Interpreting Seismic Anisotropy in Subduction Zones: The Role of Deformation History

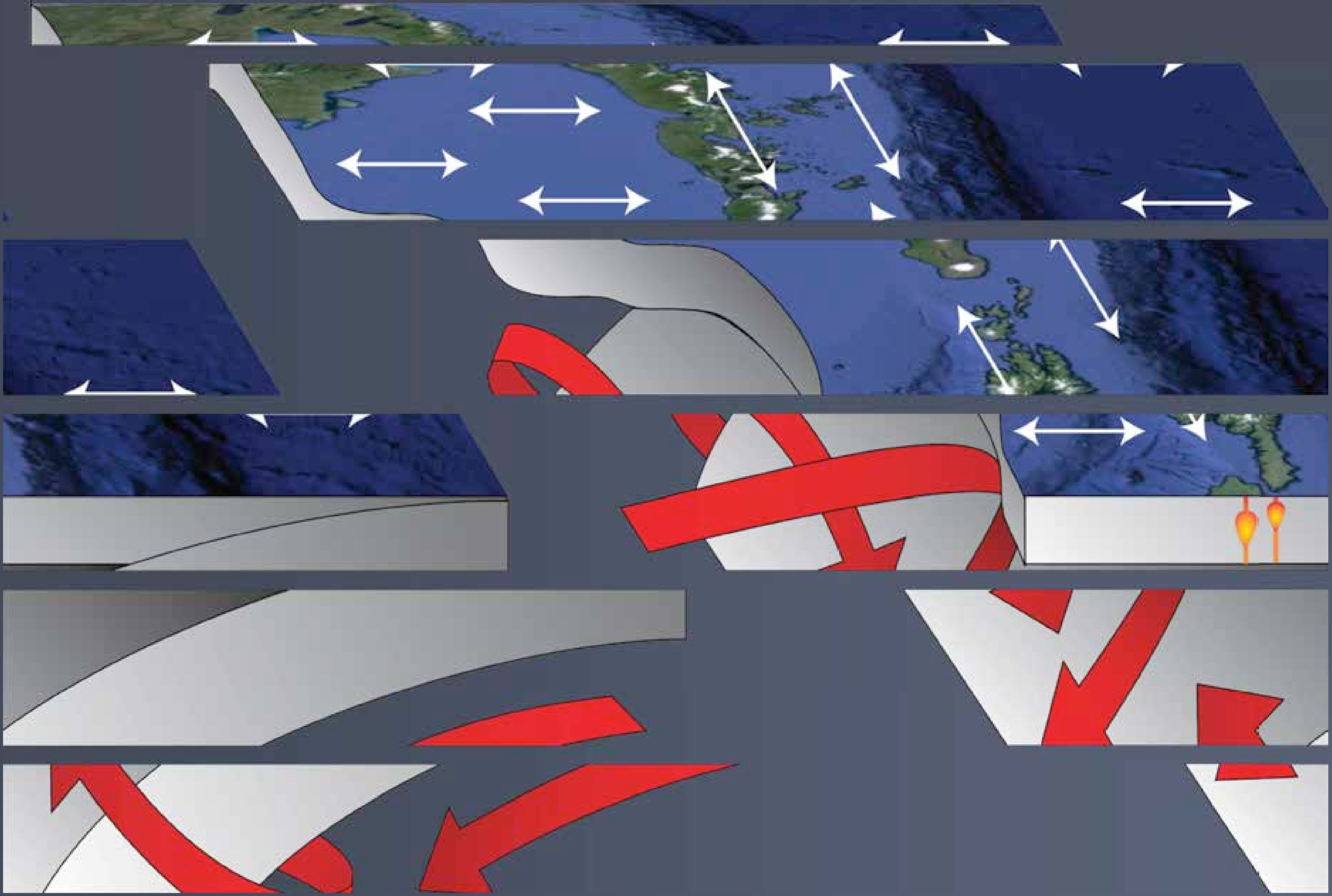
Phil Skemer
Washington University in St. Louis

GeoPRISMS SCD TEI
October 14th 2015

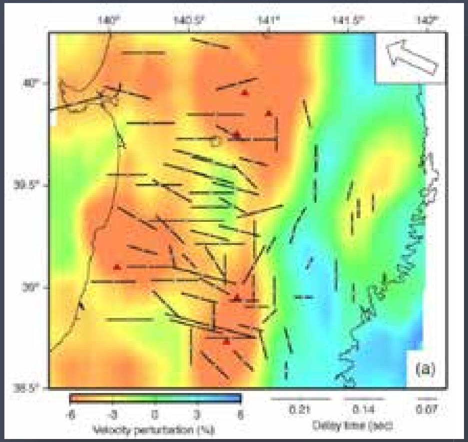
with contributions from:

Yuval Boneh, Lars Hansen, Greg Hirth, Ed Kaminski, Peter Kelemen, Luiz Morales, & Jessica Warren

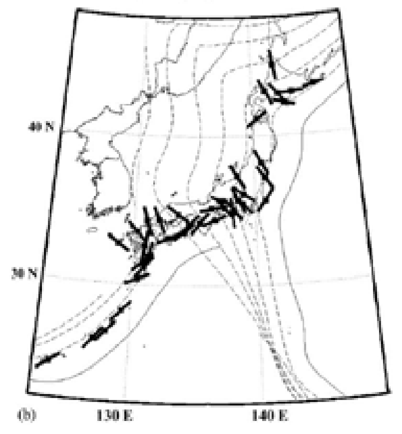
Washington University in St. Louis Earth and Planetary Sciences
ESPM Experimental Studies of Planetary Materials
McDonnell Center for the Space Sciences
imse
NSF



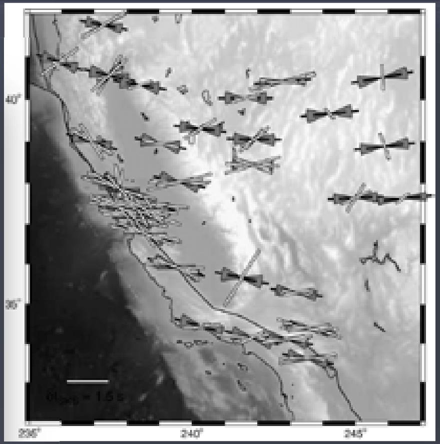
after Karato et al., 2008, AREPS



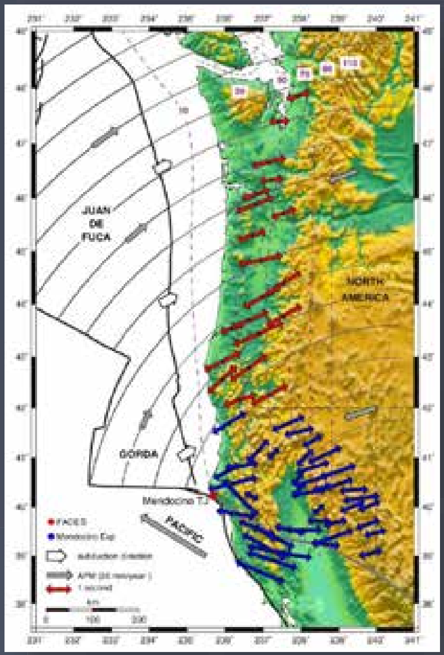
Nakajima and Hasagawa (2004)



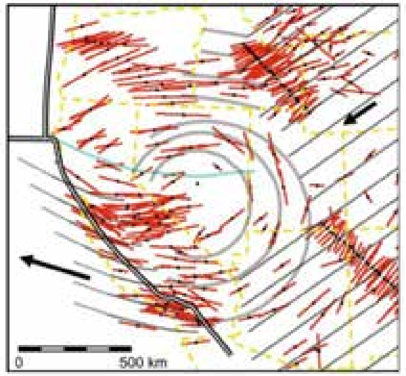
Long and van der Hilst (2005)



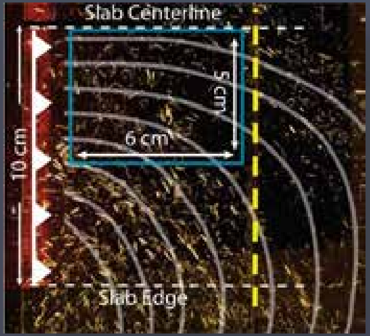
Becker et al (2006)



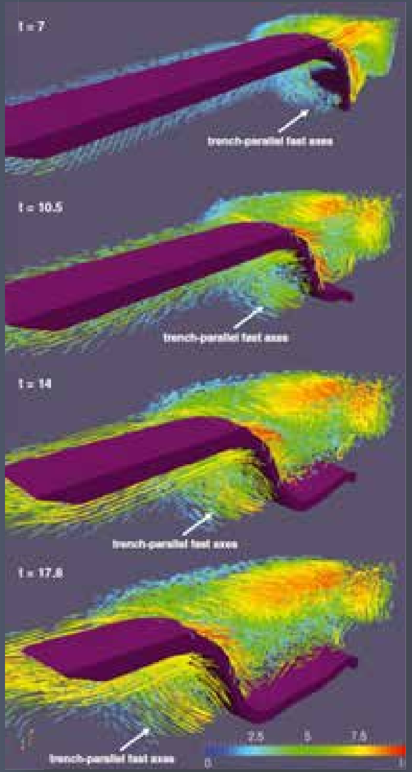
Eakin et al. (2010)



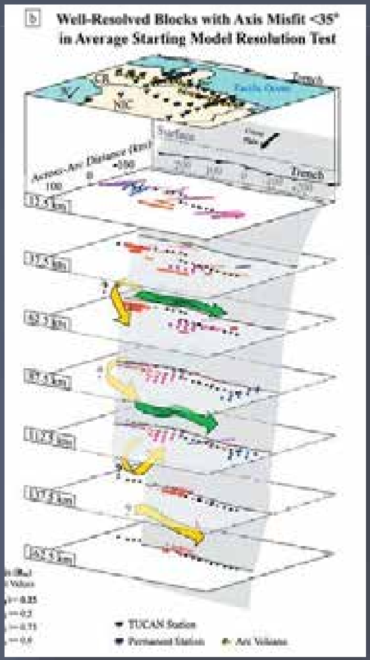
Zandt and Humphries (2008)



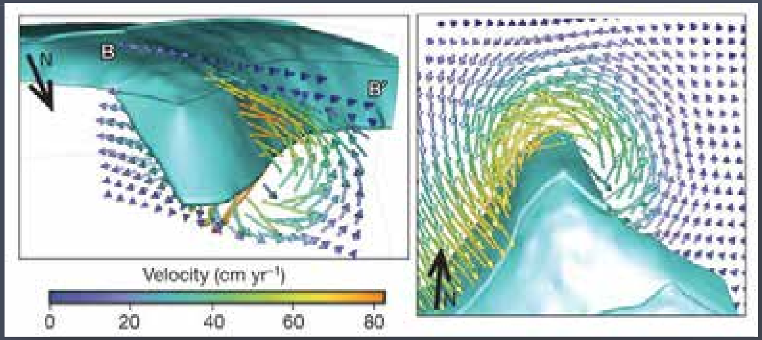
Druken et al. (2011)



Faccenda and Capitanio (2013)



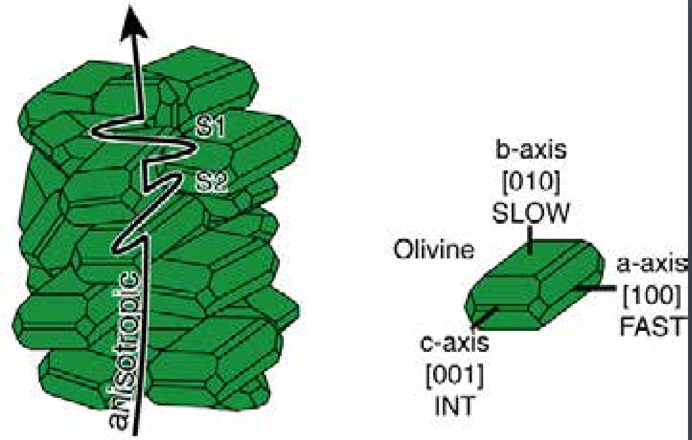
Abt et al (2009)



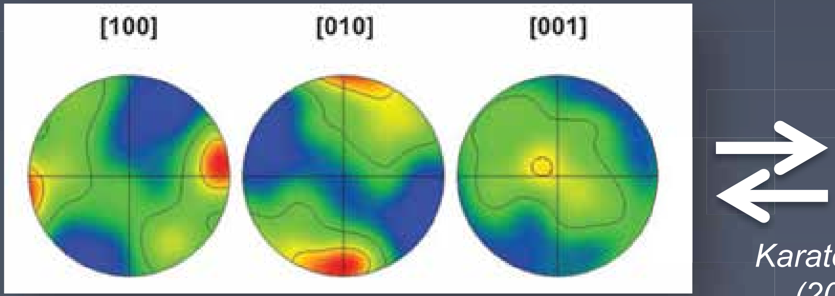
Jadamec and Billen (2010)

Lattice Preferred Orientation (LPO) describes the statistical alignment of the crystal lattices of individual grains in a polycrystalline rock.

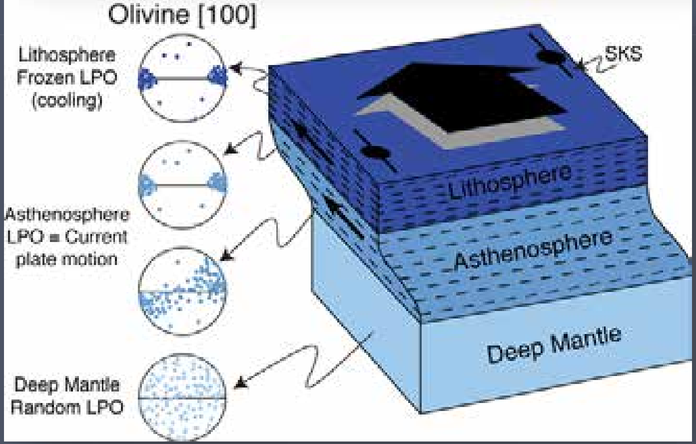
- Deformation by dislocation creep produces LPO
- Flow typically orients seismically fast [100] axes parallel to direction of flow.



Mehl (2006)



Karato et al. (2008)



Tommasi (1998)

[100] [010] [001]

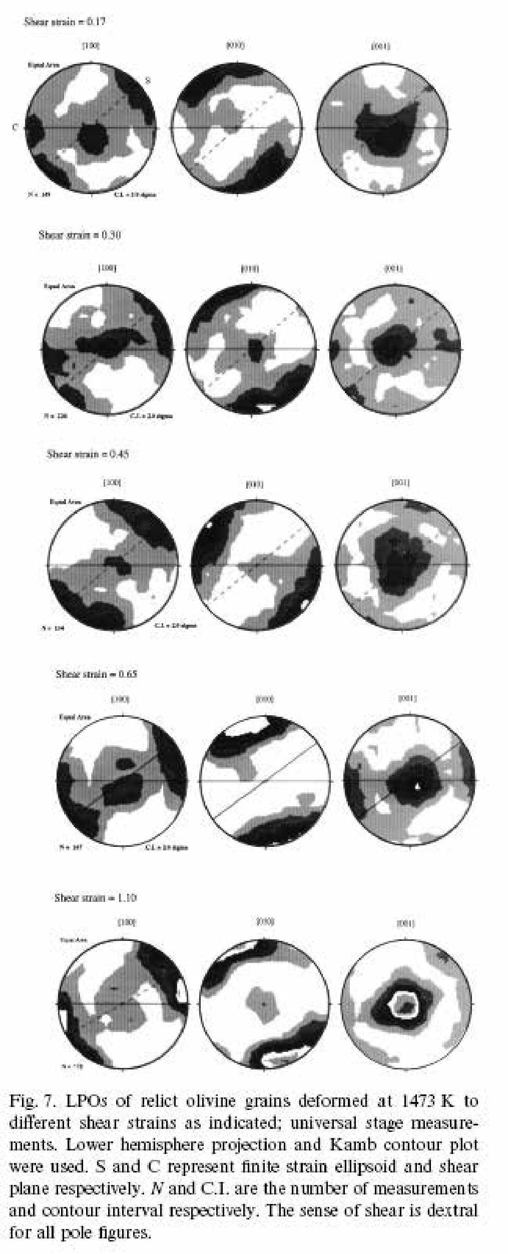
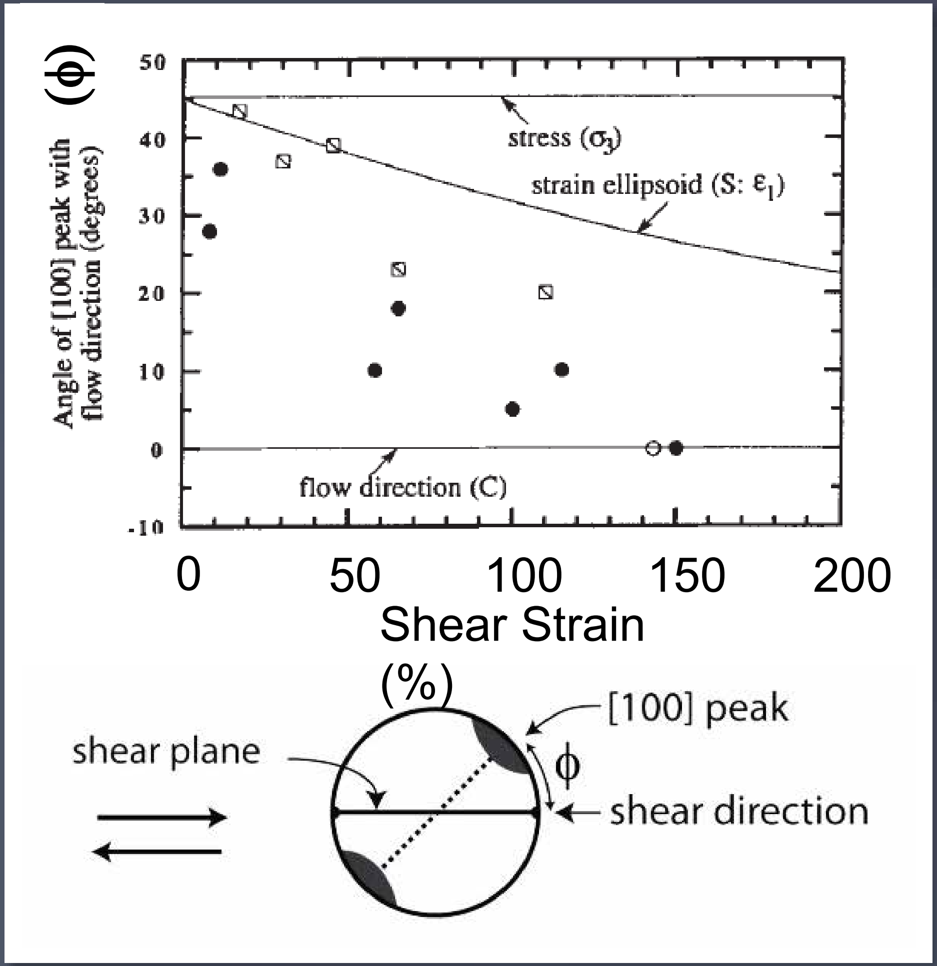


Fig. 7. LPOs of relict olivine grains deformed at 1473 K to different shear strains as indicated; universal stage measurements. Lower hemisphere projection and Kamb contour plot were used. S and C represent finite strain ellipsoid and shear plane respectively. *N* and C.I. are the number of measurements and contour interval respectively. The sense of shear is dextral for all pole figures.

$\gamma = 0.17$

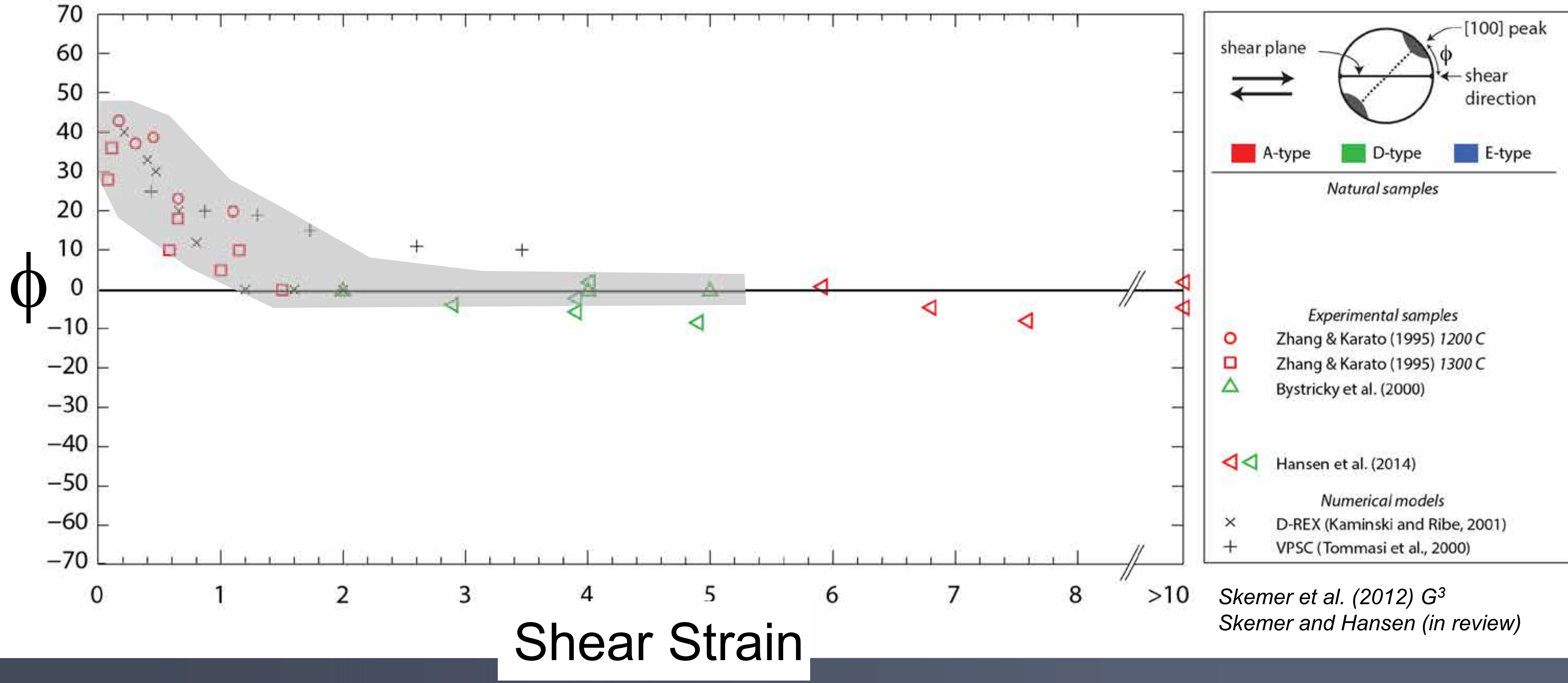
$\gamma = 1.10$



Zhang and Karato (1995) Nature
Zhang et al. (2000) Tectonophysics

ϕ = 0: fast shear wave direction parallel to flow direction

ϕ ≠ 0: fast shear wave direction oblique to flow direction



Skemer et al. (2012) G^3
Skemer and Hansen (in review)

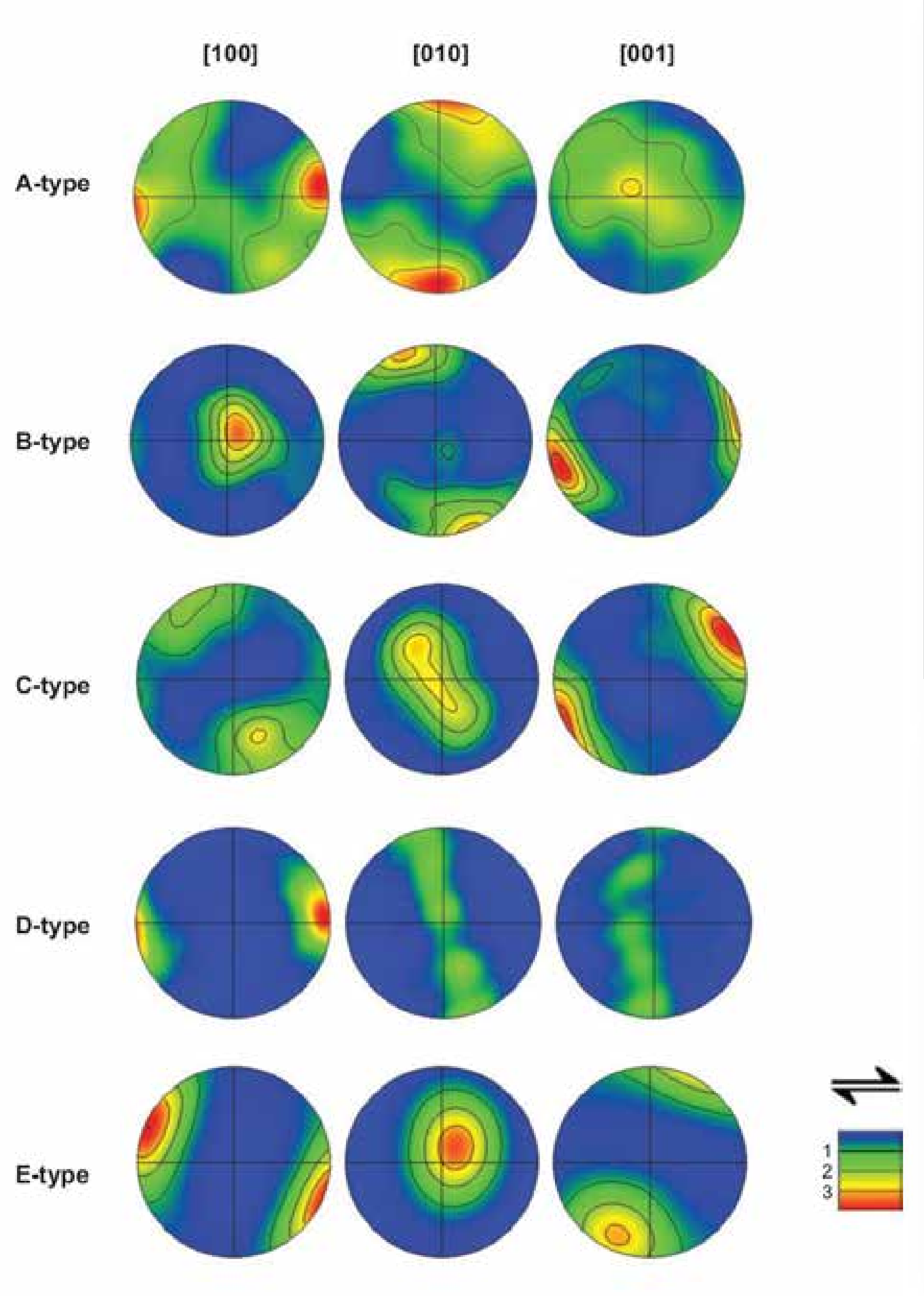
🟥 A-type ▨ Natural

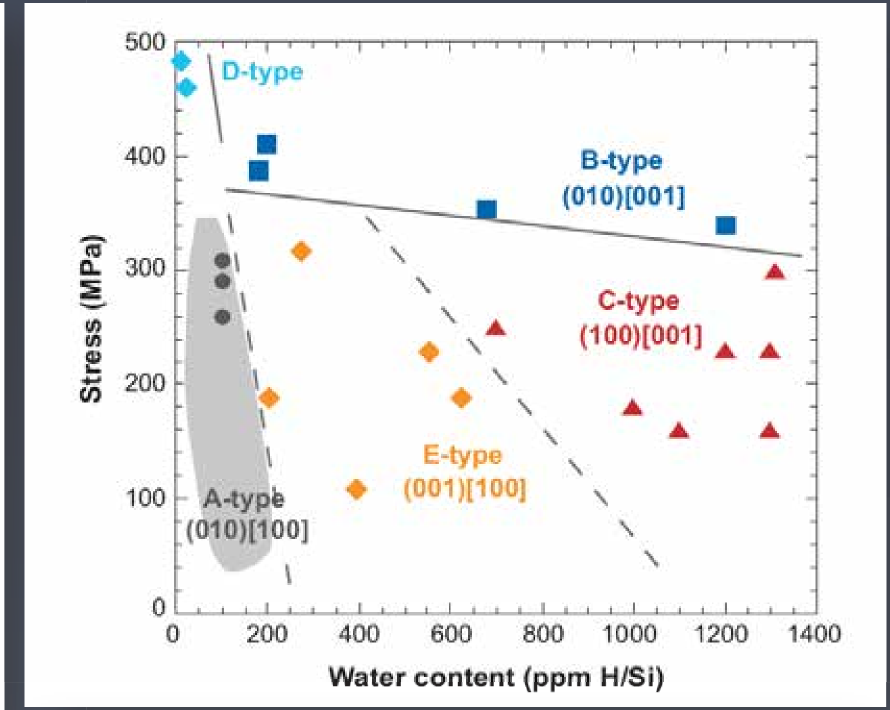
🟩 D-type ☐ Experimental

🟦 E-type × Numerical

Complexity #1 – Varied Olivine Petrofabrics

Complexity #2 – Pre-existing CPO





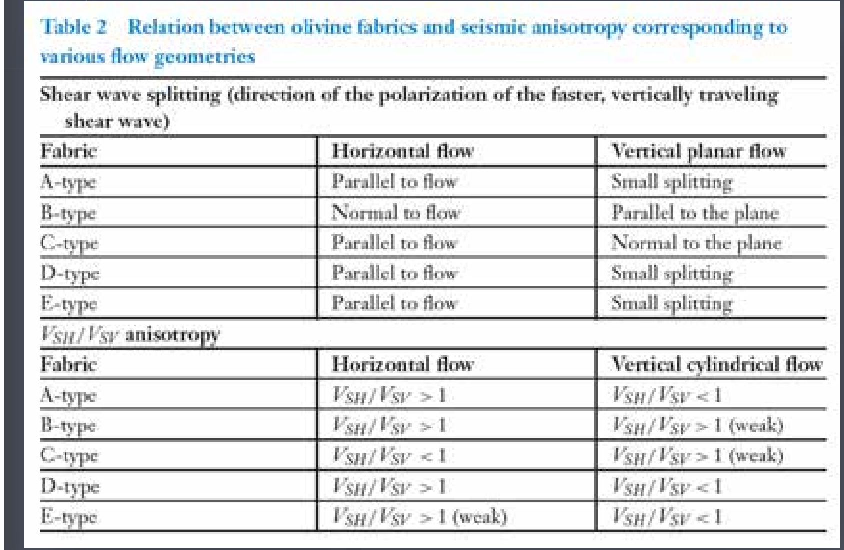


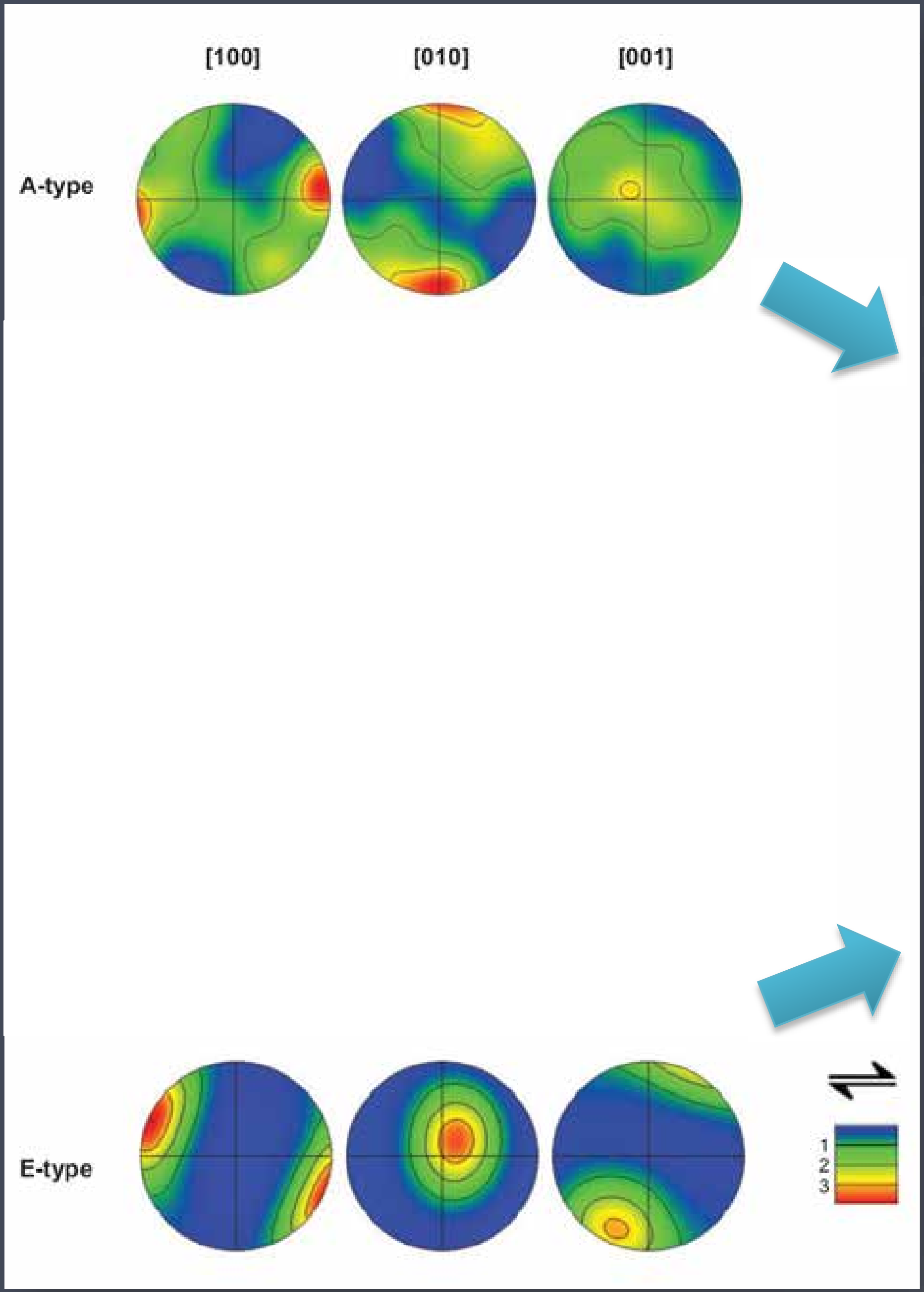
Table 2 Relation between olivine fabrics and seismic anisotropy corresponding to various flow geometries

Shear wave splitting (direction of the polarization of the faster, vertically traveling shear wave)		
Fabric	Horizontal flow	Vertical planar flow
A-type	Parallel to flow	Small splitting
B-type	Normal to flow	Parallel to the plane
C-type	Parallel to flow	Normal to the plane
D-type	Parallel to flow	Small splitting
E-type	Parallel to flow	Small splitting
V_{SH}/V_{SV} anisotropy		
Fabric	Horizontal flow	Vertical cylindrical flow
A-type	$V_{SH}/V_{SV} > 1$	$V_{SH}/V_{SV} < 1$
B-type	$V_{SH}/V_{SV} > 1$	$V_{SH}/V_{SV} > 1$ (weak)
C-type	$V_{SH}/V_{SV} < 1$	$V_{SH}/V_{SV} > 1$ (weak)
D-type	$V_{SH}/V_{SV} > 1$	$V_{SH}/V_{SV} < 1$
E-type	$V_{SH}/V_{SV} > 1$ (weak)	$V_{SH}/V_{SV} < 1$

Karato et al. (2008) Annual Reviews

Complexity #1 – Varied Olivine Petrofabrics

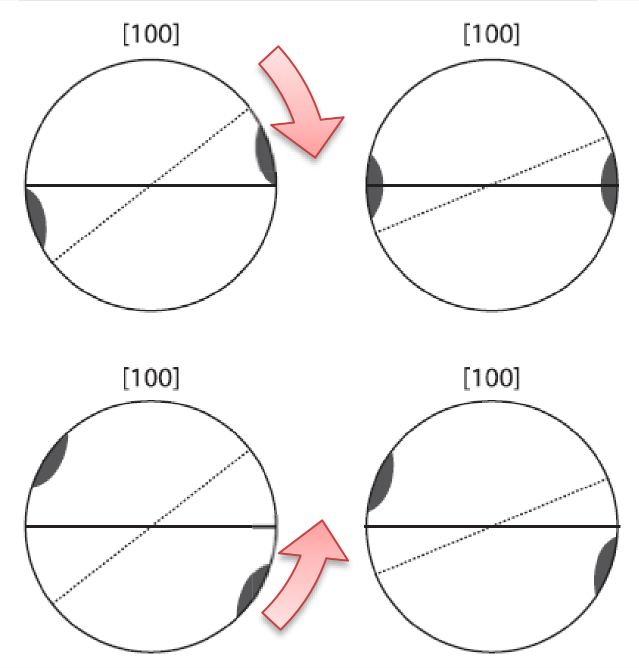
Complexity #2 – Pre-existing CPO



low strain high strain

A-type

E-type



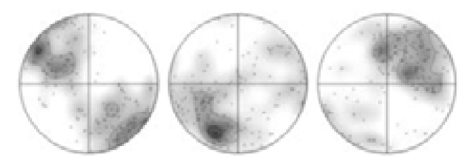
shear sense

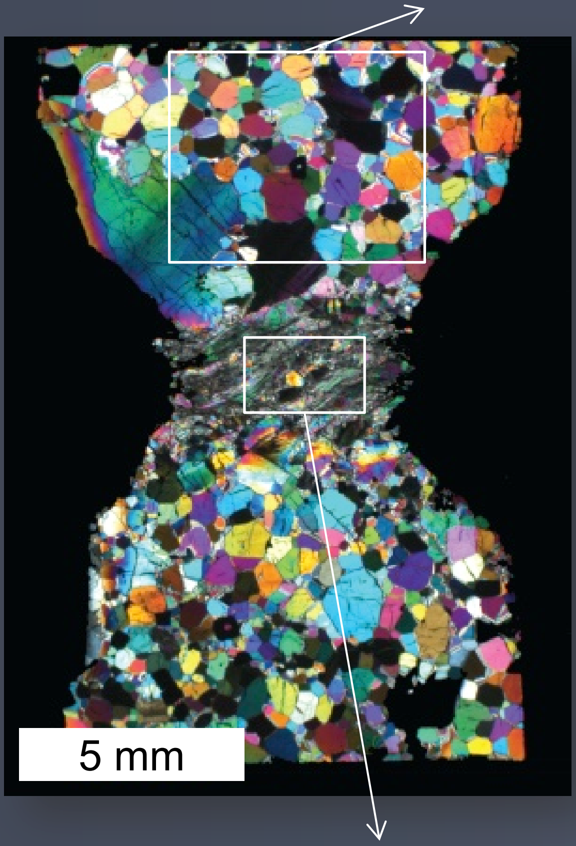
Skemer et al (2010) JPet

Complexity #2 – Pre-existing CPO

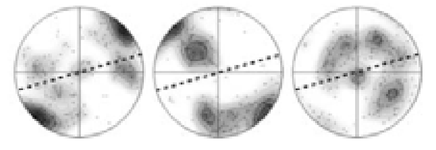
LABORATORY EXPERIMENTS

initial LPO
$\gamma = 0$





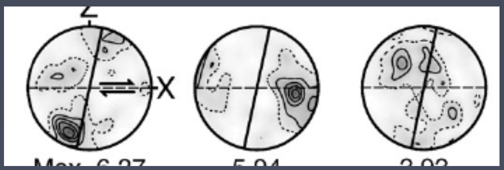
final LPO
$\gamma = 3.5$

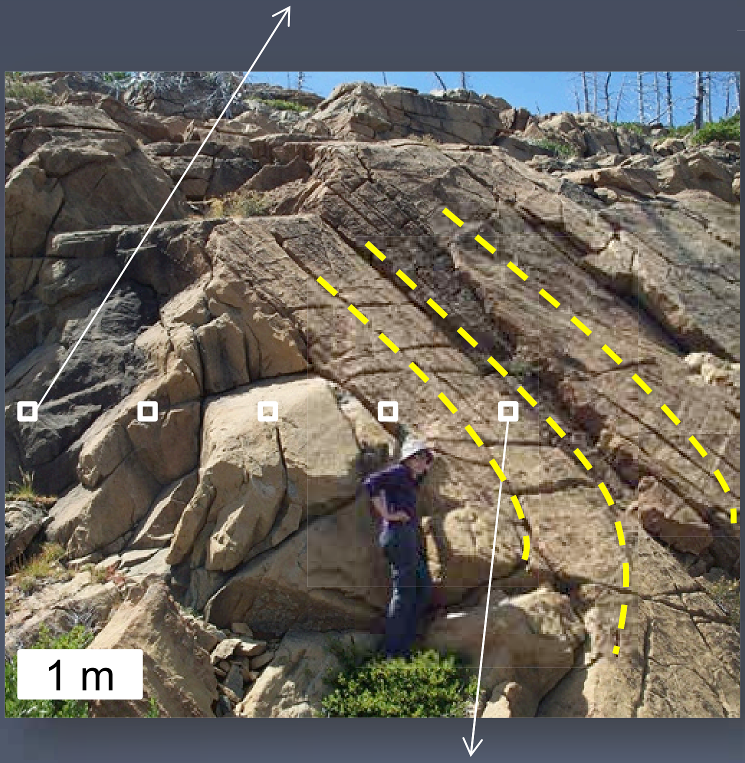


Skemer et al. (2011) Geol. Soc. London

FIELD EXPERIMENTS

initial LPO
$\gamma = 0$



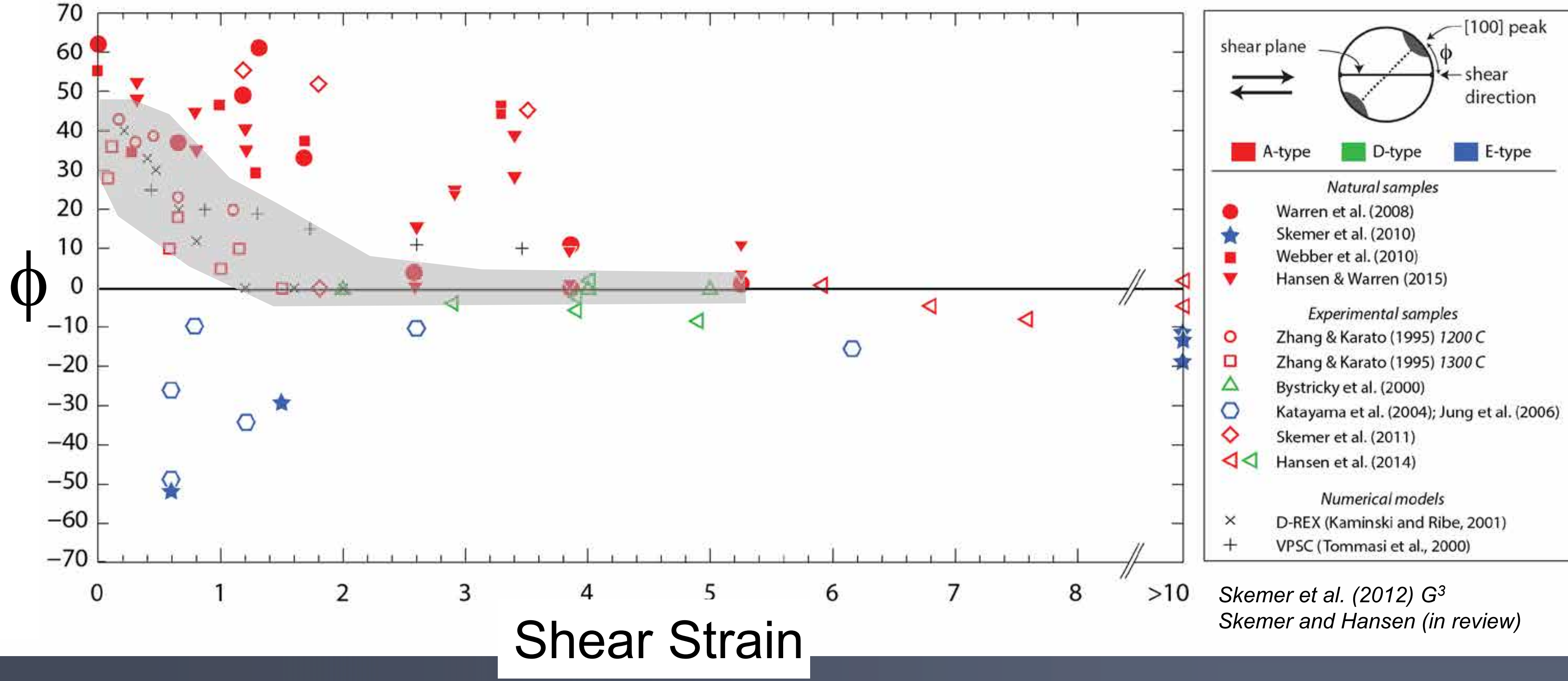


final LPO
$\gamma = 5.25$

Warren et al. (2008) EPSL; Skemer et al. (2010) JPet

$\phi = 0$: fast shear wave direction <u>parallel</u> to flow direction

$\phi \neq 0$: fast shear wave direction <u>oblique</u> to flow direction

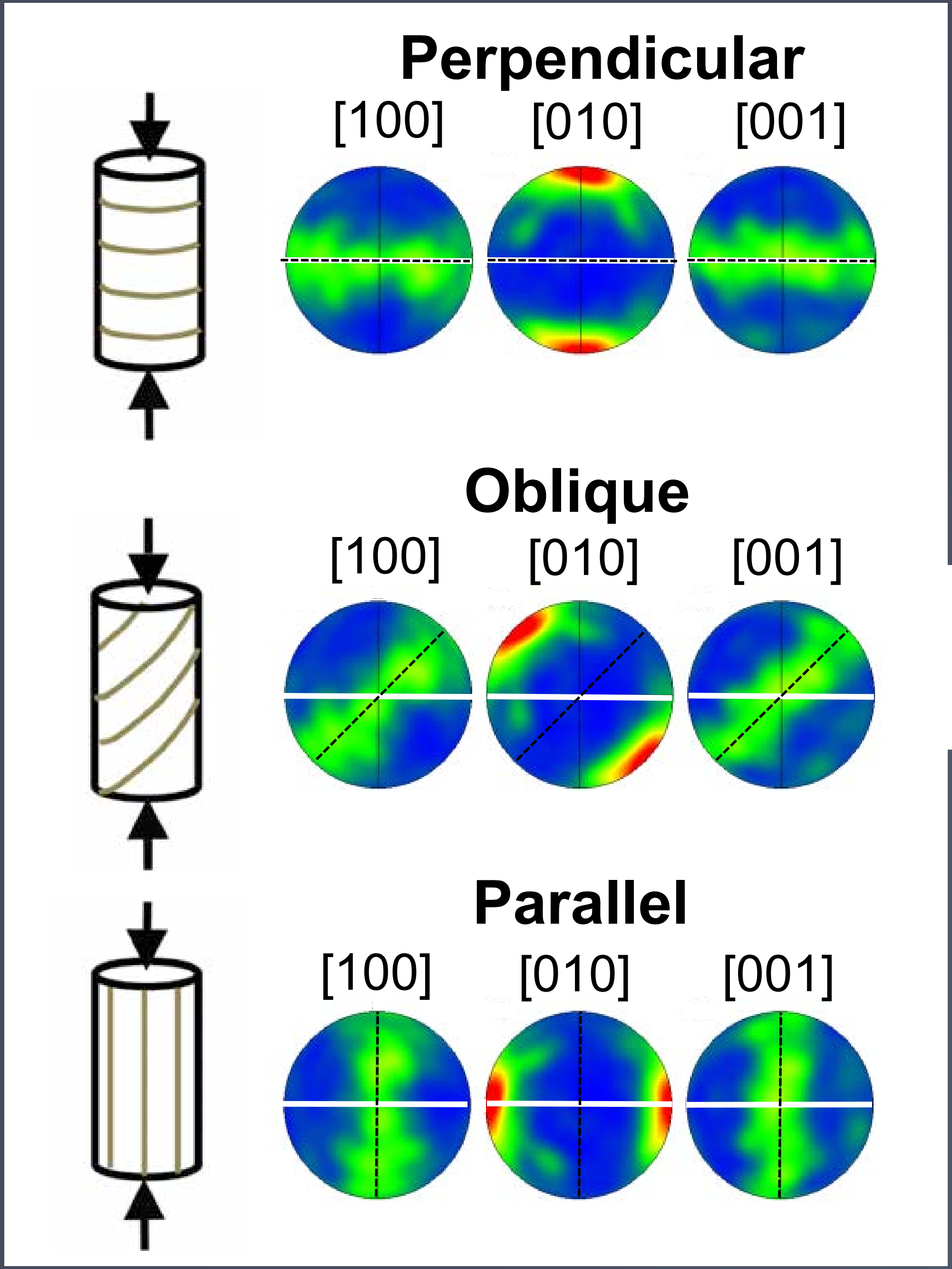


Skemer et al. (2012) G^3
Skemer and Hansen (in review)

🟥 A-type ■ Natural

🟩 D-type ☐ Experimental

🟦 E-type × Numerical



Expected steady-state

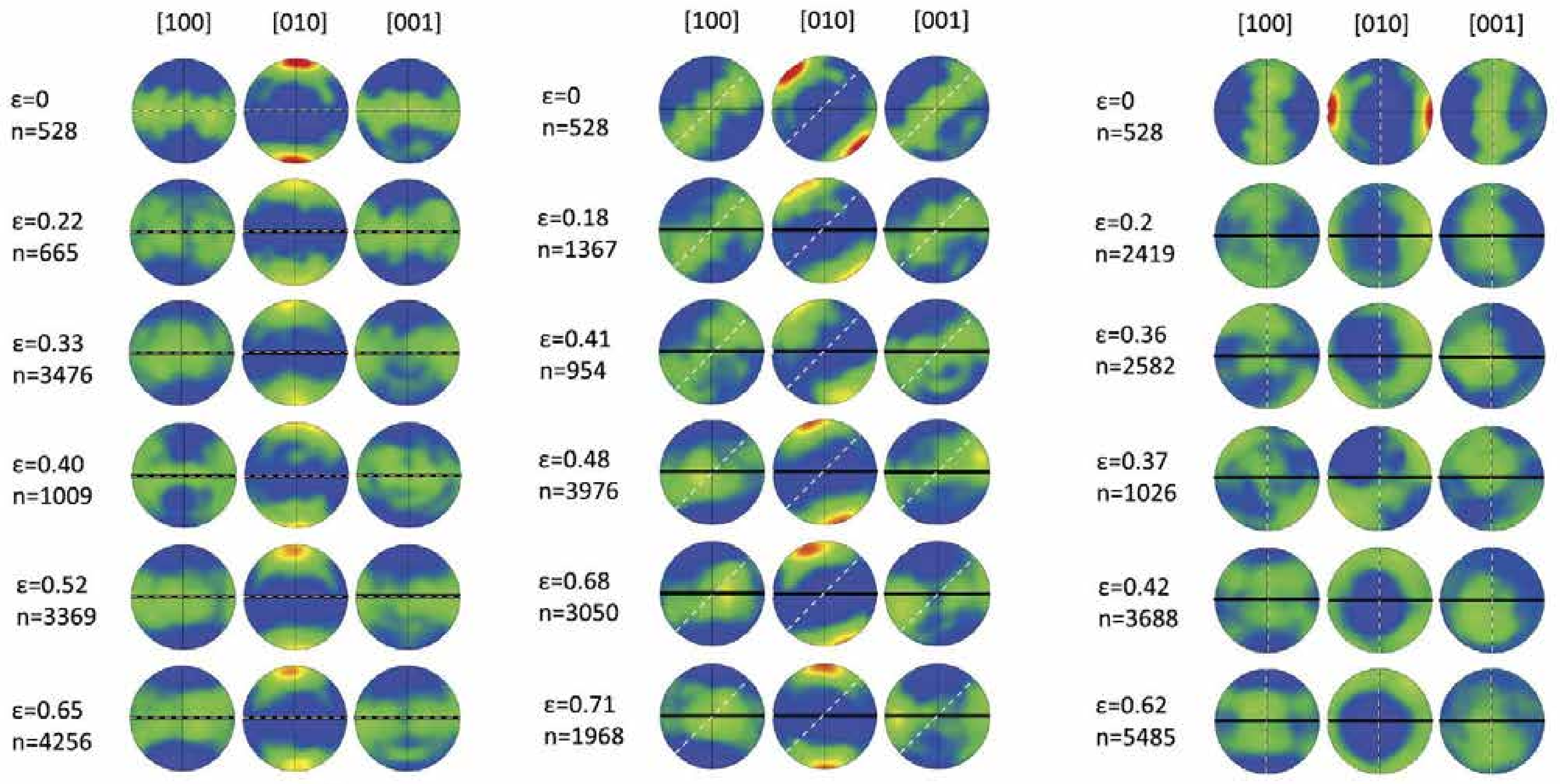
subsequent LPO evolution?

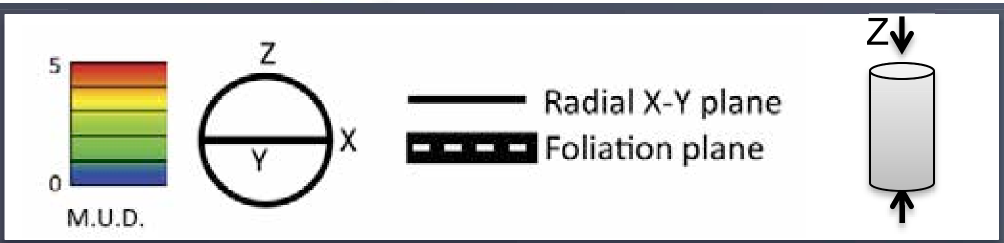
Question #2:
What are the conditions under which LPO will achieve steady state?

Boneh and Skemer (2014) EPSL; Boneh et al. (2015) G^3

LPO Evolution in Three Experimental Configurations

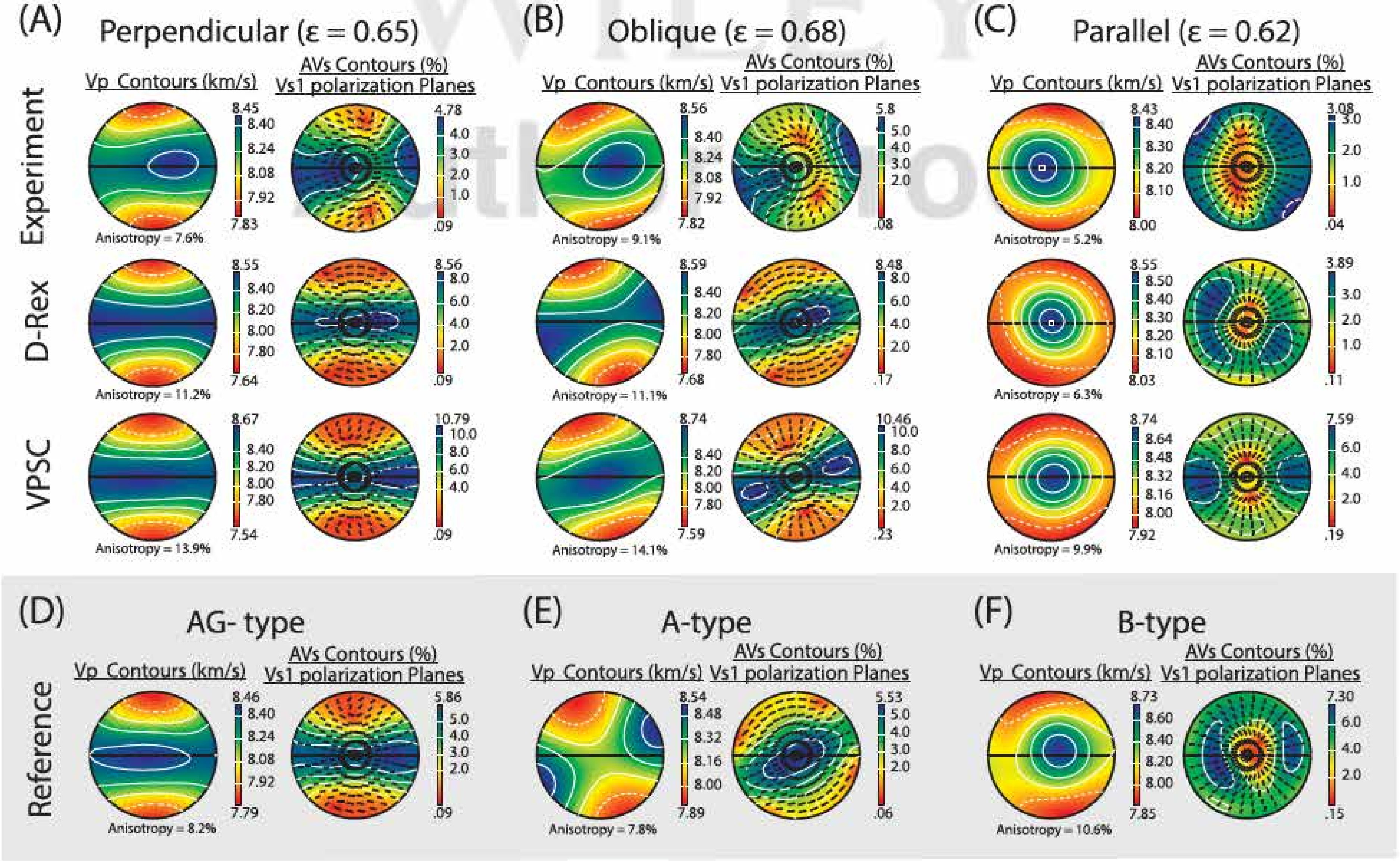
Perpendicular Oblique Parallel





Boneh and Skemer (2014) EPSL

Seismic Anisotropy in Three Experimental Configurations

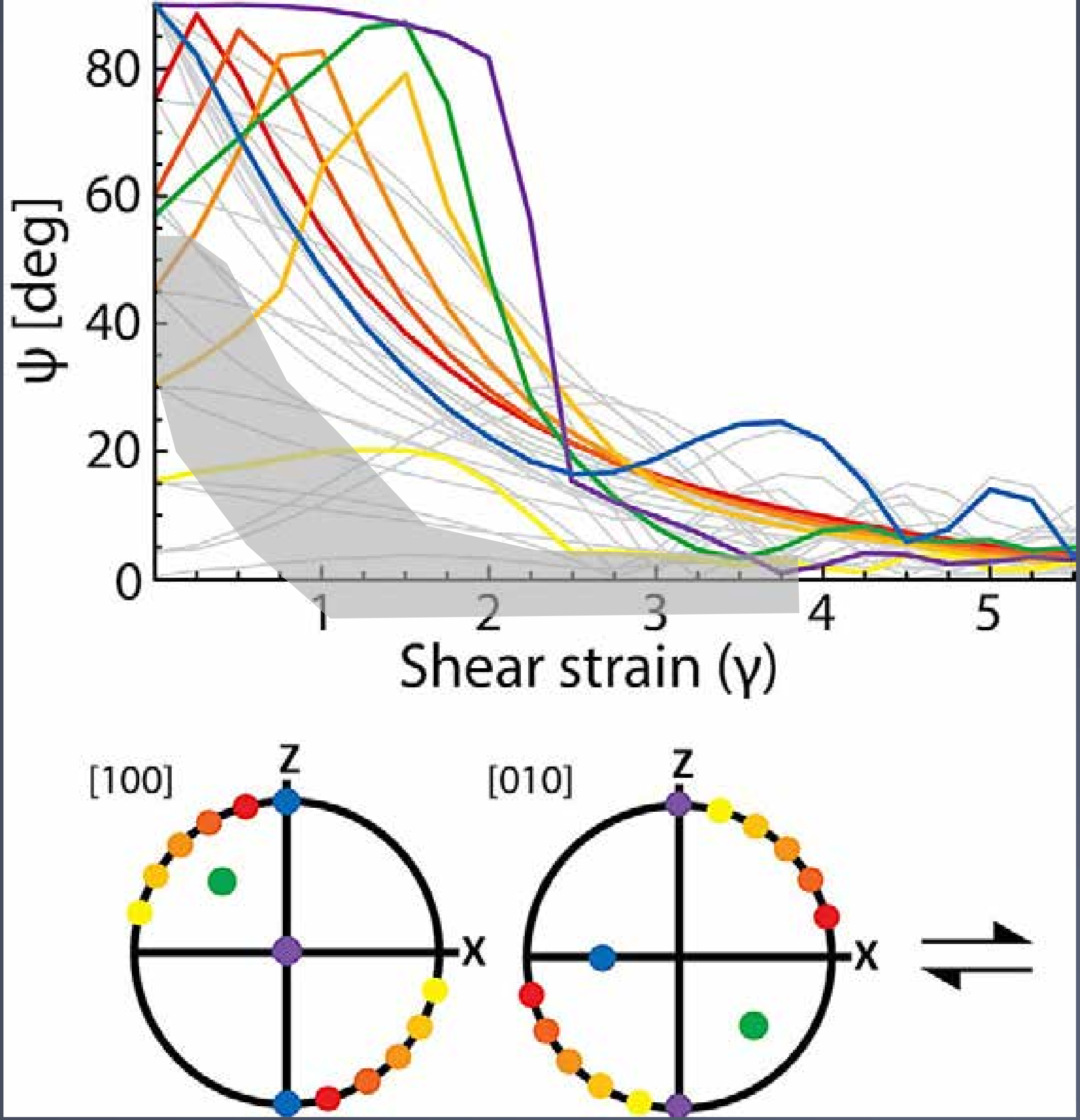


… and three reference samples:

Boneh et al (2015) G^3

Modeling LPO evolution using D-REX

Ψ = minimum angle between [100] and flow direction (X)



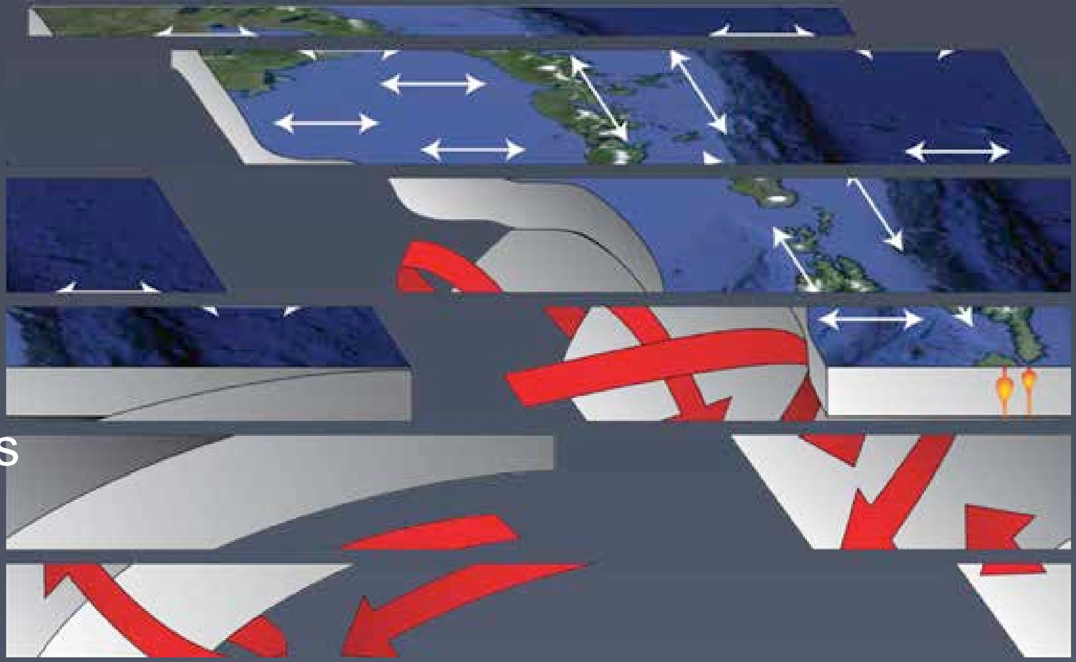
Initial LPO orientation

D-Rex model of Kaminski and Ribe calibrated against Boneh and Skemer (2014)

Boneh et al. (2015) G^3

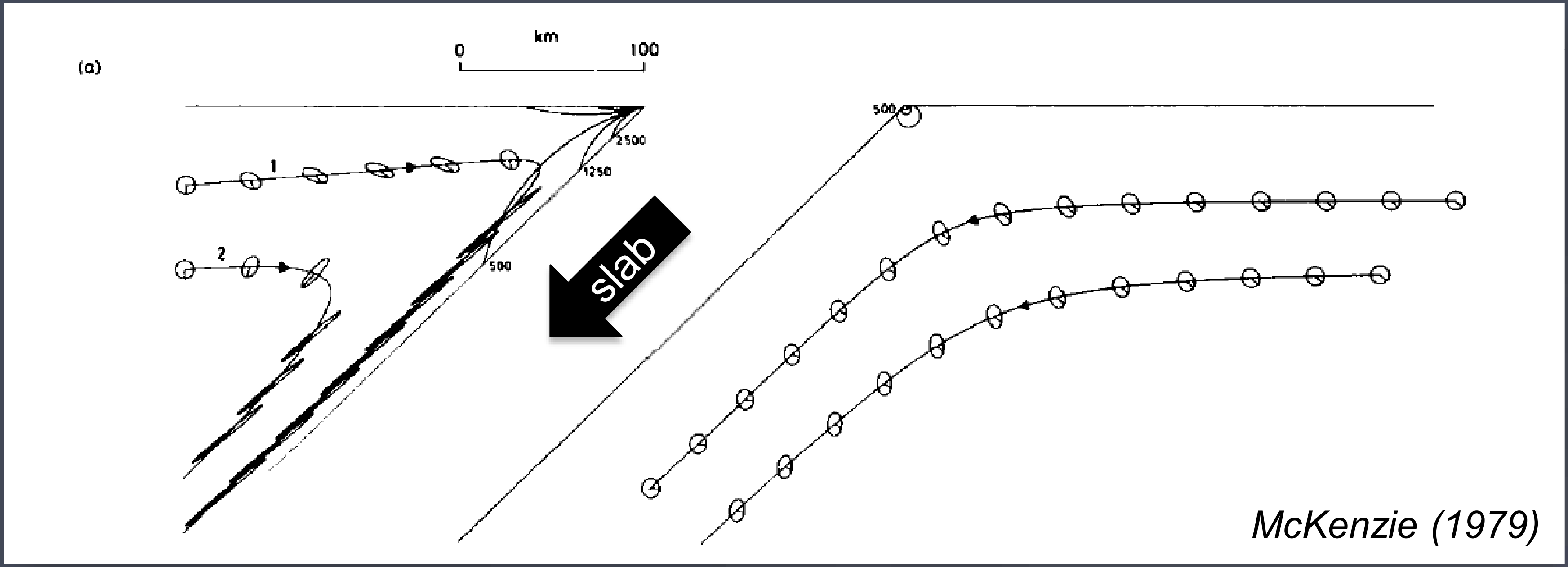
Seismic anisotropy is influenced by:

- Mineralogy
- Temperature
- Pressure
- Water concentration in NAMs
- Stress
- Partial melt
- ***Deformation history***

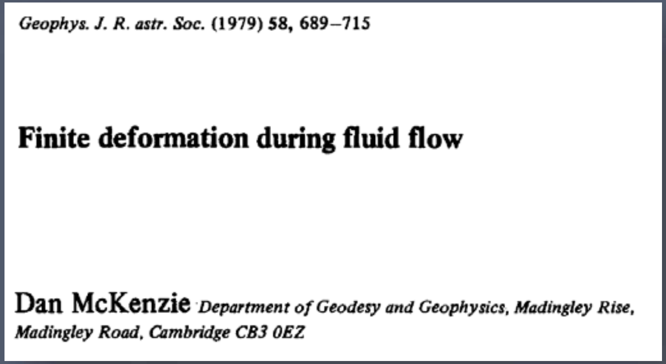


Inferring kinematics of flow in a subduction setting requires consideration of the full spectrum of deformation conditions and history.

bonus slides



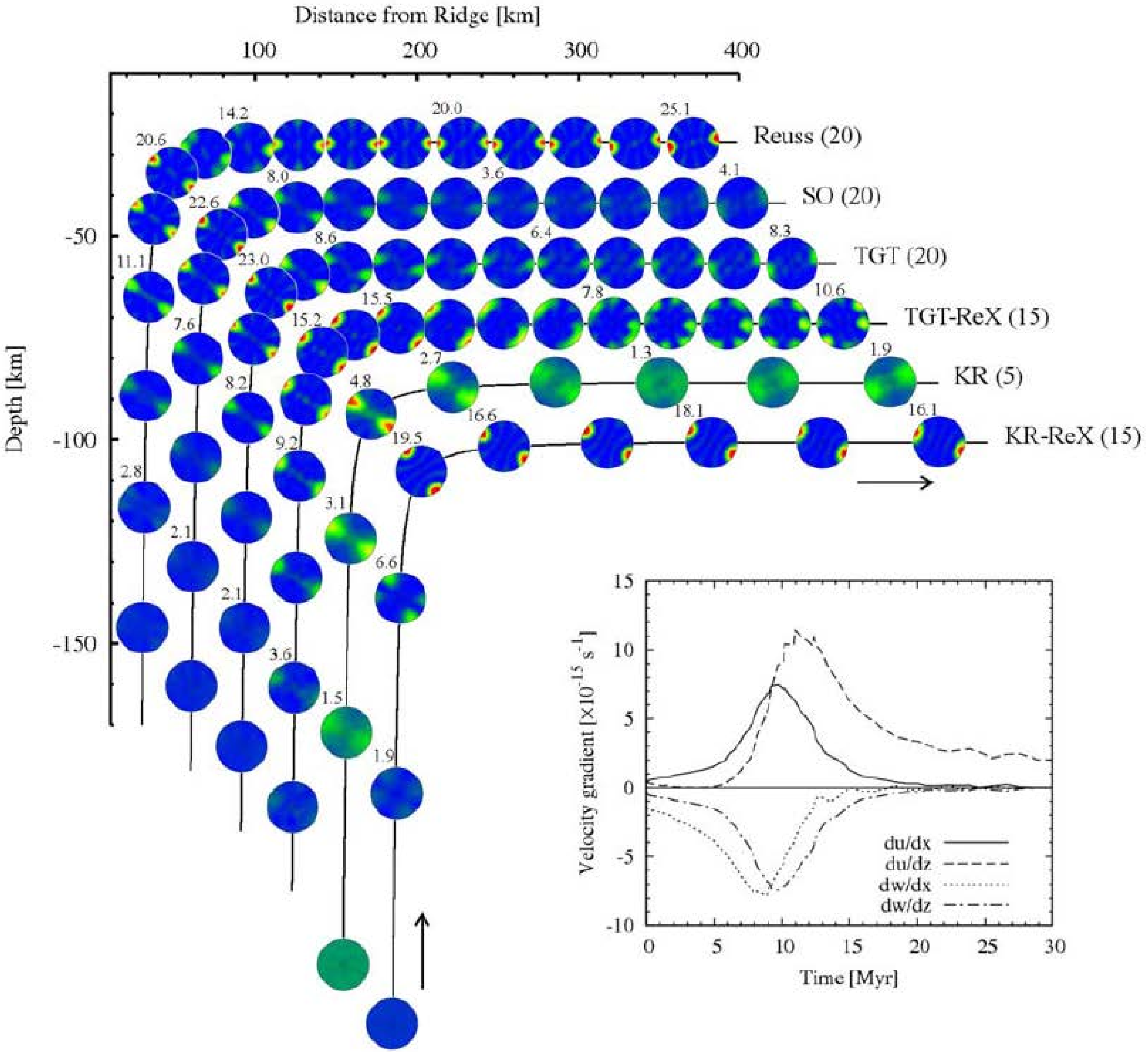
McKenzie (1979)

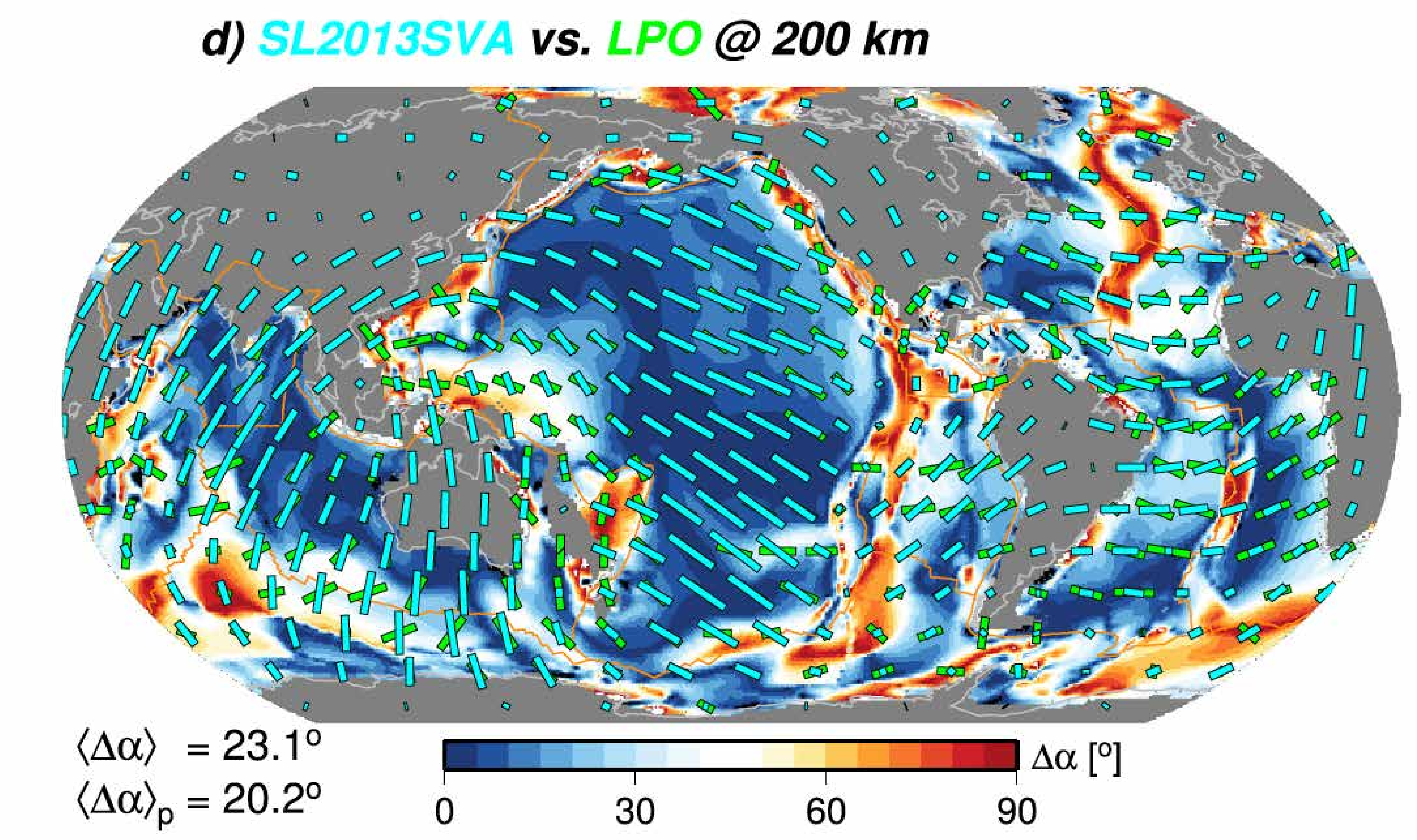


Geophys. J. R. astr. Soc. (1979) **58**, 689–715

Finite deformation during fluid flow

Dan McKenzie *Department of Geodesy and Geophysics, Madingley Rise, Madingley Road, Cambridge CB3 0EZ*

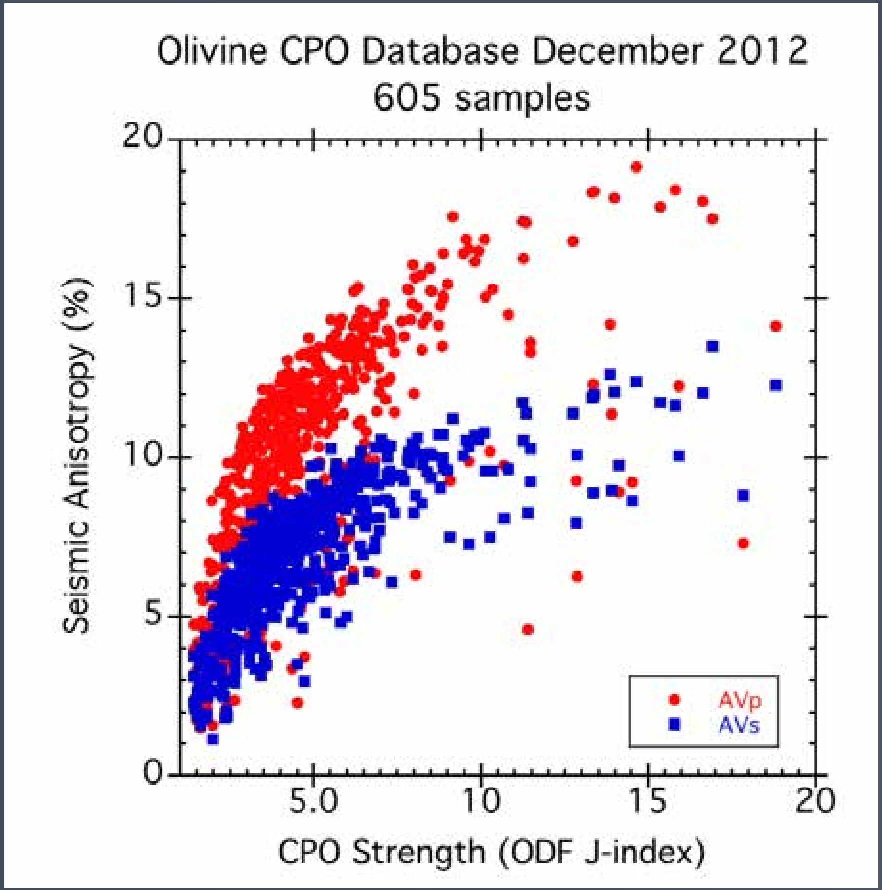

Distance from Ridge [km]
100
200
300
400
Depth [km]
-50
-100
-150
Reuss (20)
SO (20)
TGT (20)
TGT-ReX (15)
KR (5)
KR-ReX (15)
14.2
20.0
25.1
20.6
8.0
3.6
4.1
22.6
8.6
6.4
8.3
11.1
23.0
15.5
7.8
10.6
7.6
15.2
2.7
1.3
1.9
8.2
4.8
16.6
18.1
16.1
9.2
19.5
2.8
3.1
2.1
6.6
2.1
3.6
1.5
1.9
Velocity gradient [$\times 10^{-15}$ s^{-1}]
Time [Myr]
15
10
5
0
-5
-10
0
5
10
15
20
25
30
du/dx
du/dz
dw/dx
dw/dz

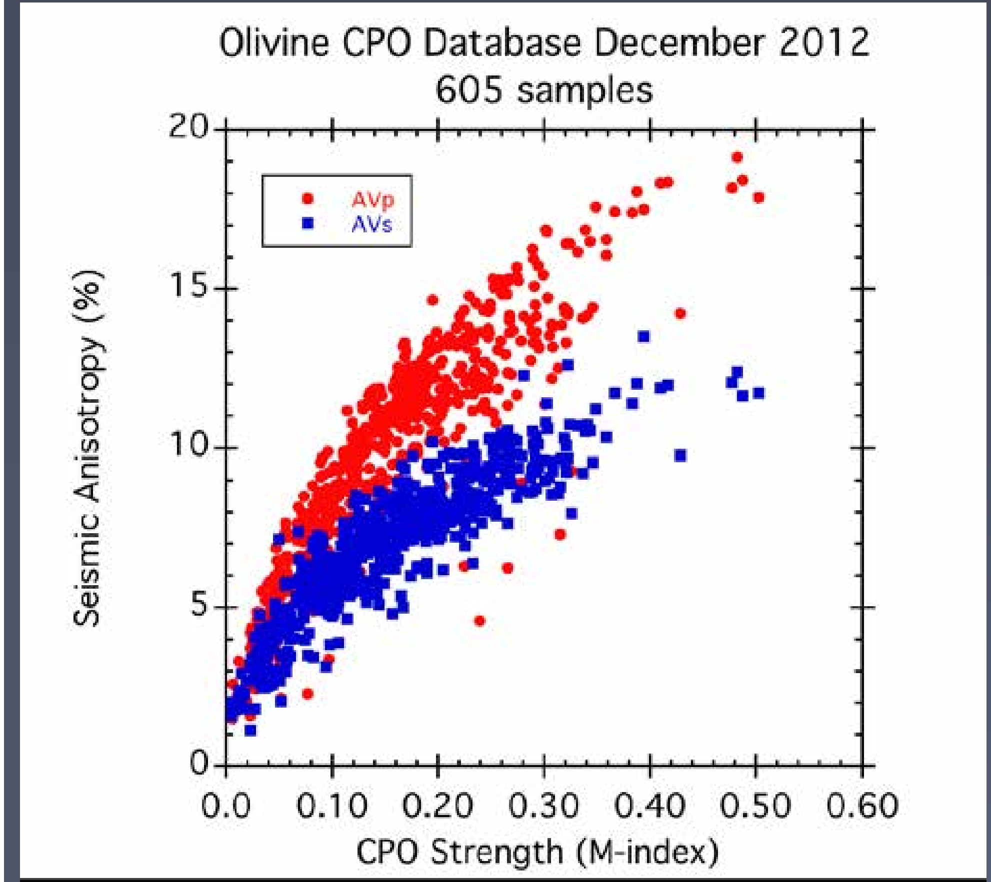


Becker et al. (2014)

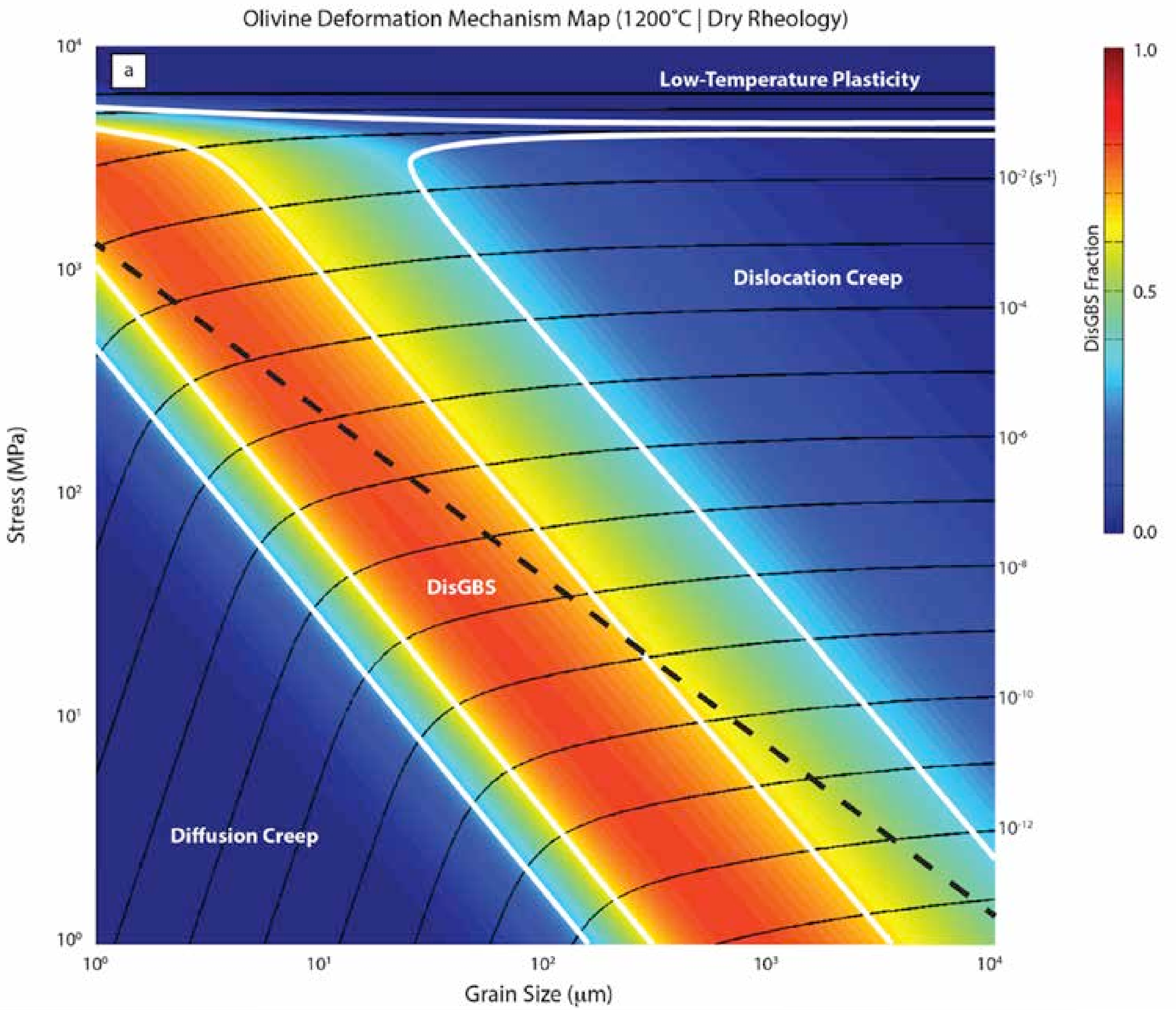
🟦 = good fit between surface wave anisotropy and LPO

🟥 = poor fit between surface wave anisotropy and LPO


Olivine CPO Database December 2012
605 samples
Seismic Anisotropy (%)
0
5
10
15
20
5.0
10
15
20
CPO Strength (ODF J-index)
● AVp
■ AVs


Olivine CPO Database December 2012
605 samples
Seismic Anisotropy (%)
0
5
10
15
20
0.0
0.10
0.20
0.30
0.40
0.50
0.60
CPO Strength (M-index)
● AVp
■ AVs

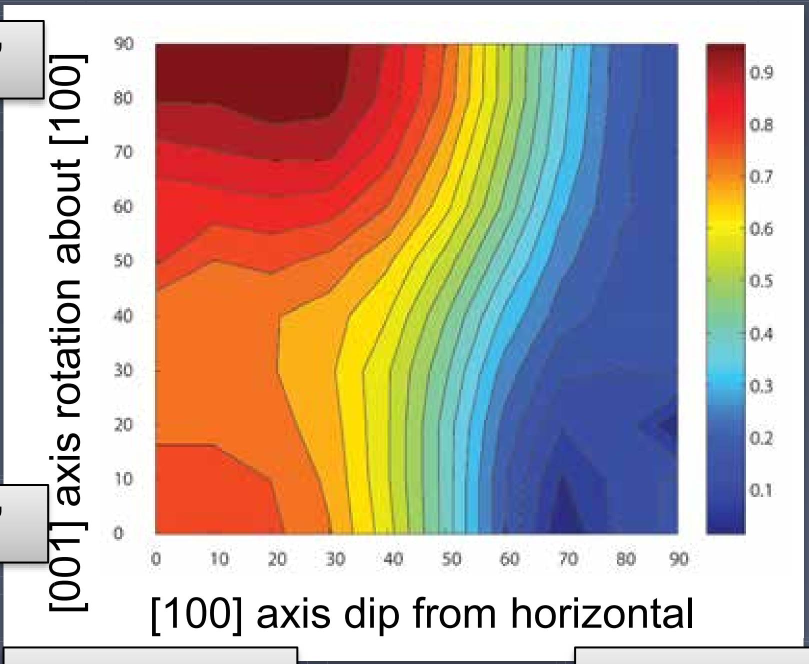
D. Mainprice


Olivine Deformation Mechanism Map (1200˚C | Dry Rheology)
a
Low-Temperature Plasticity
Dislocation Creep
DisGBS
Diffusion Creep
Stress (MPa)
10^4
10^3
10^2
10^1
10^0
Grain Size (μm)
10^0
10^1
10^2
10^3
10^4
10^{-2} (s^{-1})
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
DisGBS Fraction
1.0
0.5
0.0

For **horizontal shear** and a vertically incident wave:

- Delay times depend strongly on the dip of the LPO.
- Polarization direction does not vary significantly except for extremely steeply dipping structures (where magnitude of splitting is small).

Relative Delay Times for an Olivine Polycrystal



"E-type"

"A-type"

Shallow Dip

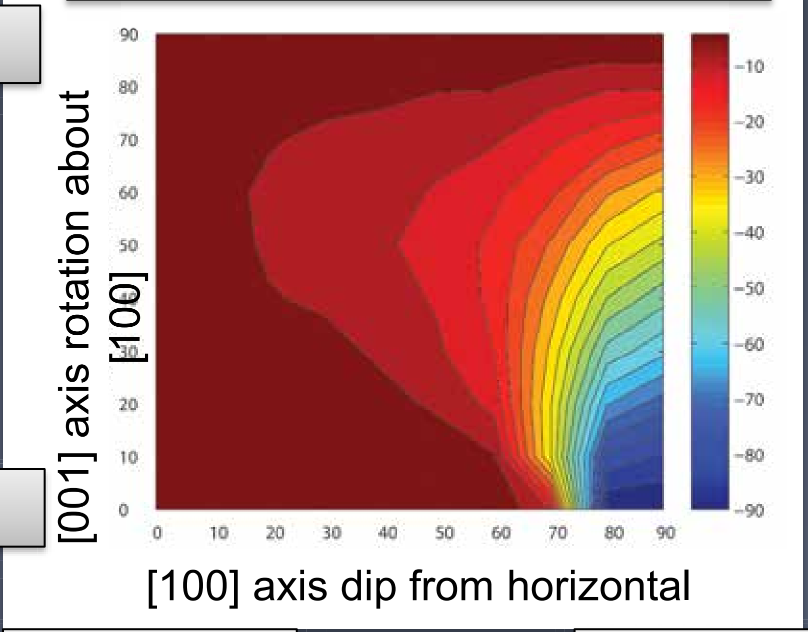
Steep Dip

Skemer et al (2012)

For **horizontal shear** and a vertically incident wave:

- Delay times depend strongly on the dip of the LPO.
- Polarization direction does not vary significantly except for extremely steeply dipping structures (where magnitude of splitting is small).

Deviation of Polarization Direction from [100] Axis Azimuth



“E-type”

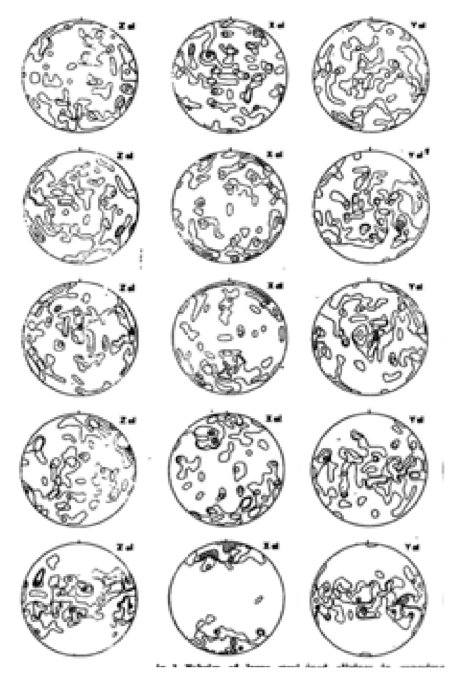
“A-type”

Shallow Dip

Steep Dip

Skemer et al (2012)

[100] [010] [001]

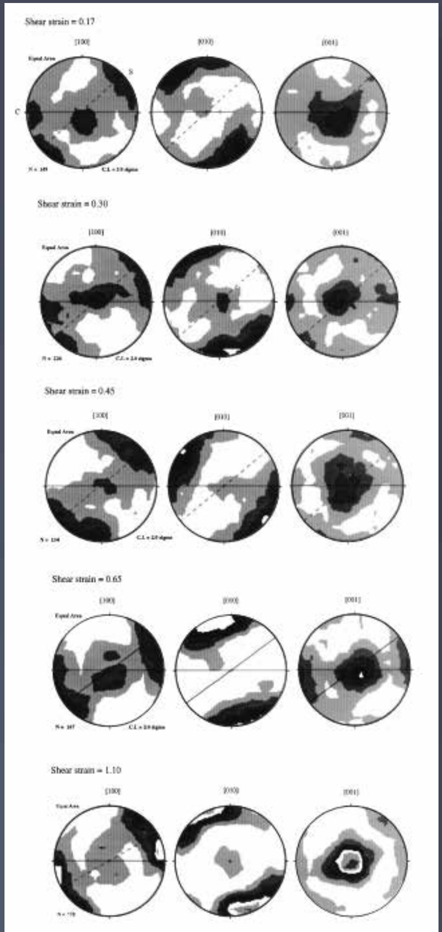


$\varepsilon = 0$

$\varepsilon = 0.58$

Nicolas et al. (1973)

[100] [010] [001]



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$\gamma = 0.17$

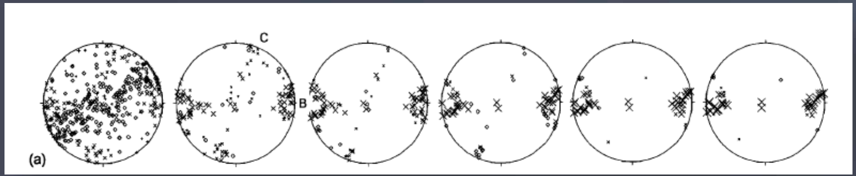
$\gamma = 1.10$

Zhang and Karato (1995)
Zhang et al. (2000)

$\gamma = 0.4$

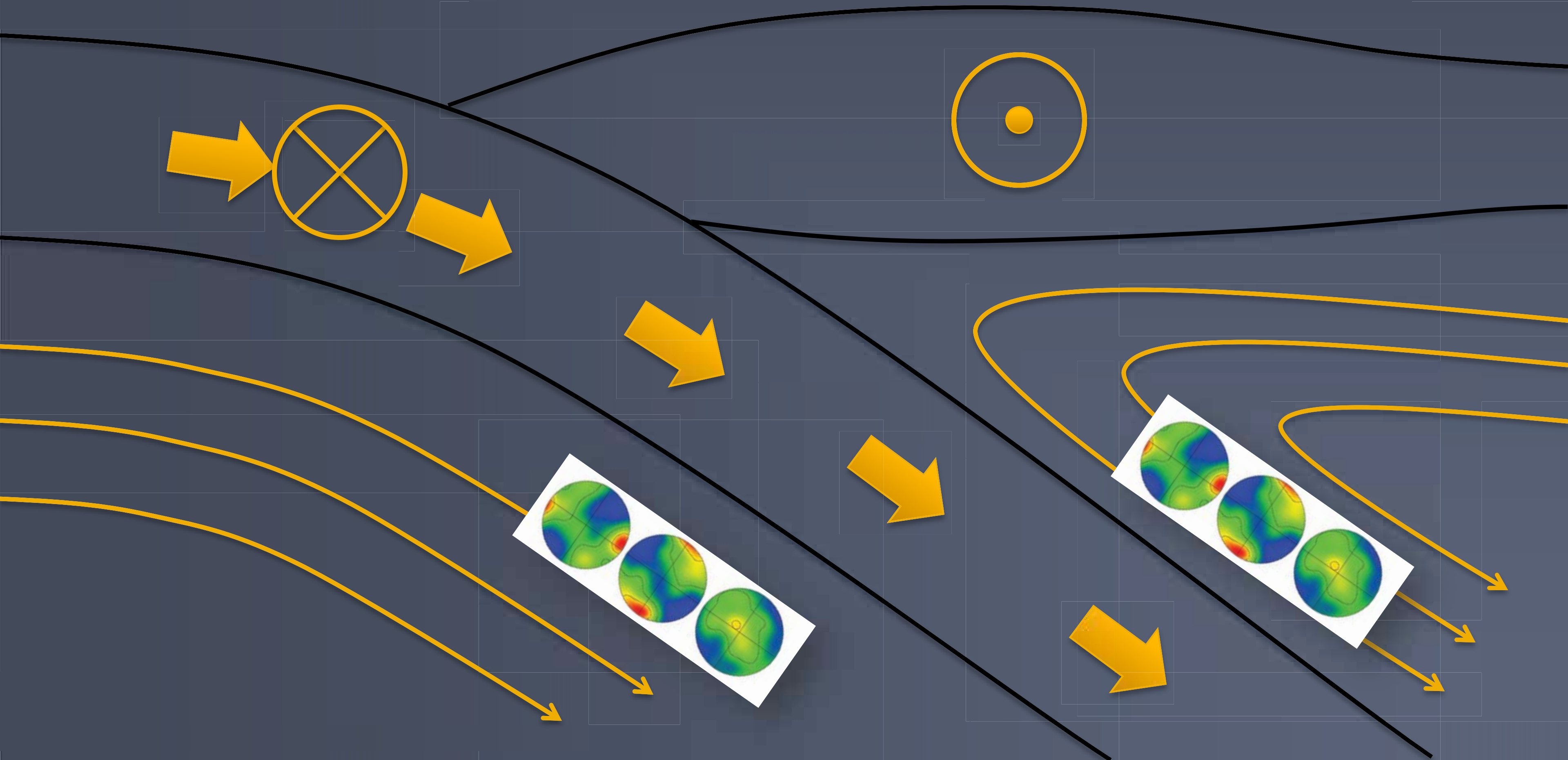
$\gamma = 1.5$

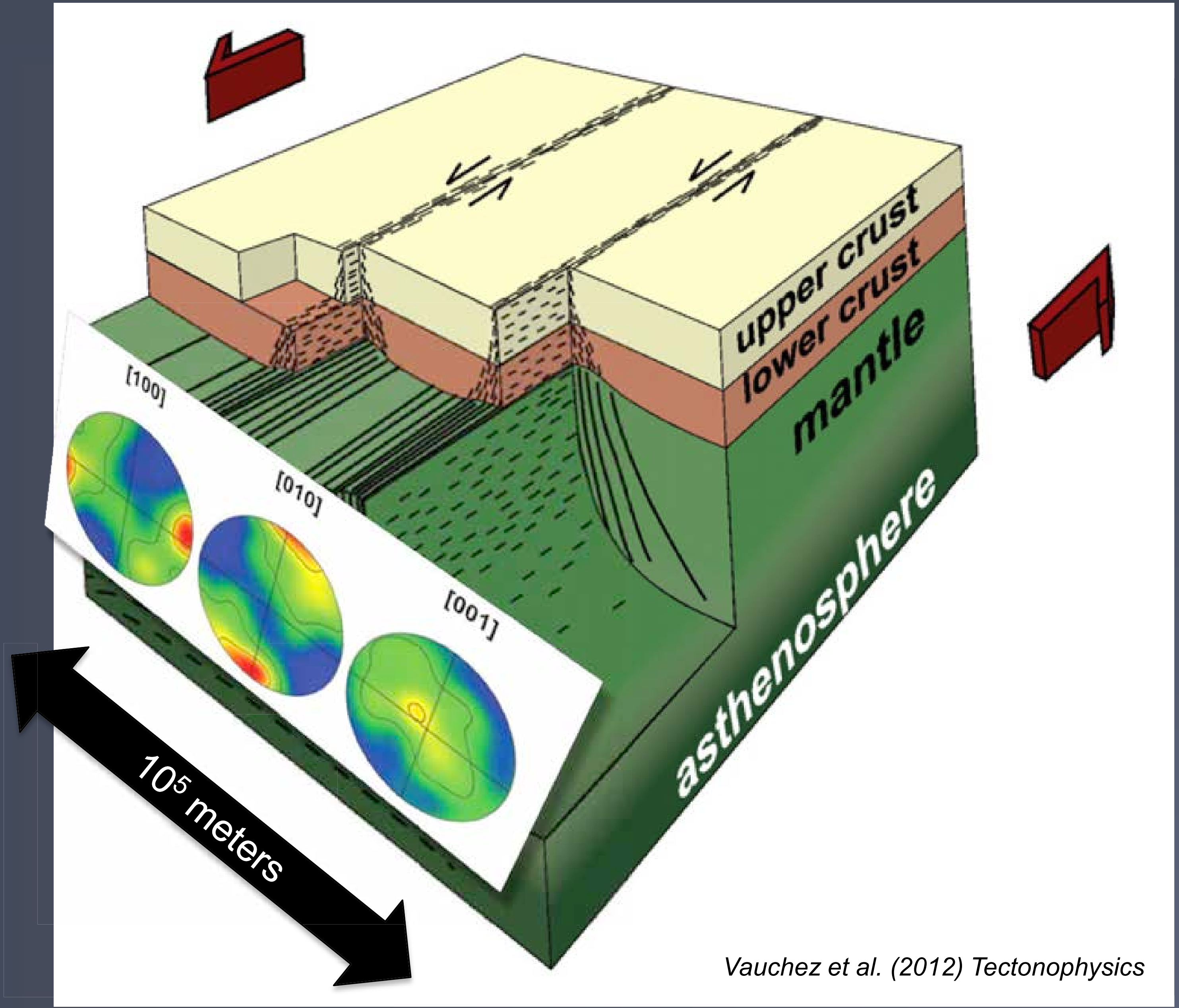
[100]



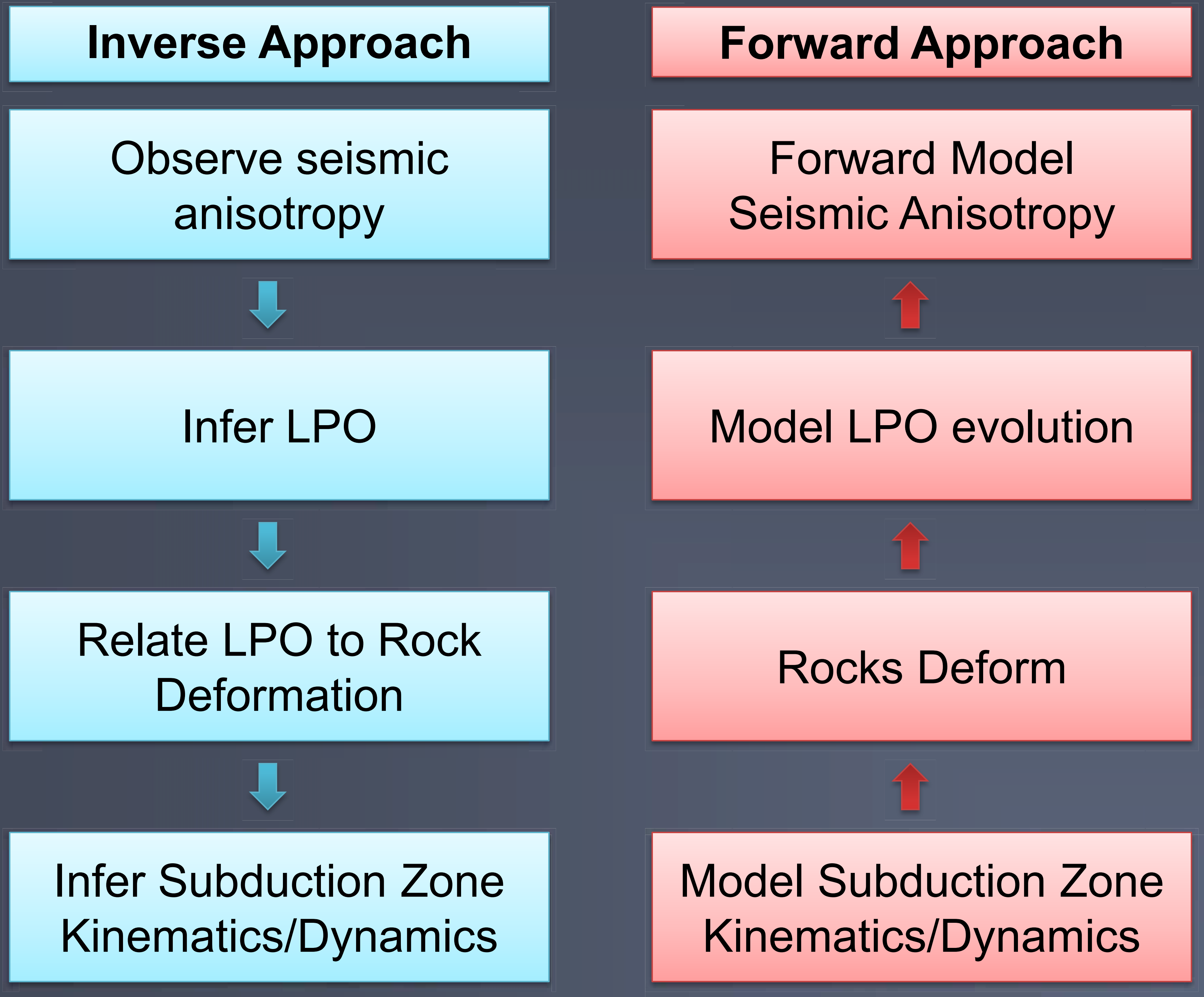
Wenk and Tomé (1999)

Issue #1: The Effects of Deformation History





Vauchez et al. (2012) Tectonophysics



Inverse Approach

Observe seismic anisotropy

Infer LPO

Relate LPO to Rock Deformation

Infer Subduction Zone Kinematics/Dynamics

Forward Approach

Forward Model Seismic Anisotropy

Model LPO evolution

Rocks Deform

Model Subduction Zone Kinematics/Dynamics