SEVENTH FRAMEWORK PROGRAMME

CRYSTAL2PLATE

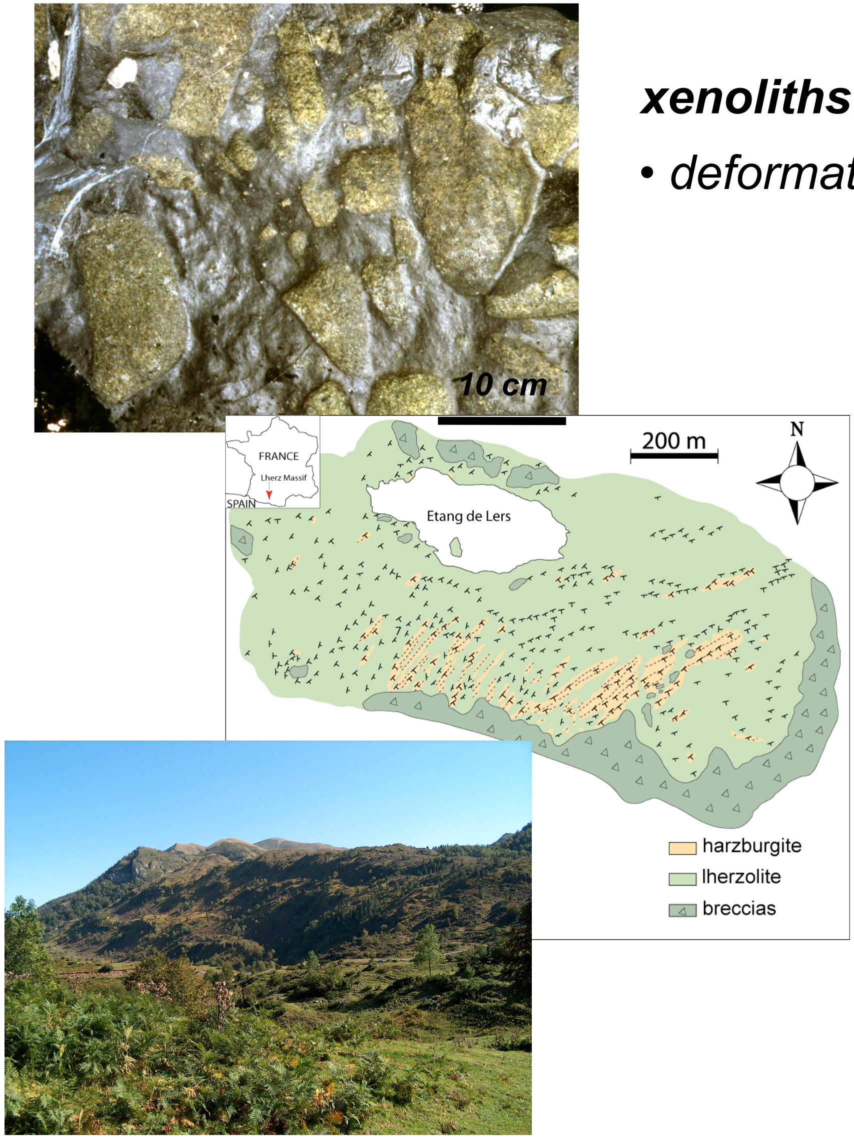
MARIE CURIE ACTIONS

How to probe the mantle deformation:

naturally deformed mantle rocks, experiments, and seismic anisotropy

Andréa Tommasi
Géosciences Montpellier

How can we "see" the mantle deformation?



xenoliths : mm to cm scale

- *deformation mechanisms*

peridotite massifs : m to 10s of km scale

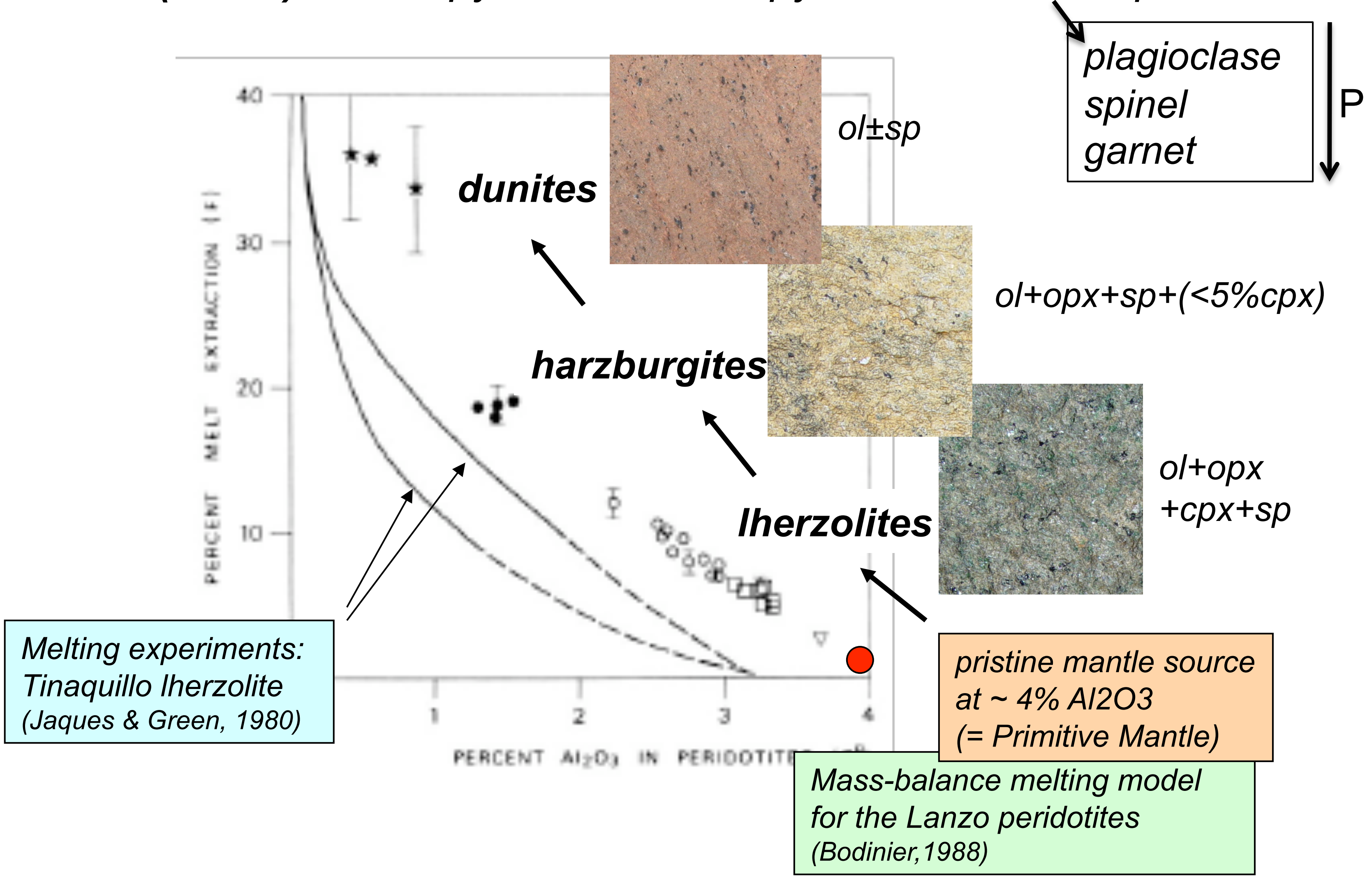
- *deformation repartition, strain localization...*
- *interaction with other processes, (melting, fluids, T gradients...)*

- ***"small" pieces extracted from the shallow mantle (<150 km):*** *cannot be used to map mantle flow*

✓ ***"in situ" indirect observations : seismic & conductivity anisotropy***

Upper mantle rocks = peridotites

olivine (>50%) *+ orthopyroxene + clinopyroxene + Al-rich phase*



plagioclase
spinel
garnet

dunites

ol±sp

harzburgites

ol+opx+sp+(<5%cpx)

lherzolites

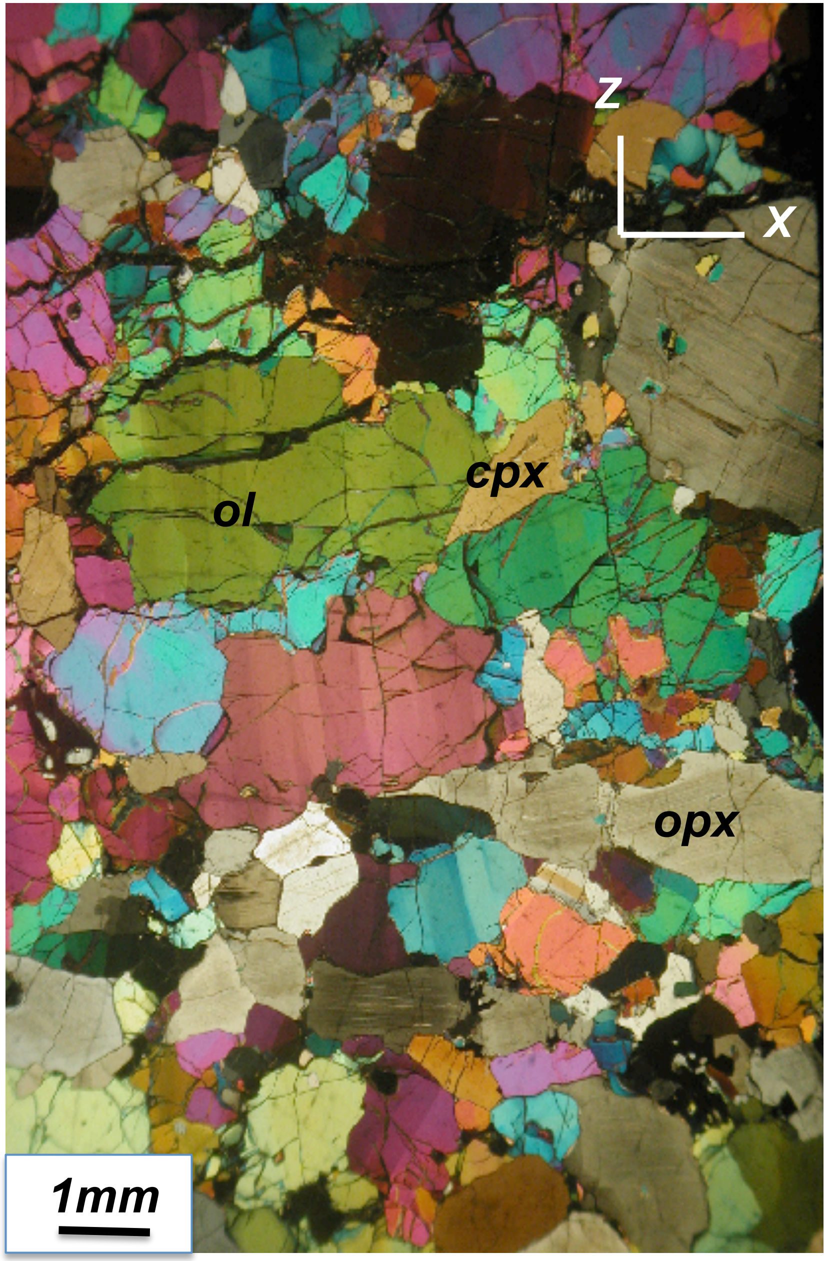
ol+opx
+cpx+sp

Melting experiments:
Tinaquillo lherzolite
(Jaques & Green, 1980)

pristine mantle source
at ~ 4% Al2O3
(= Primitive Mantle)

Mass-balance melting model
for the Lanzo peridotites
(Bodinier,1988)

Chemical and mineralogical variations in mantle rocks:
traditionally ascribed to partial melting, but refertilization also occurs



Mantle xenoliths : mm to cm scale
➢ ***deformation mechanisms***

Dominantly coarse porphyroclastic microstructures

***Olivine**:*
- *elongated crystals*
- *undulose extinction*
- *subgrains*
- *interpenetrating grain boundaries*

dislocation creep

assisted by ***diffusion***

***Opx**:*
- *elongated crystals*
- *undulose extinction*
- *kink bands*

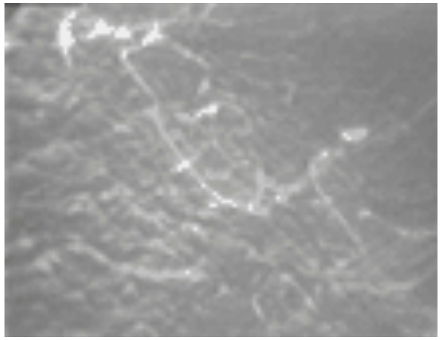
dislocation creep

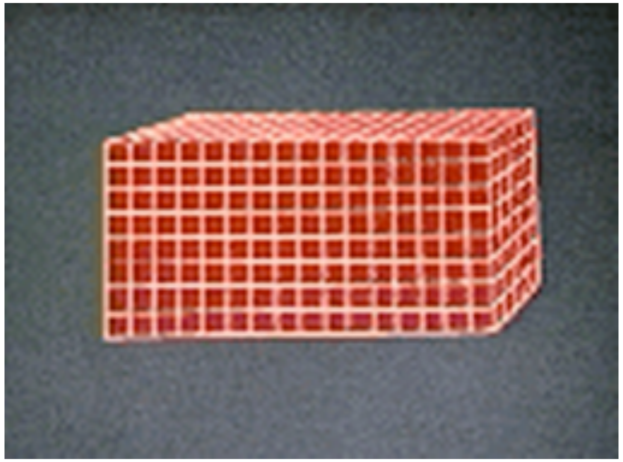
coarse grains : low deviatoric stresses

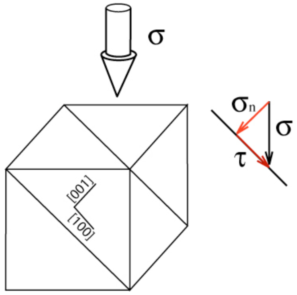
Crystal deformation by dislocation glide

within a grain (crystal):

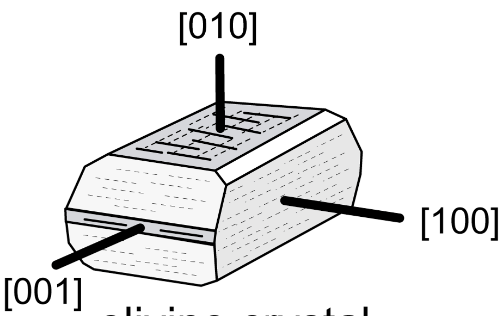
strain = motion of dislocations on well-defined crystal planes & directions



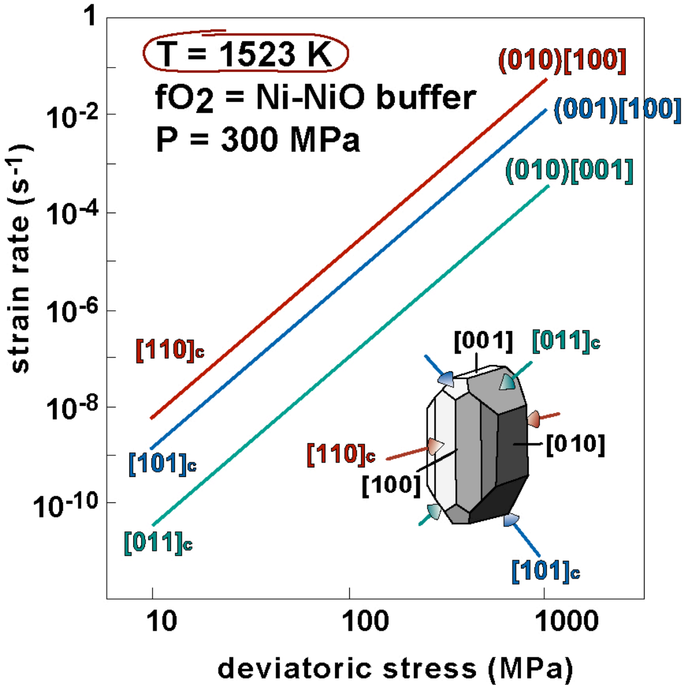




$$\dot{\gamma}^s = \left(\frac{\tau_r^s}{\tau_0^s}\right)^n$$



olivine crystal slip systems

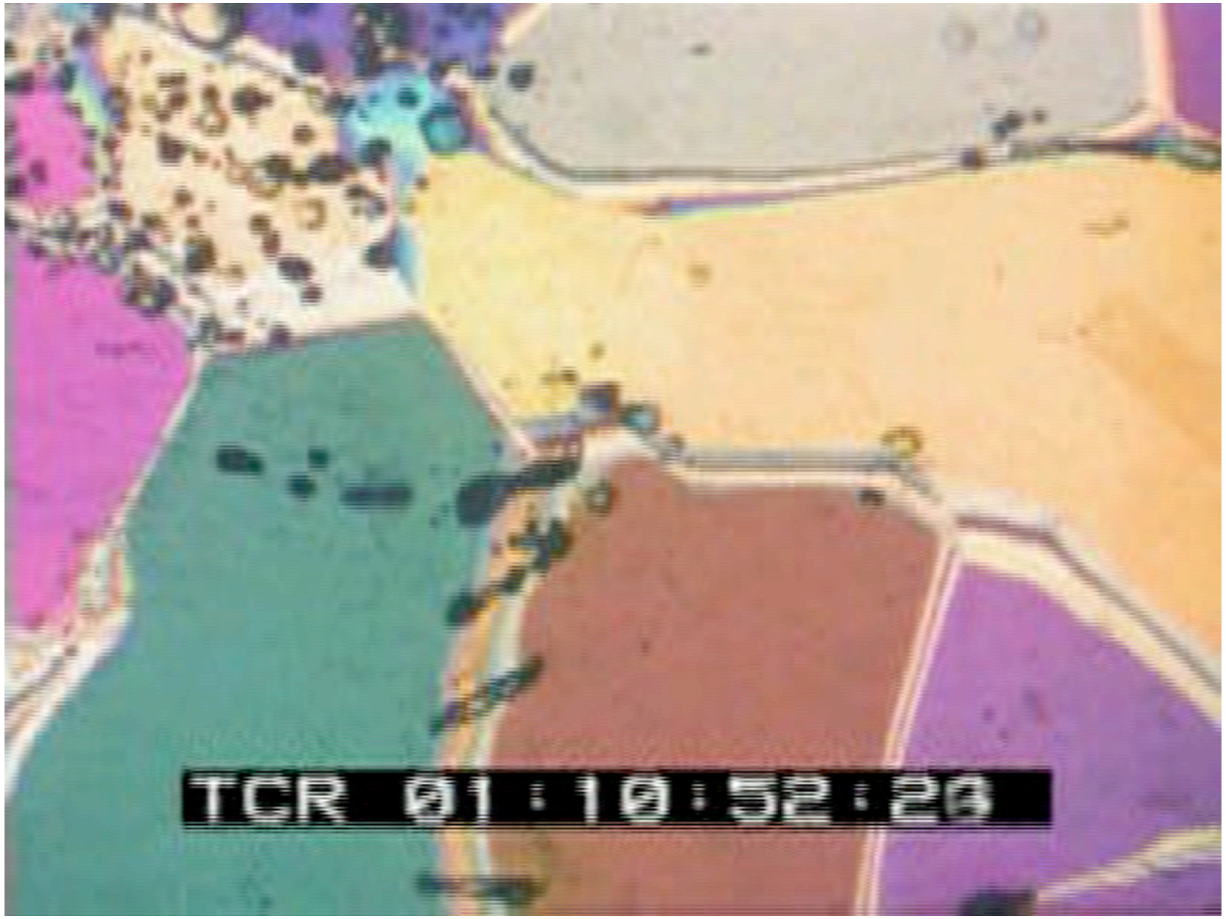


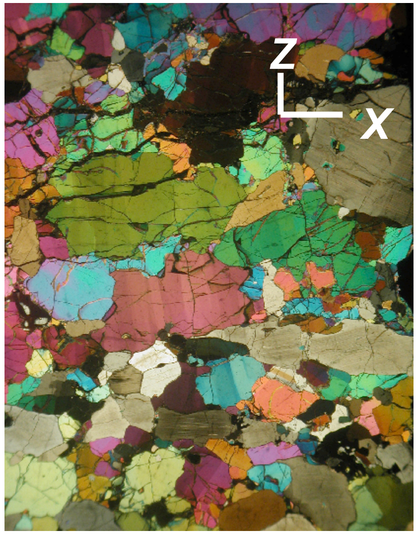
Bai et al. 1990 - JGR

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

Viscoplastic deformation & crystal preferred orientations

dislocation creep = dislocation glide + dynamic recrystallization

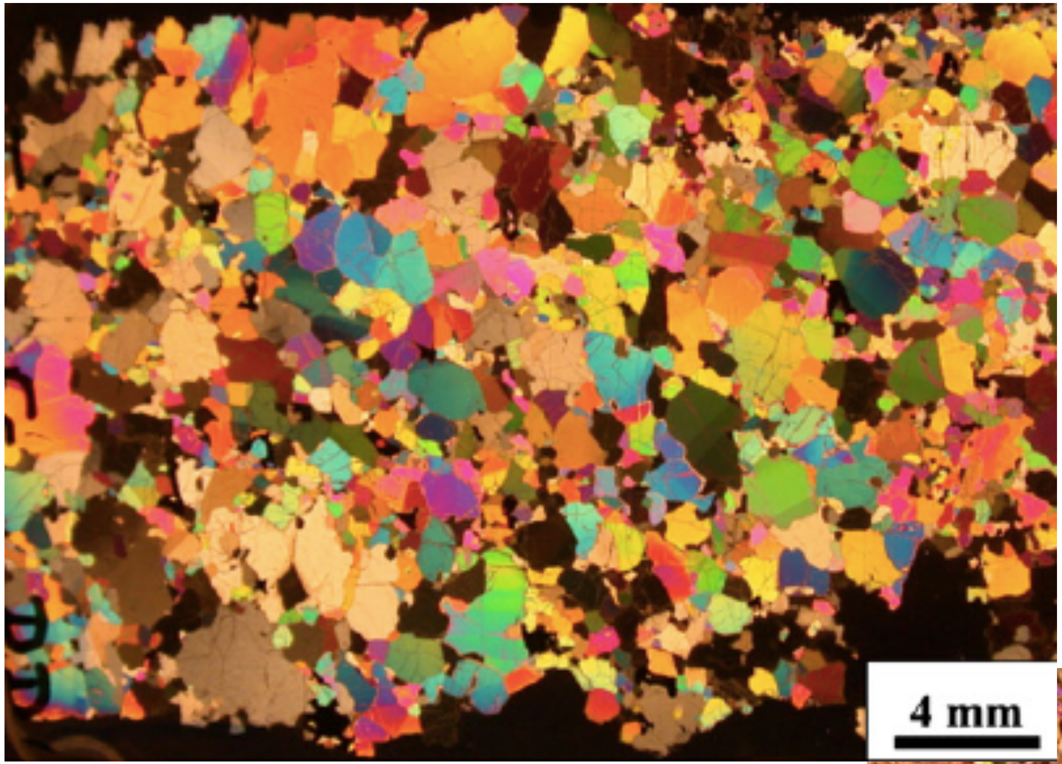




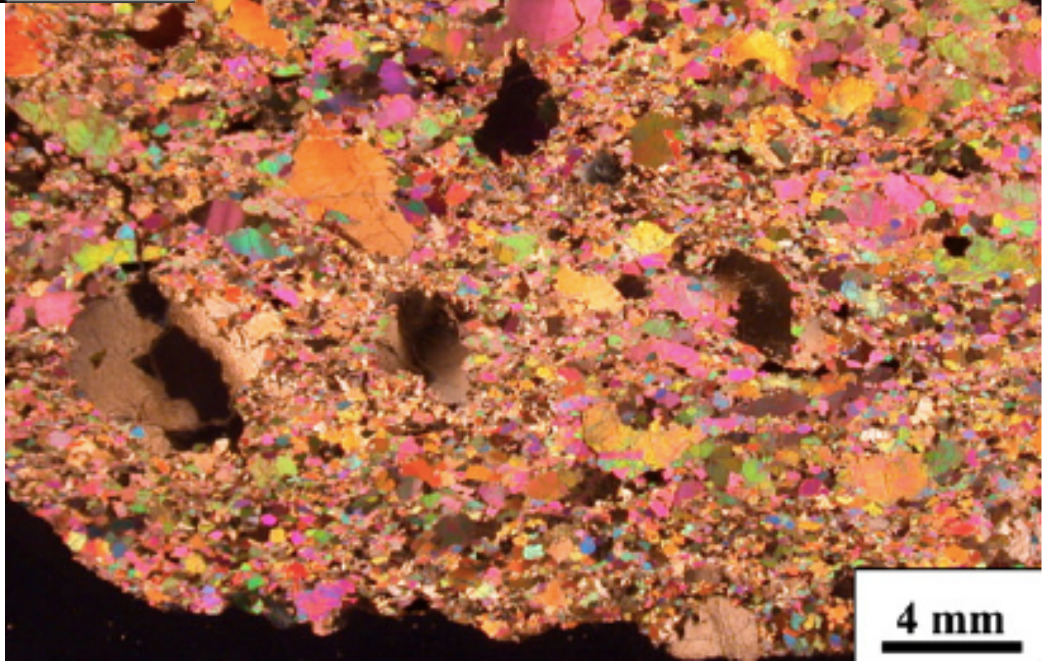
polycrystalline ice
in-situ deformation: pure shear
C. Wilson - Univ. Melbourne, Australia

Recrystallization

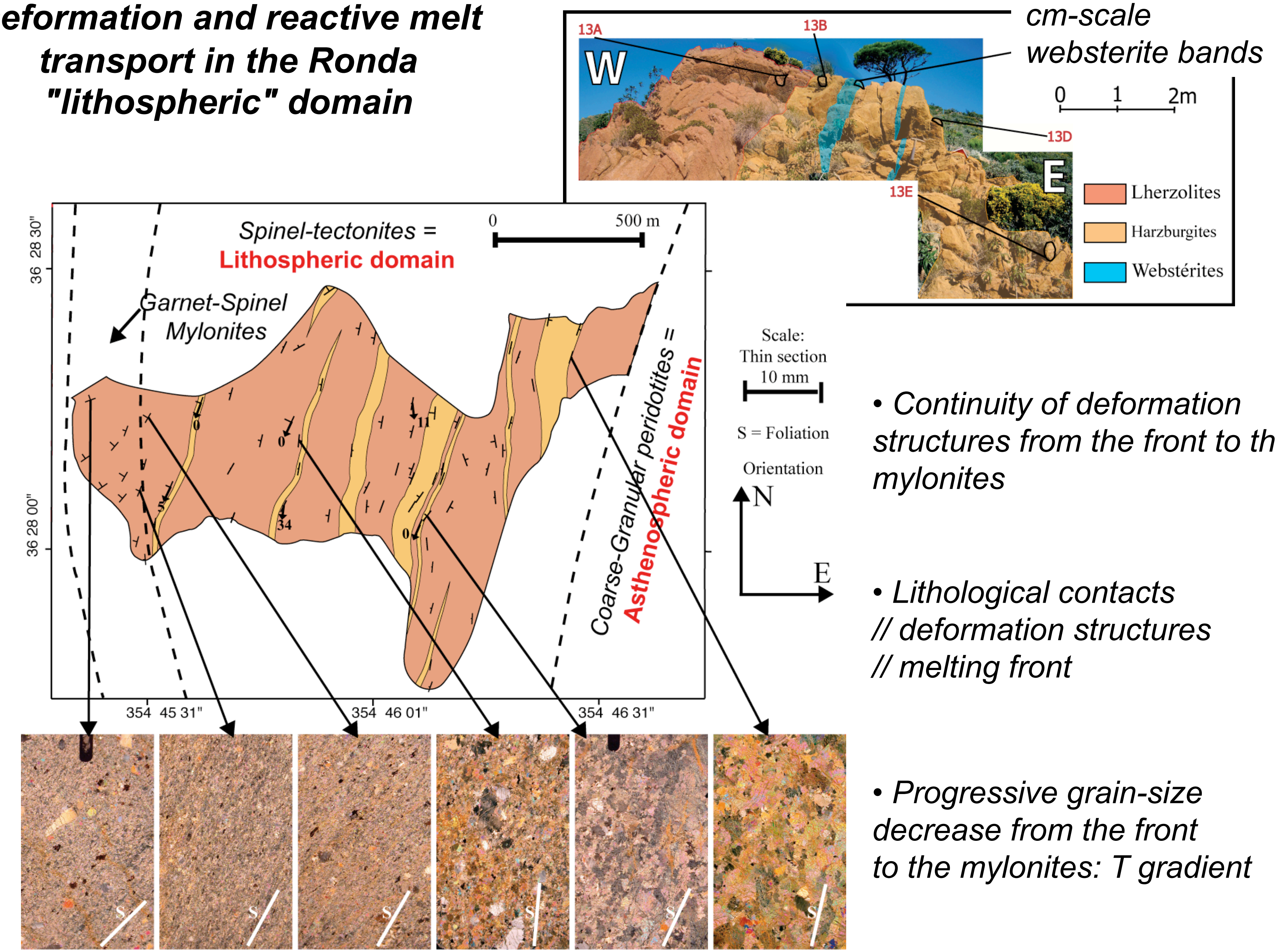
- ➢ *grain refinement*



stress ↗
T ↘ or strain rate ↗

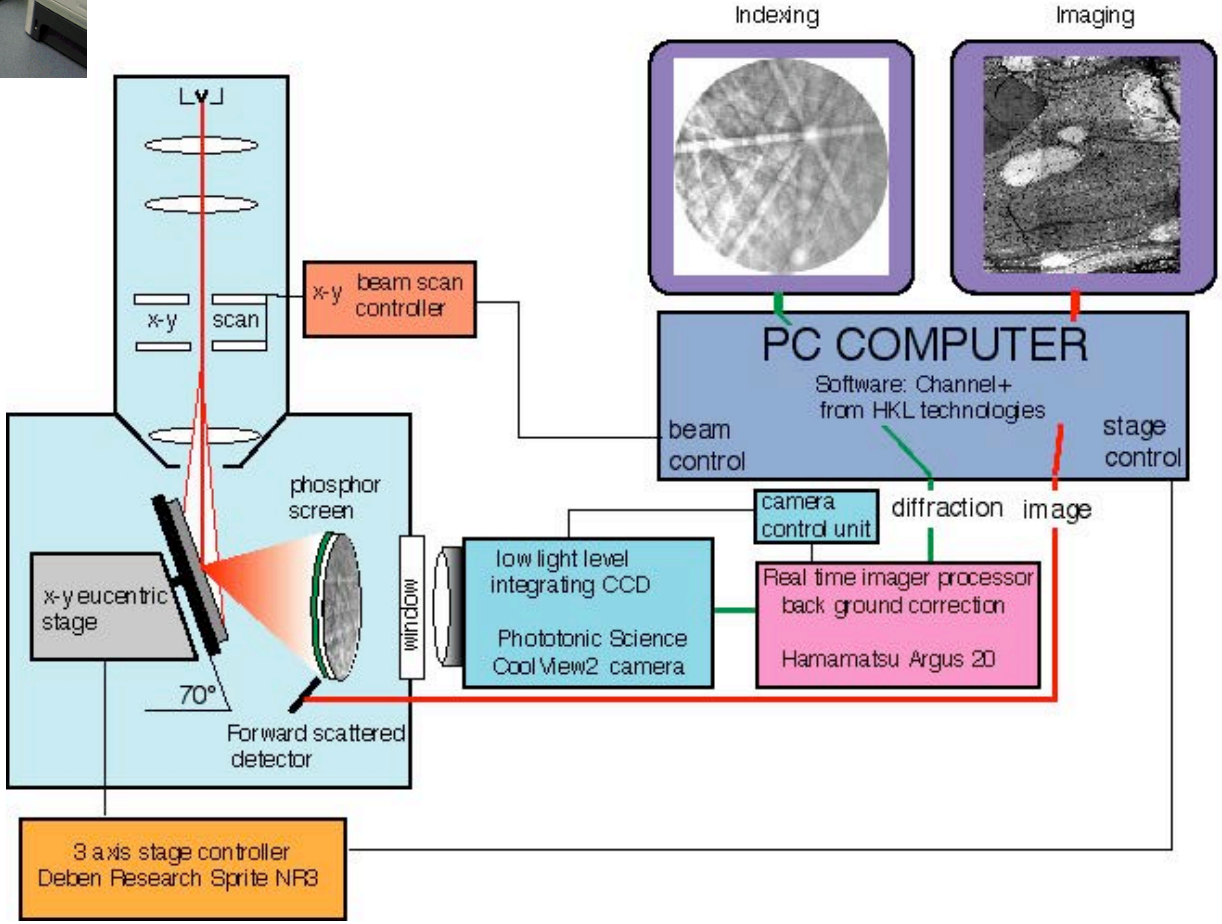


Deformation and reactive melt transport in the Ronda "lithospheric" domain

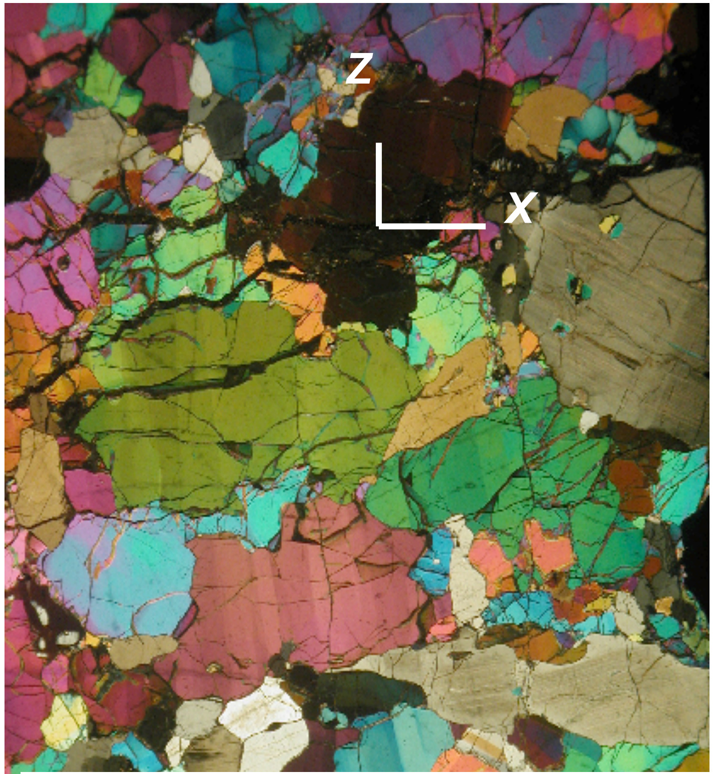


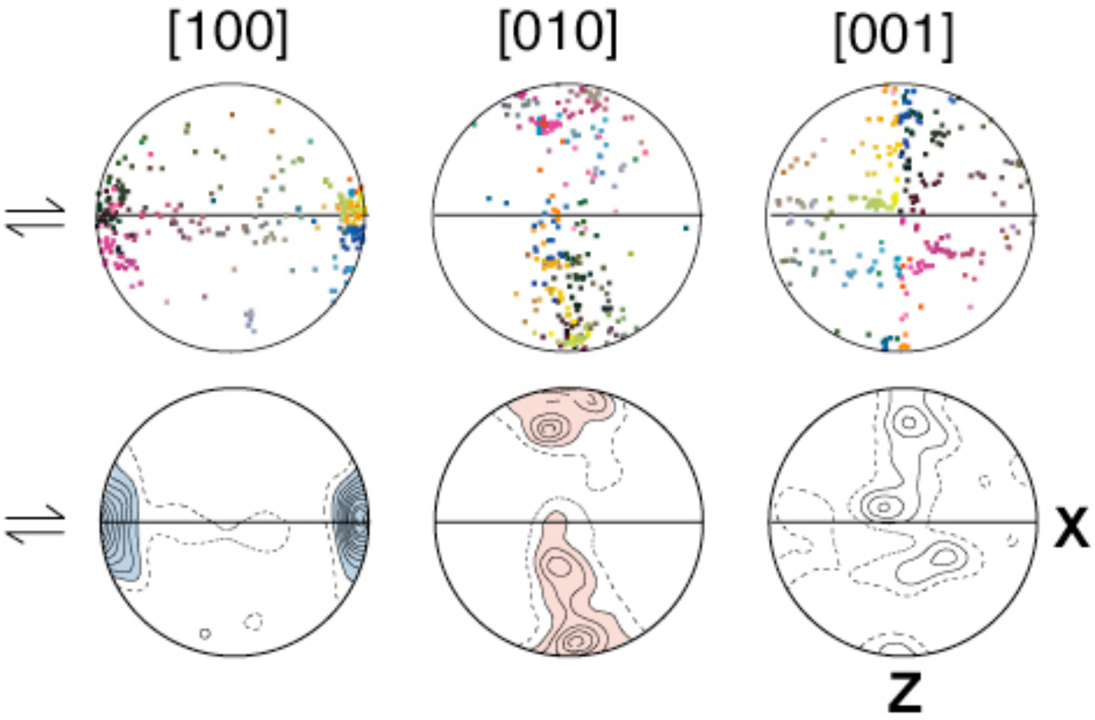
- *Continuity of deformation structures from the front to the mylonites*
- *Lithological contacts // deformation structures // melting front*
- *Progressive grain-size decrease from the front to the mylonites: T gradient*

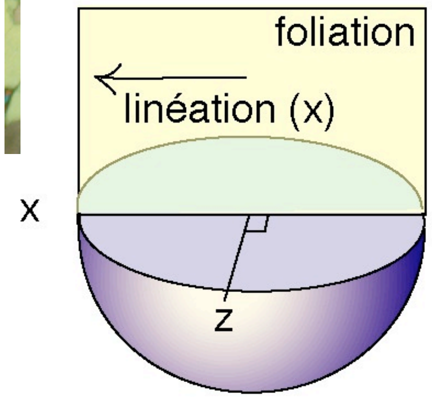
Measuring Crystal Preferred Orientations (CPO) by indexation of Electron BackScatered Diffraction (EBSD) patterns

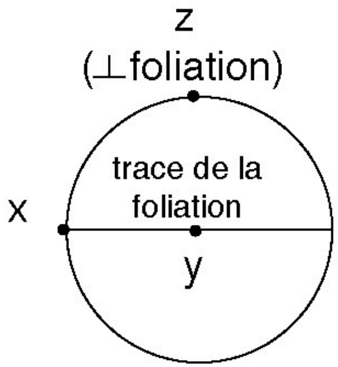


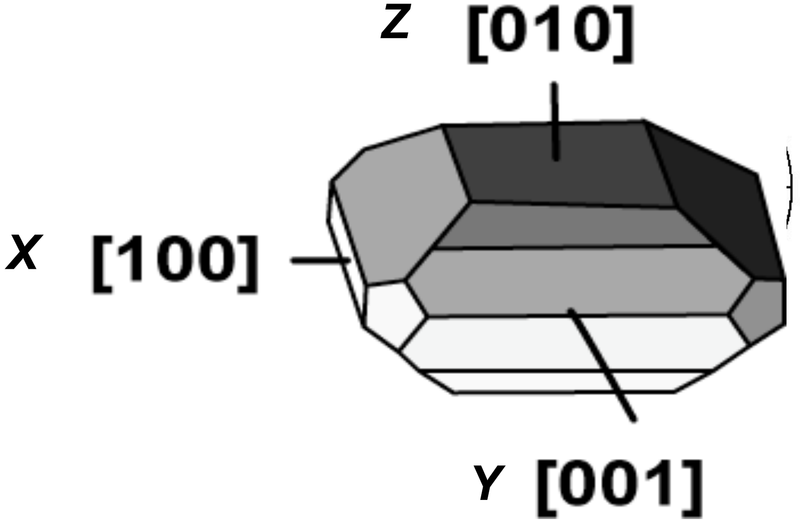
HT, low stress deformation: lherzolite, Tahiti



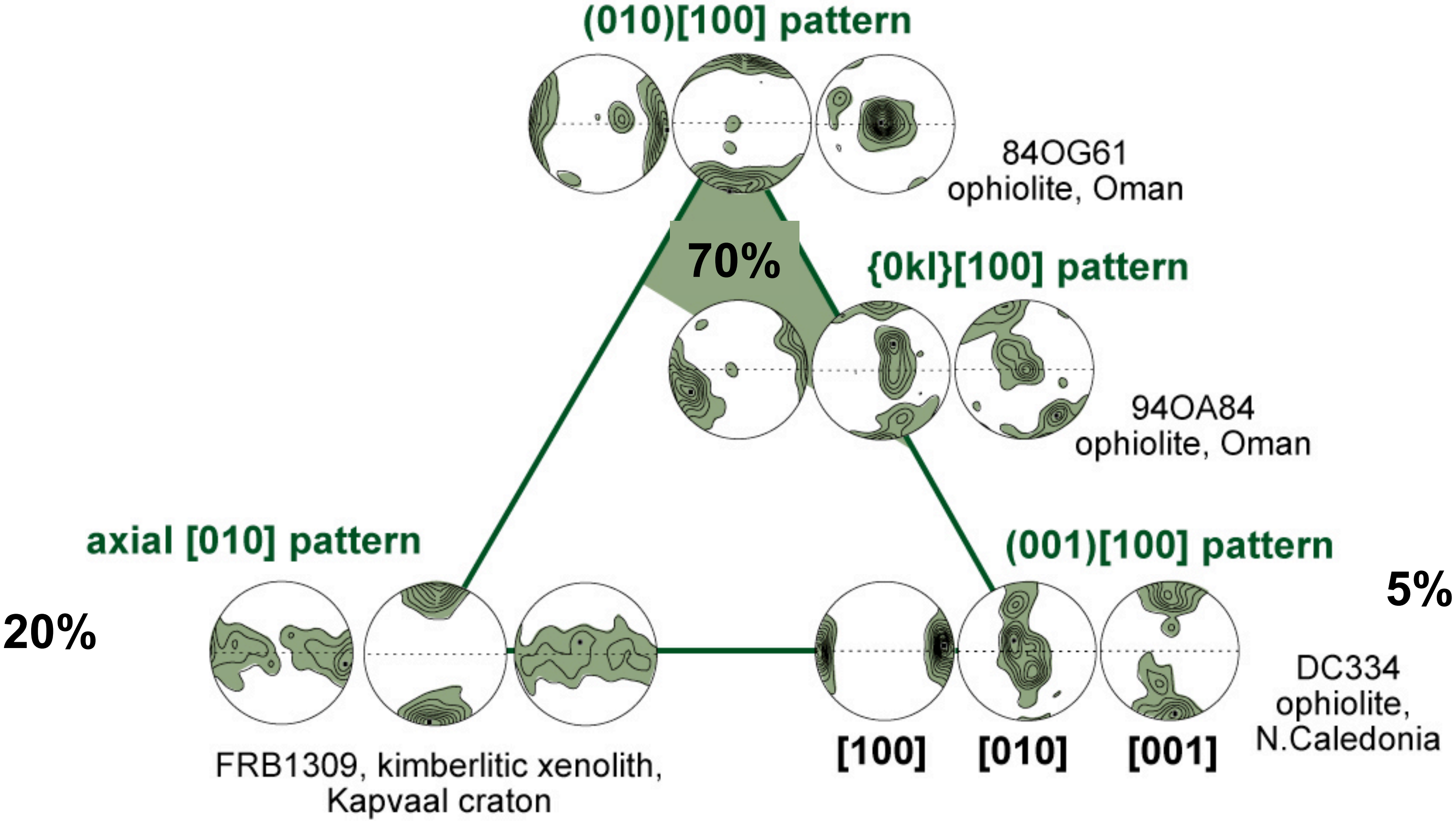








olivine database: >200 samples 3 textural end-members



(010)[100] pattern

84OG61
ophiolite, Oman

70%

{0kl}[100] pattern

94OA84
ophiolite, Oman

axial [010] pattern

20%

FRB1309, kimberlitic xenolith,
Kapvaal craton

(001)[100] pattern

5%

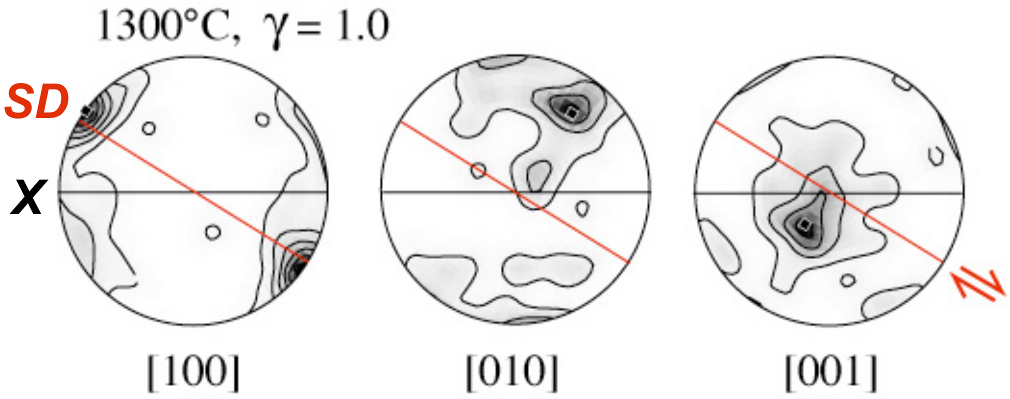
[100] [010] [001]

DC334
ophiolite,
N.Caledonia

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

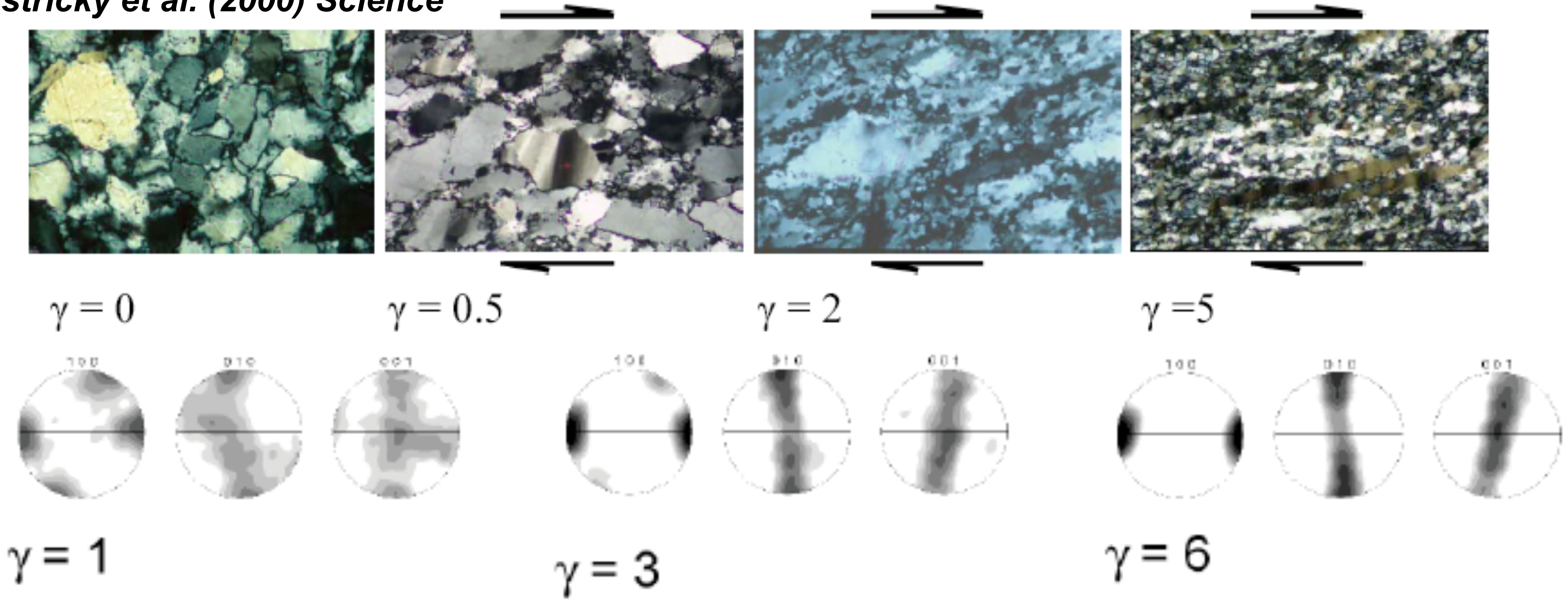
HT-LP experimental deformation: simple shear

Zhang & Karato (1995) Nature

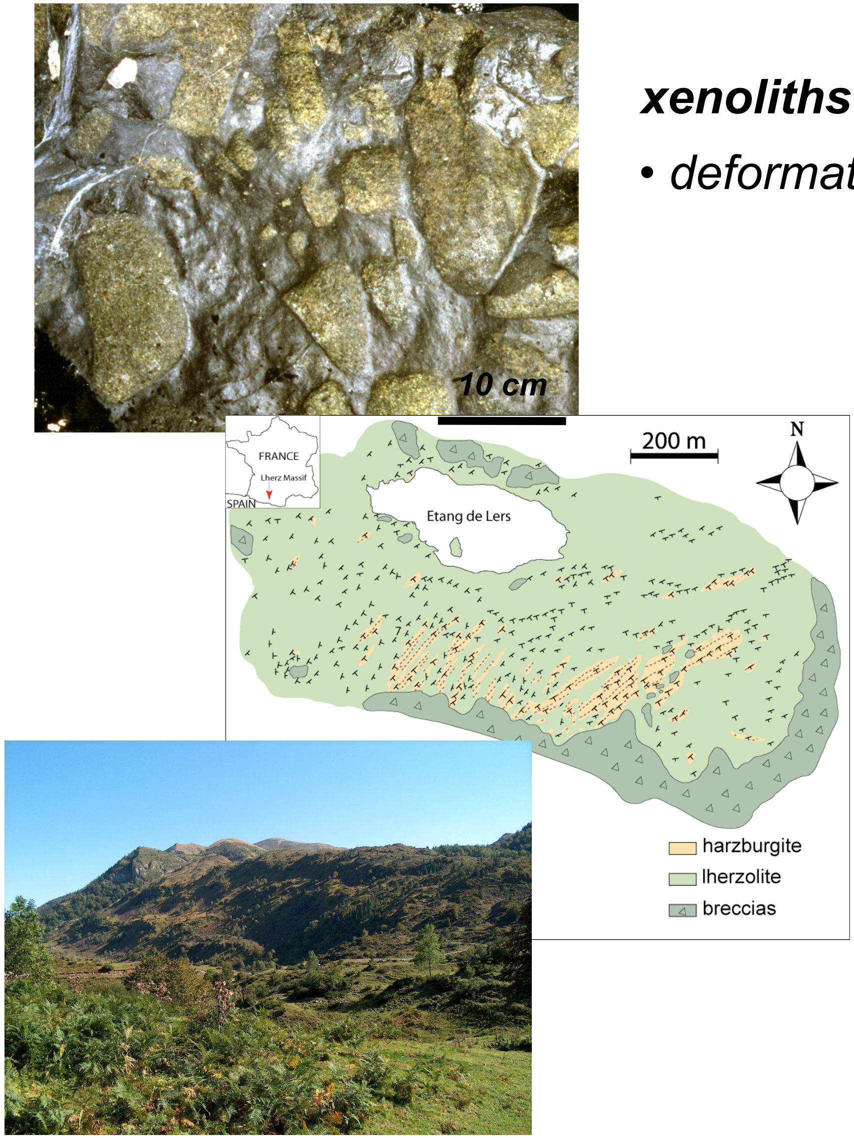


dominant slip direction : [100]
// shear direction
&
dominant slip plane : (010)
// shear plane

Bystricky et al. (2000) Science



How can we "see" the mantle deformation?



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peridotite massifs : m to 10s of km scale

- *deformation repartition, strain localization...*
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- ***"small" pieces extracted from the shallow mantle (<150 km):***
cannot be used to map mantle flow

✓ ***"in situ" indirect observations : seismic & conductivity anisotropy***

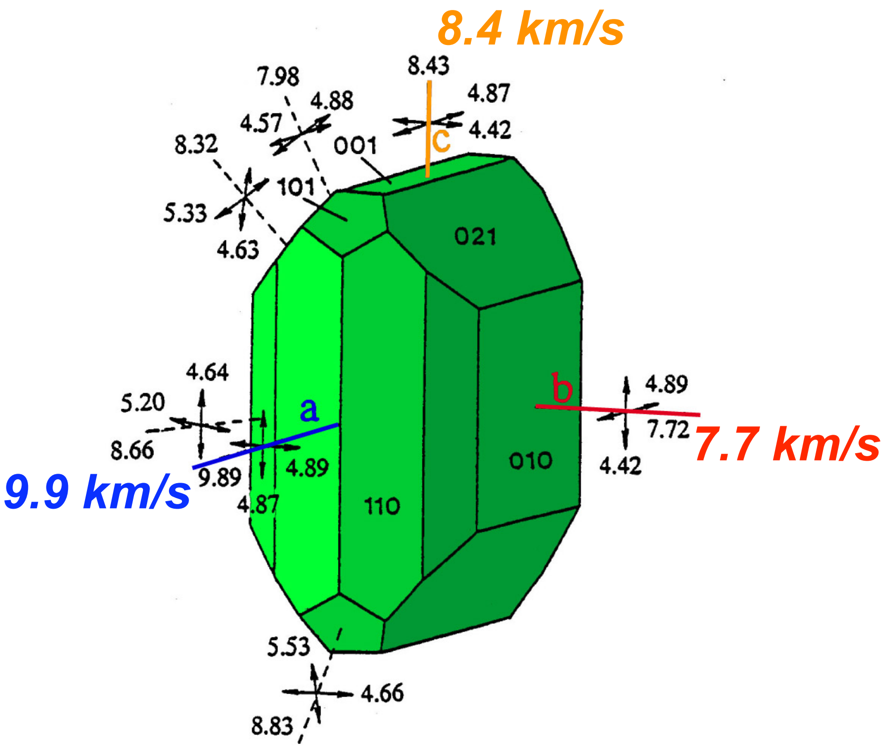
Seismic anisotropy = a tool to probe the mantle deformation

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

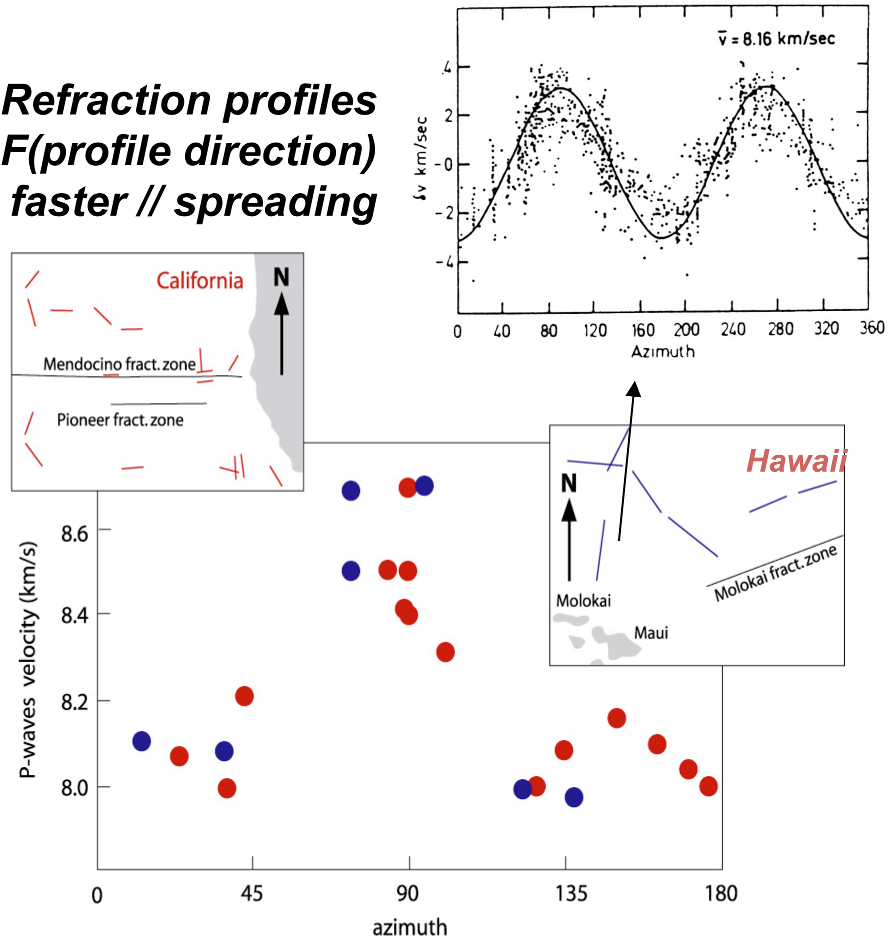
Seismic waves velocities vary as a function of:

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

Olivine cristal (μm-cm)



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



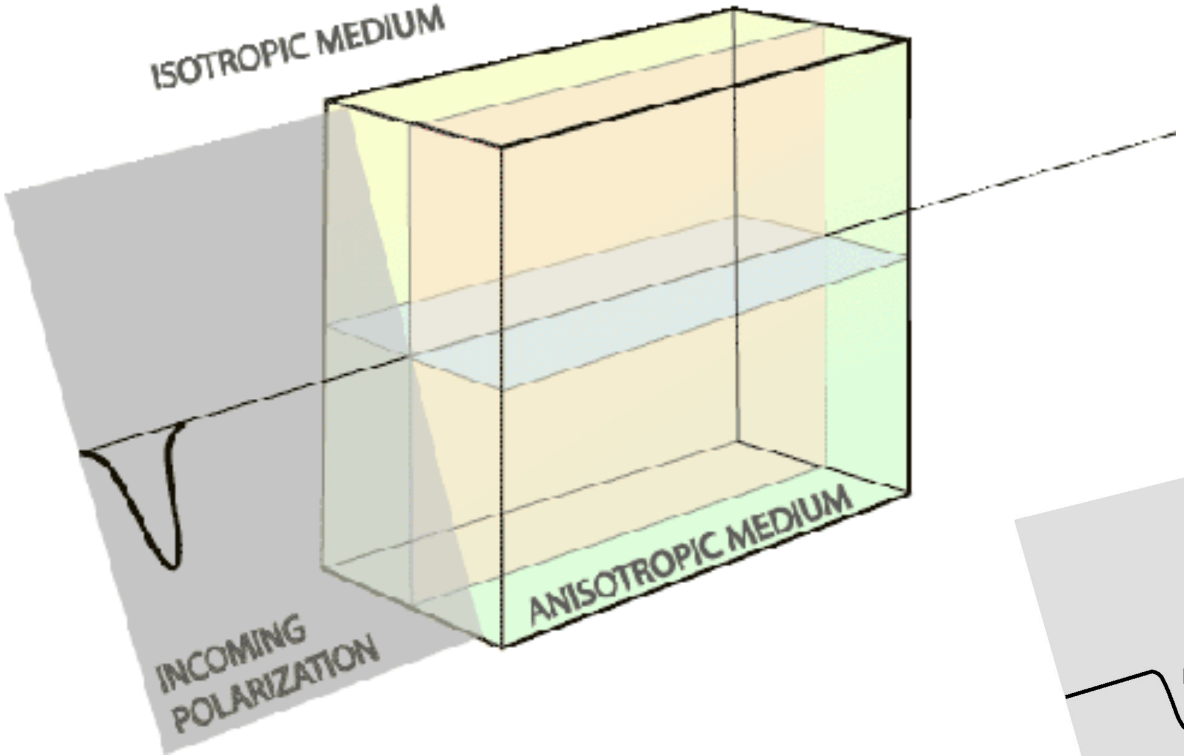
Hess (1964), Nature

P-waves azimuthal anisotropy (10s of km)

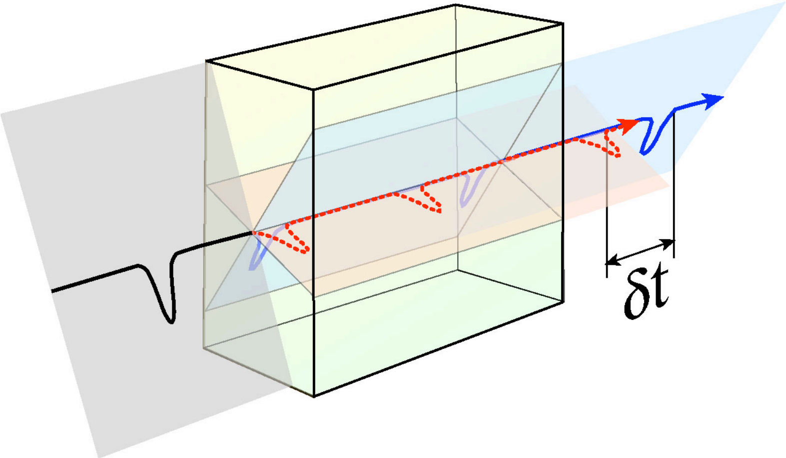
Seismic anisotropy

Seismic waves velocities vary as a function of:

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

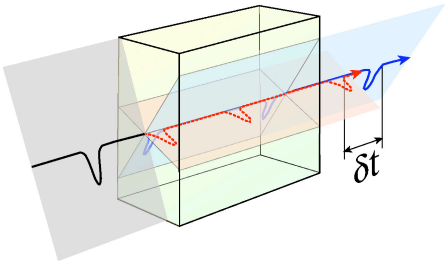


shear wave splitting

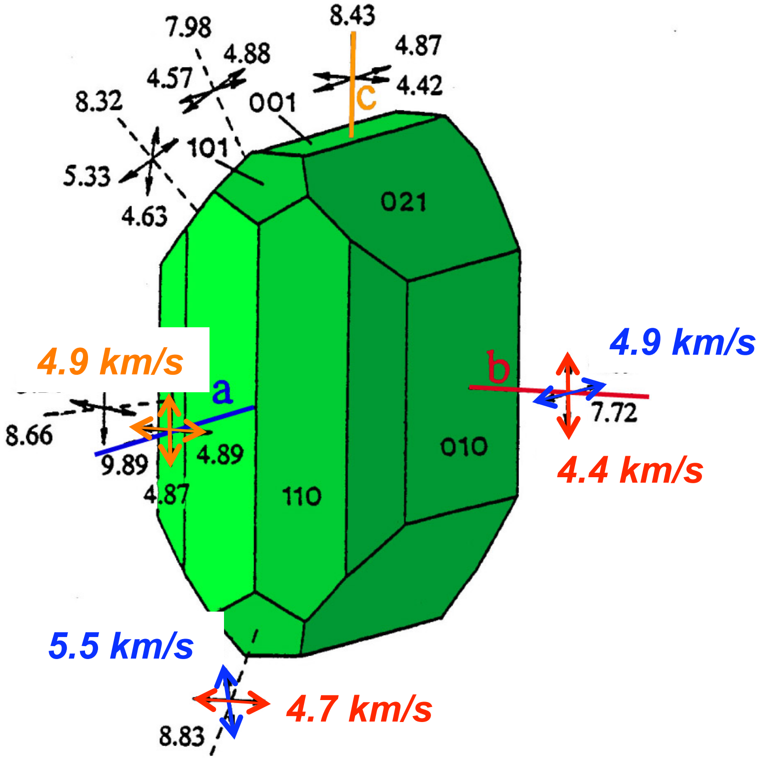


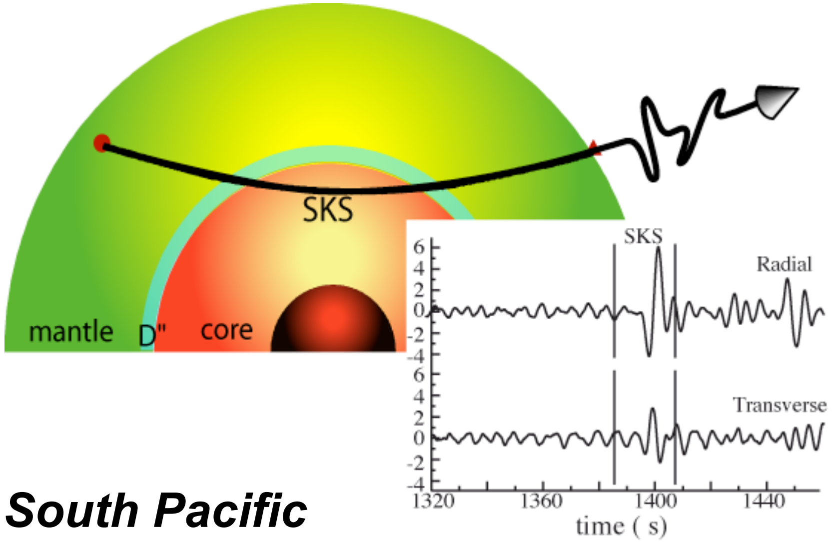
http://garnero.asu.edu

S waves polarization anisotropy - shear wave splitting

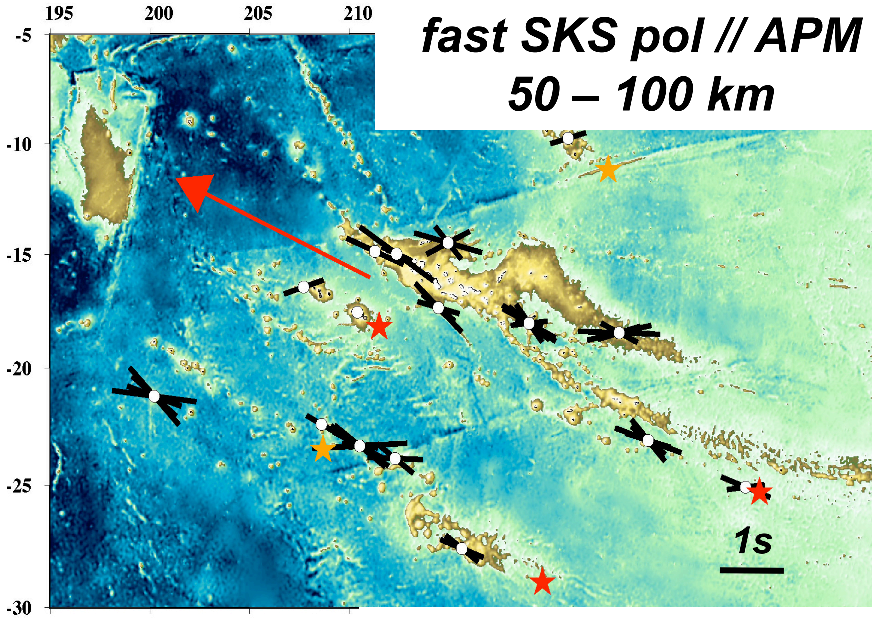


Olivine cristal (μm-cm)





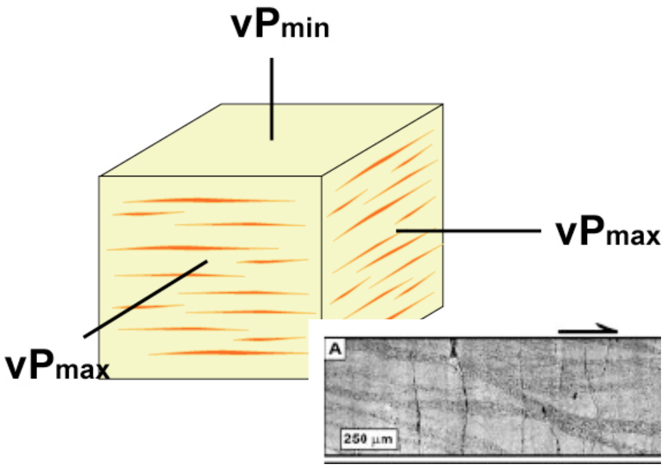
in the South Pacific



fast SKS pol // APM
50 – 100 km

Fontaine et al., GJI 2007

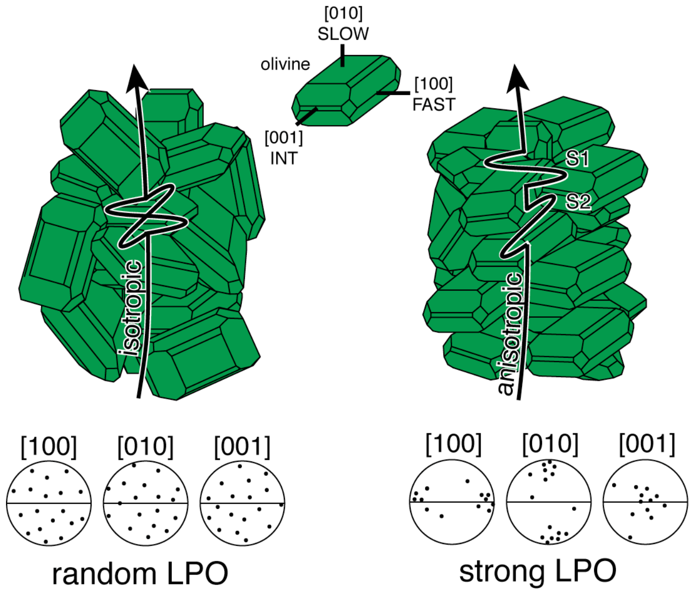
anisotropy results from



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” (?)*



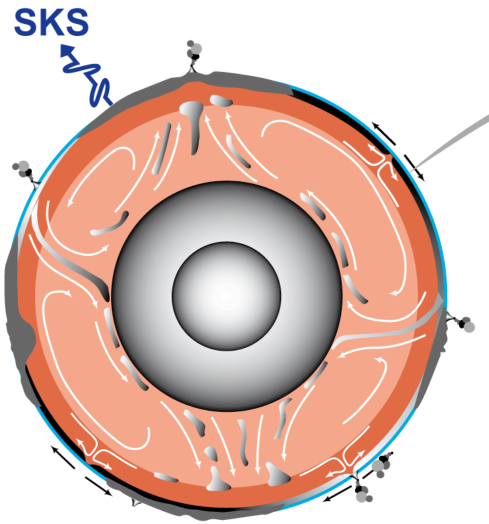
drawing by Luc Mehl

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

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

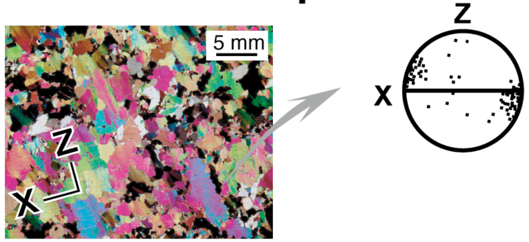
deformation plays an essential role in the development of anisotropy

How do we translate seismic anisotropy data into flow patterns?



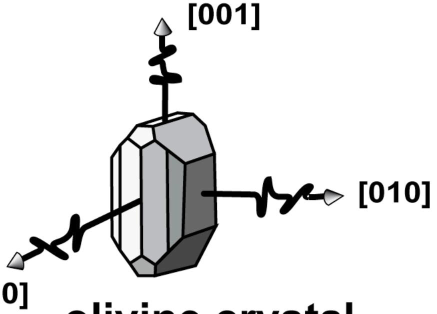
mantle flow

dislocation creep



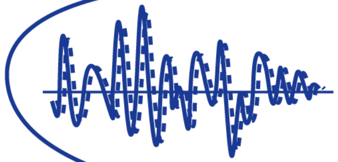
olivine
crystal
preferred
orientation

+

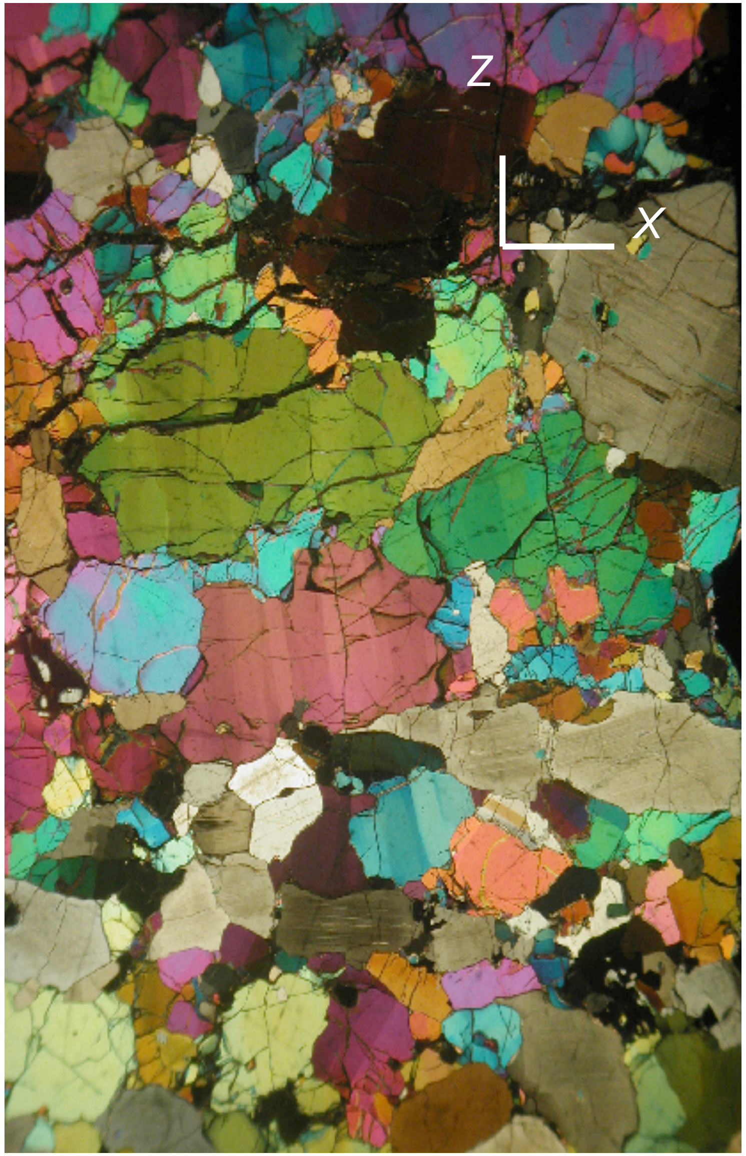


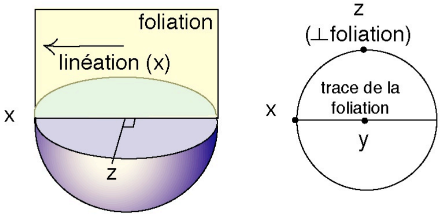
olivine crystal
anisotropy

=



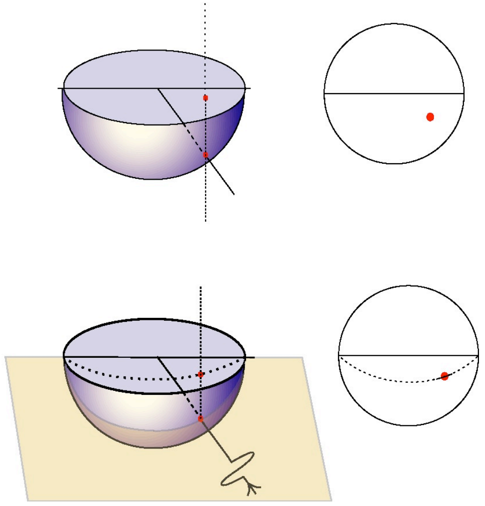
large-scale
seismic, mechanical
thermal & electrical
anisotropy
in the upper mantle

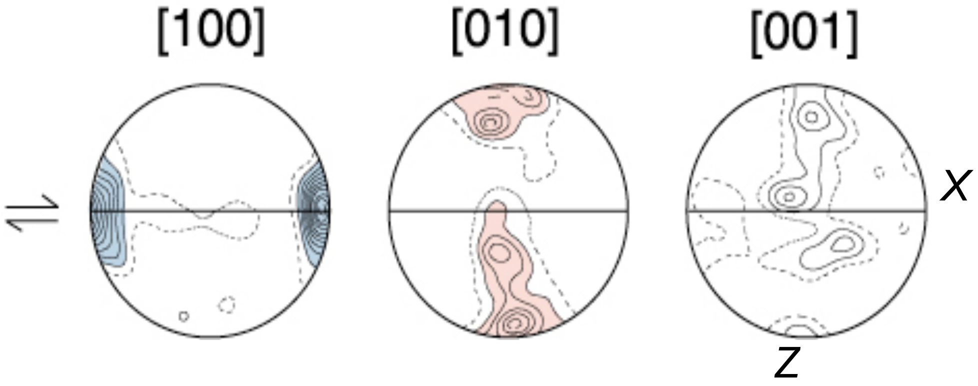


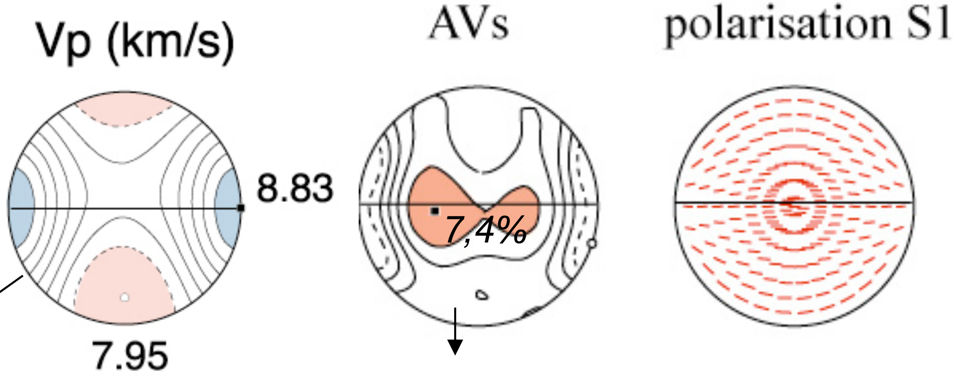


Foliation = Plan de fluage de la matière

linéation = direction de fluage de la matière






Vp (km/s)

AVs

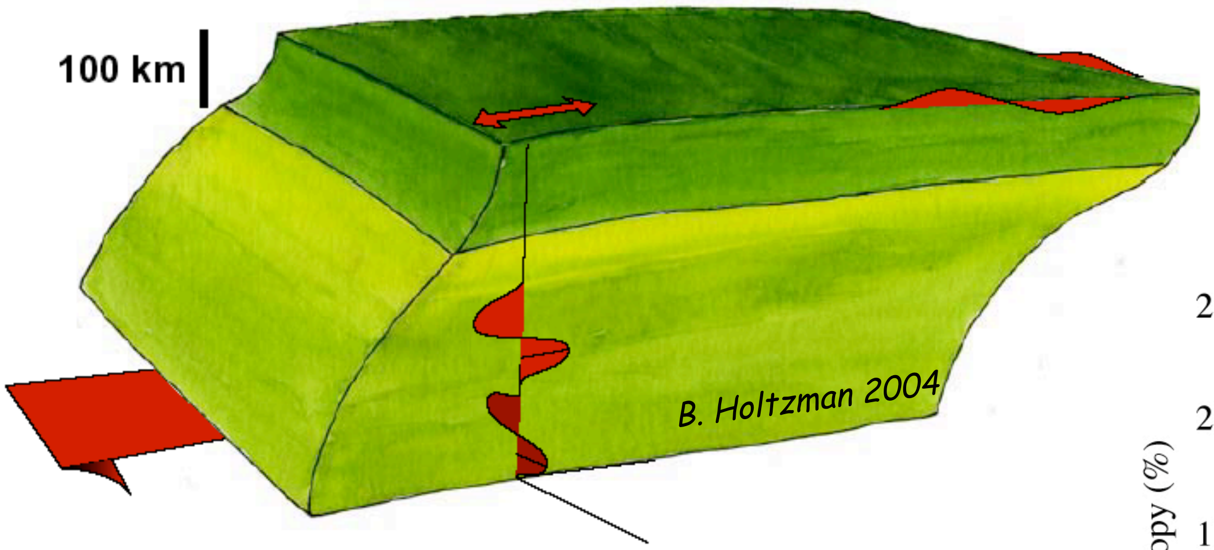
polarisation S1

P-wave velocity: F(propagation direction)

Amax=10%

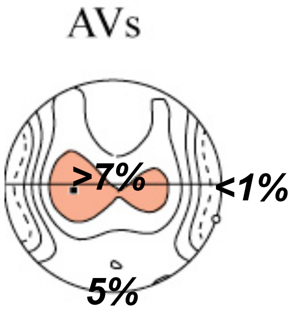
S-wave anis= (Vs1-Vs2)/Vsmean
Amax= 7.4%

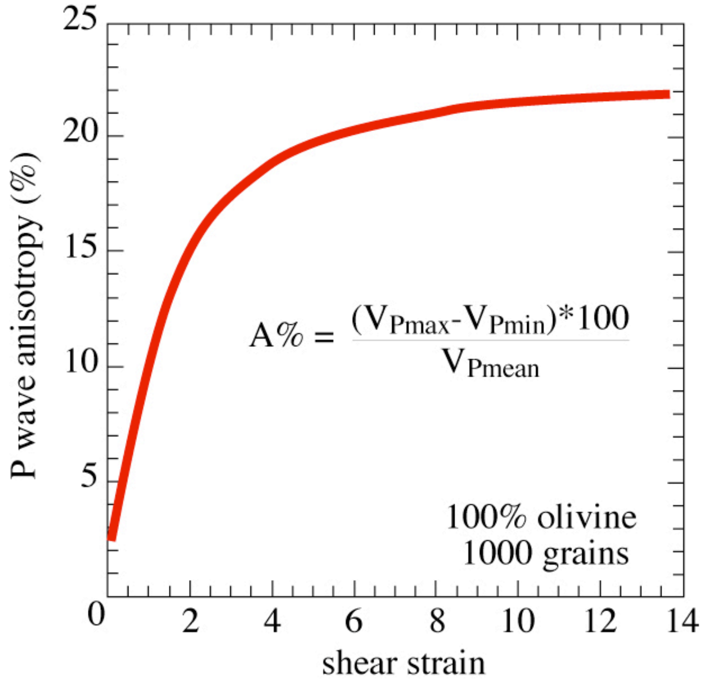
Simple key to qualitatively "read" seismic anisotropy observations in the SHALLOW MANTLE (>250 km):



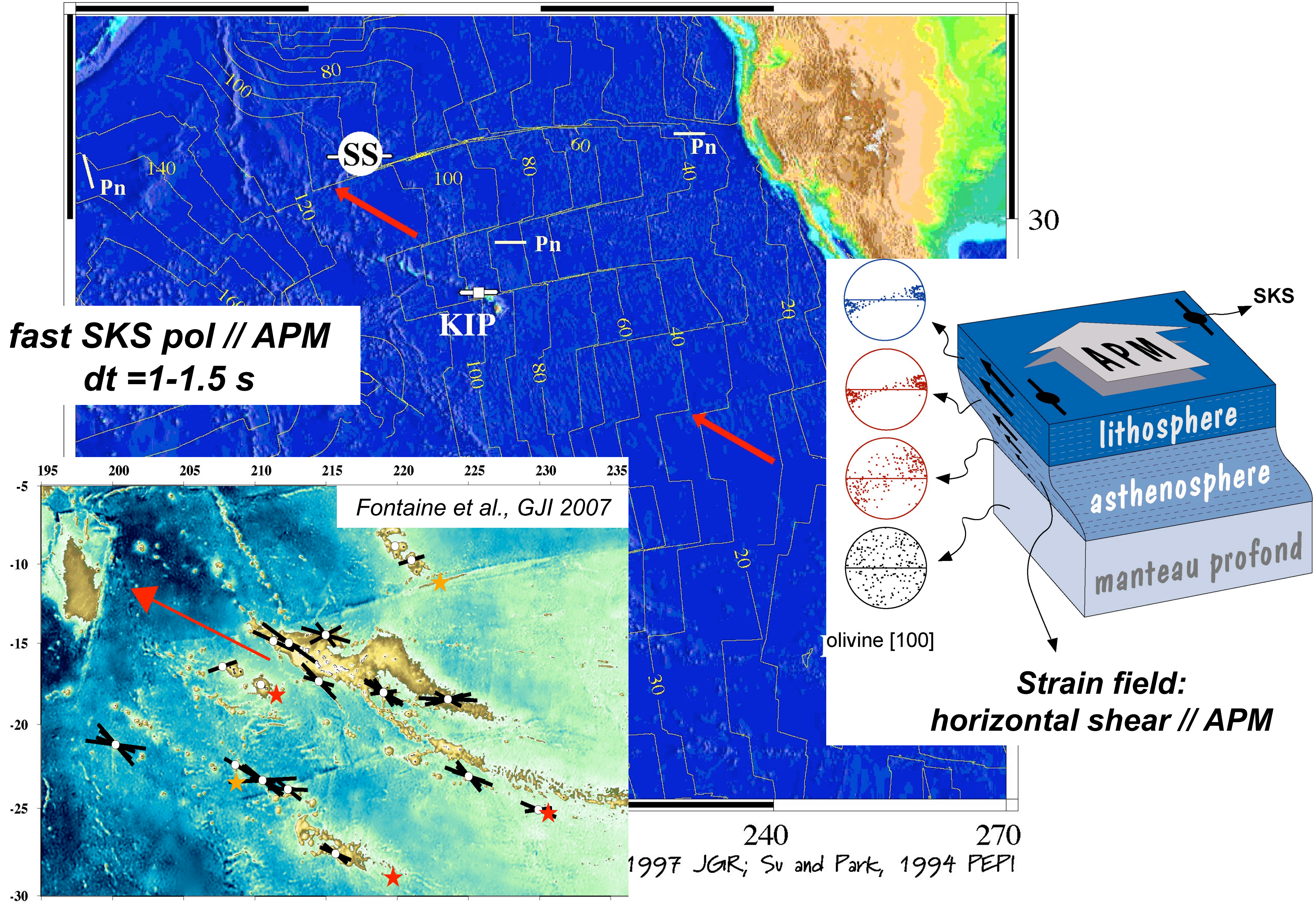
Fast direction of P & Rayleigh propagation, polarisation fast S-wave = flow direction

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





in oceanic domains: South Pacific



fast SKS pol // APM

dt =1-1.5 s

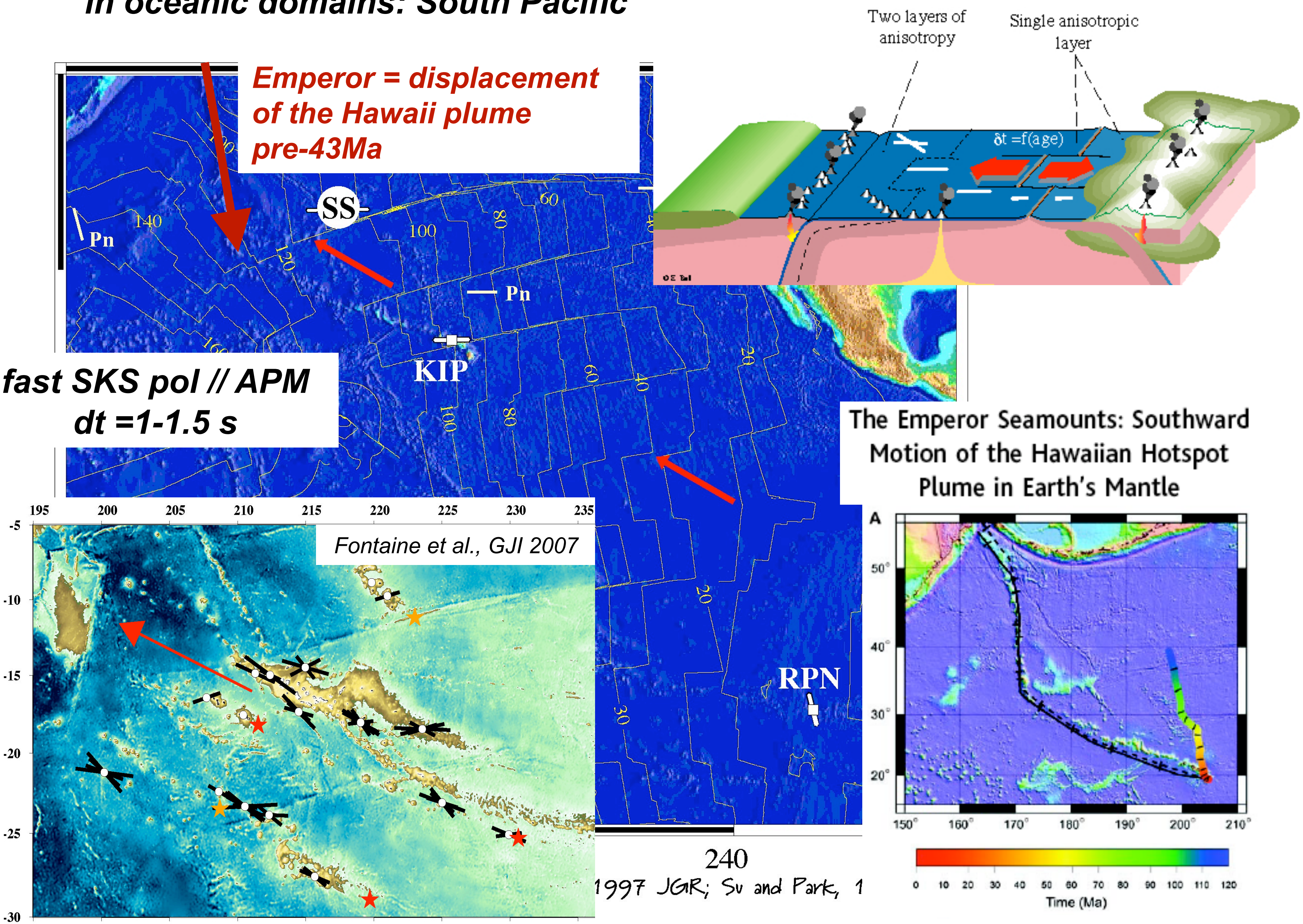
Fontaine et al., GJI 2007

1997 JGR; Su and Park, 1994 PEPI

Strain field:

horizontal shear // APM

in oceanic domains: South Pacific



Emperor = displacement of the Hawaii plume pre-43Ma

fast SKS pol // APM
dt =1-1.5 s

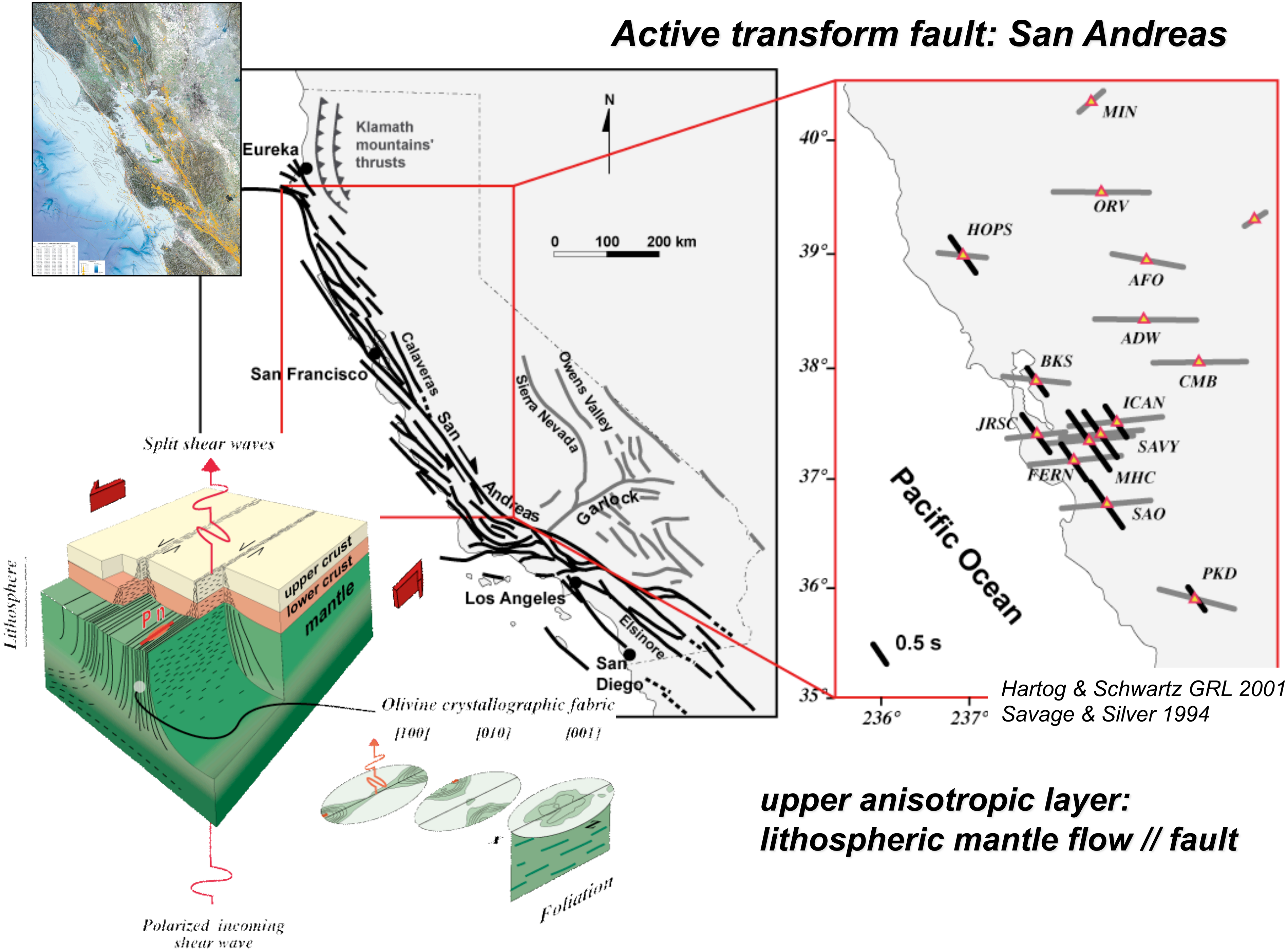
Fontaine et al., GJI 2007

1997 JGR; Sv and Park, 1

The Emperor Seamounts: Southward Motion of the Hawaiian Hotspot Plume in Earth's Mantle

Tarduno et al. Science 2003

Active transform fault: San Andreas



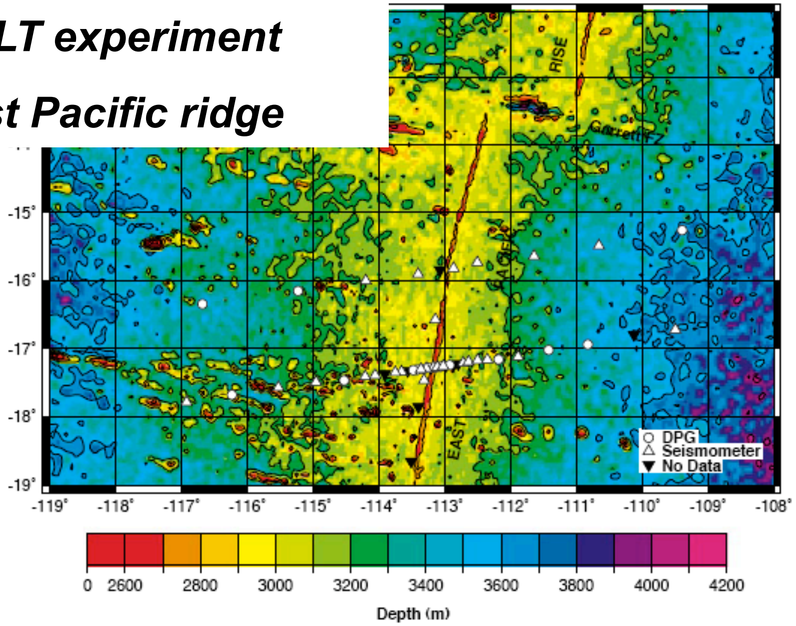
Hartog & Schwartz GRL 2001
Savage & Silver 1994

upper anisotropic layer:
lithospheric mantle flow // fault

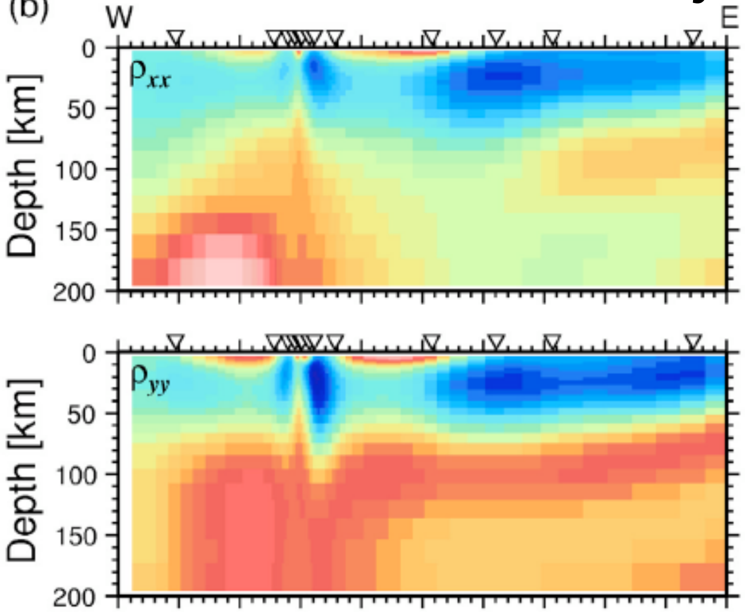
Electrical conductivity anisotropy inferred from long-period MT data: Another tool to map upper mantle deformation?

MELT experiment

East Pacific ridge



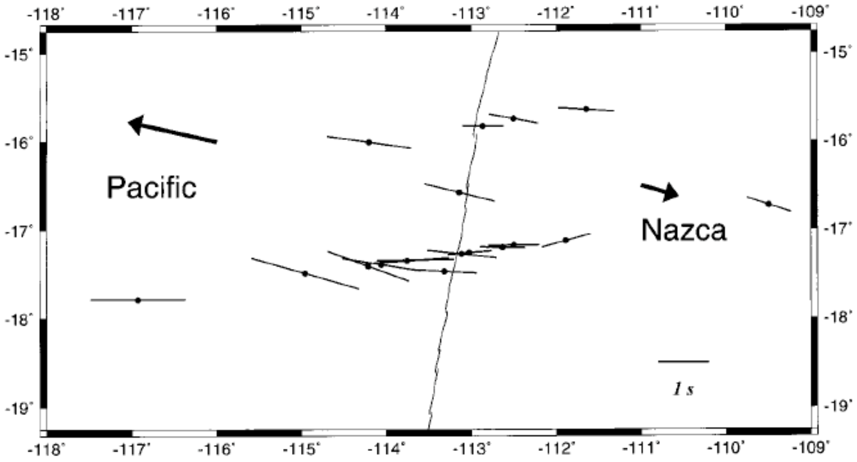
electrical conductivity



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

Baba et al. JGR 2006

SKS splitting



fast EC direction // fast SKS polarisation

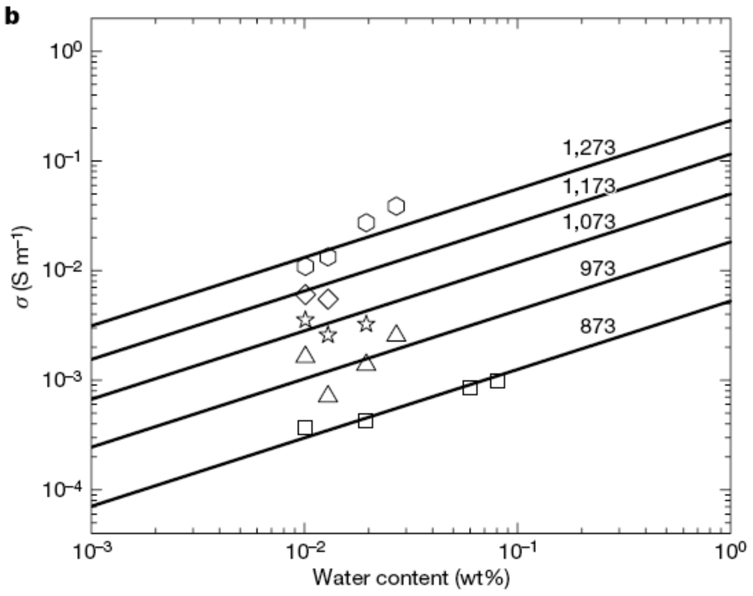
high conductivity & anisotropy below 60km
✓ EC anisotropy = faster H+ diffusion
// olivine [100]

Vol 443|26 October 2006|**doi:10.1038/nature05256** nature

LETTERS

The effect of water on the electrical conductivity of olivine

Duojun Wang[1,2,3], Mainak Mookherjee[3], Yousheng Xu[3,4] & Shun-ichiro Karato[3]

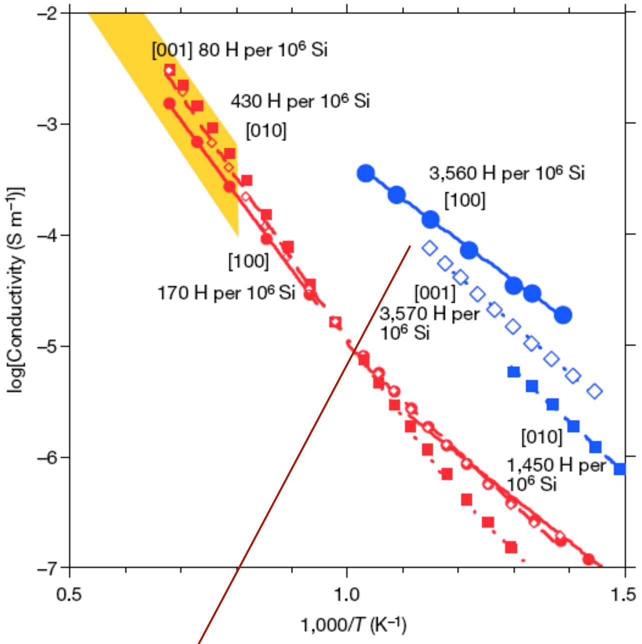


Vol 443|26 October 2006|**doi:10.1038/nature05223** nature

LETTERS

Hydrous olivine unable to account for conductivity anomaly at the top of the asthenosphere

Takashi Yoshino[1], Takuya Matsuzaki[1], Shigeru Yamashita[1] & Tomoo Katsura[1]

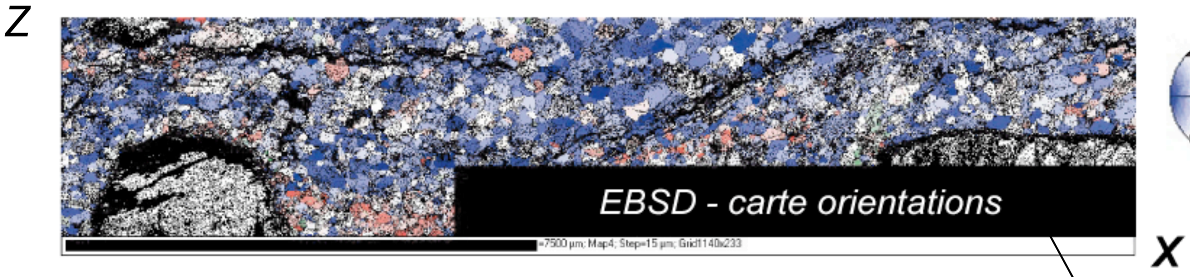


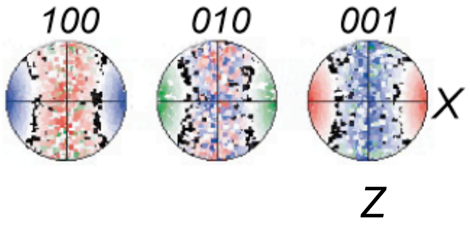
electrical conduction controlled by intracrystalline H+ diffusion in olivine

$$\boxed{\begin{array}{ll} D^{ol}_{[1\,0\,0]} \approx 10 \times D^{ol}_{[0\,0\,1]} \approx 100 \times D^{ol}_{[0\,1\,0]} & \text{(MK90)} \\ D^{ol}_{[1\,0\,0]} \approx 20 \times D^{ol}_{[0\,1\,0]} \approx 40 \times D^{ol}_{[0\,0\,1]} & \text{(MK98)} \end{array}}$$

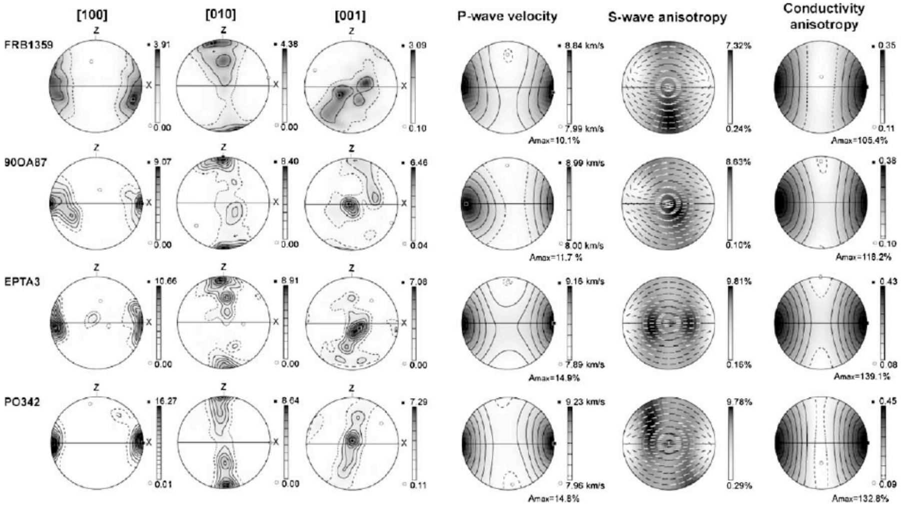
electrical conduction:
short range, "fast" diffusion
polaron migration process
Mackwell & Kohlstedt (1990)

3D FE modeling of anisotropic conduction (intracrystalline H+ diffusion) in a peridotite





$\sigma_x = 5 * \sigma_z$

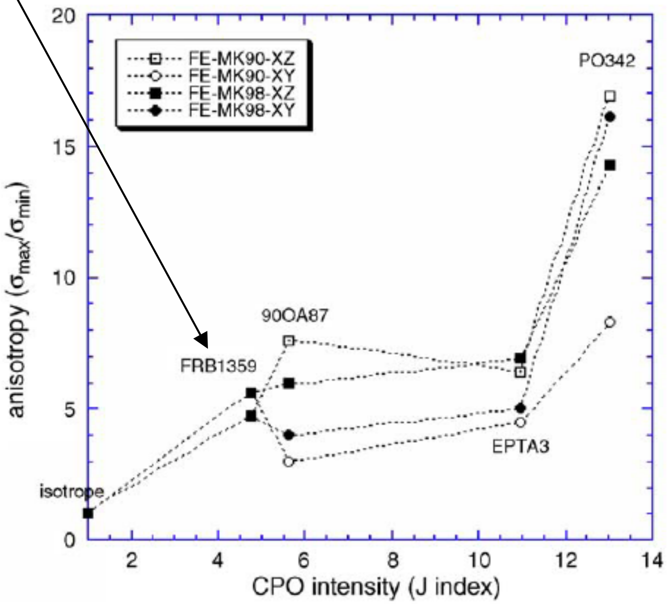


$\sigma_x = 3.2 * \sigma_z$

$\sigma_x = 3.8 * \sigma_z$

$\sigma_x = 5.4 * \sigma_z$

$\sigma_x = 5 * \sigma_z$

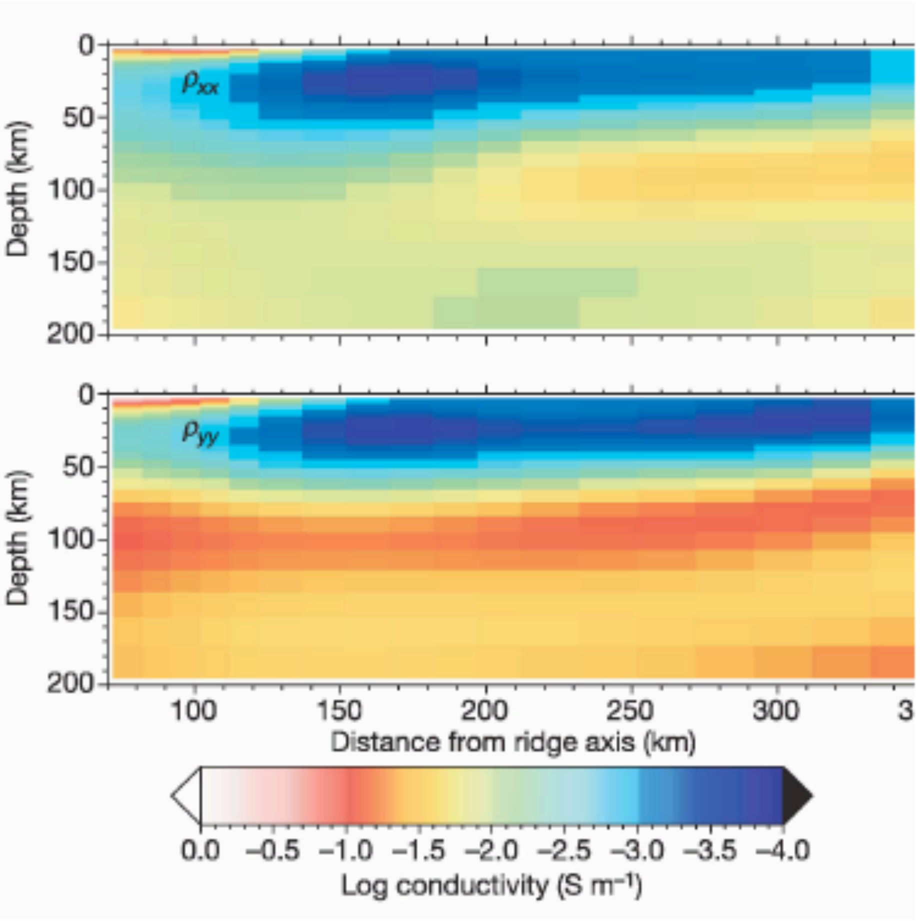


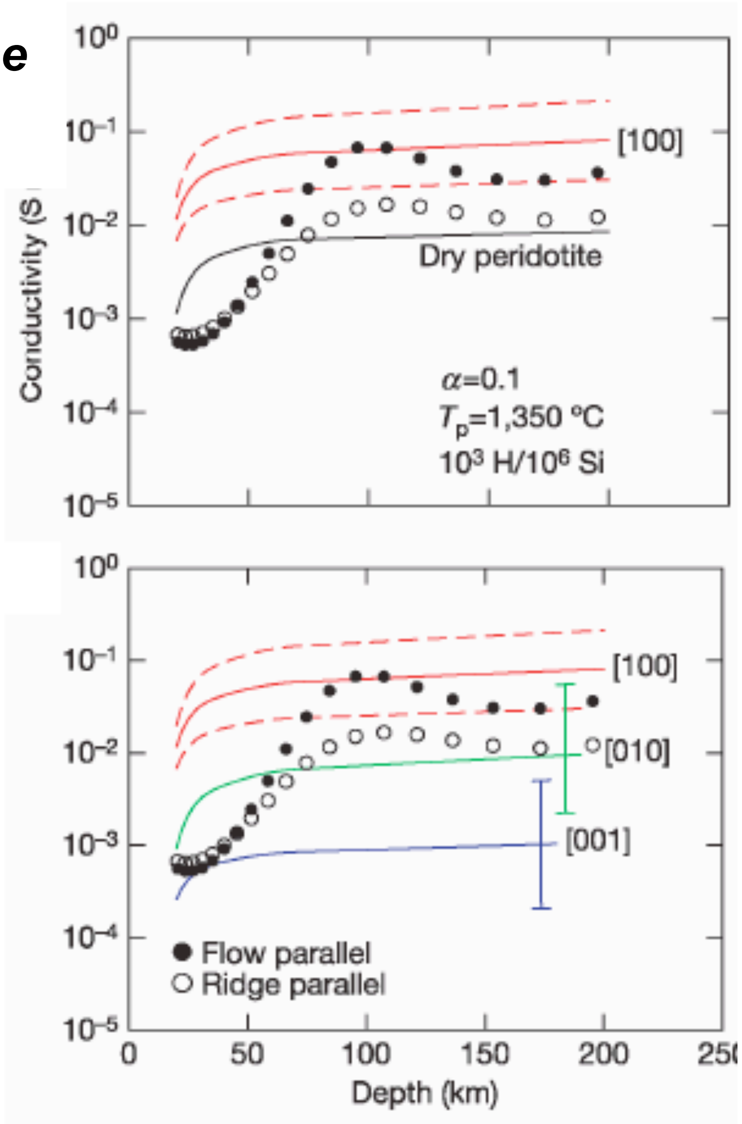
$$D^{\mathrm{ol}}_{[1\,0\,0]} \approx 10 \times D^{\mathrm{ol}}_{[0\,0\,1]} \approx 100 \times D^{\mathrm{ol}}_{[0\,1\,0]} \quad \text{(MK90)}$$

$$D^{\mathrm{ol}}_{[1\,0\,0]} \approx 20 \times D^{\mathrm{ol}}_{[0\,1\,0]} \approx 40 \times D^{\mathrm{ol}}_{[0\,0\,1]} \quad \text{(MK98)}.$$

Gatzemeier & Tommasi PEPI 2006

The MELT experiment:
electrical conductivity @ East Pacific Rise





conductivity // spreading direction
*= 5 * conductivity // ridge*

Baba et al. JGR 2006

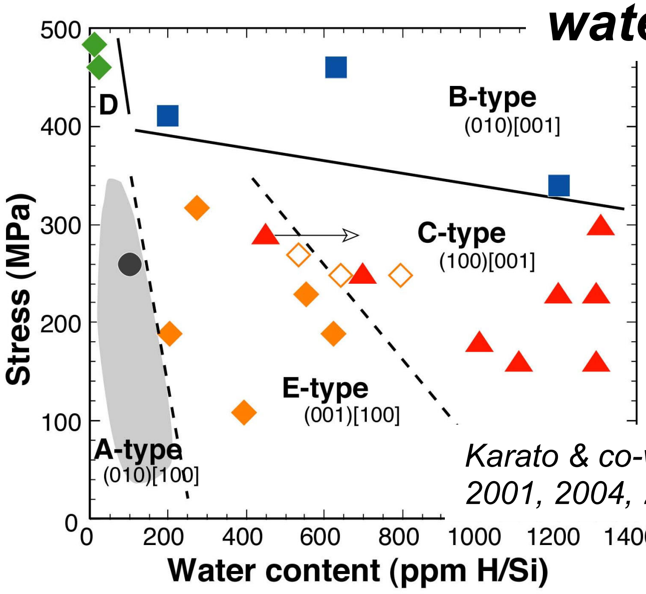
Deformation and anisotropy in the upper mantle :
XXI century observations & experimental results

effect of fluids (water and melt) and pressure on the relation between deformation & anisotropy :

- *change in deformation mechanisms:*
  ≠ CPO

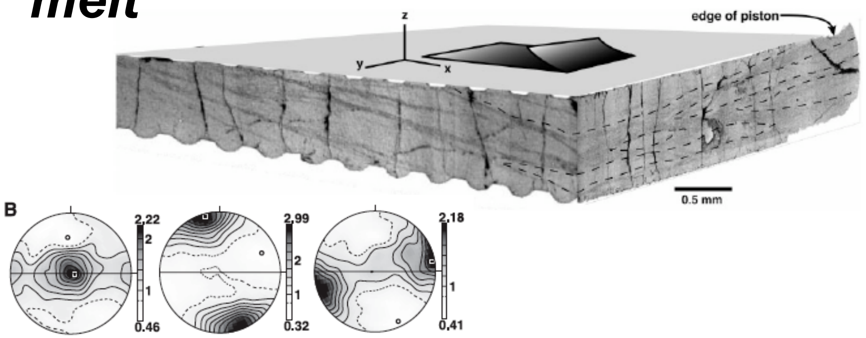
✓ fast anisotropy directions normal to the shear direction

water



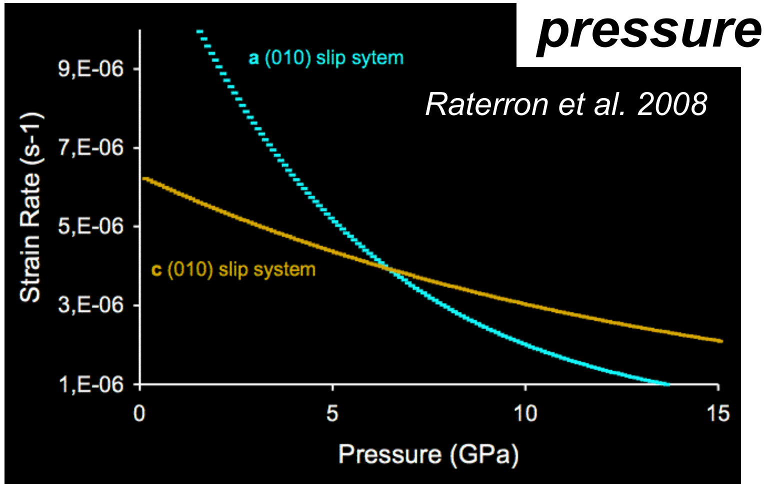
Karato & co-workers 2001, 2004, 2006 ....

melt



Holtzman et al. Science 2003

pressure



Raterron et al. 2008

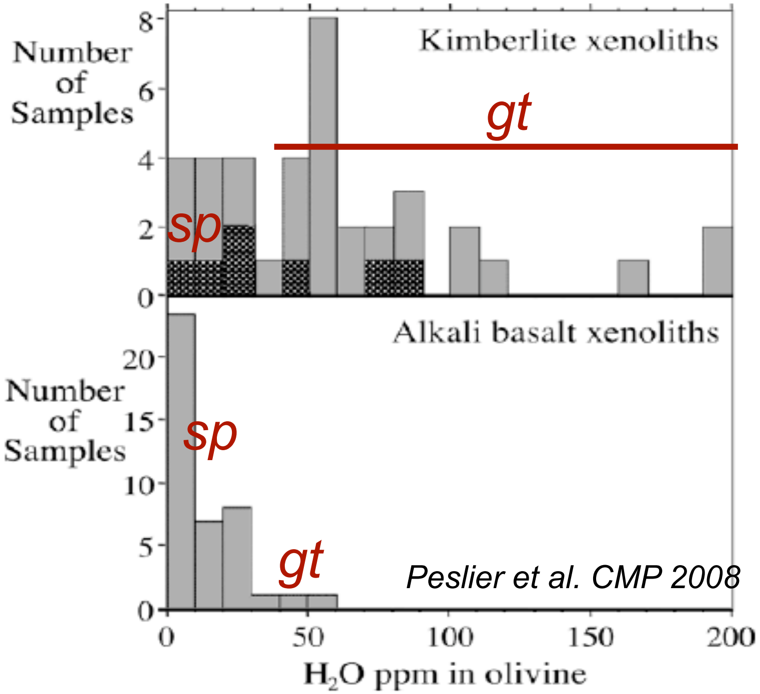
+ Couvy et al. EMJ 2005, Mainprice et al. Nature 2005

effect of water on olivine deformation
= fast anisotropy directions normal to the shear direction

but:

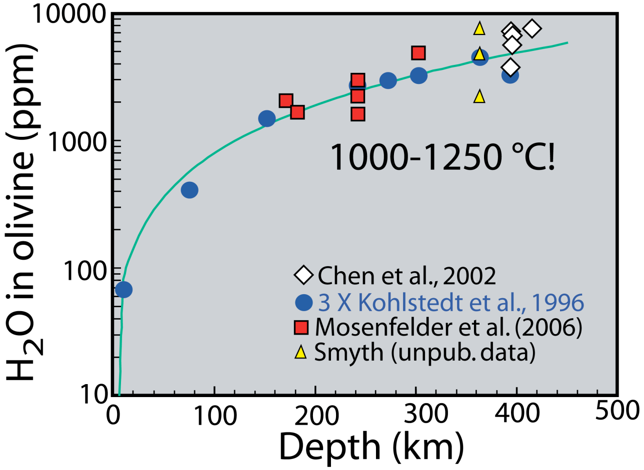
- *partial melting (H+ incompatible)*
- *water solubility in olivine ➘ P ➘*

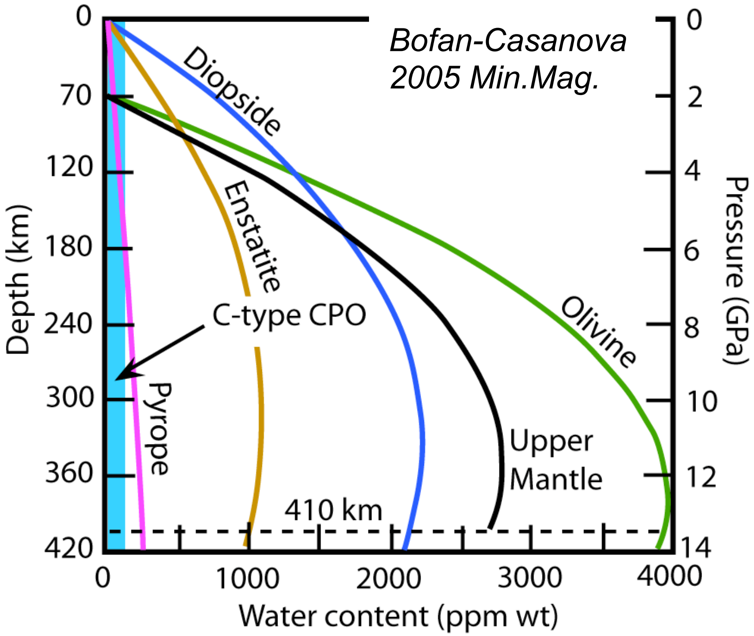
➢ *low water contents in olivine in the shallow mantle*



Peslier et al. CMP 2008

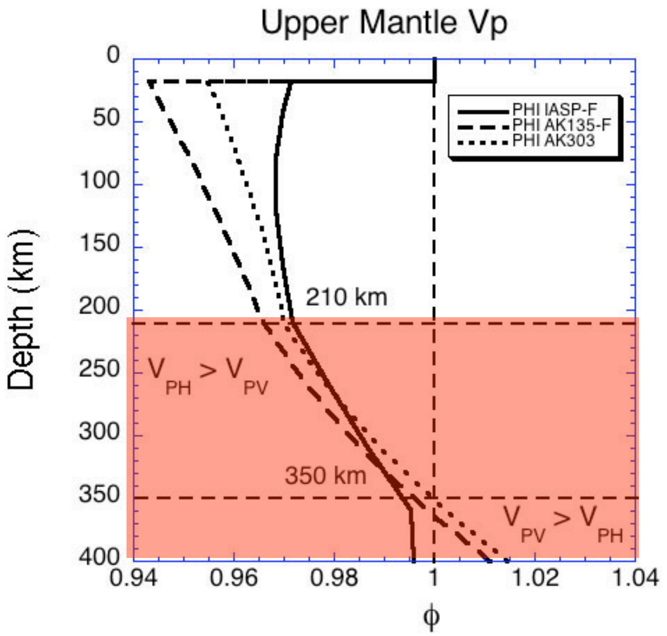
Hirschmann et al. 2005 EPSL

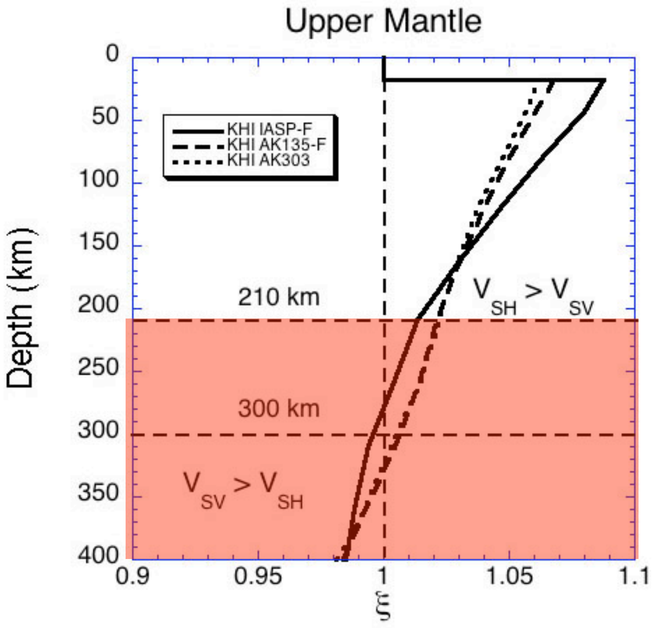




Bofan-Casanova 2005 Min.Mag.

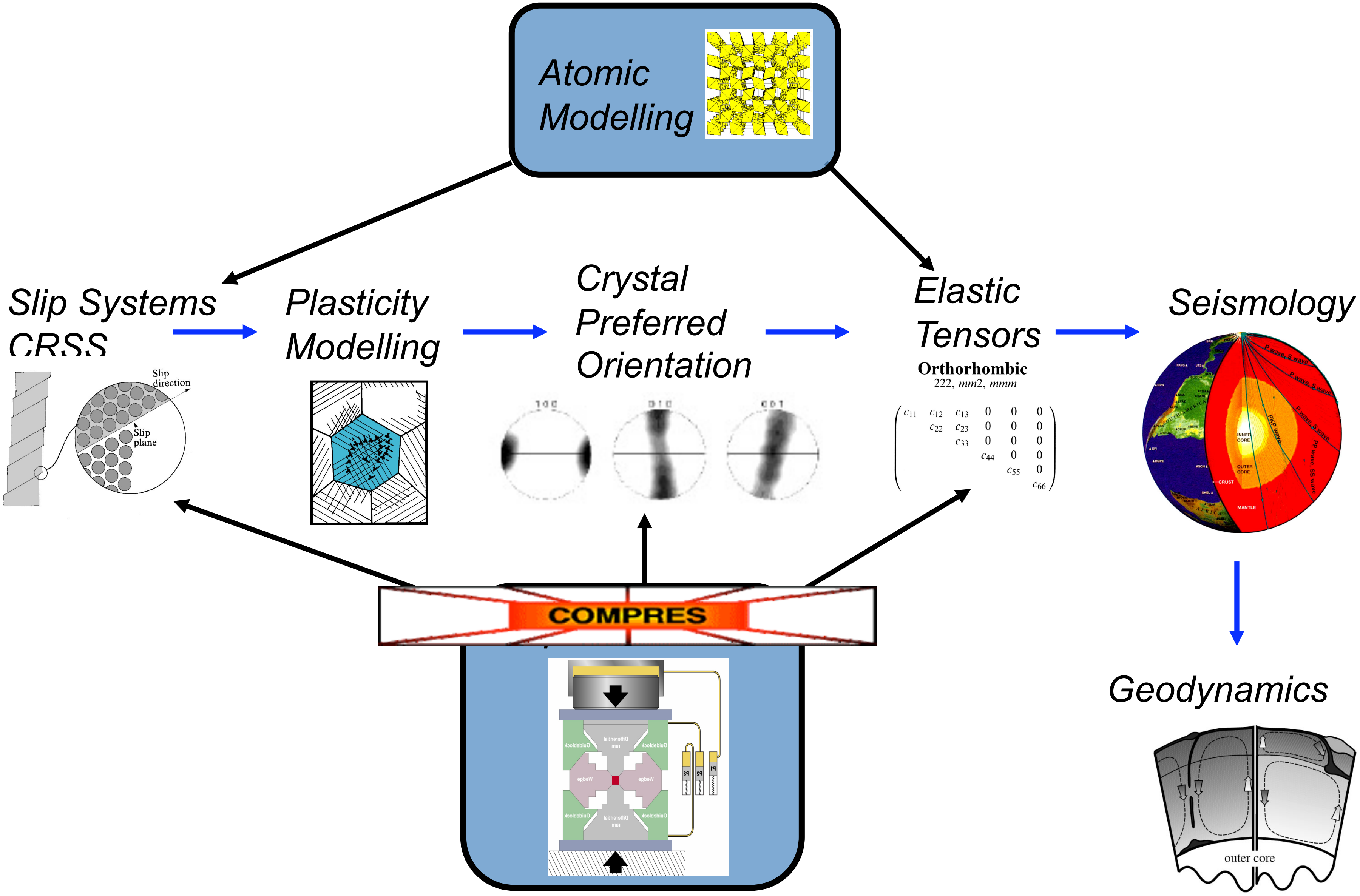
Fast decrease in anisotropy at the bottom of the upper mantle - 200 to 400 km





Transition from dislocation to diffusion creep
(no CPO -> no seismic anisotropy)
or
transition from [100] slip to [001] slip at HP?

Deformation & anisotropy in the deep mantle



Atomic Modelling

Slip Systems CRSS

Plasticity Modelling

Crystal Preferred Orientation

Elastic Tensors

Orthorhombic
222, *mm*2, *mmm*

$$\begin{pmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ & c_{22} & c_{23} & 0 & 0 & 0 \\ & & c_{33} & 0 & 0 & 0 \\ & & & c_{44} & 0 & 0 \\ & & & & c_{55} & 0 \\ & & & & & c_{66} \end{pmatrix}$$

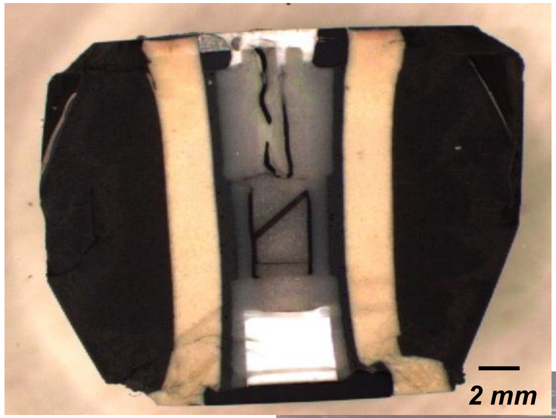
Seismology

COMPRES

Geodynamics

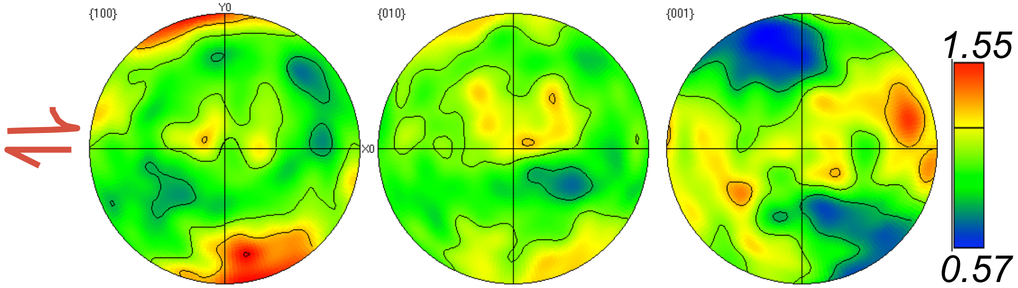
Deformation of olivine polycrystals @ 11GPa & 1400°C

H. Couvy & P. Cordier
Bayreuth/Lille



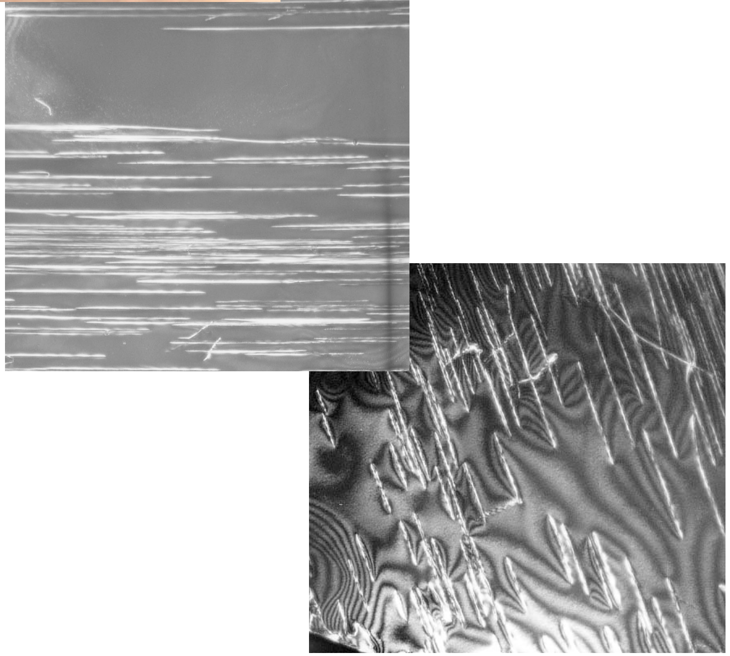
100% olivine
simple shear

EBSD: olivine CPO



$\gamma=0.3$

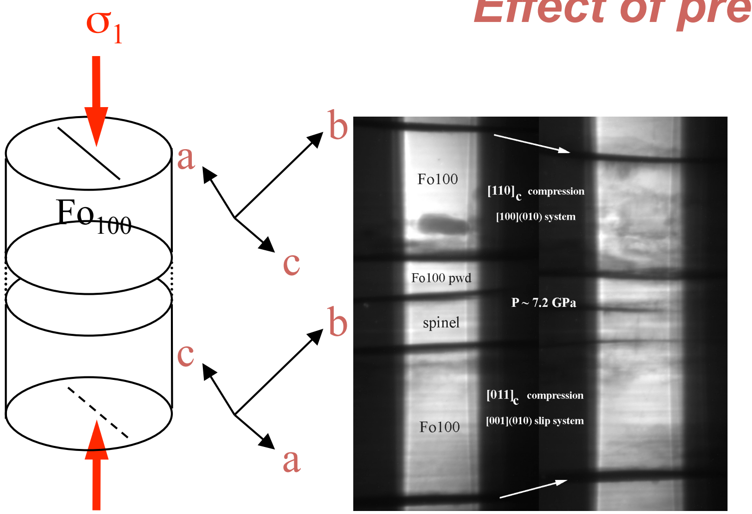
$\boxed{[001](100)}$
$\boxed{[001](010)}$



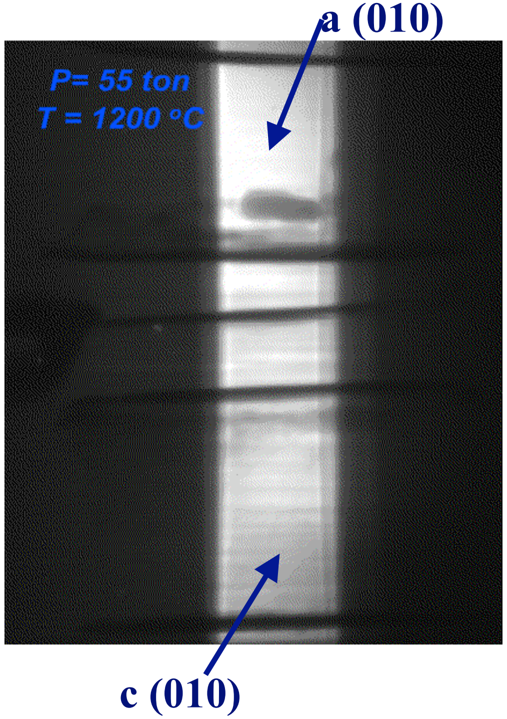
TEM: only [001] screw dislocations

Couvy et al. EJM 2004

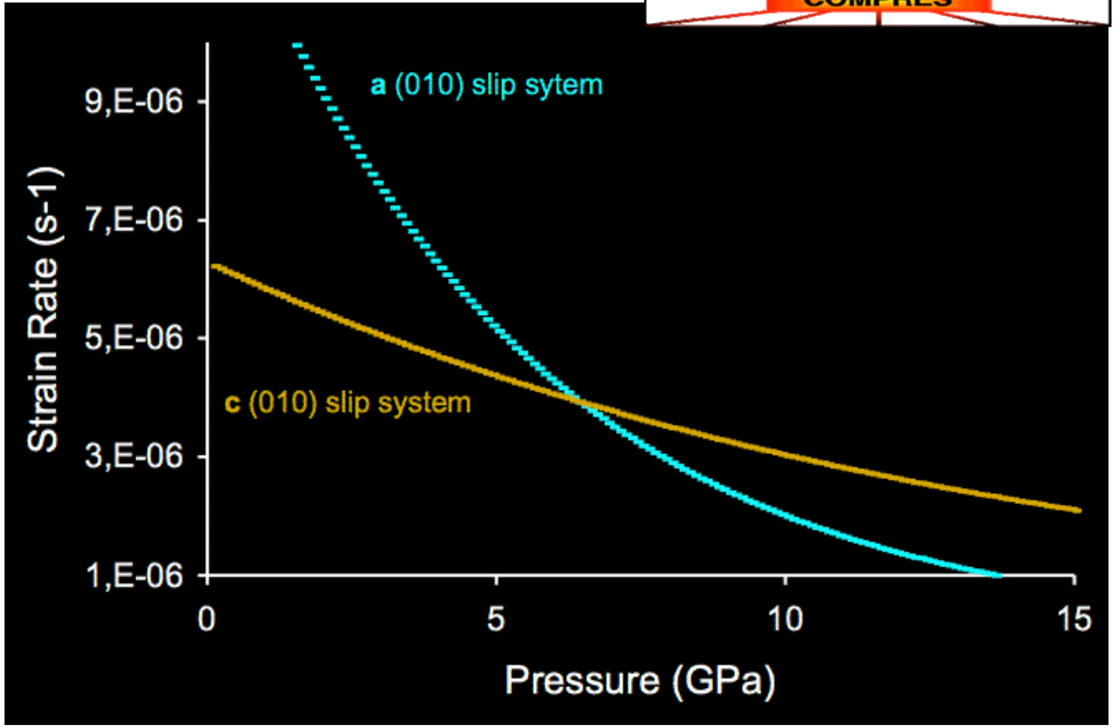
Effect of pressure on olivine deformation



bi-crystal



COMPRES



At high pressure:

- *higher strain rate in c crystal*

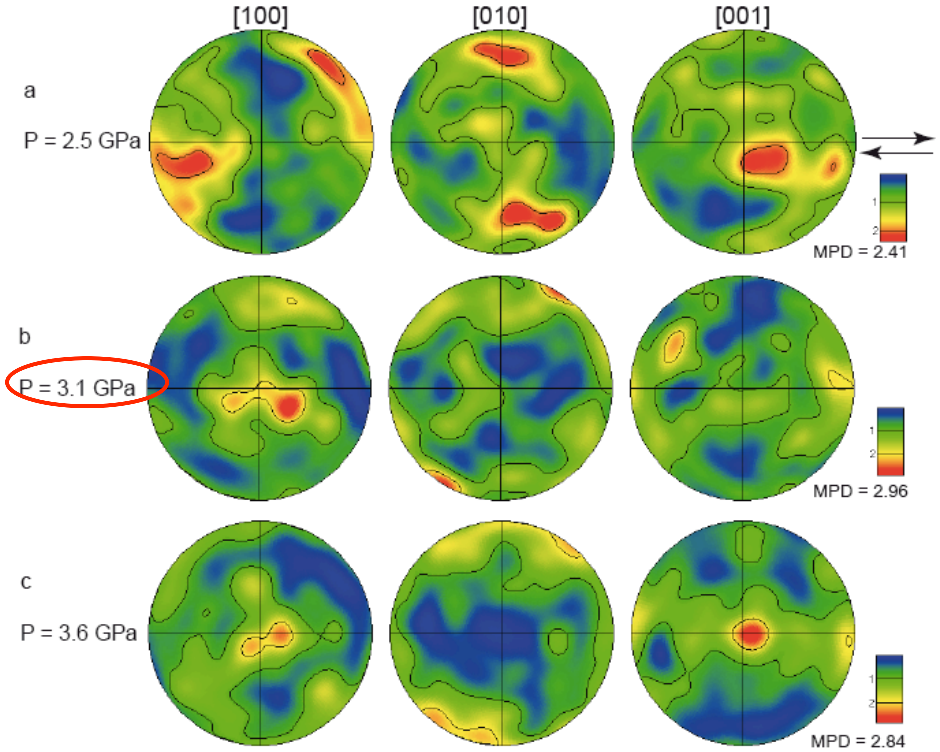
✓ *[001](010) slip easier than [100](010)*

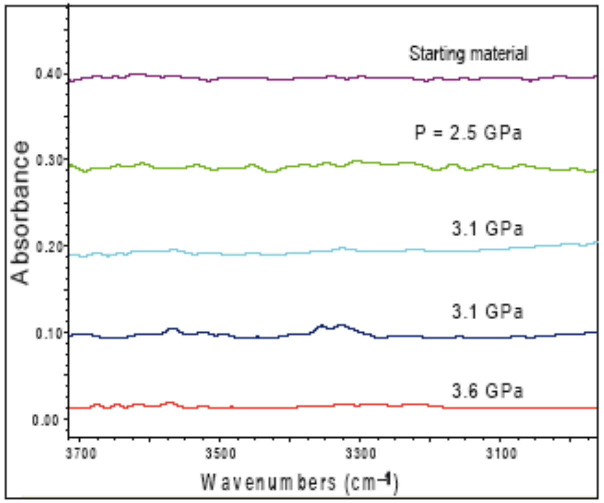
- *very low activation volume*

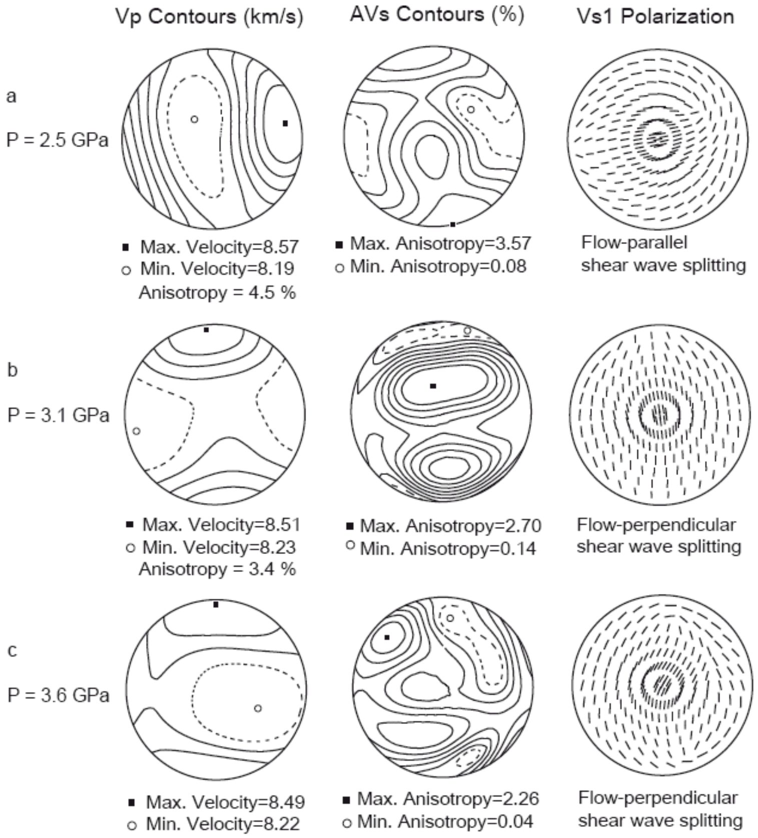
✓ *dislocation creep dominant*

Raterron et al, in press

Upper mantle seismic anisotropy resulting from pressure-induced slip transition in olivine

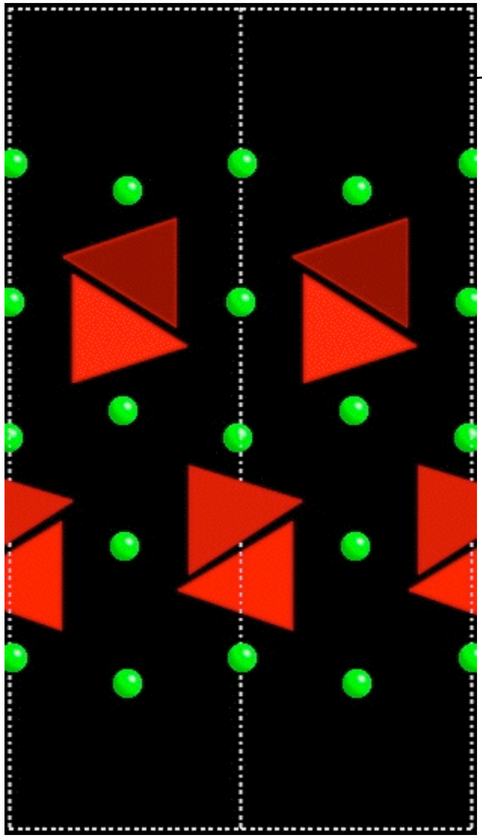






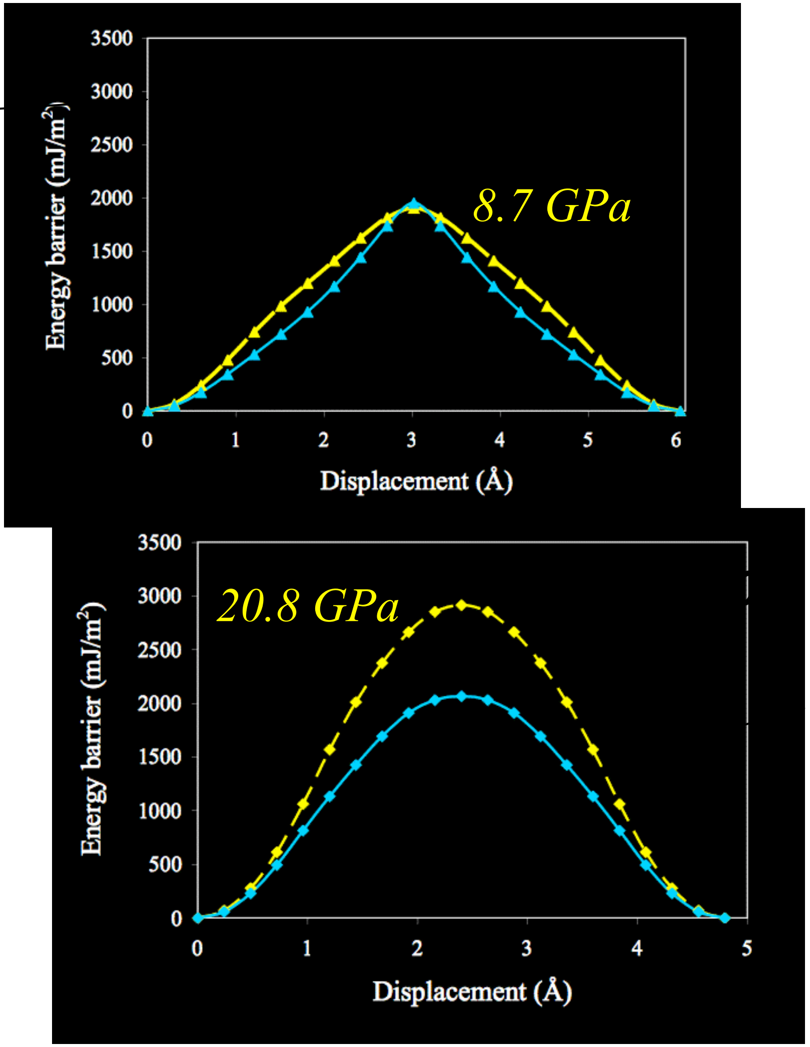
Jung et al. Nature Geoscience 2009

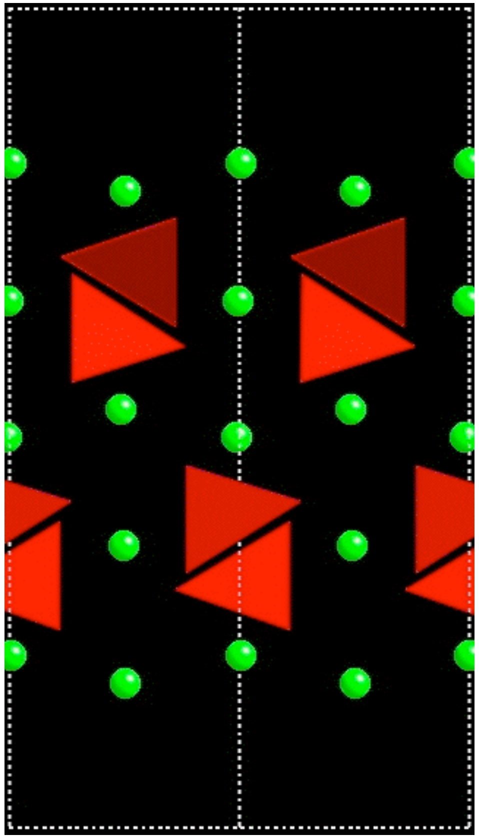
Ab-initio modeling of dislocation core properties:
Ph. Carrez, P. Cordier, D. Ferré (Lille)



⊙

[001]





➡

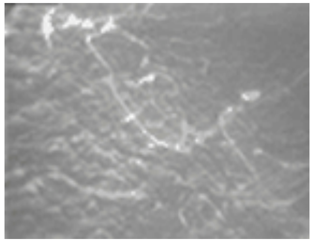
[100]

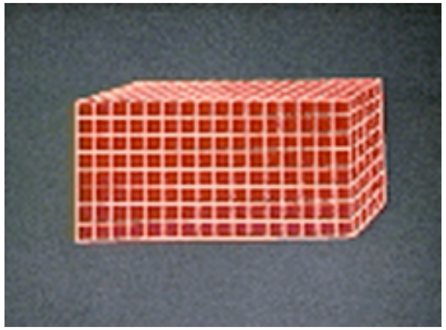
✓ *olivine: easier slip on [100](010) at high pressure*

Modeling the deformation & crystal orientation evolution

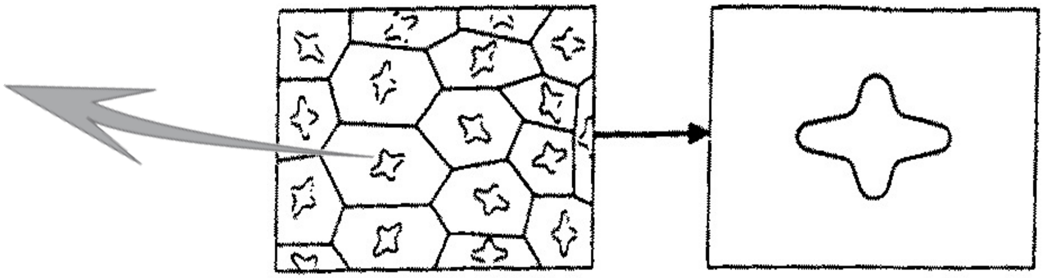
VPSC: Molinari et al. 1987, Lebensohn & Tomé 1993
Drex: Kaminsky & Ribe 2001, 2003

within a grain (crystal):





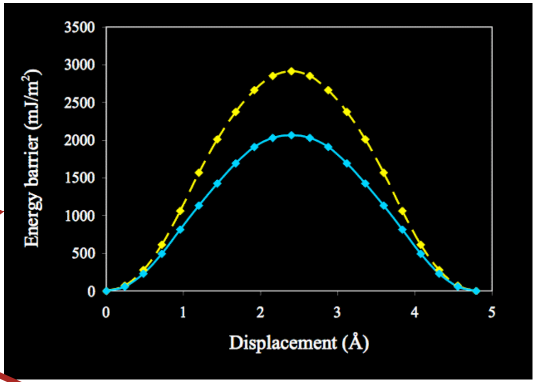
rock (polycrystal) deformation:



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

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

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



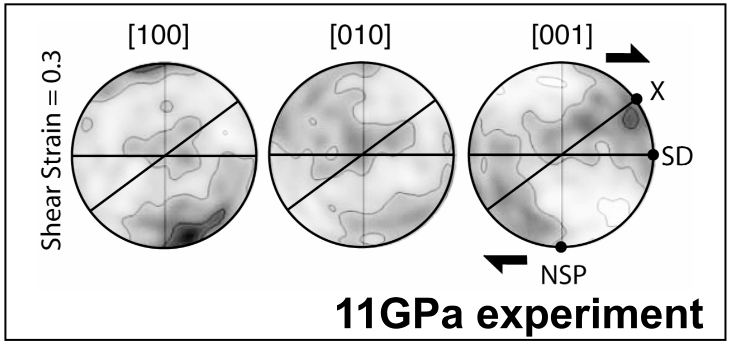
$$\dot{E}_{ij} = \langle \dot{\varepsilon}_{ij} \rangle \qquad \Sigma_{ij} = \langle \sigma_{ij} \rangle$$

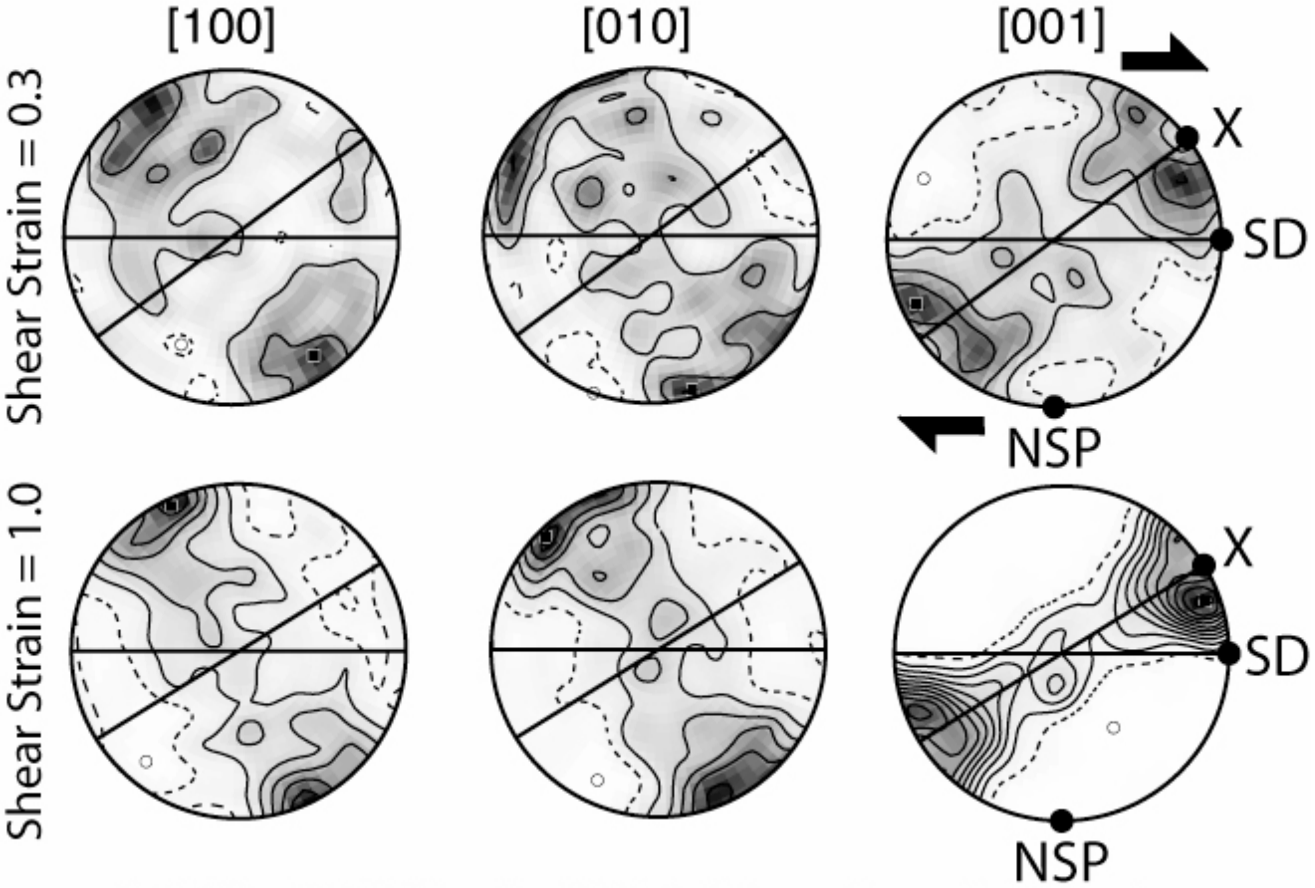
$$\dot{\varepsilon}_{kl} - \dot{E}_{kl} = -M_{ijkl} : (\sigma_{ij} - \Sigma_{ij})$$

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

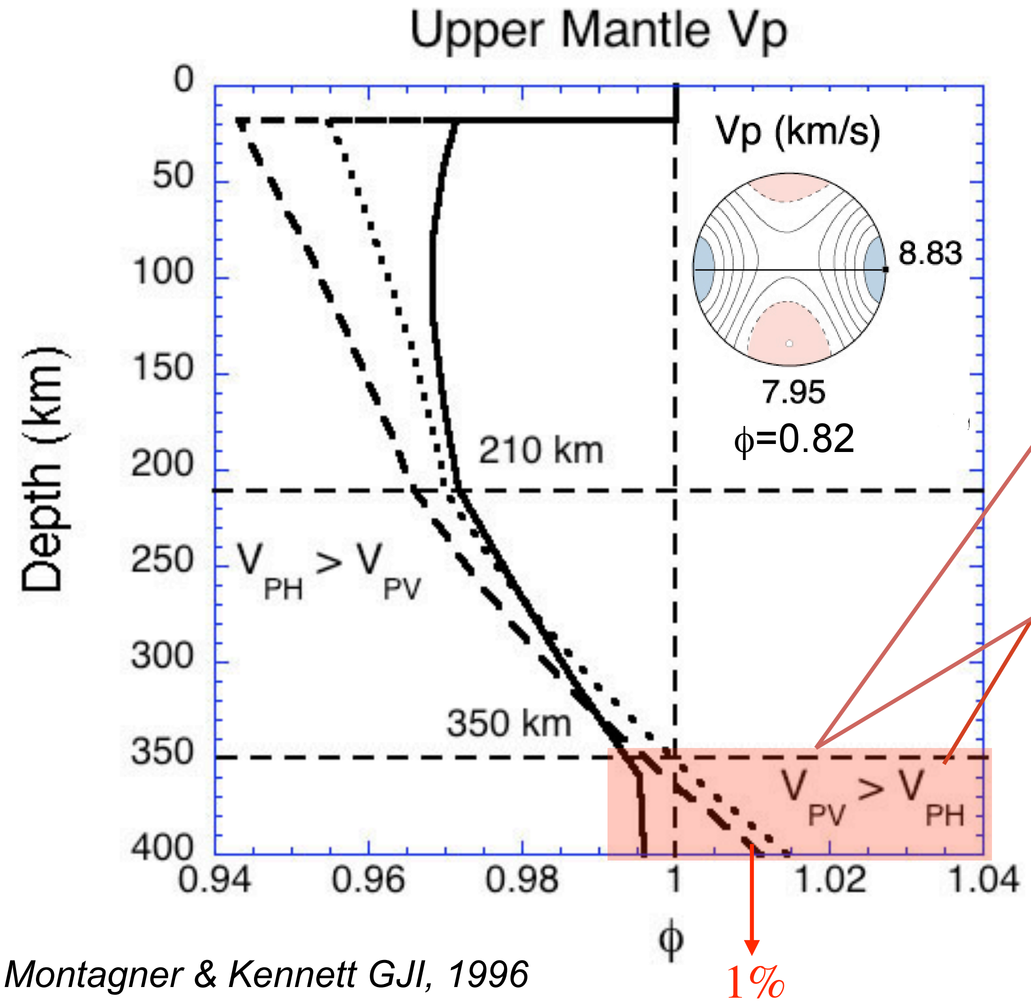




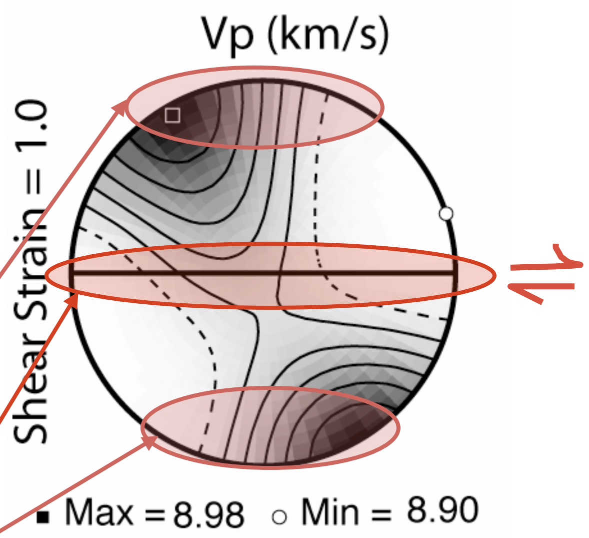
CRSS all [001] = 1 ; [100]=3(basal) or 6 (prism)

Mainprice et al. Nature, 2005

Global P-wave anisotropy in the deep upper mantle



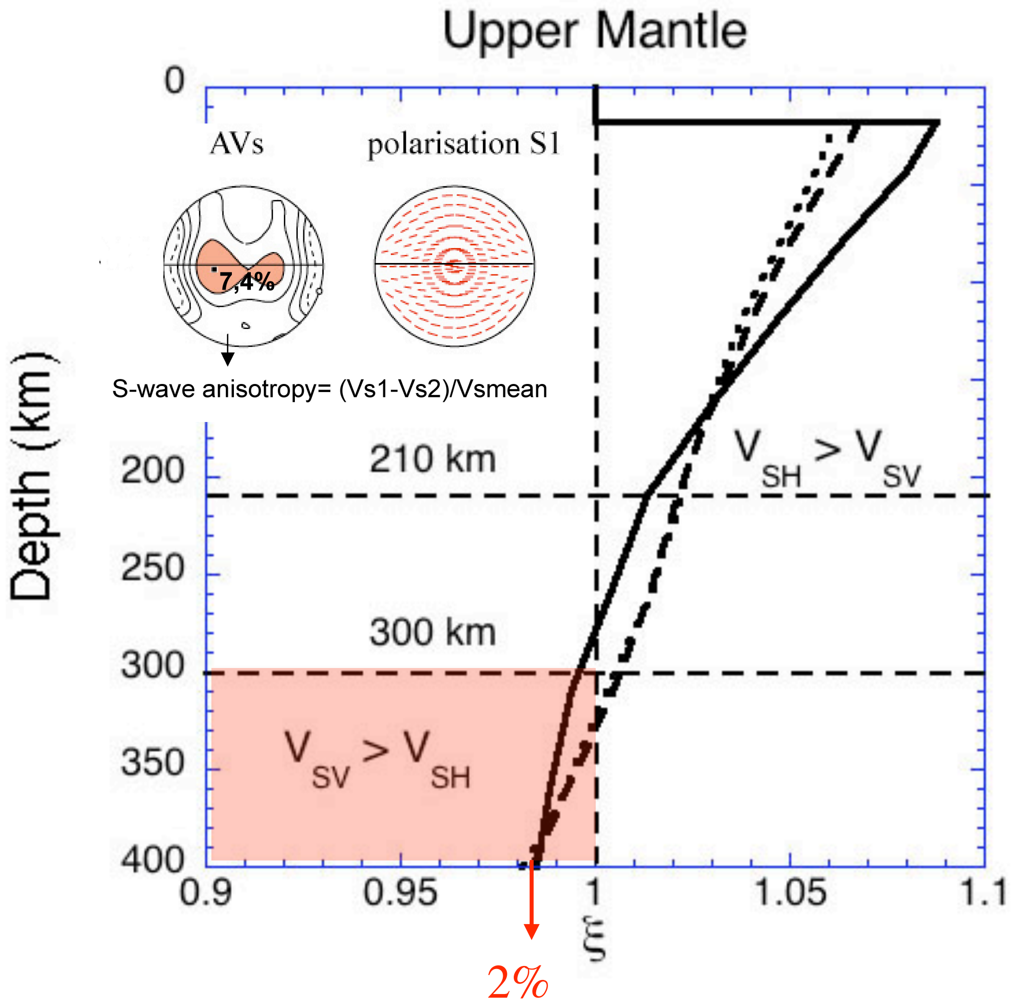
Montagner & Kennett GJI, 1996

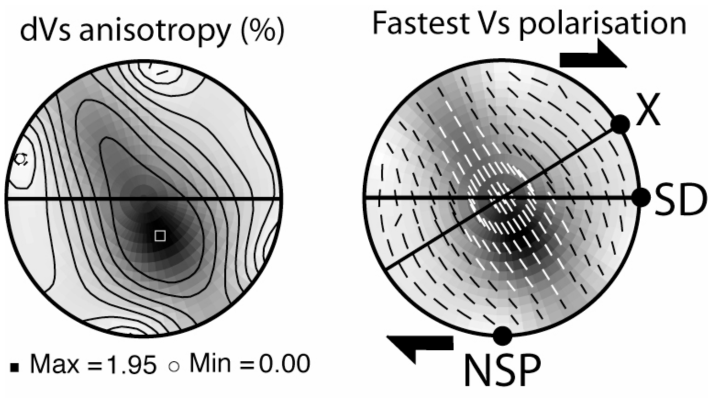


Model prediction for horizontal flow:

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

Global S-wave anisotropy in the deep upper mantle





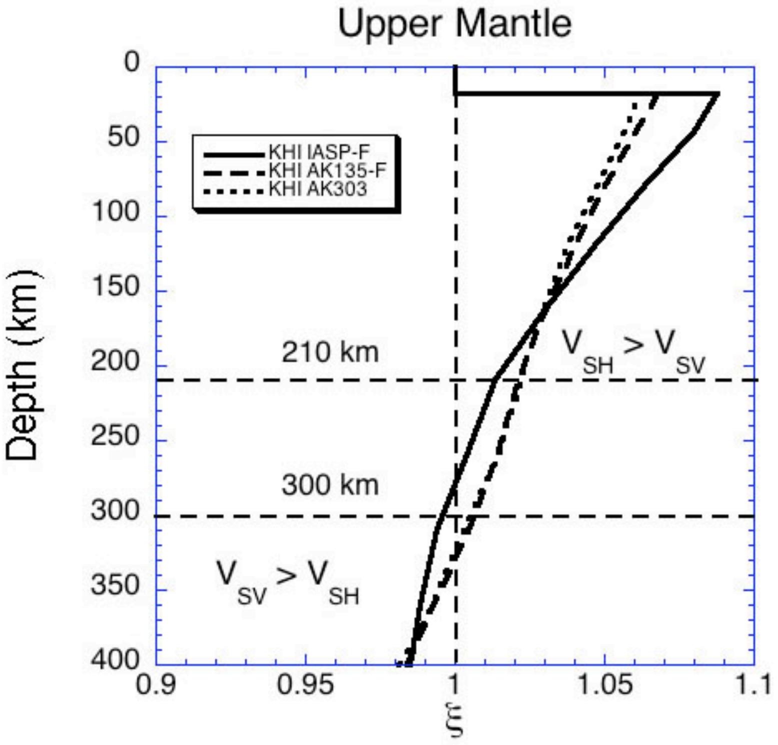
Model prediction for horizontal flow:

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***

Mainprice et al., Nature, 2005

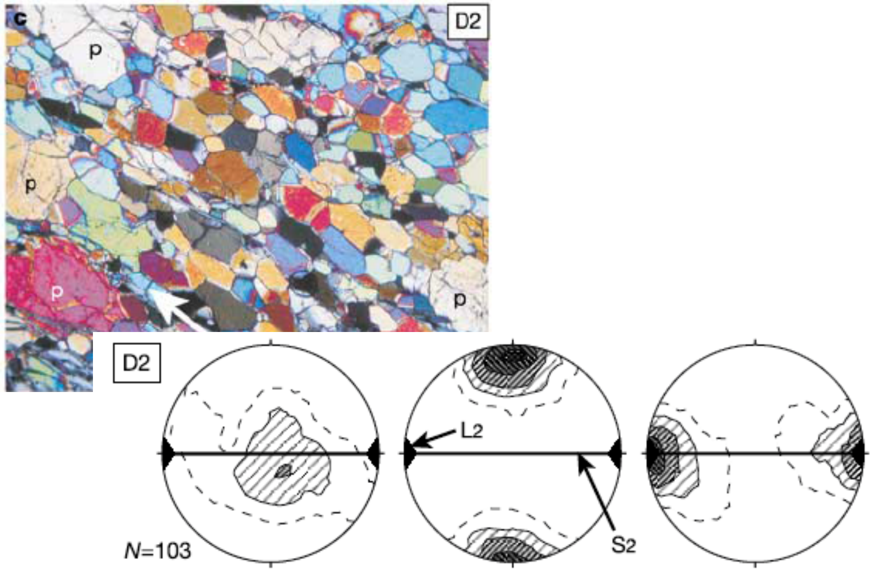
Transition from [100] slip to [001] slip in the deep upper mantle?

Experiments *: P ~ 6-7 GPa (~200 km) or P ~ 3 GPa (~90 km) : role of stress & water content?*

LPO measurements on naturally deformed peridotites:

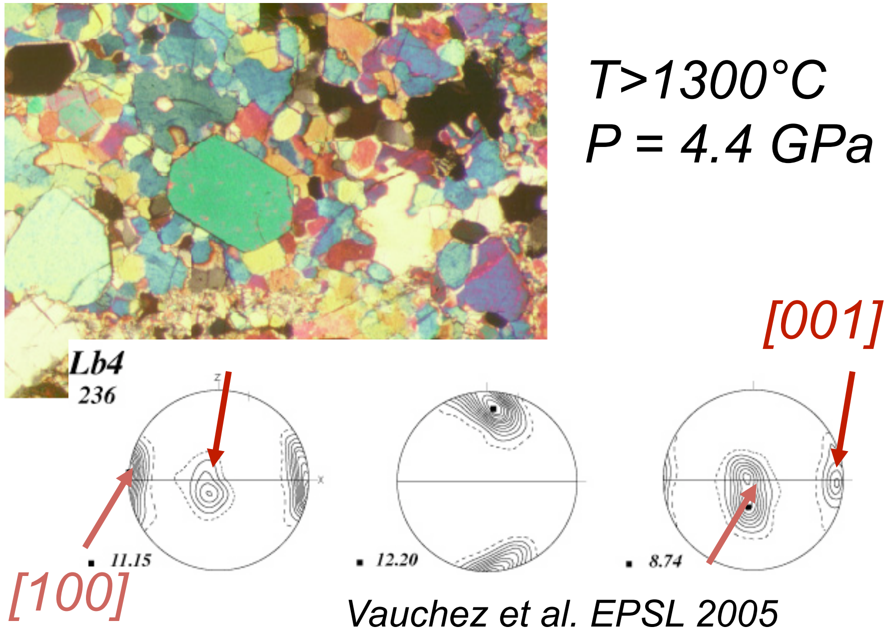
- *sp-bearing samples : [100] only (<70 km)*
- *garnet-bearing peridotites : essentially [100], except:*

high-pressure massifs (subduction)



Mizukami et al. Nature 2004

cratonic sheared lherzolites



T>1300°C
P = 4.4 GPa

Vauchez et al. EPSL 2005

Below-slab anisotropy

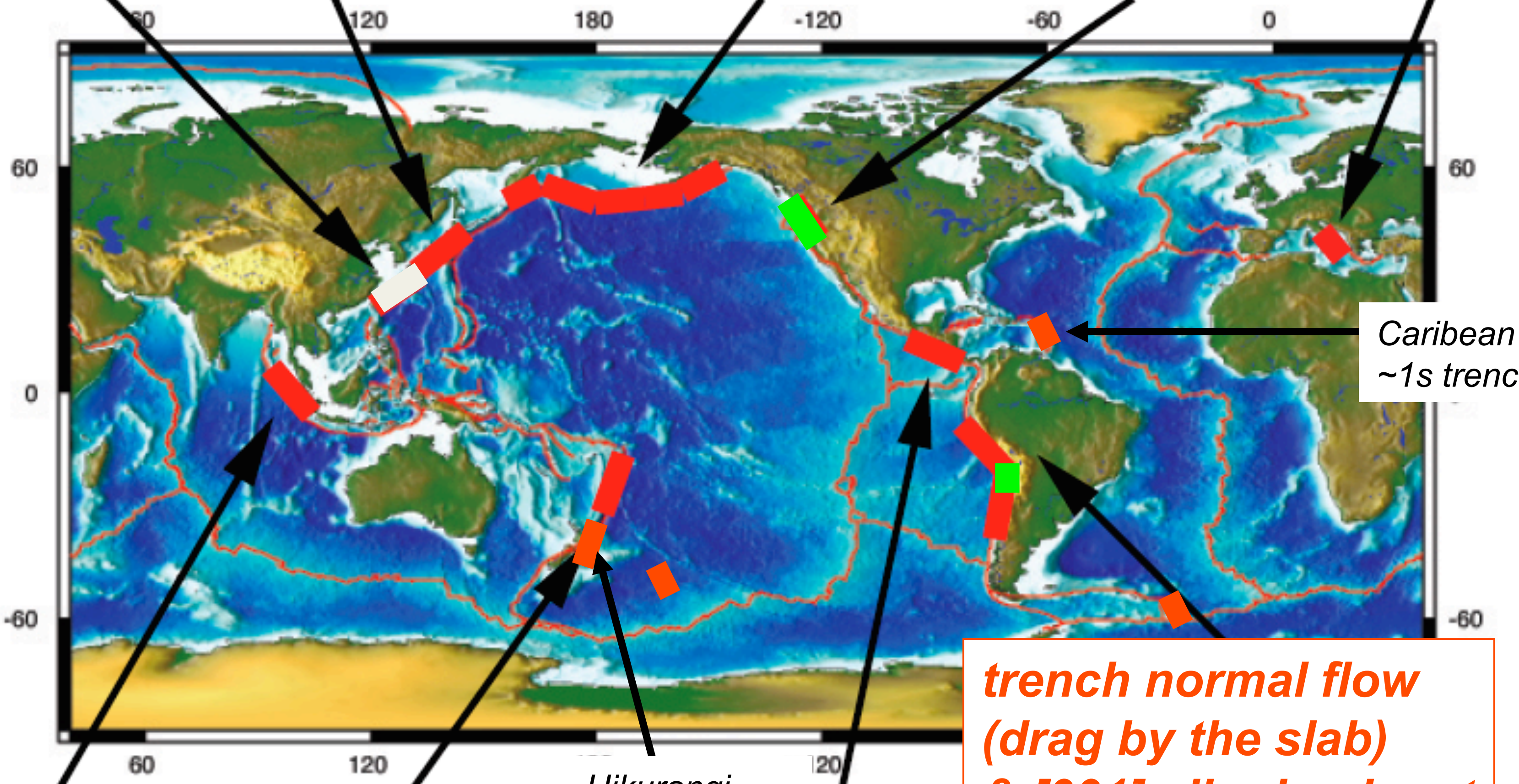
Ryukyu: negligible below-slab splitting

Japan: ~ 0.5-0.7 sec, variable orientations

Aleutians: ~ 0-0.5 sec, mostly trench-||, some oblique

Cascadia: ~ 0.5-1 sec, trench-normal

Calabria: ~ 1-2 sec, trench-||



Caribean
~1s trench //

trench normal flow
(drag by the slab)
& [001] slip dominant

Hikurangi
1-2s trench //

Indonesia: ~ 1 sec, trench-|| to oblique

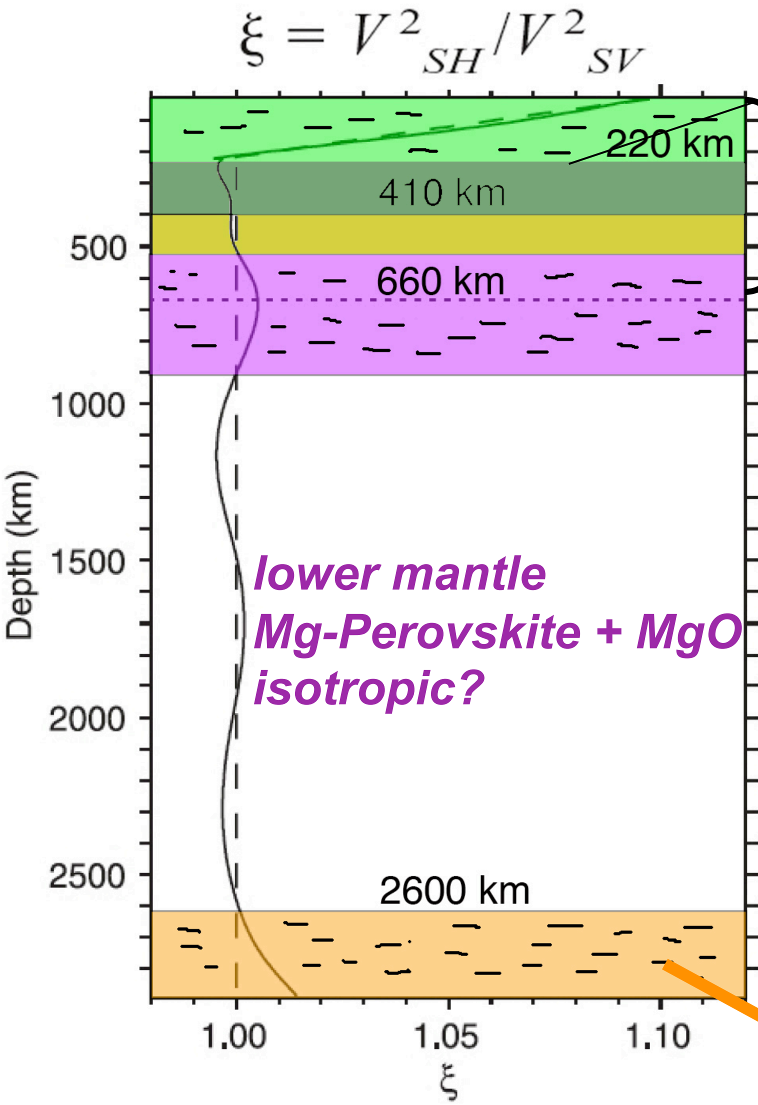
Tonga: ~ 1-2 sec, trench-||

Central America: ~ 1-1.5 sec, trench-||

S. America: ~ 0.5-1.25 sec, mostly trench-|| with some trench-normal

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

Anisotropy & deformation in the deep mantle

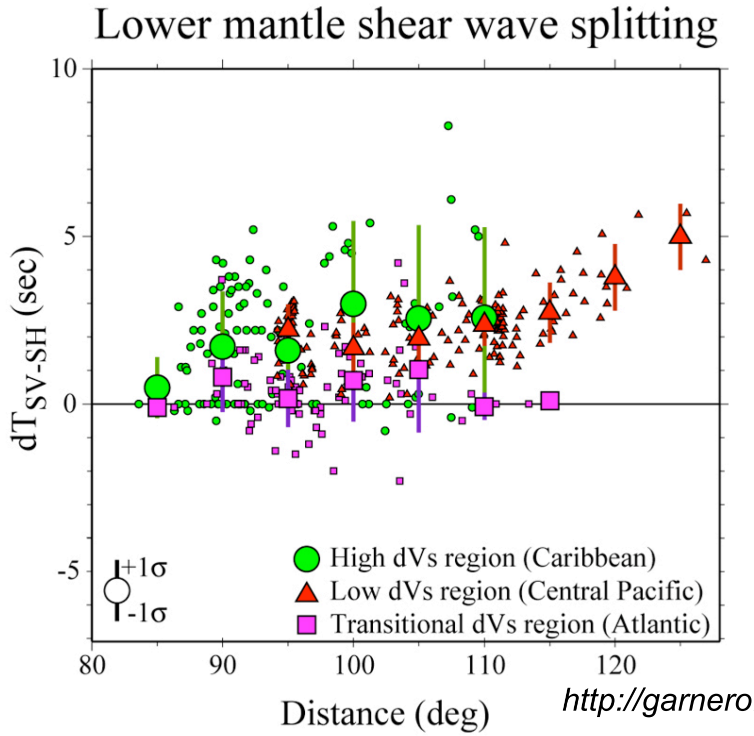


lower mantle
Mg-Perovskite + MgO
isotropic?

Panning & Romanowicz 2004 Science

Lehmann discontinuity: change in olivine deformation

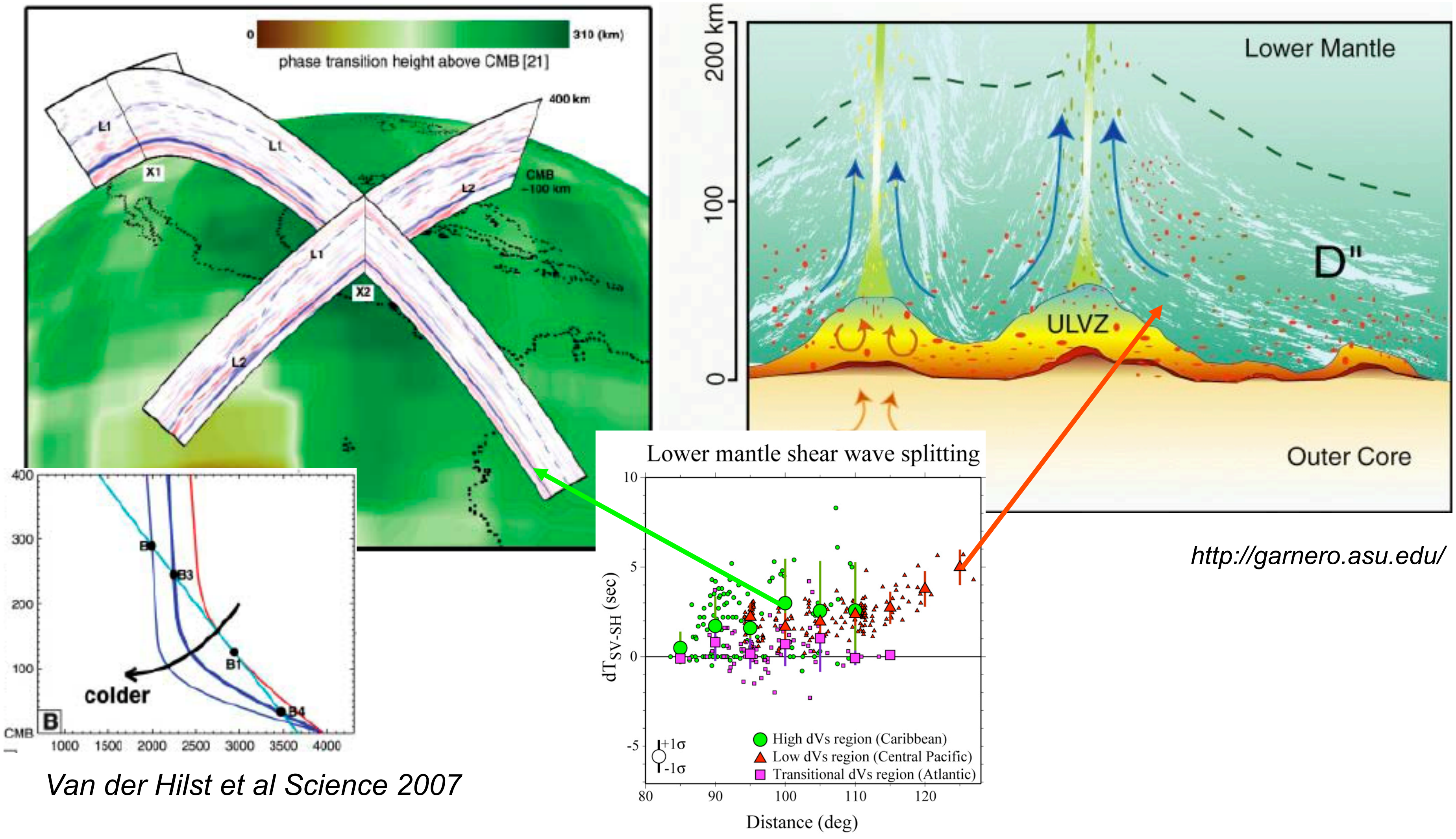
strain-induced anisotropy (CPO)
dominant horizontal flow



http://garnero.asu.edu/

D”: $Vs_H > Vs_V$, no SKS splitting, azimuthal anisotropy?

D"-Layer anisotropy: strain-induced post-perovskite CPO and/or compositional layering?



Van der Hilst et al Science 2007

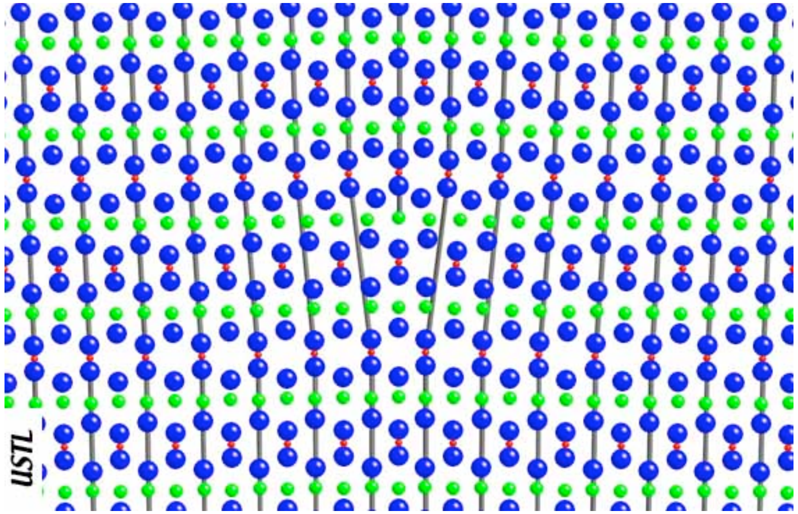
http://garnero.asu.edu/

nature Vol 446|1 March 2007|doi:10.1038/nature05593

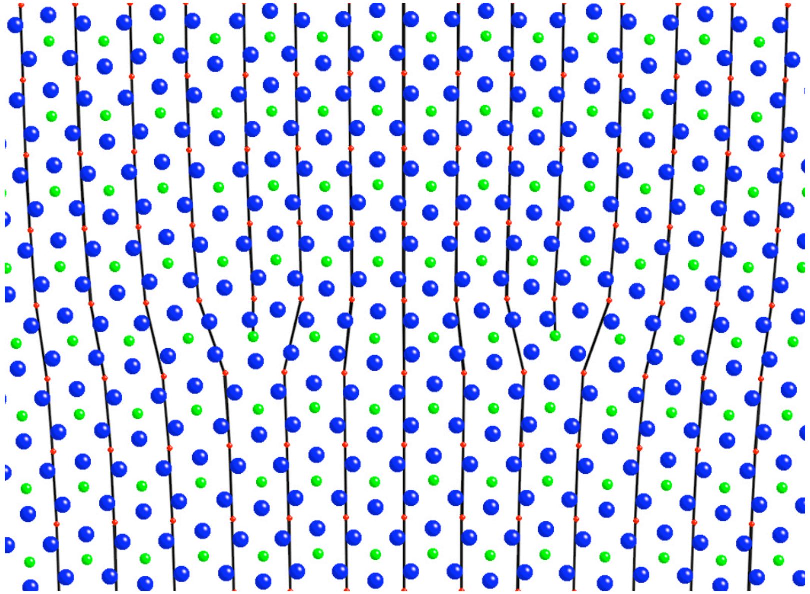
LETTERS

Implications for plastic flow in the deep mantle from modelling dislocations in $MgSiO_3$ minerals

Philippe Carrez[1]*, Denise Ferré[1]* & Patrick Cordier[1]*



(010)[100]



(010)[001]

polycrystal plasticity models ➔ post-perovskite CPO D" anisotropy

Mantle deformation & anisotropy

- *in the lithospheric mantle and asthenosphere (< 200 km):*
  ✓ deformation by dislocation creep with dominant [100] slip
    - *strong seismic & electrical anisotropy (+ thermal & mechanical!)*
    - *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 mineral phases?*
    - *D" strongly anisotropic : post-perovskite CPO and compositional layering?*