Flow and anisotropy in the (very deep) mantle: bridging the gap between the crystal and geodynamic scales

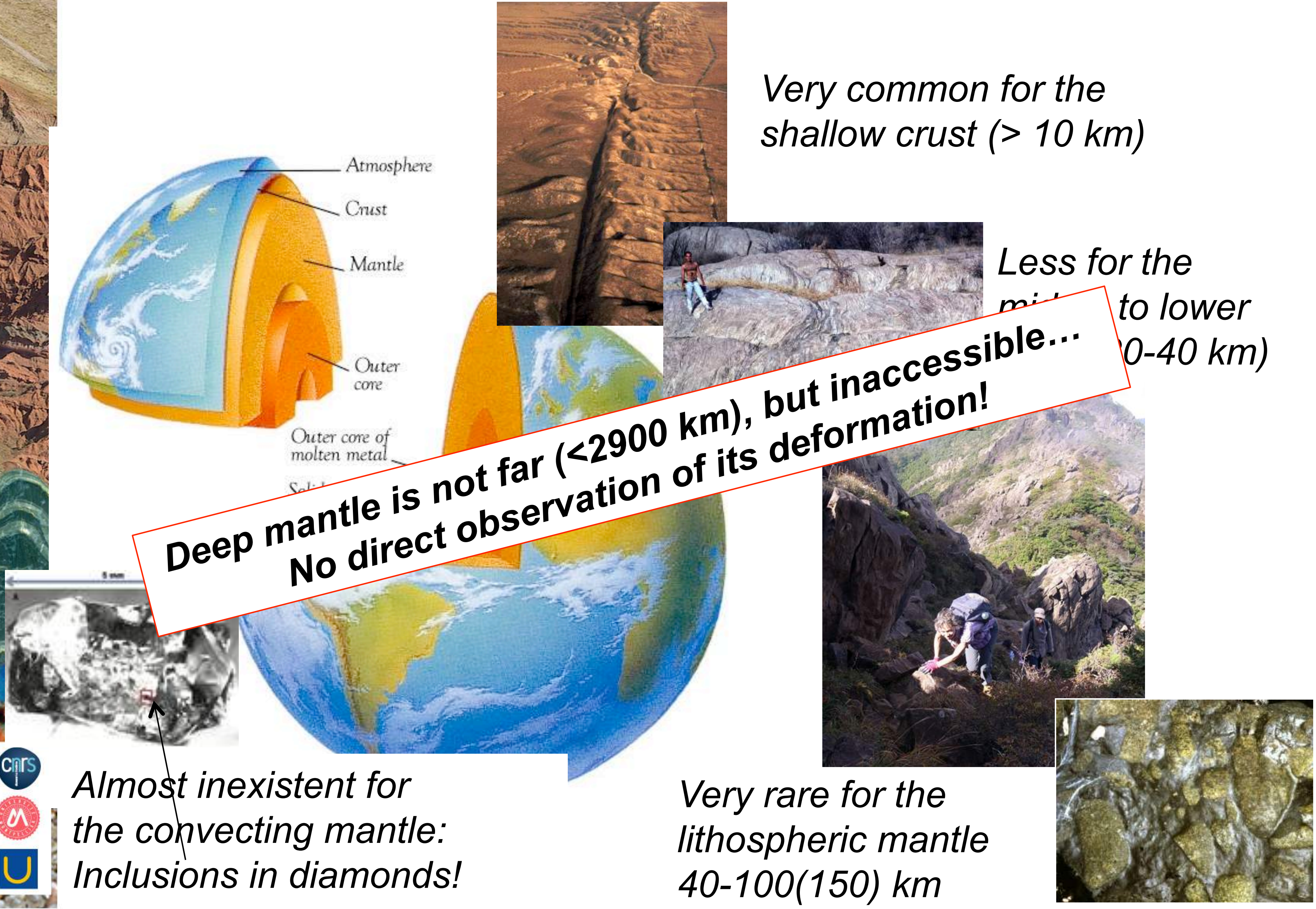
Andréa Tommasi
with major contributions from:

David Mainprice

Alexandra Goryaeva
Philippe Carrez
Patrick Cordier

Flow in the deep mantle, College de France, 1-2 December 2016

Geological (direct) data on the deformation of the Earth become more & more sparse with increasing depth…



Very common for the shallow crust (> 10 km)

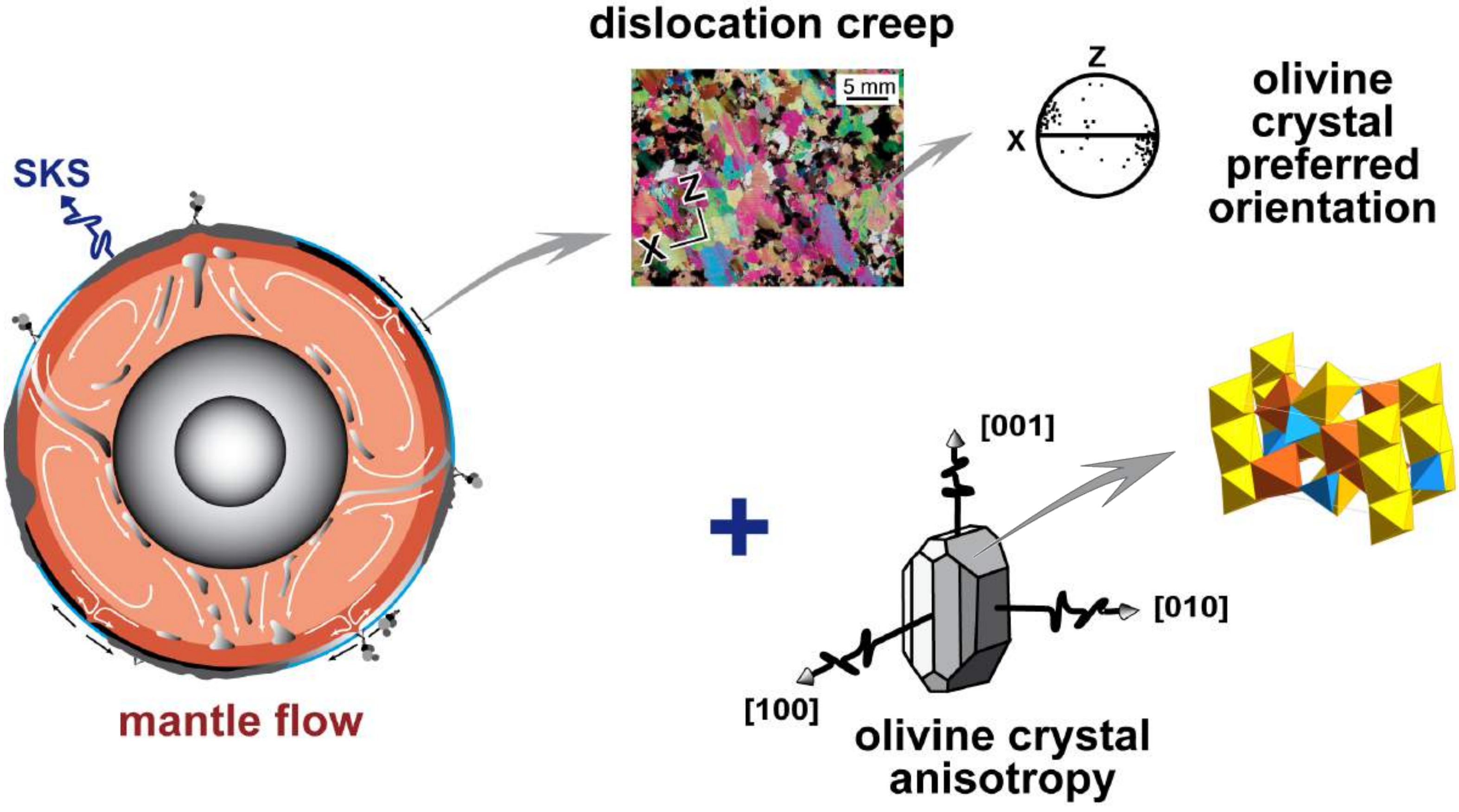
Less for the mi to lower 0-40 km)

Deep mantle is not far (<2900 km), but inaccessible…
No direct observation of its deformation!

Very rare for the lithospheric mantle 40-100(150) km

Almost inexistent for the convecting mantle: Inclusions in diamonds!

Anisotropy of physical properties may be used to study deformation in the deep Earth



dislocation creep

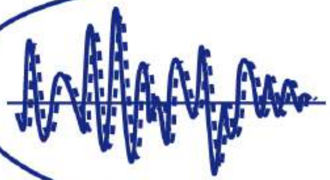
olivine crystal preferred orientation

mantle flow

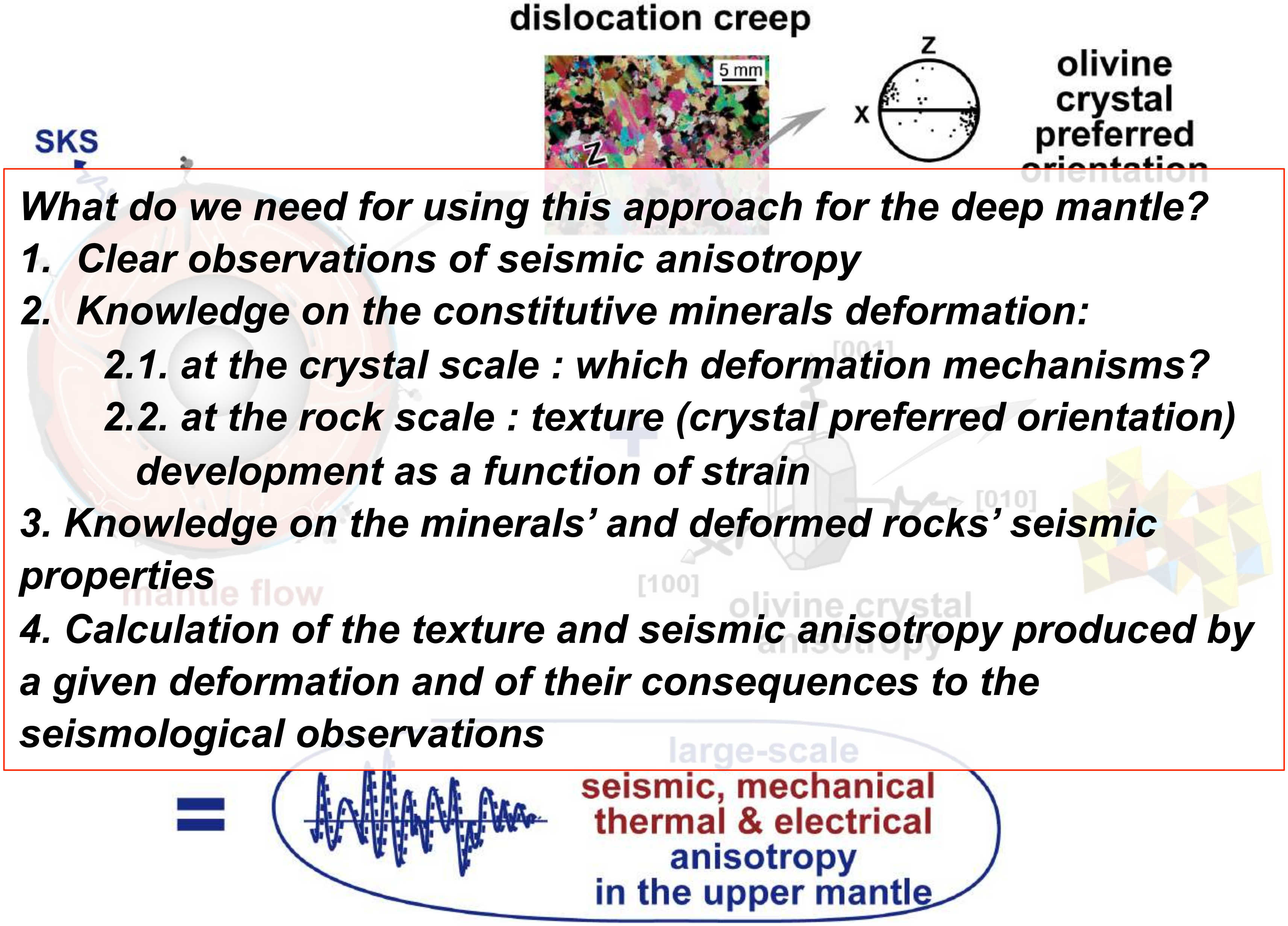
+

olivine crystal anisotropy

=



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

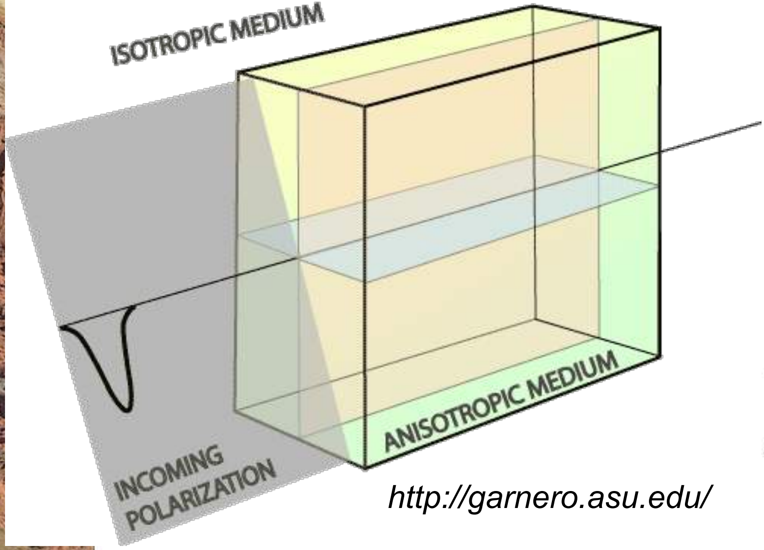


What do we need for using this approach for the deep mantle?

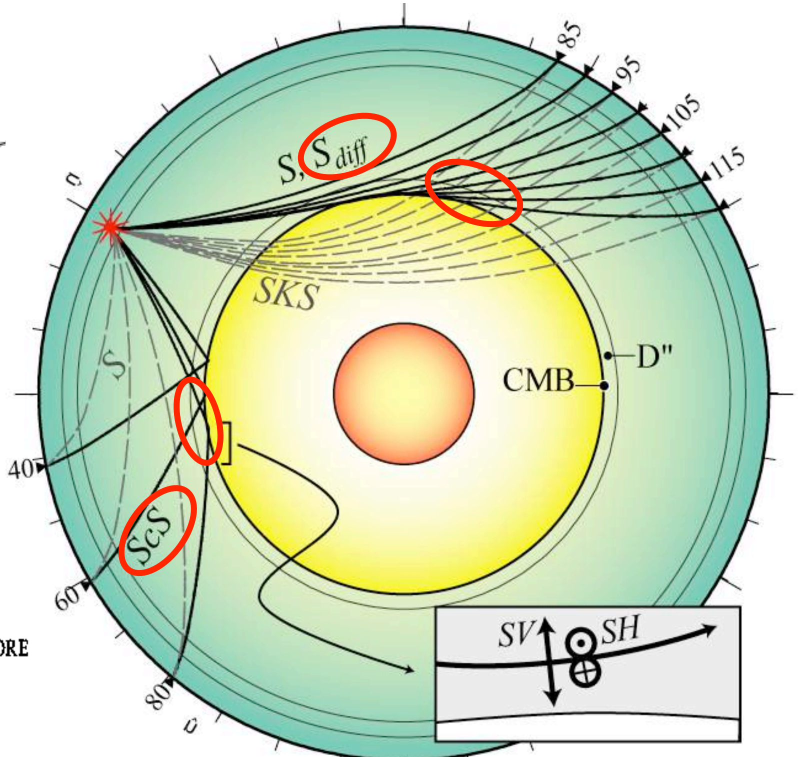
1. ***Clear observations of seismic anisotropy***
2. ***Knowledge on the constitutive minerals deformation:***
    - ***2.1. at the crystal scale : which deformation mechanisms?***
    - ***2.2. at the rock scale : texture (crystal preferred orientation) development as a function of strain***
3. ***Knowledge on the minerals' and deformed rocks' seismic properties***
4. ***Calculation of the texture and seismic anisotropy produced by a given deformation and of their consequences to the seismological observations***

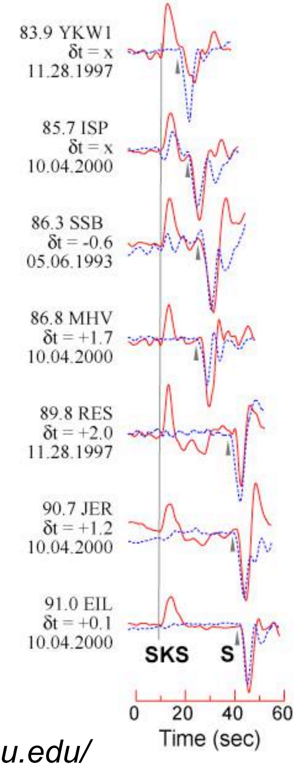
Seismic anisotropy: Observations

Shear wave splitting: in D”, S_{diff} & ScS



http://garnero.asu.edu/





http://garnero.asu.edu/

OBSERVATIONAL EVIDENCE FOR DIFFRACTED SV IN THE SHADOW OF THE EARTH'S CORE

Lev P. Vinnik[1], Veronique Farra and Barbara Romanowicz

GEOPHYSICAL RESEARCH LETTERS, VOL. 16, NO. 6, PAGES 519-522, JUNE 1989

ANALYSIS OF SEISMIC SV WAVES IN THE CORE'S PENUMBRA

Thorne Lay[1] and Christopher J. Young[2]

GEOPHYSICAL RESEARCH LETTERS, VOL. 18, NO. 8, PAGES 1373-1376, AUGUST 1991

On the possibility of anisotropy in the D″ layer
as inferred from the polarization of diffracted S waves

Valérie Maupin

Physics of the Earth and Planetary Interiors 87 (1994) 1–32

Constraints from seismic anisotropy on the nature of the lowermost mantle

J.-M. Kendall* & P. G. Silver†

NATURE · VOL 381 · 30 MAY 1996

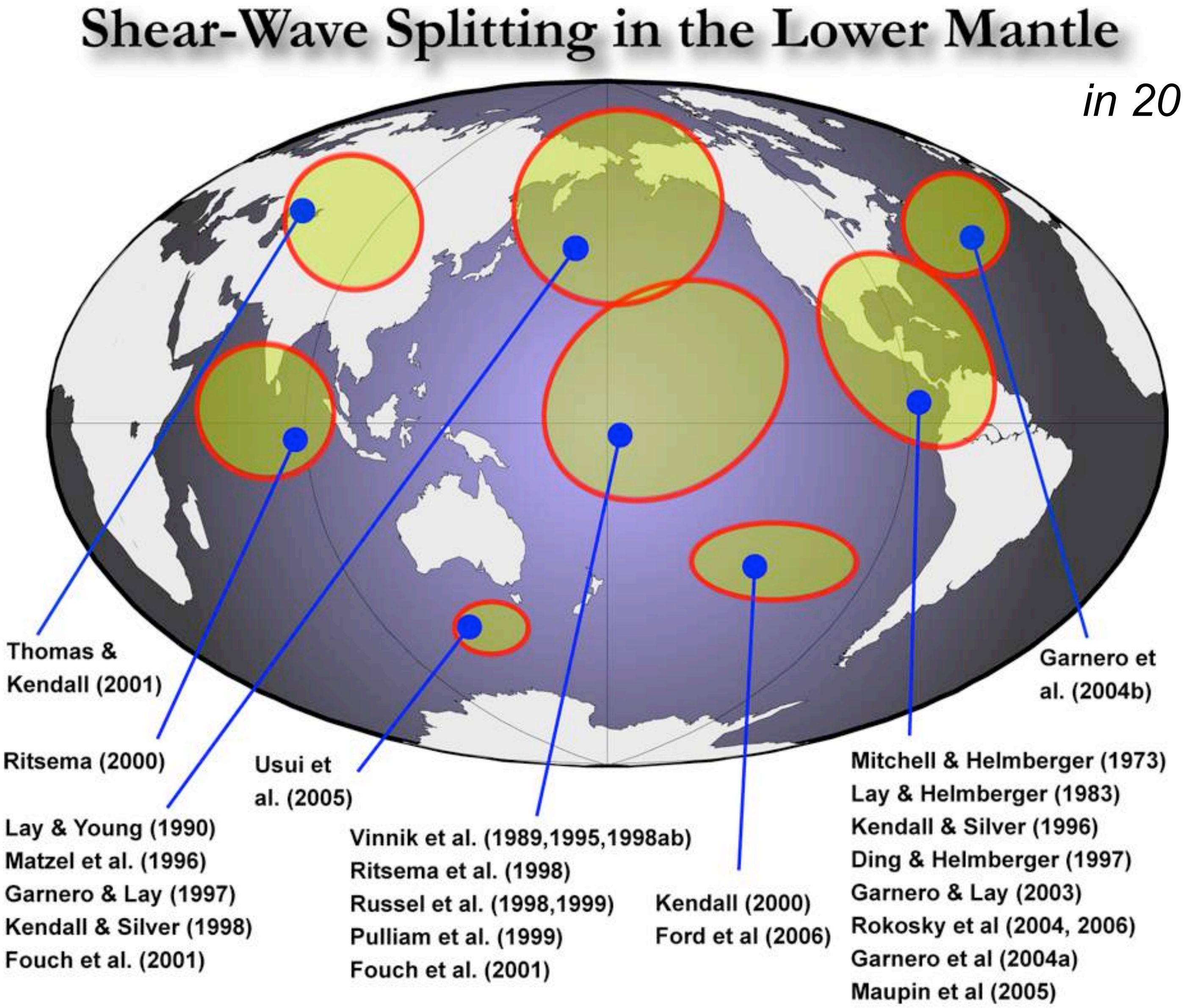
Seismic anisotropy in the D" layer

Lev Vinnik[1,2], Barbara Romanowicz[1], Yves Le Stunff[1] and Larissa Makeyeva[2]

GEOPHYSICAL RESEARCH LETTERS, VOL. 22, NO. 13, PAGES 1657-1660, JULY 1, 1995

V_{SH}>V_{SV}
Caribean
0.5-2.8% anis
1000-2500 km
long paths

Seismic anisotropy: Observations



Shear-Wave Splitting in the Lower Mantle

in 2005

Thomas & Kendall (2001)

Ritsema (2000)

Lay & Young (1990)
Matzel et al. (1996)
Garnero & Lay (1997)
Kendall & Silver (1998)
Fouch et al. (2001)

Usui et al. (2005)

Vinnik et al. (1989,1995,1998ab)
Ritsema et al. (1998)
Russel et al. (1998,1999)
Pulliam et al. (1999)
Fouch et al. (2001)

Kendall (2000)
Ford et al (2006)

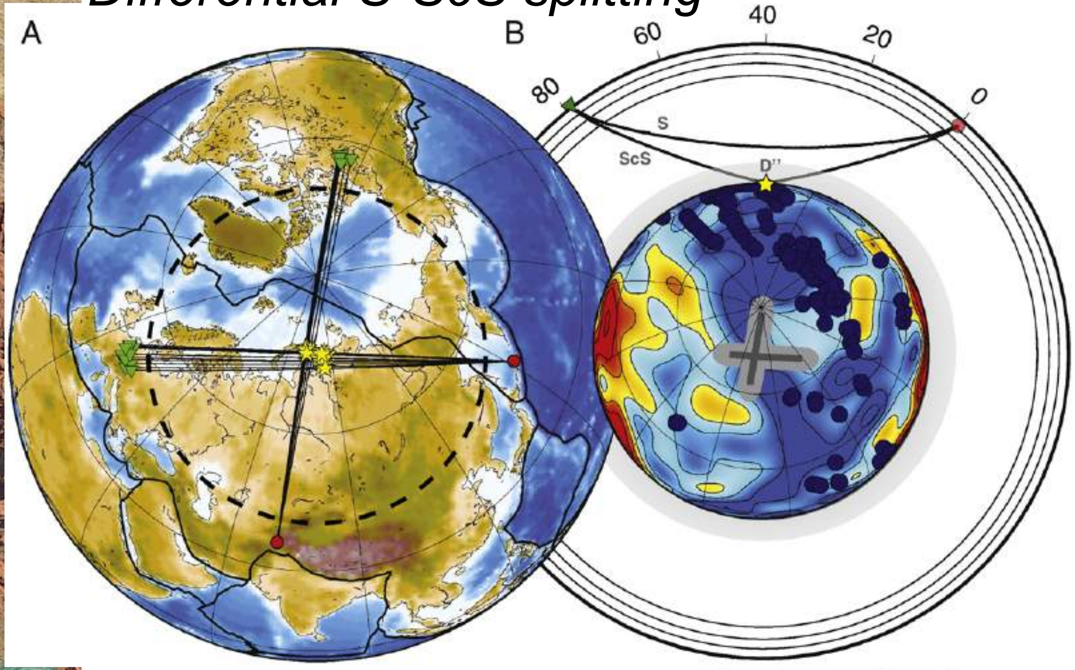
Garnero et al. (2004b)

Mitchell & Helmberger (1973)
Lay & Helmberger (1983)
Kendall & Silver (1996)
Ding & Helmberger (1997)
Garnero & Lay (2003)
Rokosky et al (2004, 2006)
Garnero et al (2004a)
Maupin et al (2005)

http://garnero.asu.edu/

Seismic anisotropy: Observations

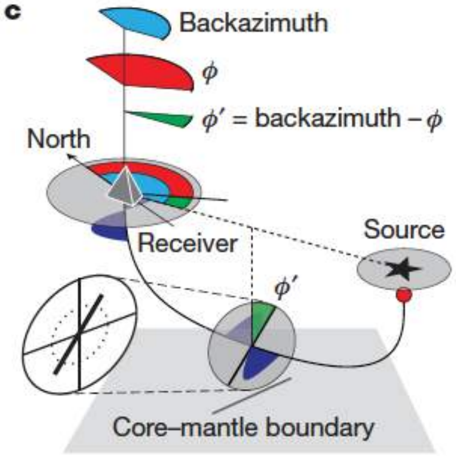
Differential S-ScS splitting

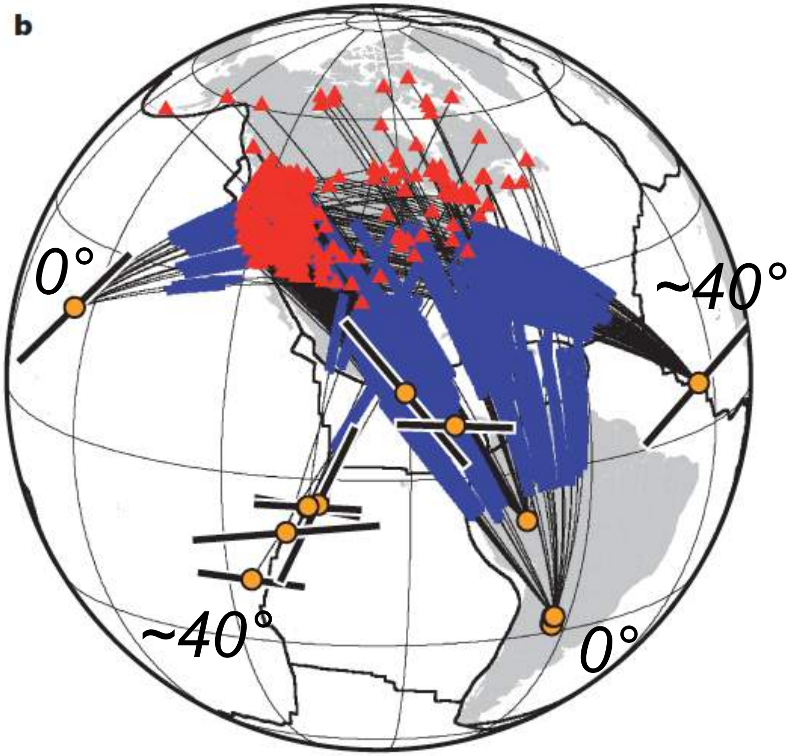


Wookey & Kendall EPSL 2008

Different splitting in cross-cutting ray paths:

- *Azimuthal anisotropy or dipping symmetry axis*

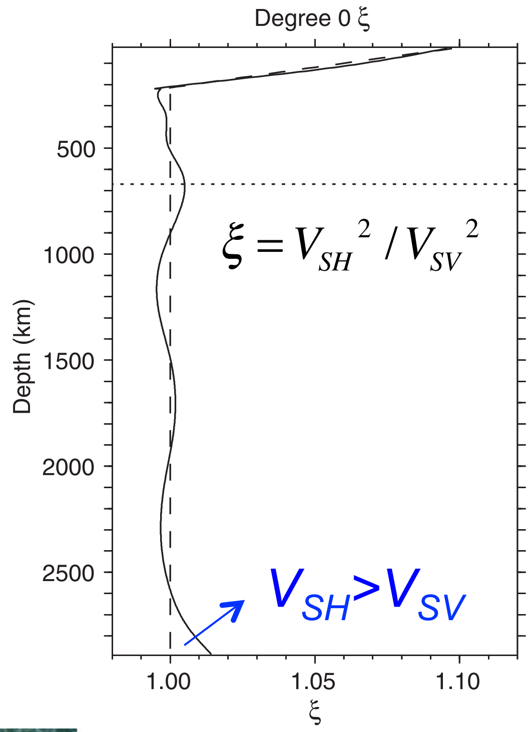




Nowacki et al Nature 2010

Seismic anisotropy: Observations

1D structure



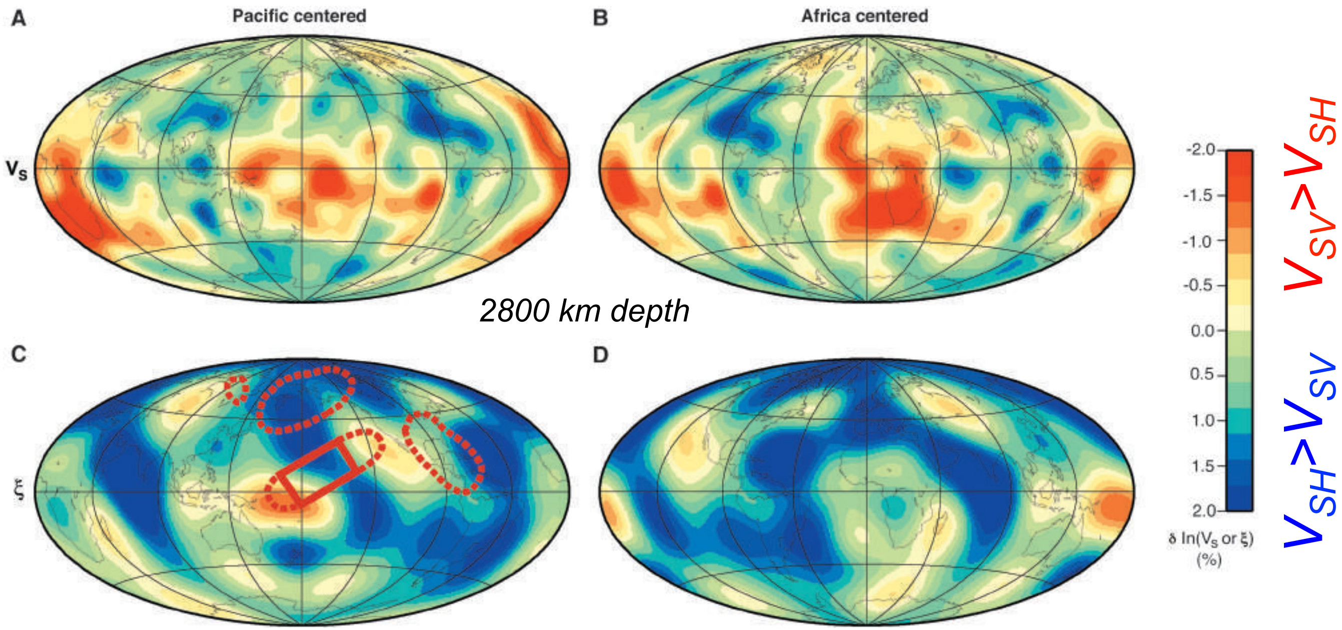
$$\xi = V_{SH}^{2} / V_{SV}^{2}$$

$V_{SH}>V_{SV}$

Panning & Romanowicz
Science 2004

Anisotropic global tomography

Isotropic S-wave velocity anomalies (A,B) and radial anisotropy (C,D)



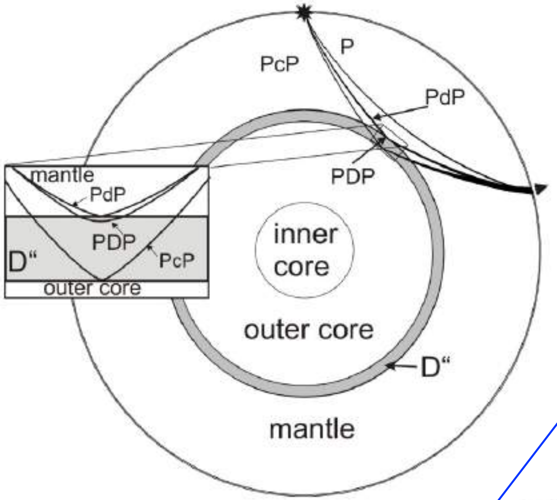
2800 km depth

$V_{SV}>V_{SH}$

$V_{SH}>V_{SV}$

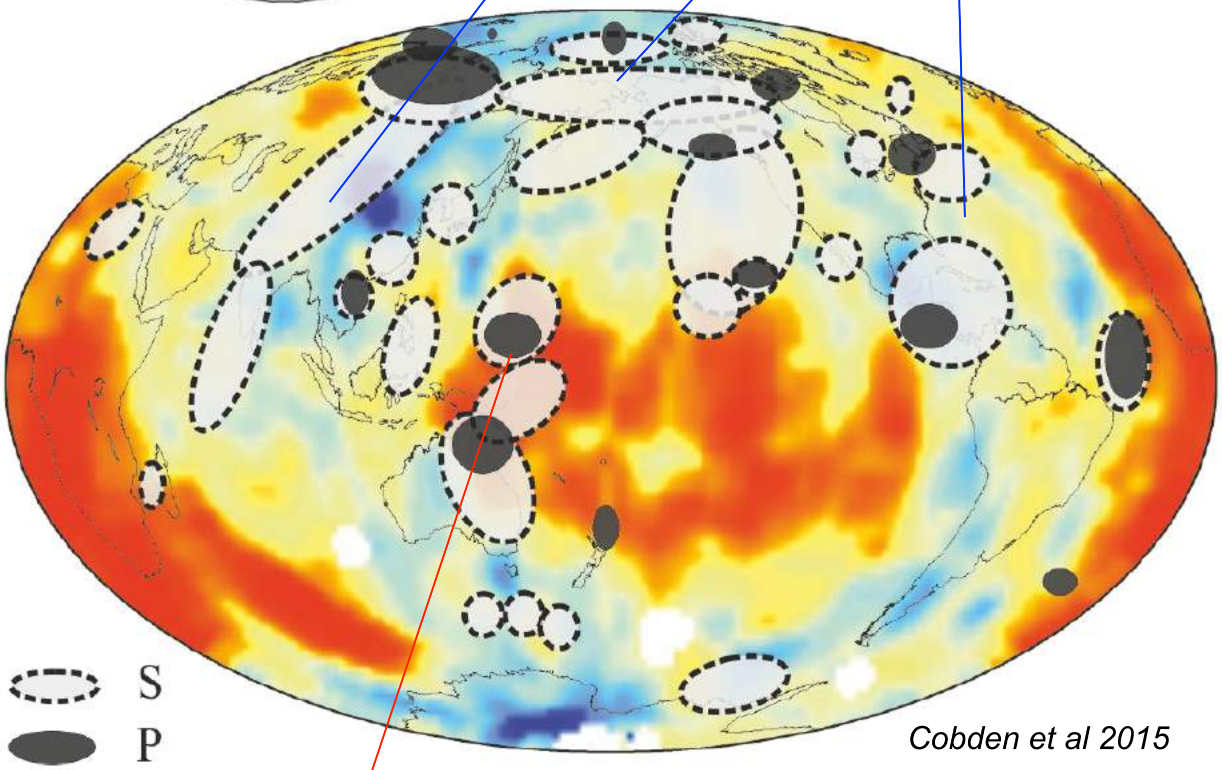
- *Predominance of $V_{SH}>V_{SV}$*
- *Strong $V_{SH}>V_{SV}$ anisotropy mainly associated with low velocity domains (paleo-slabs)*
- *$V_{SV}>V_{SH}$ = smaller areas, e.g., South Pacific low velocity anomaly*

D" reflections



more common in high velocity areas:

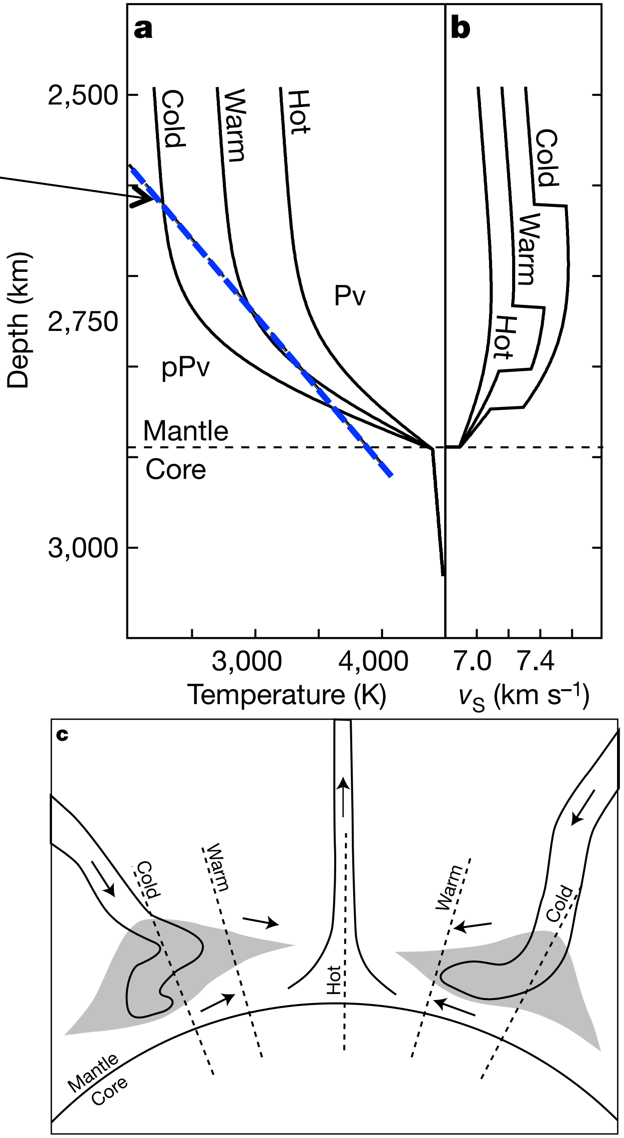
- *Bridgmanite (PV)-post-perovskite (PPV) phase-transition*



Cobden et al 2015

In low velocity domains:

- *Melt layers?*



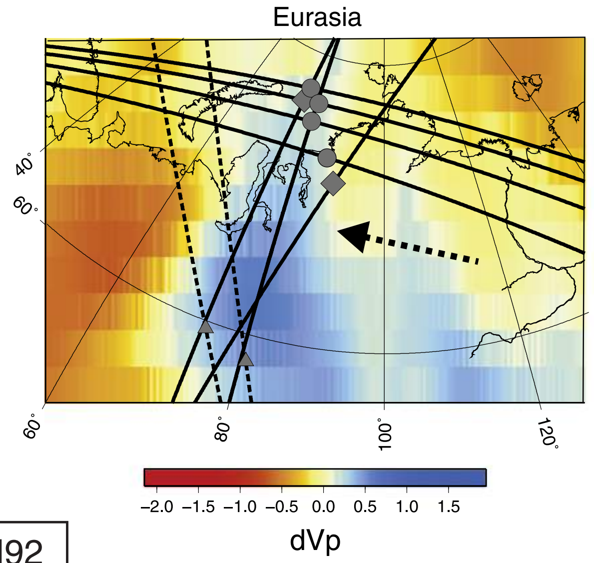
Hernlund et al 2005 Nature

D” reflections: Bridgmanite(perovskite) – Post-perovskite phase-transition + anisotropy ?

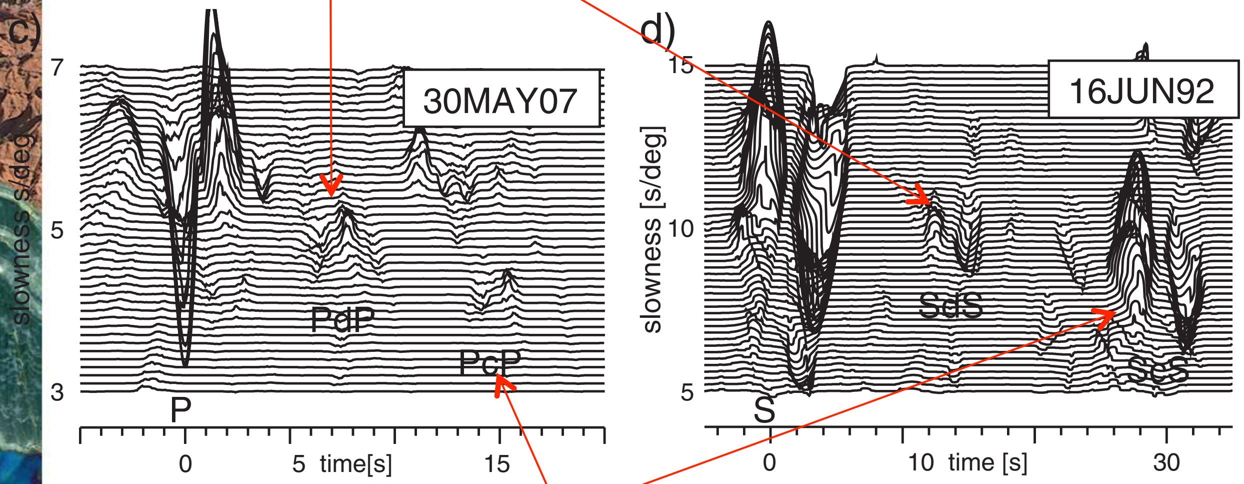
Anisotropy as cause for polarity reversals of D″ reflections

Christine Thomas [a,*], James Wookey [b], John Brodholt [c], Thomas Fieseler [a]

EPSL 2011

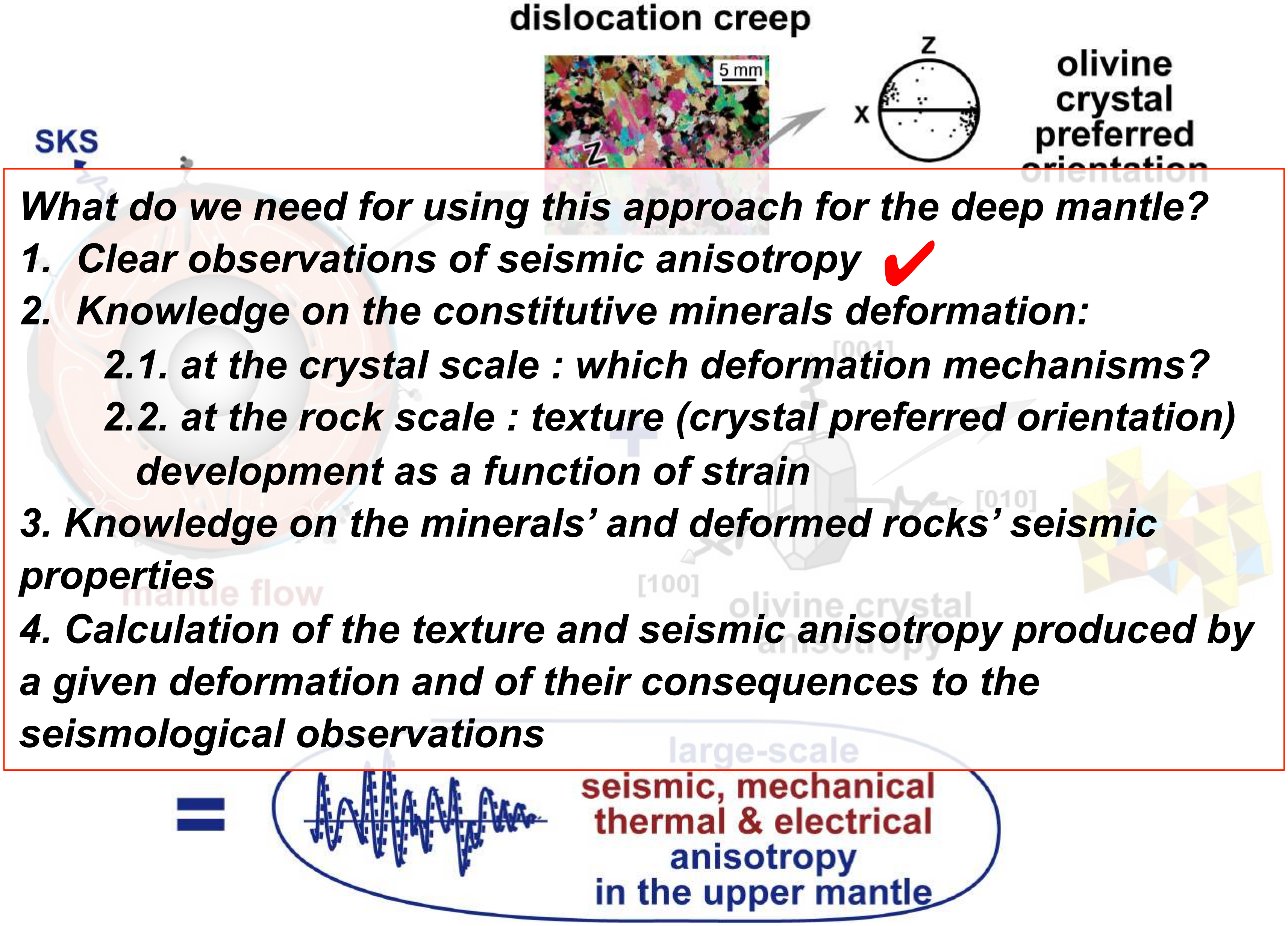


Reflected at the top of D”



Reflected at CMB

- *PdP and SdS with similar polarities to P & S (and PcP / ScS)*
- *Cannot be explained by PV-PPV phase transition only*



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

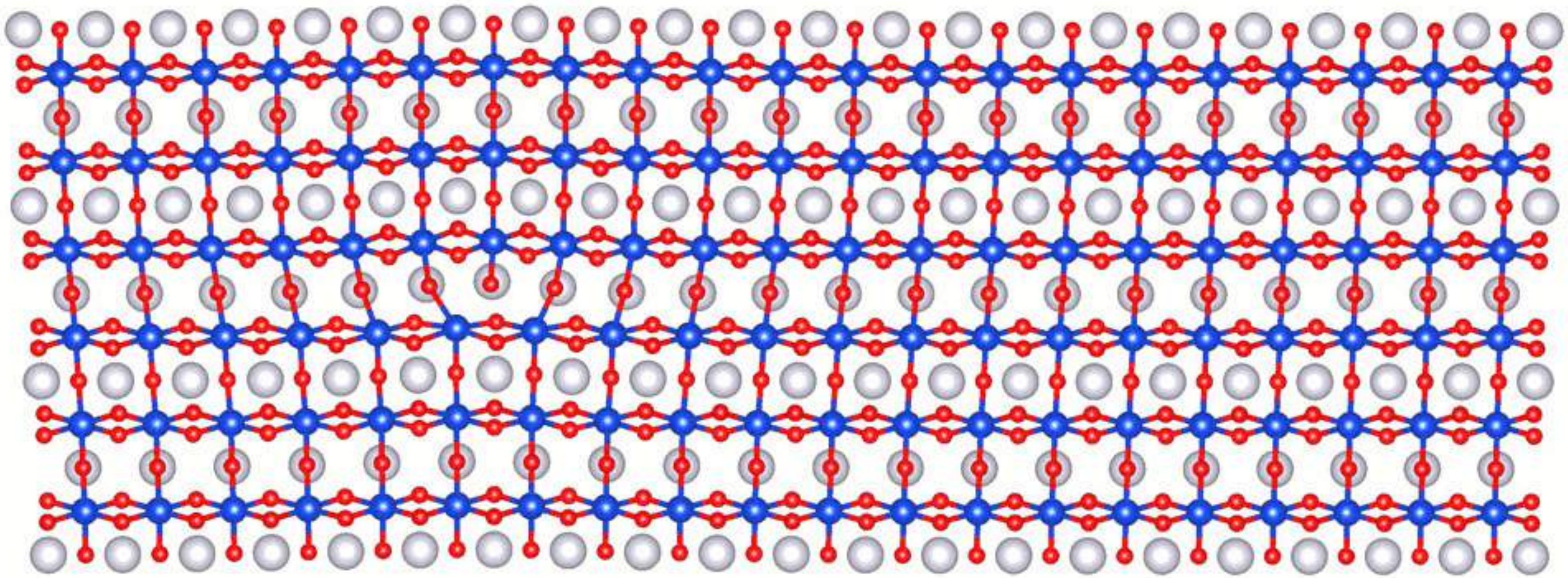
What do we need for using this approach for the deep mantle?

1. ***Clear observations of seismic anisotropy*** ✓
2. ***Knowledge on the constitutive minerals deformation:***
   - ***2.1. at the crystal scale : which deformation mechanisms?***
   - ***2.2. at the rock scale : texture (crystal preferred orientation) development as a function of strain***
3. ***Knowledge on the minerals' and deformed rocks' seismic properties***
4. ***Calculation of the texture and seismic anisotropy produced by a given deformation and of their consequences to the seismological observations***

How does PPV deform under D" conditions?

high T (>2000 K)
high P (>120 GPa)
low stresses (<1GPa)

- *Atomic-scale modeling of dislocations structure and glide*

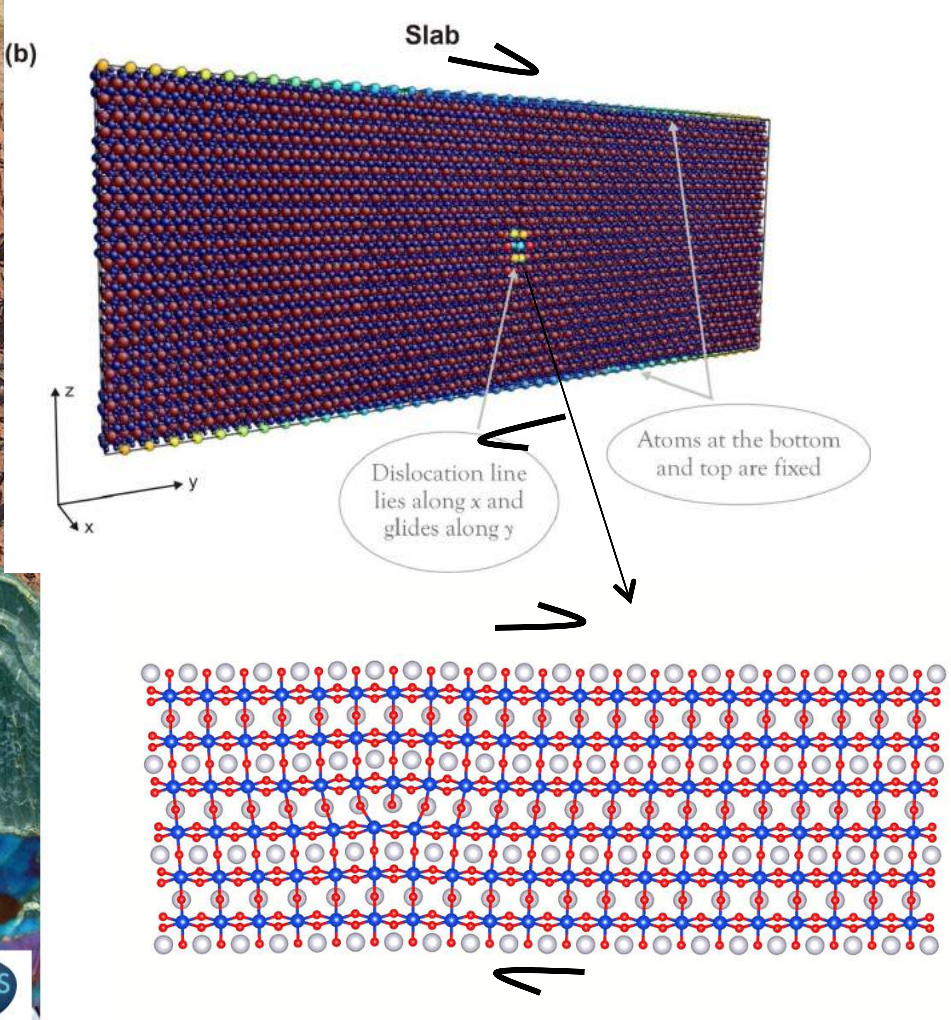


- *[100](010) edge dislocation*

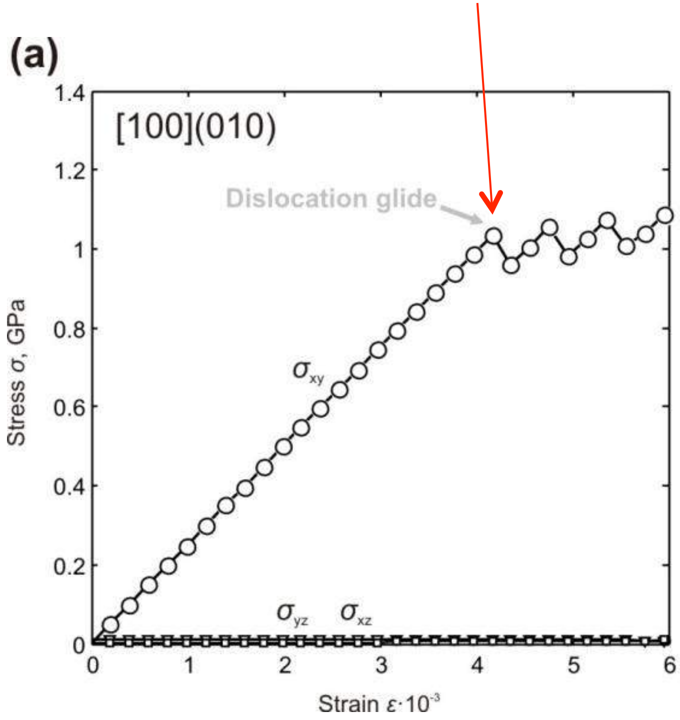
A. Goryaeva – PhD 2016

How does PPV deform?

- *Atomic-scale modeling of dislocations glide at 0 K*



Critical resolved shear stress



A. Goryaeva – PhD 2016; Goryaeva et al. PCM 2015

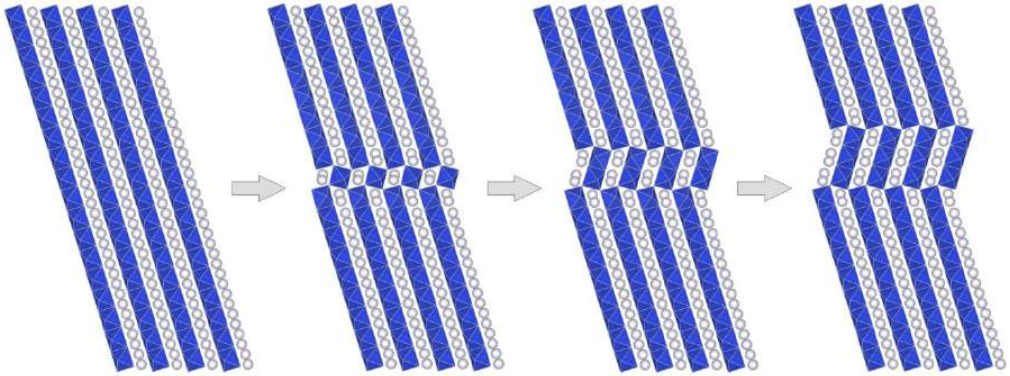
How does PPV deform?

- *Atomic-scale modeling of dislocations glide at 0 K*

Anisotropic Lattice Friction of PPV

System	Edge σ_p (GPa)	Screw σ_p (GPa)
[100](010)	< 0.1	**1**
[100](011)	~0.12	> 11
[100](001)	~0.1	17.5
[001](010)	2	**3**
½<110>{110}	**2.8 → twinning**	0.7

<110>{110} twin growth



Observed by TEM
in $CaIrO_3$ PPV
(Miyajima et al. 2010;
Niwa et al. 2012)

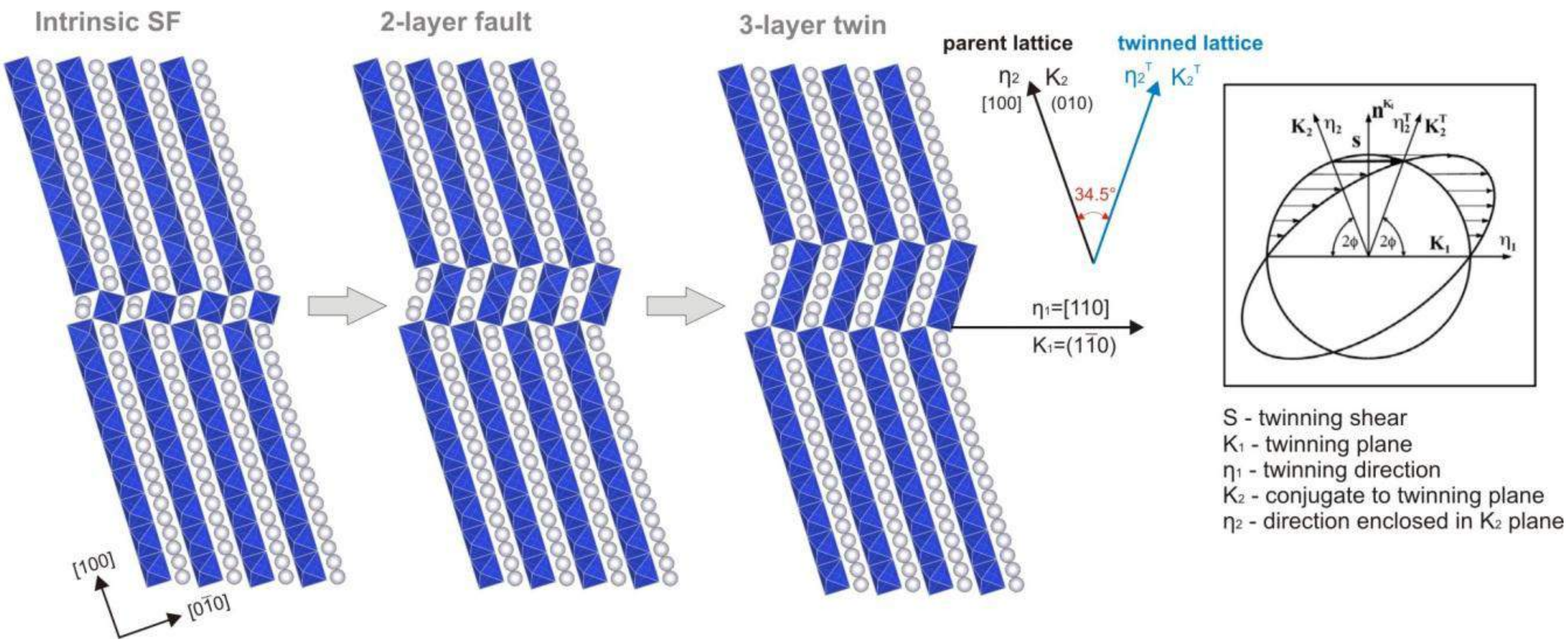
- Accommodates strains // [100] & [010]

A. Goryaeva – PhD 2016

How does PPV deform?

- *Atomic-scale modeling of dislocations glide + twinning*

<110>{110} twinning: rotation by 34.5° around [001]
Abrupt change of orientation = effect on texture evolution



A. Goryaeva – PhD 2016

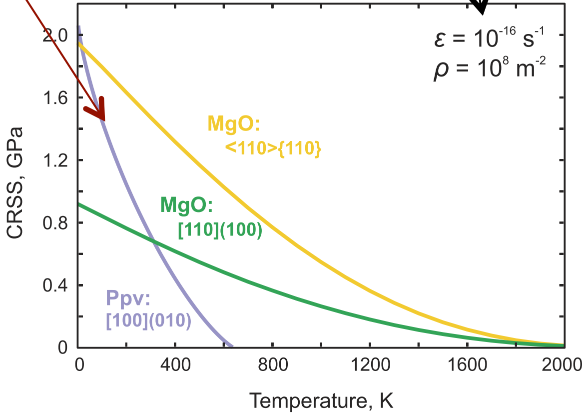
How does PPV deform under D” conditions?

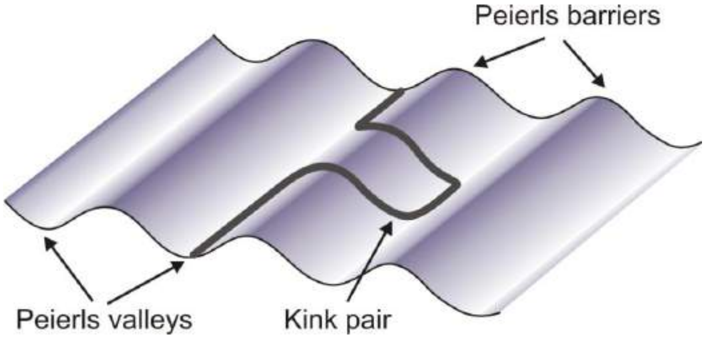
- *Atomic-scale modeling of dislocations structure and glide*

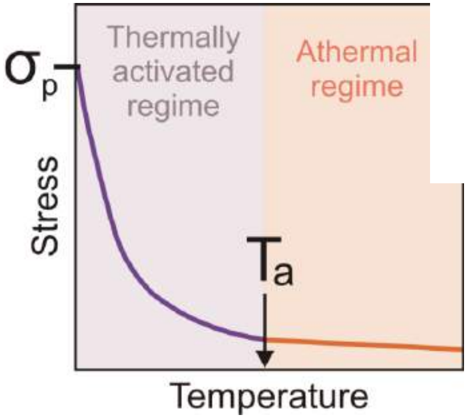
high T (>2000K)
high P (> 120GPa)
low strain rates
low stresses

Anisotropic Lattice Friction of PPV

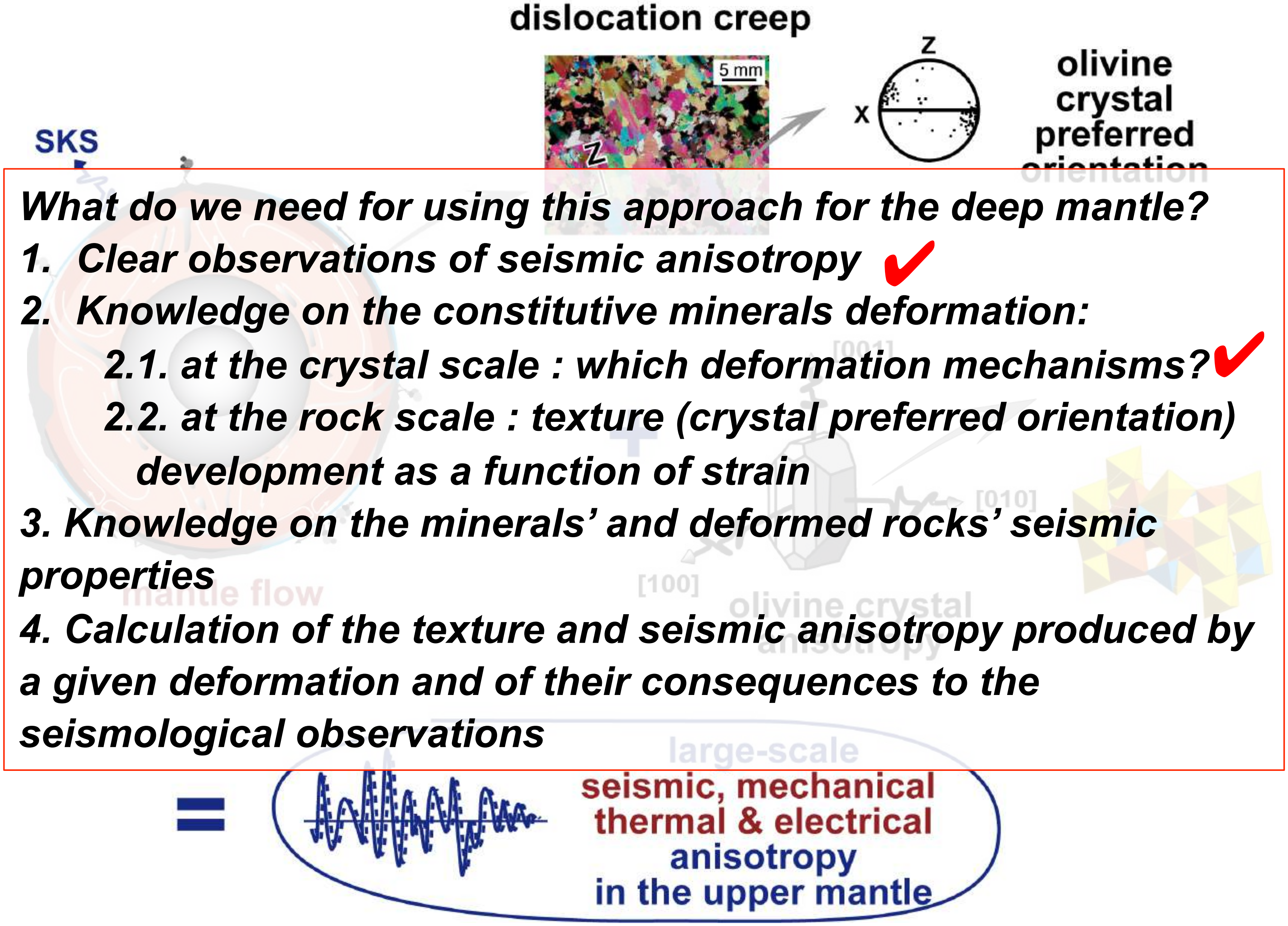
System	Edge σ_p (GPa)	Screw σ_p (GPa)
[100](010)	< 0.1	**1 → Ta ~500 K**
[100](011)	~0.12	> 11
[100](001)	~0.1	17.5
[001](010)	2	**3 → Ta ~1900 K**
½<110>{110}	**2.8 → twinning**	0.7







A. Goryaeva – PhD 2016; Goryaeva et al. PCM 2015; Goryaeva et al. Science Reports 2016



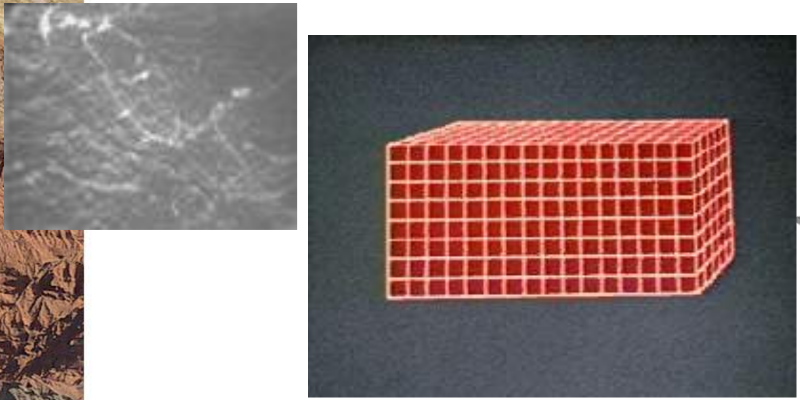
What do we need for using this approach for the deep mantle?

1. ***Clear observations of seismic anisotropy*** ✓
2. ***Knowledge on the constitutive minerals deformation:***
    2.1. at the crystal scale : which deformation mechanisms? ✓
    2.2. at the rock scale : texture (crystal preferred orientation) development as a function of strain
3. ***Knowledge on the minerals' and deformed rocks' seismic properties***
4. ***Calculation of the texture and seismic anisotropy produced by a given deformation and of their consequences to the seismological observations***

Modelling the deformation of a rock = polycrystalline aggregate

VPSC: Molinari et al. 1987, Lebensohn & Tomé 1993

within a grain (crystal):

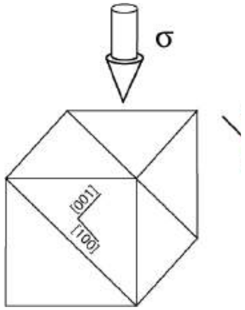


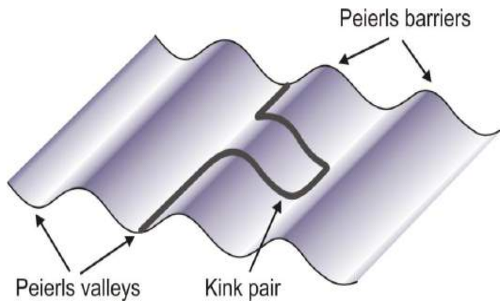
Anisotropic Lattice Friction of PPV

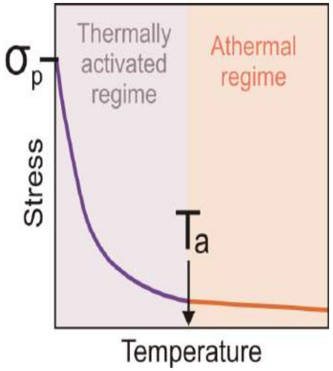
System	Edge σ_p (GPa)	Screw σ_p (GPa)
[100](010)	< 0.1	1 → Ta ~500 K
[100](011)	~0.12	> 11
[100](001)	~0.1	17.5
[001](010)	2	3 → Ta ~1900 K
½<110>{110}	2.8 → twinning	0.7

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

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







Input : slip systems' strength, initial texture &
mechanical sollicitation (stress or velocity gradient tensor)
output: evolution of crystallographic orientations &
mechanical response (strain rate or stress tensor)

Modelling the deformation of a D" rock ~ aggregate of 70% MgSiO3 PPV + 30% MgO crystals

MgSiO3 PPV

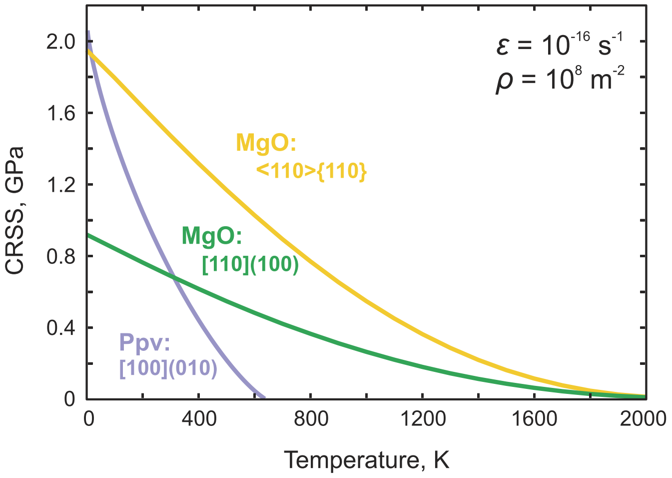
Slip system	*CRSS*
[100](010)	*1*
[100](011)	*10*
[100](001)	*20*
[001](010)	*3*
½ <110>{110} twinning	*3 / not active*

Goryaeva et al. Science Reports 2016

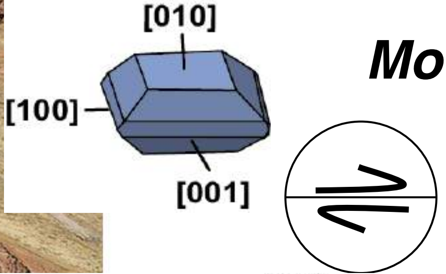
MgO

Slip system	*CRSS*
<110>{110}	*1*
<110>{111}	*5*
[100]{110}	*1*

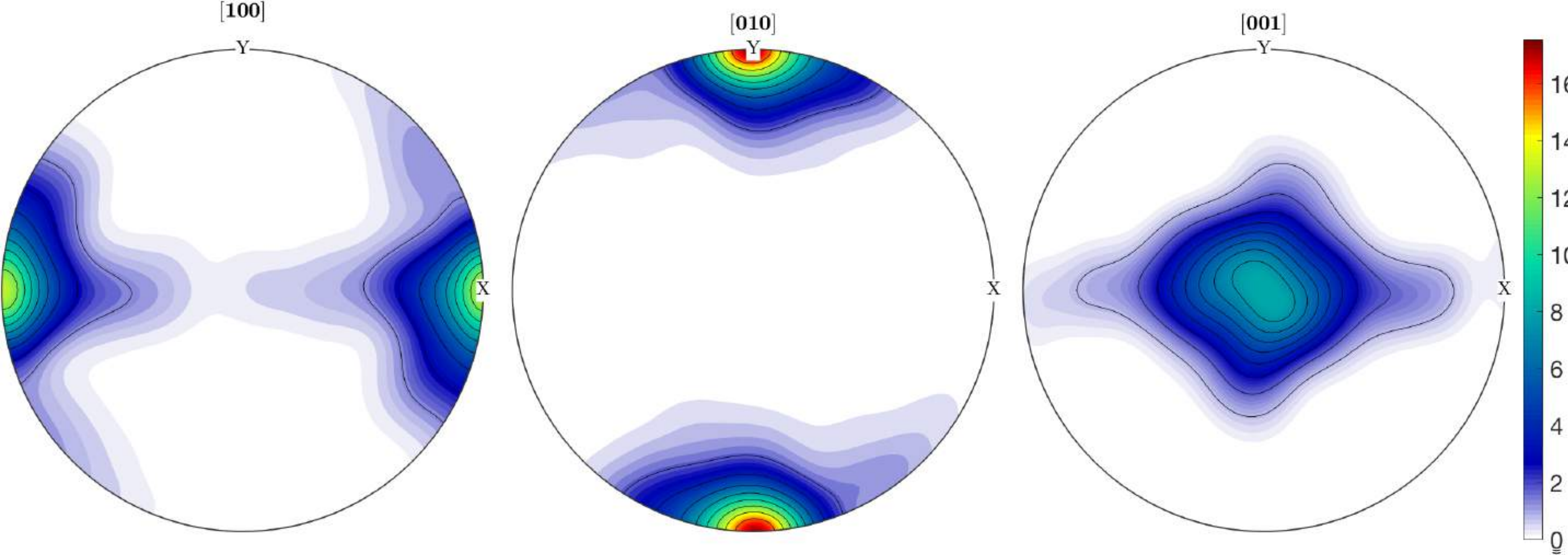
Amodeo et al Acta Mat 2011
Cordier et al Nature 2012



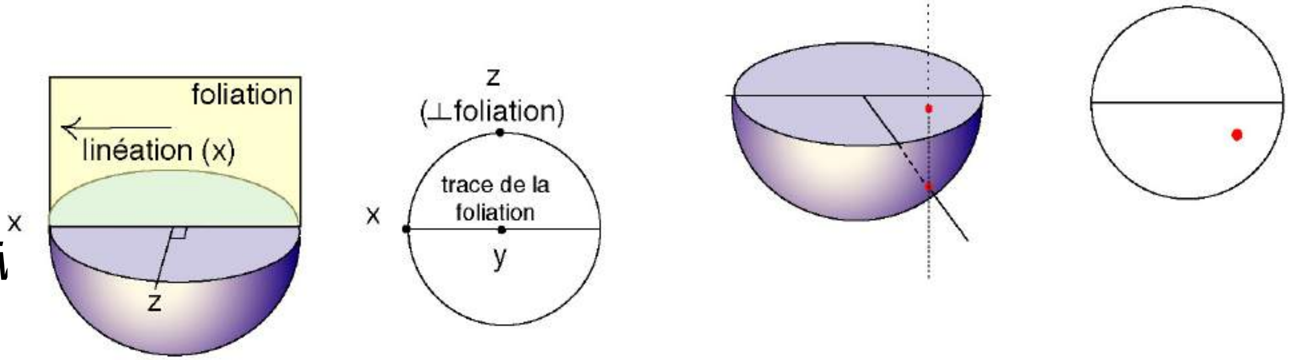
Modelling the deformation of a 100% PPV aggregate



PPV texture evolution with increasing strain



shear strain of 10



- *T*

to

ane

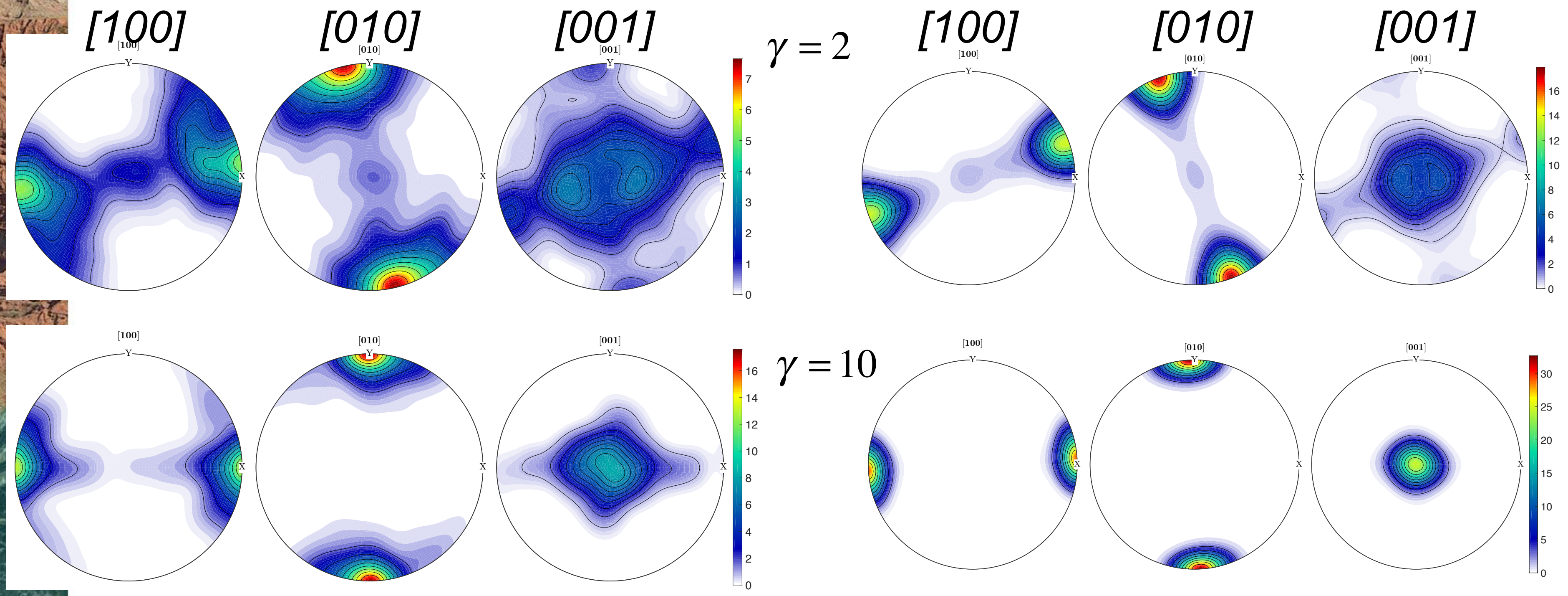
around [001]

Modelling the deformation of a pure PPV aggregate

Testing the effect of twinning on the PPV texture evolution

With twinning

Without twinning



- ➢ *Twinning slows down the evolution of texture intensity + faster rotation towards parallelism between dominant slip system and macroscopic shear*

Modelling the deformation of a pure PPV aggregate

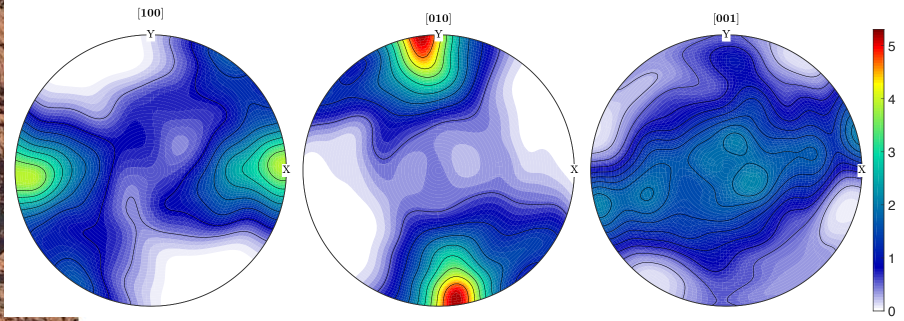
Testing the effect of stress exponent & linearisation approach

Tangent

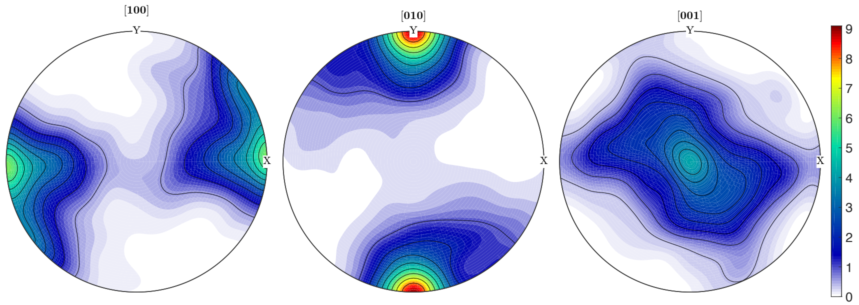
Second order

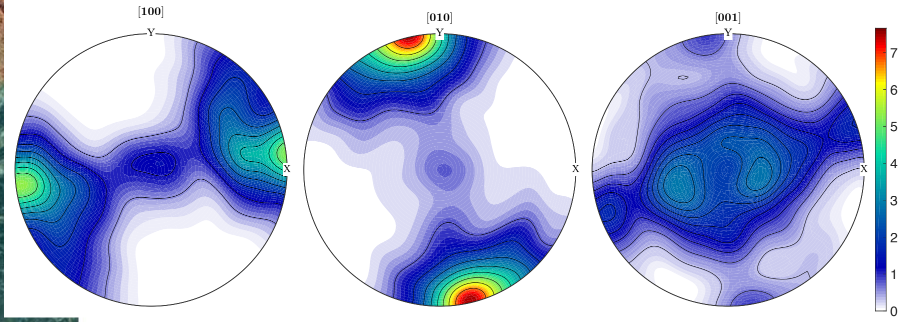
[100] [010] [001]

[100] [010] [001]



n=1



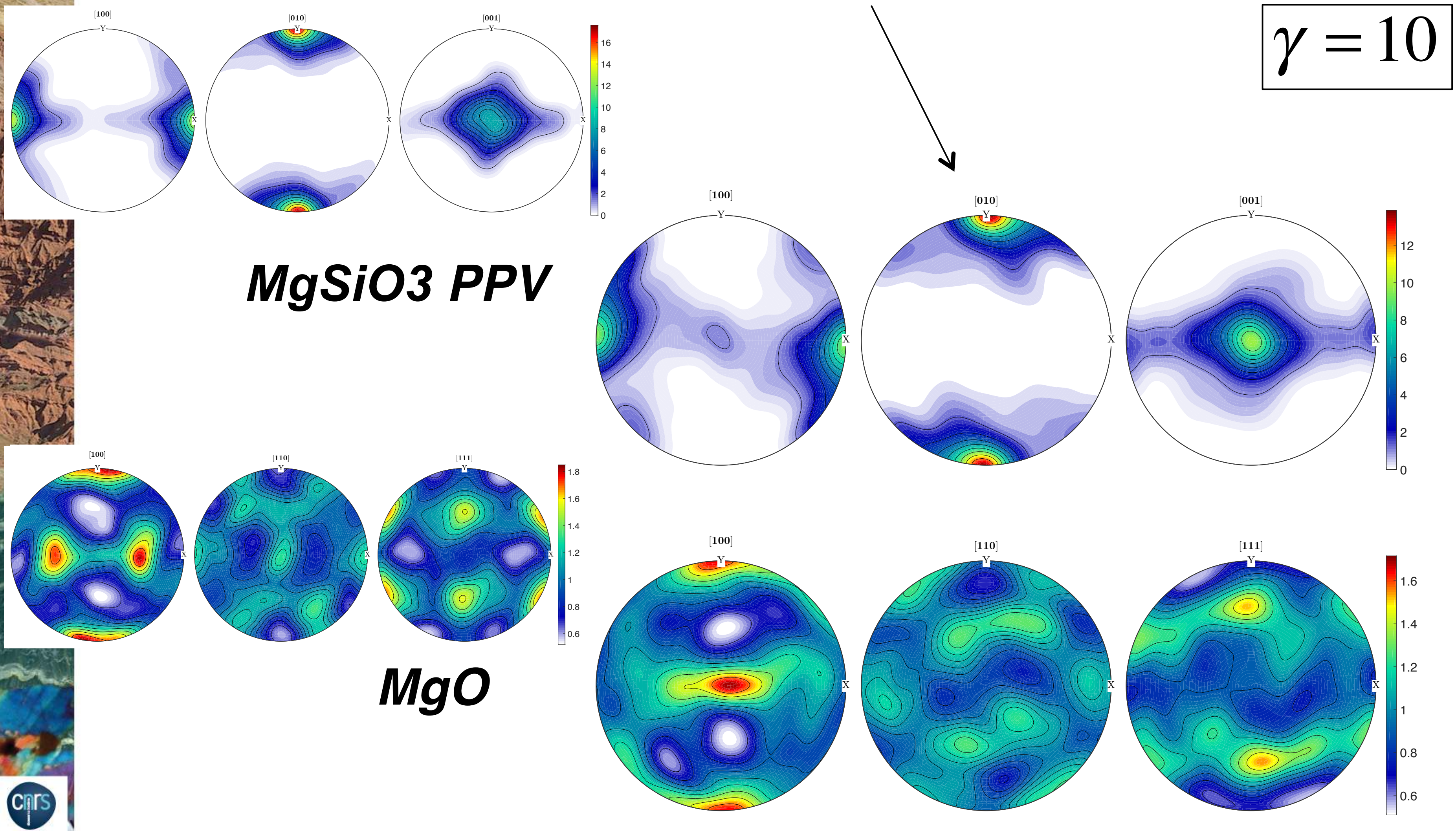


n=3

$$\boxed{\gamma = 2}$$

- ➢ *Slower texture evolution in n=1 simulations*
- ➢ *Faster evolution (lower activity of twinning) in 2nd order simulations*
- ➢ *But variations are of 2nd order, in all simulations: [100] // shear direction & [010] // normal to shear plane*

Modelling the deformation of a D" rock ~ aggregate of 70% MgSiO3 PPV + 30% MgO crystals



$$\boxed{\gamma = 10}$$

MgSiO3 PPV

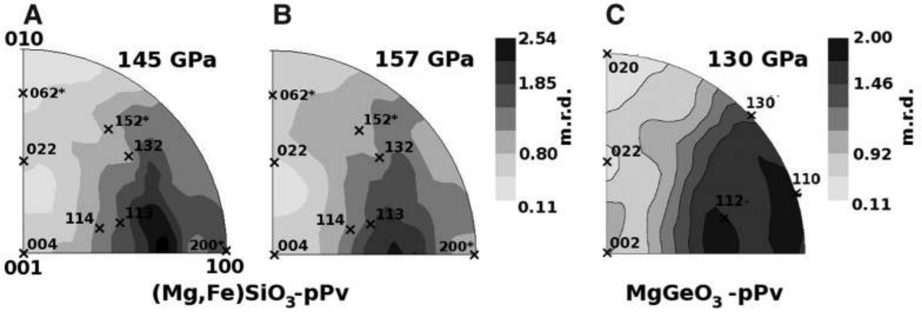
MgO

- *The two minerals have similar strengths: textures in the mixture similar to those of single phase aggregates*

What do we know about texture development in PPV?

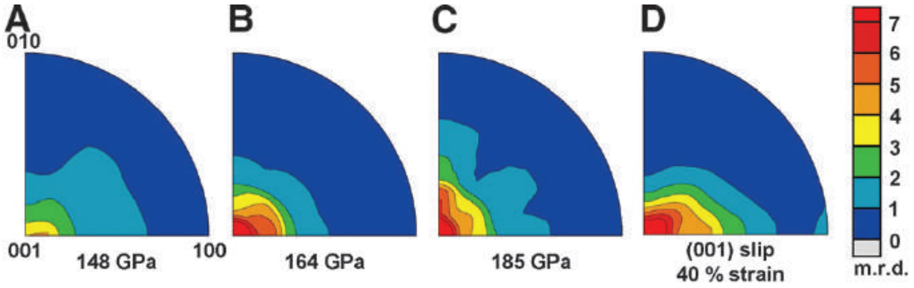
Diamond anvil cell experiments on MgSiO$_3$ PPV at D" p,T conditions
In situ texture measurements by X-ray diffraction; stresses 5-10 GPa

145-157 GPa, 1700-2000 K
stresses 7.2-8.5 GPa



Merkel et al. 2007 Science

148-185 GPa, 3500 K
stresses 5-10 GPa

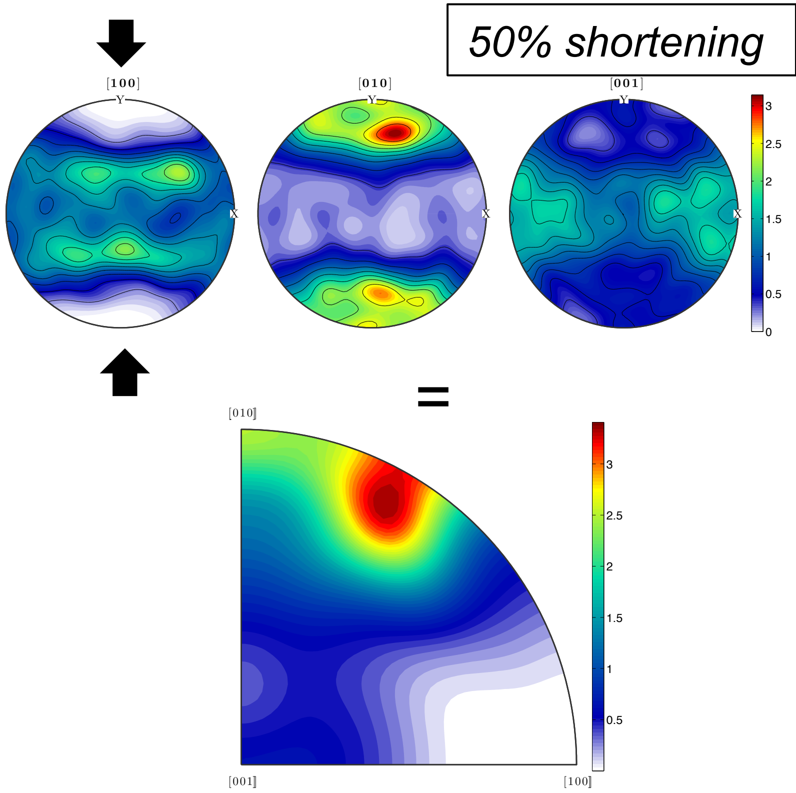


Miyagi et al. 2010 Science

Textures inherited at phase transformation + glide on (001) & {110} planes?

VPSC simulations based on atomic scale modeling of dislocation glide

50% shortening



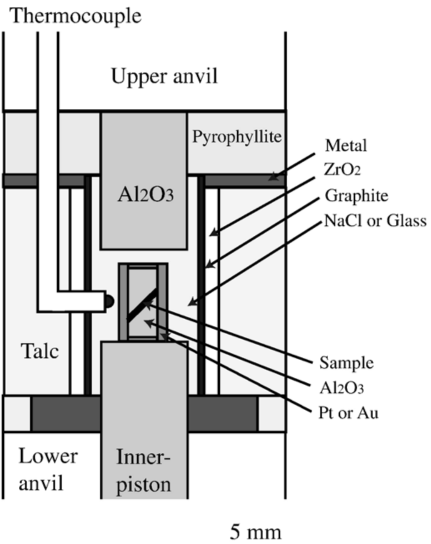
IPF compression direction

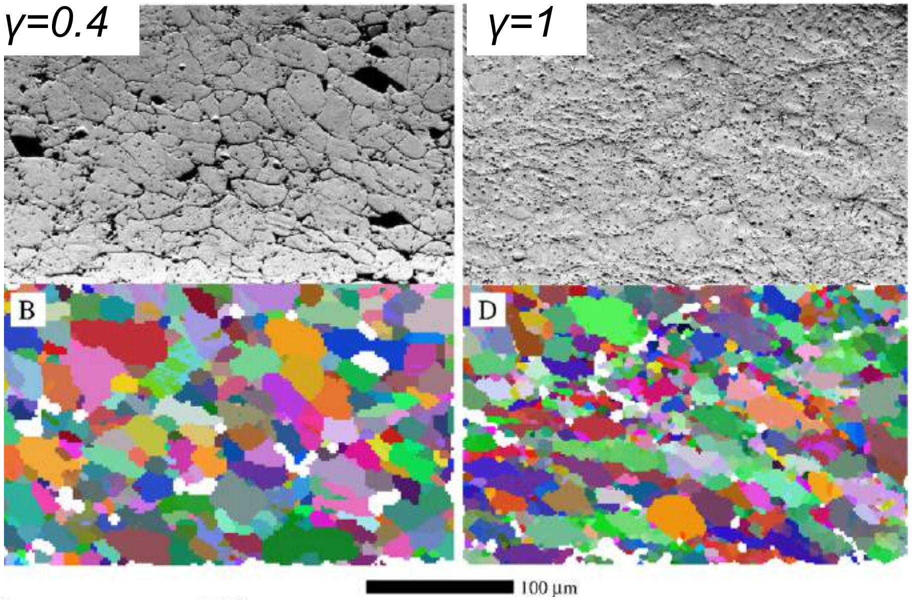
Dominant glide on [100](010)

- ***Texture inheritance + stresses in experiments >> mantle stresses (<1GPa)***

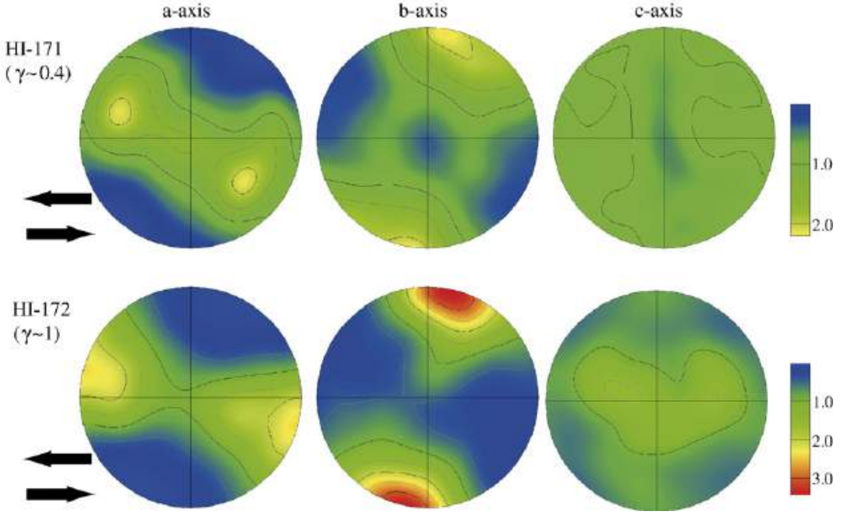
What do we know about the rock-scale deformation and texture development in PPV?

Experiments on analogs : $CaIrO_3$ PPV at 1GPa, 1173 K

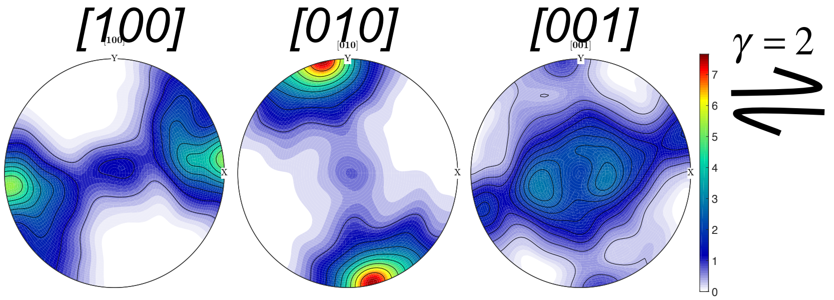


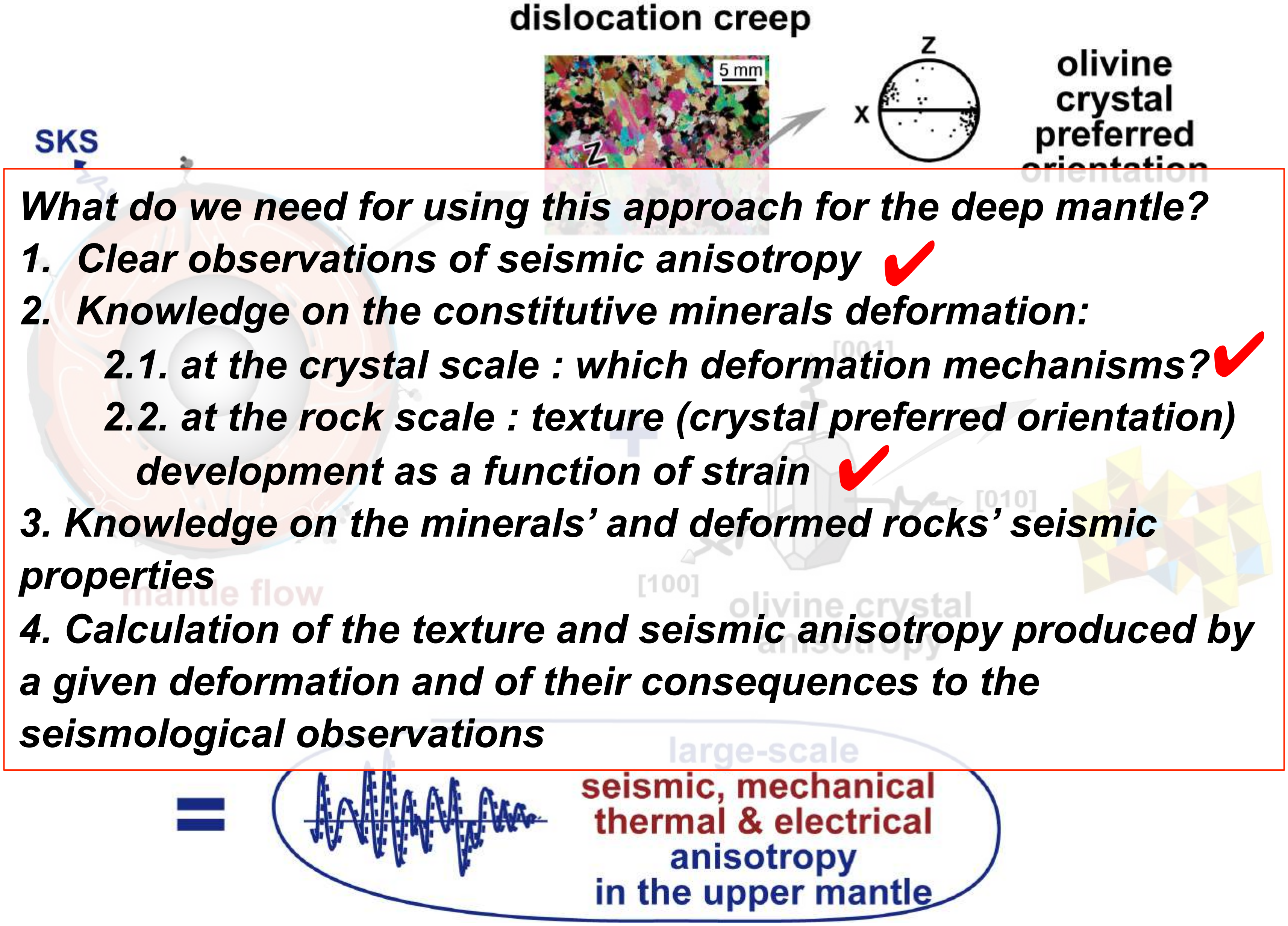


Yamazaki et al.
EPSL 2006



VPSC simulations with twinning



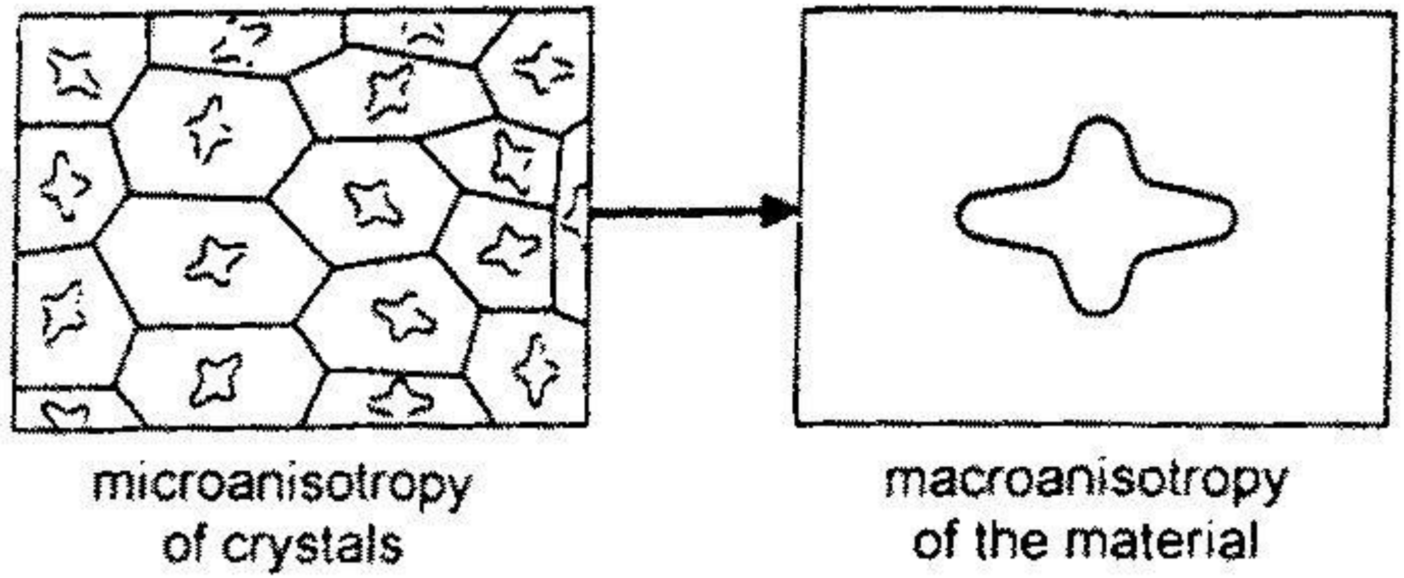


What do we need for using this approach for the deep mantle?

1. ***Clear observations of seismic anisotropy*** ✓
2. ***Knowledge on the constitutive minerals deformation:***
    2.1. at the crystal scale : which deformation mechanisms? ✓
    2.2. at the rock scale : texture (crystal preferred orientation) development as a function of strain ✓
3. ***Knowledge on the minerals' and deformed rocks' seismic properties***
4. ***Calculation of the texture and seismic anisotropy produced by a given deformation and of their consequences to the seismological observations***

How to calculate seismic anisotropy at the rock scale

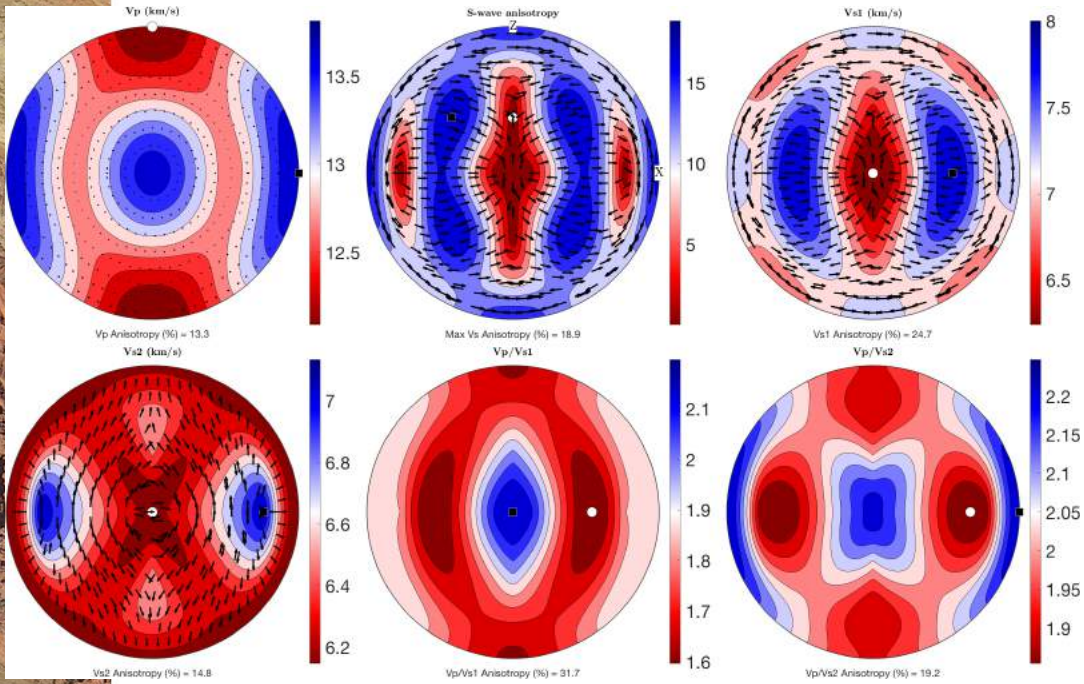
rock = aggregate of anisotropic crystals



volumetric averaging of the single crystal properties as function of:

- ***mineralogical composition***
- ***orientation of the crystals***

Seismic properties of the PPV & MgO crystals at 100 GPa – 2000 K

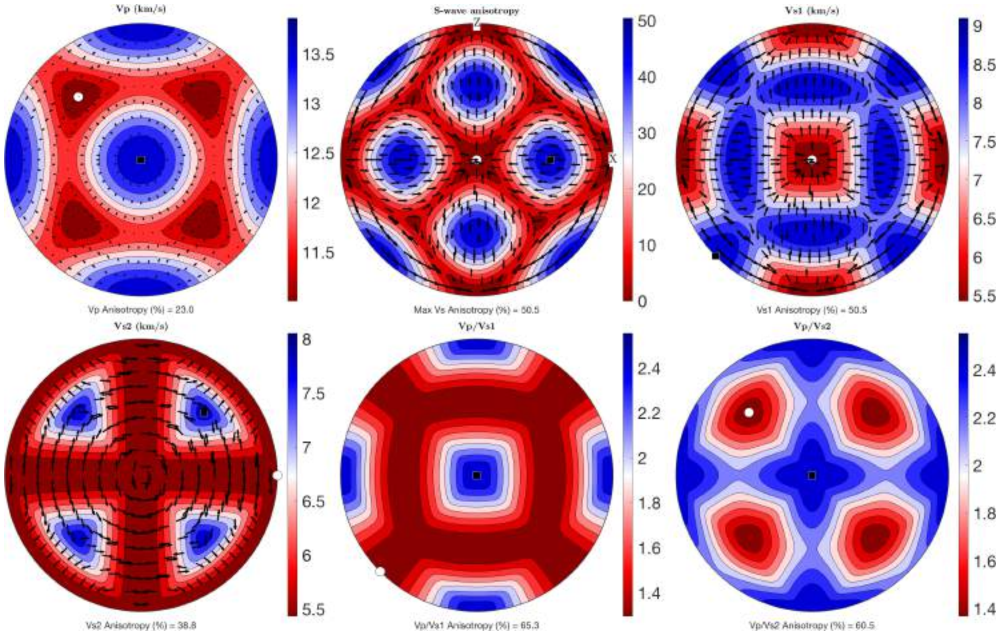


PPV ($(Mg_{0.75}Fe_{0.25})SiO_3$)

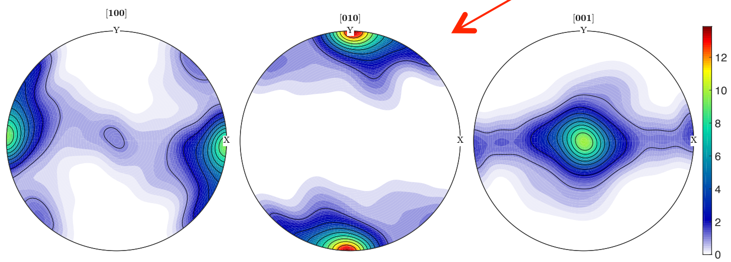
- *13% for P & 19% for S-waves*
- *Simple velocity variation pattern for P-waves, complex for S-waves*

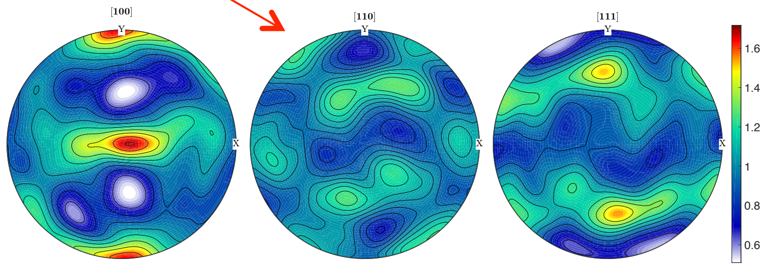
MgO

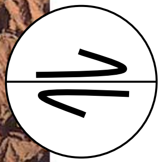
- *Cubic, but more anisotropic than PPV!*
- *23% for P & 50% for S-waves*

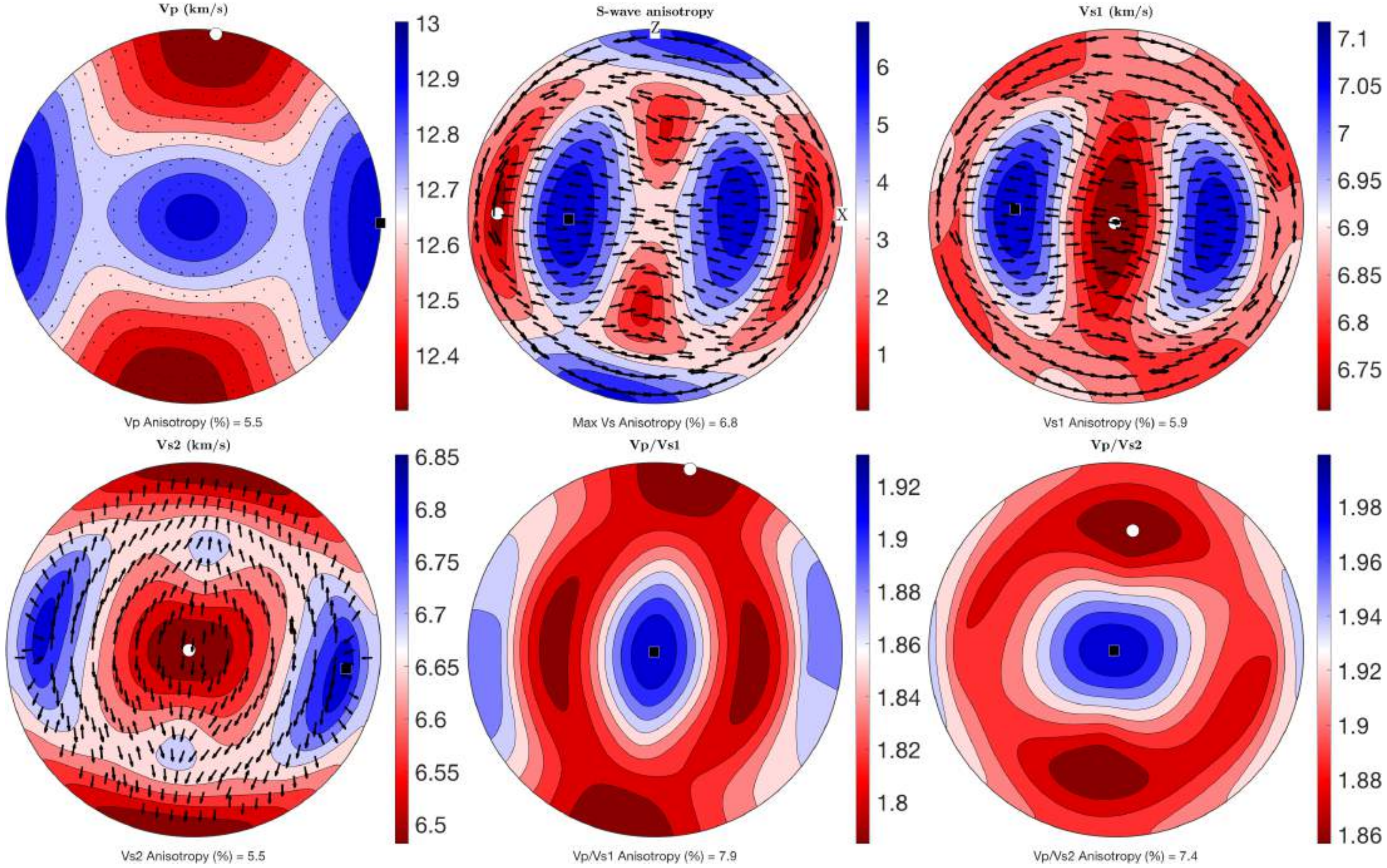


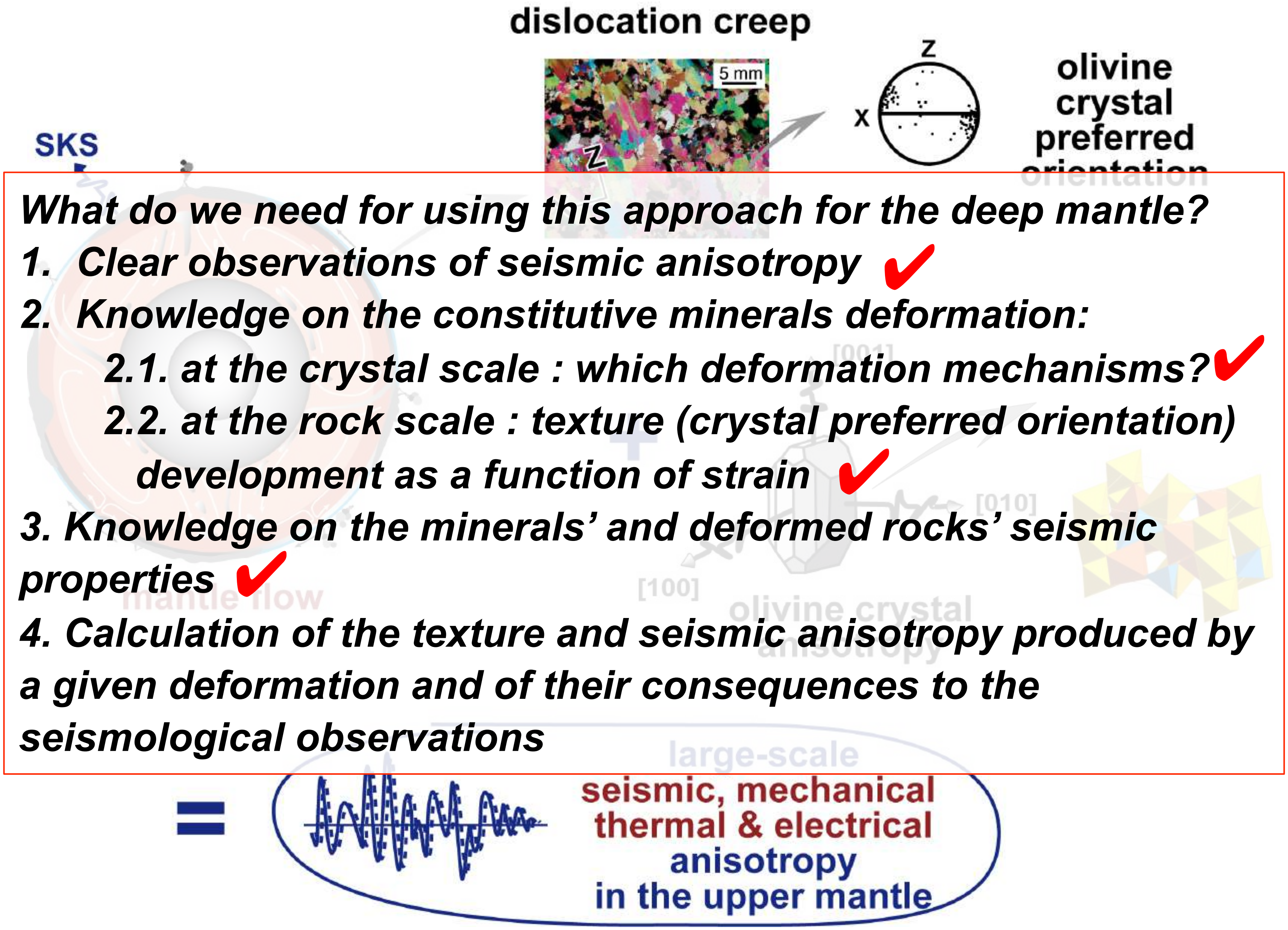
Seismic properties of a 70% PPV – 30% MgO rock at 120GPa – 2000K = top of a cold domain of D”











What do we need for using this approach for the deep mantle?

1. ***Clear observations of seismic anisotropy*** ✓
2. ***Knowledge on the constitutive minerals deformation:***
    - ***2.1. at the crystal scale : which deformation mechanisms?*** ✓
    - ***2.2. at the rock scale : texture (crystal preferred orientation) development as a function of strain*** ✓

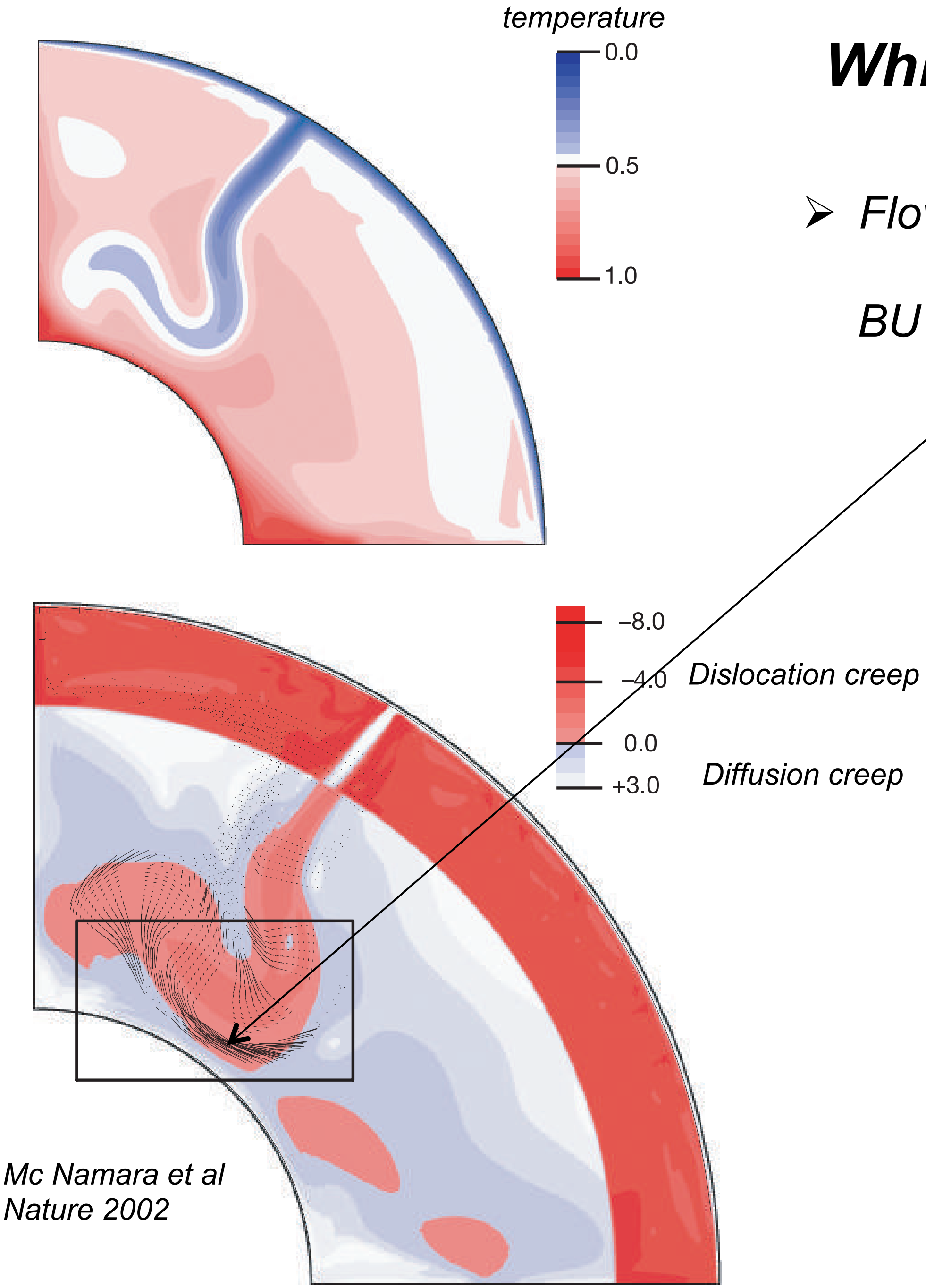
3. Knowledge on the minerals' and deformed rocks' seismic properties ✓

4. Calculation of the texture and seismic anisotropy produced by a given deformation and of their consequences to the seismological observations

Which deformation in D”?

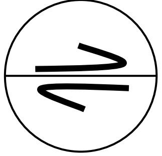
- Flow patterns can be very complex:
  - folding of the slabs…

  BUT the highest strain domains:
  stretching subparallel to CMB

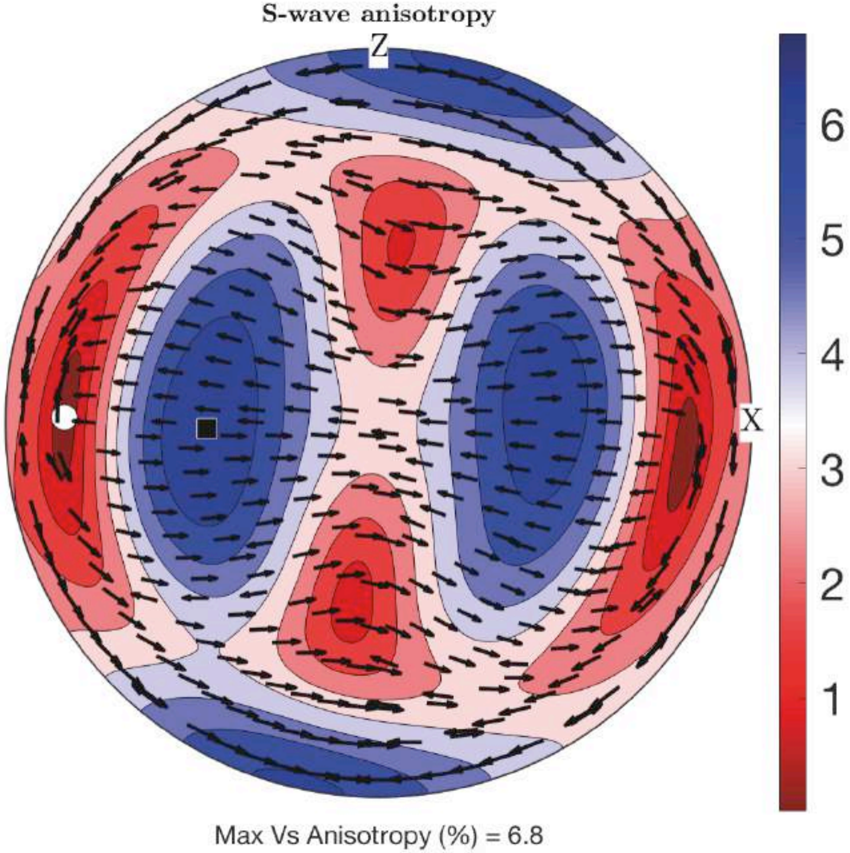


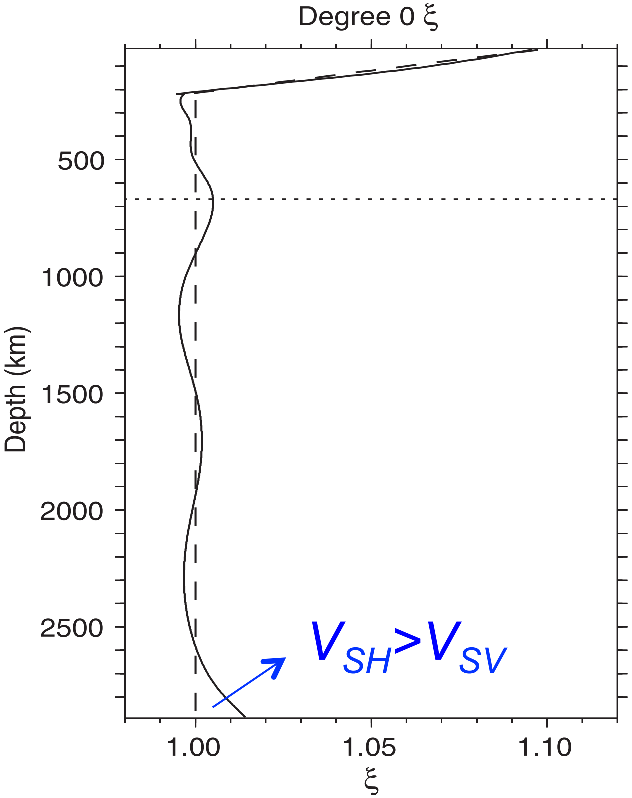
Mc Namara et al
Nature 2002

Hypothesis: strong shear // to CMB



$\gamma = 10$



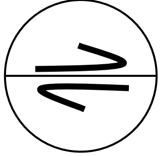


$V_{SH} > V_{SV}$

- *For most S-wave propagations, SH faster than SV*

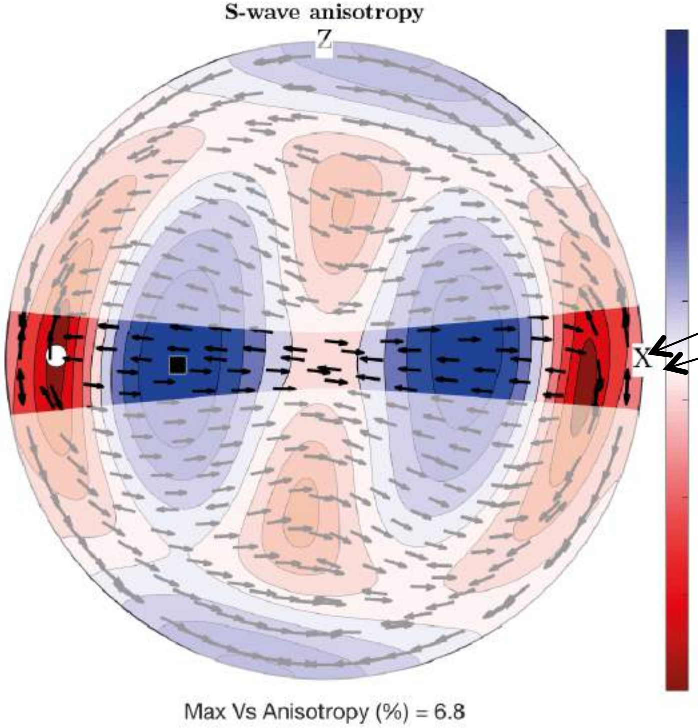
Panning & Romanowicz Science 2004

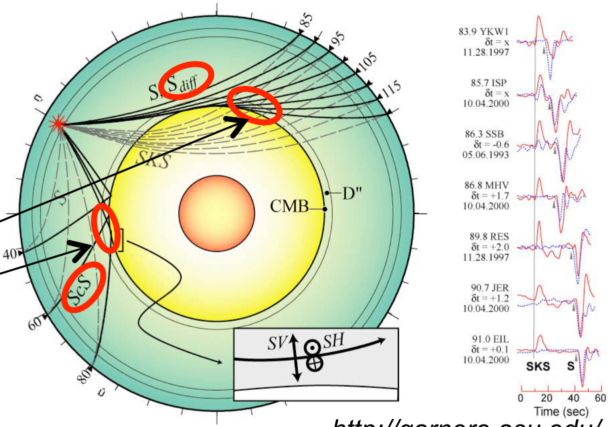
Hypothesis: strong shear // to CMB



$\gamma = 10$

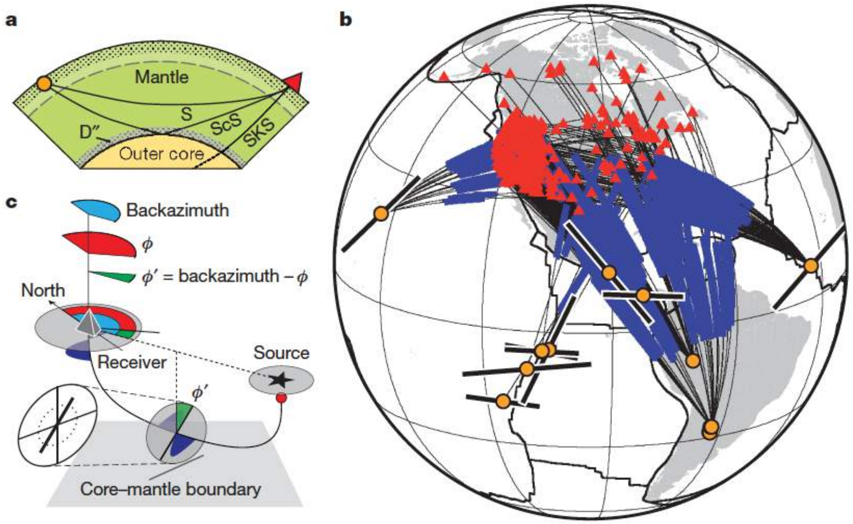
Shear wave splitting: in D”, S_{diff} & ScS





http://garnero.asu.edu/

- *Strong variation of the intensity of anisotropy as a function of the propagation direction: 90° periodicity*
- *When splitting can be observed: VSH polarized in the horizontal plane*
- *Shearing // to CMB cannot explain inclined fast polarizations*



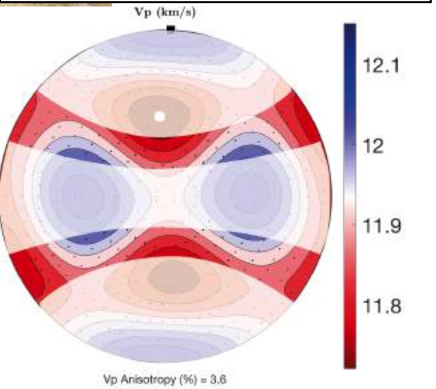
Nowacki et al
Nature 2010

D” reflections

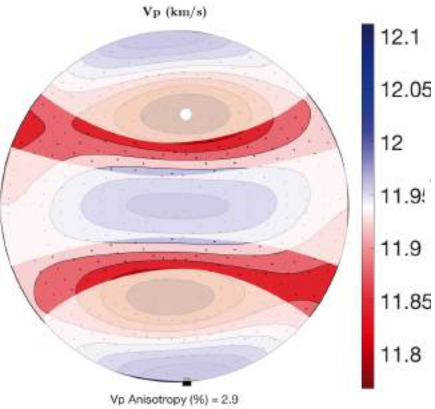
Hypothesis on the seismic properties of the upper layer:

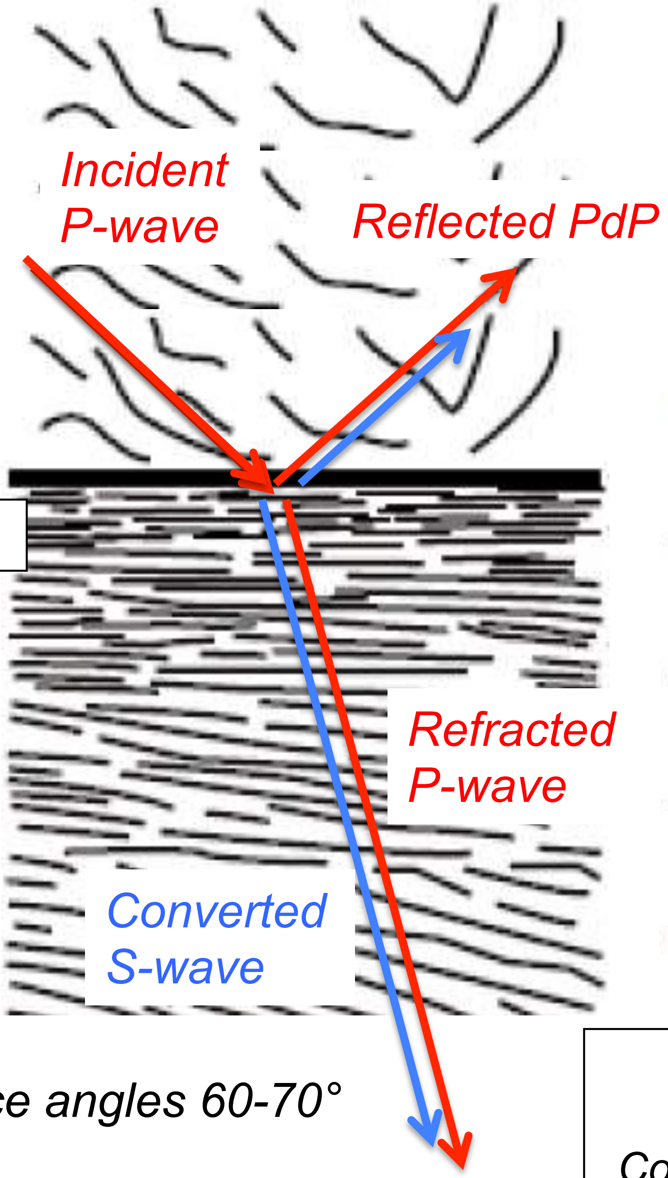
- *PV develops no texture = deformation by diffusional processes (Talk by Ph. Carrez)*

Iso PV + Anis MgO



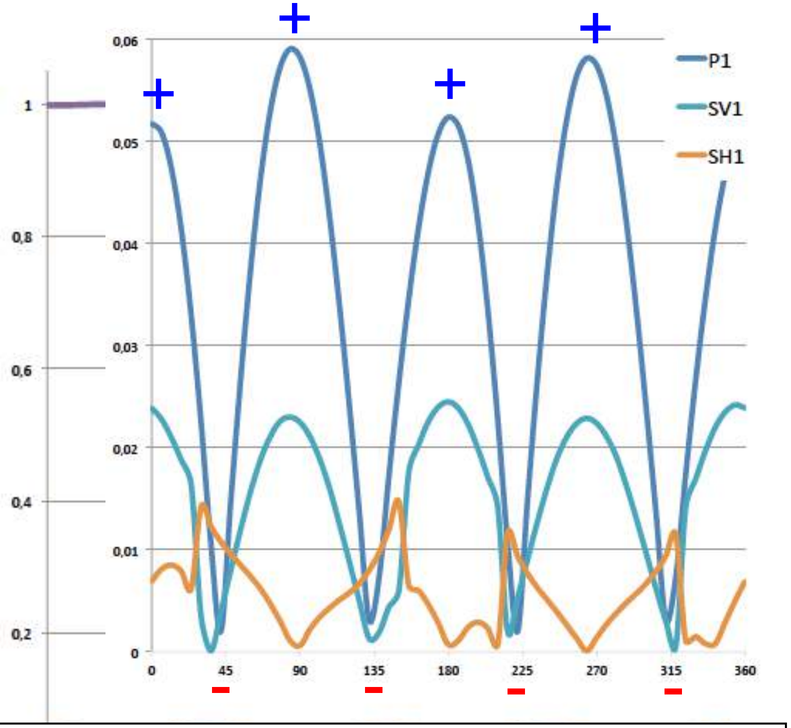
Anis PPV + Anis MgO





Actual incidence angles 60-70°

Incidence angle = 66°



Variations in intensity of PdP with a periodicity of 45°, only + observable
Consistent with Siberia, but not Caribbean

Flow and anisotropy in the (very deep) mantle

- *Interpretation of seismic anisotropy data in the deep mantle relies on multiscale deformation models*
- *Essential first step: sound knowledge on the deformation mechanisms of deep mantle phases ➔ recent advances on atomic scale modeling*
- *From single crystal to the rock-scale: viscoplastic self-consistent models produce robust 1st order predictions of the evolution of texture patterns with strain, BUT they are simple models: only simulate the effect of dislocation glide, no topology…*
- *Elastic properties of single crystals : sound advances*
  Easy scale-transfer from crystal to rock : well-tested for crustal and upper mantle rocks
- *Seismic anisotropy in D": Most, but not all observations might be explained by an anisotropic PPV-rich D", deforming by shear parallel to the CMB by dislocation creep with dominant activation of [100](010) slip (+ [001](001) and twinning).*