The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2048-11

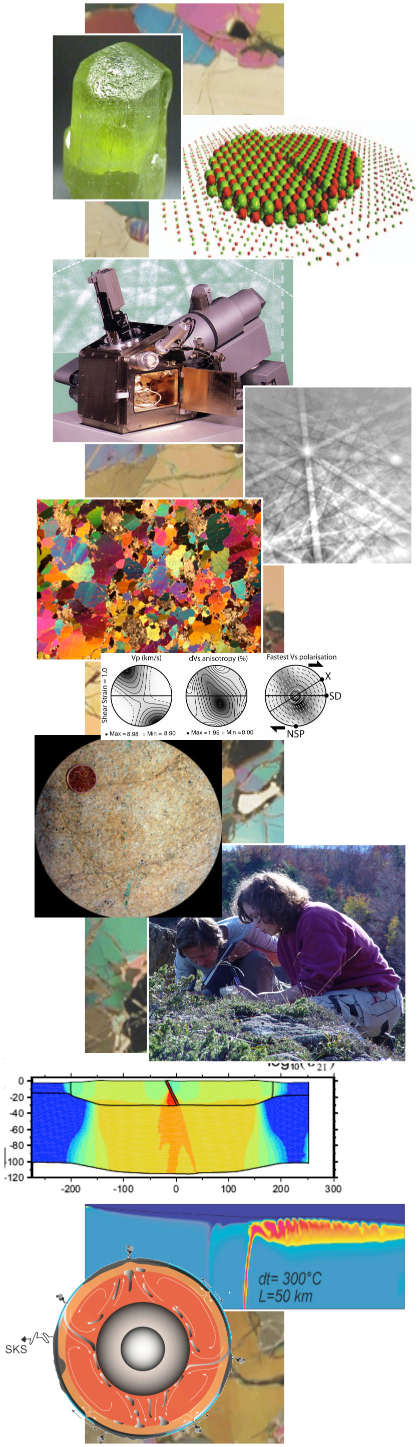
From Core to Crust: Towards an Integrated Vision of Earth's Interior

20 - 24 July 2009

Deformation and anisotropy in the mantle

A. Tommasi

Universite Montpellier 2, France



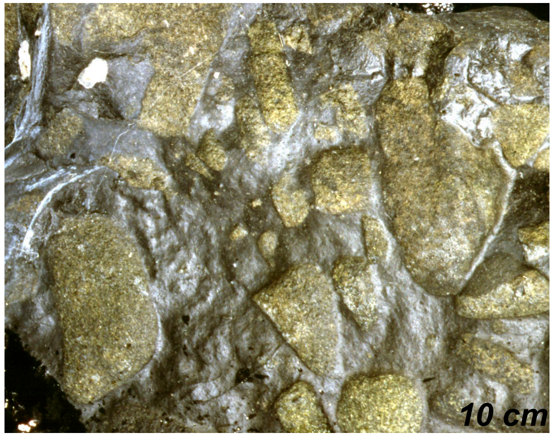
Deformation and anisotropies (seismic, electrical, thermal, mechanical...) in the mantle

Andréa Tommasi

Géosciences Montpellier

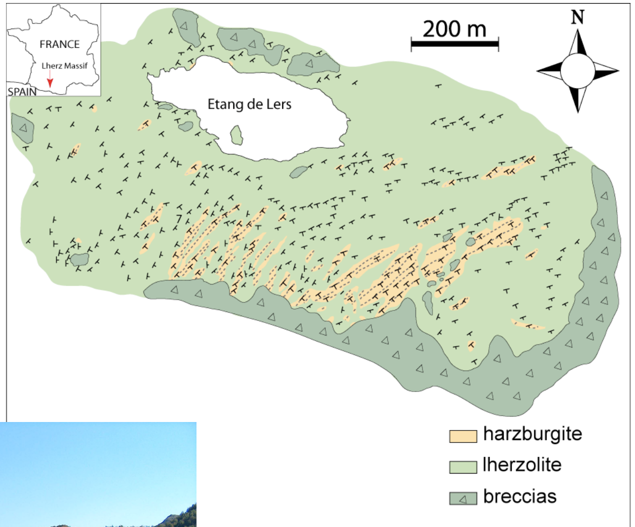
D.Mainprice, A.Vauchez, G. Barruol,
M. Knoll, B. Gibert, C. Thoraval (Montpellier, F)
R. Logé (MinesTech, F); J. Signorelli (IFIR, AR)...

How can we study the mantle deformation?



xenoliths : mm to cm scale

- *deformation mechanisms*



peridotite massifs : m to 10s of km scale

- *deformation repartition, strain localization...*
- *interaction with other processes, (melting, fluids, T gradients...)*

- *"small" pieces extracted from the shallow mantle (<150 km)*

✓ *cannot be used to map mantle flow*

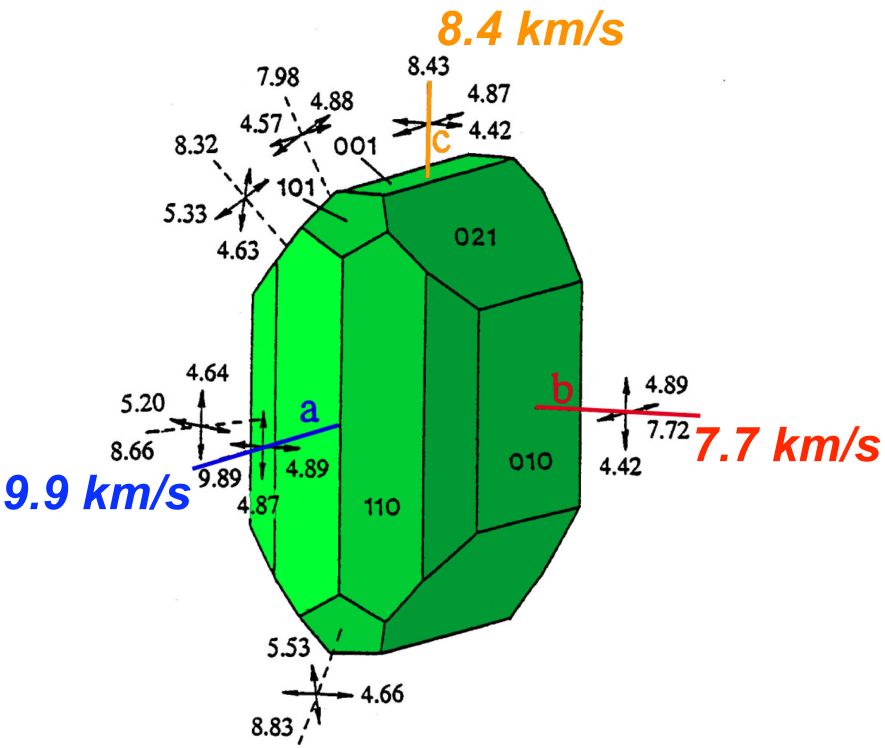
Seismic anisotropy = a tool to probe the mantle deformation

Anisotropy = dependence of a physical property on the direction of sampling

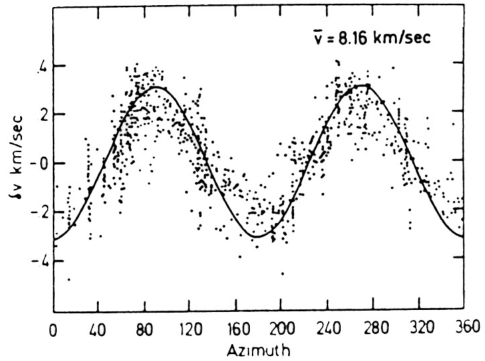
Seismic waves velocities vary as a function of:

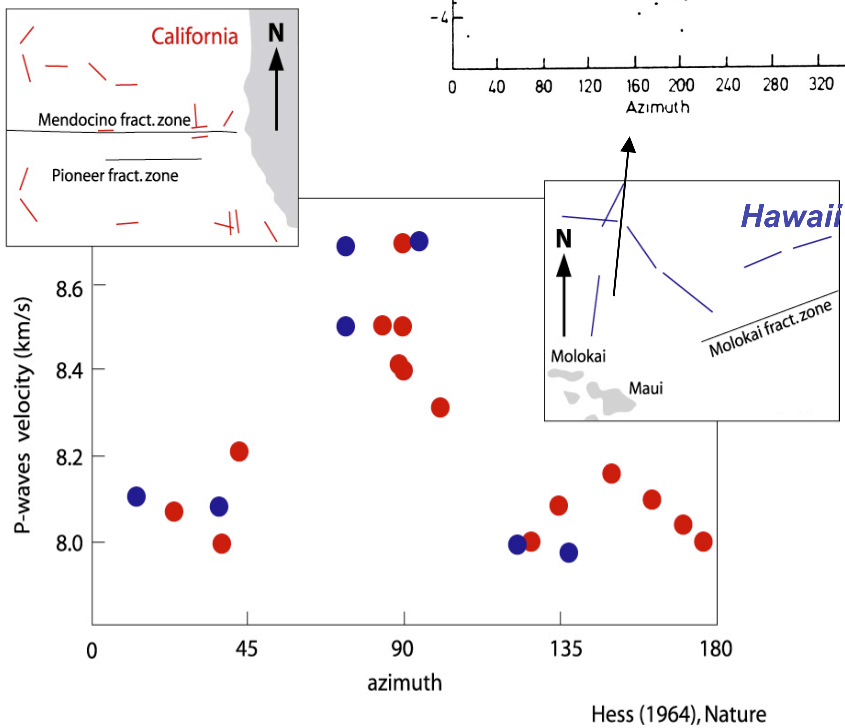
- ***the propagation direction (P & S waves)***
- ***the polarization direction***

Olivine cristal (μm-cm)



Refraction profiles
Vp=F(profile direction)
faster // spreading





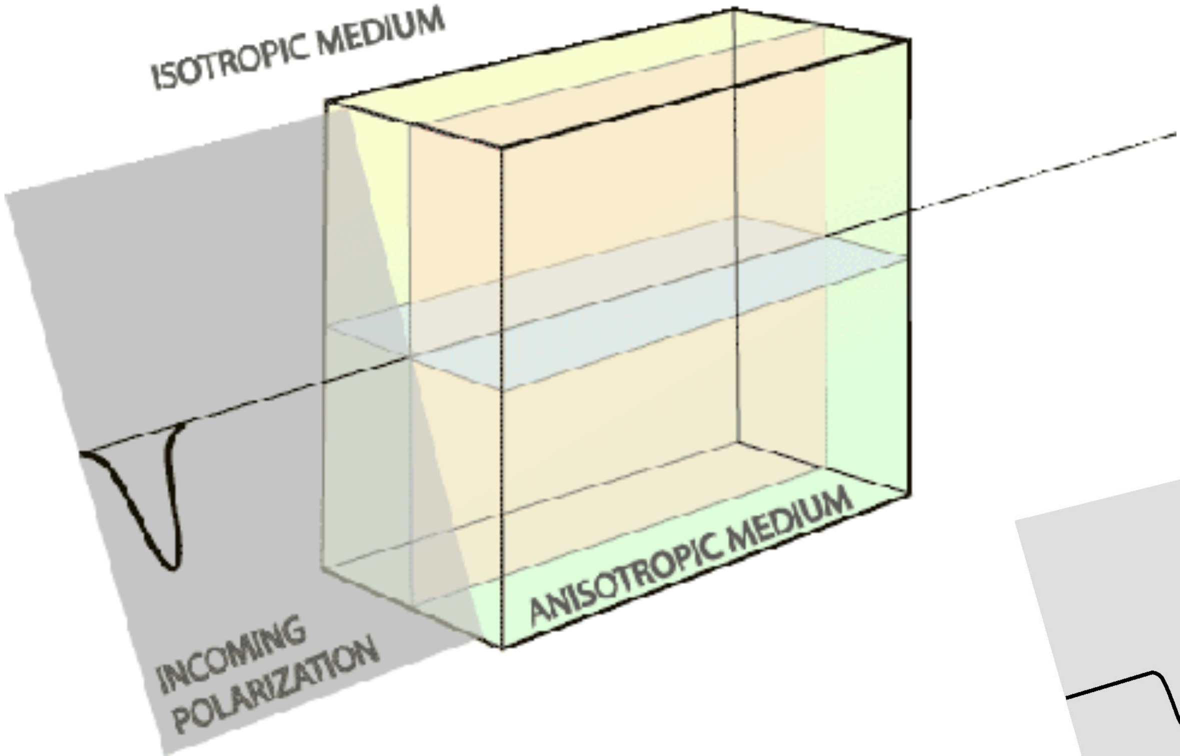
P-waves azimuthal anisotropy (10s of km)

What is seismic anisotropy?

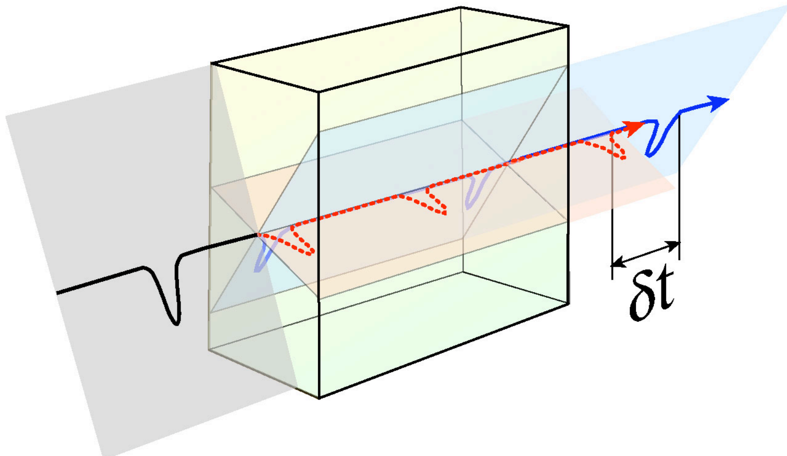
Anisotropy = dependence of a physical property on the direction of sampling

Seismic waves velocities vary as a function of:

- *the propagation direction*
- ***the polarization direction (S waves)***

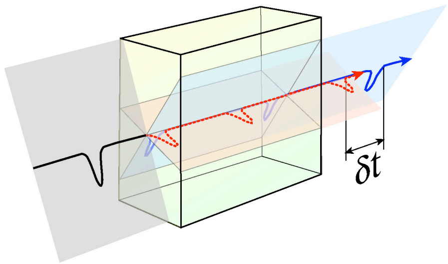


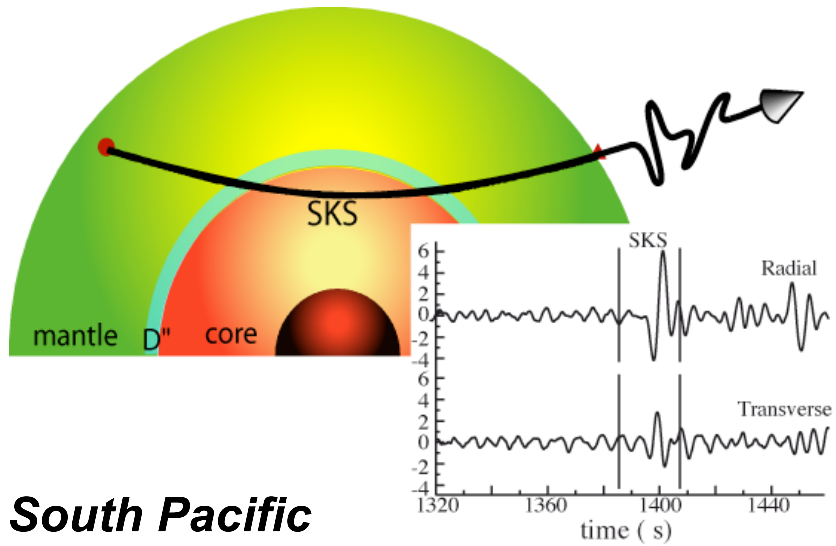
shear wave splitting



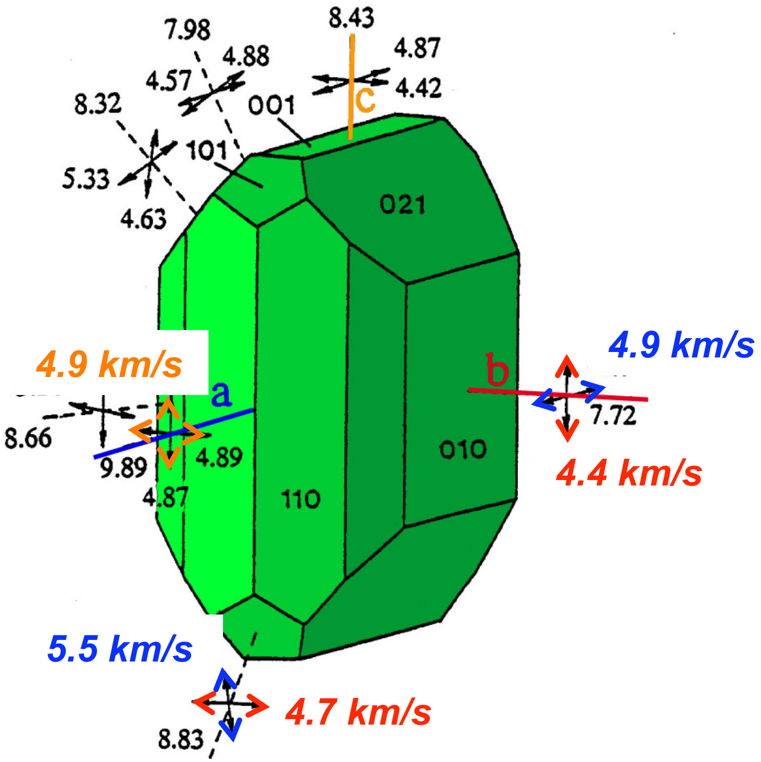
http://garnero.asu.edu

S waves polarization anisotropy - shear wave splitting

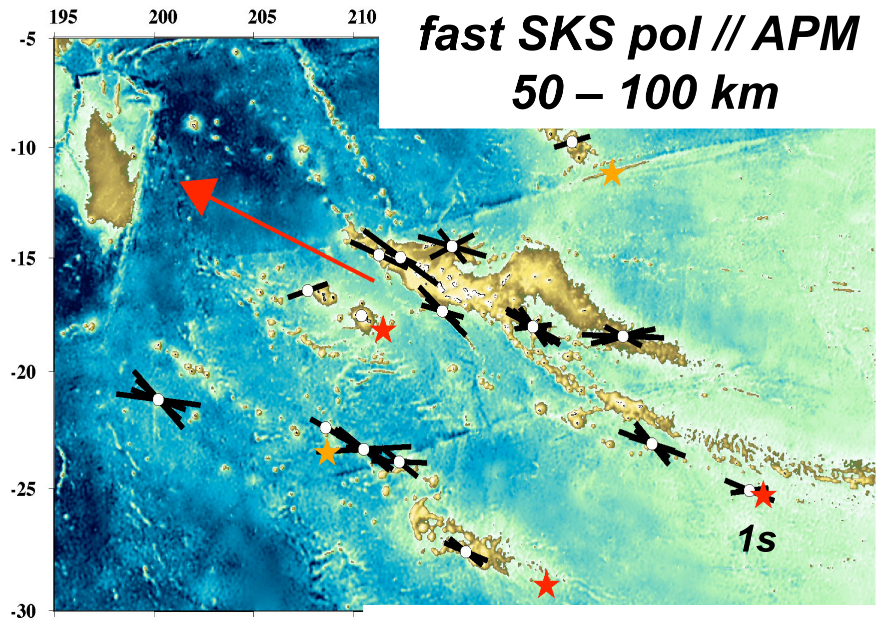




Olivine cristal (μm-cm)

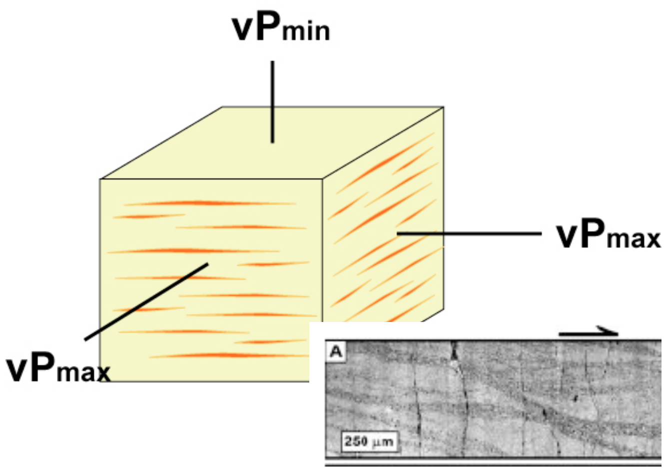


in the South Pacific



Fontaine et al., GJI 2007

anisotropy results from



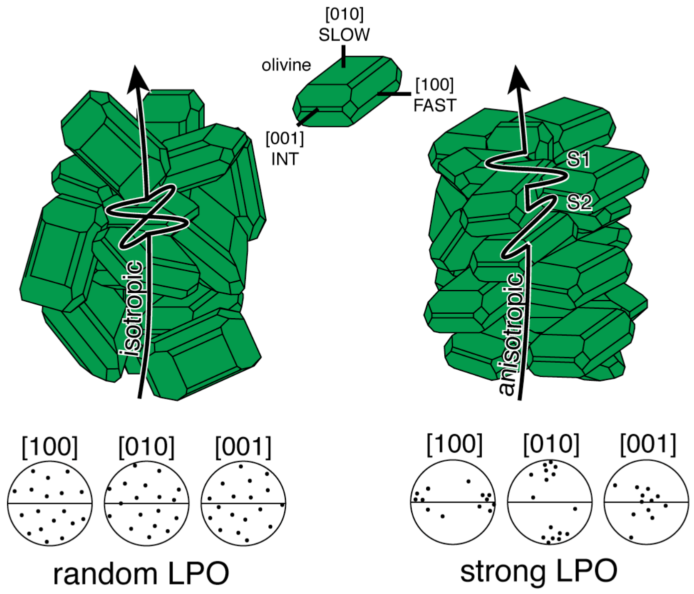
layering of materials with very ≠ properties :

- *sediments*
- *strain-induced layering in metamorphic or magmatic rocks*
  - ✓ *crust, deep mantle (?)*

- *aligned cracks, dykes or melt lenses*
  - ✓ *upper crust*
  - ✓ *middle & lower crust*
  - ✓ *upper mantle (subduction, rift…)*
  - ✓ *transition zone, D" (?)*

Crystal or Lattice Preferred Orientation (CPO or LPO) of anisotropic minerals :

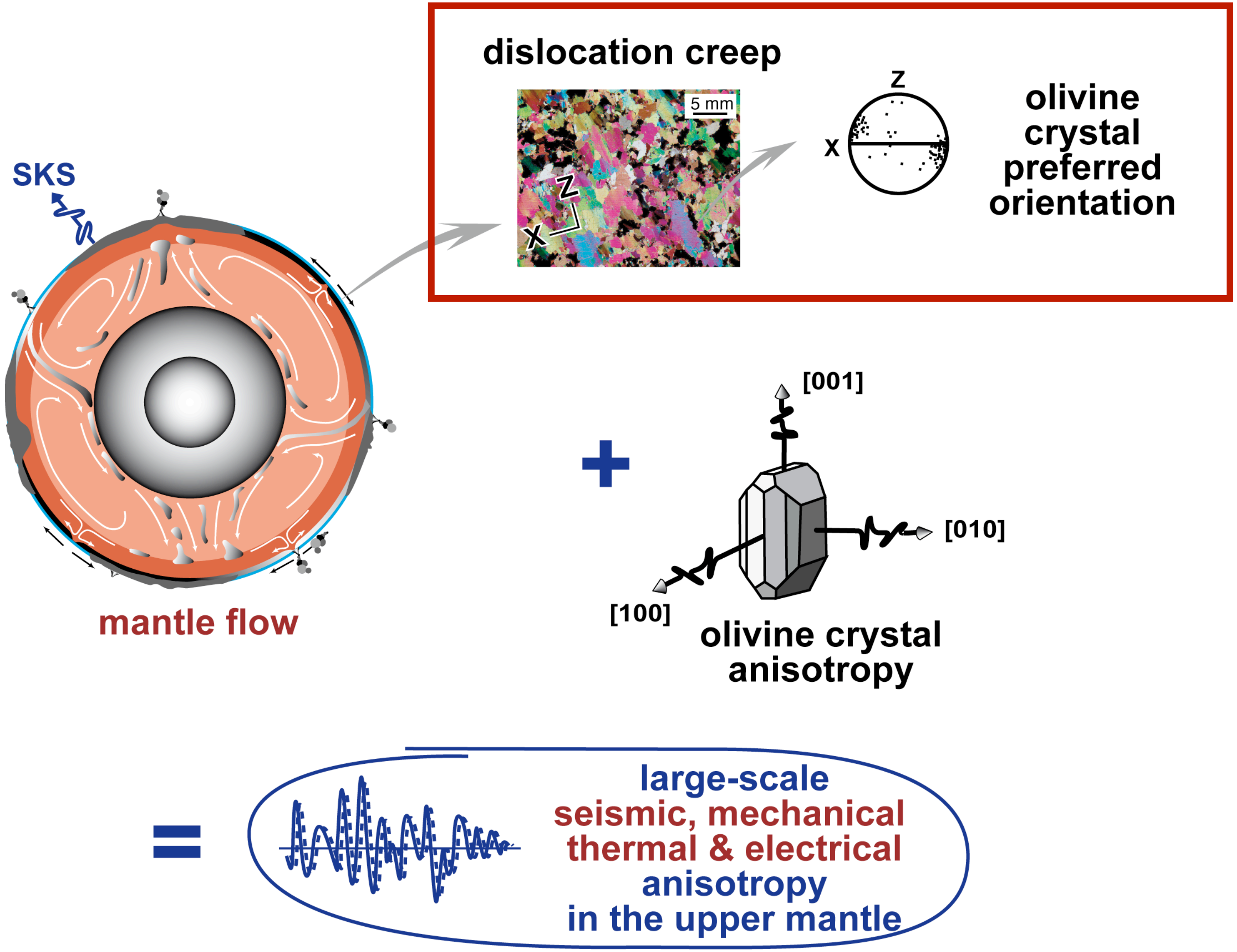
- ✓ *lower crust*
- ✓ *mantle*
- ✓ *inner core (?)*



drawing by Luc Mehl

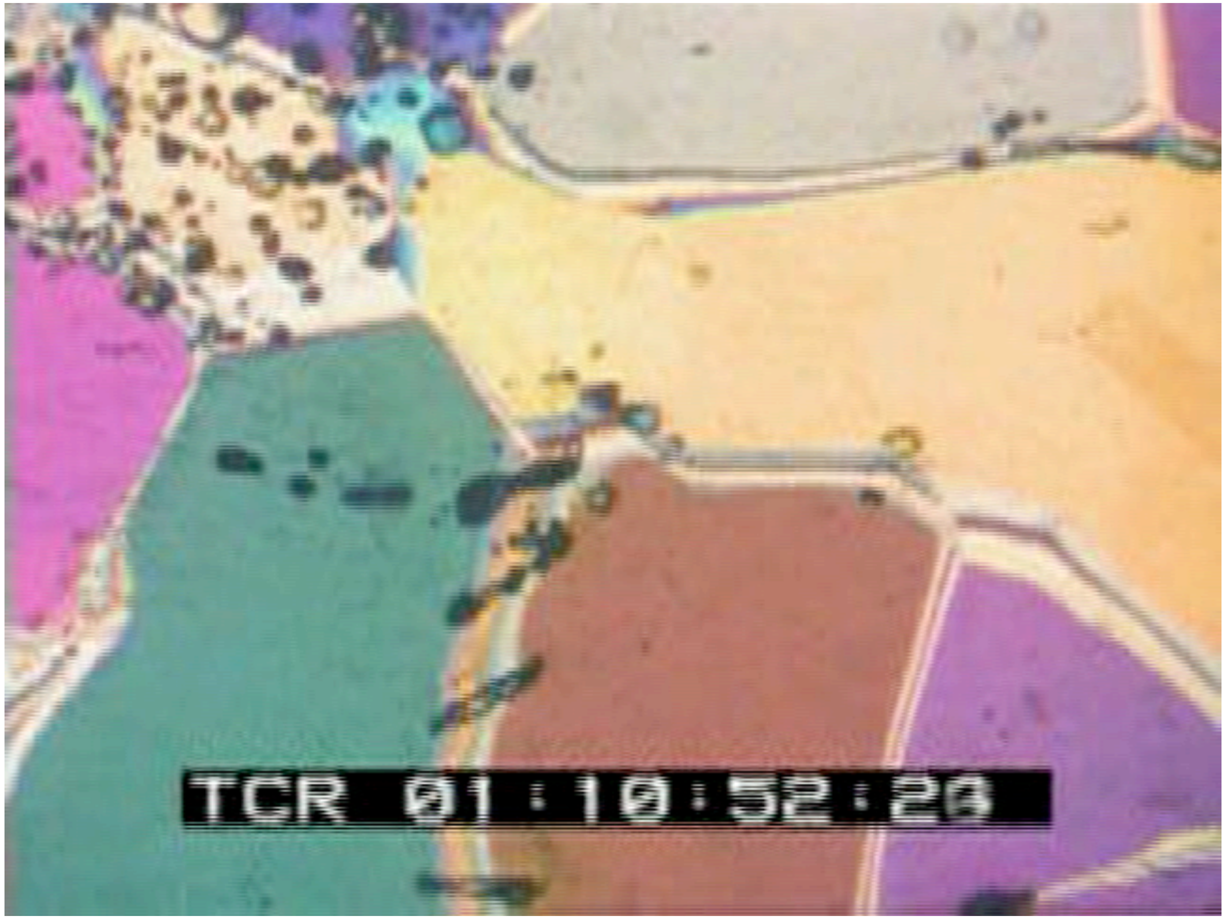
deformation plays an essential role in the development of anisotropy

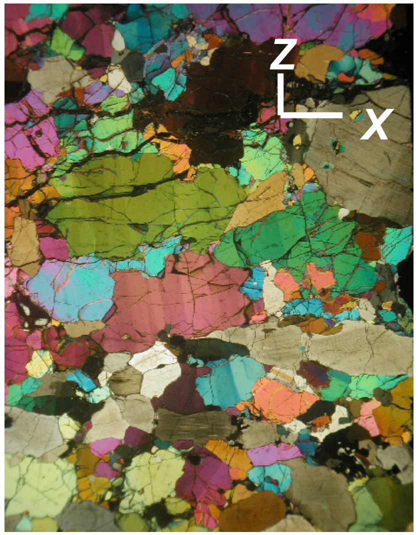
How do we translate seismic anisotropy data into flow patterns?



Viscoplastic deformation & crystal preferred orientations

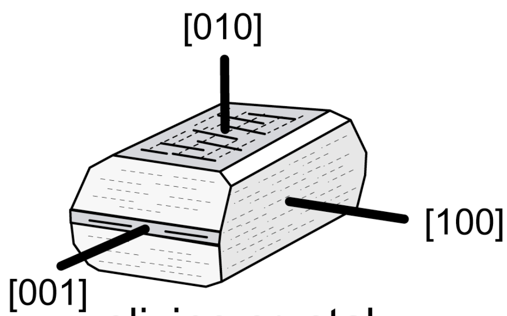
dislocation creep = dislocation glide + dynamic recrystallization





polycrystalline ice
in-situ deformation: pure shear
C. Wilson - Univ. Melbourne, Australia

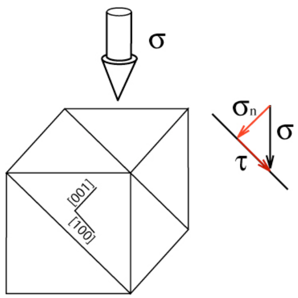
Crystal deformation by dislocation glide

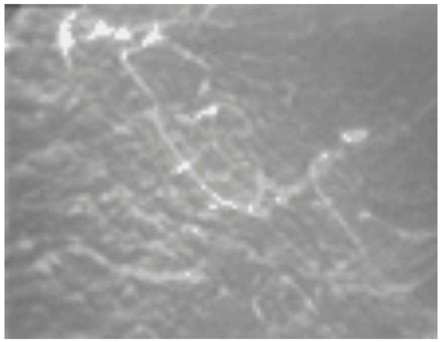


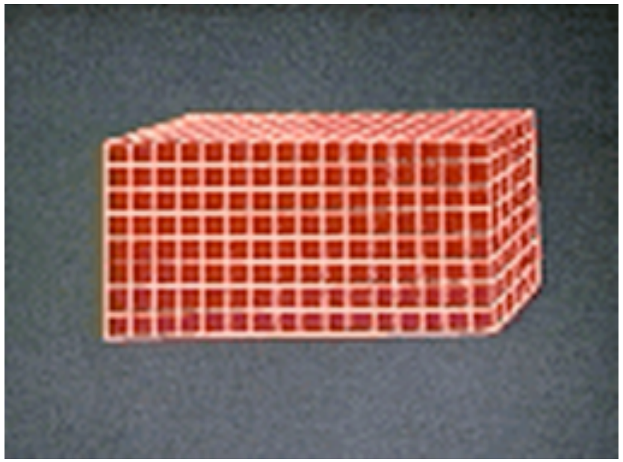
olivine crystal
slip systems

within a grain (crystal):

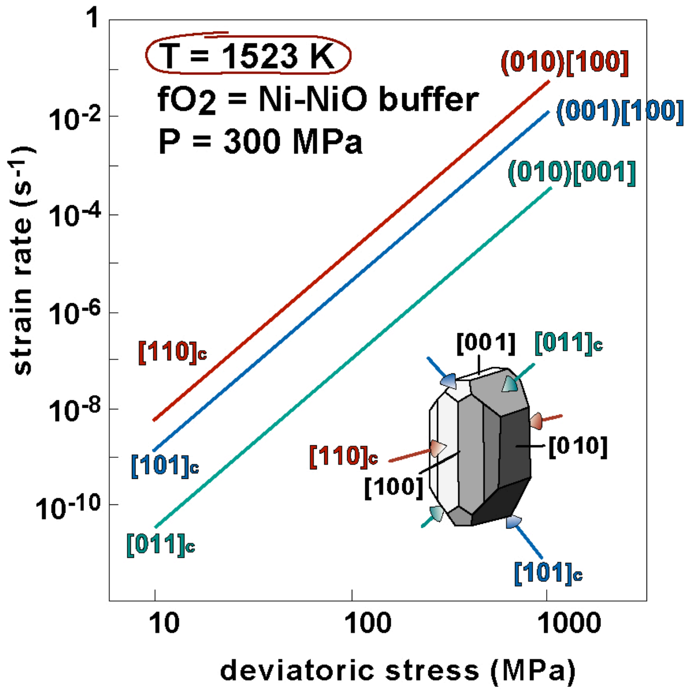
strain = motion of dislocations on well-defined crystal planes & directions







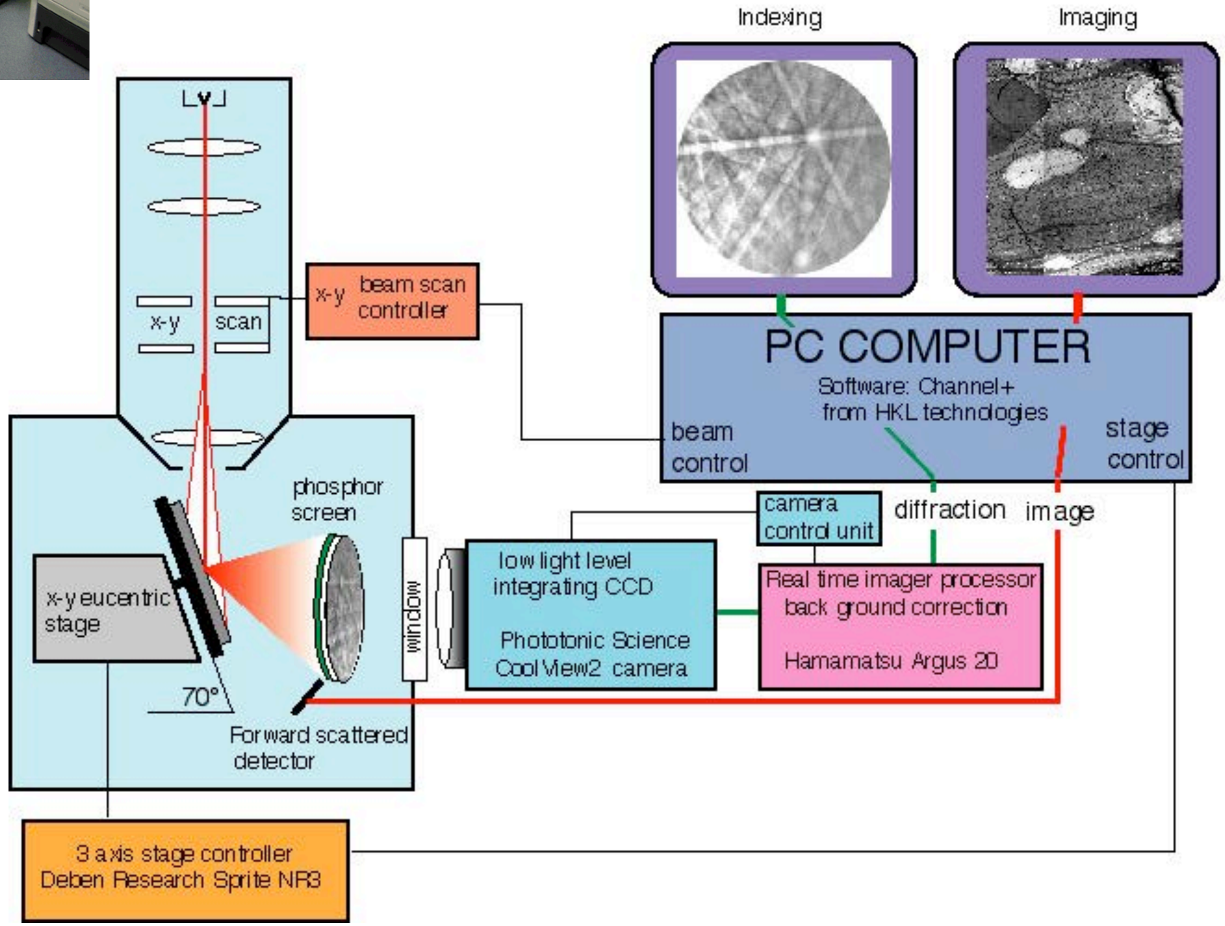
$$\dot{\gamma}^s = \left(\frac{\tau_r^s}{\tau_0^s}\right)^n$$



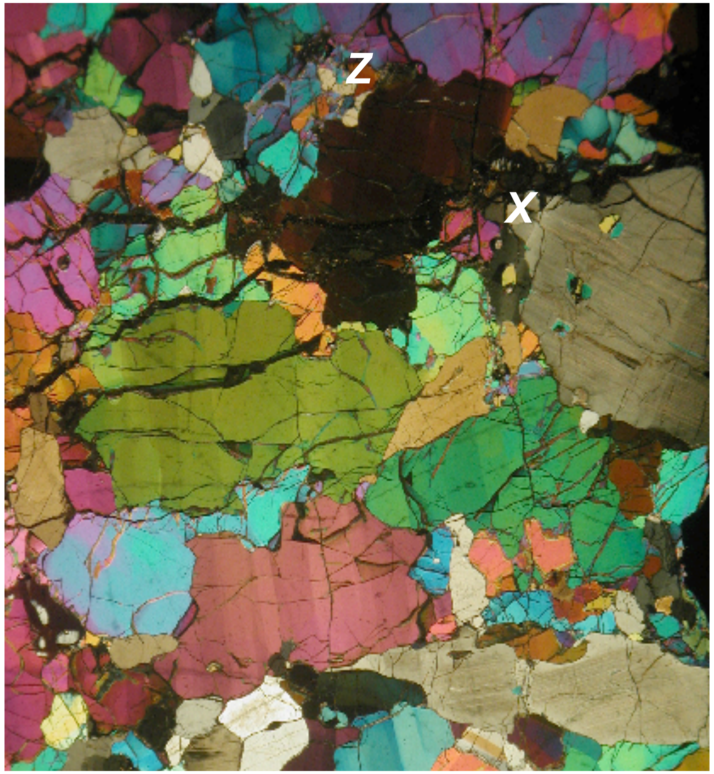
Bai et al. 1990 - JGR

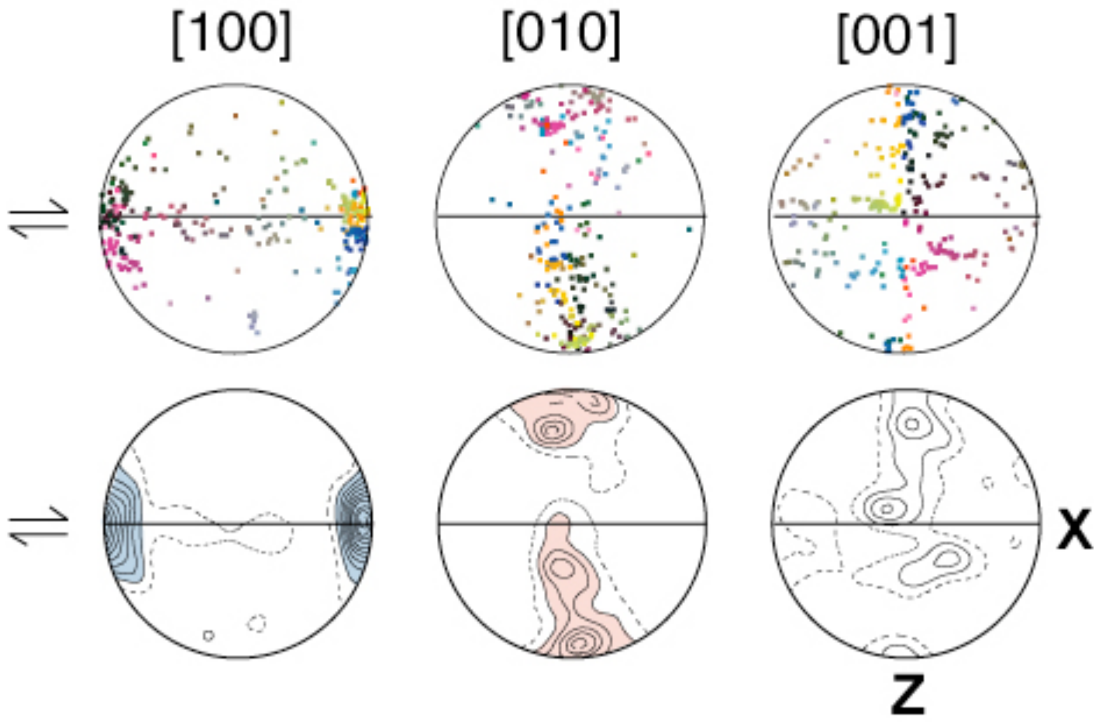
total crystal strain = sum of shear strains in all available slip systems

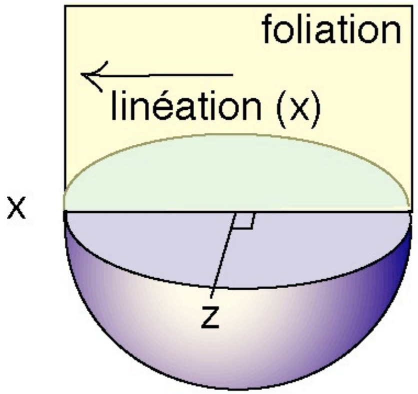
Measuring Crystal Preferred Orientations (CPO) by indexation of Electron BackScatered Diffraction (EBSD) patterns

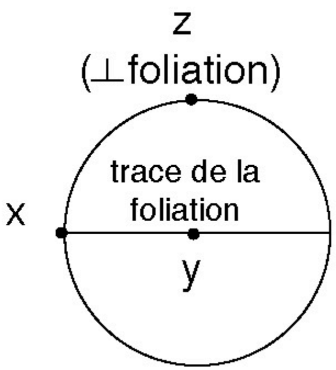


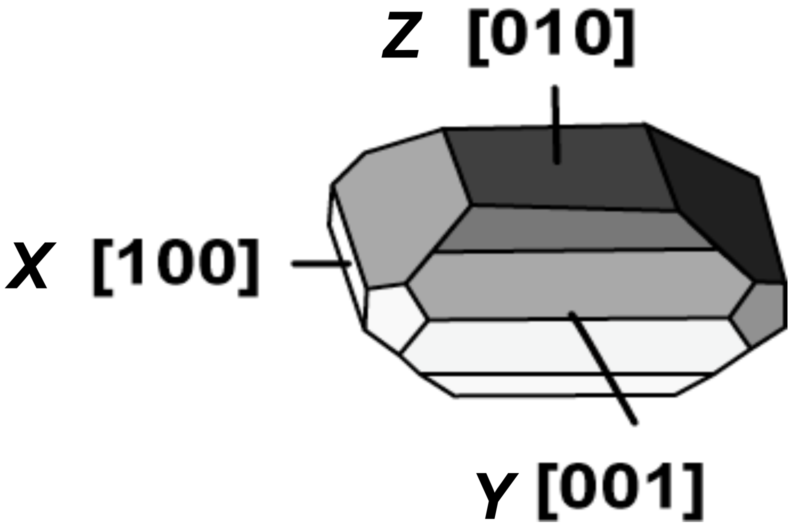
HT, low stress deformation: lherzolite, Tahiti





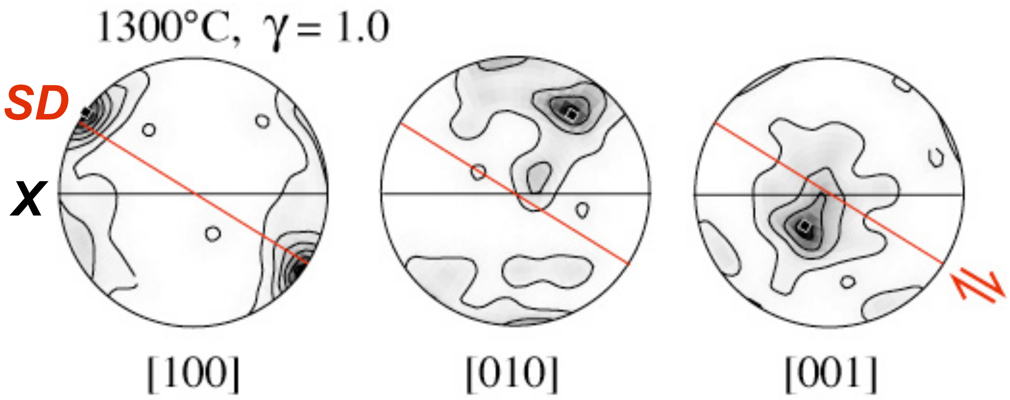






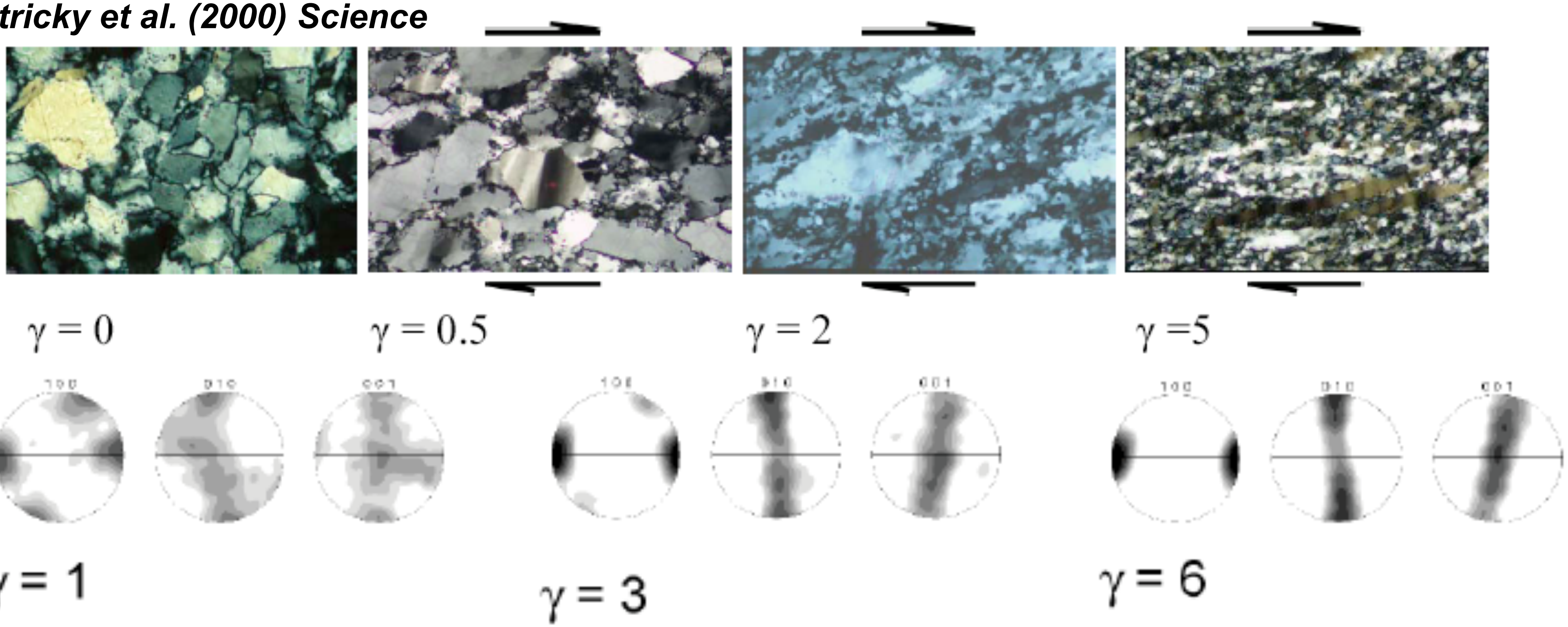
HT-LP experimental deformation: simple shear

Zhang & Karato (1995) Nature

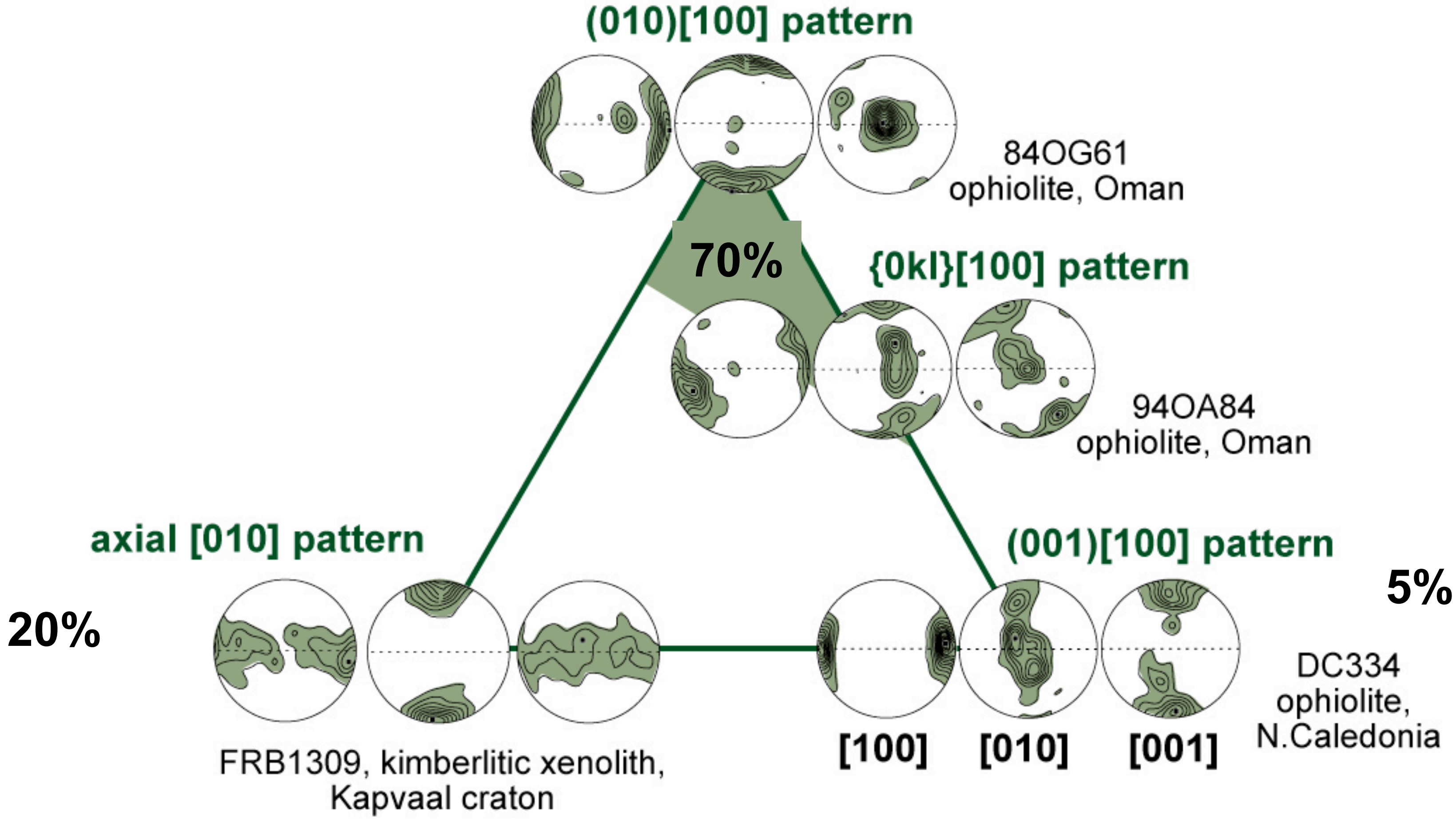


dominant slip direction : [100]
// shear direction
&
dominant slip plane : (010)
// shear plane

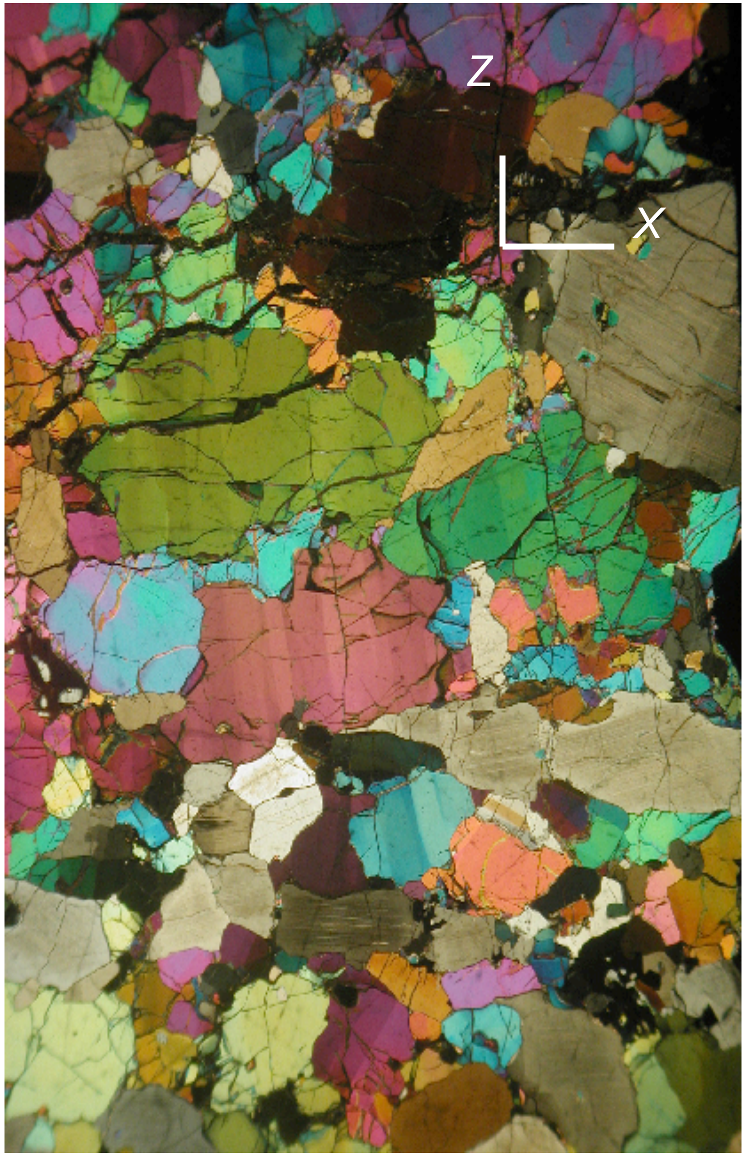
Bystricky et al. (2000) Science

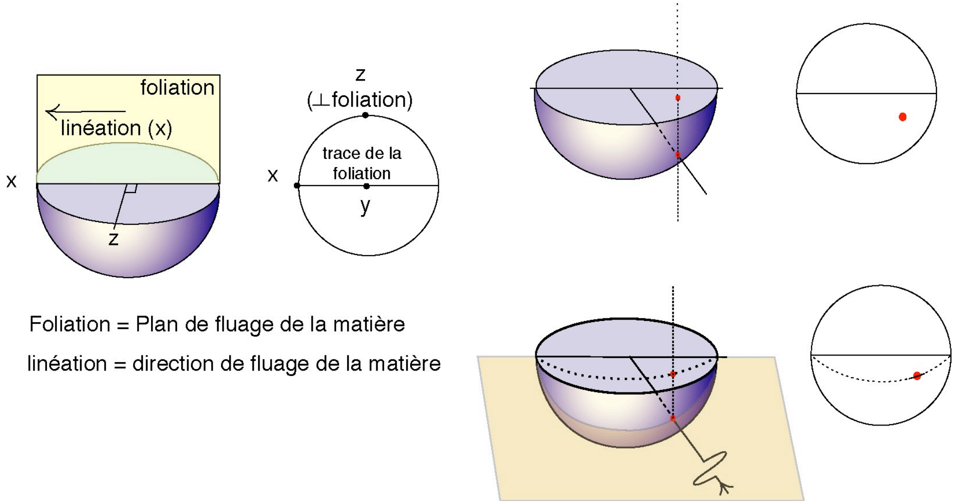


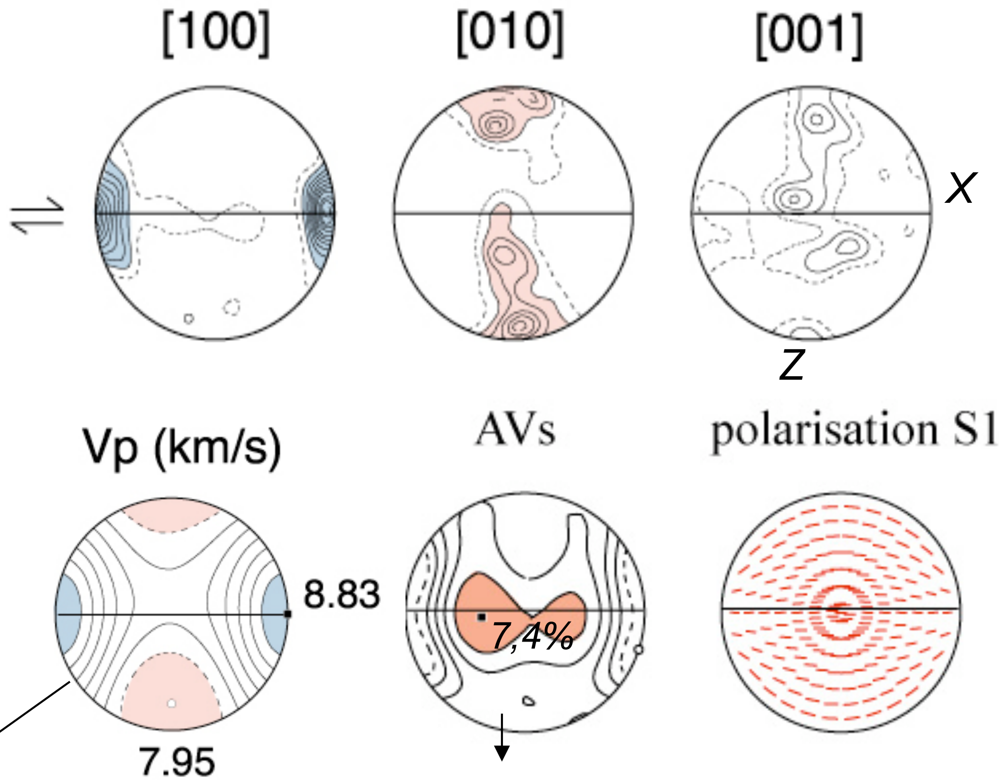
olivine database: 3 textural
>200 samples end-members



✓ ***dominant [100] slip in the shallow (lithospheric) mantle***





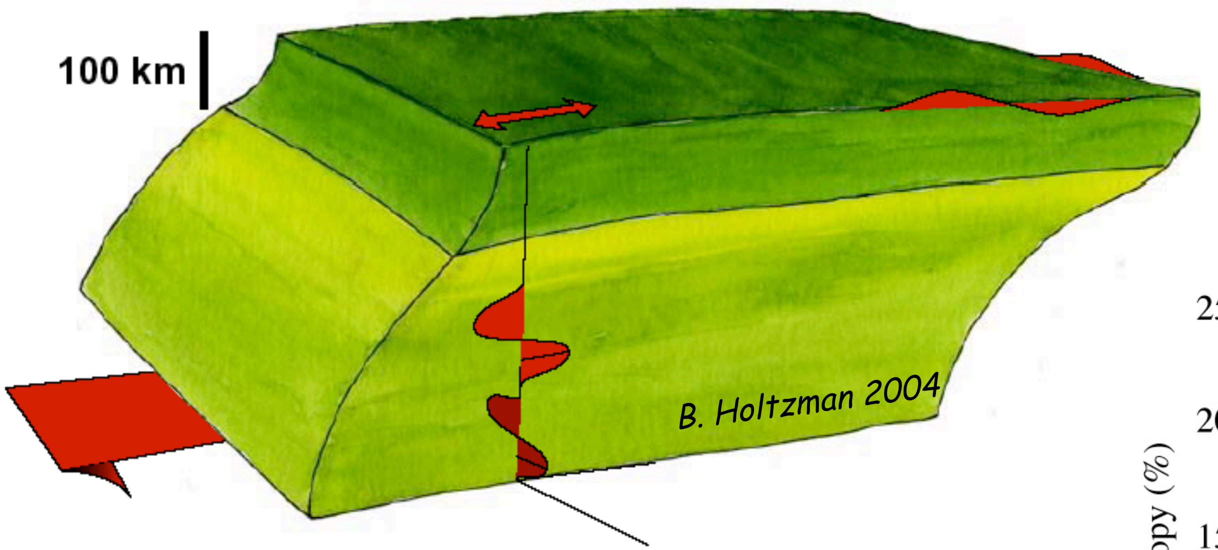


P-wave velocity: F(propagation direction)

Amax=10%

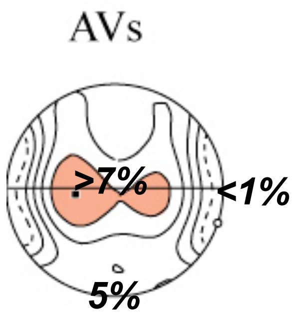
S-wave anis= (Vs1-Vs2)/Vsmean
Amax= 7.4%

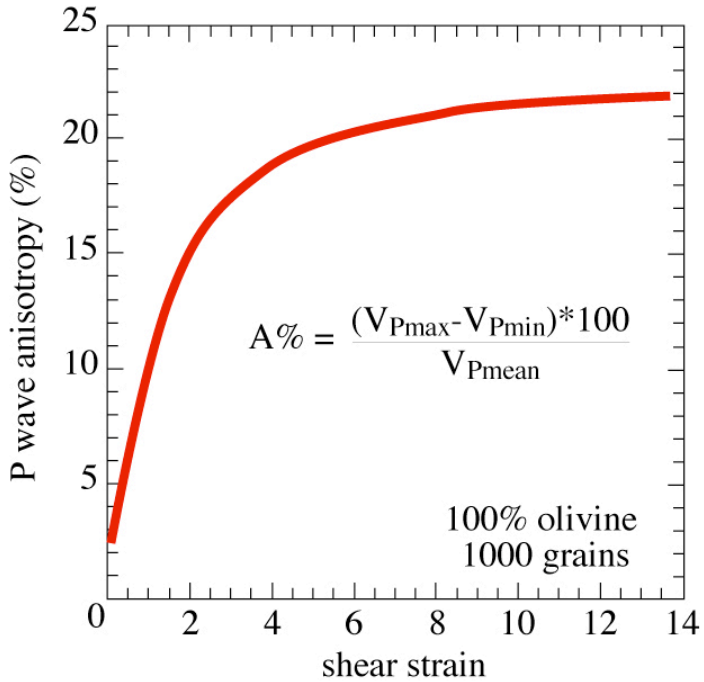
Simple key to qualitatively "read" seismic anisotropy observations in the SHALLOW MANTLE (>250 km):



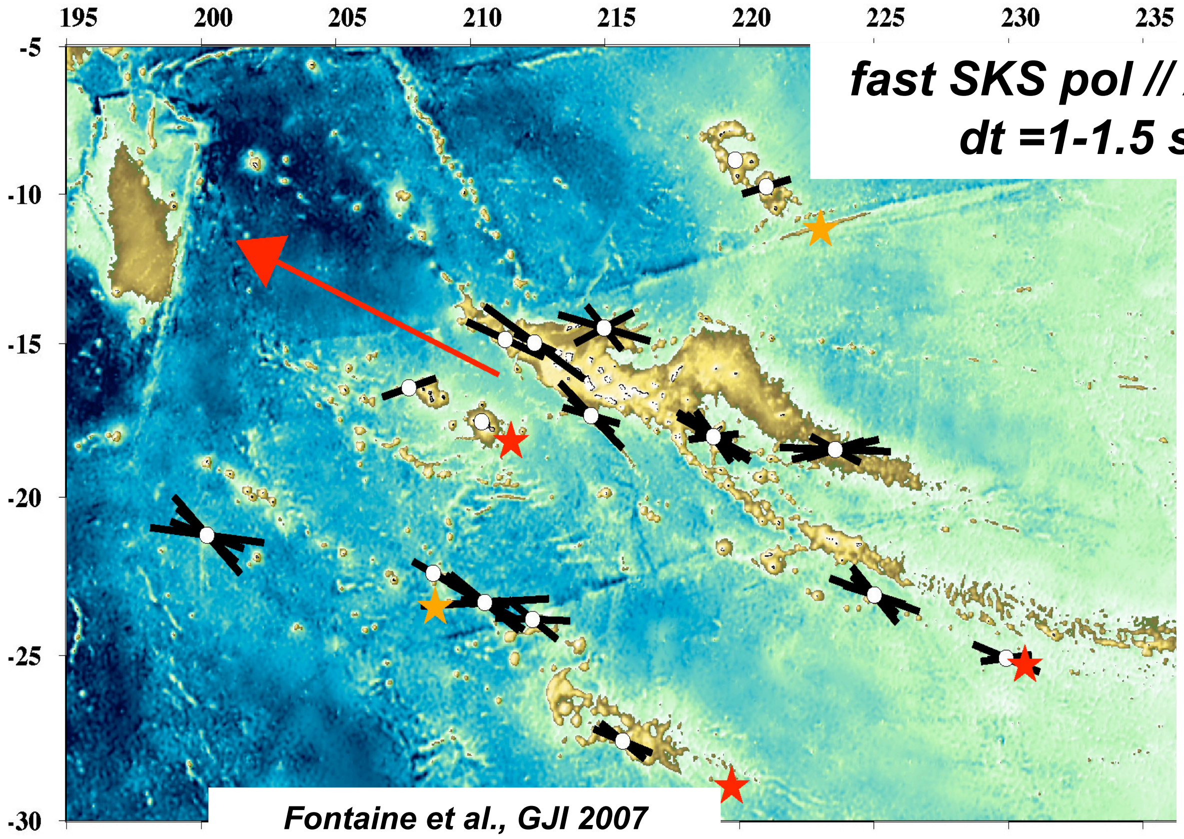
Fast direction of P & Rayleigh propagation, polarisation fast S-wave = flow direction

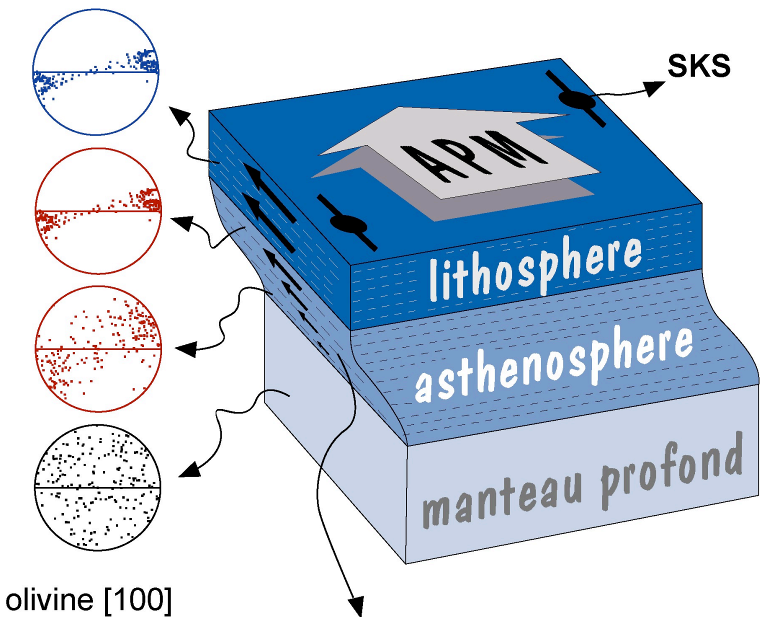
delay time ~ thickness of the anisotropic layer and orientation of the flow plane





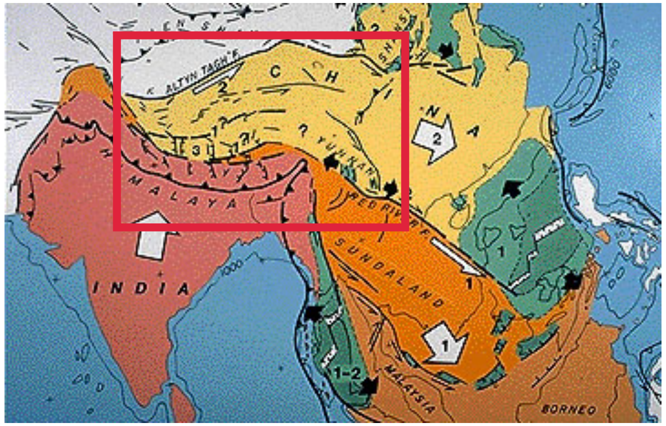
in oceanic domains: South Pacific

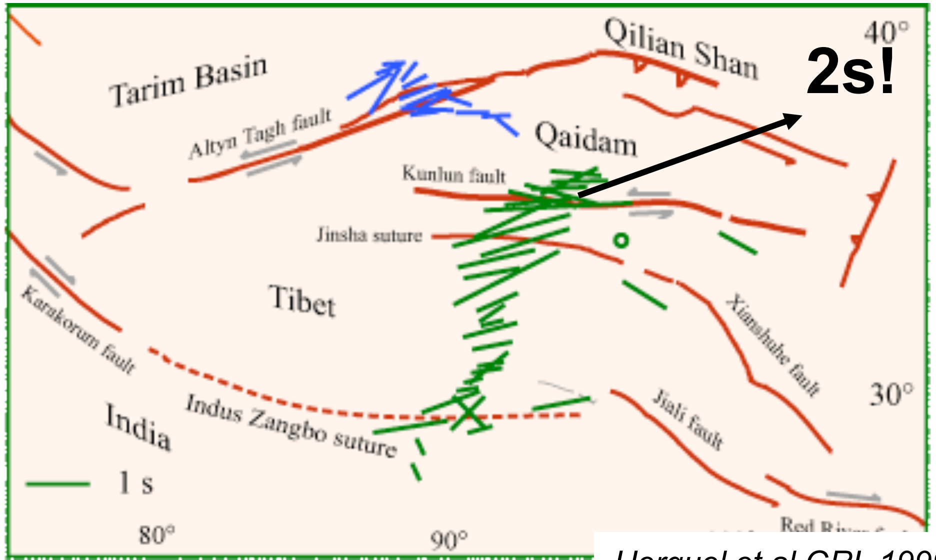




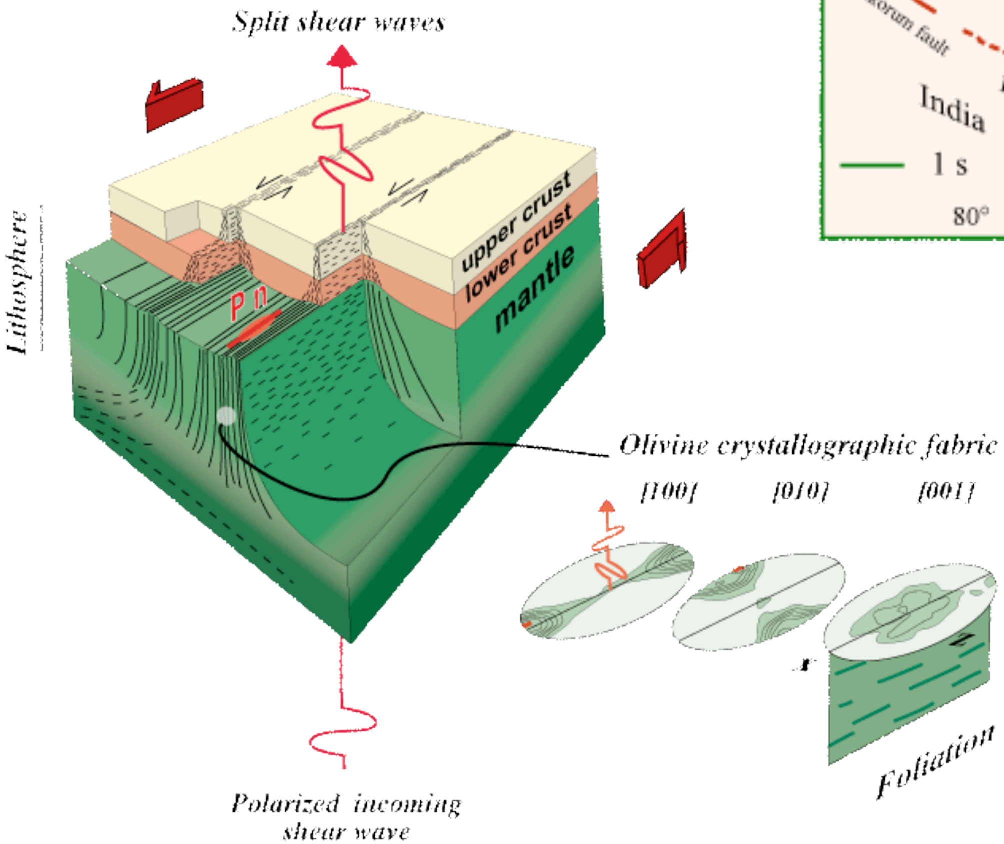
Strain field: horizontal shear // APM

Active strike-slip faults: Himalaya

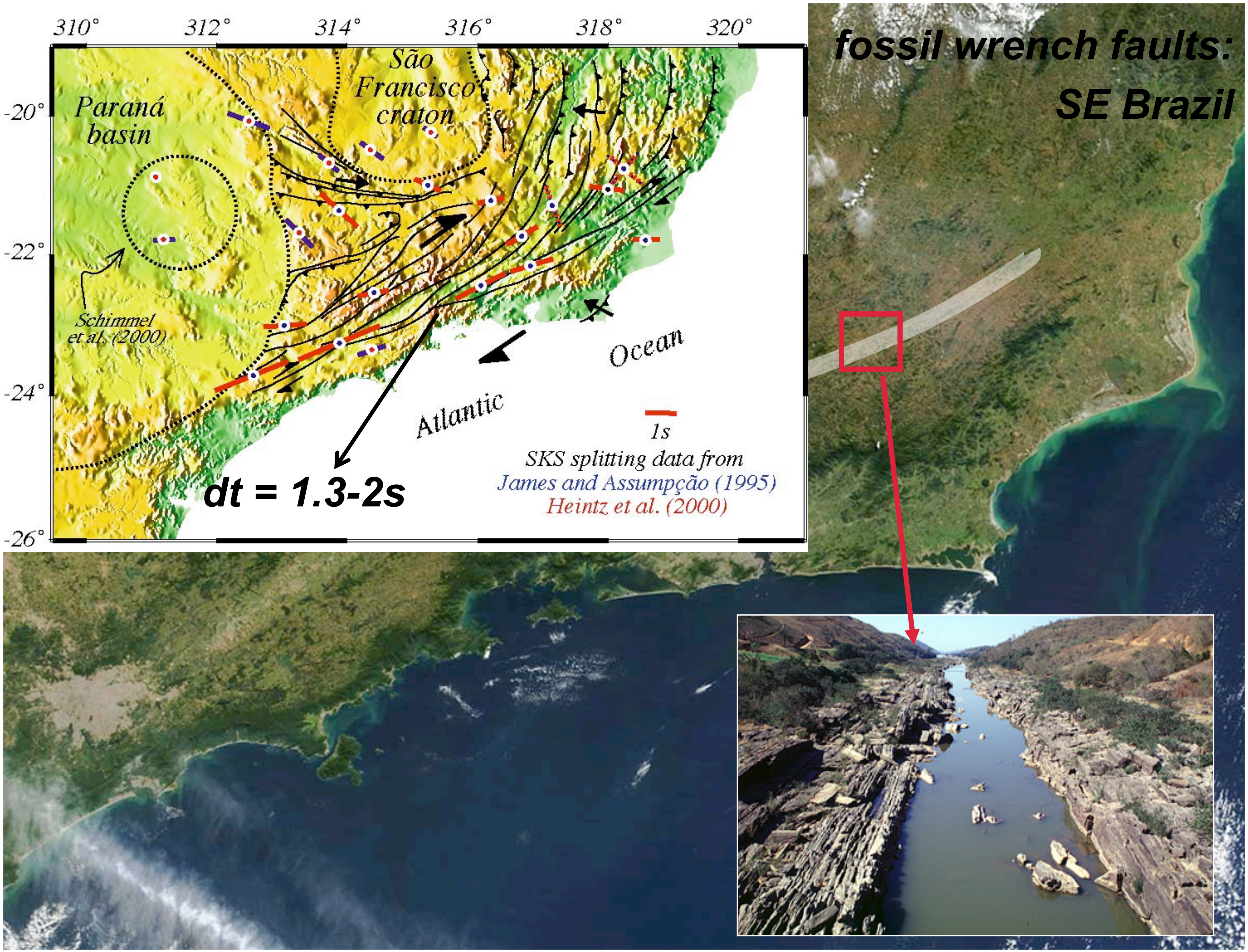




Herquel et al GRL 1999

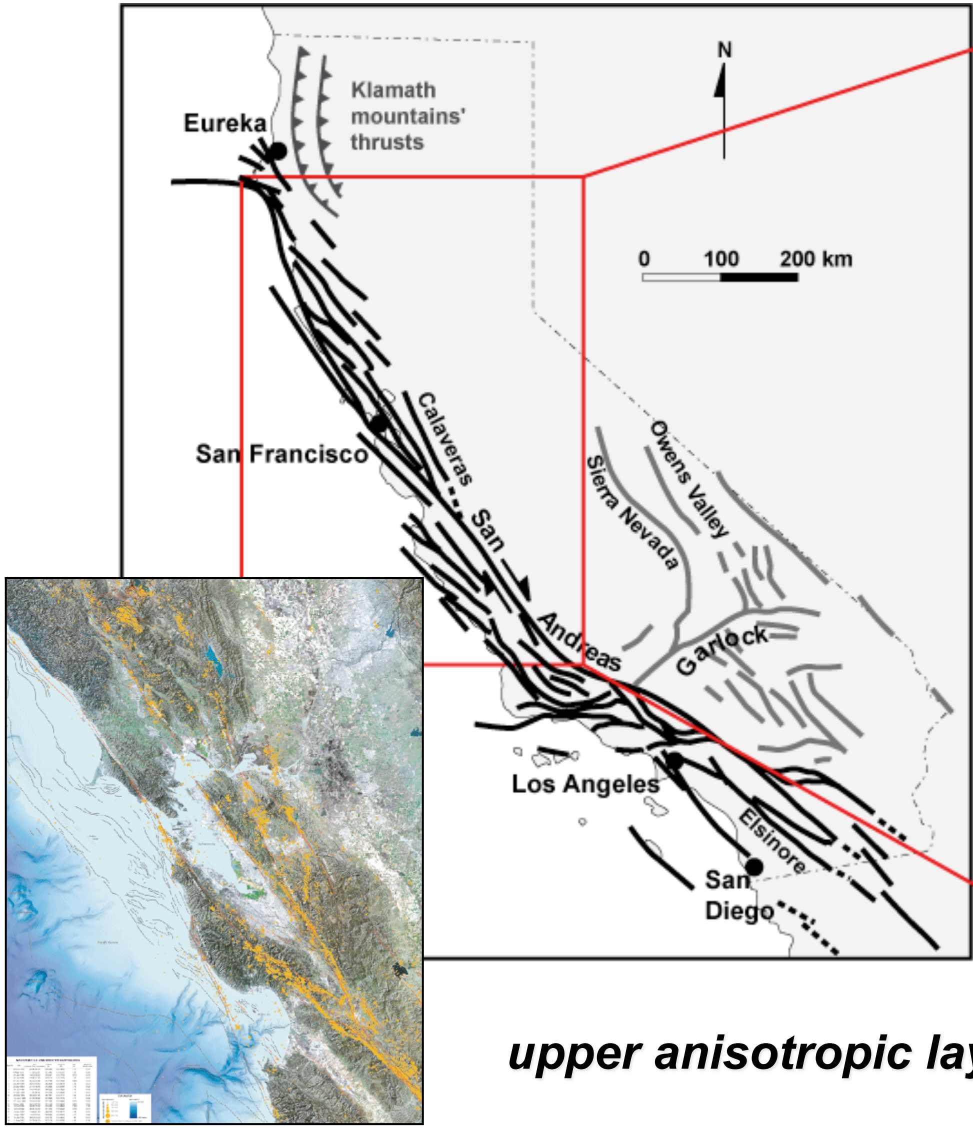


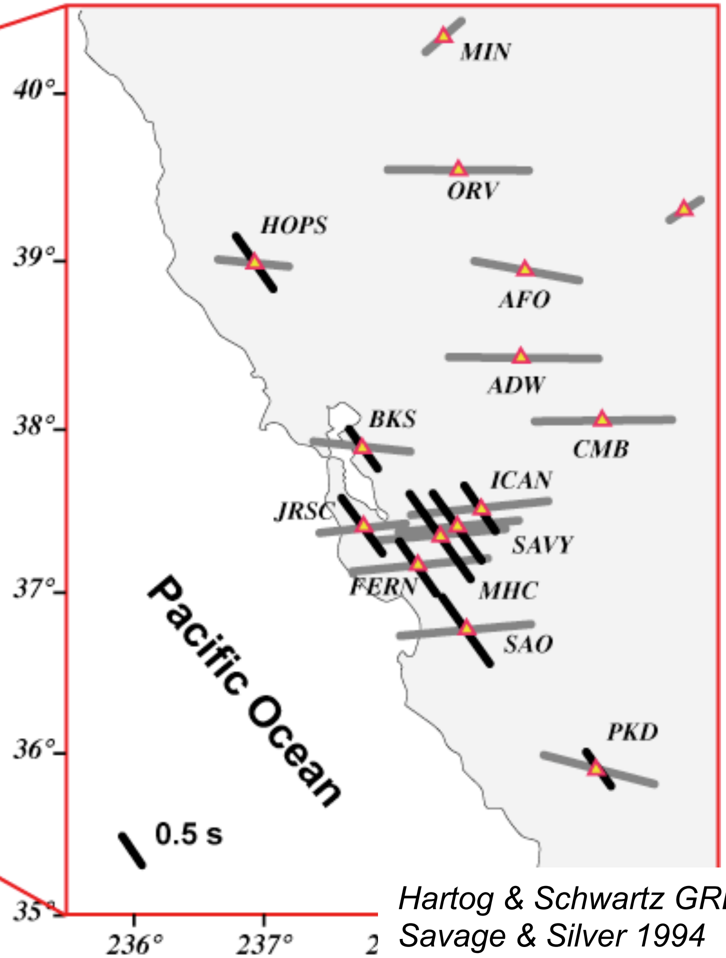
fast S wave polarized
// to the fault
strong delay times



fossil wrench faults:
SE Brazil
310° 312° 314° 316° 318° 320°
-20° -22° -24° -26°
São Francisco craton
Paraná basin
Schimmel et al. (2000)
Atlantic Ocean
dt = 1.3-2s
1s
SKS splitting data from
James and Assumpção (1995)
Heintz et al. (2000)

Active transform fault: San Andreas

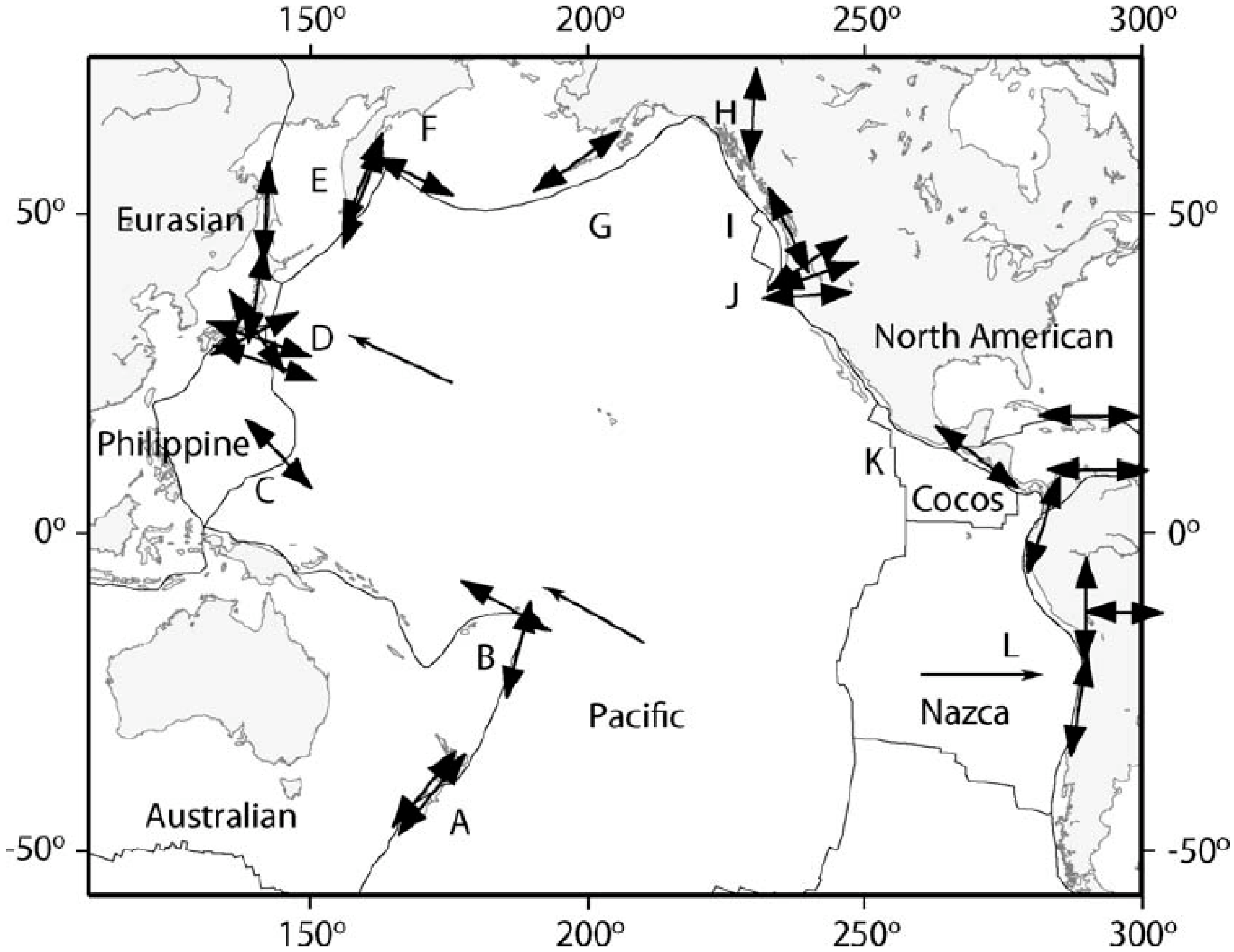




Hartog & Schwartz GRL 2001
Savage & Silver 1994

upper anisotropic layer: lithospheric mantle flow // fault

Subduction zones : relation between deformation and anisotropy in the upper mantle not so simple!



Lassak et al 2006 EPSL

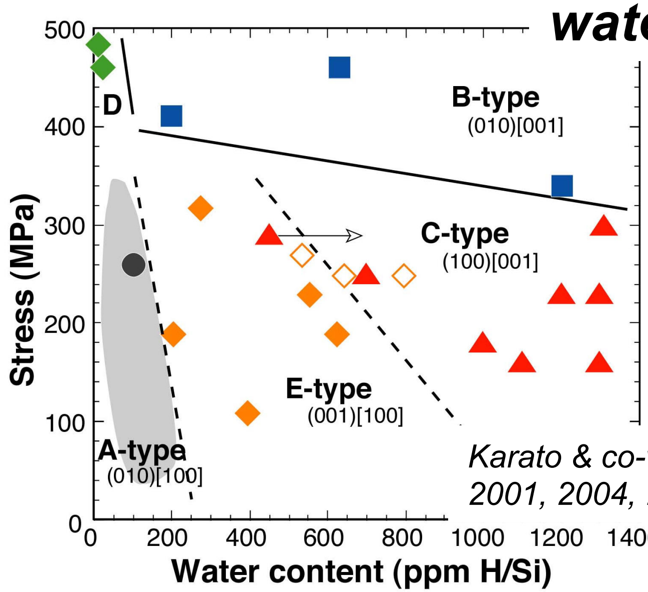
Deformation and anisotropy in the upper mantle : XXI century observations & experimental results

fluids (water, melt) & pressure change the relation between deformation & anisotropy :

• *change in olivine deformation ➔ ≠ CPO*

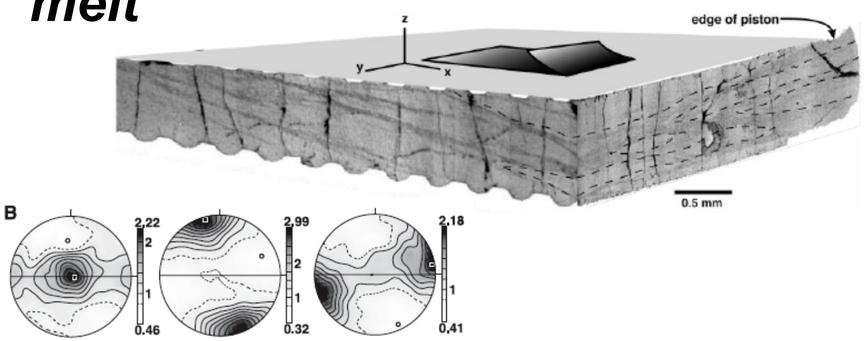
✓ *fast anisotropy directions normal to the shear direction*

water



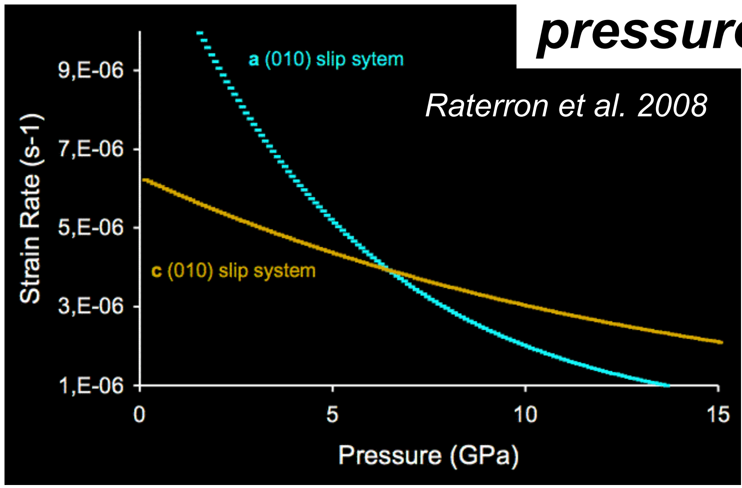
Karato & co-workers 2001, 2004, 2006 ....

melt



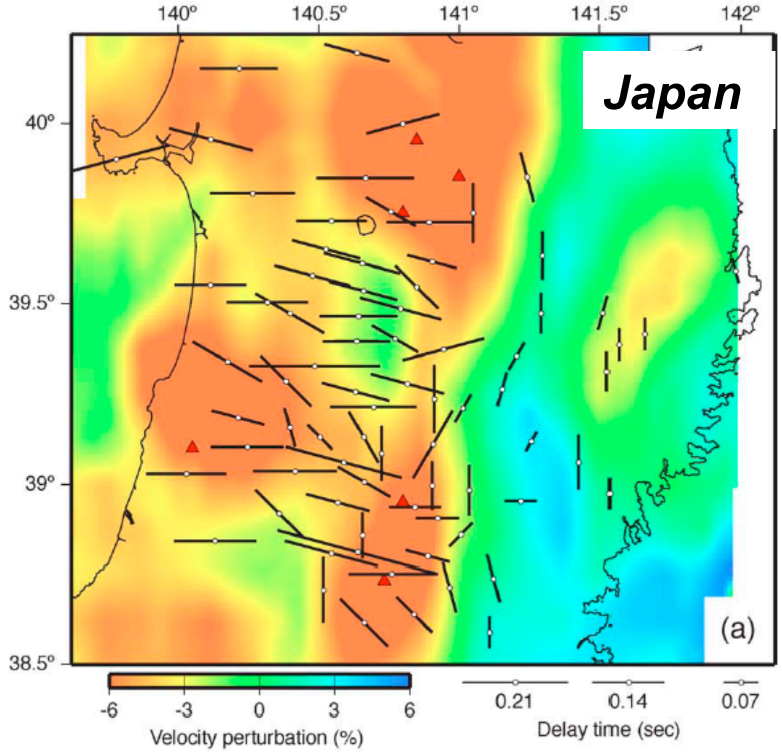
Holtzman et al. Science 2003

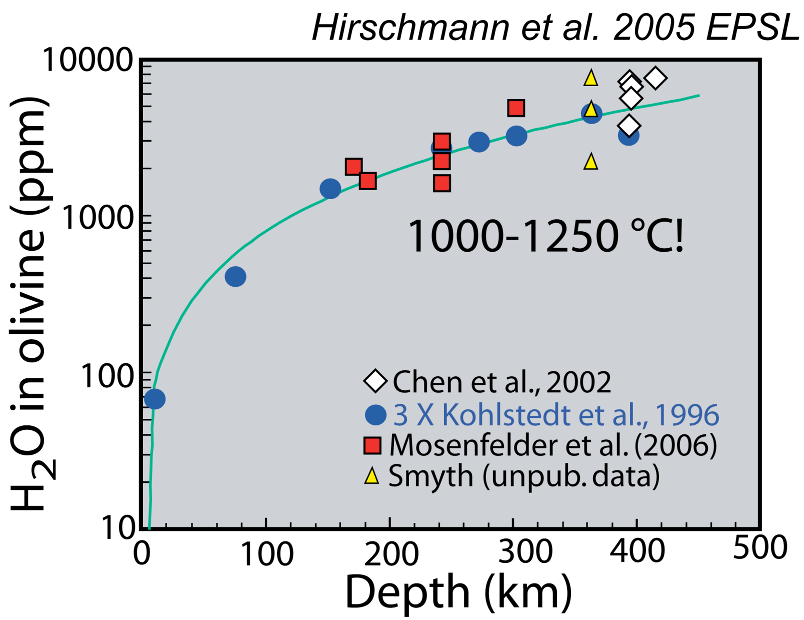
pressure



+ Couvy et al. EMJ 2005, Mainprice et al. Nature 2005…

Water, olivine deformation & shear wave splitting in the mantle wedge





water solubility in olivine = f(p)

forearc : trench normal fast S-waves polarization

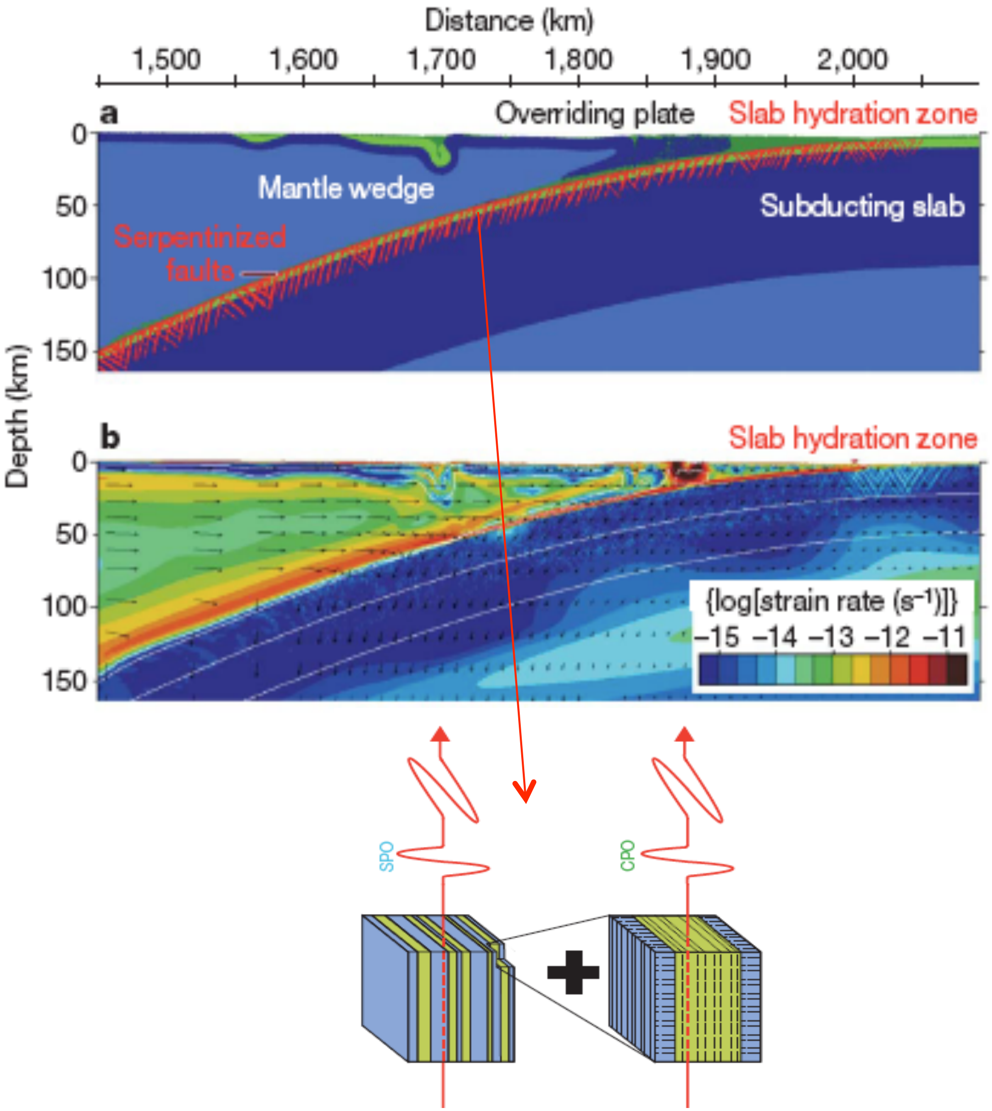
water contents & stress high enough for dominant activation of (010)[001]?

- water solubility in olivine depends strongly on pressure

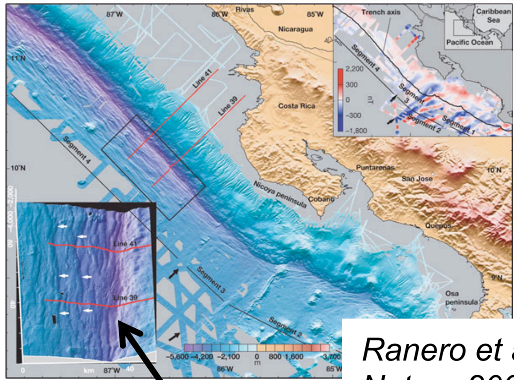
- water reduces viscosity

delay times < 0.2s!

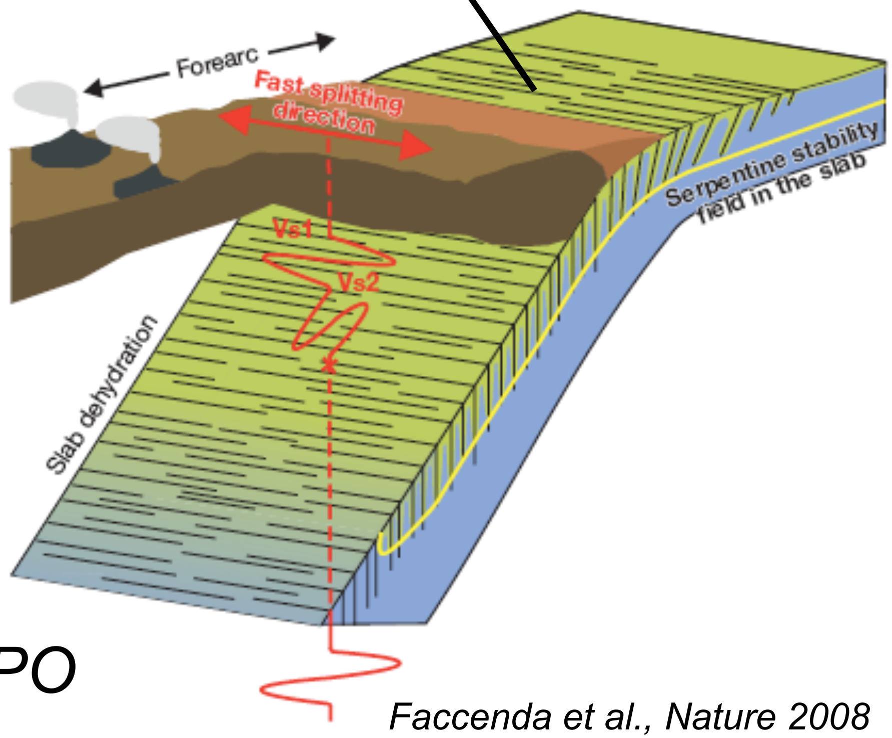
Fore-arc trench // fast S-waves polarization due to serpentinization along tensional faults in the slab



layering + antigorite CPO

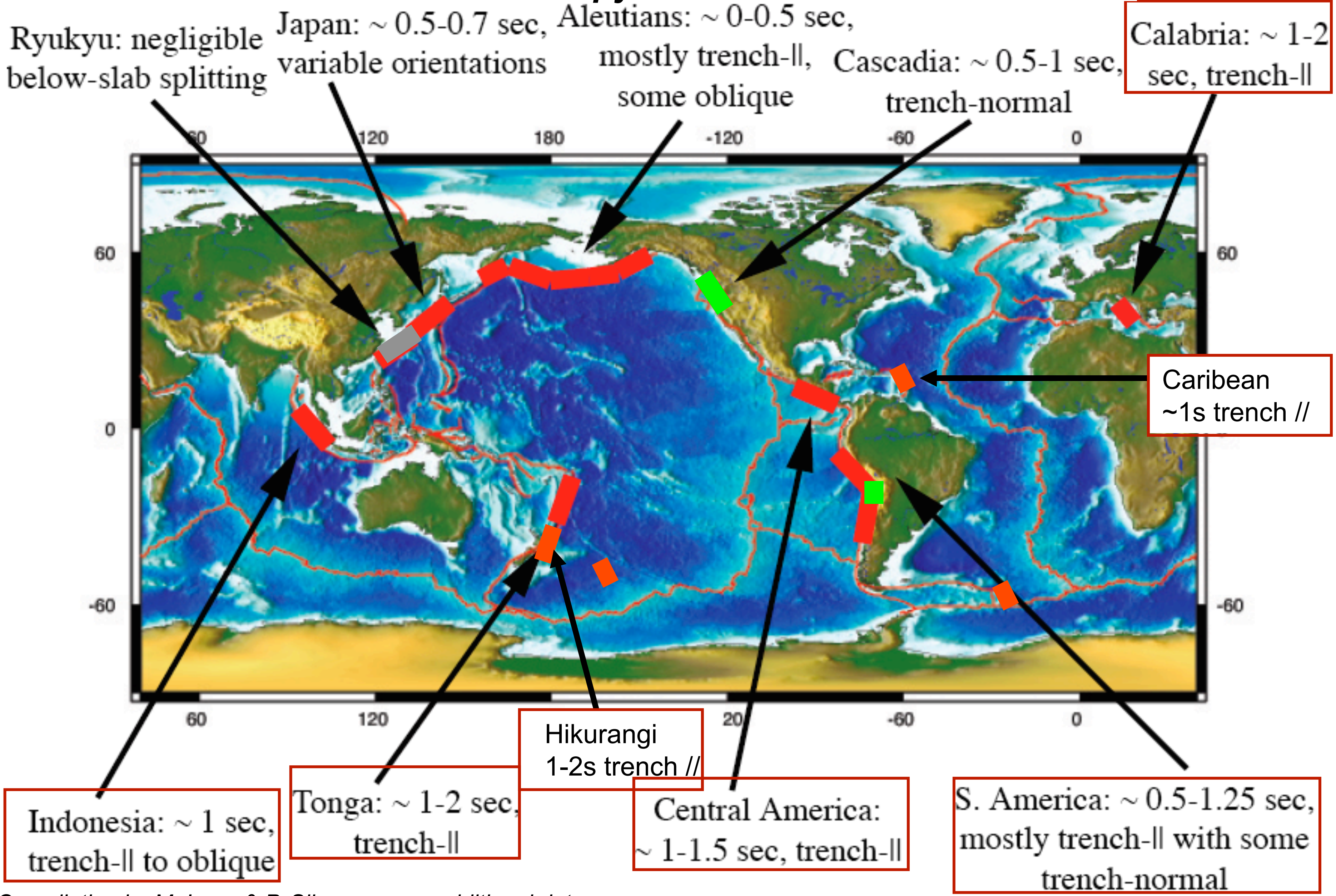


Ranero et al. Nature 2003



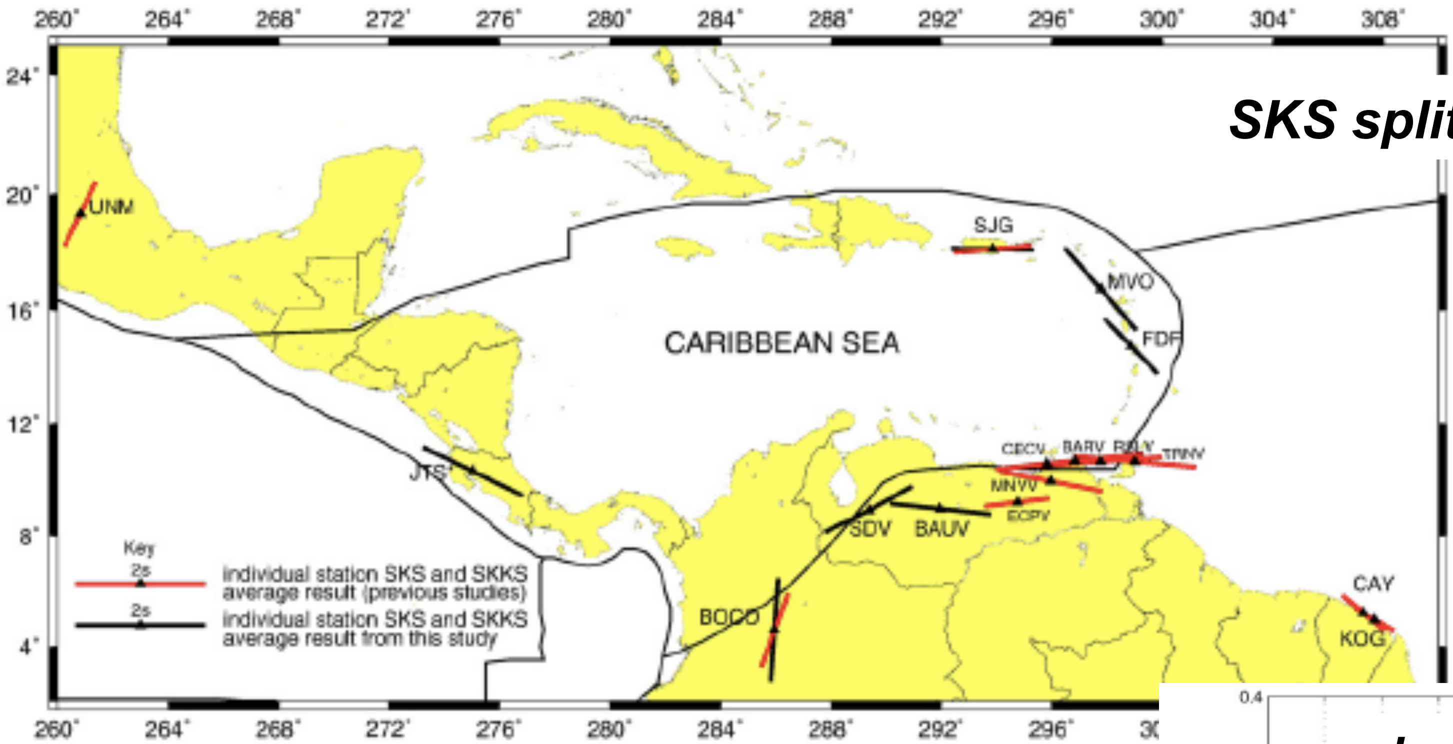
Faccenda et al., Nature 2008

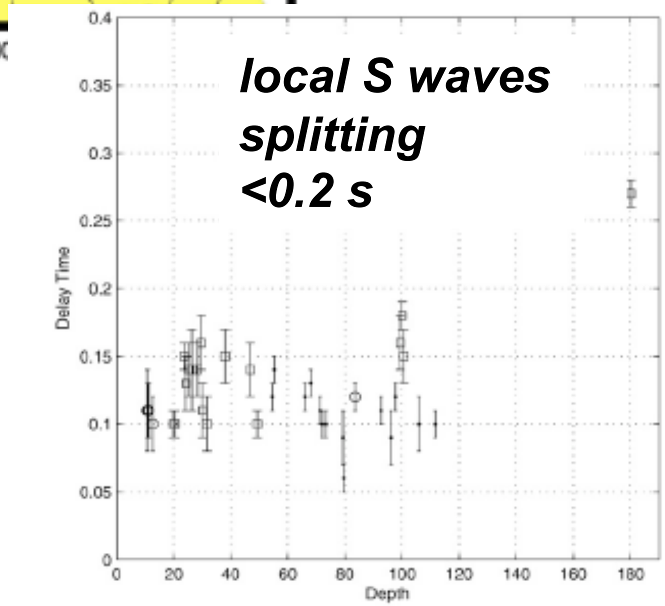
SKS delay times (1-2s)>> local S delays (<0.5s): most of the anisotropy is below the slab!

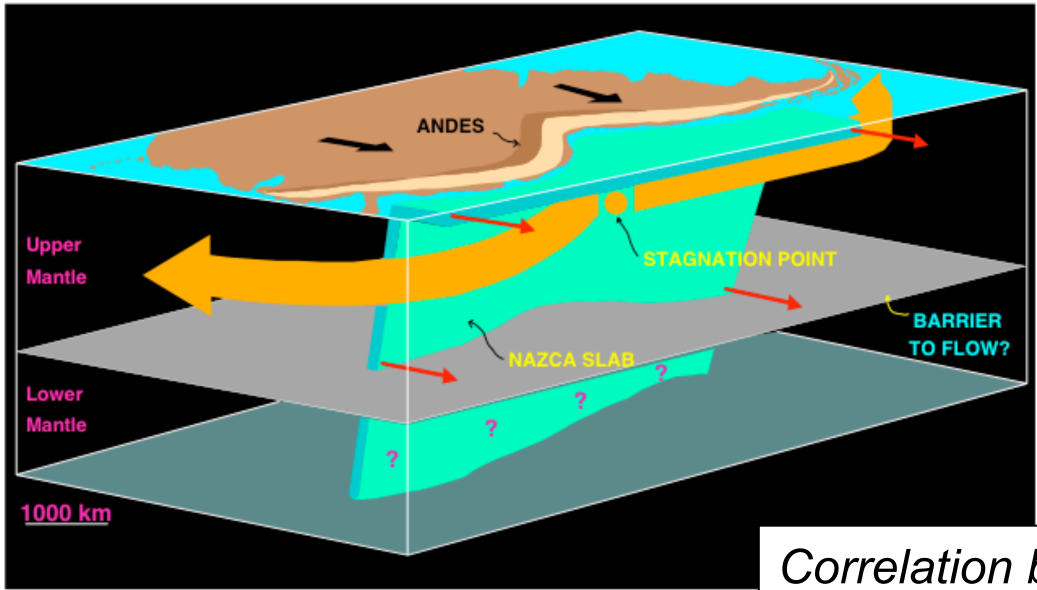


Compilation by M. Long & P. Silver + some additional data

L.T. Piñero-Feliciangeli, J.-M. Kendall / Tectonophysics 462 (2008) 22–34



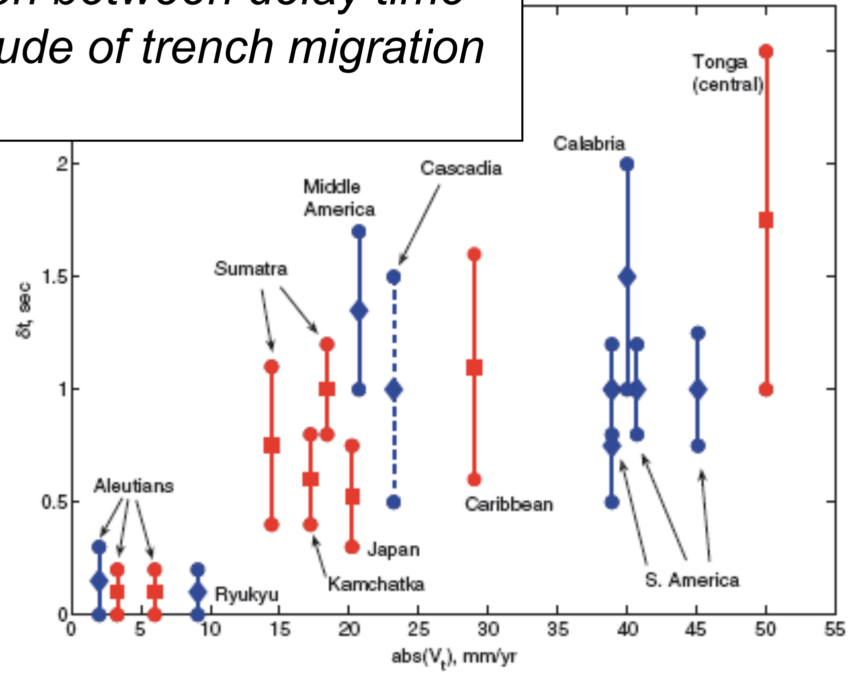




Russo & Silver Science 94

Trench // flow beneath slab
(pressure gradient :
- trench retreat
- barrier to flow @ depth
(lower mantle)

Correlation between delay time & magnitude of trench migration velocity

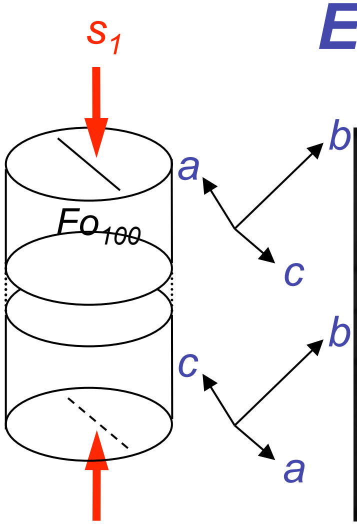


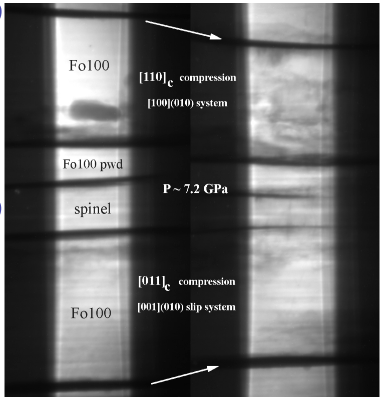
Long & Silver Science 2008

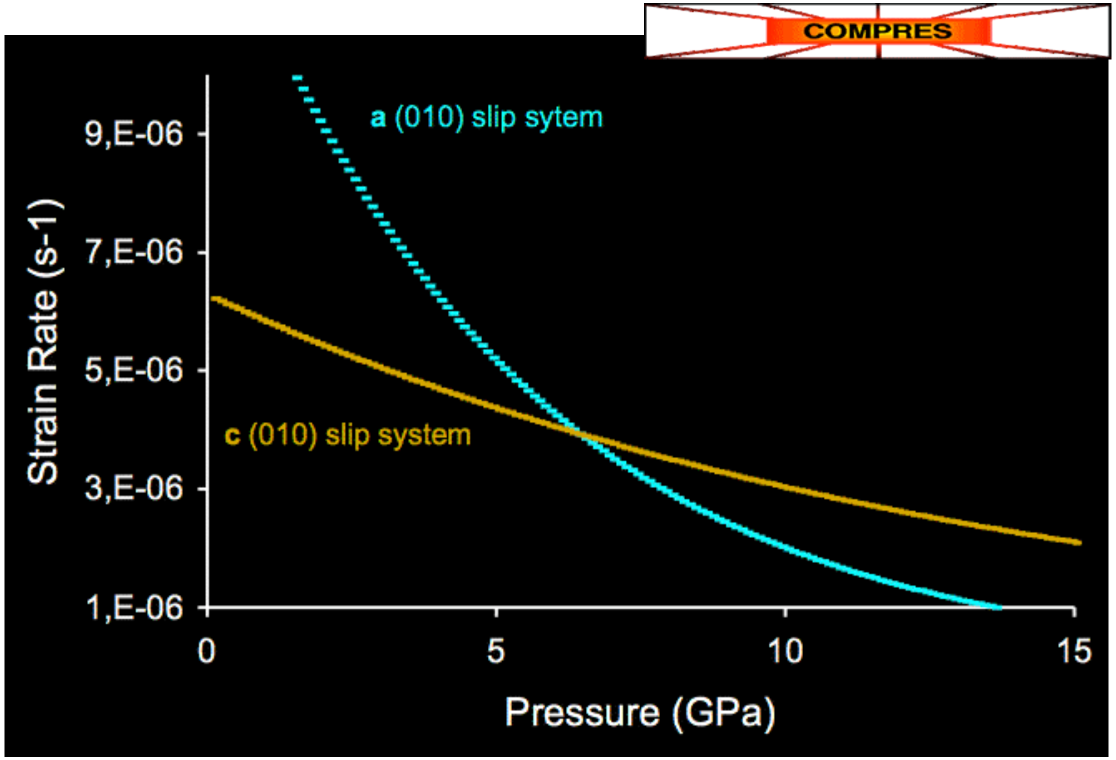
Problem: decoupling between the slab and underlying mantle!

Alternative interpretation:
Trench normal flow beneath the slab, but dominant [001] slip due to HP?

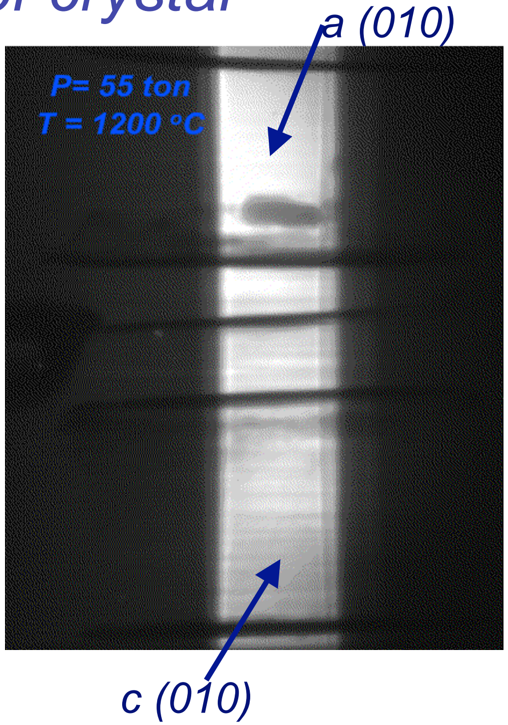
Effect of pressure on olivine deformation







bi-crystal



At high pressure:

higher strain rate in c crystal

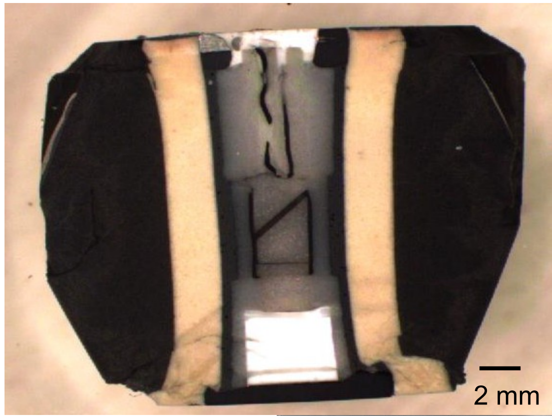
✓ ***[001](010) slip easier than [100](010)***

very low activation volume

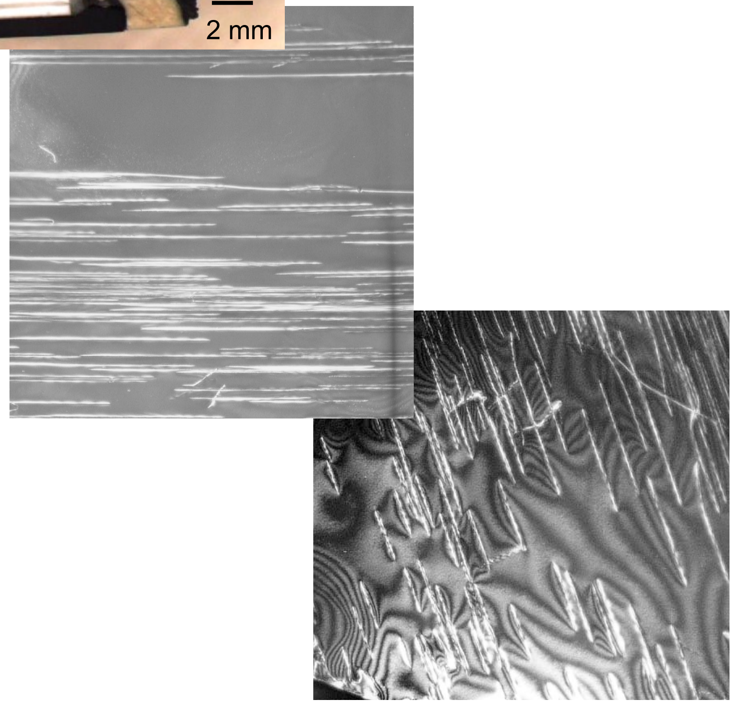
✓ ***dislocation creep dominant***

Raterron et al. 2007

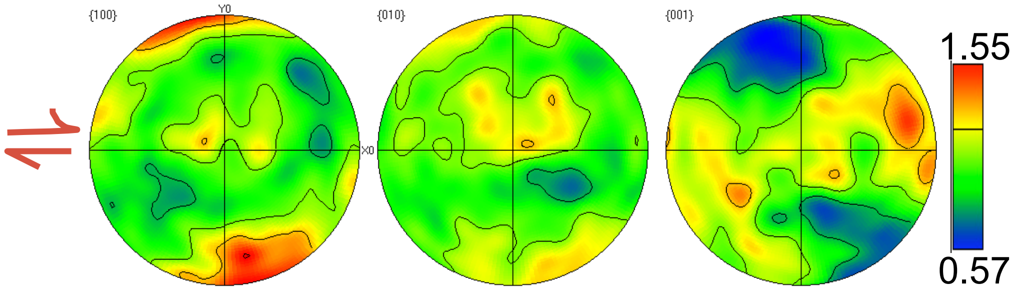
Simple shear deformation of olivine polycrystals



11GPa & 1400°C



EBSD: olivine CPO



γ=0.3

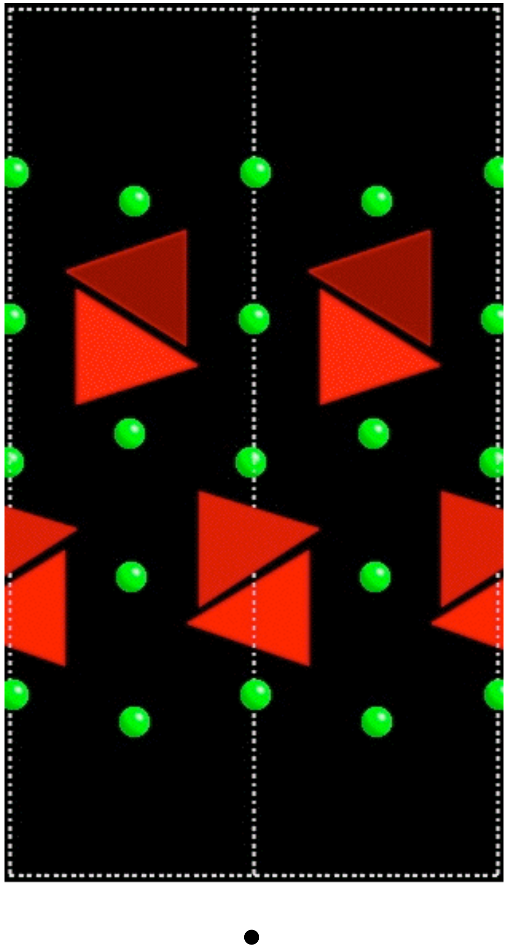
[001](100)
[001](010)

TEM: only [001] screw dislocations

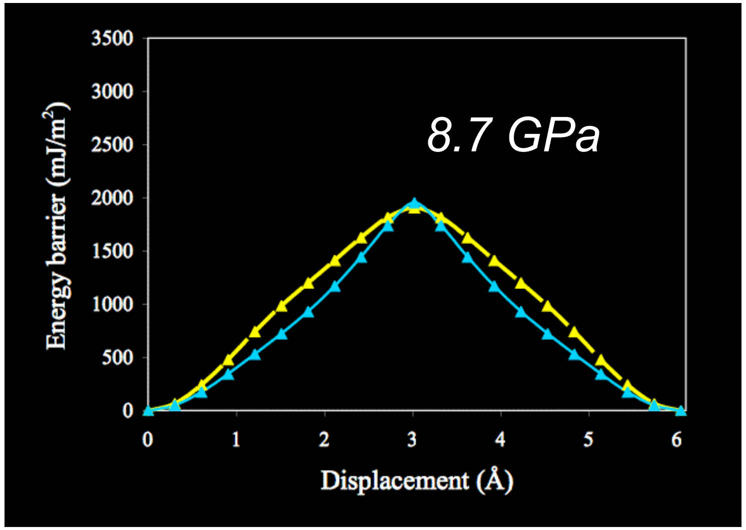
Couvy et al. EJM 2004

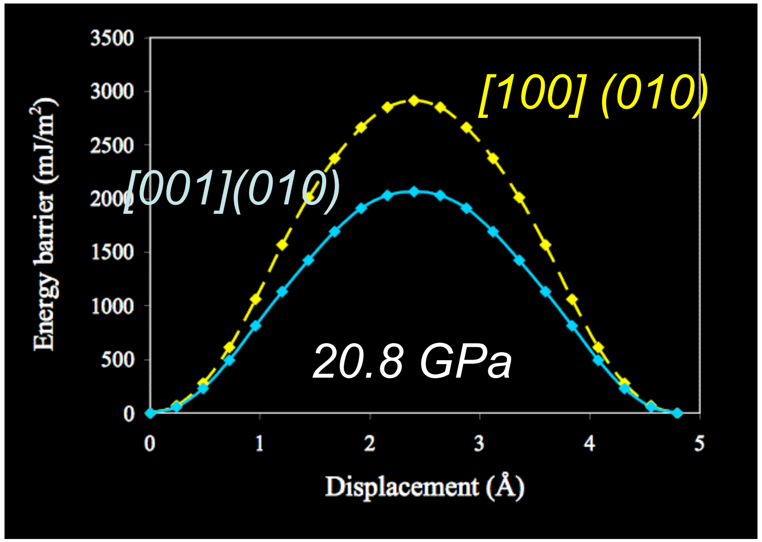
Ab-initio modeling of dislocation core properties:

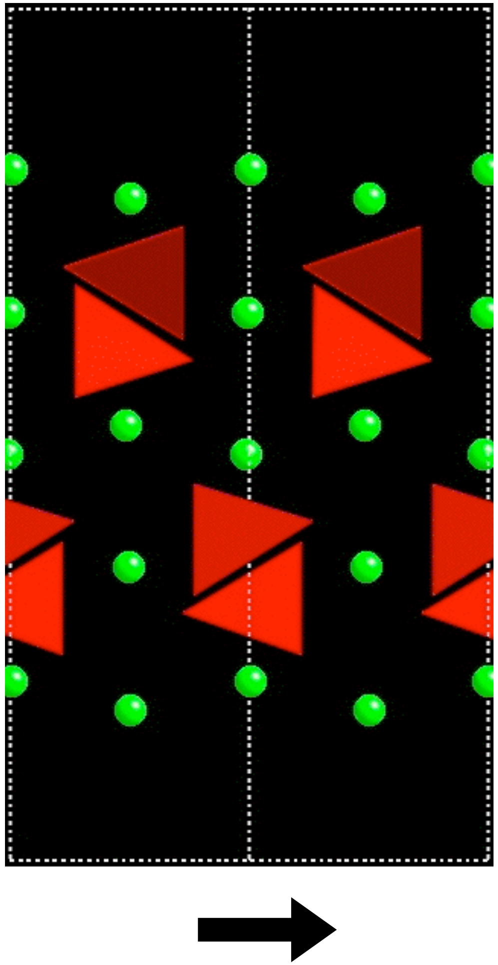
Ph. Carrez, P. Cordier, D. Ferré (Lille)



[001]







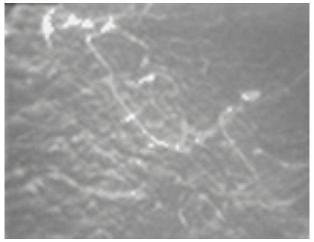
[100]

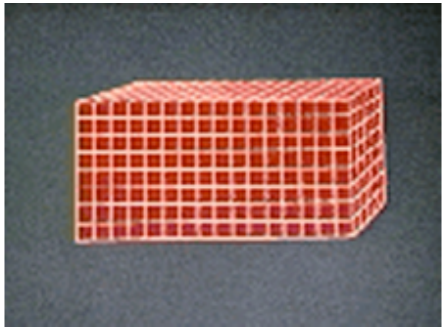
✓ ***olivine: [001](010) slip easier than [100](010) at high pressure***

Modeling the deformation & crystal orientation evolution

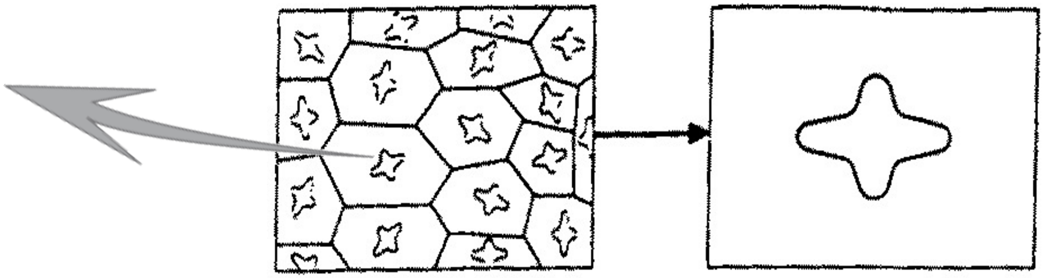
VPSC: Molinari et al. 1987, Lebensohn & Tomé 1993
Drex: Kaminsky & Ribe 2001, 2003

within a grain (crystal):





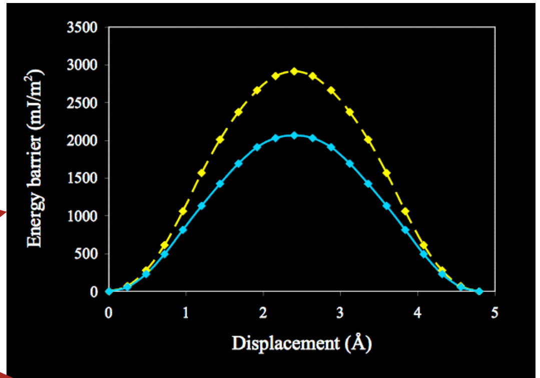
rock (polycrystal) deformation:



strain = motion of dislocations on well-defined crystal planes & directions

behavior of the aggregate (rock) = average of crystals' behaviors

$$\dot{\gamma}^s = \left(\frac{\tau_r^s}{\tau_0^s}\right)^n$$



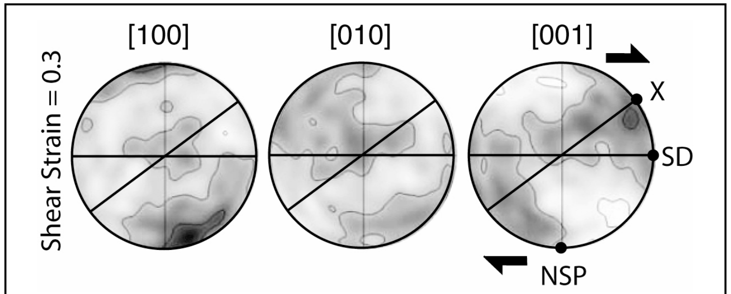
$$\dot{E}_{ij} = \langle \dot{\varepsilon}_{ij} \rangle \qquad \Sigma_{ij} = \langle \sigma_{ij} \rangle$$

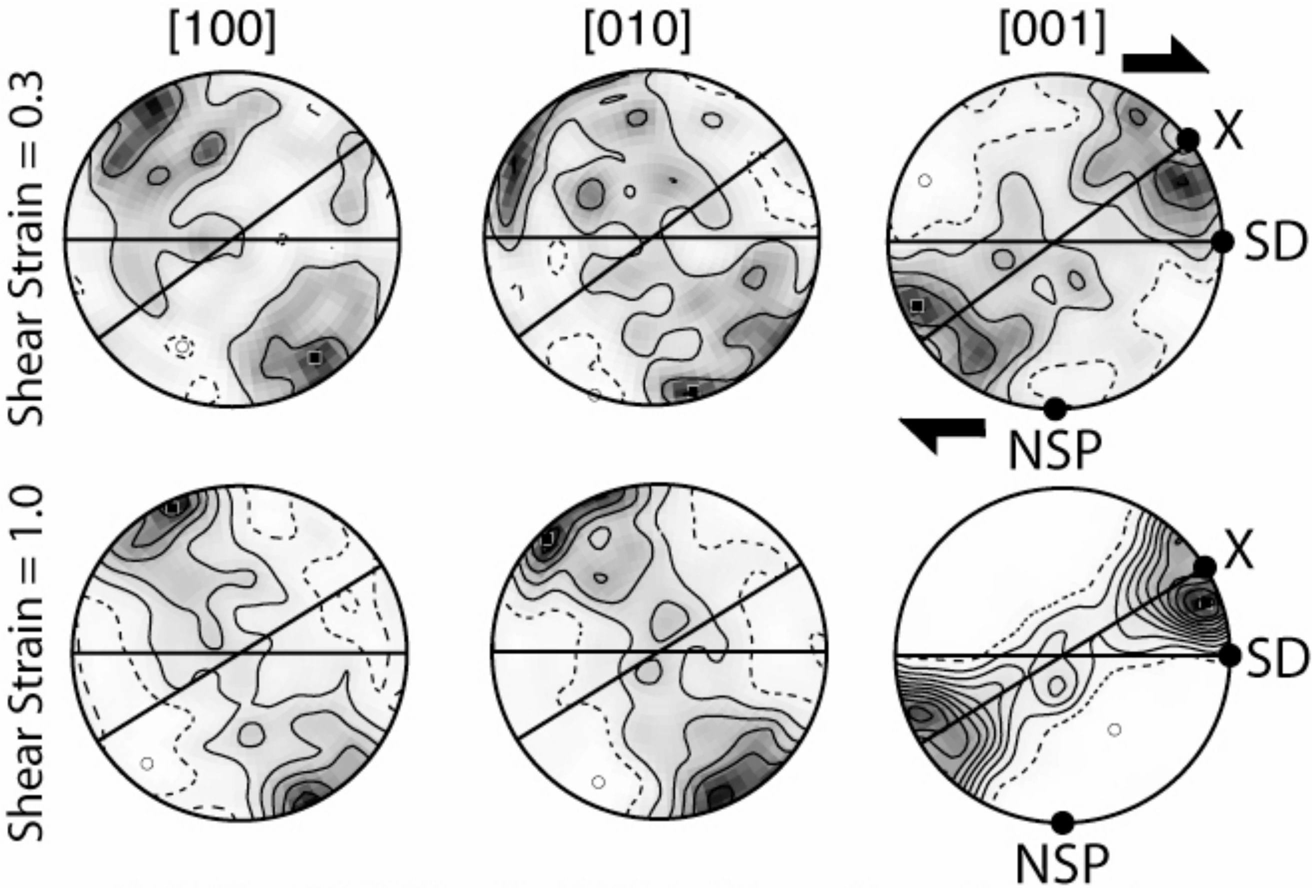
$$\dot{\varepsilon}_{kl} - \dot{E}_{kl} = -M_{ijkl} : (\sigma_{ij} - \Sigma_{ij})$$

***input parameters: slip systems' strength*, initial texture, and macroscopic sollicitation (stress or velocity gradient tensor)**

***output: evolution of crystallographic orientations* and macroscopic response (strain rate or stress tensor)**

Crystal plasticity modeling based on calculated Peierls stresses for olivine slip systems @ 10 GPa

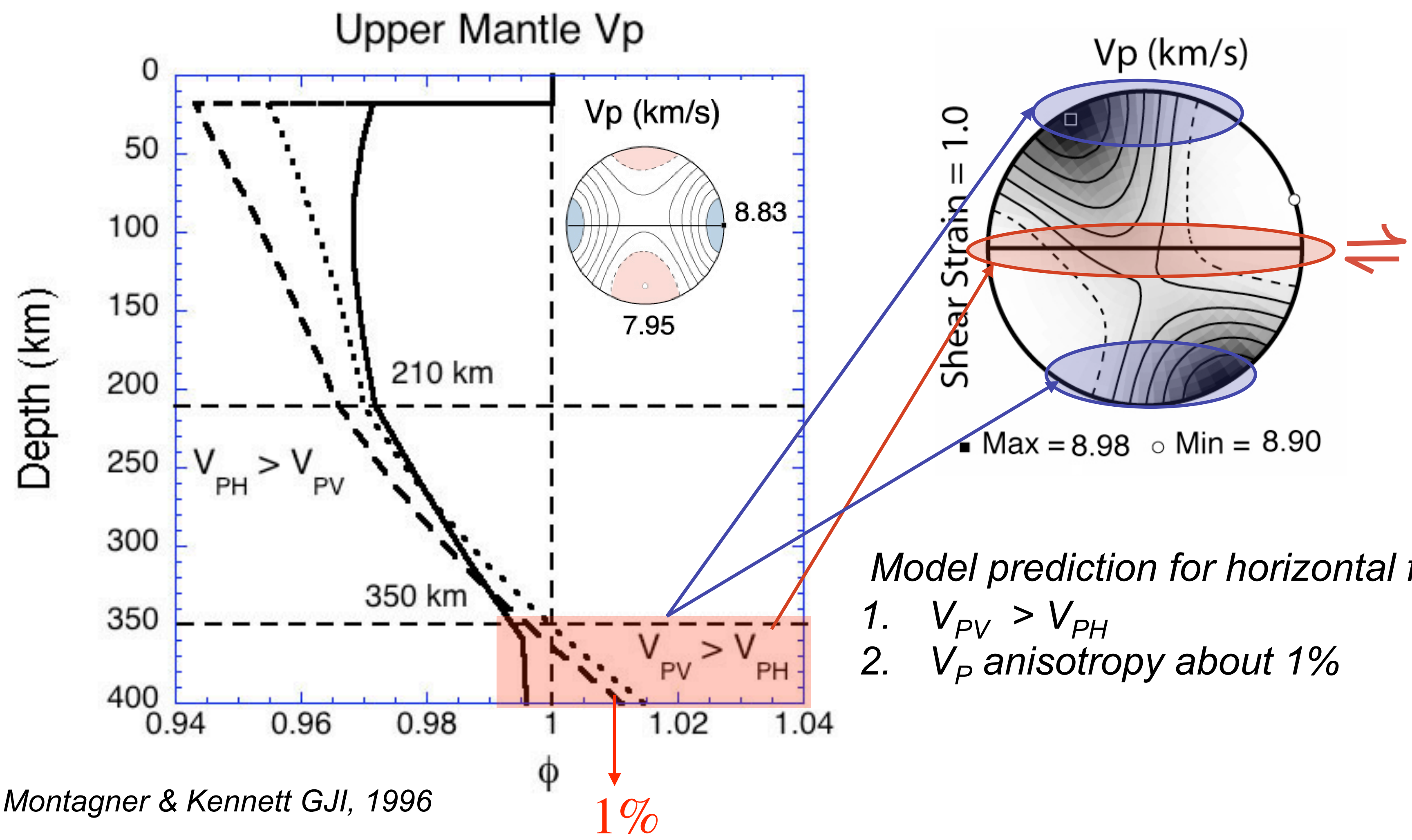




CRSS all [001] = 1 ; [100]=3(basal) or 6 (prism)

Mainprice et al. Nature, 2005

Global P-wave anisotropy in the deep upper mantle

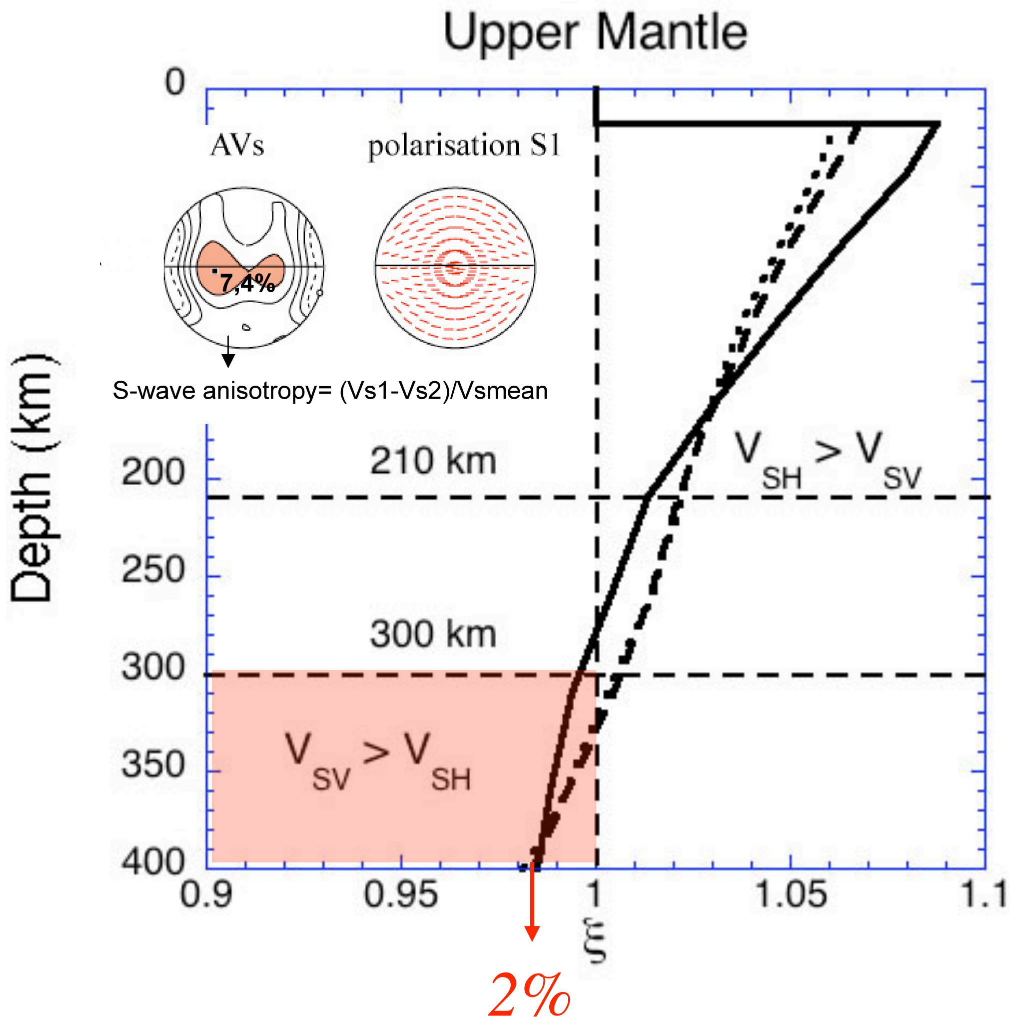


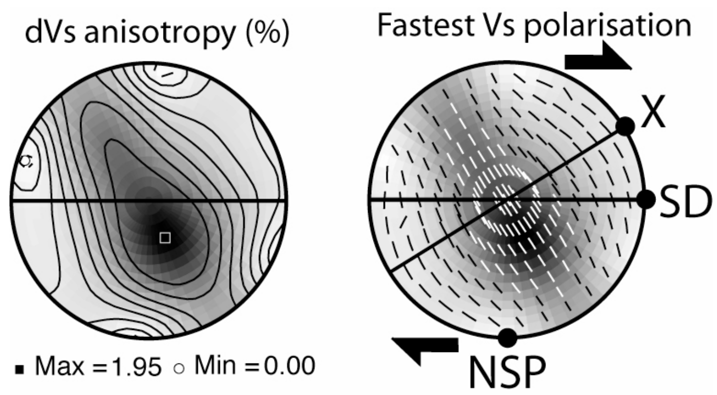
Montagner & Kennett GJI, 1996

Model prediction for horizontal flow:

1. $V_{PV} > V_{PH}$
2. V_P *anisotropy about 1%*

Global S-wave anisotropy in the deep upper mantle



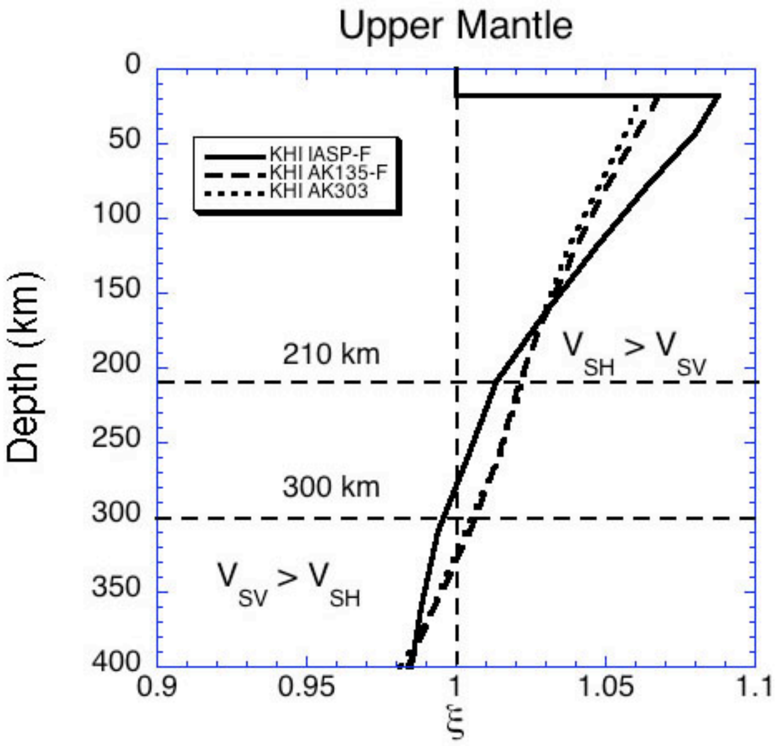


Model prediction for horizontal flow:

1. *$V_{SV} > V_{SH}$*
2. *Vs anisotropy ≤ 2%*

Montagner & Kennett GJI, 1996

olivine deformation = f(P)
change in dominant slip direction from [100] to [001]



- ***strong decrease in seismic anisotropy with depth***

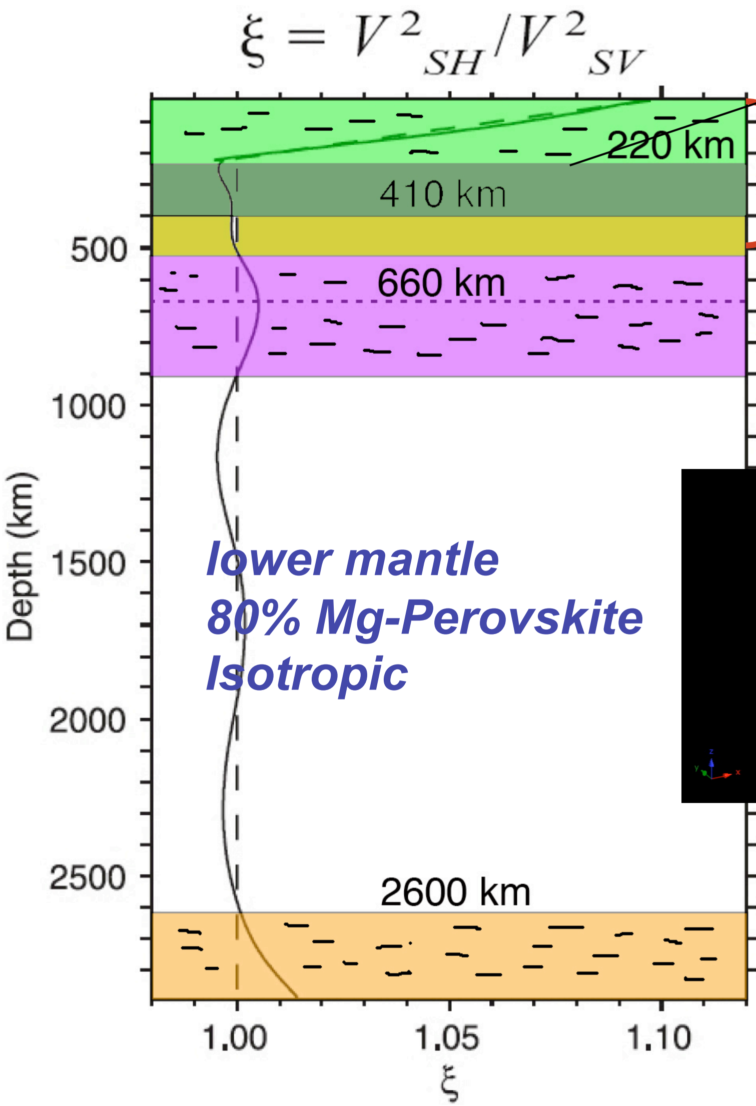
- ***fast P-wave propagation & fast S-wave polarisation directions in the deep upper mantle normal to shallow ones***

- ***global 1D seismic anisotropy data : horizontal shearing accommodated by dislocation creep***

- ***lack of anisotropy does not imply diffusion creep!***

Mainprice et al., Nature, 2005

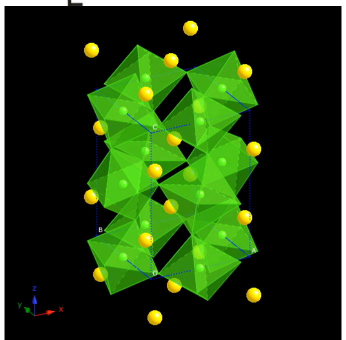
Anisotropy & deformation in the deep mantle



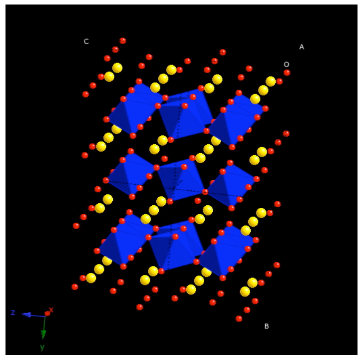
Lehmann discontinuity: transition from LP to HP slip in olivine ?

strain-induced anisotropy (CPO) dominant horizontal flow

$Vs_H > Vs_V$: ringwoodite & garnet weak CPO & very low anisotropy : which mechanism?

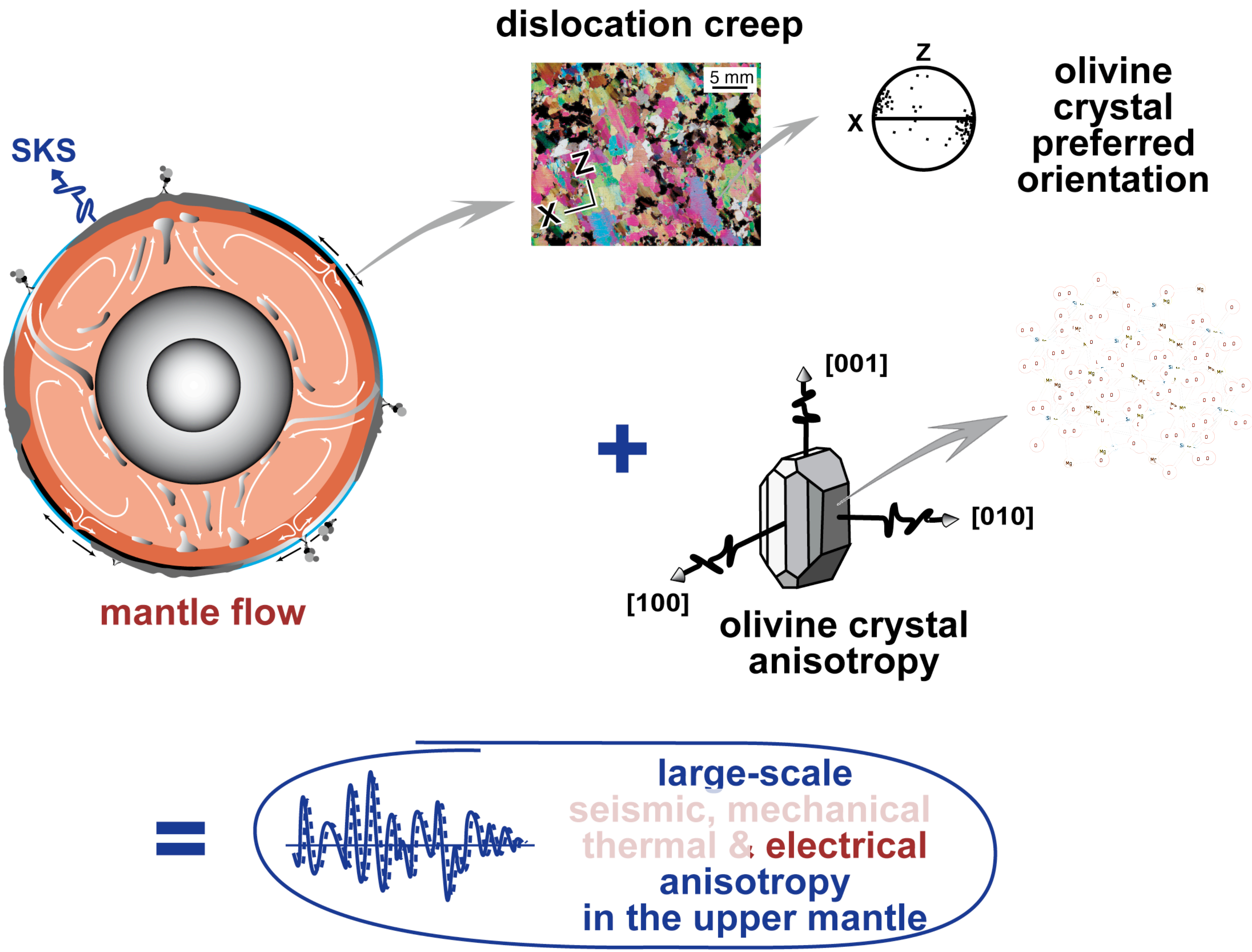


D": $Vs_H > Vs_V$
PPV CPO or layering?



Panning & Romanowicz 2004 Science

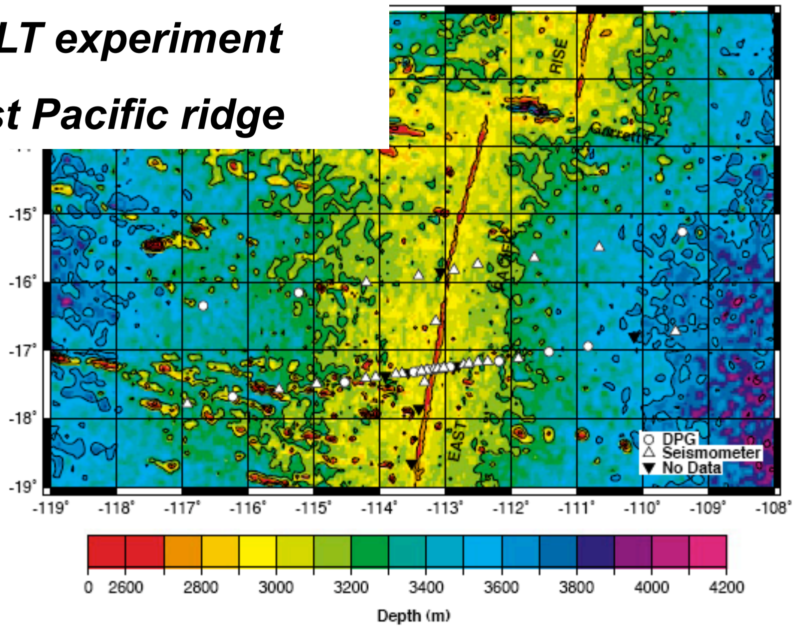
Other anisotropic properties …



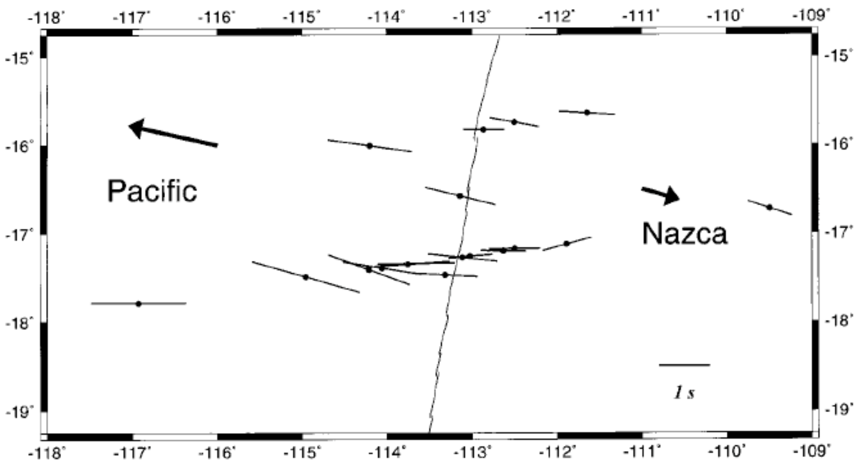
Electrical conductivity anisotropy inferred from long-period MT data: Another tool to map upper mantle deformation?

MELT experiment

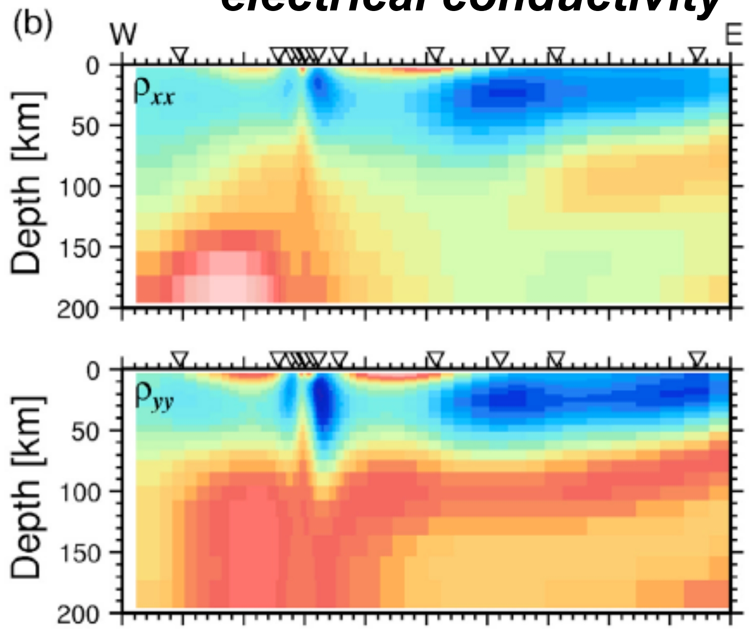
East Pacific ridge



SKS splitting



electrical conductivity



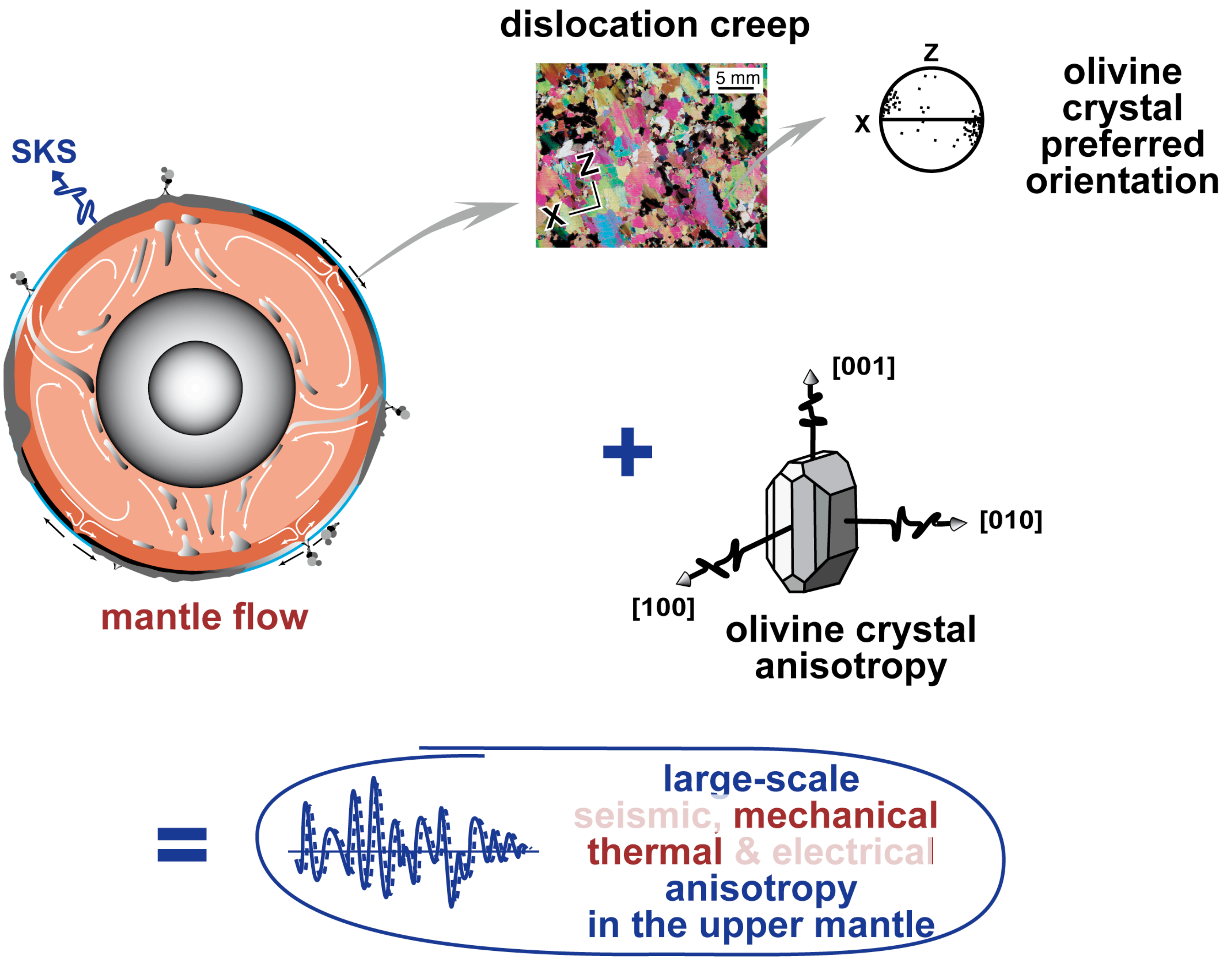
resistivity // spreading direction
*= 1/5 * resistivity // ridge*

Baba et al. JGR 2006

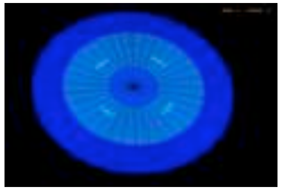
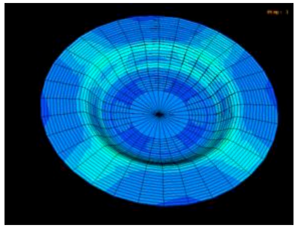
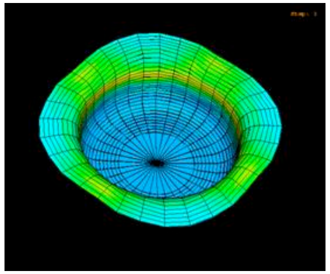
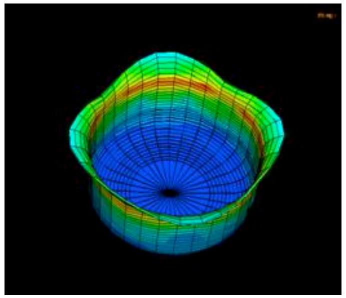
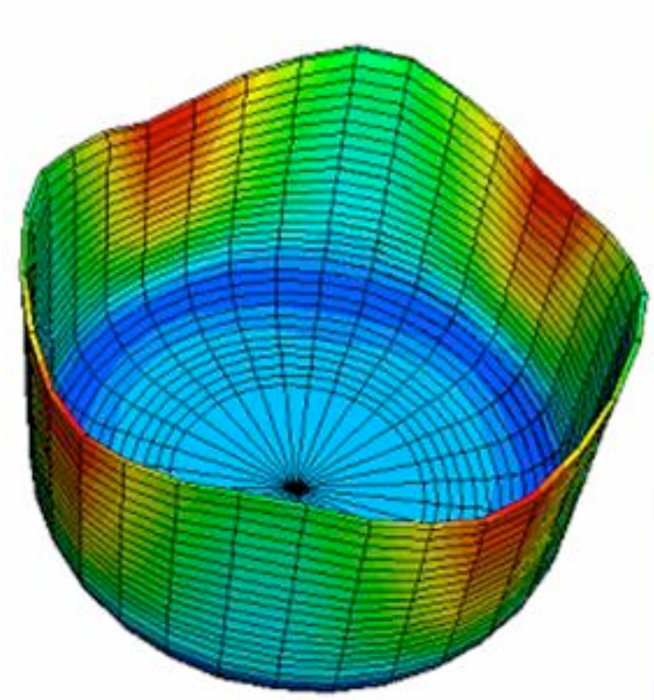
fast EC direction // fast SKS polarisation

high conductivity & anisotropy below 60km
✓ EC anisotropy = faster H+ diffusion
// olivine [100]

Other anisotropic properties …



metallurgy: CPO-induced mechanical anisotropy = 1st order parameter

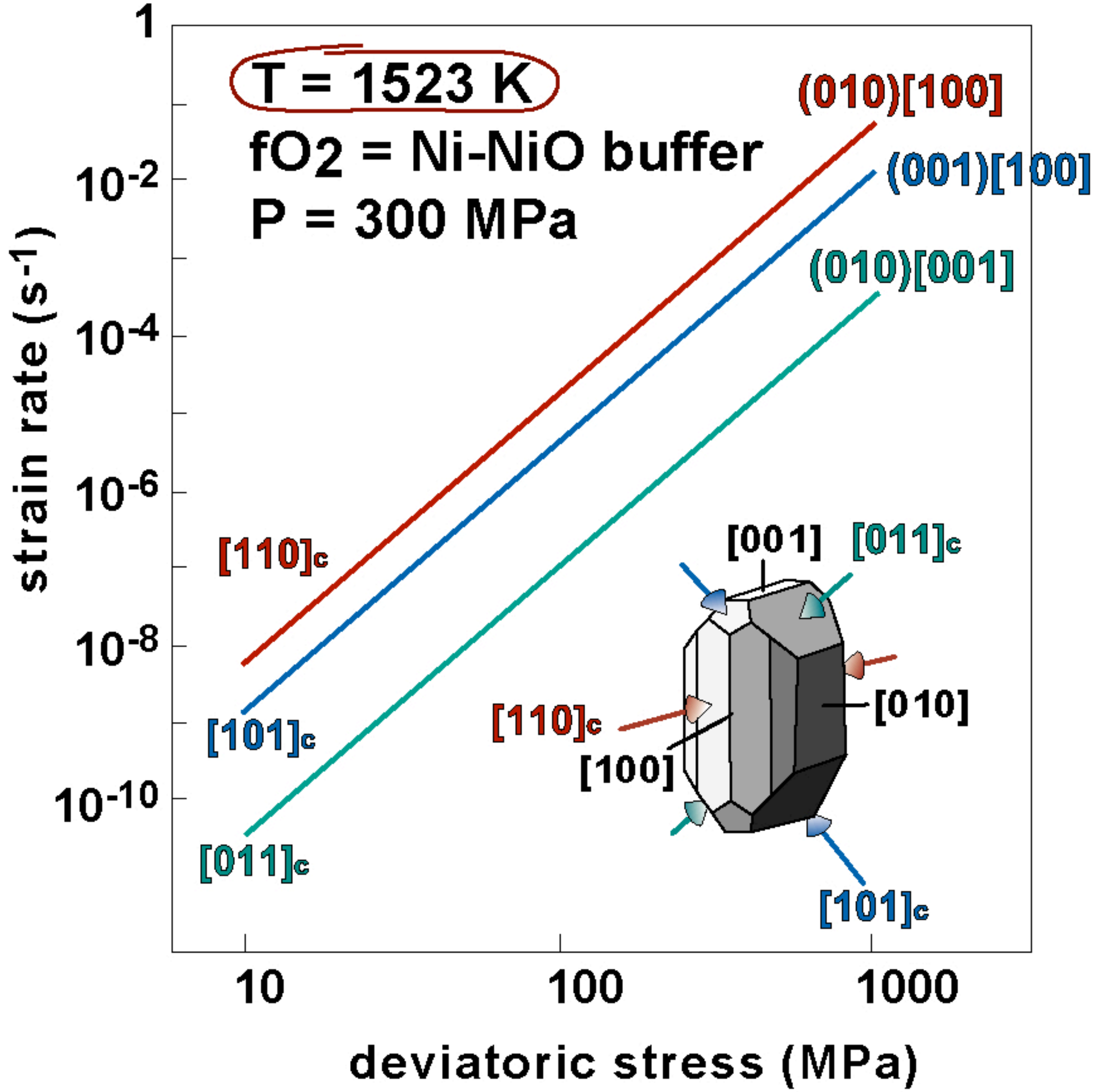







D.Raabe, Max Planck Institut

Earing of Al cans: mechanical anisotropy Al crystal & preferred orientation of crystals in the Al sheet

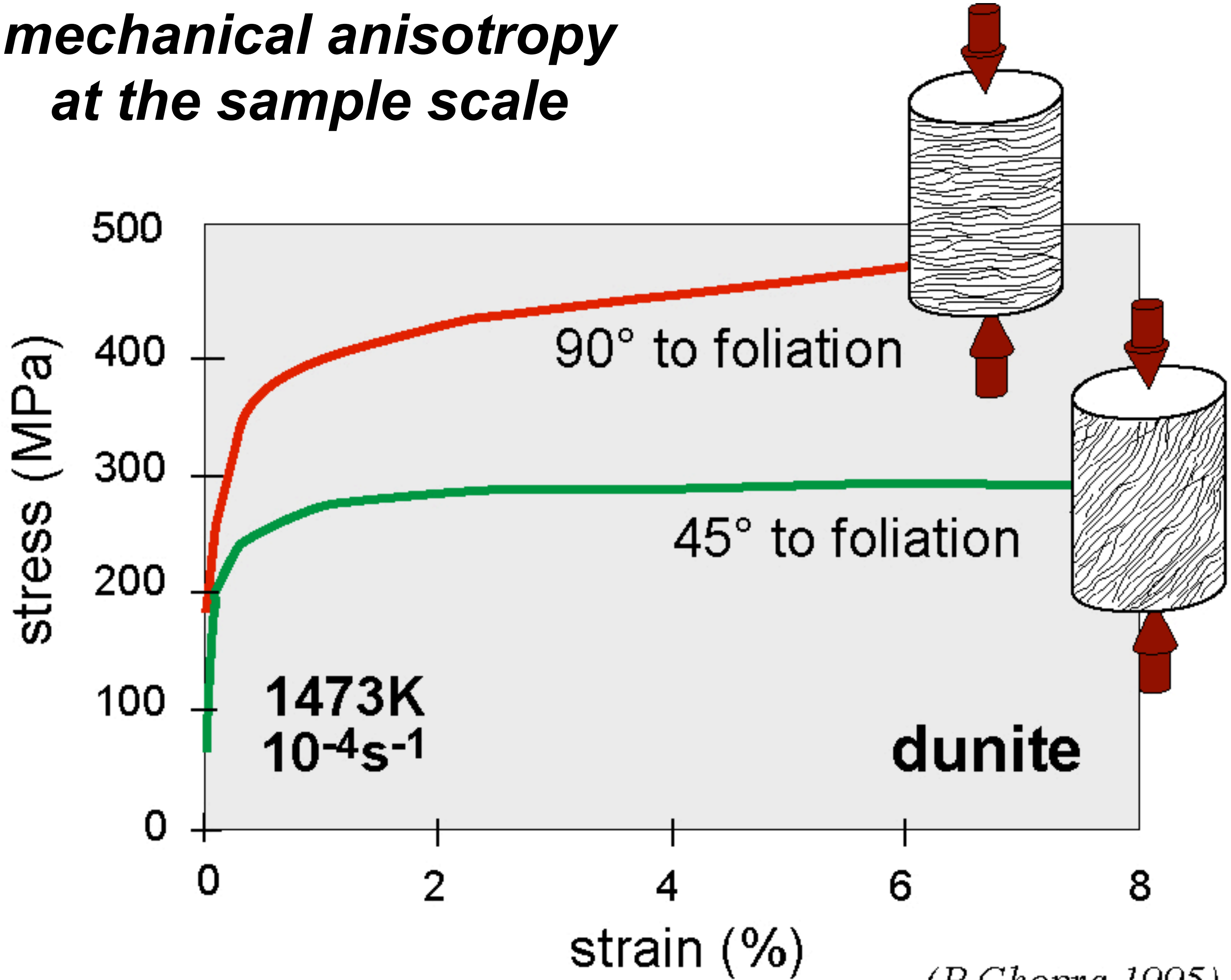
ductile deformation of a olivine crystal is anisotropic:

few slip systems with highly ≠ strenghts



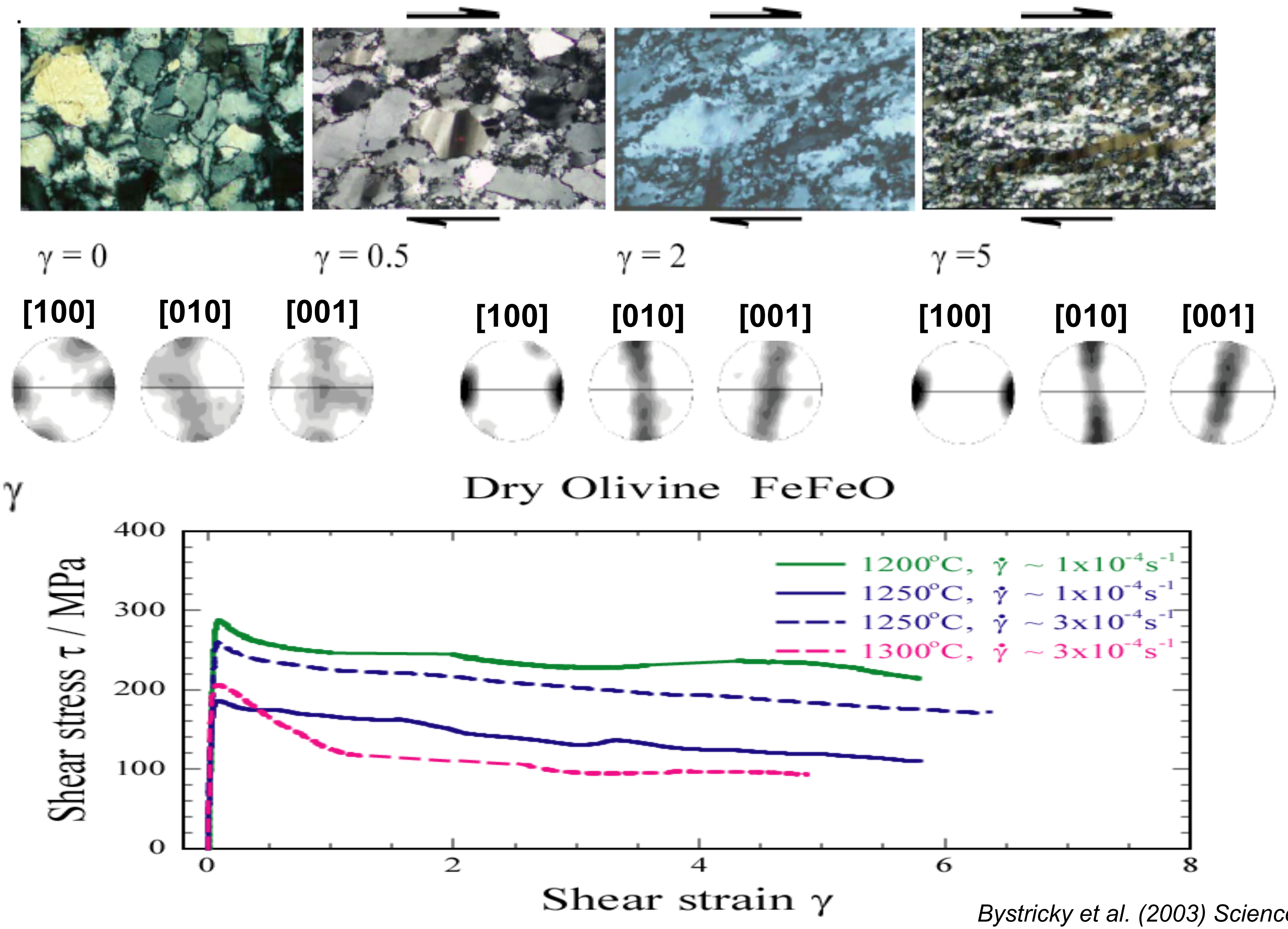
Bai et al. 1990 - JGR

olivine crystal anisotropy + cristallographic orientations (CPO) = mechanical anisotropy at the sample scale



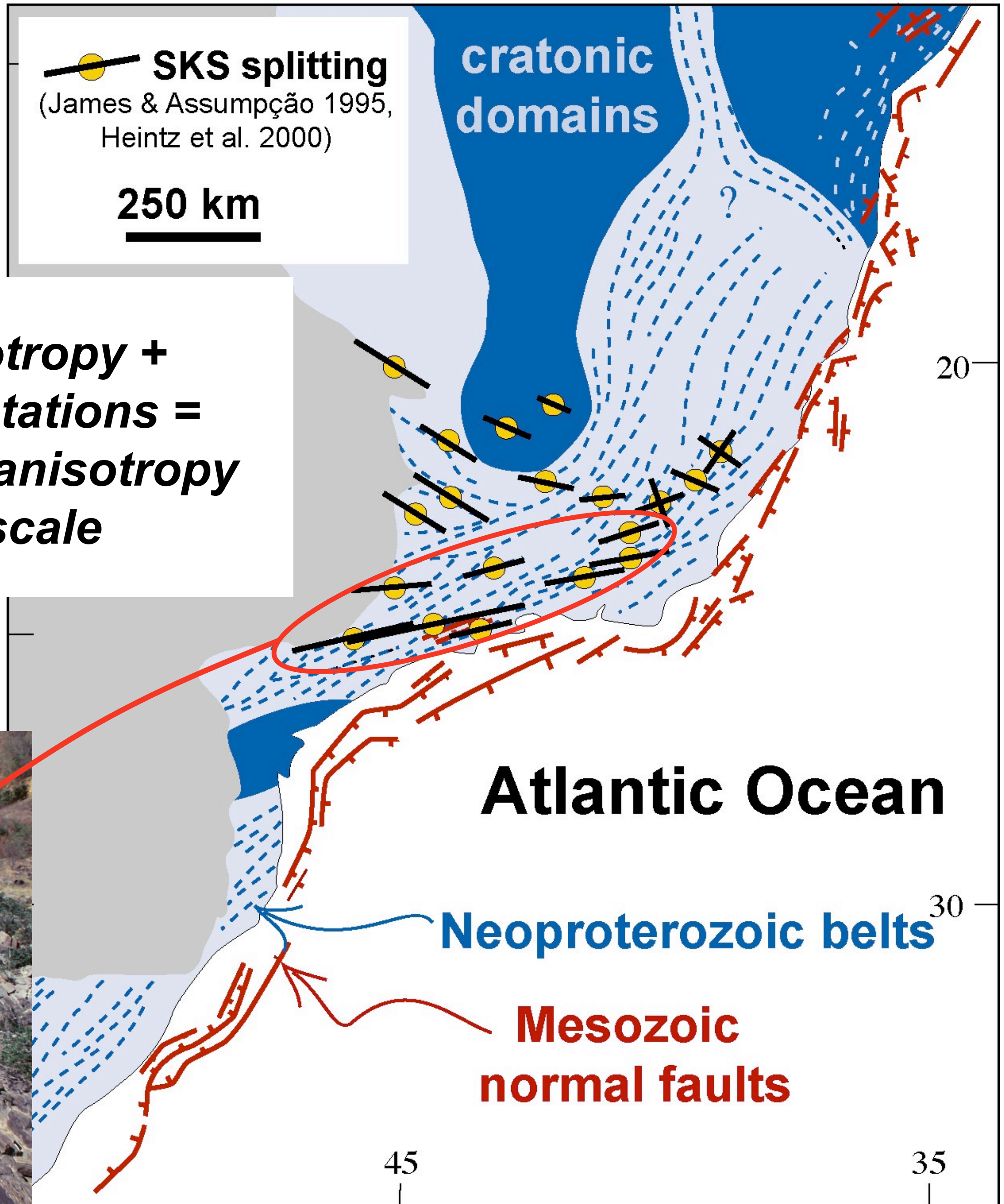
(P.Chopra,1995)

Strain weakening in torsion experiments ⇔ olivine CPO evolution ?

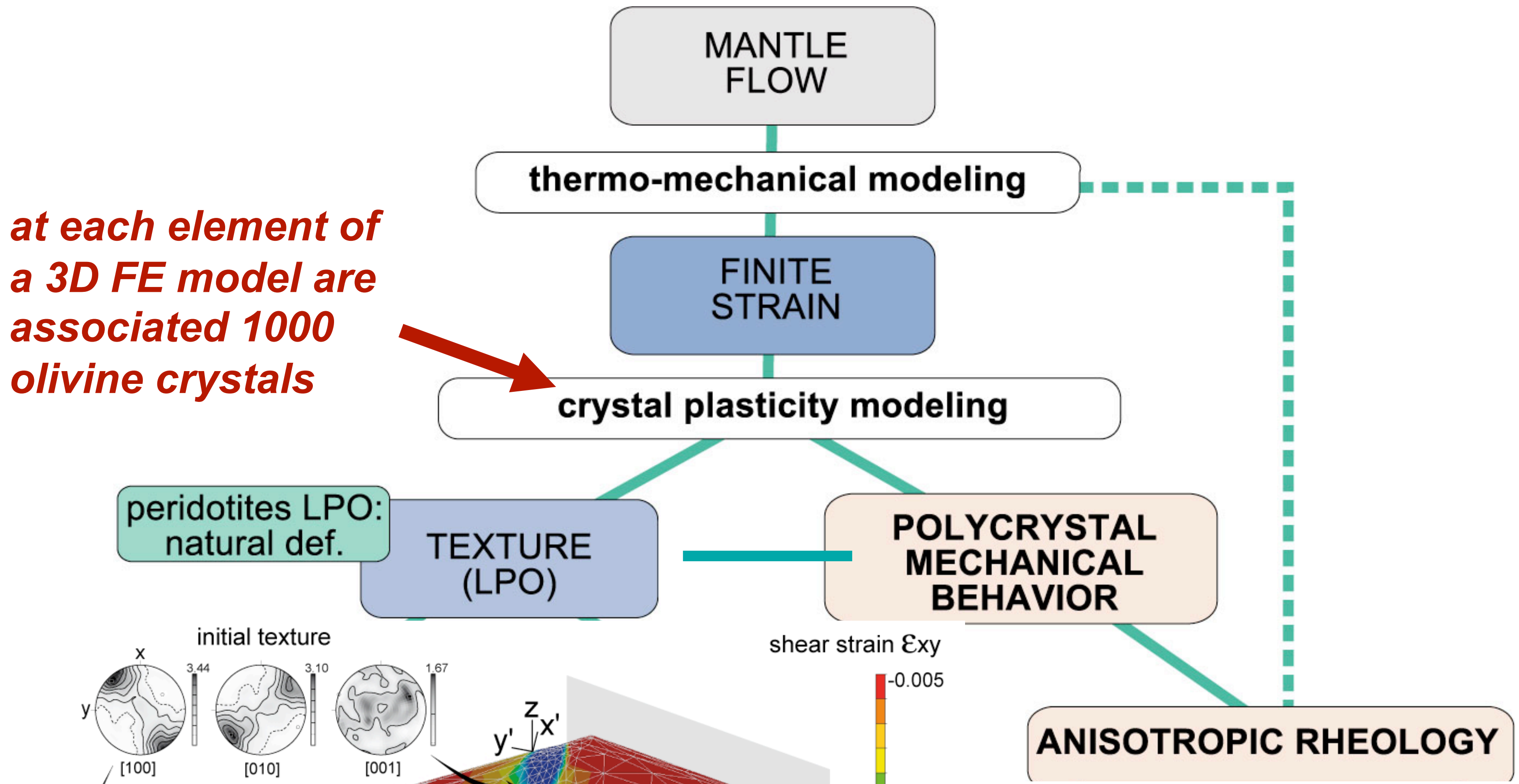


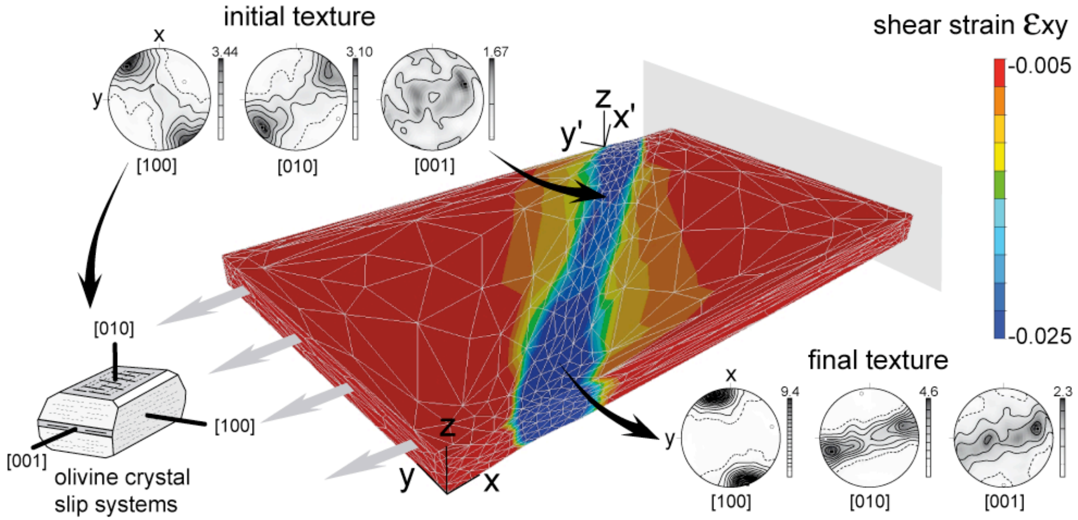
Bystricky et al. (2003) Science
M. Bystricky, pers. commun.

olivine crystal anisotropy +
cristallographic orientations =
seismic & mechanical anisotropy
at the continent scale



coupled 3D geodynamic & crystal plasticity models: evolution of olivine orientations and anisotropy



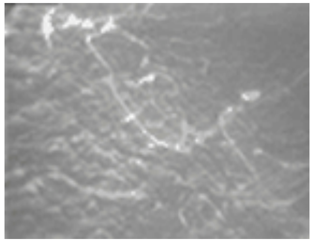


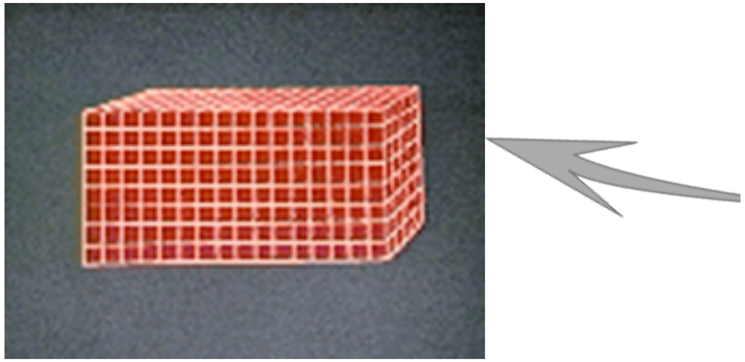
PhD thesis Mickael Knoll
coll. A. Vauchez,
J. Signorelli (IFIR, AR)
R. Logé (CEMEF, F)

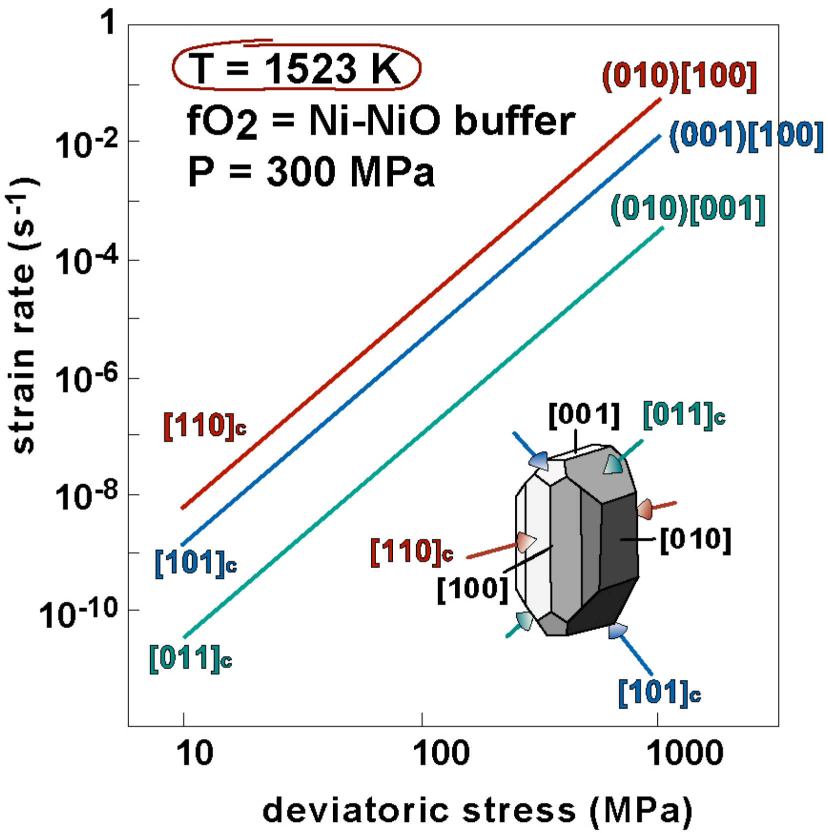
Modeling the deformation & crystal orientation evolution

VPSC: Molinari et al. 1987, Lebensohn & Tomé 1993
Drex: Kaminsky & Ribe 2001, 2003

within a grain (crystal):



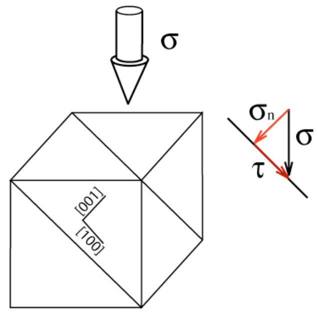




Bai et al. 1990 - JGR

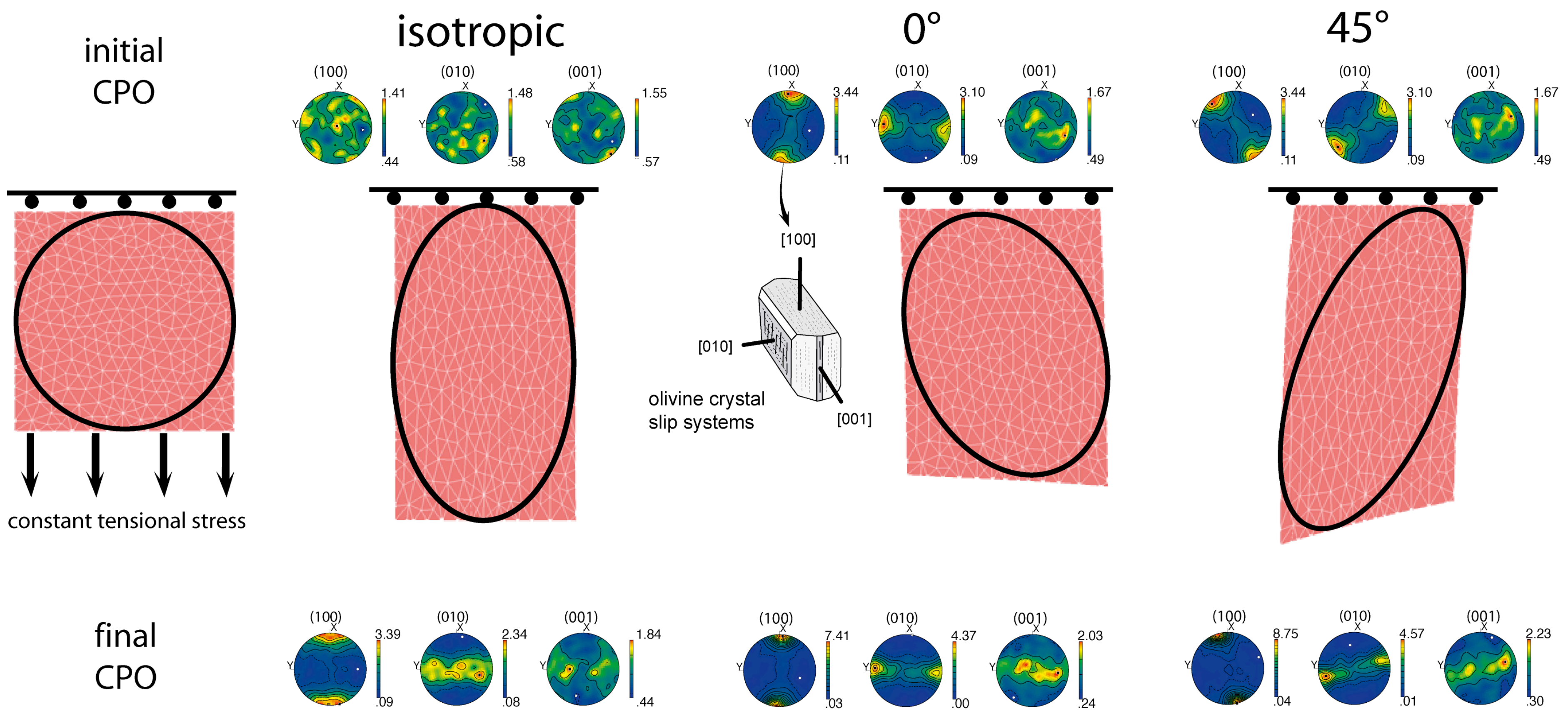
strain = motion of dislocations
on well-defined crystal
planes & directions

$$\dot{\gamma}^s = \left(\frac{\tau_r^s}{\tau_0^s}\right)^n$$



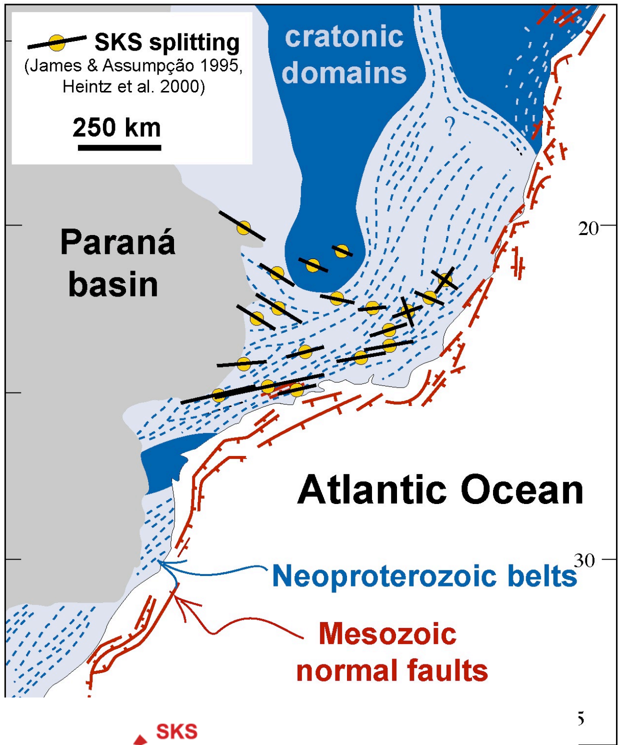
input parameters: ***slip systems' strength, initial texture, and***
macroscopic sollicitation (stress or velocity gradient tensor)
output: ***evolution of crystallographic orientations and***
macroscopic response (strain rate or stress tensor)

Deformation of a homogeneous, BUT textured plate is strongly anisotropic

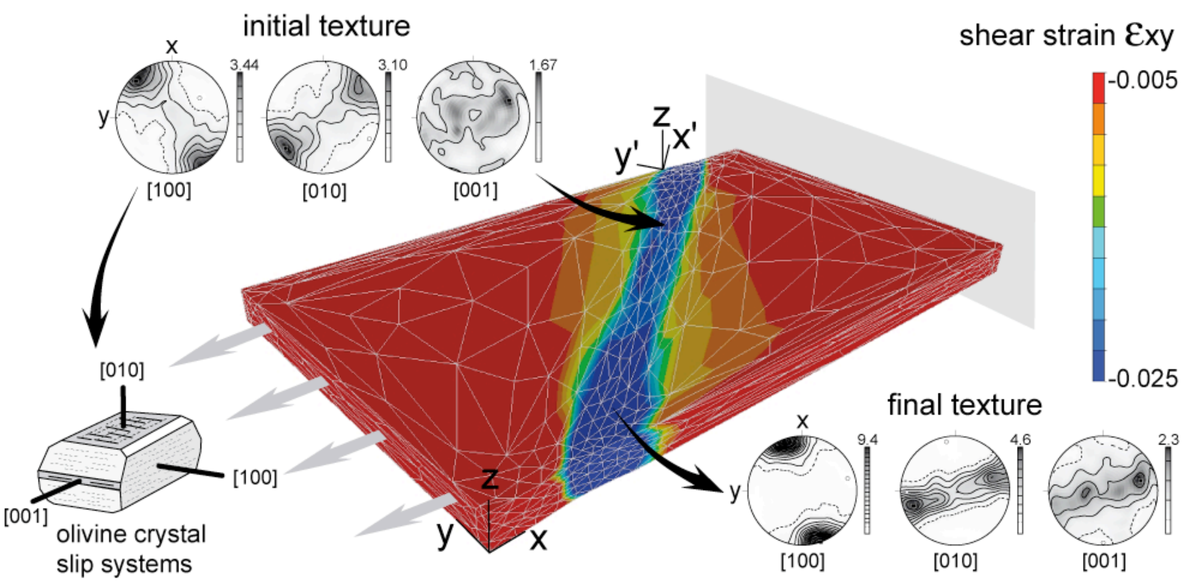


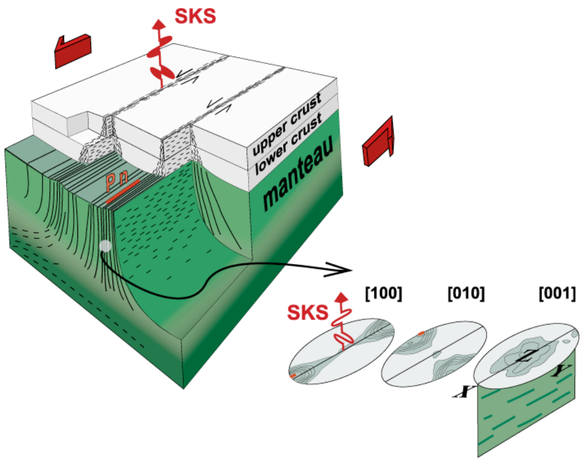
- *strength & final deformation depend on the initial CPO*
- *finite strain ellipsoid axes are not parallel to stress ones*
  - ➢ *shearing // to average orientation of main olivine slip systems*

Multi-domain models: Reactivation of lithospheric-scale strike-slip faults



within the "old" fault

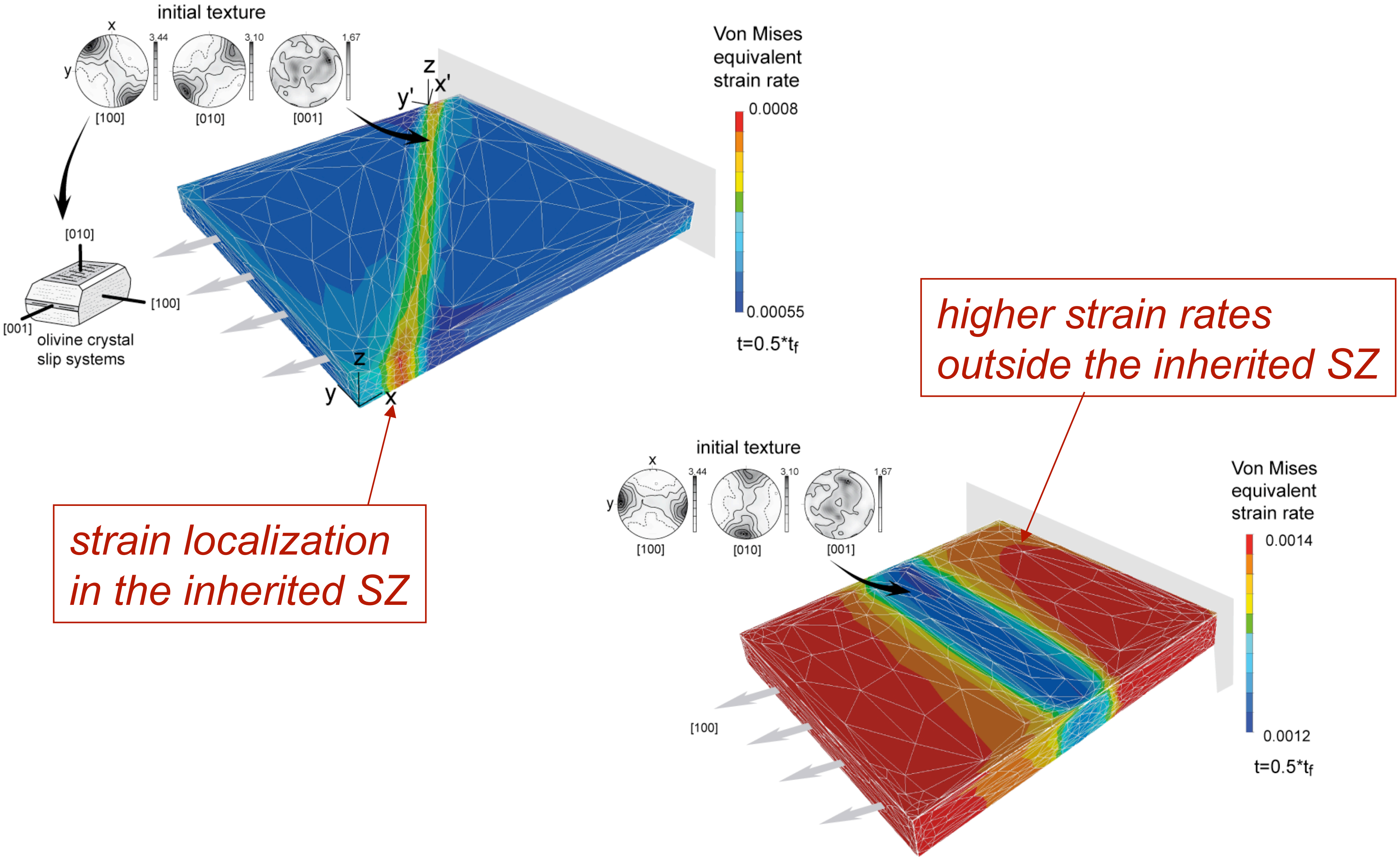




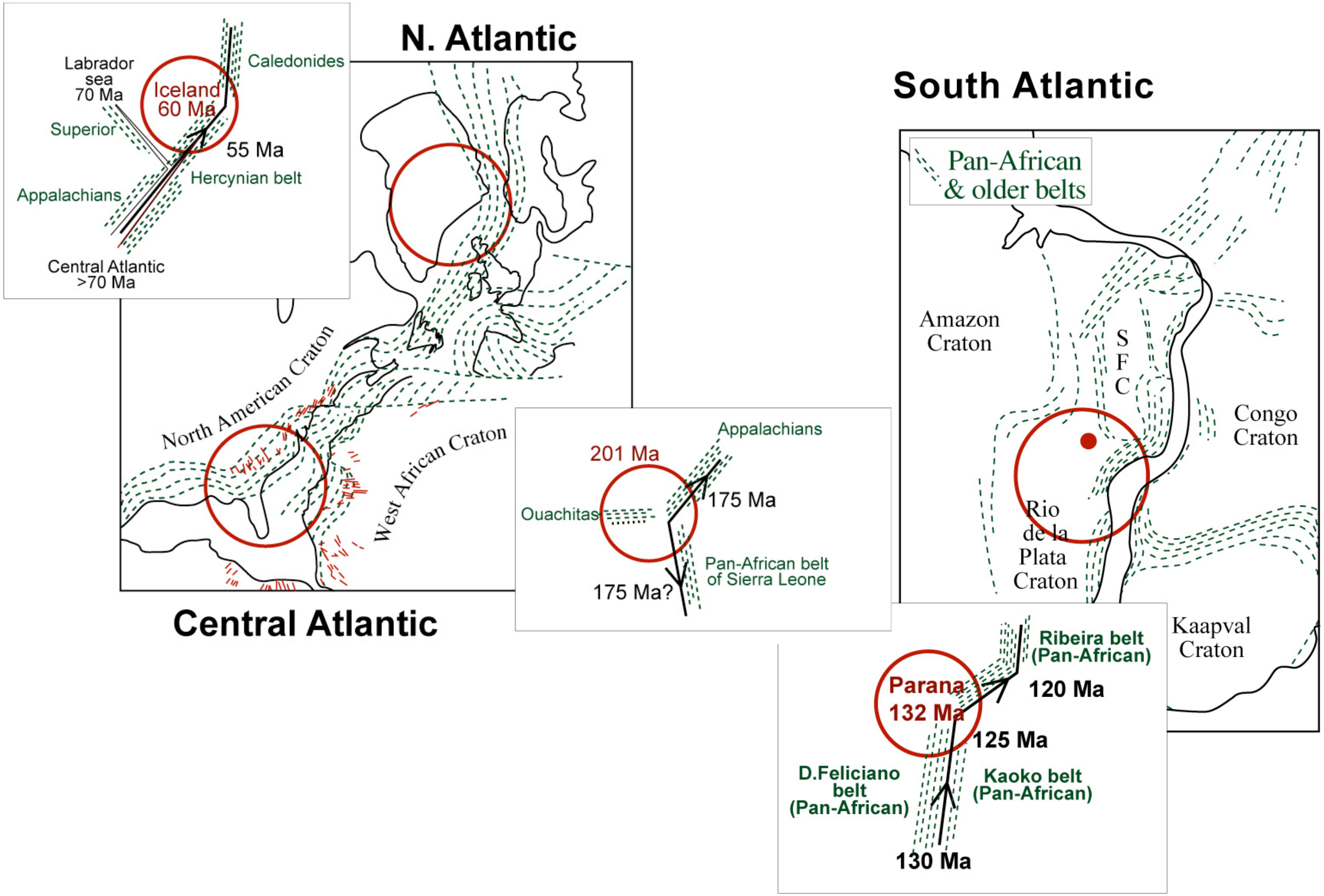
outside = CPO initially random

Reactivation of a lithospheric-scale strike-slip zone due to mechanical anisotropy of the lithospheric mantle

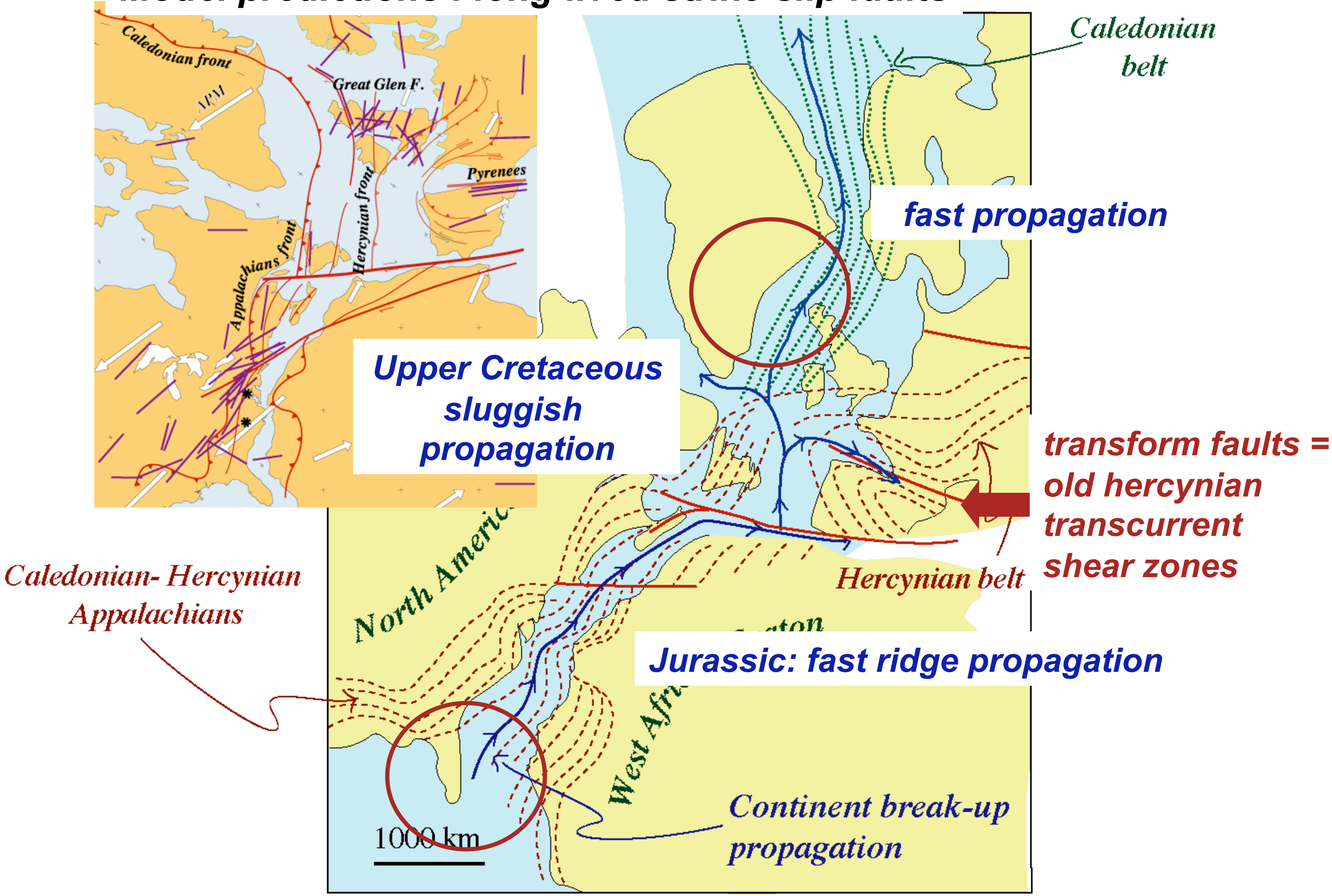
(frozen-in olivine crystal preferred orientations)



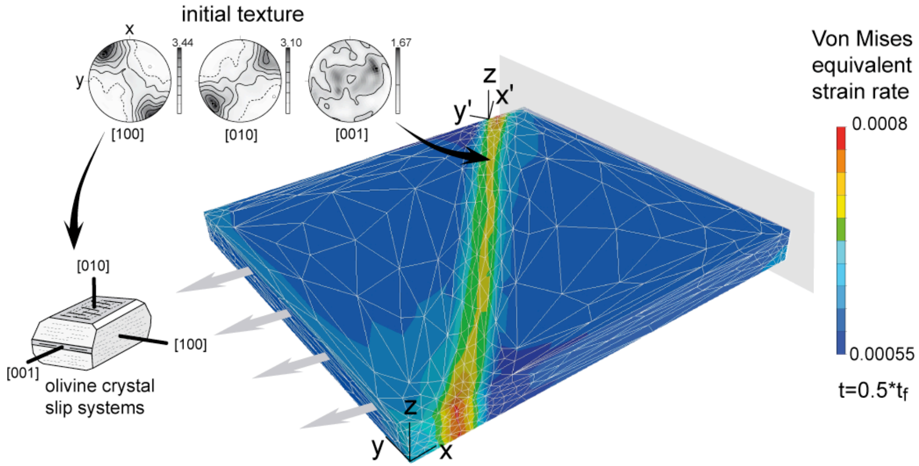
Continental breakup parallel to ancient collisional belts

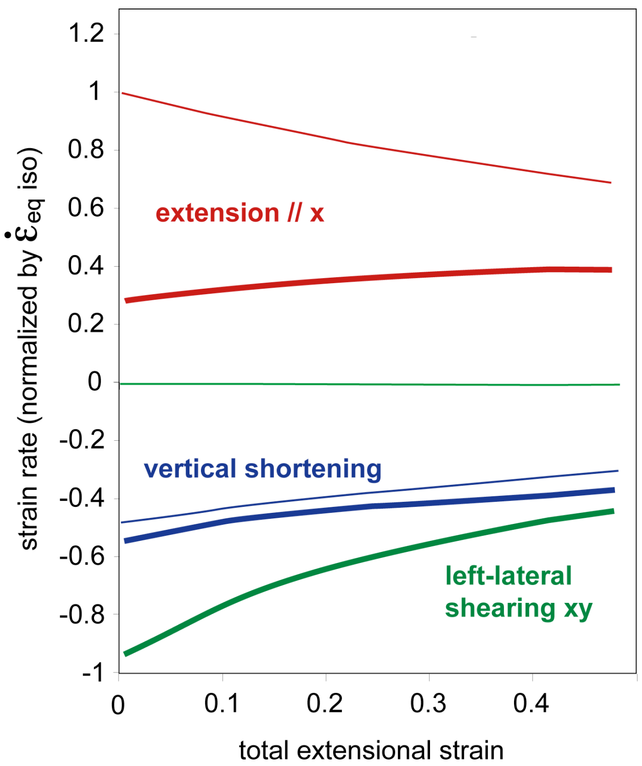


Model predictions : long-lived strike-slip faults



Reactivation of a lithospheric-scale strike-slip zone due to mechanical anisotropy of the lithospheric mantle
(frozen-in olivine crystal preferred orientations)

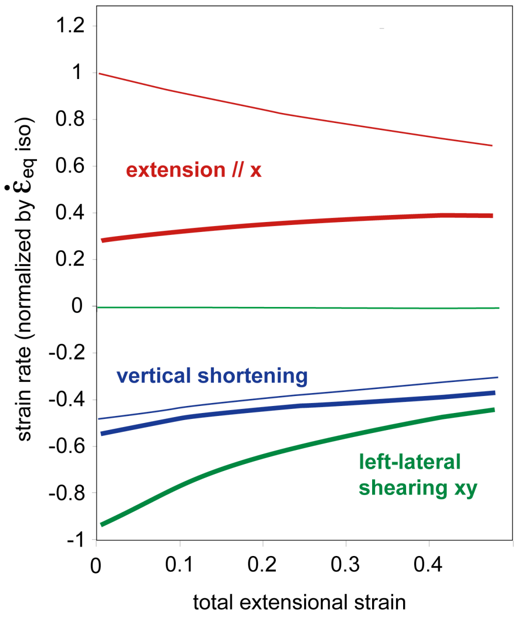


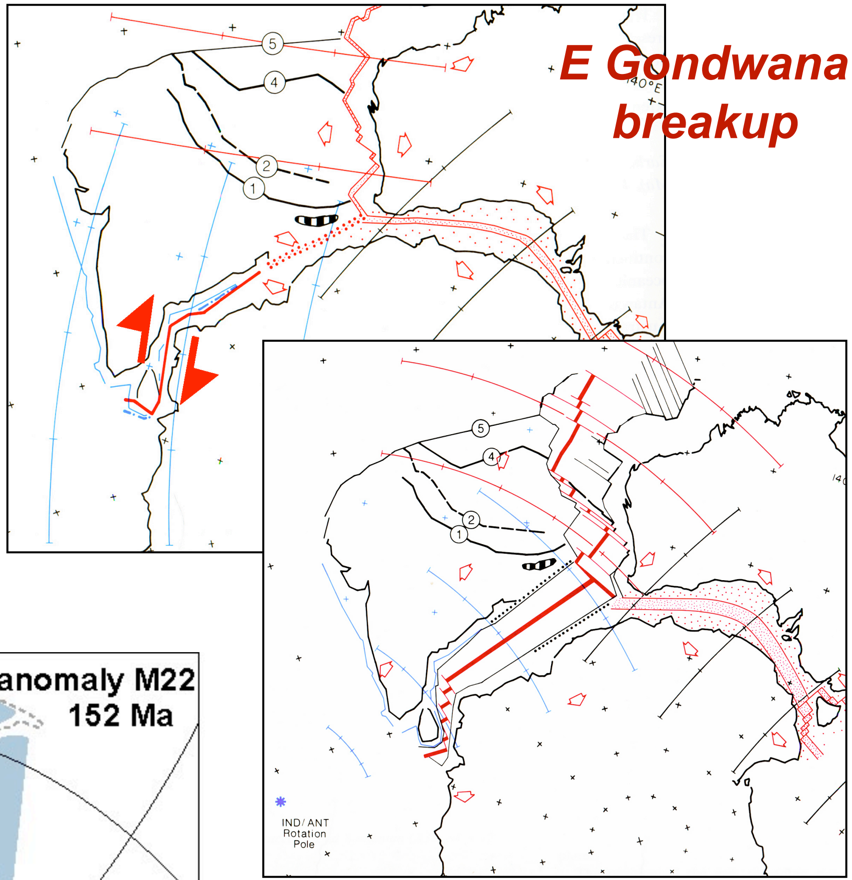


transtension in the inherited shear zone, but shearing decreases with increasing strain

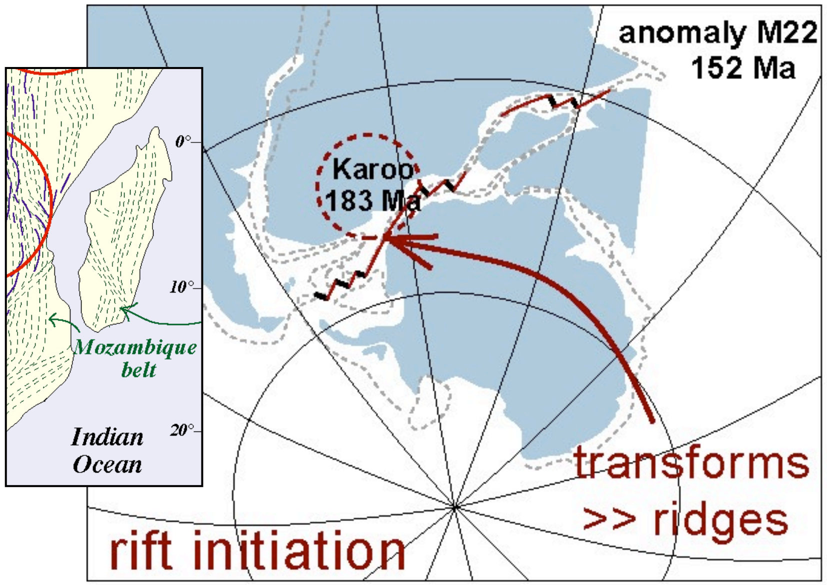
normal extension outside

Model predictions : reactivation of preexisting faults in transtension in the initial stages of rifting followed by normal extension





Powell et al., Tectonophysics, 1988



Lawer et al., Tectonophysics, 1985

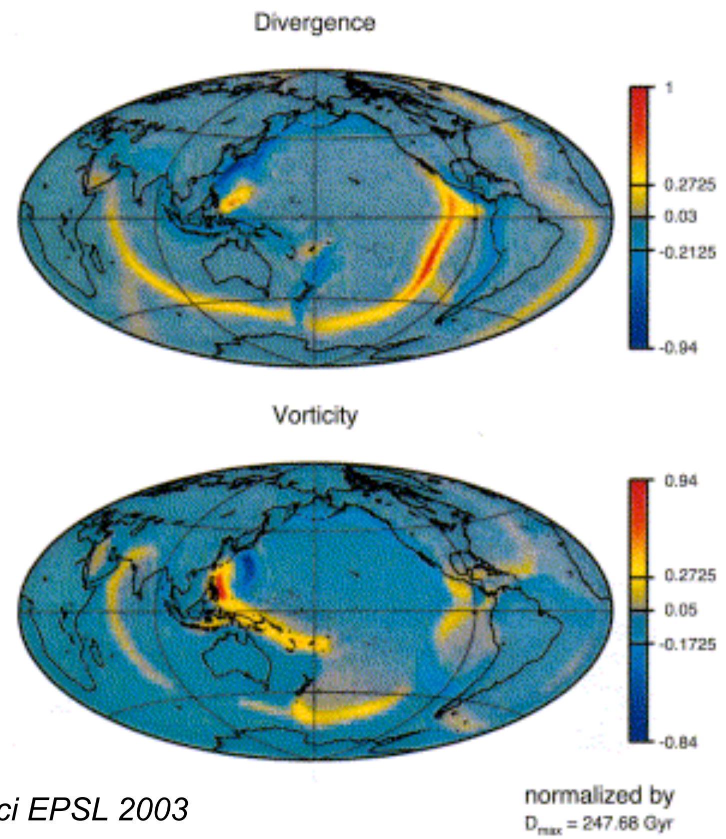
Mechanical anisotropy of the lithospheric mantle

effective in transforming convection-induced poloidal motions (plate convergence or divergence) into toroidal (strike-slip) flow

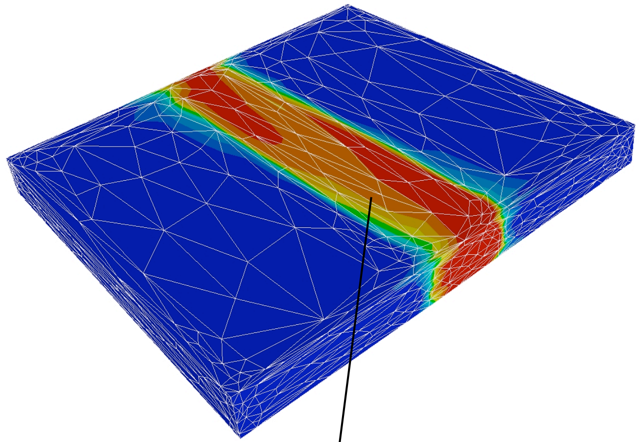
=> no need to invoke "exotic" rheologies

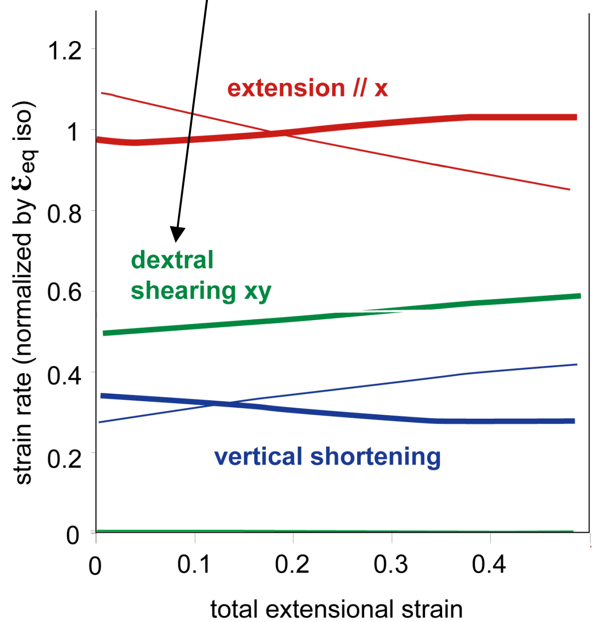
models

Earth: poloidal to toroidal ratio = 1

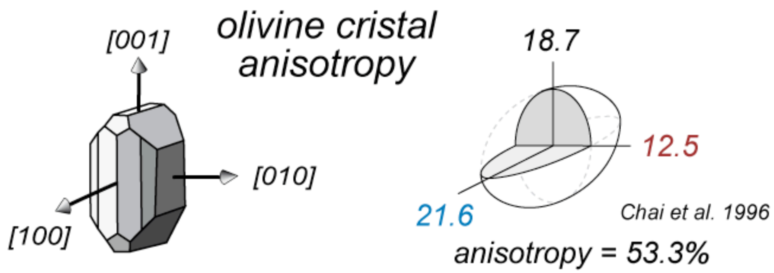


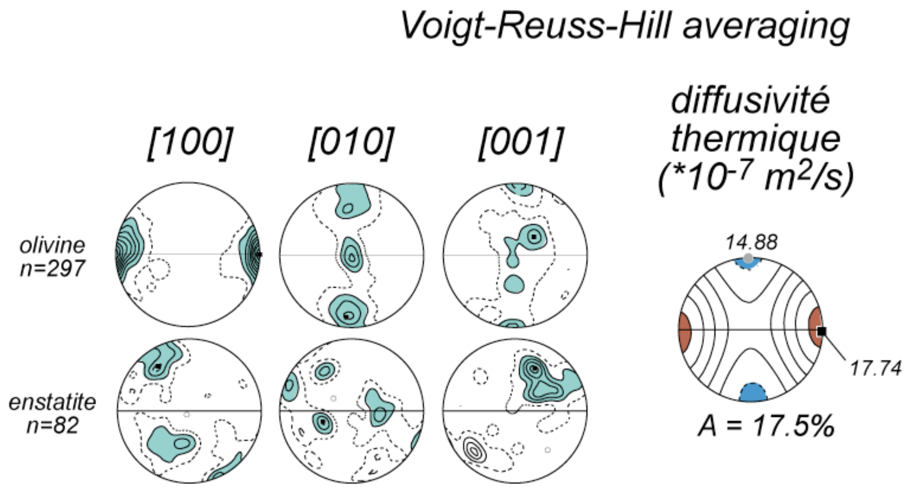
Bercovici EPSL 2003

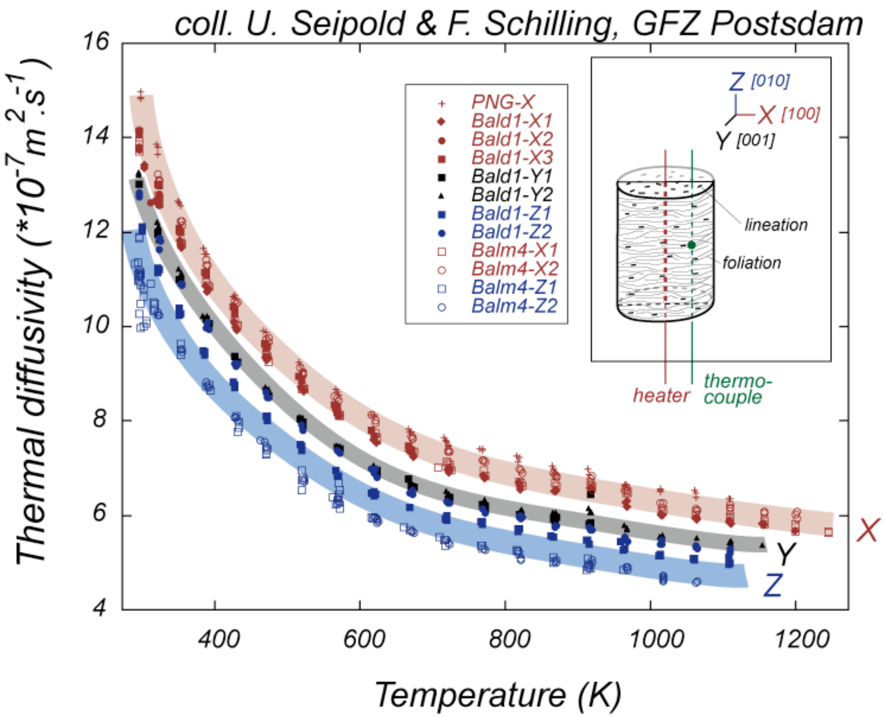




Anisotropic thermal diffusivity in the upper mantle







Tommasi, Gibert, Seipold & Mainprice, Nature 2001
Gibert, Seipold, Tommasi & Mainprice, JGR 2003
Gibert, Schilling, Tommasi & Mainprice, GRL 2003
Gibert, Schilling, Gratz & Tommasi, PEPI 2005

fastest heat conduction // [100] // to flow direction
slowest heat conduction // [010] normal to flow plane
• channelling of heat along preexisting faults

mantle deformation & anisotropy

- *in the lithospheric mantle and asthenosphere (< 200 km):*

  ✓ *deformation by dislocation creep with dominant [100] slip*

  - *strong seismic, electrical, thermal & mechanical anisotropy*
  - *fast seismic directions map flow*
  - *delay times = path length + orientation flow plane/direction relative to propagation, not finite strain*

- *>200 km : due to P + $H_2 0$ (?) in olivine: [001] slip*

  - *seismic anisotropy decreases, fast directions normal to flow direction*
  - *explain trench-// SKS splitting at subduction zones?*

- *deeper in the mantle : deformation mechanisms of main minerals?*

- *olivine CPO-induced mechanical anisotropy in the upper mantle*

  = 1st order parameter in plate tectonics

  - *initiates strain localization (reactivation of preexisting lithospheric faults)*
  - *transforms convection-related poloidal flow (divergence or convergence) into toroidal (strike-slip) motions*
    - *thermal conductivity anisotropy should enhance this effect*