Rheologic effects of Crystal Preferred Orientation in upper mantle flow near plate boundaries

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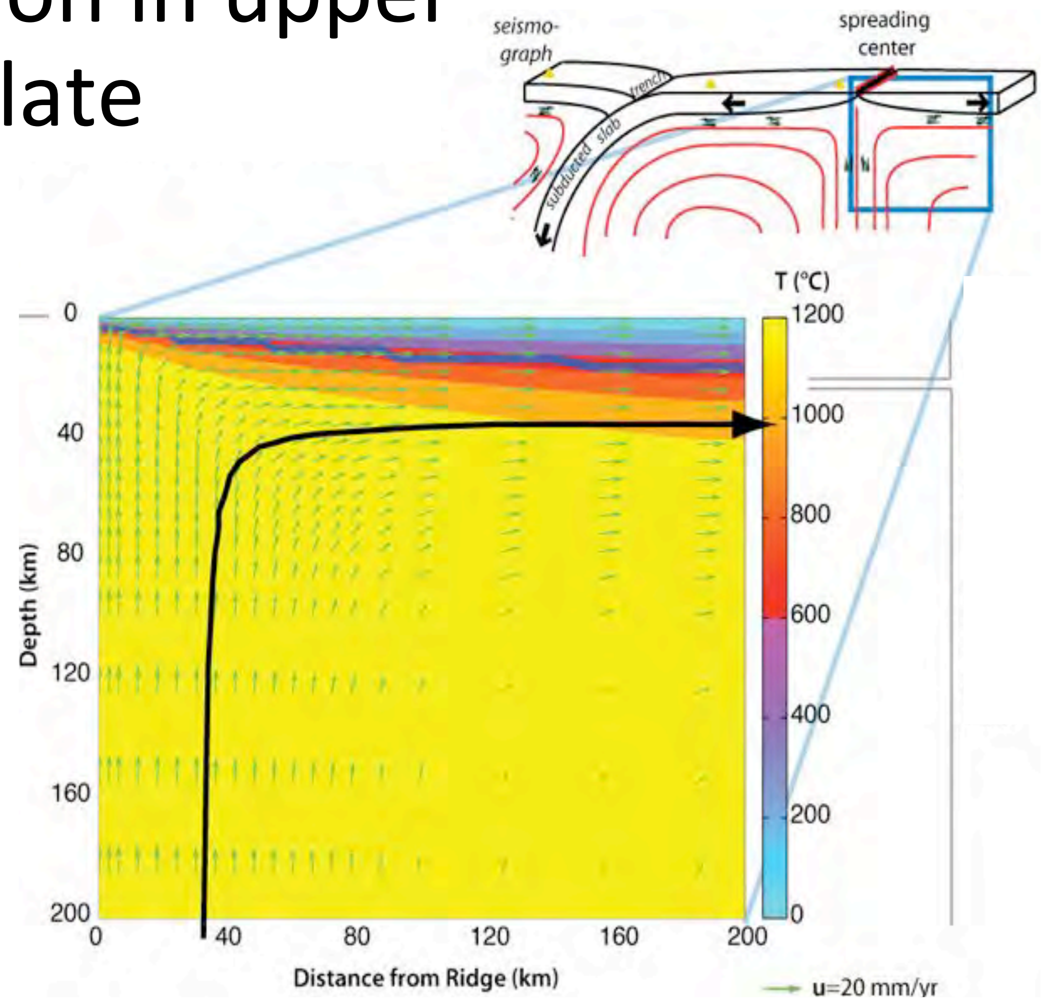
Goal- are fully-coupled models of mantle flow & microstructural (CPO) evolution required ?

Motivation- understand regional flow patterns and processes

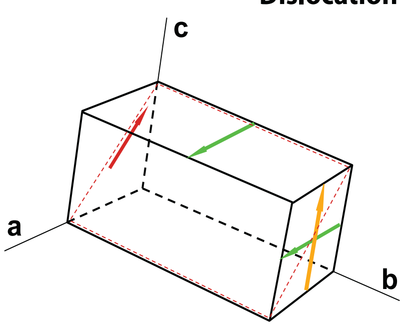
>>> improve interpretation of seismic anisotropy



Linked Micro-Macro Numerical Modeling

- Compute regional mantle flow field using ***Isaiah***
  Cornell 3D parallel FEM: deformation in Eulerian frame, coupled flow & temperature fields
- Calculate velocity gradient tensor along streamlines ending at all elements
- Calculate CPO at each element using Second Order Self Consistent scheme
  Castelnau et al. (JGR 2008; GRL 2009); 1000-grain polycrystals, dislocation glide dominant
- Determine effective viscosity tensor for polycrystal at each element
  specify stress:strain-rate behavior of polycrystal (linear vs power law n=2-3)
- Re-compute flow field using updated anisotropic viscosity tensor (V_{ijkl})
- Iterate (flow, V_{ijkl} stabilize) , compute seismic anisotropy

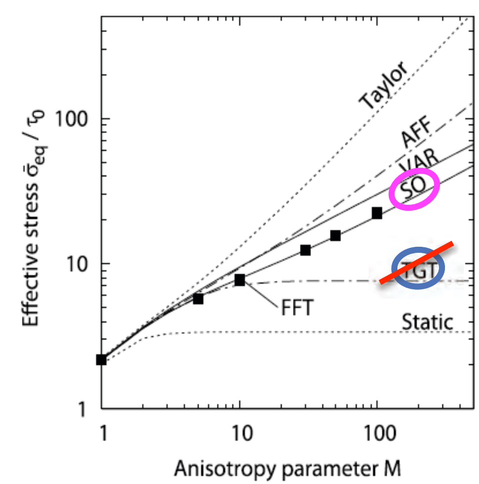
Dislocation slip systems for Olivine crystals



MPa

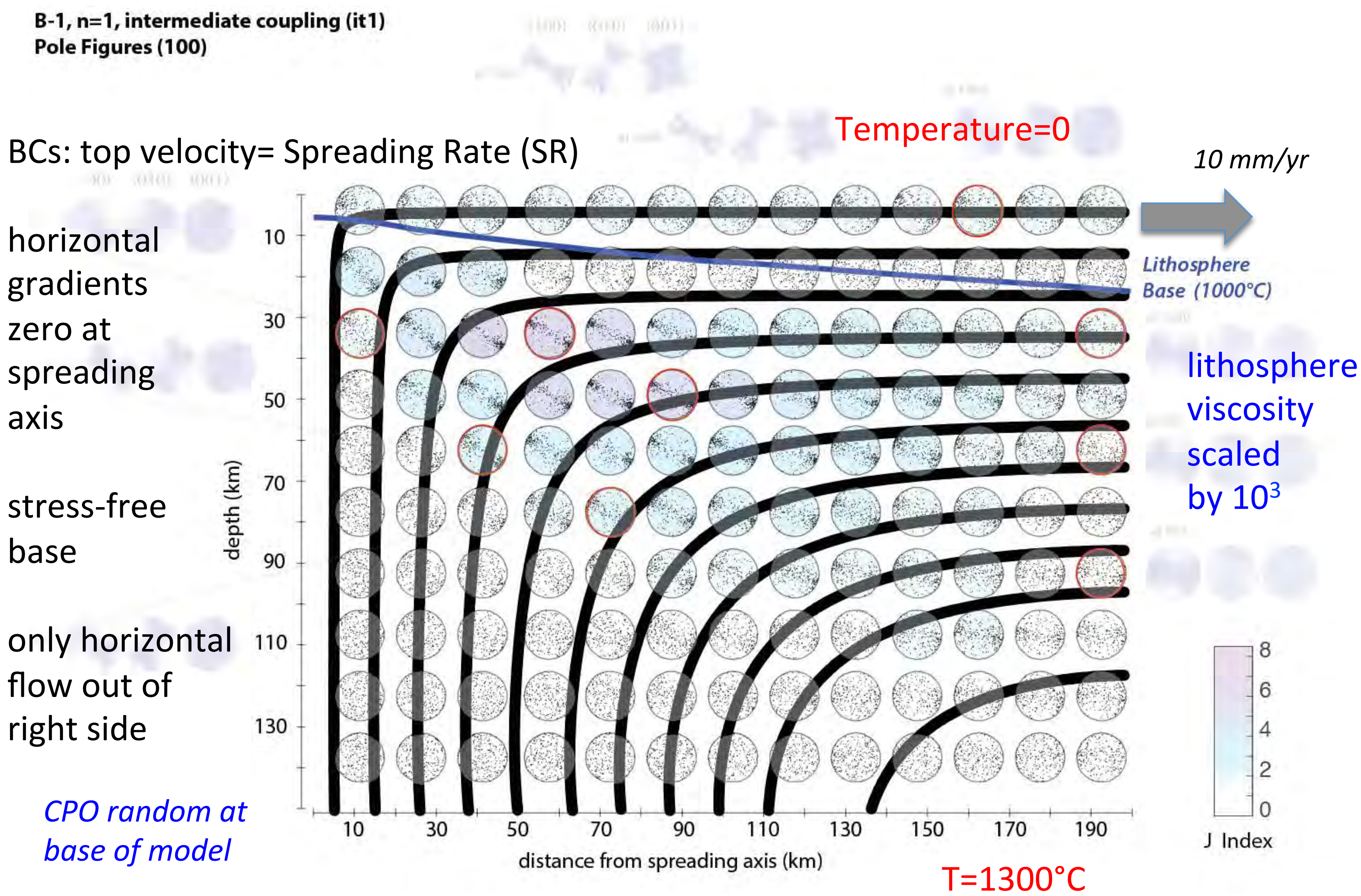
Slip system	Reference stress
● (010)[100]	5.5×10^{-4}
● (001)[100]	5.5×10^{-4}
● (010)[001]	5.5×10^{-3}
● $\{101\} < \bar{1}01 >$	5.5×10^{-2}

4th ‘hard’ system allows general deformation

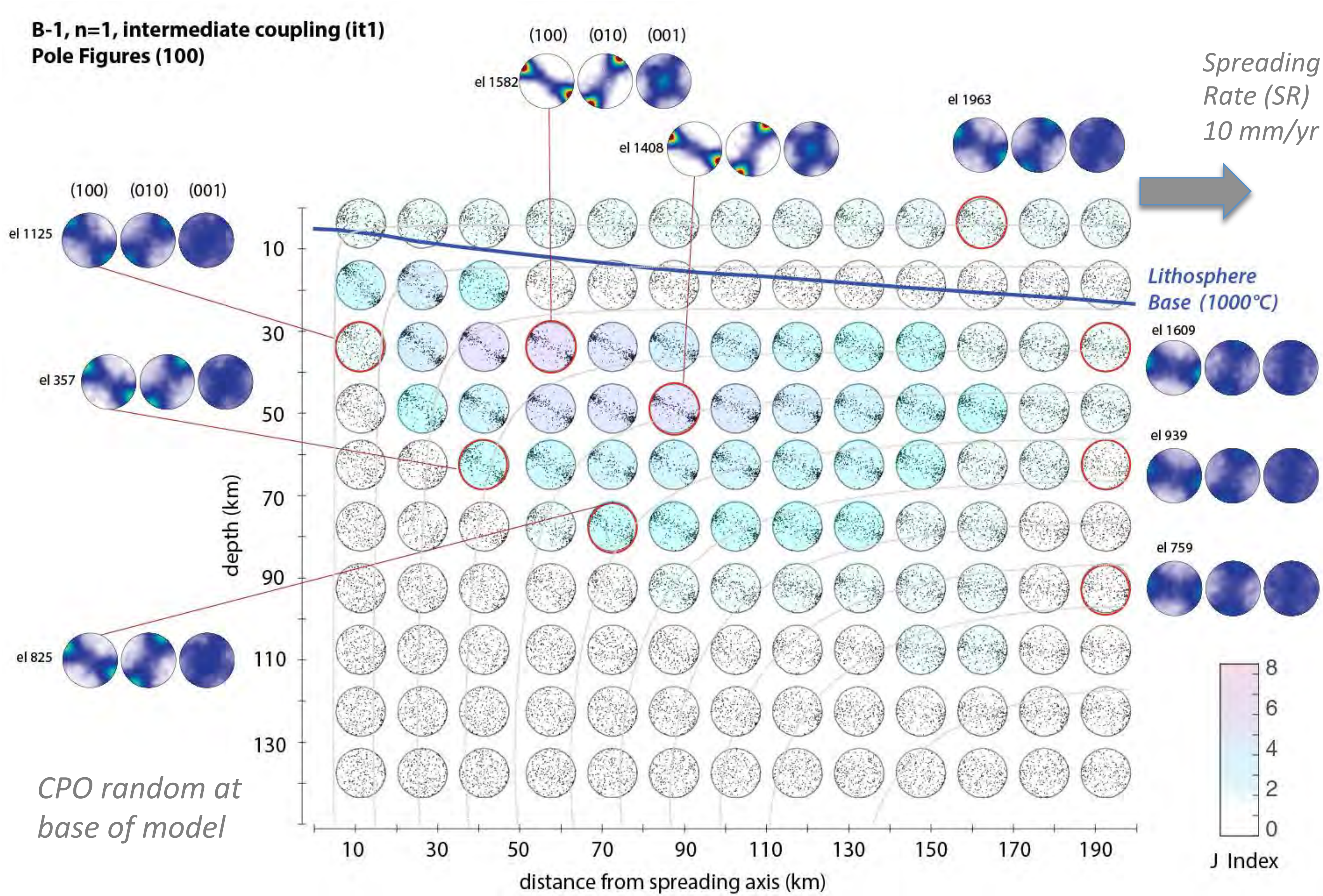


TGT = VPSC

Flow-Induced Crystal Preferred Orientation



Flow-Induced Crystal Preferred Orientation



Viscosity Tensor

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{bmatrix} = \begin{bmatrix} V_{1111} & V_{1122} & V_{1133} & V_{1123} & V_{1113} & V_{1112} \\ V_{2211} & V_{2222} & V_{2233} & V_{2223} & V_{2213} & V_{2212} \\ V_{3311} & V_{3322} & V_{3333} & V_{3323} & V_{3313} & V_{3312} \\ V_{2311} & V_{2322} & V_{2333} & V_{2323} & V_{2313} & V_{2312} \\ V_{1311} & V_{1322} & V_{1333} & V_{1323} & V_{1313} & V_{1312} \\ V_{1211} & V_{1222} & V_{1233} & V_{1223} & V_{1113} & V_{1212} \end{bmatrix} \begin{bmatrix} \dot{e}_{11} \\ \dot{e}_{22} \\ \dot{e}_{33} \\ 2\dot{e}_{23} \\ 2\dot{e}_{13} \\ 2\dot{e}_{12} \end{bmatrix}$$

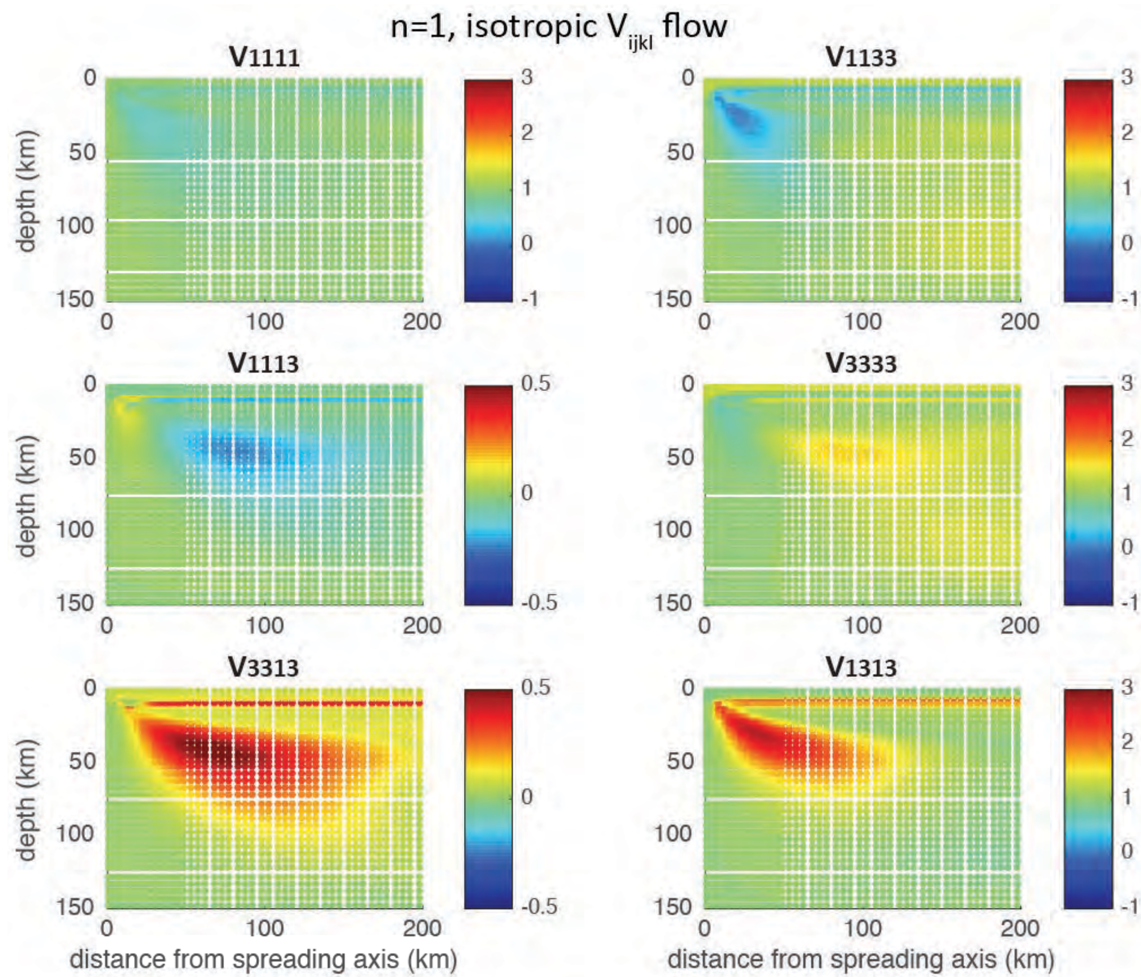
calculate polycrystal strain rate ($\dot{e}$) response to applied stress (σ)

polycrystal has CPO that evolved along flowline to element

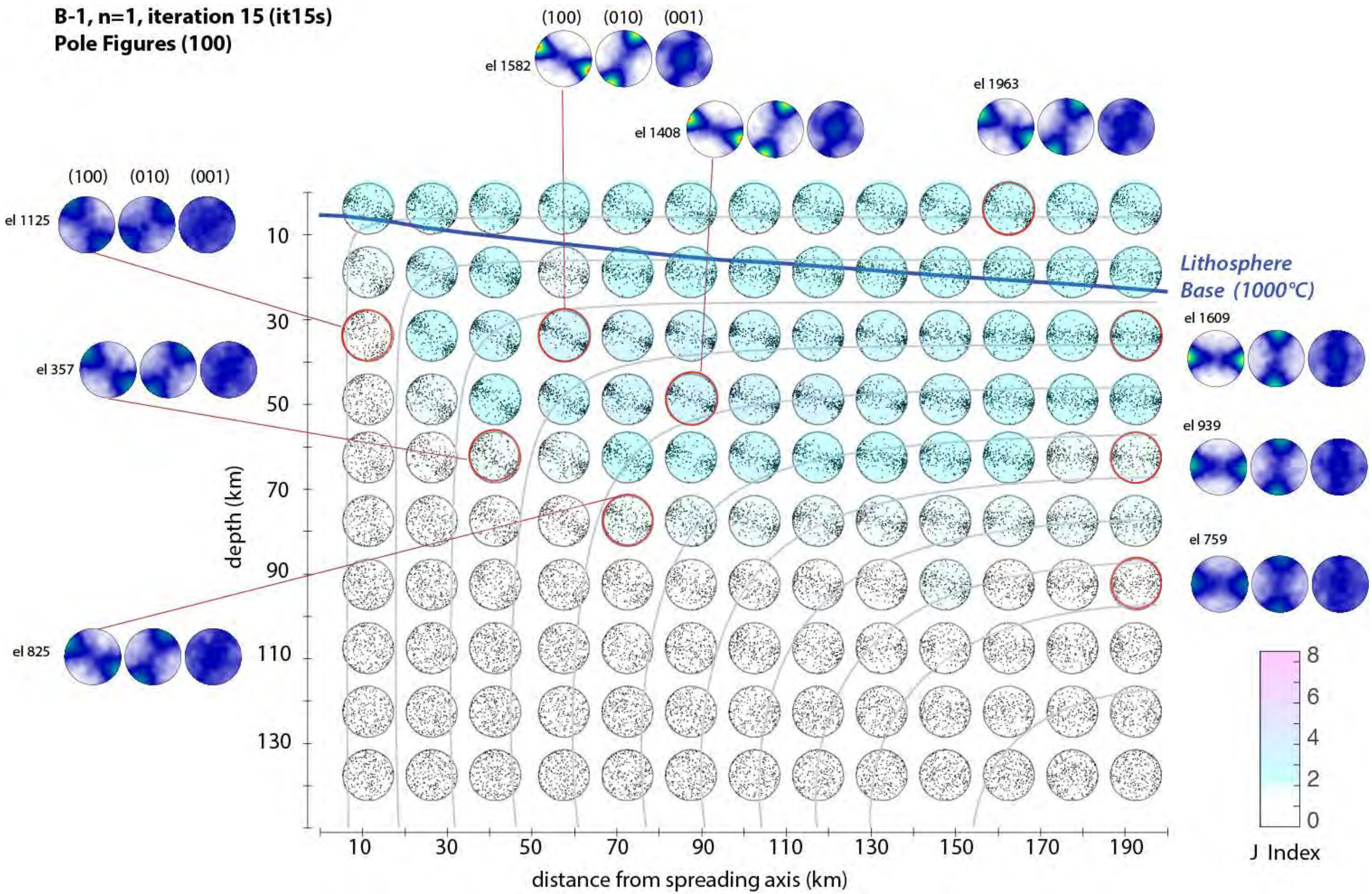
flow is 2-D, although model & texturing are calculated in 3-D

6 independent V_{ijkl} components

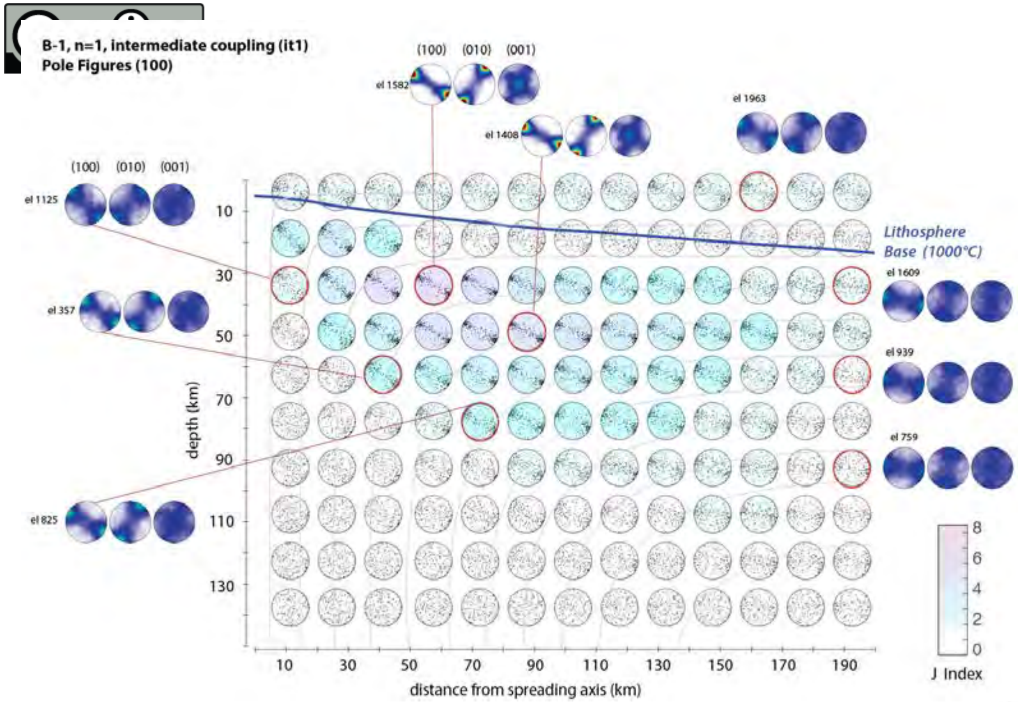
x: spreading direction (1)
z: vertical (3)
y: $\perp$ to plane (2)

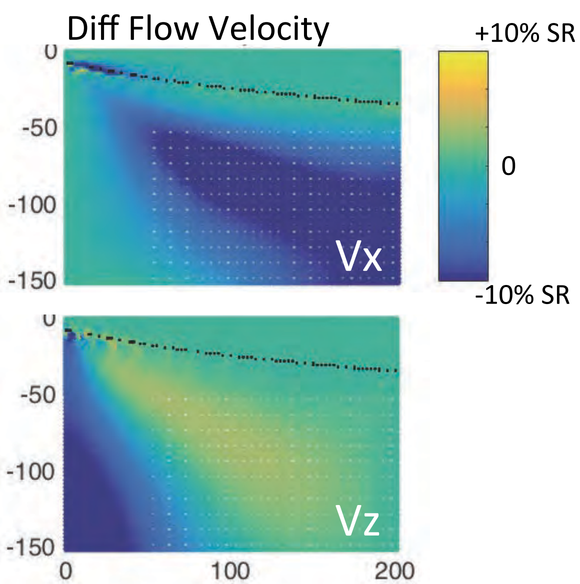


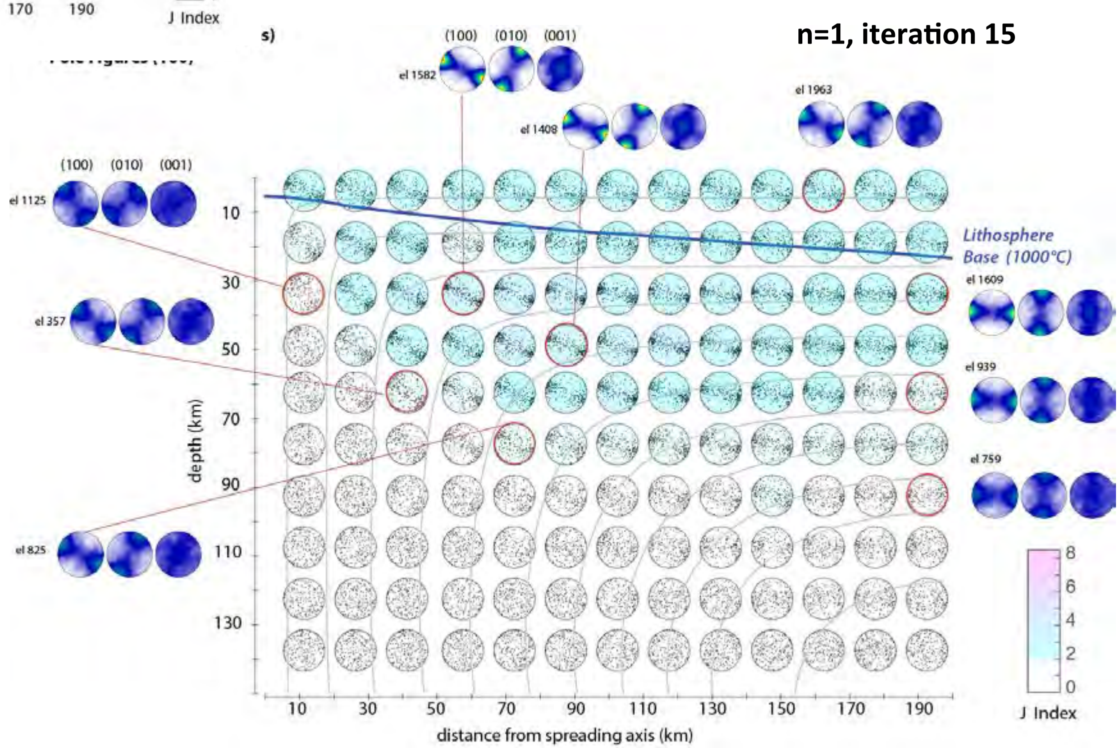
Coupled flow/CPO Result



Compare CPO, flowlines & flow velocities

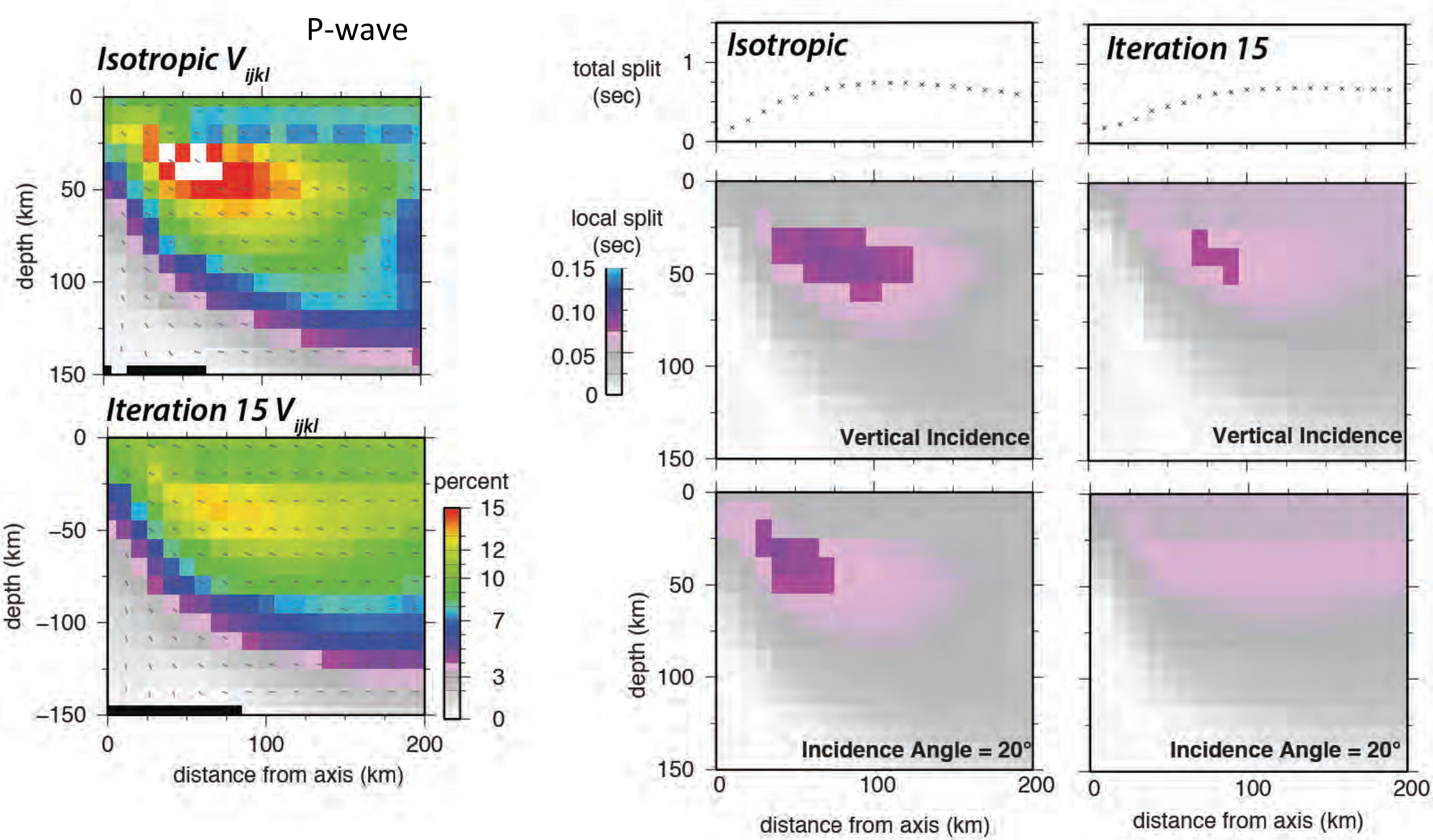






Predicted Seismic Anistropy

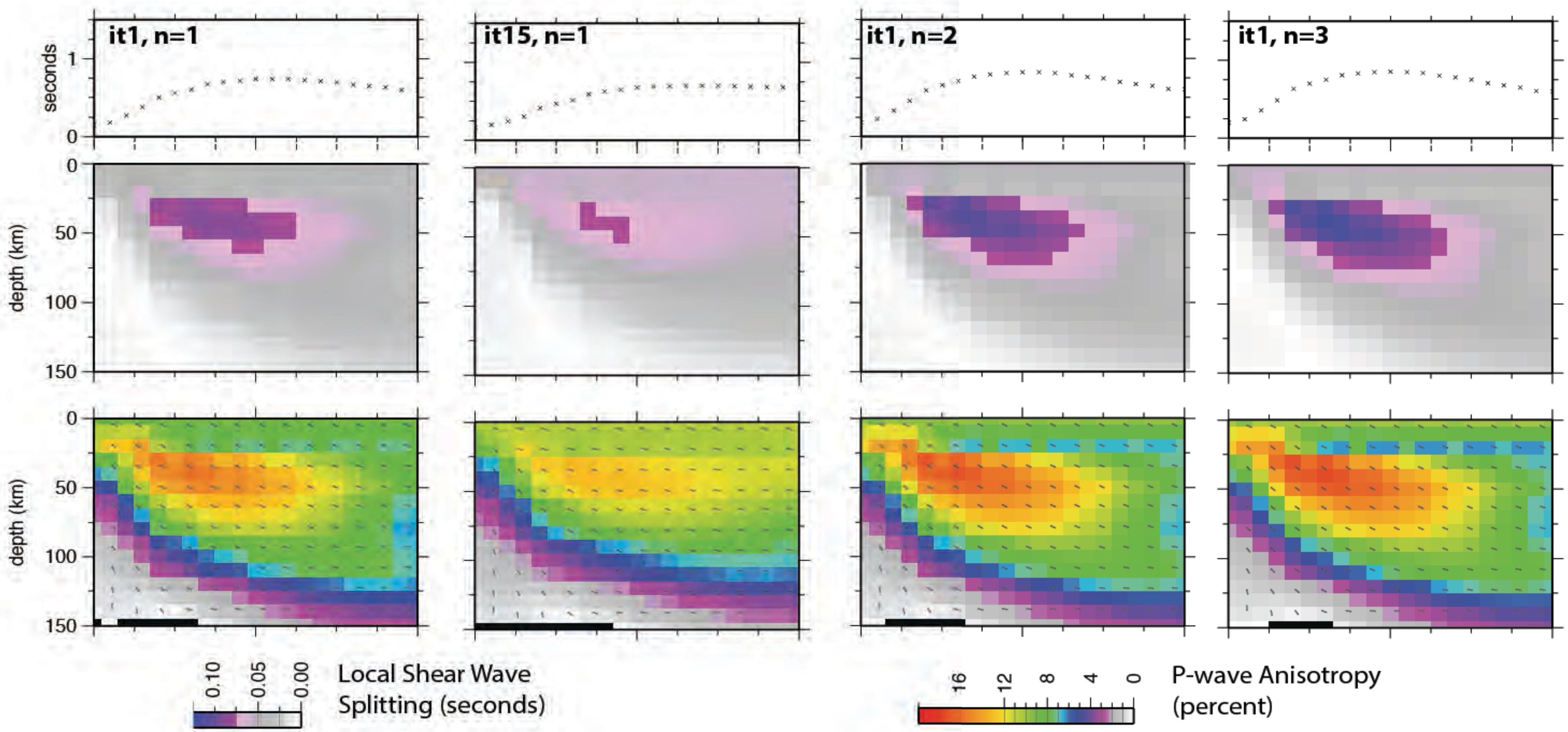
Linear (n=1) case



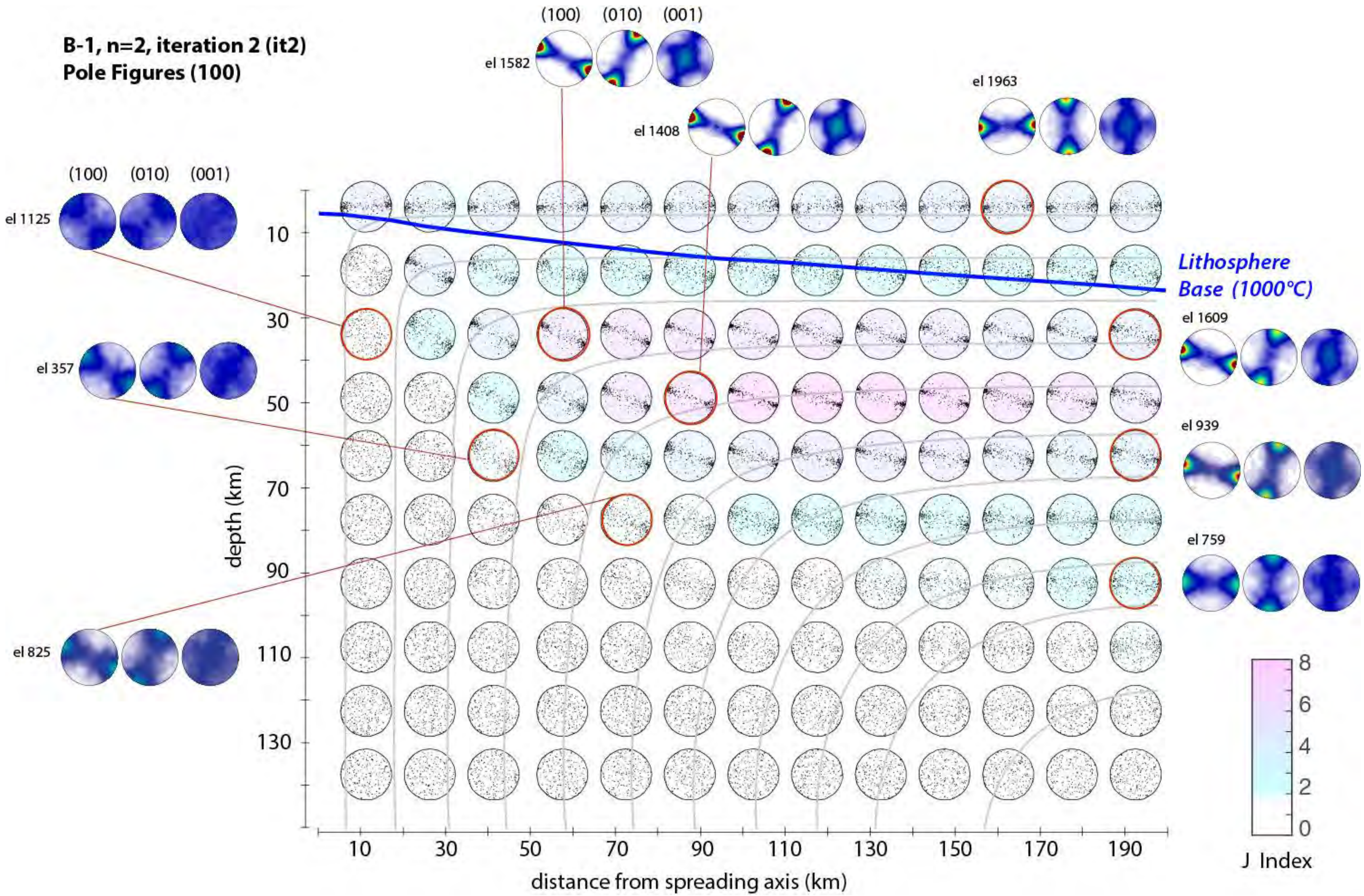
Predicted Seismic Anistropy

compare linear & power law cases, intermediate coupling

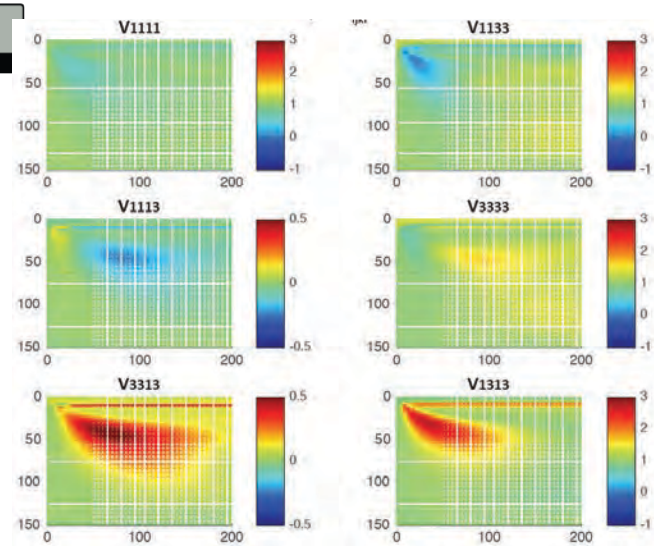
>> anisotropy a few percent stronger in flow 'corner', seismic effects modest



Coupled flow, power law polycrystal

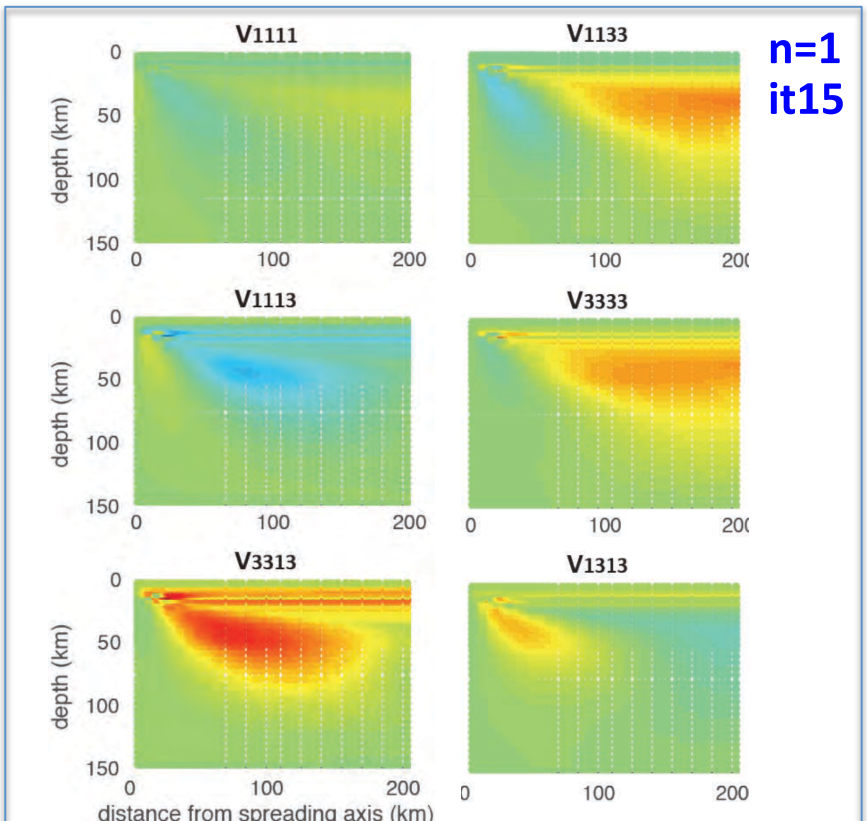


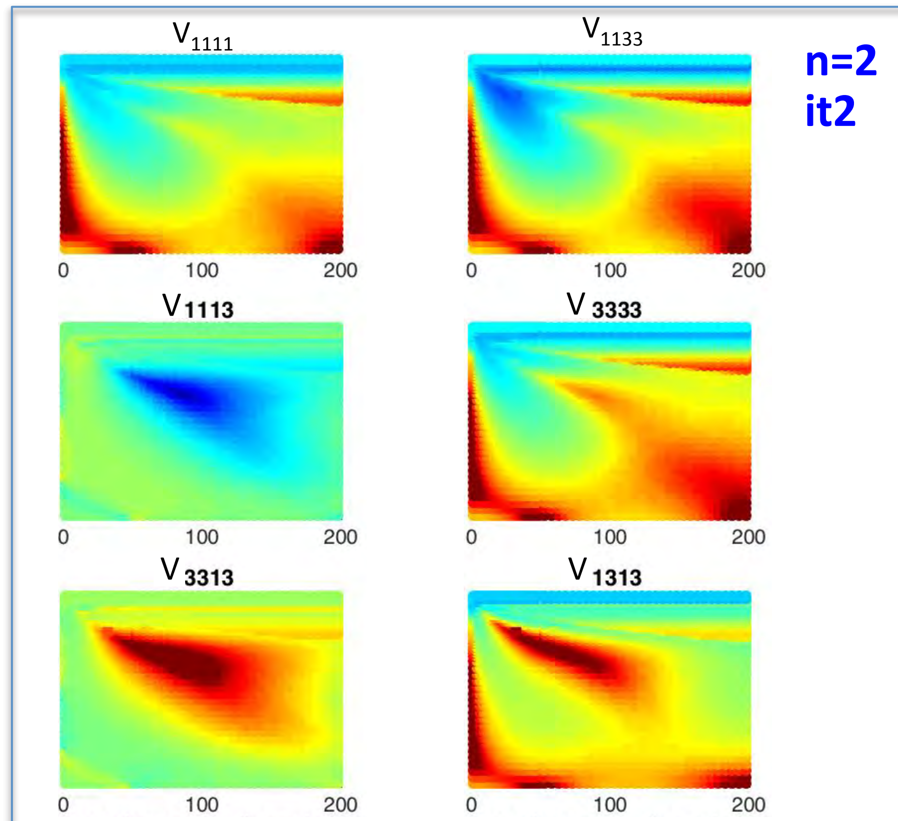
Variation of V_{ijkl} Between Models



n=1
it1

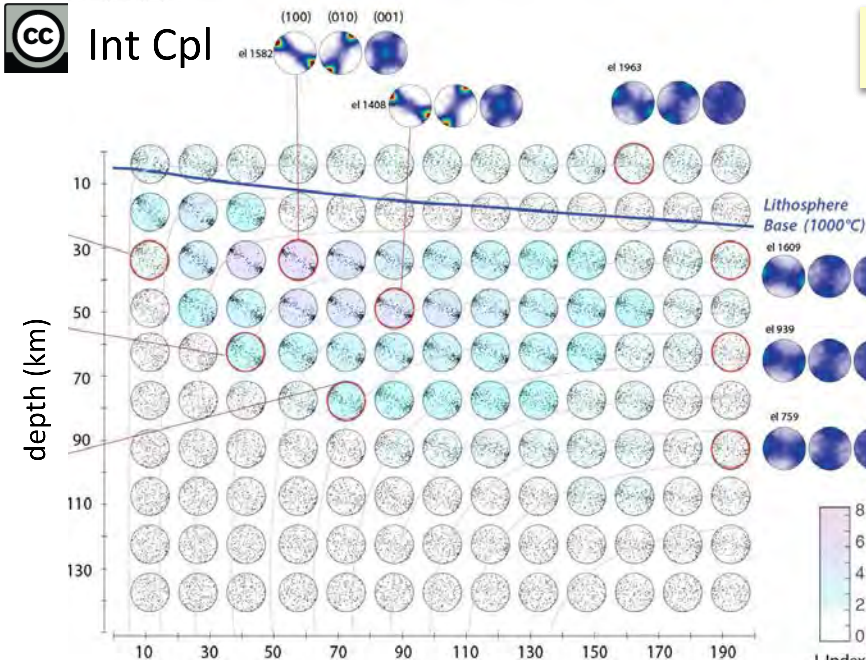
scaled by isotropic value, green ~ isotropic
color scale constant for a given V_{ijkl} component



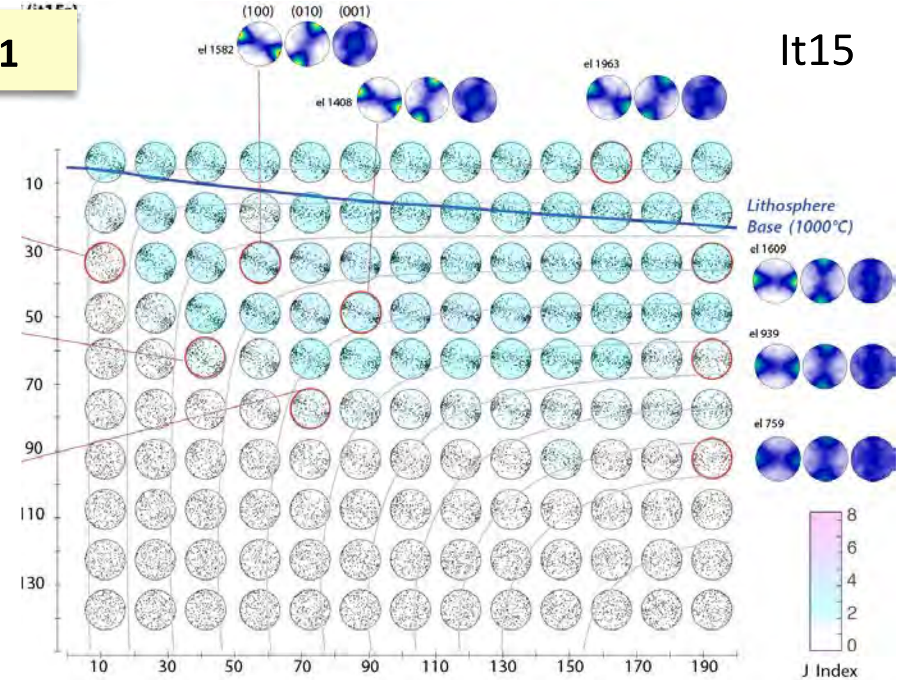


Int Cpl

n=1

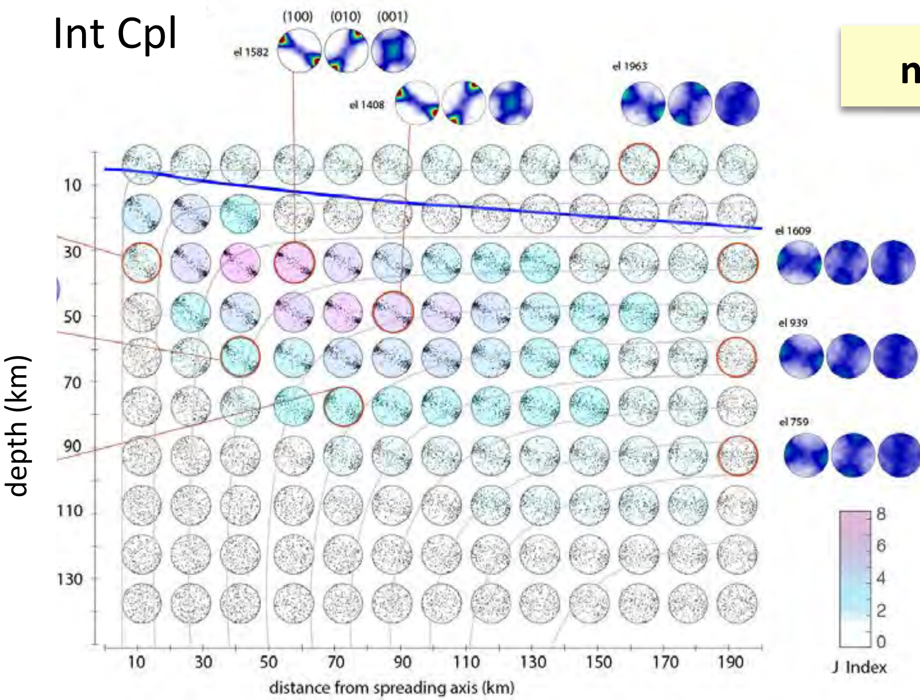


It15

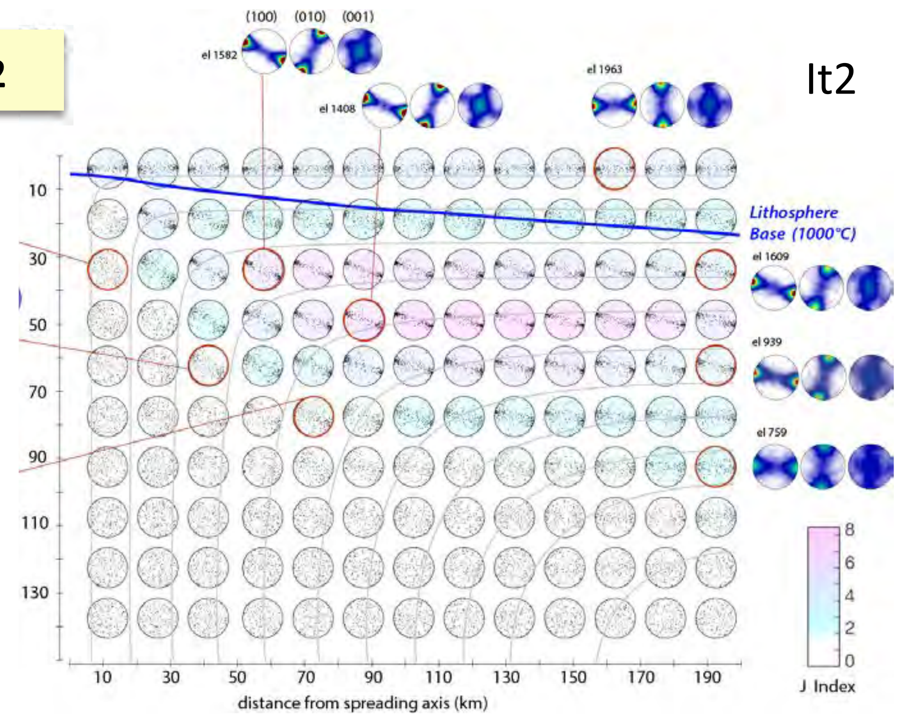


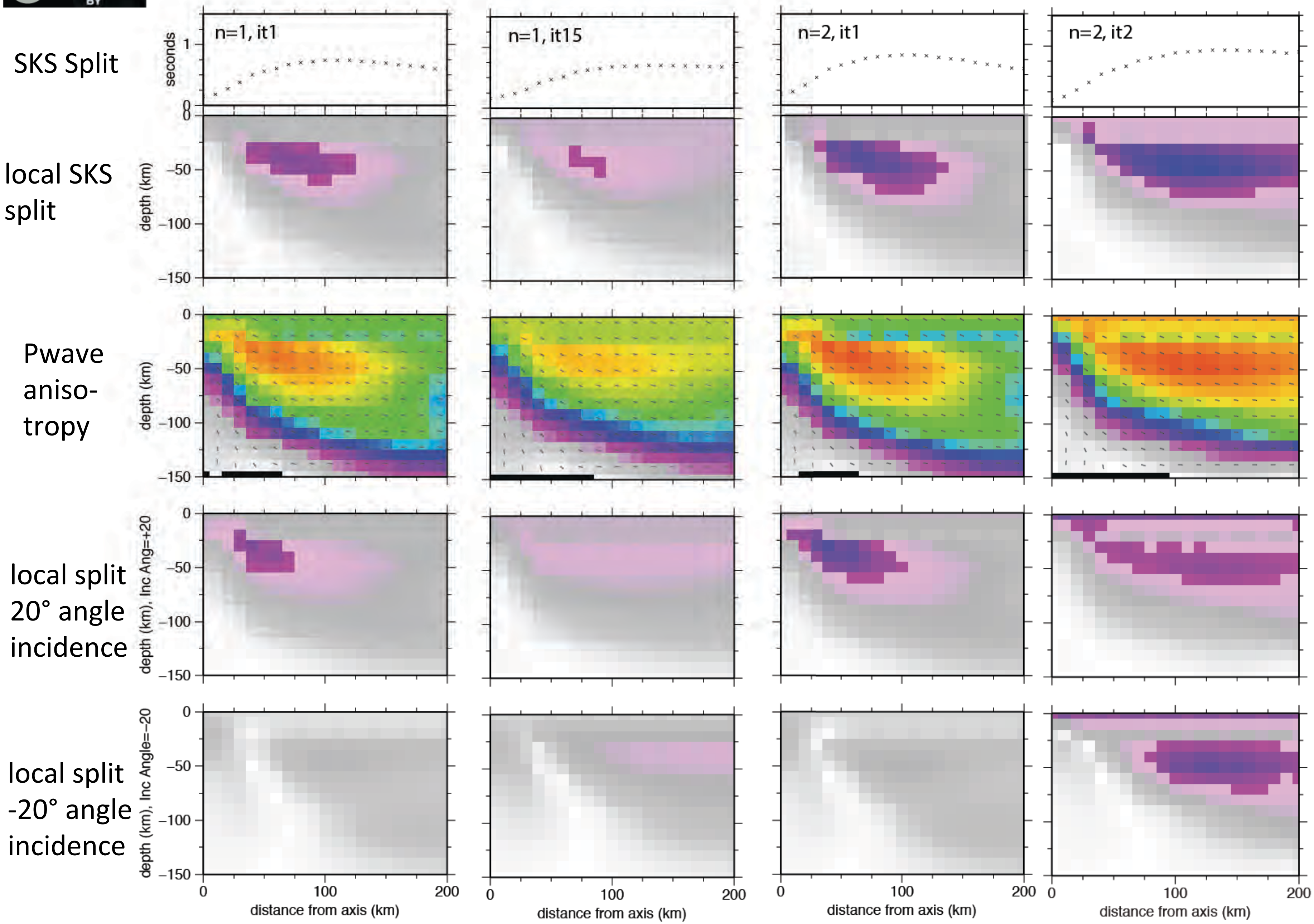
Int Cpl

n=2



It2




SKS Split
local SKS split
Pwave aniso-tropy
local split 20° angle incidence
local split -20° angle incidence
n=1, it1
n=1, it15
n=2, it1
n=2, it2
seconds
depth (km)
depth (km), Inc Ang=+20
depth (km), Inc Angle=−20
distance from axis (km)
0
1
−50
−100
−150
100
200

Summary

- **Fully-coupled micro-macro scale modeling is possible**

    Linear, low resolution runs 10-12 hrs each model iteration— full streamlines (sl), single processor

- **Flow field & anisotropy are affected by CPO rheologic feedback**

  Linear case— modest differences relative to isotropic V_{ijkl} intermediate coupling case

  Power law case— more notable differences: off axis anisotropy is stronger & extends deeper below lithosphere, increased shallow anisotropy rotates to horizontal, subaxial zone reduction for B-1

  Magnitude of difference off axis is seismically detectable (need larger model space to quantify)

- **Computational implications of (more realistic) power law polycrystal behavior**

    major increase in convergence time for CPO evolution & viscosity tensor calculation

    >> multi-processor, high-speed computing required for further work, update sl from last element

- **Details of axial lithosphere will influence shallow results**