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

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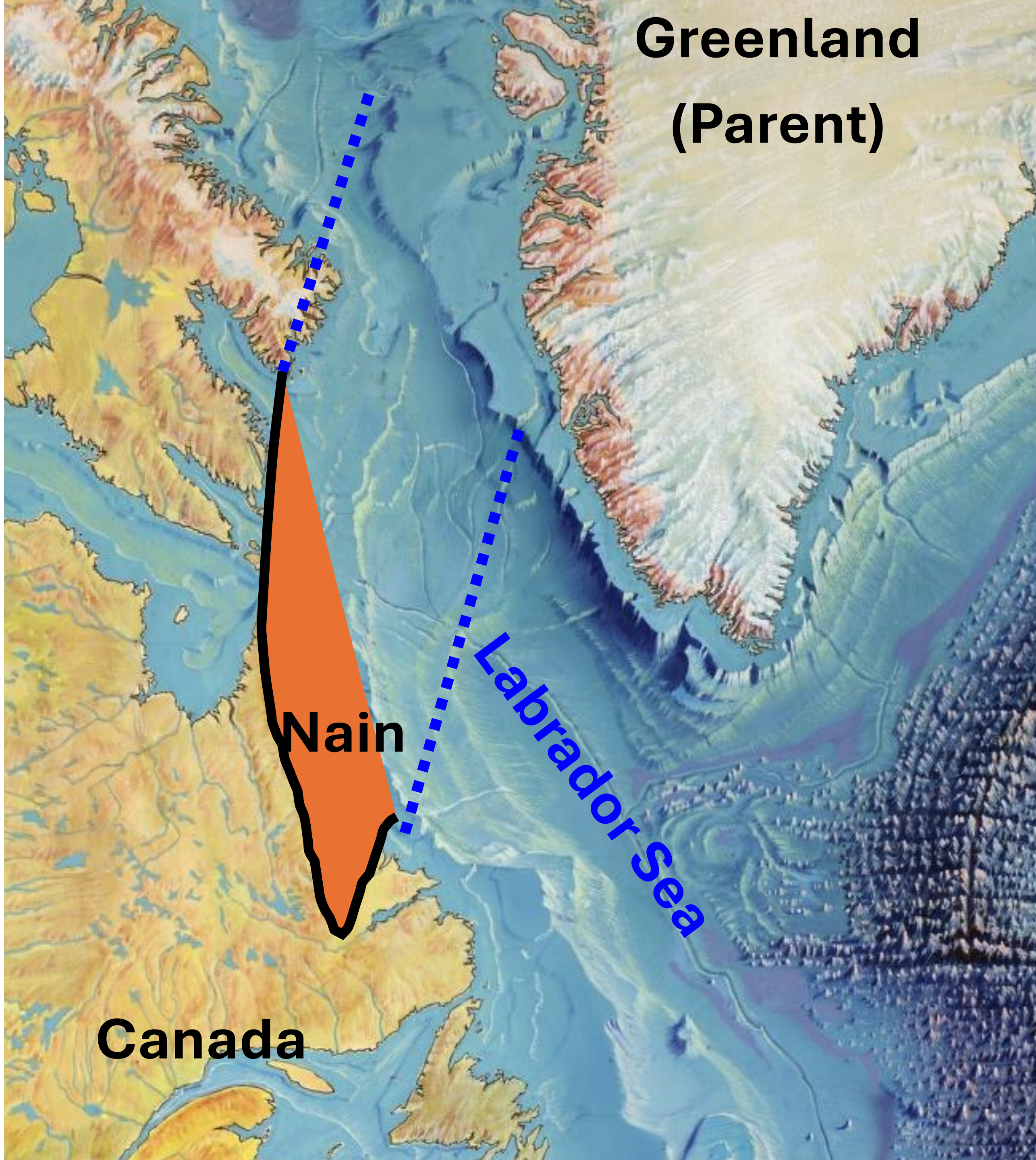
Introduction

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

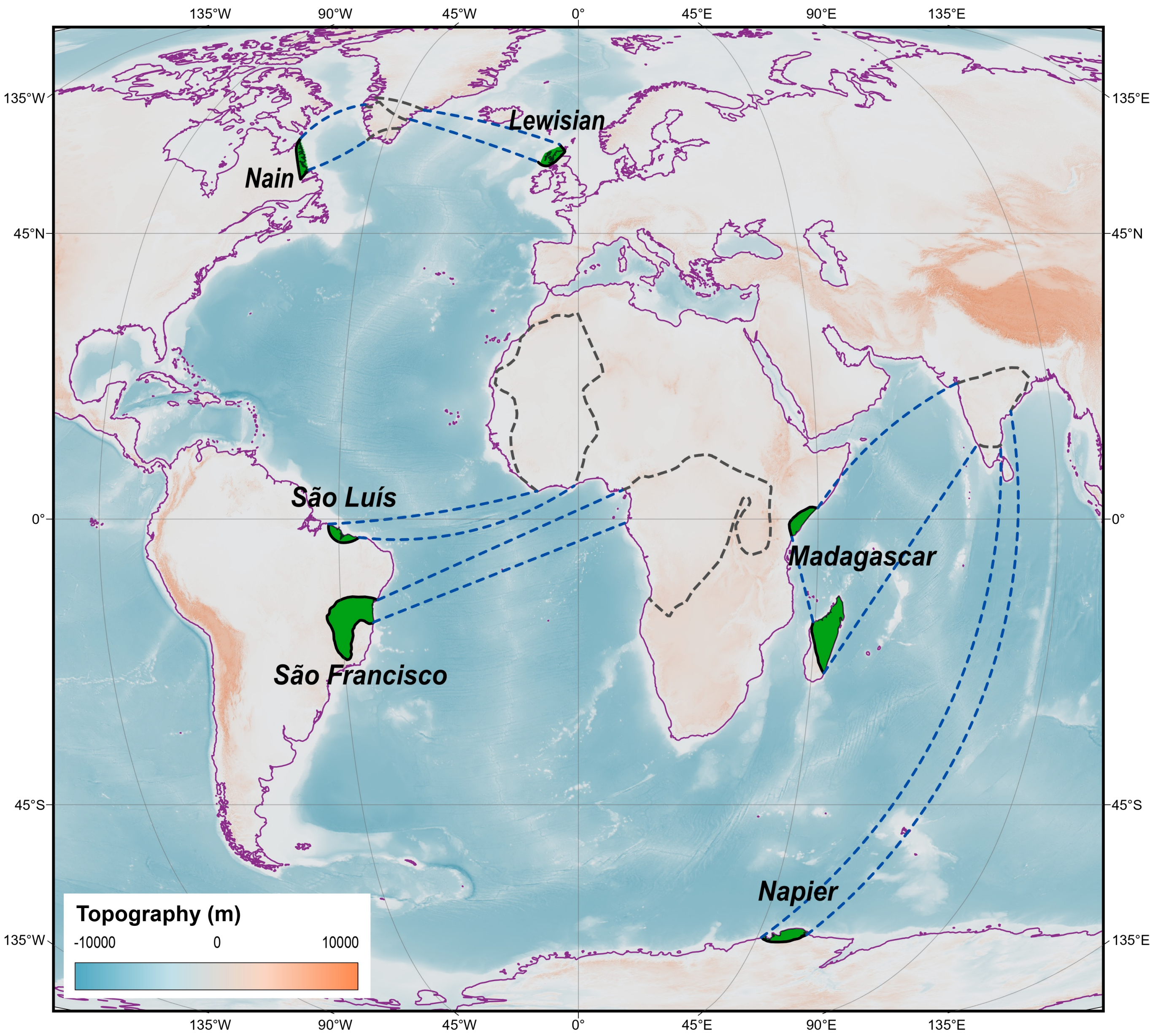
South Atlantic Ocean:

- São Luís Craton
- São Francisco Craton

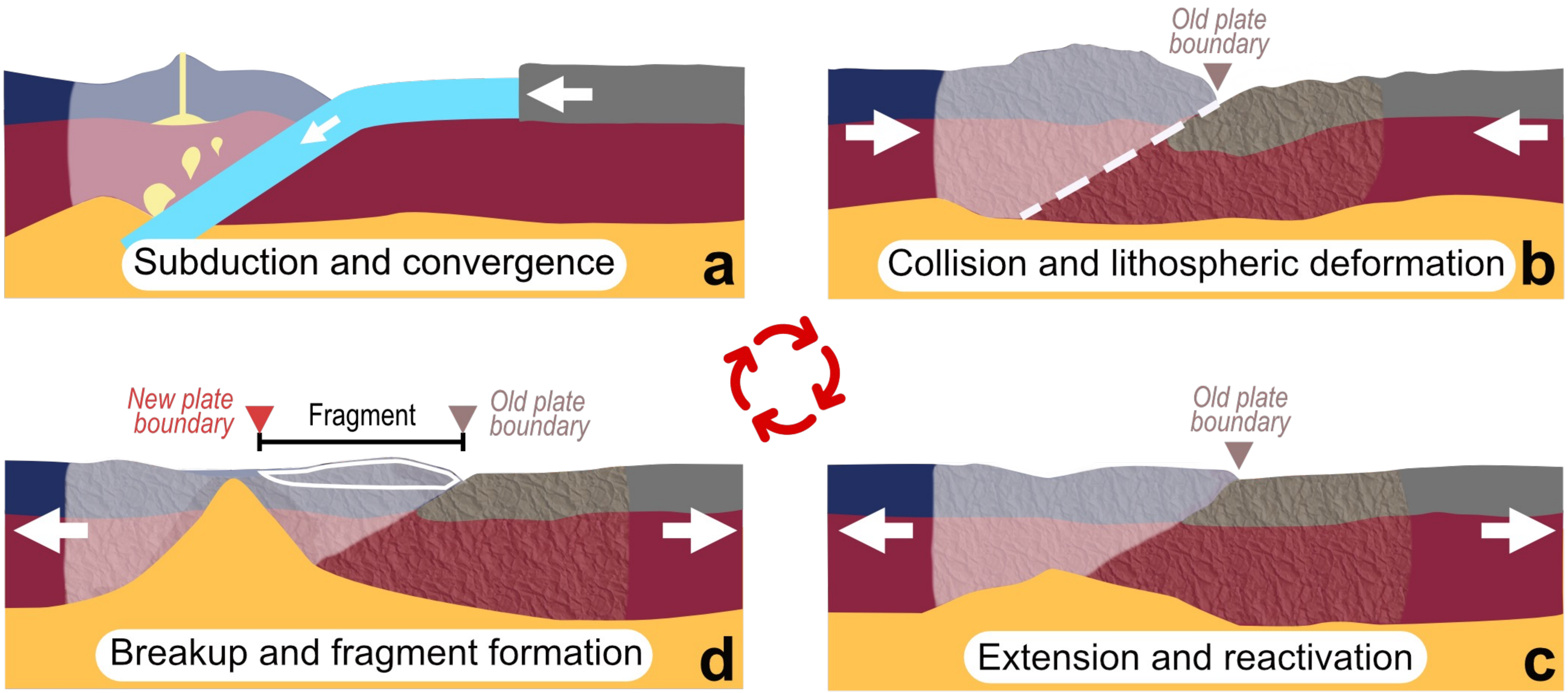
Indian Ocean:

- Madagascar
- Napier Complex

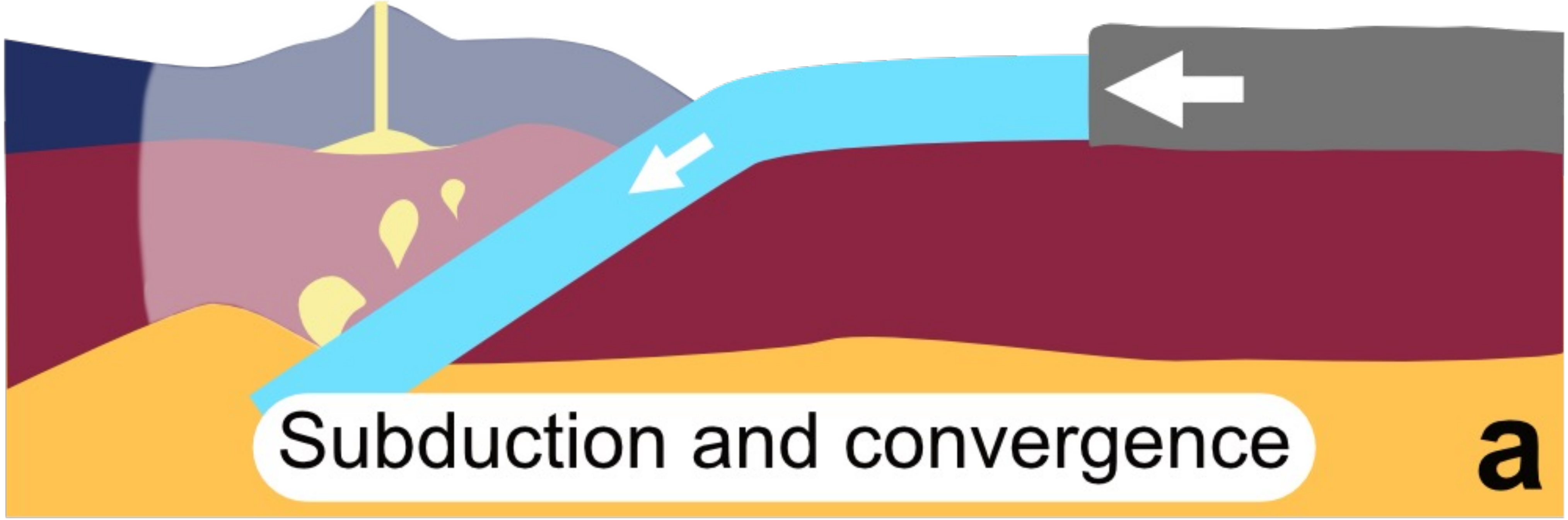
How did they form?



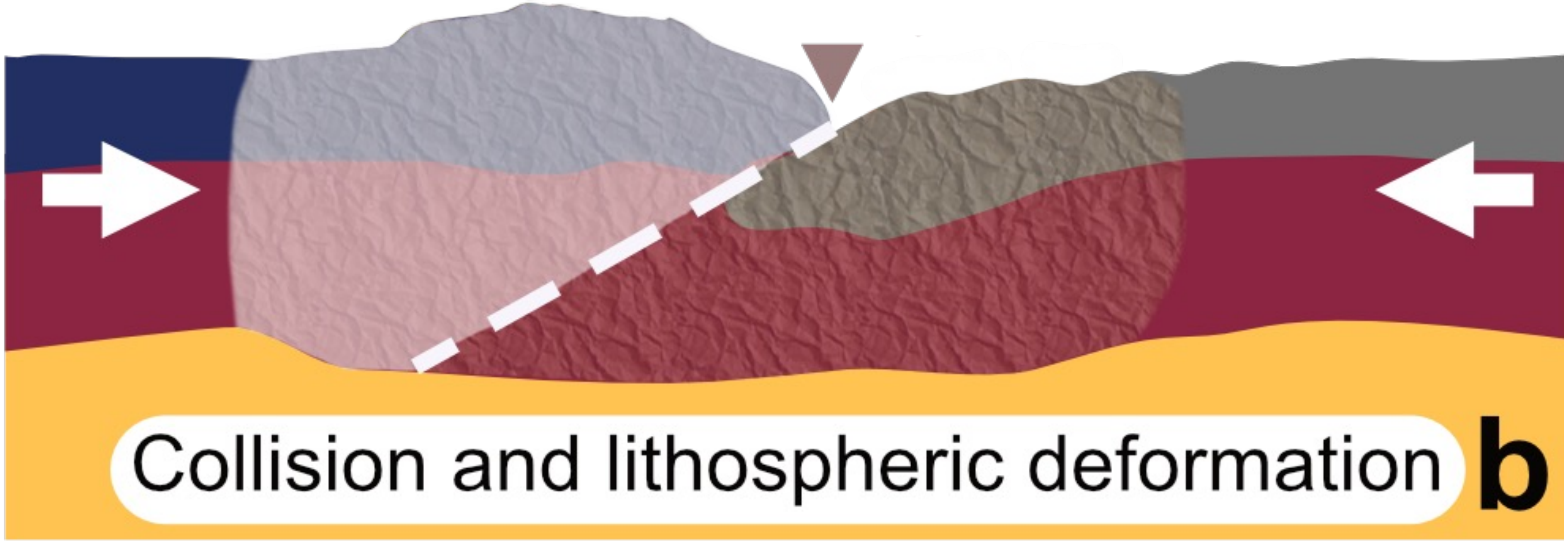
Wilson Cycle



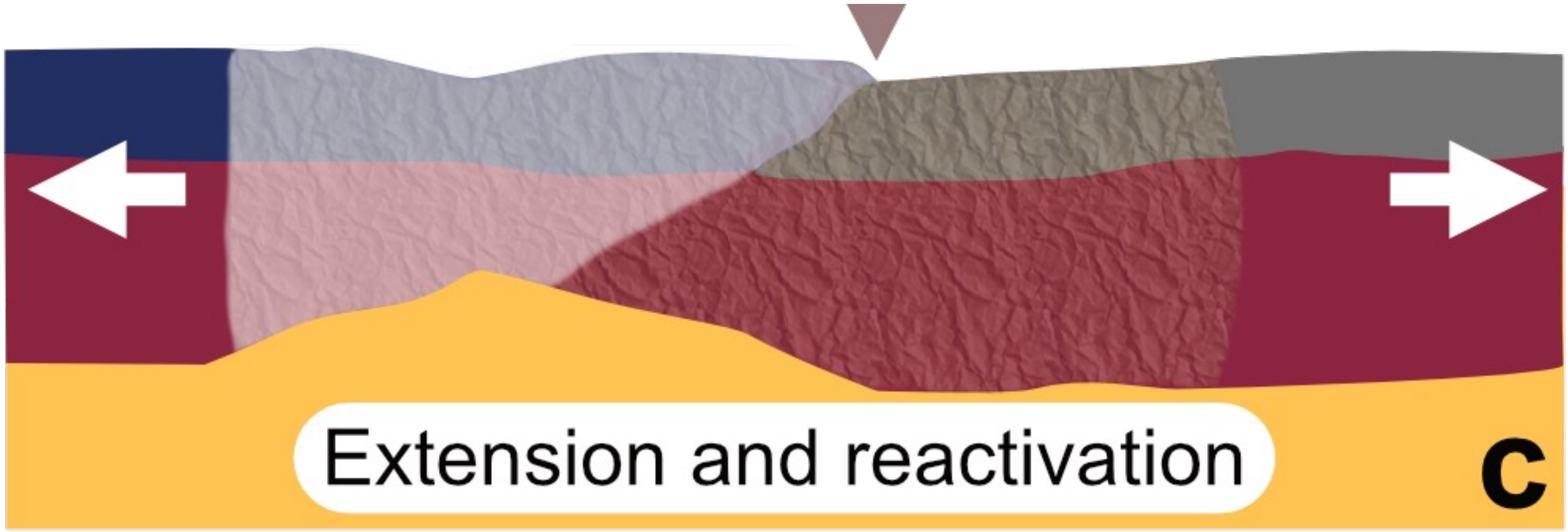
Convergence



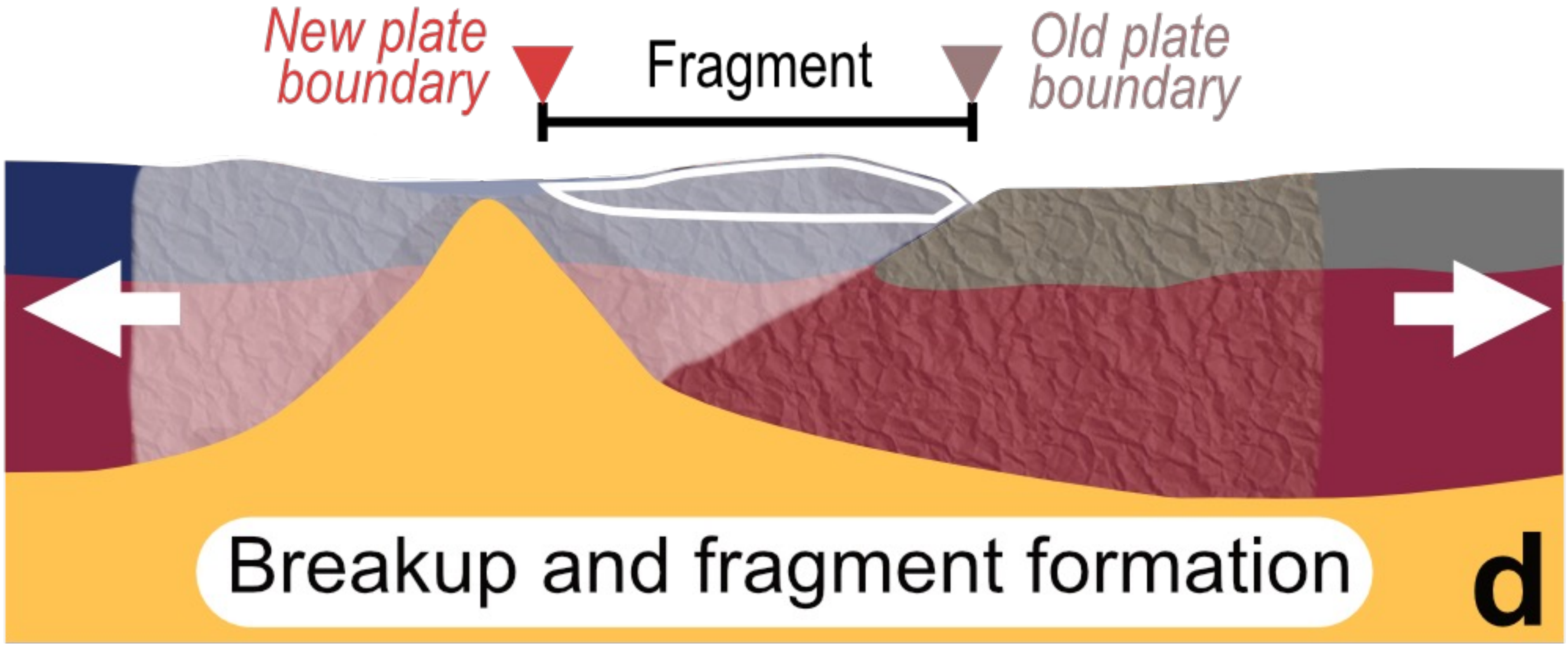
Convergence



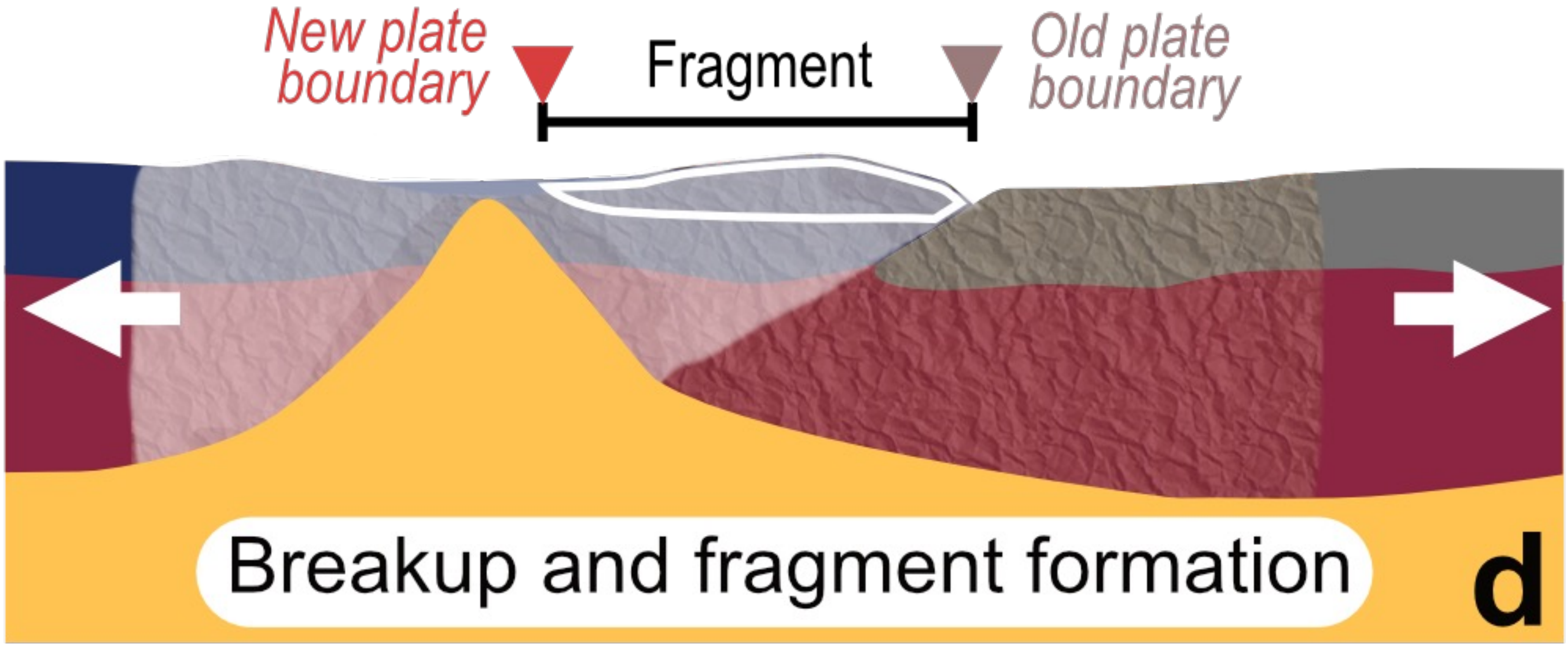
Divergence



Divergence


New plate boundary
Fragment
Old plate boundary
Breakup and fragment formation
d

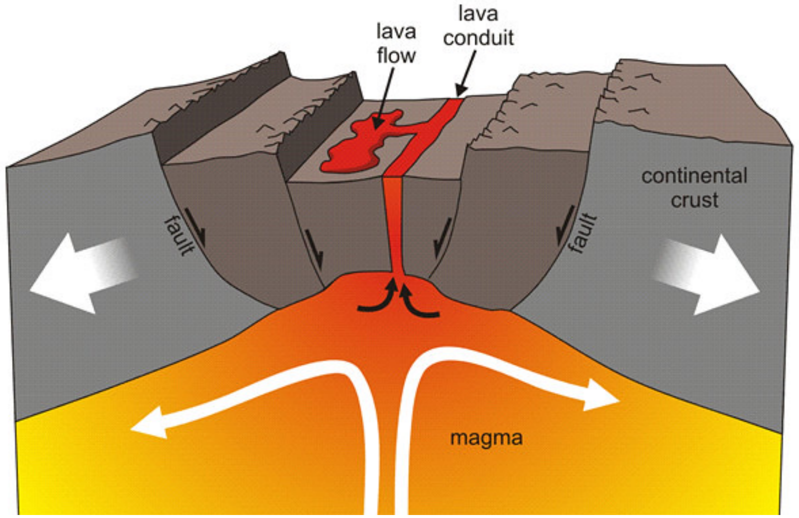
Objectives



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

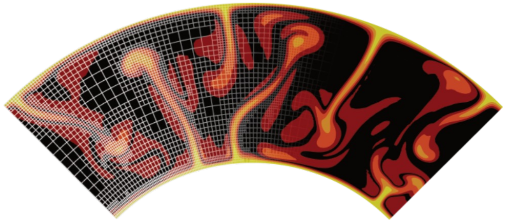
Methods

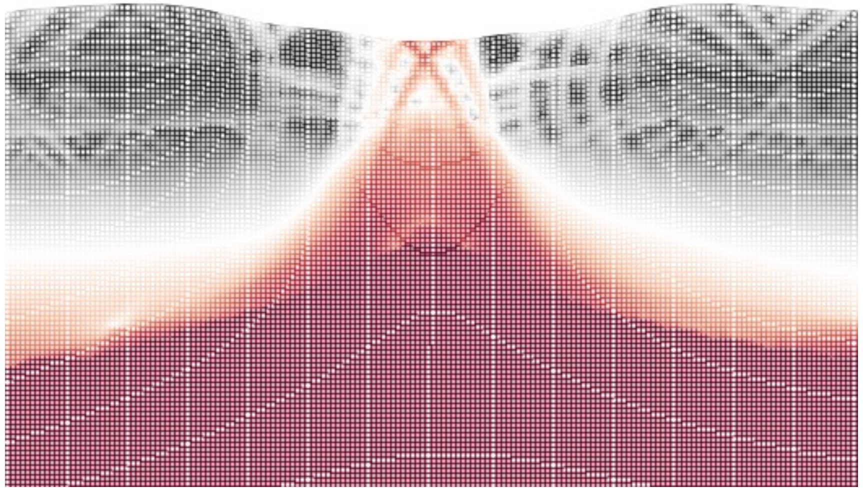
Numerical modelling



Tectonic process

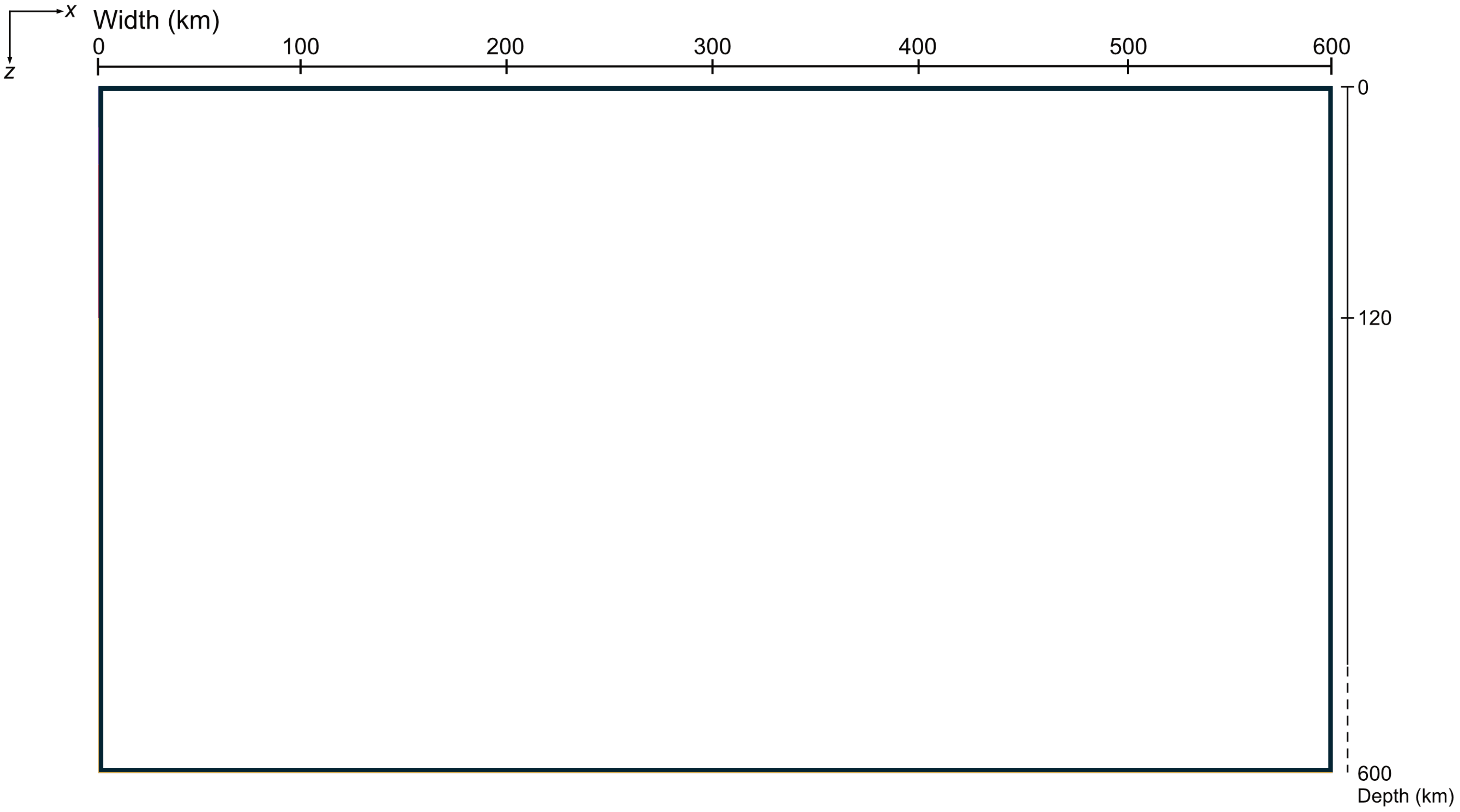
Discretize



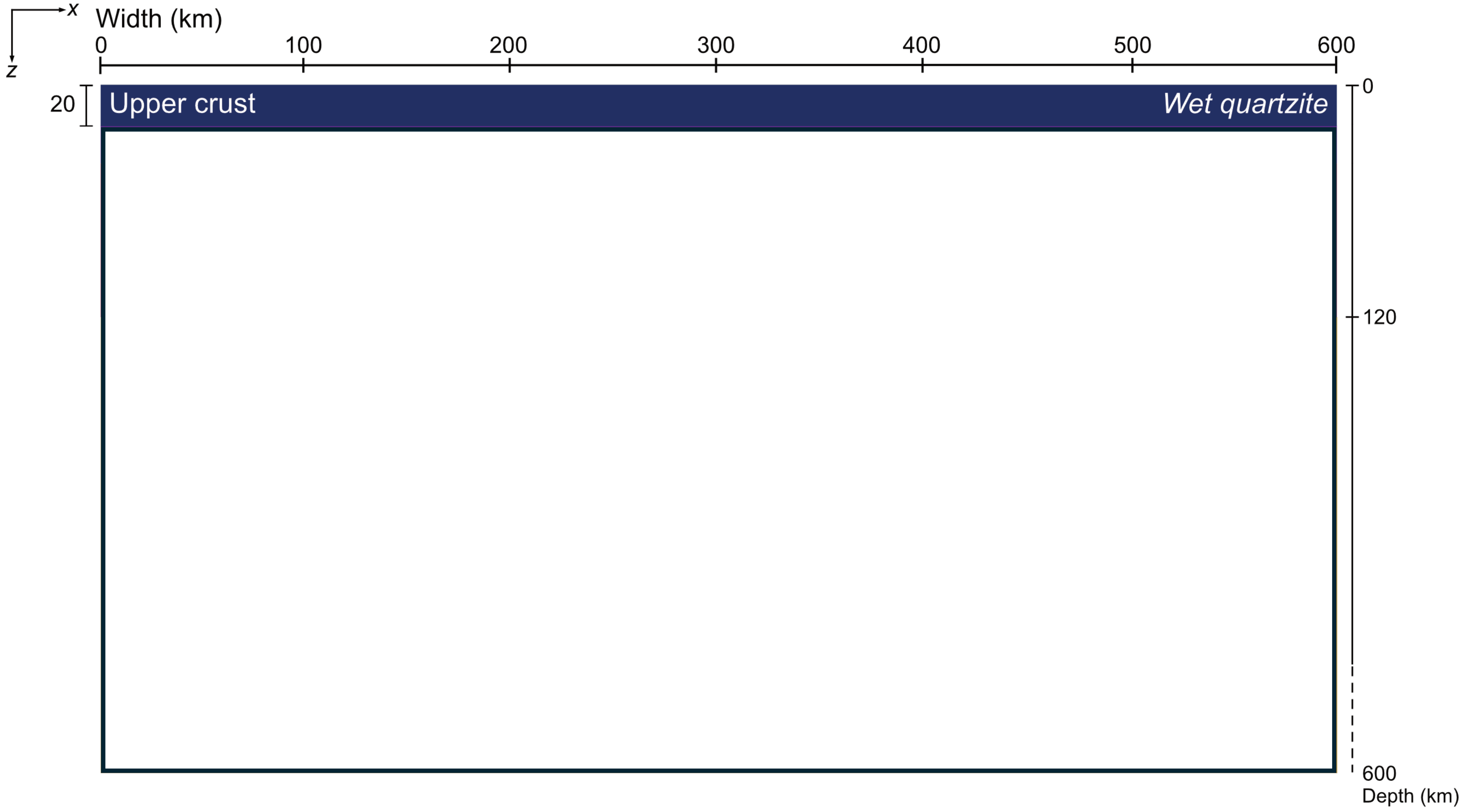


Numerical models

Model setup

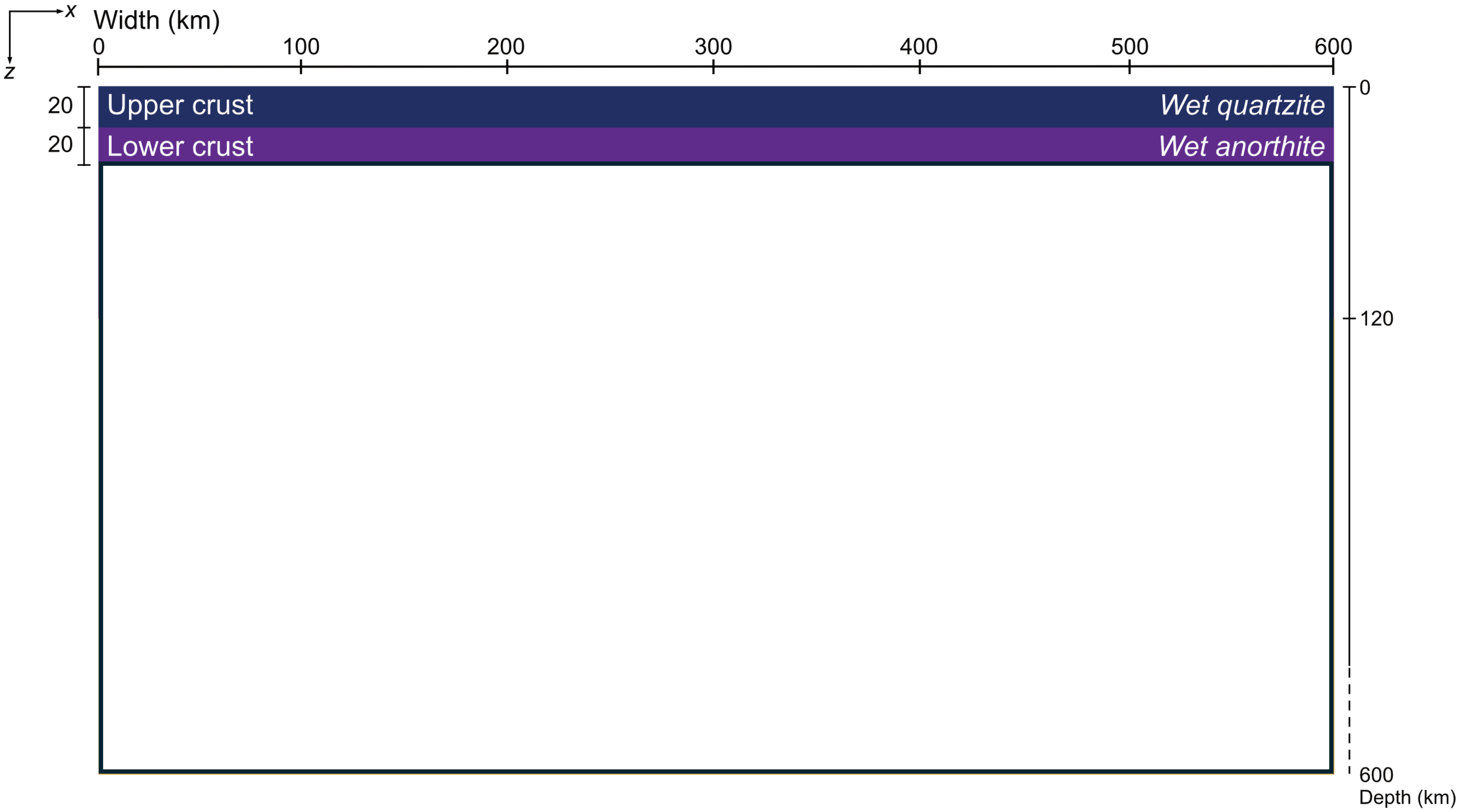


Model setup



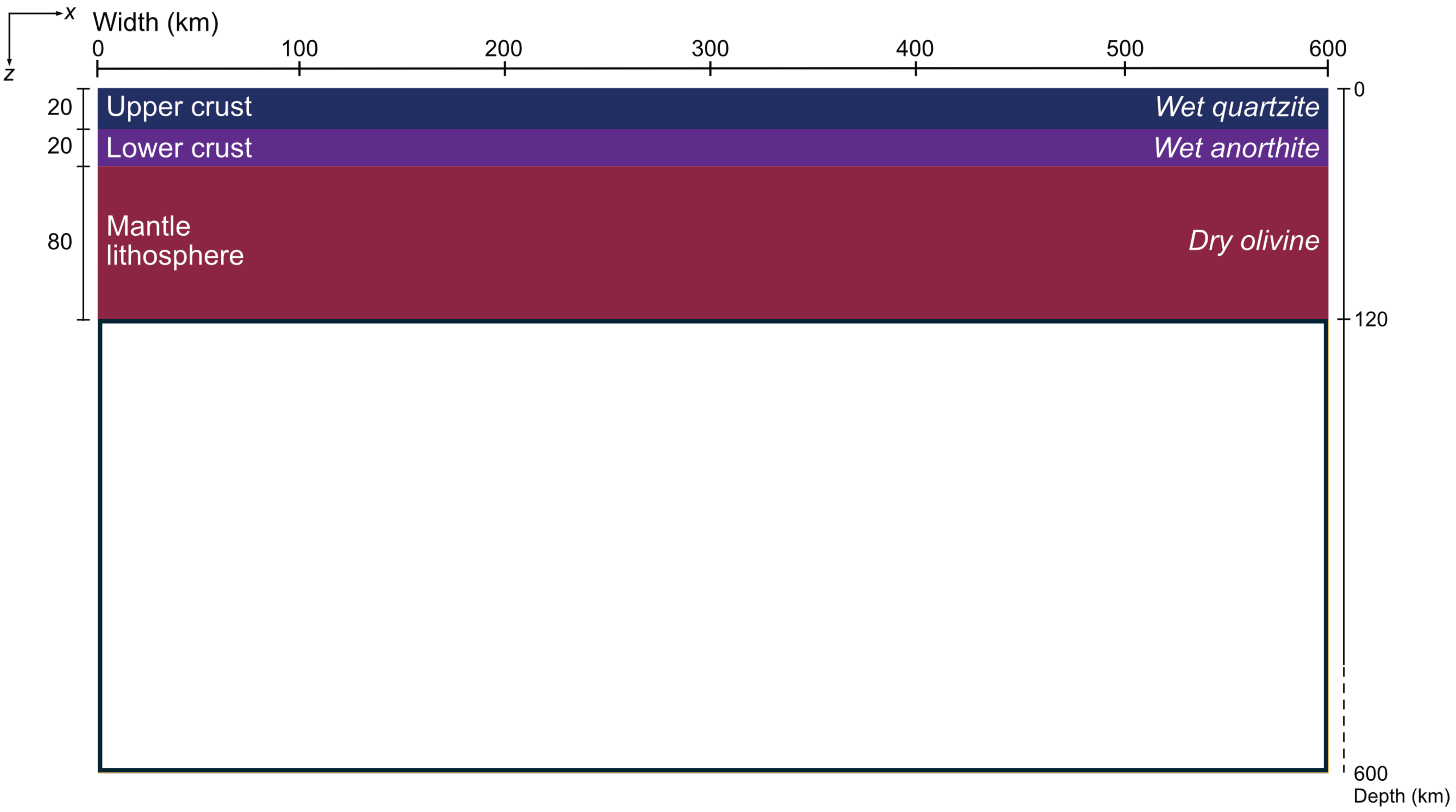
x
z
Width (km)
0
100
200
300
400
500
600
20
Upper crust
Wet quartzite
0
120
600
Depth (km)

Model setup



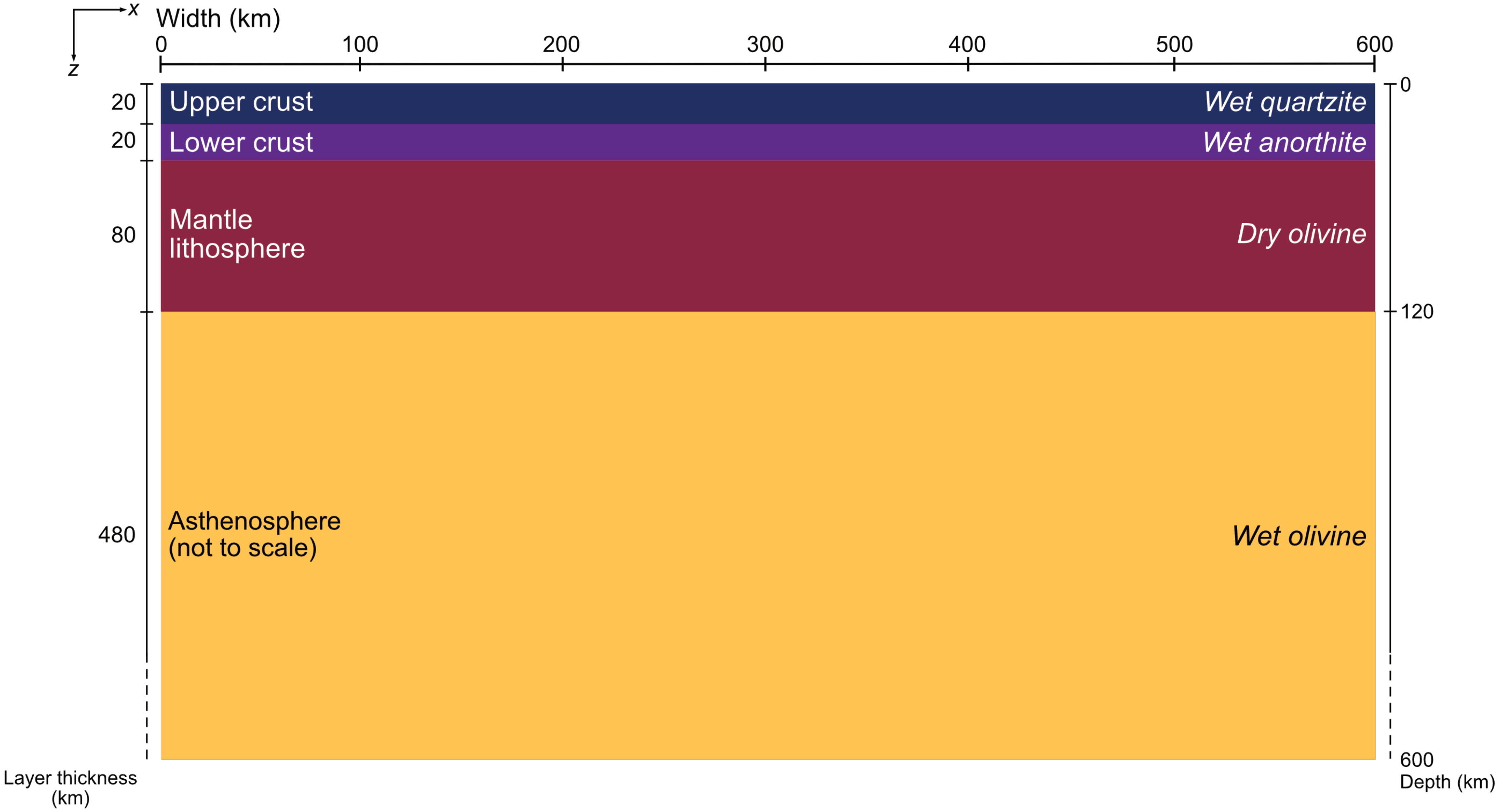
x
z
Width (km)
0
100
200
300
400
500
600
20
20
Upper crust
Wet quartzite
Lower crust
Wet anorthite
0
120
600
Depth (km)

Model setup

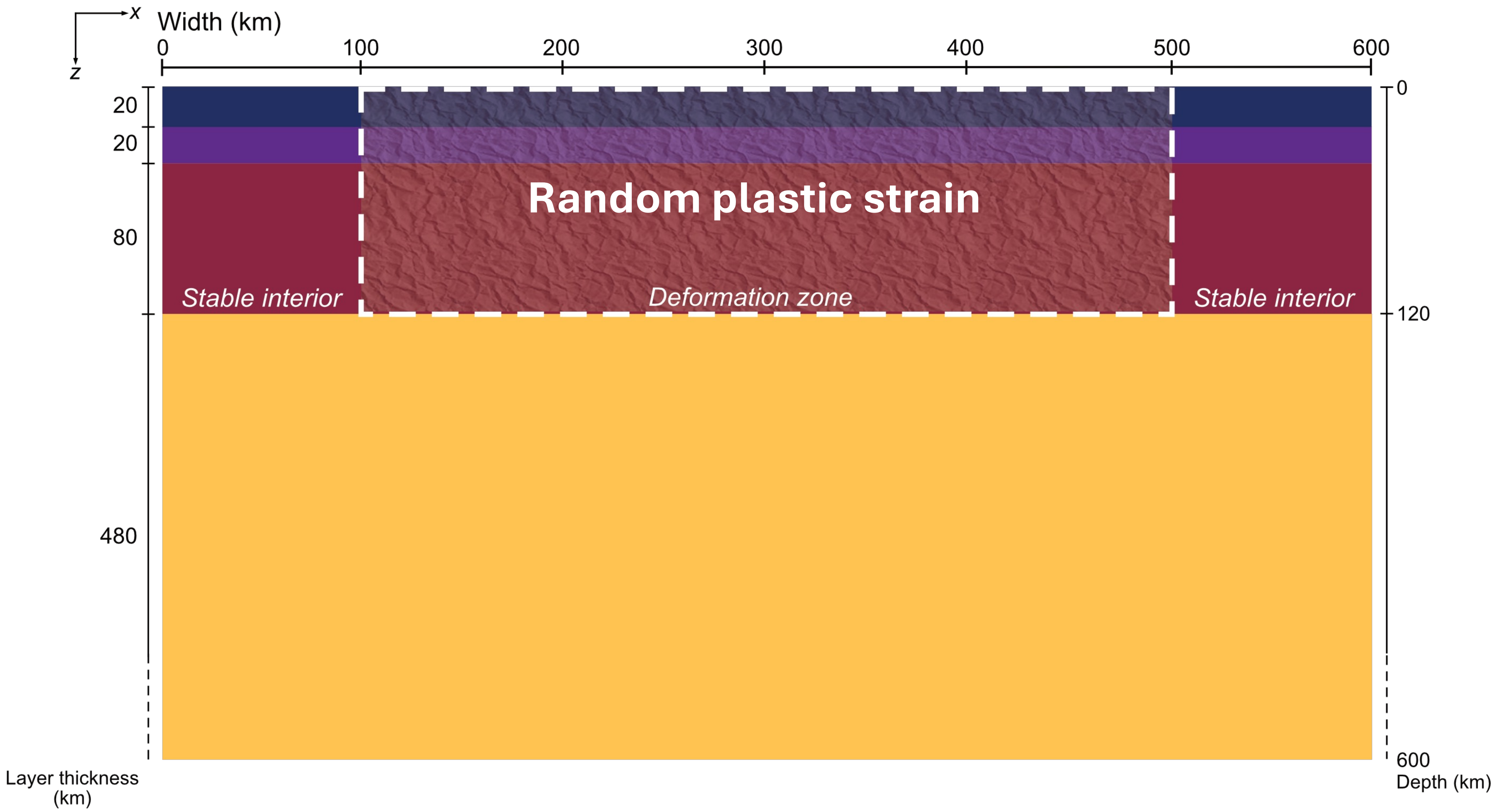


x
z
Width (km)
0
100
200
300
400
500
600
20
20
80
Upper crust
Wet quartzite
Lower crust
Wet anorthite
Mantle
lithosphere
Dry olivine
0
120
600
Depth (km)

Model setup

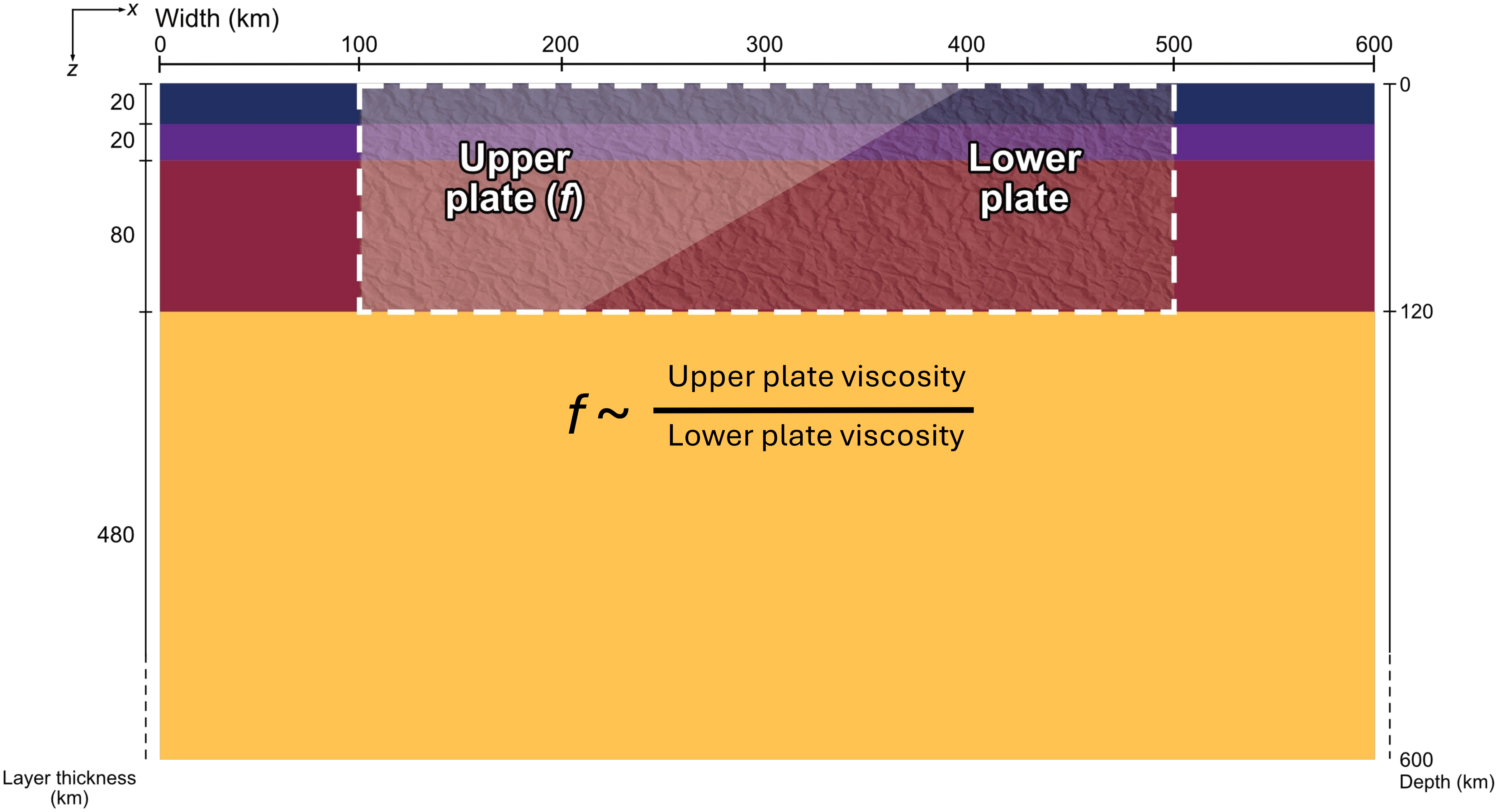

x
z
Width (km)
0
100
200
300
400
500
600
20
20
80
480
Upper crust
Wet quartzite
Lower crust
Wet anorthite
Mantle
lithosphere
Dry olivine
Asthenosphere
(not to scale)
Wet olivine
0
120
600
Layer thickness
(km)
Depth (km)

Model setup



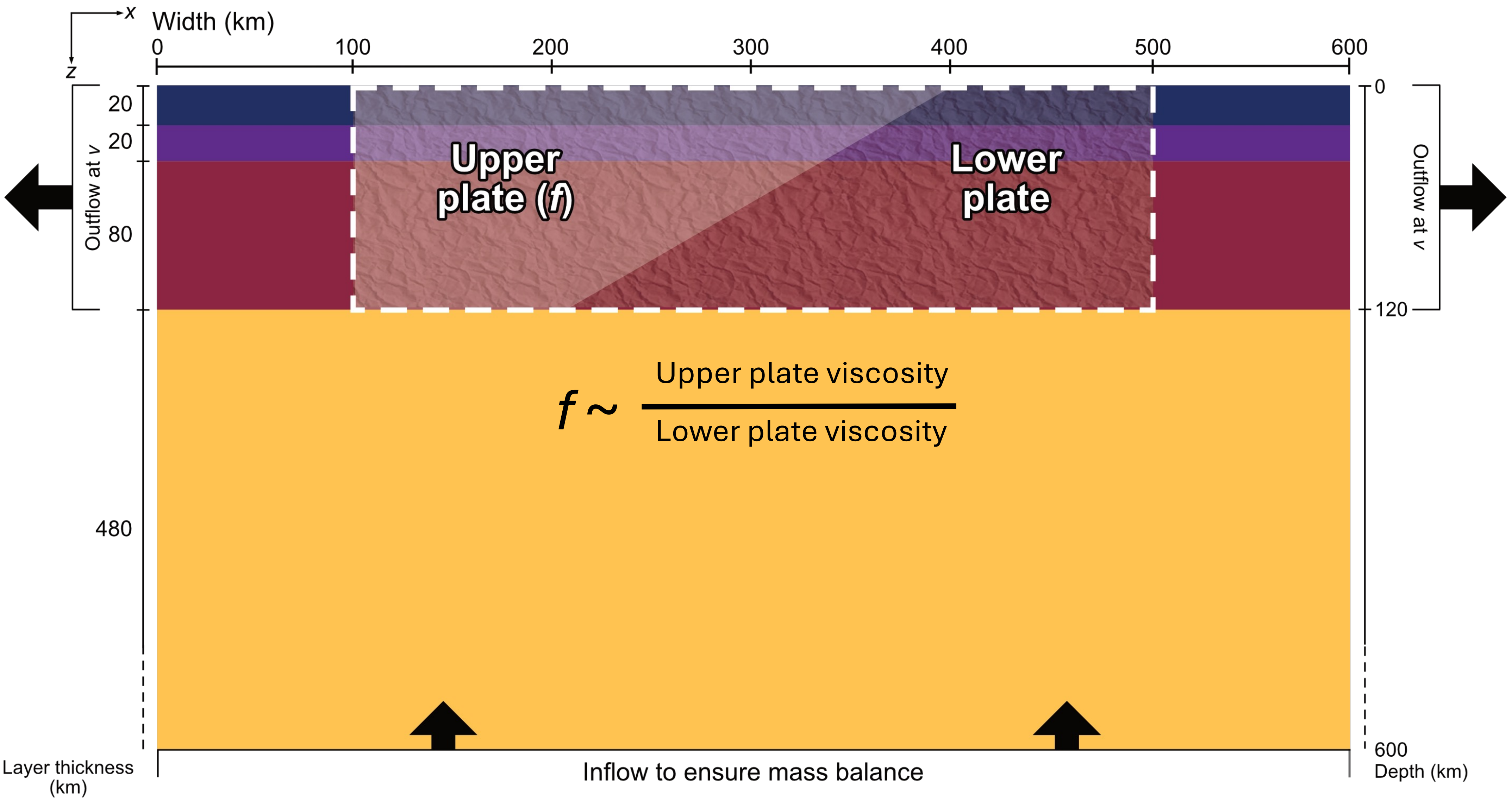
x
z
Width (km)
0
100
200
300
400
500
600
20
20
80
480
Layer thickness (km)
0
120
600
Depth (km)
Random plastic strain
Stable interior
Deformation zone
Stable interior

Model setup



Width (km)
0
100
200
300
400
500
600
x
z
20
20
80
480
Layer thickness (km)
0
120
600
Depth (km)
Upper plate (f)
Lower plate
f ~ Upper plate viscosity / Lower plate viscosity

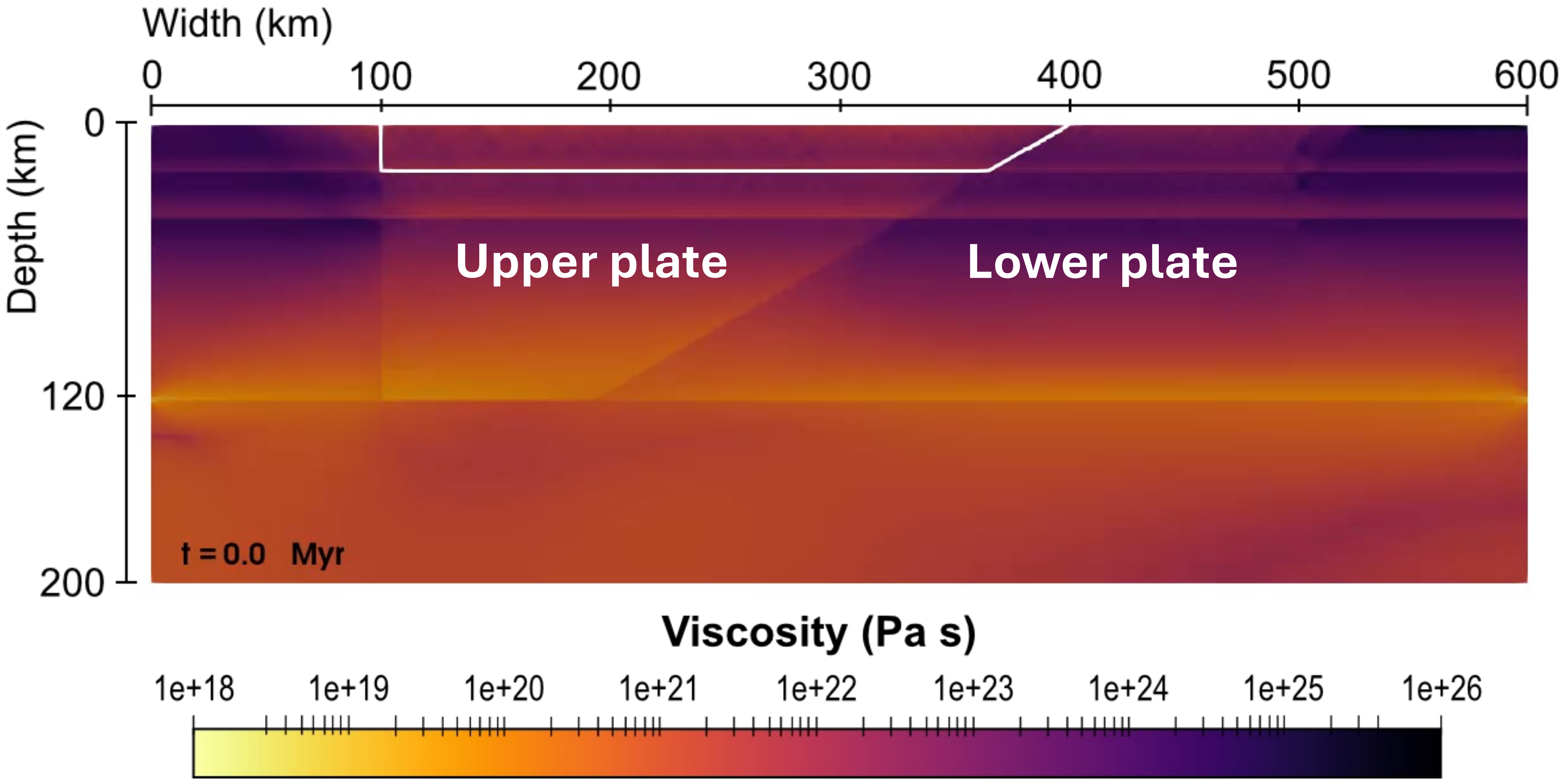
Model setup



x
z
Width (km)
0
100
200
300
400
500
600
20
20
80
480
Outflow at v
Upper plate (f)
Lower plate
Outflow at v
0
120
600
Depth (km)
$f \sim \frac{\text{Upper plate viscosity}}{\text{Lower plate viscosity}}$
Layer thickness (km)
Inflow to ensure mass balance

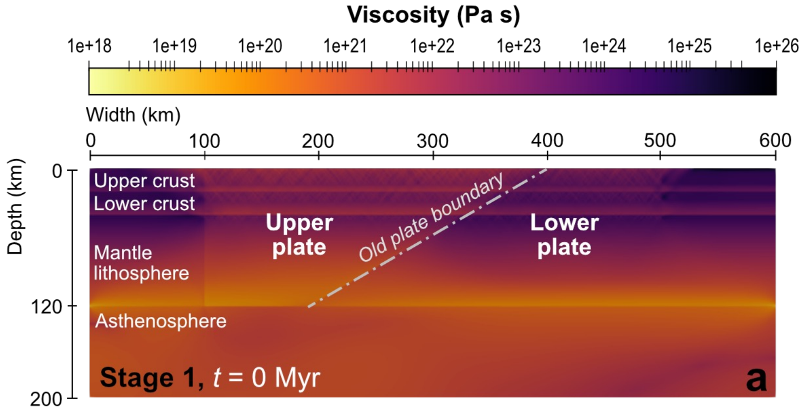
Results

Reference model



Reference model

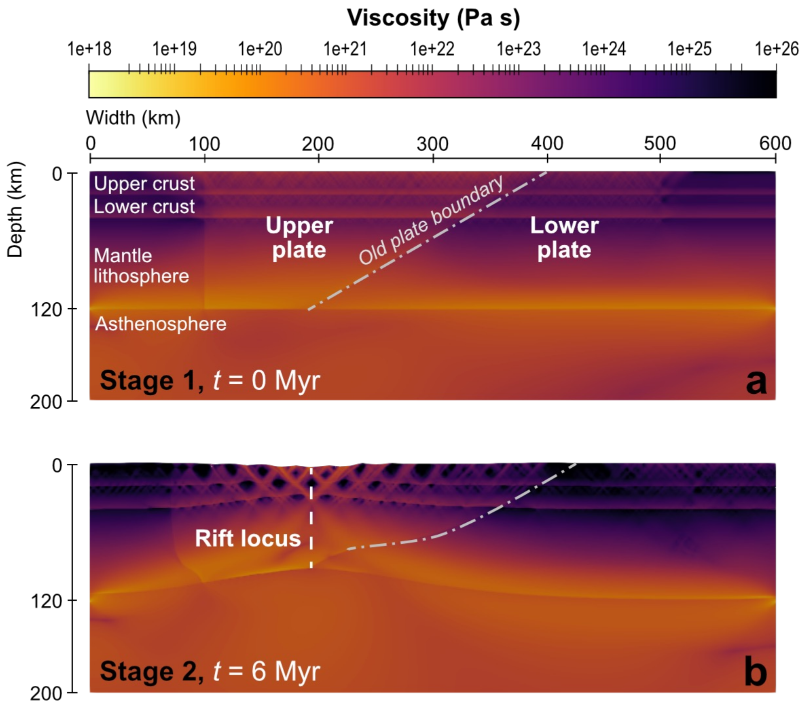
Stage 1: widespread faulting



Reference model

Stage 1: widespread faulting

Stage 2: strain localization

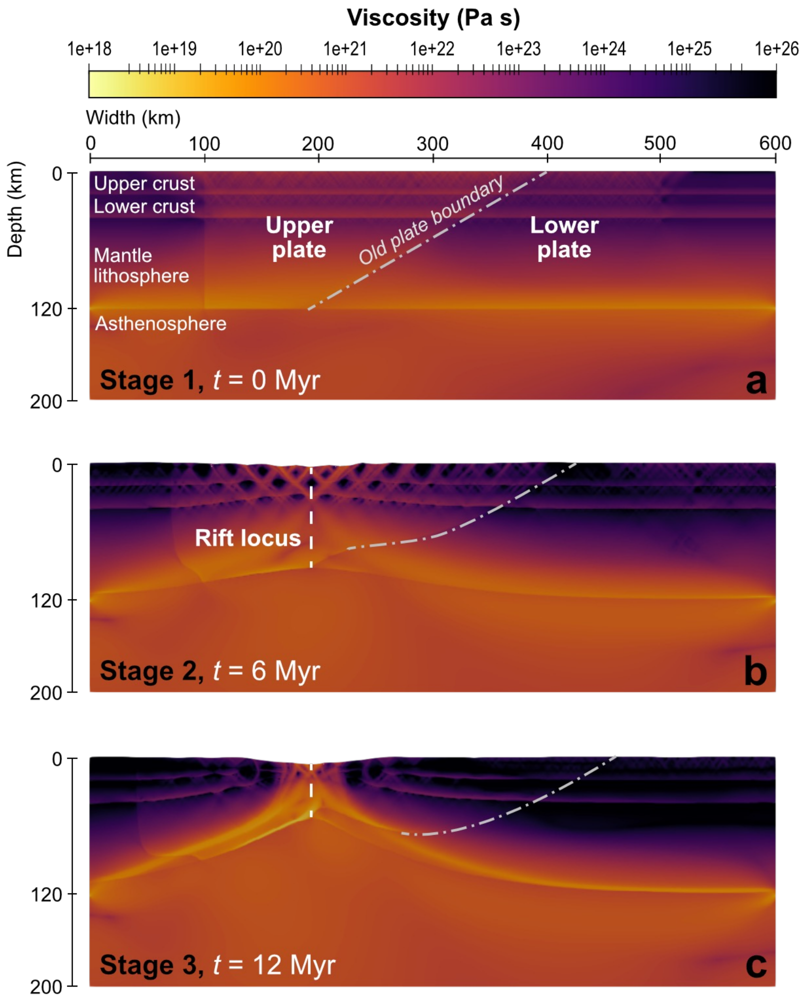


Reference model

Stage 1: widespread faulting

Stage 2: strain localization

Stage 3: lithospheric thinning



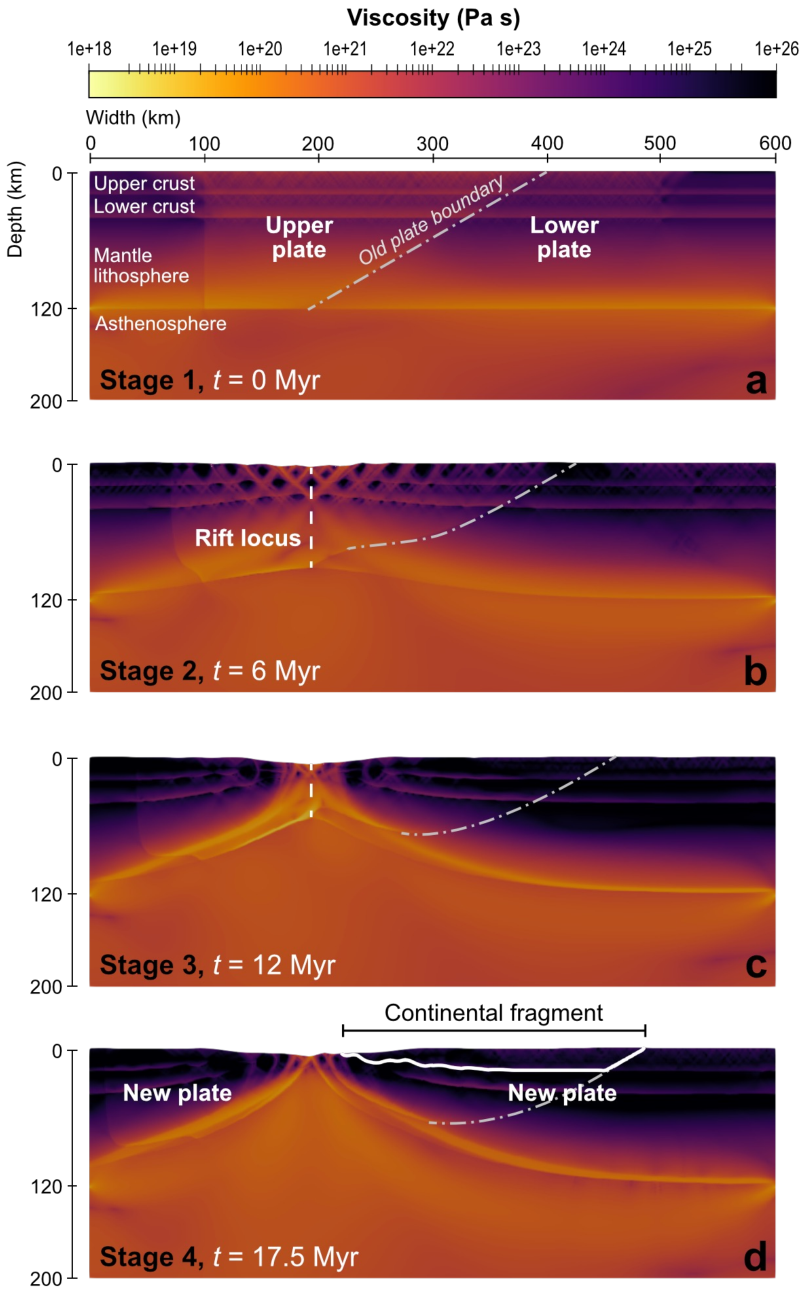
Reference model

Stage 1: widespread faulting

Stage 2: strain localization

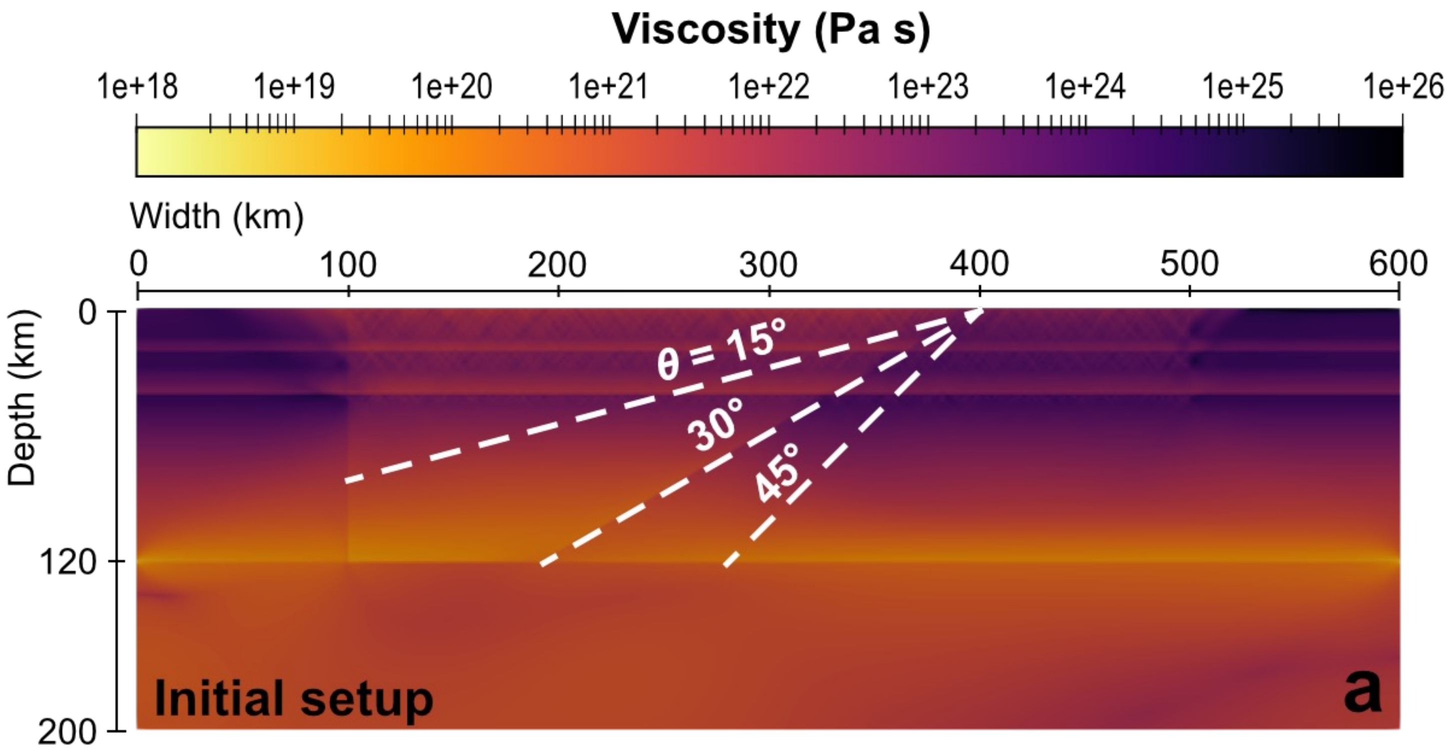
Stage 3: lithospheric thinning

Stage 4: continental breakup



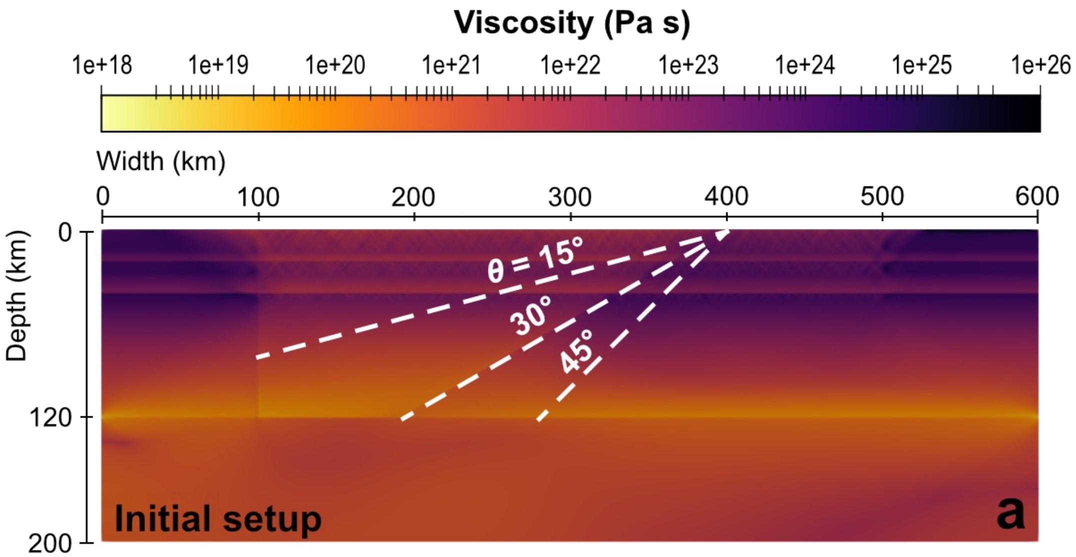
Parameter testing

Parameter testing – dip angle



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

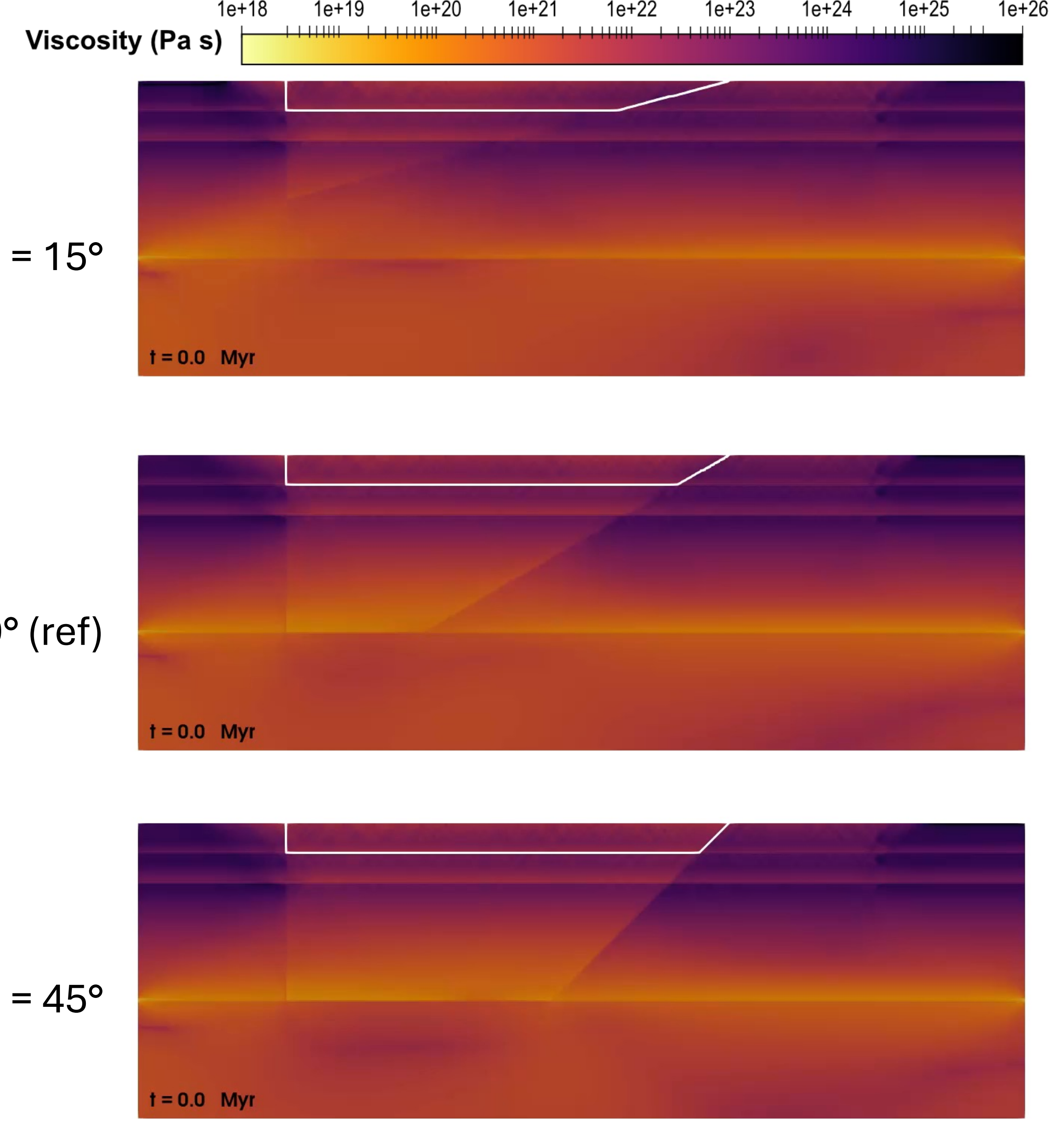
Dip angle



θ = 15°

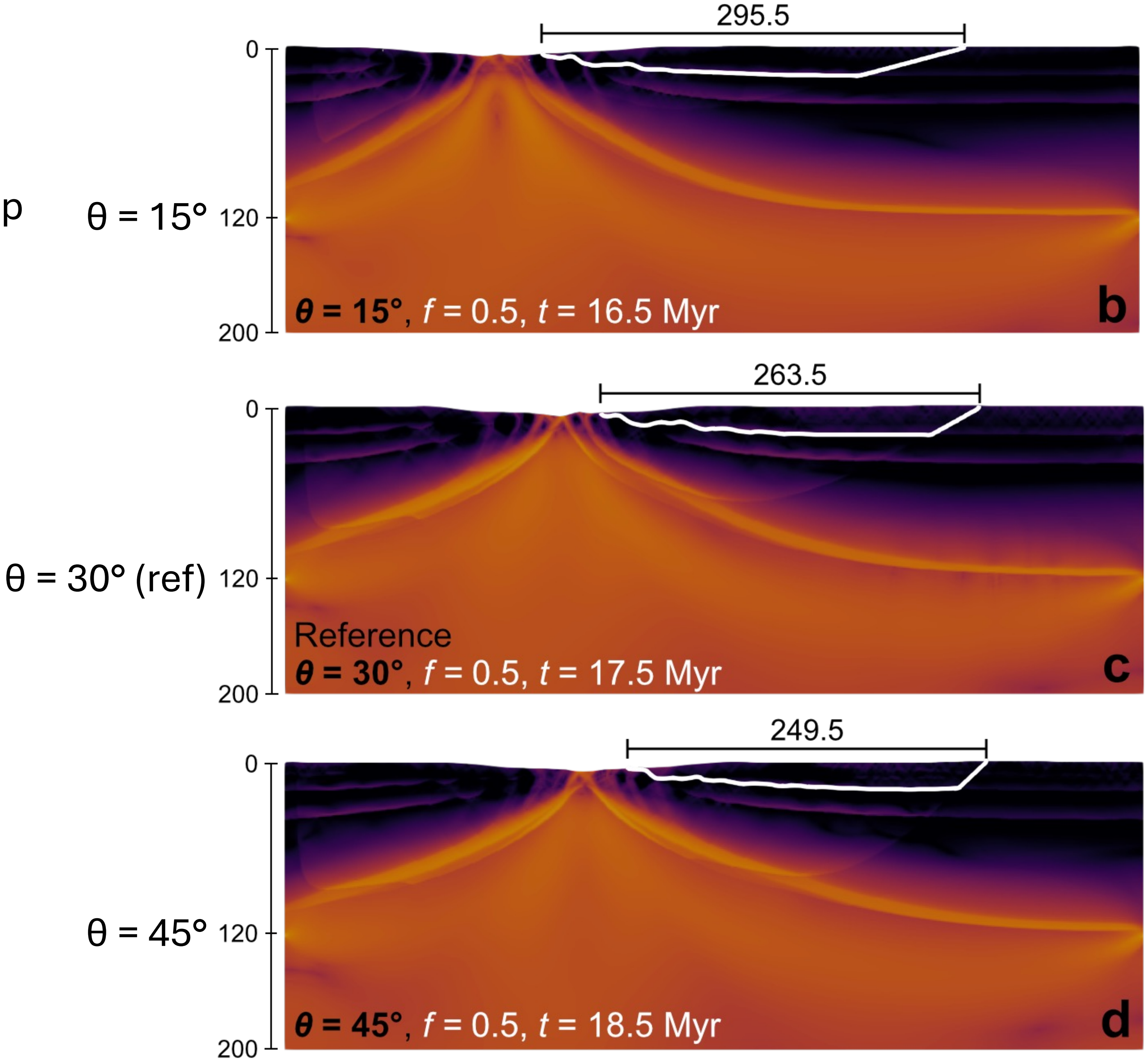
θ = 30° (ref)

θ = 45°



Dip angle

- Between θ = 15° and 45°, a larger dip angle creates a smaller fragment.



Dip angle

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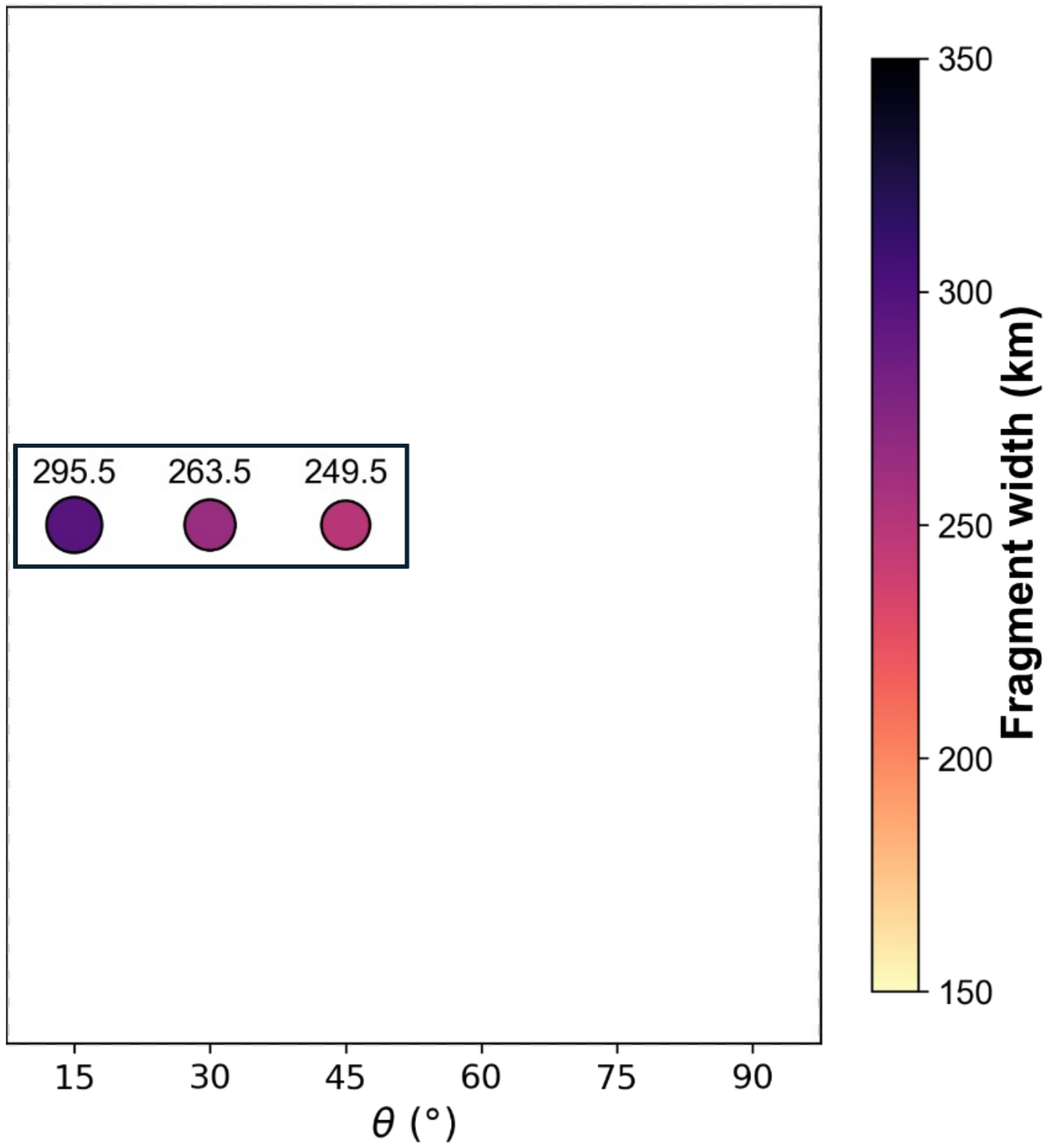
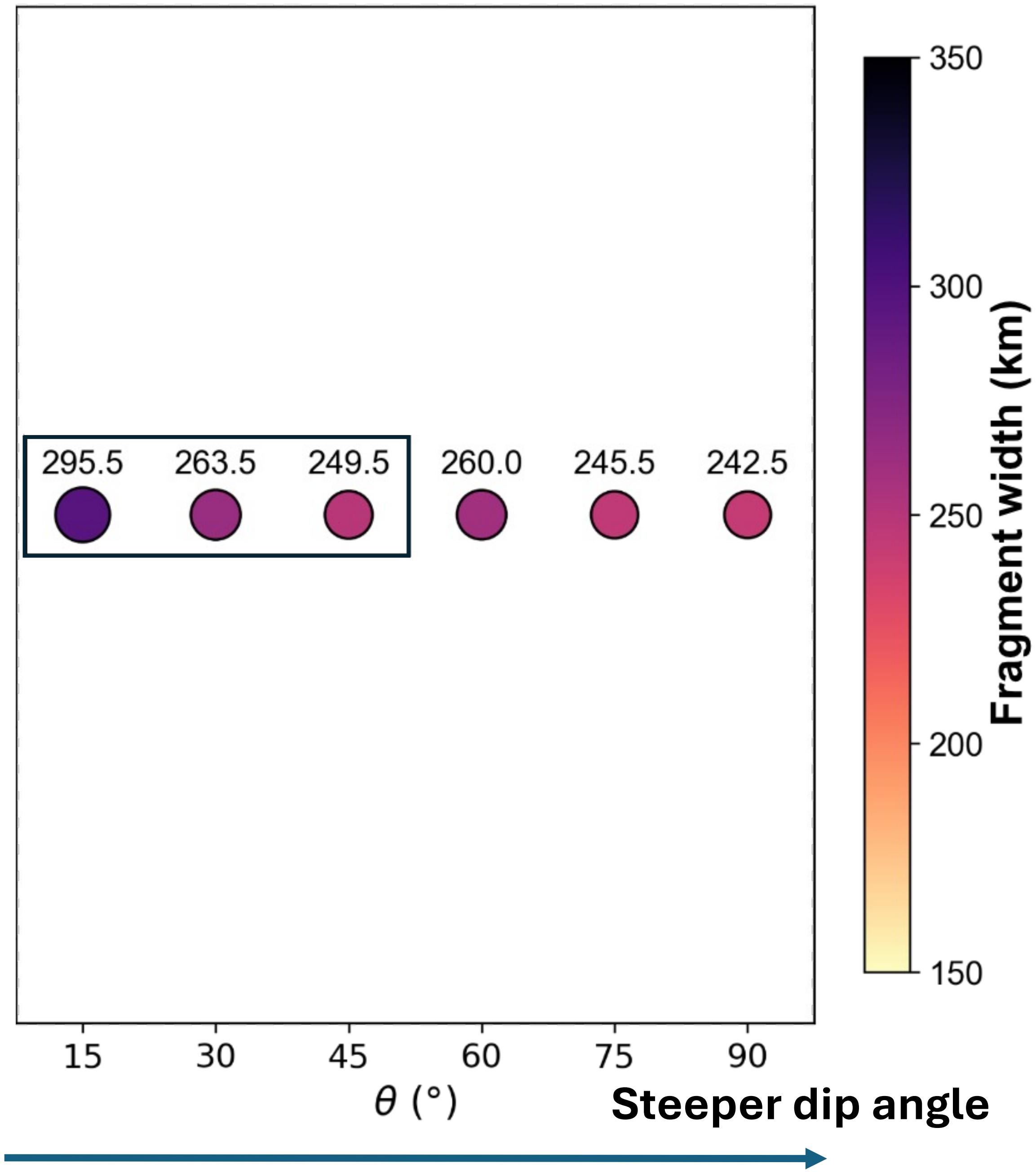


Dip angle

- Between θ = 15° and 45°, a larger dip angle creates a smaller fragment.

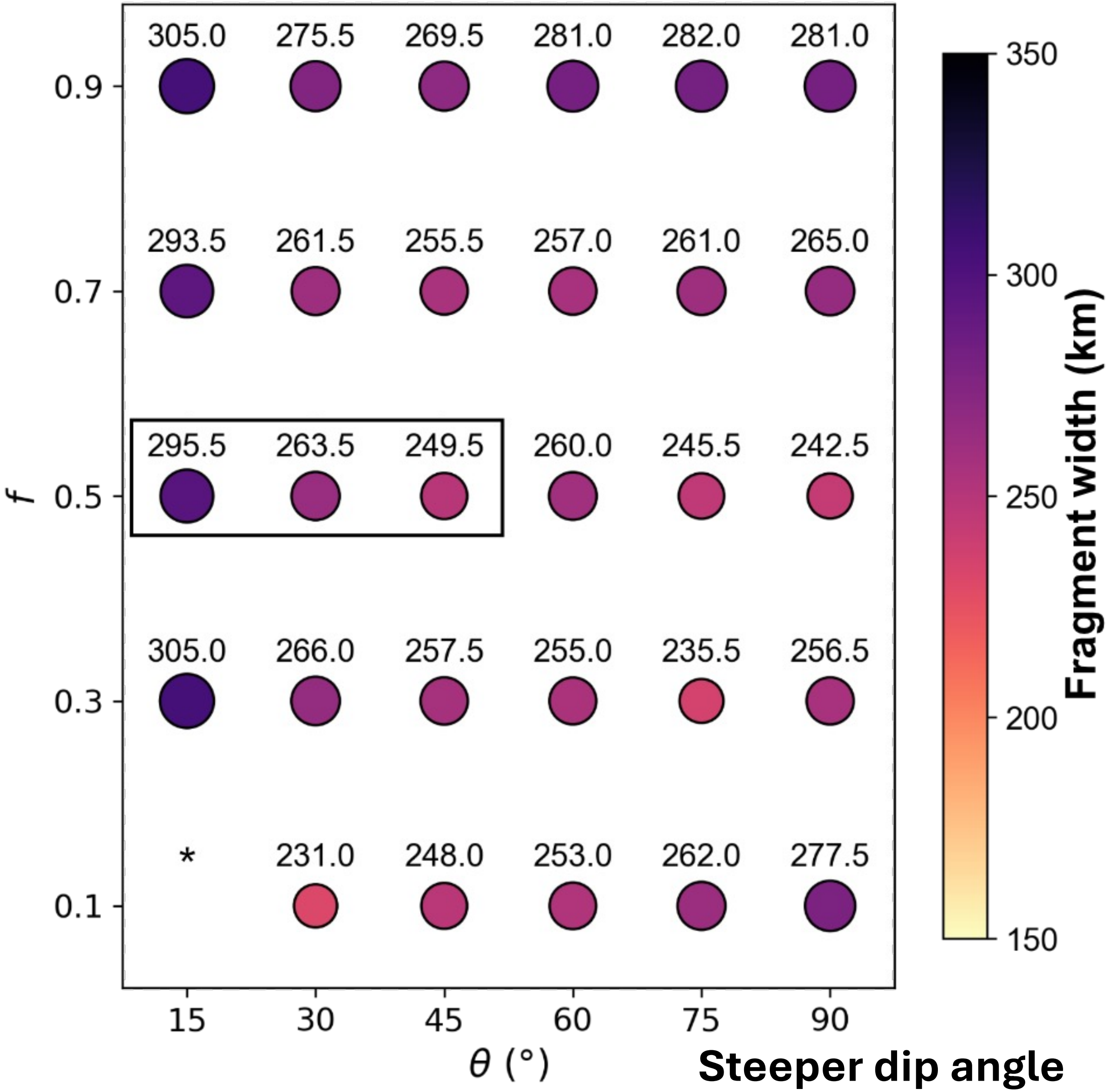


Dip angle

- Between θ = 15° and 45°, a larger dip angle creates a smaller fragment.

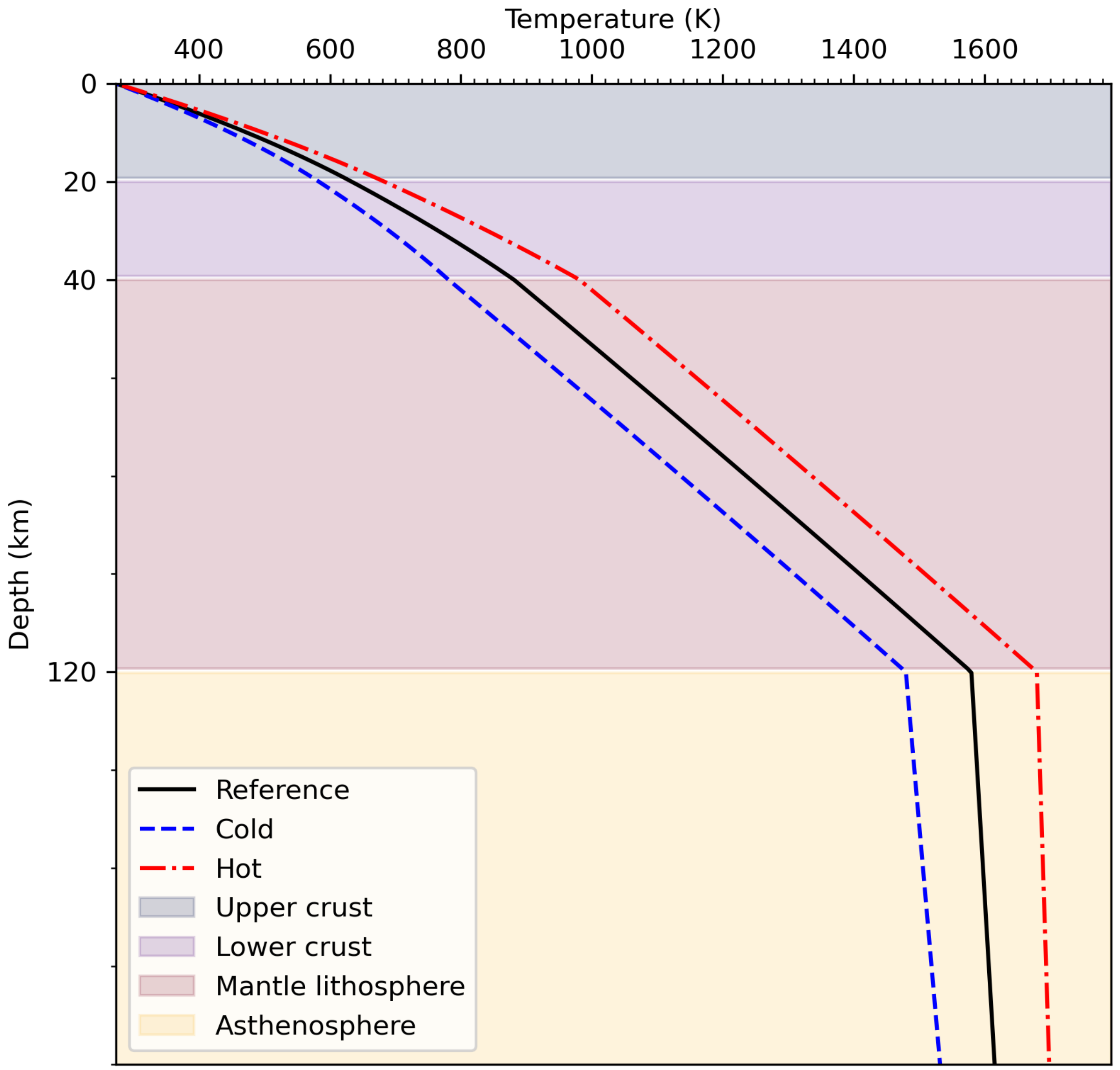
- Between θ = 60° and 90°, more random variations in fragment widths are observed.

Weaker upper plate

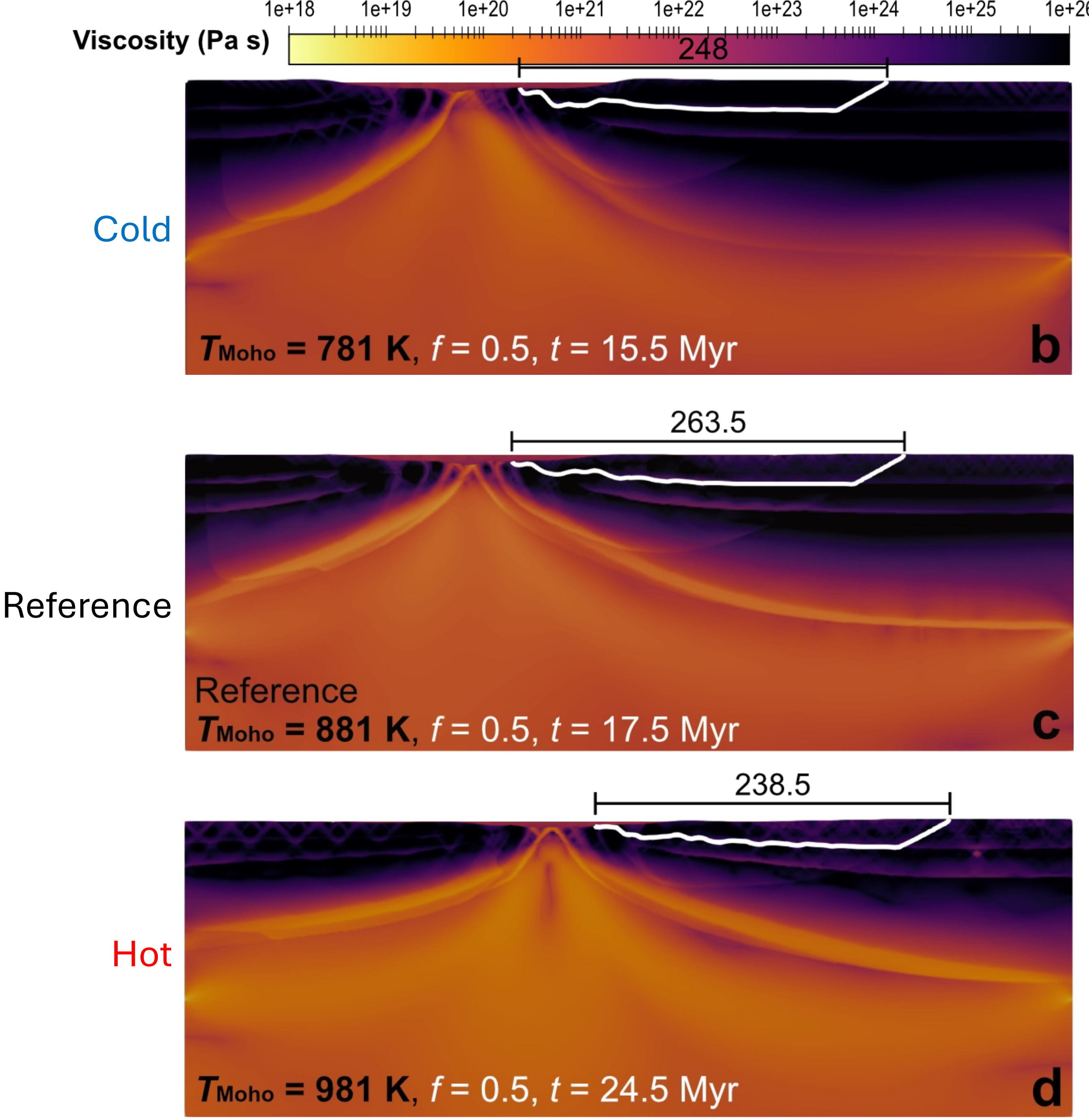


Steeper dip angle

Parameter testing – initial geotherm

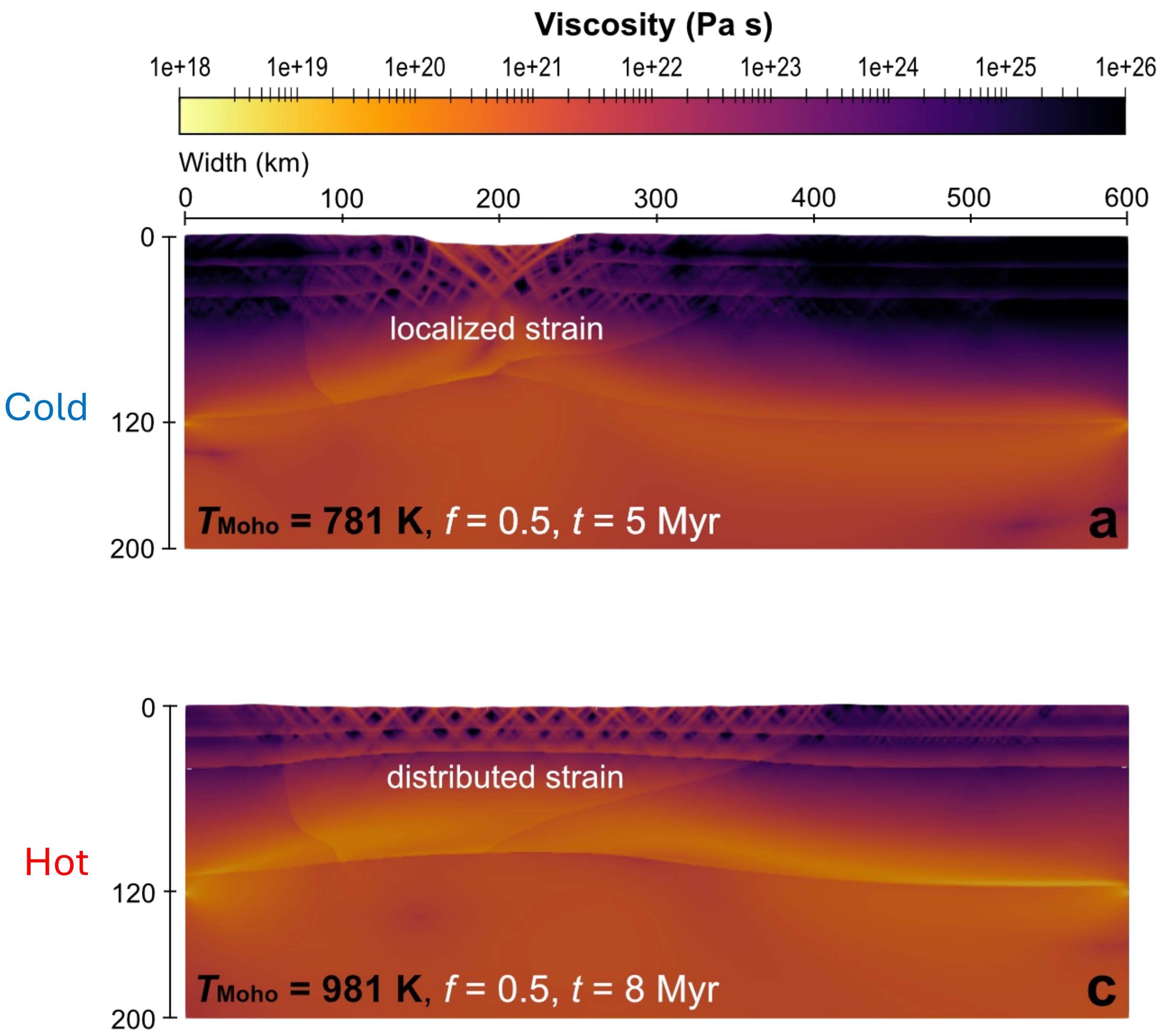


Initial geotherm

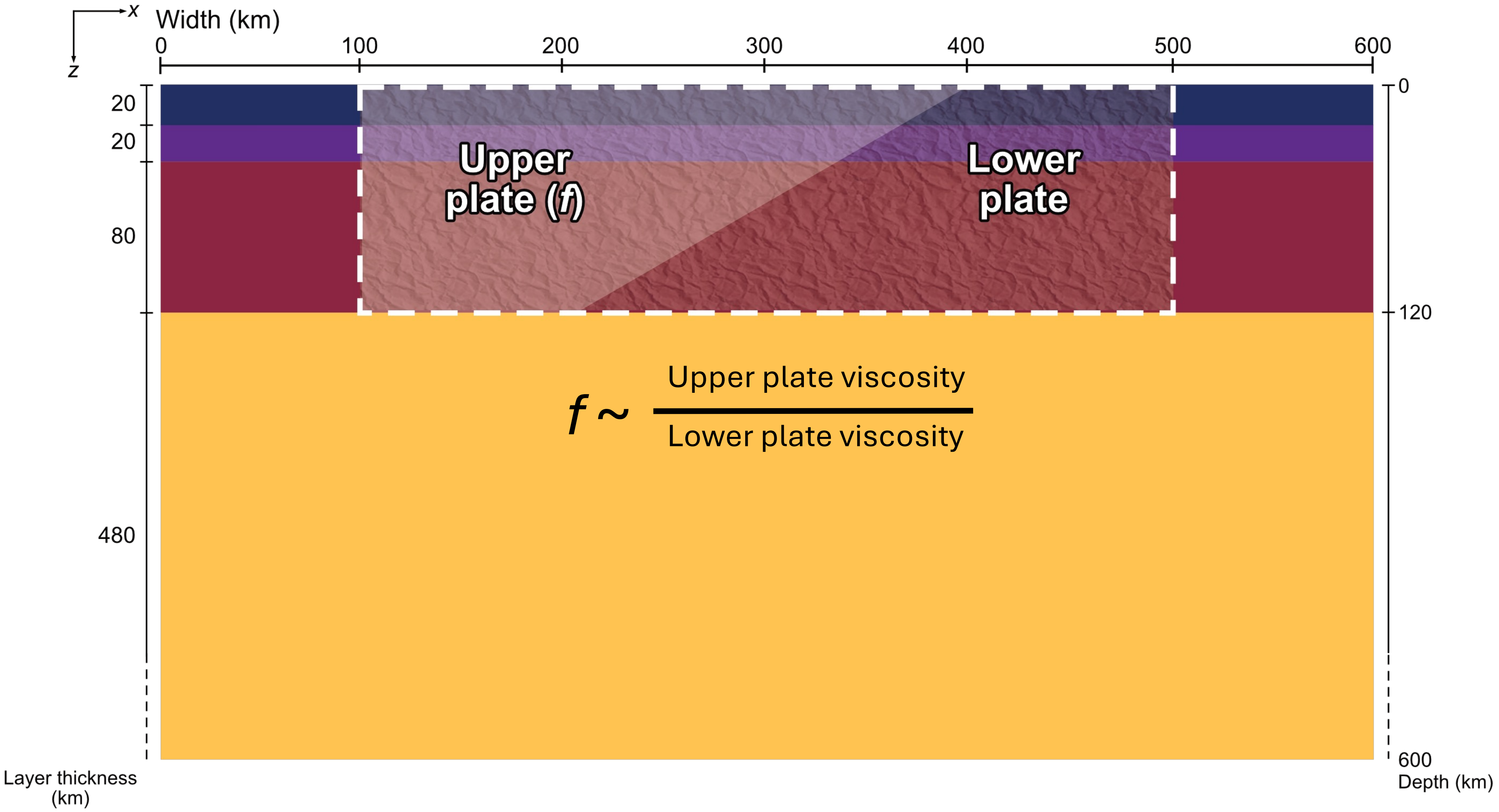


Initial geotherm

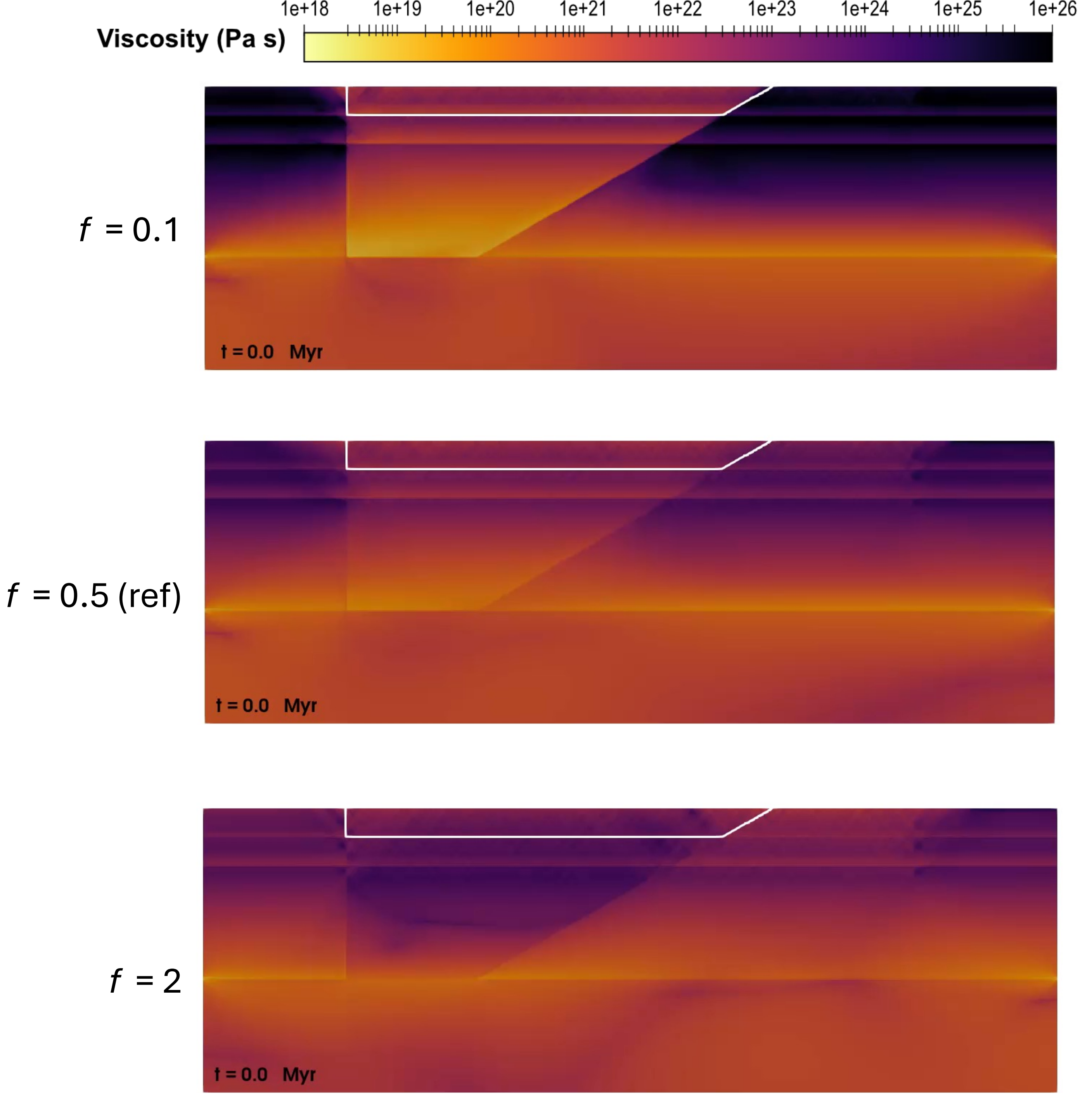
- A colder lithosphere creates a **narrower** rift.
- A hotter lithosphere creates a **wider** rift.



Parameter testing – upper plate strength

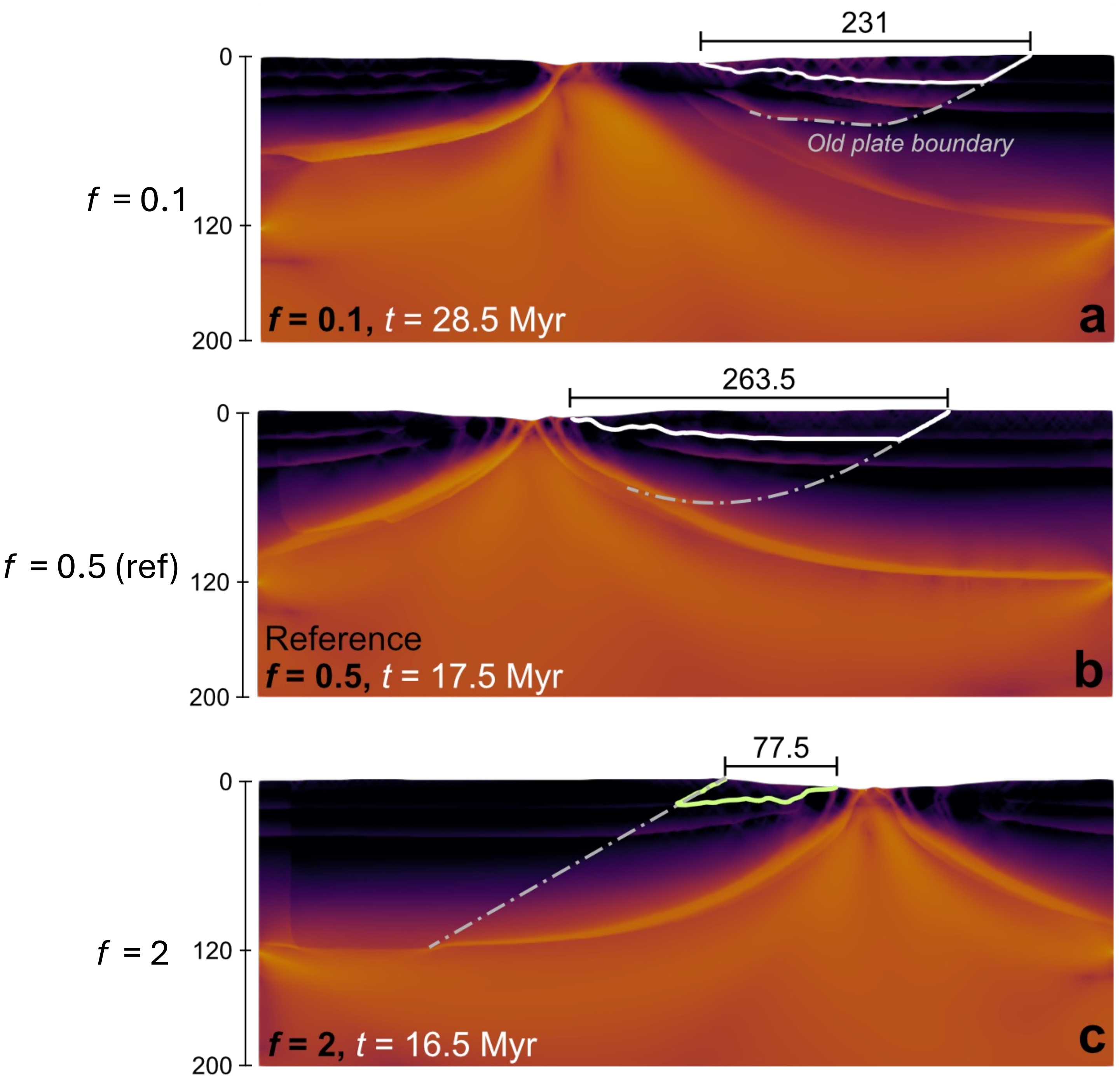


Upper plate strength



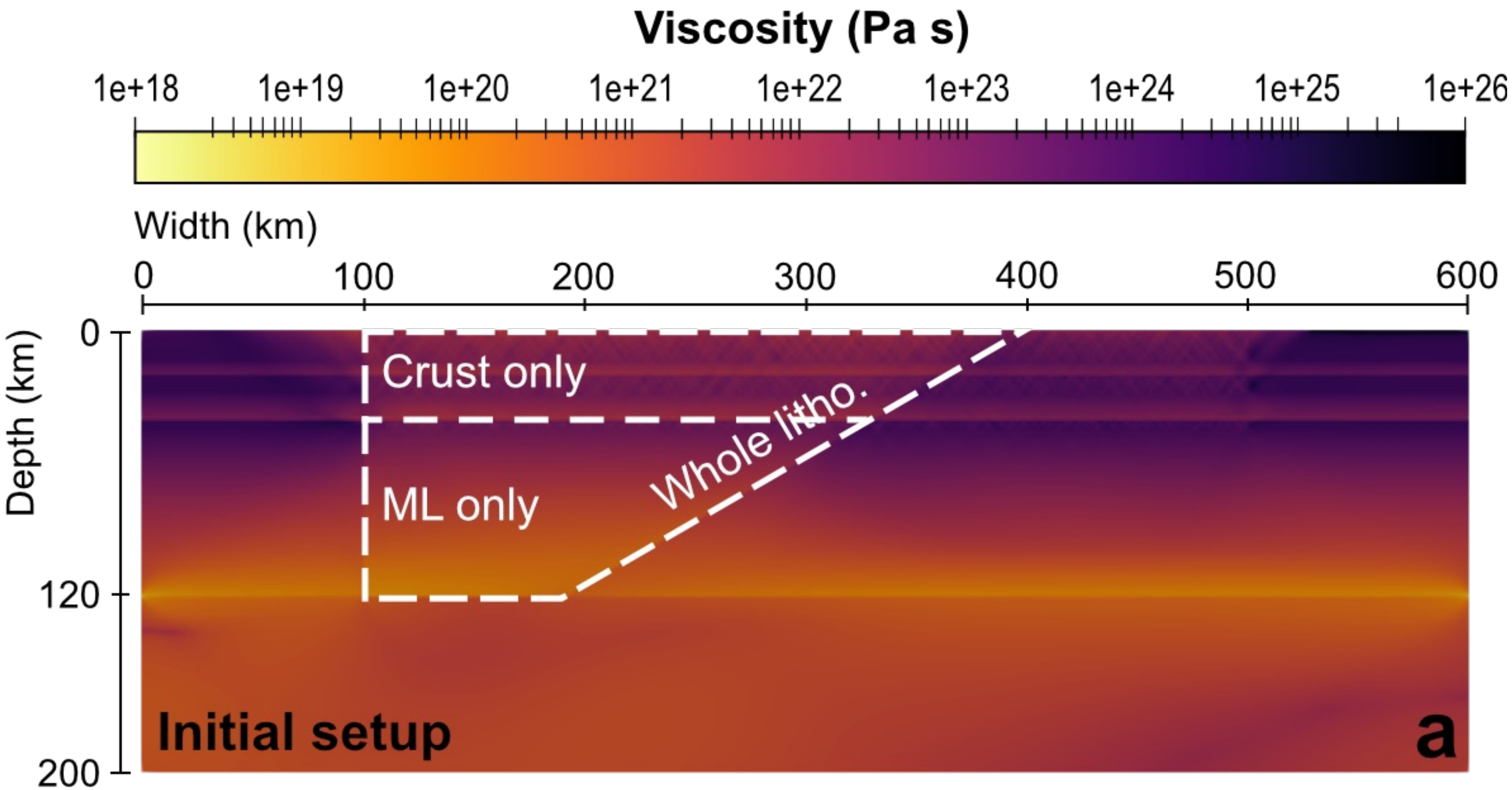
Upper plate strength

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

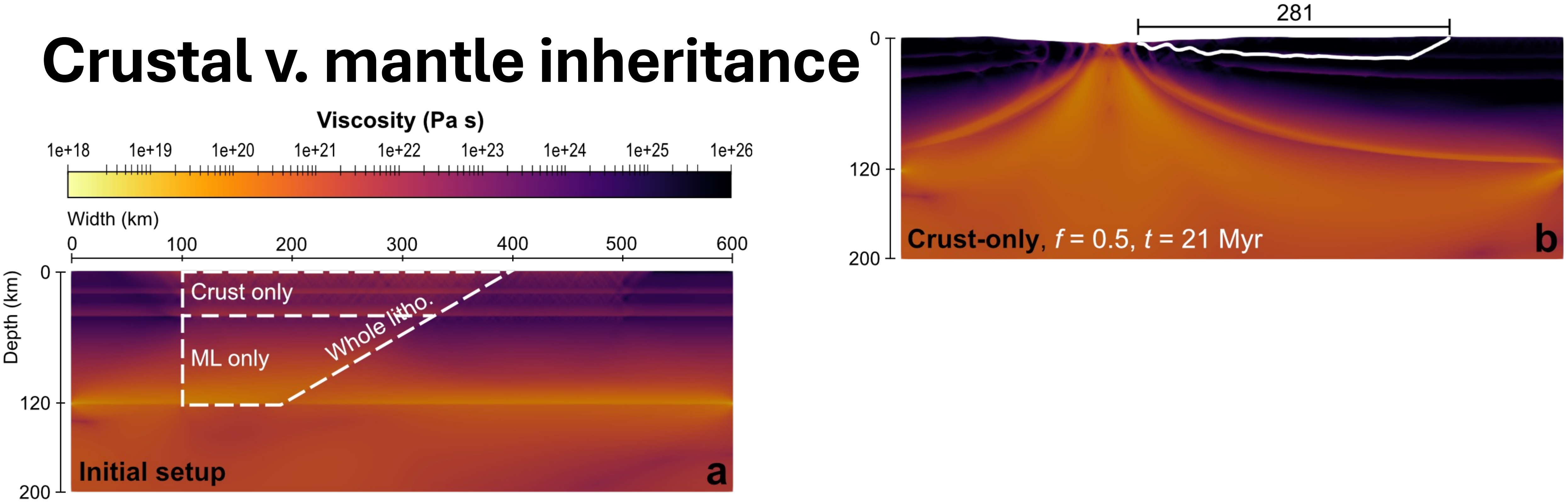


Crustal v. mantle lithospheric inheritance

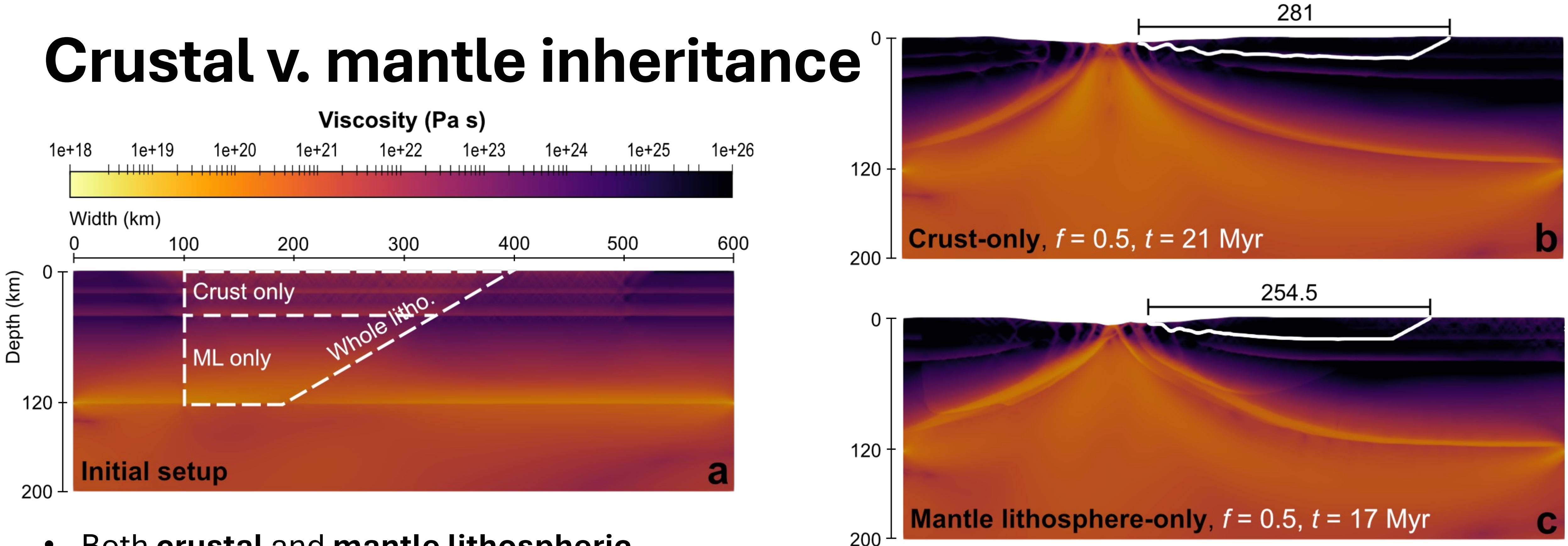
- Where *f* is applied to:



Crustal v. mantle inheritance

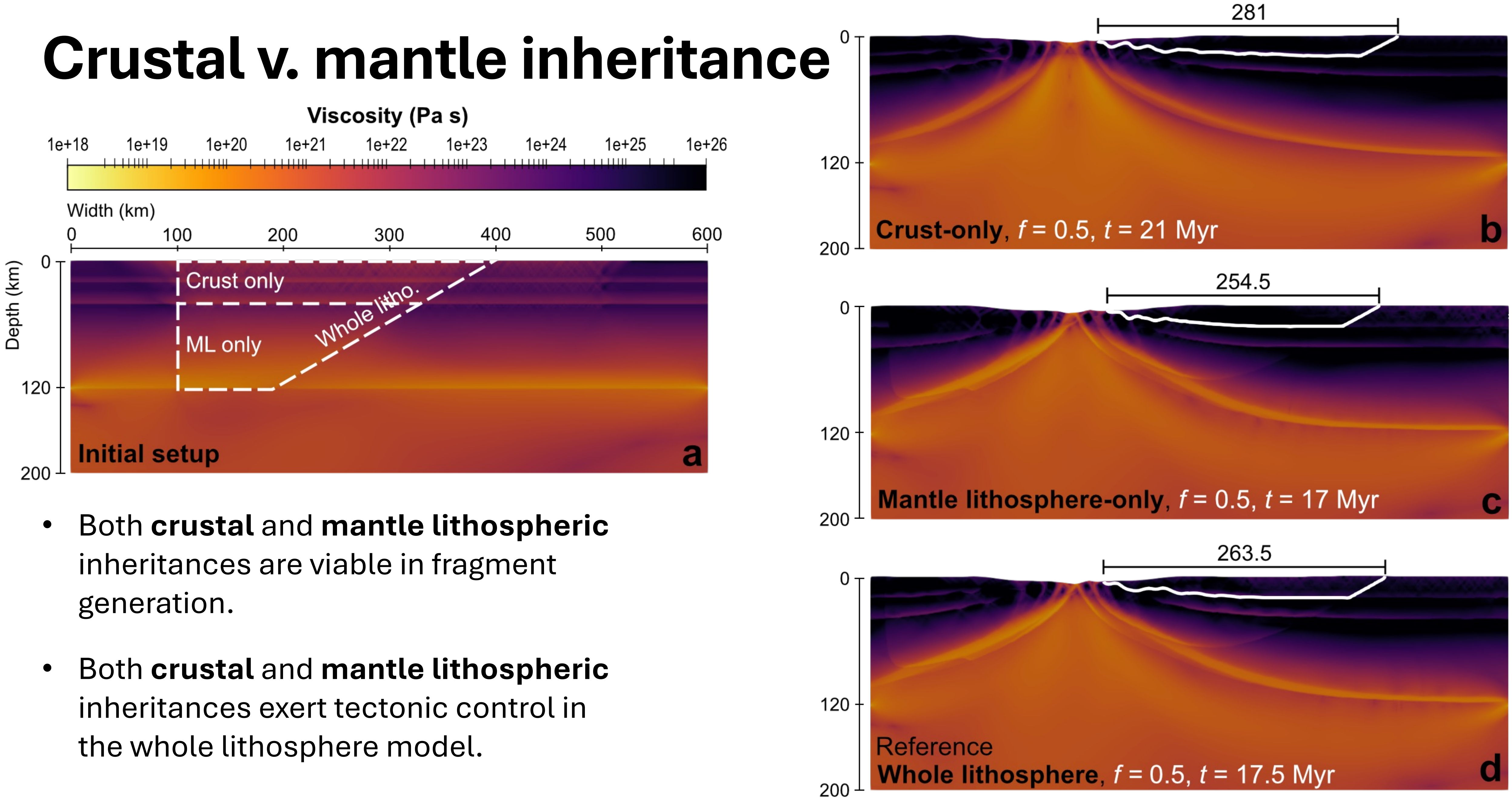


Crustal v. mantle inheritance



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

Crustal v. mantle inheritance

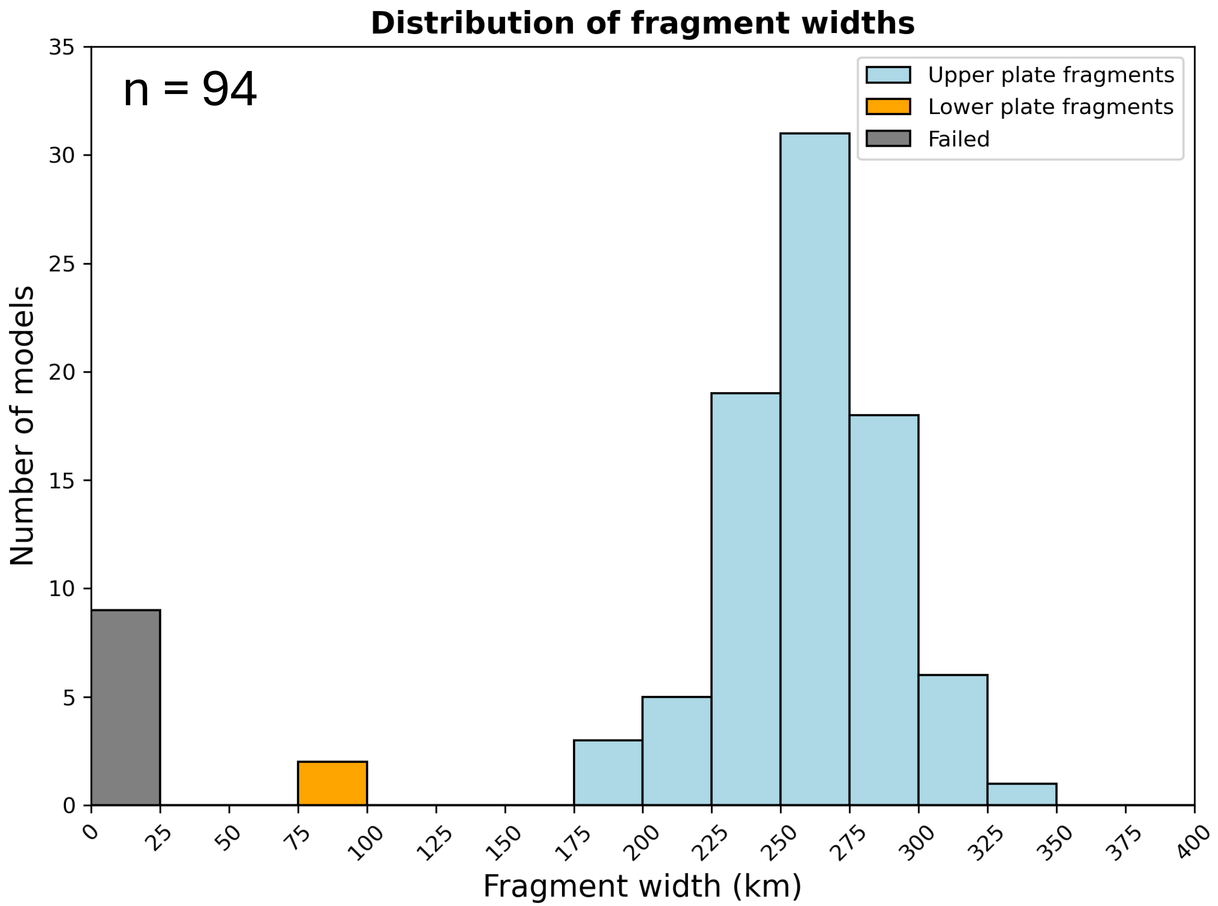


- Both **crustal** and **mantle lithospheric** inheritances are viable in fragment generation.

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

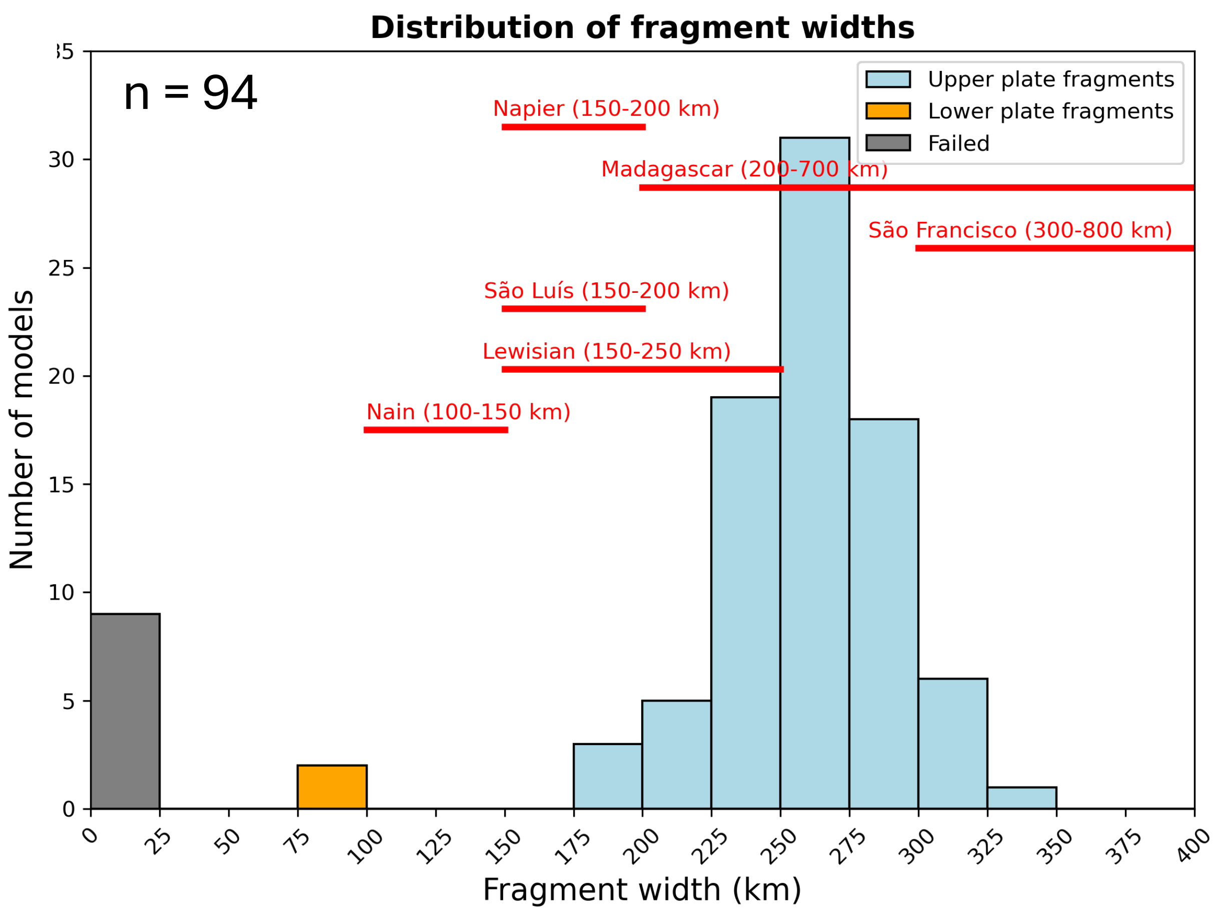
Summary

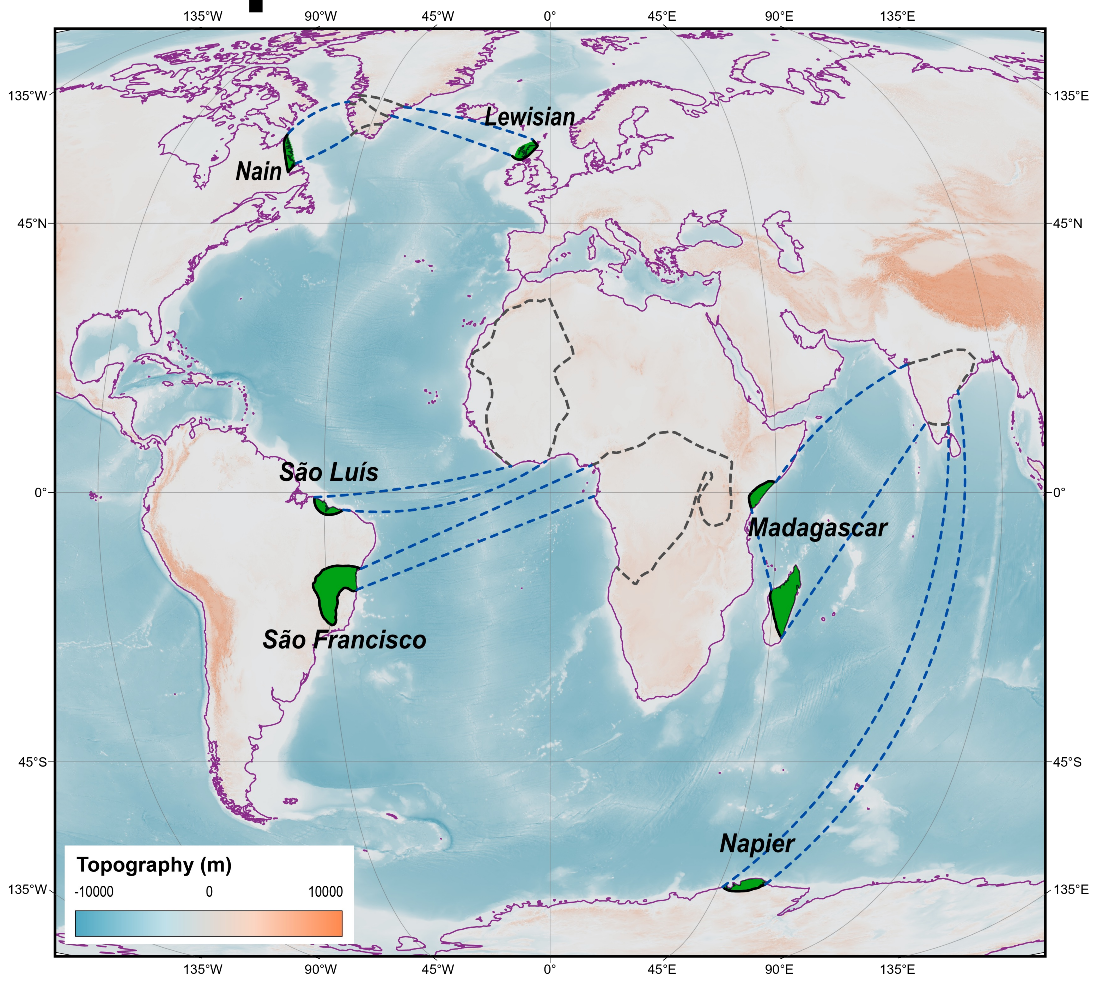
Fragment widths



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

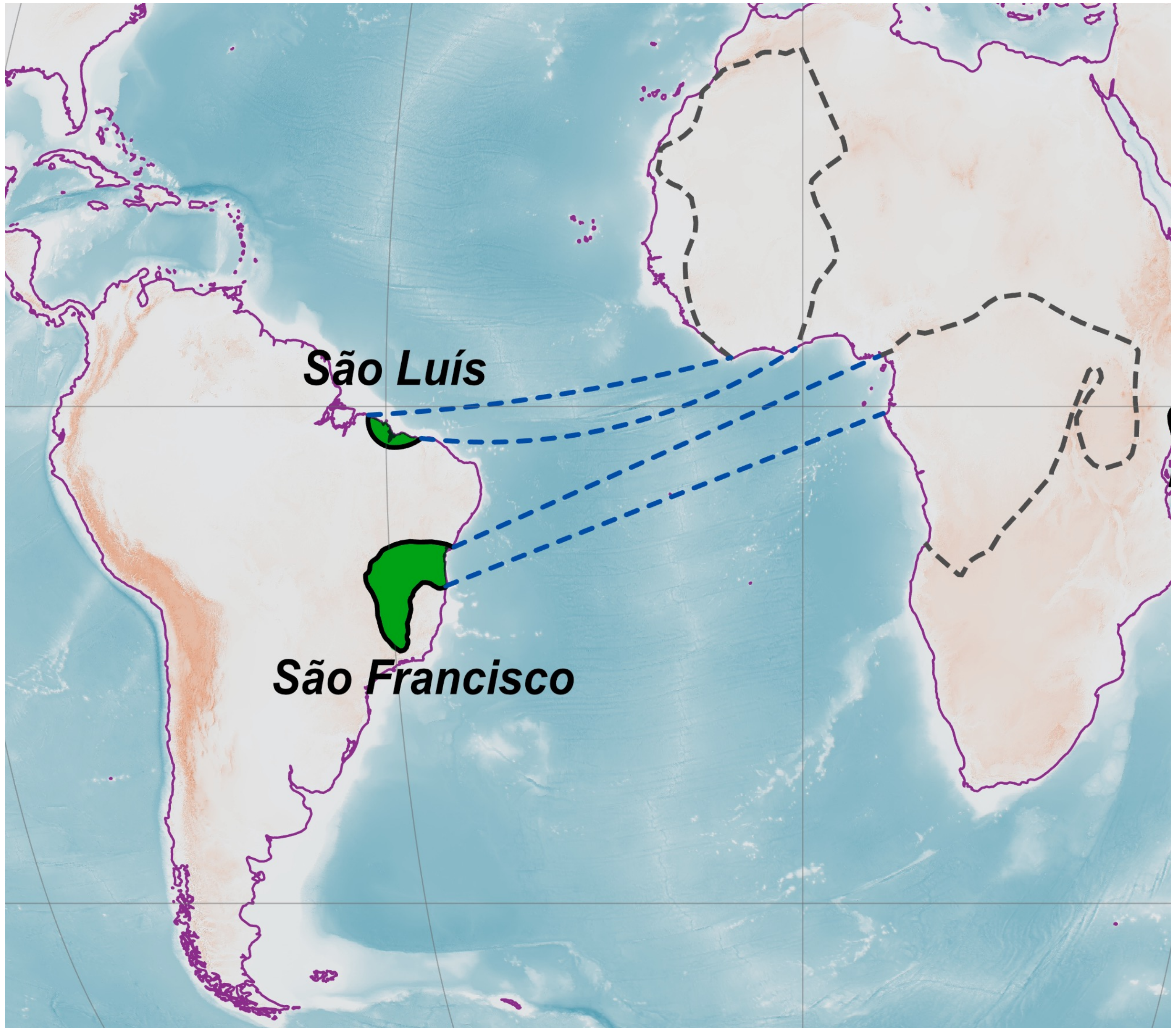
Comparison with geological examples





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

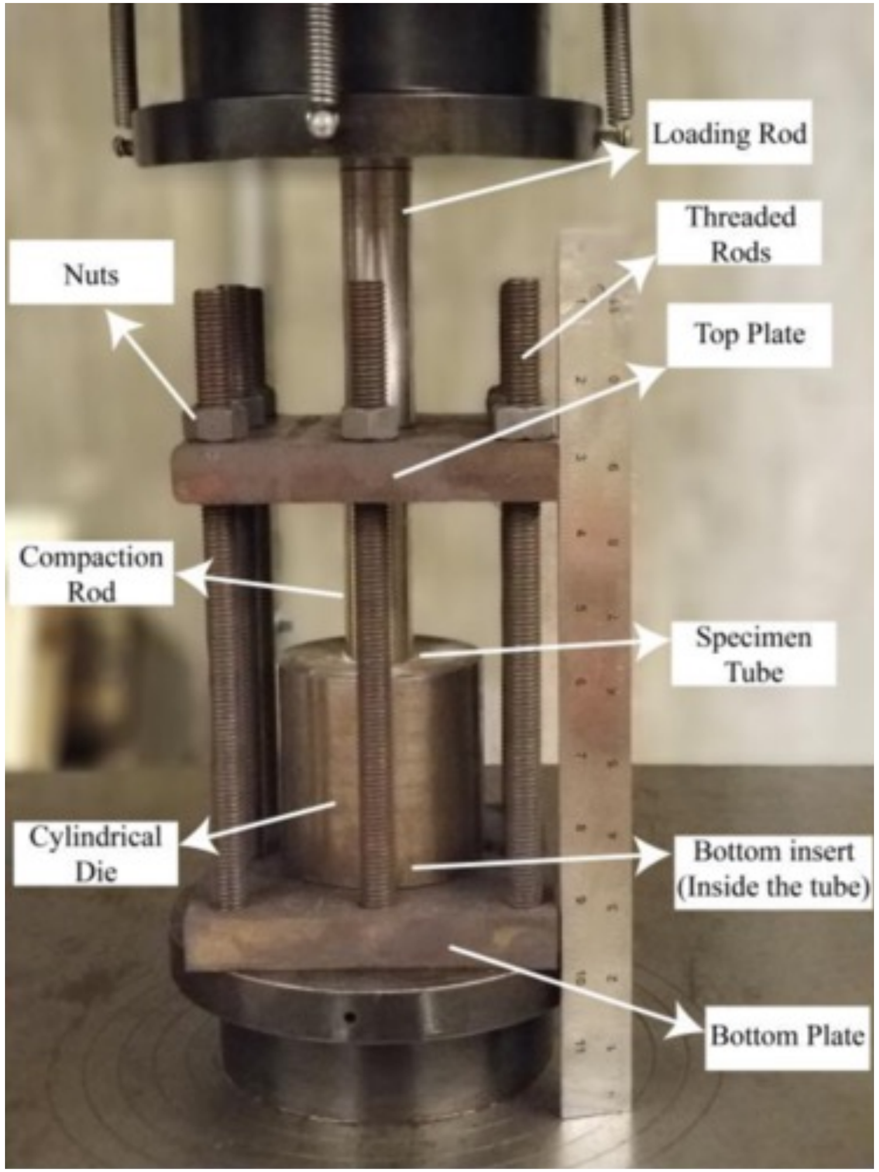
- We quantify the influence of structural inheritance in fragment formation.
- We ran 94 models, testing 8 parameters
- The geometry of inherited structures controls the fragment width.
- Our generated fragments align with real-world examples.
- We provide a tectonic recipe for future regional models.

Thank you!

Access to setup, code, and data

Rheology and flow laws

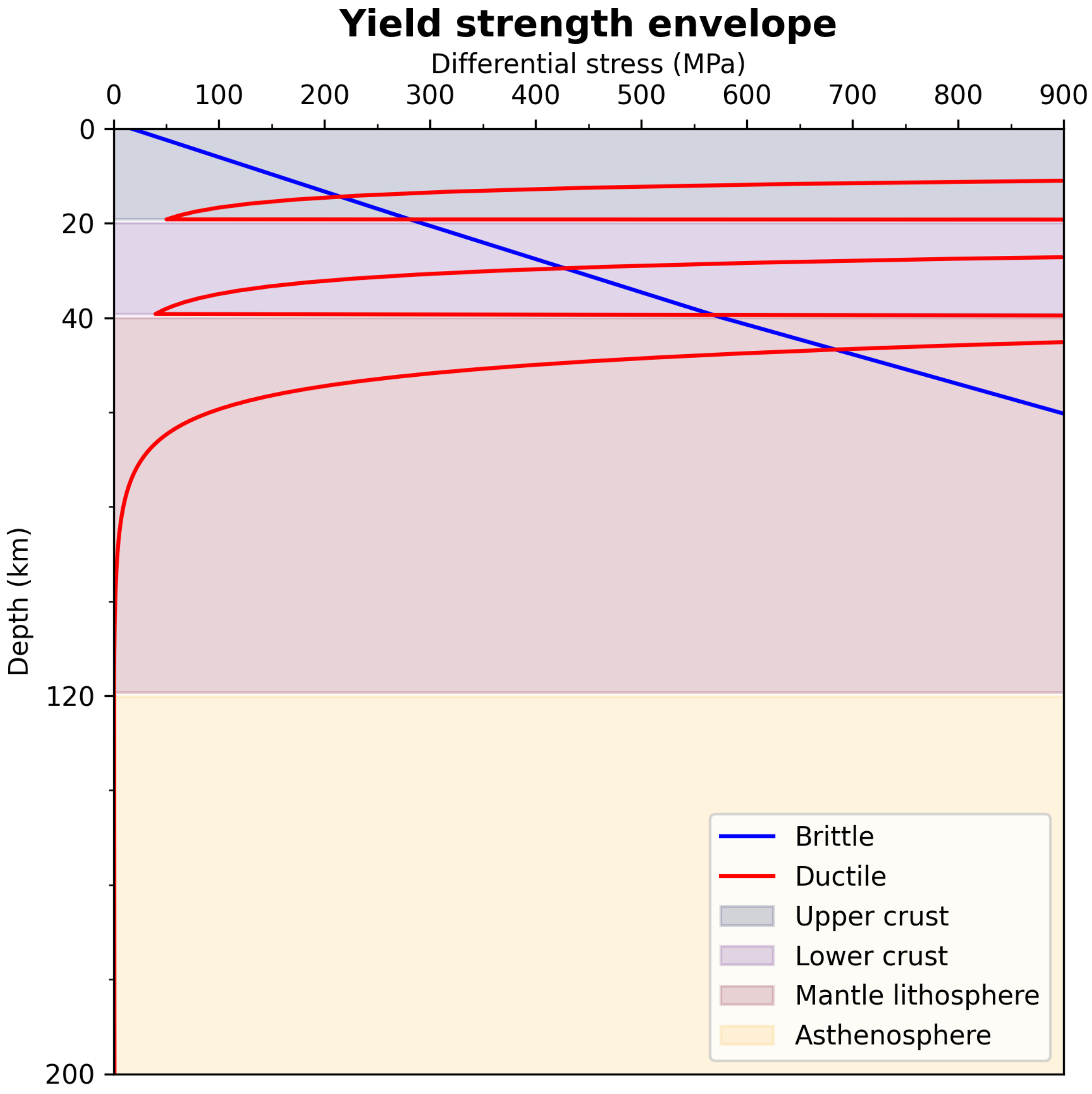
- Rheology describes the deformation of material.
- Most rocks are brittle at room temperature and atmosphere.
- However, they transition to a ductile state under mantle-like pressure and temperature.
- The ductile strength of rocks are measured in laboratory experiments (i.e., flow laws).



Moslehy & Alshibli, 2021. *Journal of Rock Mechanics and Geotechnical Engineering*. https://doi.org/10.1016/j.jrmge.2020.09.010

Rheology and flow laws

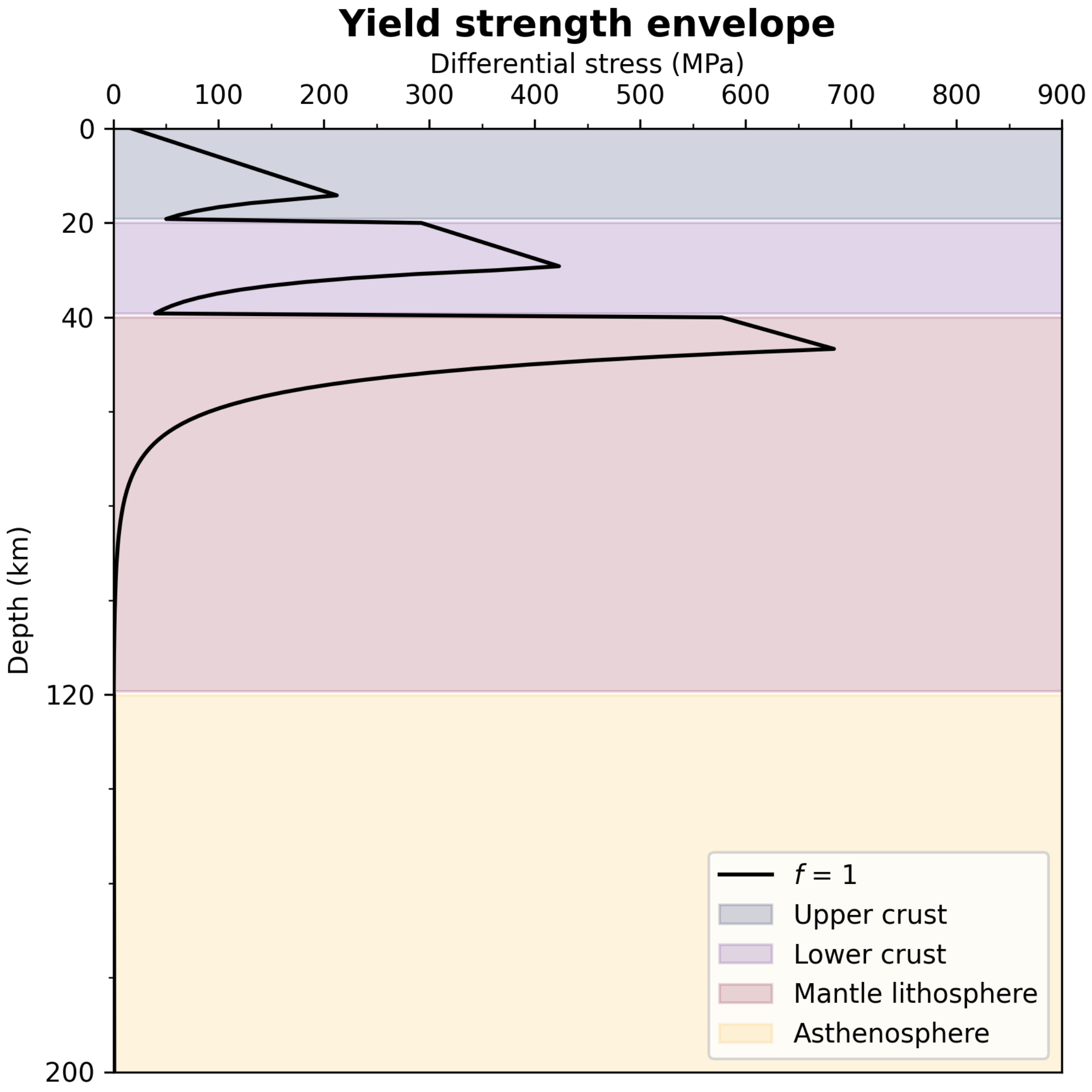
- ASPECT can simulate both brittle and ductile deformation.



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

- Good for analyzing one model.
- Can record analytical procedures in Python.

+

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

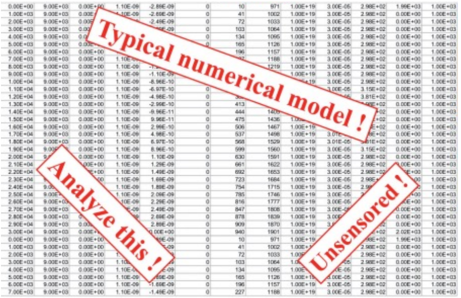
solution-00003.0000.vtu

solution-00004.pvtu

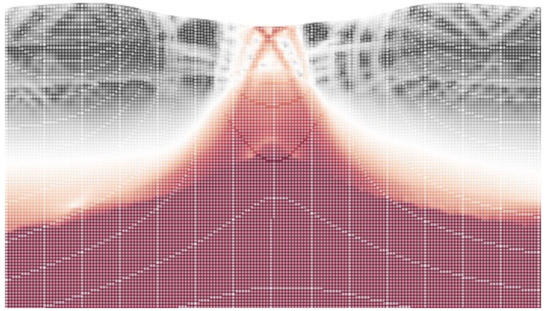
solution-00004.0000.vtu

...

Solution at timestep 0



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

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

Mass

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

Linear momentum

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

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 $\rho\boldsymbol{g}$.
- 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

- $Pr = \frac{\text{momentum diffusivity}}{\textit{thermal diffusivity}}$ $=10^{25}$ 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)

Forward model (in time)

Model results

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

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

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

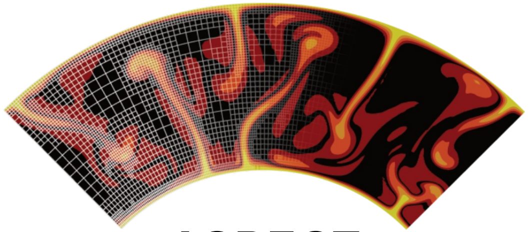
$$\rho = \rho_0(1 - \alpha(T' - {T_0}'))$$

$$\nabla \cdot \boldsymbol{u}$$

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

$$\rho C_p\left(\frac{\partial T}{\partial t} + \boldsymbol{u} \cdot \nabla T\right.$$

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

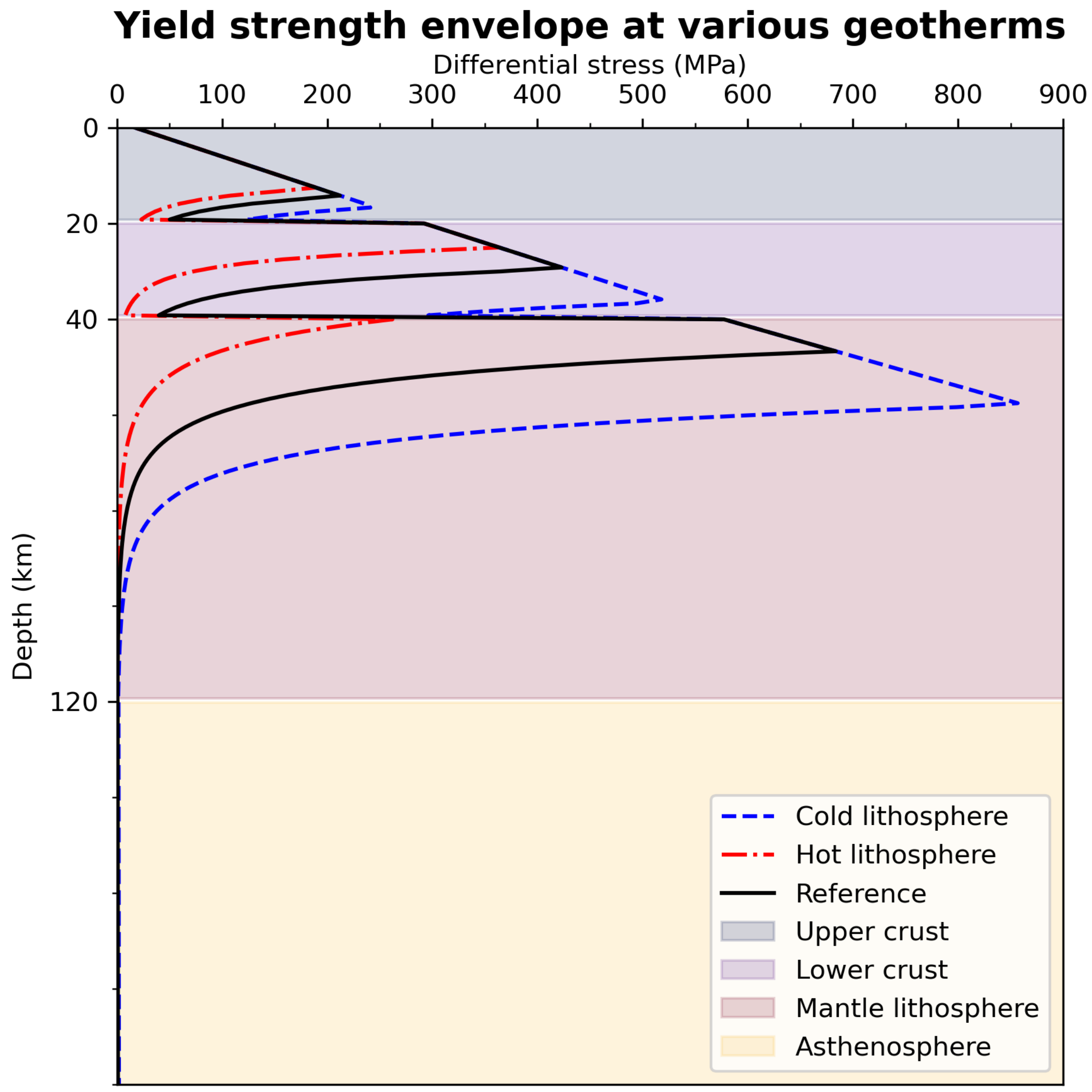


ASPECT

Gerya (2019). Cambridge University Press.
https://doi.org/10.1017/9781316534243

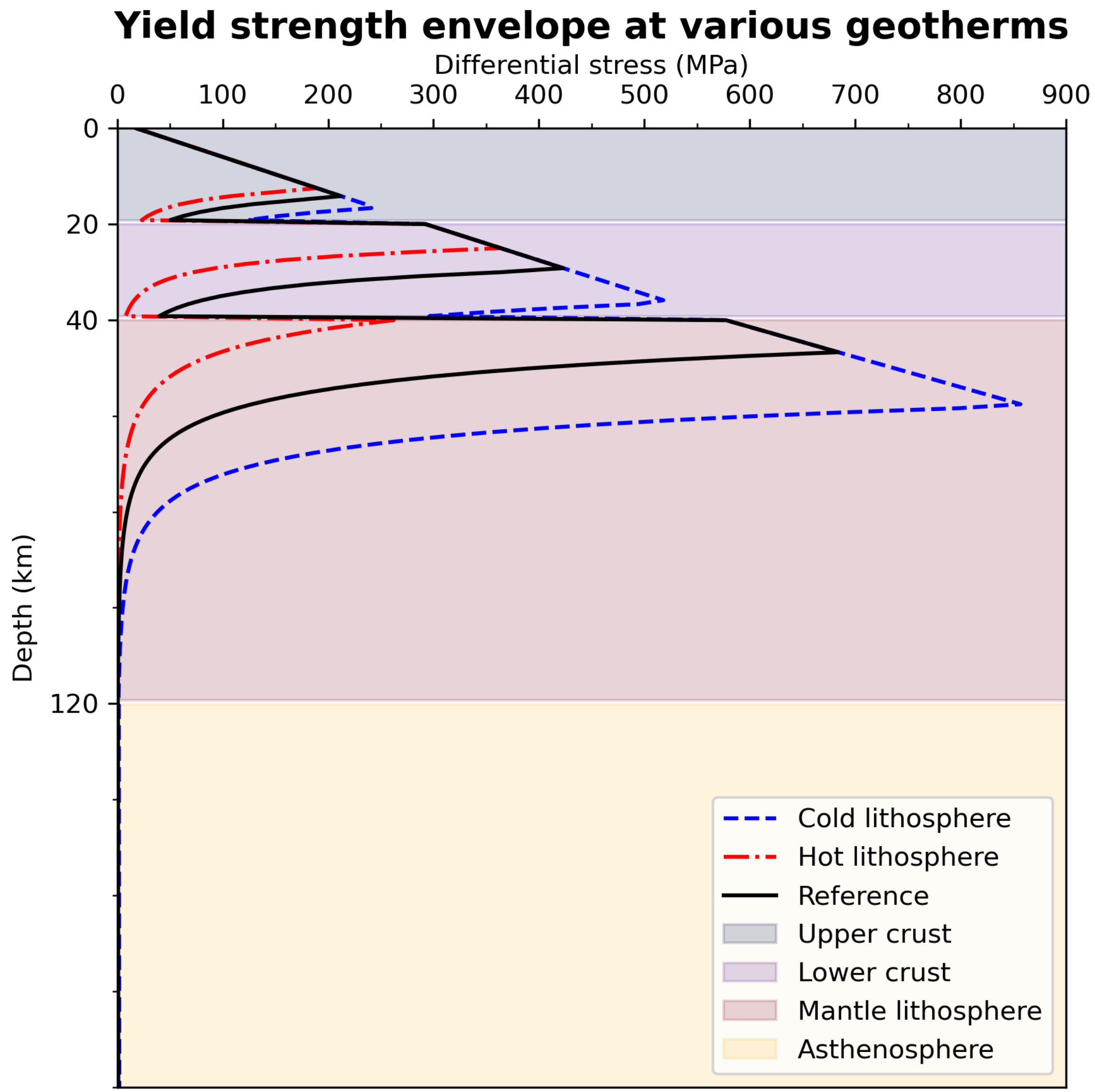
Initial geotherm

- 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.



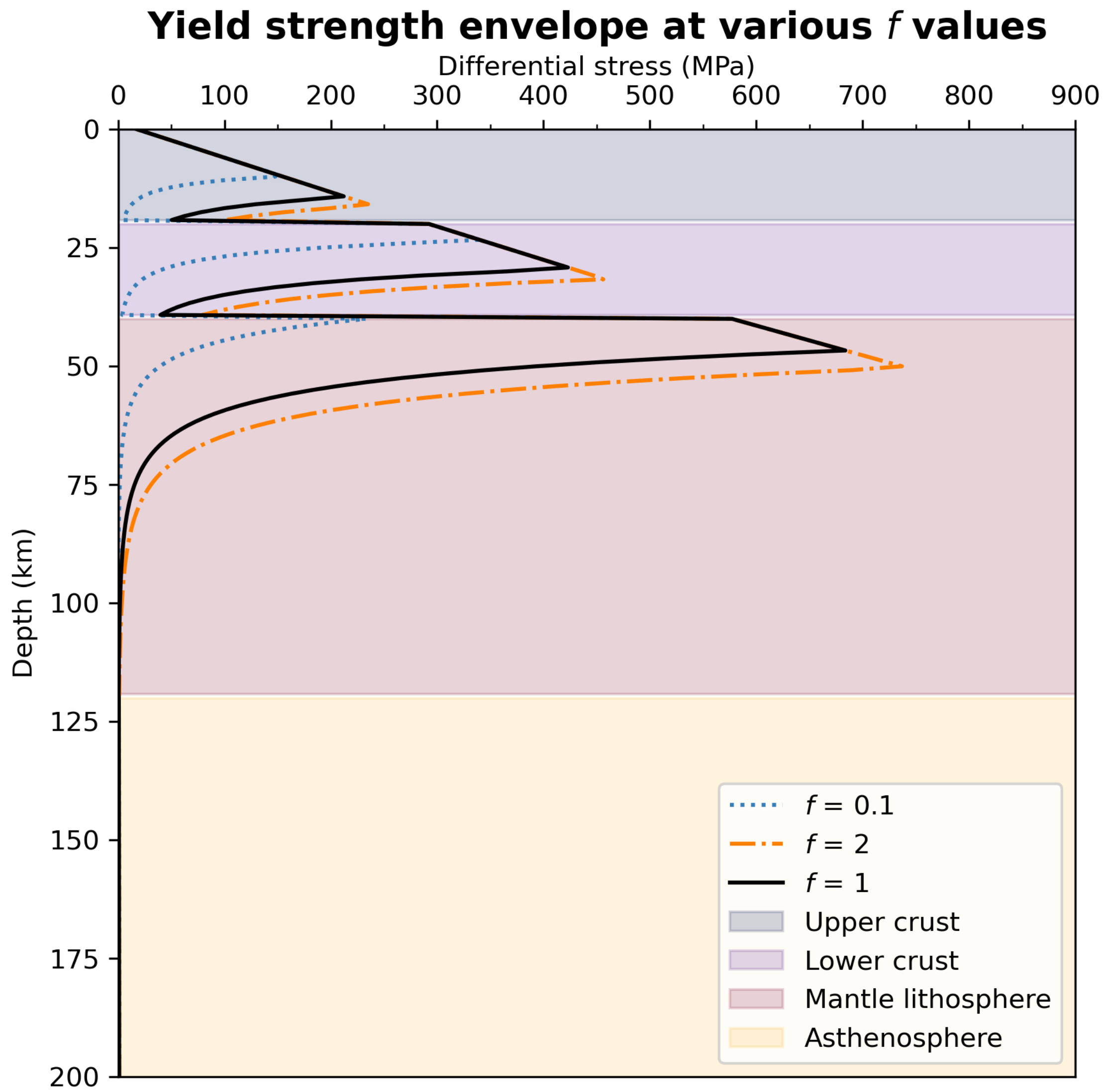
Initial geotherm

- 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.



Strength parameter

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

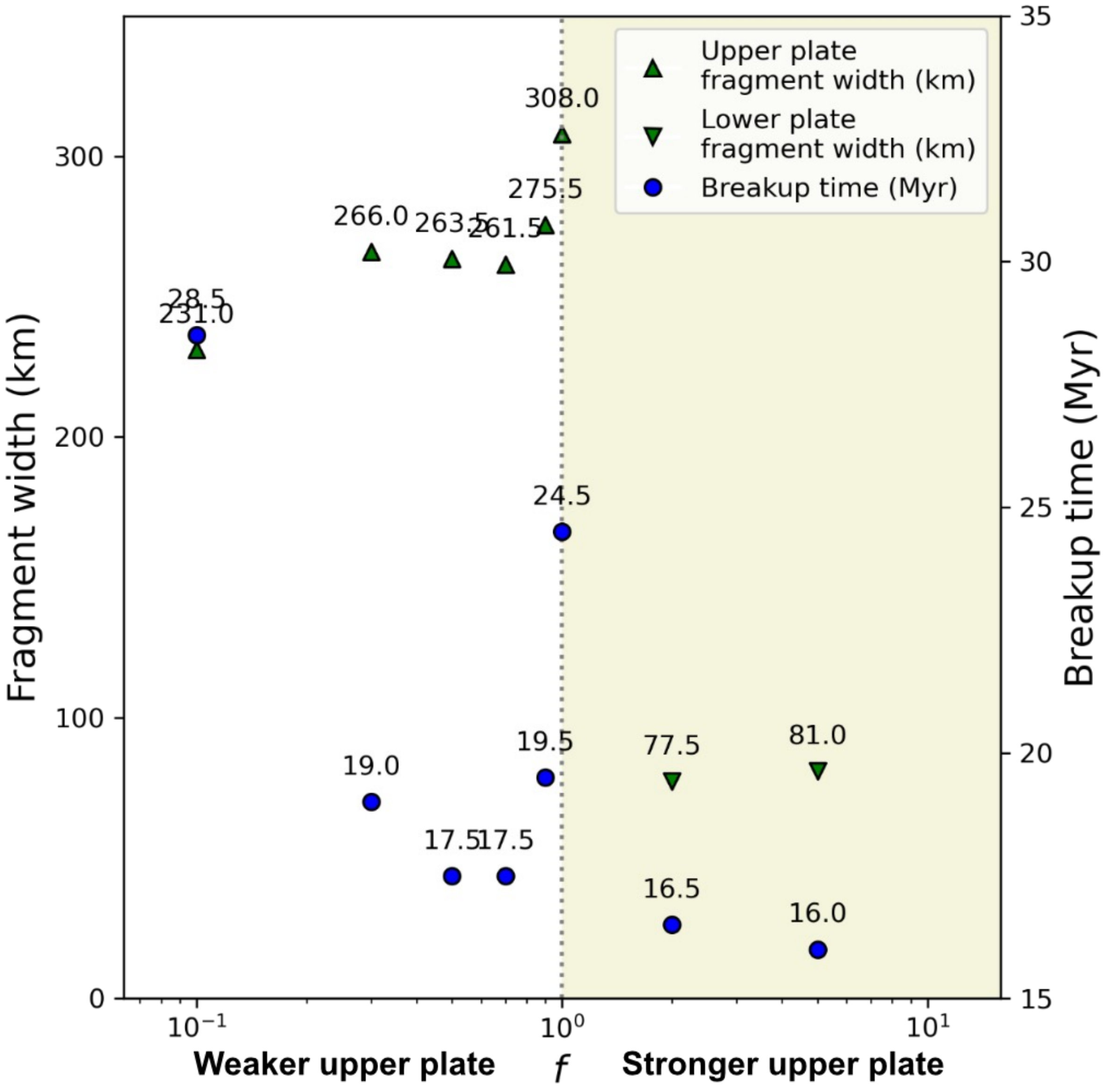


Strength parameter

- 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* ≤ 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.