Convection in Europa's icy shell: composite rheology and dynamic grain size evolution

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EGU23-6132

MOTIVATION

Europa is a prime target for exploring extraterrestrial habitability. Convection and tectonics in its ice shell control heat and material transport, thus surface-ocean exchange. The style of convection and its link to surface observables is poorly understood though. Here we are interested in:

- **How does Europa's ice shell deform (in which deformation mechanism?**
- **How sensitive are the ice shell dynamics to grain-size evolution (GSE)?**

APPROACH

Code StagYY *[3]*; incompressible extented boussinesq; 160x20 km box (1024x128 cells), 64 markers/cell. Ra =2.57x10^7, n=(1, 2.4, 1.8, 4) for (dif,bsl,gbs,dis), m=(2, 0, 1.4, 0), E=(60, 60, 50, 60) kJ/mol *[1,2]*, p=4, D*=4 mm, f=10^{-2}, k~4.4x10^{-11} m^4/s.

- **Composite rheology** as experimentally inferred for ice *[1]*. 4 different deformation mechanisms *i [2]*: diffusion creep **(dif),** basal slip **(bsl),** grain boundary sliding **(gbs),** and dislocation creep **(dis)**, with different dependencies on stress and grain size (e.g. exponents n_i, m_i).

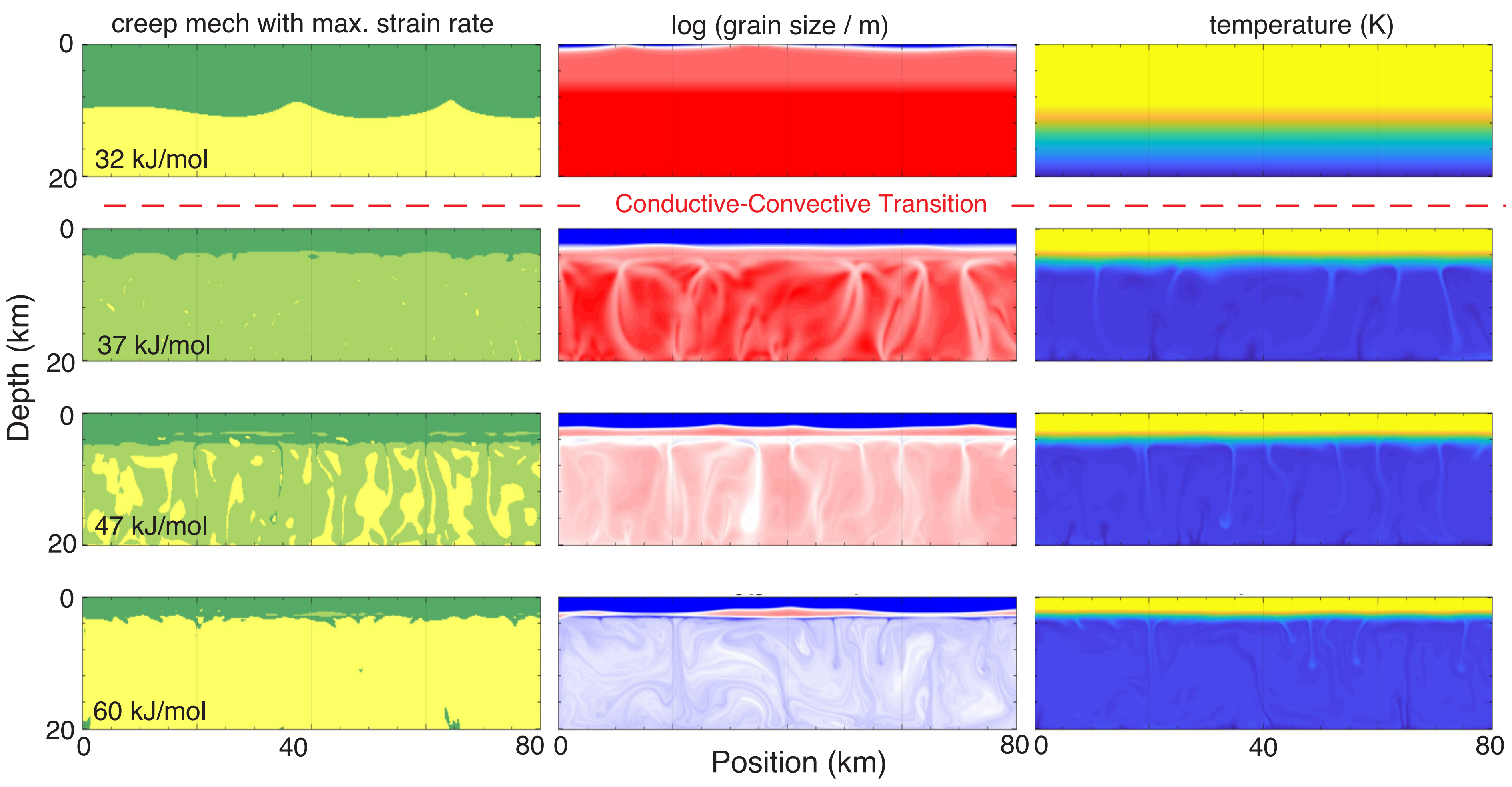
$$\eta_i = B_i\left(\frac{\tau}{\tau_i^*}\right)^{1-n_i}\left(\frac{D}{D_i^*}\right)^{m_i}\exp\left(\frac{E_i}{RT}\right) = \tilde{B}_i\tau^{1-n_i}D^{m_i}\exp\left(\frac{E_i}{RT}\right)$$

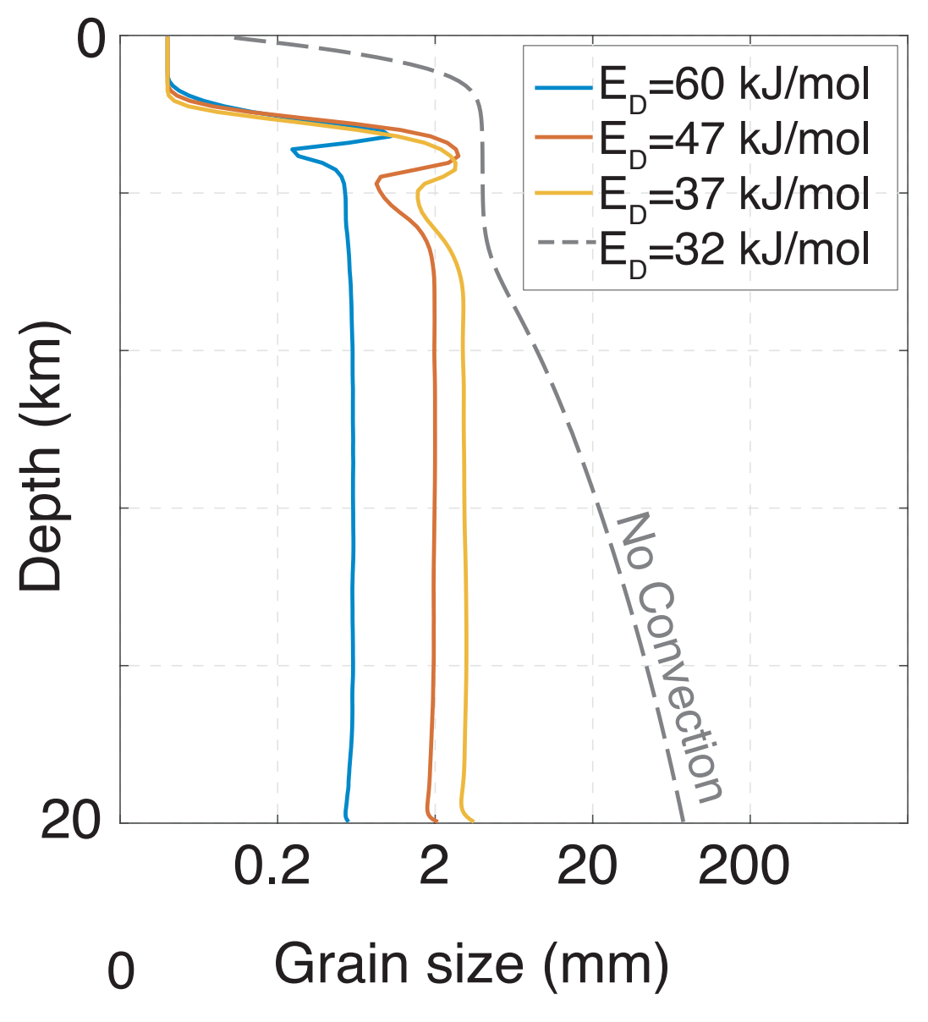
$$\eta = \left(\frac{1}{\eta_{dif}} + \frac{1}{\eta_{bsl}+\eta_{gbs}} + \frac{1}{\eta_{dis}}\right)^{-1}$$

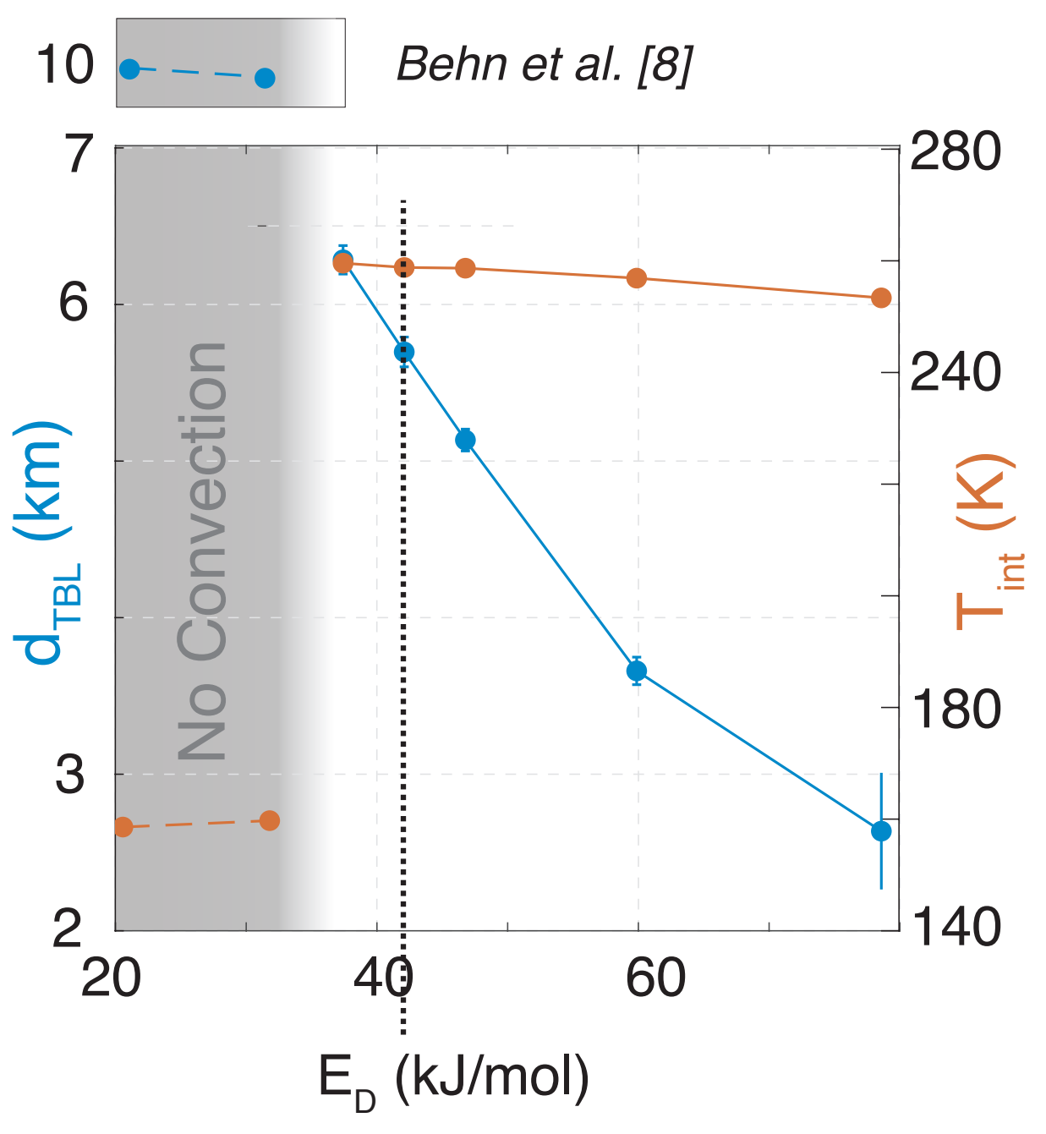
- **Grain size evolution (GSE)** *[4,7]*: on tracers; balance of grain growth and reduction; *Ψ*=viscous dissipation (without the fraction done in DIF creep):

$$\dot{D} = \frac{k\exp\left(-E_D/RT\right)}{pD^{p-1}} - CfD^2\Psi$$

GSE PARAMETERS (here only E_D)





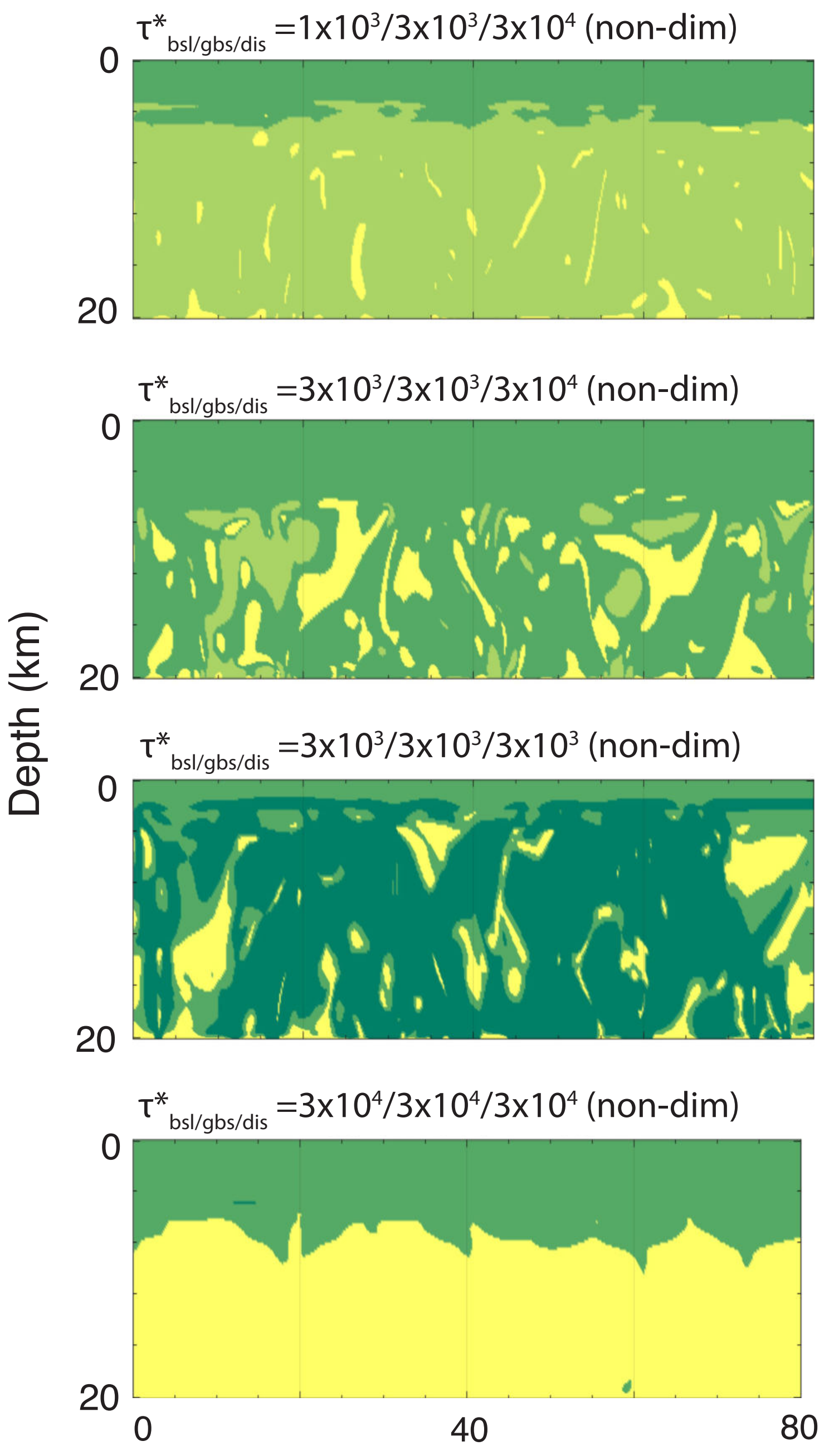


- **Reducing E_{GS}**: Grain growth is less sensitive to temperature
- Faster grain growth in interior, therefore higher viscosity that can eventually cause **convection to cease (conductive ice shell)**.
- Other GSE parameters (k, f) indicate similar, but less pronounced effects. The system should also be very sensitive to the grain size expoent (*p*, to be tested).

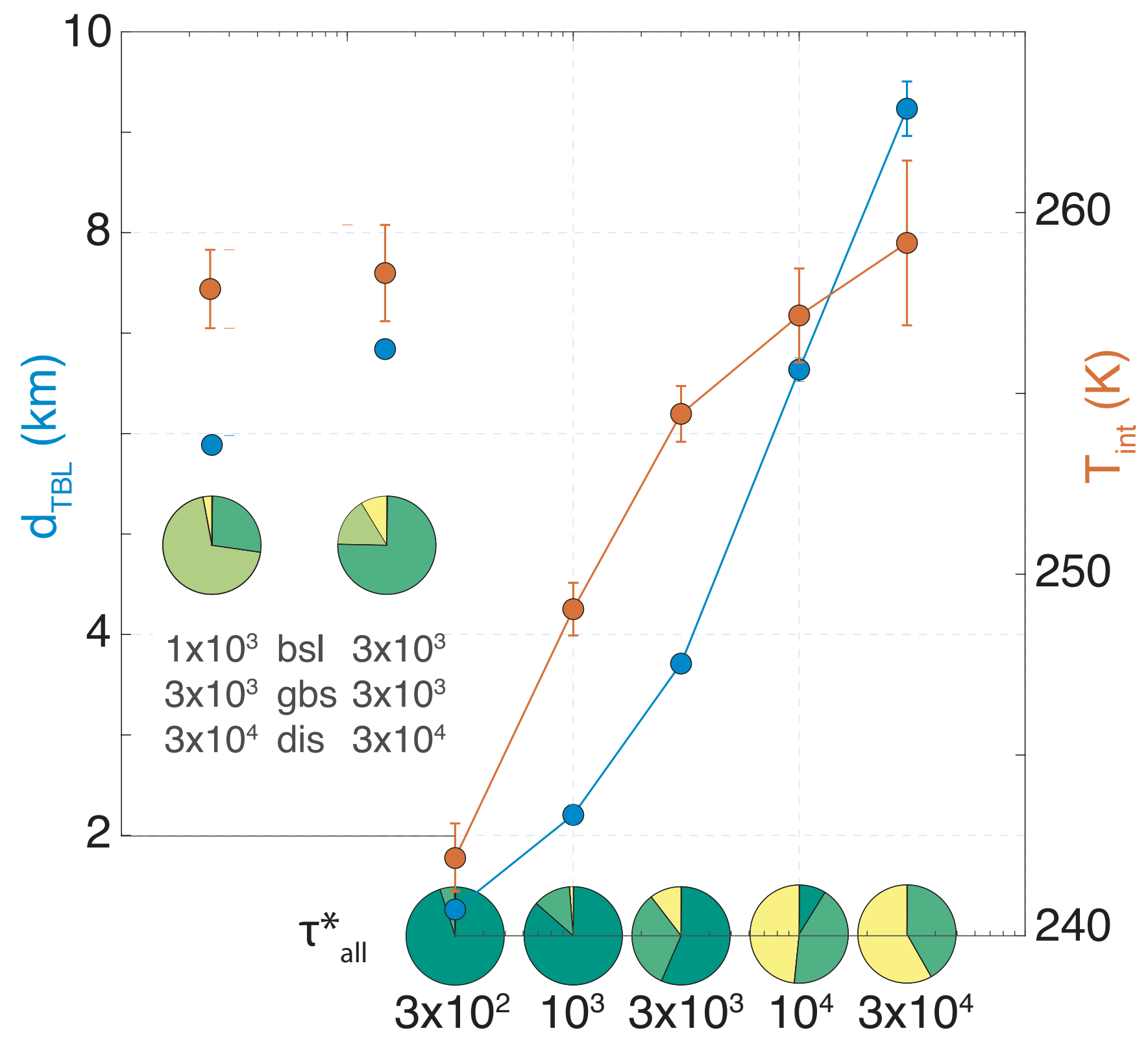
d_{TBL}: Thickness of the thermal boundary layer (~the immobile layer)

T_{int}: Characteristic temperature of the convecting interior. Value not meaningful if purely conductive!

TRANSITION STRESSES

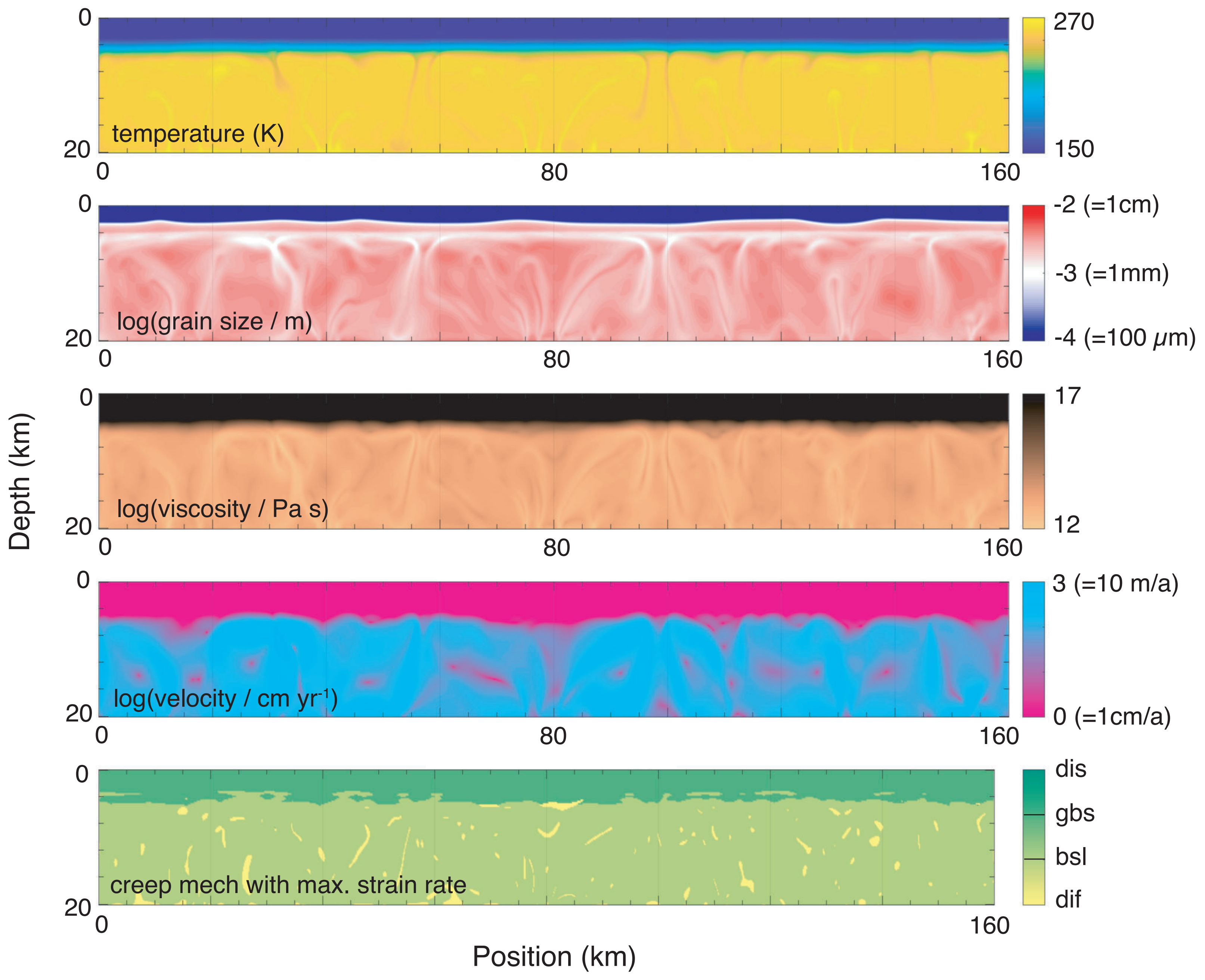


- Reference stresses **crucial for dominant creep mechanism**. Equal values for all mechanisms promote the one with largest stress exponent.
- **Immobile layer thinner with more abundant nonlinear creep** (especially DIS) *[see 4,5]*, because of lower viscosity and more vigorous convection
- Laboratory data *[1]* suggests that here $\tau^*_{bsl} << \tau^*_{gbs} << \tau^*_{dis}$ as already used. But results are very sensitive to chosen ratios and values! Values matching the laboratory constraints are to be tested!



EXAMPLE

- **Immobile surface layer:** ~6 km thick, small grains (<100µm), high viscosity (since strongly T-dependent viscosity), max. strain rates occur in GBS creep
- **Convecting interior:** Larger grains (several mm), mild variation in viscosity (~1.5 order of magnitude) and grain size (<1 order), highest strain rates in BSL creep, or in DIF (some pockets)

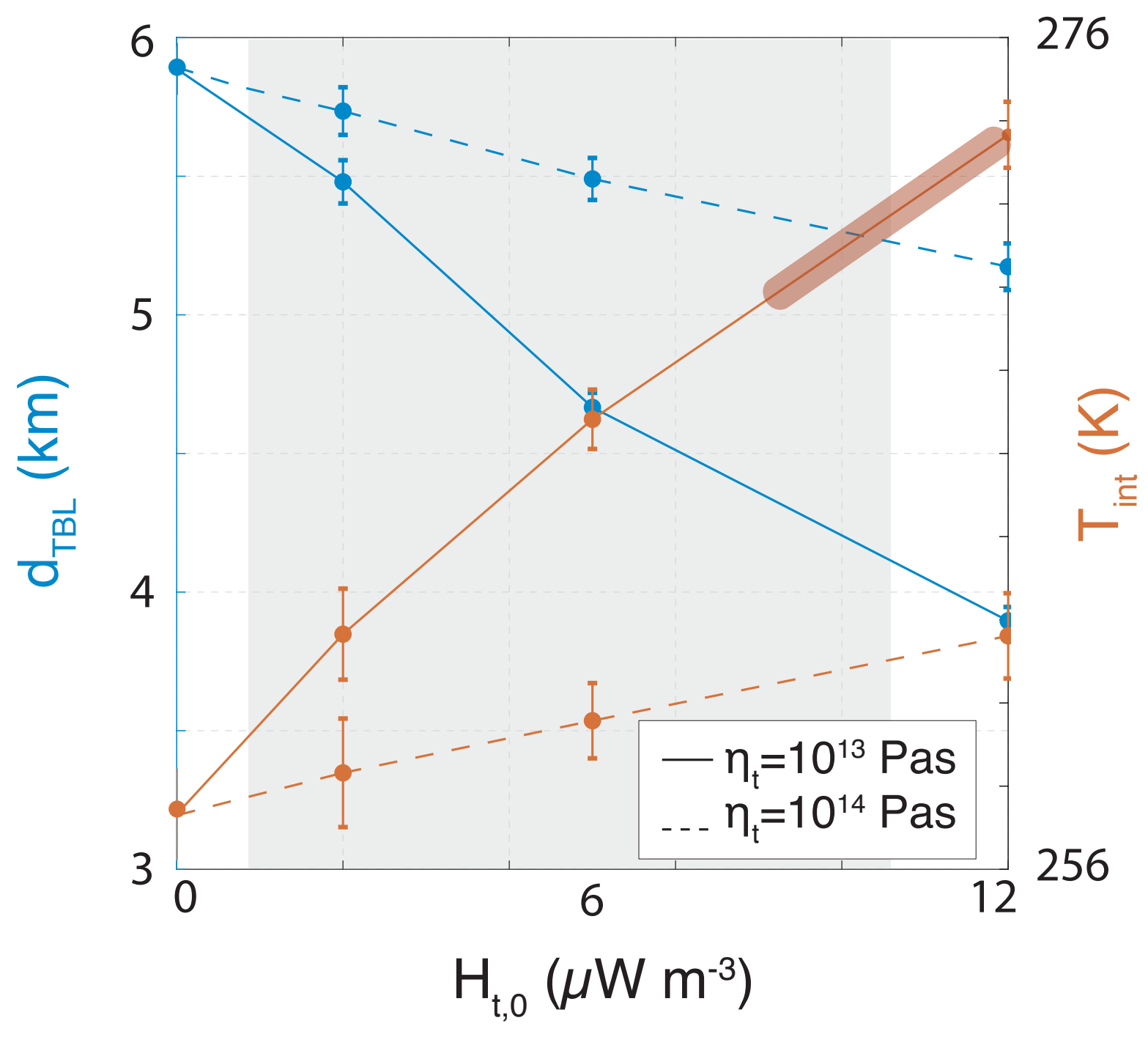


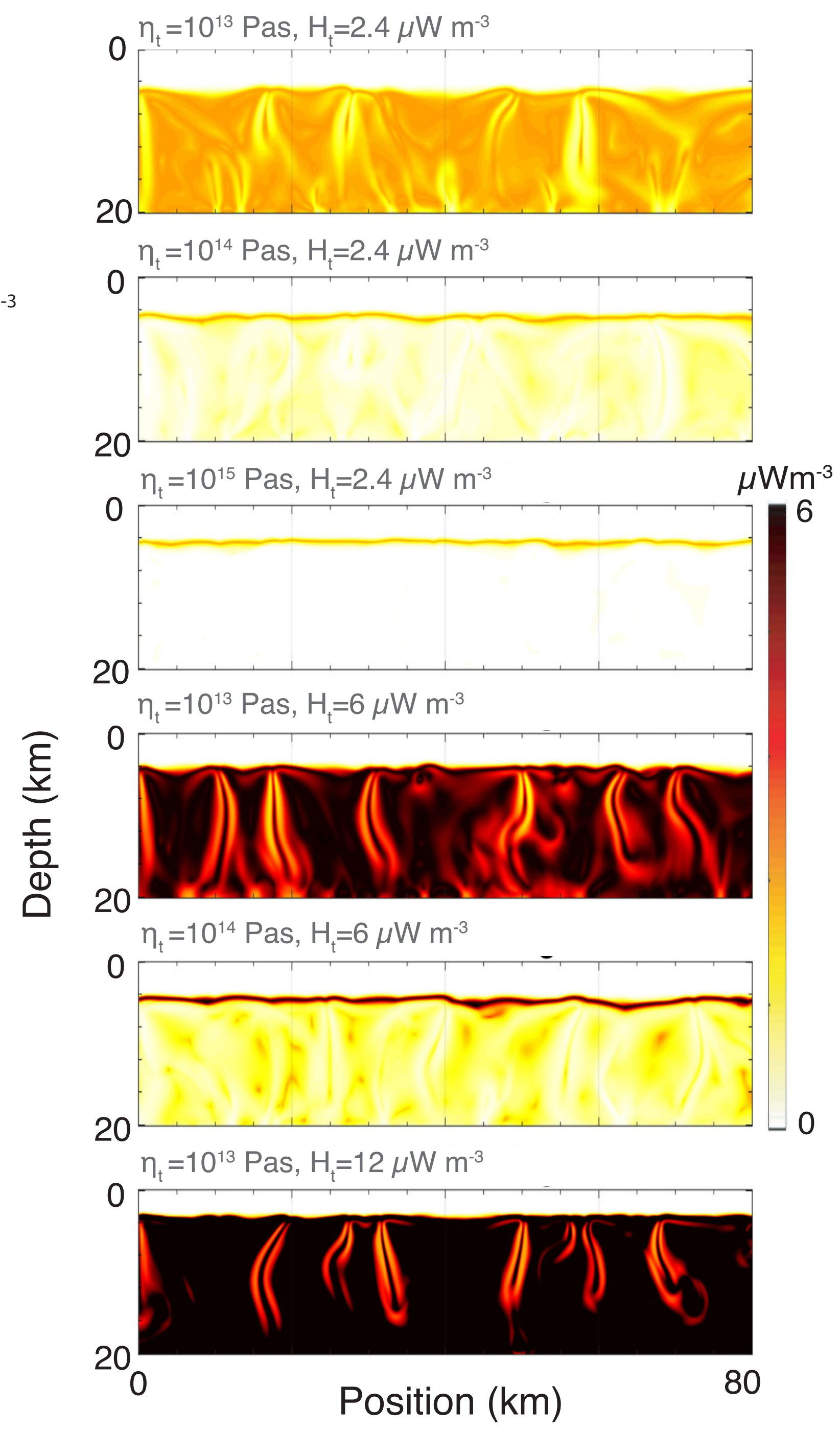
TIDAL HEATING

$$H_t = H_{t,0}\left(\frac{2\eta\eta_t}{\eta^2+\eta_t^2}\right)$$

$H_{t,0}$: Optimal tidal heating rate at η_t. Europa: ~1-10 µW m^{-3}

η_t: Optimal viscosity for tidal heating, ~ratio of shear modulus & orbital period. Europa: ~10^{13} - 10^{14} Pas.





- No tidal heating in immobile layer, but higher $H_{t,0}$ in interior **increases internal temperature** (T_{int}) and **thins the immobile layer** (d_{TBL}).

- Higher T_{int} tends to **promote diffusion creep** compared to the other creep mechanisms.
- For small η_t =10^{13} Pas and large H_t, large portions of the ice shell would just melt!

TAKE HOME

- Convection in Europa's ice shell features a conductive, immobile layer over a convecting interior. The dominant creep mechanism and the amount of tidal heating determin immobile layer thickness.
- GSE affects the dominant creep mechanism, the thickness of the immobile layer and also thepossibility of convection. It should not be omitted when investigating the dynamics of planetary ice shells!
- While aboratory experiments neither confirm nor reject the occurence of diffusion creep, our simulations predict DIF to be a feasible mechanism in the convecting deeper interior.
- Composite rheology coupled to GSE does not generate a mobile surface by itself; no presented cases displays any notable surface mobility. Plastic yielding may still be required as an additional weakening mechanism.

TO-DO

- Transition stresses in line with laboratory experiments
- Plastic Yielding (for surface mobilisation)
- Ice impurities and their effect on GSE

REFERENCES [1] Goldsby & Kohlstedt, 2001, JGR, 106, 11017-11030, [2] Harel et al., 2020, Icarus, 338, 113448, [3] Tackley, 2008, PEPI, 171, 7-18, [4] Rozel & Ricard, 2014, GJI, 184, 719-728, [5] Schulz et al., 2019, GJI, 220, 18-36, [6] Arnould et al., 2023, submitted to GRL, [7] Cordoba et al., 202*, in prep., [8] Behn et al., 2021, The Cryosphere, 15, 4589-4605.