MANTLE FLOW AND ANISOTROPY

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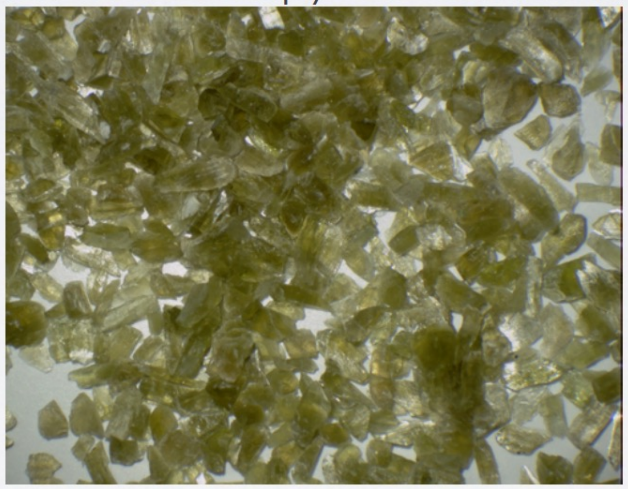
UiO : University of Oslo

Recap – What we know about the mantle?

Olivine

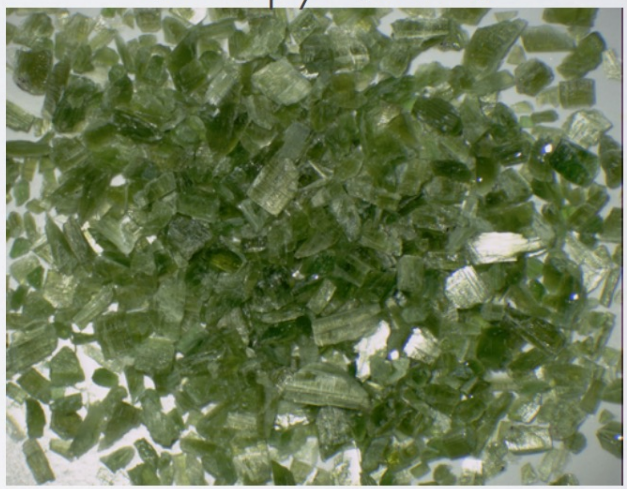
1 cm

Orthopyroxene



1 cm

Clinopyroxene

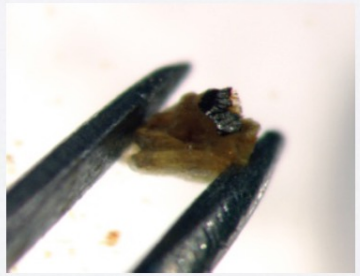


1 cm

Spinel

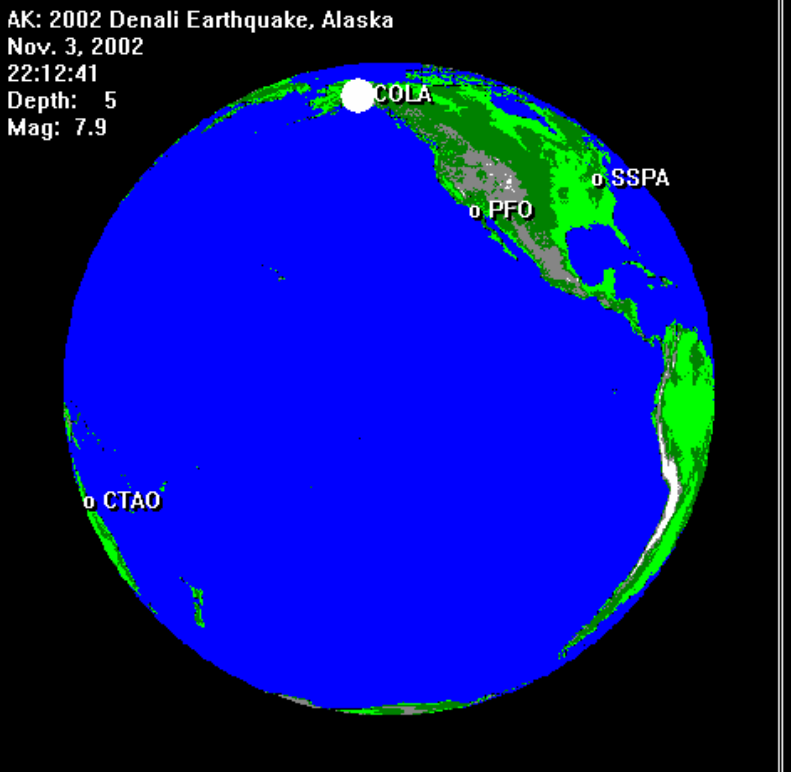
1 mm

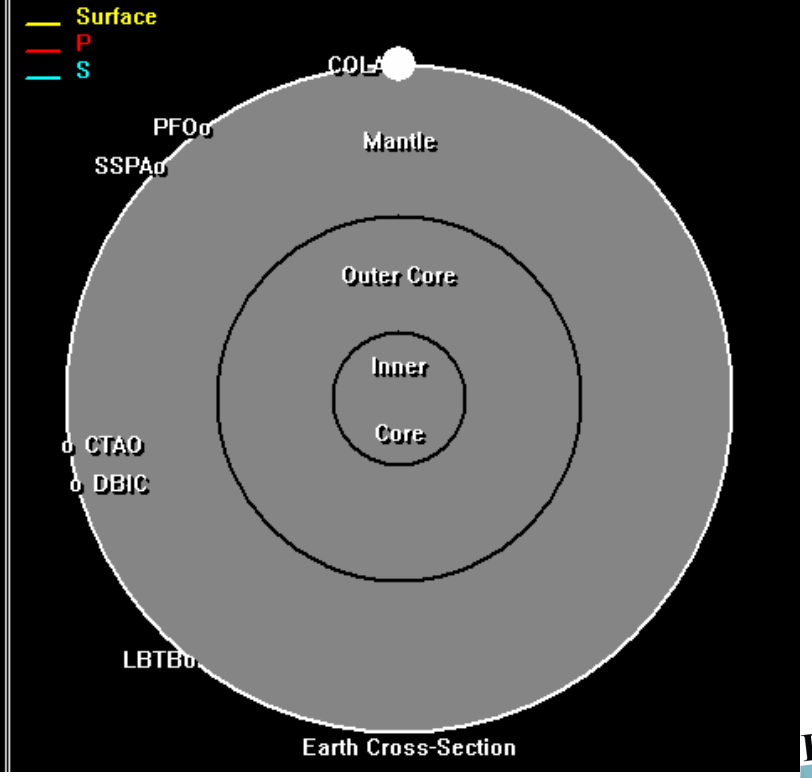
Sulfide



1 mm

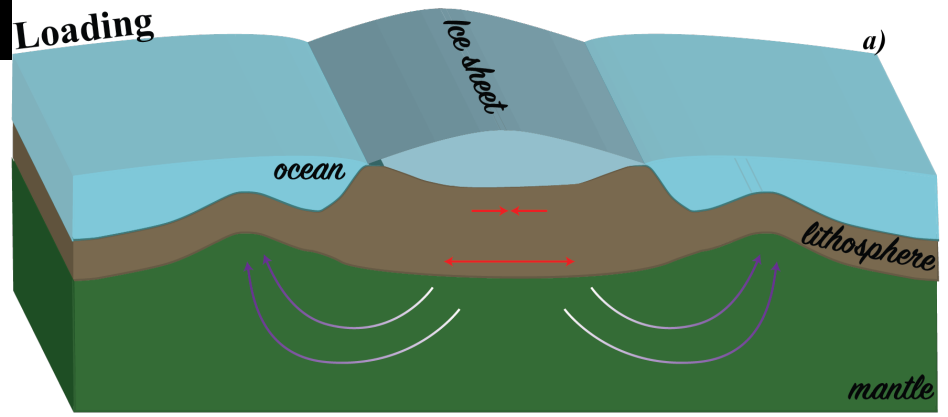
Recap – What we know about the mantle?

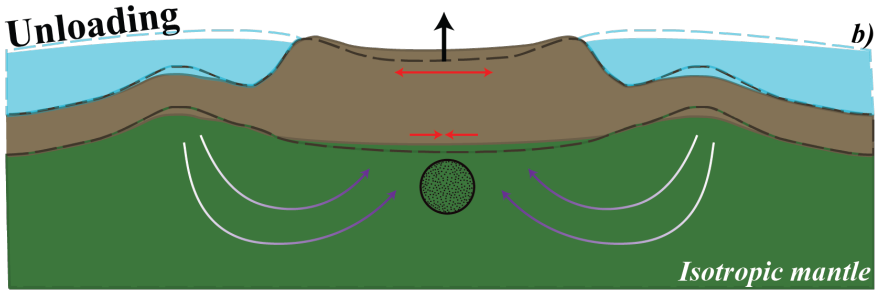




SOLID

FLUID





Rheology

Describes the ability of stressed materials to deform, or flow, using fundamental parameters including stress, strain rate, elasticity and viscosity (from Greek, rheos, to stream or flow)

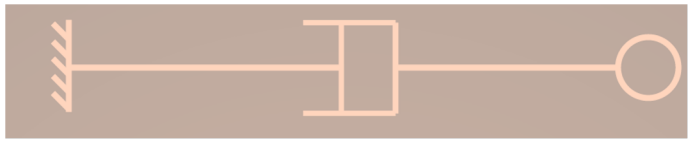
van der Pluijm and Marshak (2017)

Deformation styles

- **Elastic deformation**

$Hook's\ law\colon\ \sigma_{ij} = C_{ijkl}\varepsilon_{kl}$

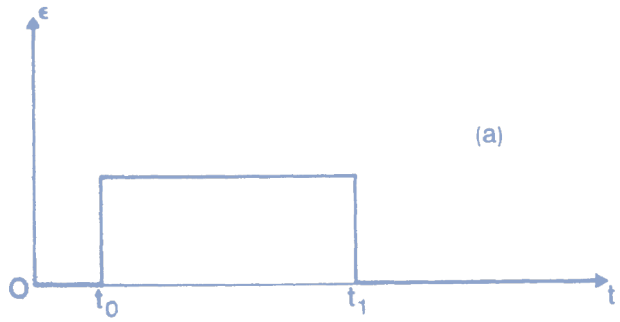
- **Viscous deformation**

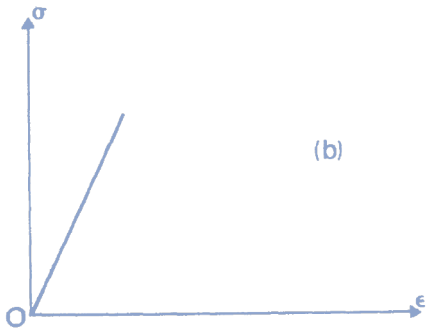


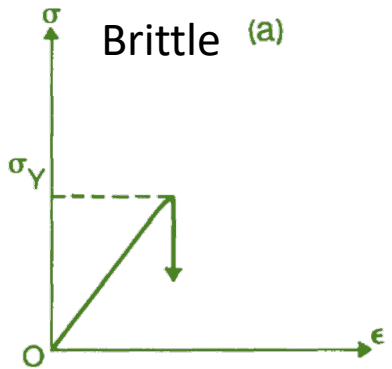
$\sigma_{ij} = \eta_{ijkl}\dot{\varepsilon}_{kl}$

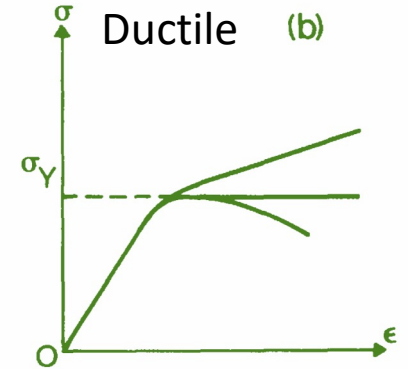
- **Plastic deformation**

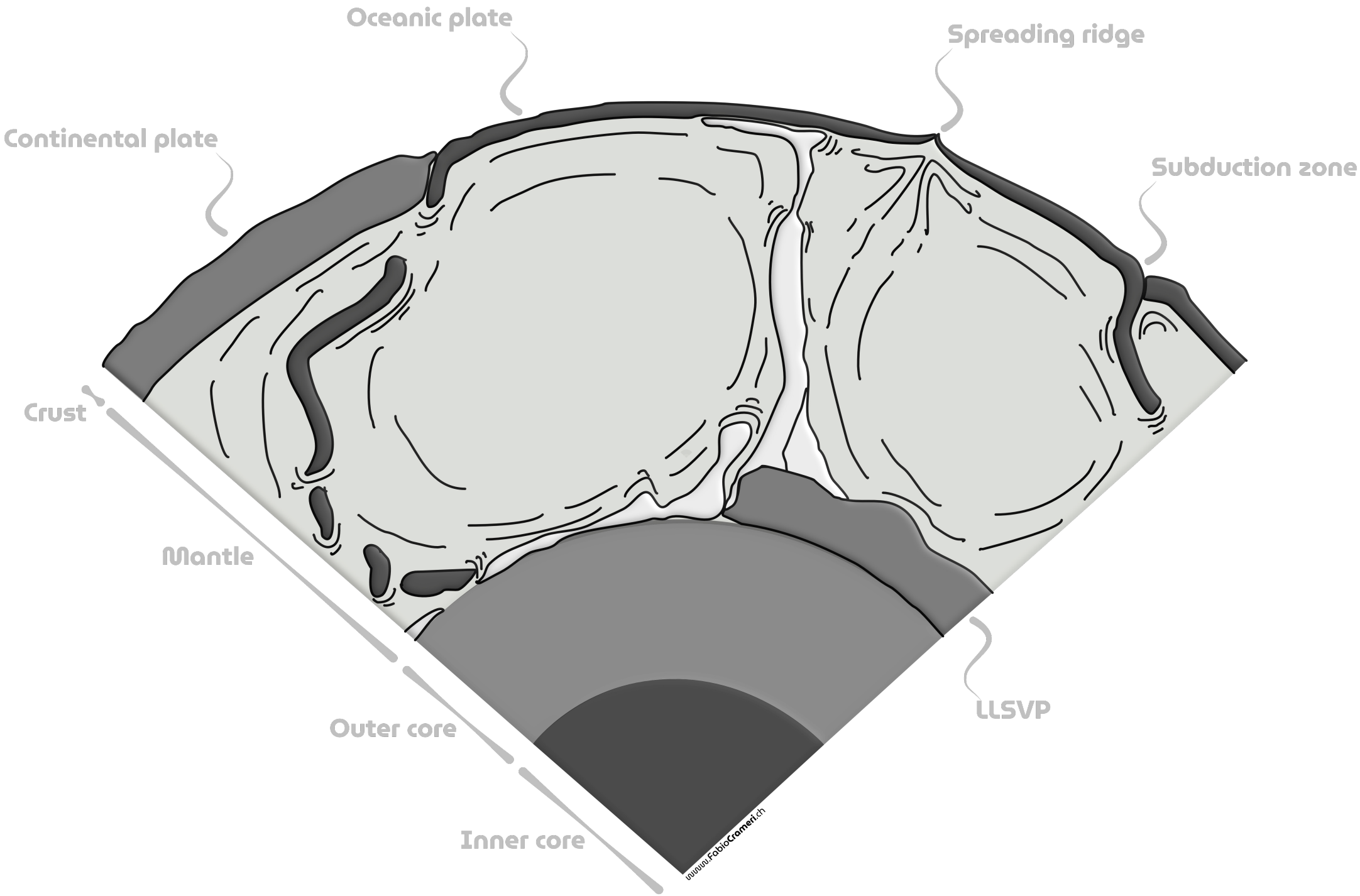
Irreversible deformation happens when a yield stress is achieved

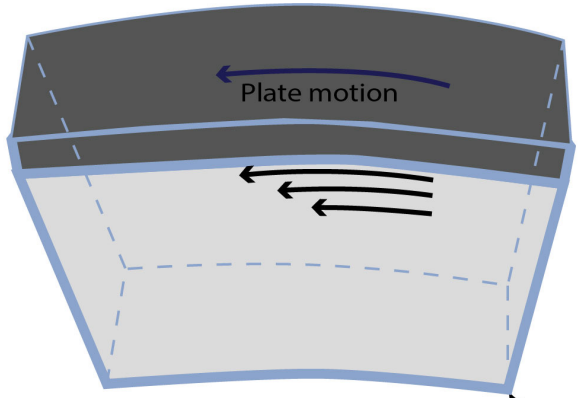


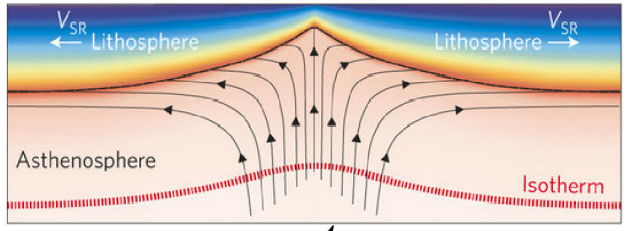


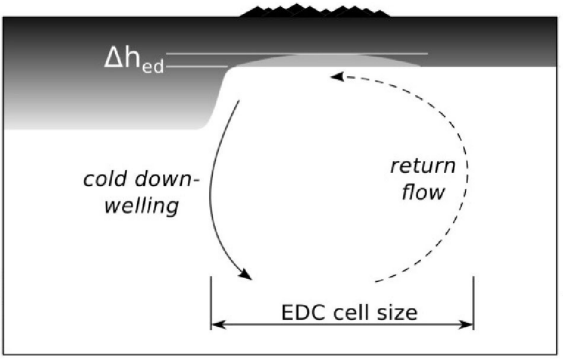


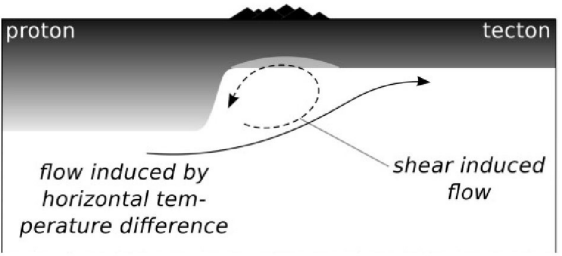


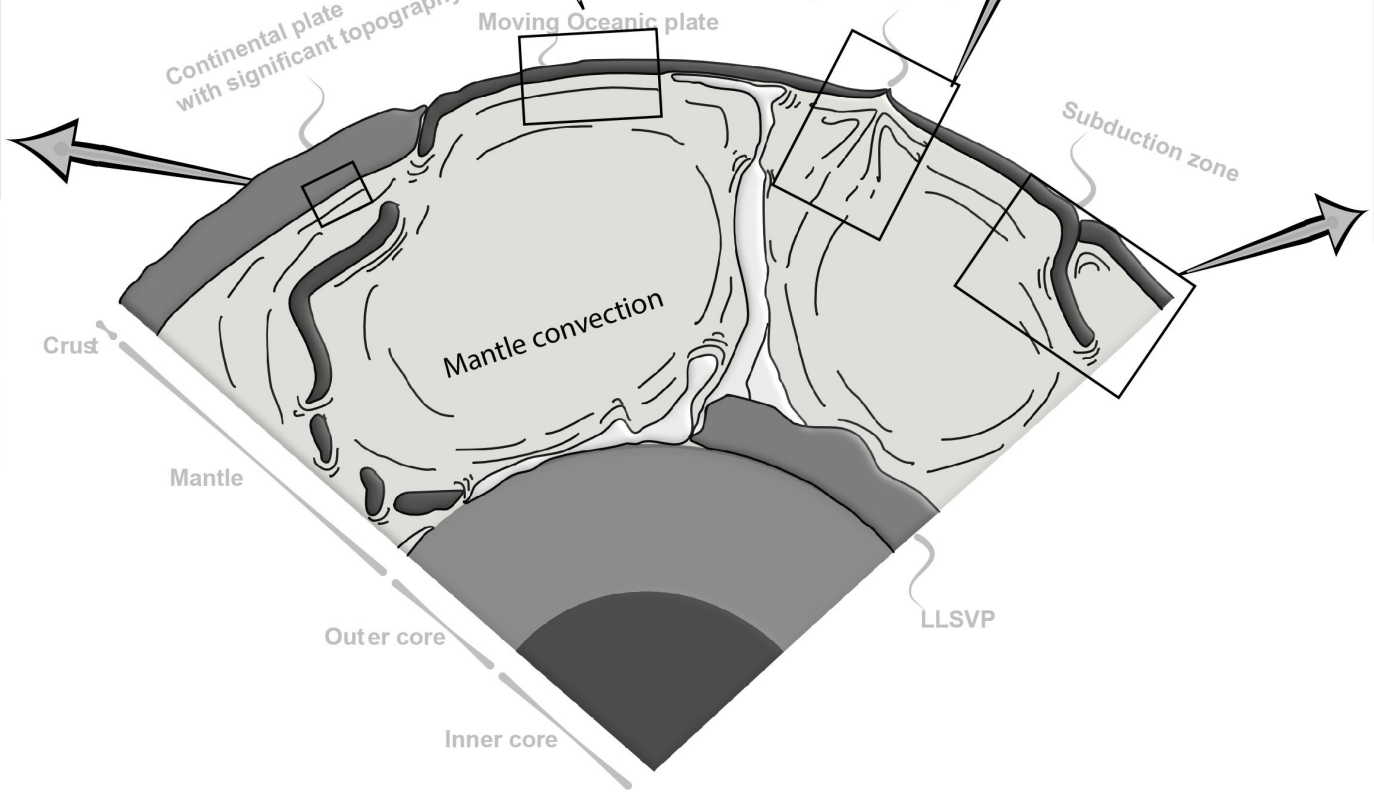

Oceanic plate
Spreading ridge
Continental plate
Subduction zone
Crust
Mantle
Outer core
LLSVP
Inner core
www.FabioGrameri.ch

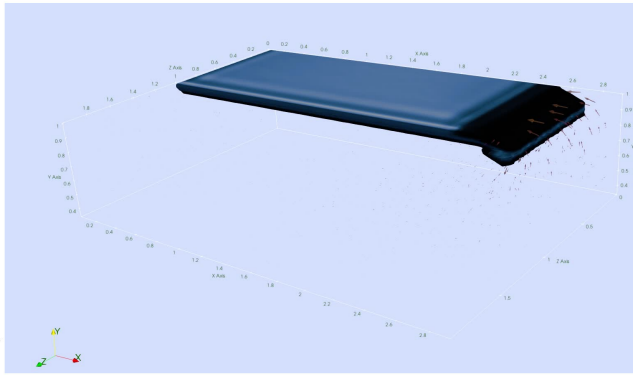






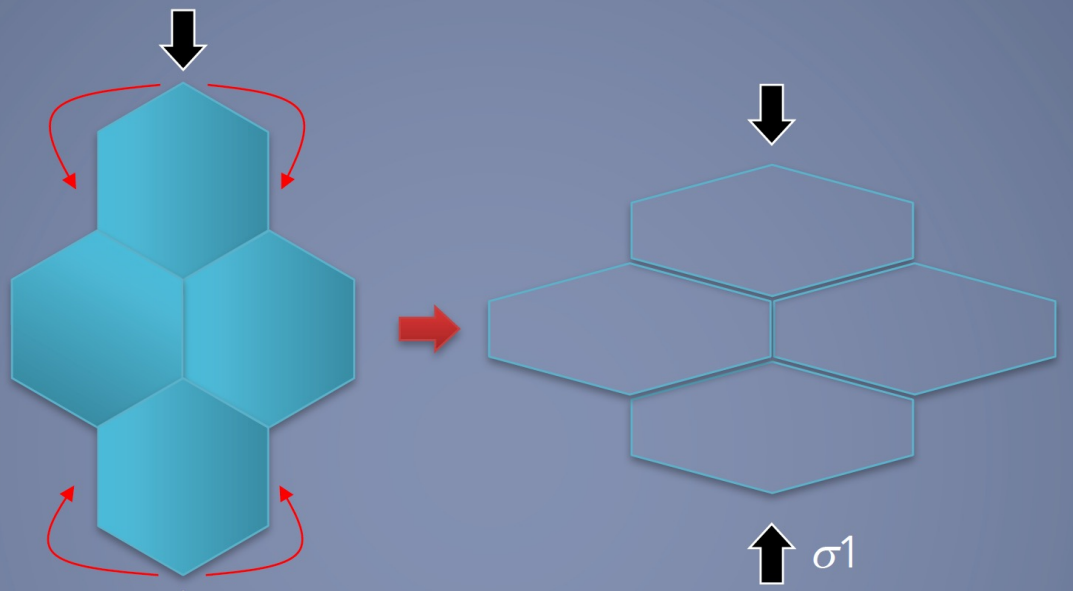






Ref.: F. Crameri – S-ink.org; Király et al., 2017; Whittaker et al., 2015; Kaislaniemi and van Hunen, 2014

Diffusion creep



$$\dot{\varepsilon} \propto \frac{\sigma^n}{d^m}$$

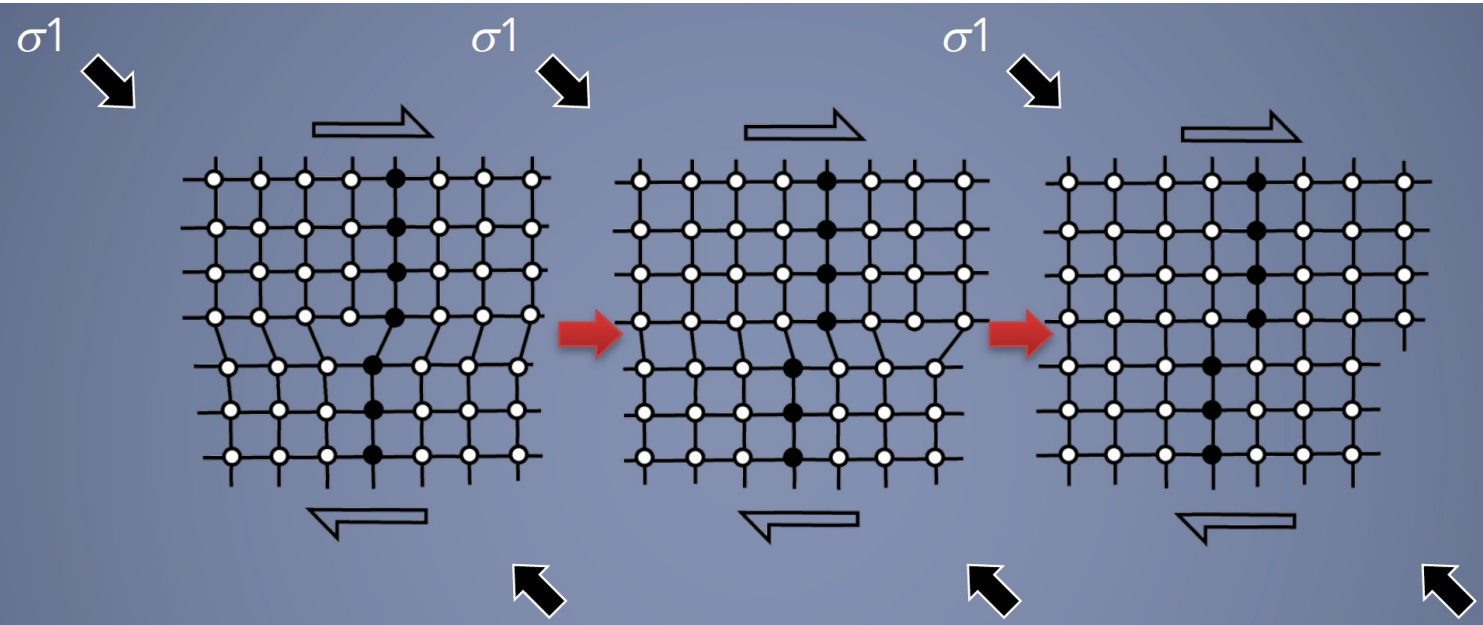
n = 1

m = 2-3

Microstructural Effects:

1. Changes grain shape, not size
2. Does not produce LPO

Dislocation creep



$$\dot{\varepsilon} \propto \frac{\sigma^n}{d^m}$$

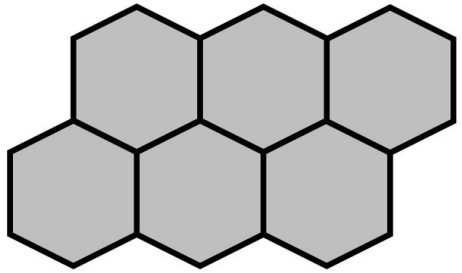
n = 3-5

m = 0

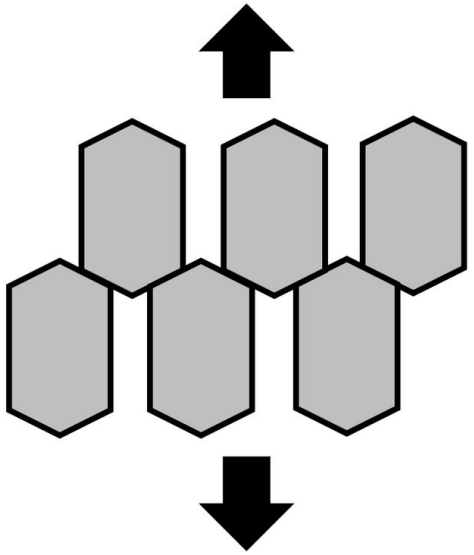
Microstructural Effects:

1. Changes grain size and shape
2. Produces LPO

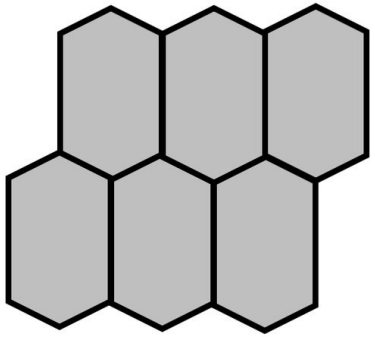
Grain boundary sliding



1) Initial configuration of six grains in a polycrystalline material



2) When a tensile load is applied, the grains are elongated creating gaps in between the grains called voids



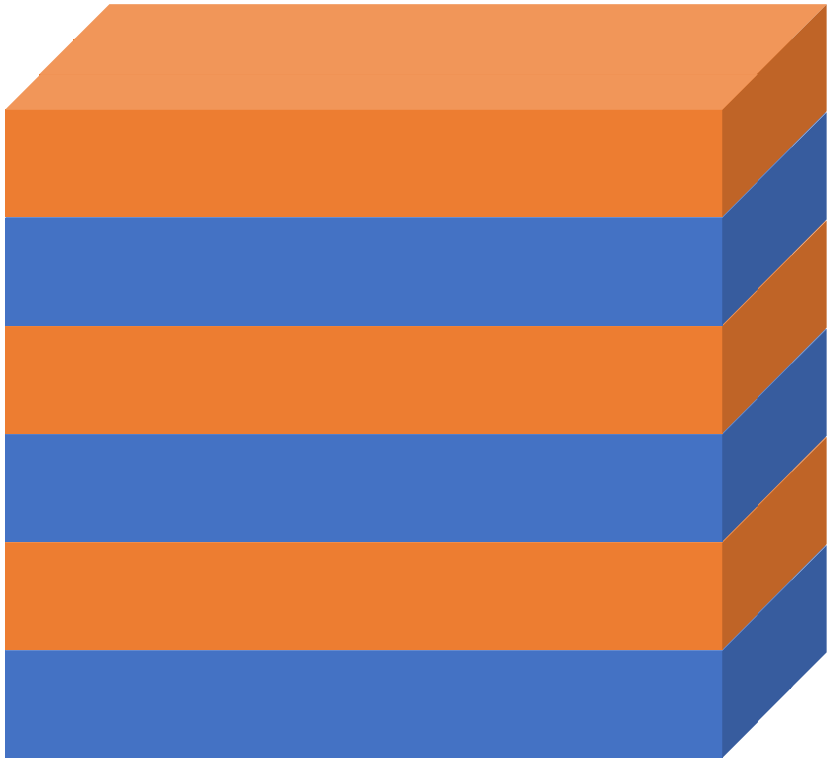
3) In order to prevent void presence in the material, the grains slide to fill in the gaps

Isotropy

Same behavior in every direction

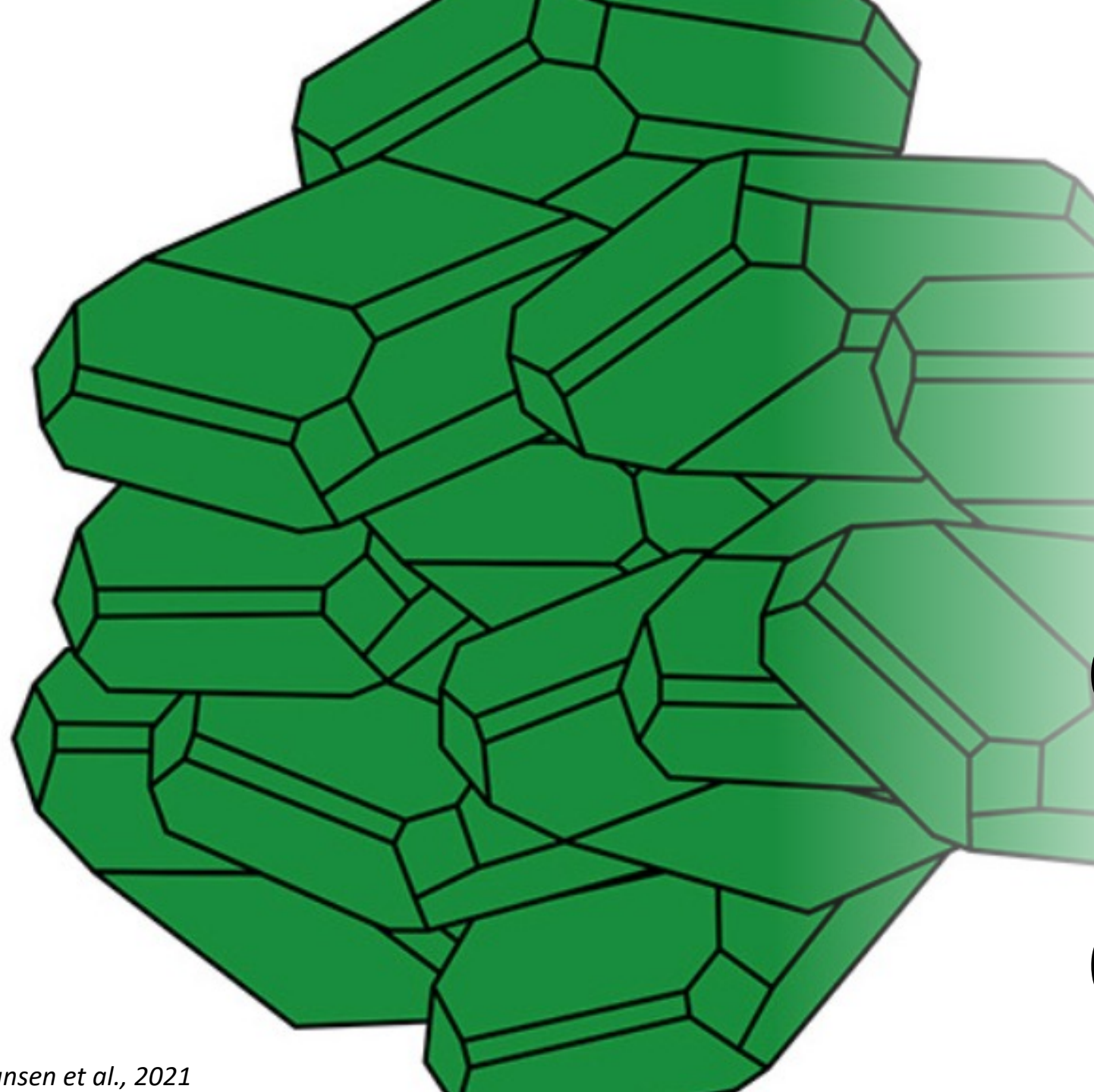
Anisotropy

Material property is direction dependent



SPO

Shape
Preferred
Orientation

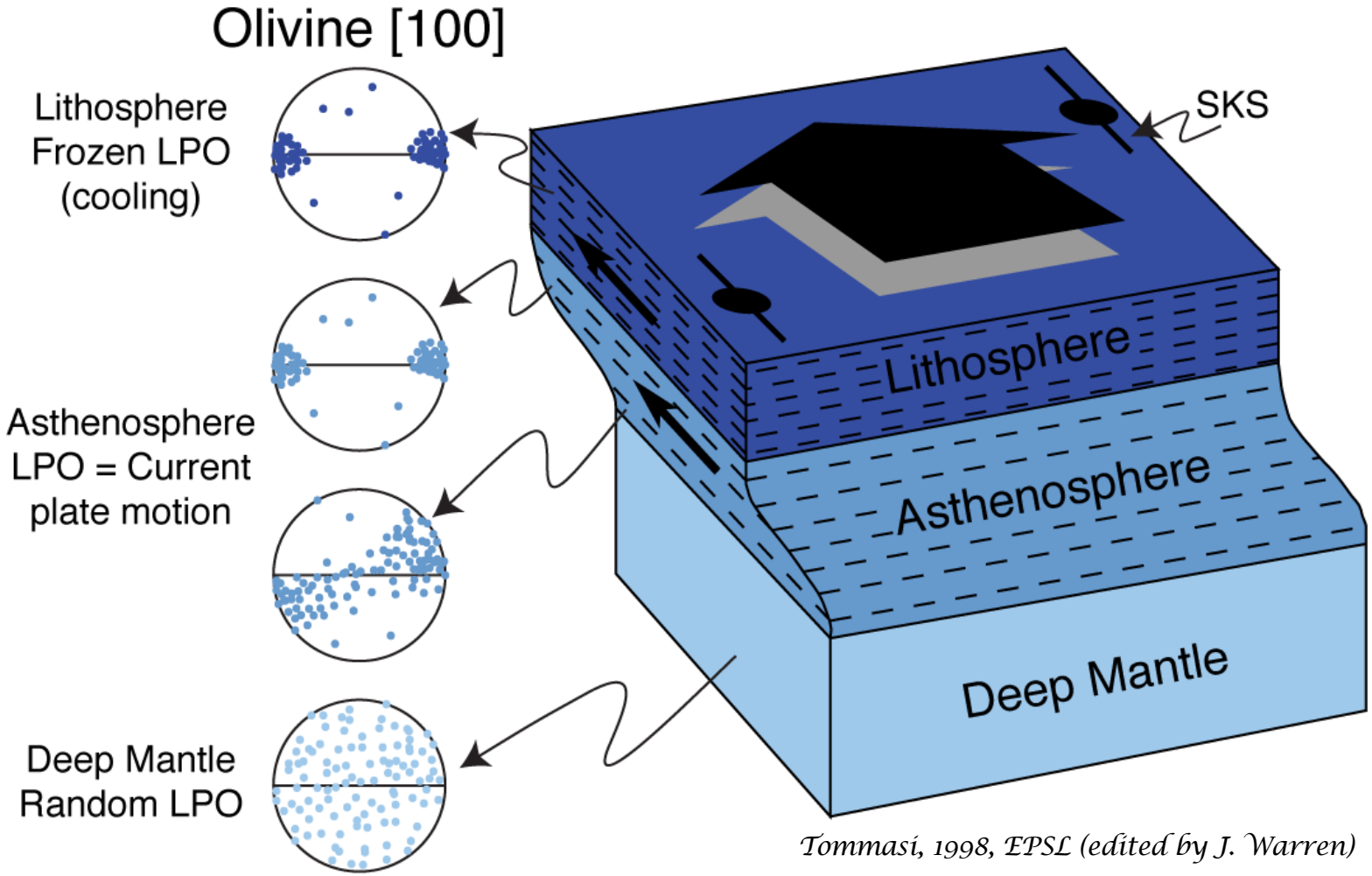


LPO / CPO

Lattice / Crystallographic Preferred Orientation

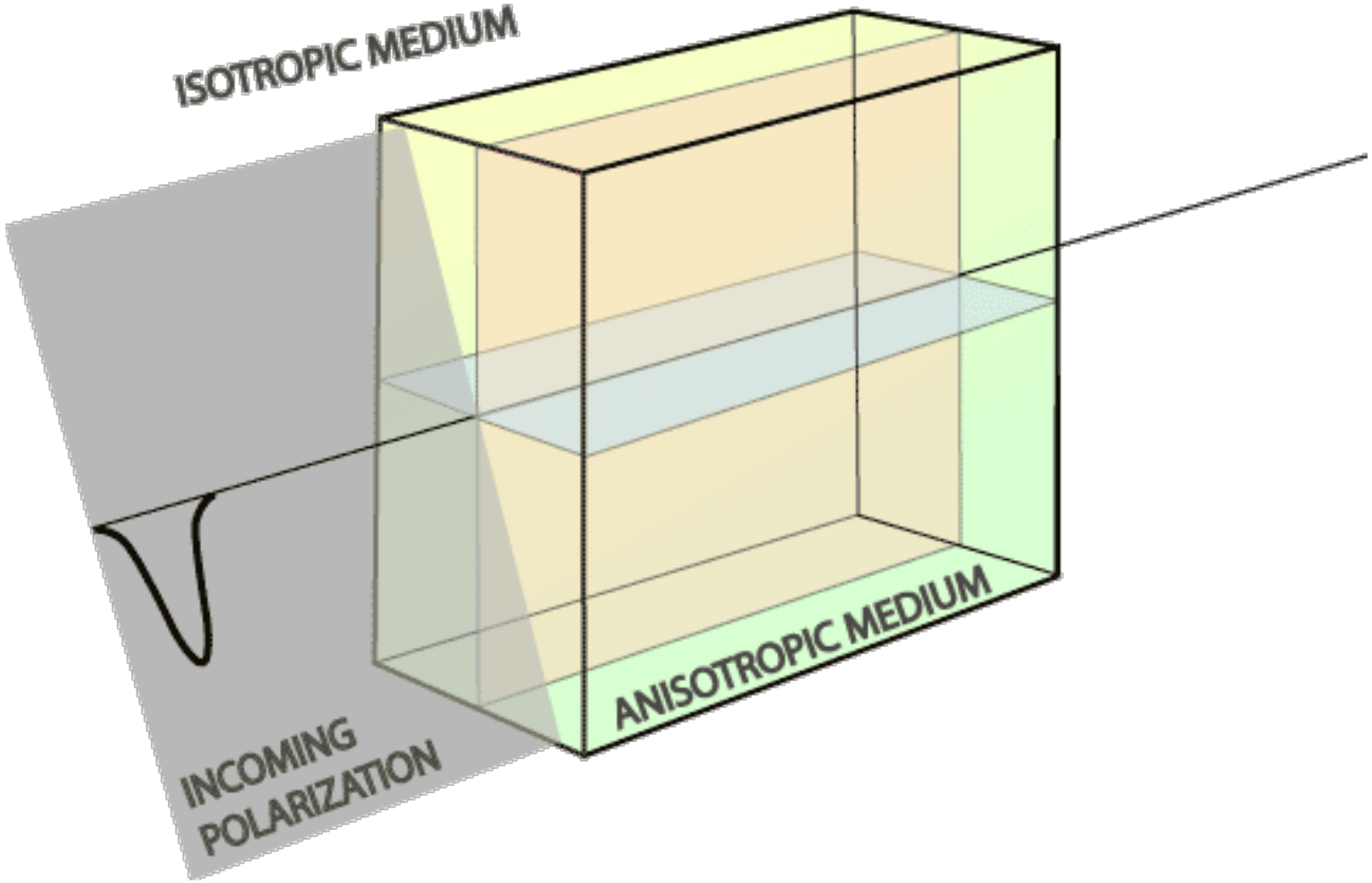
Hansen et al., 2021

Lattice preferred orientation

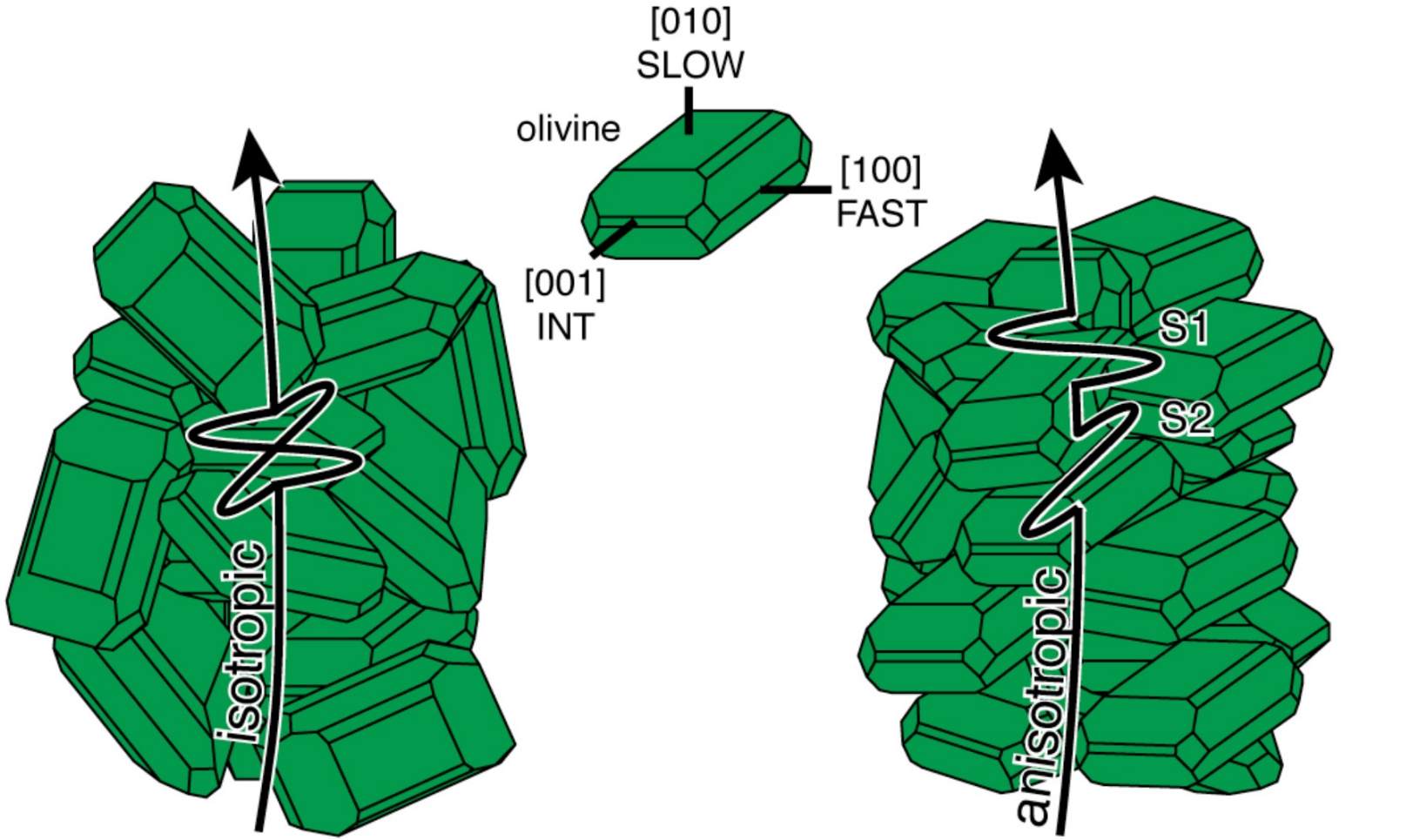


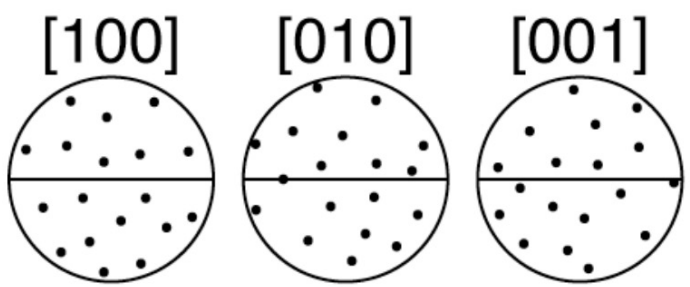
Tommasi, 1998, EPSL (edited by J. Warren)

Seismic anisotropy

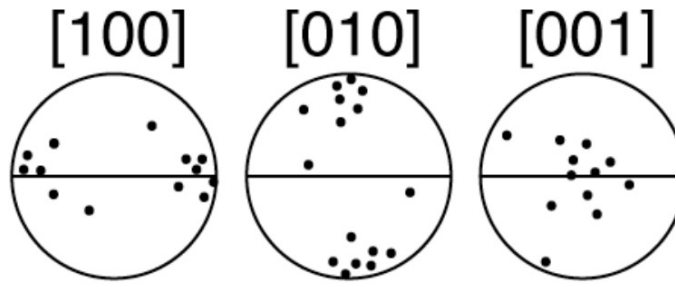


Seismic anisotropy in the mantle



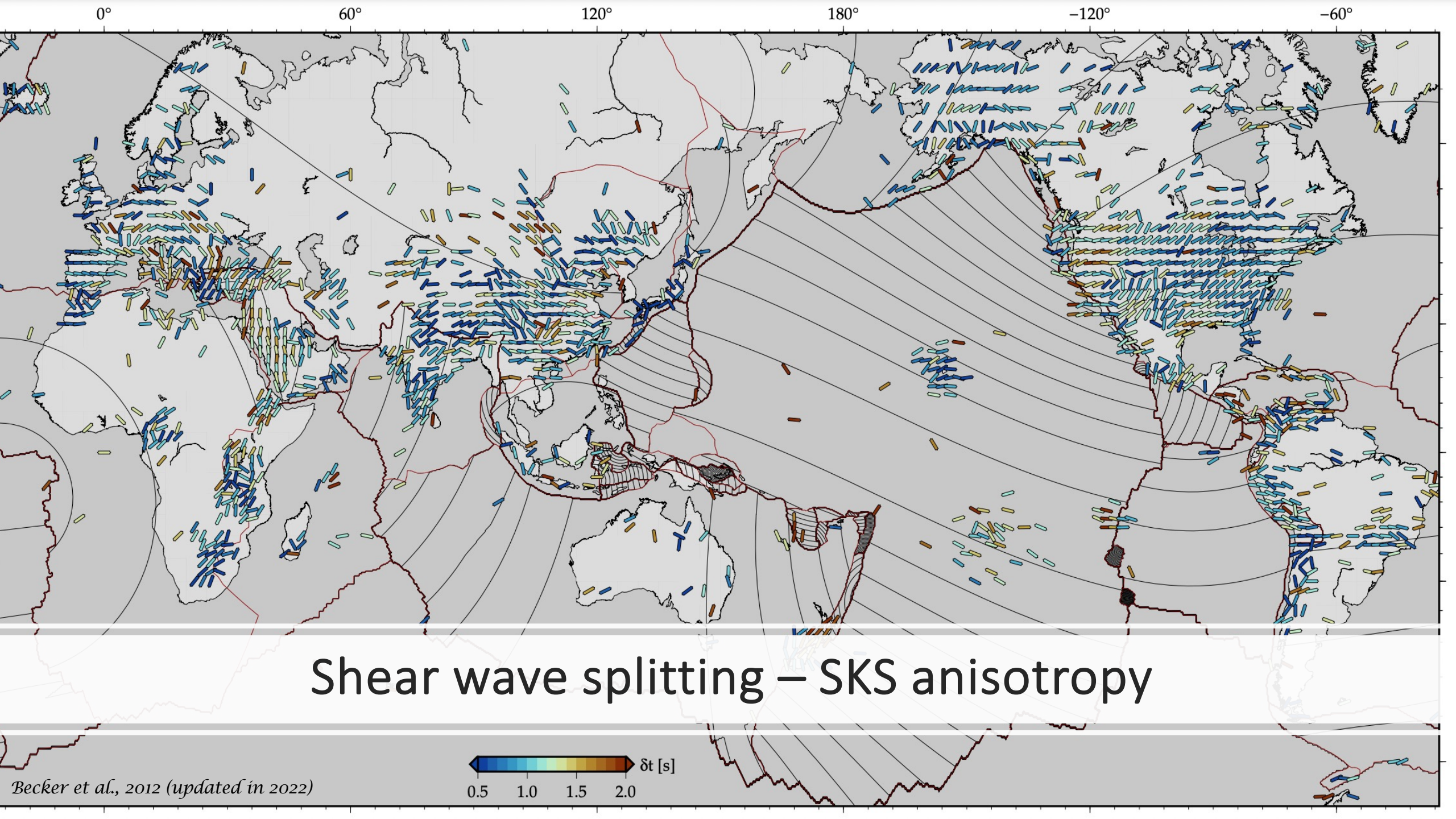


random LPO

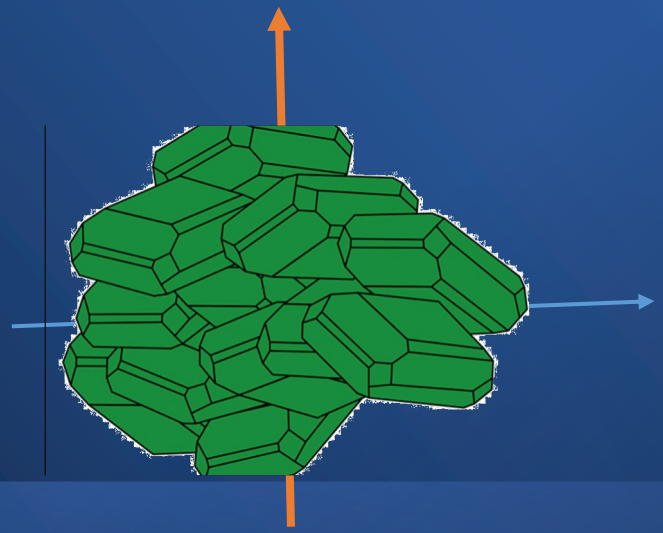


strong LPO

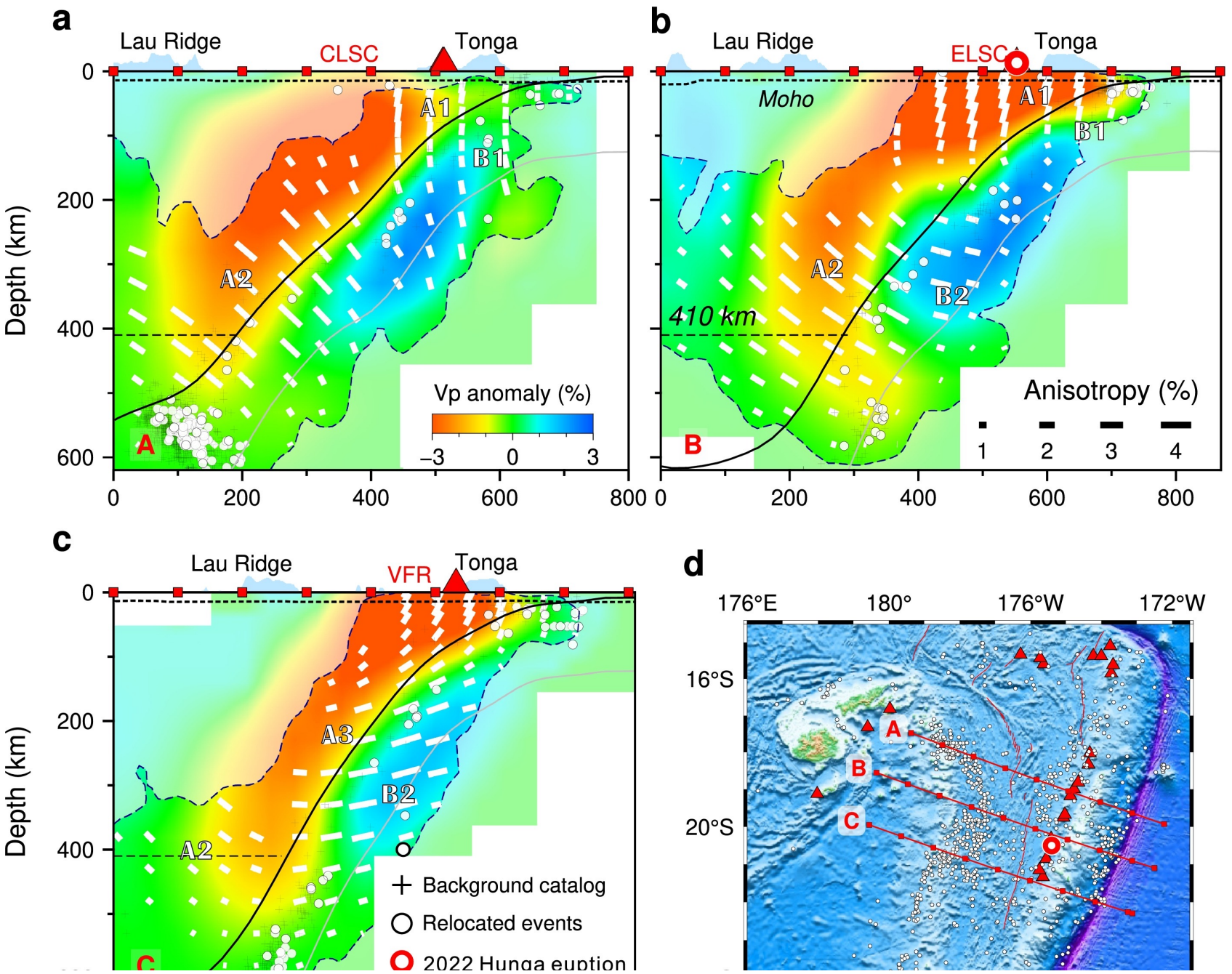
drawing by Luc Mehi



Shear wave splitting – SKS anisotropy

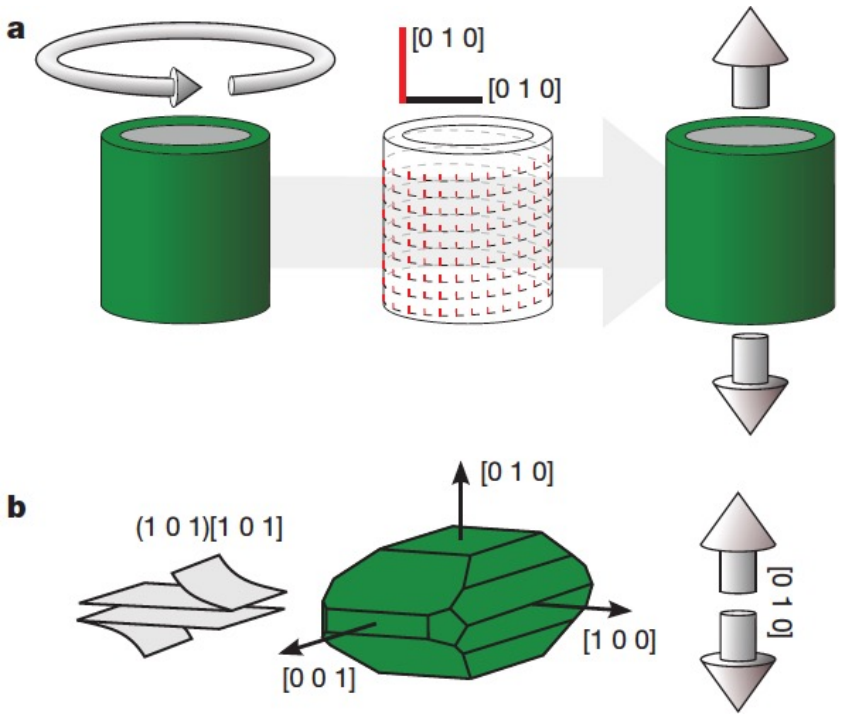


P-wave anisotropy



Yu et al., 2022

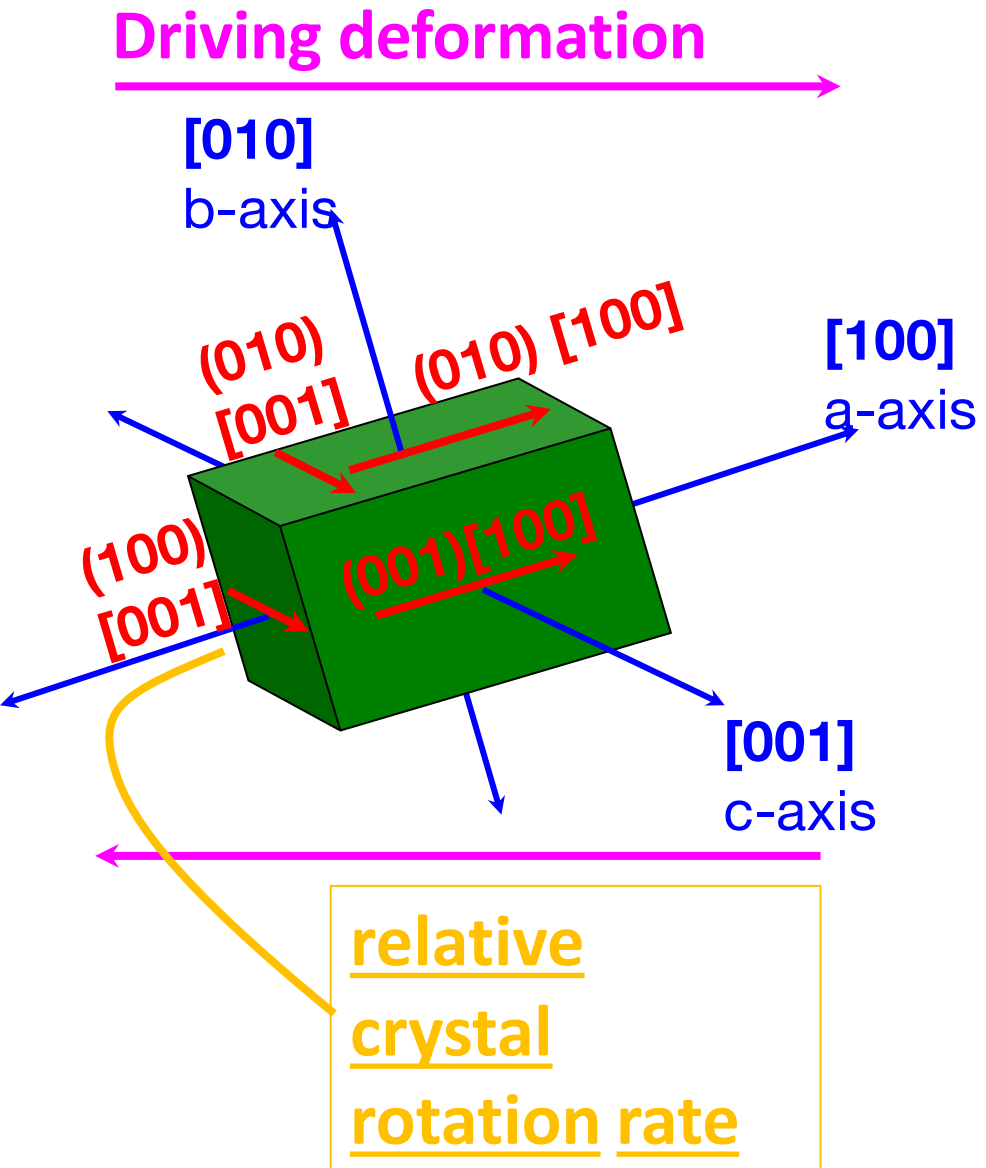
Lattice preferred orientation

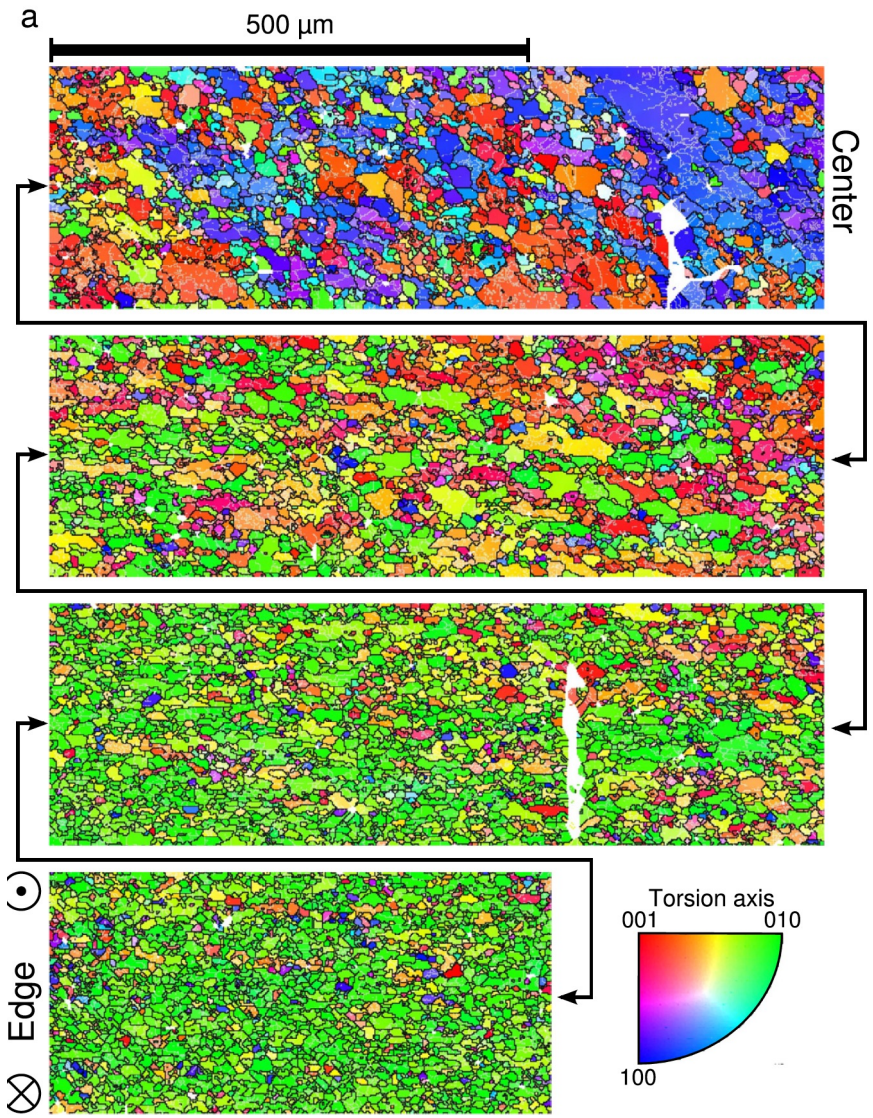


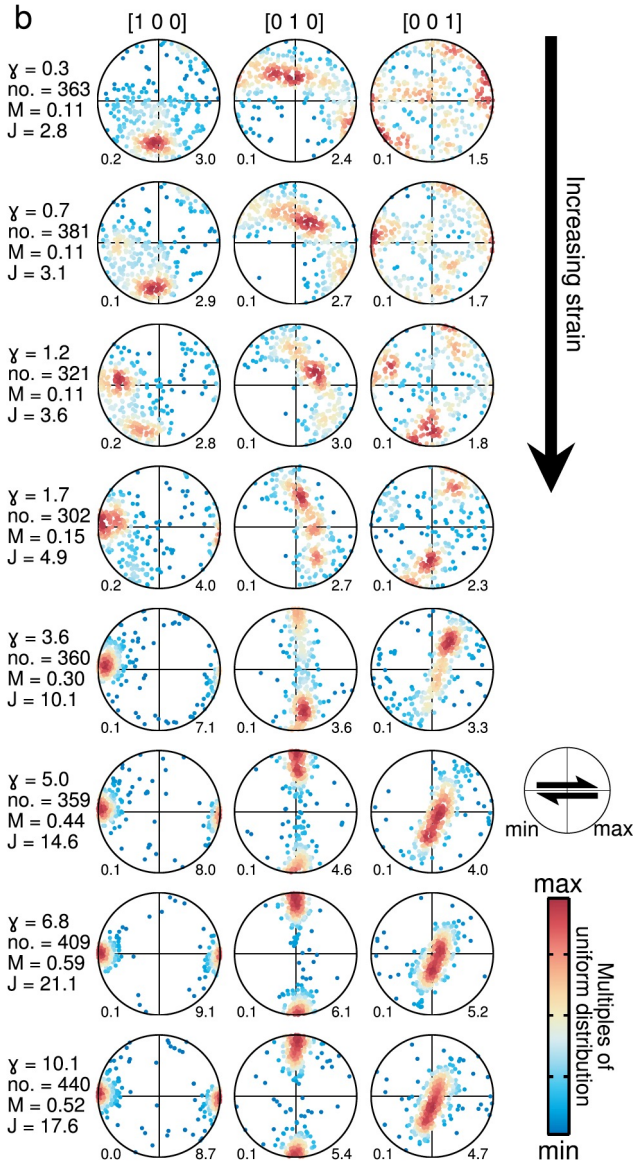
Hansen et al., 2012, Nature

Numerical models of LPO development that aim to reproduce a set of laboratory experiment

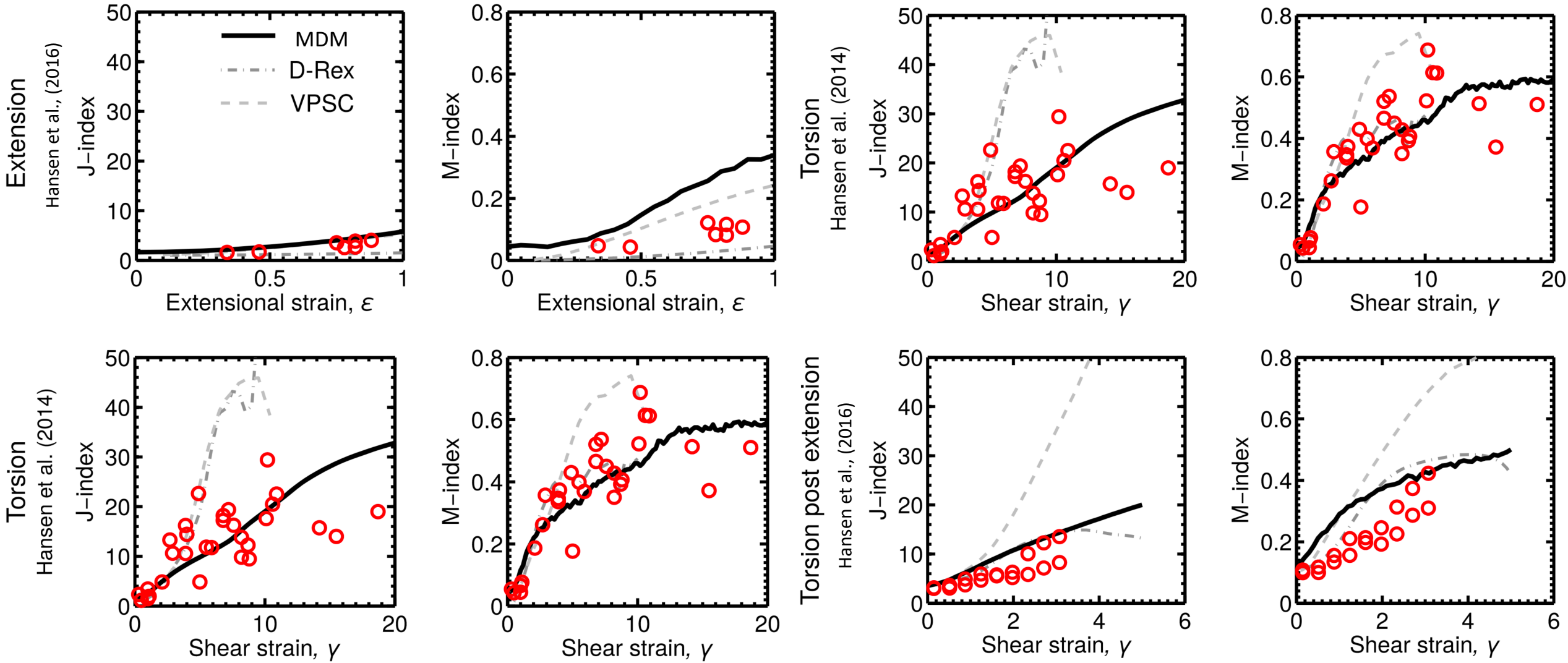
EBDS measurements



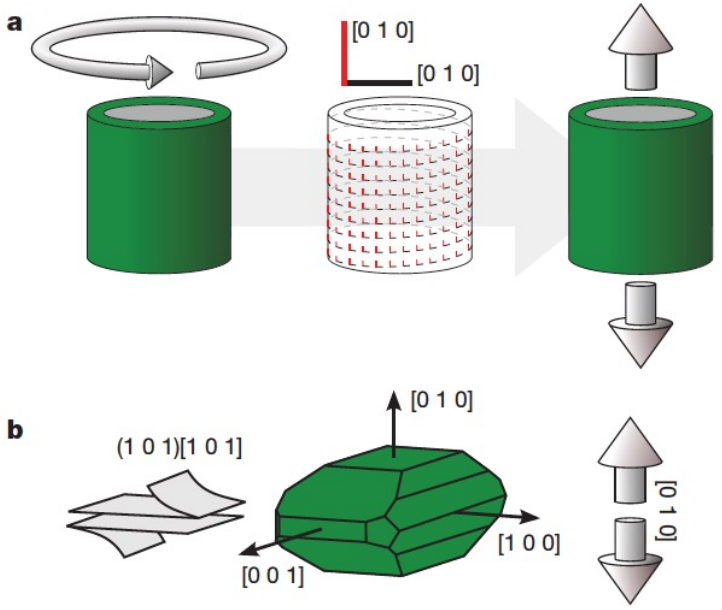




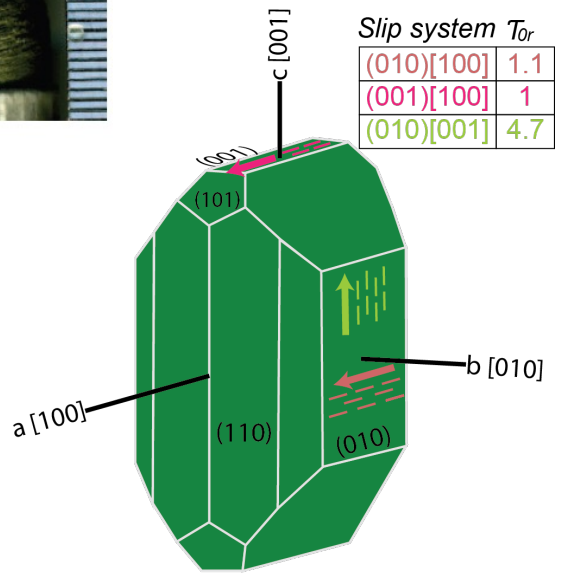
Hansen et al., 2016, EPSL


Extension
Hansen et al., (2016)
J–index
M–index
MDM
D-Rex
VPSC
Extensional strain, ε
Torsion
Hansen et al. (2014)
Shear strain, γ
Torsion post extension
Hansen et al., (2016)

Viscous anisotropy

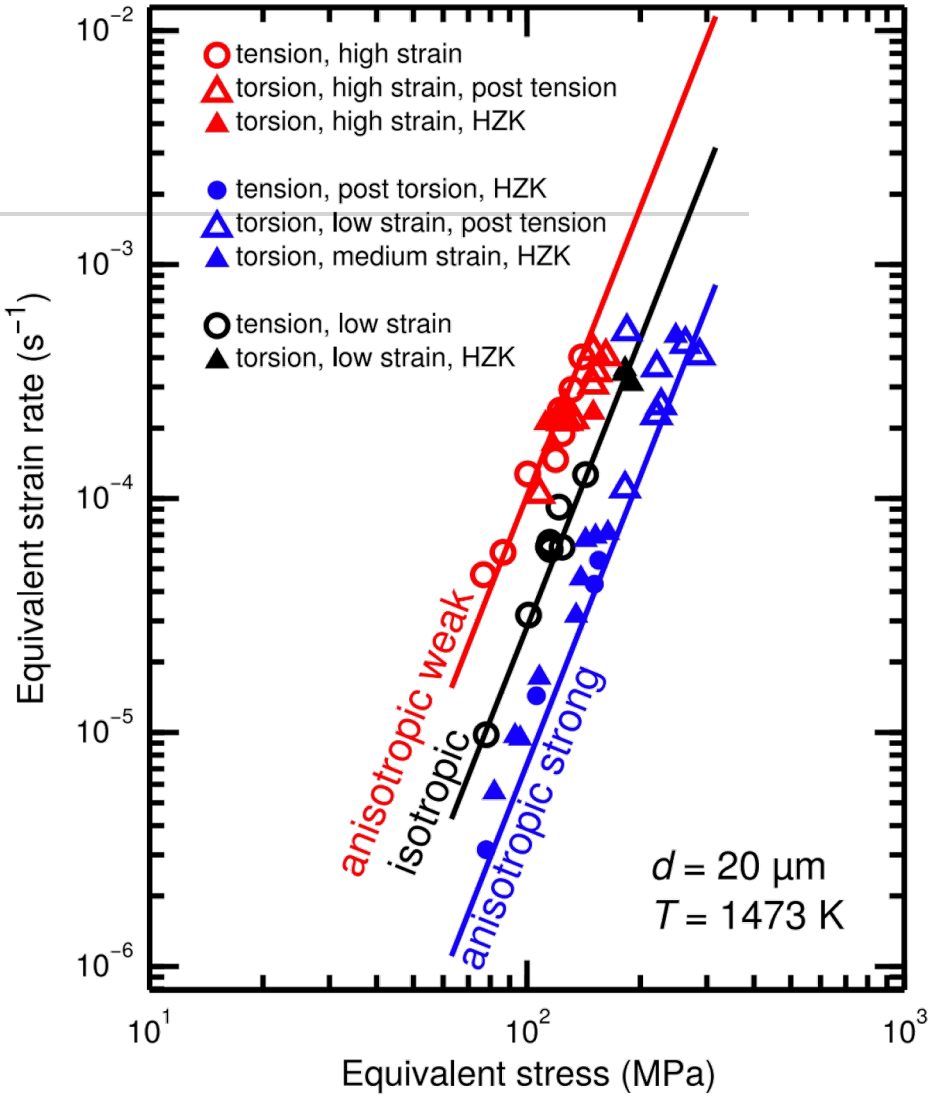


Slip system	τ_{0r}
(010)[100]	1.1
(001)[100]	1
(010)[001]	4.7

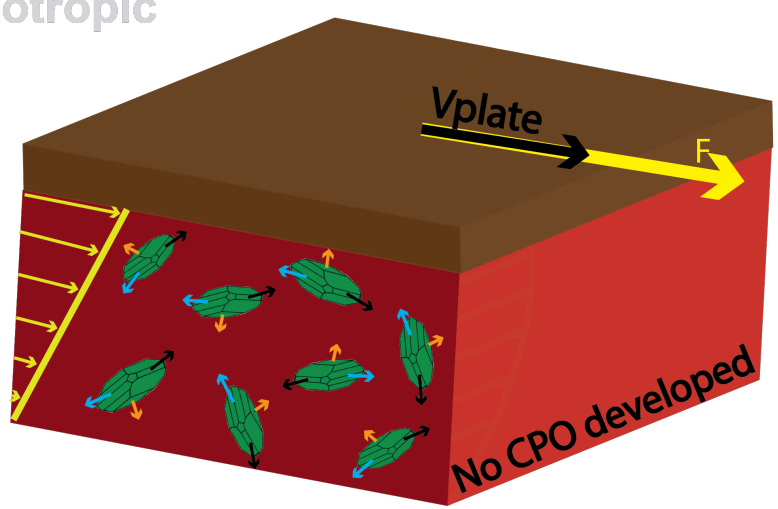


Slip system activity

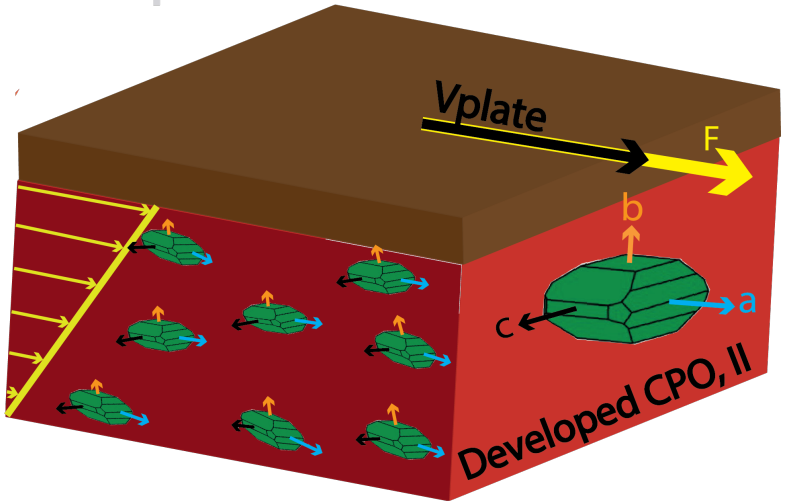
Weak — Hard



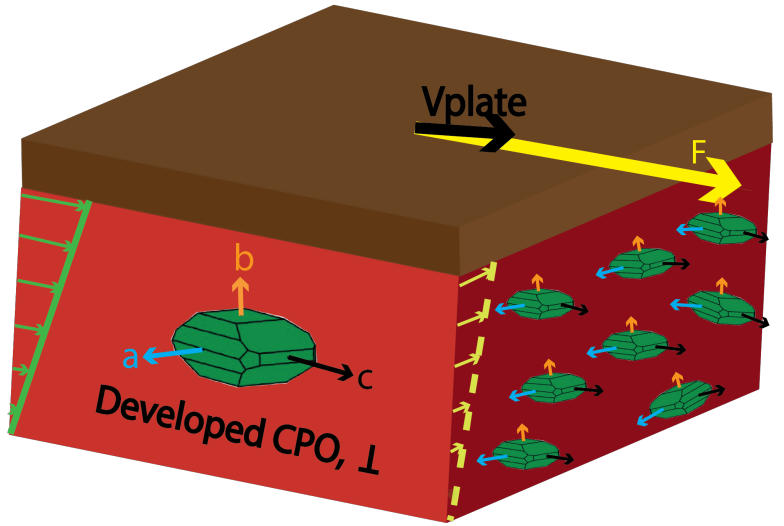
Isotropic



Anisotropic weak



Anisotropic strong



So, what does ANISOTROPIC VISCOSITY mean

Direction dependent viscosity

- In general, we define $\boldsymbol{\sigma} = 2\eta\dot{\boldsymbol{\varepsilon}}$

- Anisotropic Viscosity: $\sigma_{ij} = \eta_{ijkl}\dot{\varepsilon}_{kl}$

- In Kelvin Notation

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sqrt{2}\sigma_{23} \\ \sqrt{2}\sigma_{13} \\ \sqrt{2}\sigma_{12} \end{bmatrix} = \begin{bmatrix} \eta_{1111} & \eta_{1122} & \eta_{1133} & \sqrt{2}\eta_{1123} & \sqrt{2}\eta_{1113} & \sqrt{2}\eta_{1112} \\ \eta_{1122} & \eta_{2222} & \eta_{2233} & \sqrt{2}\eta_{2223} & \sqrt{2}\eta_{2213} & \sqrt{2}\eta_{2212} \\ \eta_{1133} & \eta_{2233} & \eta_{3333} & \sqrt{2}\eta_{3323} & \sqrt{2}\eta_{3313} & \sqrt{2}\eta_{3312} \\ \sqrt{2}\eta_{1123} & \sqrt{2}\eta_{2223} & \sqrt{2}\eta_{3323} & 2\eta_{2323} & 2\eta_{2313} & 2\eta_{2312} \\ \sqrt{2}\eta_{1113} & \sqrt{2}\eta_{2213} & \sqrt{2}\eta_{3313} & 2\eta_{2313} & 2\eta_{1313} & 2\eta_{1312} \\ \sqrt{2}\eta_{1112} & \sqrt{2}\eta_{2212} & \sqrt{2}\eta_{3312} & 2\eta_{2312} & 2\eta_{1312} & 2\eta_{1212} \end{bmatrix} \cdot \begin{bmatrix} \dot{\varepsilon}_{11} \\ \dot{\varepsilon}_{22} \\ \dot{\varepsilon}_{33} \\ \sqrt{2}\dot{\varepsilon}_{23} \\ \sqrt{2}\dot{\varepsilon}_{13} \\ \sqrt{2}\dot{\varepsilon}_{12} \end{bmatrix}$$

NOTE: η_{ijkl} *is a function of* $(T, P, \boldsymbol{\sigma}^n, \varepsilon, dm, CO_H)$

Transverse Isotropy

$$\sigma_{ij} = \eta_{ijkl}\dot{\varepsilon}_{kl}$$

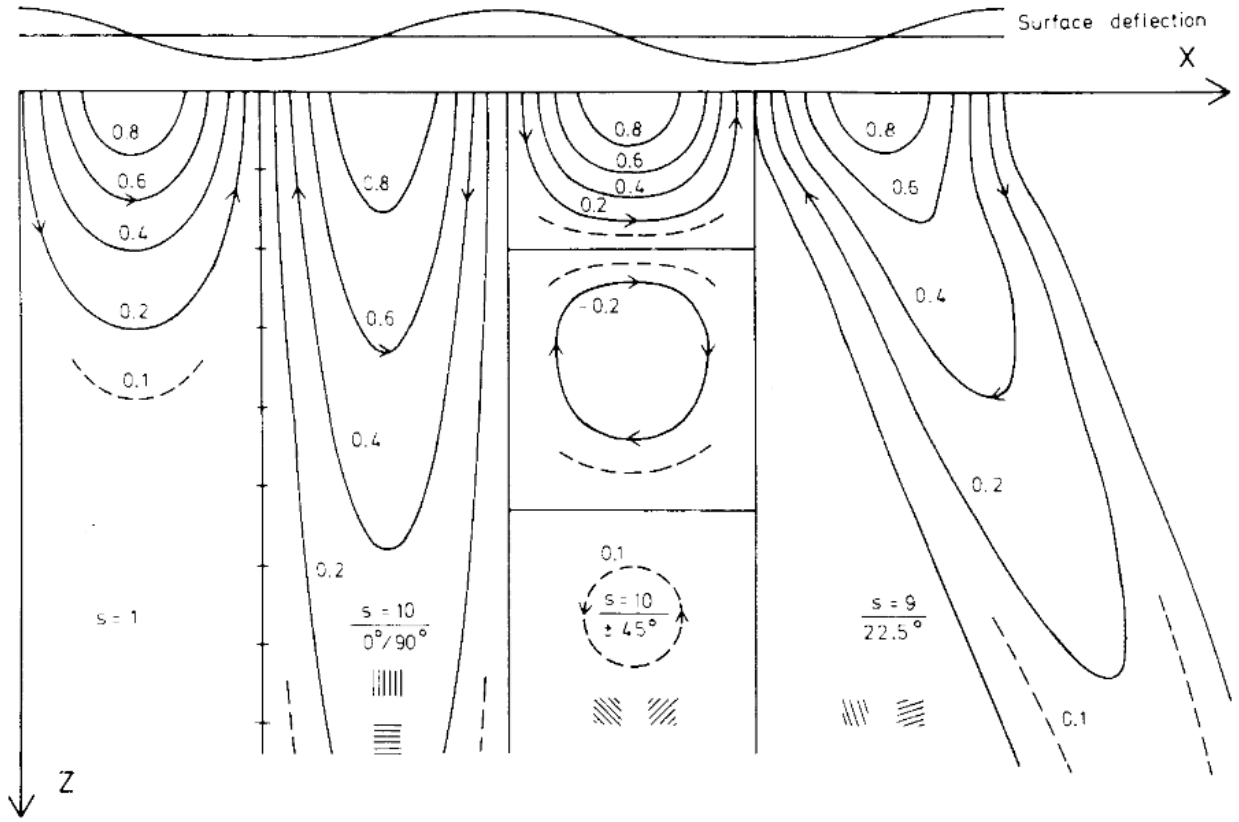
$$\begin{Bmatrix}\sigma_{xx}\\ \sigma_{xz}\end{Bmatrix} = \begin{bmatrix}\eta_{xxxx} & \eta_{xxxz}\\ \eta_{xzxx} & \eta_{xzxz}\end{bmatrix} \begin{Bmatrix}\dot{\epsilon}_{xx}\\ \dot{\epsilon}_{xz}\end{Bmatrix}$$

- 2D, Normal and Shear viscosities (s - ratio)

$$\eta_{xxxx} = \eta_N \cos^2 2\theta + \eta_S \sin^2 2\theta$$

$$\eta_{xzxz} = \eta_N \sin^2 2\theta + \eta_S \cos^2 2\theta$$

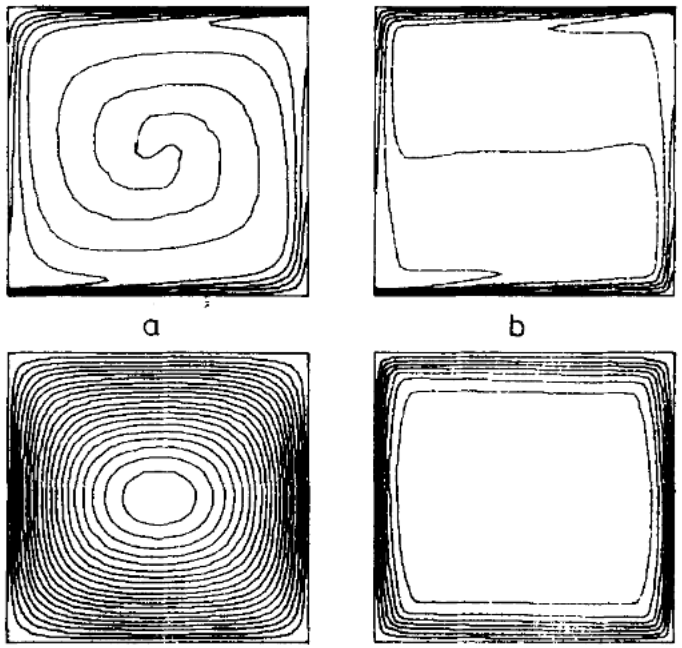
$$\eta_{xxxz} = (\eta_N - \eta_S) \cos 2\theta \sin 2\theta .$$



Viscous relaxation

Christensen, 1987

Isotropic *Anisotropic (s=50)*



Mantle convection

anima-nfr.com

Transverse isotropy – director method

- Director oriented normal to the slip plane. Isotropic relation corrected with the director (anisotropy) tensor $\sigma_{ij} = 2\eta D'_{ij} - 2(\eta - \eta_s)\Lambda_{ijlm} D'_{lm} - p\delta_{ij}$

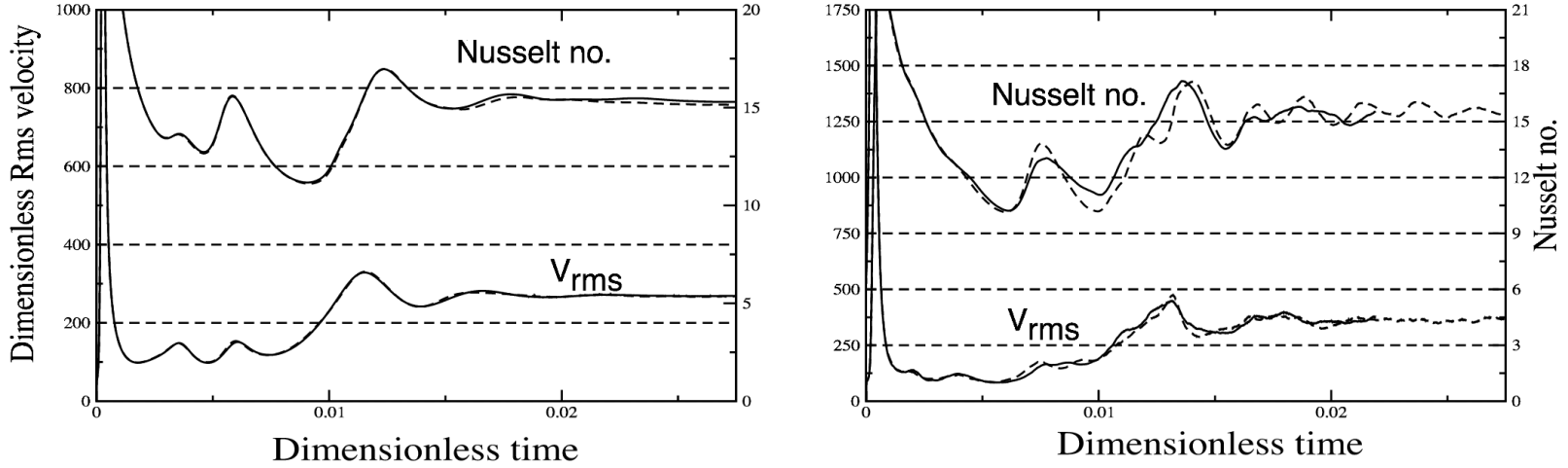
$$\Lambda_{ijkl} = \frac{1}{2}(n_i n_k \delta_{lj} + n_j n_k \delta_{il} + n_i n_l \delta_{kj} + n_j n_l \delta_{ik}) - 2 n_i n_j n_k n_l .$$

- Directors rotate with the flow

Isotropic

Mantle convection

Anisotropic



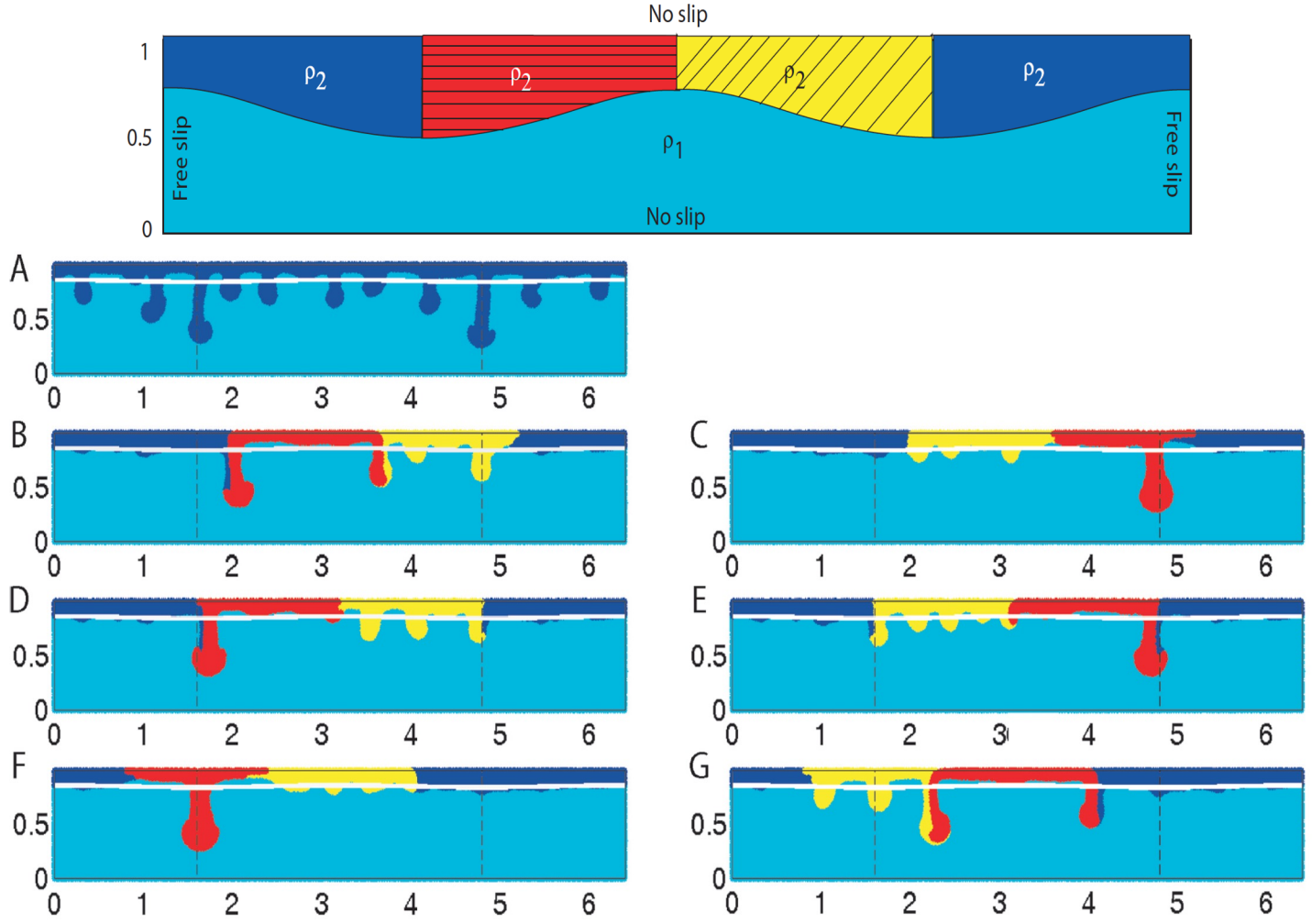
$$\mathrm{Nu}_L = \frac{\text{Convective heat transfer}}{\text{Conductive heat transfer}} = \frac{h}{k/L} = \frac{hL}{k}$$

Mühlhaus et al., 2003

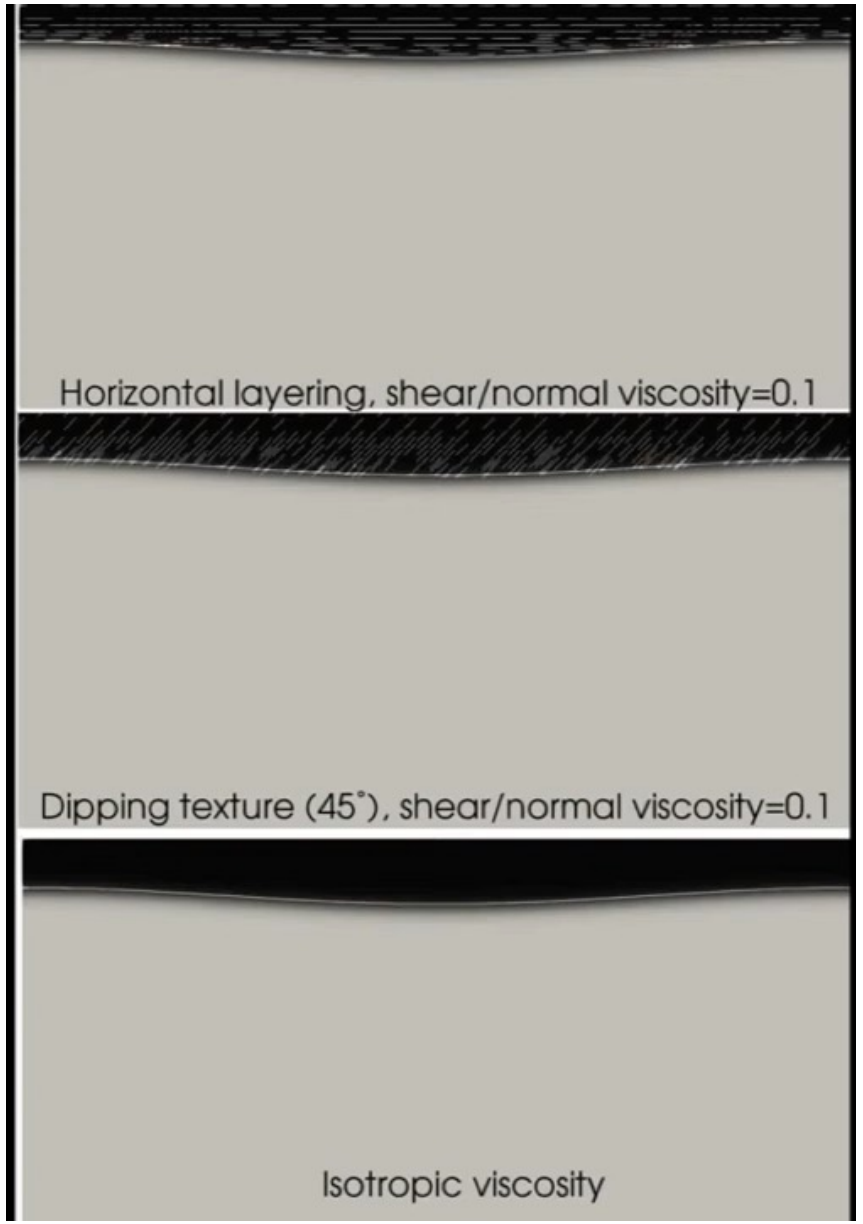
- Increased velocity
- More stable convection cells
- Directors aligned at the edge of the cell

Transverse isotropy – director method

- Rayleigh-taylor instabilities

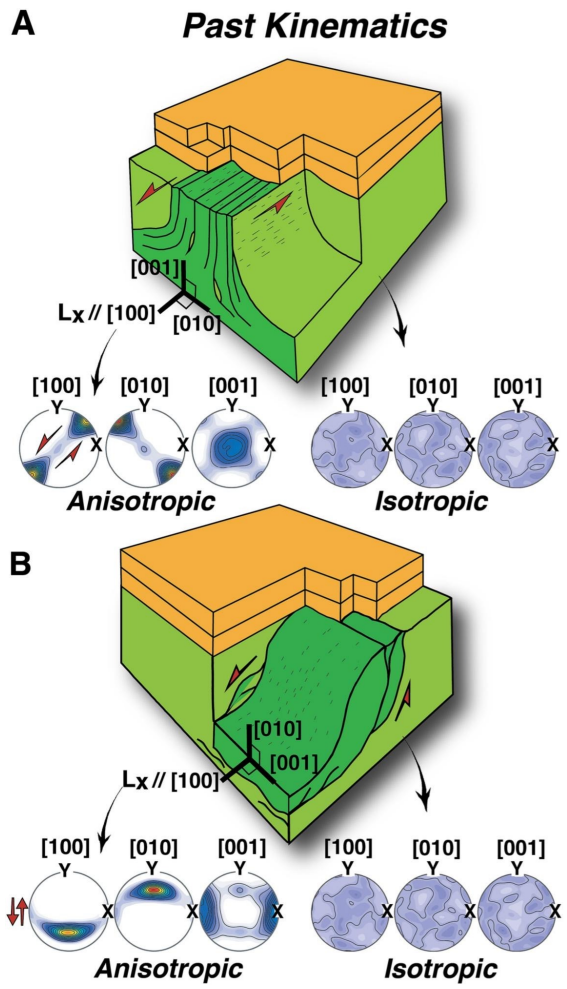


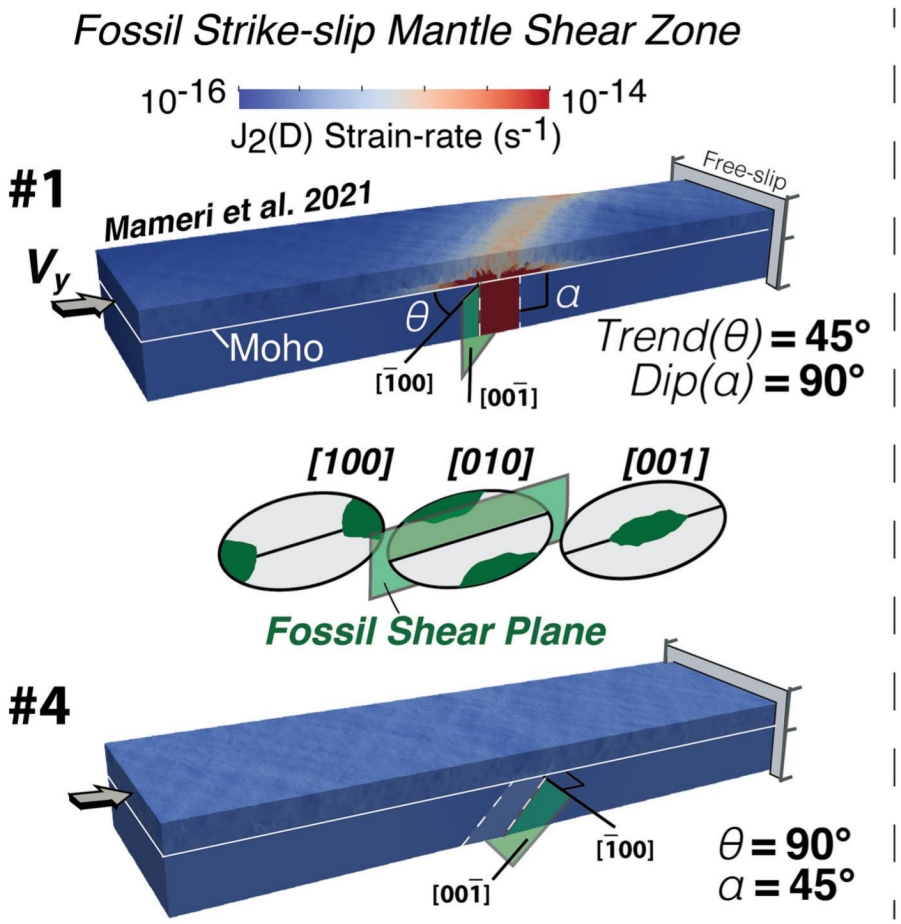
Lev and Hager., 2008

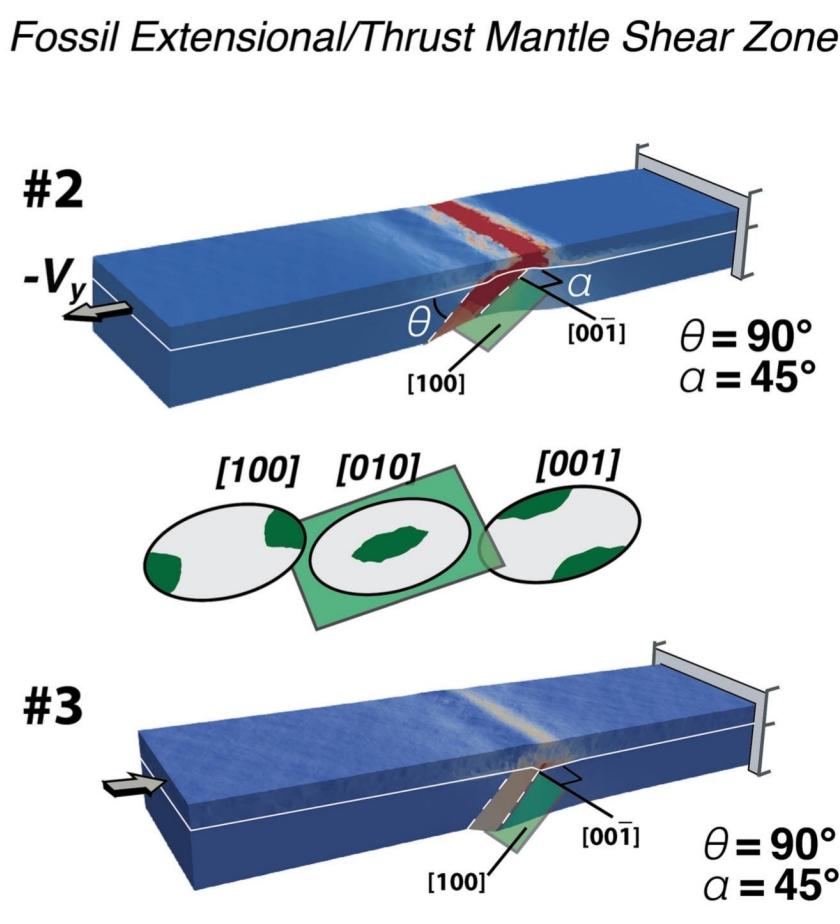


Instantanous/steady state models

Reactivation of fossil mantle shear zones is favoured for 30–50° dip and trend to the tectonic load



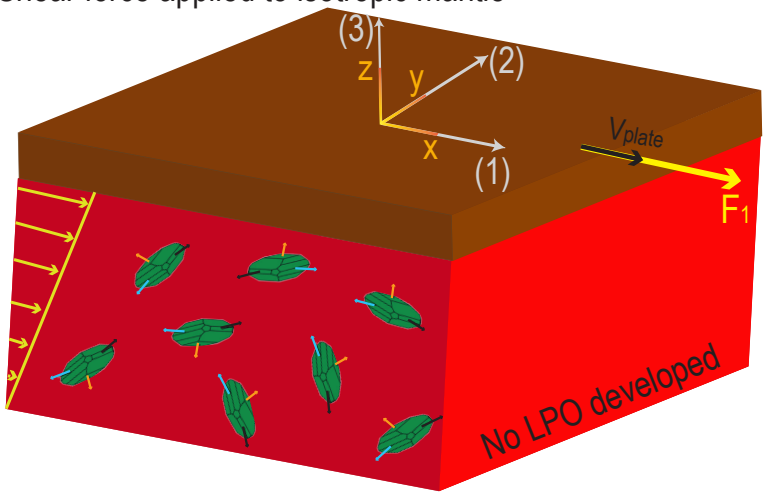




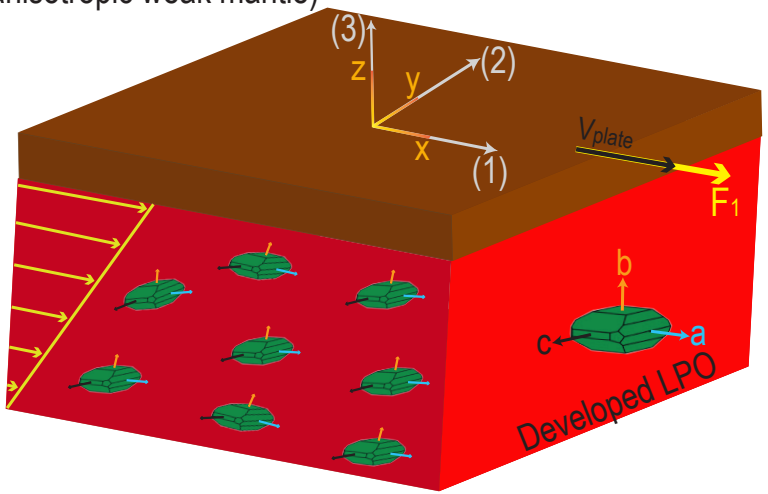
Mameri et al.,, 2023

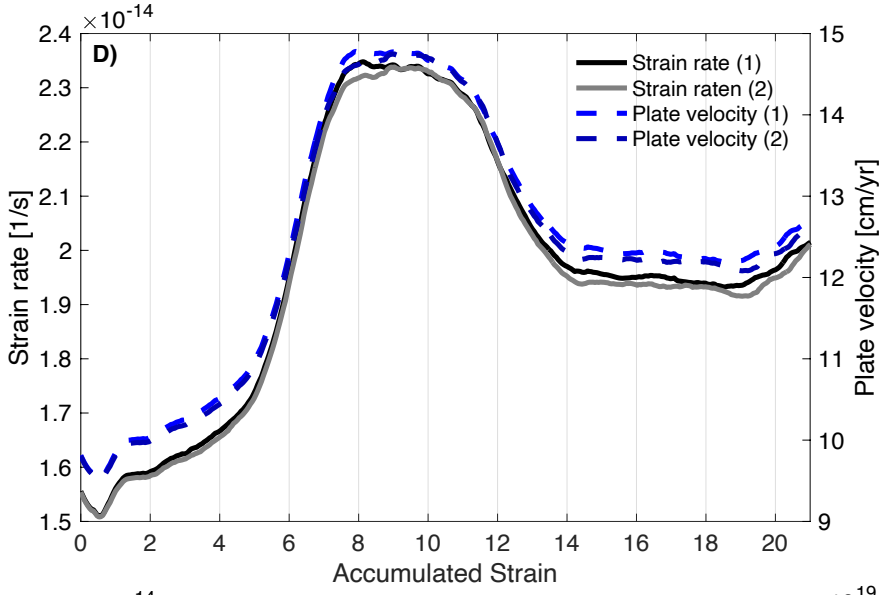
Evolving CPO and anisotropic viscosity

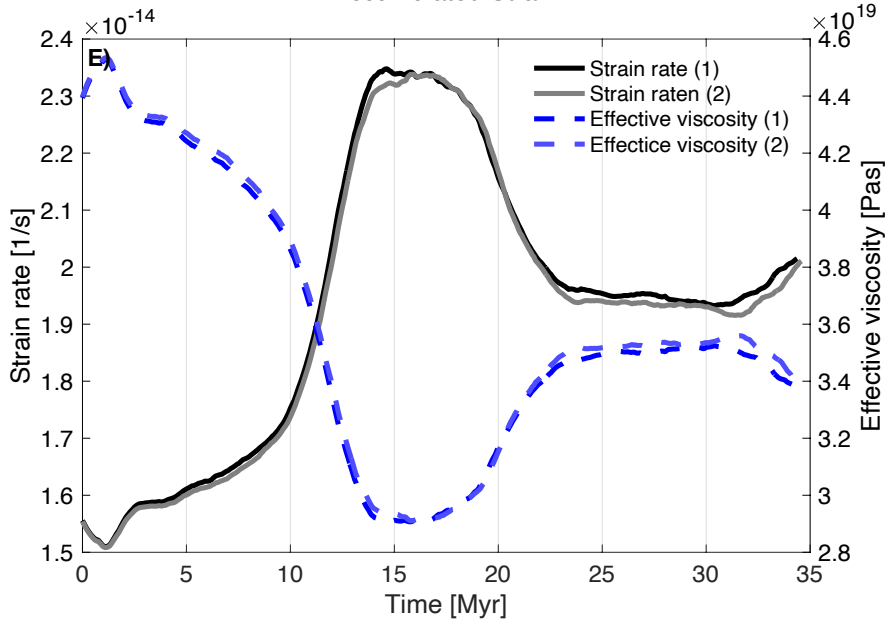
A) Shear force applied to isotropic mantle

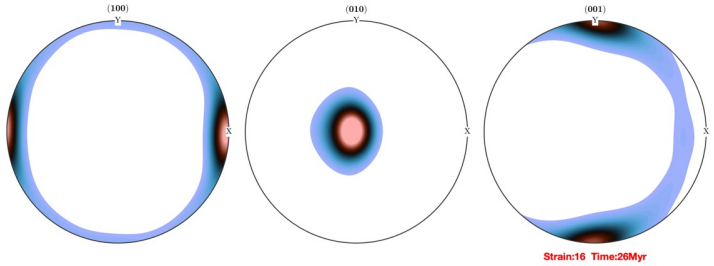


B) Shear force applied parallel to developed LPO (anisotropic weak mantle)



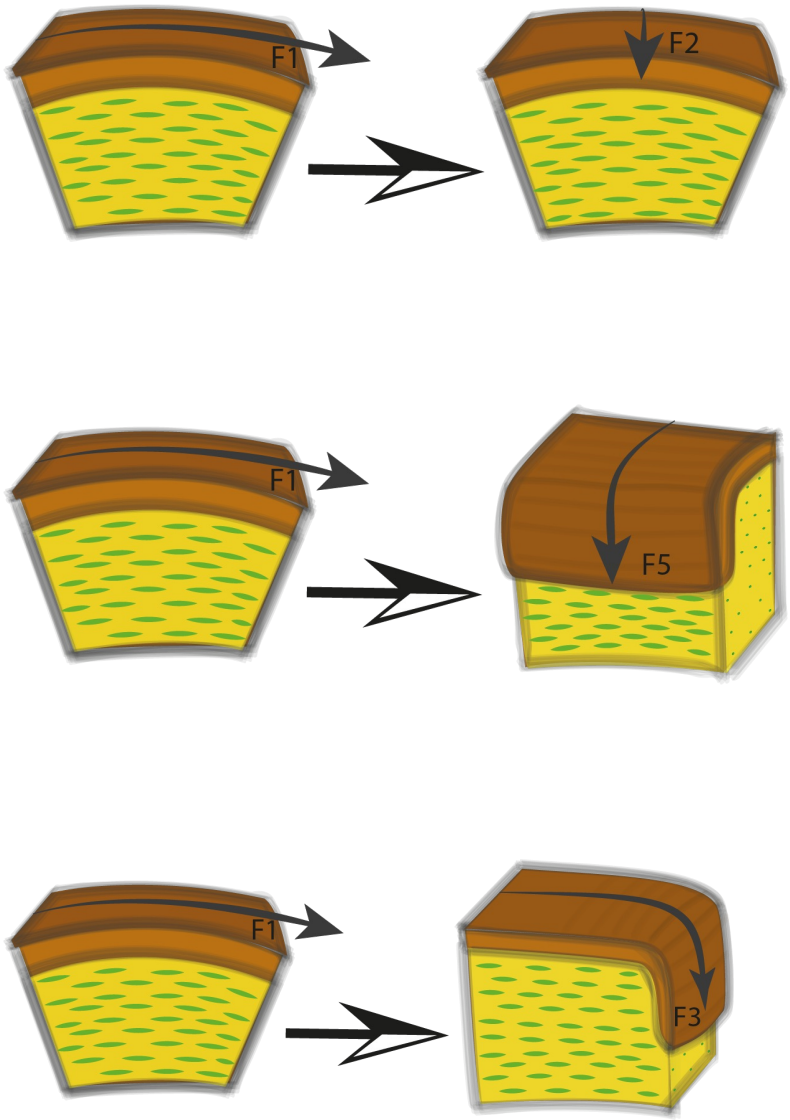




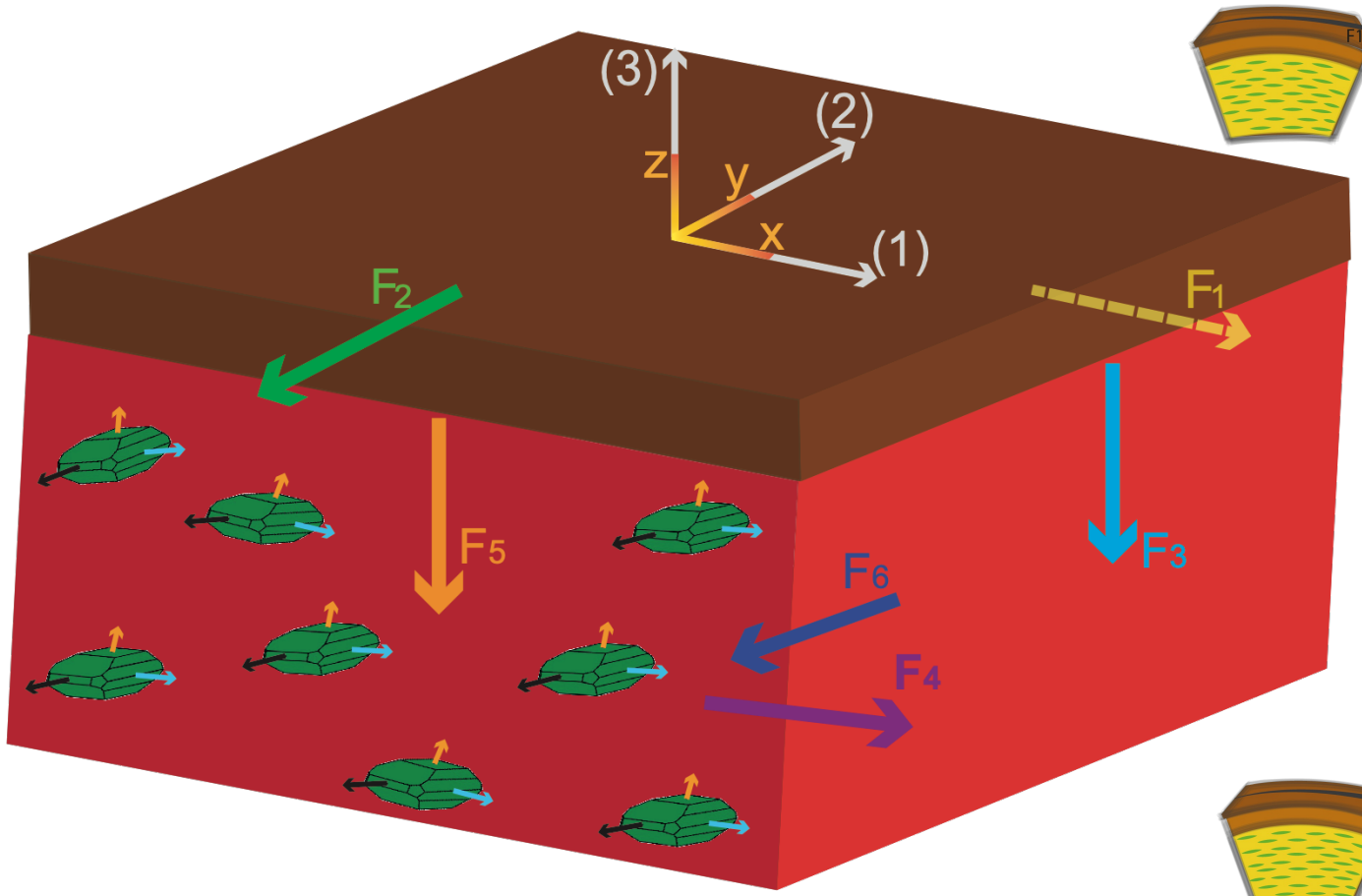


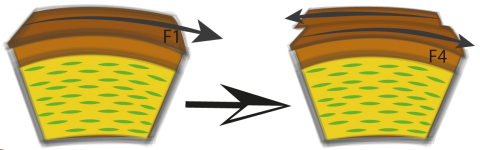
Király et al., 2020, G³

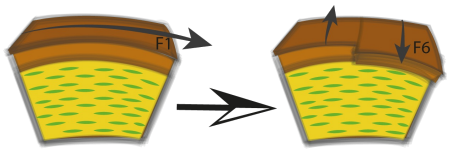
Change in the shear direction



Possibilities for changing the shear force

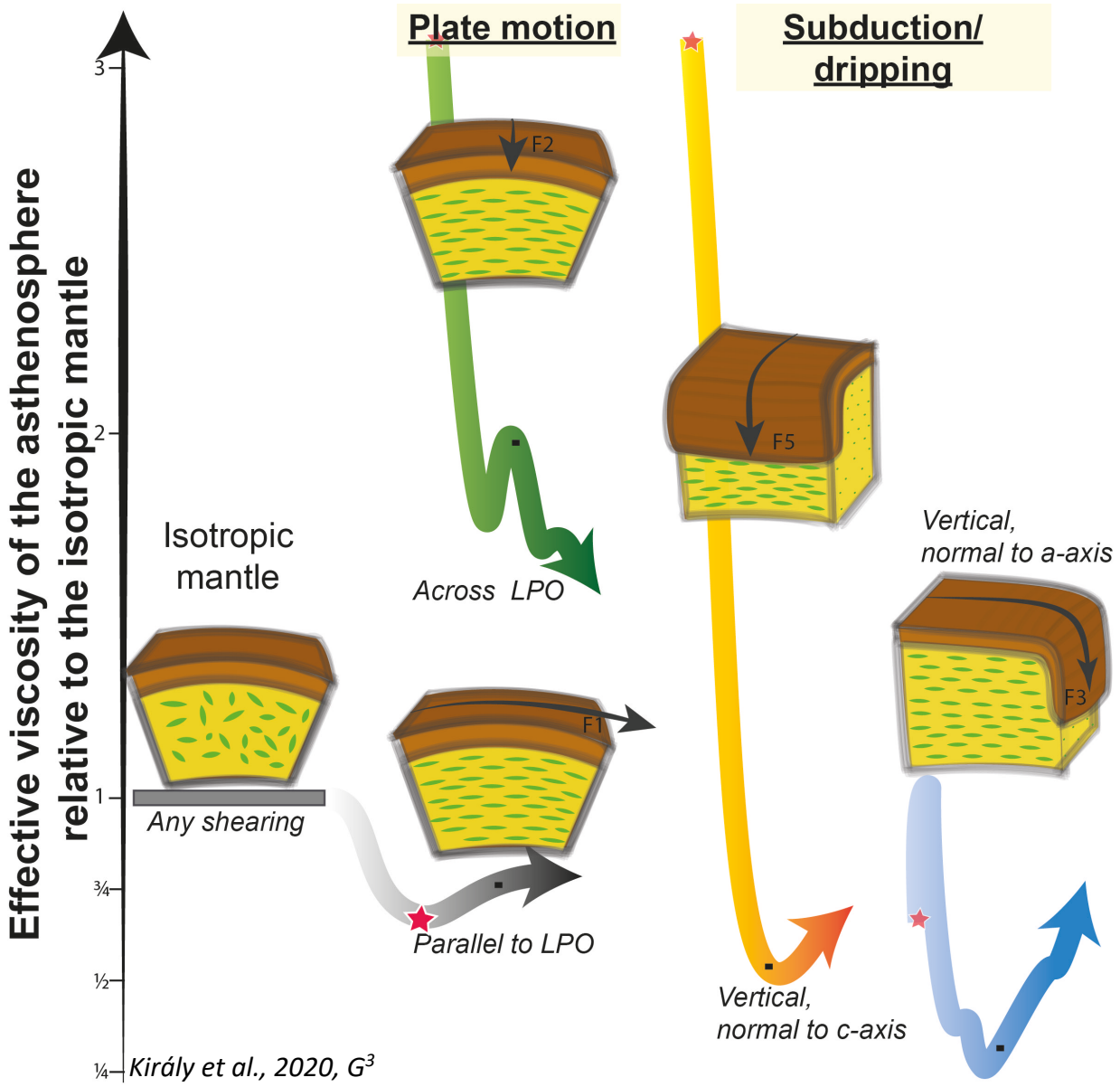


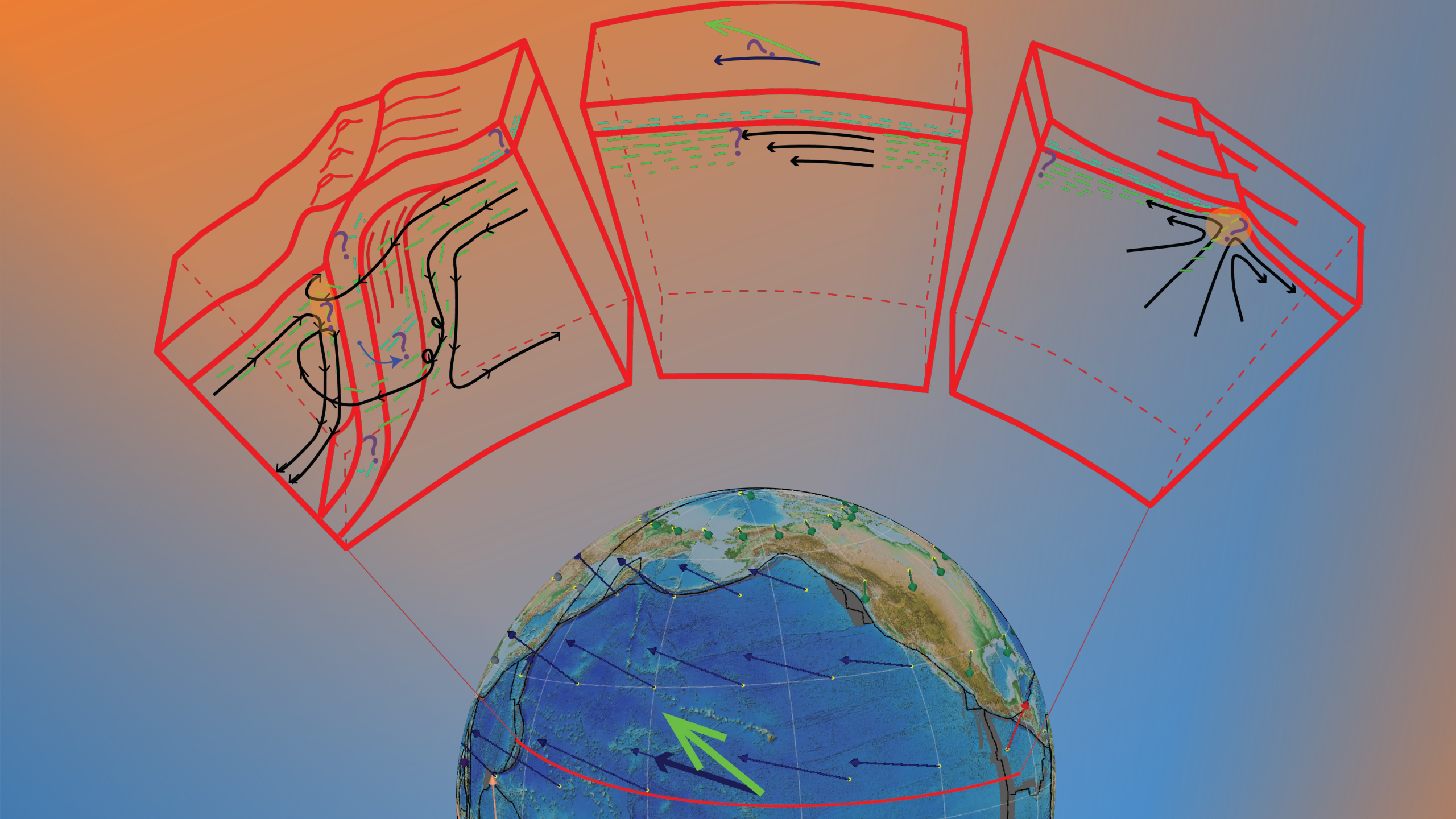




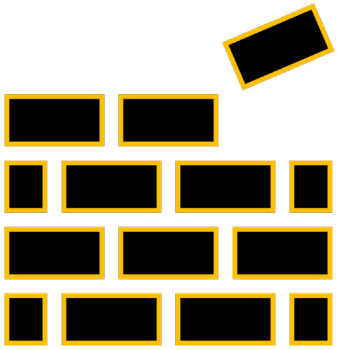
Király et al., 2020, G³

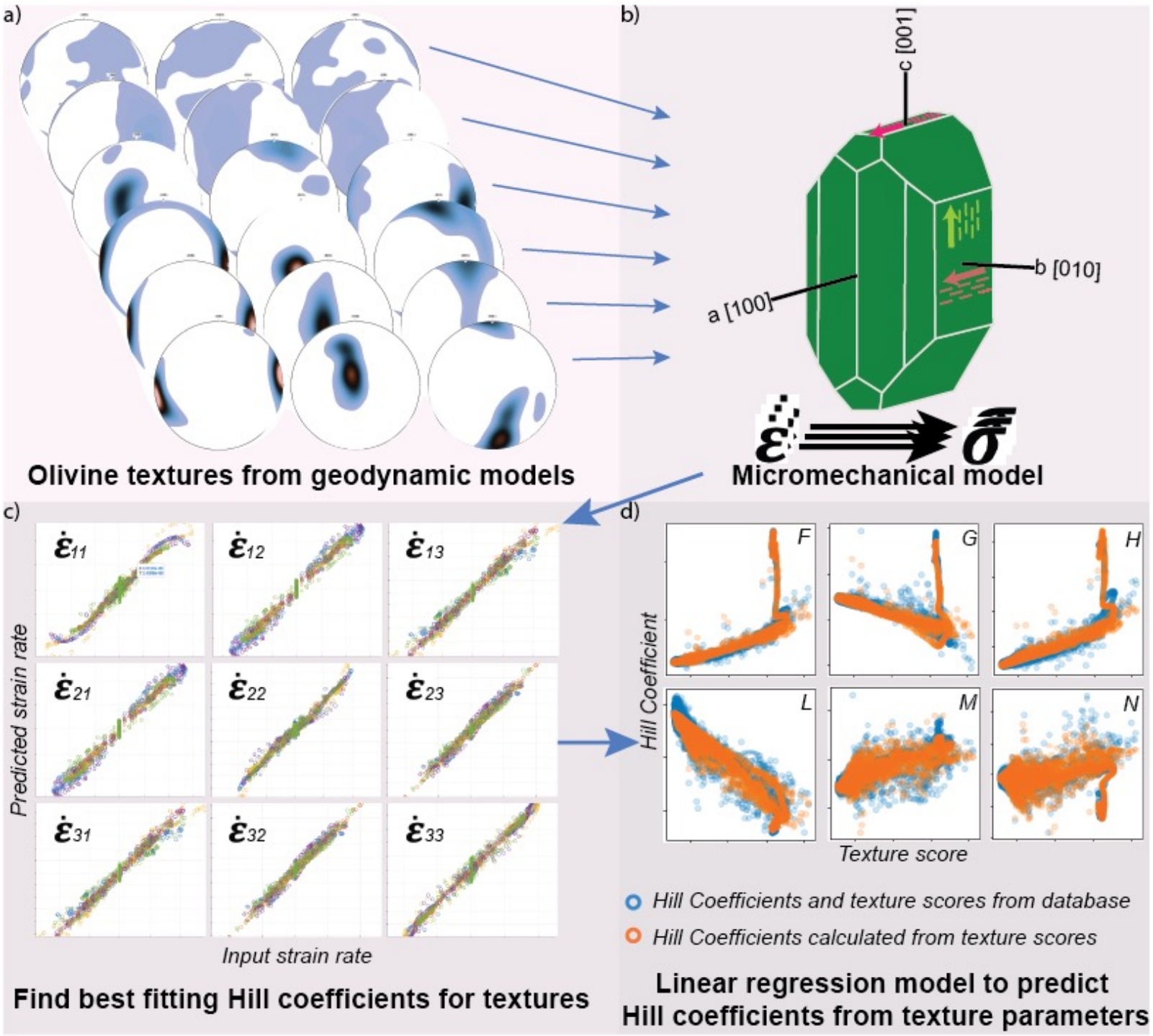
Interpretation – AV in geodynamics processes



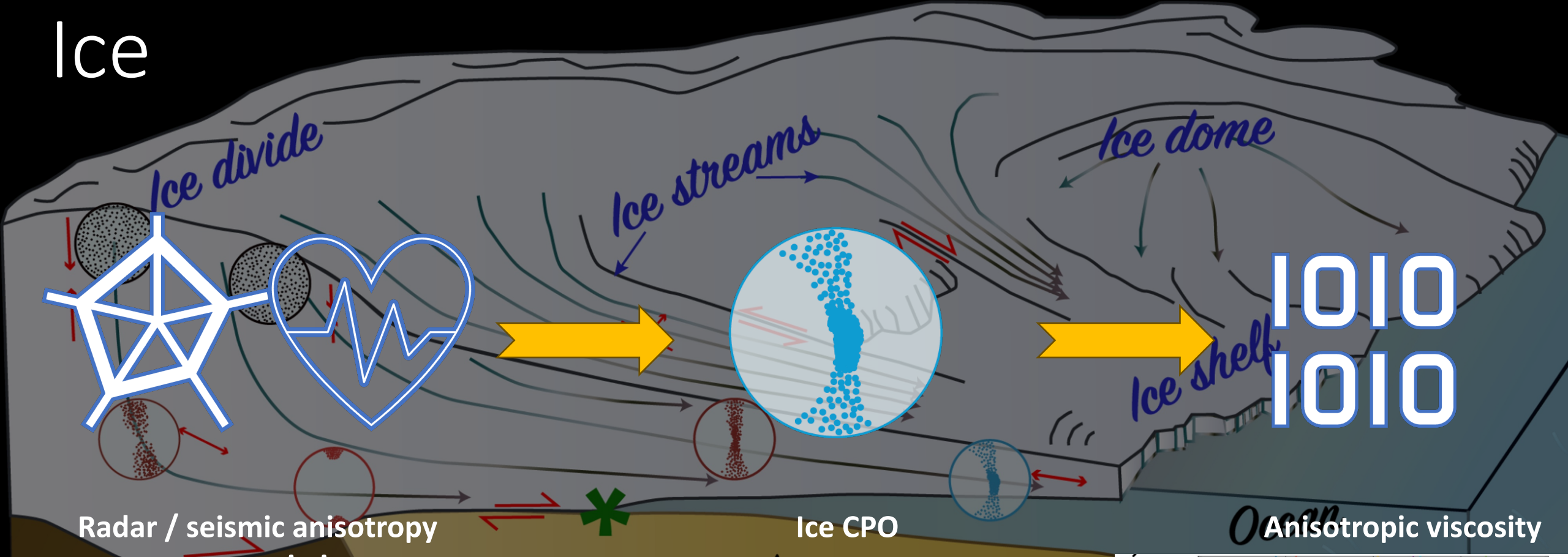


We can predict the anisotropic viscosity tensor from the LPO!





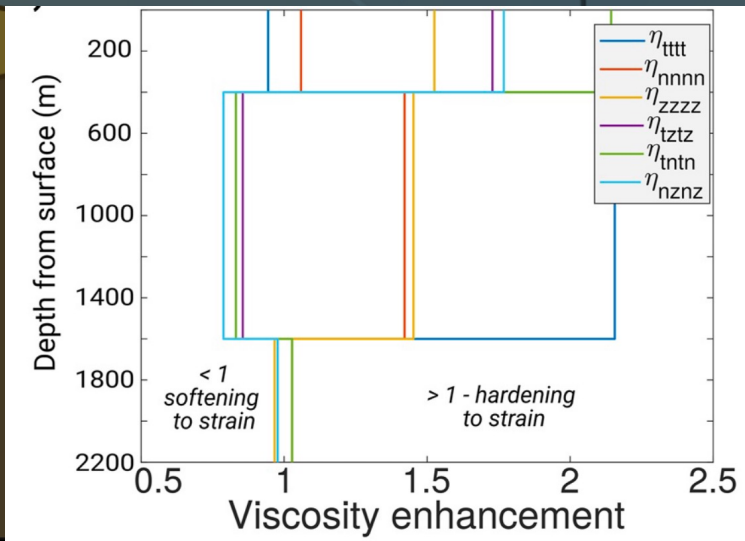
Ice



Radar / seismic anisotropy measurements in ice

Ice CPO

Anisotropic viscosity



Kufner et al., 2023
Jordan et al., 2022

What did you learn about anisotropy?