considered except in the buoyancy term ρg .
- Density is loosely related to temperature.

$$\rho = \rho_0(1 - \alpha(T' - T_0'))$$

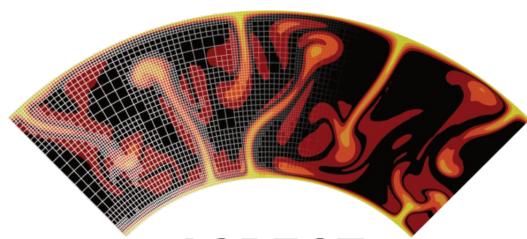
$\alpha = -\frac{1}{\rho_0} \left(\frac{\partial \rho}{\partial T}\right)_P$ is the thermal expansivity.

Infinite Prandtl number

- $Pr = \frac{\text{momentum diffusivity}}{\text{thermal diffusivity}} = 10^{25}$ for Earth's mantle
- In physical terms, infinite Pr means that heat conduction is very slow compared to momentum diffusion.

Numerical modelling

Initial physical
model (pre-rift)



ASPECT



Forward model (in time)

$$\nabla \cdot \mathbf{u} = 0$$

$$-\nabla \cdot \mu \dot{\varepsilon}(\mathbf{u}) + \nabla P = \rho \mathbf{g}$$

$$\rho C_p \left(\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) - \nabla \cdot k \nabla T = \rho H$$

$$\rho = \rho_0 (1 - \alpha (T' - T_0'))$$

Model
results

$$\mathbf{v} \cdot \mathbf{u}$$

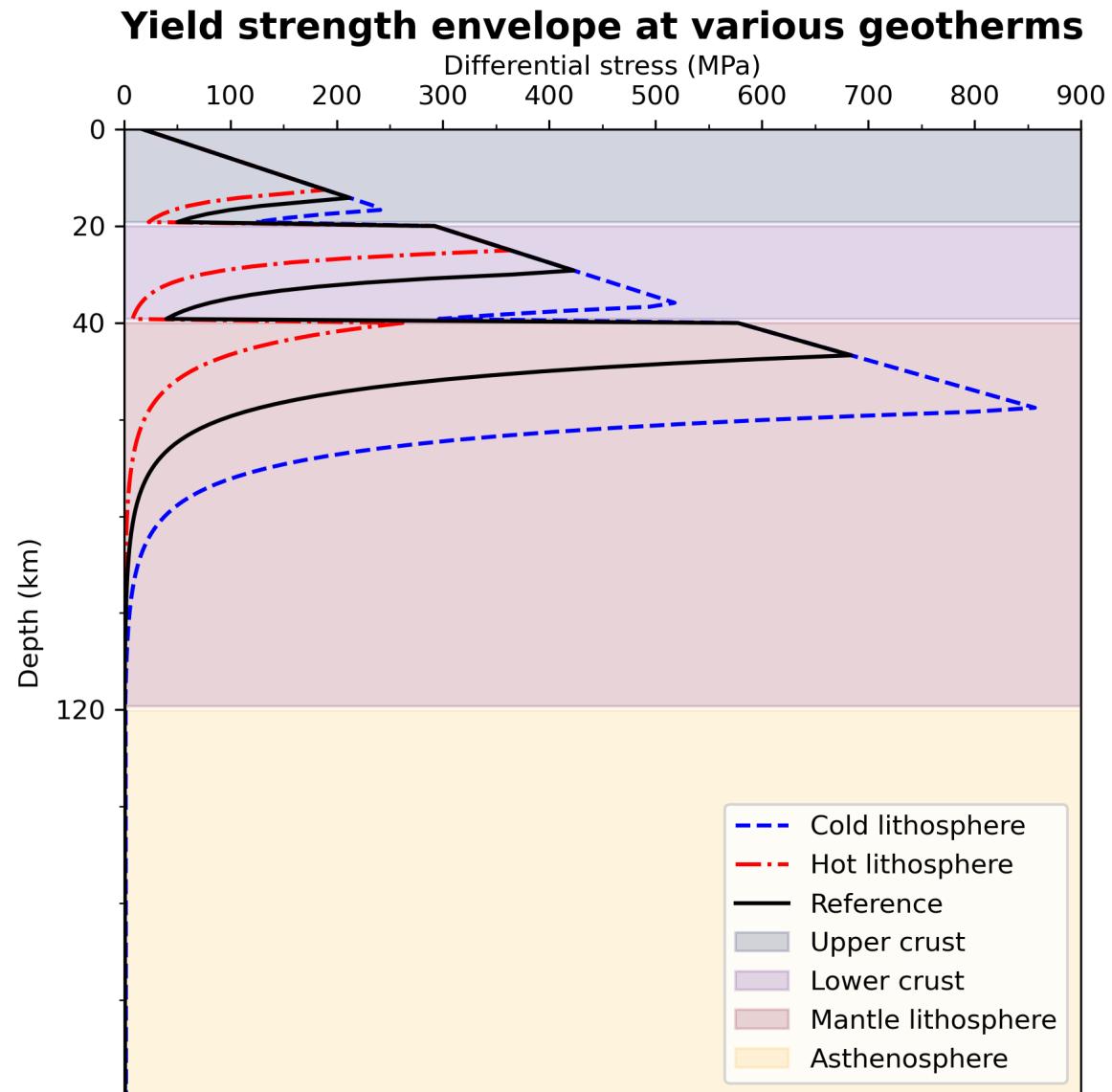
$$-\nabla \cdot \mu \dot{\varepsilon}(\mathbf{u})$$

$$\rho C_p \left(\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) - \nabla \cdot k \nabla T$$

$$\rho = \rho_0 (1 -$$

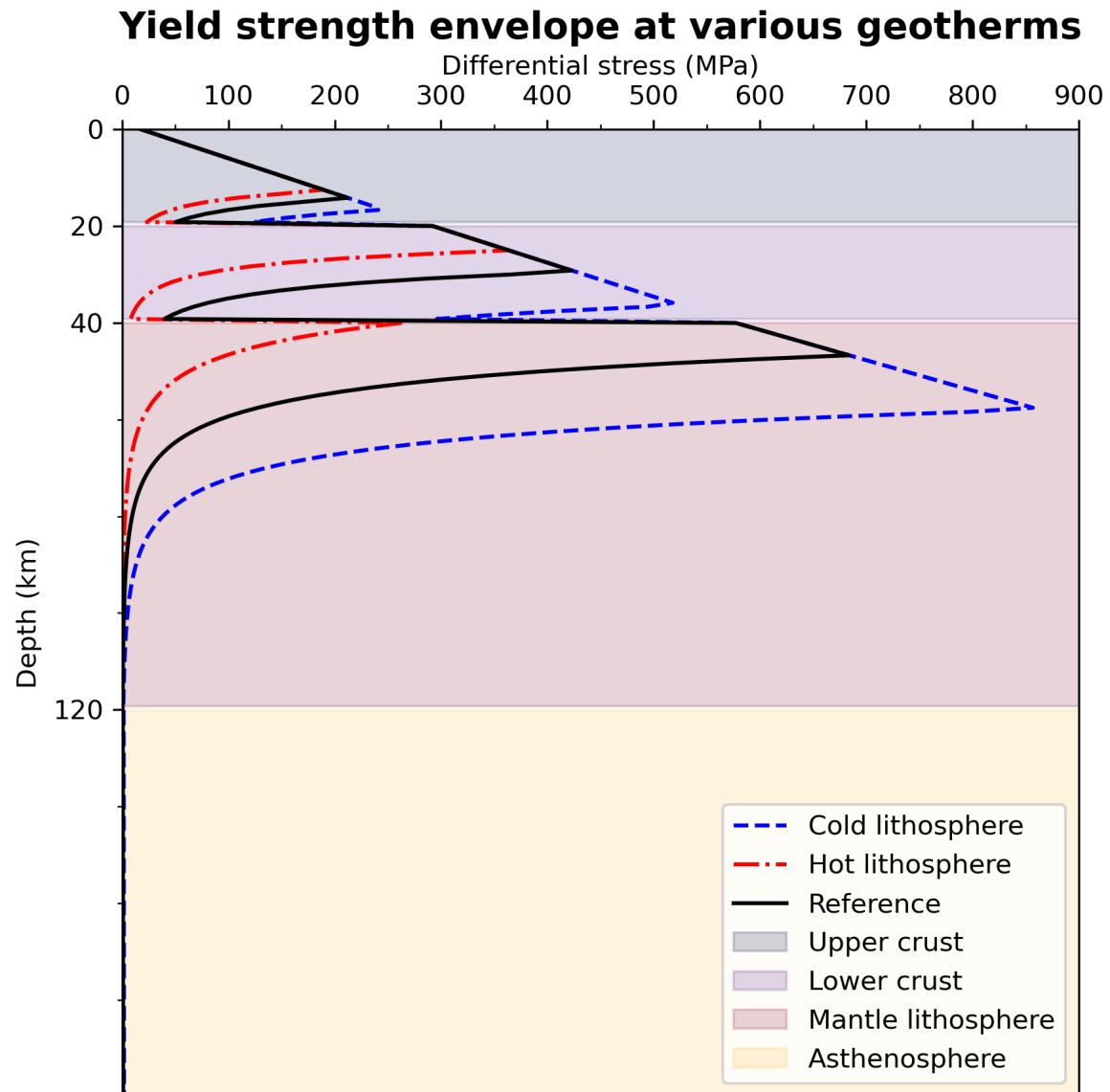
Initial geotherm

- Initial temperature profile (i.e., geotherm) affect the rheology of rocks.
- A **hotter** geotherm leads to a more ductile lithosphere.
- A **colder** geotherm leads to a more brittle lithosphere.



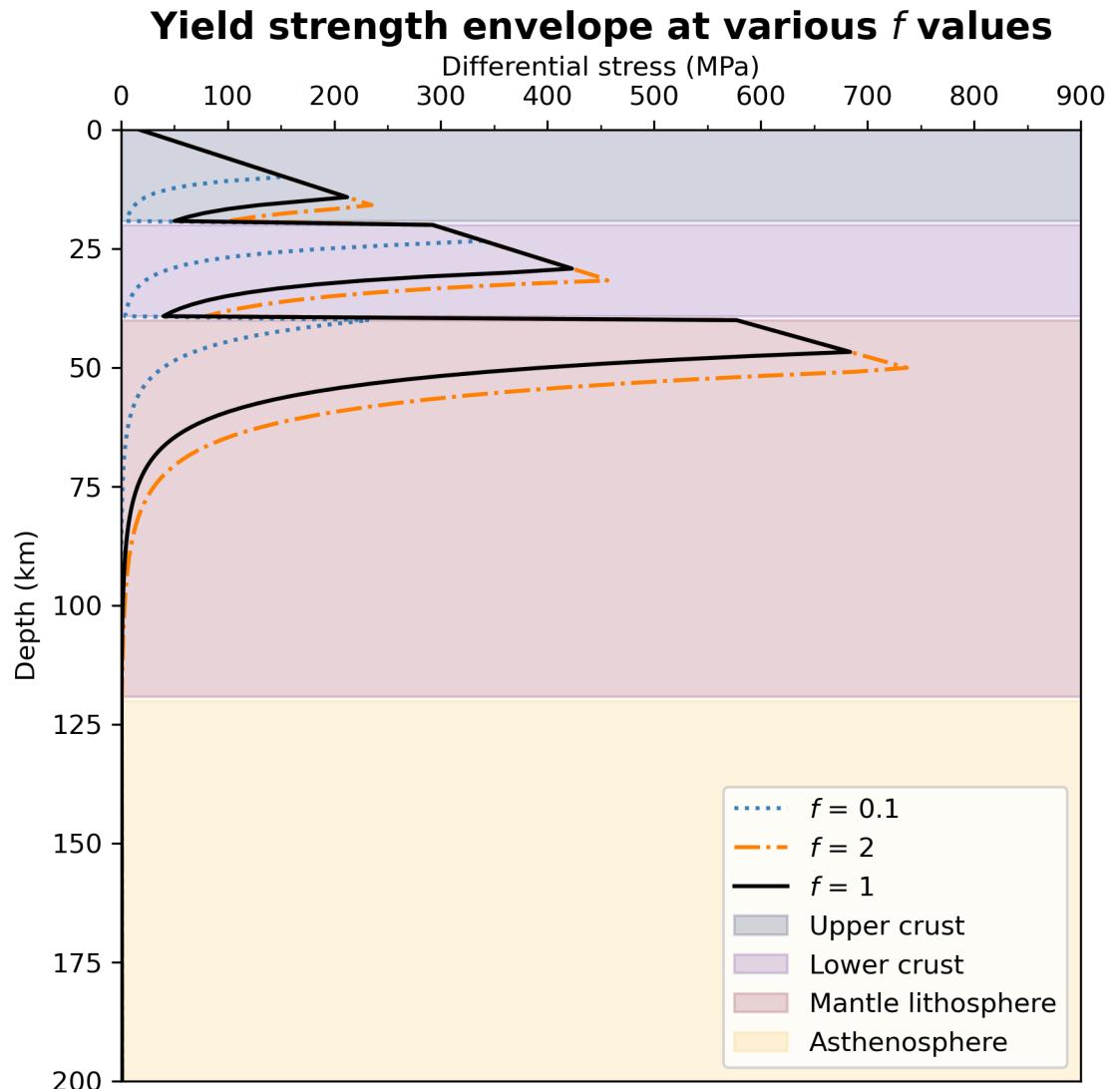
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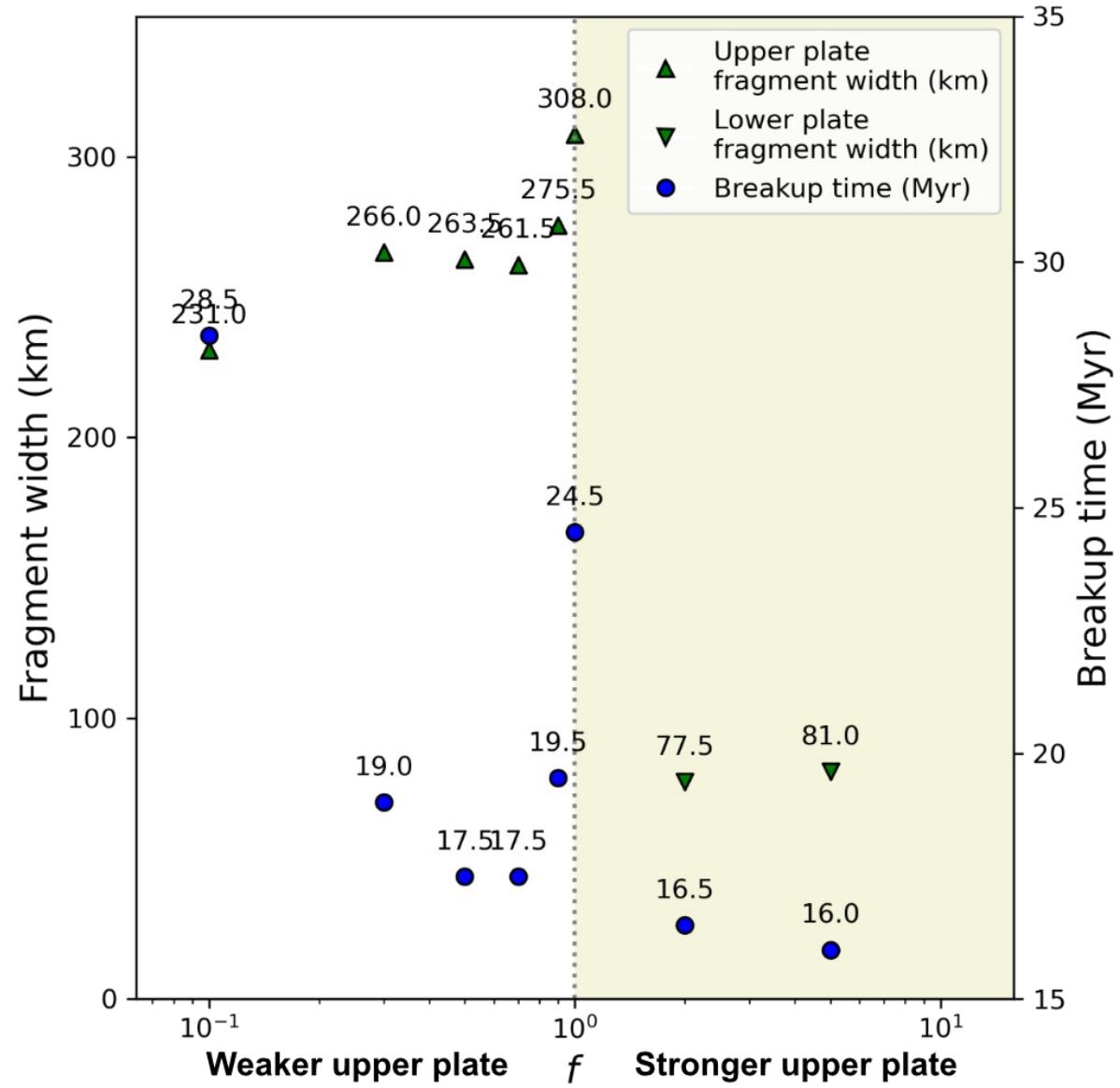
Strength parameter

- The strength parameter changes the depth of brittle-ductile transition (only for the upper plate margin).



Strength parameter

- The strength parameter changes the depth of brittle-ductile transition for the upper plate.
- When $f > 1$, the fragment formed instead in the weaker lower plate.
- When $f \leq 0.1$, the ductile lithosphere prolongs the strain localization process and the final breakup.



Crustal v. mantle lithospheric inheritance

- Both crustal and mantle lithospheric inheritance exert tectonic influence during the fragment formation process.

