CRYSTAL2PLATE

How does plate tectonics work:
From crystal-scale processes to mantle convection with self-consistent plates

MARIE CURIE ACTIONS

From crystal & rock-scale anisotropic properties to large-scale dynamics

Andréa Tommasi

Short course on "Microstructures, textures & anisotropy"
Geosciences Montpellier (F) - 28 June - 2 July, 2010

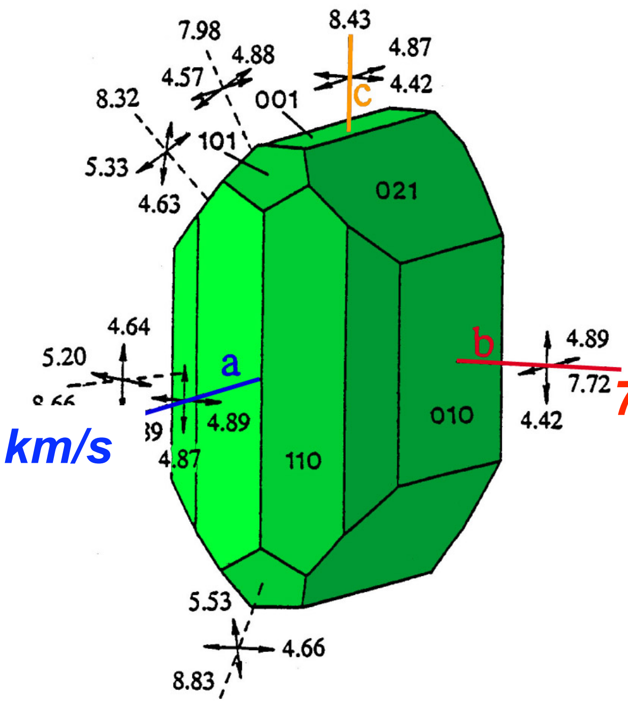
Anisotropy = dependence of a physical property on the sampling direction

Seismic waves velocities vary as a function of:

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

Olivine cristal (μm-cm)

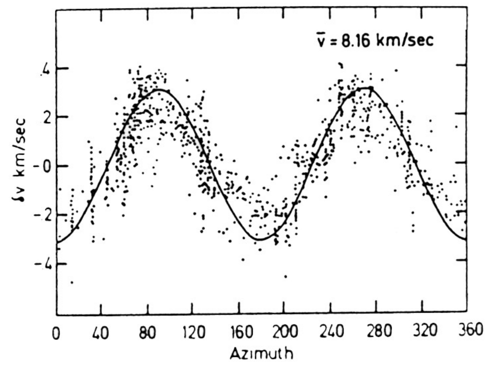
8.4 km/s

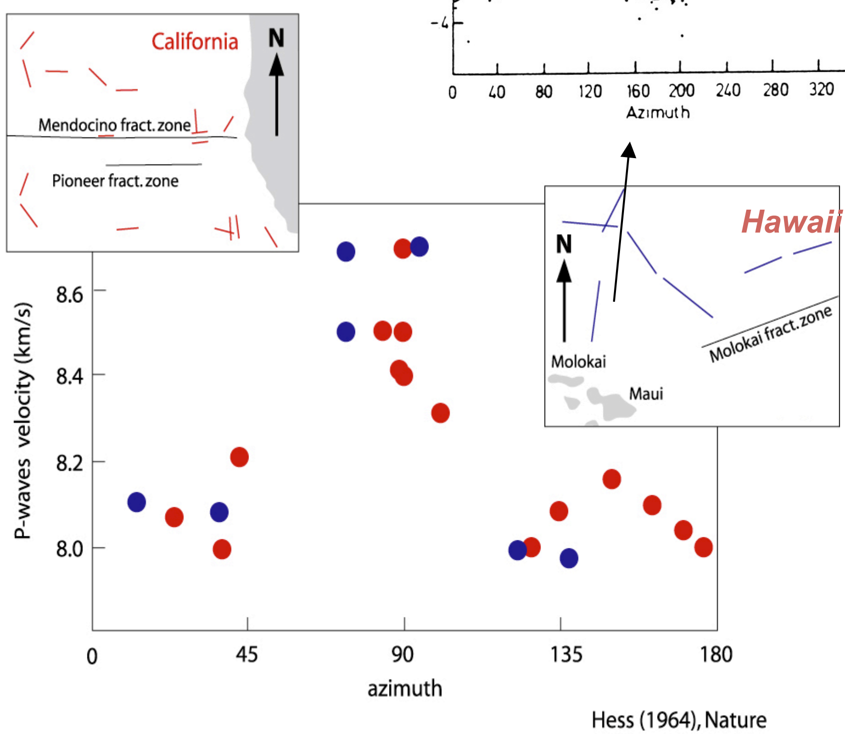


9.9 km/s

7.7 km/s

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



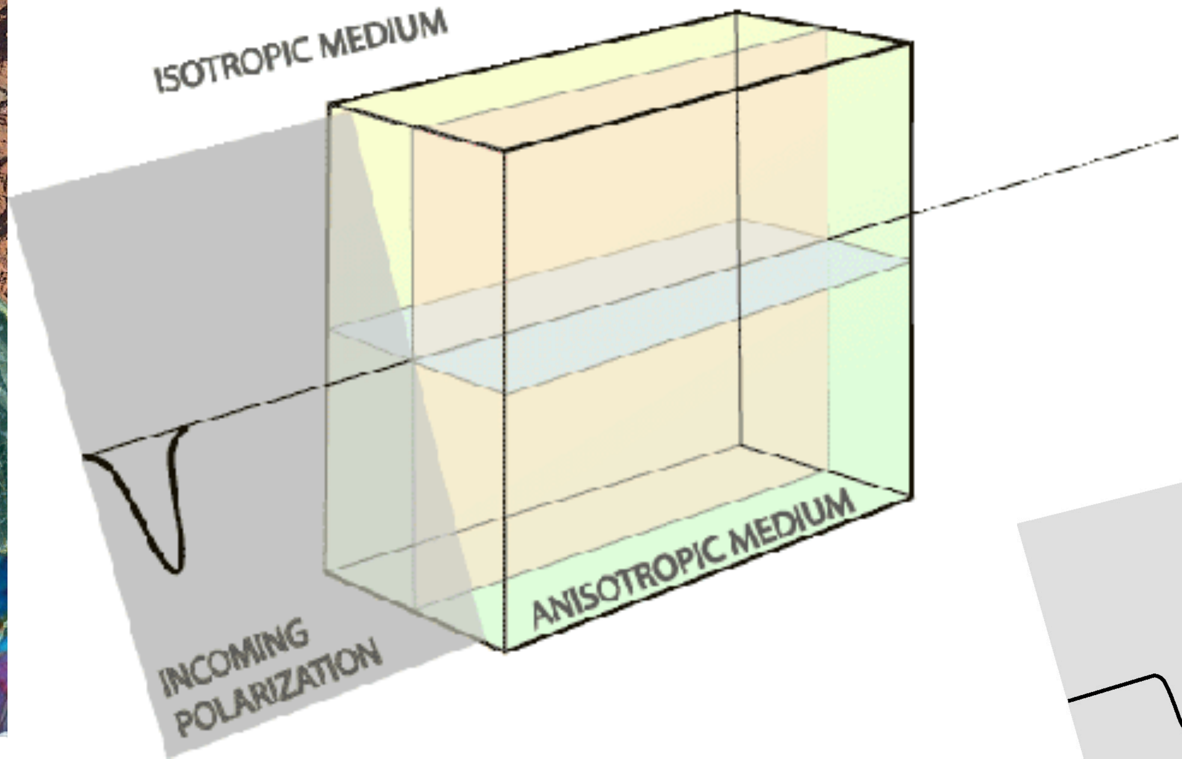


P-waves azimuthal anisotropy (10s of km)

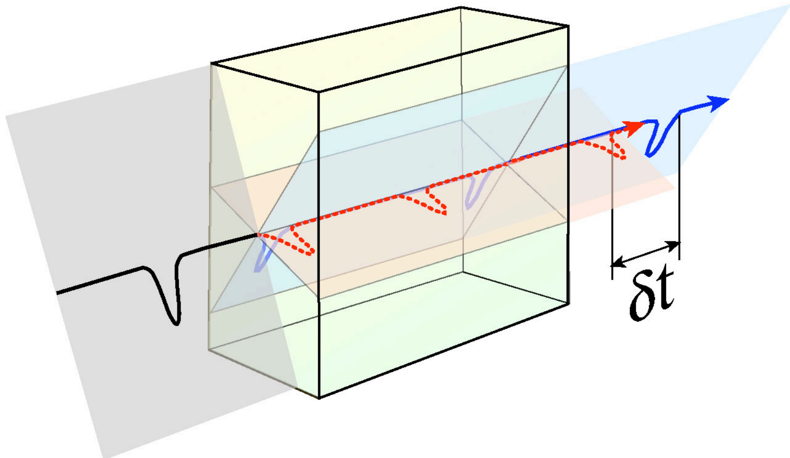
Seismic anisotropy

Seismic waves velocities vary as a function of:

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

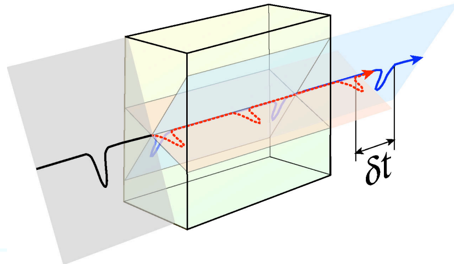


shear wave splitting

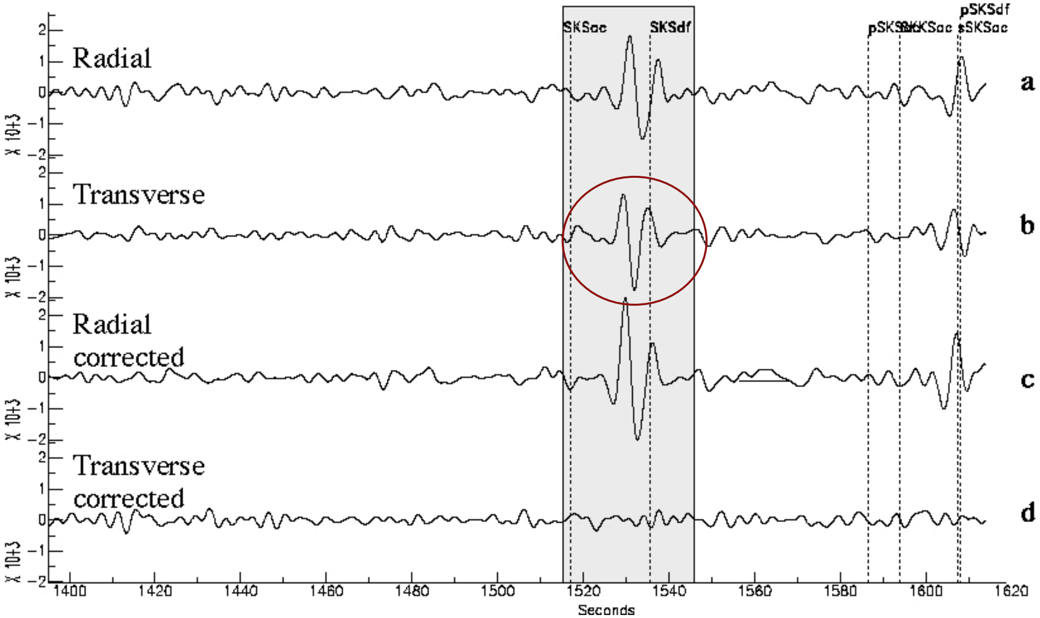


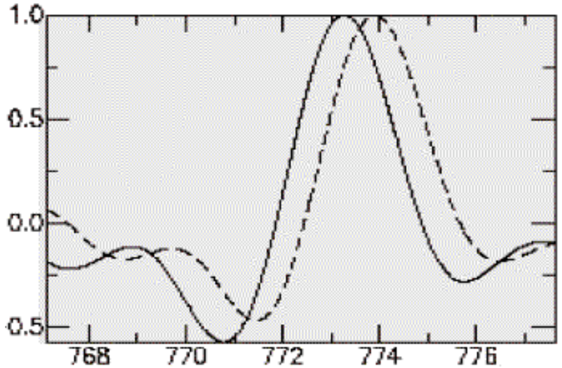
http://garnero.asu.edu

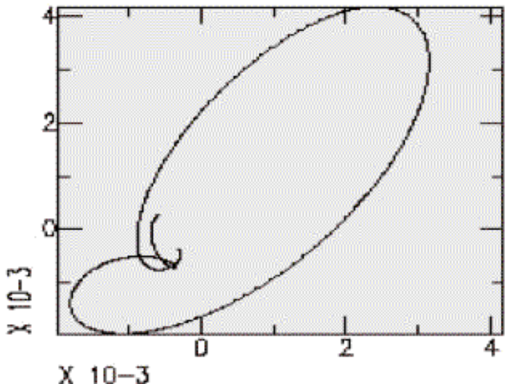
Shear-Wave Splitting



ATD, event 97245 Backaz N280°E, dist. 117°,
lat. 3.849°N, long. -75.749°E, depth 199 km.



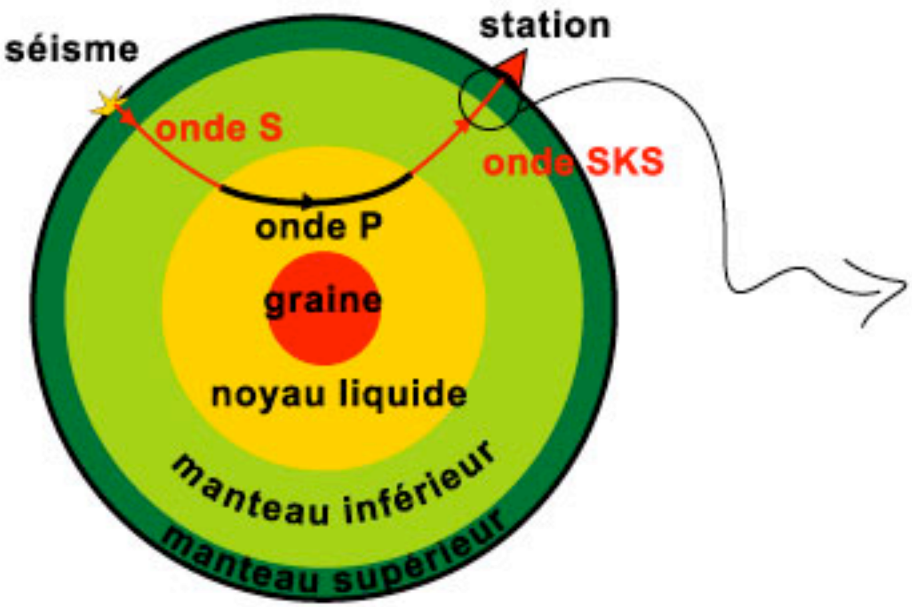




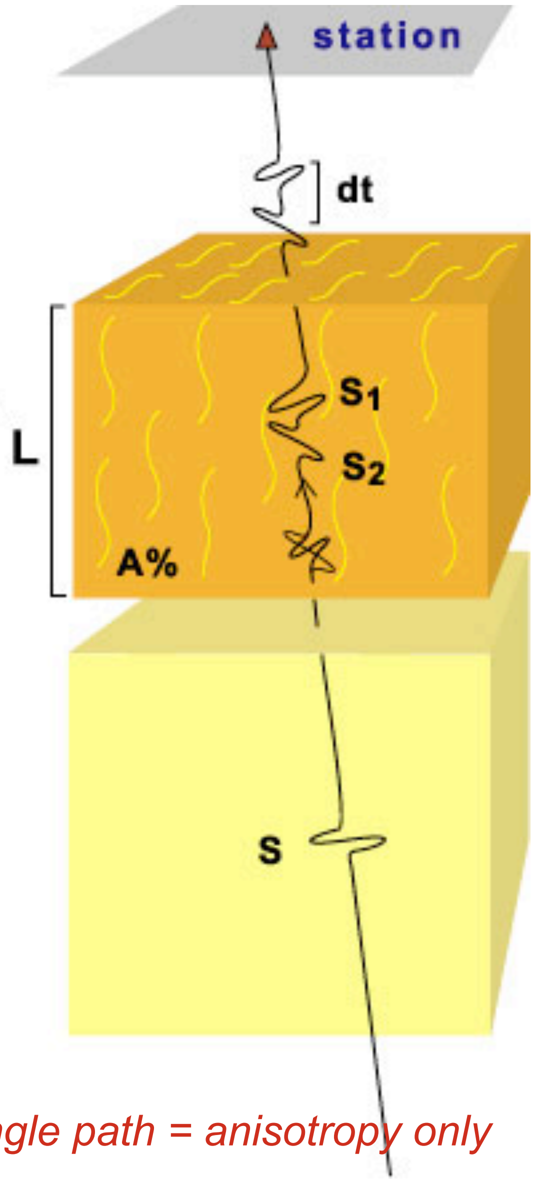
Characteristics of an anisotropic medium

- *Energy on the transverse component (arrival of the S_2)*
- *Elliptic particle motion*
- *Both may be removed by correcting the data with the estimated anisotropy*

S waves polarization anisotropy - shear wave splitting

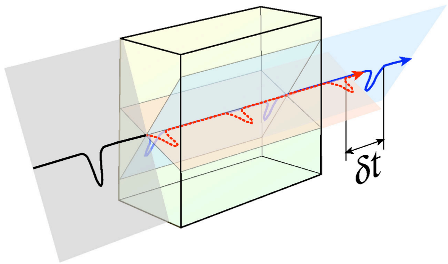


No vertical resolution verticale, but the upper 250 km of the mantle = dominant contribution

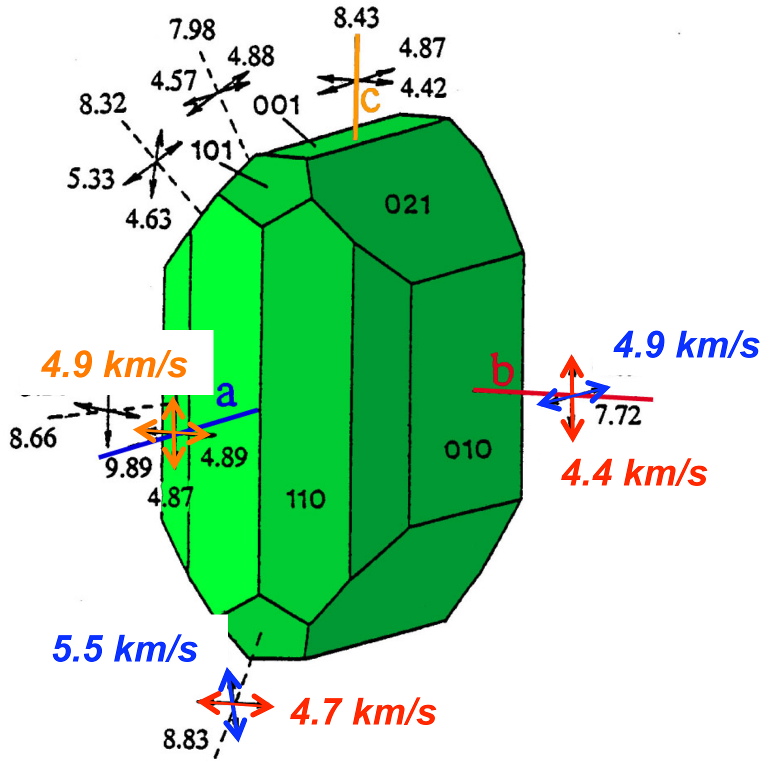


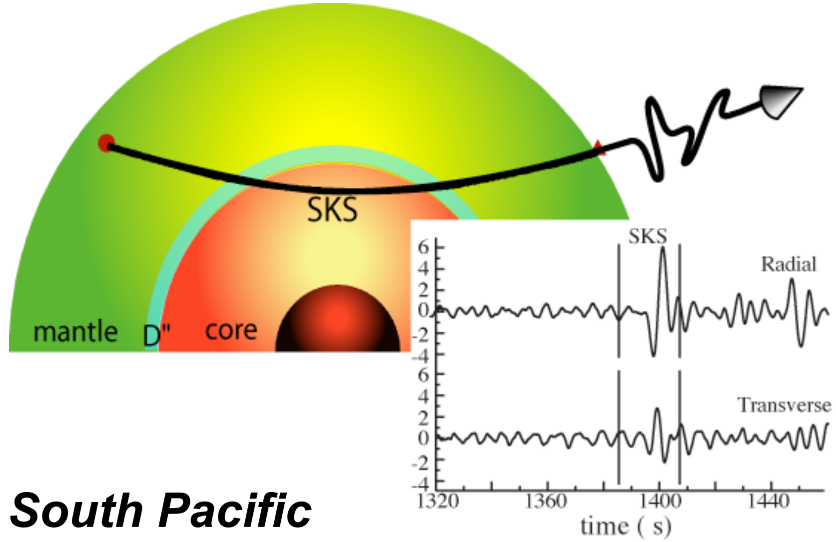
Single path = anisotropy only

S waves polarization anisotropy - shear wave splitting

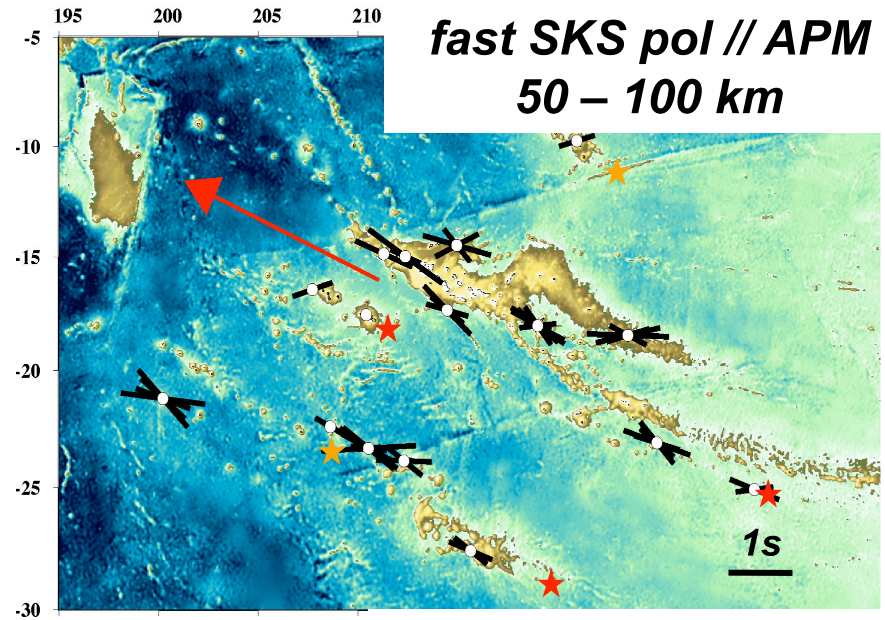


Olivine cristal (µm-cm)



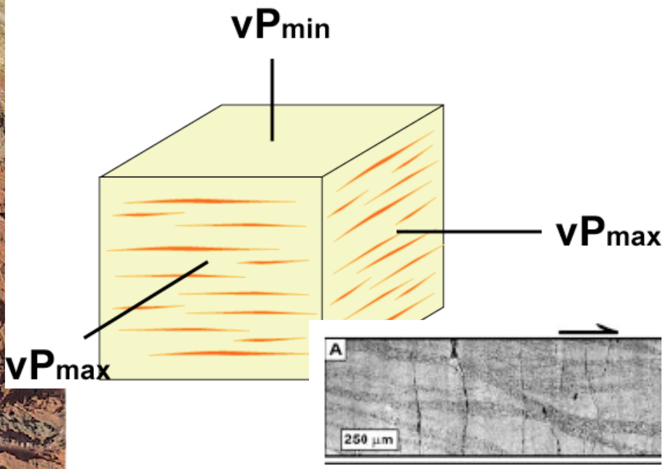


in the South Pacific



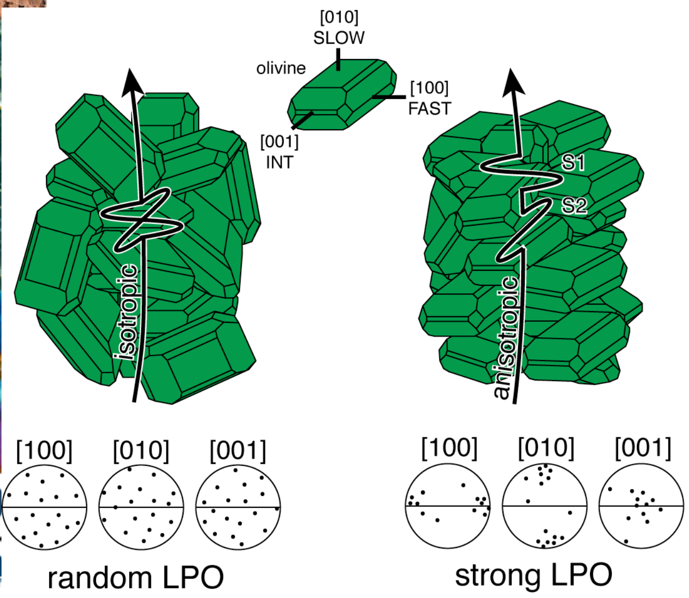
Fontaine et al., GJI 2007

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" (?)***

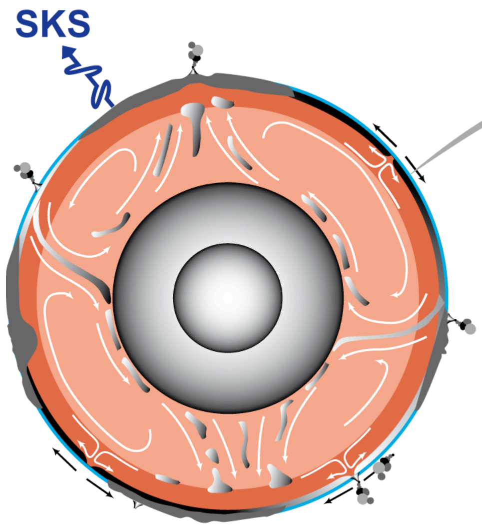


drawing by Luc Mehl

Crystal or Lattice Preferred Orientation (CPO or LPO) of anisotropic minerals :
- ✓ ***lower crust***
- ✓ ***mantle***
- ✓ ***inner core (?)***

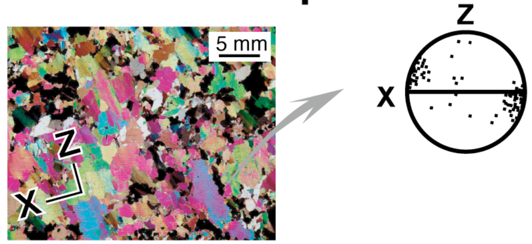
deformation plays an essential role in the development of anisotropy

Mantle deformation, olivine CPO & seismic anisotropy



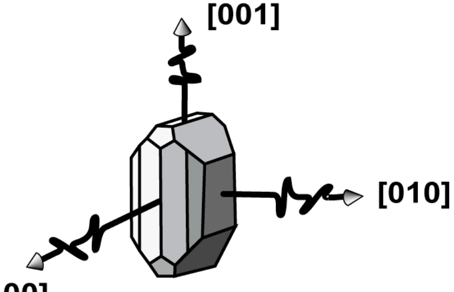
mantle flow

dislocation creep



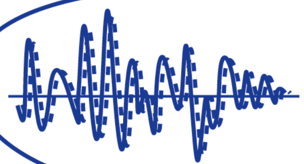
olivine crystal preferred orientation

+



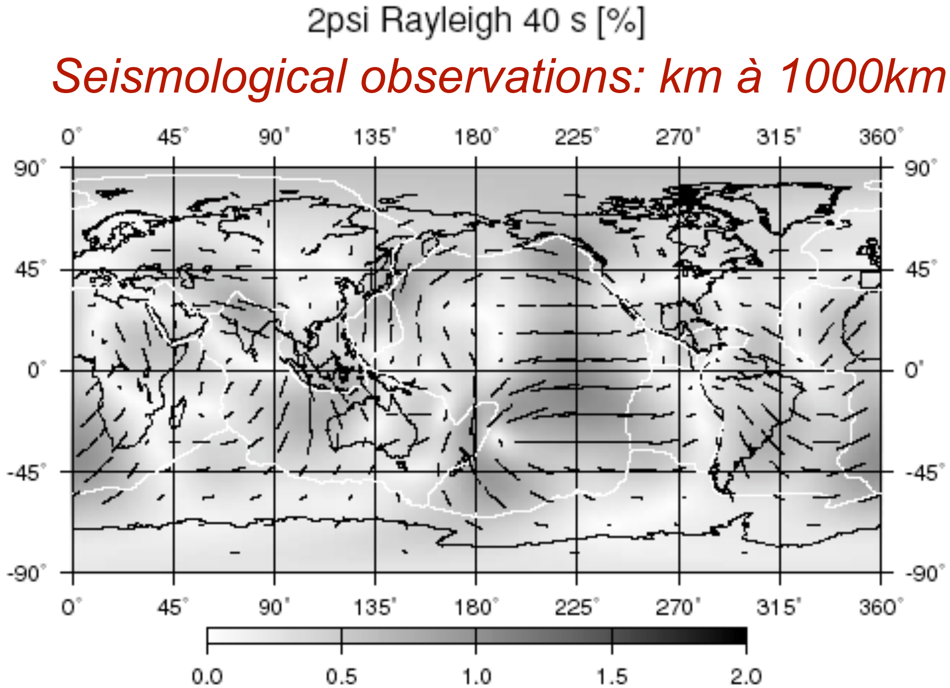
olivine crystal anisotropy

=



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

Seismological observations: km à 1000km

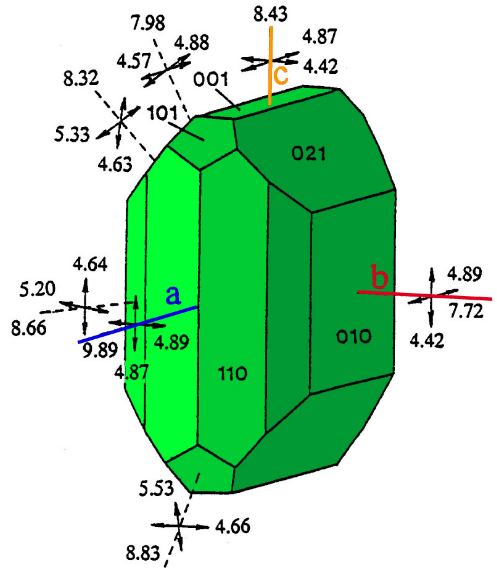


Trampert & Woodhouse, GJI 2003

Change in scale

?

crystal: μm à cm

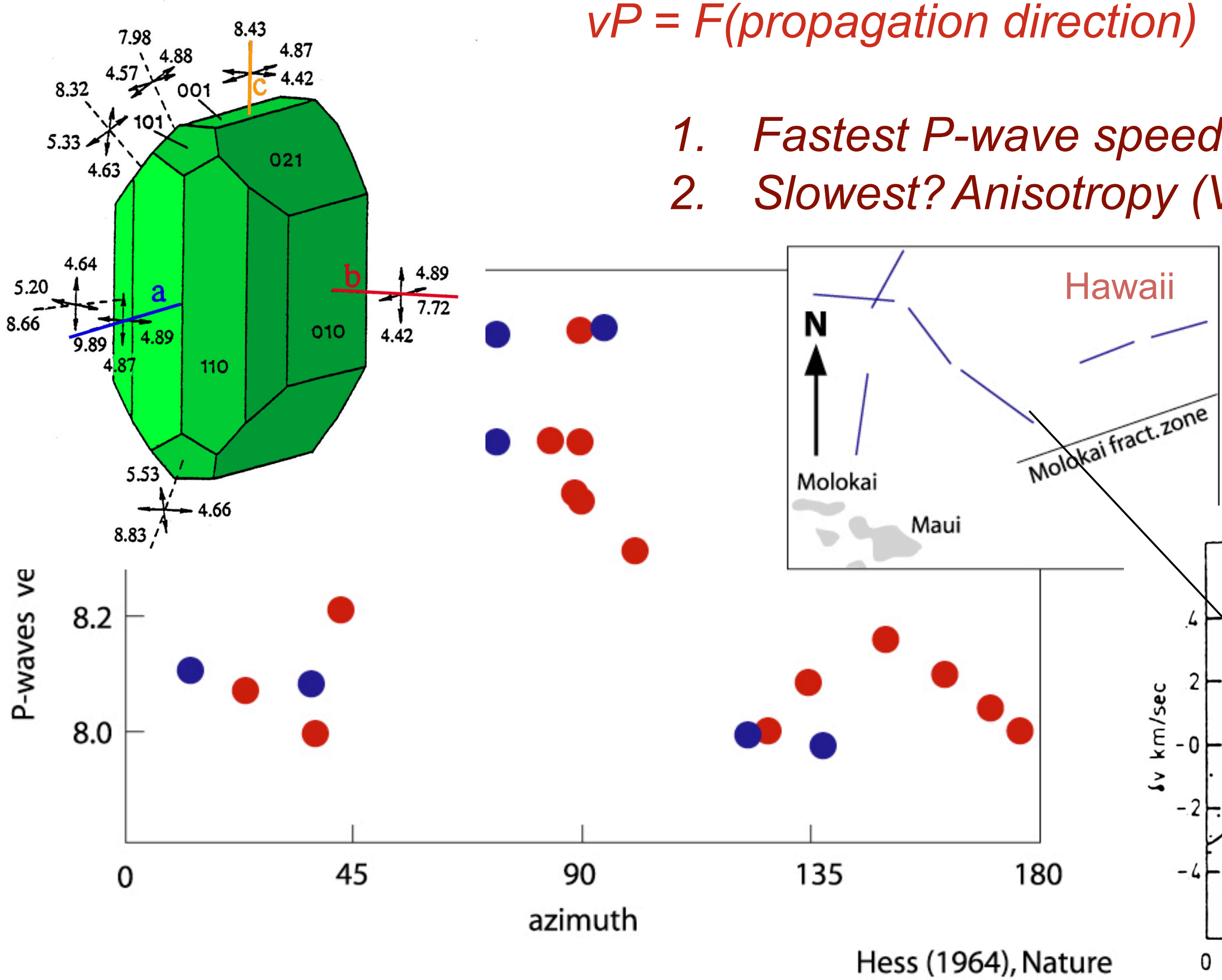


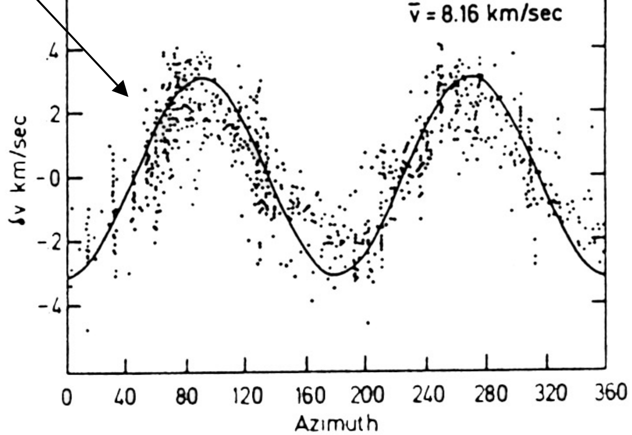
How do we translate seismic anisotropy data into flow patterns?

P waves – refraction profiles

vP = F(propagation direction)

1. *Fastest P-wave speed?*
2. *Slowest? Anisotropy (Vmax-Vmin/Vmean)?*



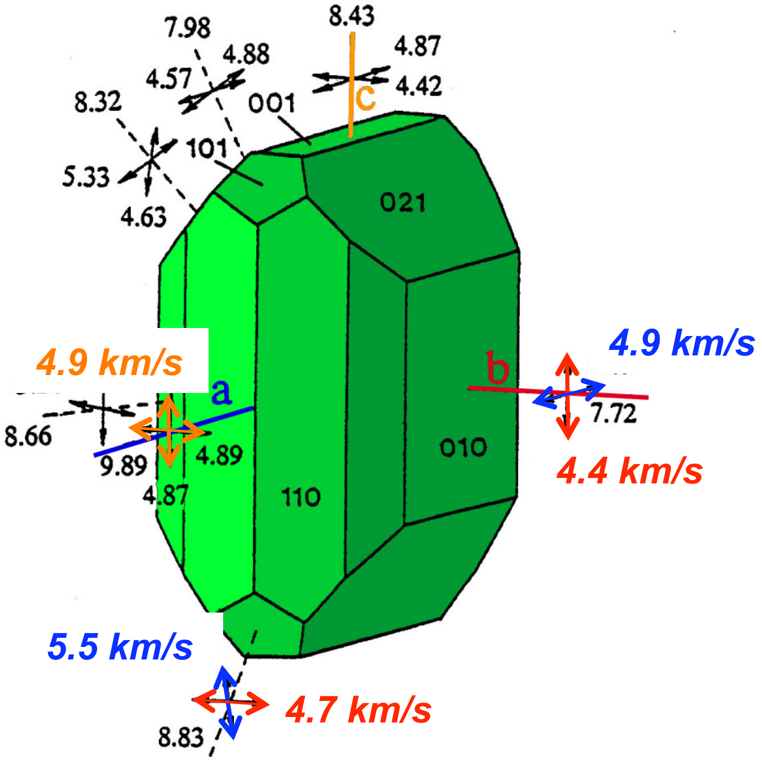


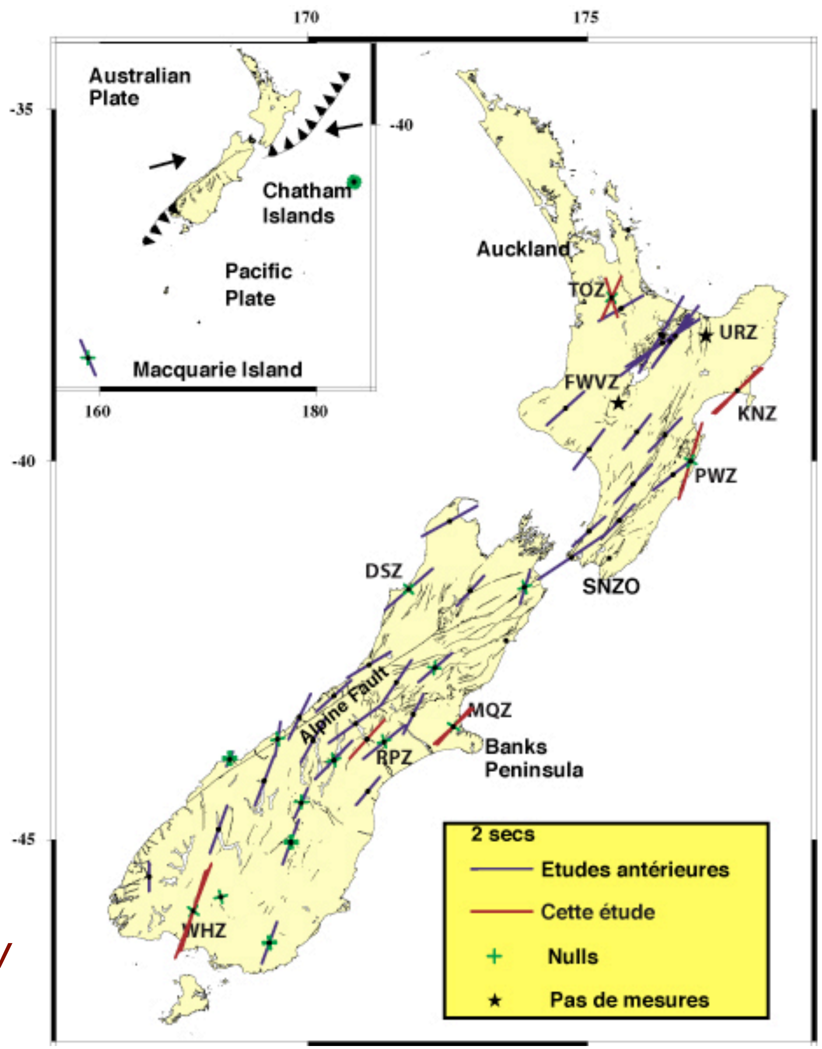
If the mantle beneath these profiles was composed by a single olivine crystal, how should it be oriented?

Morris et al.(1969),JGR

S waves polarization anisotropy - shear wave splitting

Olivine cristal (μm-cm)

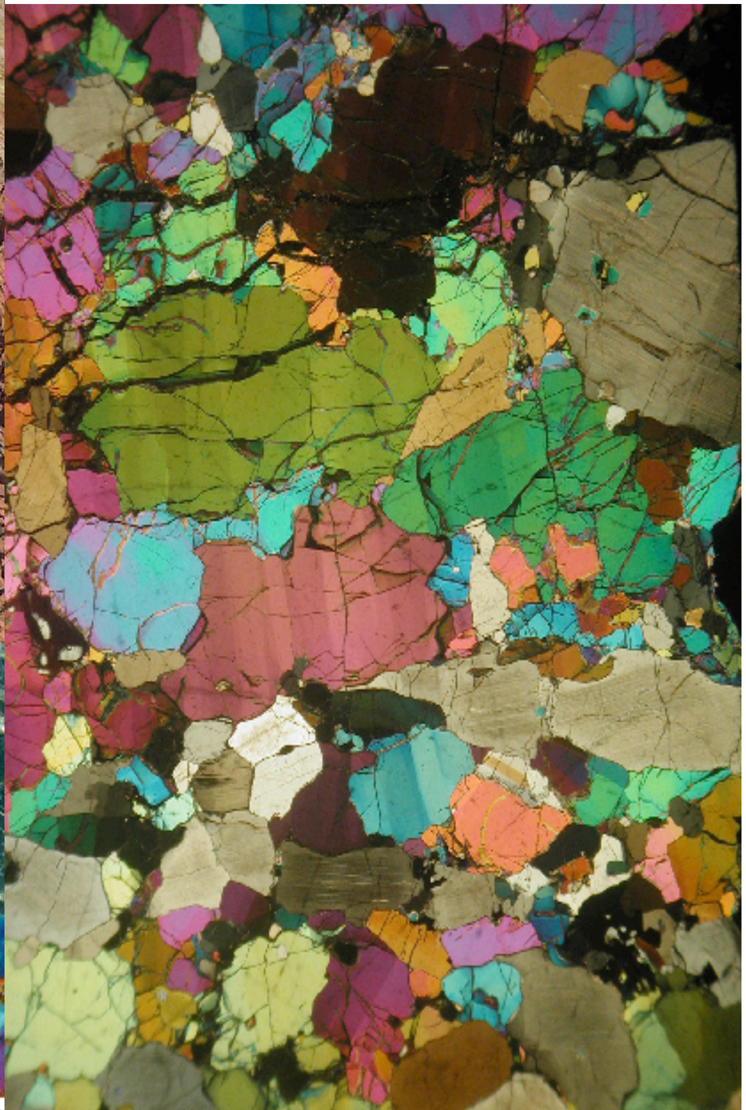


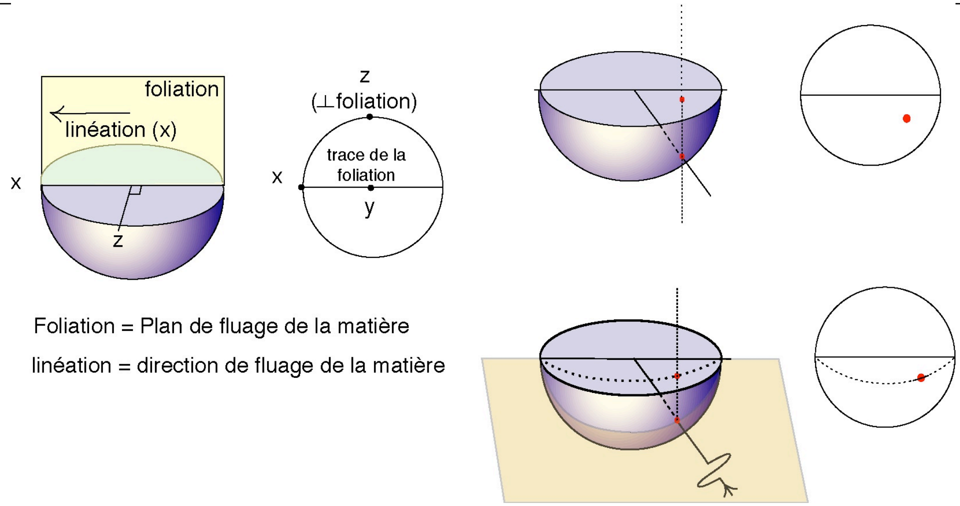


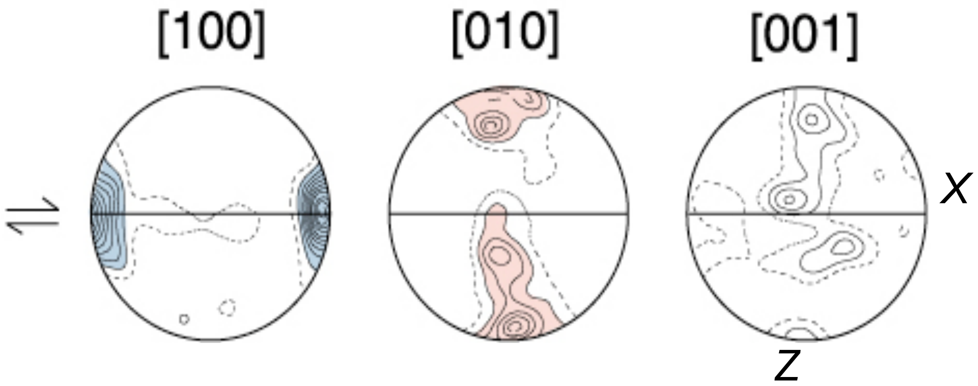
If the mantle beneath these stations was composed by a single olivine crystal, how should it be oriented?

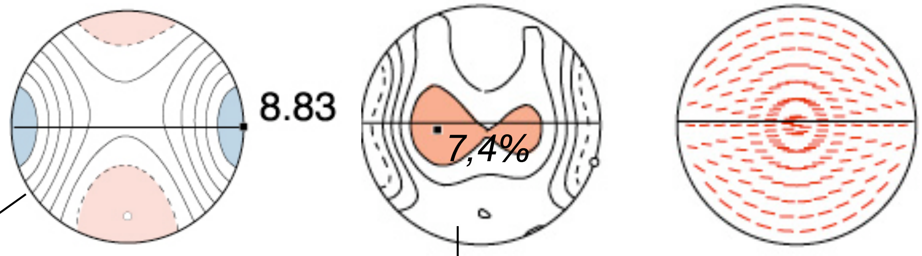
Single path = anisotropy only

The upper mantle is composed by peridotite = a polycrystalline aggregate (~60% olivine – 40% pyroxenes)…







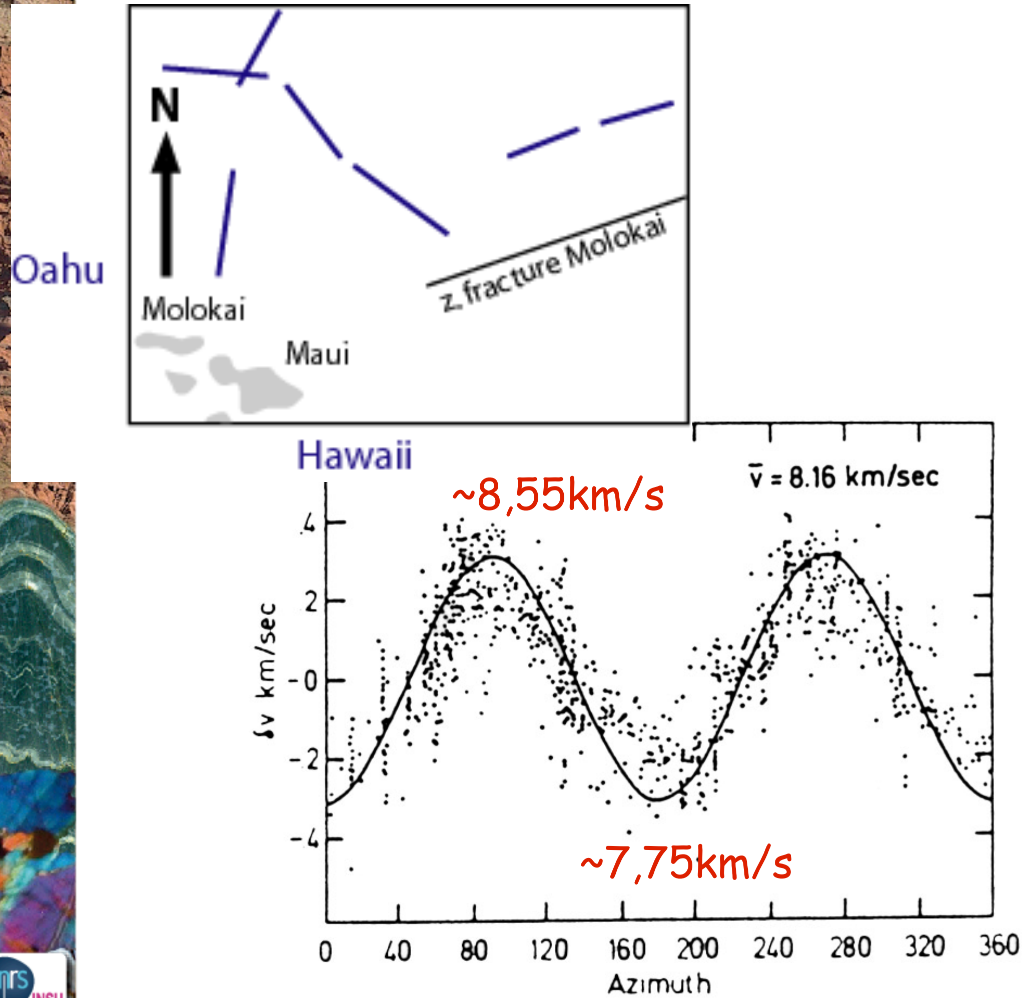


P-wave velocity: F(propagation direction)

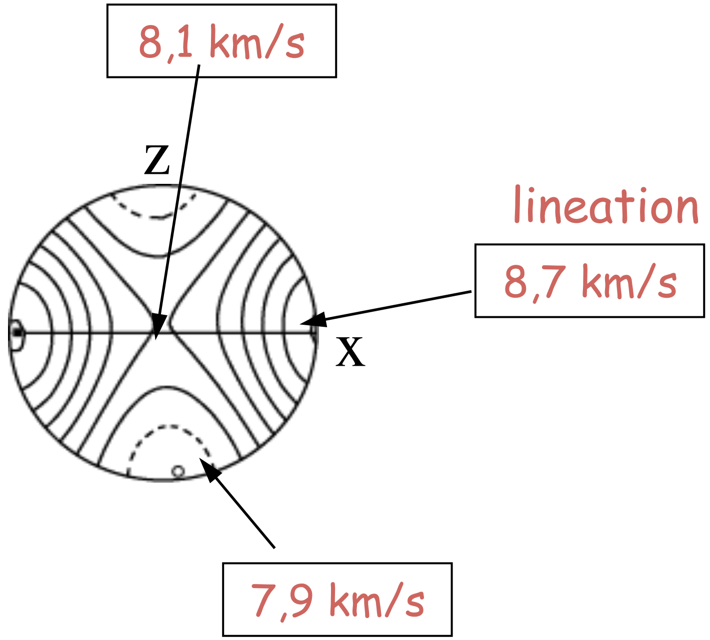
Amax=10%

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

And for a peridotite, how should the foliation and lineation be oriented to explain the N Pacific refraction data?

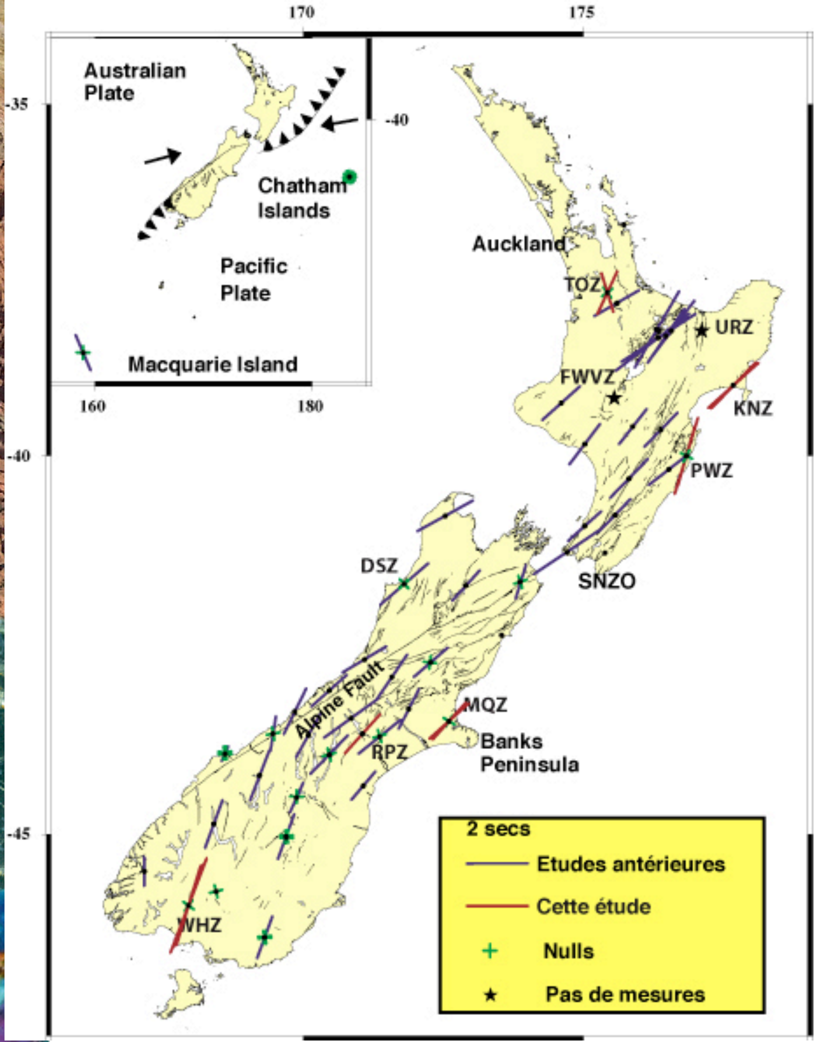


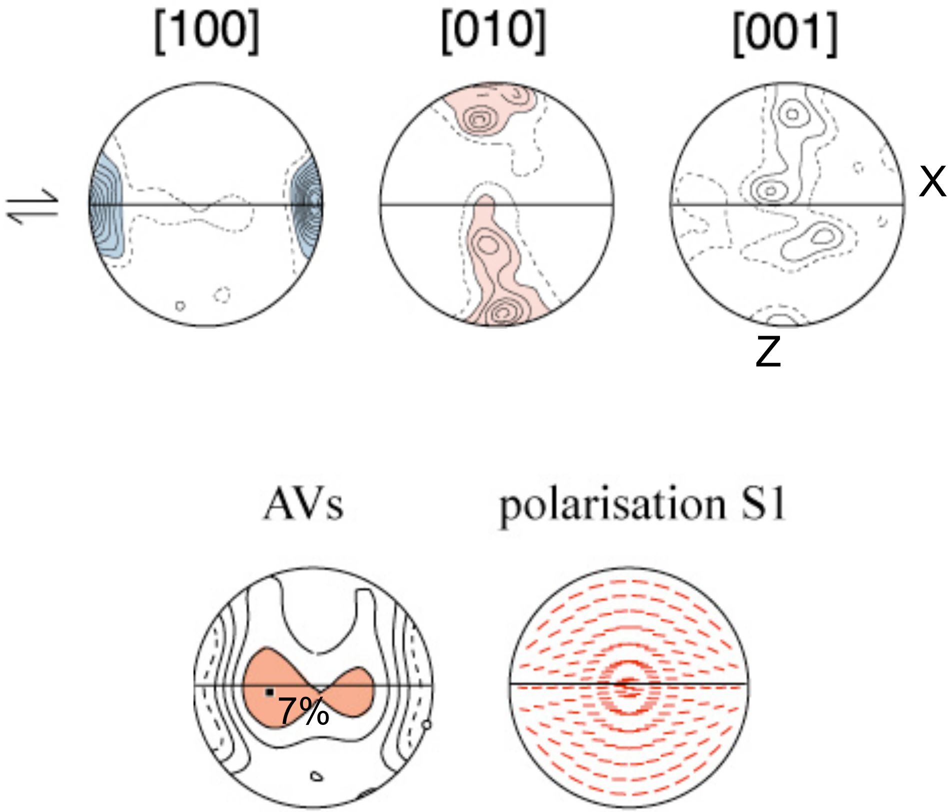
Morris et al., 1969



Is this consistent with what we expect in the shallow oceanic lithospheric mantle?

The upper mantle is composed by peridotite (~60% olivine – 40% pyroxenes)… How should the foliation and lineation be oriented to explain the New Zealand SKS splitting?



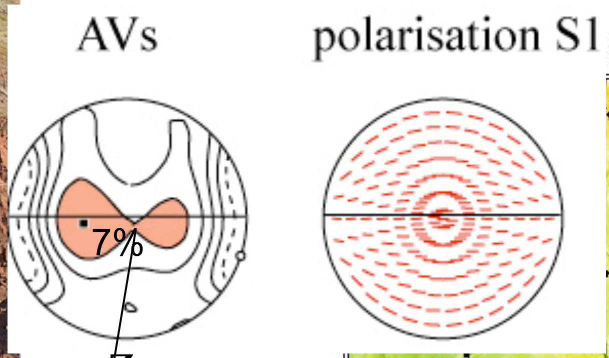


Vs1=4.9km/s
Vs2=4.6km/s

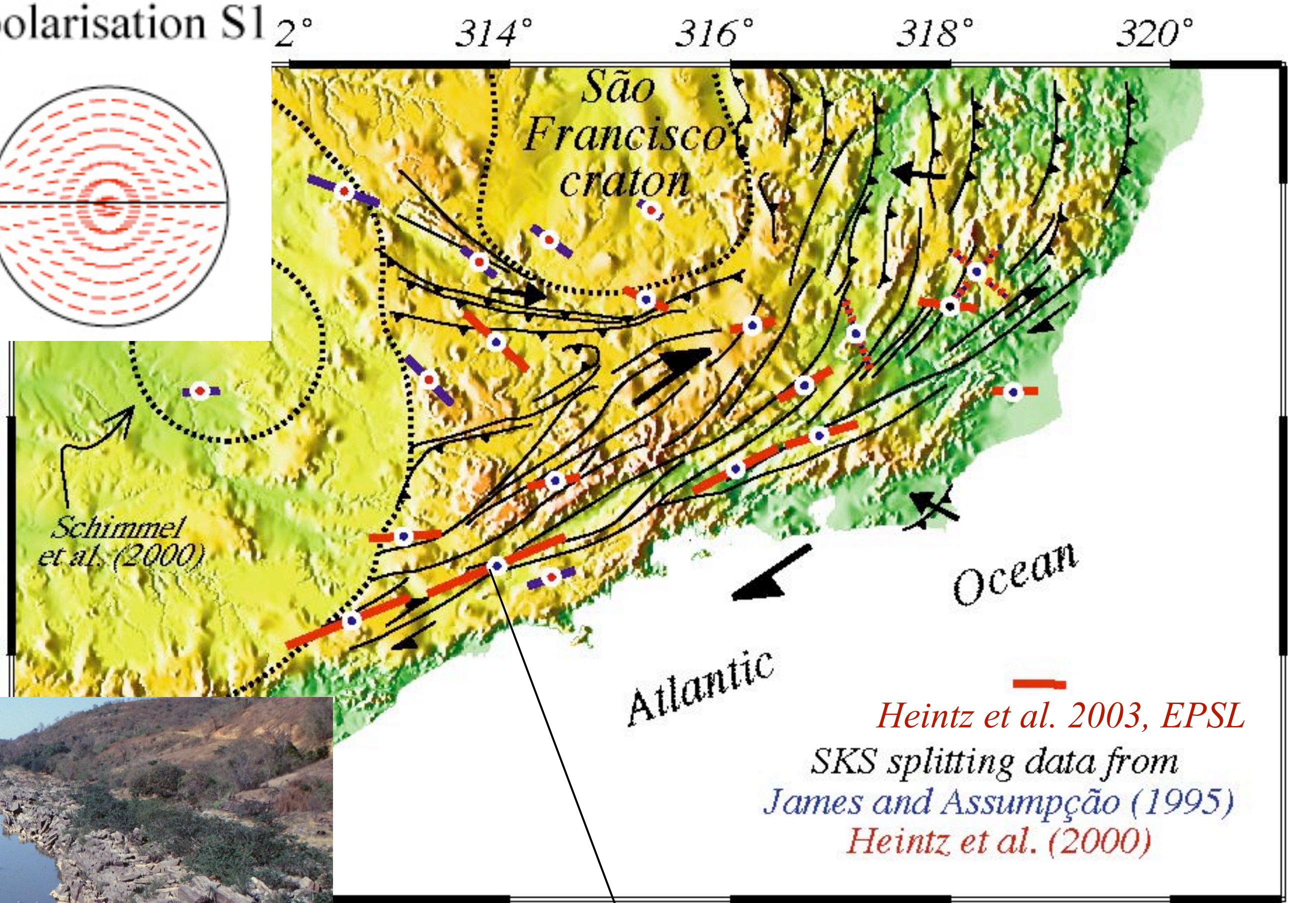
Is this consistent with what we expect beneath a transform? And in a subduction zone?

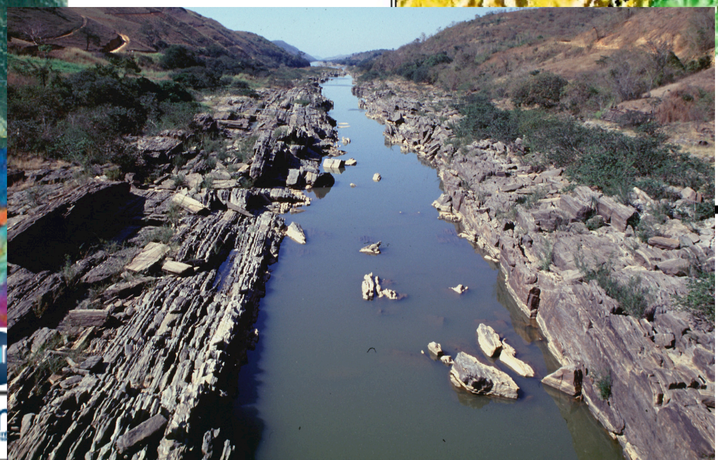
Shear wave splitting beneath an ancient tranpressive belt

in the Neoproterozoic Ribeira belt, SE Brazil



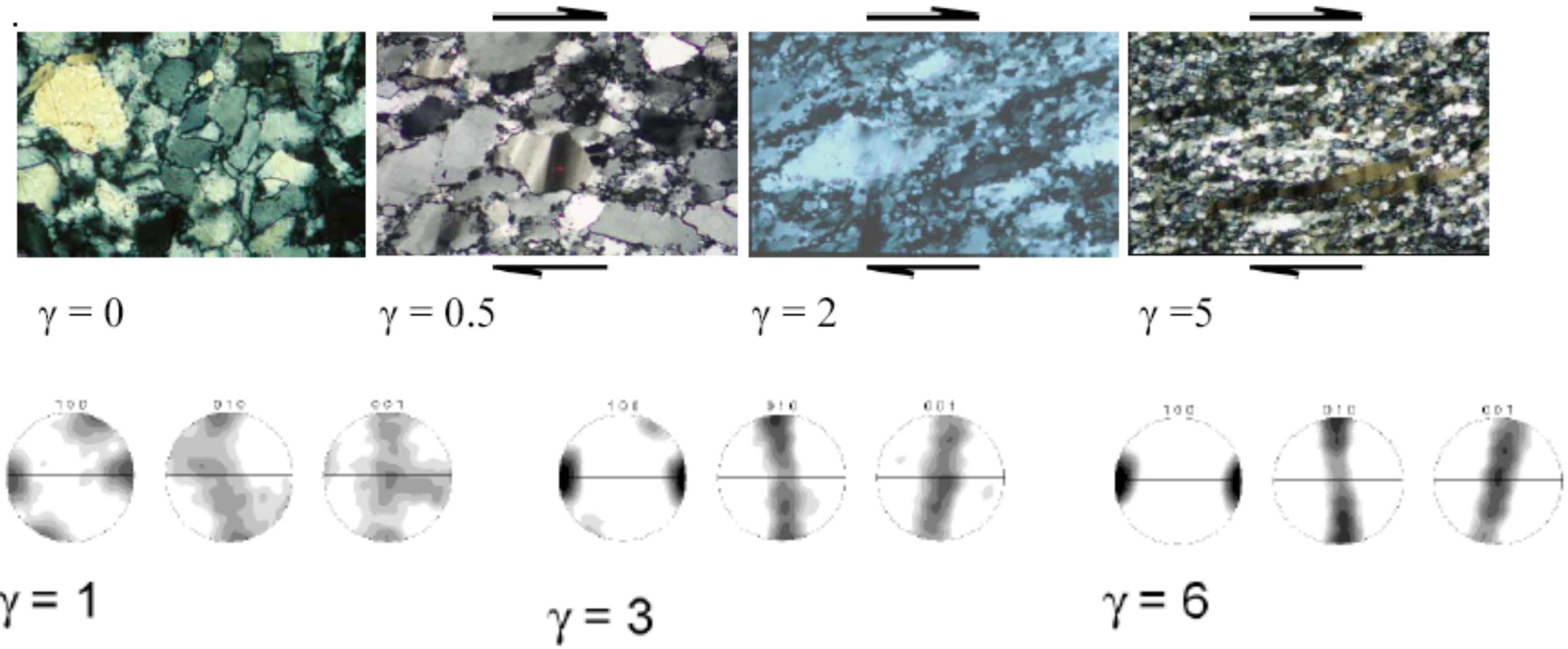
Vs1=4.9km/s
Vs2=4.6km/s





orientation of the lineation & foliation?
dt=2.5s: what does it mean?

Torsion experiments - high shear strains
CPO evolution as a function of strain



low strain:
fast CPO evolution

high strain:
very slow CPO evolution
[100] // shear direction

Bystricky et al. Science 2003

Seismic anisotropy - finite strain relationship

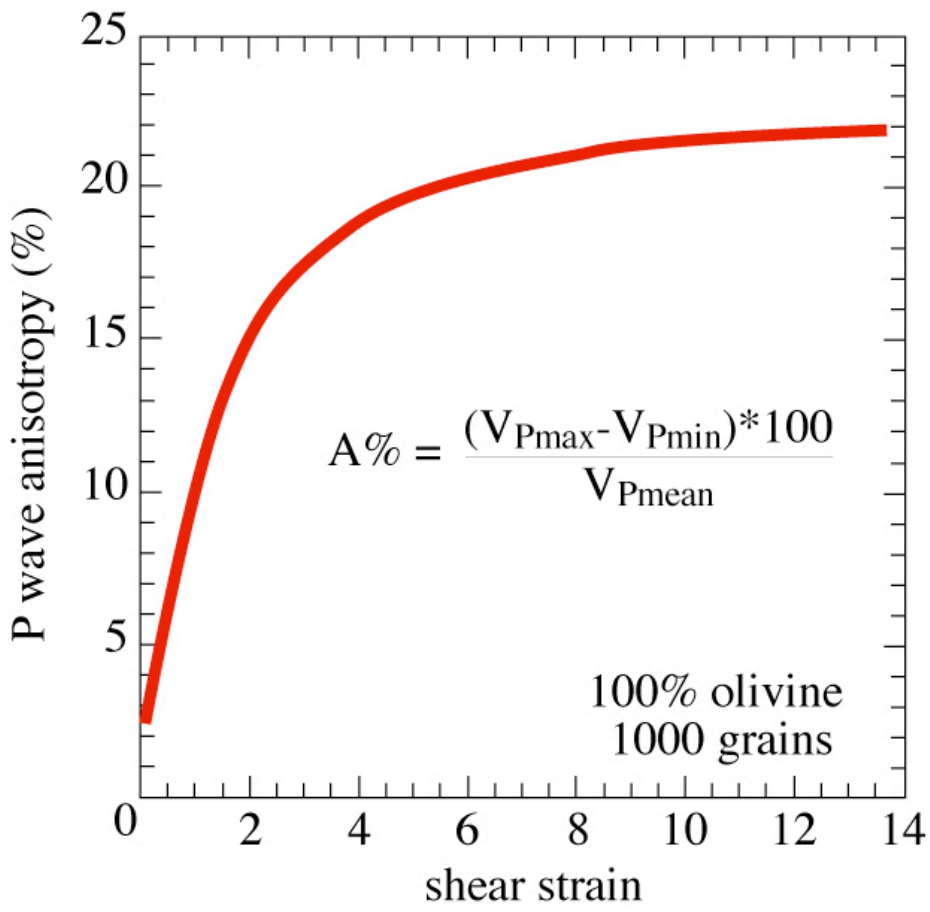
fast CPO development at low strain,
then stabililization

+

similar seismic anisotropy
dependence on CPO intensity

seismic anisotropy increases fast
for small strains, constant at high strains

✓ *shear wave splitting : delay times*
F(thickness of anisotropic layer)



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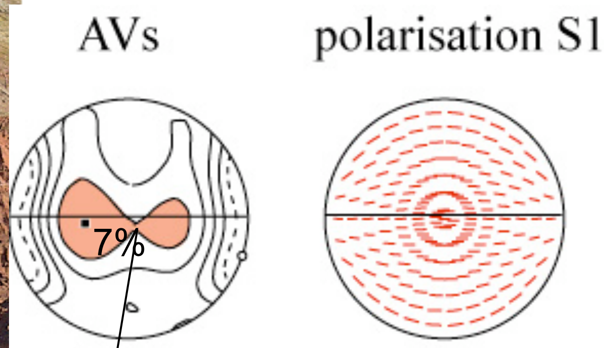
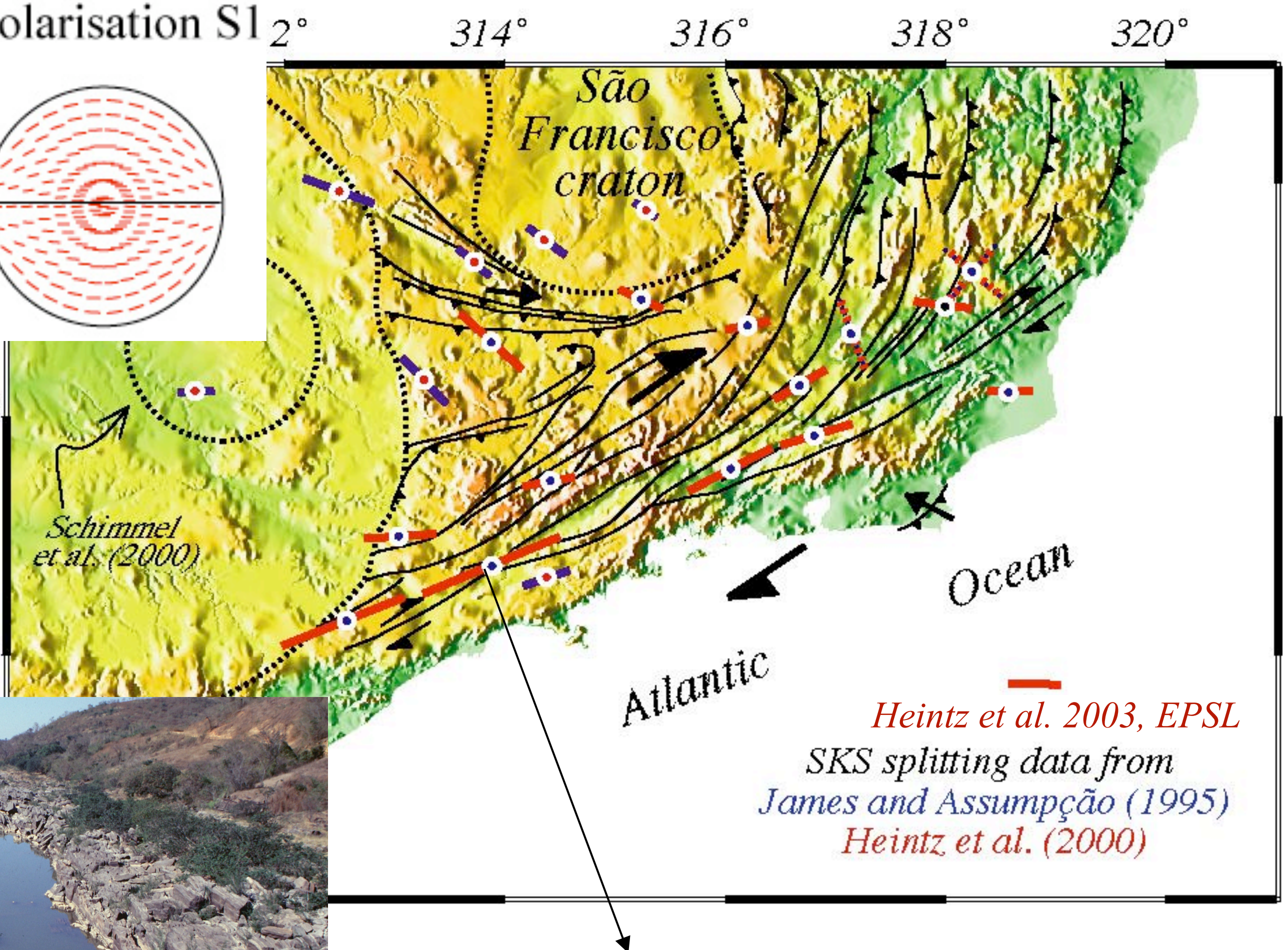
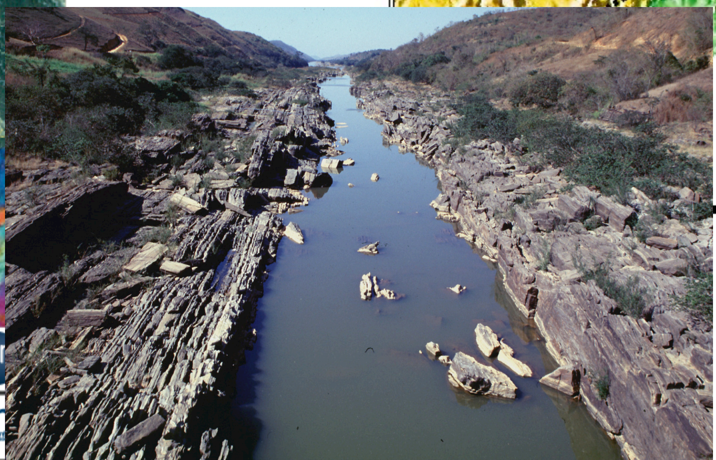
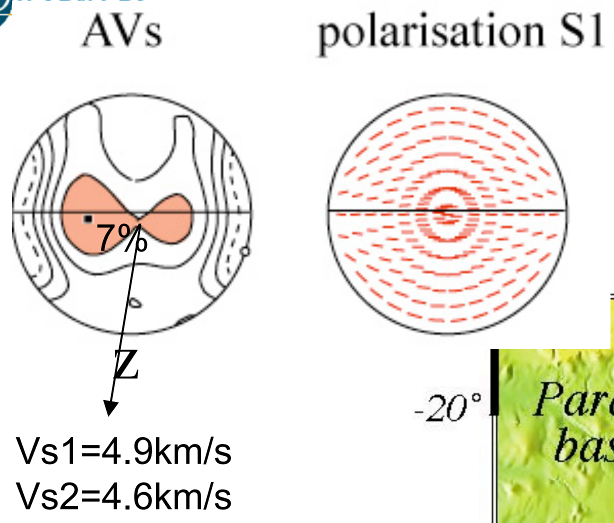
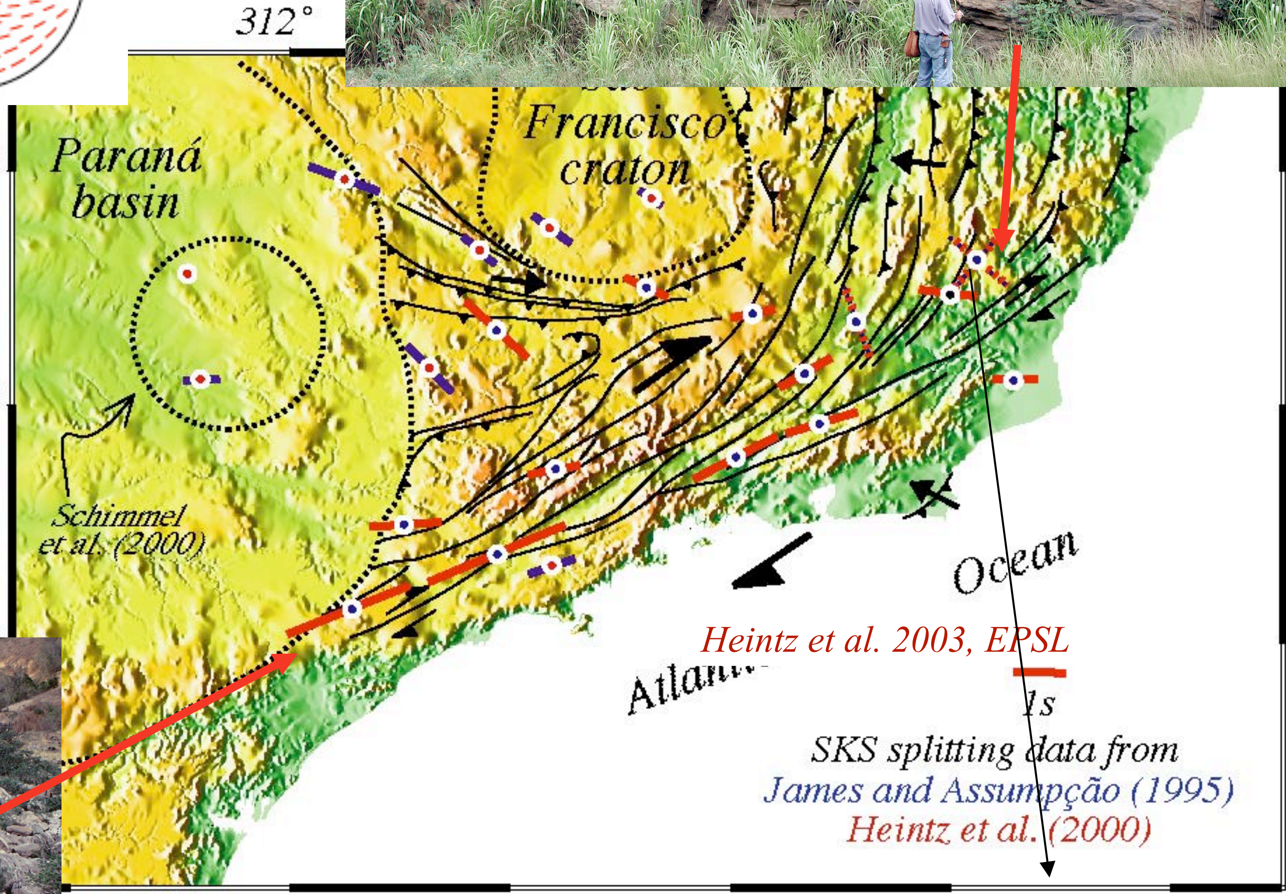






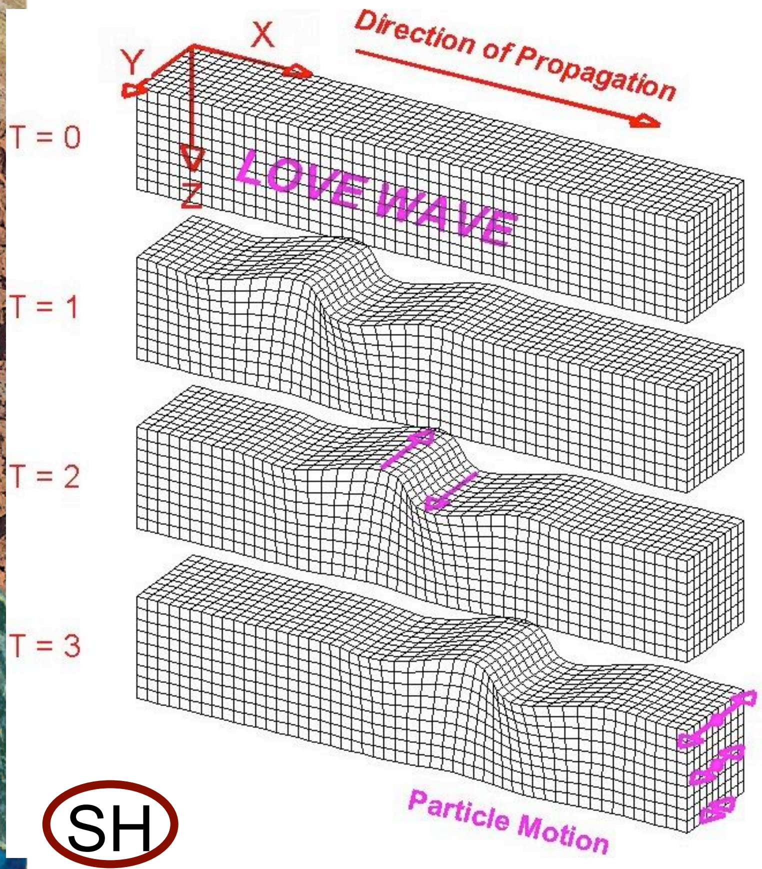
dt=2.5s: how thick is the anisotropic layer?

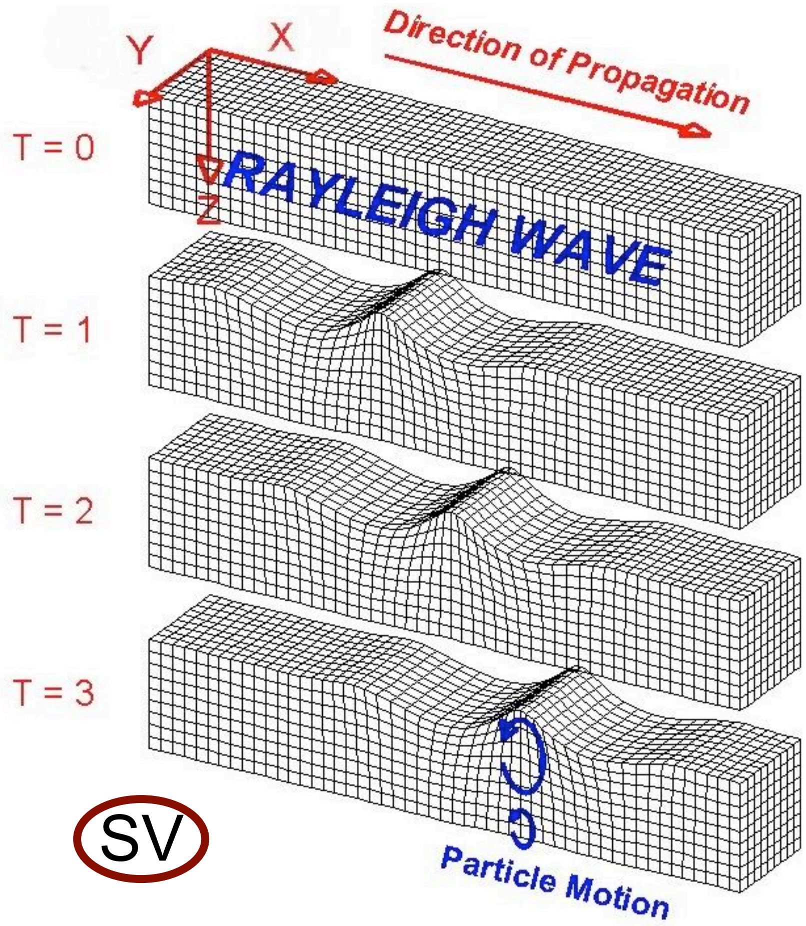




How can we explain the N-S difference in delay time?

Surface waves: Love & Rayleigh

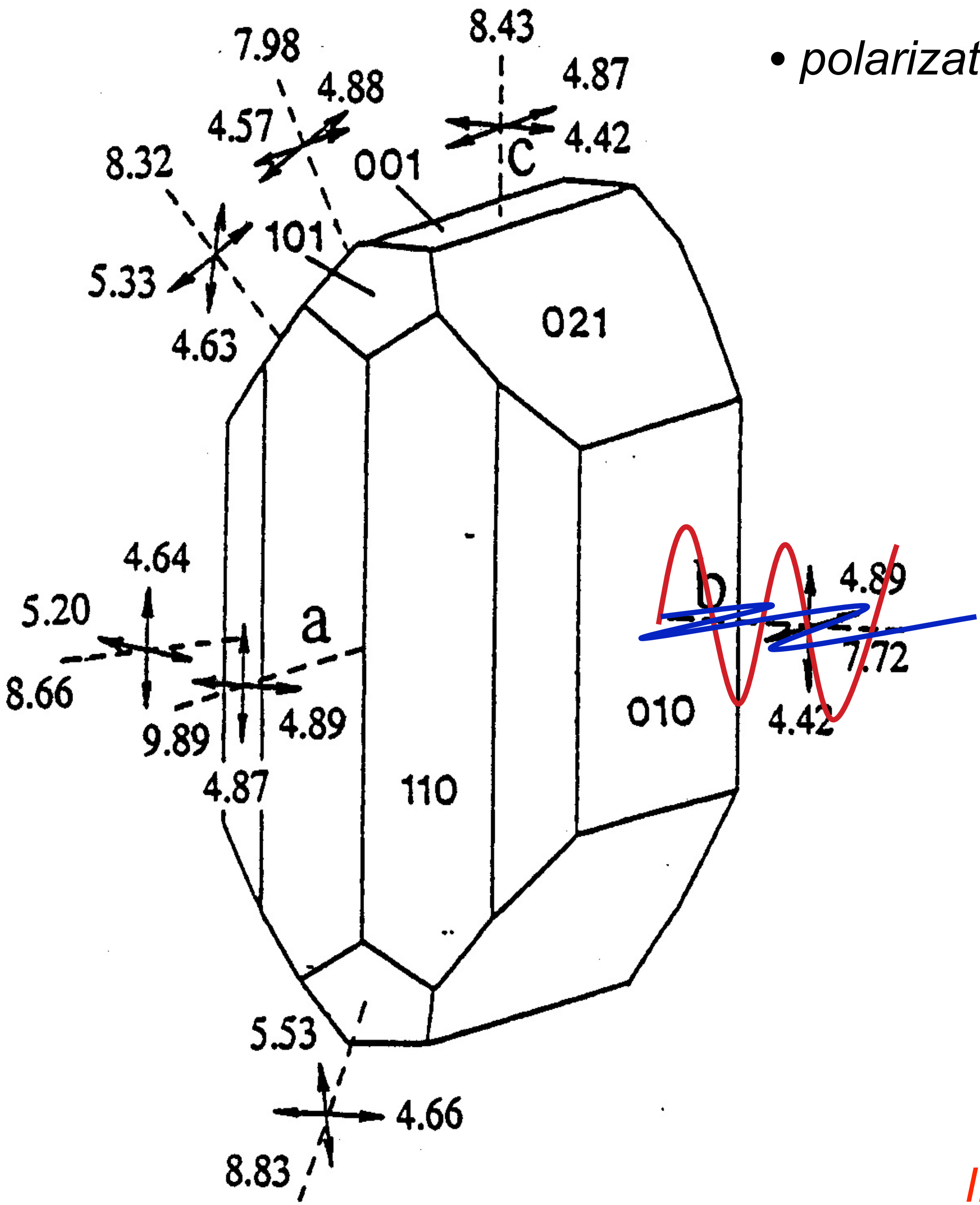




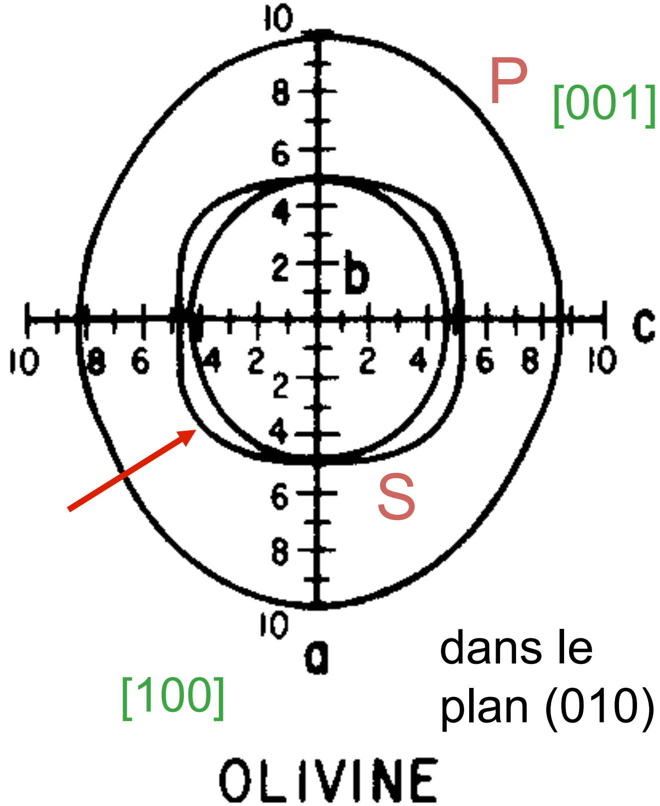
- *Why SH et SV?*
- *How can we measure a propagation and a polarization anisotropy?*

Surface waves: Love (SH) & Rayleigh (SV)

- *polarization anisotropy*



vitesses P e S (km/s)



dans le plan (010)

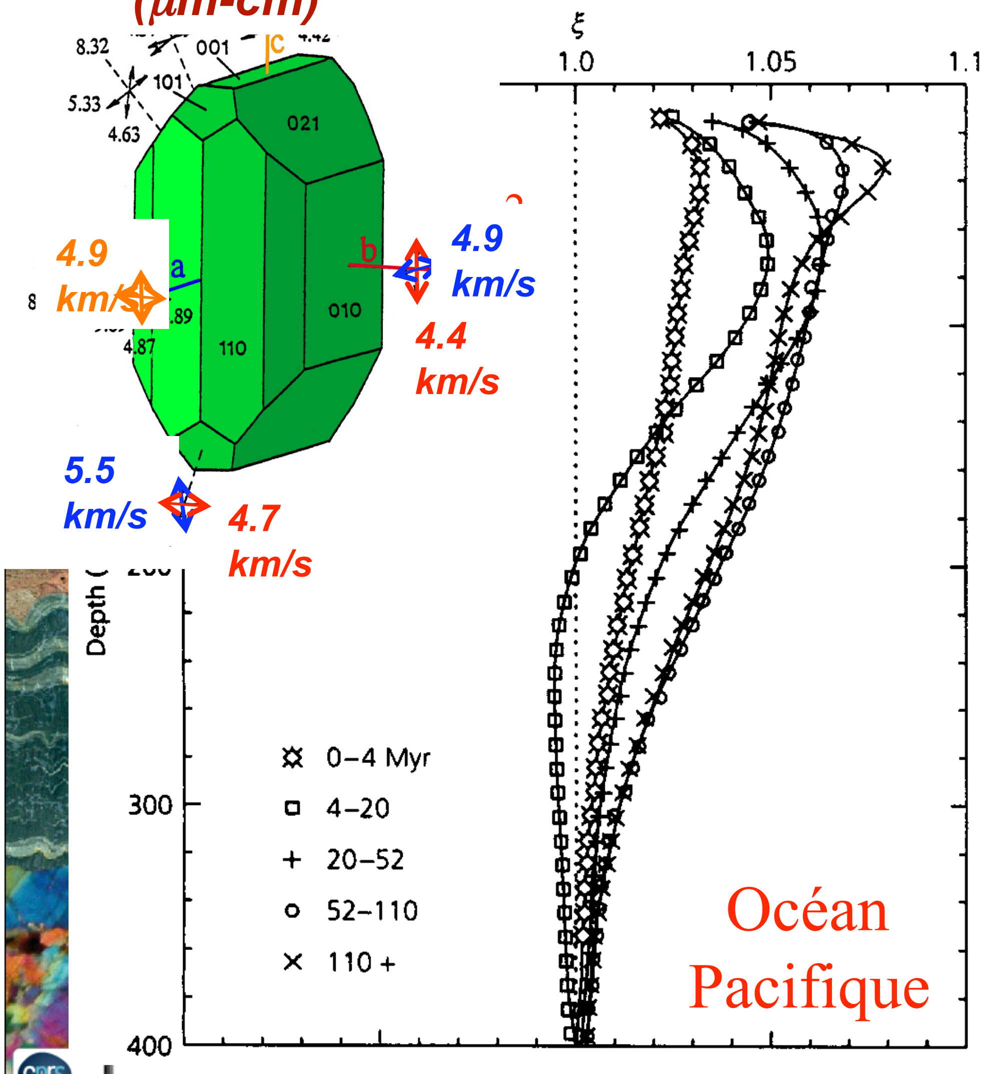
Nicolas & Christensen, AGU, 1987

If the represented plane is horizontal, who is faster? SV ou SH?

Surface waves: Love (SH) & Rayleigh (SV)

- *polarization anisotropy*

Olivine cristal (μm-cm)

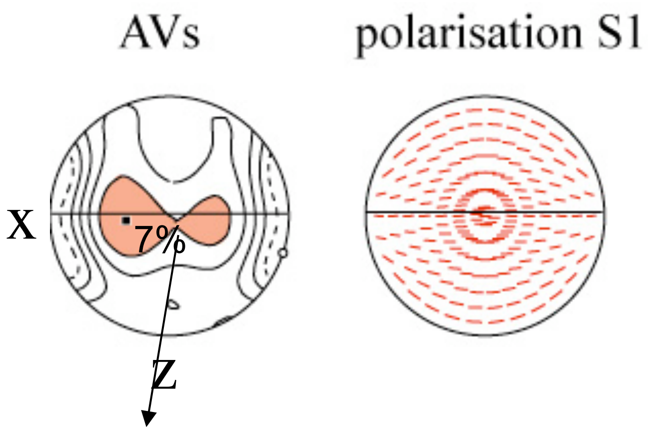


Nishimura & Forsyth, 1989

If the mantle beneath these stations was composed by a single olivine crystal, how should it be oriented?

1. *Propagation direction(s)?*
2. *Which is the fast polarisation for this propagation?*

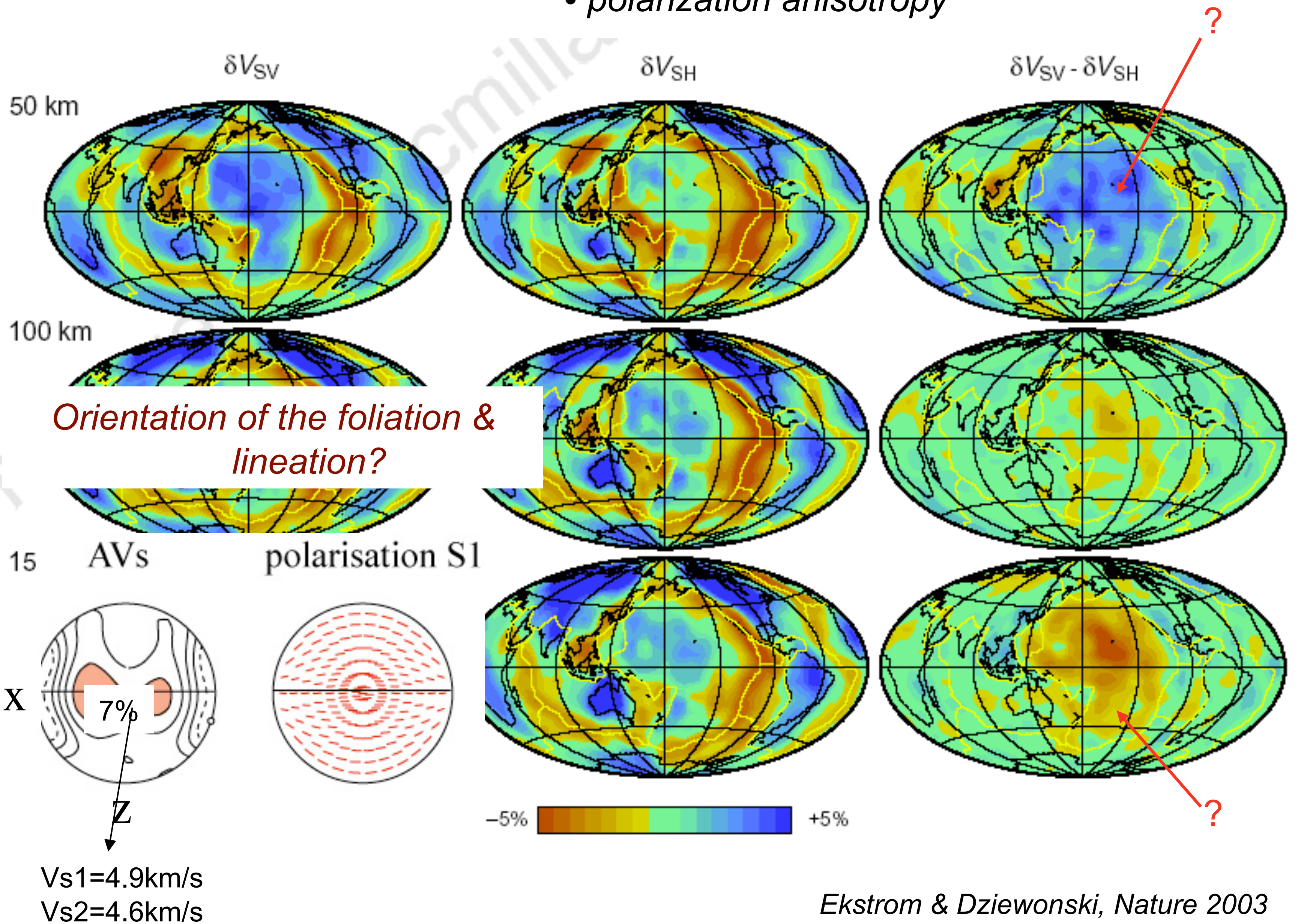
And a peridotite?



Vs1=4.9km/s
Vs2=4.6km/s

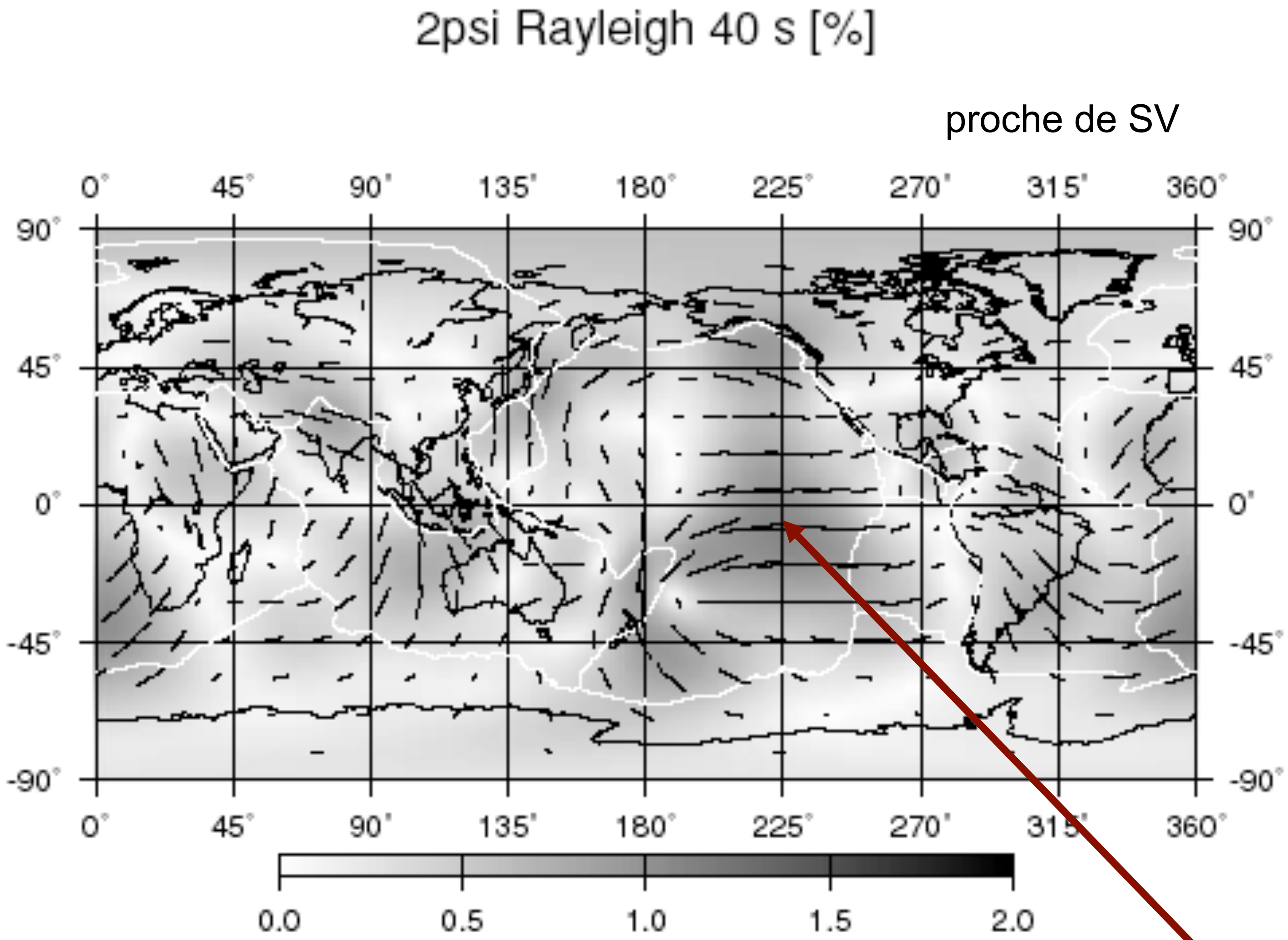
Surface waves: Love (SH) & Rayleigh (SV)

- *polarization anisotropy*



Ekstrom & Dziewonski, Nature 2003

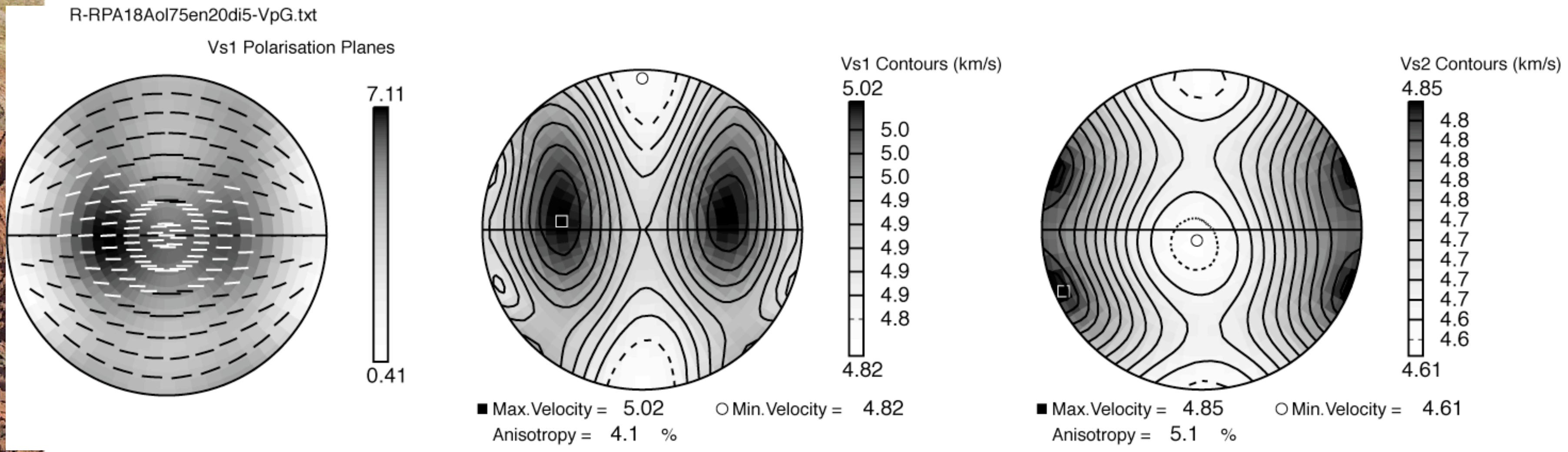
Rayleigh azimuthal anisotropy

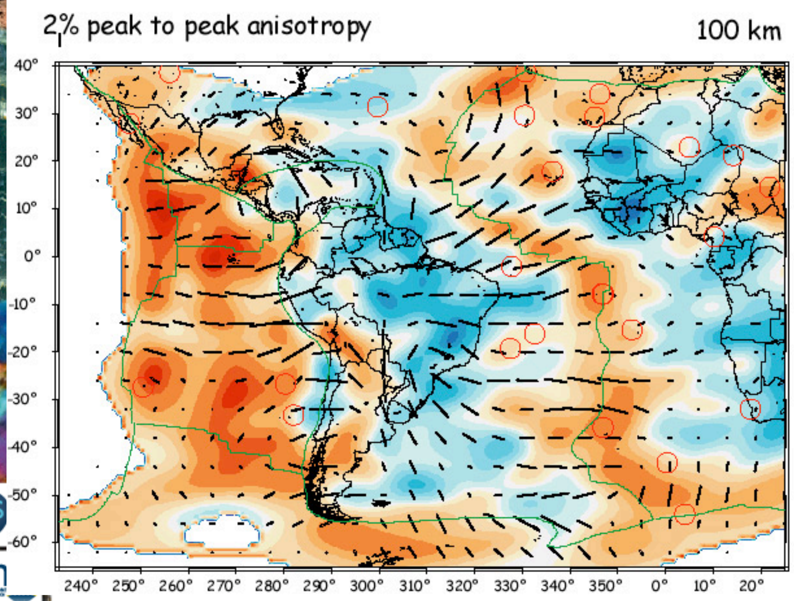


Olivine crystal orientation needed to explain SH>SV + propagation anis of Rayleigh?

Trampert & Woodhouse, GJI 2003

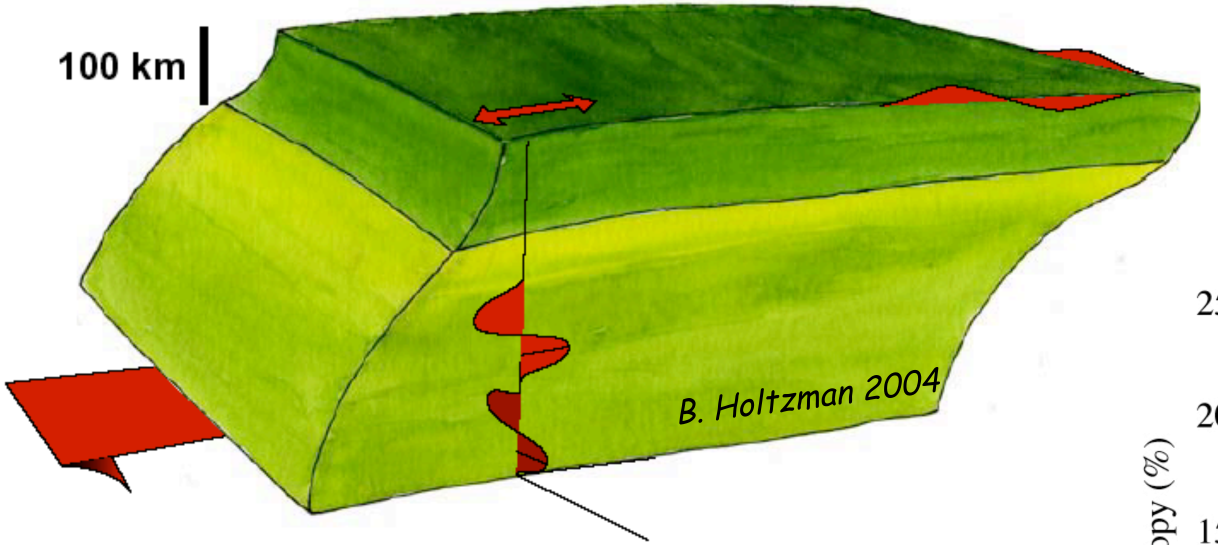
Rayleigh azimuthal anisotropy





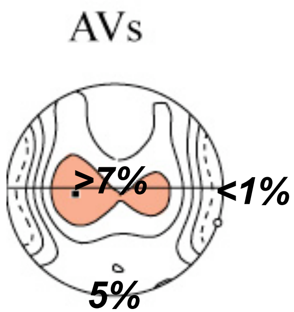
Orientation of the foliation & lineation to explain the azimuthal propagation anis of Rayleigh in the oceanic basins, knowing that SH>SV in oceans?

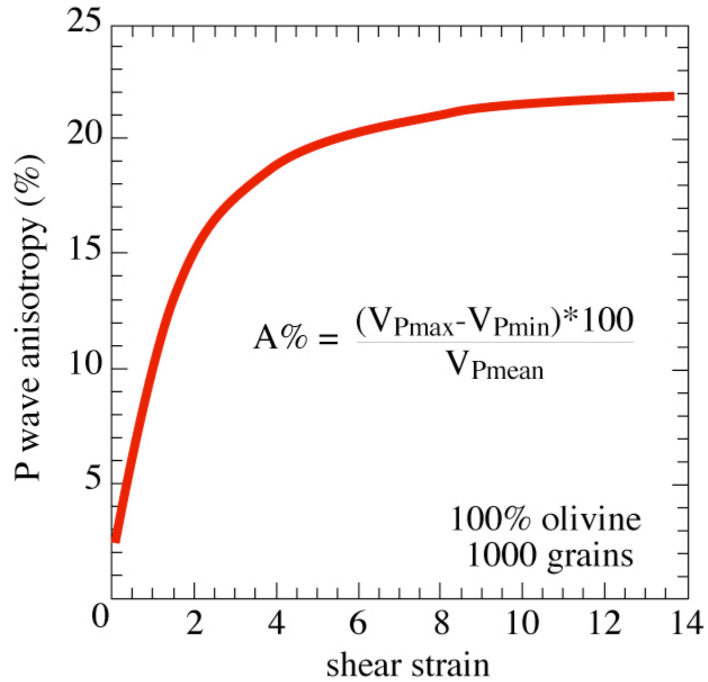
Simple key to qualitatively "read" seismic anisotropy observations in the SHALLOW MANTLE (>250 km):



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

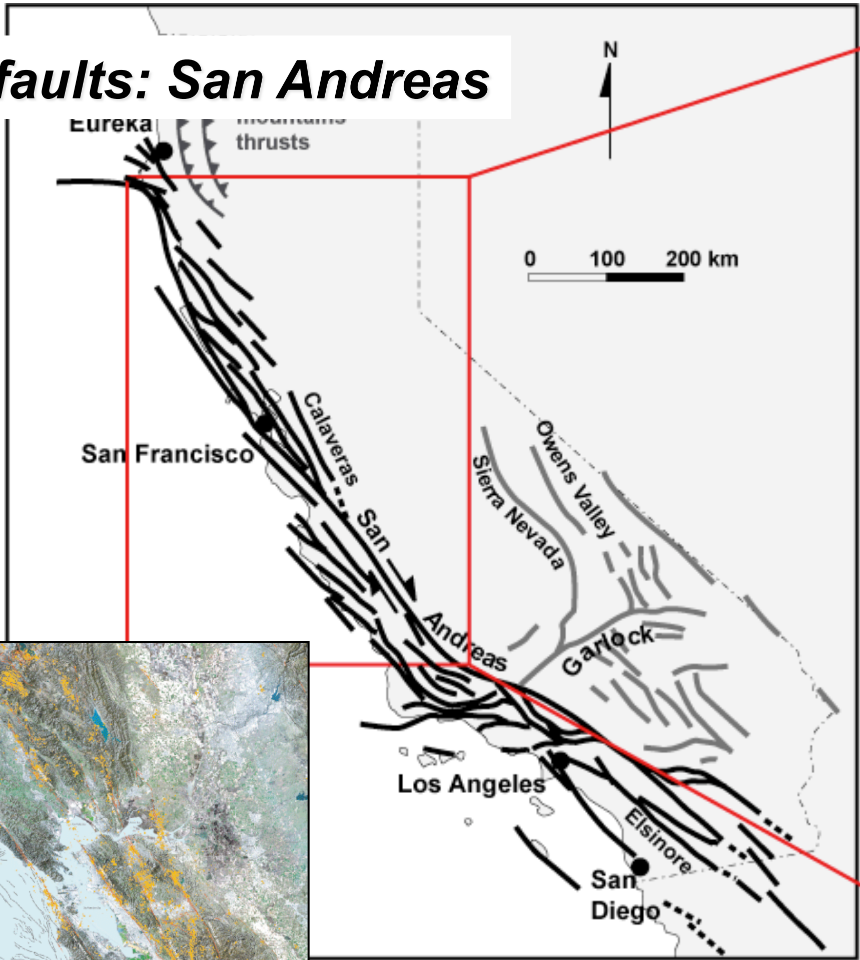
delay time ~ thickness of the anisotropic layer and orientation of the flow plane

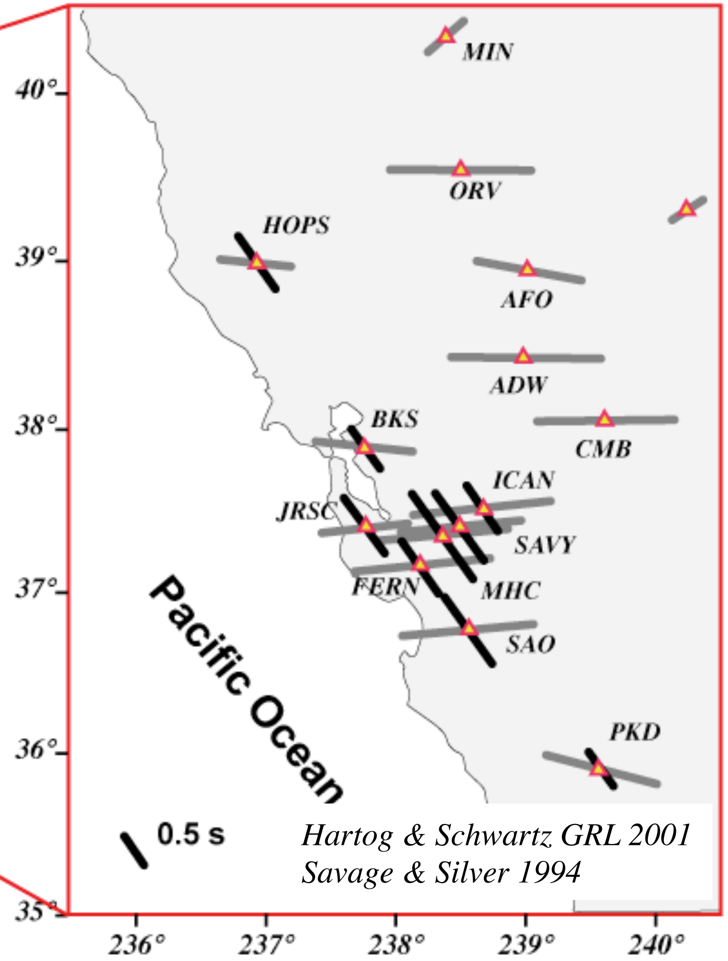


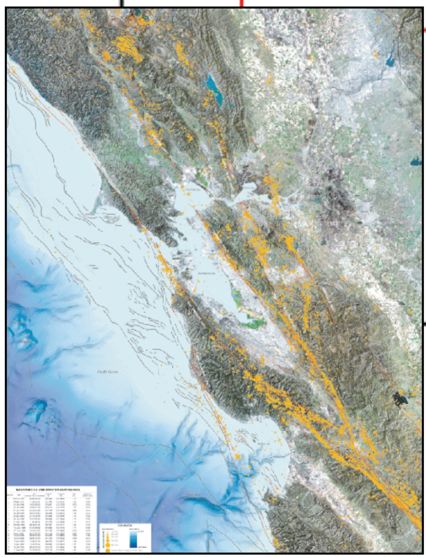


Seismic anisotropy in large-scale strike-slip faults: crust - mantle coupling

Active faults: San Andreas

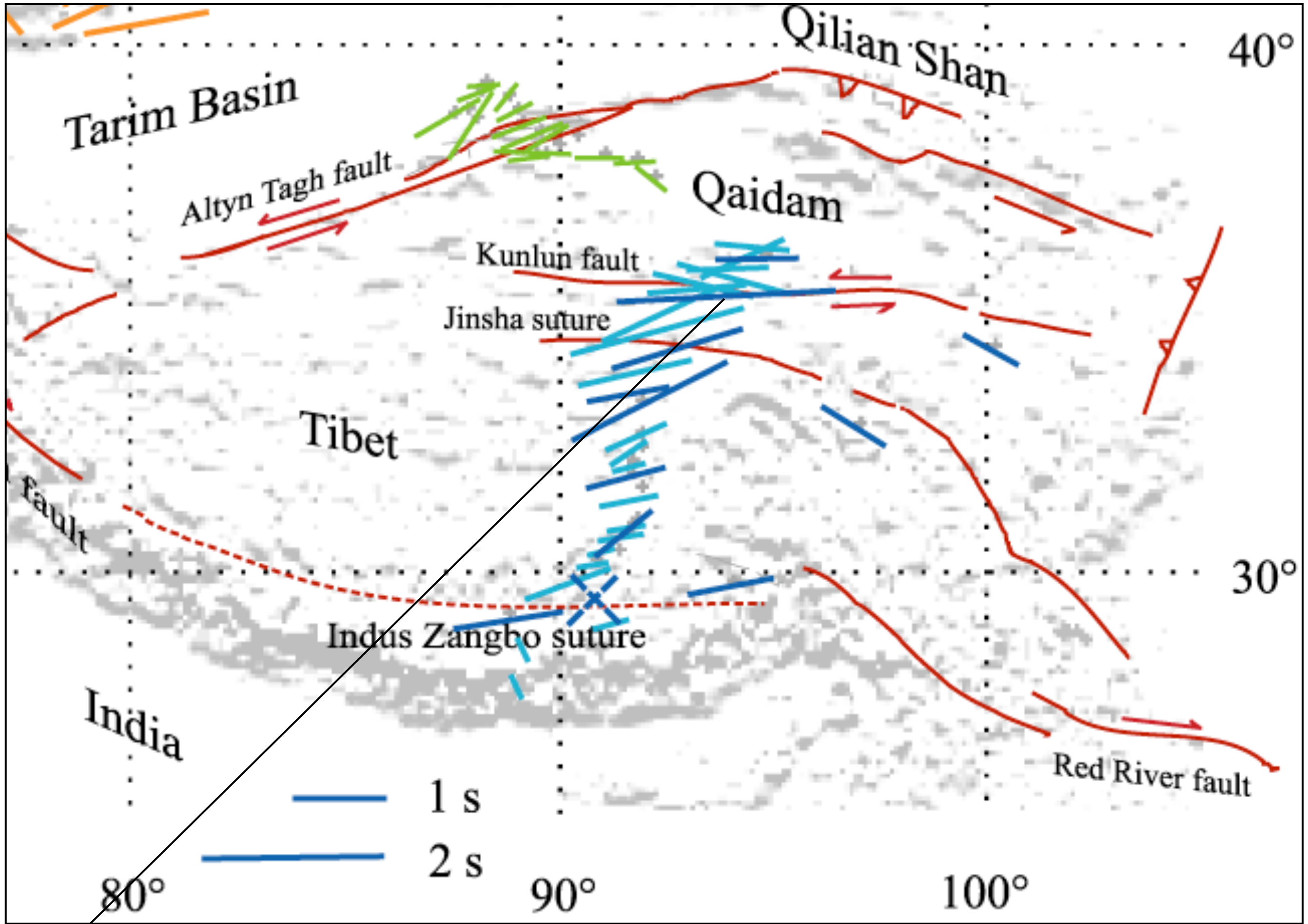






upper anisotropy layer: lithospheric mantle flow // fault

Tibet large strike-slip faults



Herquel et al. 1999

>2s! lithosphere-asthenosphere coupling?

North Anatolian Fault: no associated anisotropy?

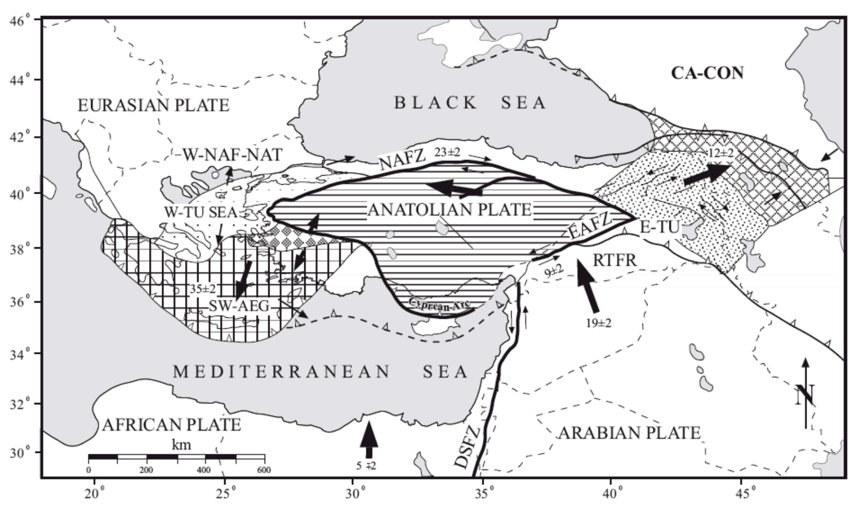
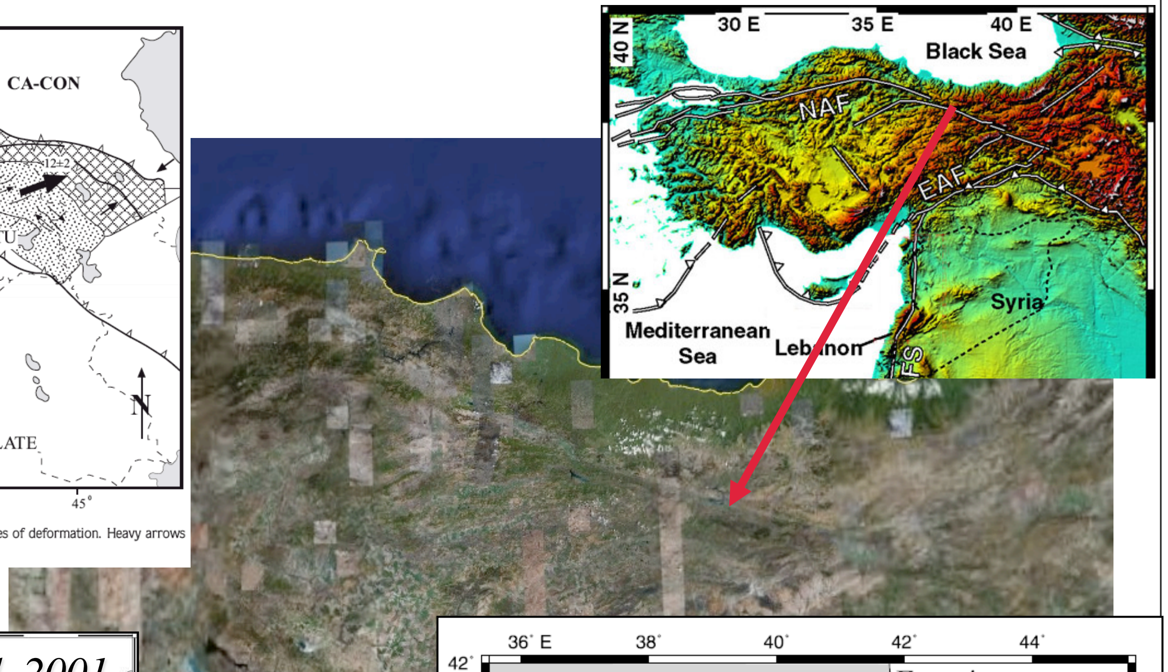
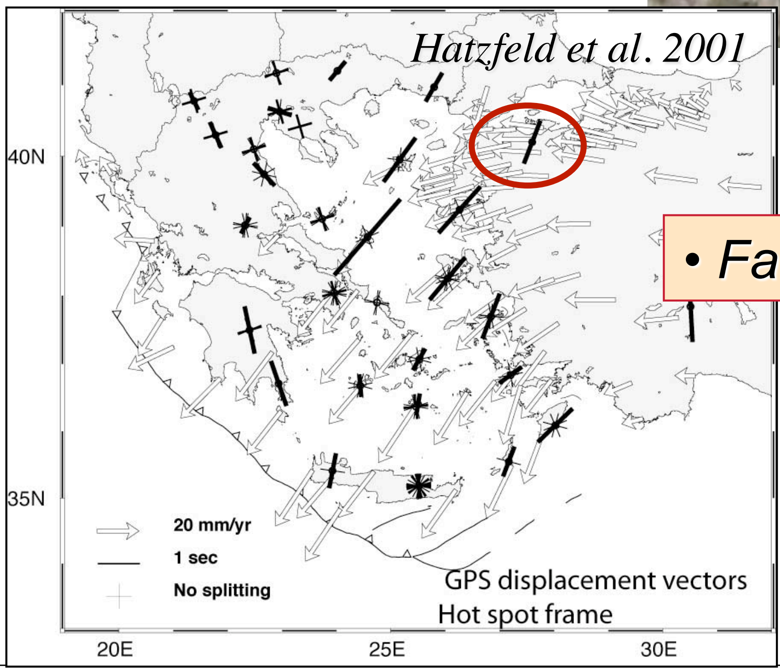
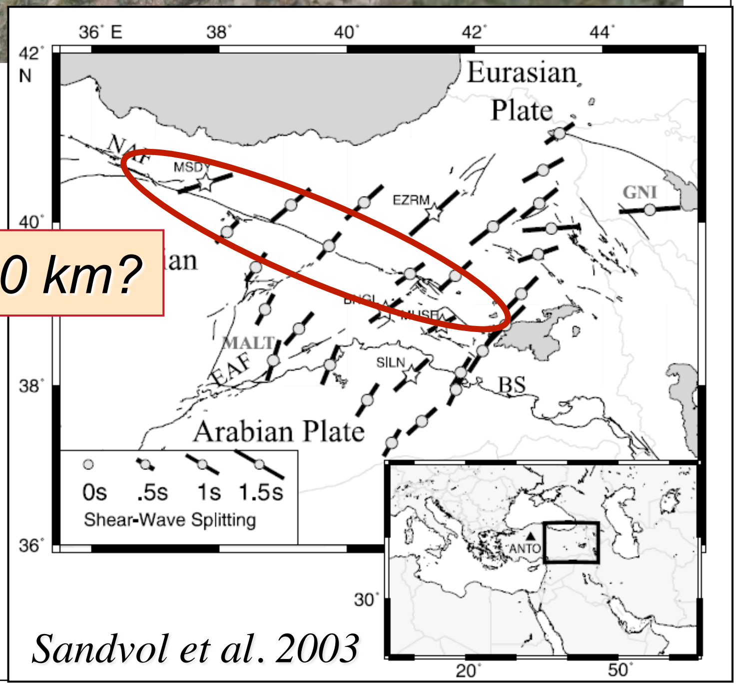


Figure 1. Kinematics of Turkey and surrounding area. Hatched areas show the coherent motion of specific zones of deformation. Heavy arrows indicate the generalised regional motions in mm/yr (after McClusky *et al.* 2000).

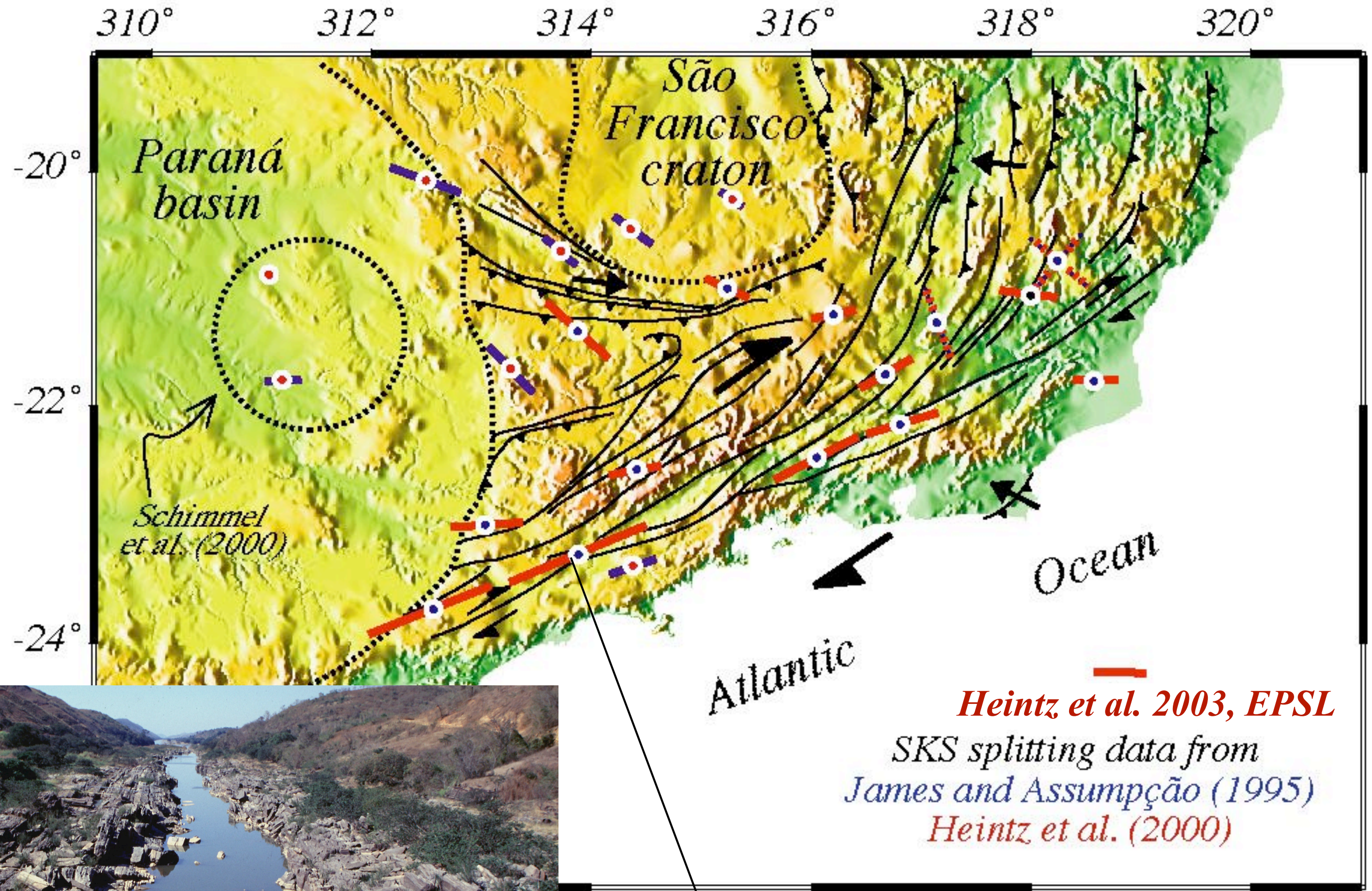


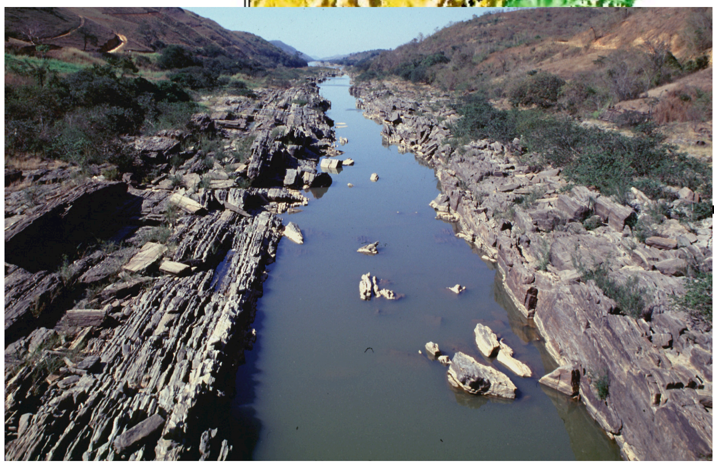


• *Fault width < 50 km?*



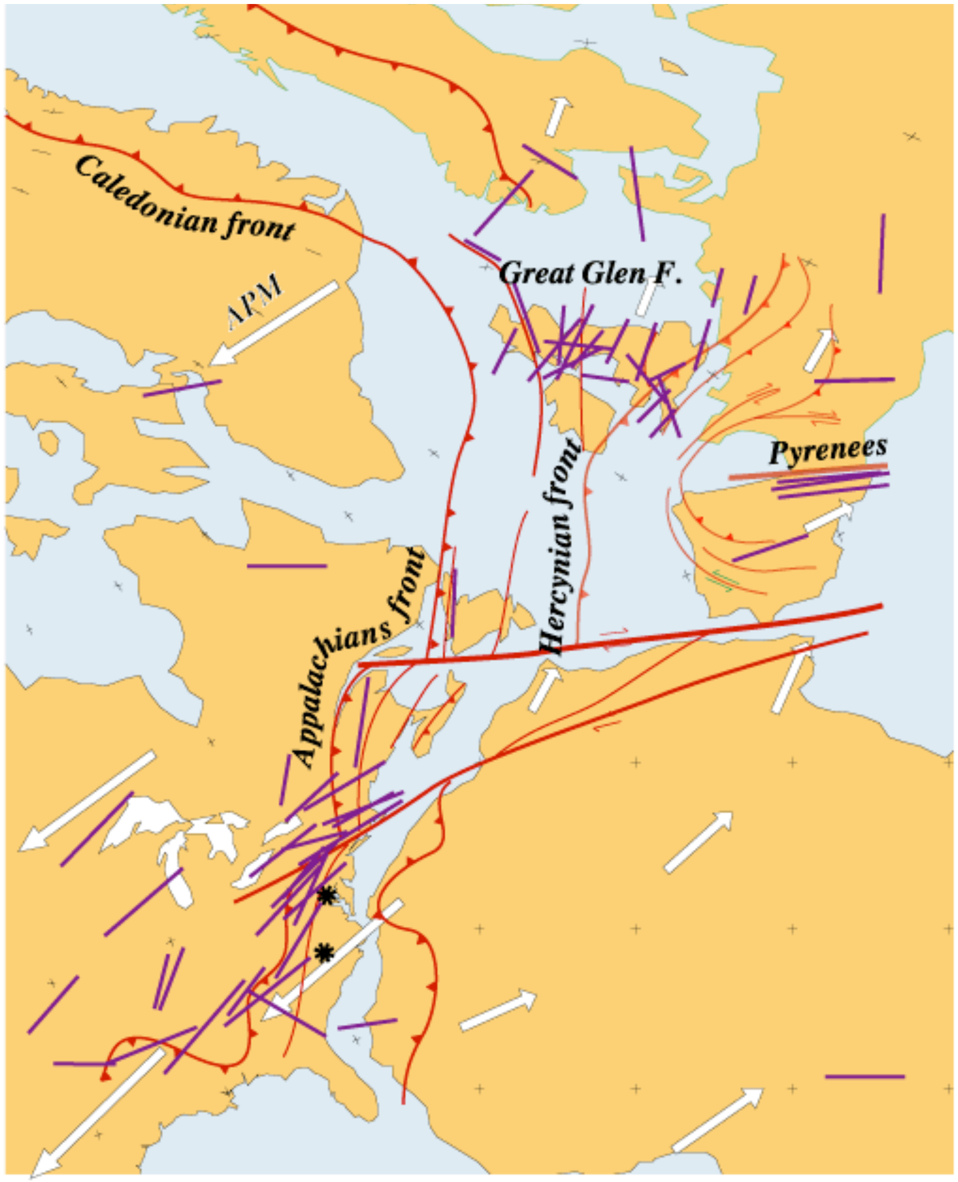
Old transpressional belts: large scale strike-slip faults
frozen-in lithospheric fabric



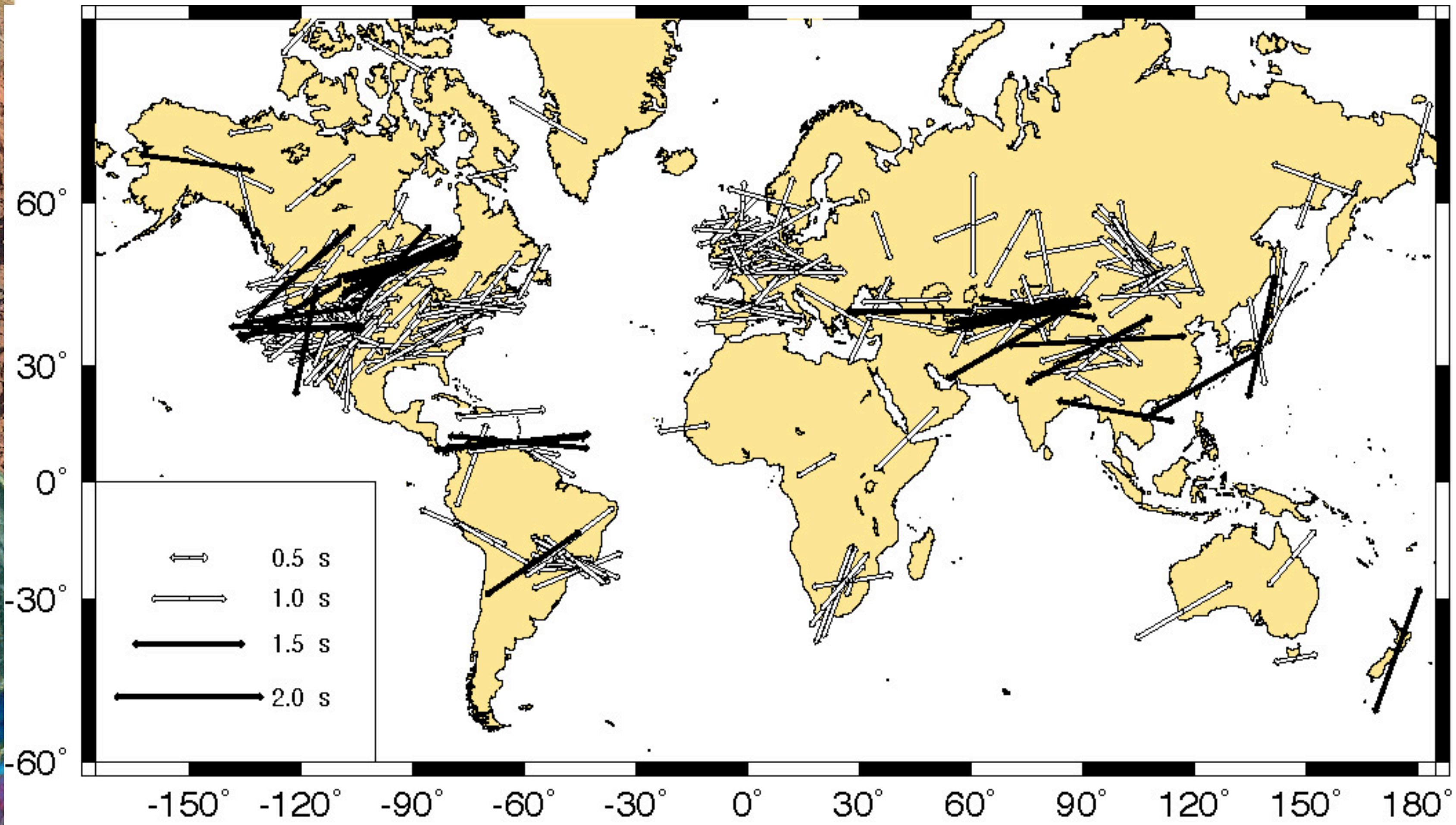


dt=2.5s
coherent asthenospheric flow?

Old transpressional belts: large scale strike-slip faults frozen-in lithospheric fabric

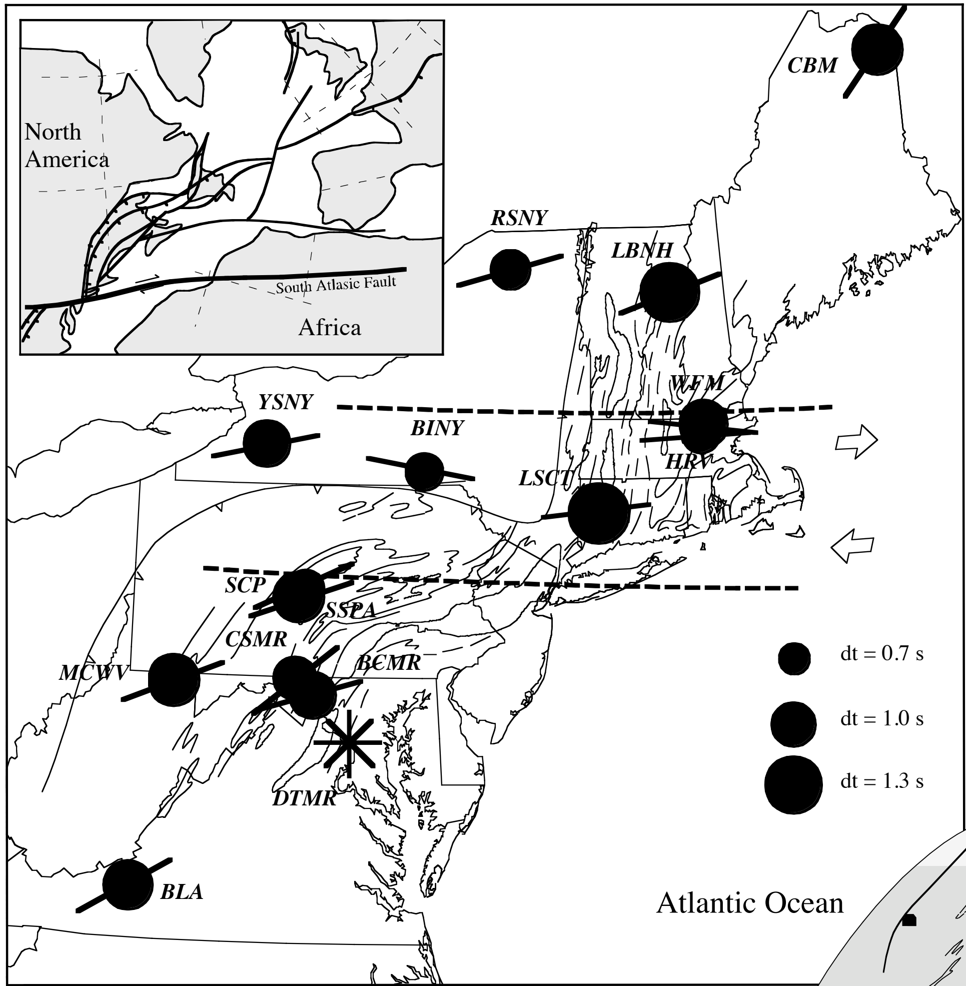


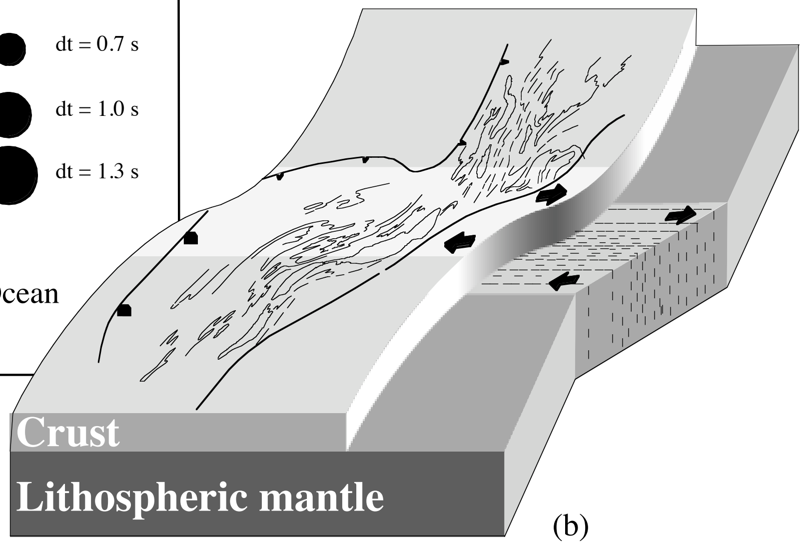
Shear wave splitting: polarization anisotropy



Silver (1996)

SKS : lithospheric or asthenospheric deformation?



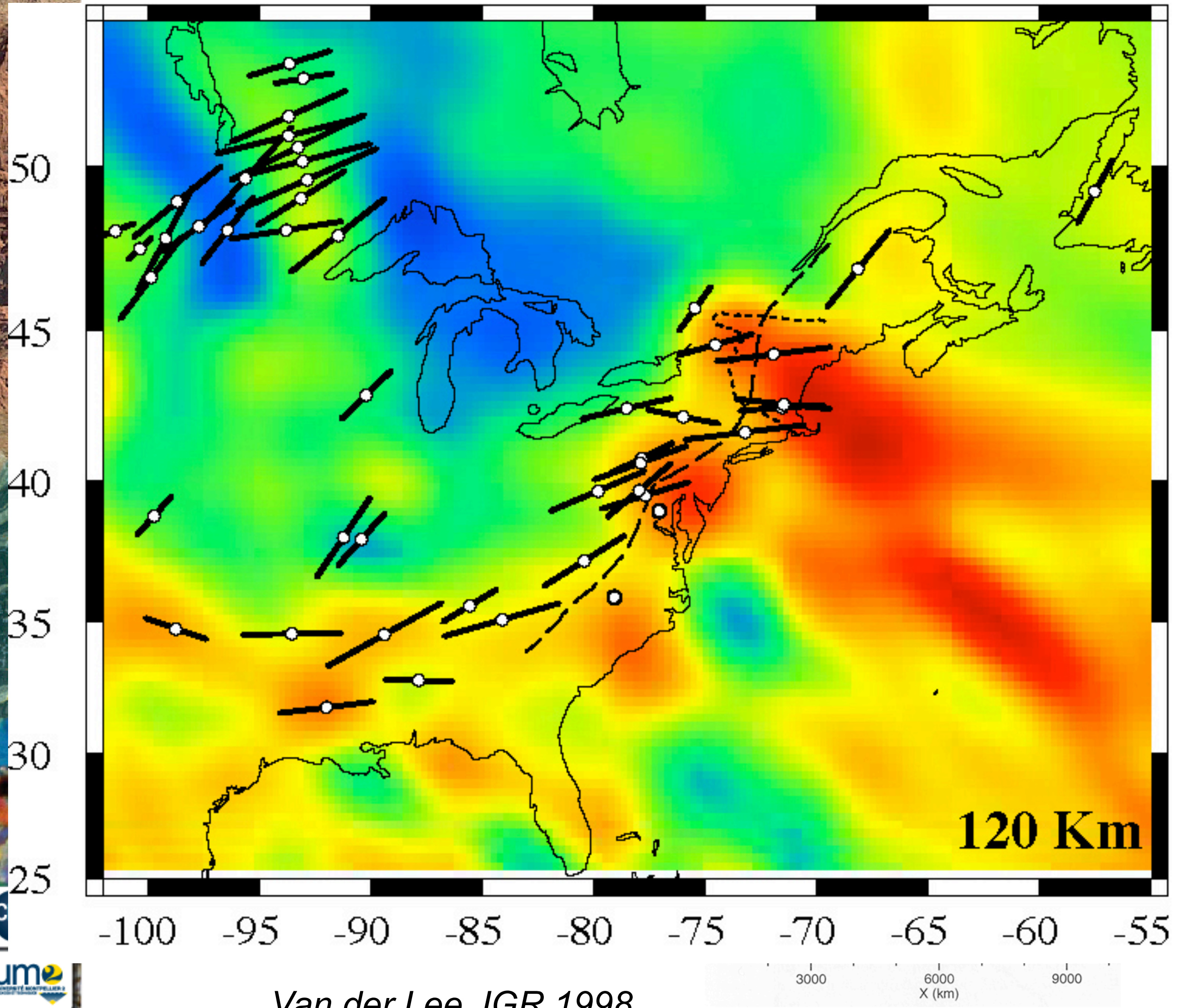


(b)

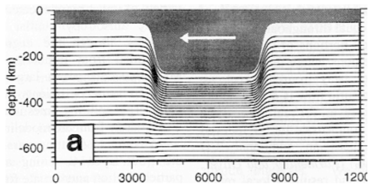
Barruol et al. JGR 1997

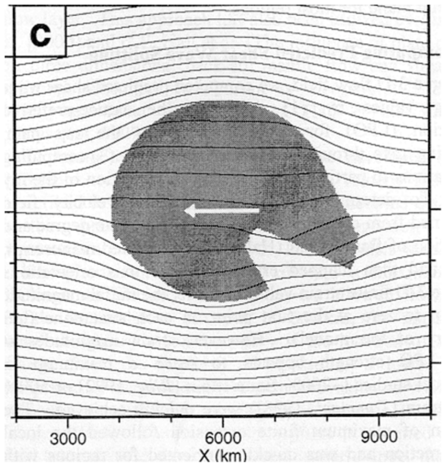
SKS : lithospheric or asthenospheric deformation?

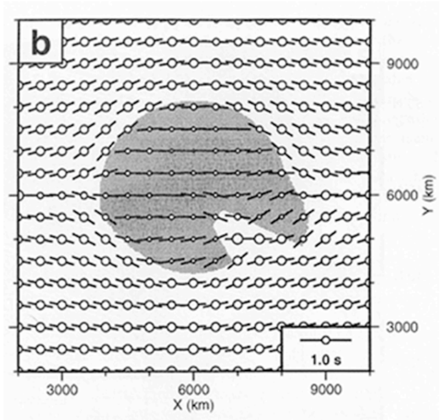
Scale -5% to +5%



Van der Lee JGR 1998

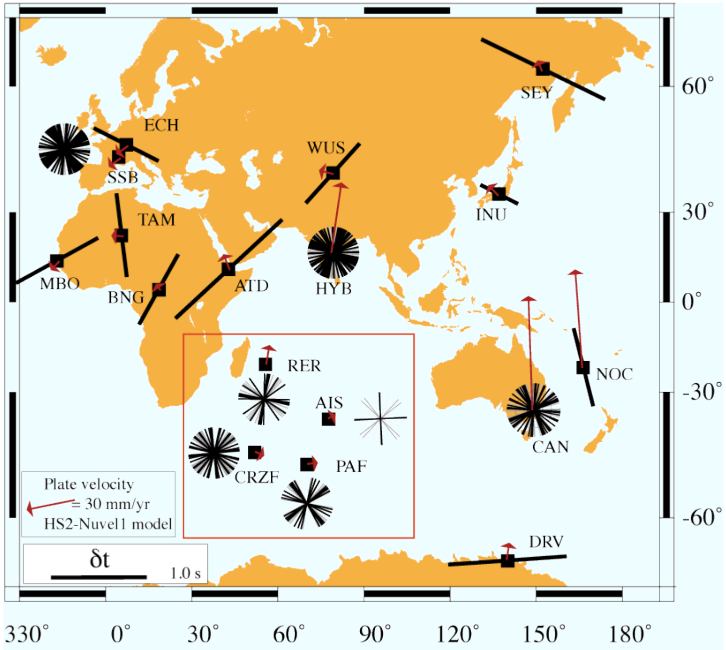




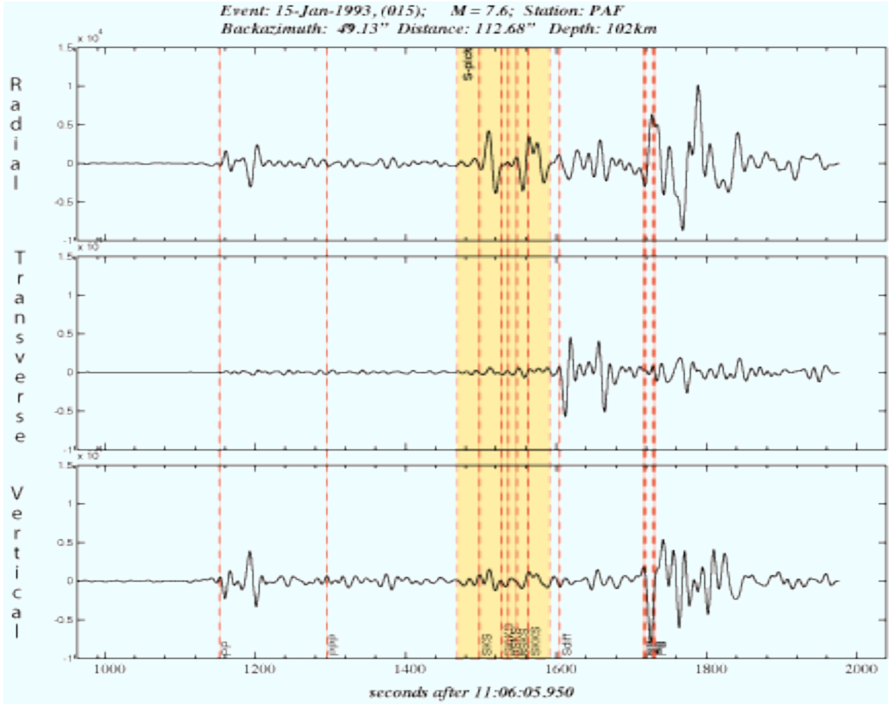


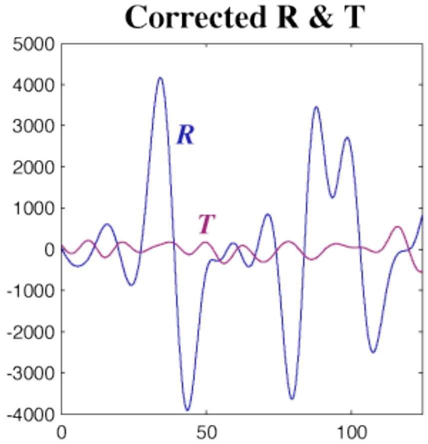
Fouch et al. JGR 2000

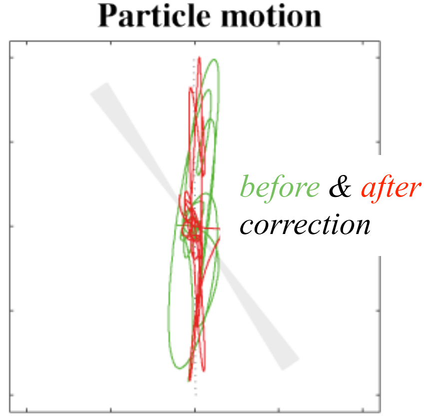
Kerguelen – inconsistent SKS and surface wave anisotropies



Barruol. & Hoffmann 1997 PEPI





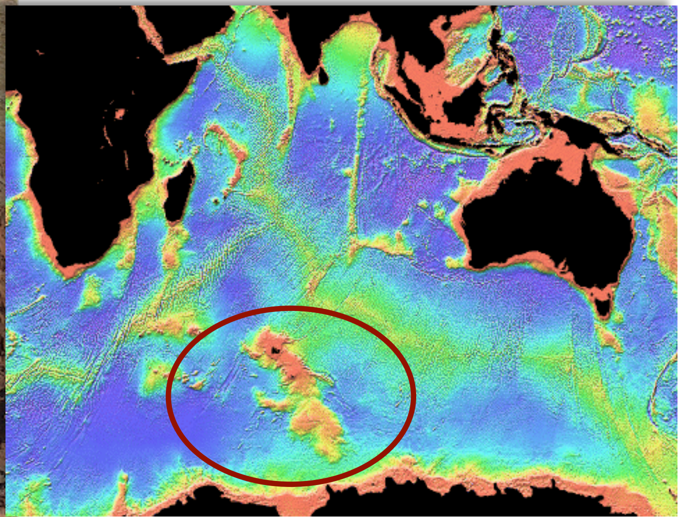


A typical SKS measurement…

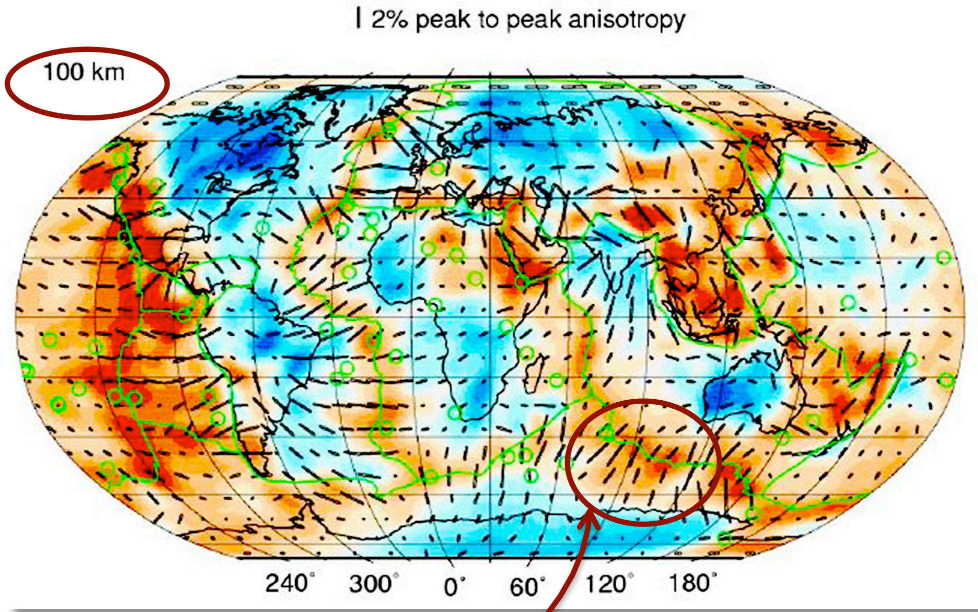
No energy on the transverse component

No ellipticity of the particle motion

No SKS anisotropy despite a good azimuthal coverage



Smith and Sandwell 1996



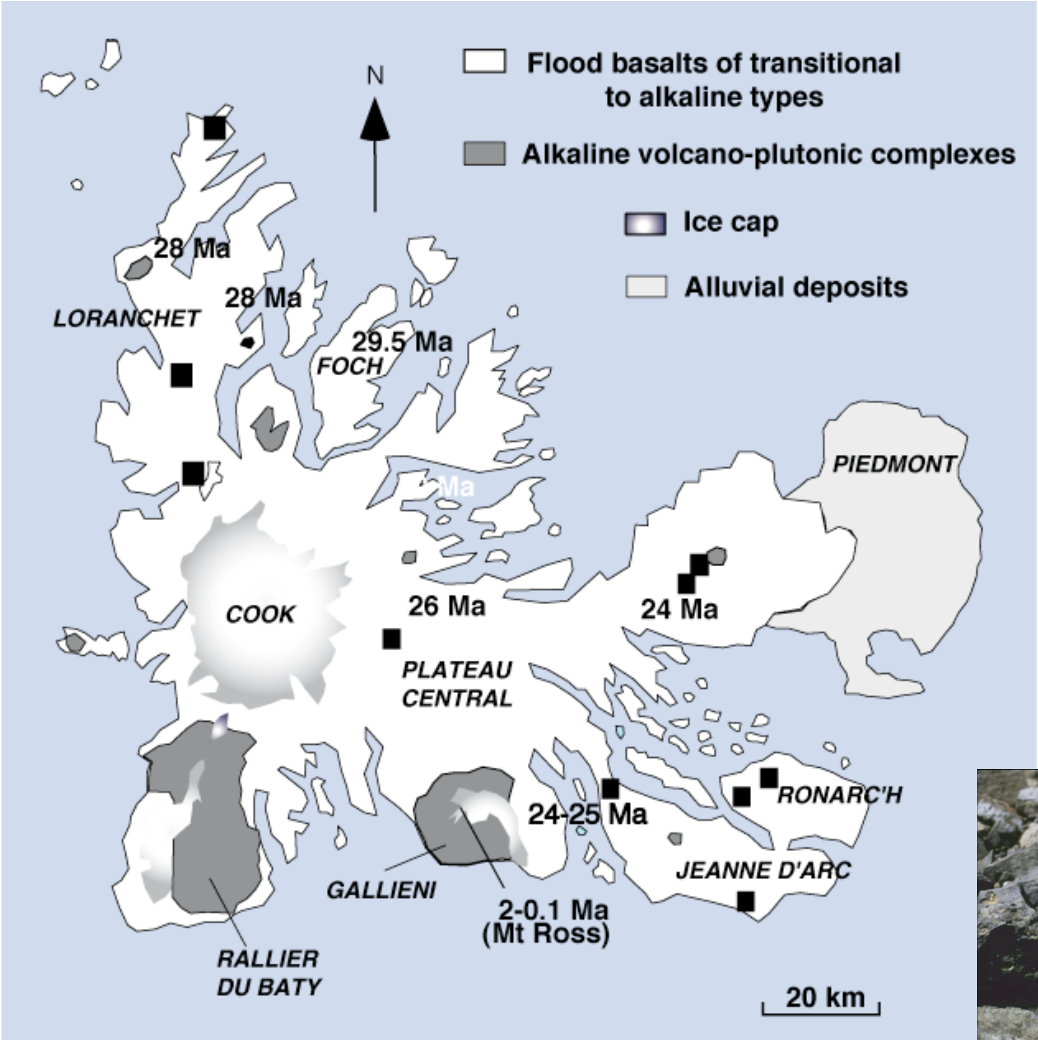
Debayle et al. 2005

But strong S_V (Rayleigh) azimuthal anisotropy

+ Rayleigh waves with periods 20 to 50 s (lithospheric depths) have very strong polarisation anomalies for some wavepaths.

Pedersen and Maupin 2002

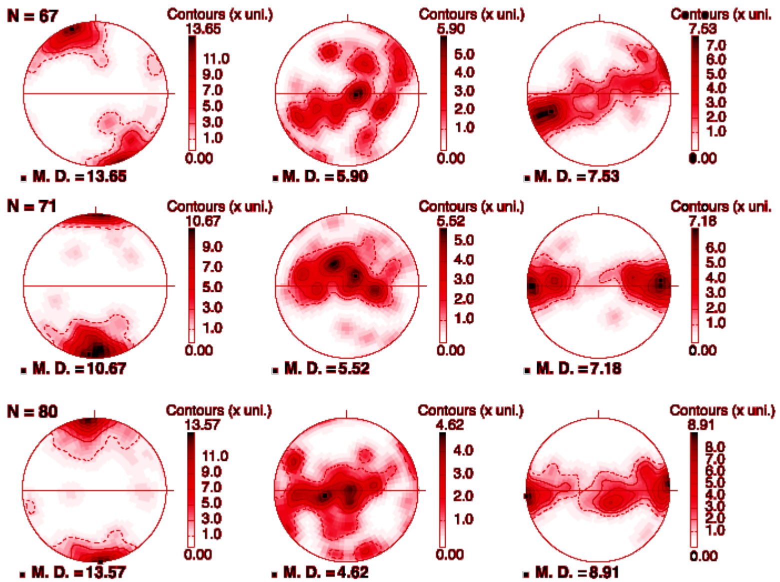
Kerguelen: Mantle xenoliths



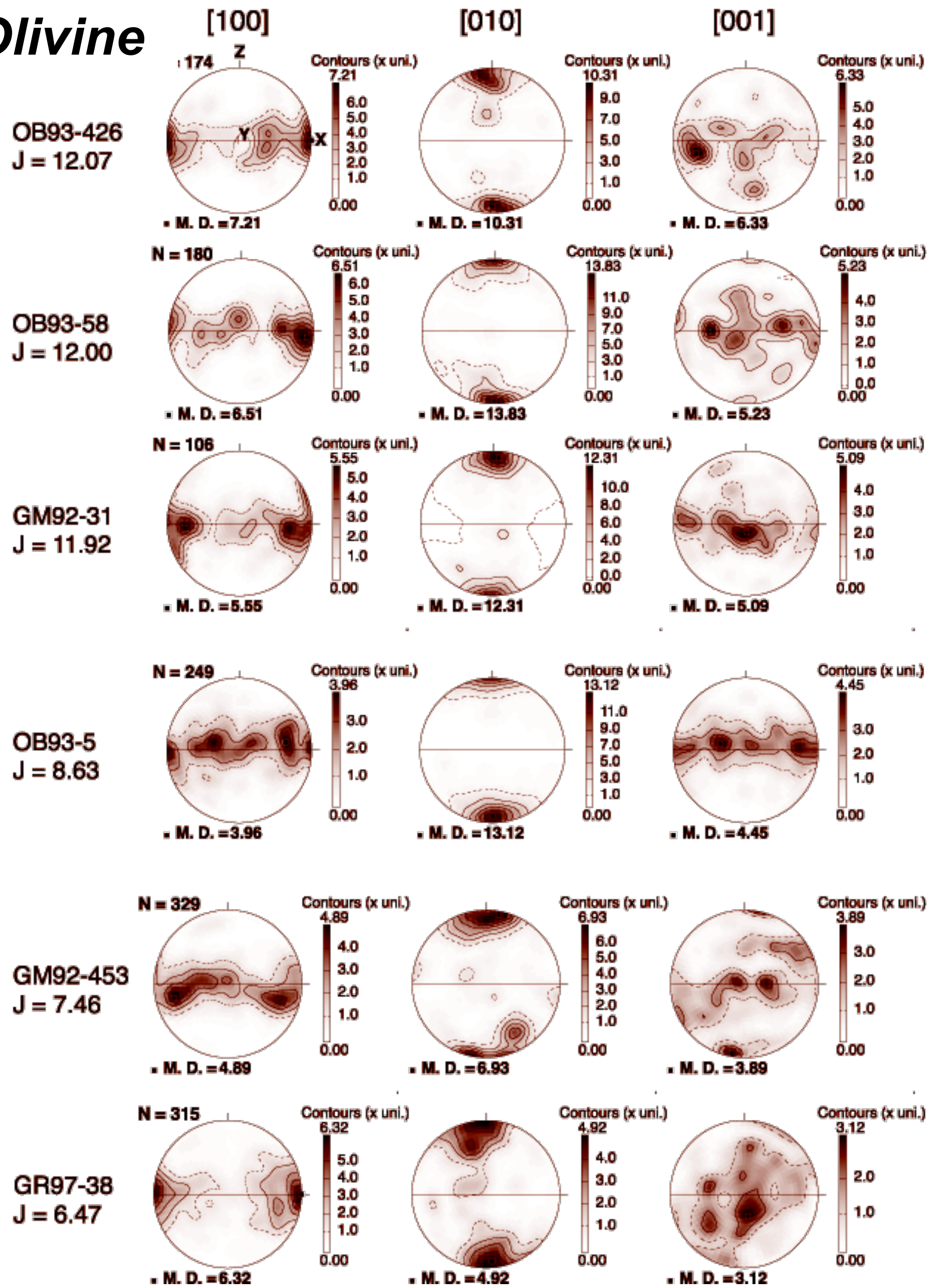
Harzburgites

Crystallographic preferred orientations

OPx

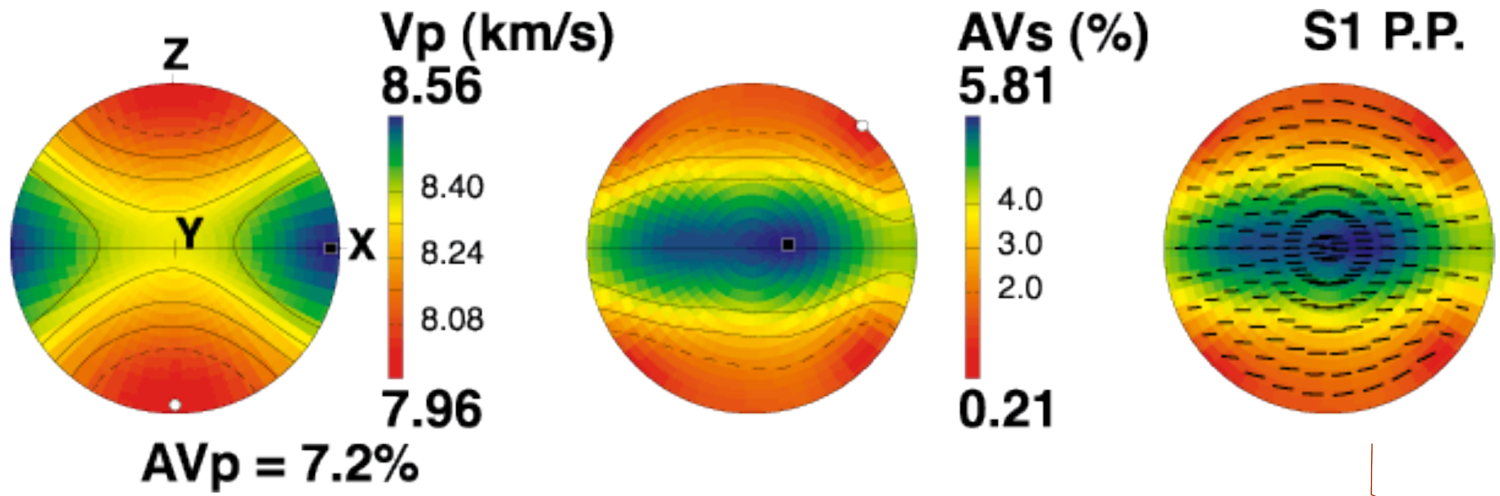


Olivine

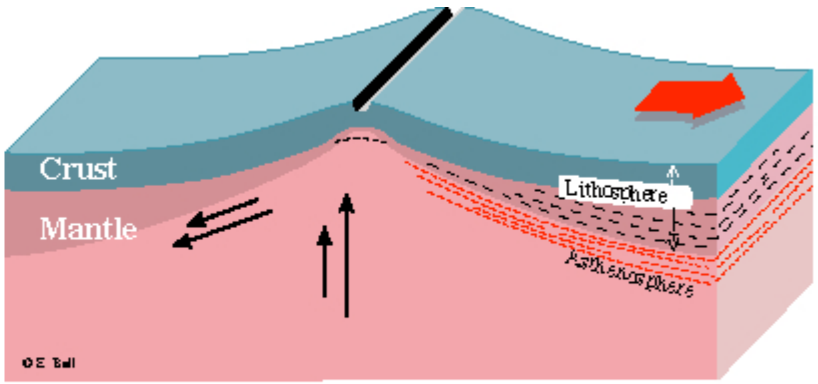


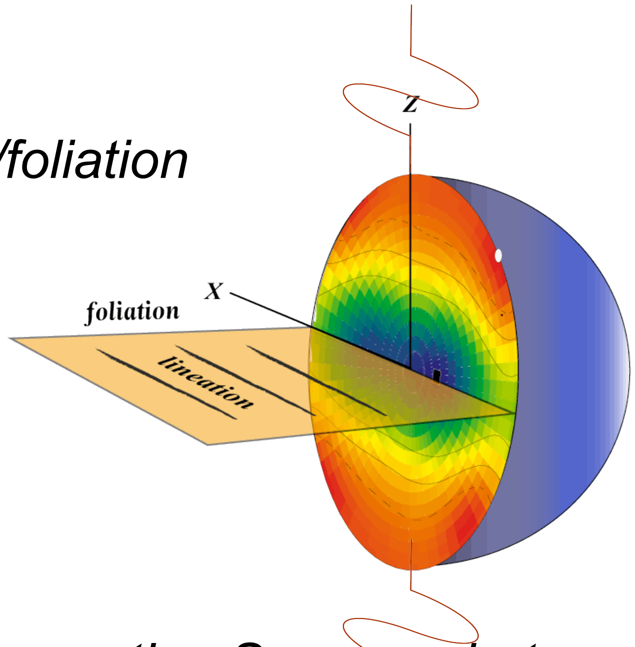
- ✓*Strong to medium CPO*
- ✓*CPO ↘ with ↗ magma-rock interaction*
- ✓*[010]-fiber symmetry*
- ✓*OPx [100]-fiber symmetry*

Mean Seismic Properties (whole dataset)

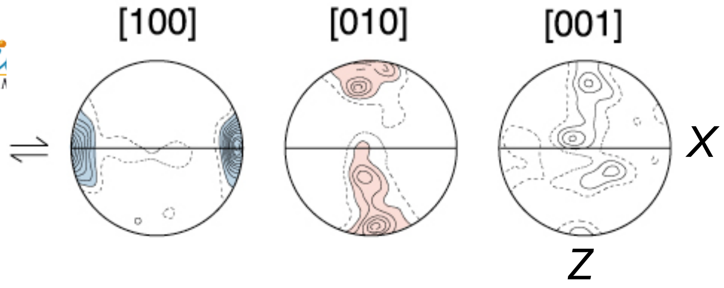


Assuming ~ horizontal flow/foliation

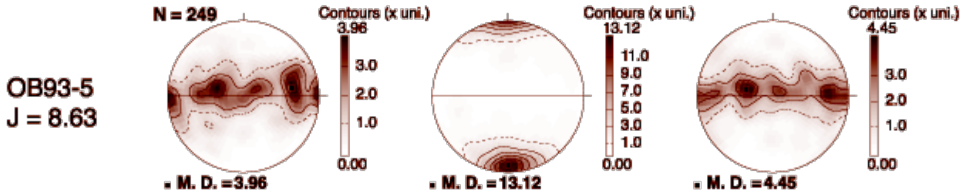




No anisotropy/splitting for ~ vertically propagating S-waves, but strong anisotropy for horizontally propagating ones (surface waves)

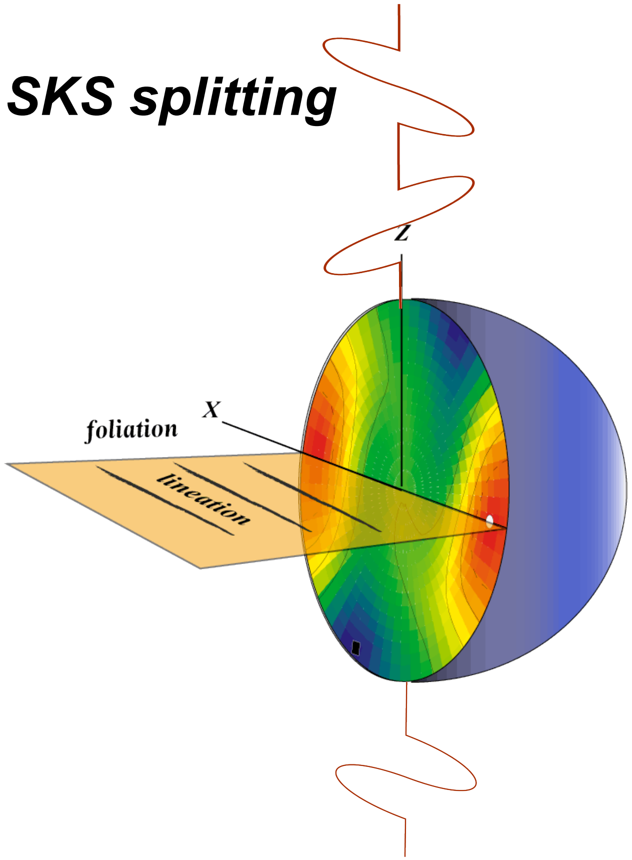


- *Usual olivine CPO with an orthorhombic symmetry*

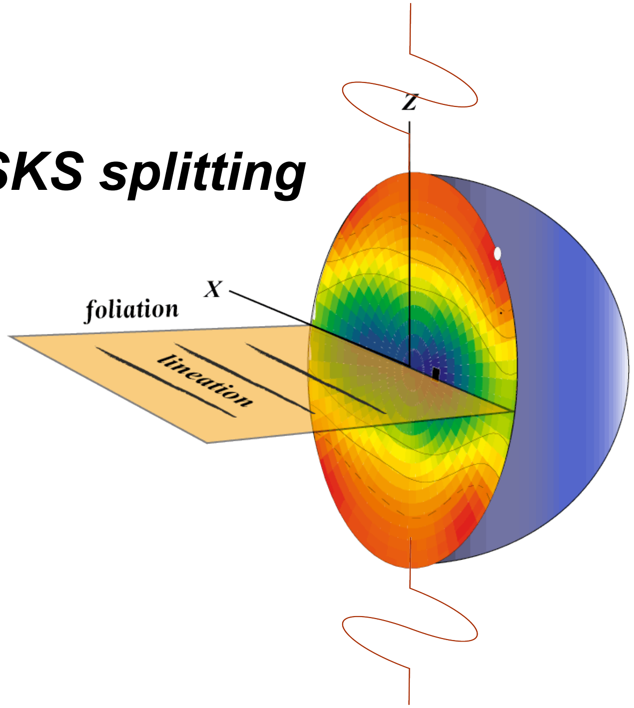


- *Kerguelen Islands: CPO with a [010] axial symmetry*

SKS splitting



No SKS splitting



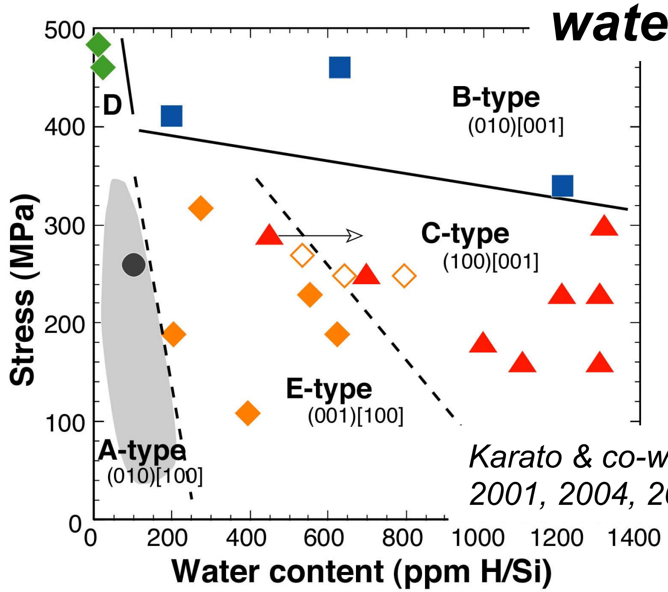
Deformation and anisotropy in the upper mantle : XXI century observations & experimental results

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

- *change in deformation mechanisms: ≠ CPO*

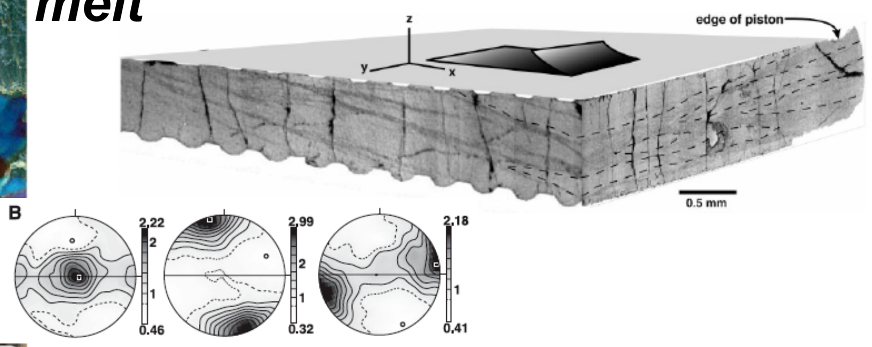
✓ fast anisotropy directions normal to the shear direction

water



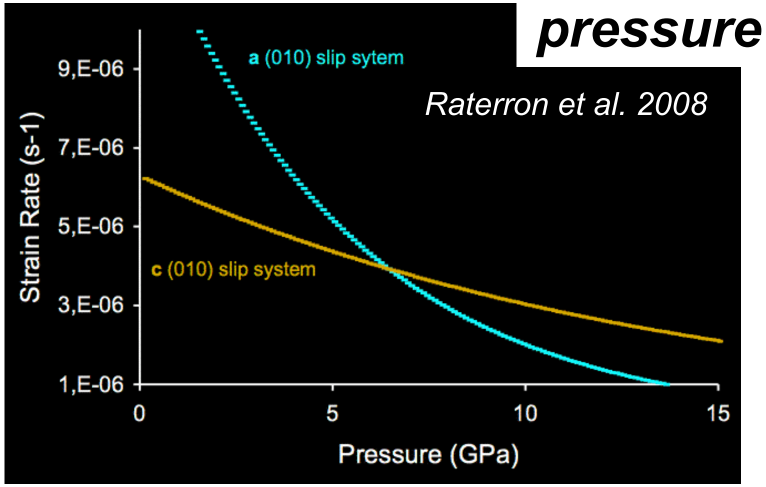
Karato & co-workers 2001, 2004, 2006 ....

melt



Holtzman et al. Science 2003

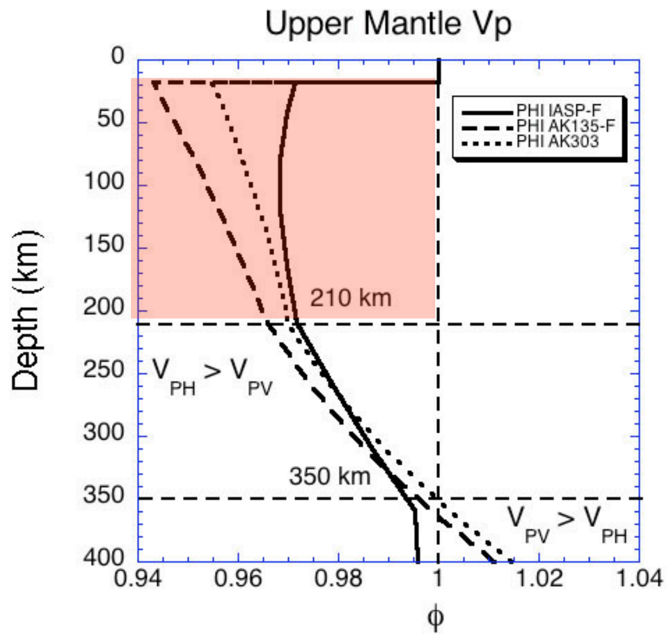
pressure

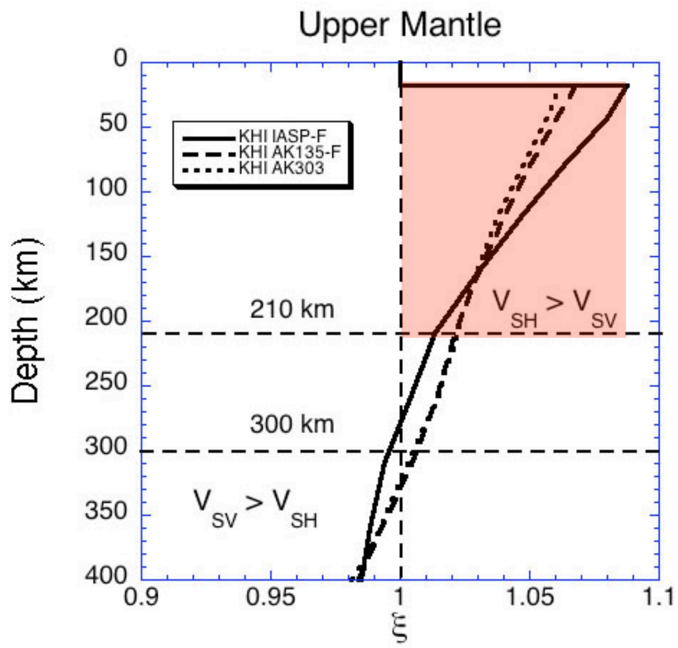


Raterron et al. 2008

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

[100] slip in olivine & anisotropy upper 210 km:

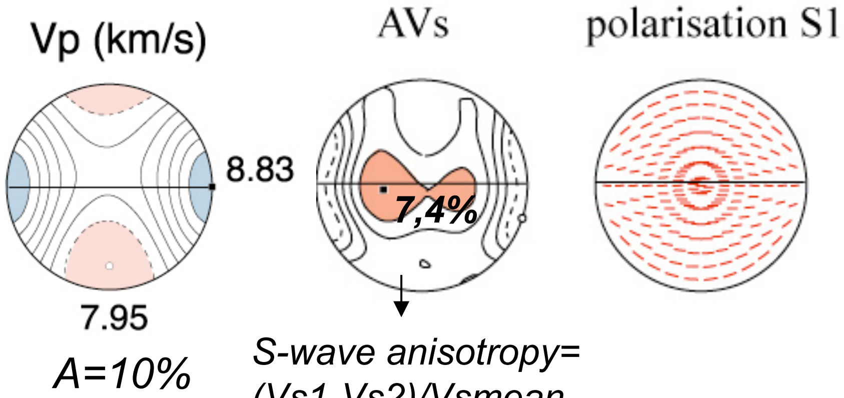




Observations for horizontal flow:

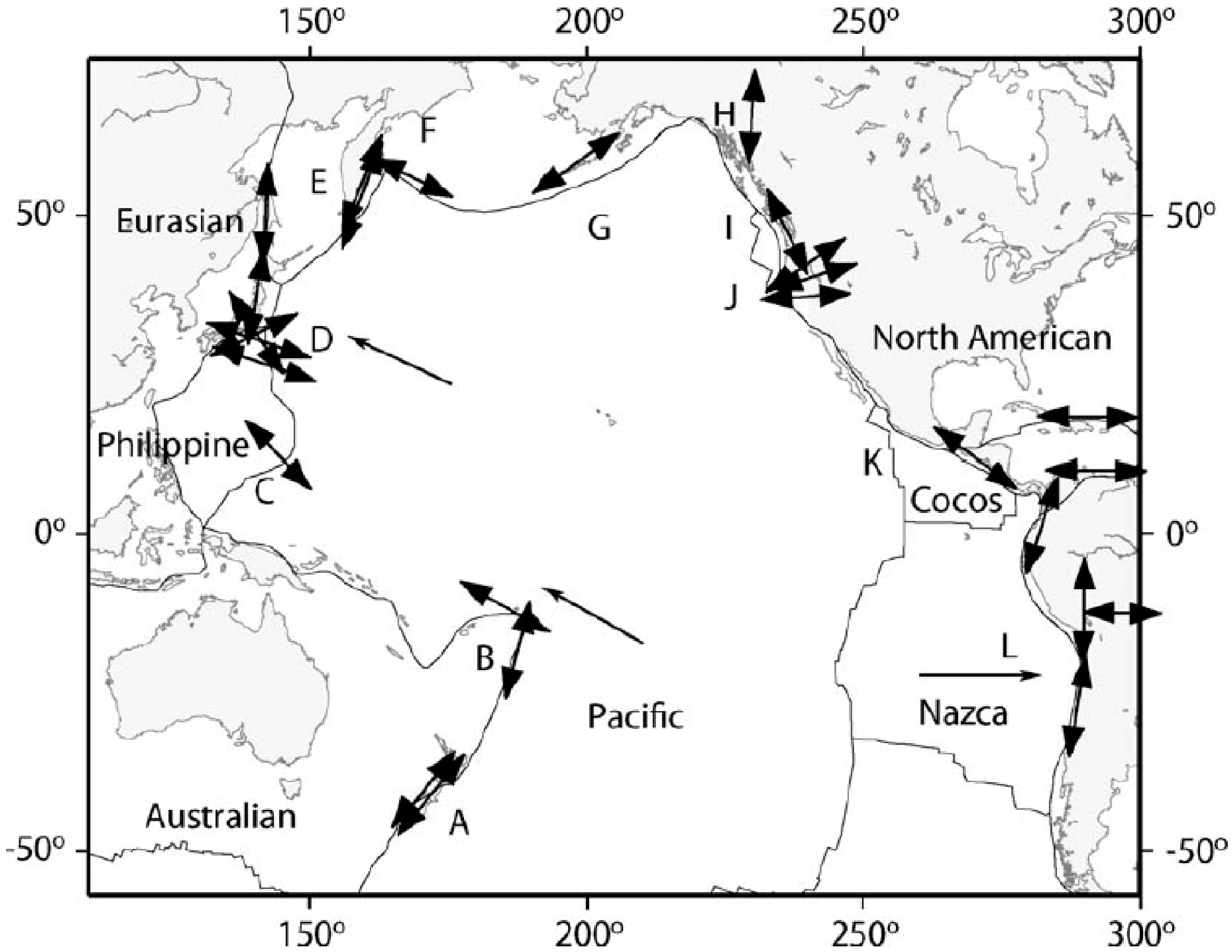
1. $V_{PH} >> V_{PV}$
2. *P wave anisotropy > 5%*
3. $V_{SH} > V_{SV}$
4. *S-wave anisotropy > 4%*

Strike-slip faults : higher anisotropy

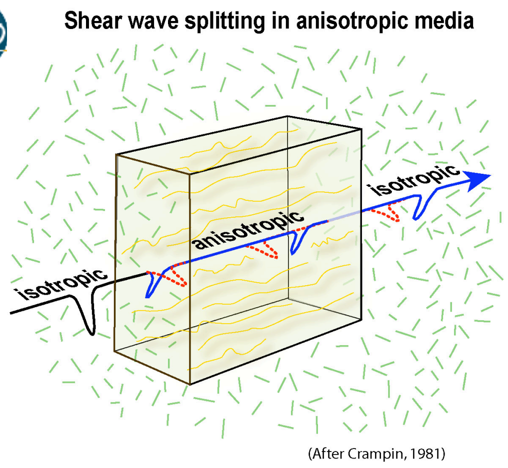


S-wave anisotropy=
(Vs1-Vs2)/Vsmean

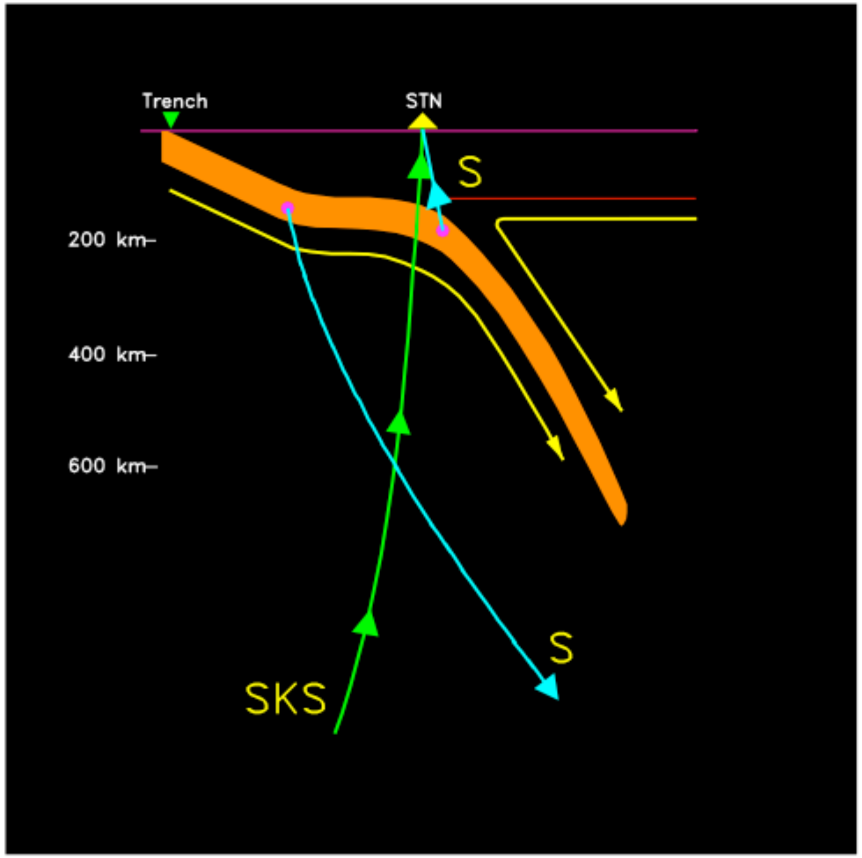
Subduction zones : relation between deformation and anisotropy in the upper mantle not so simple!



Lassak et al 2006 EPSL

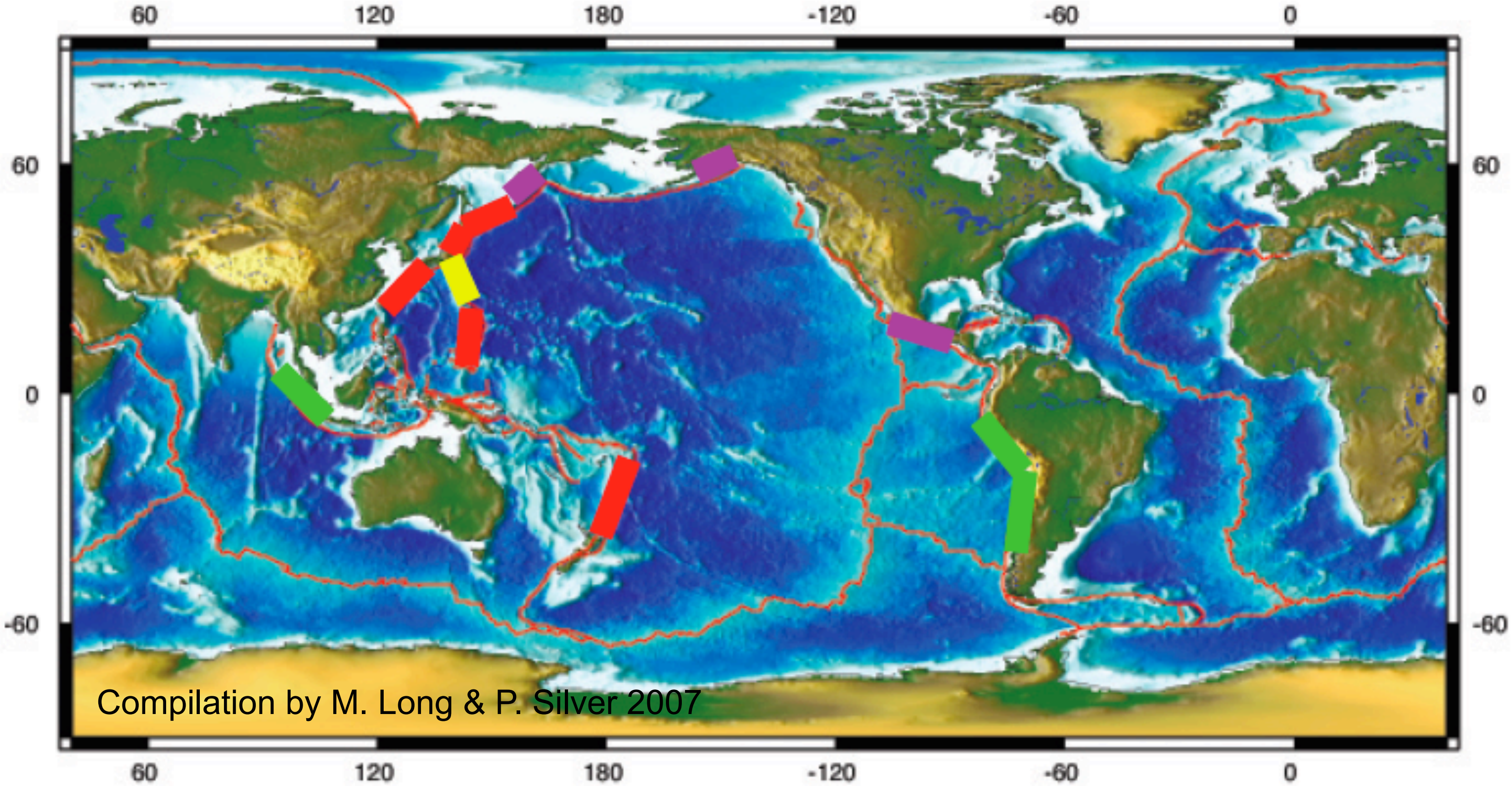


Observing the Subduction Zone Flow Field Using Shear Wave Splitting



- ***SKS waves sample below-slab flow, slab anisotropy & flow in the mantle wedge.***
- ***local S waves mainly sample wedge, but they may also propagate path in the slab or even below it*** *(deep events).*

Anisotropy in the mantle wedge



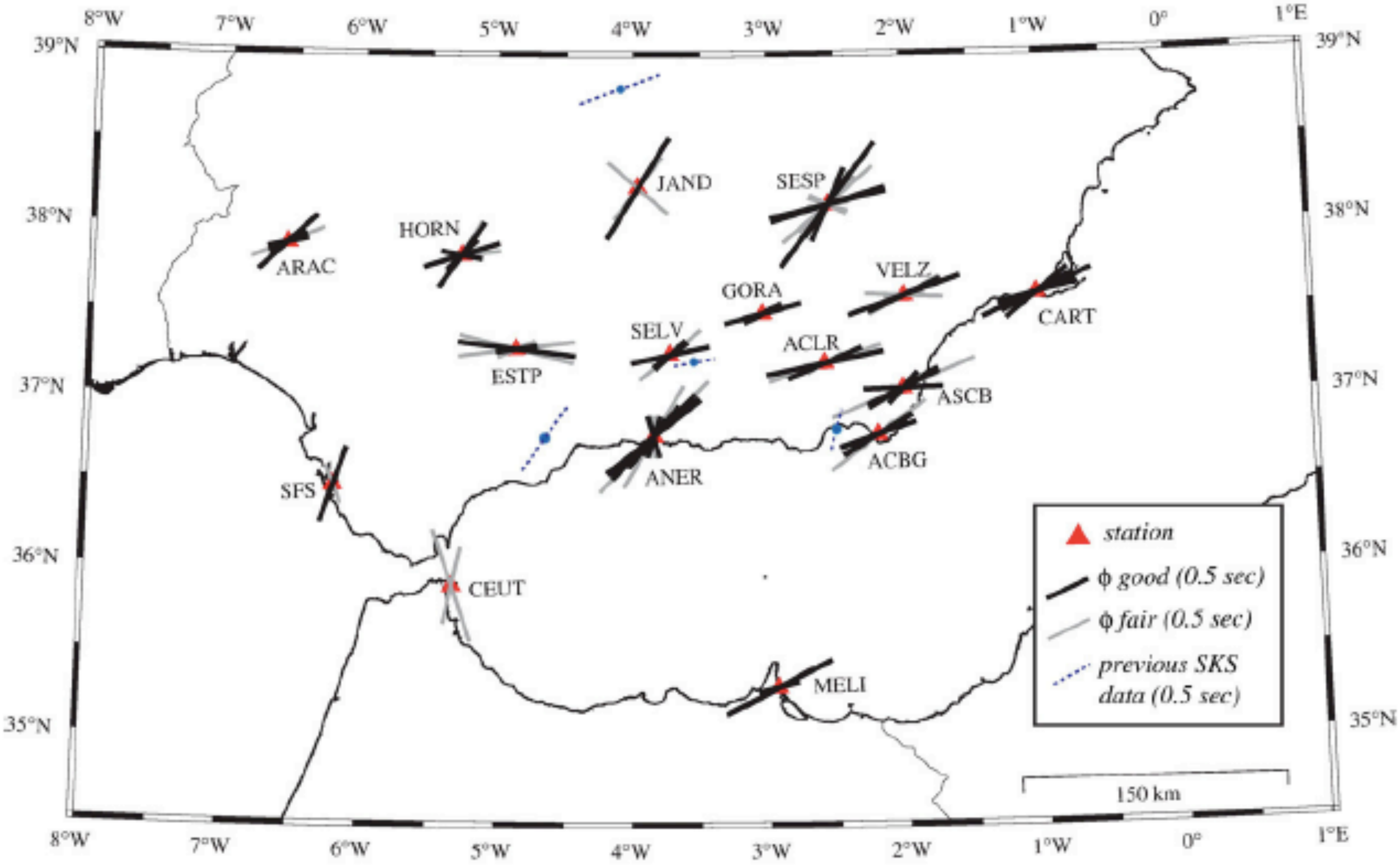
Trench-|| forearc to trench-normal backarc transition

Wedge splitting observed, pattern not clear-cut

Trench-normal forearc to trench-|| backarc transition

Little or no splitting in wedge

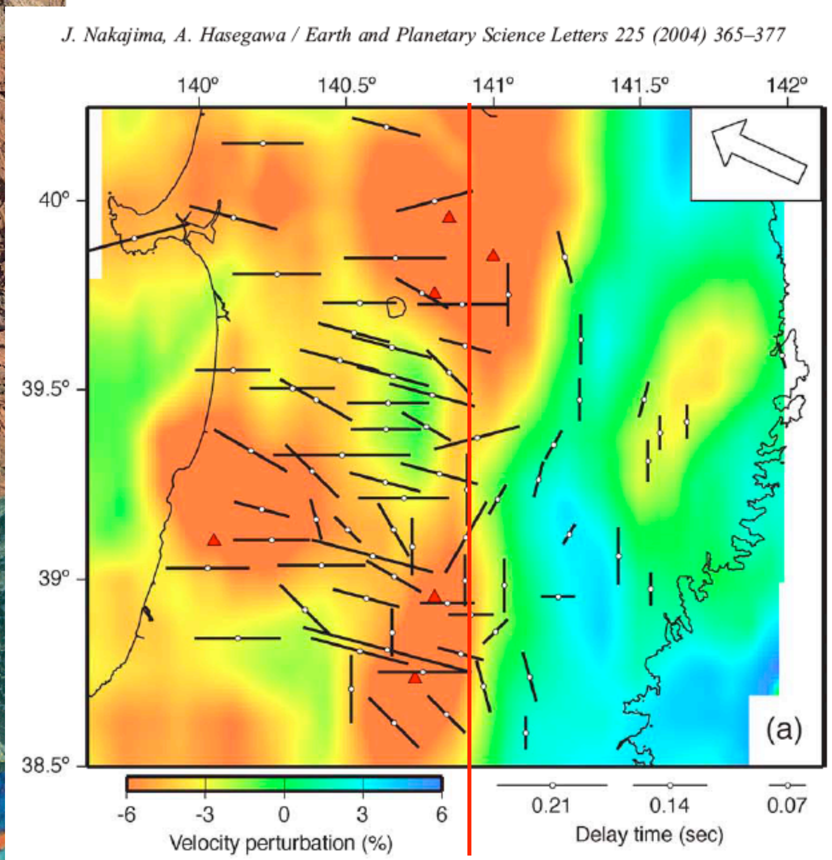
I. Buontempo et al. / Earth and Planetary Science Letters 273 (2008) 237–250



Above the plate : local S, shallow sources

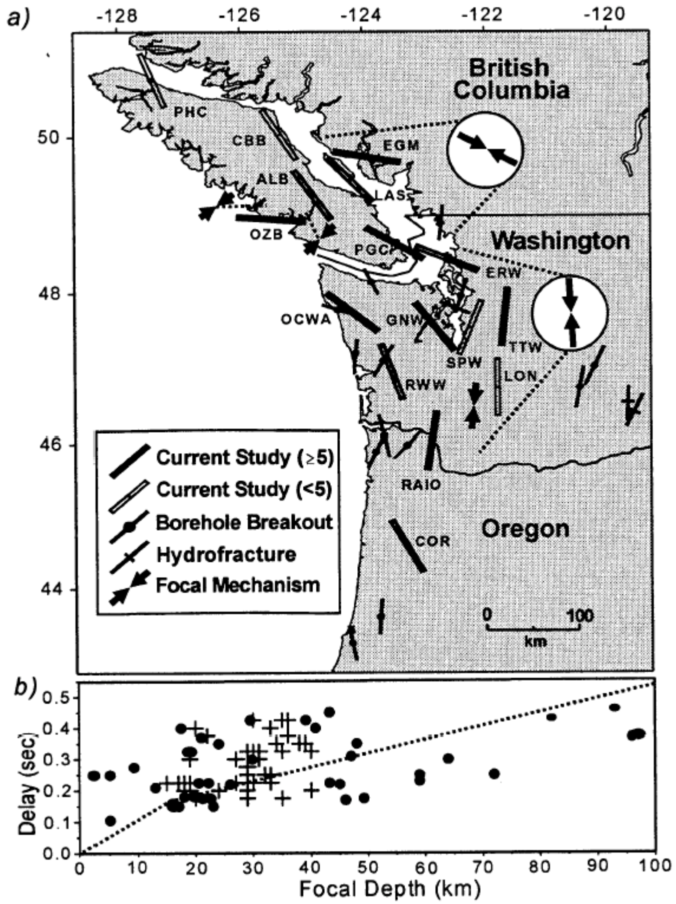
Variable polarization directions & low delay times <0.4s

NE Japan



Volcanic arc = 50-60 km

Cascadia



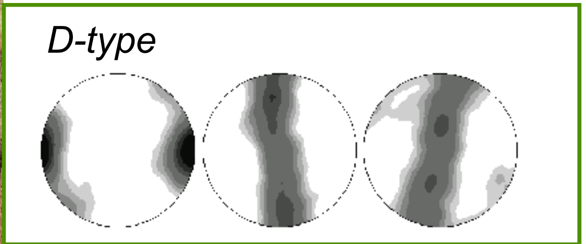
Currie et al 2001 GRL

Trench // flow?

Experimental data : incorporation of water (H+) IN OLIVINE changes the relation between deformation & anisotropy

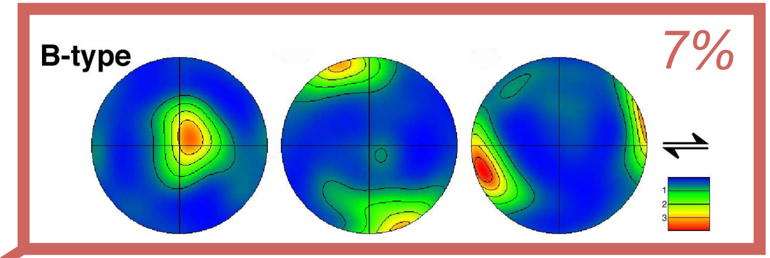
Influence of water (H+) on olivine CPO @ T≥1200°C, P=2GPa

natural samples & low P experiments (Bystricky et al. 2000)
D-type = low deviatoric stresses!



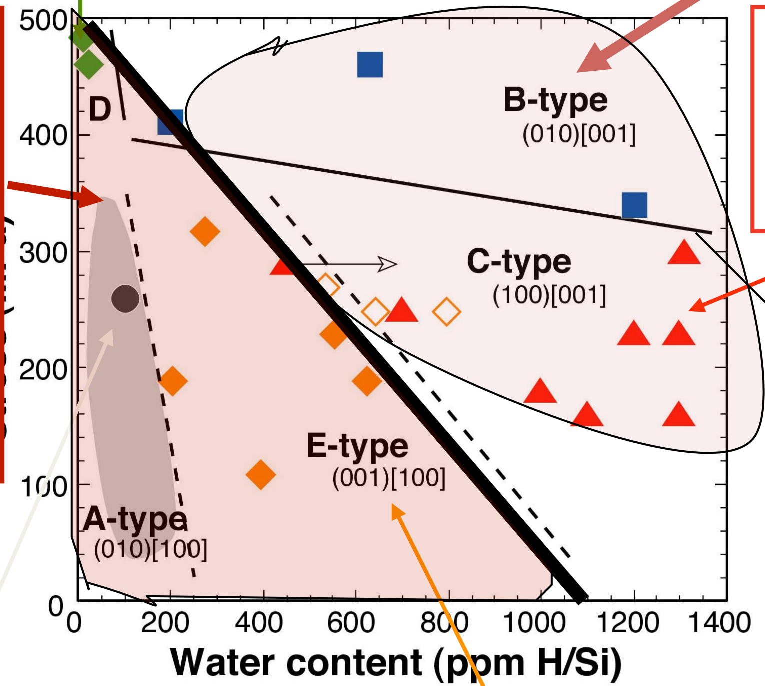
B & C type : [001] slip

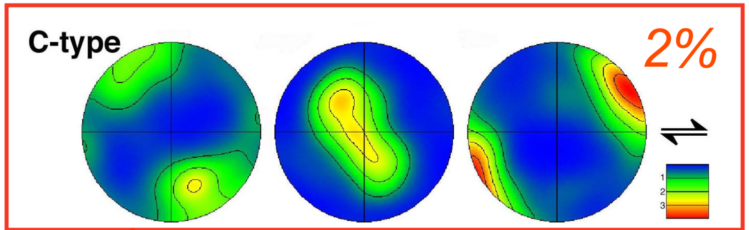
fast S ⊥ shear direction



High water

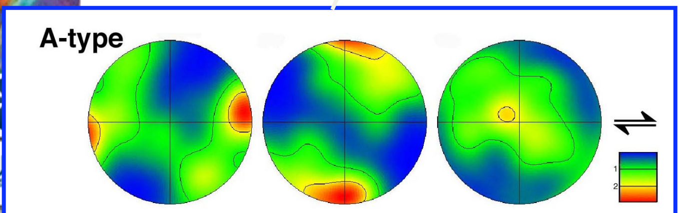
>90% naturally deformed peridotites:
A, D & E type
[100] slip
fast s // shear direction

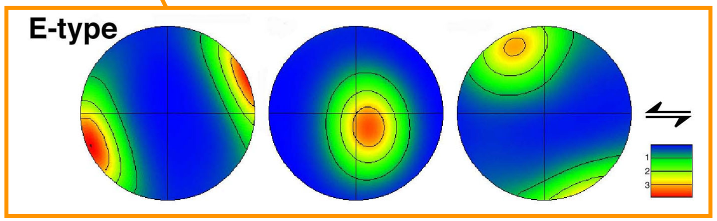




lower T: transition B-C
@ lower stresses

Low stress
Low water

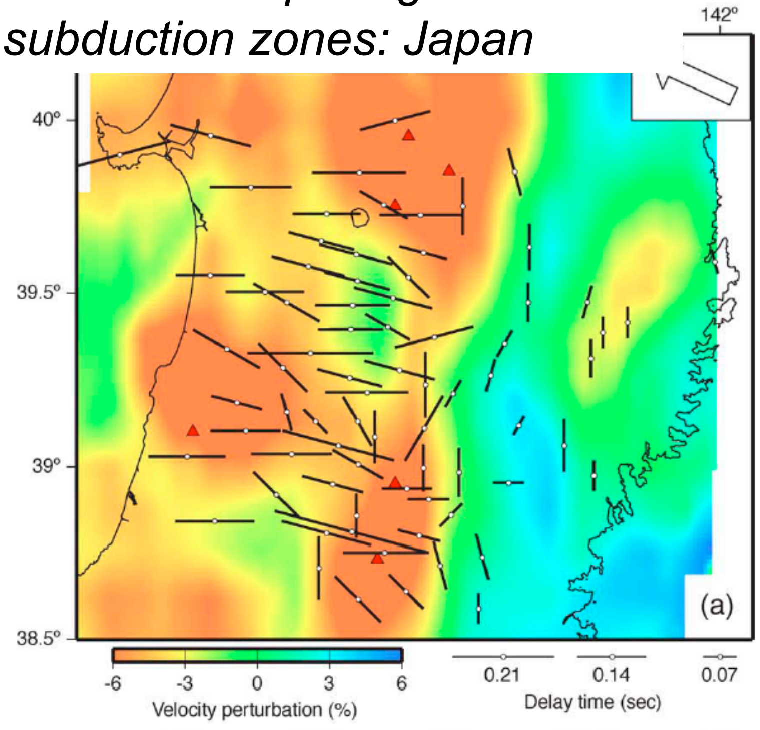




Jung & Karato 2001
Katayama et al. 2004
Katayama & Karato 2006…

Trench // anisotropy in the forearc

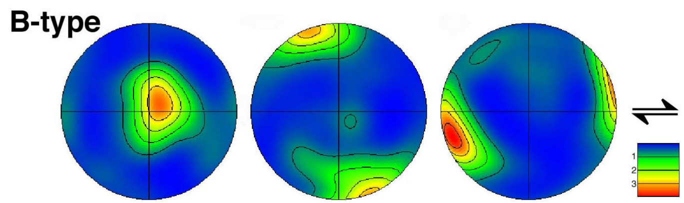
shear wave splitting above subduction zones: Japan



Nagajima & Hasegawa EPSL 2004

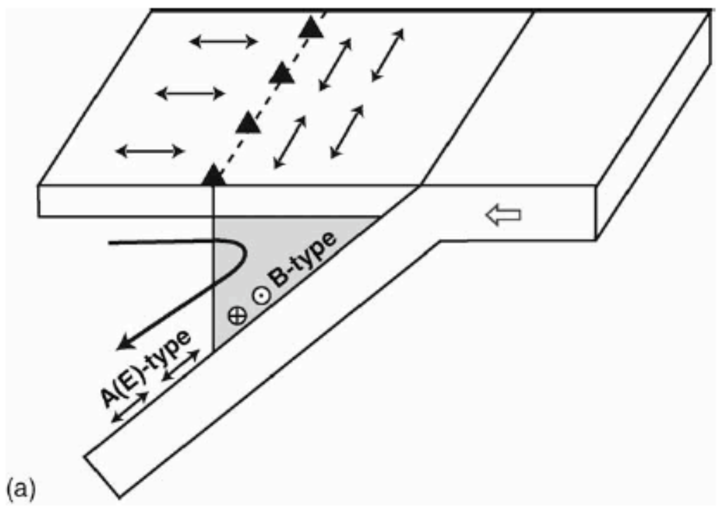
Water-rich olivine:

- *dominant [001] slip*



✓ *fast S-wave polarization normal to the shear direction*

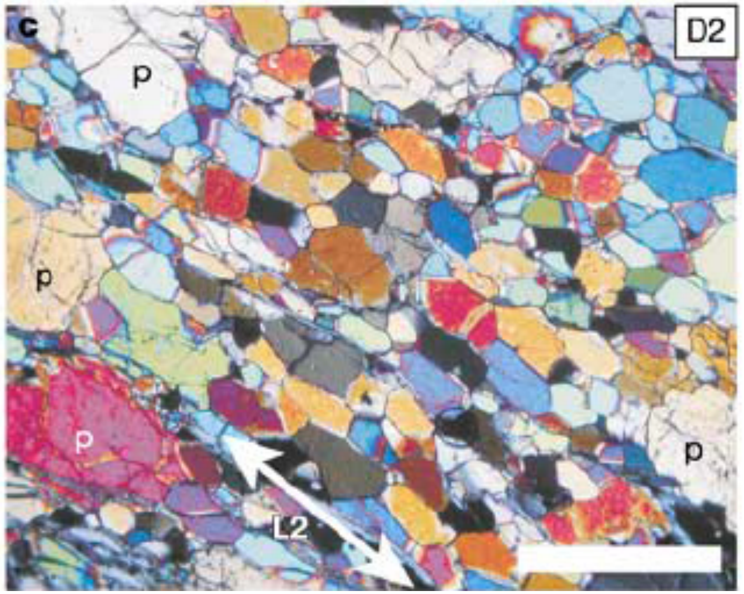
✓ *weak anisotropy*



Natural examples of olivine lattice preferred orientation patterns with a flow-normal *a*-axis maximum

Tomoyuki Mizukami[1,2], Simon R. Wallis[2] & Junji Yamamoto[3*]

NATURE | VOL 427 | 29 JANUARY 2004 | www.nature.com/nature

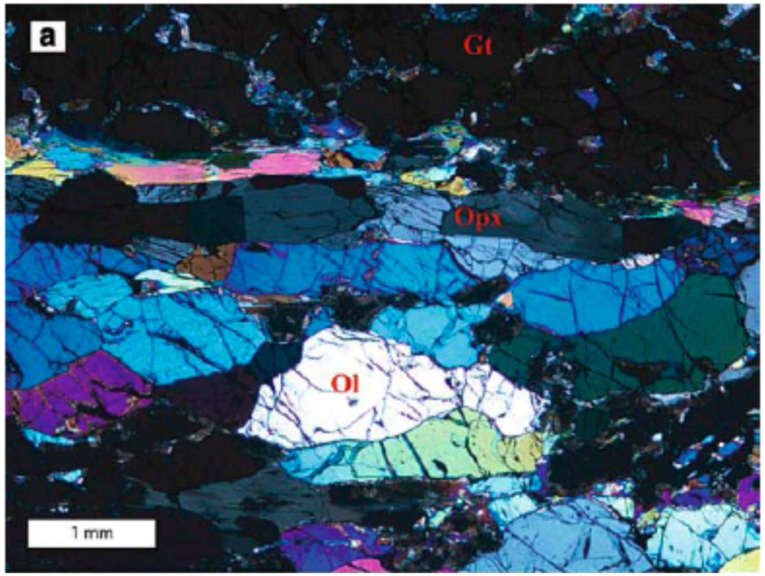


Contrib Mineral Petrol (2006) 152: 43–51
DOI 10.1007/s00410-006-0093-4

ORIGINAL PAPER

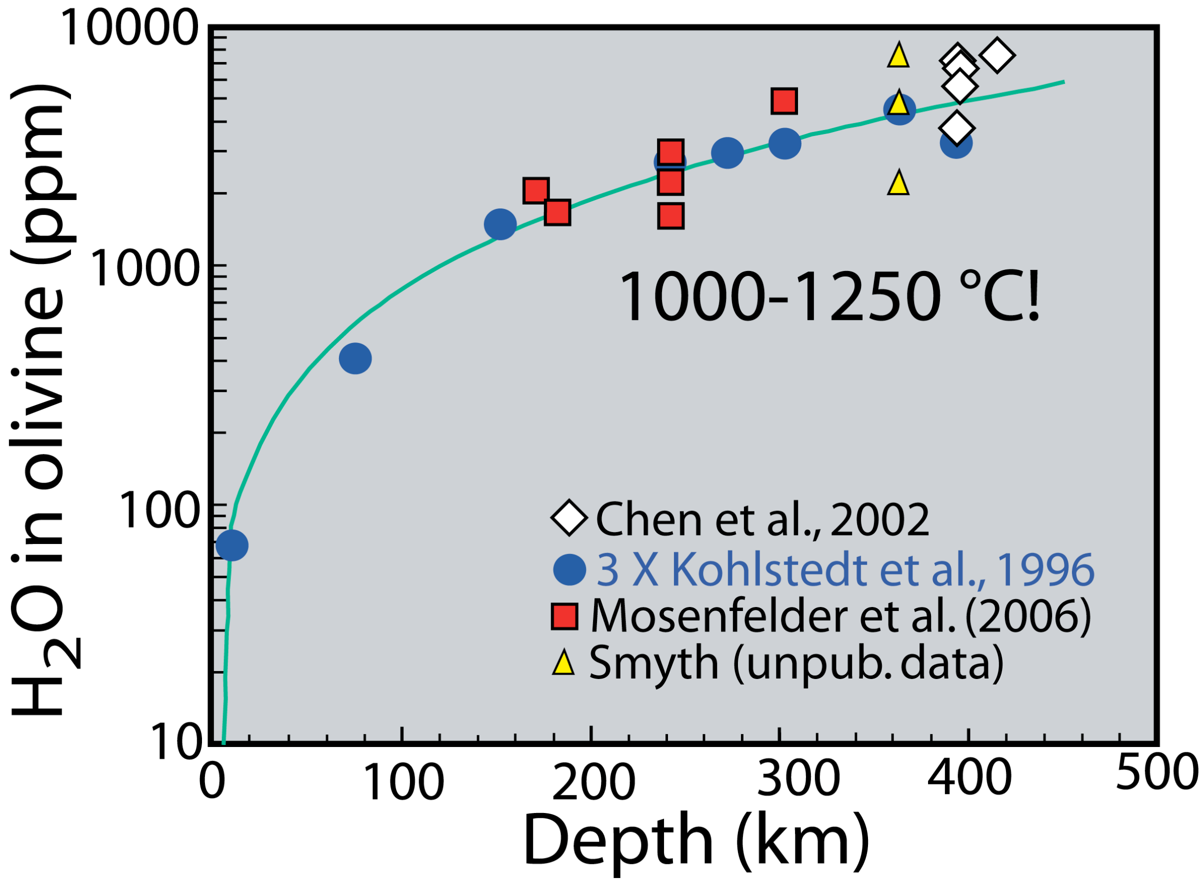
Philip Skemer · Ikuo Katayama · Shun-ichiro Karato

Deformation fabrics of the Cima di Gagnone peridotite massif, Central Alps, Switzerland: evidence of deformation at low temperatures in the presence of water



[001] glide olivine CPO essentially observed in HP garnet peridotites
➔ role of pressure ?

Same change in slip systems @ high pressure & water solubility in olivine ↘ strongly with pressure ↘

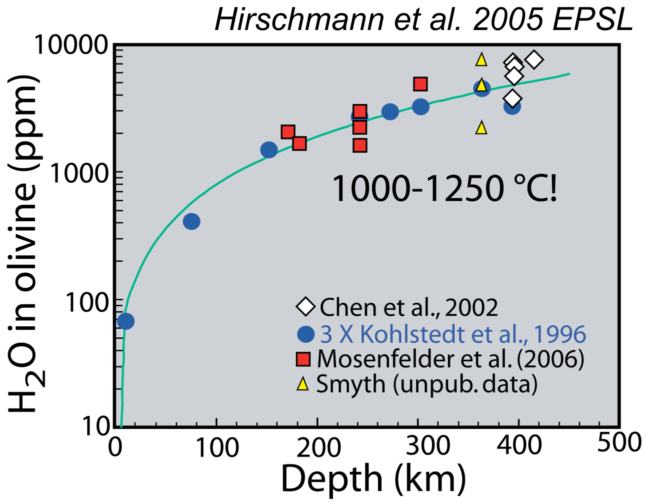


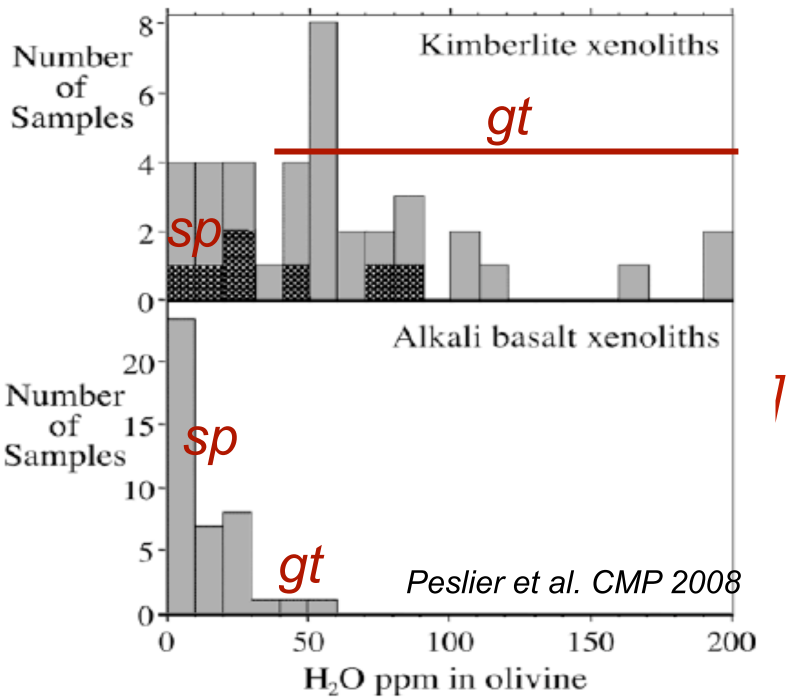
Hirschmann et al. 2005 EPSL

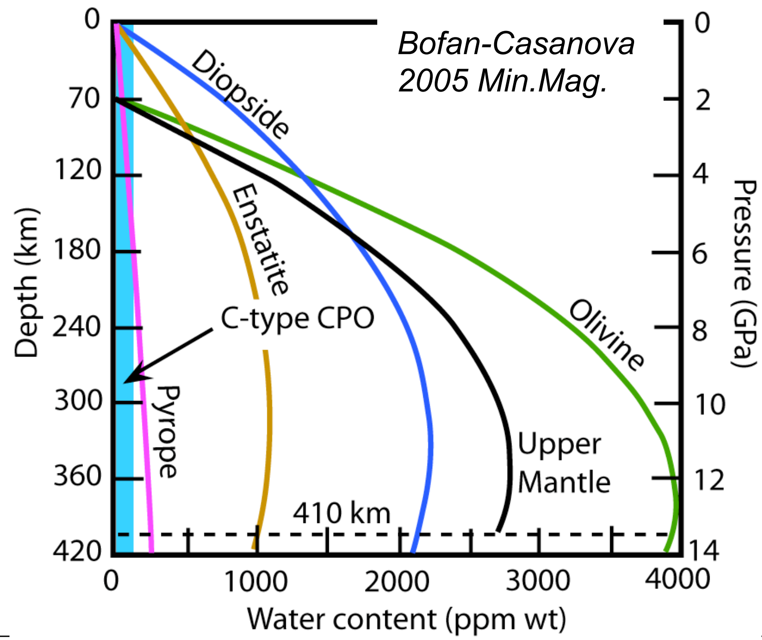
fast anisotropy directions normal to the shear direction due to the effect of fluids (water and melt) and pressure on olivine deformation

✓ ***asthenospheric mantle only!***

- *partial melting*
- *water solubility ➘ P ➘*
- *change in slip systems under dry conditions @ depths > 200 km*

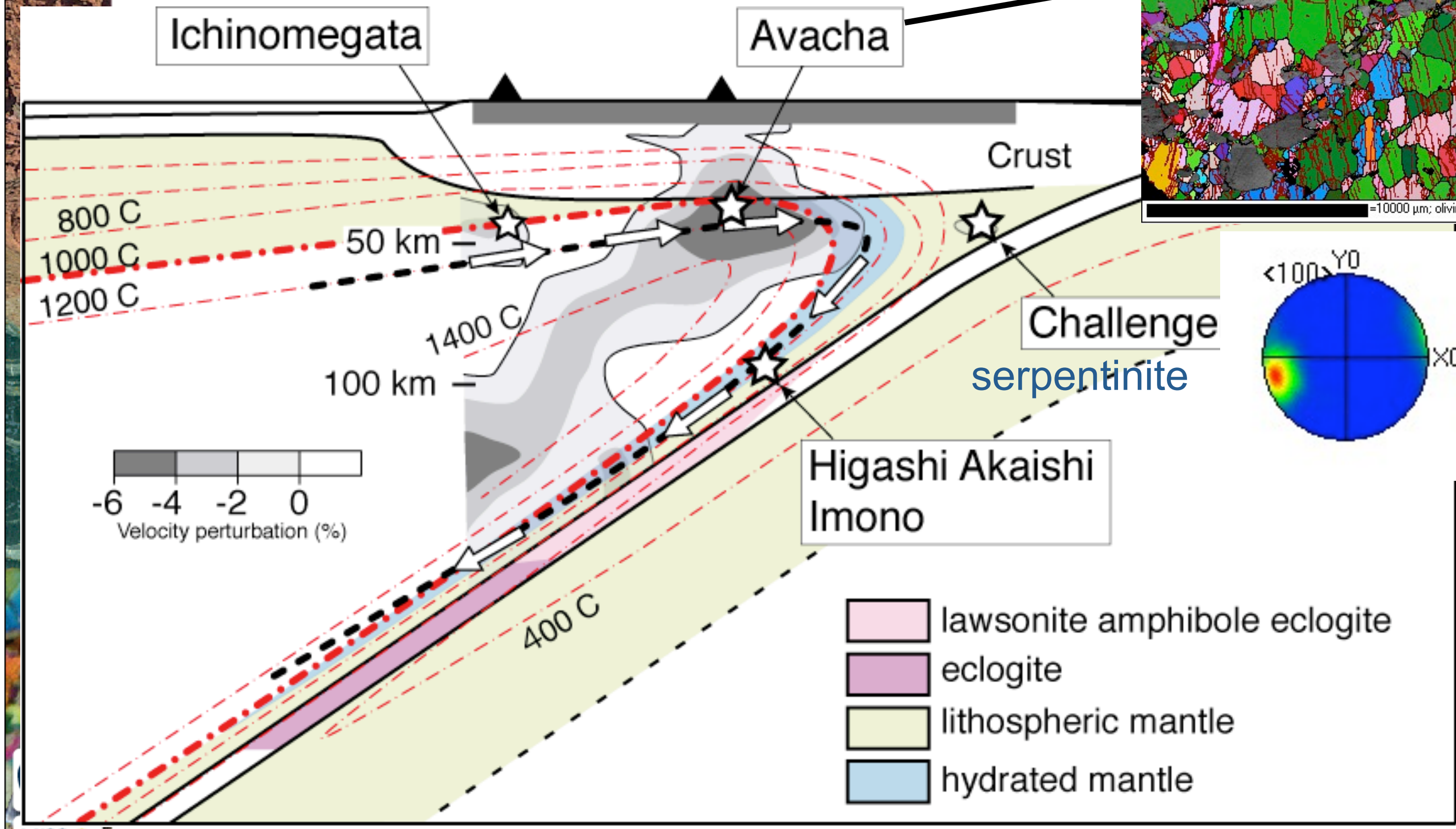


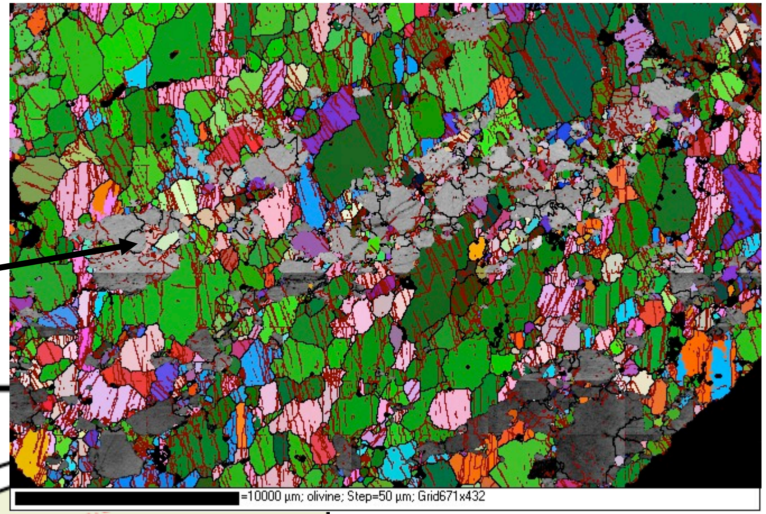


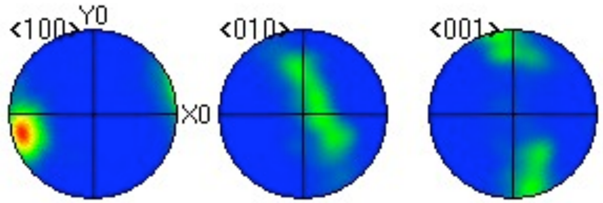


Interactions between reactive fluid transport, partial melting, and olivine deformation in the mantle wedge?

Xenoliths in calco-alkaline volcanos from NE Pacific subduction zones





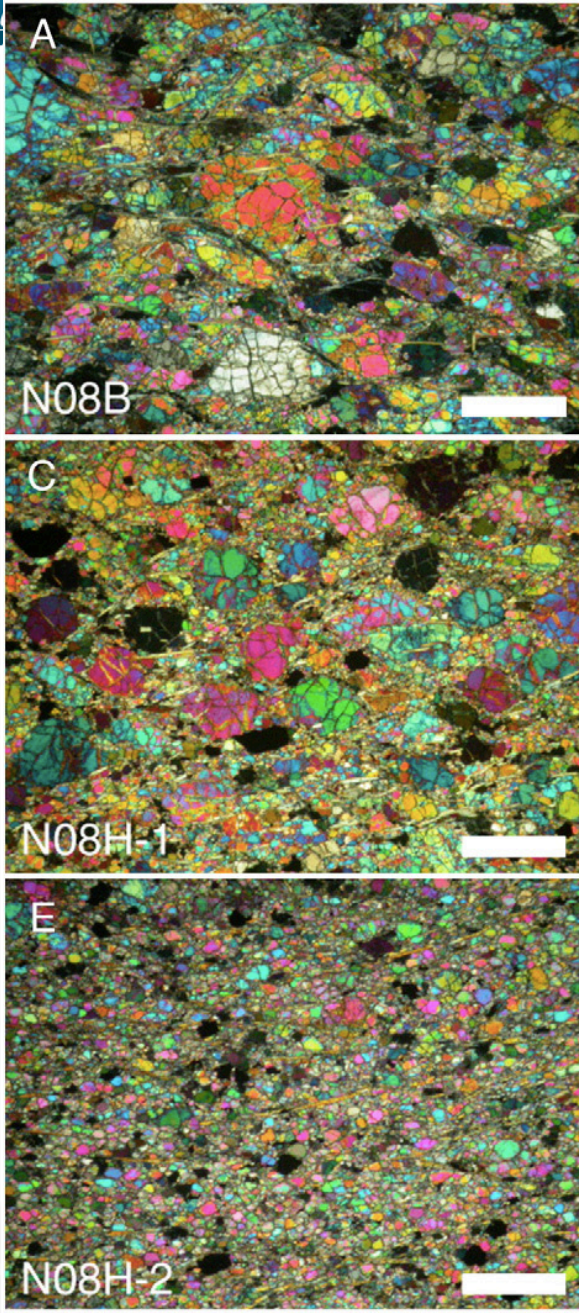


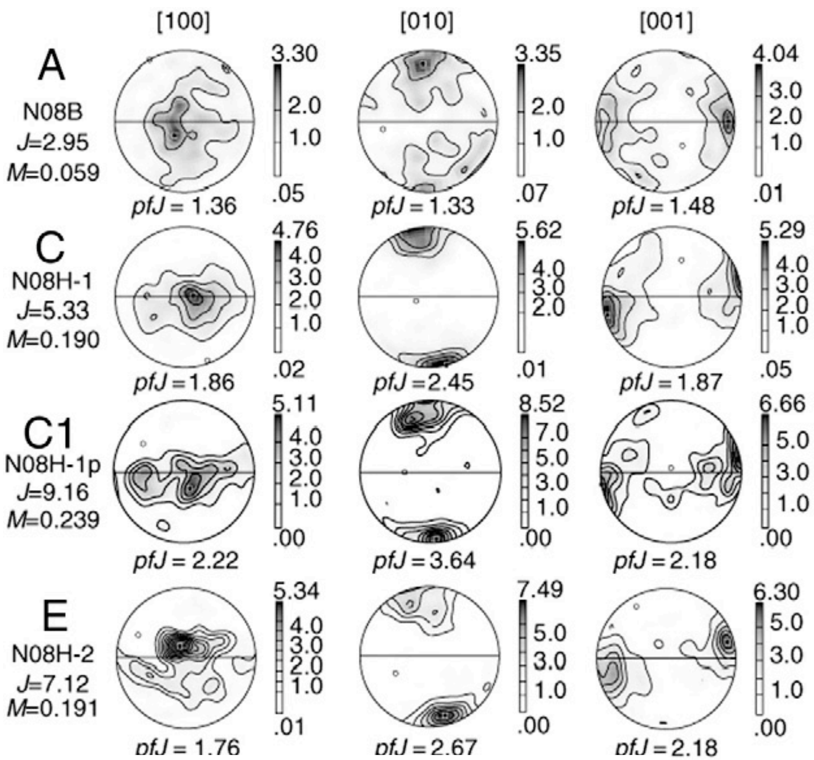
[100] glide only

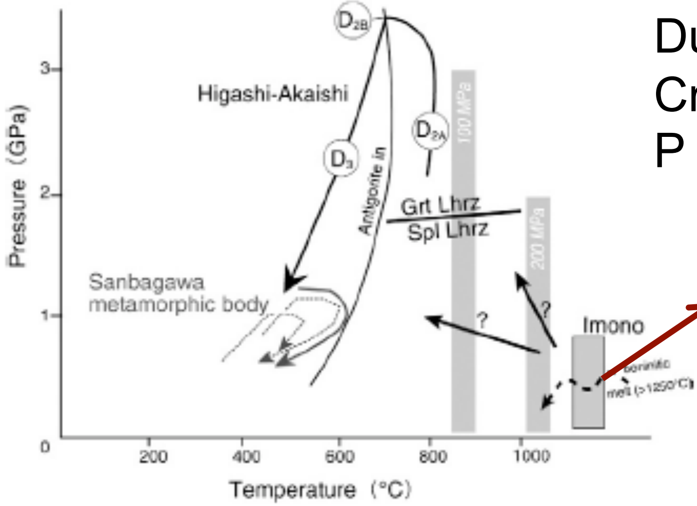
Soustelle et al JPet 2010

Figure by K. Michibayshi

Imono peridotite, Japan







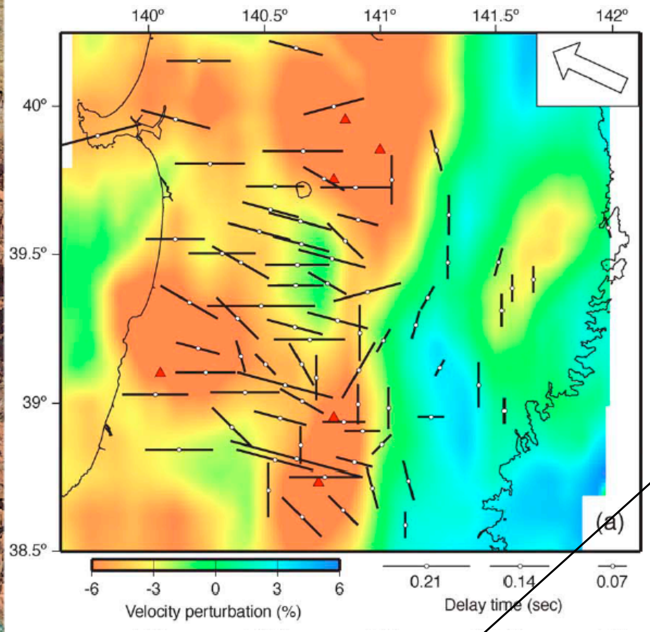
Dunites with
Cr-rich spinels
P history?

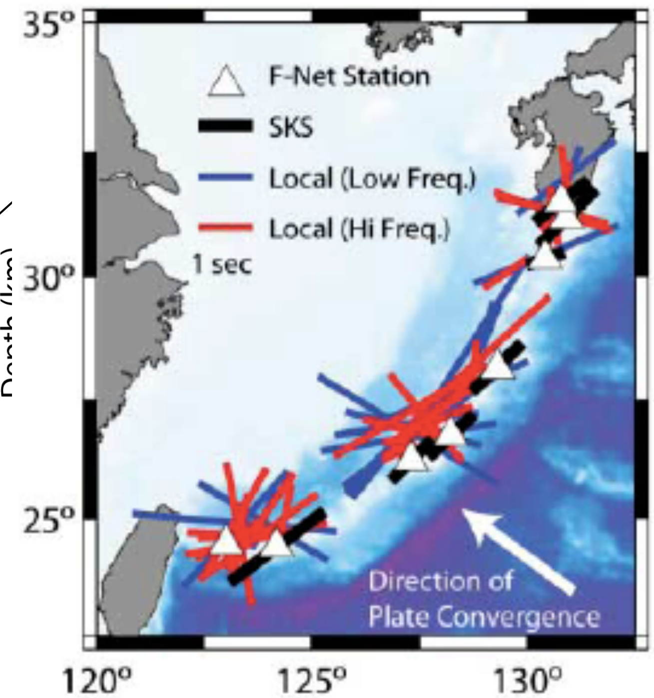
Melting
= dehydration

Tasaka et al. EPSL 2008

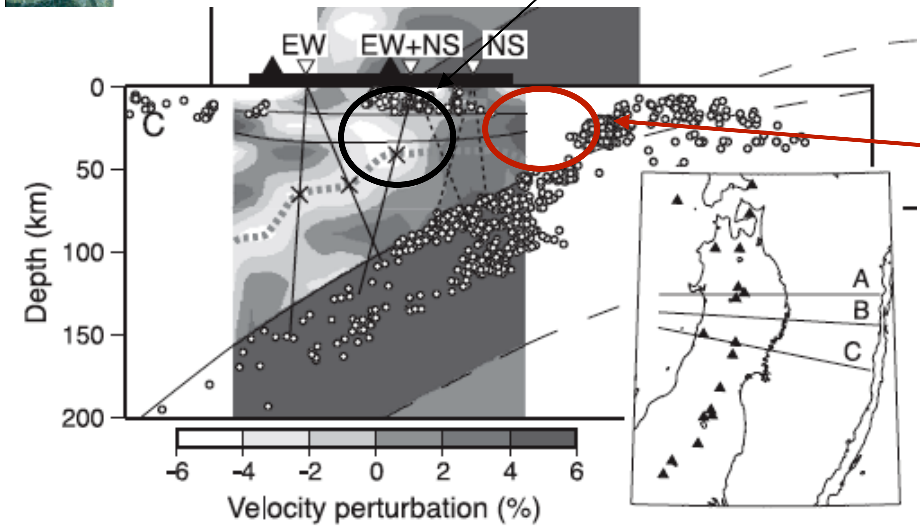
Pressure-dependence of water solubility in olivine + melting

Japan: shear wave splitting in the wedge



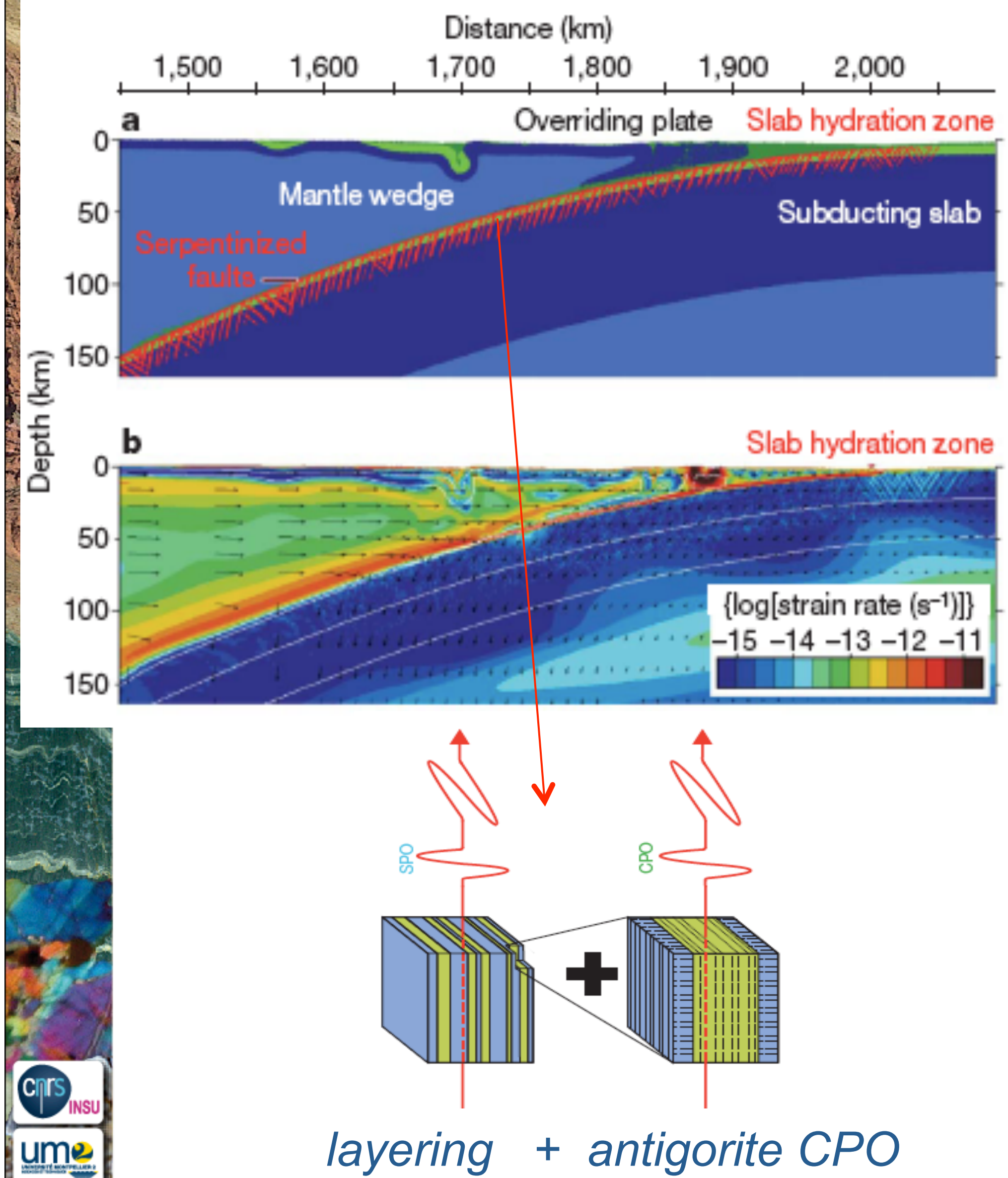


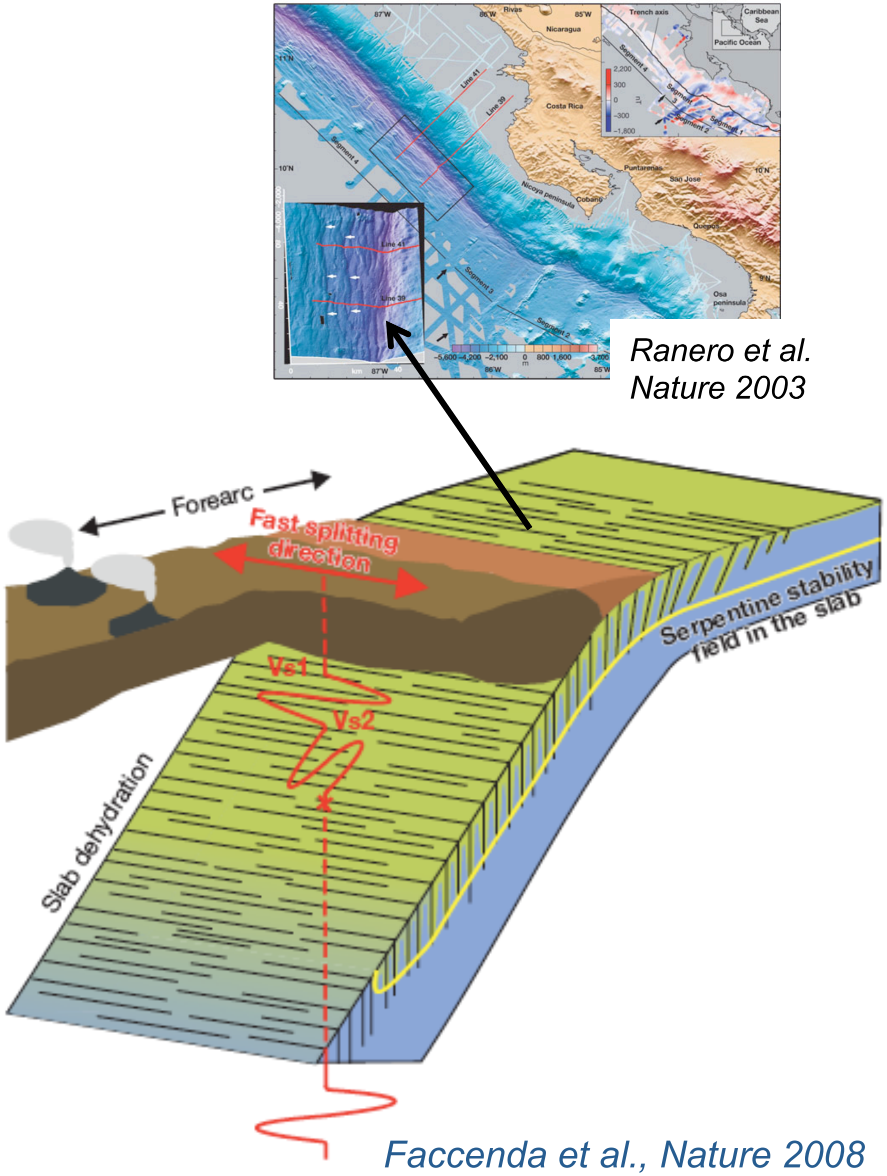
arc: melting, olivine dry

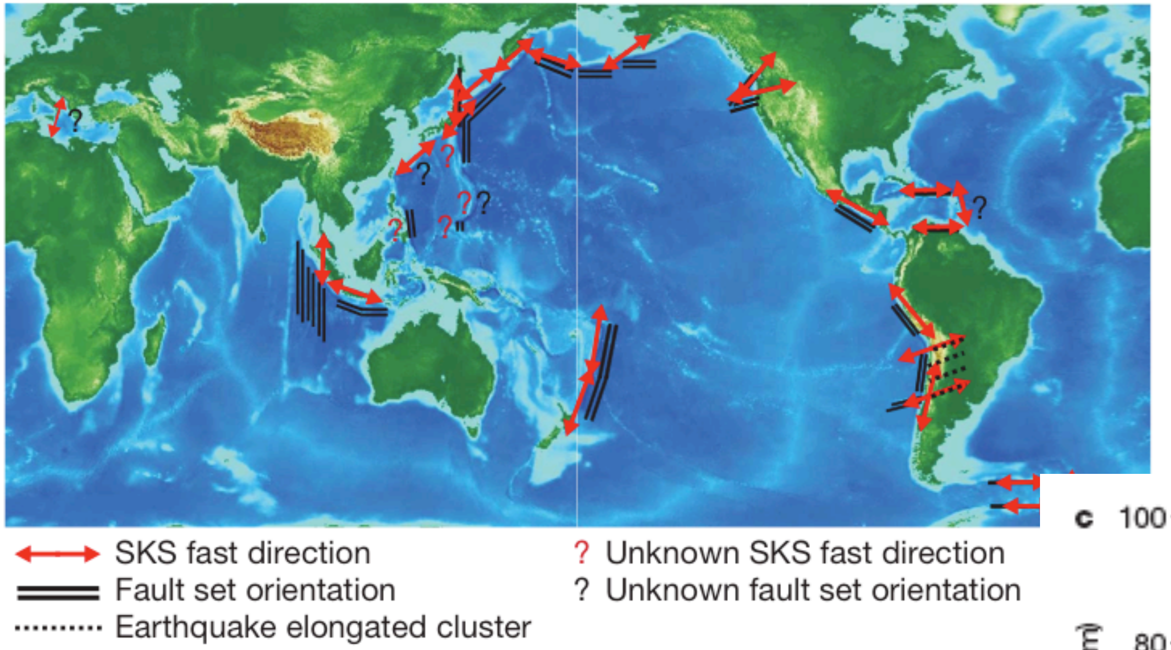


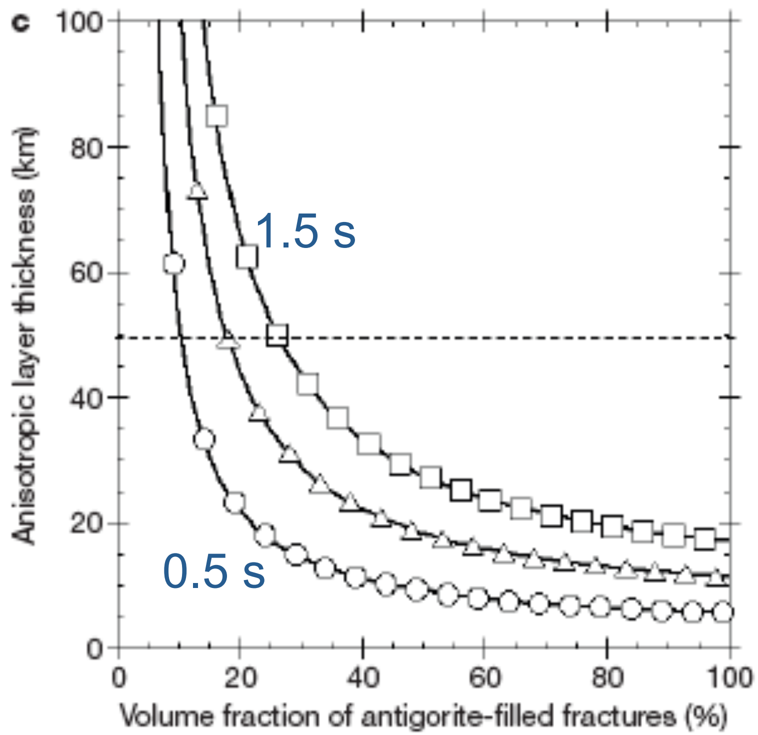
forearc : low T, olivine water-saturated, but are water contents & stress high enough for dominant activation of (010)[001]?
- water reduces viscosity
+ very short paths (≤50km)
= very low delay times!

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





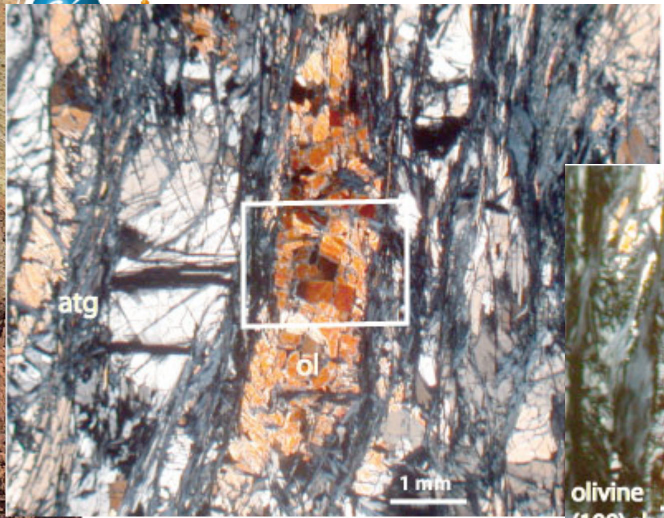


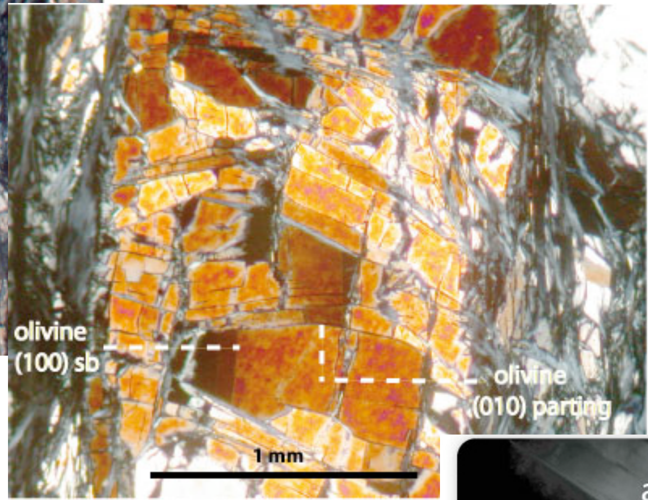


fault spacing < sampling wavelength
strong antigorite CPO
delay time = F (depth of serpentinization, volume fraction of serpentinized mantle)

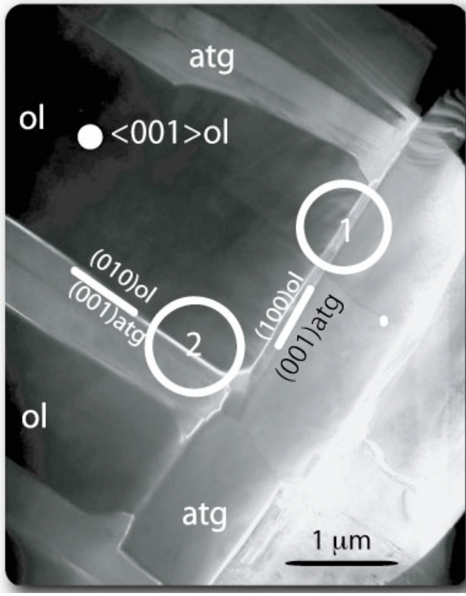
Orientation inheritance from olivine may also contribute…

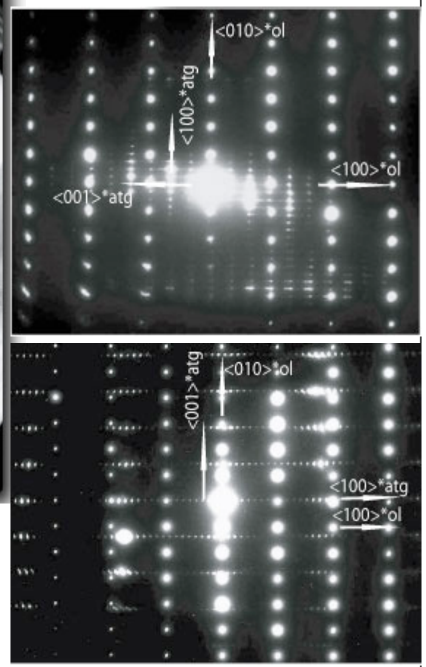
Antigorite – olivine crystallographic relations & seismic anisotropy

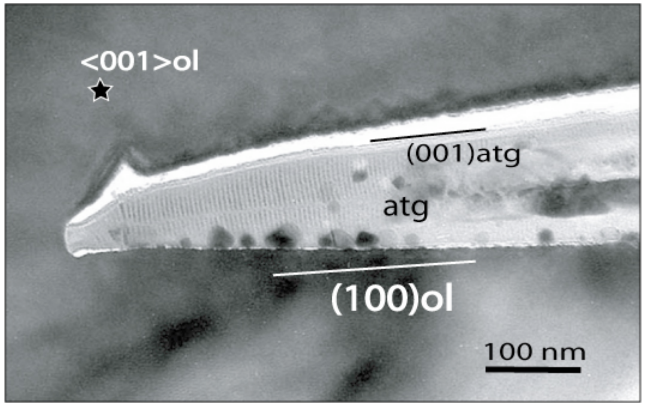




ANTIGORITE SCHIST
FROM
COLORADO PLATEAU

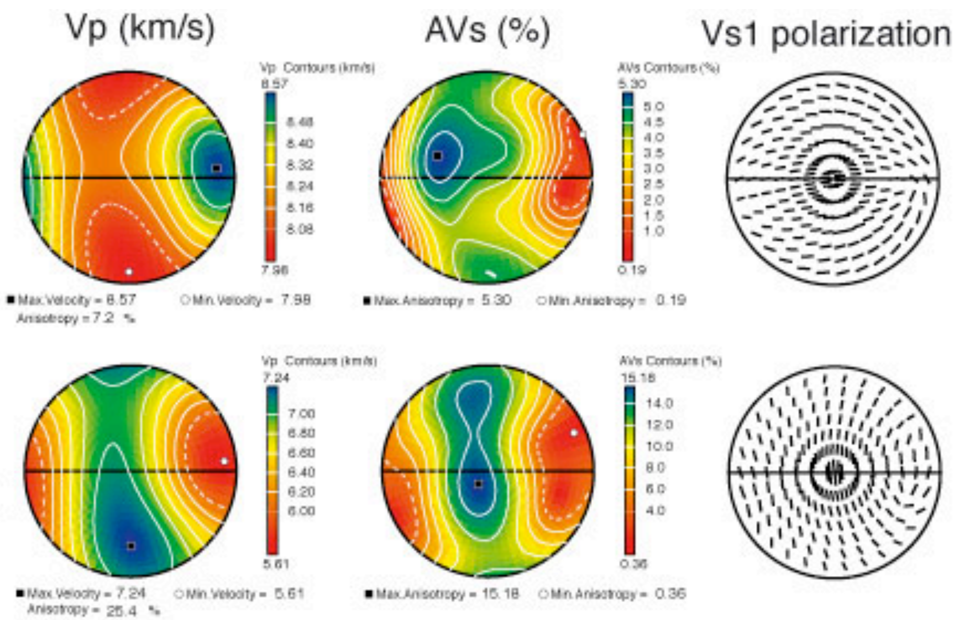


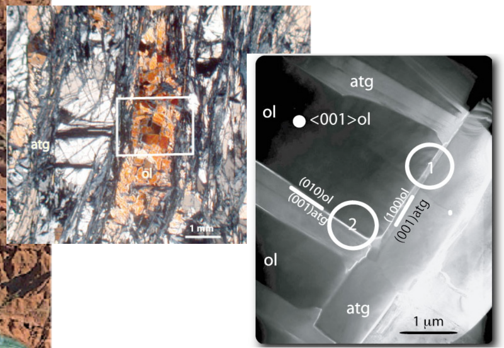


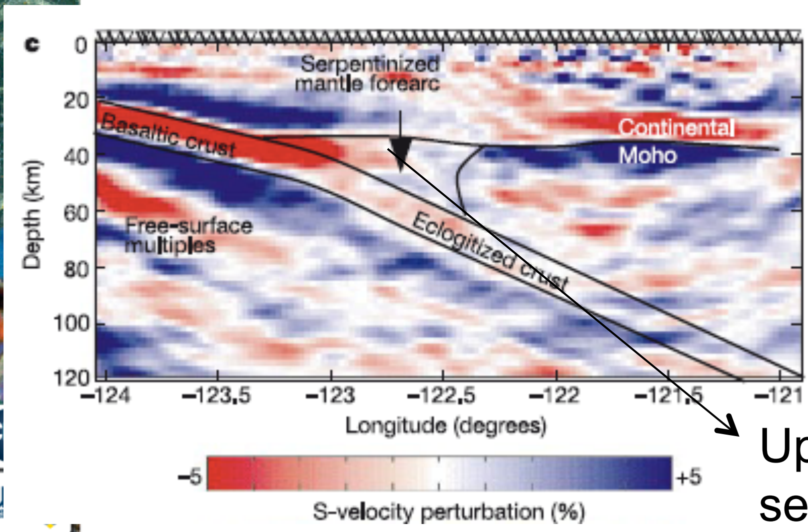


BOUDIER, BARONNET, MAINPRICE (J Petrol 2010)

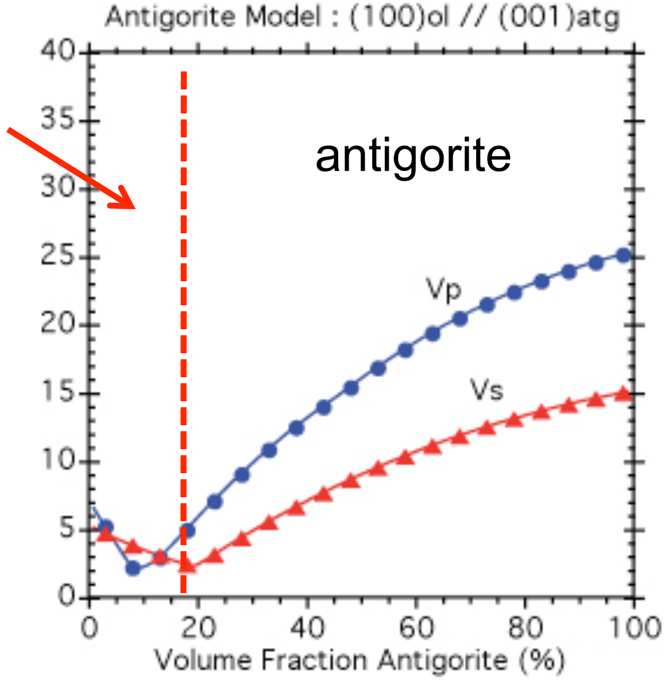
Olivine - antigorite CPO relations & seismic anisotropy







Up to 50-60% serpentine

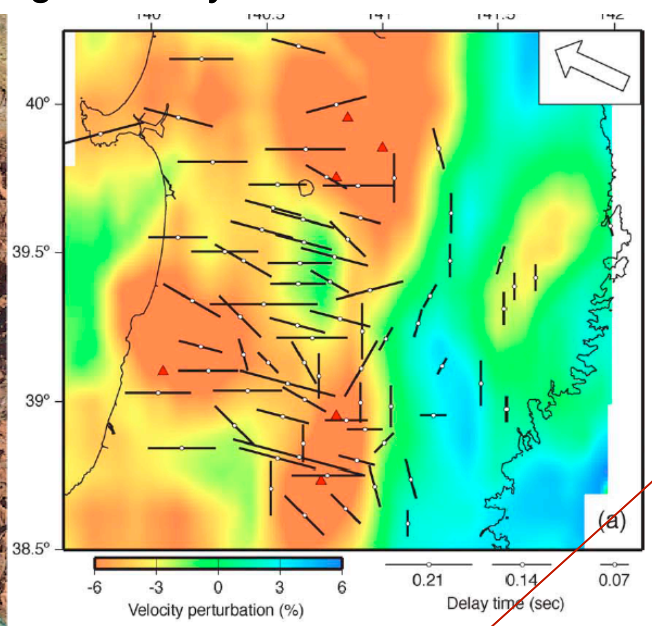


Bostock et al. Nature 2010

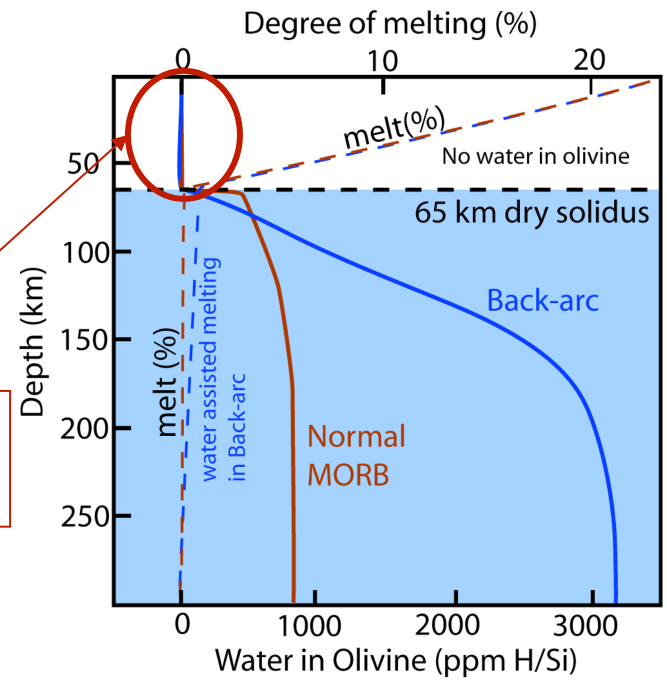
BOUDIER, BARONNET, MAINPRICE (J Petrol. 2010)

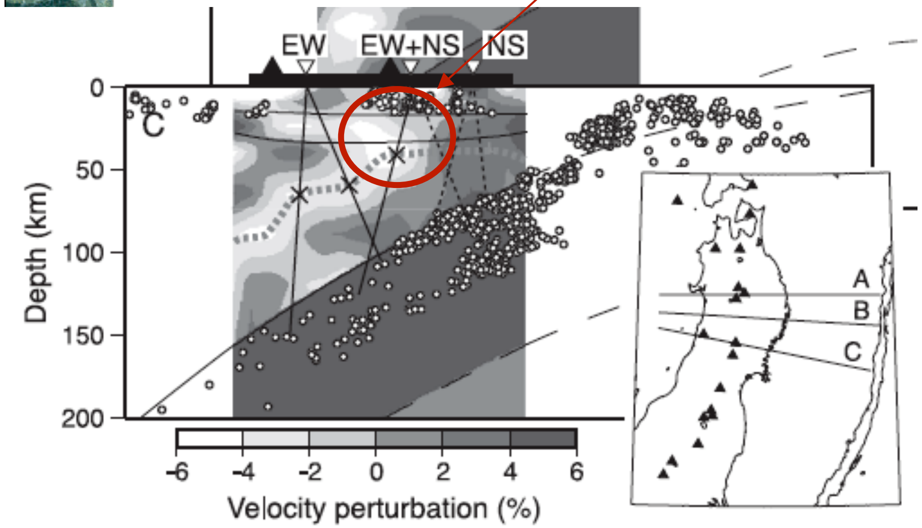
Below the arc…

Japan: trench-normal polarization & higher delay times

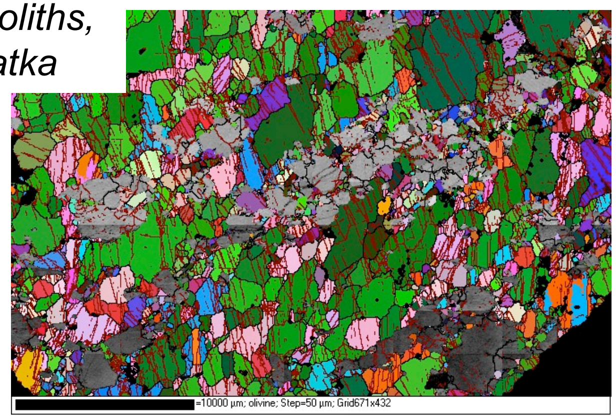


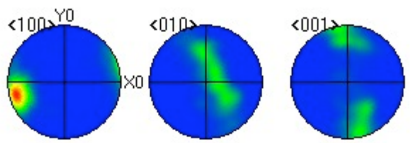
arc: melting, olivine dry





Arc xenoliths, Kamchatka

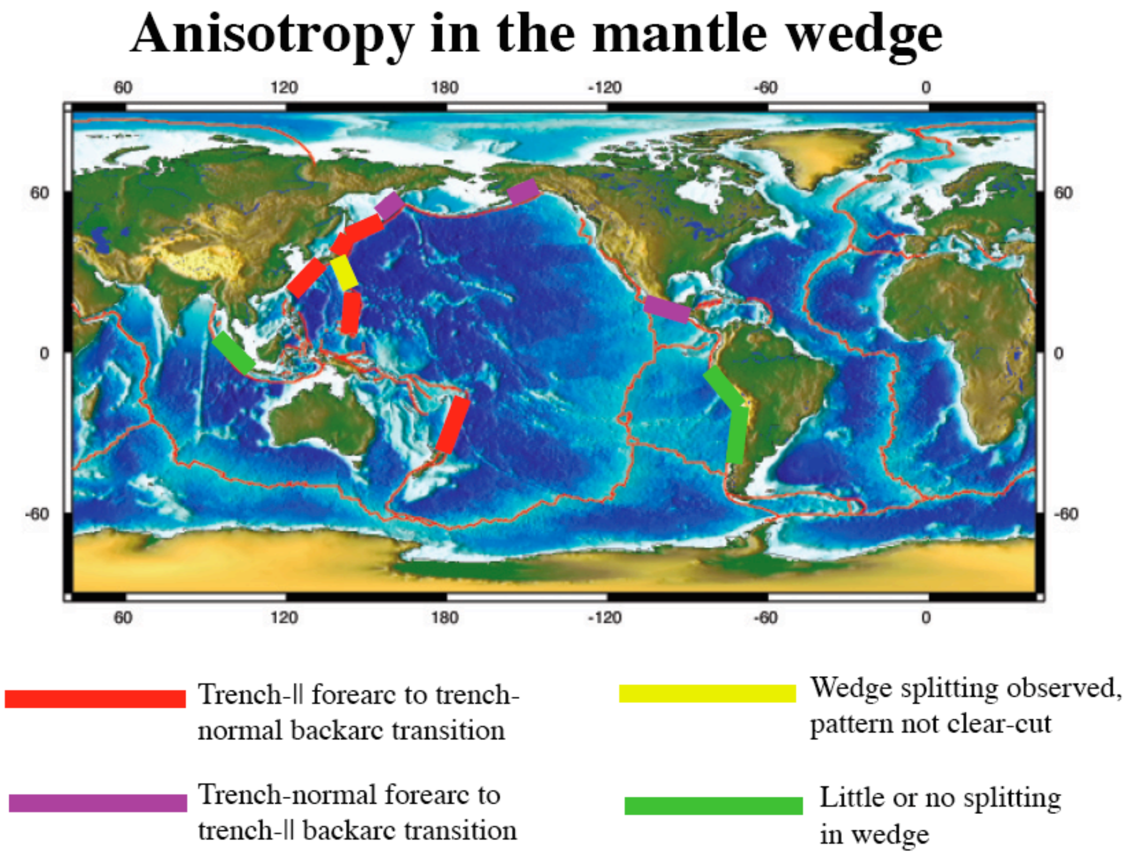




<a> glide only

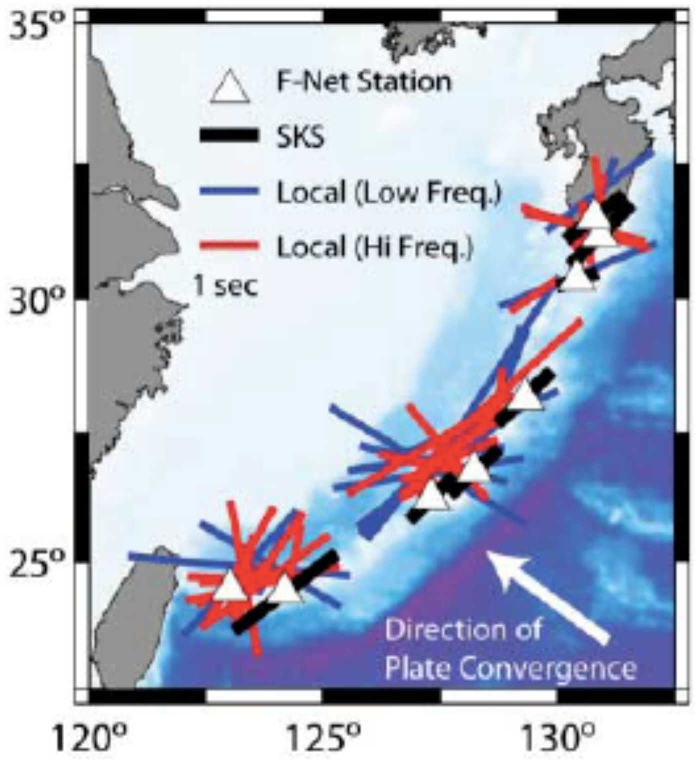
Soustelle et al. J Pet 2010

Trench // S-waves polarization below the arc…



Compilation by M. Long and P. Silver

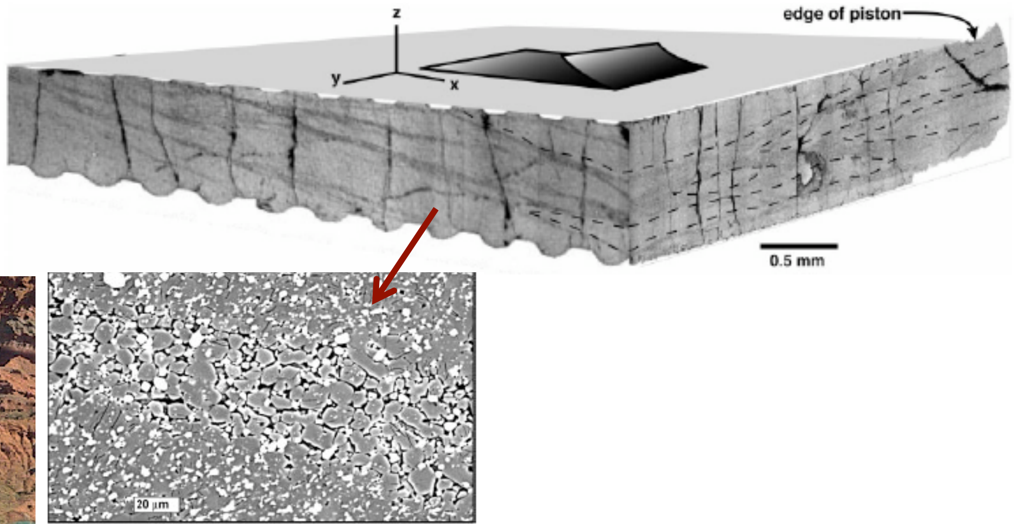
Ryukyu

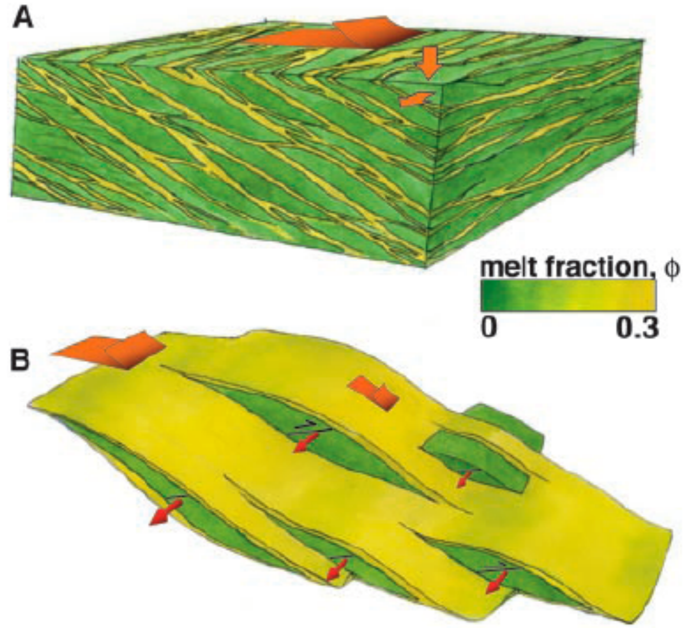


Behn et al. 2007 Science

Effect of partial melting?

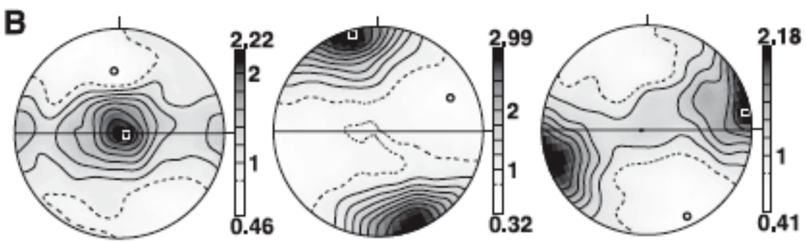
in lab experiments:





Holtzman et al. Science 2003

- *deformation => melt segregation*
- *melt-induced strain partition*
- ➢ *olivine [100] normal to shear direction*

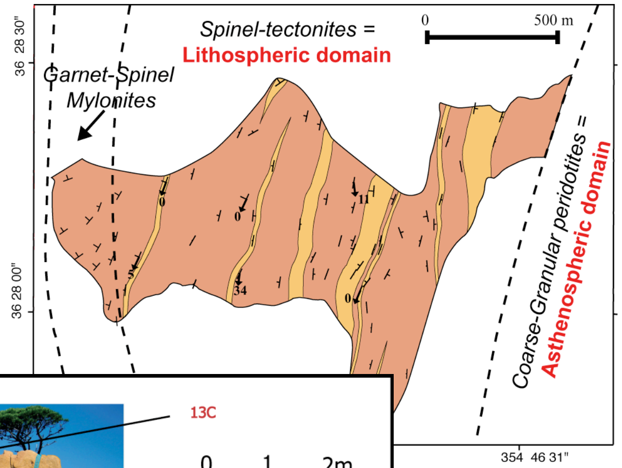


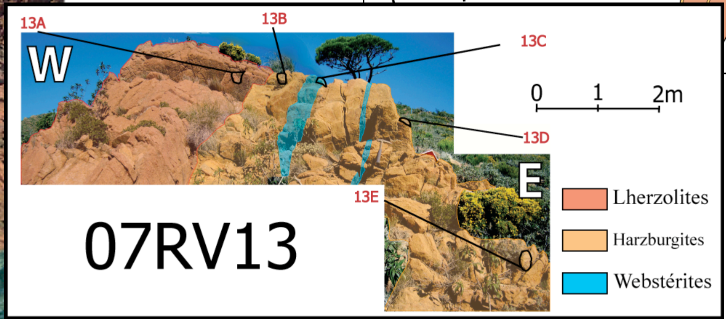
olivine CPO weak (diffusion):
anisotropy controlled by melt distribution

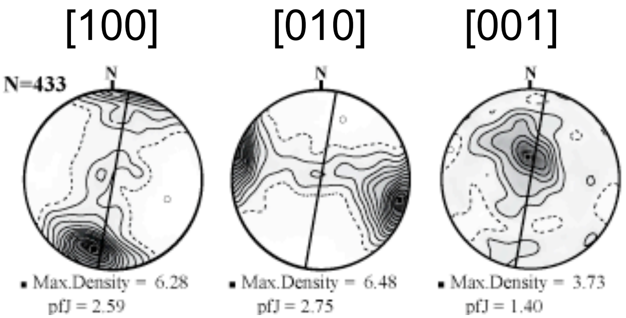
⇒ fast S-wave polarization sub-parallel to flow plane

In peridotite massifs, compositional layering // to foliation (flow plane), but diffuse contacts

Ronda, Spain

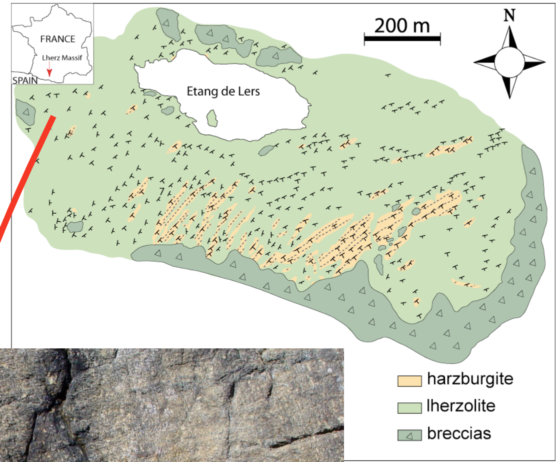


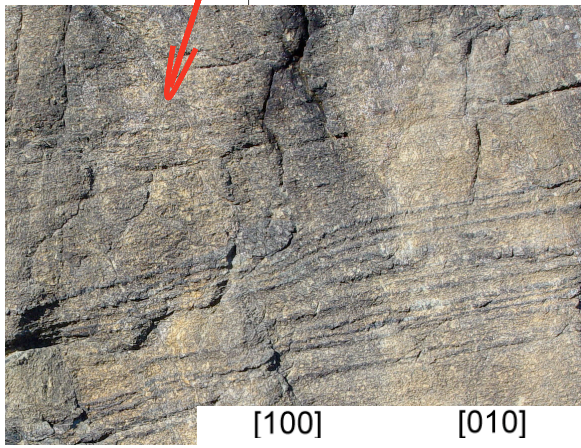


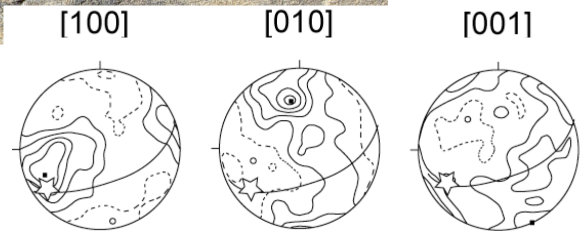


Soustelle et al. J.Petrol, 2009

Lherz, France





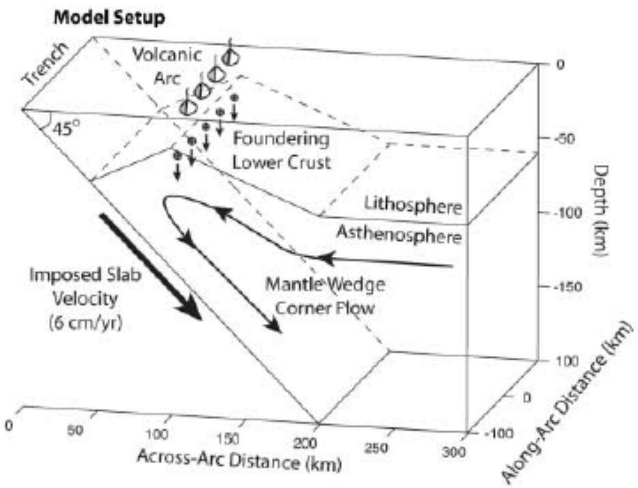


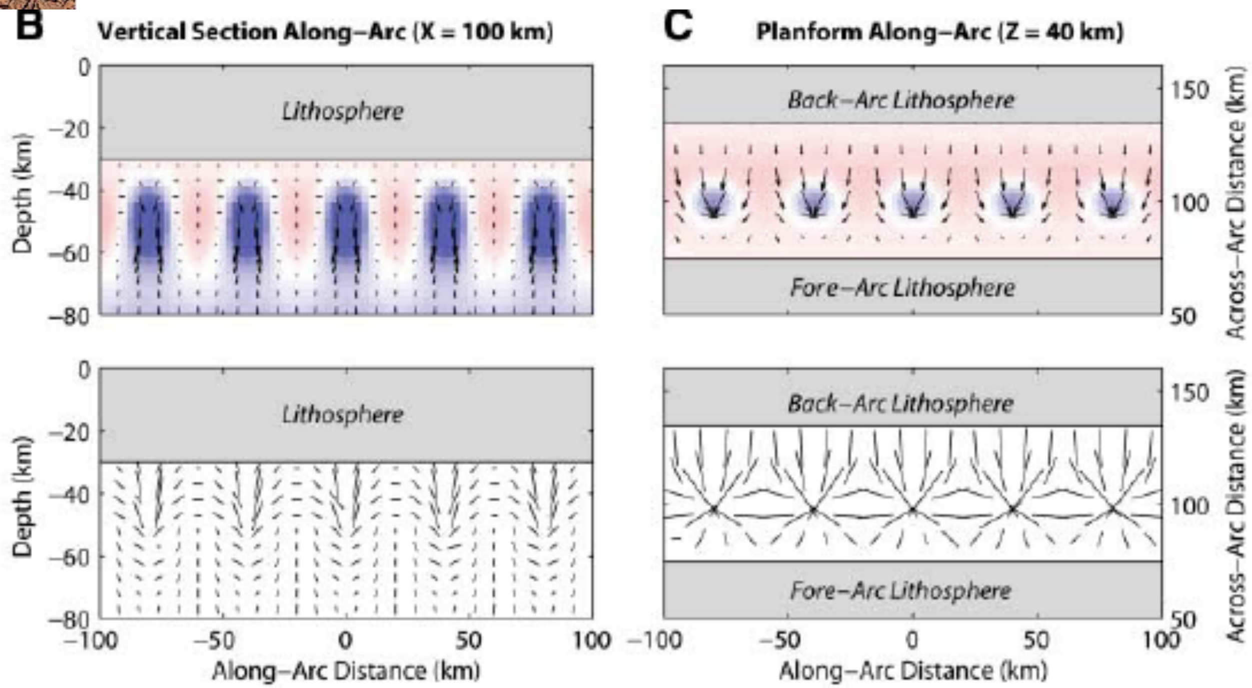
Le Roux et al EPSL 2008

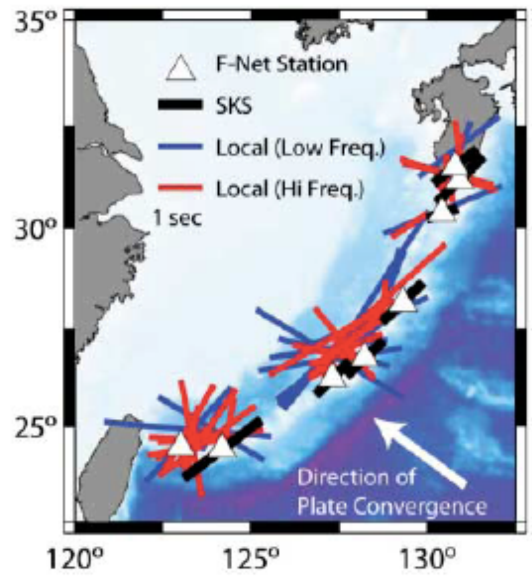
Melt transport/segregation controlled by deformation, but A-type CPO = [100] slip

Trench-Parallel Anisotropy Produced by Foundering of Arc Lower Crust

Mark D. Behn,[1*] Greg Hirth,[1] Peter B. Kelemen[2]



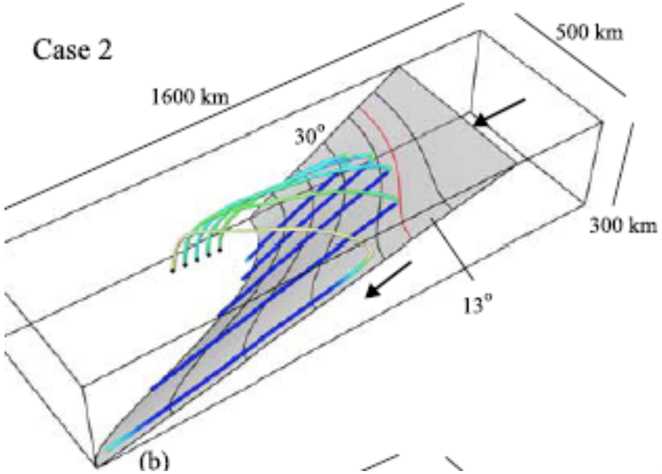


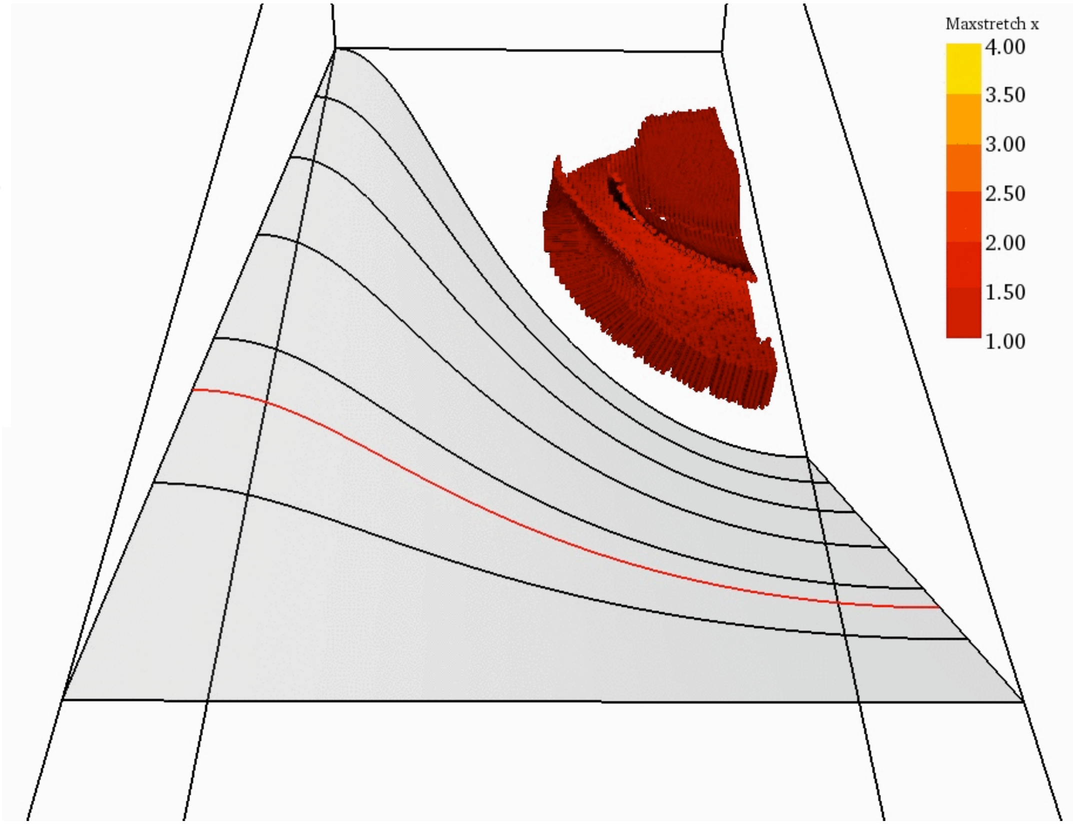


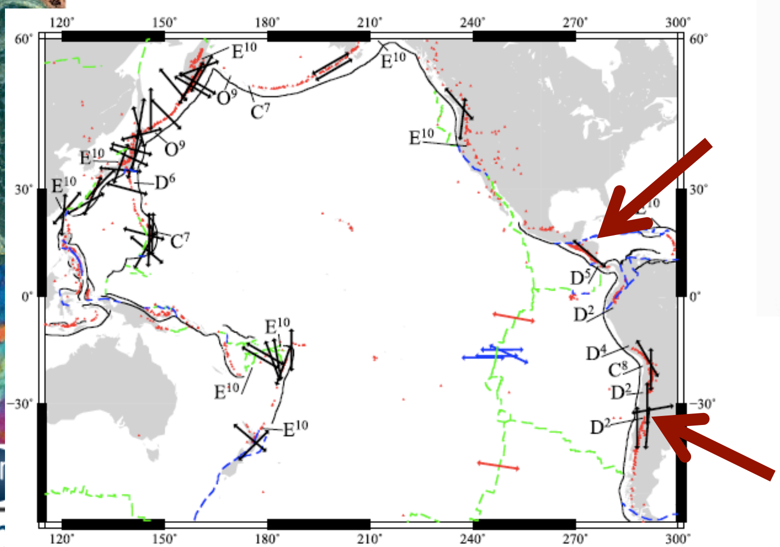
Mark D. Behn, *et al.*
Science **317**, 108 (2007)

Should we completely abandon the trench-// flow interpretation?

may be produced by pressure gradients due to changes in slab geometry





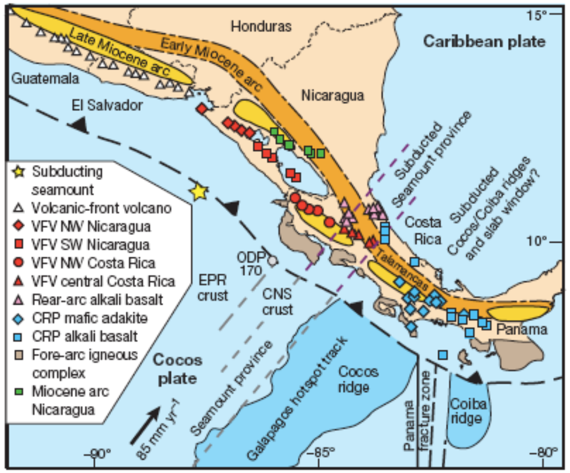


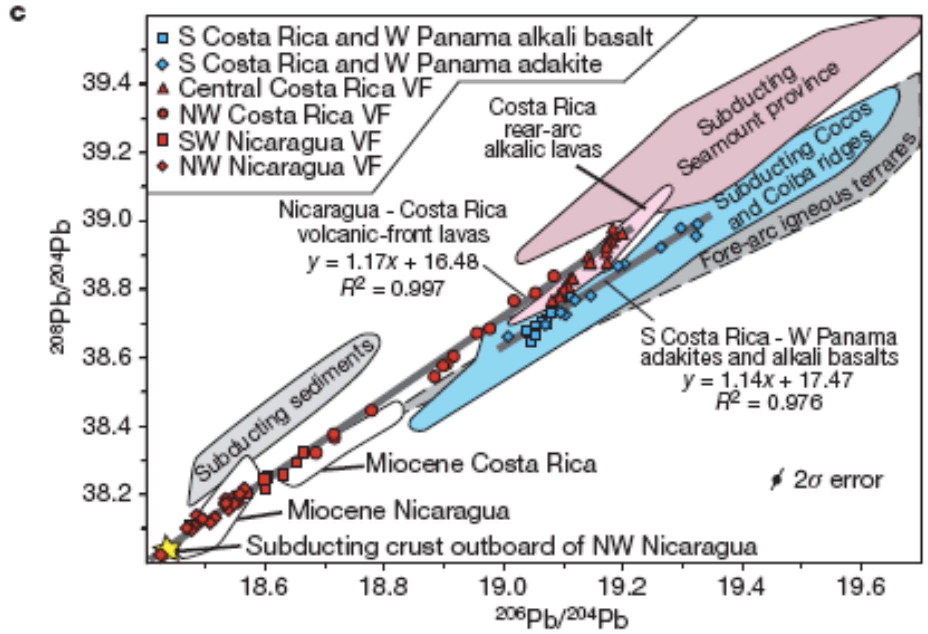
Change in slab dip:
stronger effect for transition to <15° dip

Kneller & Van Keken G3 2007

Arc-parallel flow in the mantle wedge beneath Costa Rica and Nicaragua

Hoernle et al. Nature 2008





Nd, Pb isotopes : NW flow of mantle wedge material

Local S waves splitting

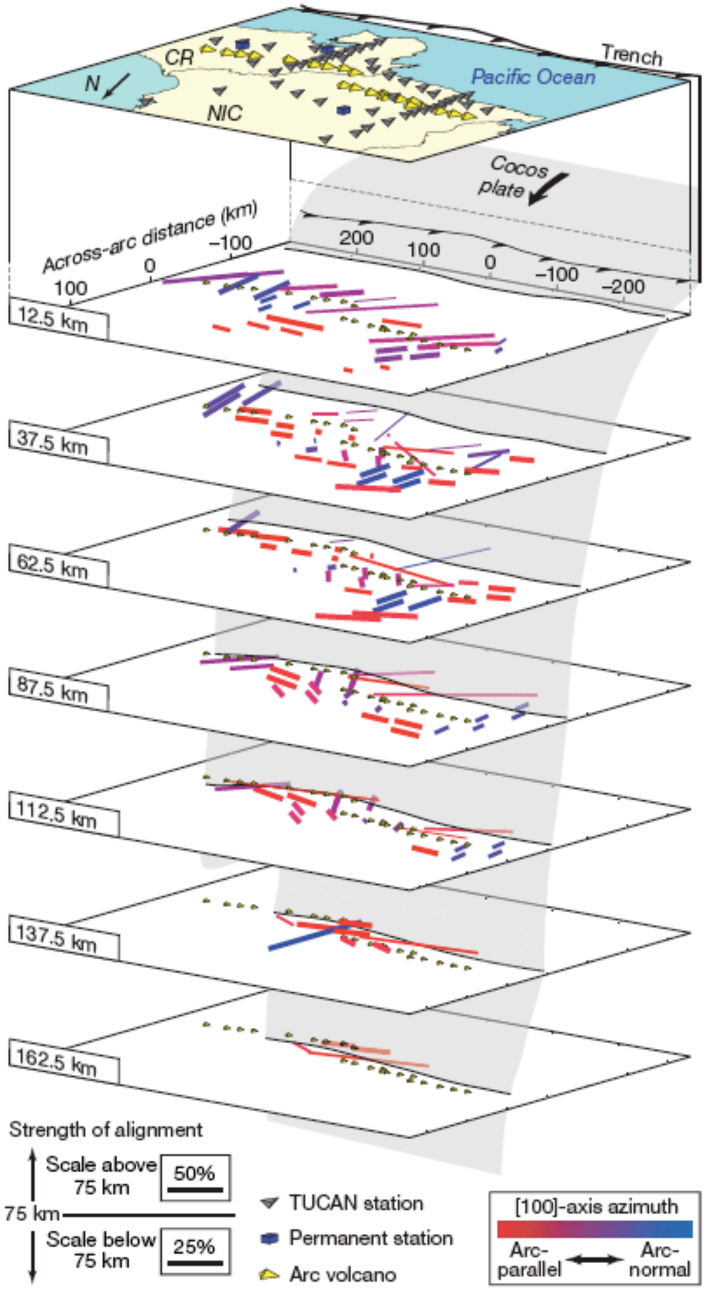
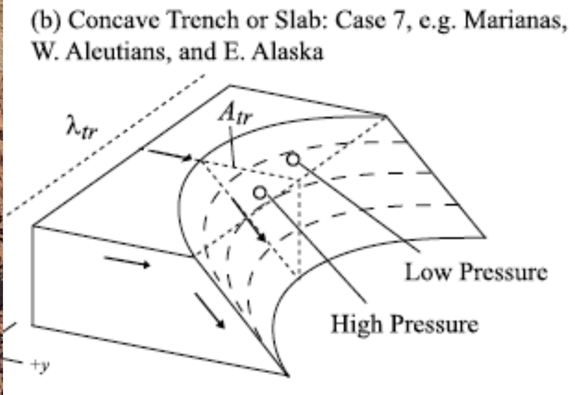
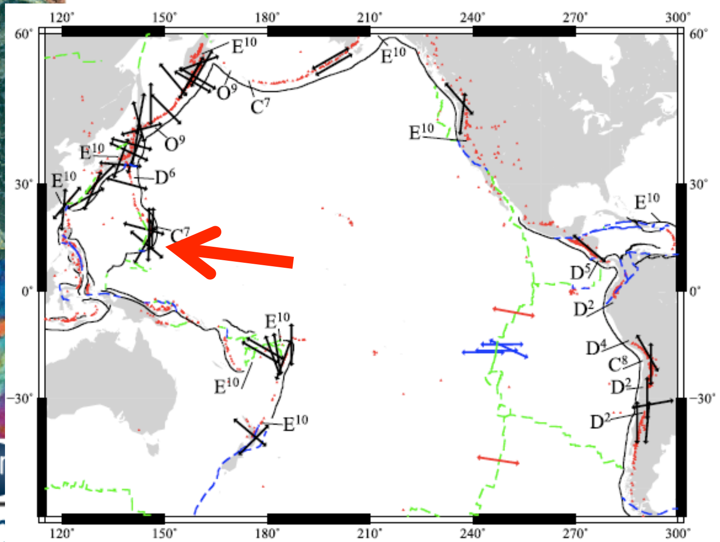
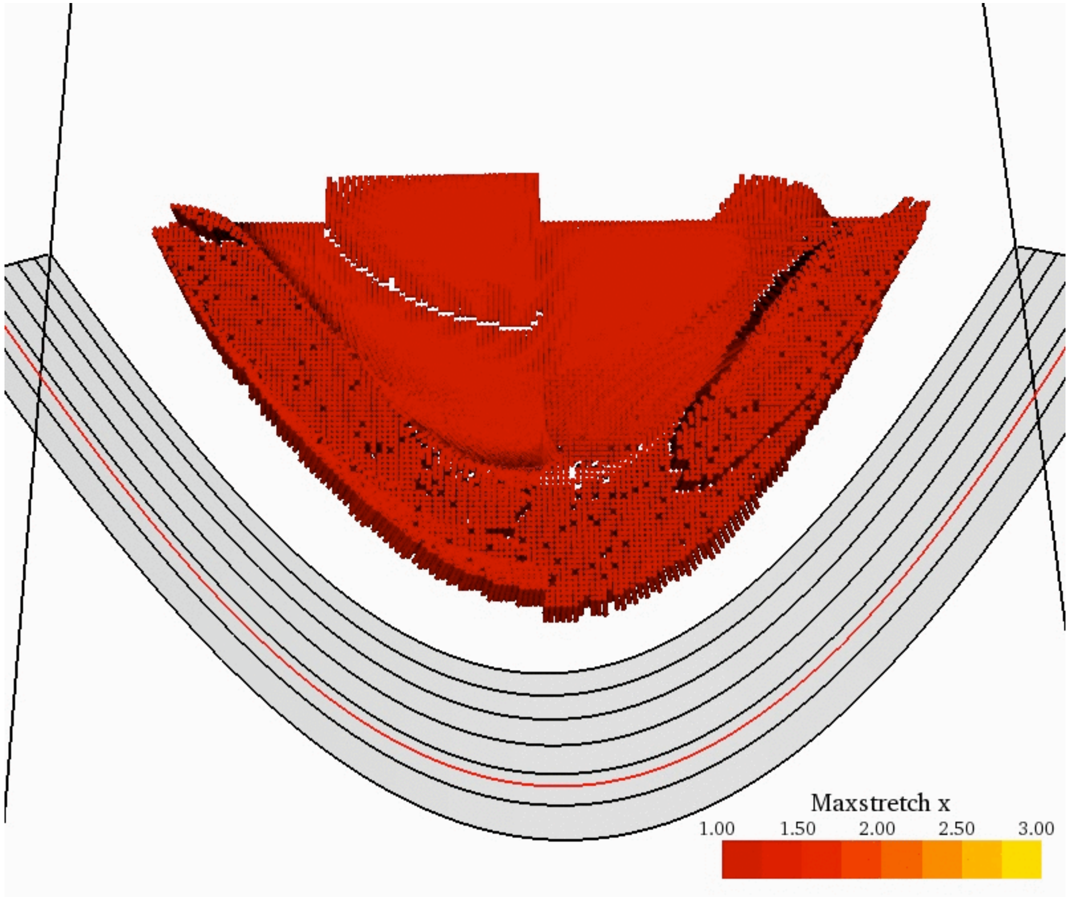


Figure 3 | Model of anisotropy obtained by inverting shear-wave splitting measurements from events in the Nicaragua (NIC)-Costa Rica (CR)

Strong slab curvature also may produce trench // anisotropy



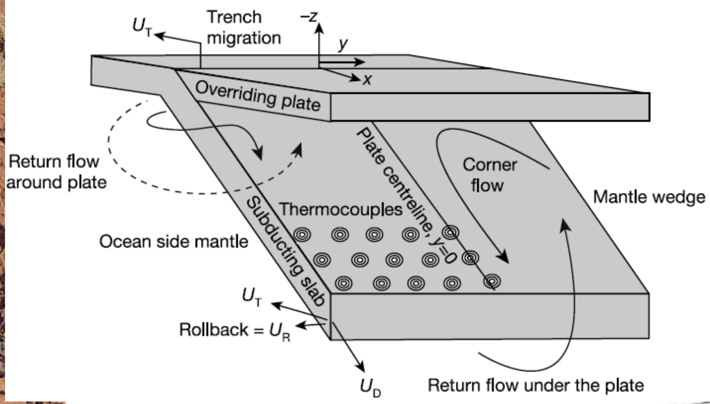


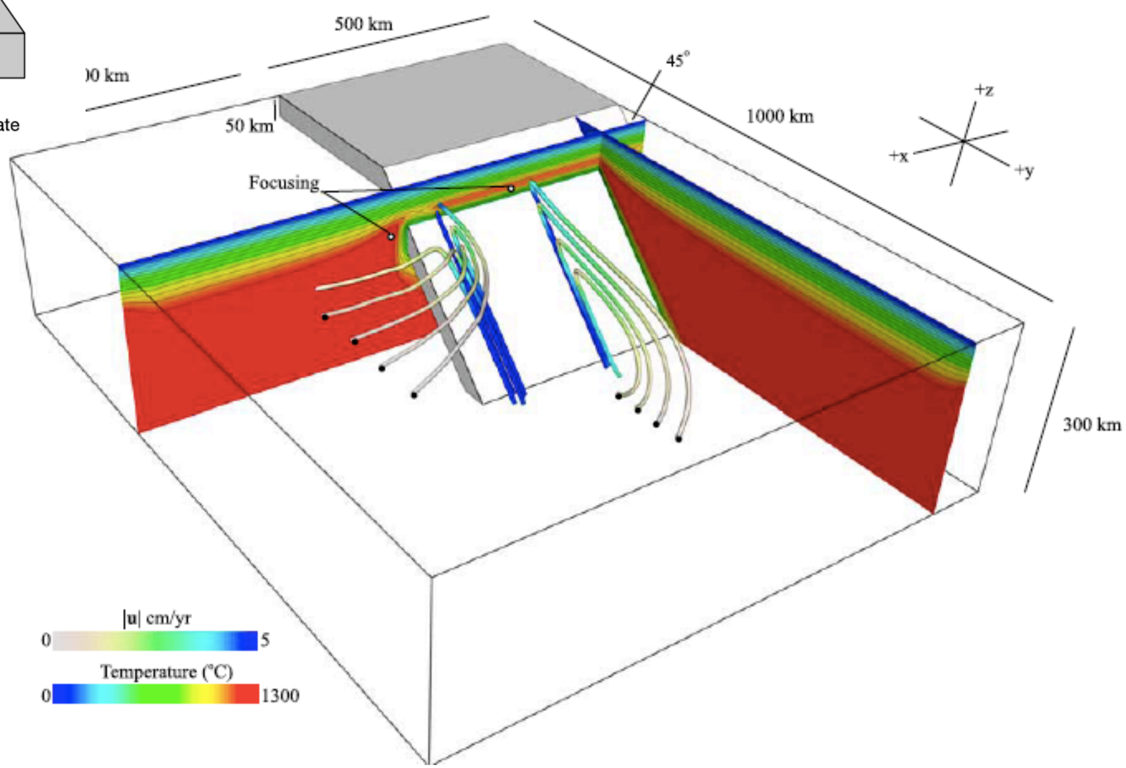


Kneller & Van Keken G3 2007

Should we completely abandon the trench // flow interpretation?

Toroidal flow near slab termination? Only <100 km from the termination!

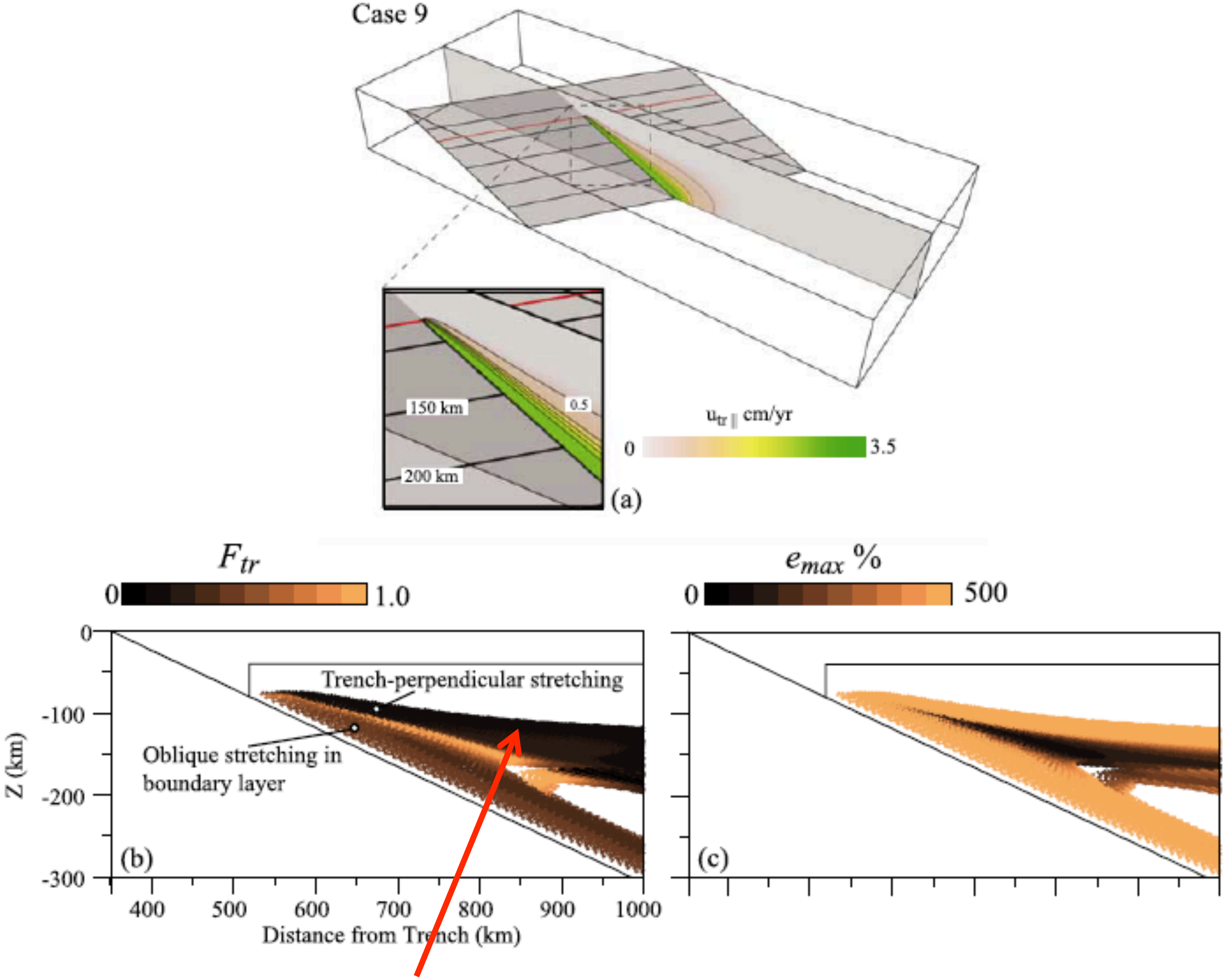




Kneller & Van Keken G3 2007

Should we completely abandon the trench // flow interpretation?

Oblique subduction?

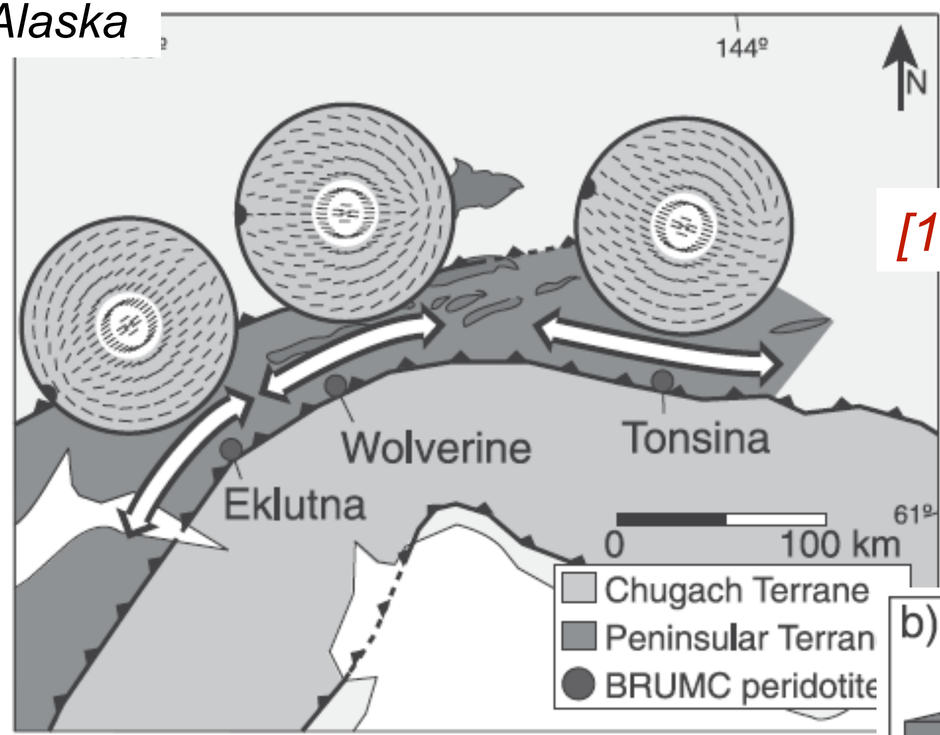


Very limited trench // flow

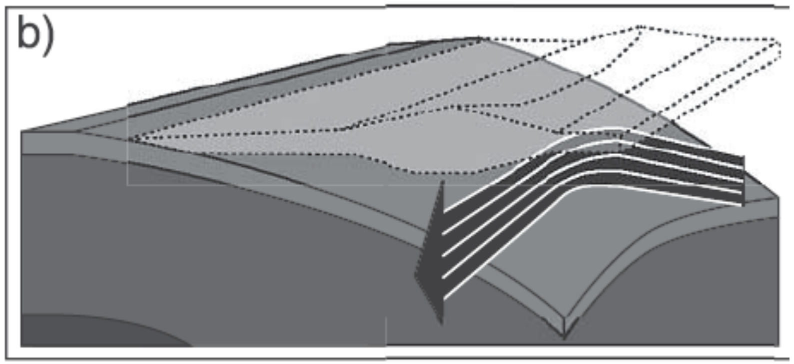
Kneller & Van Keken G3 2007

Arc-parallel flow within the mantle wedge: observations

Alaska



[100] slip

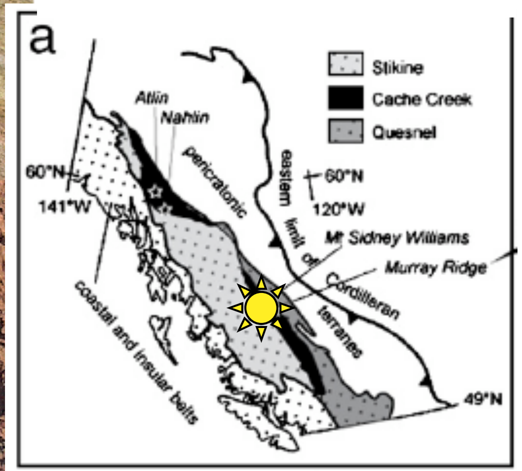


Mehl et al. JGR 2003

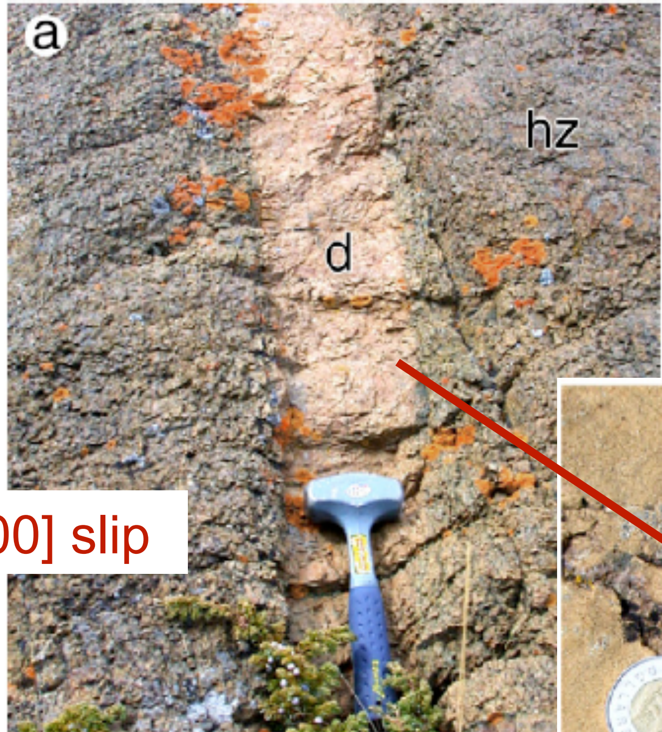
Flow // trench = strong trench-parallel anisotropy

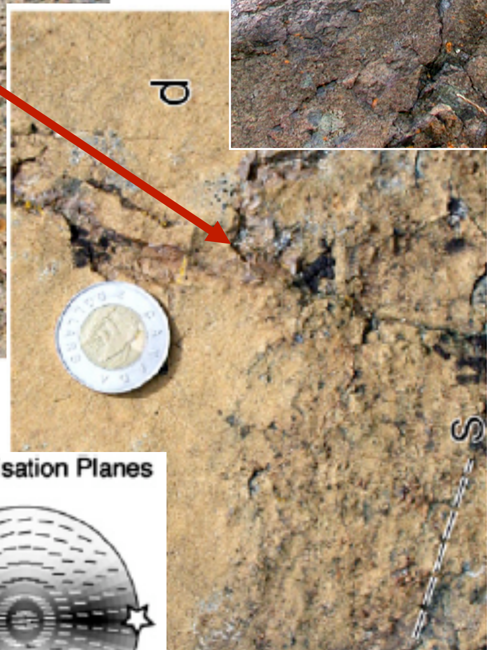
Flow + melt transport // trench in the wedge:
strong trench-parallel anisotropy

Canadian Cordillera

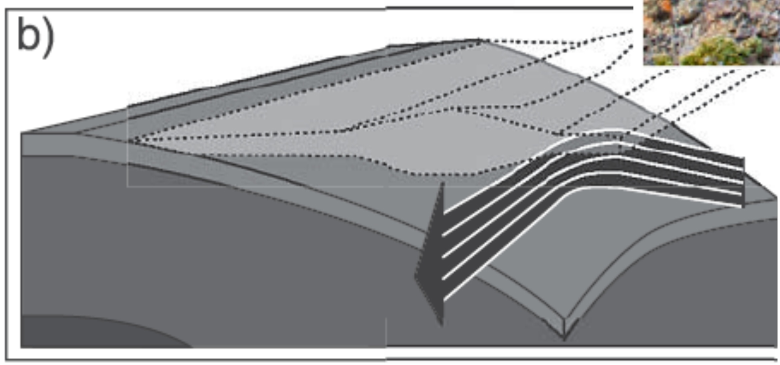


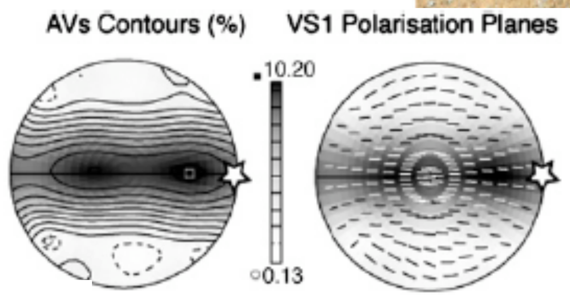
solid state foliation // dunite bands // pyroxenite dykes





[100] slip

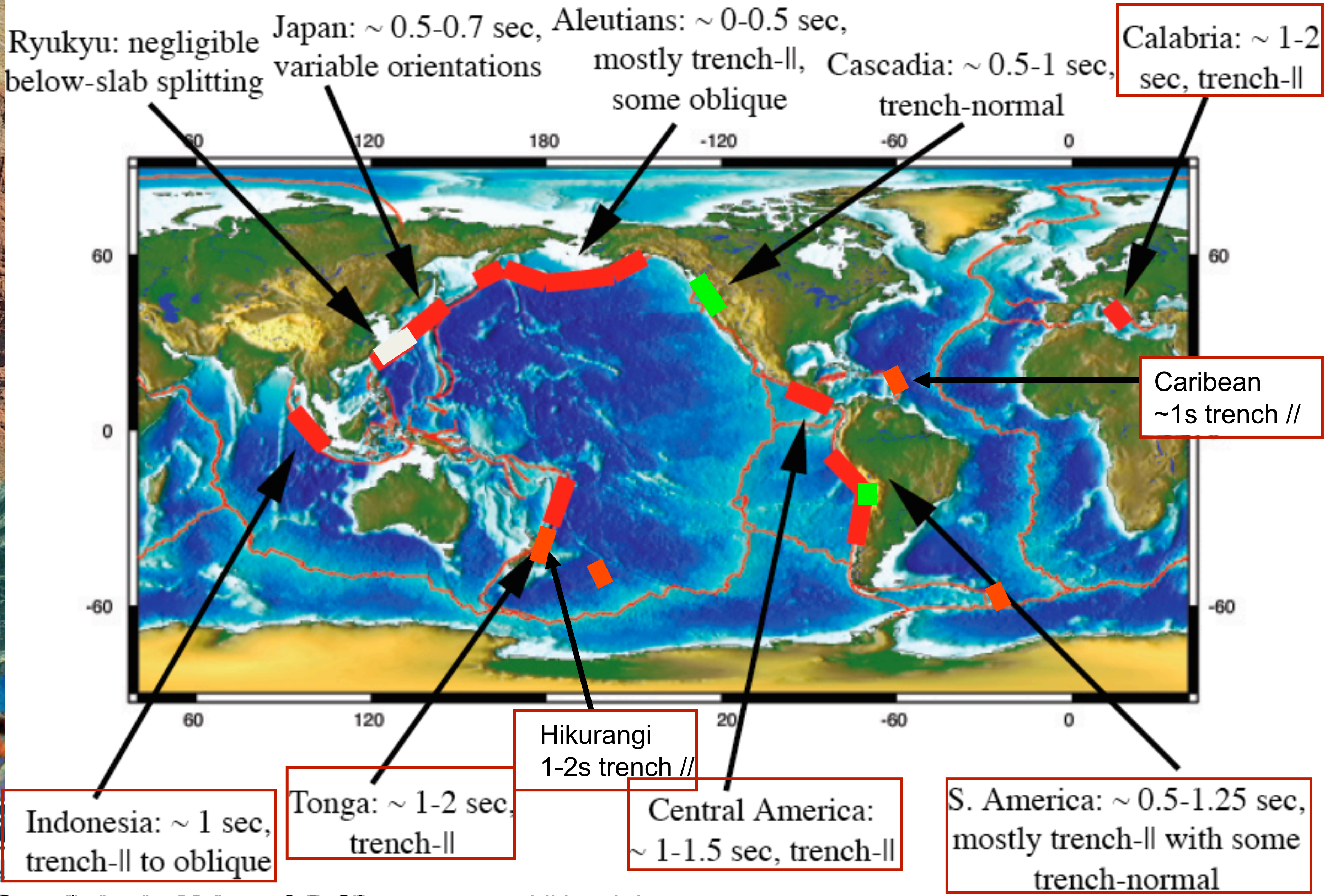




2 % melt = 10 % P & S anisotropy

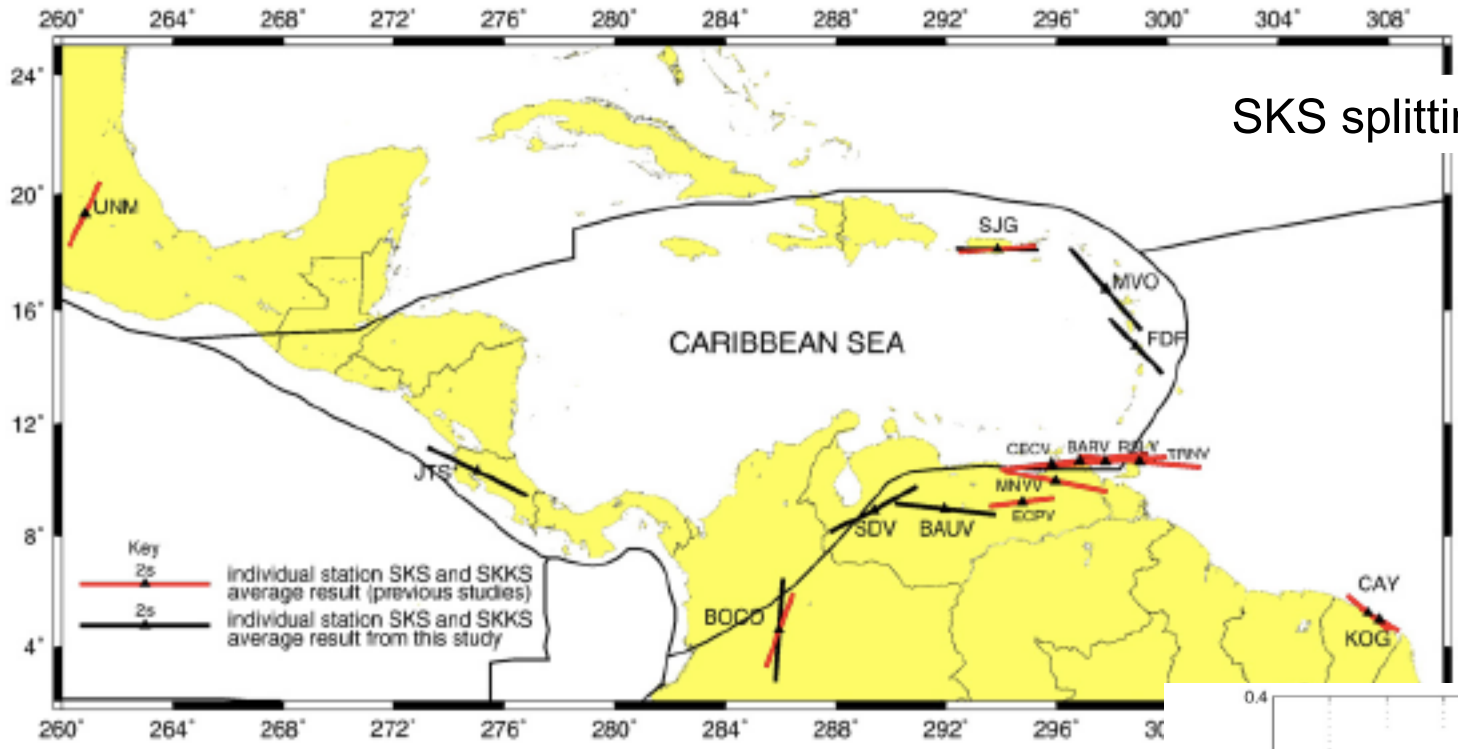
Tommasi et al EPSL 2006

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

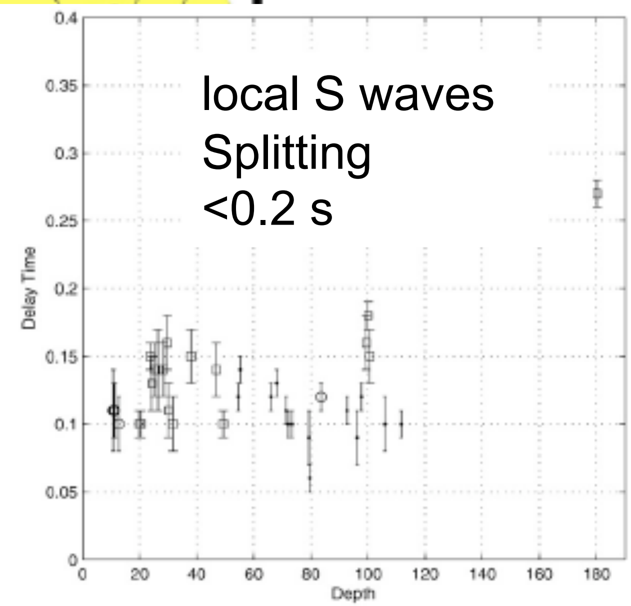


Compilation by M. Long & P. Silver + *some additional data*

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



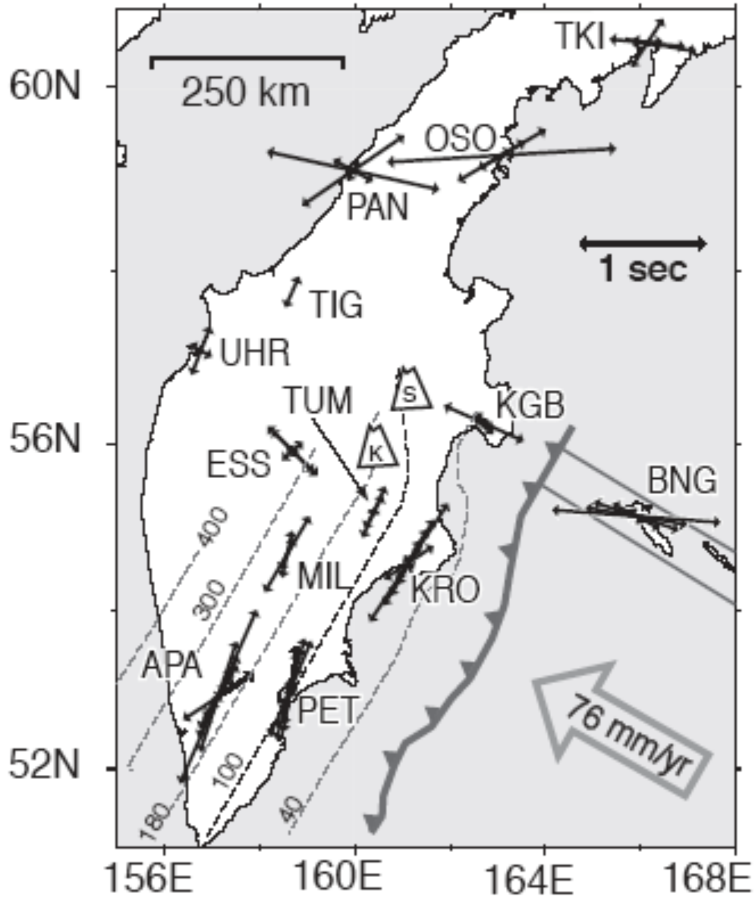
SKS splitting : 1 - 2 s



local S waves
Splitting
<0.2 s

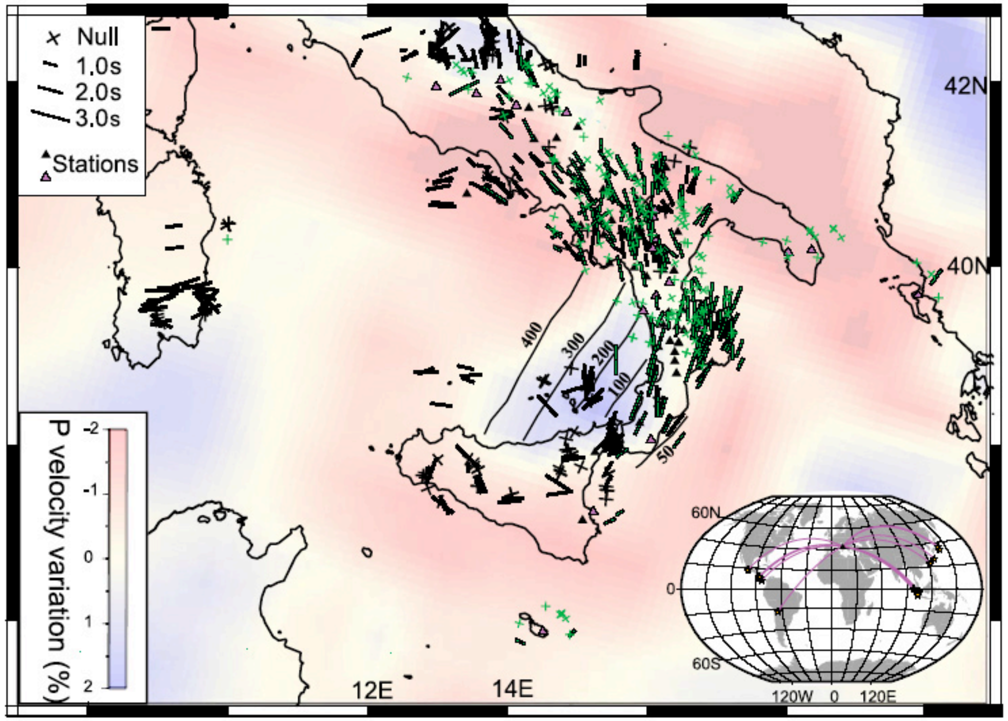
Below slab anisotropy

Kamchatka

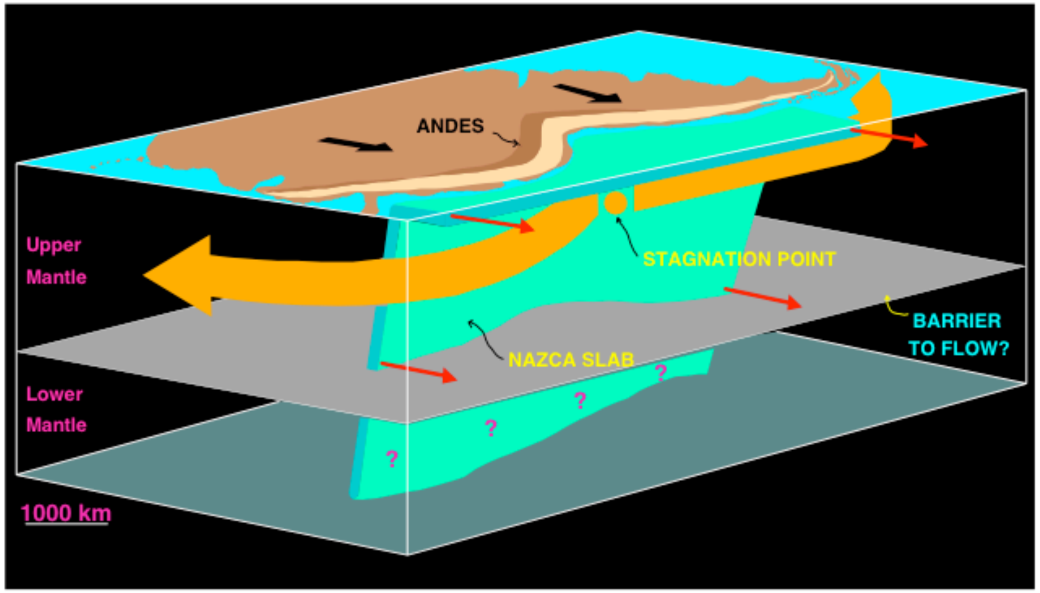


(Peyton et al., 2001)

Calabria



(Baccheschi et al., 2007; Civello and Margheriti, 2004)

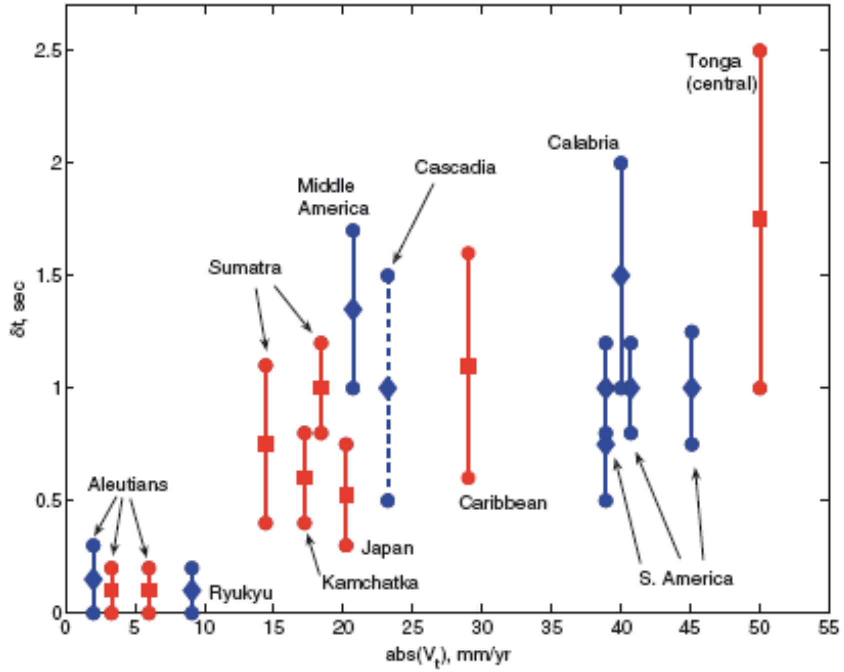


Trench // flow beneath slab
➔ pressure gradient :
- trench retreat
- barrier to flow @ depth (lower mantle)

Russo & Silver Science 94

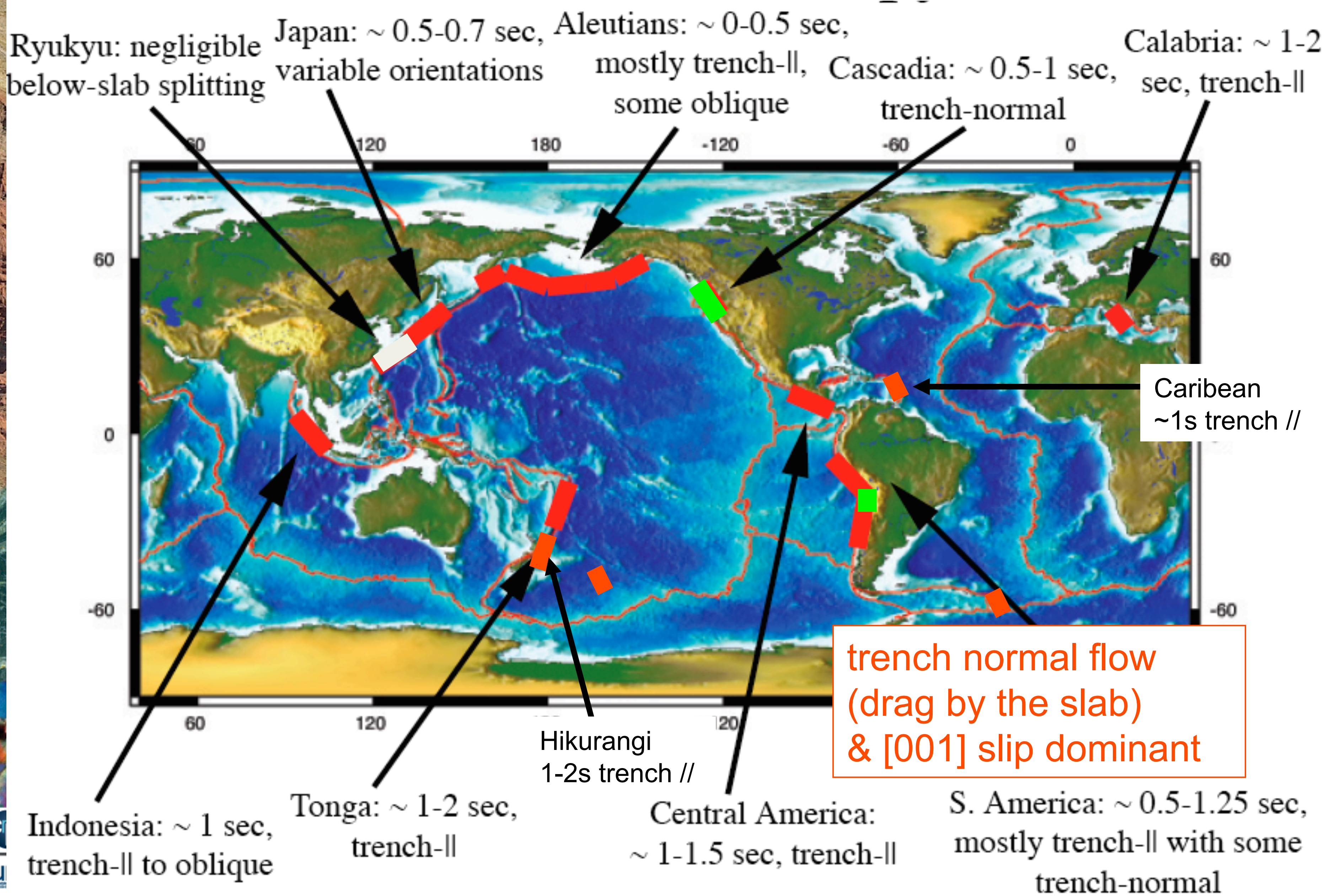
Trench // flow beneath slab: Correlation between delay time & magnitude of trench migration velocity

Problem: decoupling between the slab and underlying mantle!



Long & Silver Science 2008

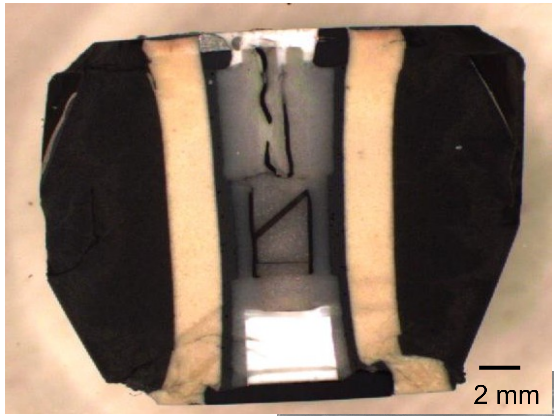
An alternative interpretation…



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

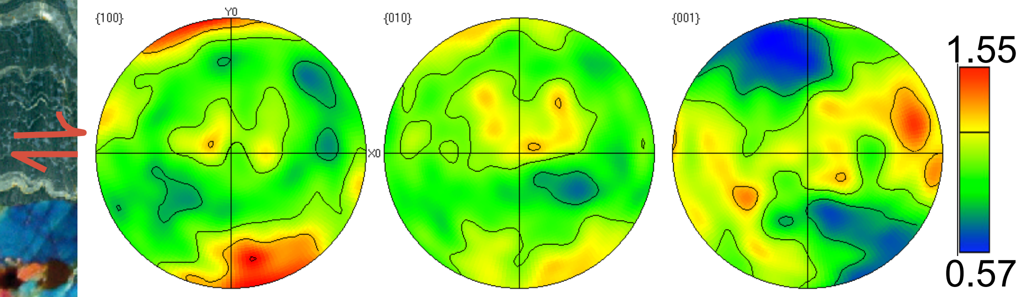
Deformation of olivine polycrystals @ 11GPa & 1400°C

H. Couvy & P. Cordier
Bayreuth/Lille



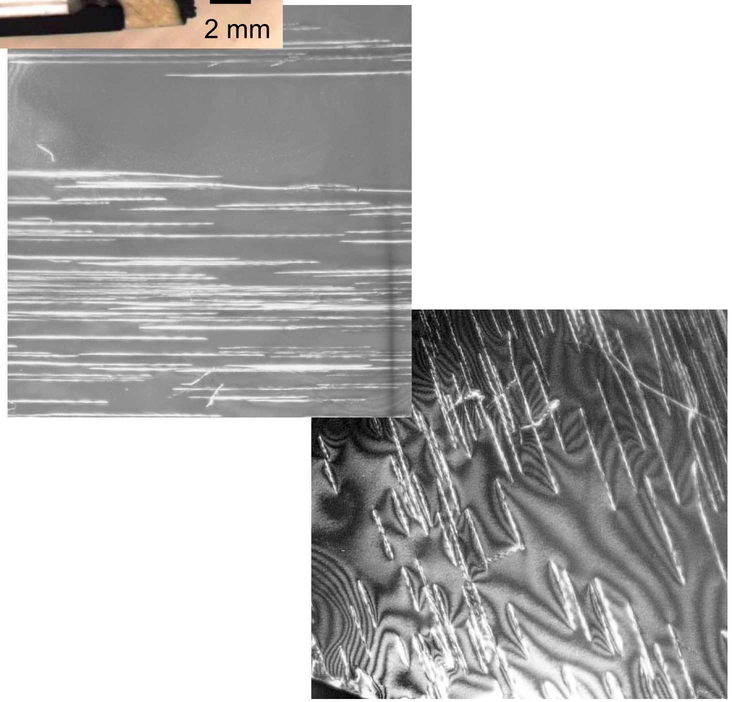
100% olivine
simple shear

EBSD: olivine CPO



γ=0.3

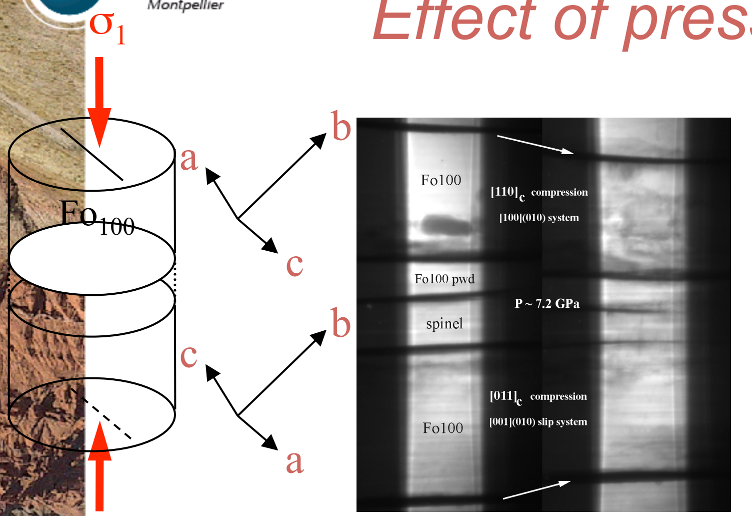
[001](100)
[001](010)



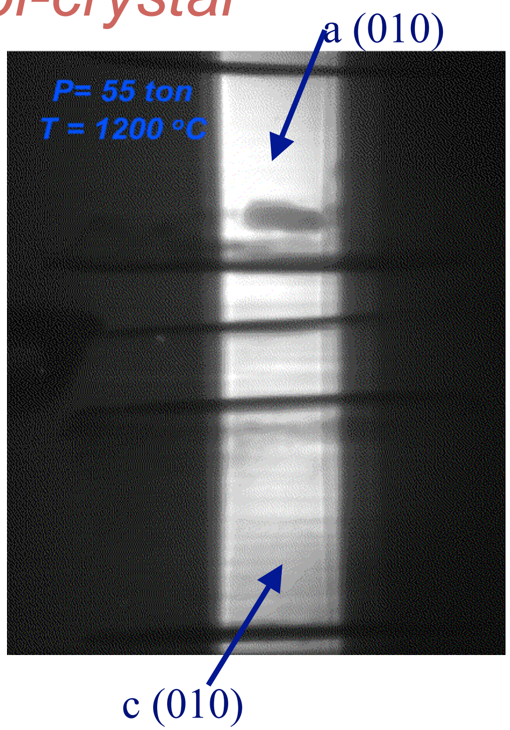
TEM: only [001] screw dislocations

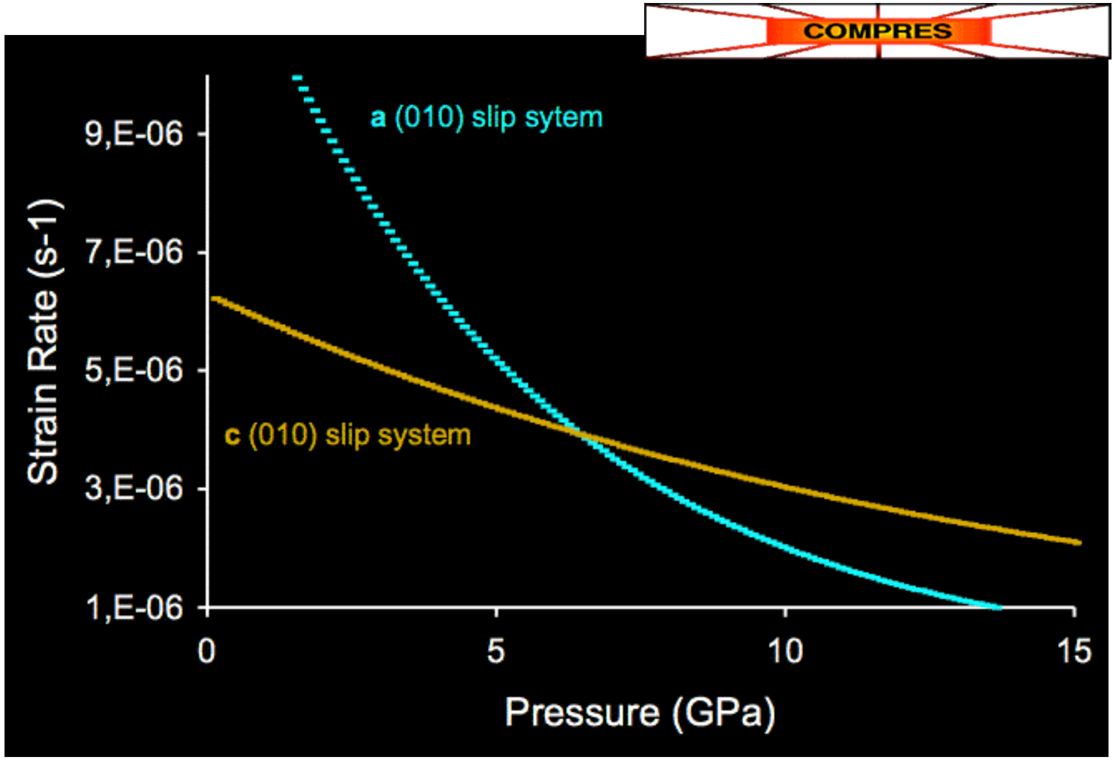
Couvy et al. EJM 2004

Effect of pressure on olivine deformation



bi-crystal





At high pressure:

- *higher strain rate in c crystal*

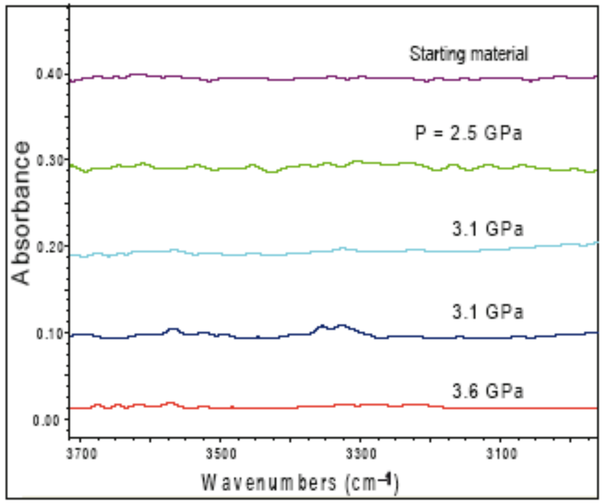
✓ *[001](010) slip easier than [100](010)*

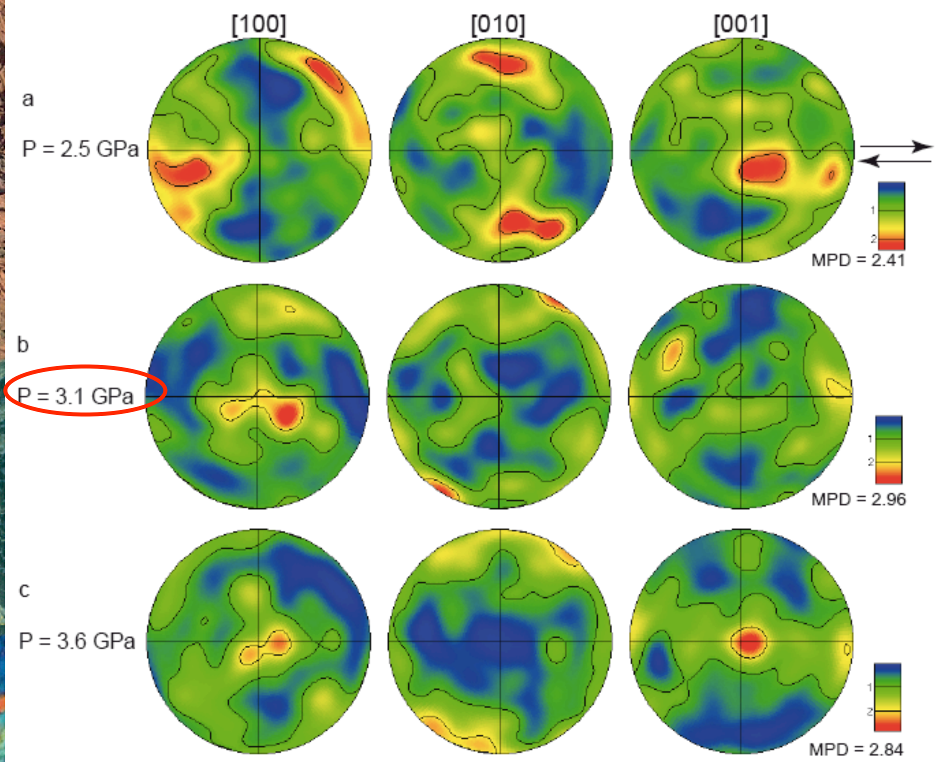
- *very low activation volume*

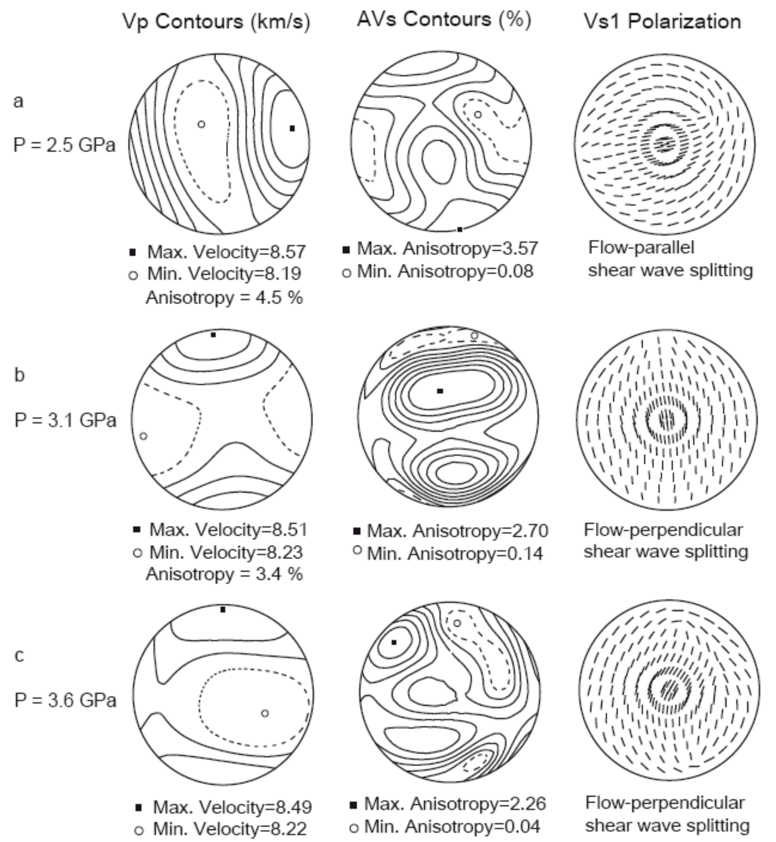
✓ *dislocation creep dominant*

Raterron et al. 2007

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







Jung et al. Nature Geoscience 2009

Summary

- In most of the upper mantle, seismic anisotropy behaves nicely:
  < 200 km : strong anisotropy, SH>SV, fast directions // APM (oceans)
  or // lithospheric structure (continents)
  • dominant [100] slip
  • delay times = path lenght
  > 200 km : anisotropy decreases : effect of pressure = [001] slip

- In subduction zones…

- In the wedge : local S waves – complex patterns, usually delay times <0.4s

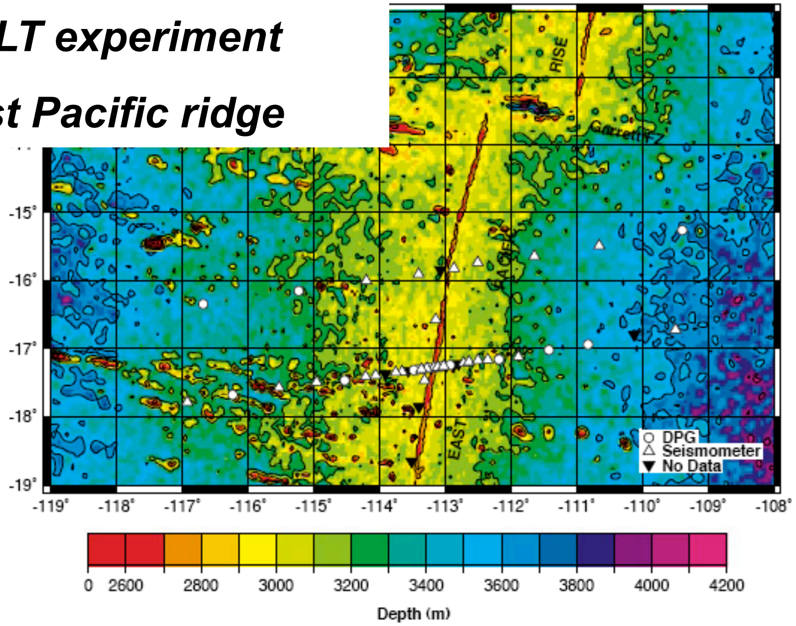
  3D flow, role of fluids (H_20, magmas) on olivine deformation, direct contribution of melt to seismic anisotropy (aligned melt lenses & dykes), and role of serpentine…

- SKS splitting generally // trench & delay times > 1.5s
  - Slab anisotropy : Serpentines?
  - Sub-slab mantle flow : [100] slip & trench // flow : decoupling?
    [001] slip - HP olivine deformation : why this signal is not seen elsewhere?

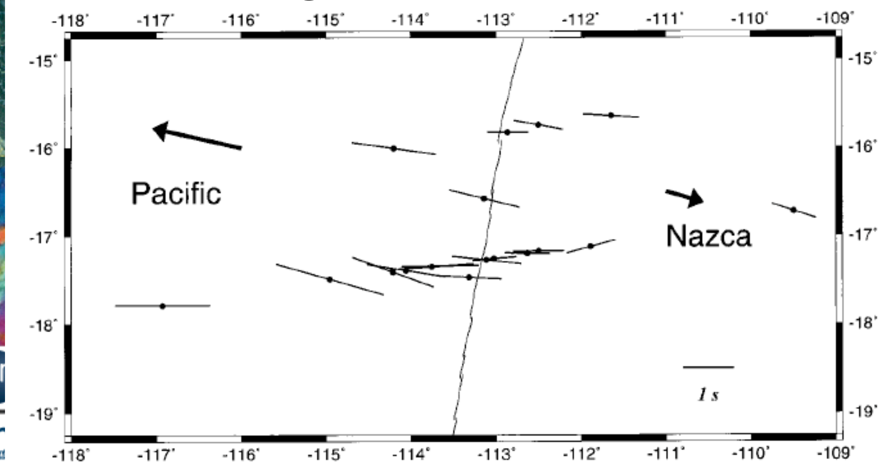
Electrical conductivity anisotropy inferred from long-period MT data: Another tool to map upper mantle deformation?

MELT experiment

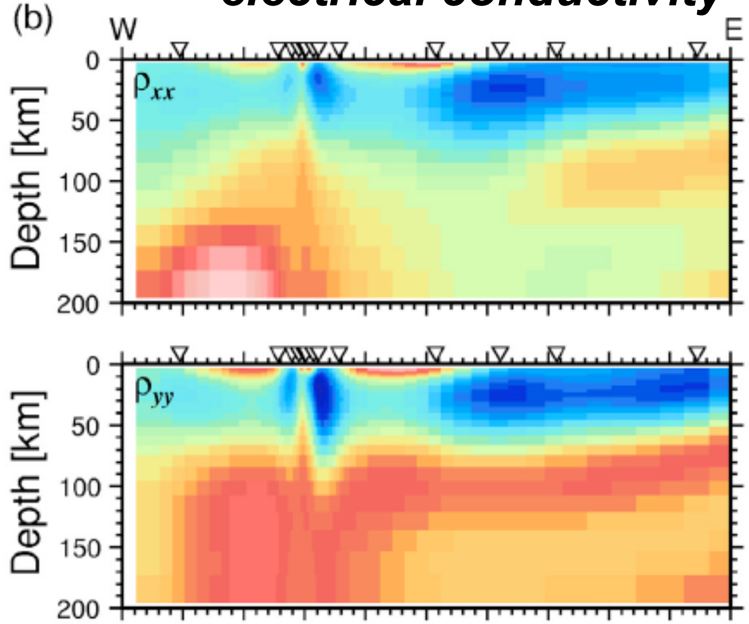
East Pacific ridge



SKS splitting



electrical conductivity



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

Baba et al. JGR 2006

fast EC direction // fast SKS polarisation

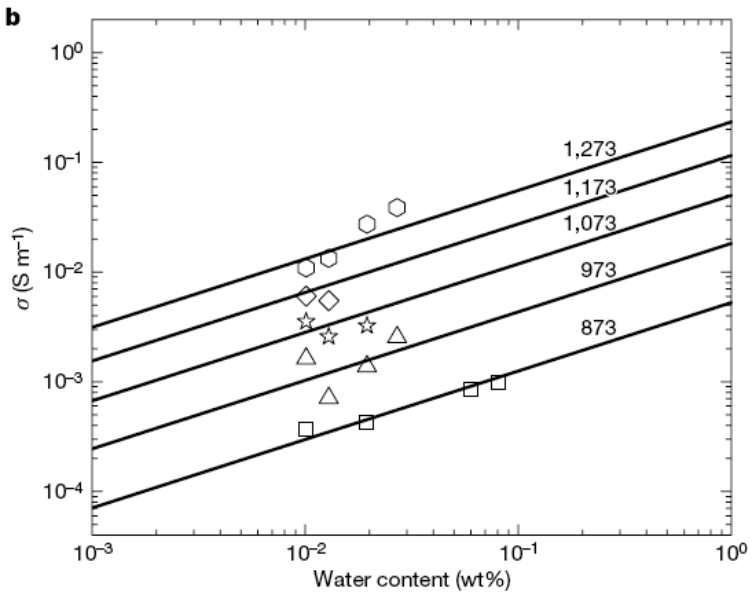
high conductivity & anisotropy below 60km
✓ EC anisotropy = faster H+ diffusion
// olivine [100]

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]

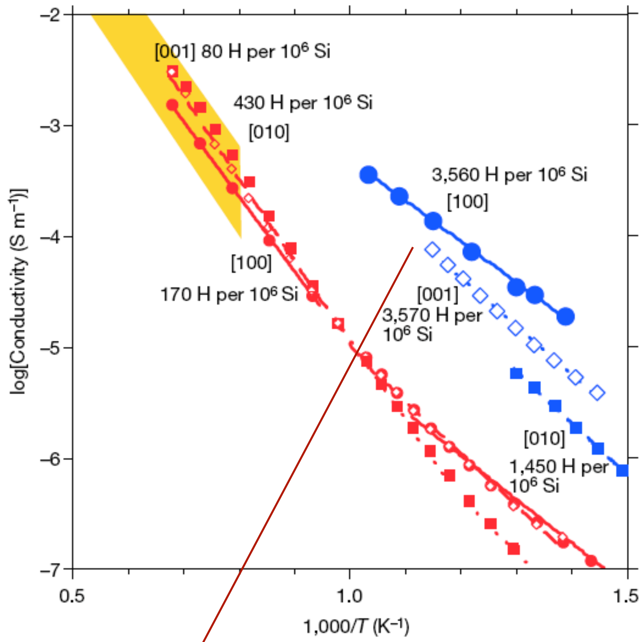


Vol 443 | 26 October 2006 | doi:10.1038/nature05223 nature

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]



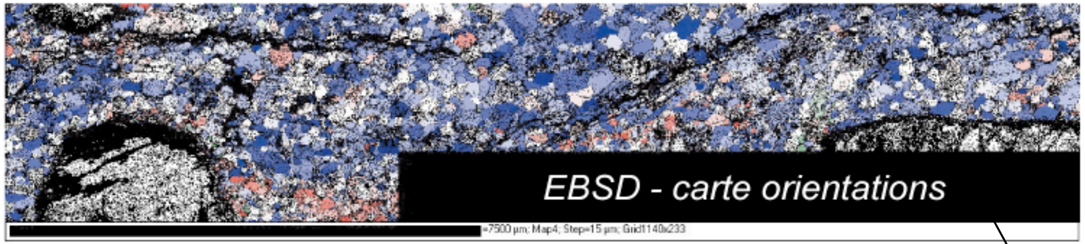
electrical conduction controlled by intracrystalline H+ diffusion in olivine

$$D^{ol}_{[100]} \approx 10 \times D^{ol}_{[001]} \approx 100 \times D^{ol}_{[010]} \quad \text{(MK90)}$$
$$D^{ol}_{[100]} \approx 20 \times D^{ol}_{[010]} \approx 40 \times D^{ol}_{[001]} \quad \text{(MK98)}$$

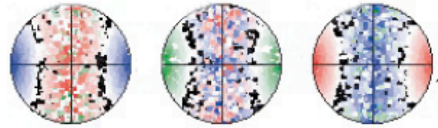
electrical conduction:
short range, "fast" diffusion
polaron migration process
Mackwell & Kohlstedt (1990)

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

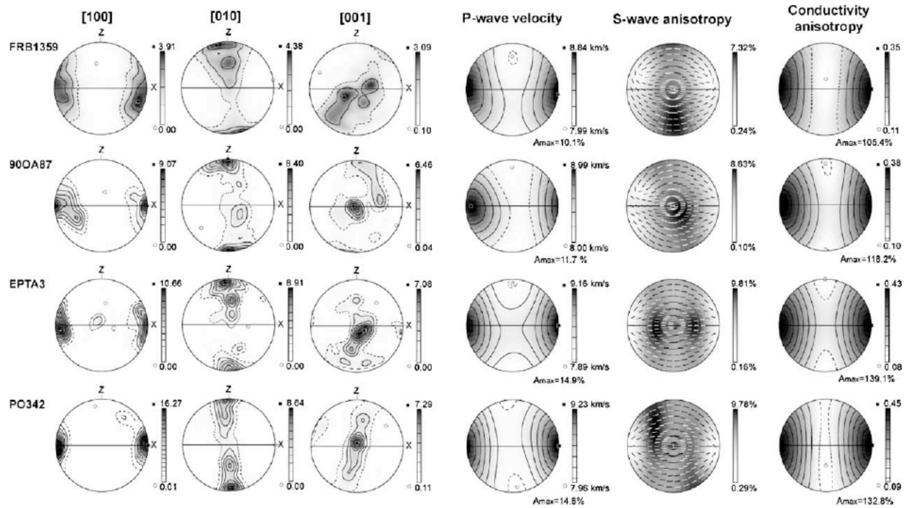
Z



X



$\sigma_x=5*\sigma_z$

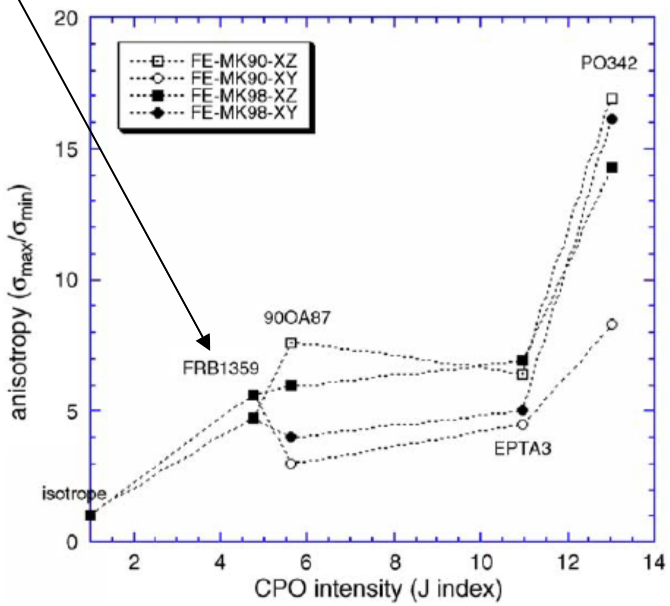


$\sigma_x=3.2*\sigma_z$

$\sigma_x=3.8*\sigma_z$

$\sigma_x=5.4*\sigma_z$

$\sigma_x=5*\sigma_z$

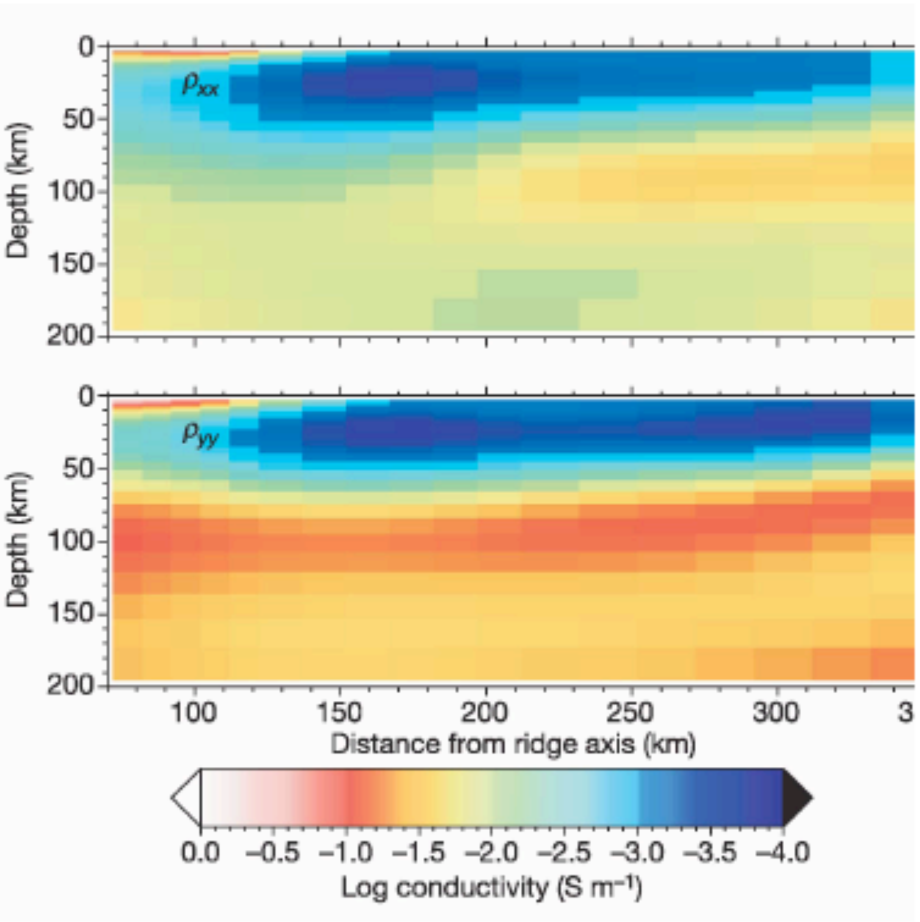


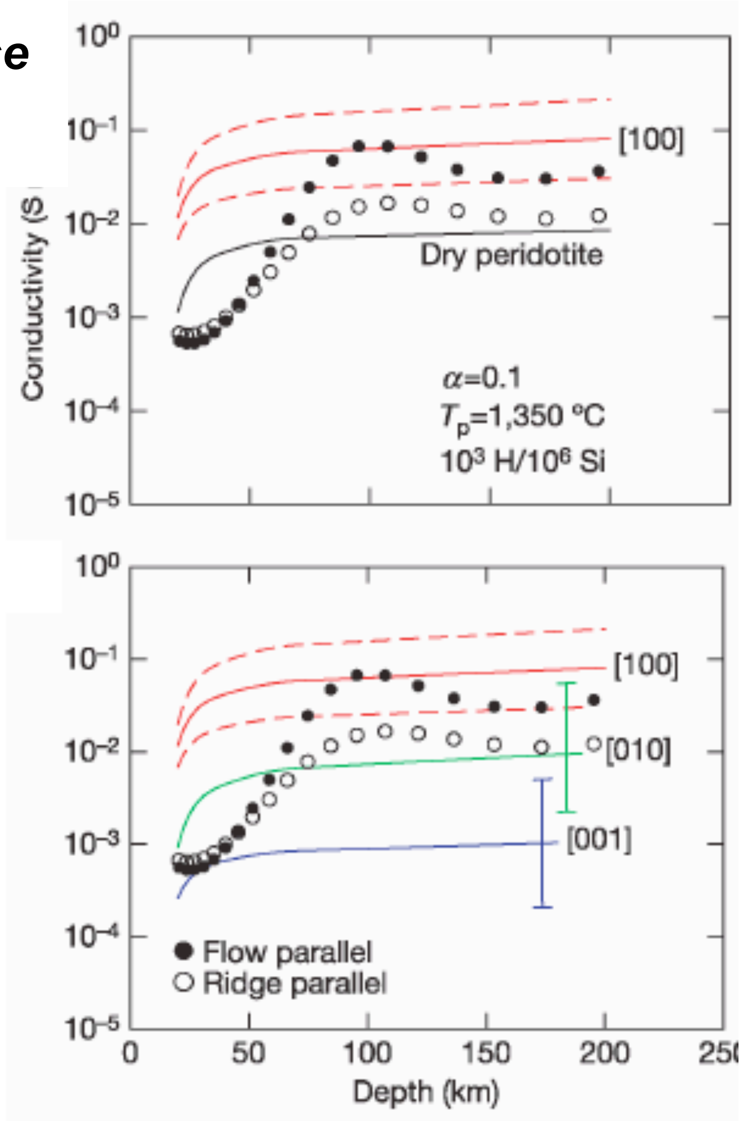
Gatzemeier & Tommasi PEPI 2006

$$D^{ol}_{[100]} \approx 10 \times D^{ol}_{[001]} \approx 100 \times D^{ol}_{[010]} \quad \text{(MK90)}$$
$$D^{ol}_{[100]} \approx 20 \times D^{ol}_{[010]} \approx 40 \times D^{ol}_{[001]} \quad \text{(MK98)}.$$

The MELT experiment:

electrical conductivity @ East Pacific Rise





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

Baba et al. JGR 2006