The effect of composite rheology on mantle convection models with plate-like behavior

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Earth's mantle rheology…

Experimentalists say [e.g. Karato and Wu, 1993]: strain-rate ($\dot{\varepsilon}$) depends on temperature (T), pressure (P), grain-size (d), stress (σ), water fugacity (f_{H_2O}) and melt fraction (ϕ):

$$\dot{\varepsilon} = A d^{-m} \sigma^{n} \exp\left(-\frac{E + PV}{RT}\right)$$

E = activation energy ; V = activation volume ; R = gas constant
n and m are the stress and the grain-size exponents.
A is here a pre-factor, also containing the dependence of $\dot{\varepsilon}$ on f_{H_2O} and ϕ.

Composite rheology:

Diffusion creep: Linear stress dependence (n = 1) non-linear grain size dependence (m = 2-3).
Dislocation creep: Non-linear stress dependence (n = 3.5) no grain-size dependence (m = 0).

Most numerical models of mantle convection assume diffusion creep only, neglect grain-size and use low activation energy for diffusion creep to mimic a composite rheology.

BUT:

- **Observations:** Earth's upper mantle would at least partly deform by dislocation creep (e.g., as revealed by olivine lattice-preferred orientation in the uppermost mantle [e.g. Karato, 1992], generating seismic anisotropy).
- **Numerical studies:** composite rheology affects the planform of convection in the stagnant-lid regime [e.g. Schulz et al., 2019]

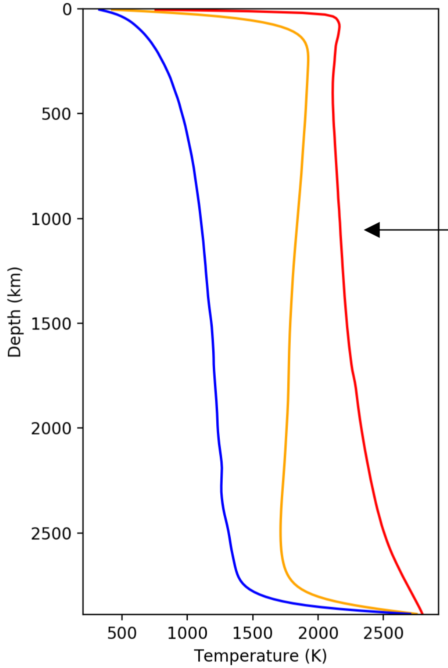
QUESTION:

How does composite rheology affect mantle flow, the generation and style of plate-like behavior and its surface expressions?

Transition stress for olivine [Karato and Wu, 1993]

Transition stress σ_t (defined at $\dot{\varepsilon}_{dif} = \dot{\varepsilon}_{disl}$): the stress separating dislocation- and diffusion-creep dominated deformation.

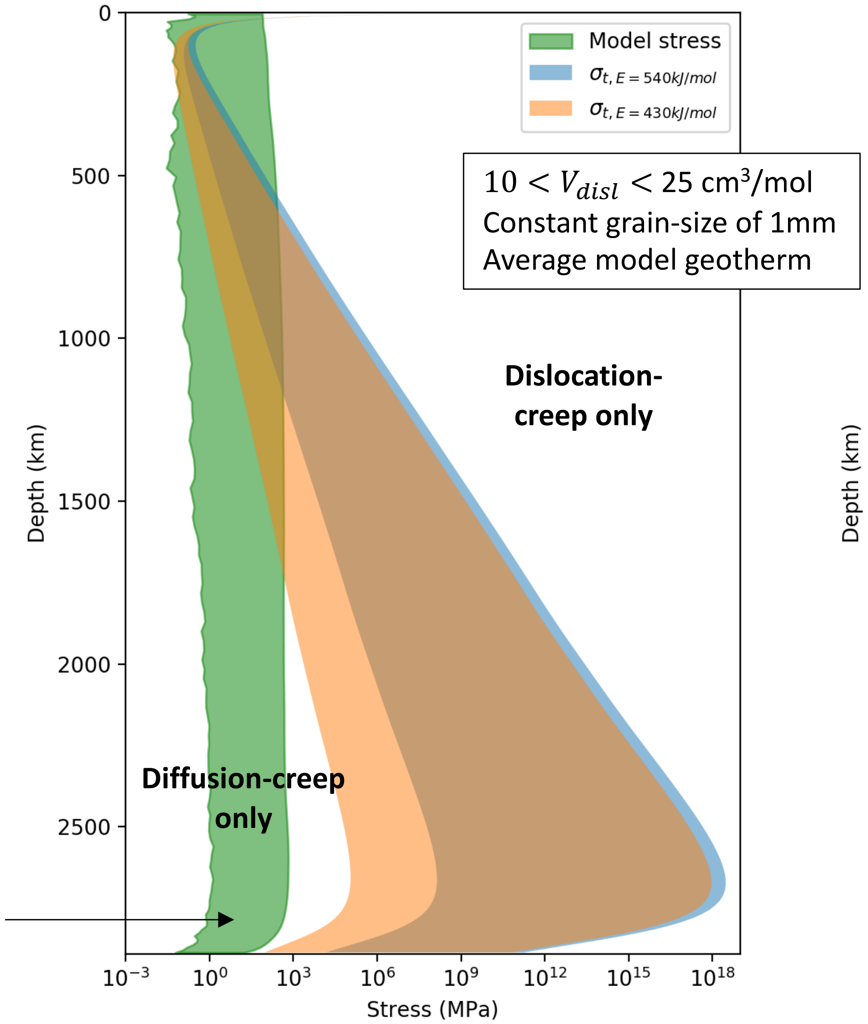
- $\boldsymbol{\sigma_t}(E_{disl}, V_{disl},$ **P**, **T**) notably
- $\boldsymbol{\sigma_t}$ **controls the spatial distribution of diffusion and dislocation creep.**



Here, σ_t is calculated from a radial profile of lithostatic pressure and the **minimum**, **average** and **maximum** geotherm of a reference model with plate-like behavior using diffusion-creep only.

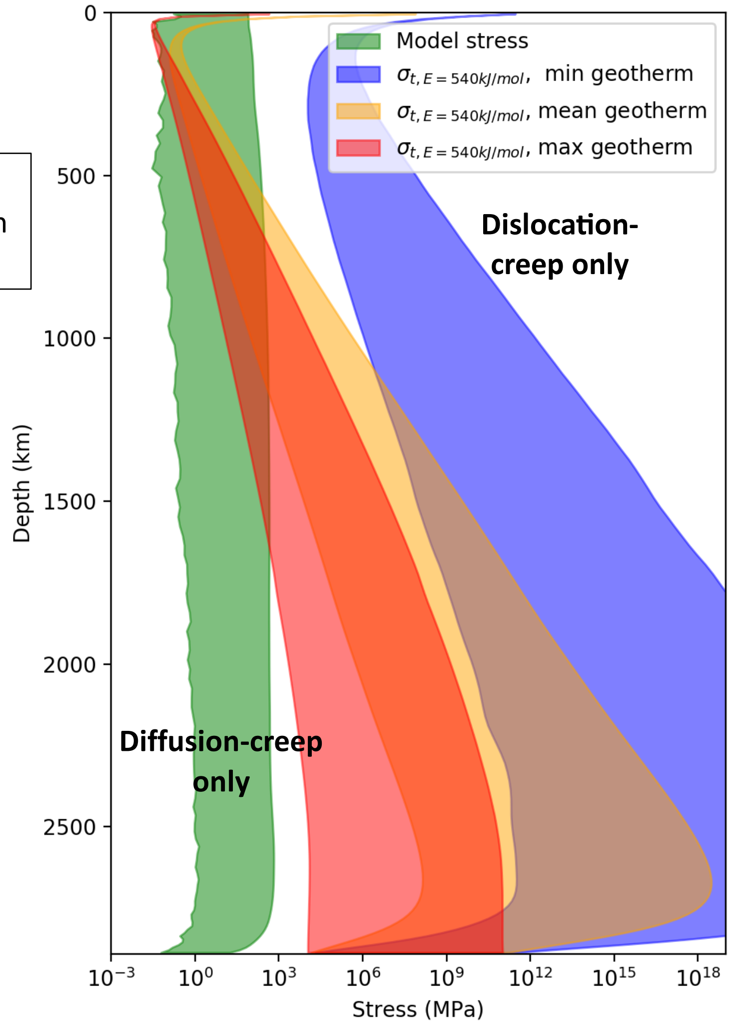
The green area contours the range of stresses present in our reference model with a plate-like behavior and diffusion-creep only

E_{disl}, V_{disl} dependence



Large range of variations of activation energies and volumes for dislocation creep → large variability of $\boldsymbol{\sigma_t}$

T and P dependence



$\boldsymbol{\sigma_t}$ increases with increasing pressure and decreasing temperature

Numerical models

Numerical setup [based on Arnould et al., 2018]:

- StagYY code [Tackley et al., 2008]
- Cartesian geometry (4x1, 512x128 cells)
- Boussinesq approximation
- Rayleigh number of $5.10^5 – 5.10^7$
- Mixed mantle heated from within (~80 %) and core (~20%)
- 6–8 orders of magnitude of viscosity variation
- Pseudo-plastic rheology (yield stress)
- E_{dif} = 127 kJ/mol and V_{dif} = 14 cm^3/mol
- Constant grainsize

Constitutive laws (dependence on T, P, d and σ):

$$\dot{\varepsilon}_{dif} = A_{dif} \left(\frac{d_0}{d}\right)^m \exp\left(-\frac{E_{dif} + PV_{dif}}{RT}\right) \sigma$$

$$\dot{\varepsilon}_{disl} = A_{disl}\, \sigma^n \exp\left(-\frac{E_{disl} + PV_{disl}}{RT}\right)$$

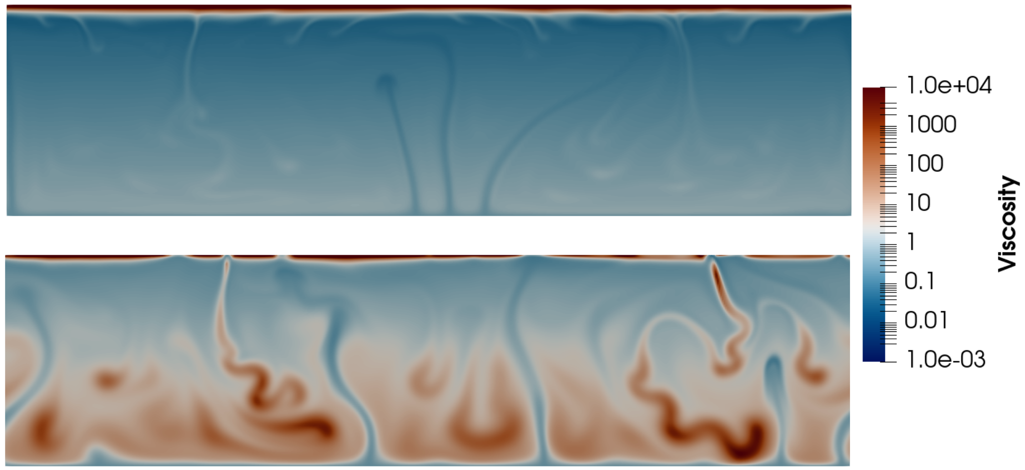
Transition stress σ_t:

$$\sigma_t(T, P, d) \equiv \left(\frac{d_0}{d}\right)^{\frac{m}{n-1}} \left[\exp\left(\frac{(E_{disl} - E_{dif}) + P(V_{disl} - V_{dif})}{RT}\right)\right]^{\frac{1}{n-1}}$$

Check next slide to see how model σ_t varies with E_{disl}, V_{disl}, **P** and **T**!

Two diffusion-creep only reference models:

- Stagnant-lid convection (yield-stress = 300 MPa)
- Plate-like behavior, no viscosity jump (yield-stress = 64 MPa)



Investigation:

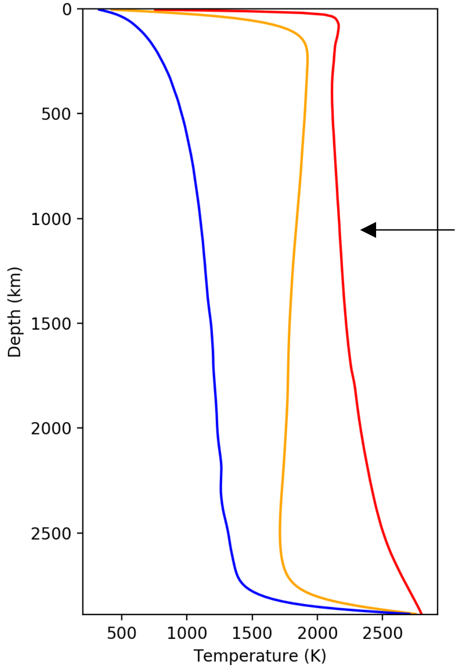
How does variation of E_{disl}, V_{disl} and Ra affect the distribution of dislocation creep?

Effects on mantle flow and surface behavior?

Transition stress – this study

⇒ Model E_{disl} and V_{disl} are smaller than experimental values for practical reasons.
(computation would be more difficult with realistic values).

⇒ We obtain trends for the dependence of σ_t on P, T, E_{disl}, V_{disl}. d similar to experimental laws.

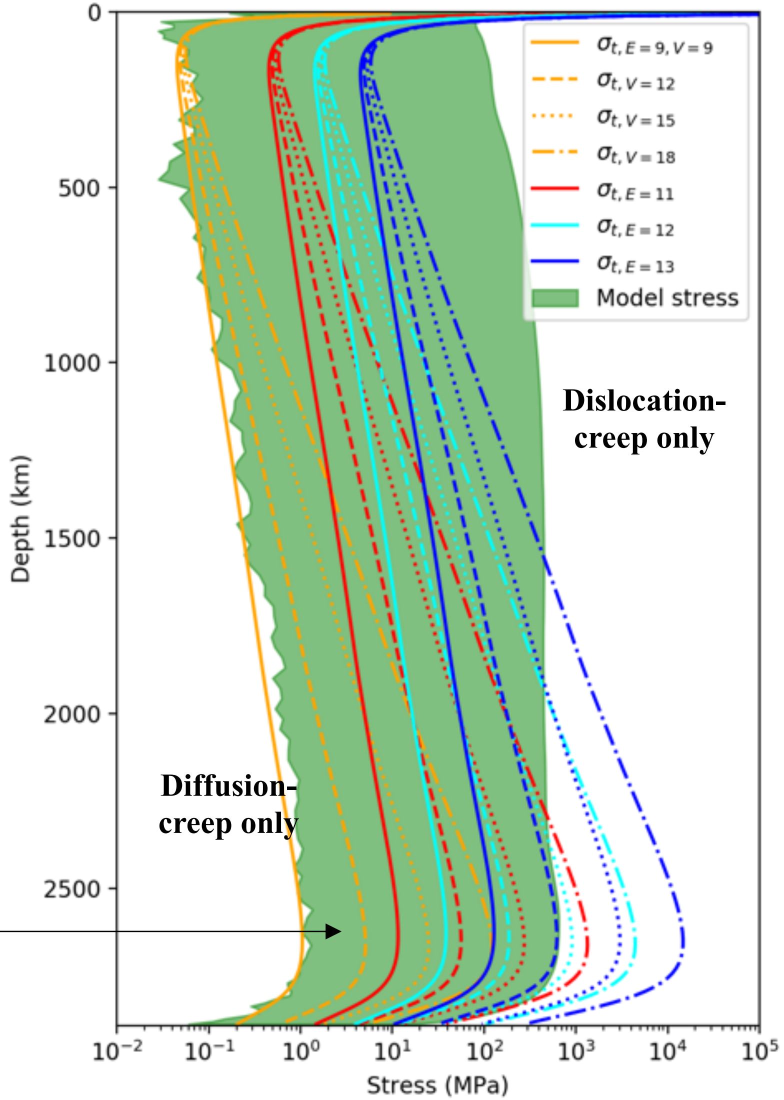


Here, σ_t is calculated from a radial profile of lithostatic pressure and the **minimum**, **average** and **maximum** geotherm of a reference model with plate-like behavior using diffusion-creep only.

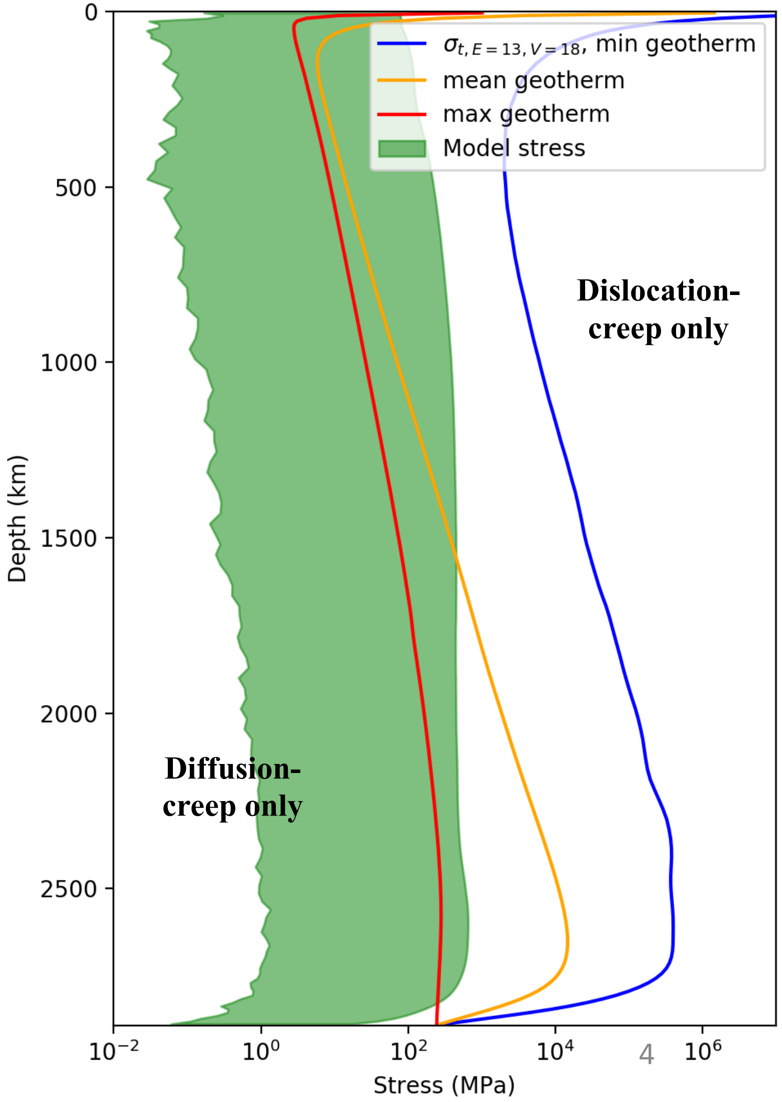
The green area contours the range of stresses present in our reference model with a plate-like behavior and diffusion-creep only

$190 < E_{disl} < 275$ kJ/mol
$41 < V_{disl} < 83$ cm³/mol
Average model geotherm
Lithostatic pressure

E_{disl} and V_{disl} dependence



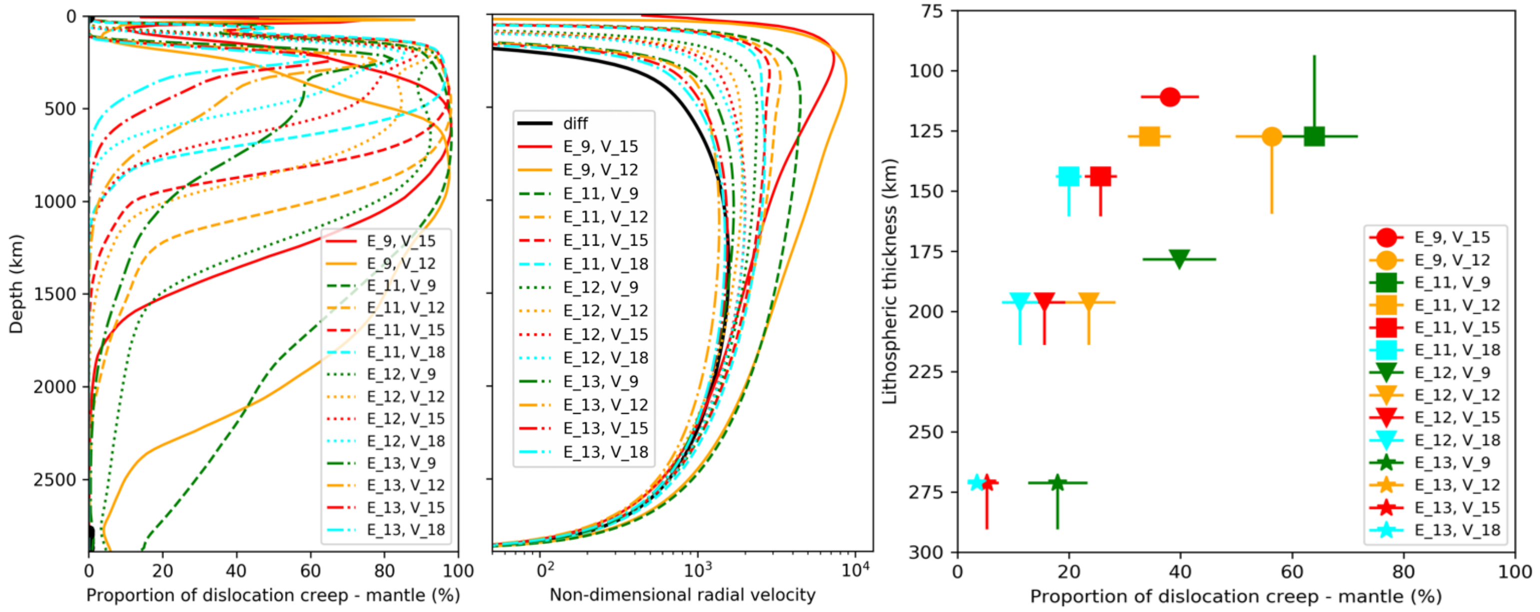
T and P dependence



Effect of varying the activation energy and volume – stagnant-lid models

⇒ Proportion of dislocation creep decreases with increasing activation energy and its maximal depth decreases with increasing activation volume.
It dominates in the upper mantle.

⇒ The increasing proportion of dislocation creep favors lower viscosity in the asthenosphere, promoting more vigorous upper-mantle convection and generating a thinner lithospheric lid.



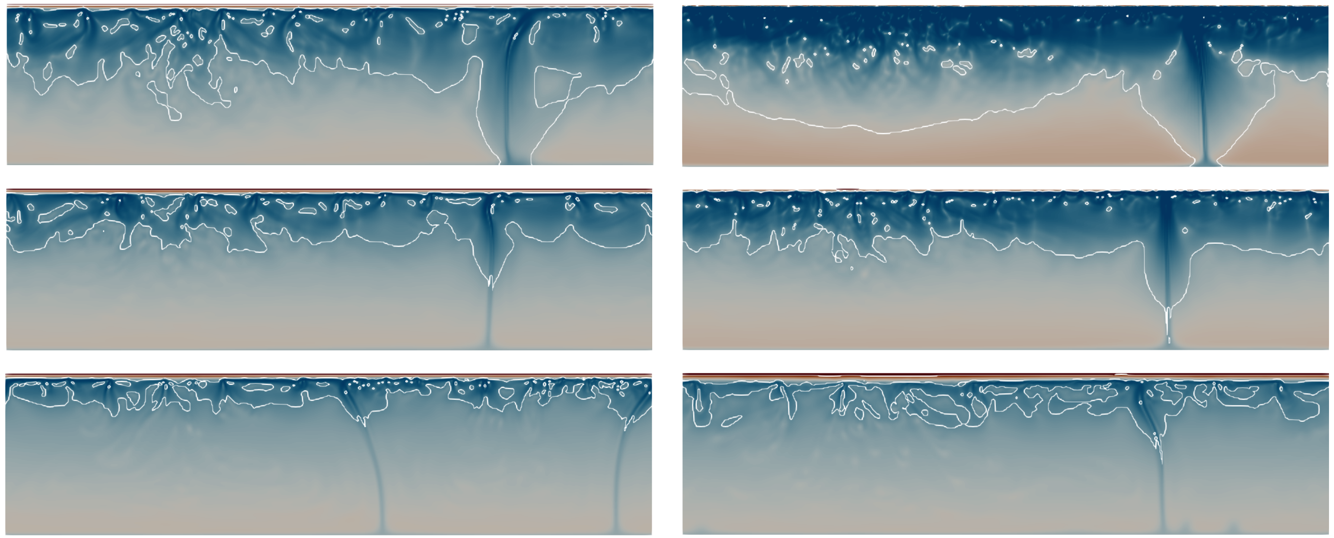
Constant E_{disl} = 12 (254 kJ/mol)

Constant V_{disl} = 12 (55 cm^3/mol)

V_{disl} = 9 (41 cm^3/mol)

V_{disl} = 12 (55 cm^3/mol)

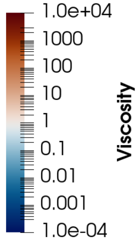
V_{disl} = 18 (83 cm^3/mol)



E_{disl} = 9 (190 kJ/mol)

E_{disl} = 11 (233 kJ/mol)

E_{disl} = 13 (275 kJ/mol)



$190 < E_{disl} < 275$ kJ/mol
$41 < V_{disl} < 83$ cm^3/mol
Constant grain-size

The white contours delineate portions of the mantle deforming in pure **(100%)** dislocation creep.

Effect of varying the activation energy and volume – mobile-lid models

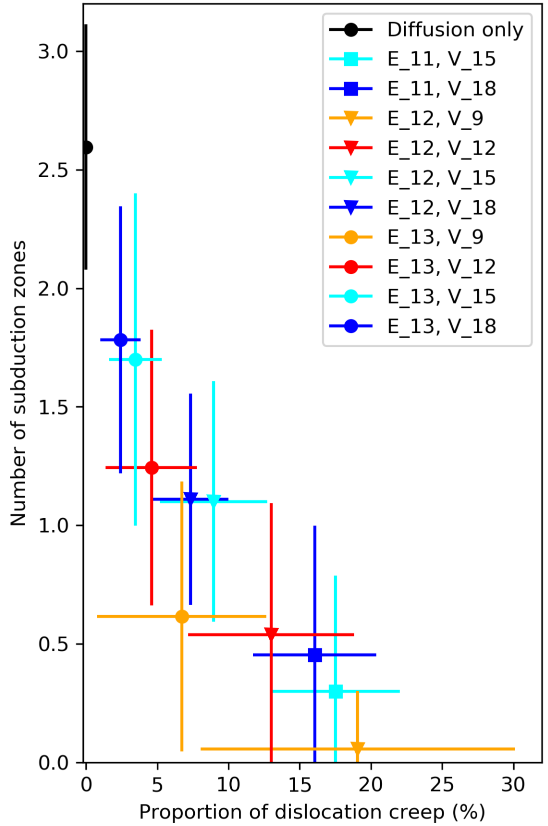
⇒ Same trend for the proportion of dislocation creep with increasing E_{disl} and V_{disl} as in stagnant-lid models

⇒ Plumes are more likely deforming in dislocation creep while slabs are dominantly deforming in the diffusion-creep regime. Dislocation creep likely occurs around slabs.

⇒ The shape of slabs depends on the proportion of dislocation creep:

- large proportion of dislocation-creep => slabs break often.
- intermediate proportion of dislocation-creep => slabs are weak and highly buckled
- small proportion of dislocation-creep => slabs are stiffer and less buckled.

⇒ An increased proportion of dislocation creep reduces upper mantle viscosity which makes surface plate-like behavior more episodic



$233 < E_{disl} < 275$ kJ/mol
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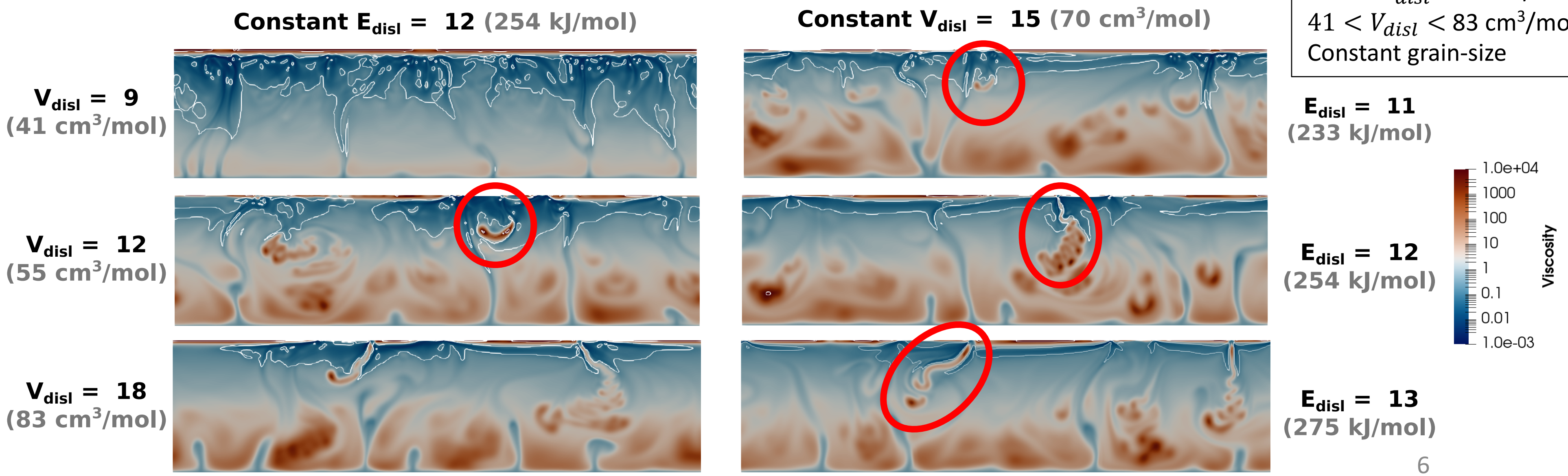
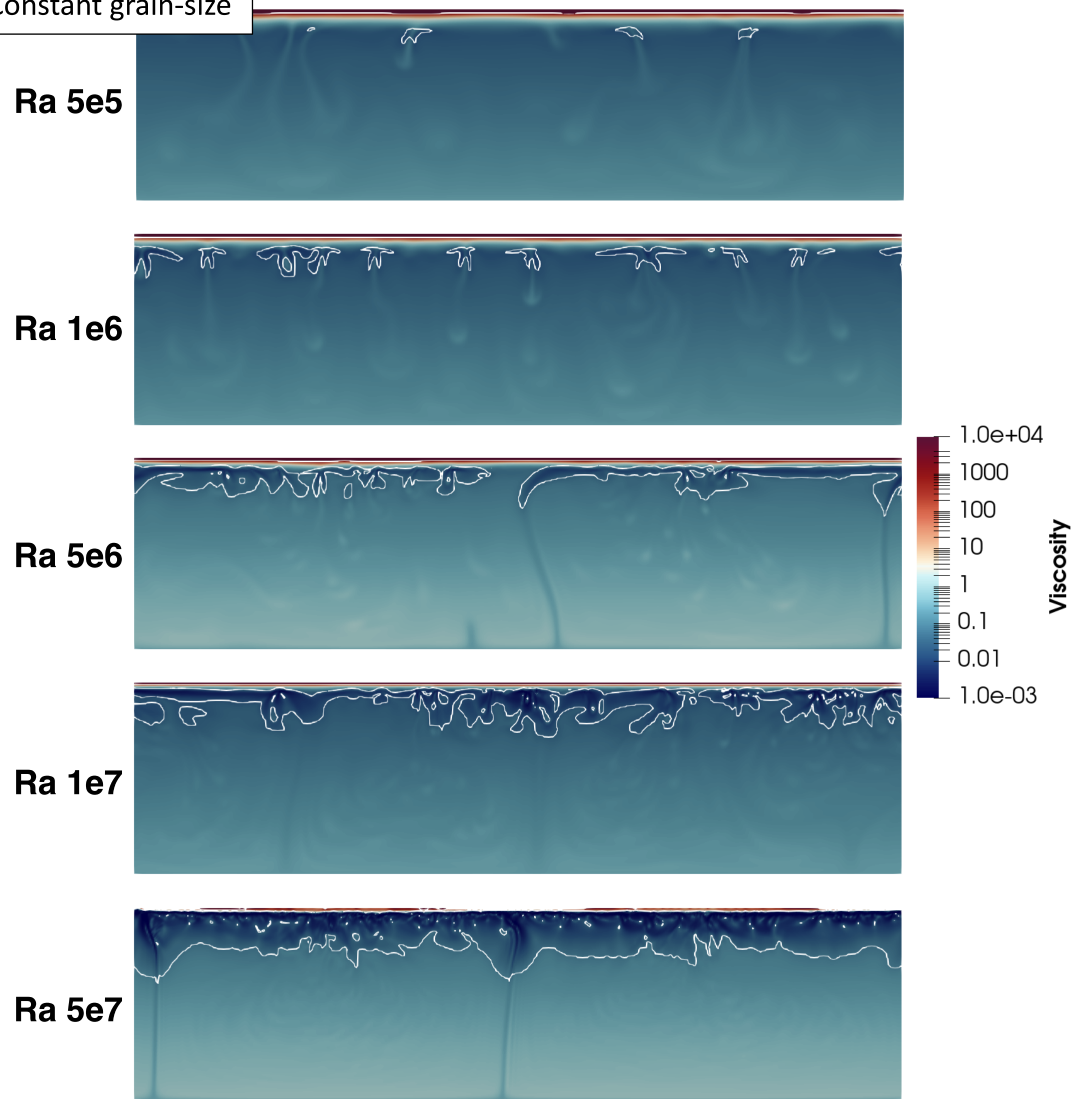
Constant grain-size



The white contours delineate portions of the mantle deforming in pure **(100%)** dislocation creep.

Effect of varying the Rayleigh number – stagnant-lid models

E_{disl} = 275 kJ/mol
V_{disl} = 83 cm^3/mol
Constant grain-size

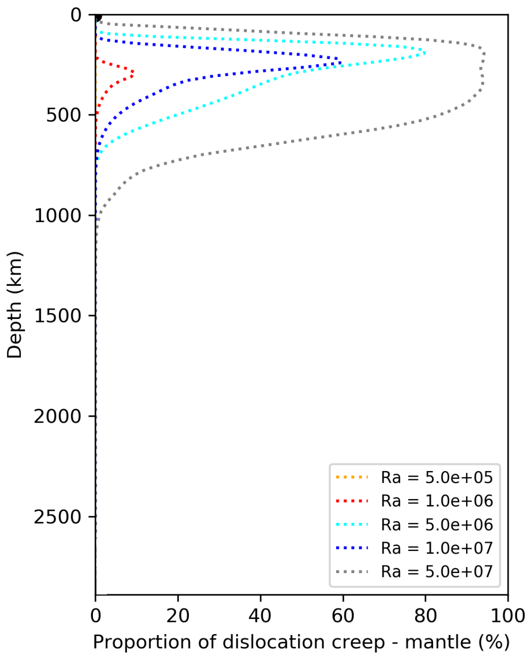


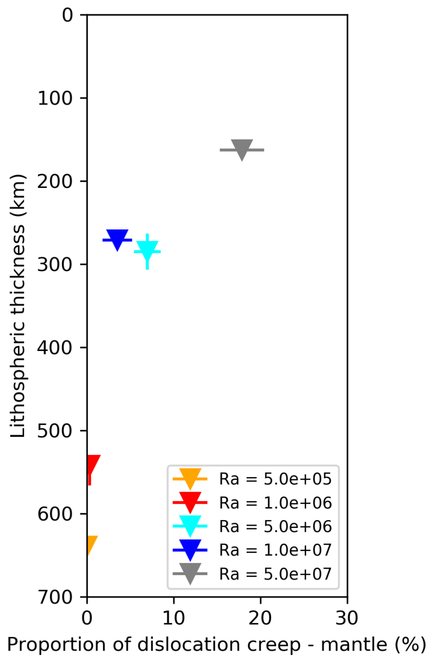
The white contours delineate portions of the mantle affected by at least **30%** dislocation

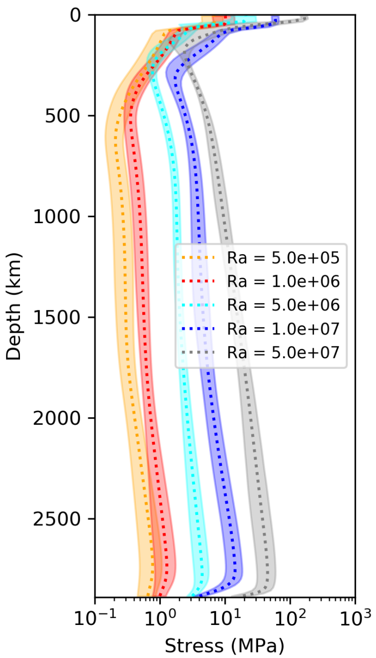
⇒ Increasing the reference Rayleigh number **Ra** while keeping E_{disl}, V_{disl} and **d** constant results in increased stresses within the convective system.

⇒ As a result, larger portions of the mantle exceed the transition stress and deform in dislocation creep.

⇒ Upper mantle viscosity is lower and lithosphere is thinner with increasing **Ra**.







Conclusions:

Stagnant-lid models:
increasing E_{disl} and V_{disl} or Ra results in an **increased proportion of dislocation creep** in the upper mantle, which generates **lower viscosities**, **thinner lithospheric lids** and **larger mantle velocities** than models in pure diffusion creep only.

Models with plate-like behavior:
at **a given yield–stress**, **different tectonic behaviors can arise** depending on the amount of dislocation creep in the mantle through the **modulation of the asthenospheric and upper-mantle viscosity.**

Perspectives:

- What is the role of **grain-size and its spatiotemporal evolution** on mantle and plate-like behaviour?
- Under which conditions are model predictions of dislocation creep distribution **comparable to predictions seismic anisotropy distribution** in Earth's upper mantle?
- Moving to 2D spherical annulus and/or to 3D geometry?
- What are the implications of a composite rheology on the **surface dynamics of other planetary bodies with different surface conditions** (e.g. Venus, icy bodies)?