CRYSTAL2PLATE

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

MARIE CURIE ACTIONS

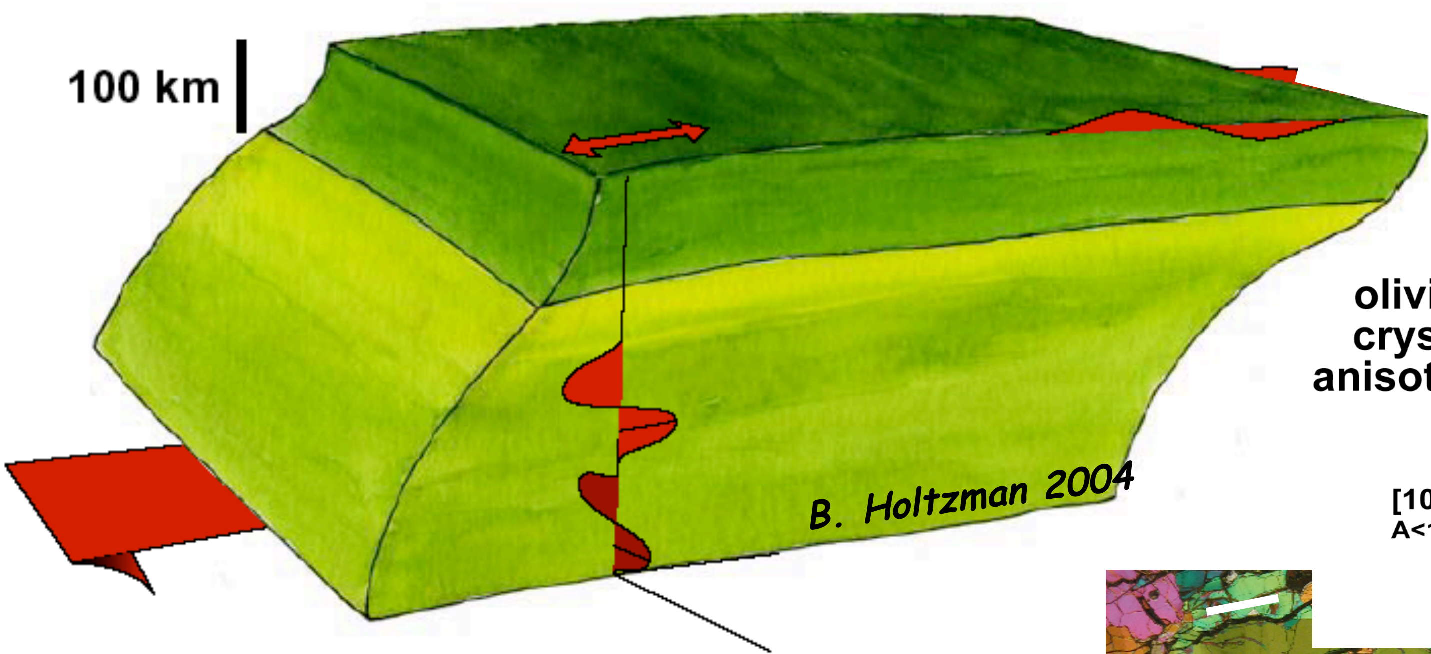
Numerical models of CPO evolution…

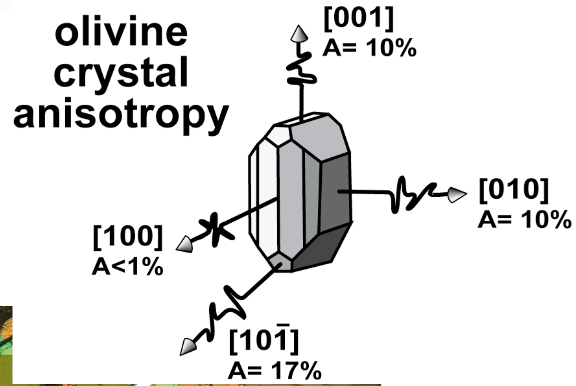
Andréa Tommasi

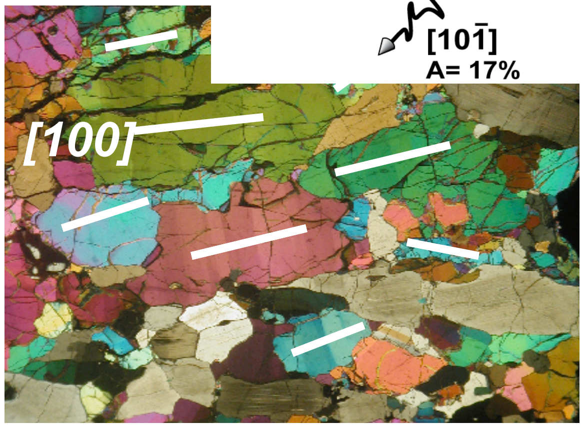
Short course on "Microstructures, textures & anisotropy"
Geosciences Montpellier (F) - 28 June - 2 July, 2010

Géosciences Montpellier

how do we "see" mantle deformation?







fast seismic axis = flow direction

P & Rayleigh propagation,
S-wave polarisation

Can we go farther? Quantify the anisotropy produced by mantle flow at different depths or geodynamic environments (ridges, subduction zones...)

Multi-scale models of mantle deformation and seismic anisotropy

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 98, NO. B10, PAGES 17,757–17,771, OCTOBER 10, 1993

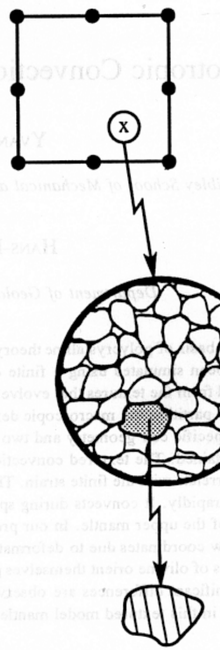
Anisotropic Convection With Implications for the Upper Mantle

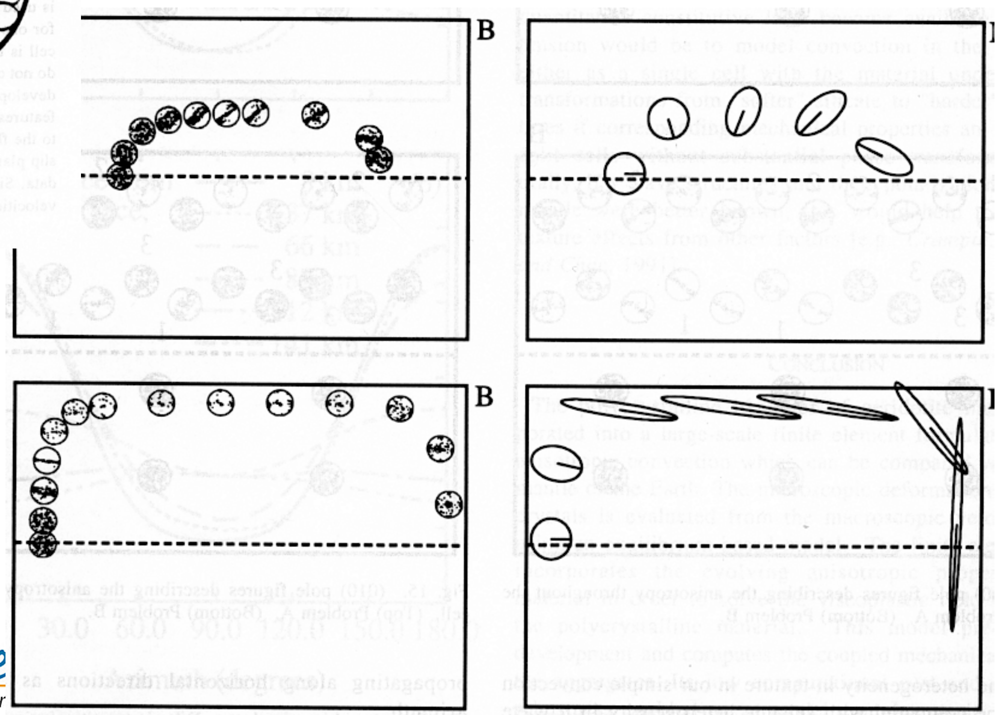
Yvan B. Chastel and Paul R. Dawson

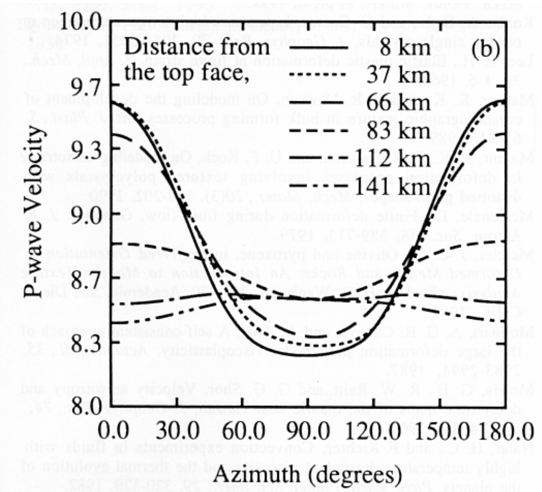
Sibley School of Mechanical and Aerospace Engineering, Cornell University, Ithaca, New York

Hans-Rudolf Wenk and Kristin Bennett

Department of Geology and Geophysics, University of California, Berkeley





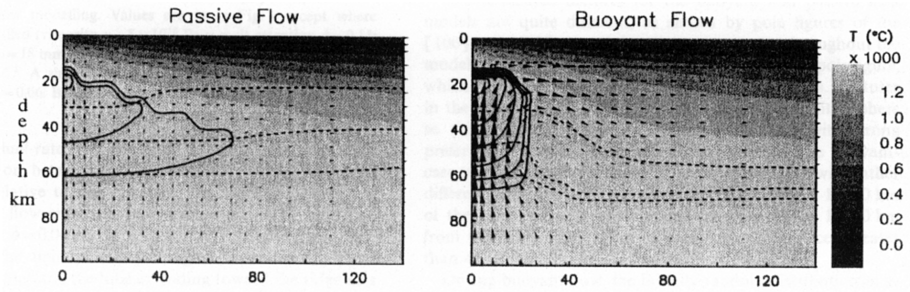


Multi-scale models of mantle deformation and seismic anisotropy

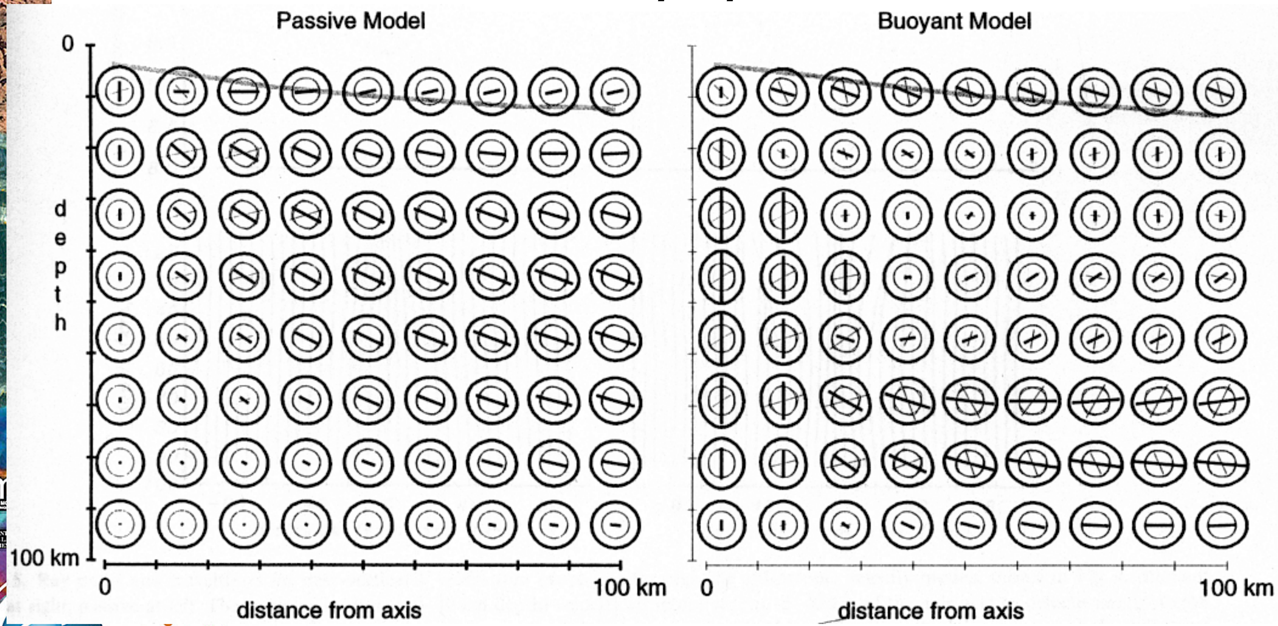
Teleseismic imaging of subaxial flow at mid-ocean ridges: traveltime effects of anisotropic mineral texture in the mantle

Donna K. Blackman,[1] J.-Michael Kendall,[2,*] Paul R. Dawson,[3] H.-Rudolgh Wenk,[4] Donald Boyce[3] and Jason Phipps Morgan[1]
[1] IGPP, Scripps Institution of Oceanography, La Jolla, CA 92093-0225, USA
[2] Department of Physics, University of Toronto, Toronto, Ontario, Canada
[3] Sibley School of Mechanical & Aerospace Engineering, Cornell University, Ithaca, NY 14853-7501, USA
[4] Department of Geology & Geophysics, University of California, Berkeley, CA 94720, USA

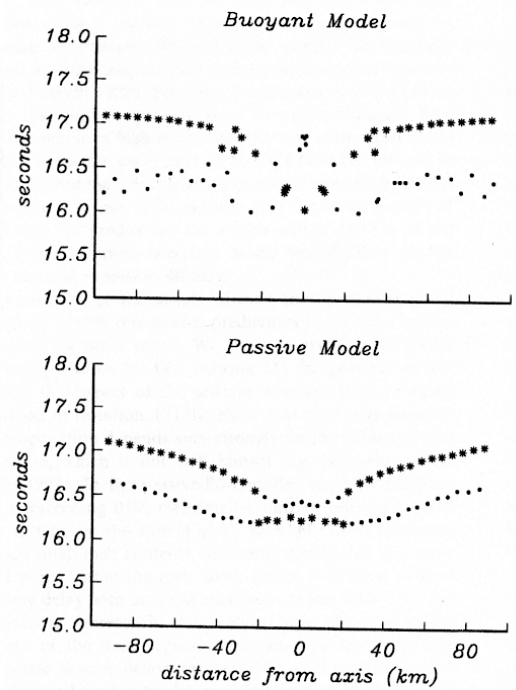
mantle flow modeling



seismic properties

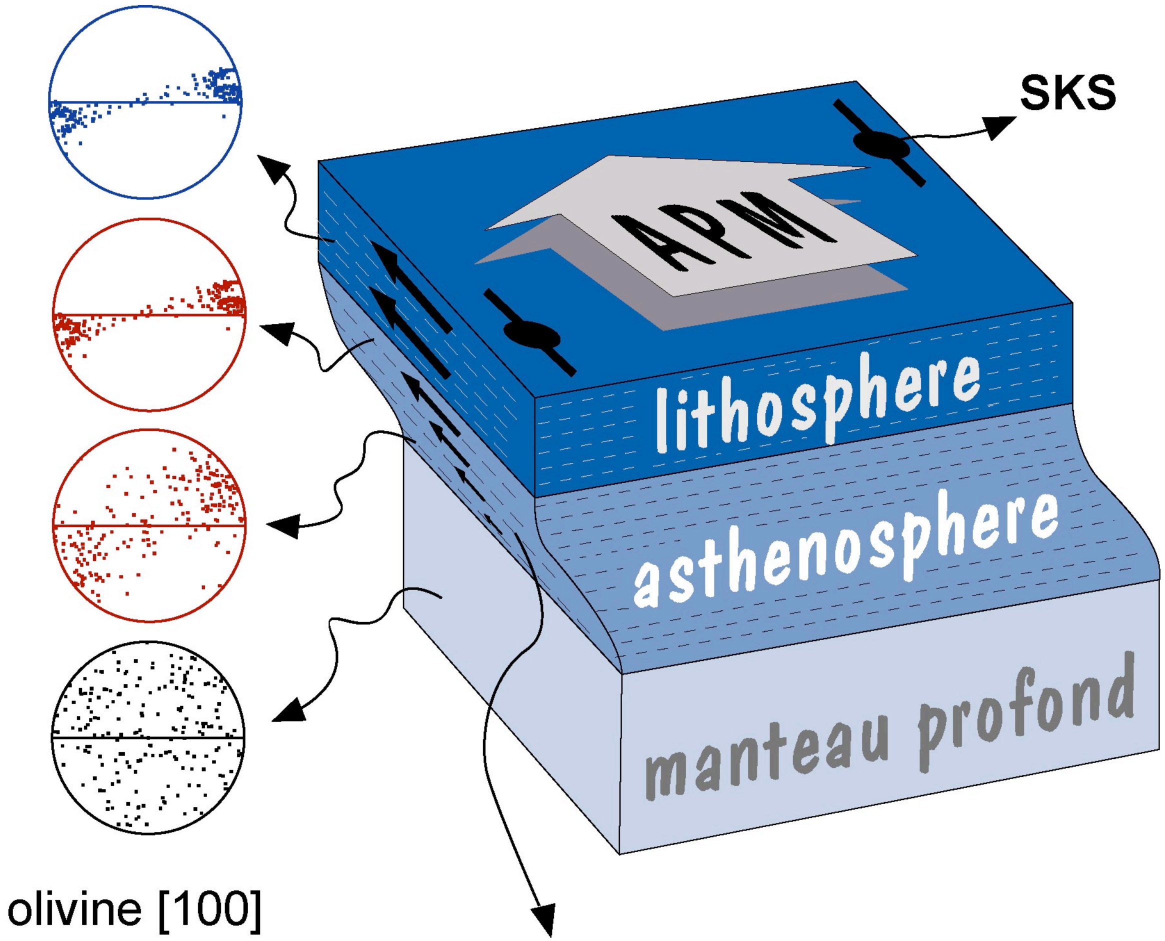


s



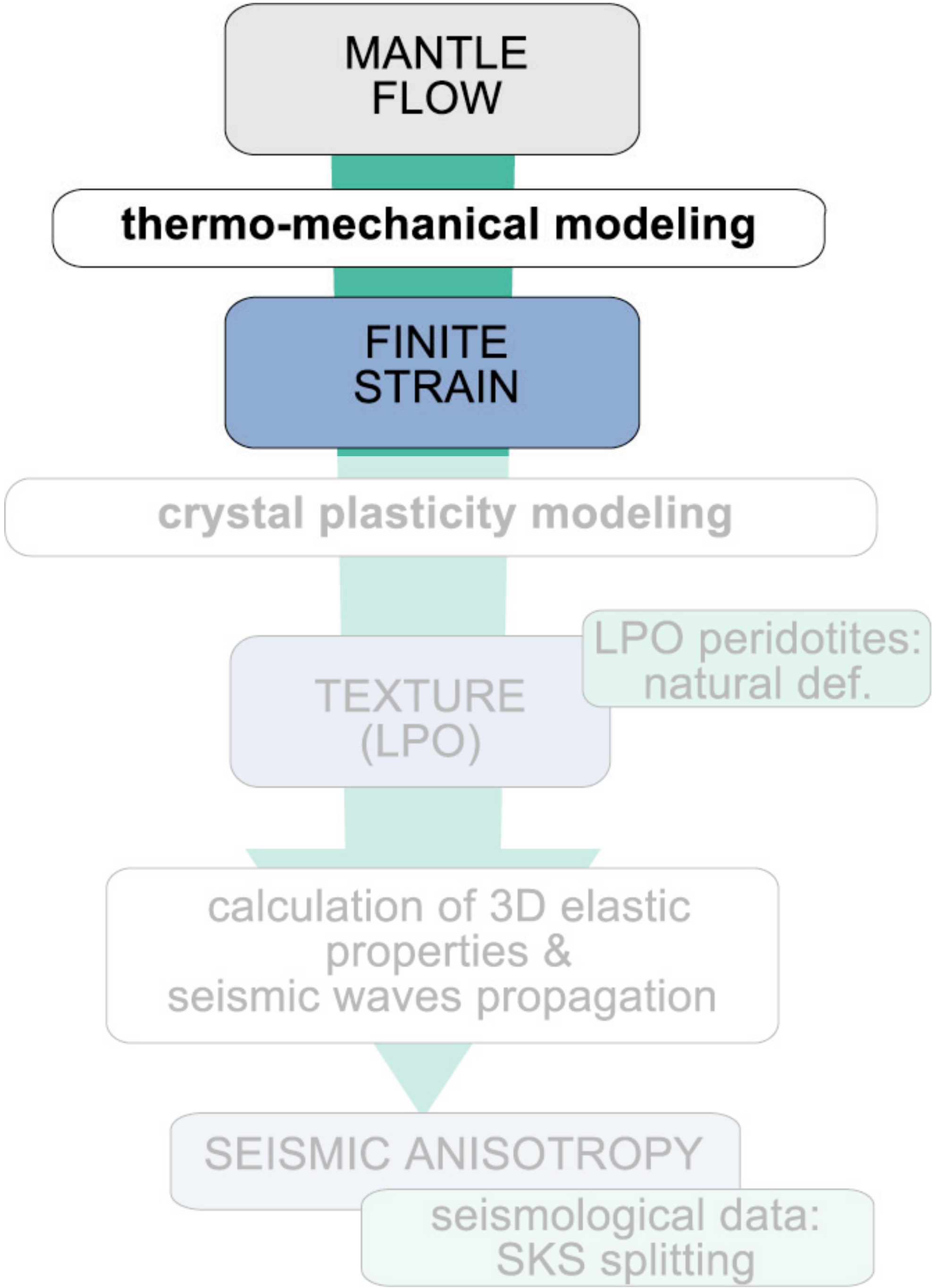
Blackman et al. 1996 Geophys. J. Intern.127: 415-426

Seismic anisotropy in oceanic basins



Strain field: horizontal shear // APM

Tommasi et al. 1995 GRL, Tommasi 1998 EPSL, Rümpker et al. 1999 JGR



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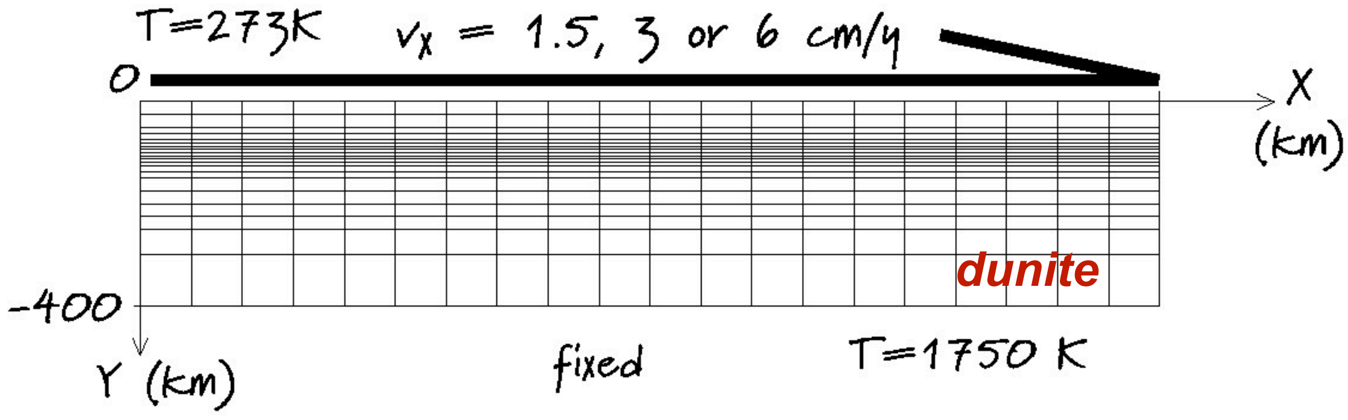
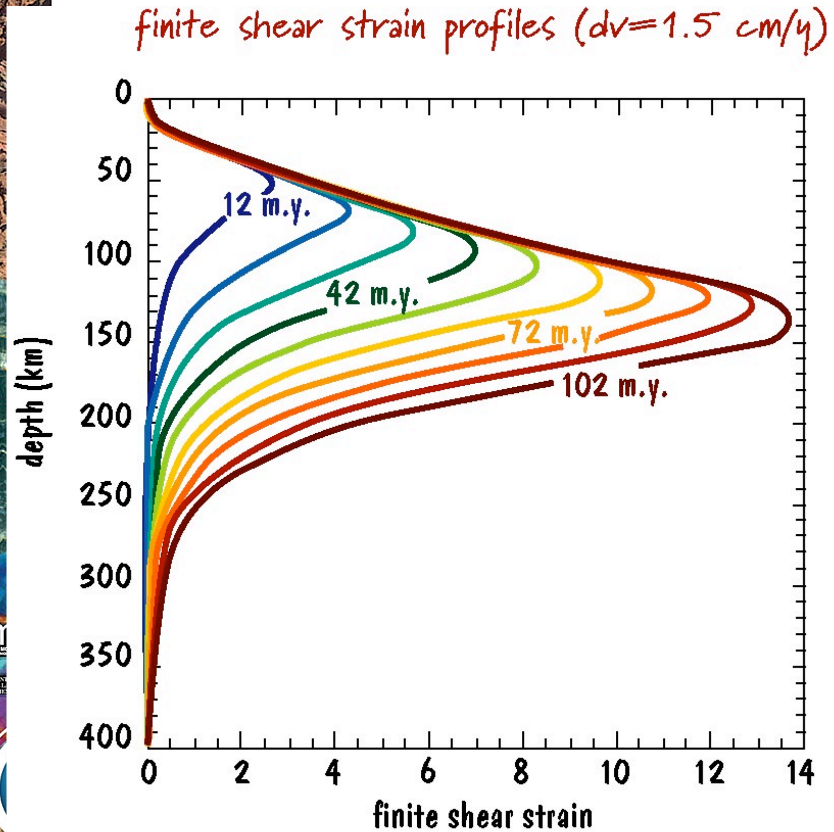
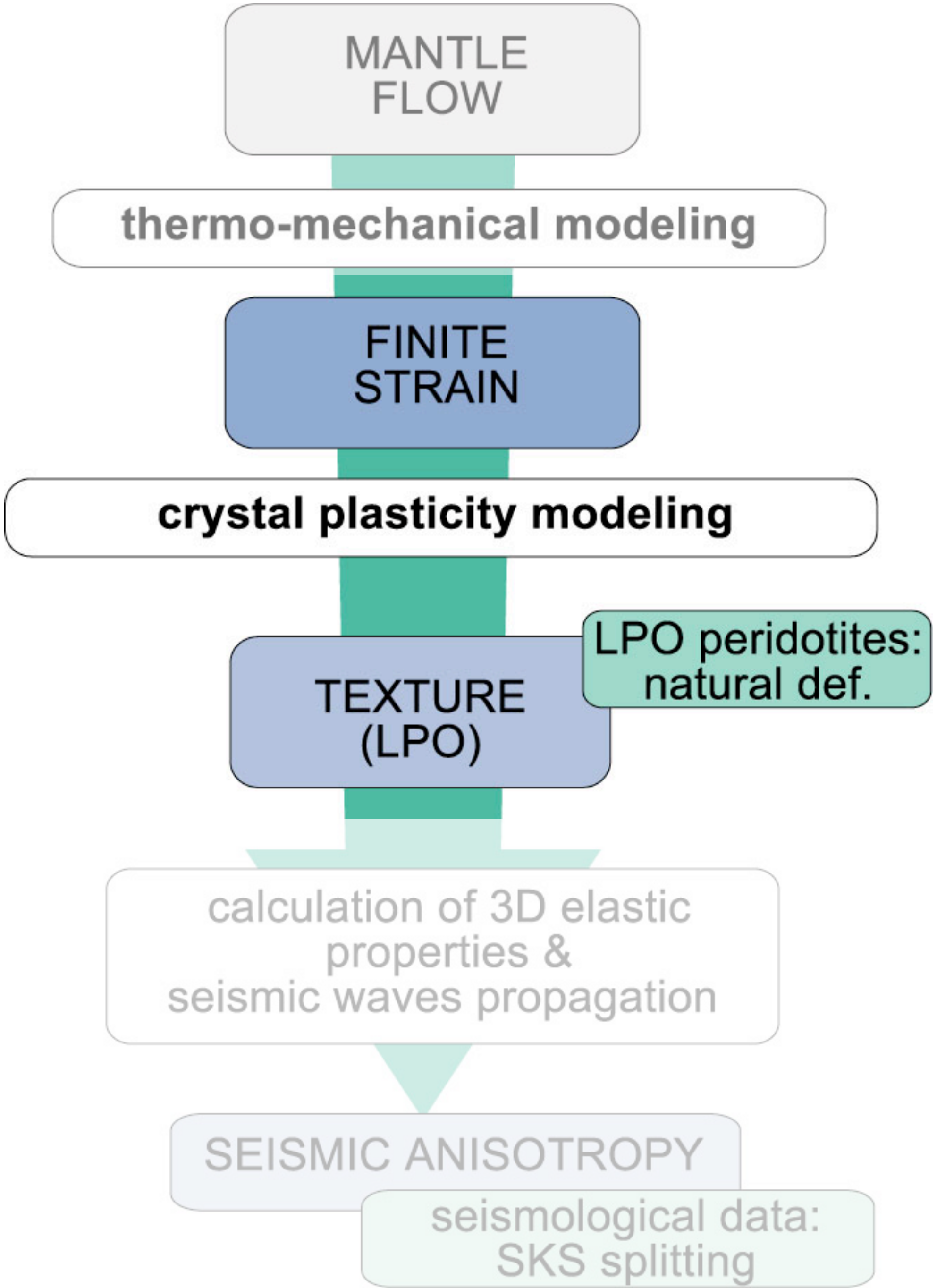




finite strain = $F(v_x, age)$

- ✓ *viscous drag : strain & LPO development in the asthenosphere*
- ✓ *cooling : freezes LPO in the lithosphere*



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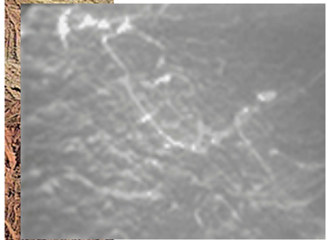
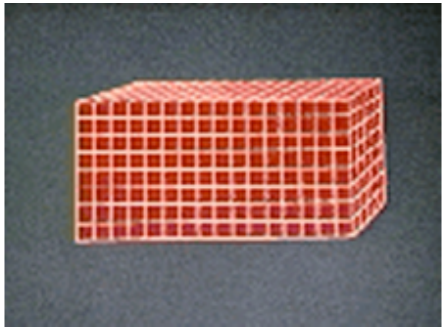
Modeling the deformation & crystal orientation evolution

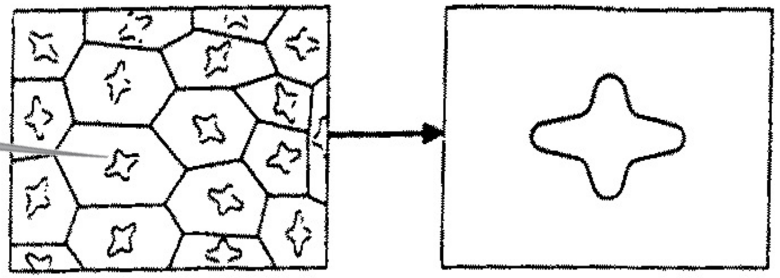
VPSC: Molinari et al. 1987, Lebensohn & Tomé 1993
Drex: Kaminsky & Ribe 2001, 2003

within a grain (crystal):





rock (polycrystal) deformation:



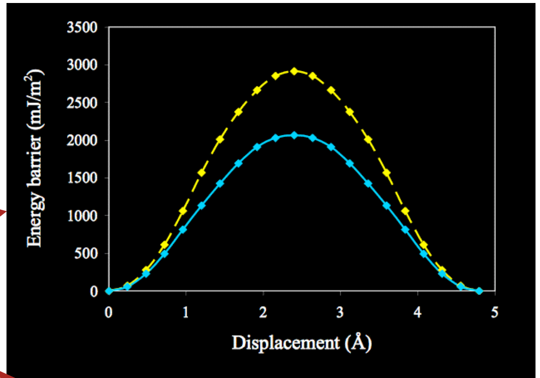
strain = motion of dislocations on well-defined crystal planes & directions

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

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

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

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



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

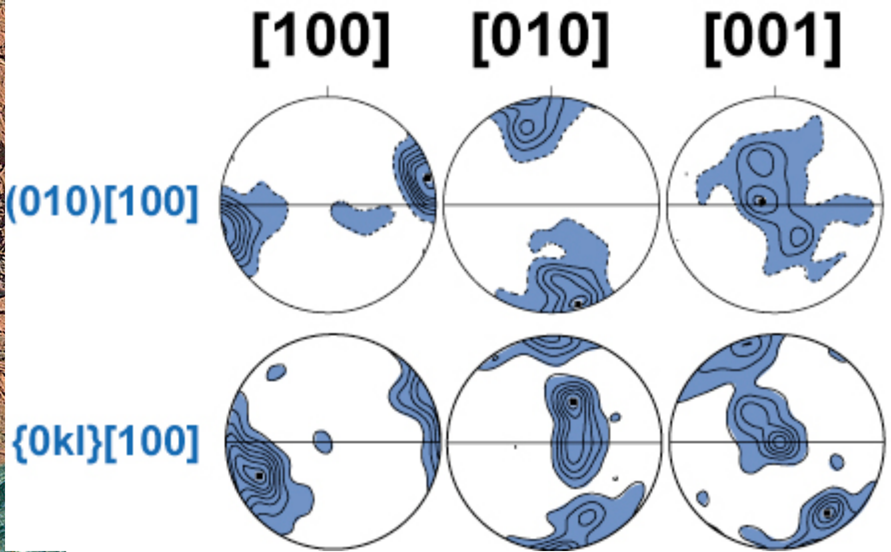
output: evolution of crystallographic orientations and macroscopic response (strain rate or stress tensor)

Olivine CPO:

Naturally deformed peridotites:

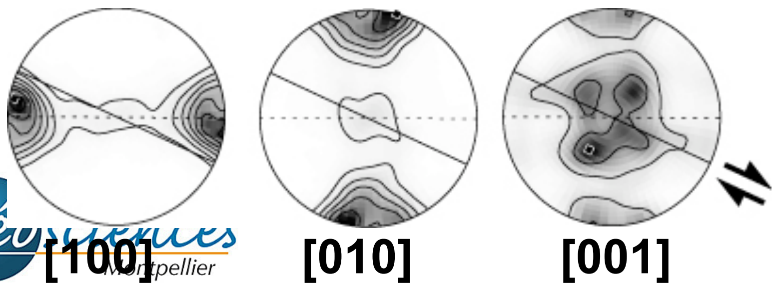
olivine LPO database (Montpellier): >300 samples

~ 80% of the samples



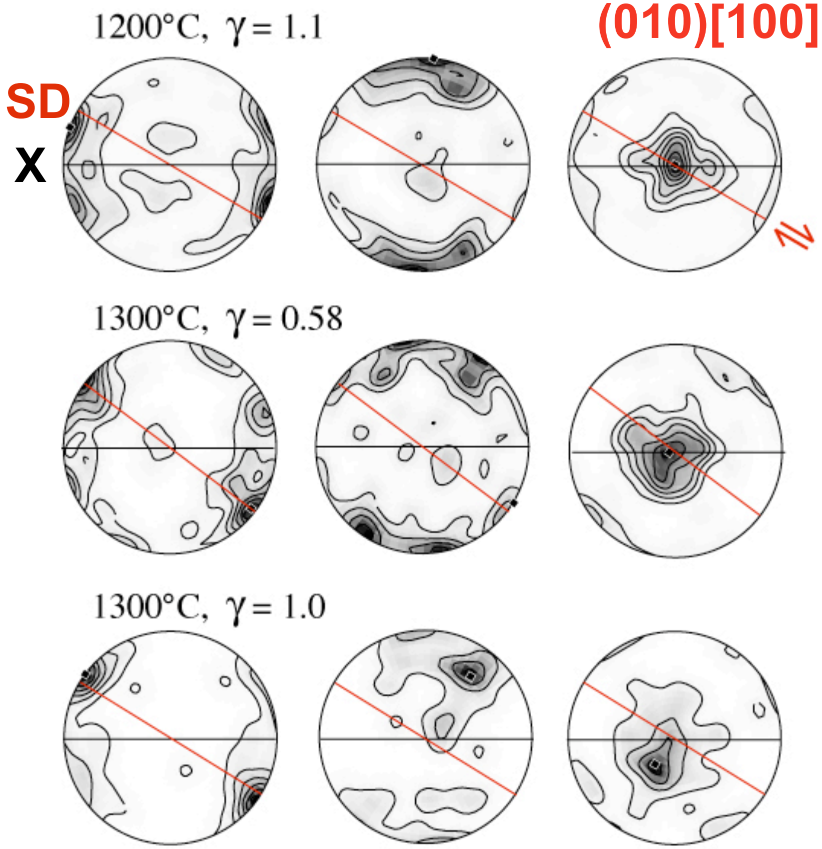
CPO/SPO asymmetry: simple shear

Polycrystal plasticity models:

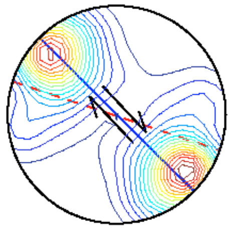


Experimental deformation: simple shear

Zhang & Karato (1995) Nature



dynamic recrystallization: faster reorientation of [100] // SD



Kamisnki & Ribe 2001 EPSL

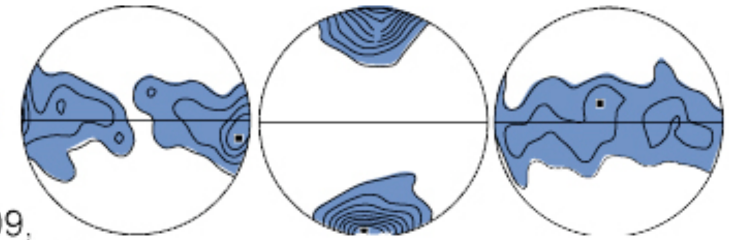
Naturally deformed peridotites

olivine LPO database (Montpellier): >300 samples

20-30% of the samples (continental)

[100] [010] [001]

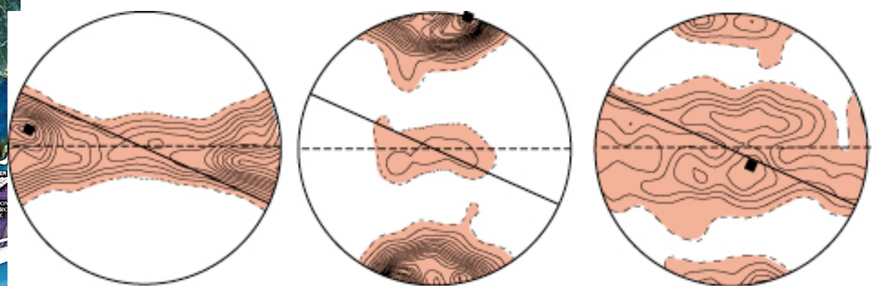
[010] fiber



FRB1309,
kimberlitic xenolith,
Kapvaal craton

axial compression or transpression

Polycrystal plasticity models: transpression



[100] [010] [001]

Experimental deformation: axial compression

Nicolas et al. (1973) Am. J. Sci.

initial LPO

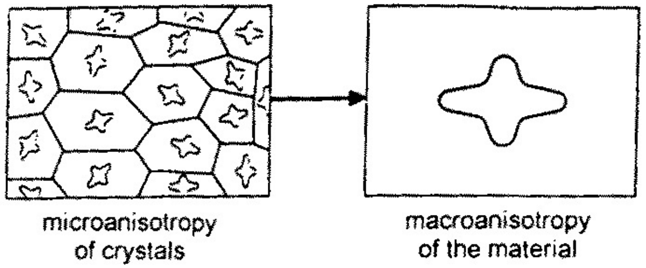
ε_{eq} = 0.58 - porphyroclasts

ε_{eq} = 0.58 - recrystallized grains

[100] [010] [001]

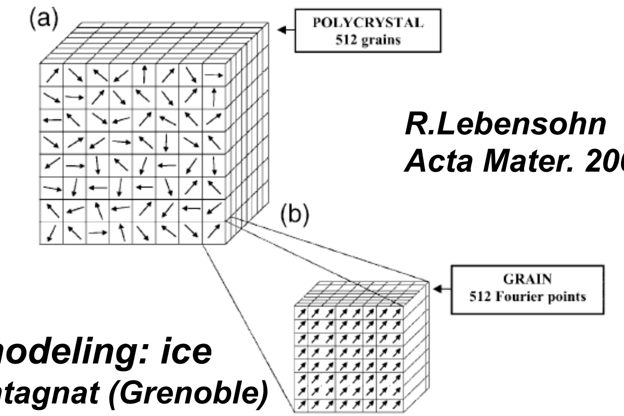
Modeling plastic deformation & development of CPO at the "rock" scale: polycrystalline aggregate

homogeneization models:



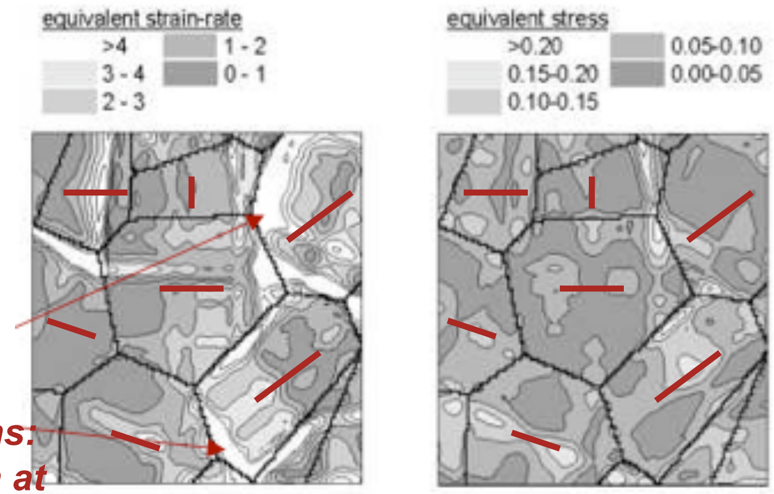
- ***Sachs 1928: stress equilibrium***
- ***Taylor 1938: homogeneous strain***
- ***Lister 1978: Taylor in Earth Sciences***
- ***Molinari et al. 1987: VPSC***
- ***Wenk et al. 1989: VPSC in Earth Sciences***
- ***Ribe & Yu 1991: strain fluctuations min.***
- ***Lebensohn & Tomé 1993: anisotropic SC***
- ***Wenk et al. 1997: VPSC + recrystallization***
- ***Kaminski & Ribe 2001: DRex***

Fast-Fourier Transform



R.Lebensohn
Acta Mater. 2001

FFT modeling: ice
M. Montagnat (Grenoble)
R. Lebensohn



easy glide orientations: high strain at grain boundaries

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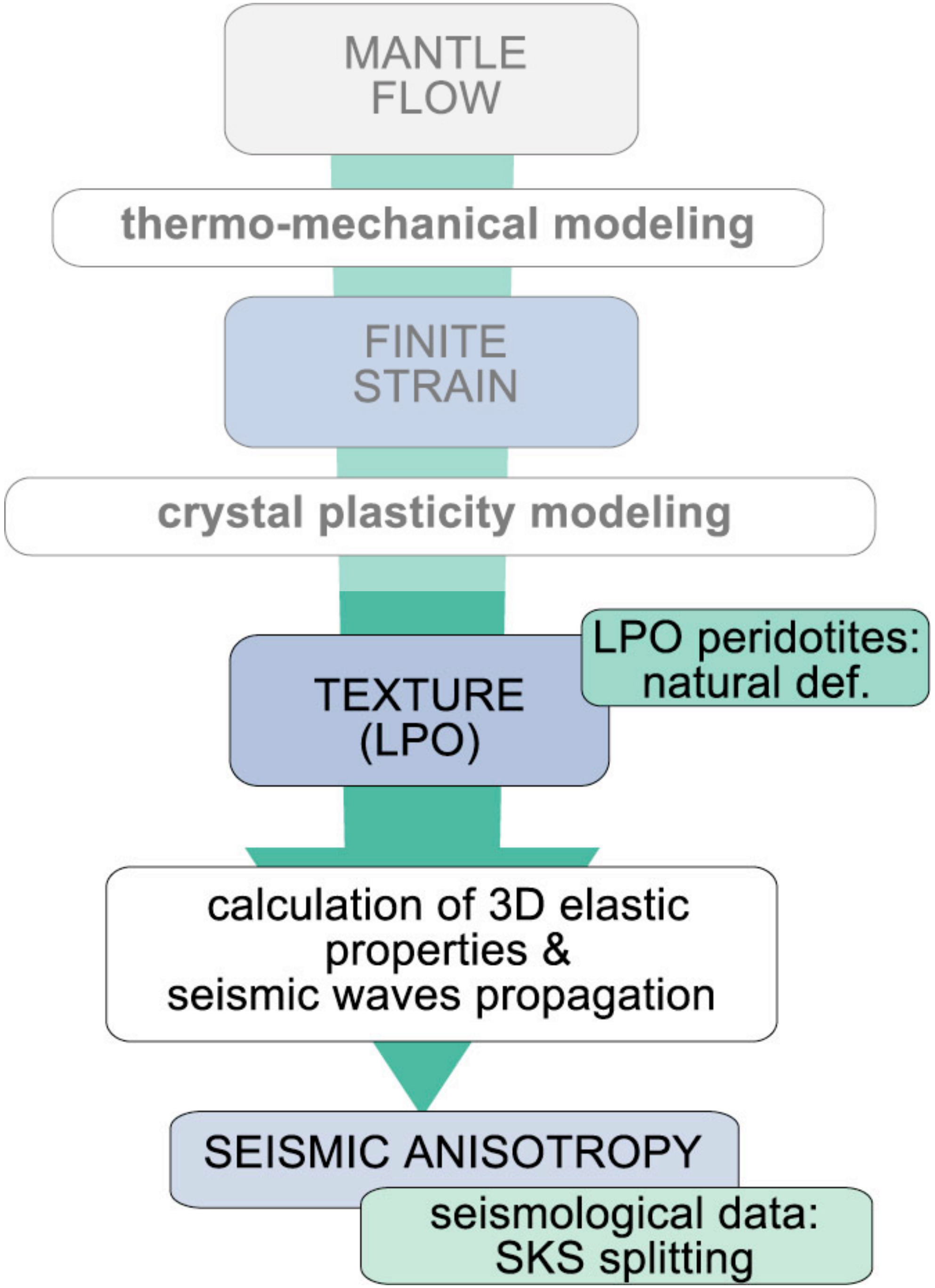
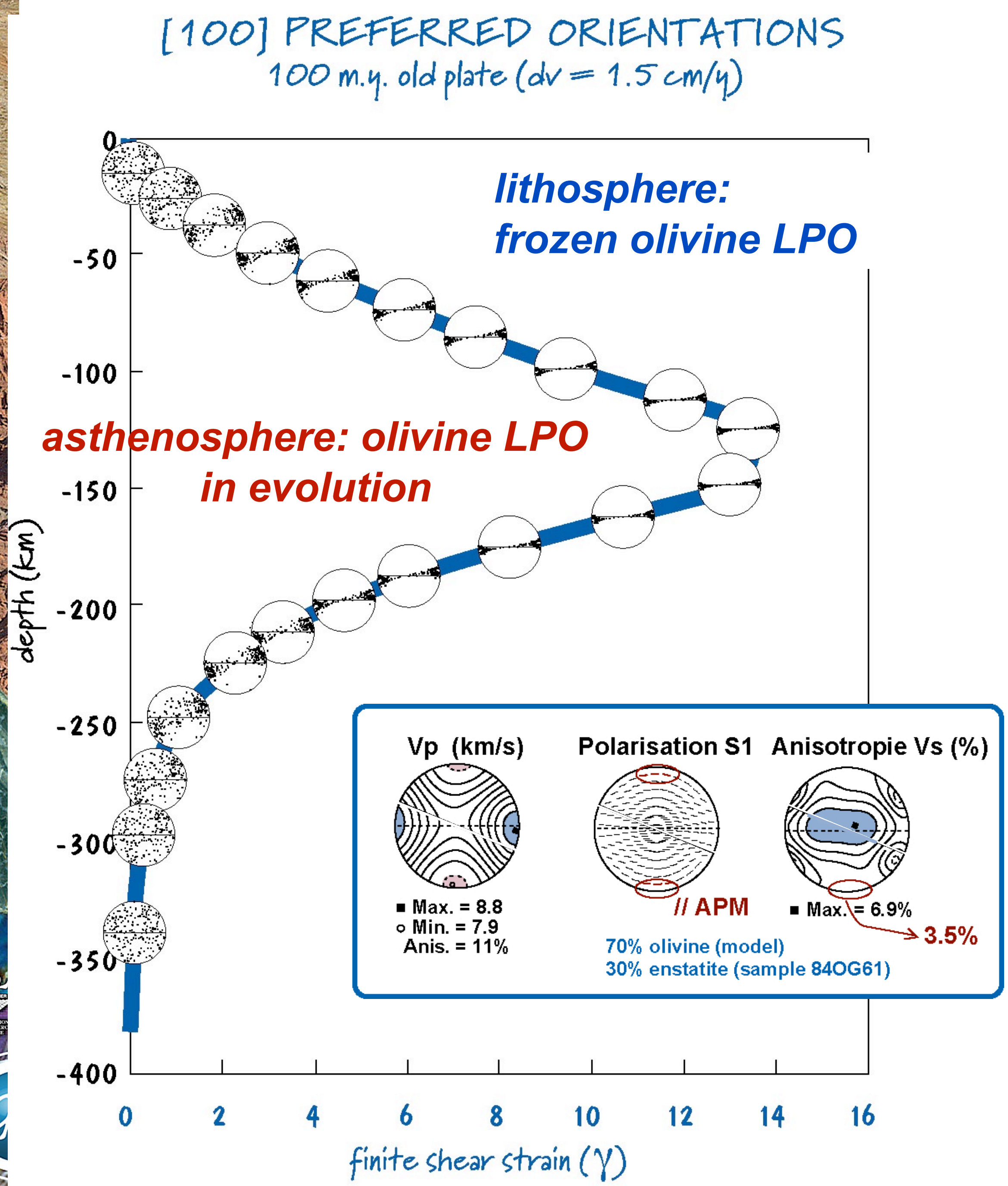
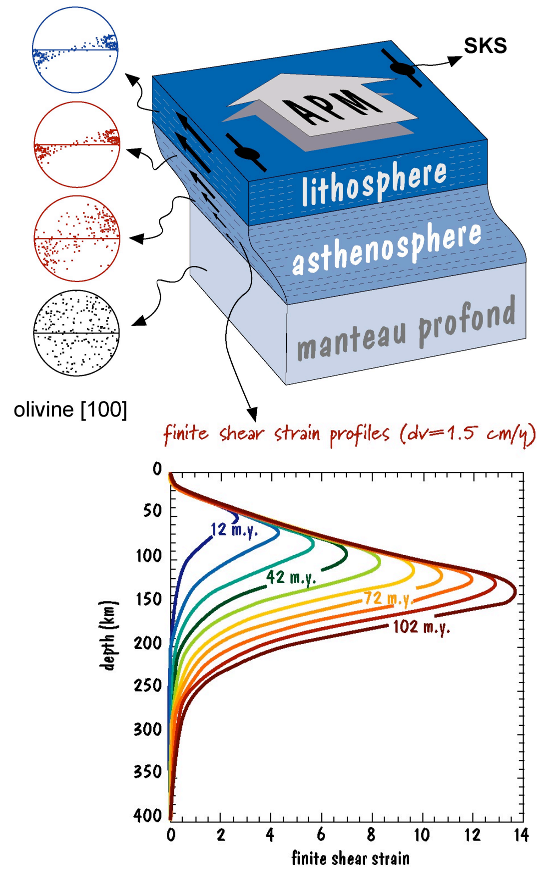

MANTLE FLOW
thermo-mechanical modeling
FINITE STRAIN
crystal plasticity modeling
TEXTURE (LPO)
LPO peridotites: natural def.
calculation of 3D elastic properties &
seismic waves propagation
SEISMIC ANISOTROPY
seismological data: SKS splitting





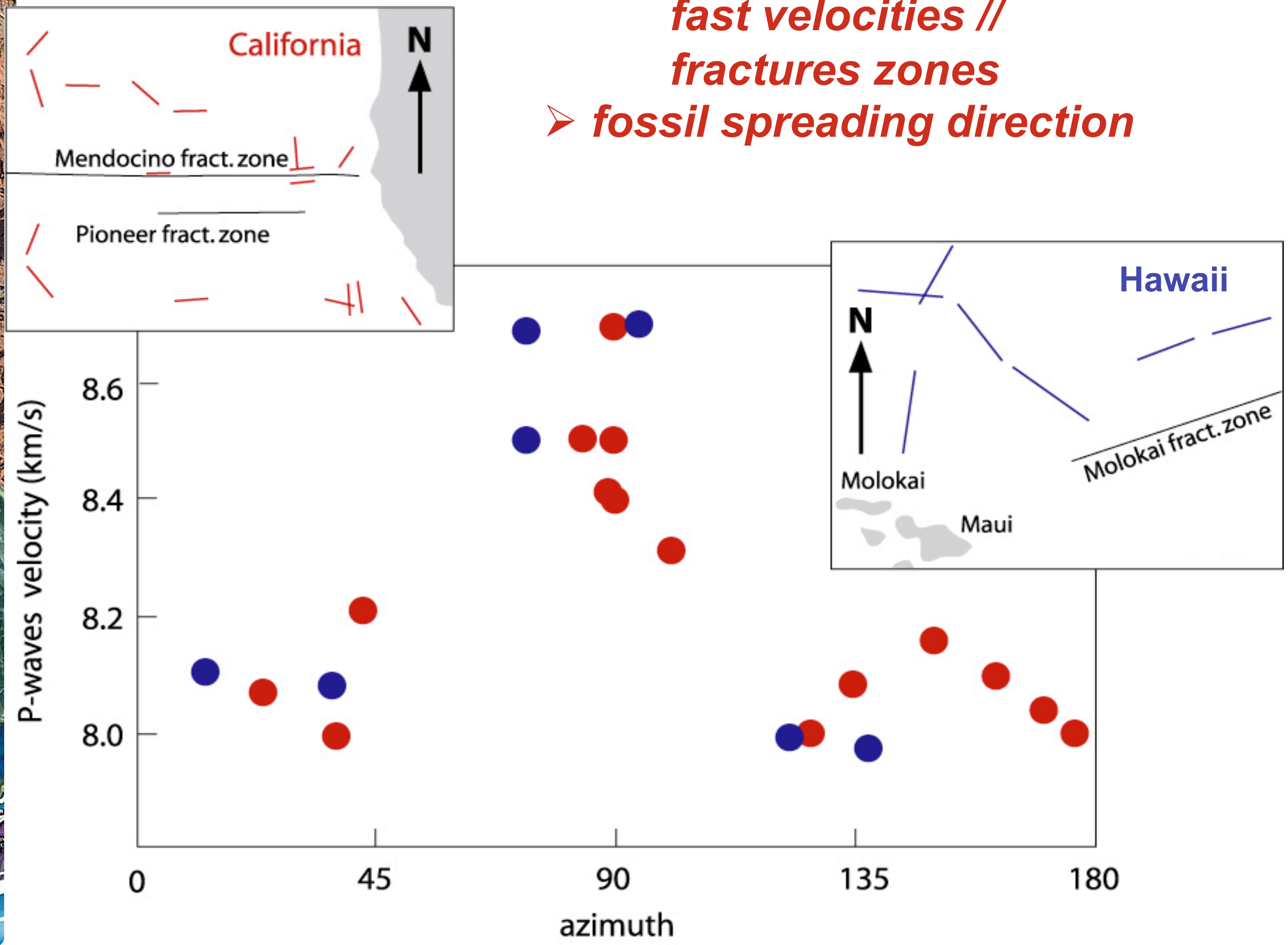
$dt = \int dt_i = 2.3s$

Seismic anisotropy: P waves

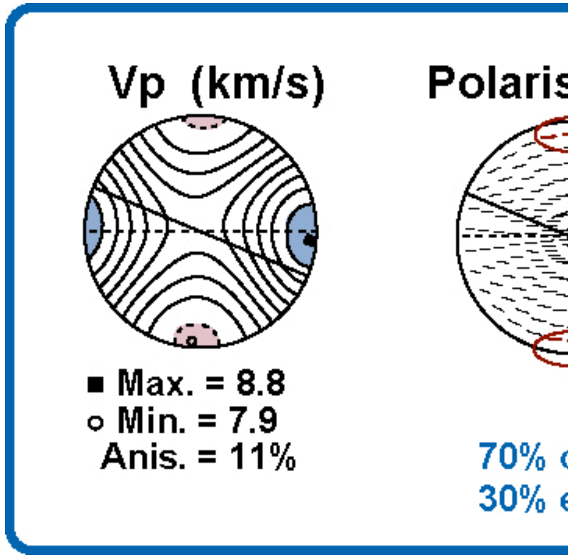
vP = F(propagation direction)

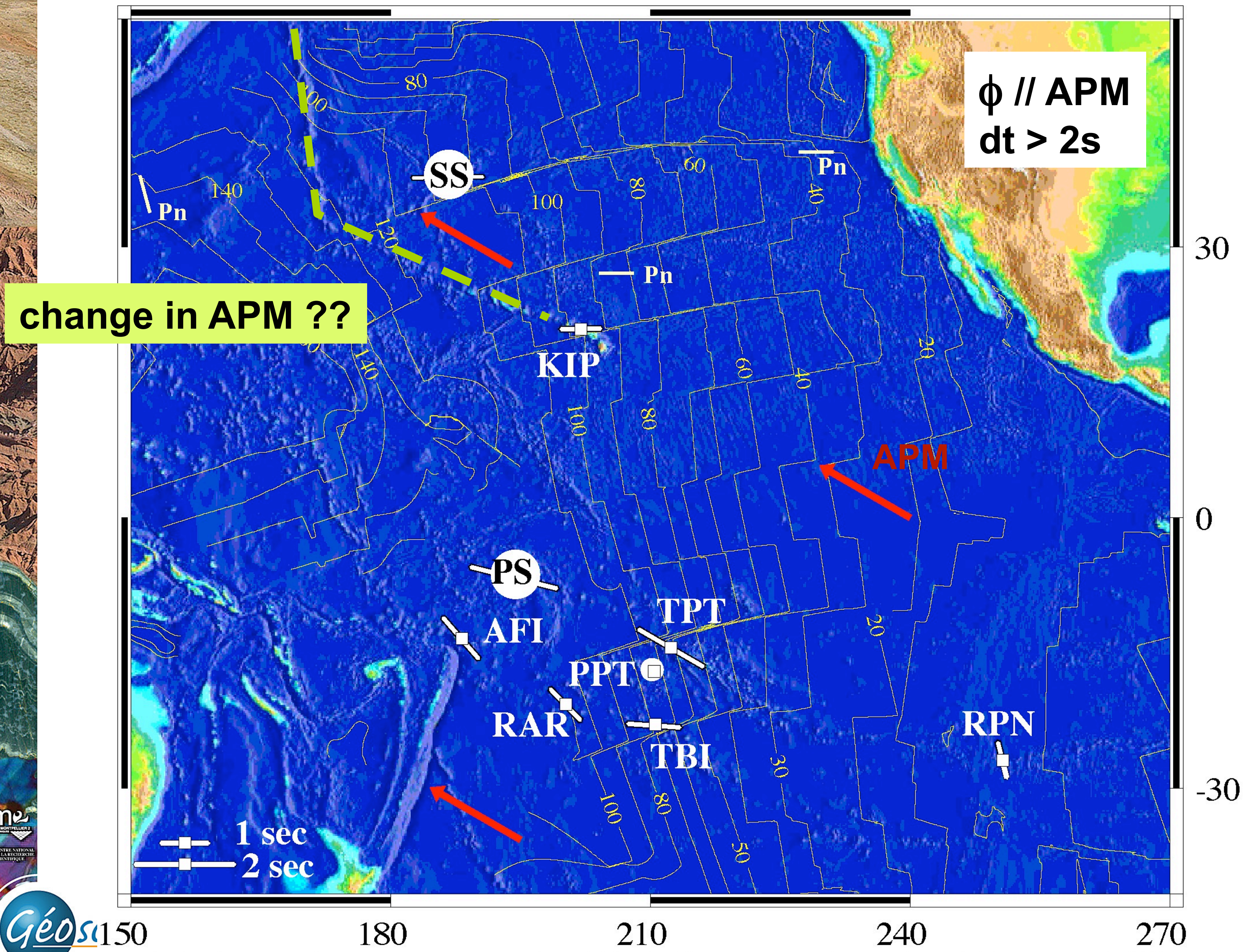
fast velocities //
fractures zones

➢ *fossil spreading direction*



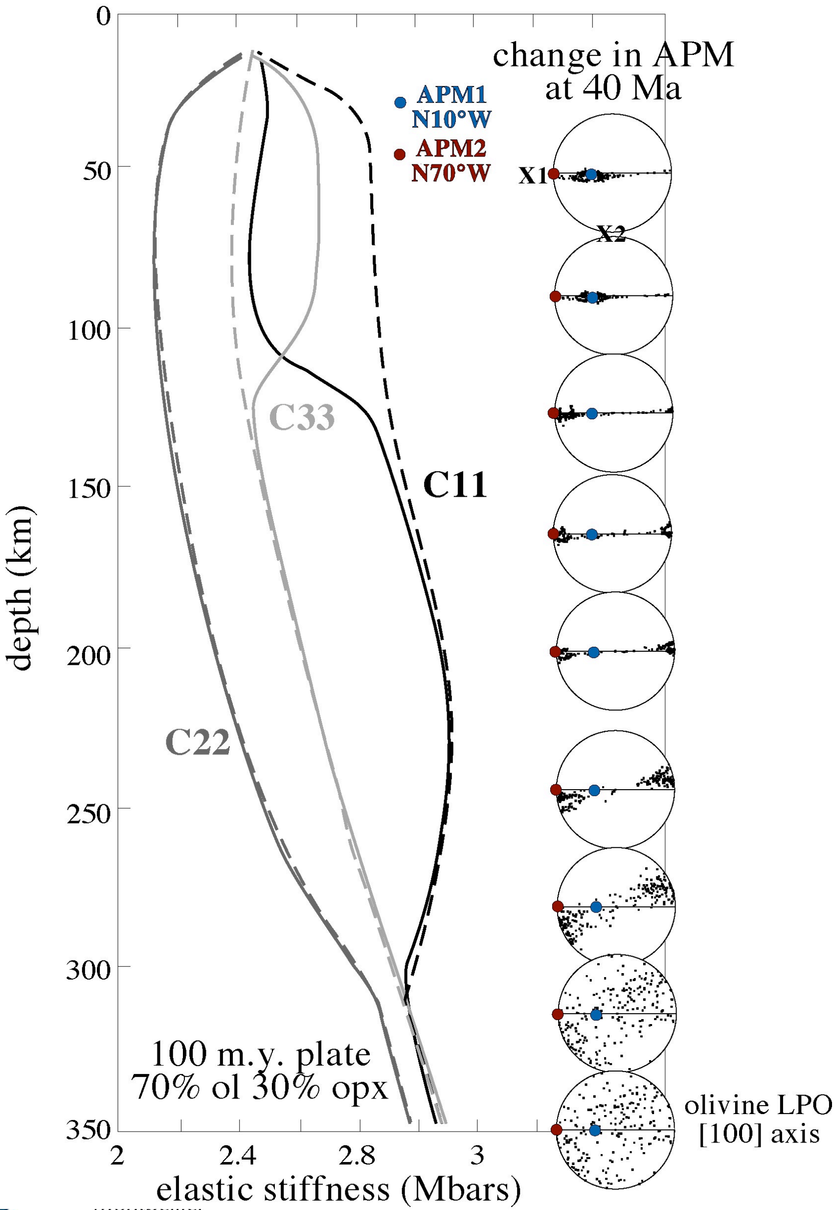
Hess (1964), Nature

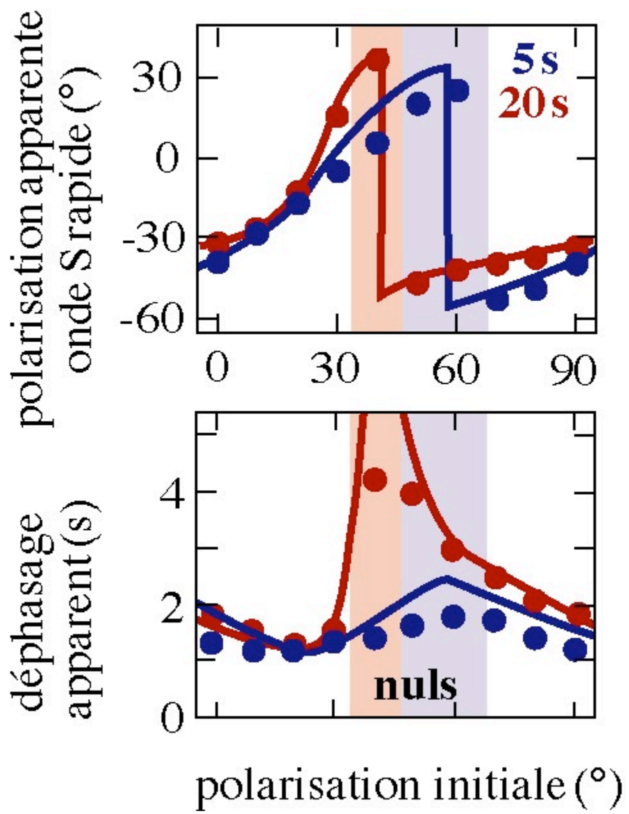




Data from Okal & Russo 1997 GJI, Wolfe & Silver 1997 JGR; Su and Park, 1994 PEPI

APM variation = vertical variation of anisotropy





Hawaii (KIP)

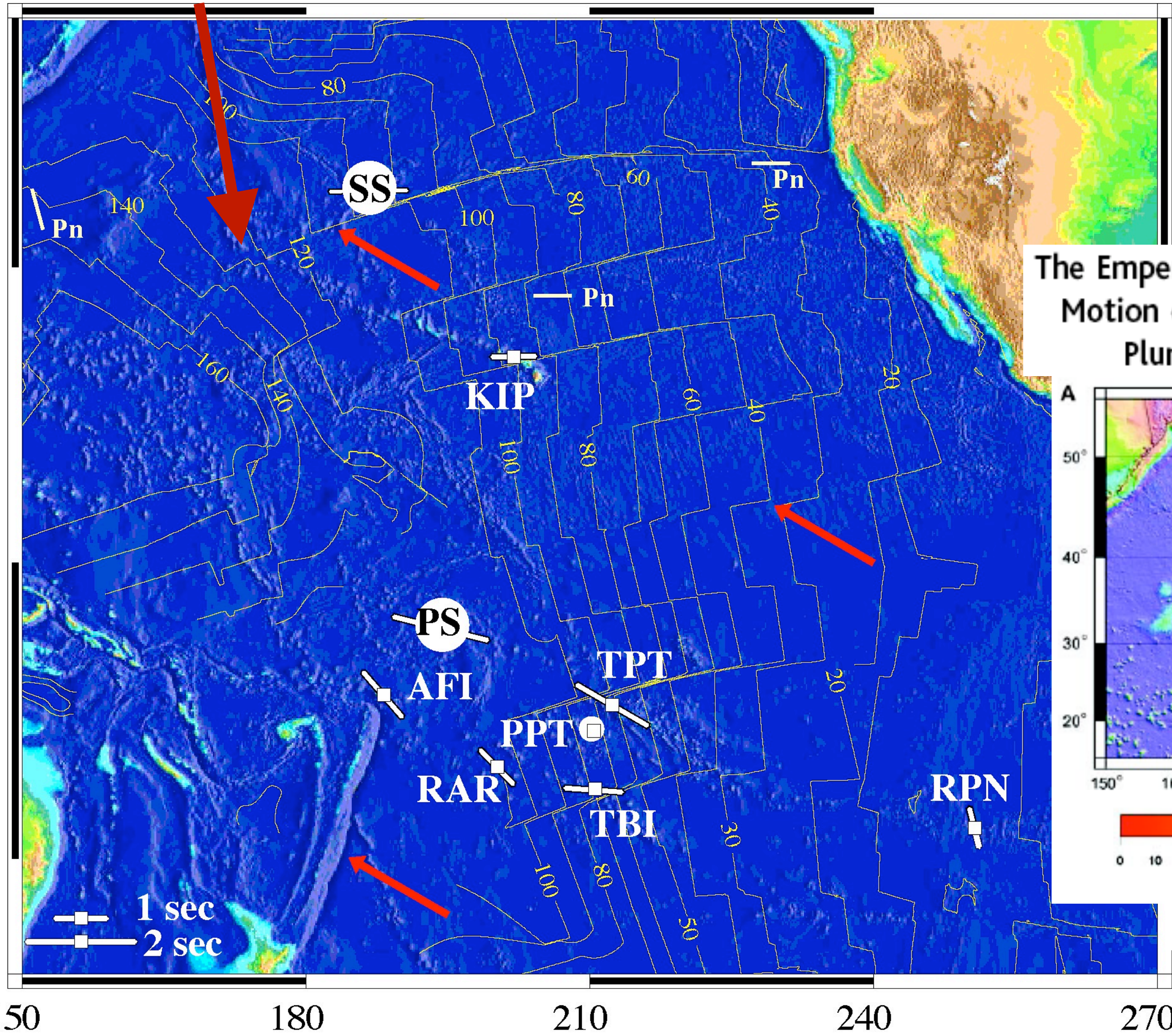
SKS: ϕ=E-W; dt=0.9s

ϕ=45°; dt=1s

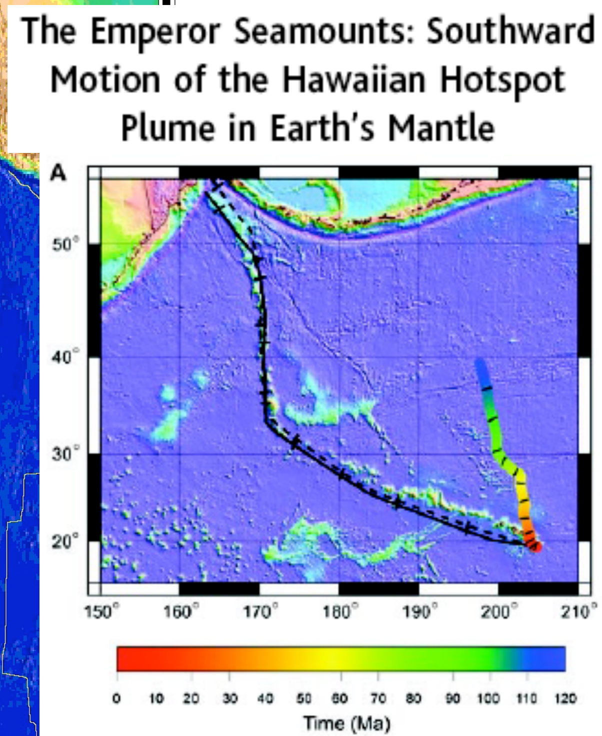
Pn: fast propagation = E-W

Tommasi 1998, Rümpker et al.. 1999

Emperor = displacement of the Hawaii plume pre-43Ma



Data from Okal & Russo 1997 GJI, Wolfe & Silver 1997 JGR; Su and Park, 1994 PEPI

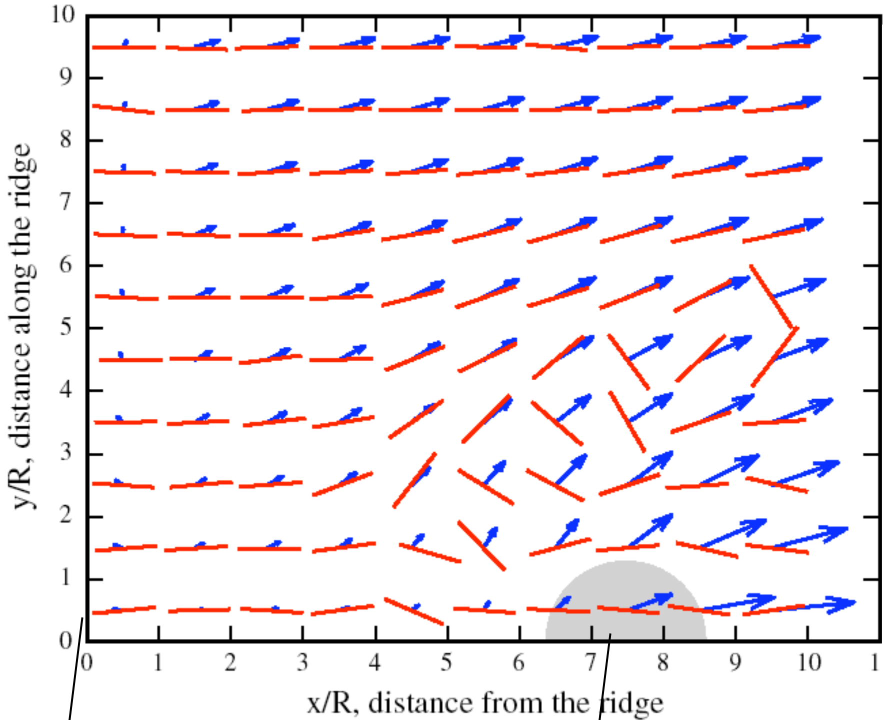


Tarduno et al. Science 2003

When is the full calculation of the CPO evolution needed?

- ***complex 3D strain field***
- ***evolution of CPO slower than changes in strain pattern***

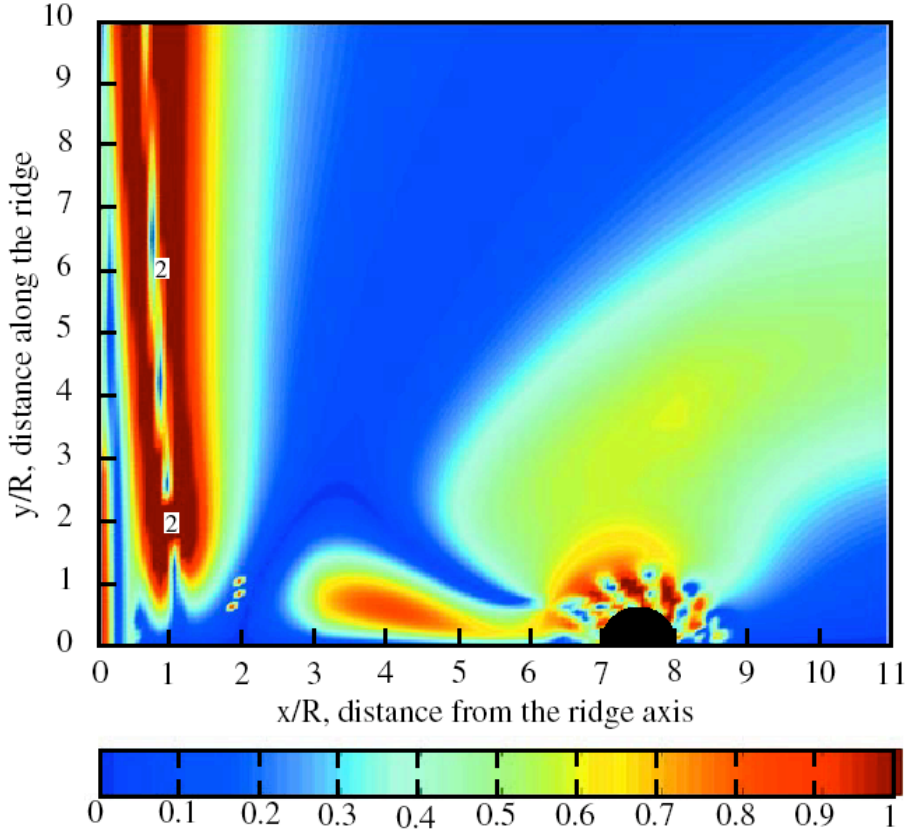
ex: plume-ridge interaction



ridge

plume

grain orientation lag parameter π



Kaminski & Ribe (2002) G3

Geochemistry Geophysics Geosystems G3
AN ELECTRONIC JOURNAL OF THE EARTH SCIENCES
Published by AGU and the Geochemical Society

Article
Volume 3, Number 9
20 September 2002
8602, doi:10.1029/2001GC000247
ISSN: 1525-2027

Seismic anisotropy in the upper mantle
2. Predictions for current plate boundary flow models

Donna K. Blackman and J.-Michael Kendall

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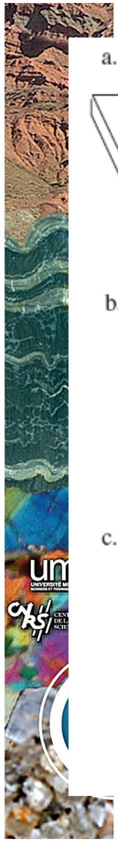
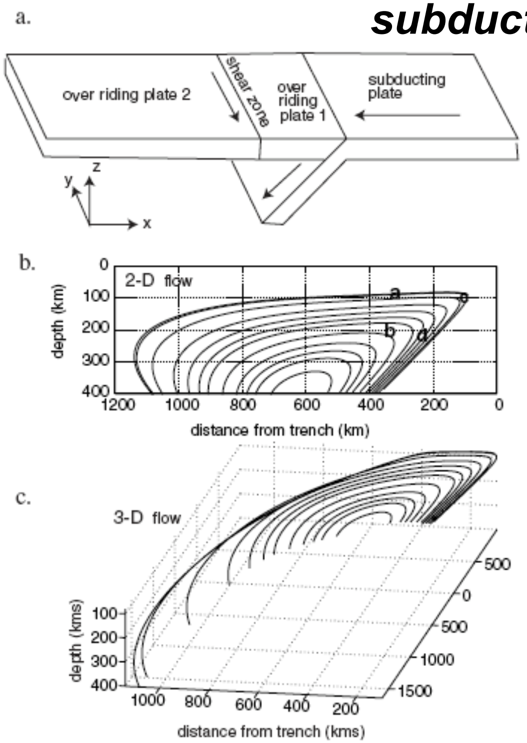
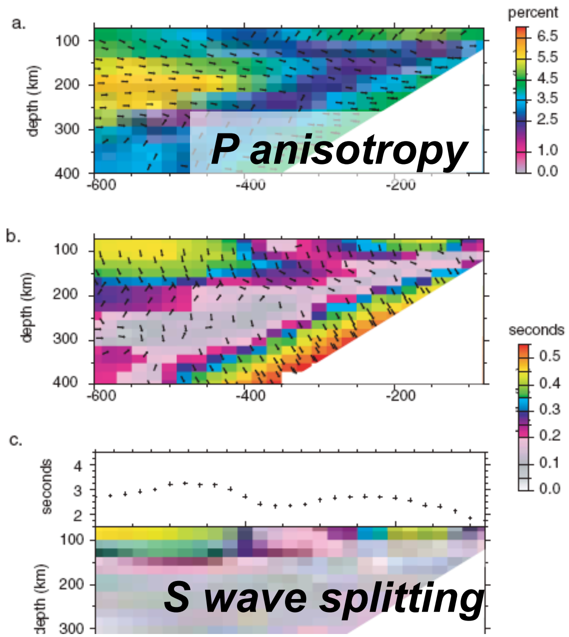
Department of Earth Sciences, University of Leeds, Leeds LS2 9JT, UK (kendall@earth.leeds.ac.uk)

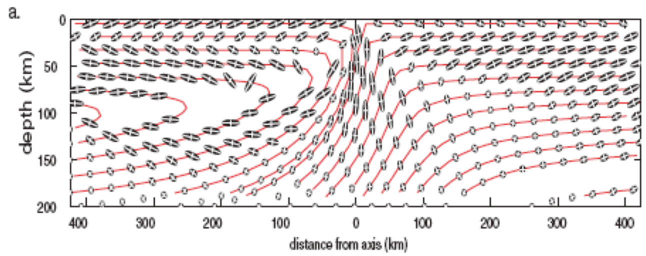


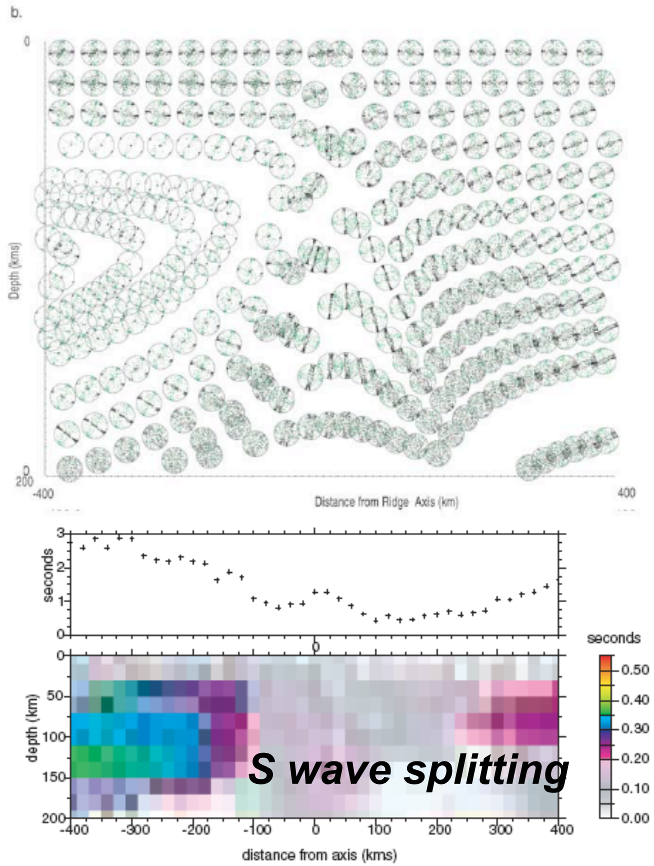
subduction zones

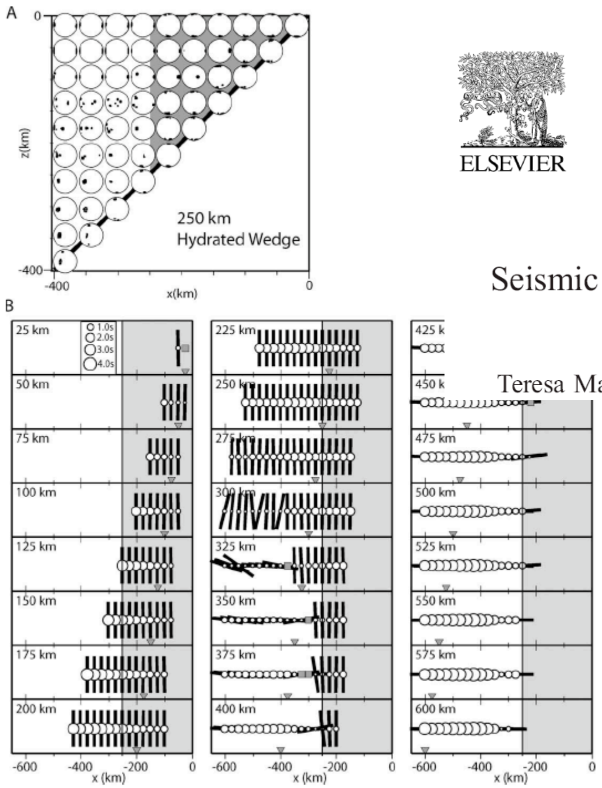




ridge + shallow T anomaly







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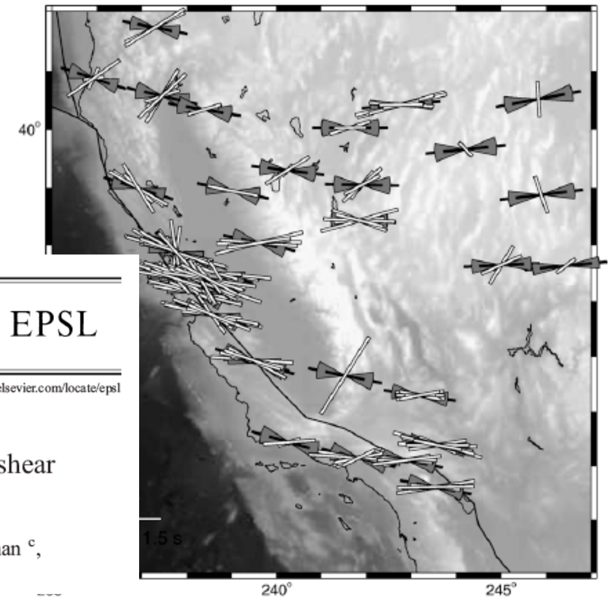
Earth and Planetary Science Letters 243 (2006) 632 – 649
EPSL
www.elsevier.com/locate/epsl

Seismic characterization of mantle flow in subduction systems: Can we resolve a hydrated mantle wedge?

Teresa Mae Lassak [a,*], Matthew J. Fouch [a], Chad E. Hall [b], Édouard Kaminski [c]

deformation mechanisms at crystal scale?



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Earth and Planetary Science Letters 247 (2006) 235 – 251
EPSL
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Mantle flow under the western United States from shear wave splitting

Thorsten W. Becker [a,*], Vera Schulte-Pelkum [b], Donna K. Blackman [c], James B. Kellogg [d], Richard J. O'Connell [e]

Géosciences Montpellier

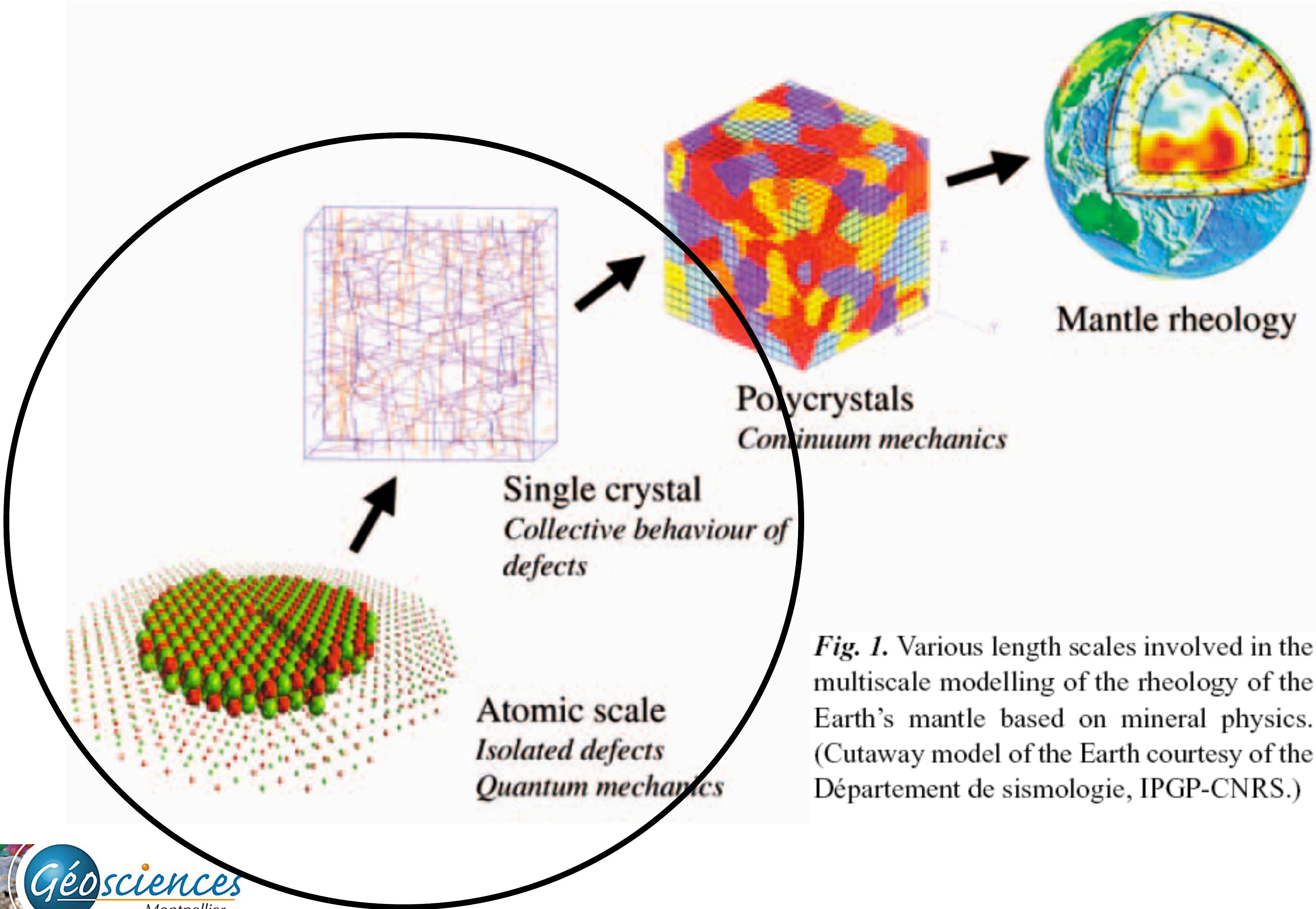

Fig. 1. Various length scales involved in the multiscale modelling of the rheology of the Earth's mantle based on mineral physics. (Cutaway model of the Earth courtesy of the Département de sismologie, IPGP-CNRS.)

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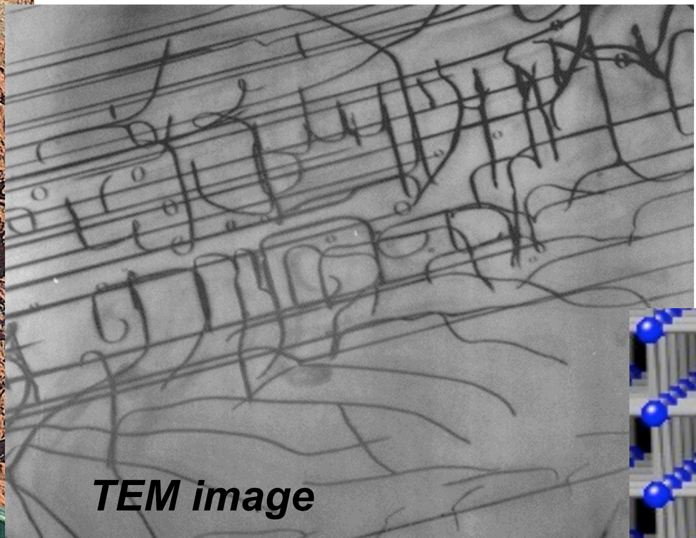
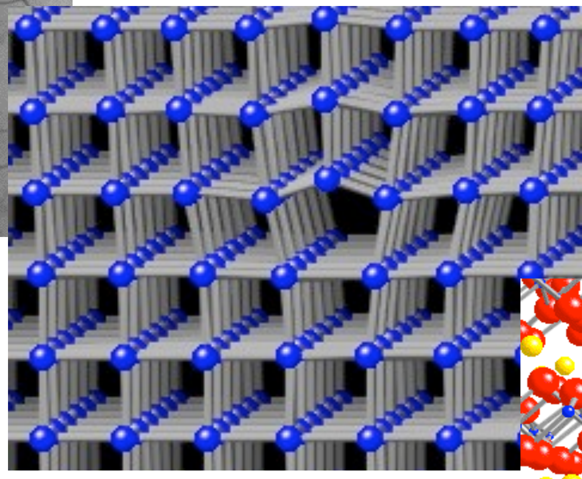
Cordier et al. EMU 2005

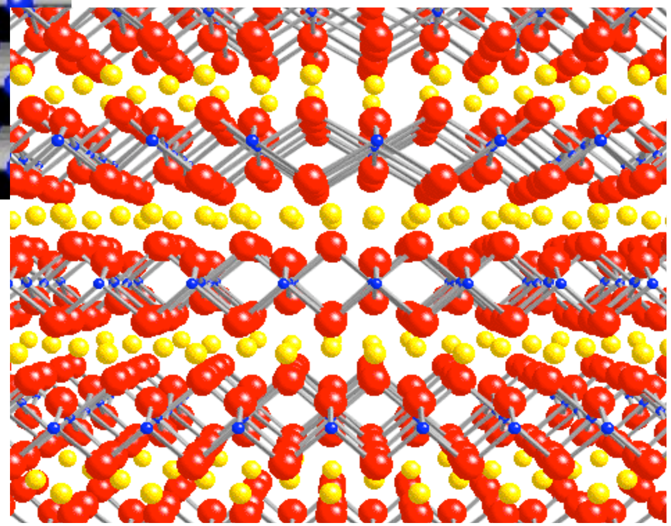
Ab-initio modeling of dislocation core properties: the Peierls-Nabarro model

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





"traditional" dislocation model

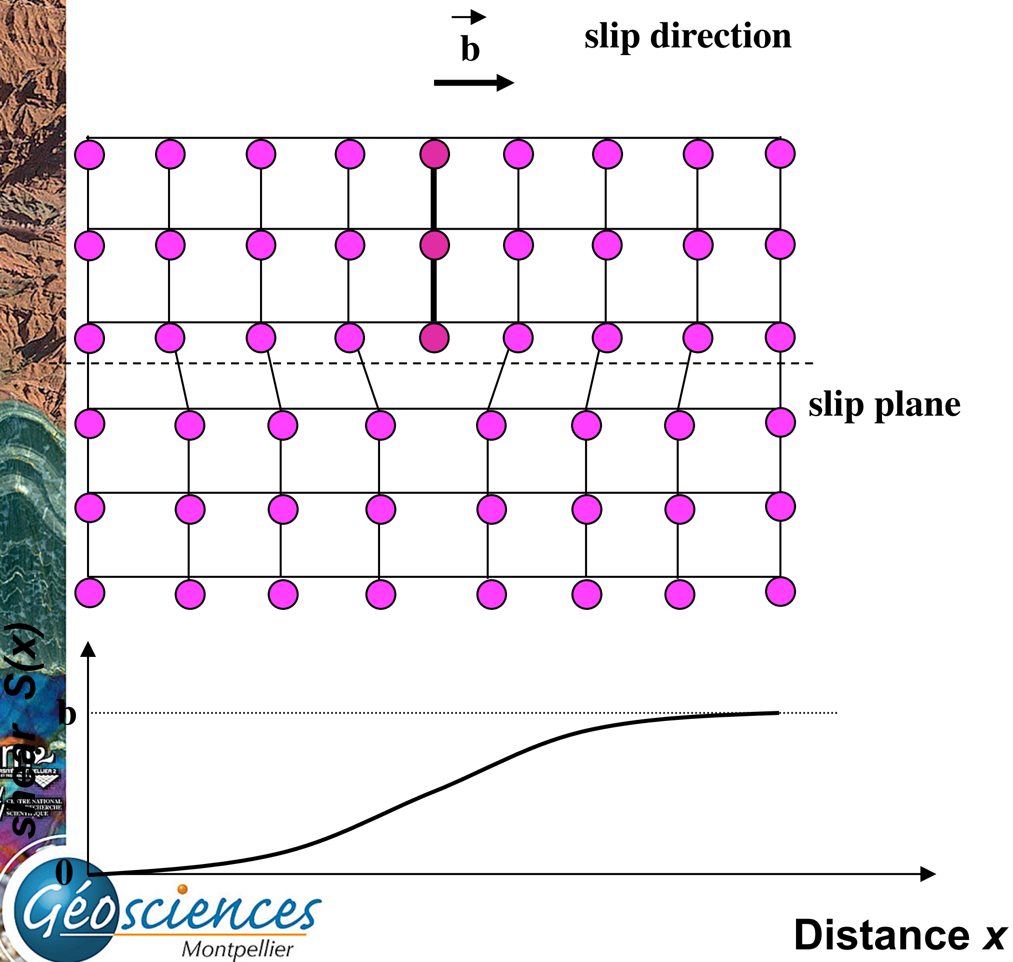


[100](010) edge dislocation in PPV (Carrez 2006)

Ab-initio modeling of dislocation core properties: the Peierls-Nabarro model

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

shear strain in the vicinity of the dislocation core

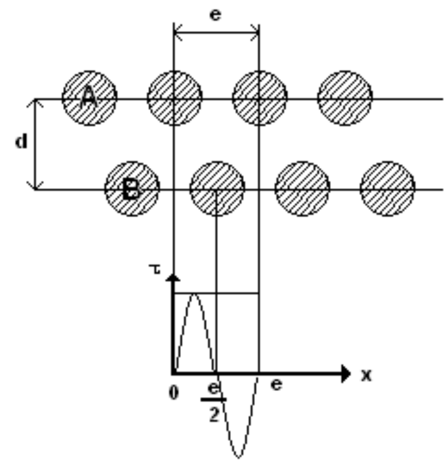


shear ⇔ dislocation density

$$\int_{-\infty}^{+\infty} \rho(x)dx = \int_{-\infty}^{+\infty} \frac{dS(x)}{dx} dx = b$$

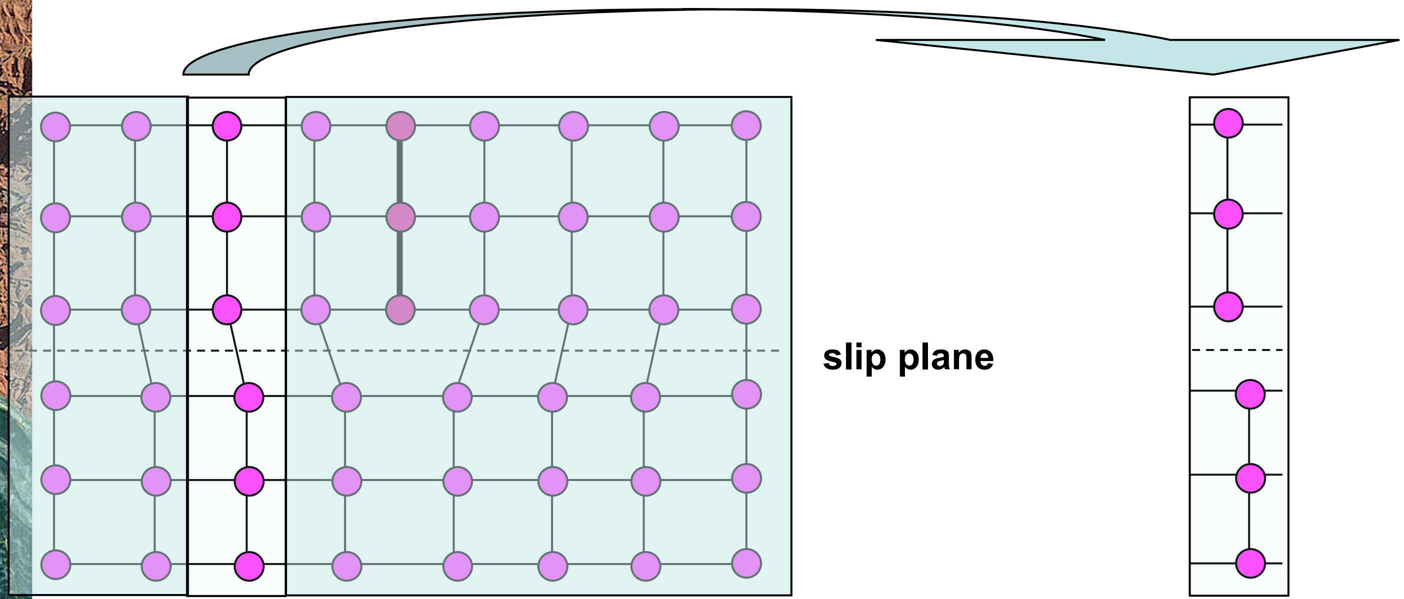
stress ⇔ misfit of crystal planes

$$F(S(x)) = \tau^{max} \sin\left(\frac{2\pi S(x)}{b}\right)$$

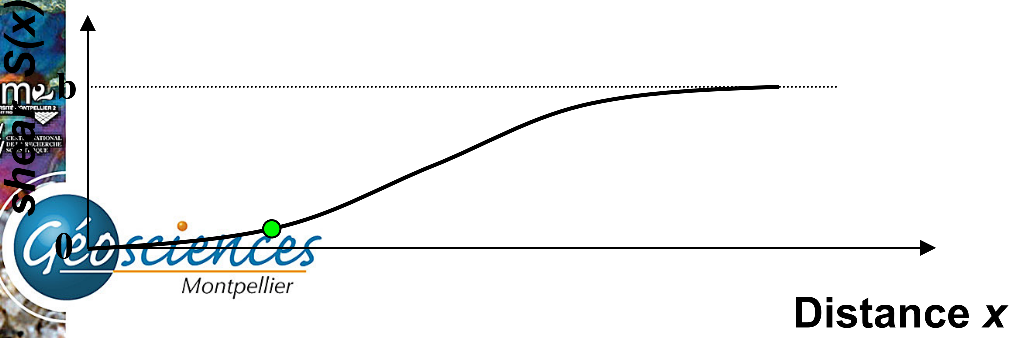


Ab-initio modeling of dislocation core properties: Generalised Stacking Fault (GSF) model

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

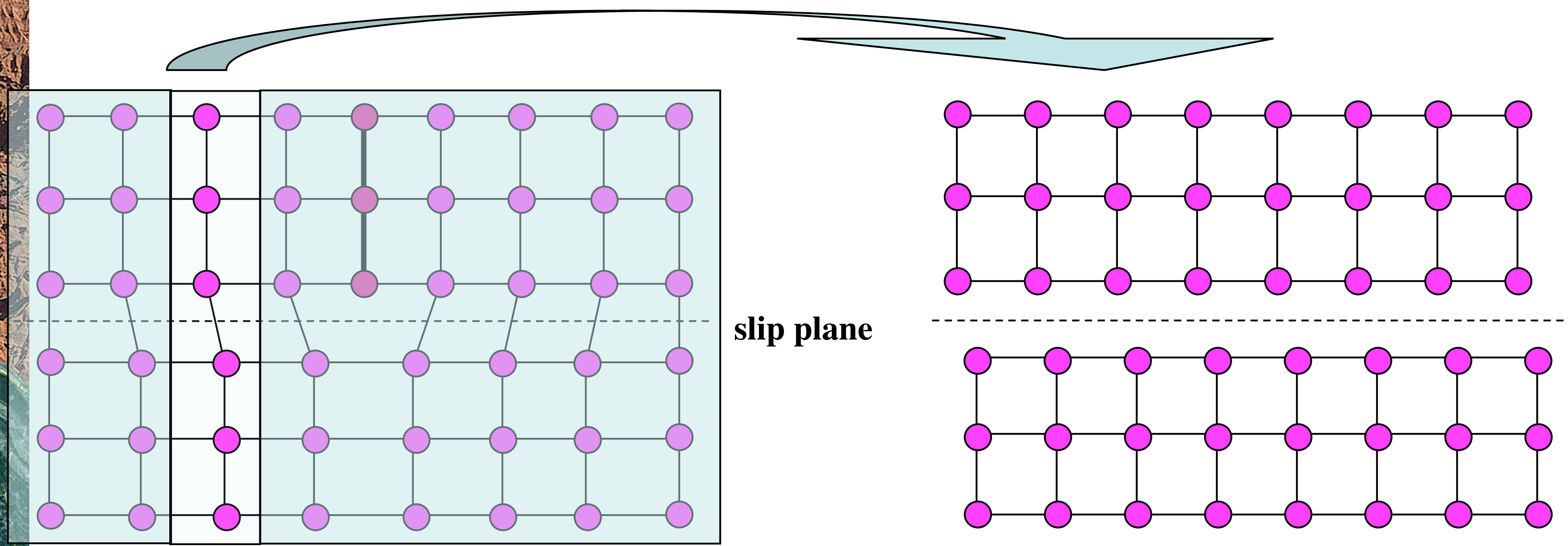


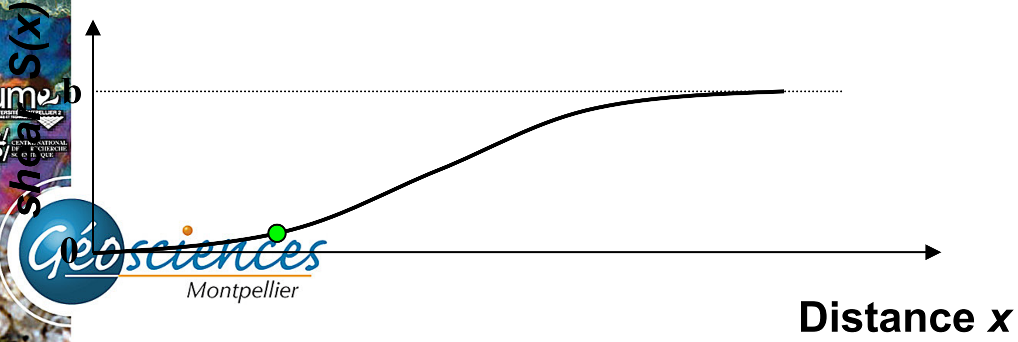
isolate a piece of the crystal



Ab-initio modeling of dislocation core properties: Generalized Stacking Fault (GSF) model

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

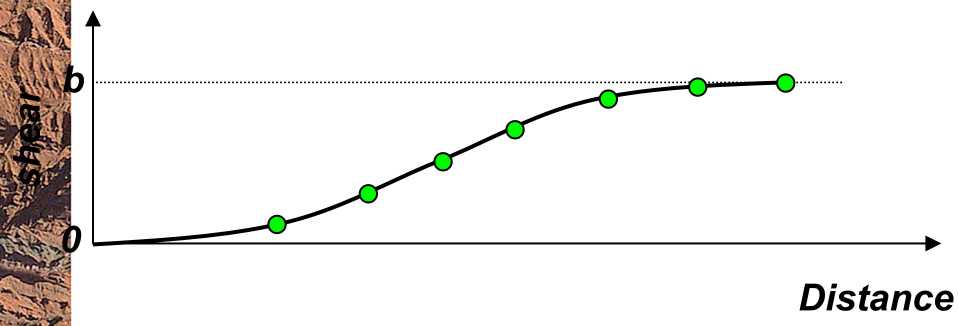


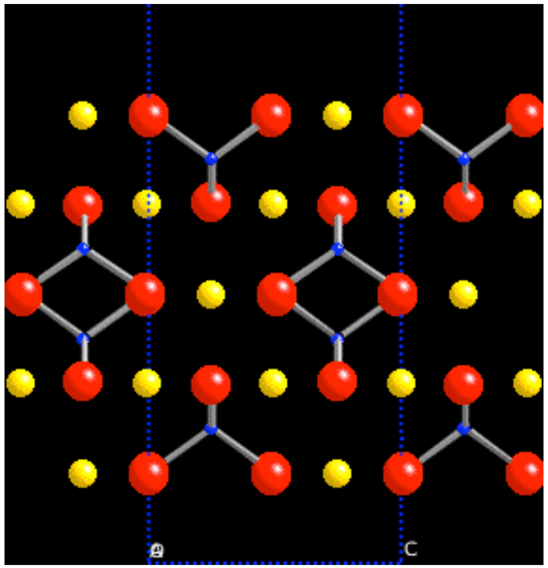


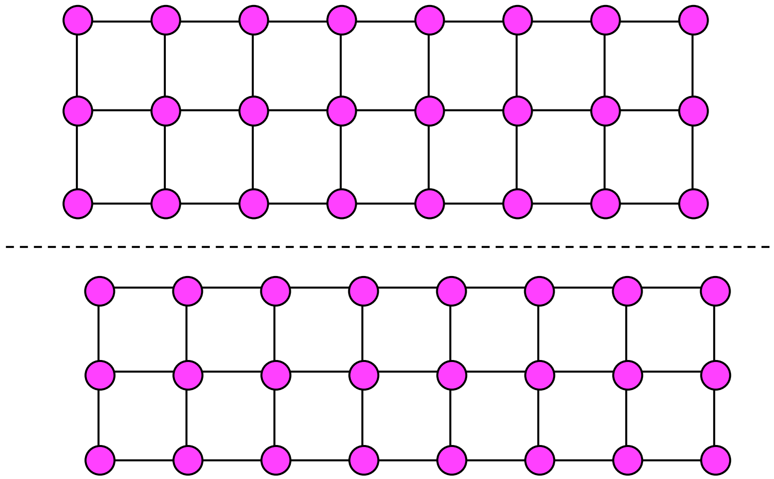
Generalised Stacking Fault (GSF): equivalent to a homogeneous shear

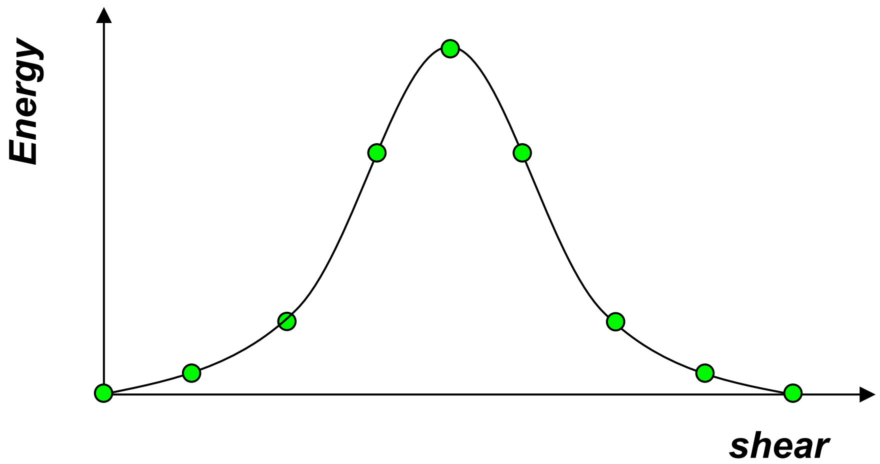
Ab-initio calculation of GSF

impose the shearing & for each position calculate the energy of the atomic configuration

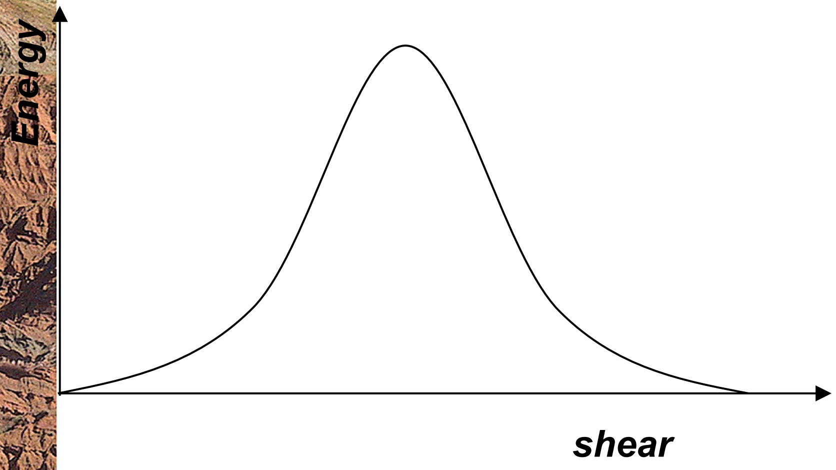




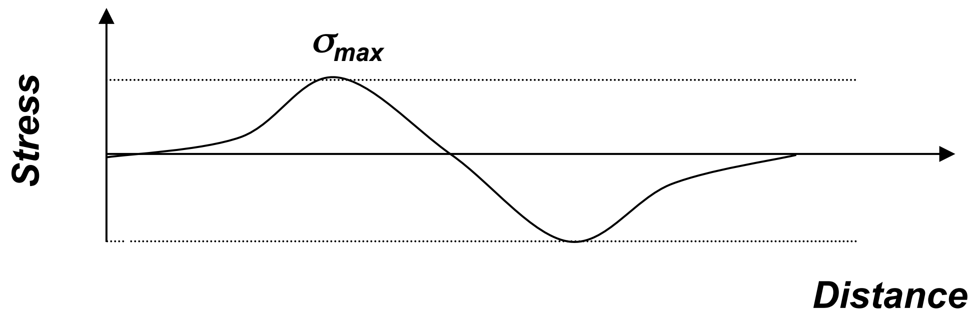




Ideal Shear Stress: intrinsic resistance to shear



ISS : derivative of the energy barrier



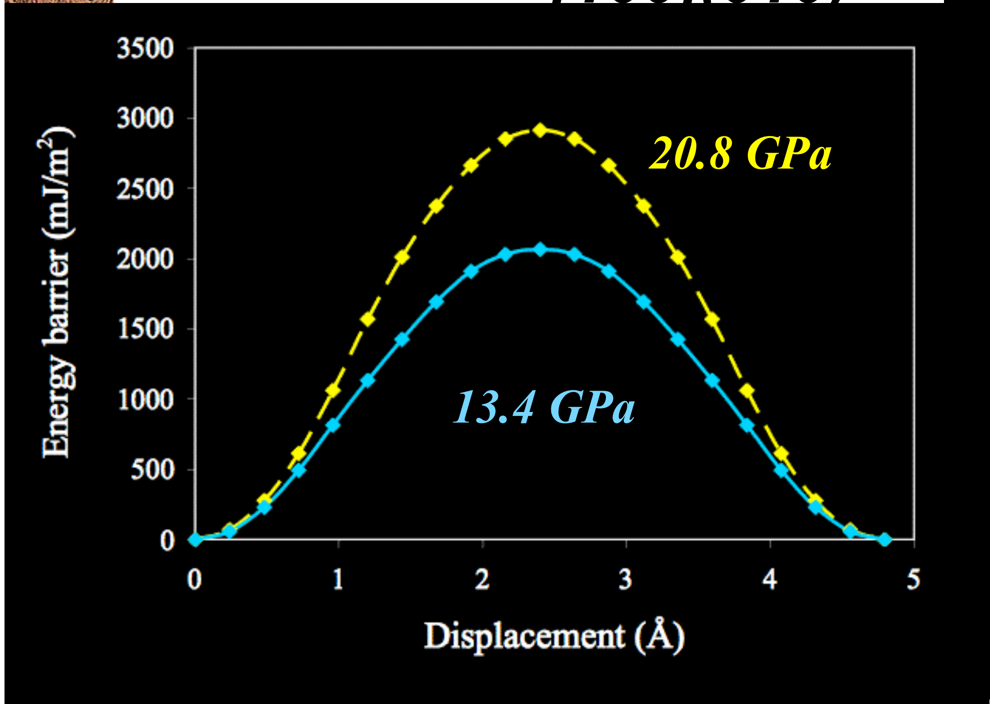
first order approximation of the resolved shear stress of a given slip system = input for viscoplastic models (aggregate-scale deformation)

$$\frac{\dot{\gamma}^s}{\dot{\gamma}_0} = \left(\frac{\tau_r^s}{\tau_0^s}\right)^{n^s} = \left(\frac{R_{ij}^s \sigma_{ij}}{\tau_0^s}\right)^{n^s}$$

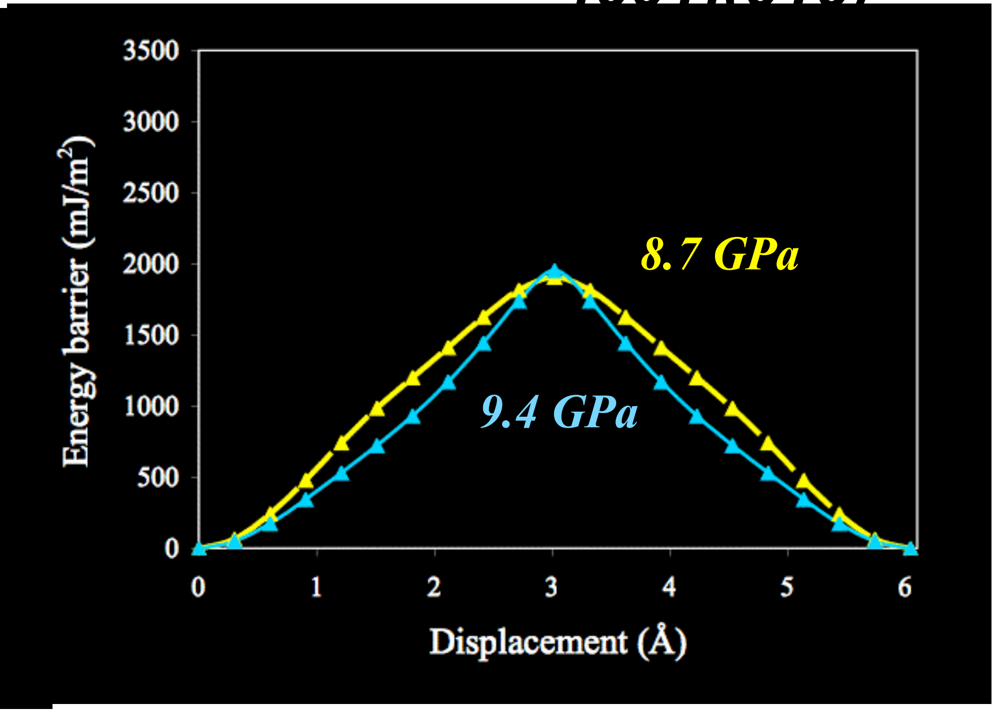
GSF + Crystal periodicity → Peierls-Nabarro model = Peierls stress (lattice friction)

Olivine: energy barriers for [100](010) and [001](010) dislocations at 0 GPa & 10 GPa

[100](010)



[001](010)



- ✓ *easy slip on [100](010) at high pressure*
- ✓ *consequences to seismic anisotropy in the deep upper mantle?*

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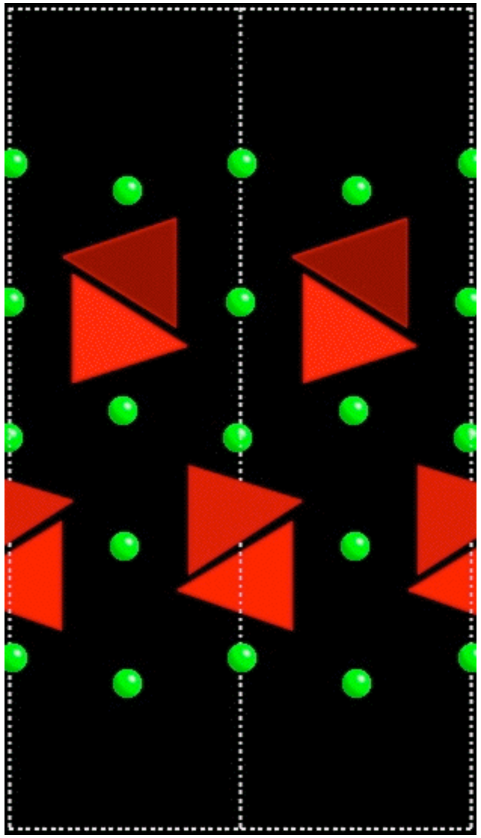
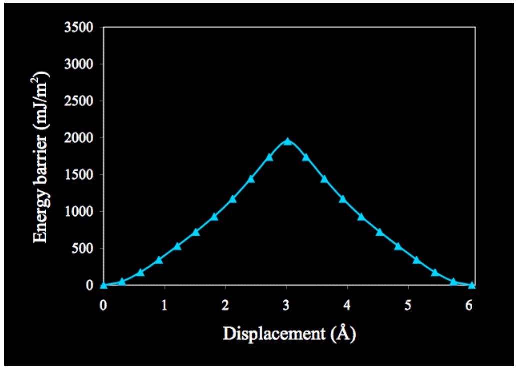
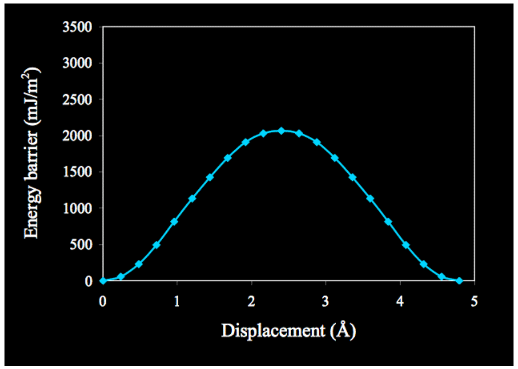
Ab-initio calculation of GSF

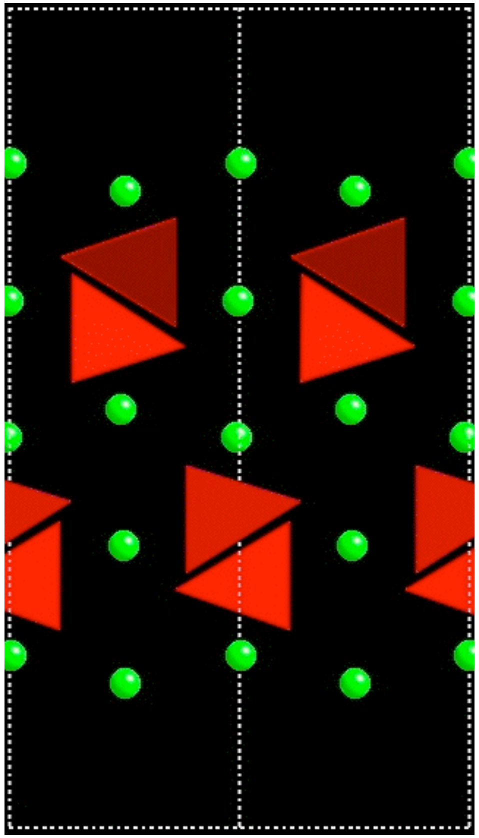
1. ***Construct crystal structure***
2. ***Impose shear on various planes & directions & calculate energy barriers (fixed + relaxed structure)***

[001](010)









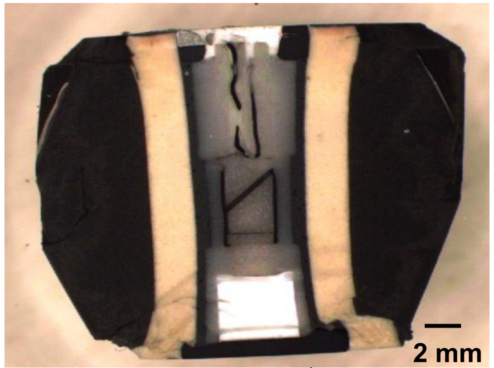
[100] (010)

[001]

[100]

HP experimental deformation of olivine

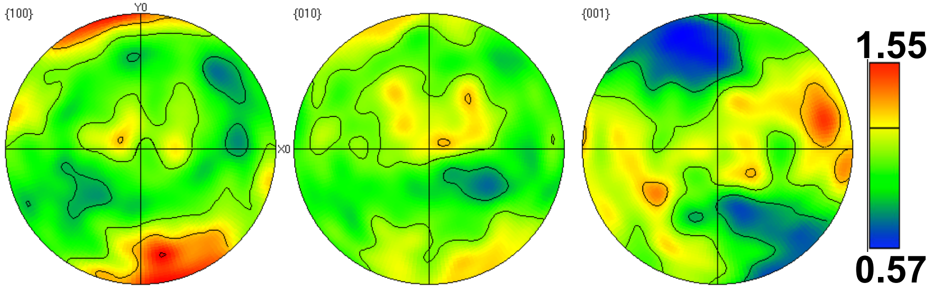
H. Couvy & P. Cordier
Bayreuth/Lille



simple shear

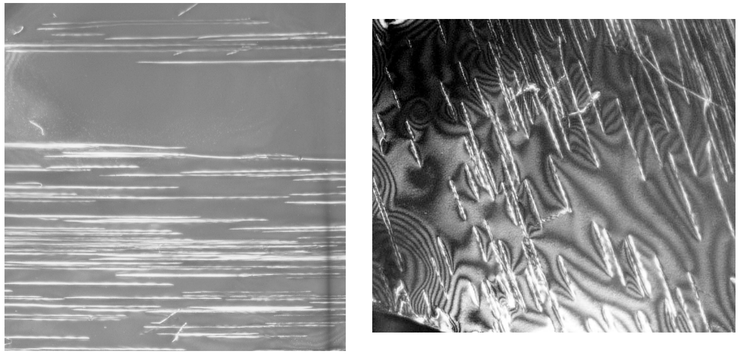
100% olivine aggregate
11 GPa e 1400°C

EBSD: olivine CPO



γ=0.3

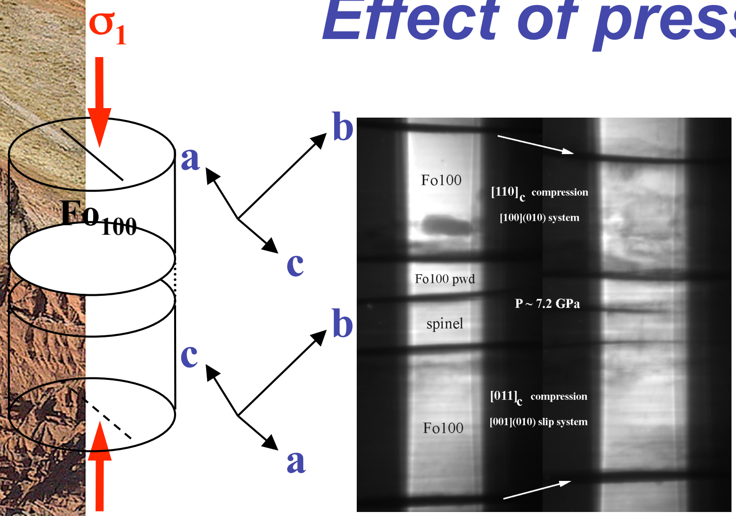
[001](010)
[001](100)



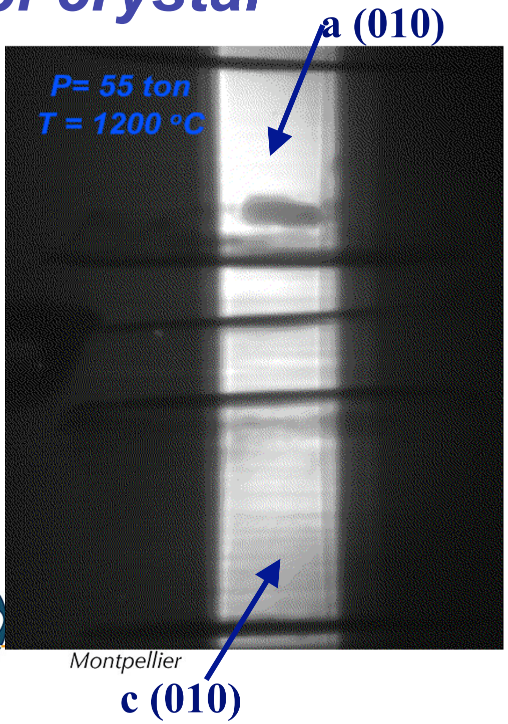
TEM: only [001] screw dislocations

Couvy et al. EJM 2004

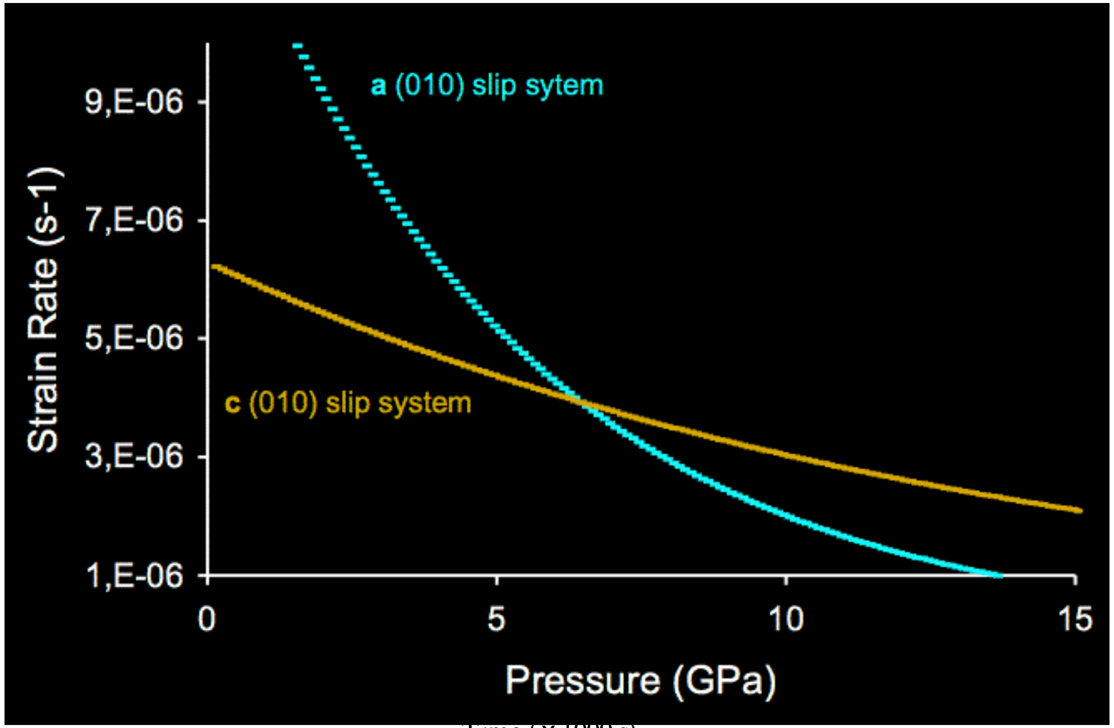
Effect of pressure on olivine deformation



bi-crystal



P= 7.2 GPa



Time (x 1000 s)

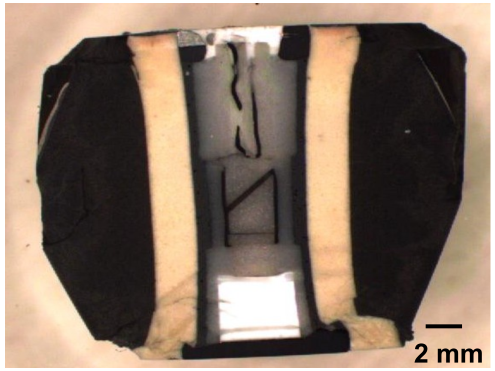
- *higher strain on c crystal*
  - ✓ *[001](010) slip easier than [100](010)*
- *very low activation volume*
  - ✓ *dislocation creep dominant*

Paul Raterron, pers. commun.

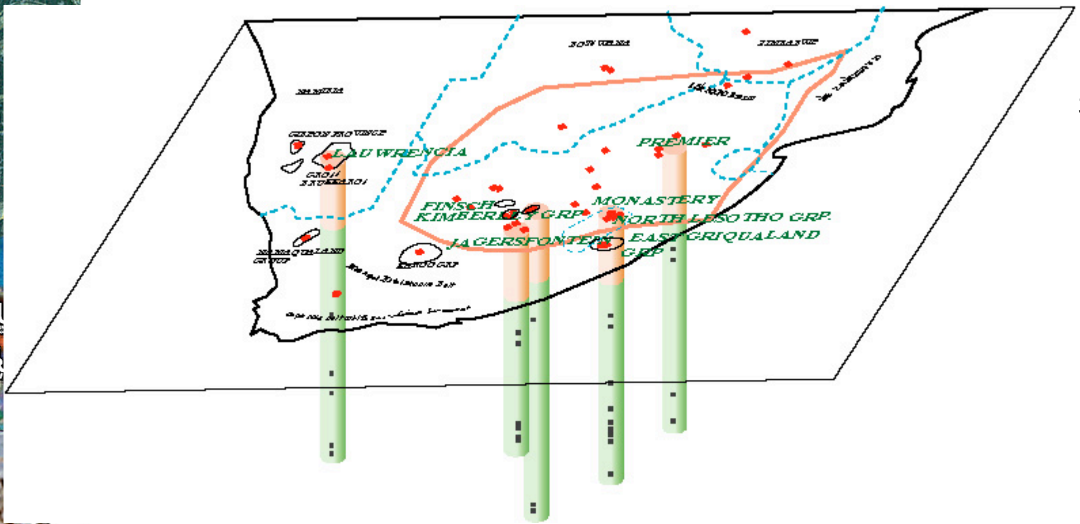
Depth of the transition from [100] slip to [001] slip?

HP-HT experiments (*Cordier, Couvy, Raterron…)*

- P ≤ 3GPa (~90 km) : [100] slip dominant
- P ≥ 7 GPa (~215 km): [001] slip dominant
  - ✓ transition stress-dependent?



CPO data on naturally deformed peridotites (depths ≤ 160 km)



sp- and garnet-bearing peridotites :

✓ [100] CPO only

[001] CPO only observed in :

high-pressure massifs (subduction)

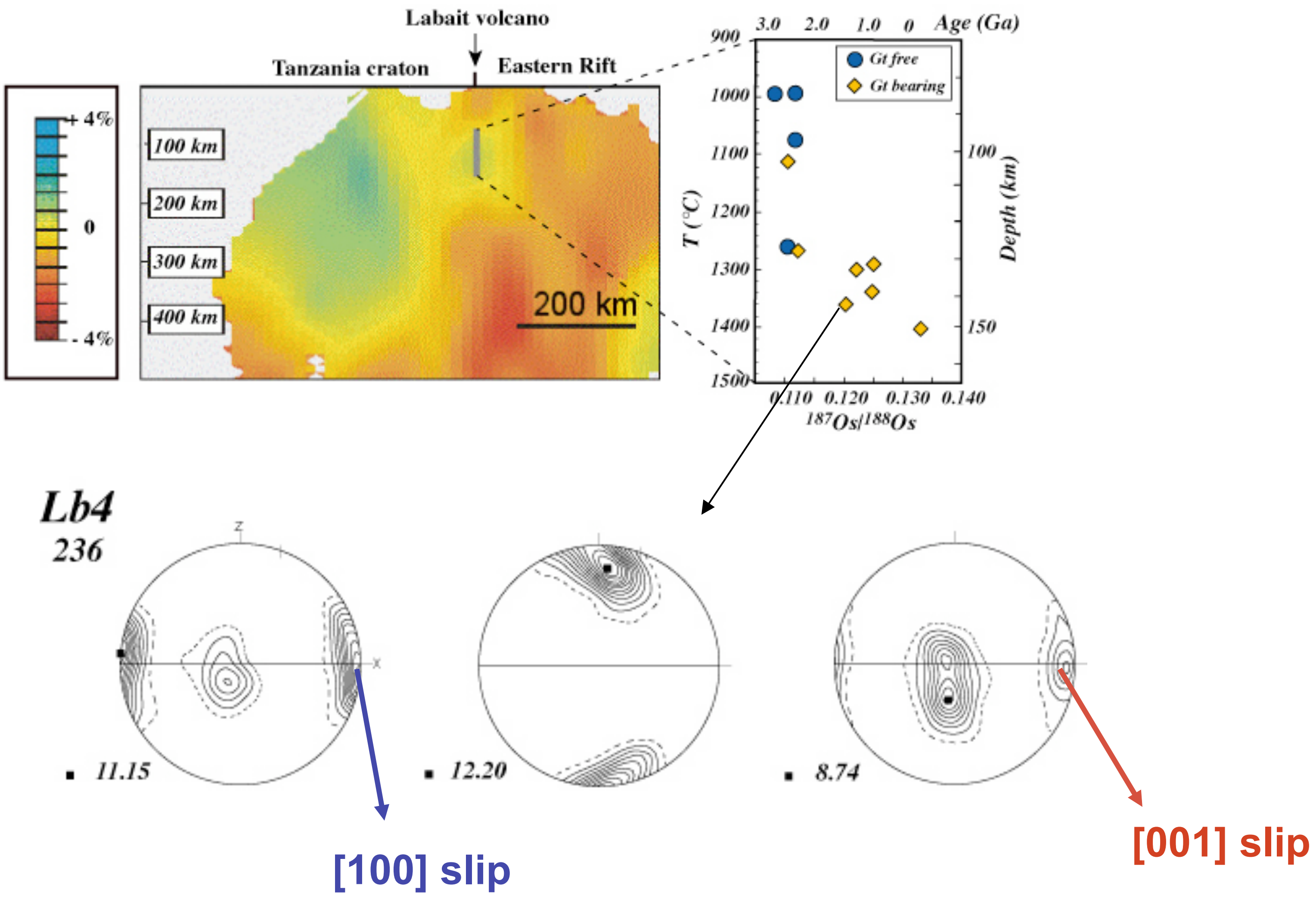
✓ effect of pressure or water ?

(Jung and Karato Science 2001)

some deep cratonic xenoliths…

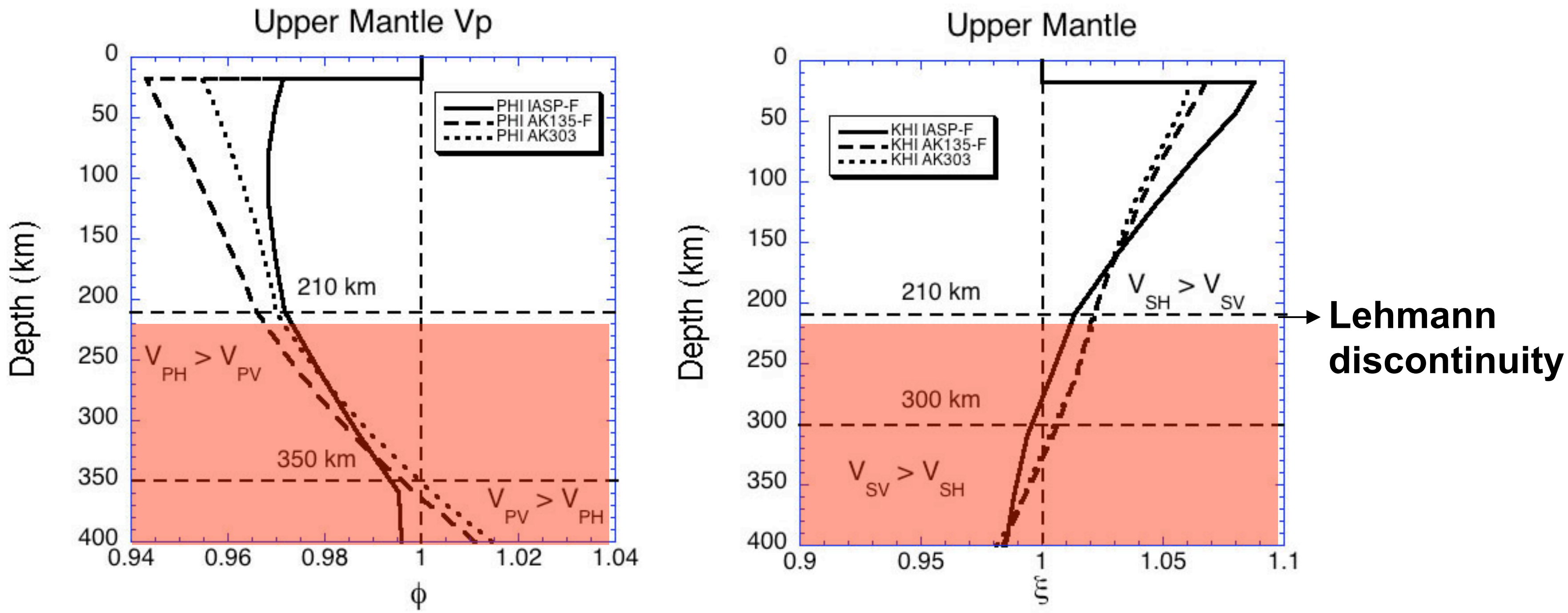
deep samples from the Tanzanian and South African craton

Vauchez et al, EPSL, in press



bimodal olivine CPO : activation of [100](010) and [001](010) slip systems?

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



Transition from dislocation to diffusion creep (no CPO -> no seismic anisotropy)

yet … recent experimental data:
olivine at high pressure deforms by dislocation creep, but with a change in slip direction from [100] to [001]

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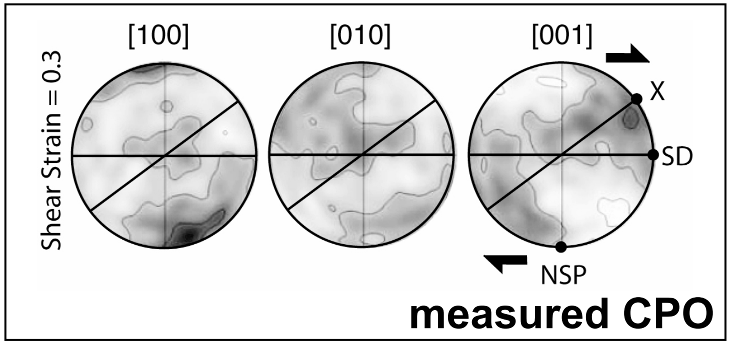
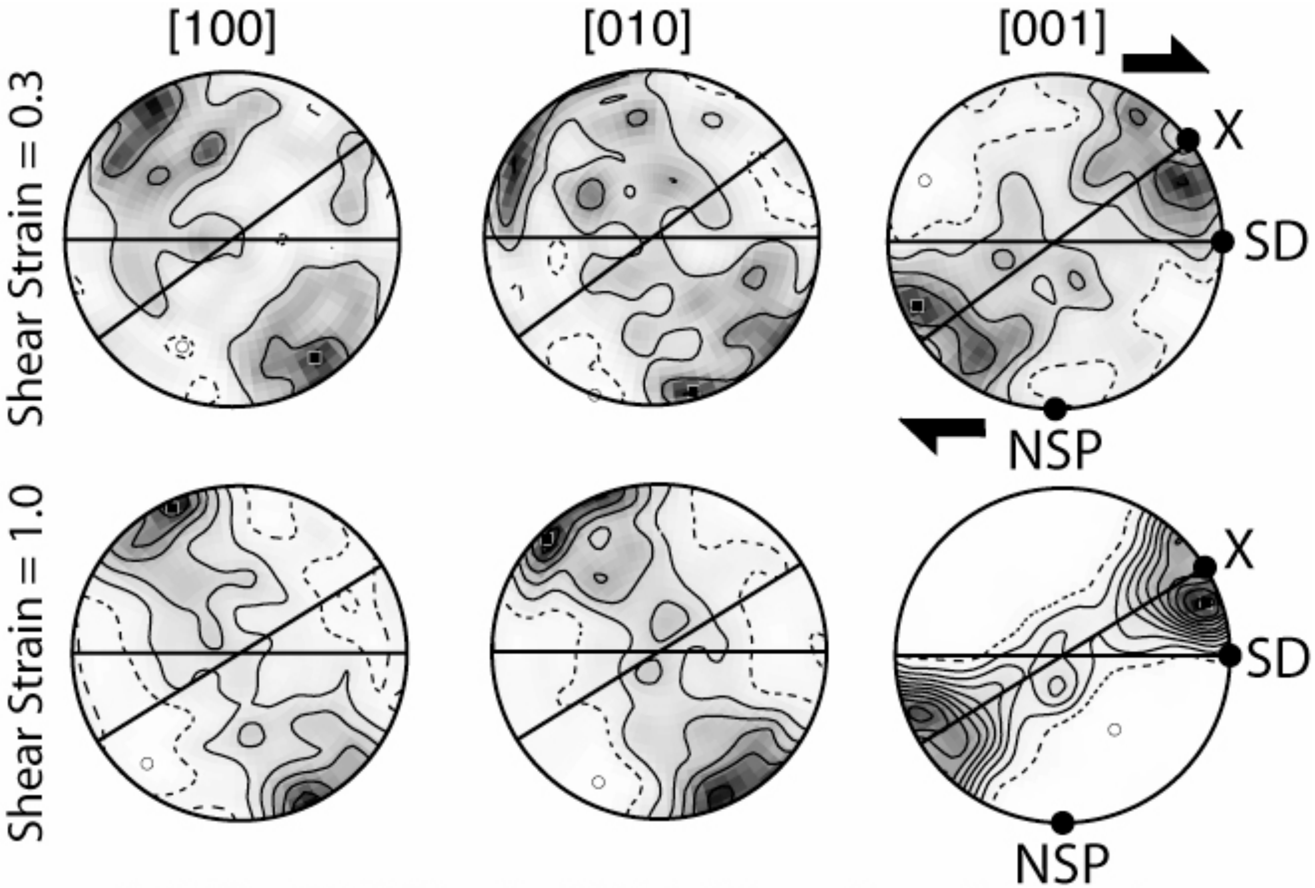
Texture evolution as function of strain: crystal plasticity modeling





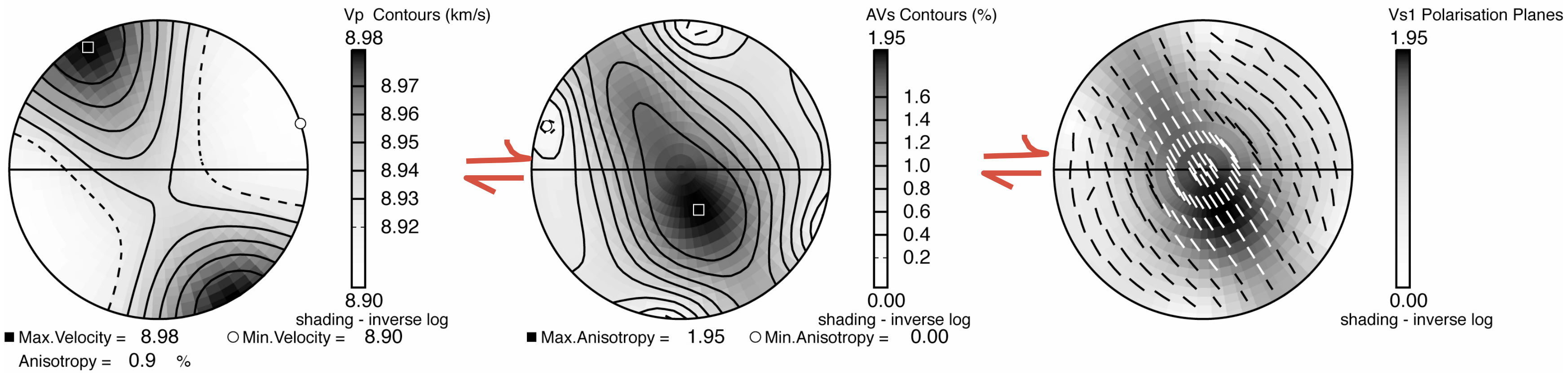
CRSS all [001] = 1 ; [100]=3(basal) or 6 (prism)

Mainprice et al., Nature, 2005

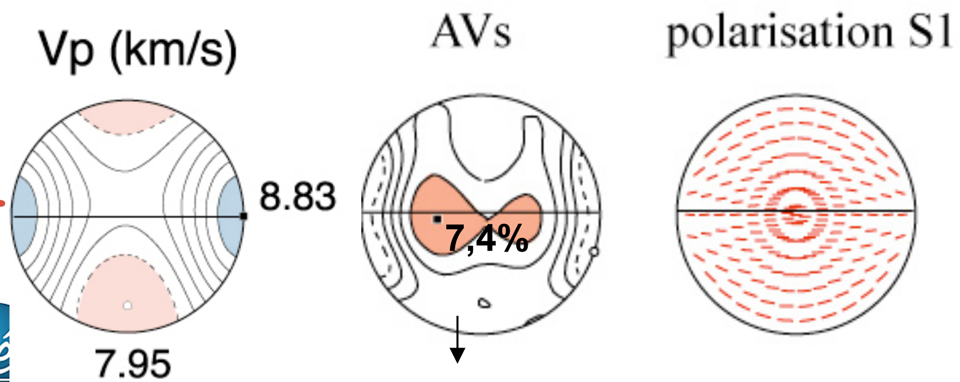
Seismic anisotropy

high-pressure olivine LPO : [001] glide

Model at 355 km depth for a compsition of 63% olivine, 17% garnet and 20% diopside at shear strain of one



A~1% **A~2%**

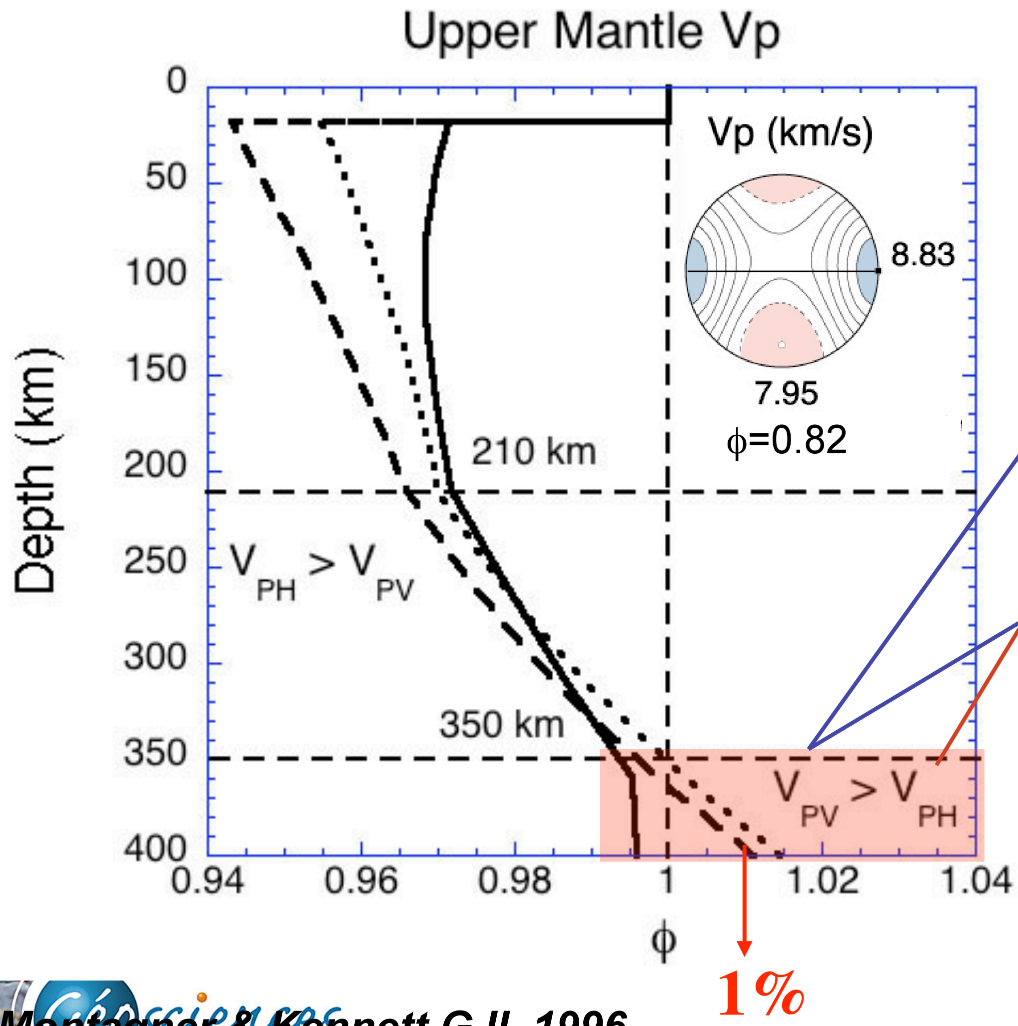


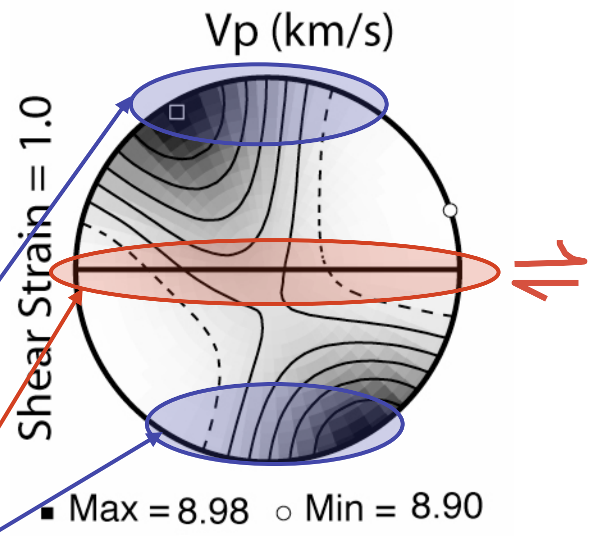
A=10%

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

« typical upper mantle peridotite seismic anisotropy »
low-pressure olivine LPO
[100] glide

Global P-wave anisotropy in the deep upper mantle



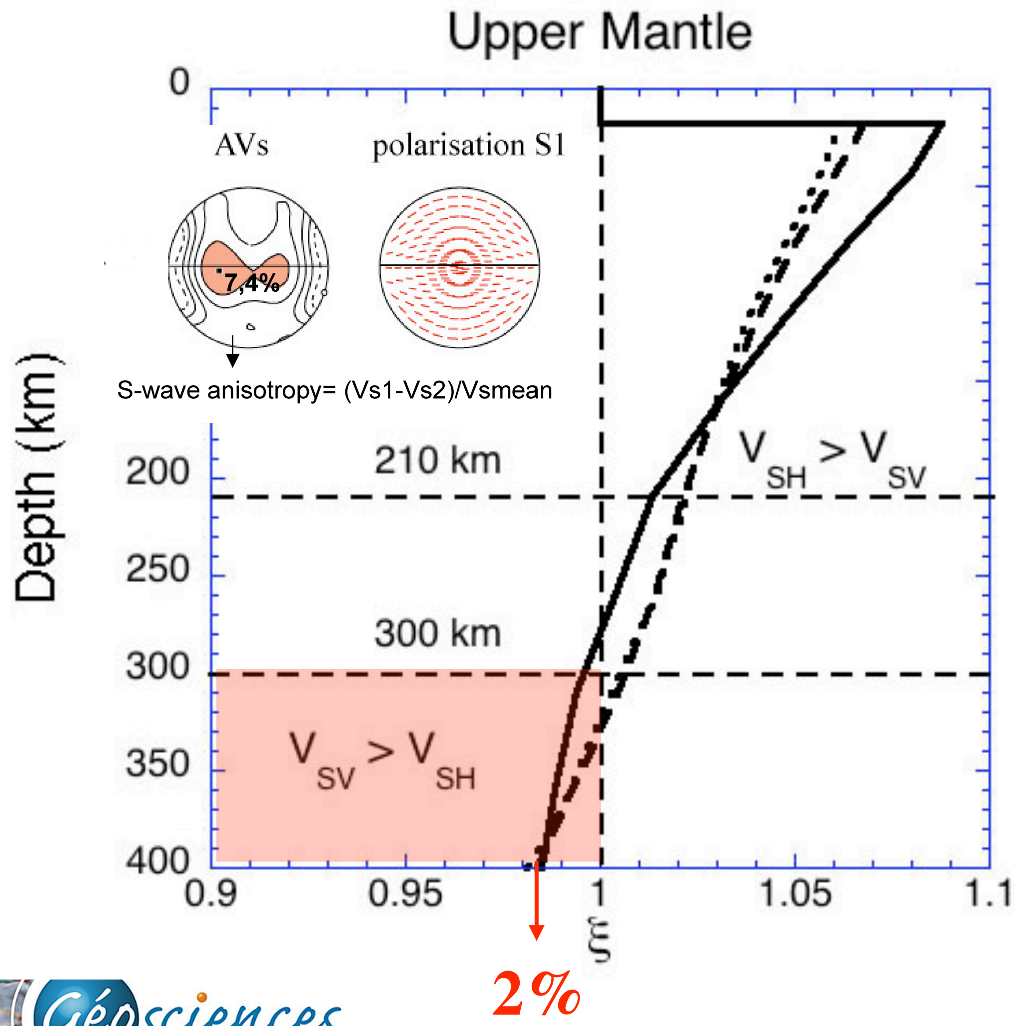


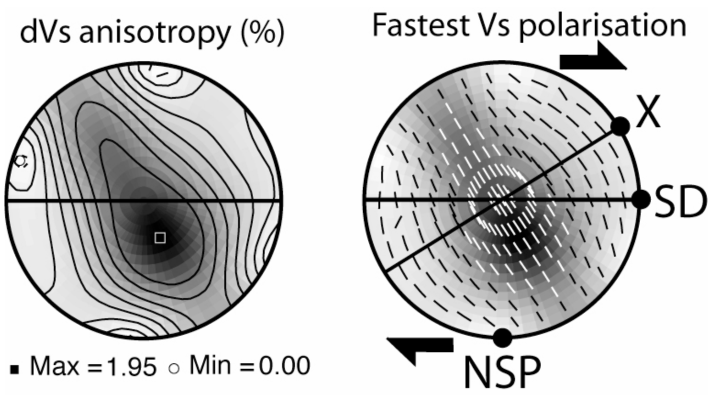
Model prediction for horizontal flow:

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

Montagner & Kennett GJI, 1996

Global S-wave anisotropy in the deep upper mantle





Model prediction for horizontal flow:

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

Montagner & Kennett GJI, 1996

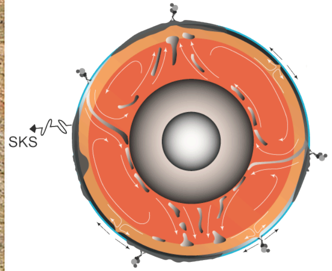
olivine deformation = f(P)

change in dominant slip direction from [100] to [001]

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

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

- **seismic anisotropy data : dislocation creep in the entire upper mantle horizontal shearing dominant**

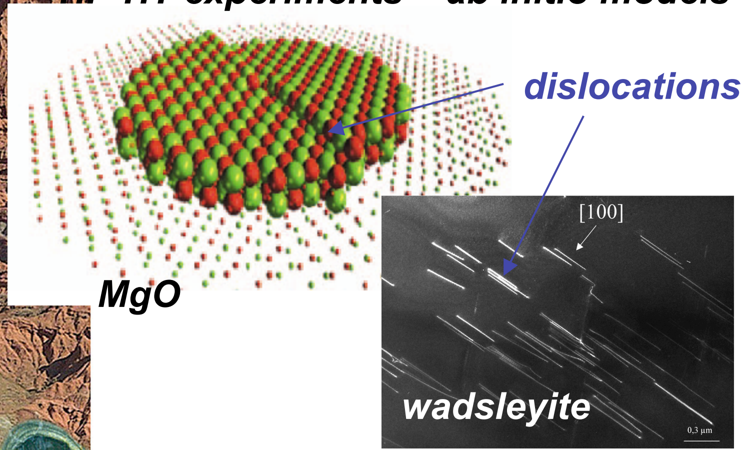


Déformation & anisotropy in the deep mantle

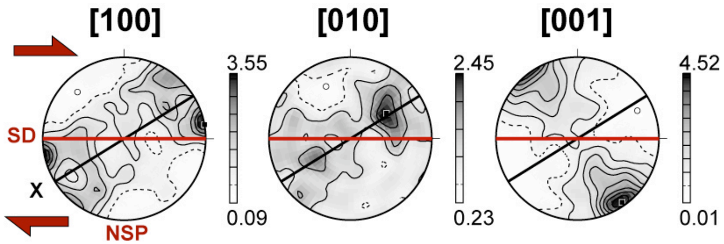
coll. P. Cordier, P. Carrez, D. Ferré (Lille), D.Mainprice et C. Thoraval (Montpellier)

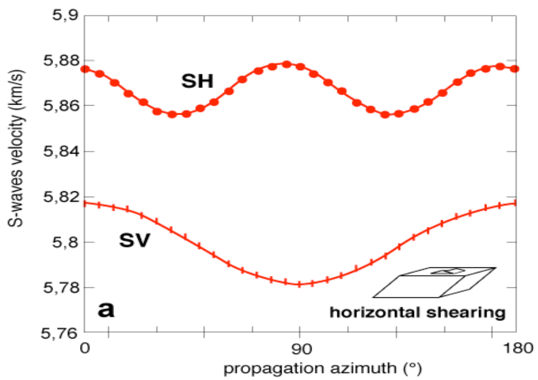
deformation of HP mantle minerals

HP-HT experiments + ab initio models



VPSC + seismic properties models (rock-scale) + mantle flow models

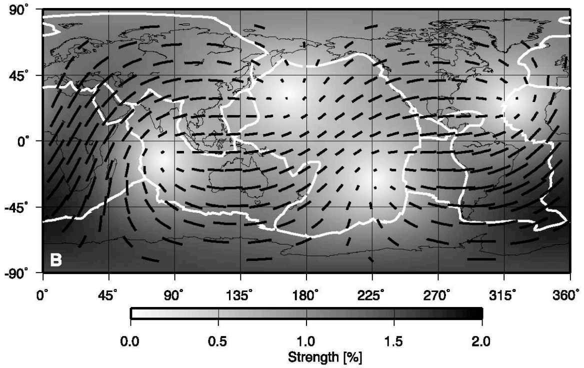




horizontal flow dominant in TZ except in the vicinity of subduction

Tommasi et al., JGR, 2004

seismic anisotropy data transition zone



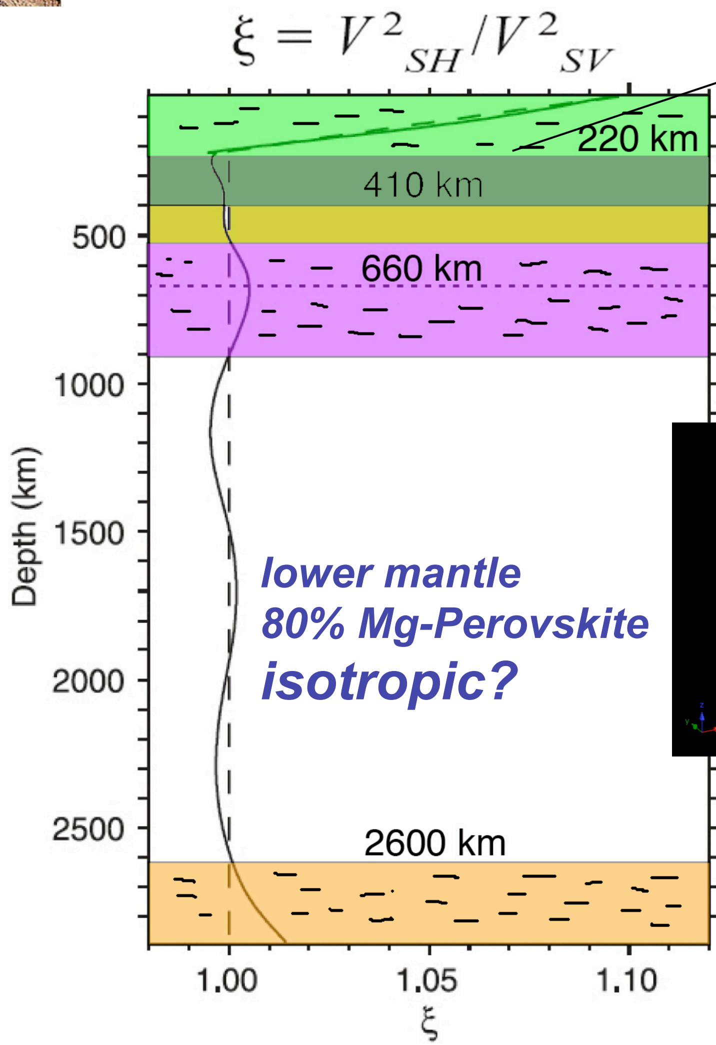
Trampert & VanHeijst Science 2002

Carrez et al., Eur.J.Miner. 2006 (ringwoodite)

Cordier et al. 2005 EMU Notes

Anisotropy & deformation in the deep mantle?

Ab-initio dislocation models + HT-HP experiments + CPO modeling

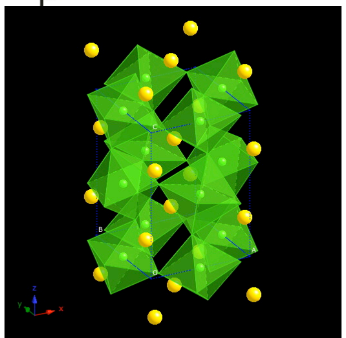


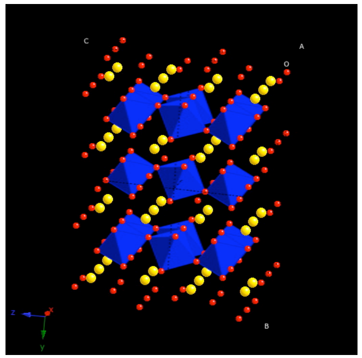
Lehmann discontinuity: transition from LP to HP slip in olivine?

strain-induced anisotropy (CPO) dominant horizontal flow

Vs_H >Vs_V : ringwoodite & garnet isotropic, which mechanism?

lower mantle
80% Mg-Perovskite
isotropic?

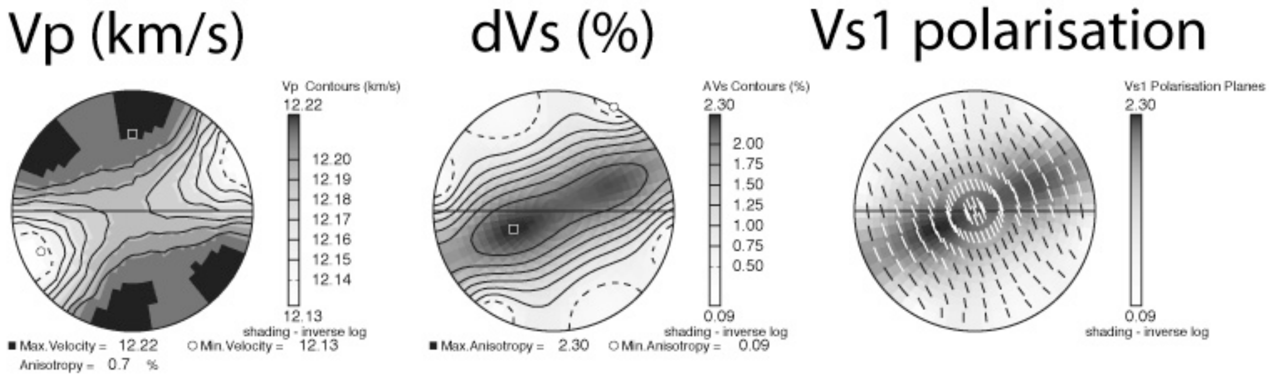




D" layer: Vs_H >Vs_V
80% Post-Perovskite
CPO-induced anisotropy?

Panning & Romanowicz 2004 Science

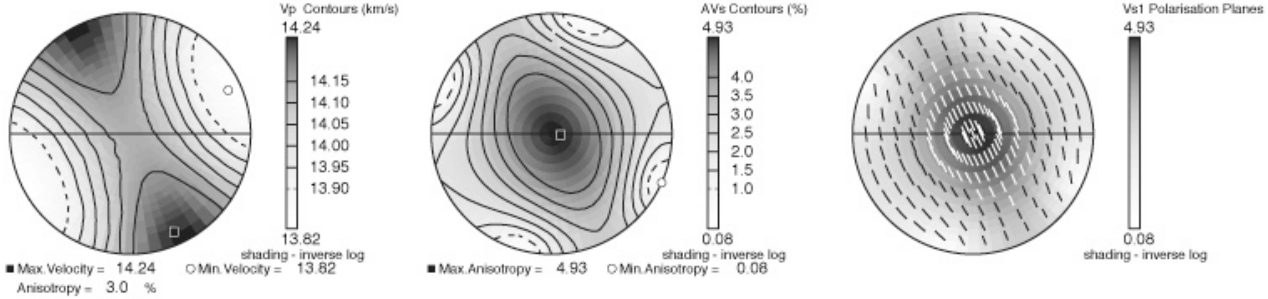
Lower mantle and D" anisotropy: work in progress...



Perovskite 30 GPa

[100](001) dominant

PV>PH OK
SV>SH OK
SKS isotropic OK



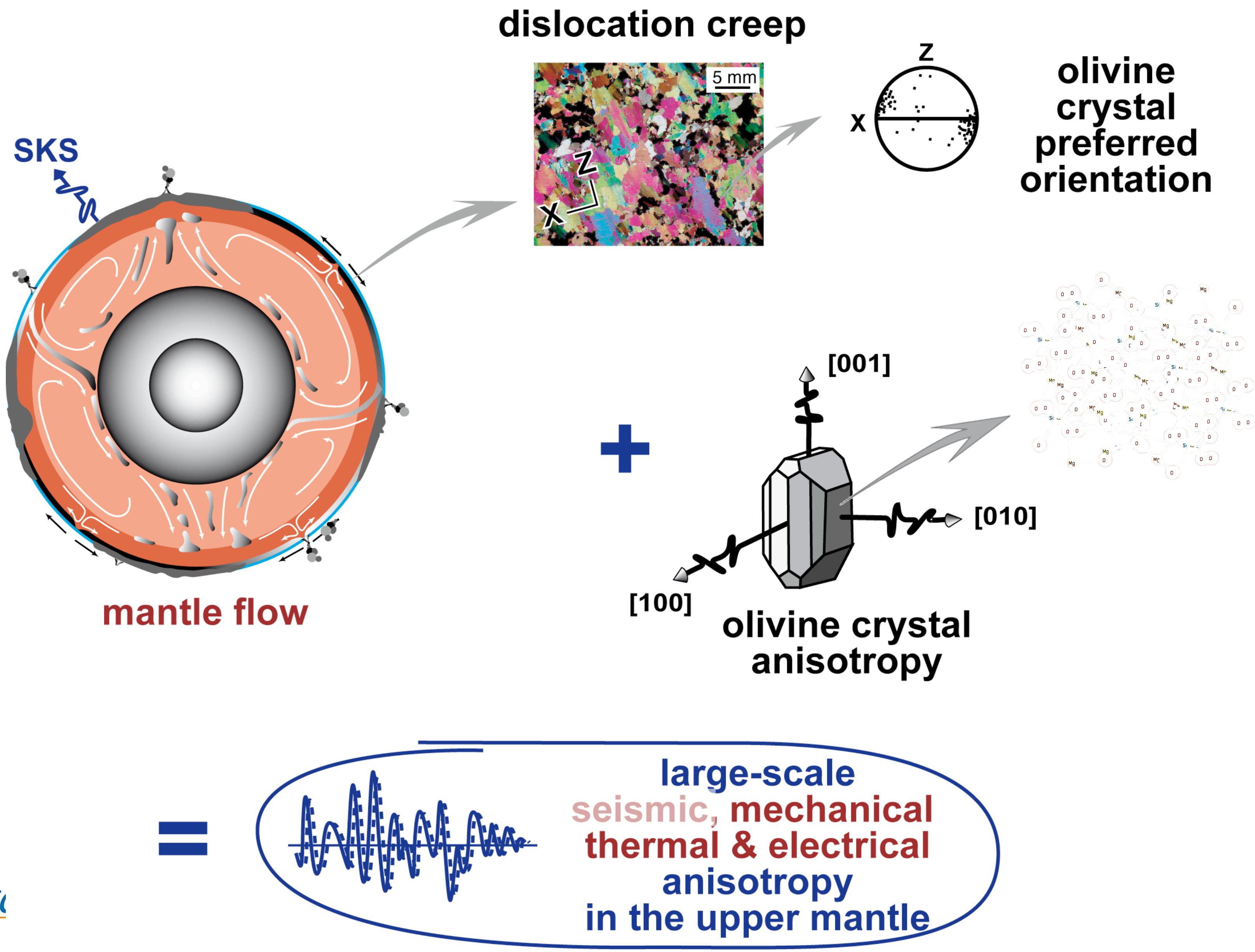
Perovskite 100 GPa

[010](001),[100] (001) & [100](010)

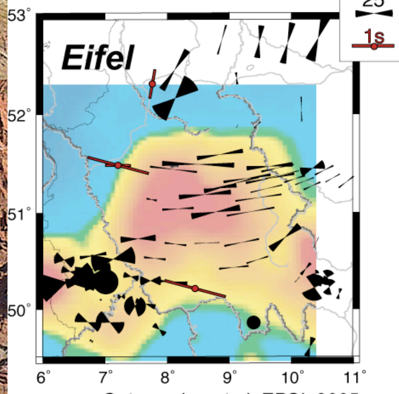
anisotropy increases!

PV>PH OK
SV>SH OK
2% SKS anisotropy?

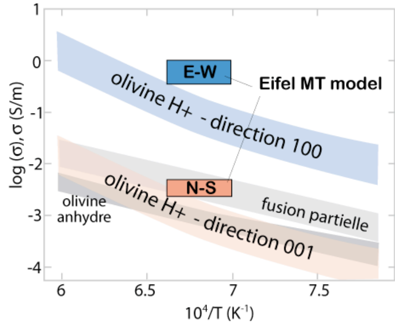
Other anisotropic properties..



Anisotropie de conductivité électrique (données MT longue période): un outil complémentaire pour cartographier la déformation mantellique?



Gatzemeier et al. EPSL 2005



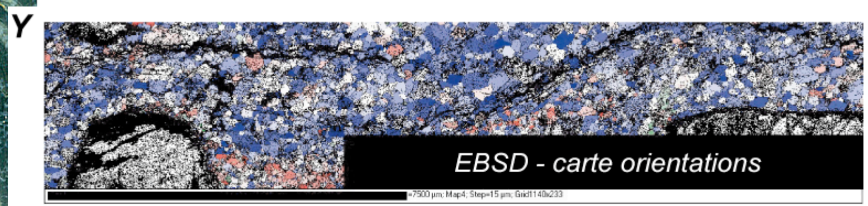
groupe de travail:

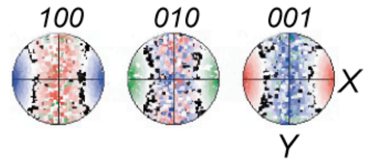
B. Gibert, D. Mainprice, moi (Montpellier)
A. Gatzemeier, F. Simpson, K. Bahr (Goettingen)
J. Ingrin, M. Bystricky, M. Jessel (Toulouse)
I. Vittorello, A. Padilha (Brésil)

- ***anisotropies électrique MT // sismique***
- ***mais anisotropie électrique MT = cristal !!***

Causes physiques de l'anisotropie électrique dans le manteau?

- modélisation numérique de l'anisotropie d'une roche mantellique





$\sigma_y = 6 * \sigma_x$

Conduction = diffusion intracristalline H+

Réseau resistances 2D: Simpson & Tommasi GJI 2005

EF 2,5D: Gatzemeier & Tommasi PEPI sous presse

→ modélisation conduction intracristalline en 3D et aux joints de grains en 2D

- mesure en laboratoire de l'anisotropie de conductivité électrique dans une roche mantellique à HT et fH2O contrôlée (DyETI Gibert 2006)

Géosciences Montpellier

Structural reactivation in plate tectonics controlled by olivine crystal anisotropy

Andréa Tommasi, Mickael Knoll,
Alain Vauchez, Catherine Thoraval,
Javier W. Signorelli,
Roland Logé

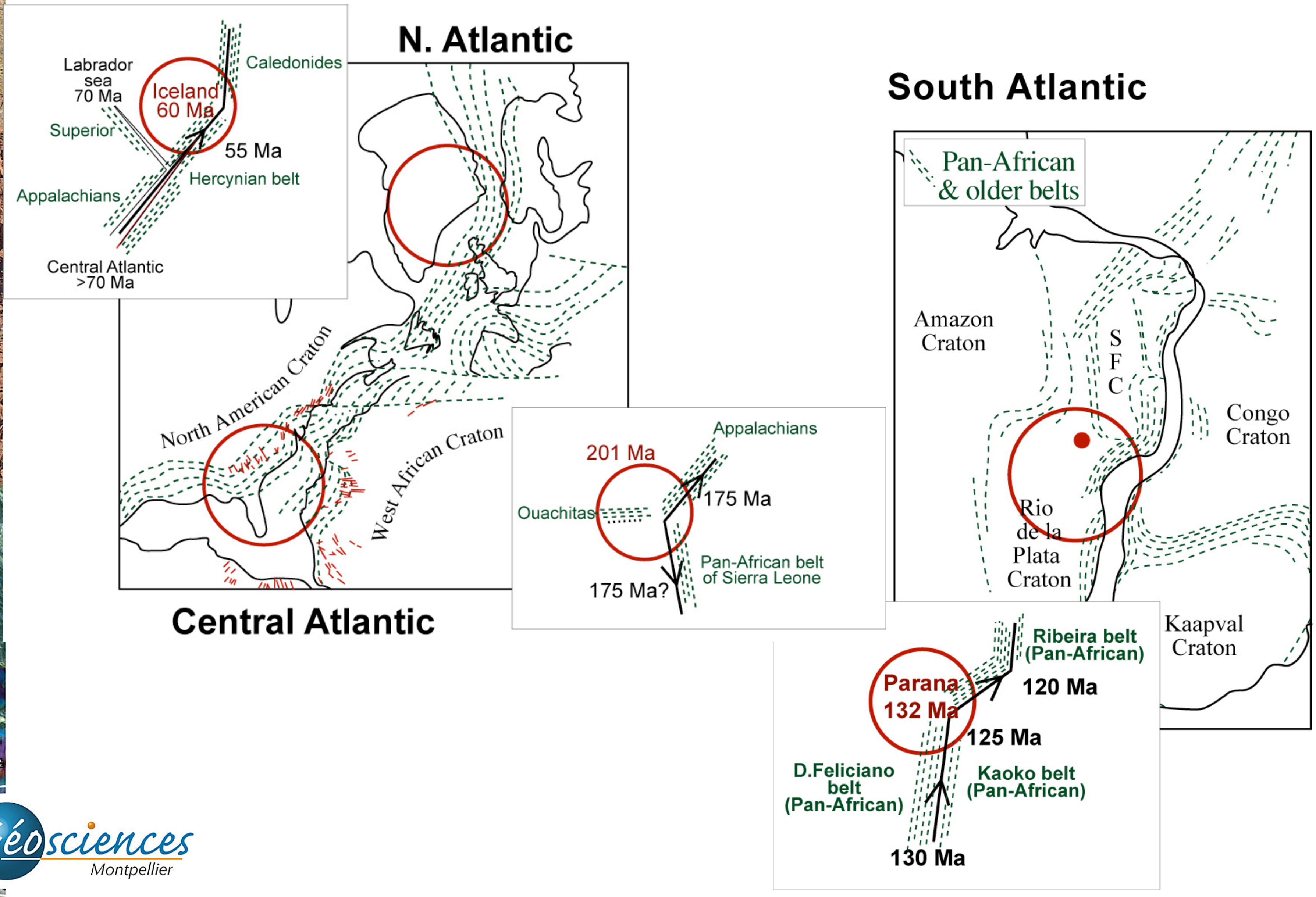
Géosciences Montpellier

IFIR CONICET UNR

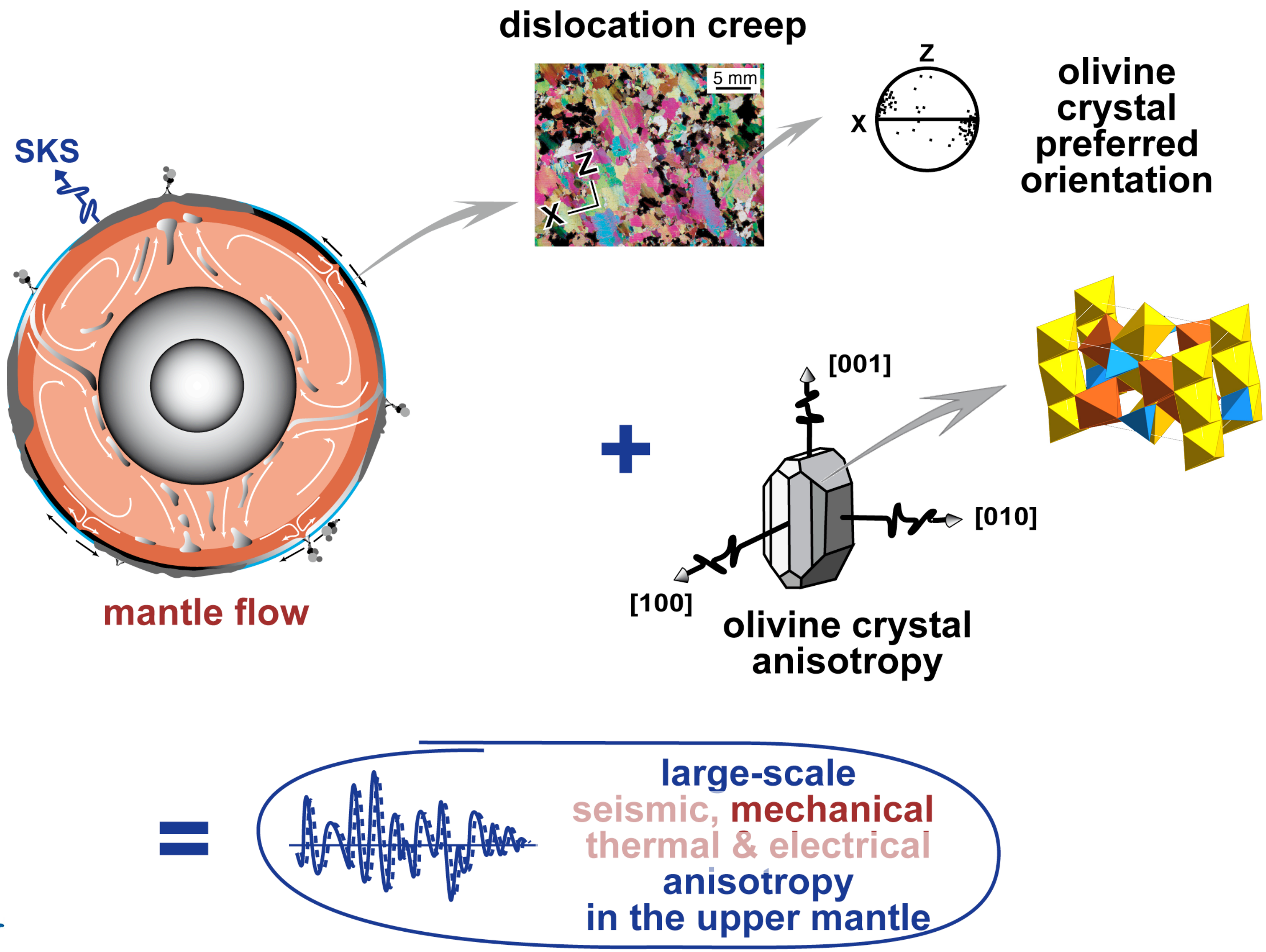
MINES ParisTech

Fall AGU 2009

Structural reactivation: Continental breakup parallel to ancient collisional belts

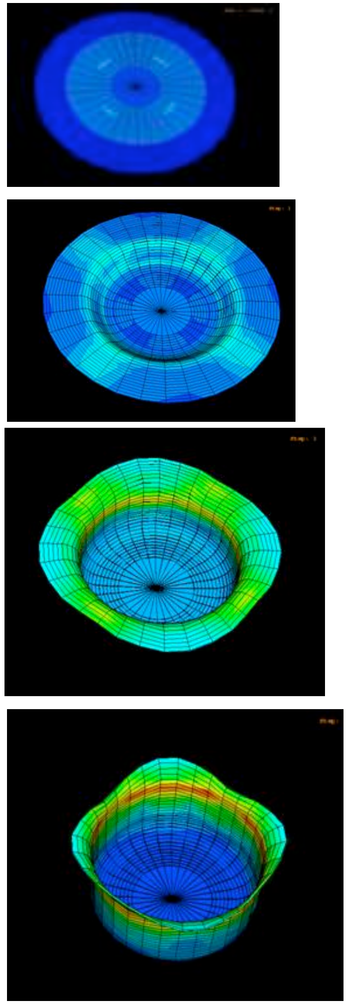


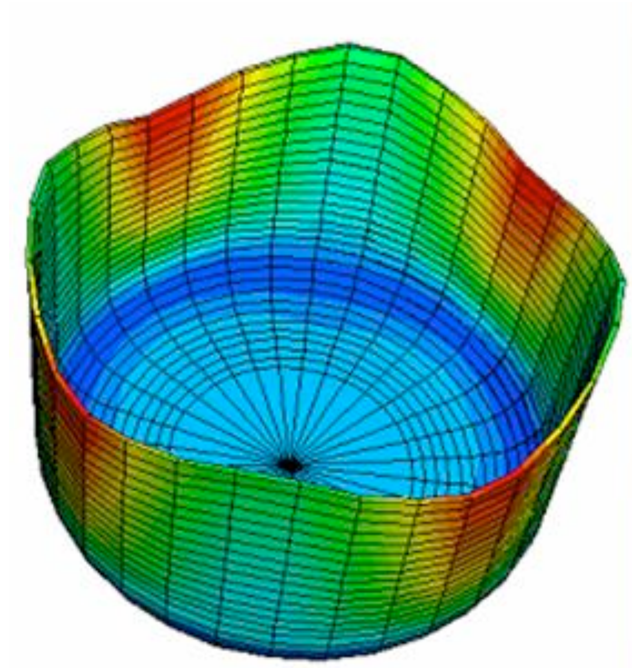
Why? ➔ mechanical anisotropy of the lithospheric mantle due to preferred orientation of anisotropic olivine crystals



In metallurgy:

CPO-induced mechanical anisotropy = 1st order parameter



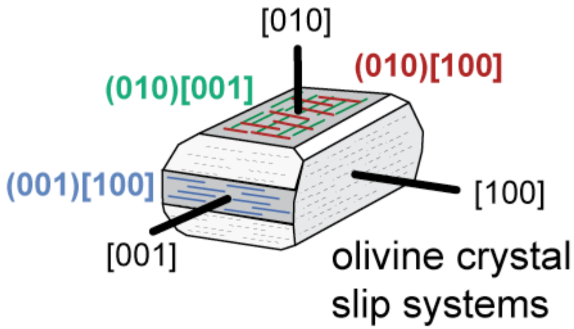


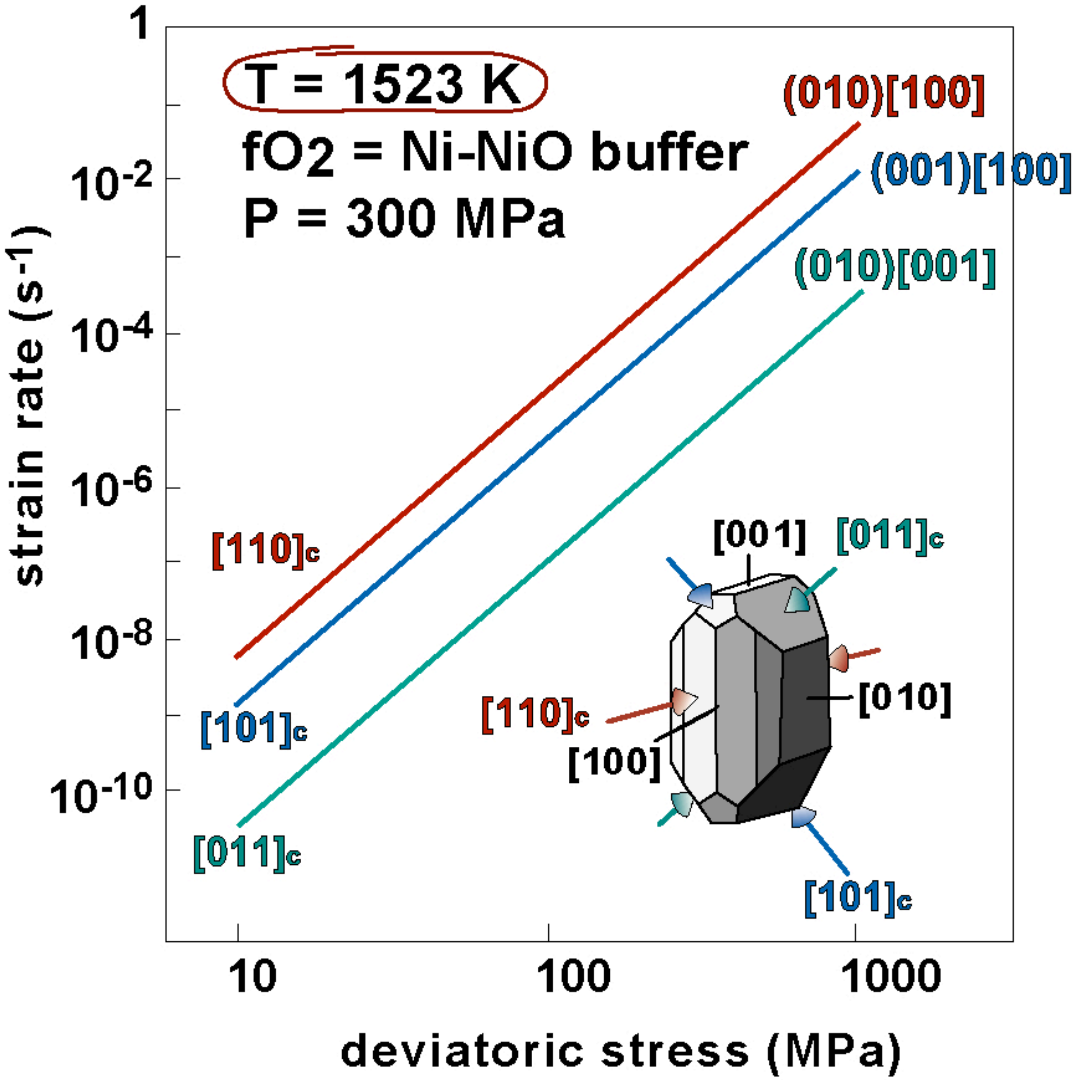
D.Raabe, Max Planck Institut

Earing of Al cans ➔ mechanical anisotropy Al crystal + preferred orientation of crystals developed during the production of the sheet (rolling)

ductile deformation of an olivine crystal is anisotropic:

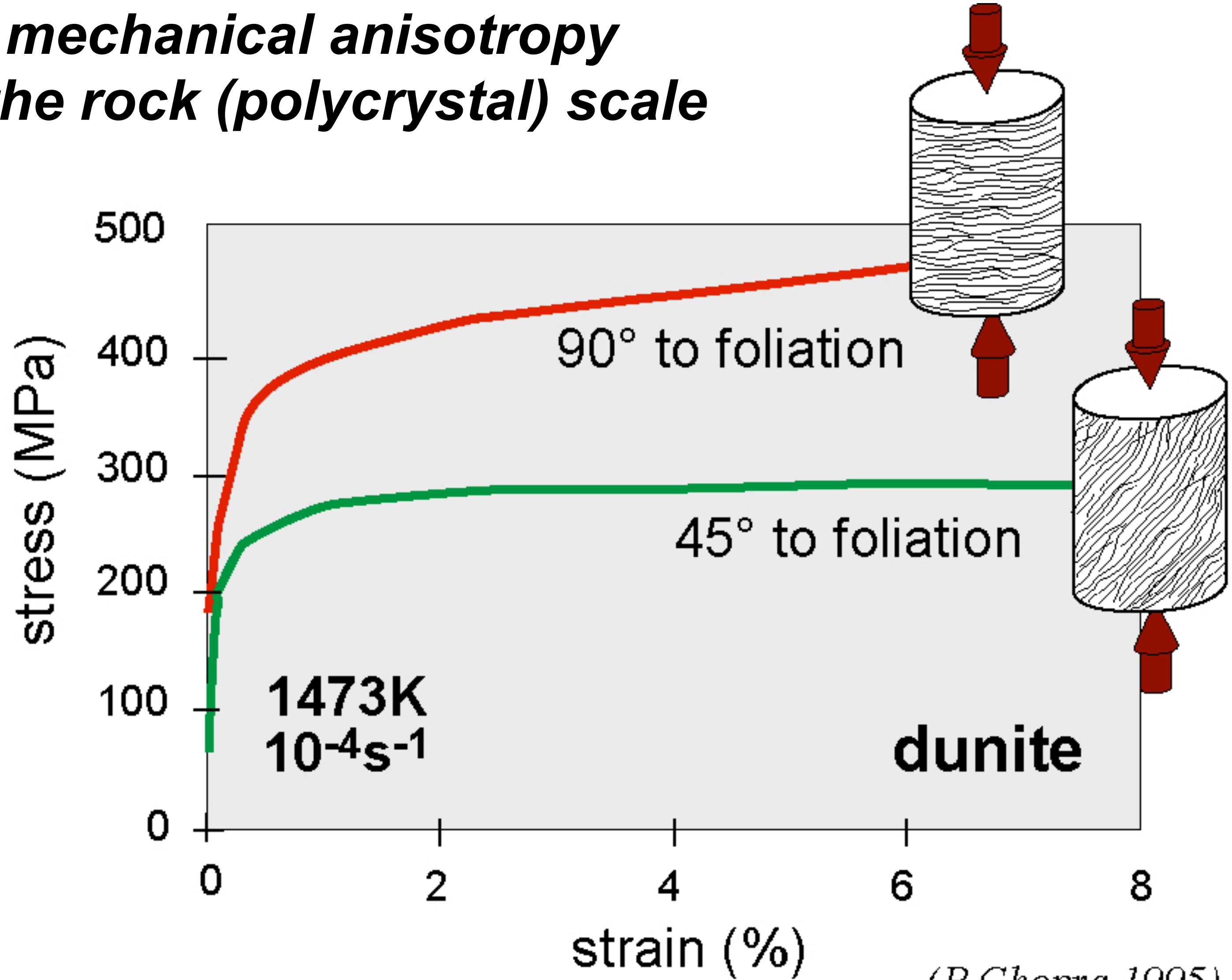
few slip systems with highly ≠ strenghts





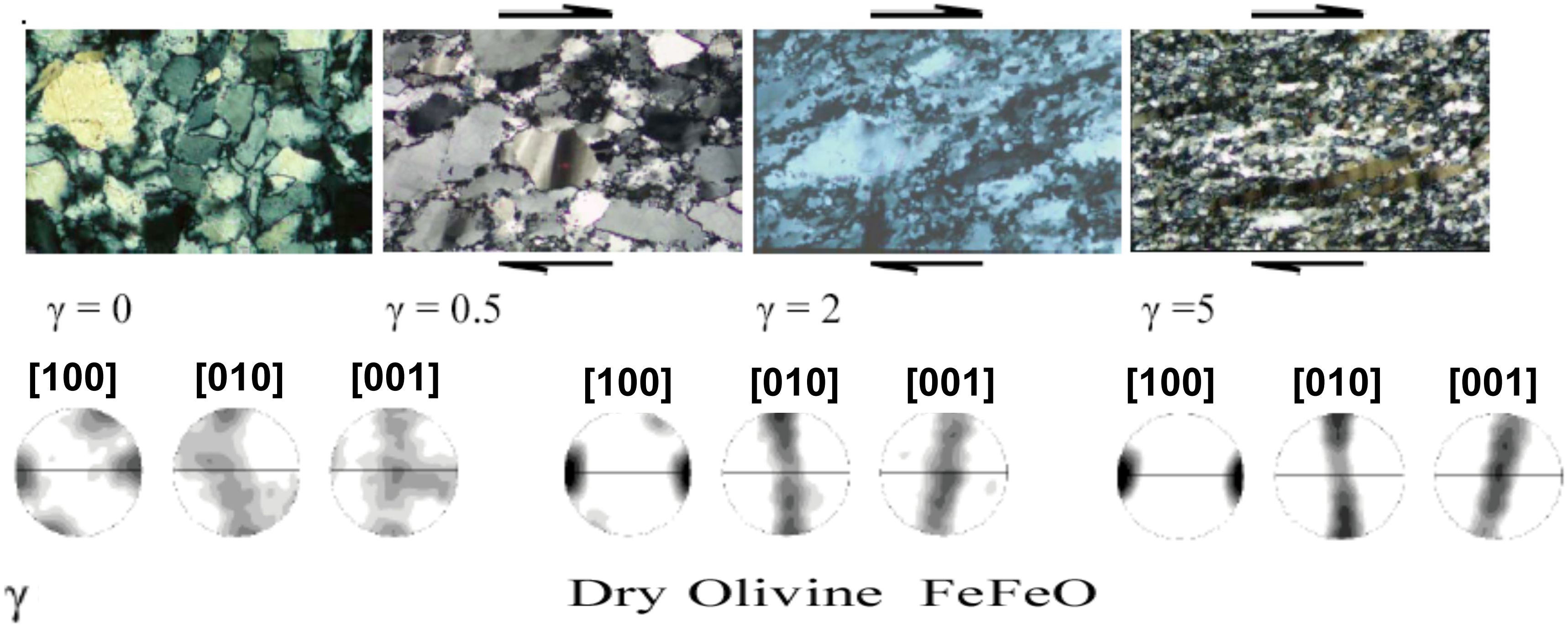
Bai et al. 1990 - JGR

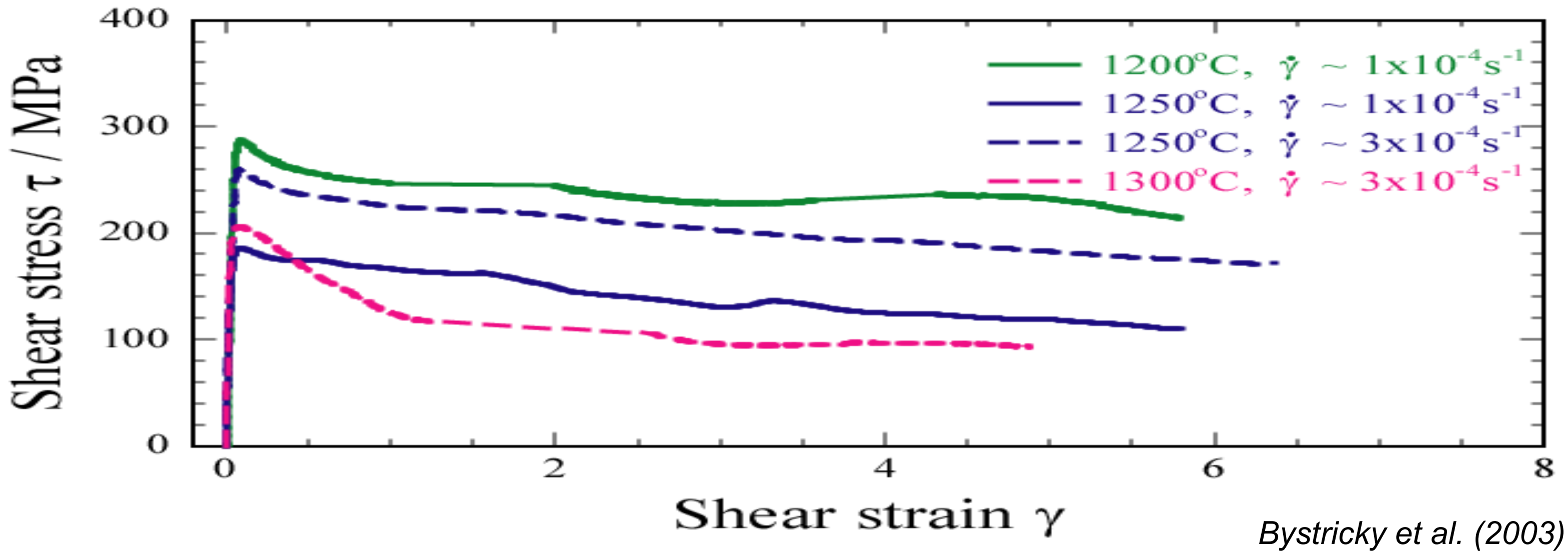
olivine crystal anisotropy + cristallographic orientations (CPO) = mechanical anisotropy at the rock (polycrystal) scale



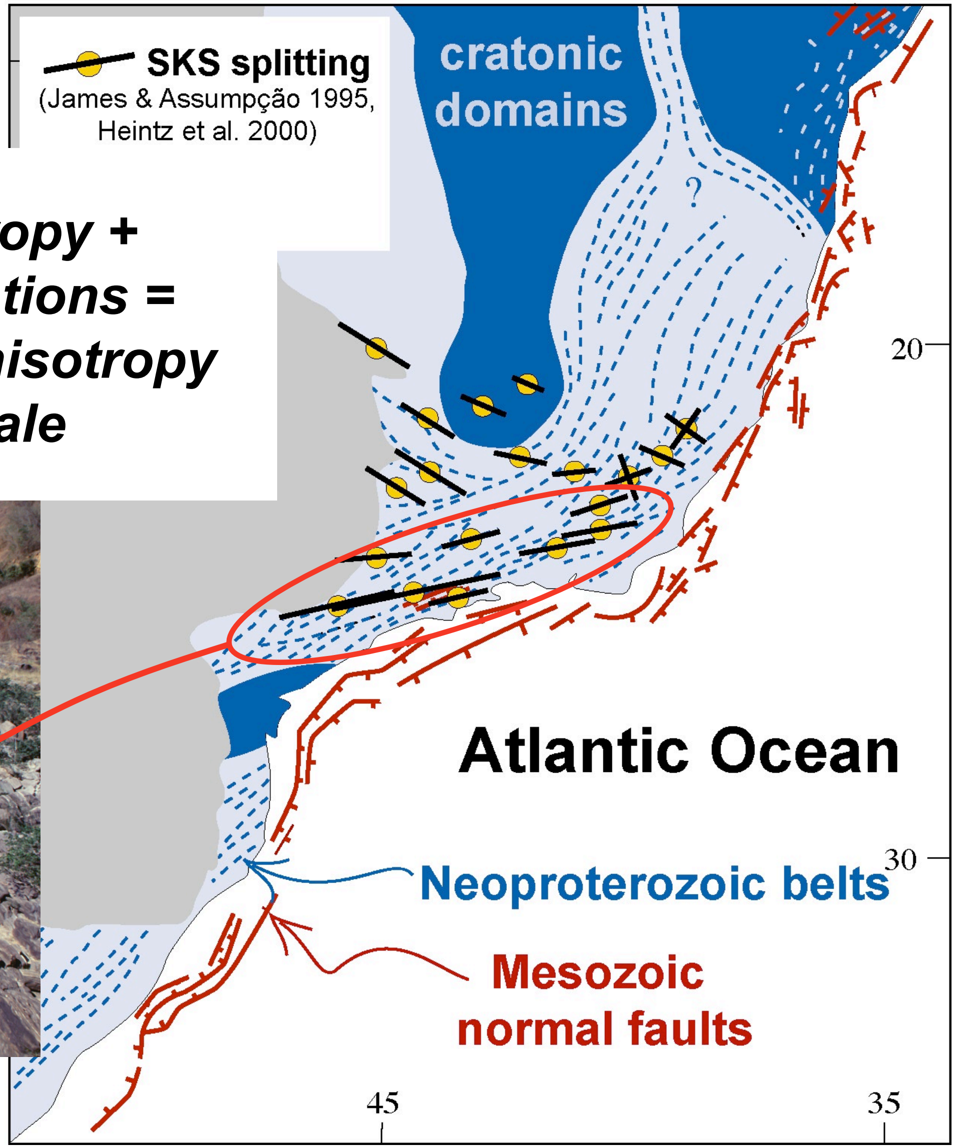
(P.Chopra, 1995)

Strain weakening in torsion experiments ⇔ olivine CPO evolution ?





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

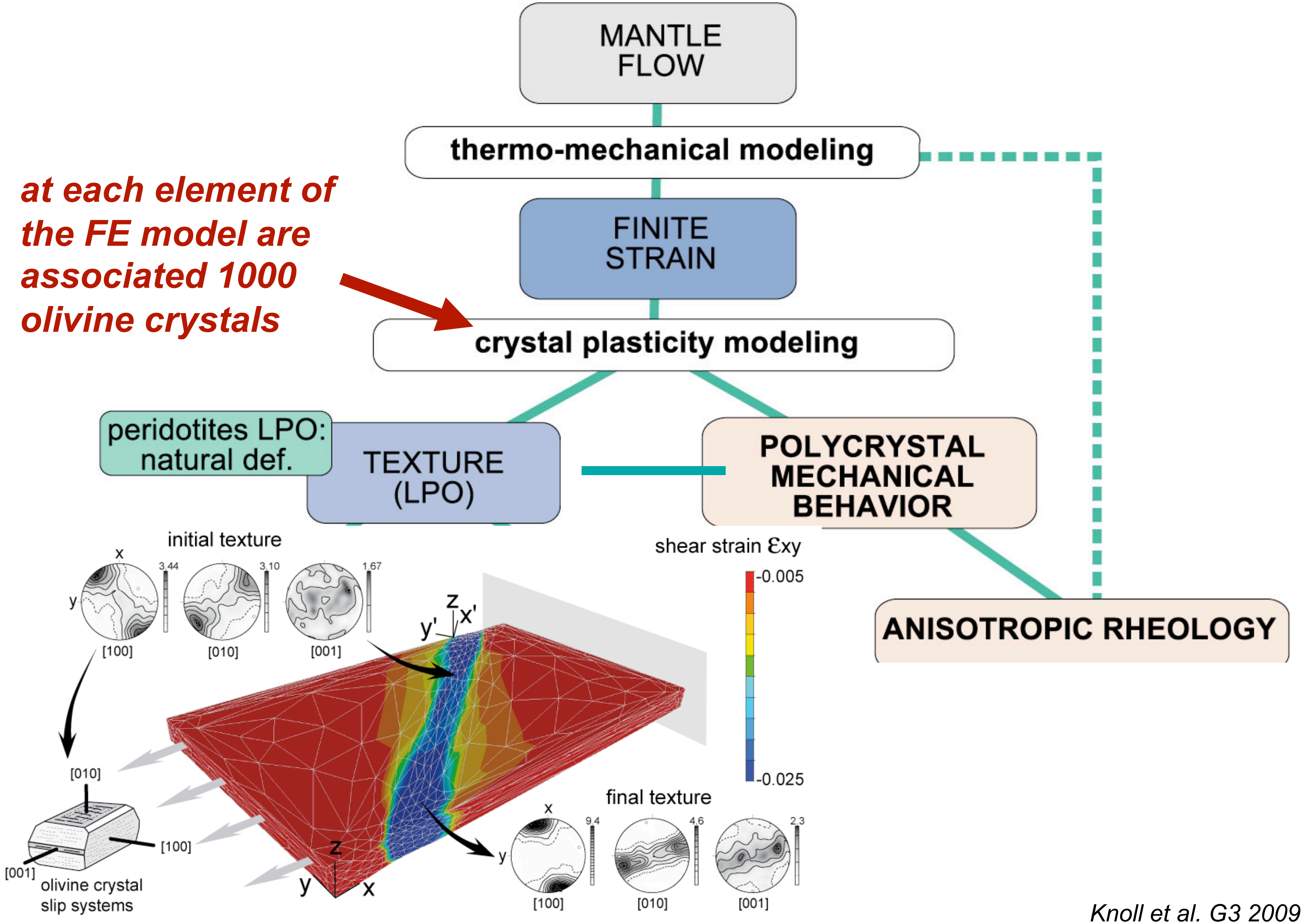


olivine crystal anisotropy + cristallographic orientations = seismic & mechanical anisotropy at the continent scale

Control the formation of new plate boundaries: rifting?

Géosciences Montpellier

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

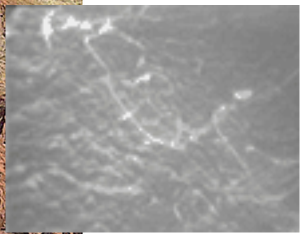


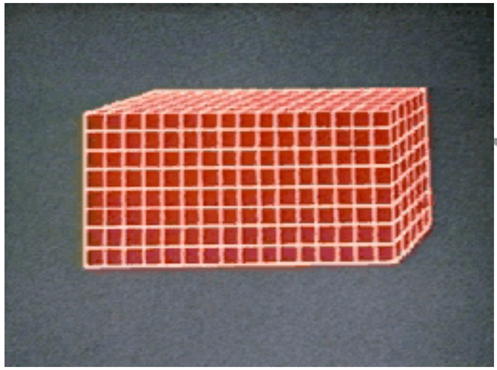
Knoll et al. G3 2009

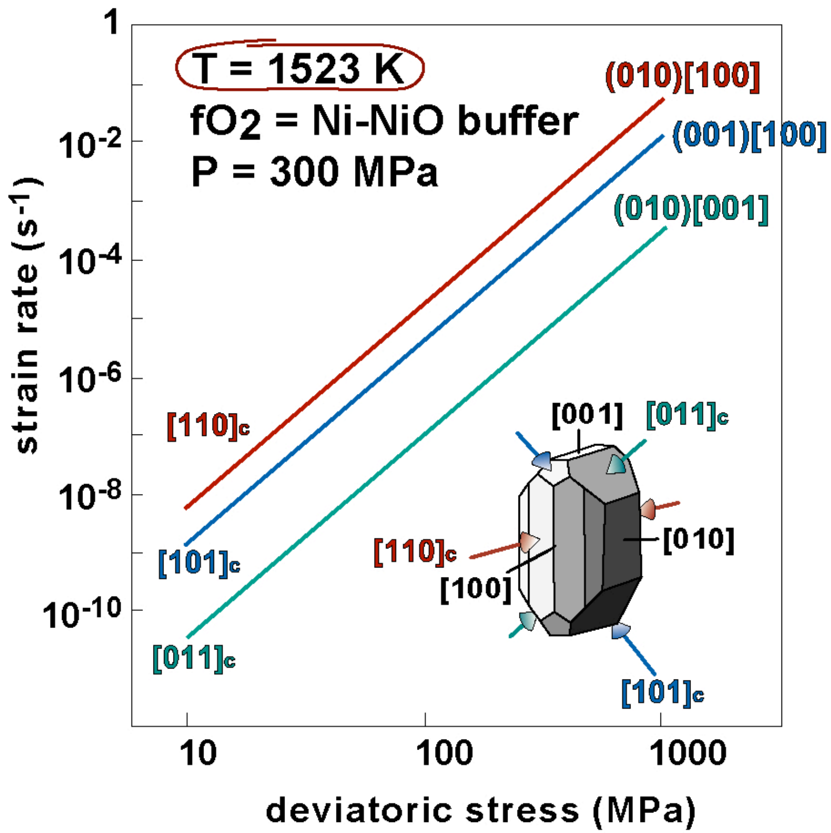
Modeling the deformation of a polycrystalline aggregate

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

within a grain (crystal):



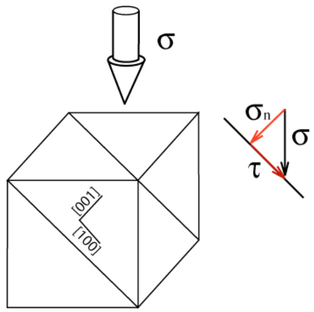




Bai et al. 1990 - JGR

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

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



Input : slip systems' strength, initial texture & mechanical sollicitation (stress or velocity gradient tensor)

output: evolution of crystallographic orientations & mechanical response (strain rate or stress tensor)

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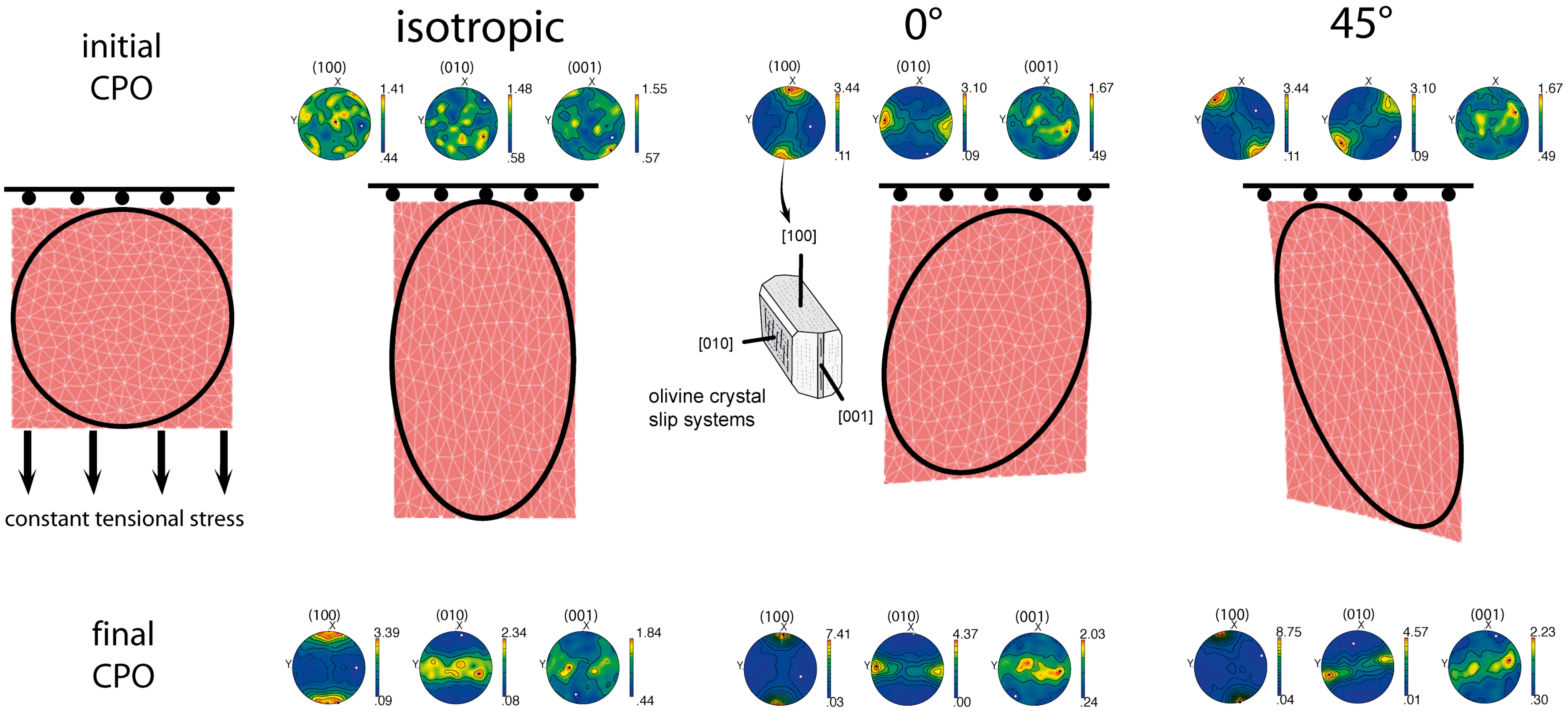
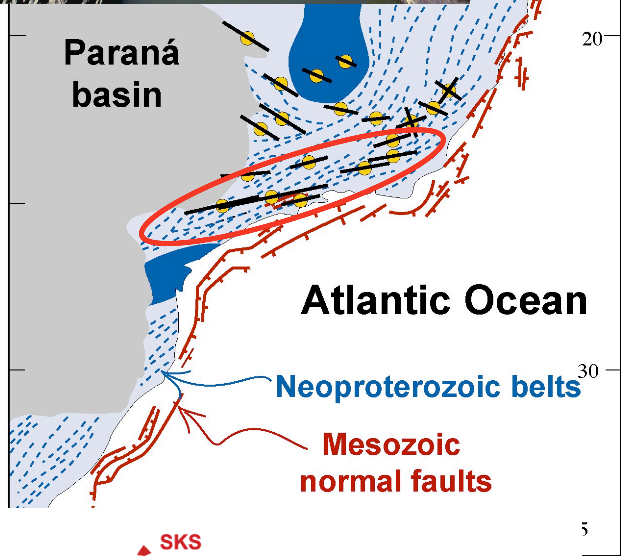
Deformation of a homogeneous, BUT textured plate is strongly anisotropic

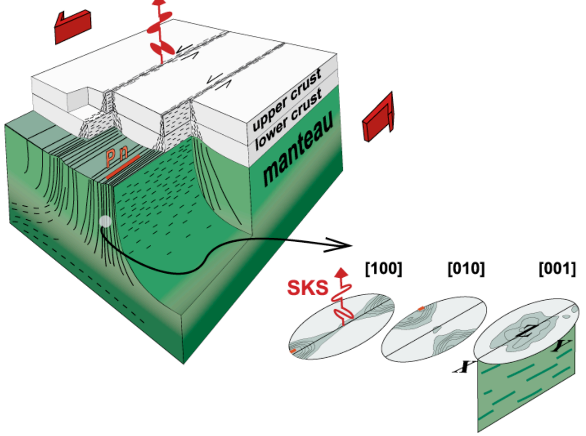


- *strength & final deformation depend on the initial CPO*
- *finite strain ellipsoid axes are not parallel to stress ones*
  - ➢ *shearing // to average orientation of main olivine slip systems*

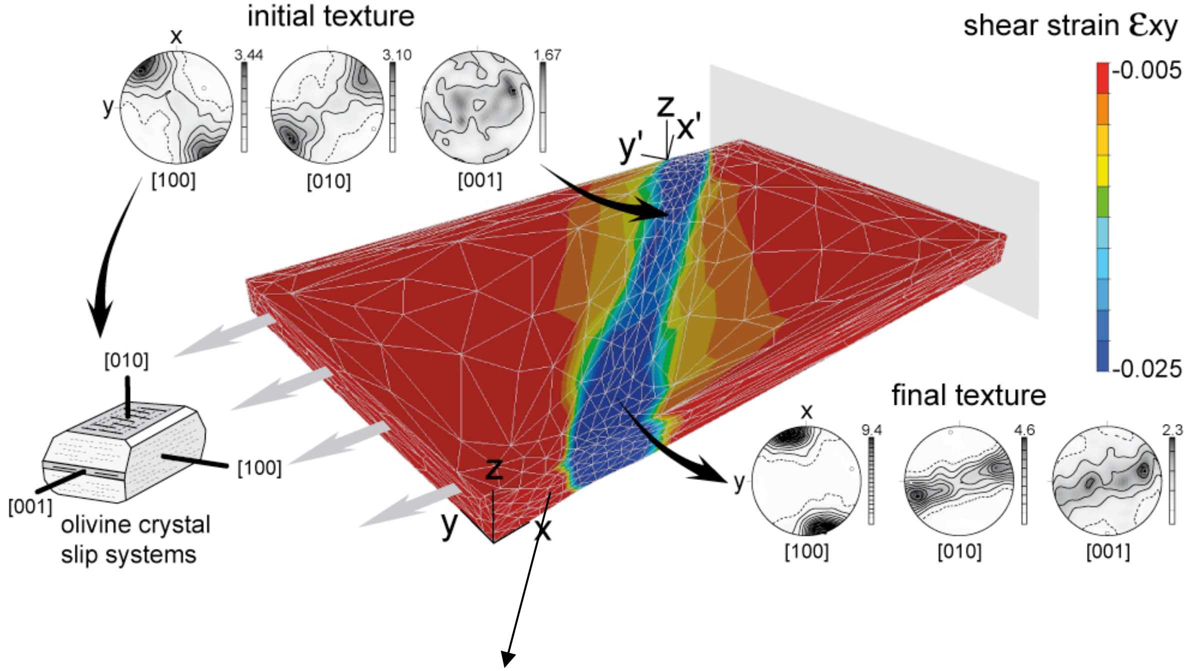
Knoll et al. G3 2009

Multi-domain models: Reactivation of a transpressional belt
(lithospheric-scale strike-slip faults)





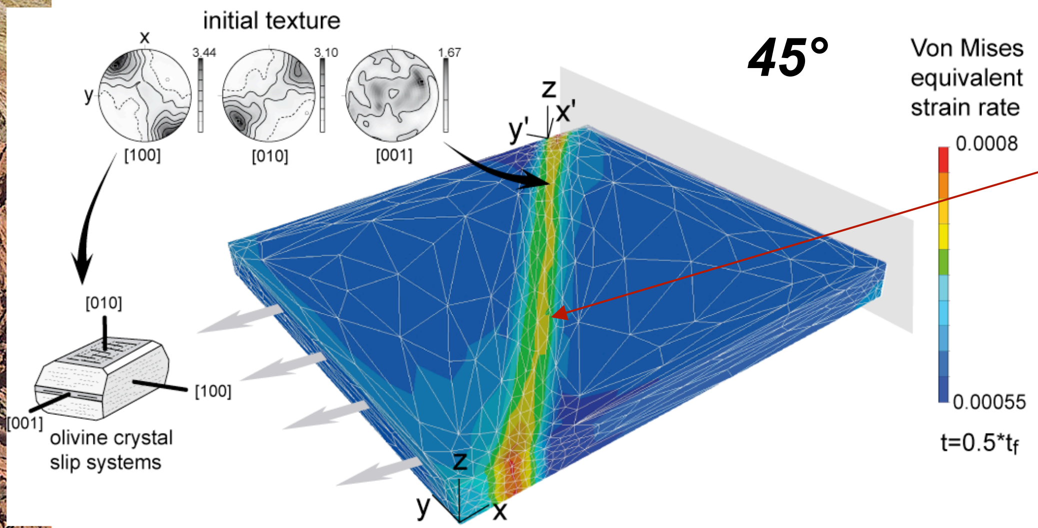
within the "old" strike-slip domain



outside = CPO initially random

Tommasi et al Nature Geoscience 2009

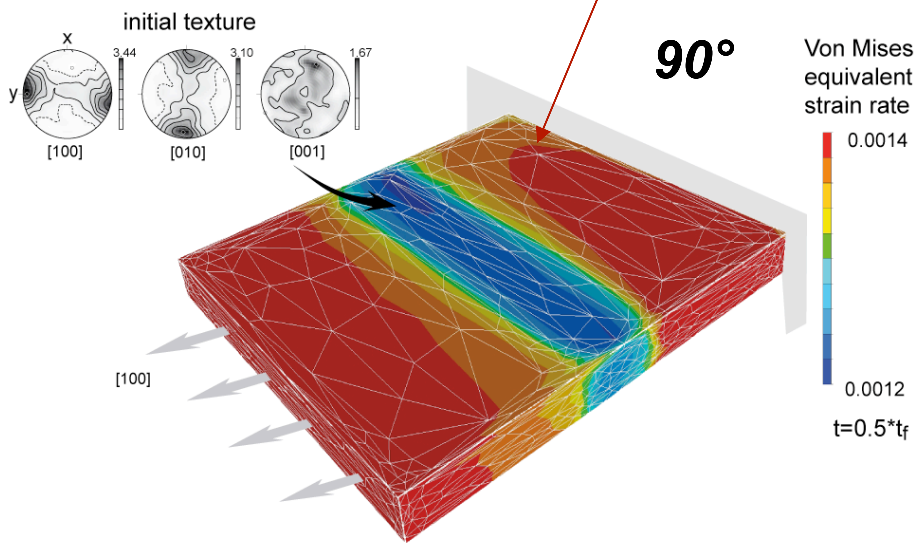
Mechanical anisotropy of the lithospheric mantle (frozen-in olivine crystal preferred orientations):



strain localization in the inherited SZ

higher strain rates outside the inherited SZ

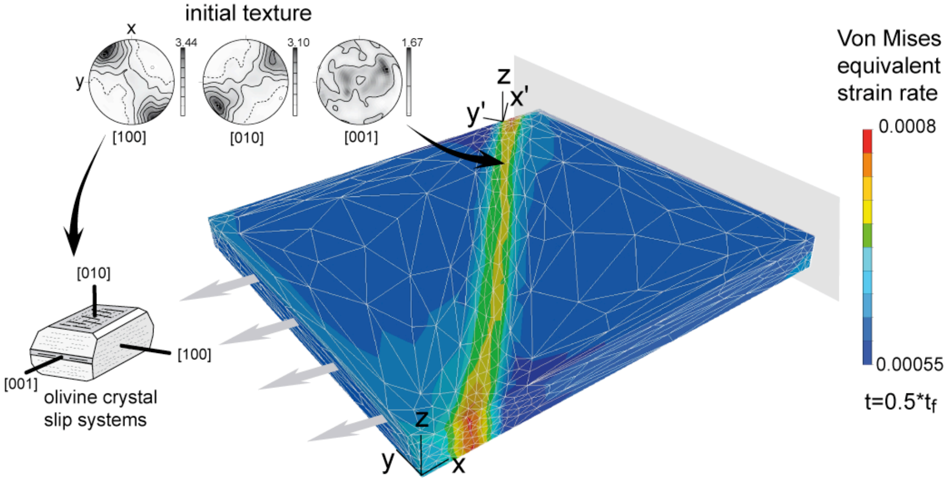
Strain distribution depends on the orientation of the preexisting mantle fabric relative to the imposed stress field

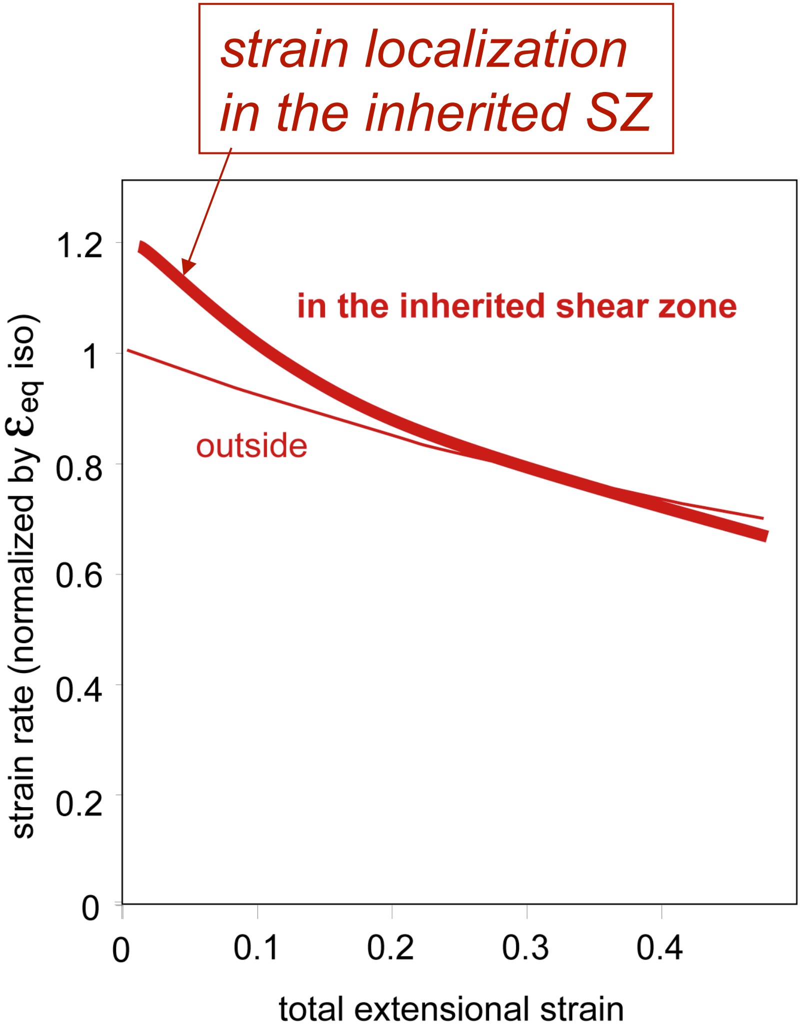


Géosciences Montpellier

Tommasi et al Nature Geoscience 2009

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

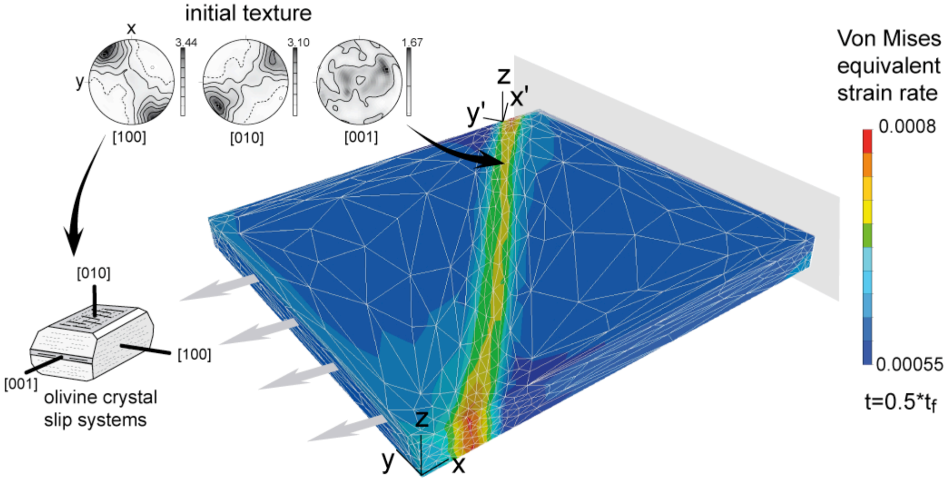


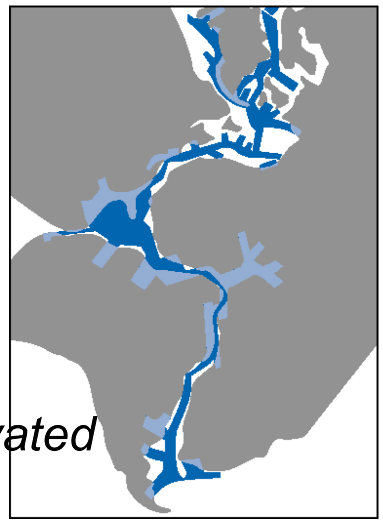


Géosciences Montpellier

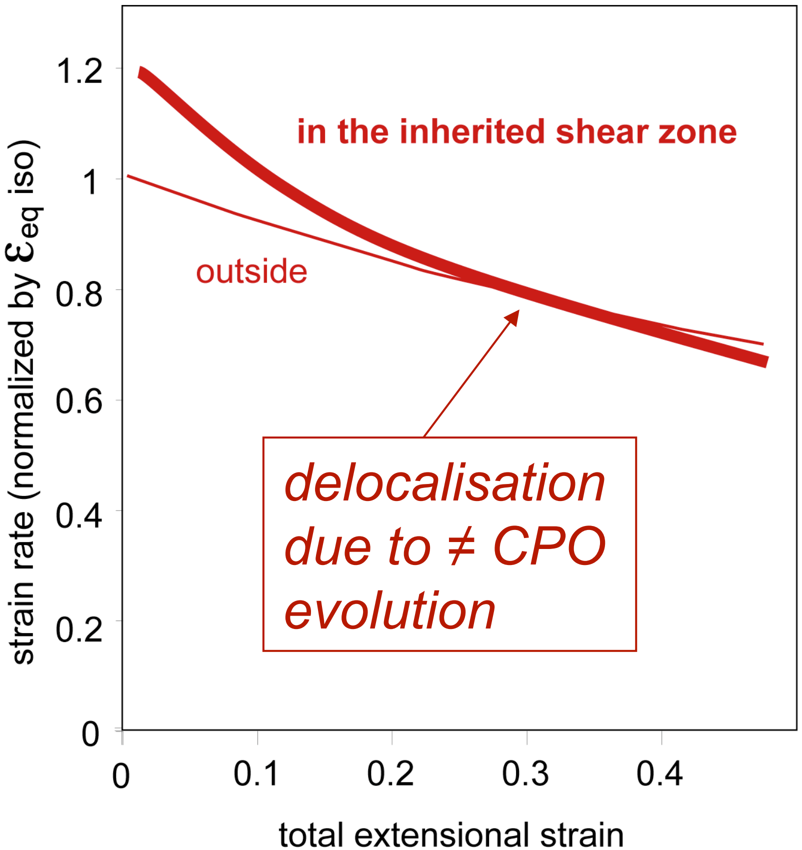
Reactivation of a lithospheric-scale strike-slip zone due to mechanical anisotropy of the lithospheric mantle

(frozen-in olivine crystal preferred orientations)



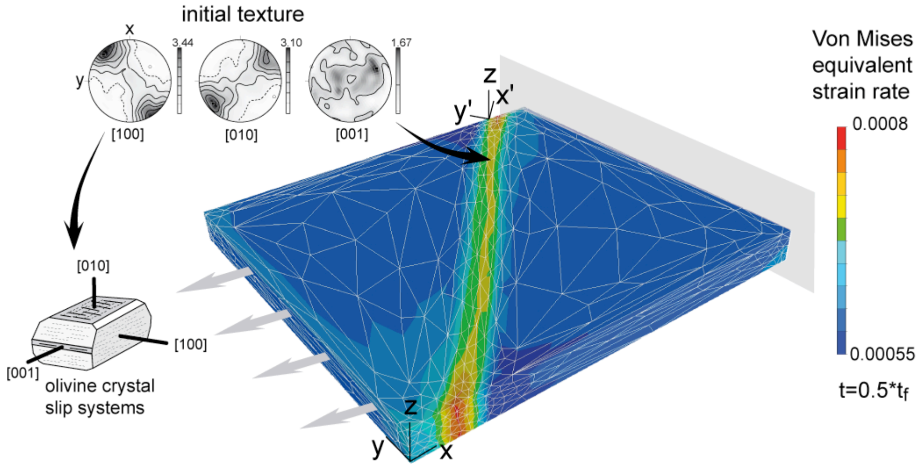


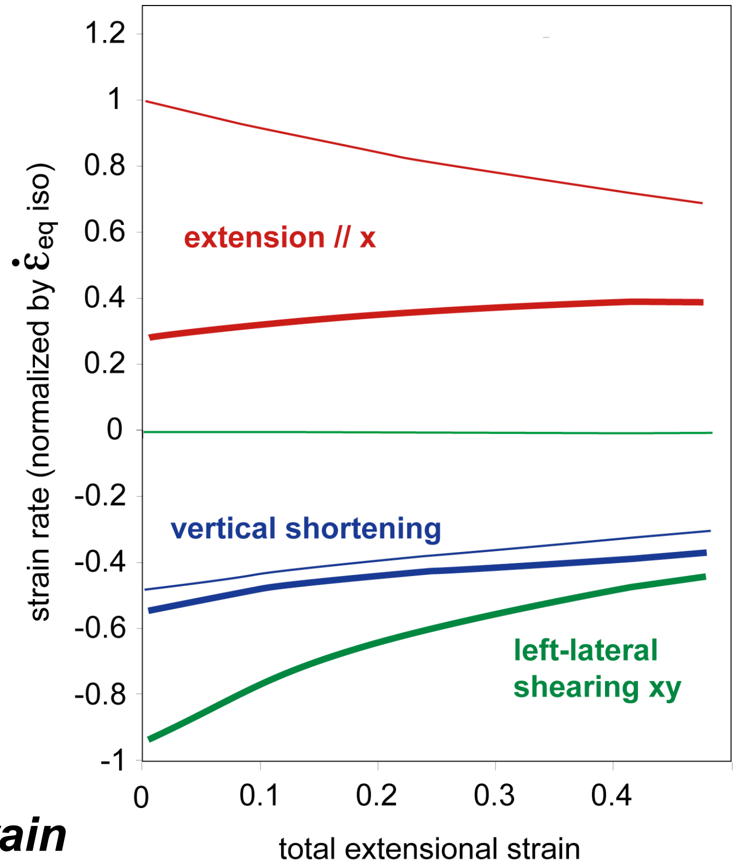
rift avorts if another strain localisation mechanism is not activated



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

(frozen-in olivine crystal preferred orientations)





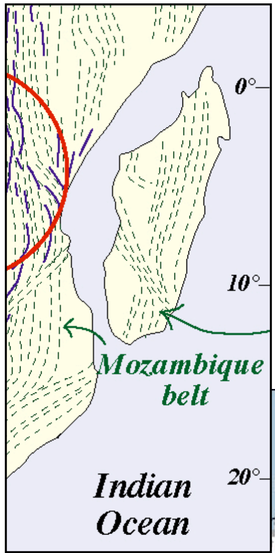
transtension in the inherited shear zone,
but shearing decreases with increasing strain

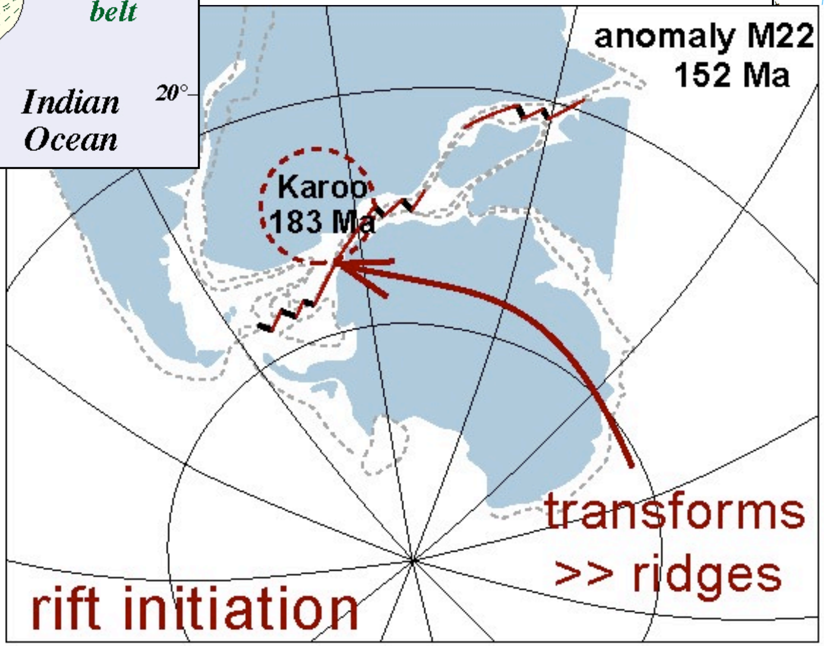
normal extension & thinning outside

Tommasi et al Nature Geoscience 2009

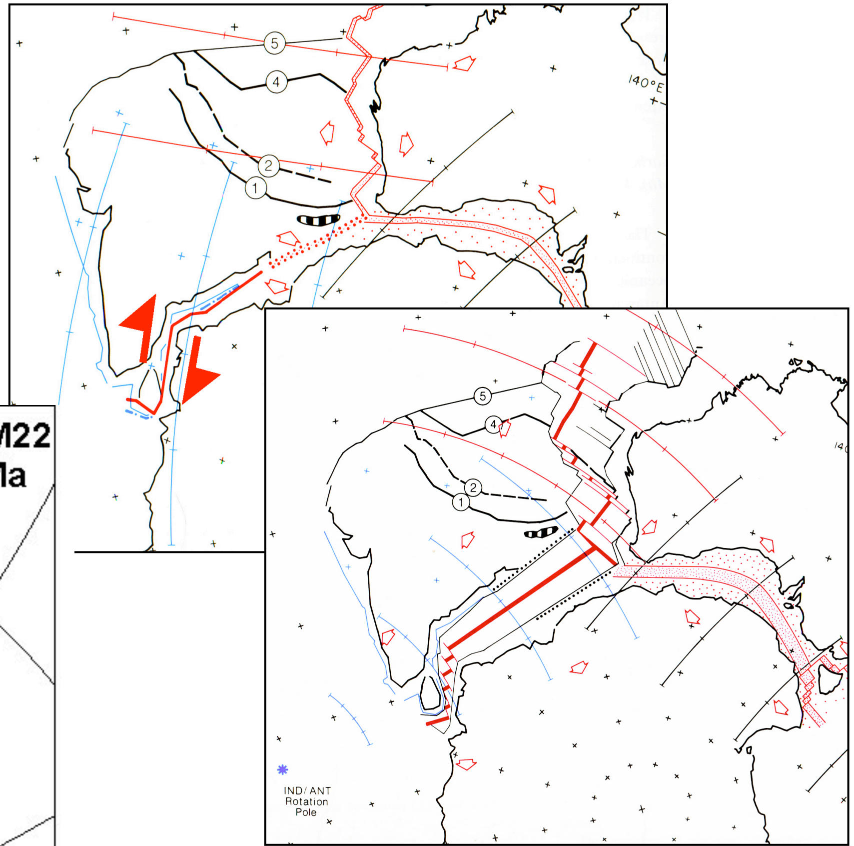
Model predictions : reactivation of preexisting faults in transtension in the initial stages of rifting followed by normal extension

E Gondwana breakup



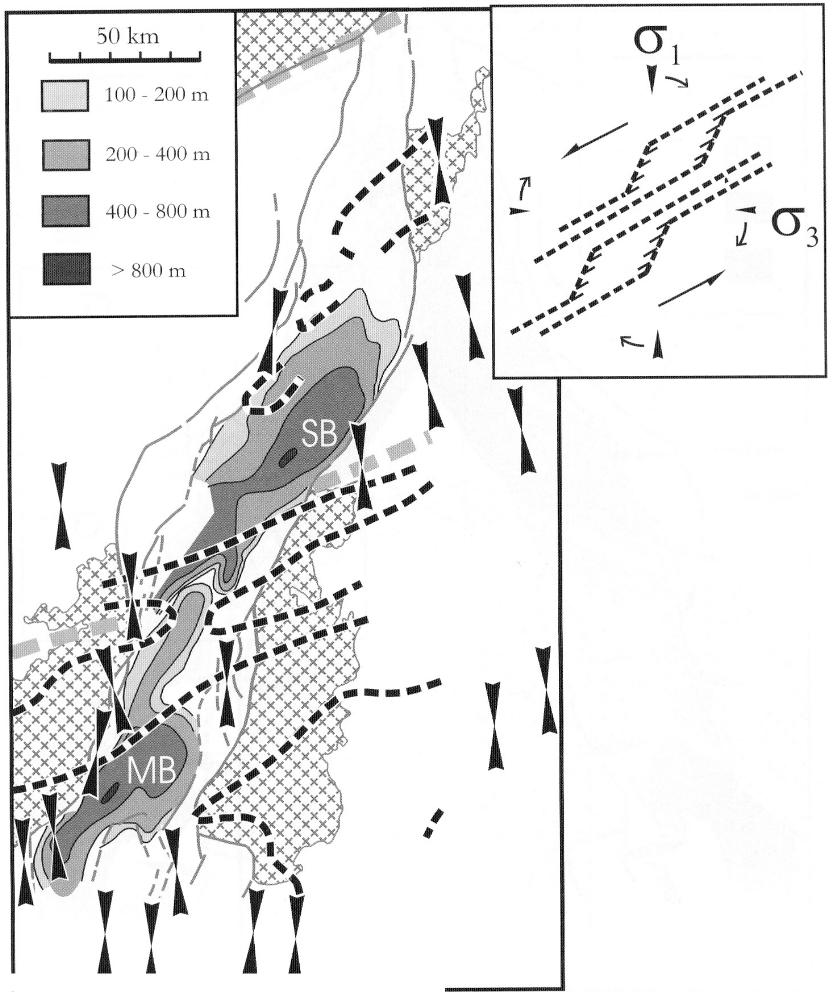


Lawer et al., Tectonophysics, 1985



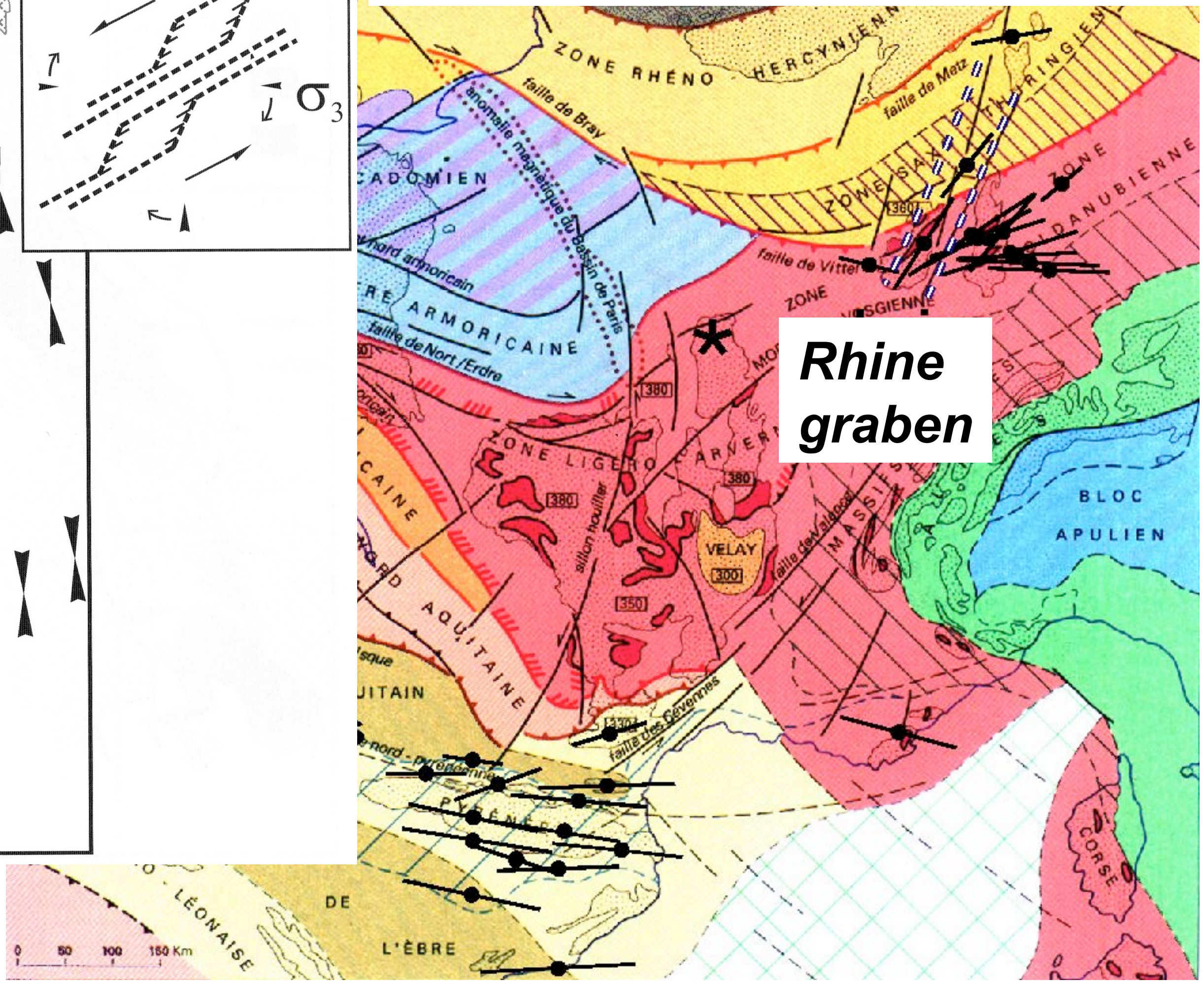
Powell et al., Tectonophysics, 1988

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



Schumacher Tectonics 2002

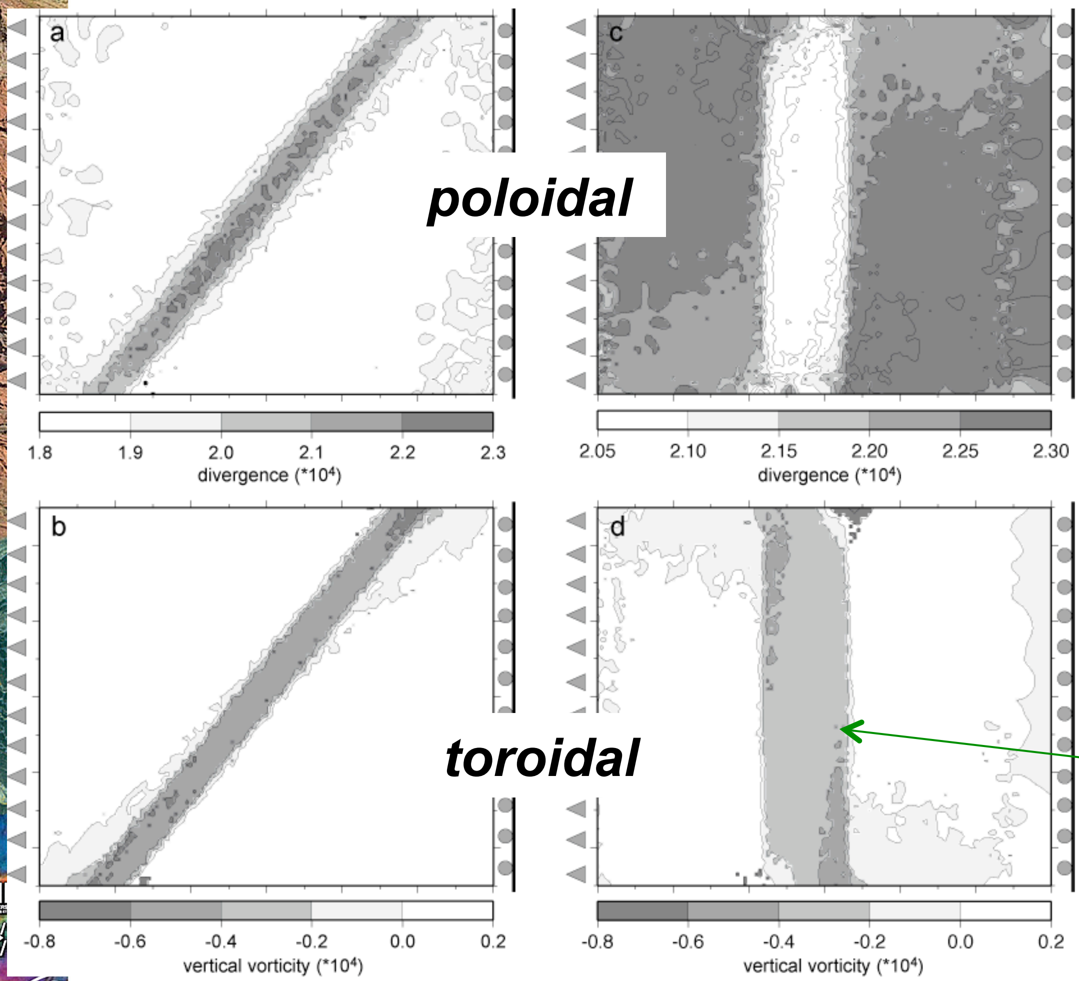
Eocene : pull apart basins
shearing // to Hercynian structures

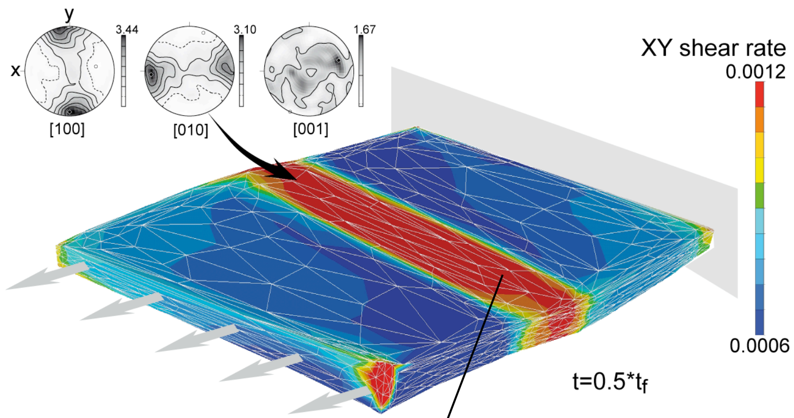


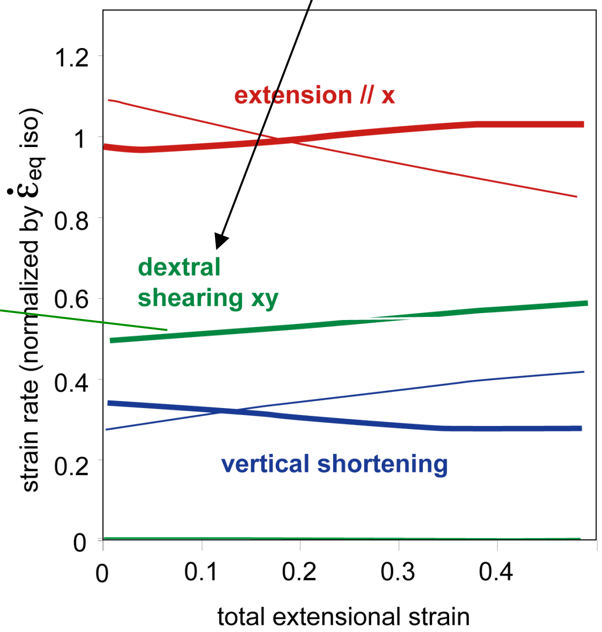
Montpellier

CPO-induced mechanical anisotropy = shearing // to preexisting mantle fabric

Reactivation of prexisting strike-slip faults:
transforms convection-induced poloidal sollicitations
(plate convergence or divergence) into toroidal (strike-slip) flow







Tommasi et al Nature Geoscience 2009

Mechanical anisotropy of the lithospheric mantle
(frozen-in olivine crystal preferred orientations)

- *Intrinsic characteristic of the plates: olivine CPO are preserved in the lithospheric mantle until a new deformation occurs*

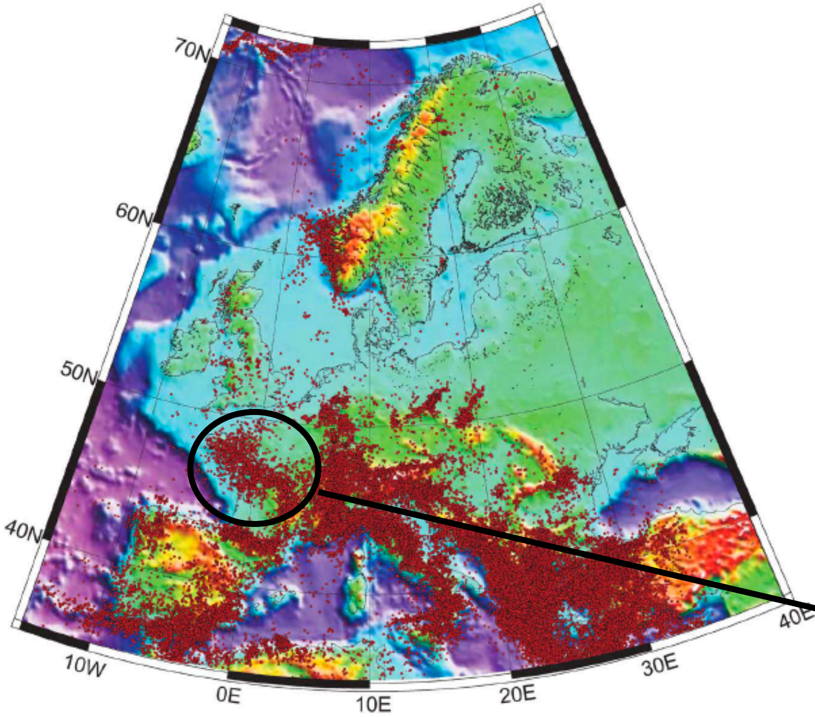
- *1st order parameter in plate tectonics :*
  together with rheological heterogeneity, anisotropy leads to intraplate strain localization:
  - *- initiation of rifting*
  - *- linear belts of intraplate seismicity + volcanism?*
    // to ancient lithospheric faults

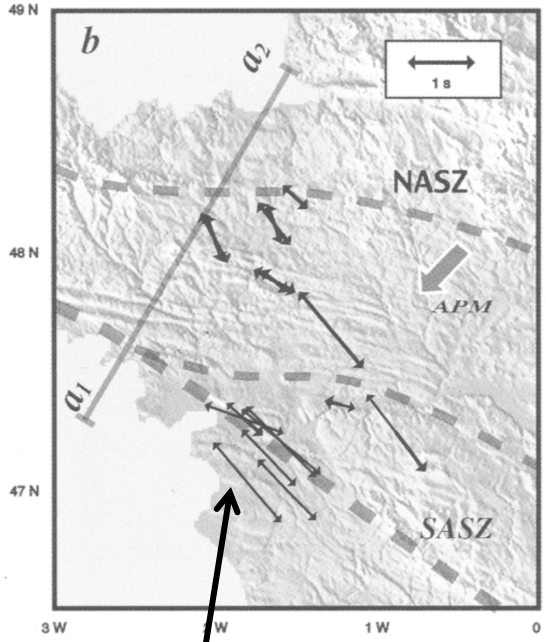
- *highly effective in transforming convection-related poloidal flow into toroidal (strike-slip) motions*

- *except for shearing // to preexisting faults, olivine CPO evolution results in hardening ➔ delocalization unless other strain softening mechanisms are activated*

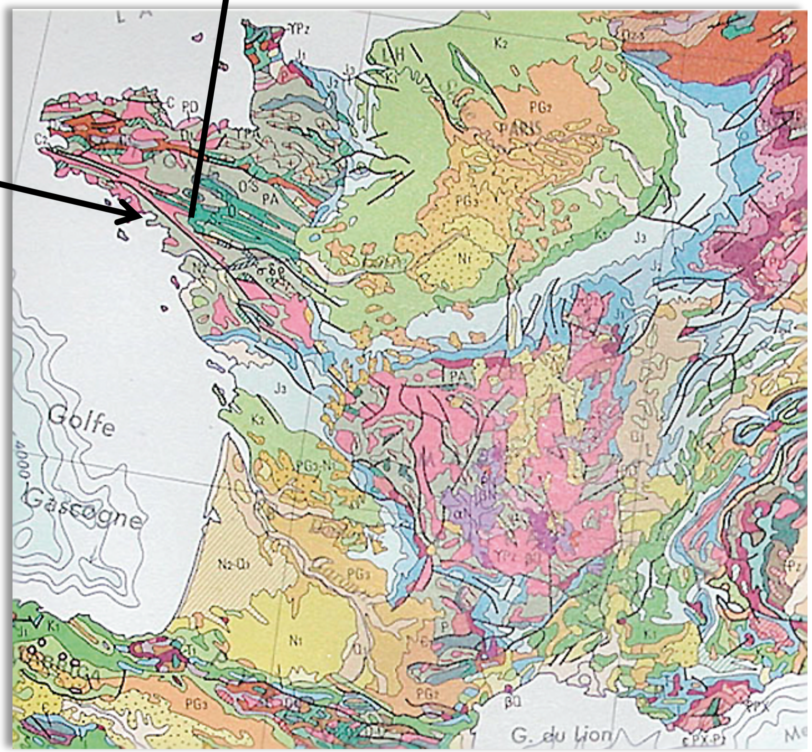
Intraplate seismicity

S. Cloetingh et al. / Quaternary Science Reviews 24 (2005) 241–304



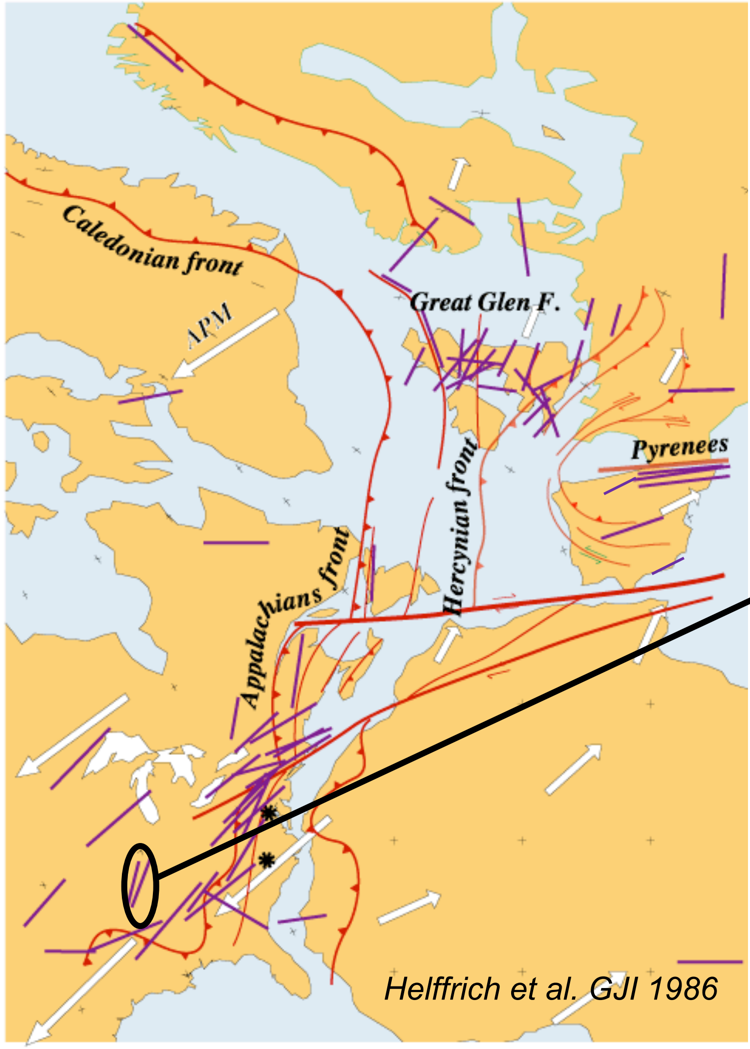


SKS splitting,
Judenherc et al.
BSGF 2003



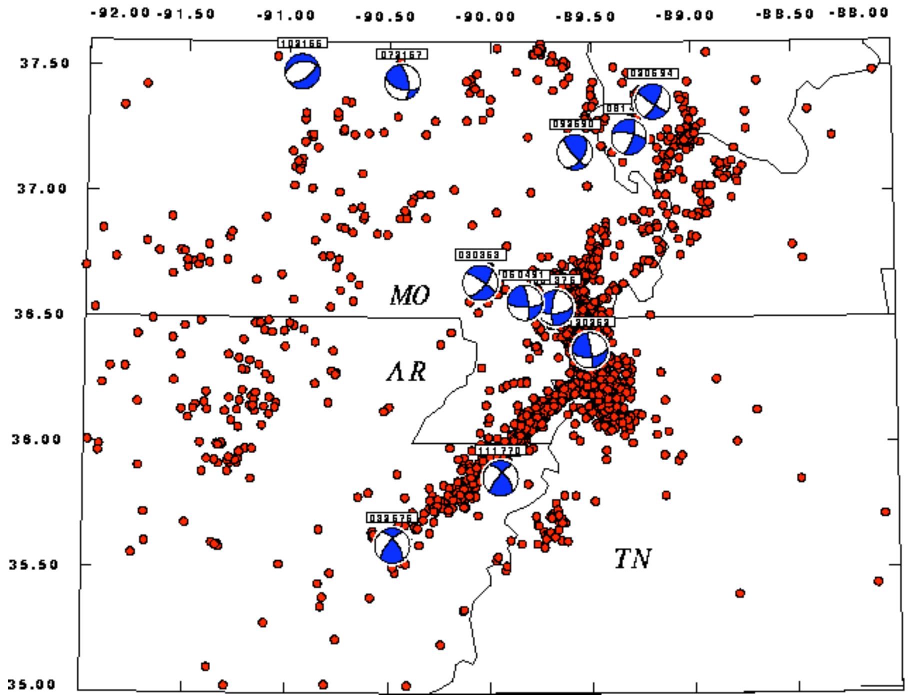
Reactivation of Hercynian shear zones in France

Structural reactivation: Linear belts of intraplate seismicity



Helffrich et al. GJI 1986

New Madrid Seismic Zone, US
reactivation of Precambrian Reelfoot rift:

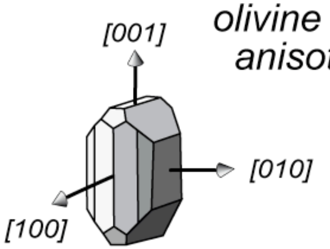


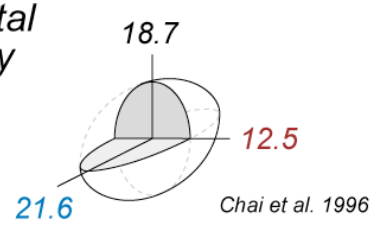
http://www.eas.slu.edu/Earthquake_Center/SEISMICITY/focalmech.html

predominance of strike-slip focal mechanisms

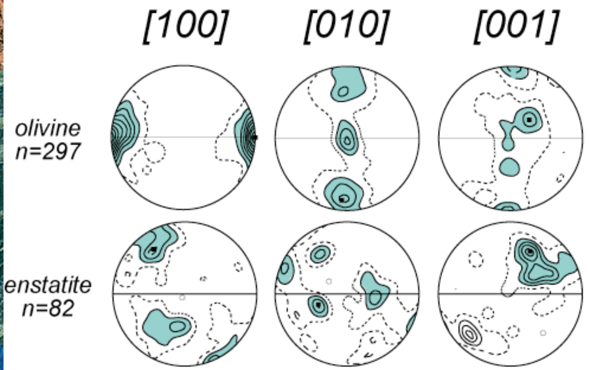
Anisotropic thermal diffusivity in the upper mantle

olivine cristal anisotropy

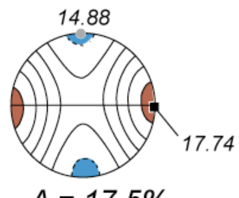




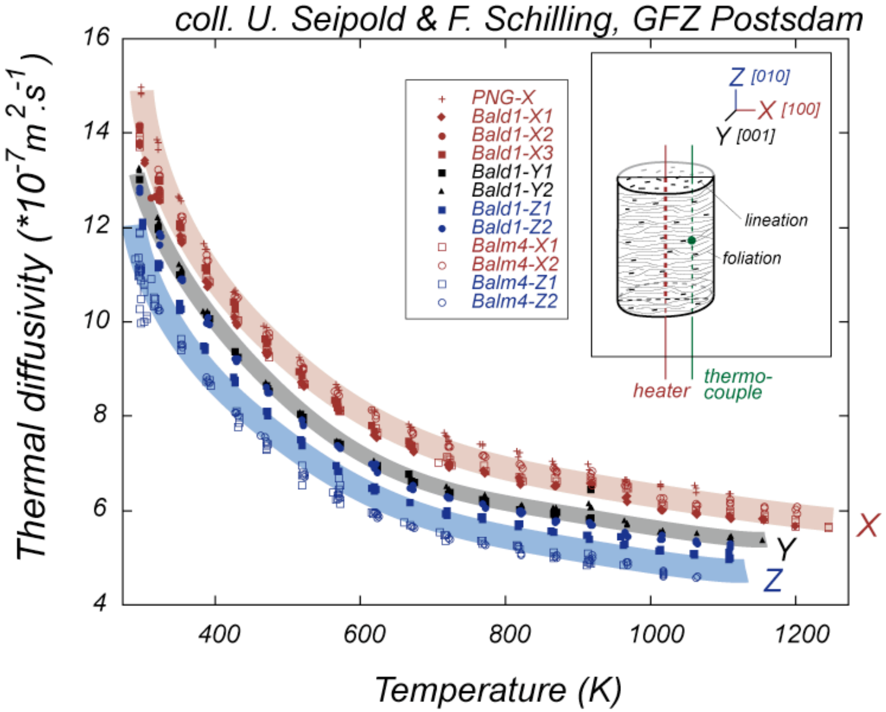
Voigt-Reuss-Hill averaging



diffusivité thermique ($*10^{-7}$ m^2/s)



coll. U. Seipold & F. Schilling, GFZ Postsdam



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

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

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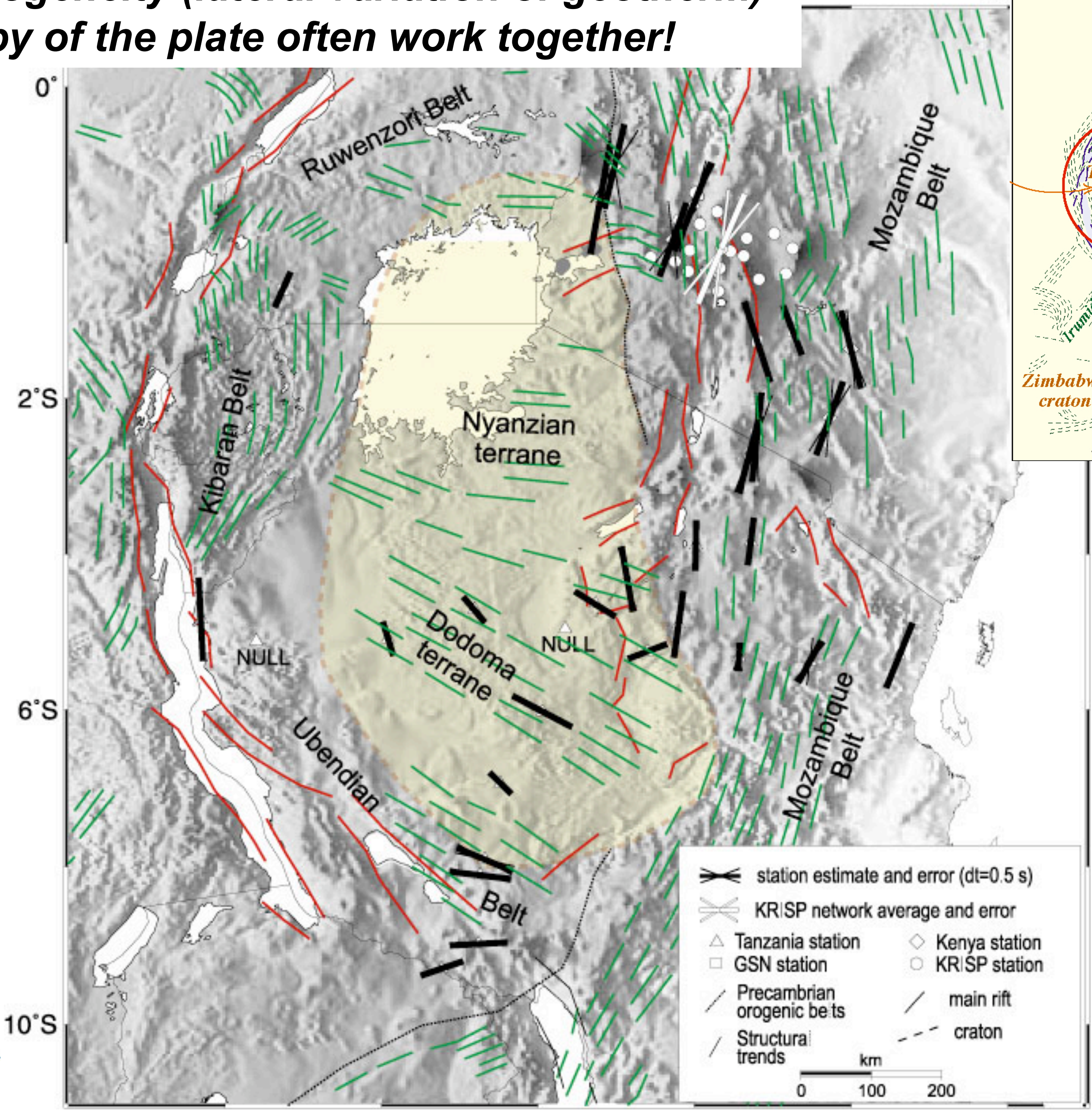
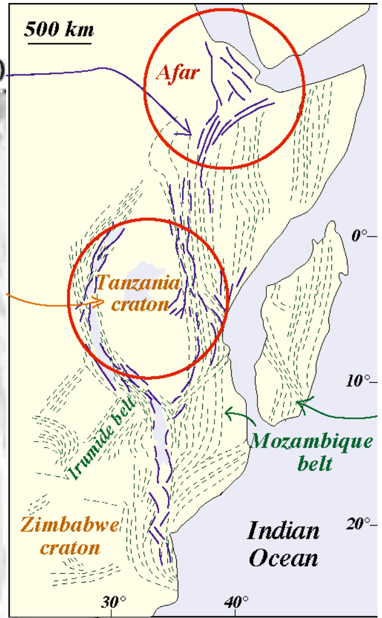
rifting : heterogeneity (lateral variation of geotherm) & anisotropy of the plate often work together!





Walker et al JGR 2004

Heterogeneity vs. anisotropy

Rheological heterogeneity

= *lateral variations in the* ***thermal structure*** *(****tectonic age*** *or enhanced* ***heat production*** *in the lithospheric mantle due to metasomatism)*

or lateral variations of the ***Moho depth***

Mechanical & thermal anisotropy

= preferred orientation of olivine crystals in the lithospheric mantle

= intrinsic features of continental plates

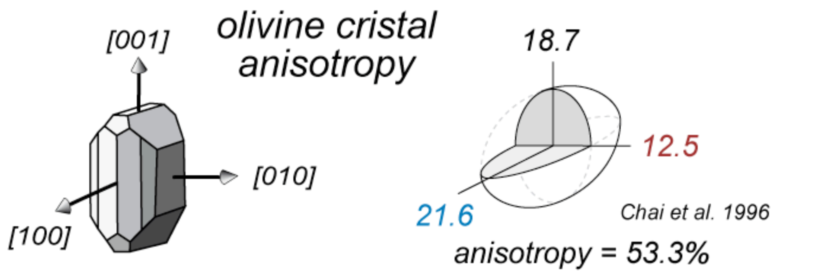
➔ ***essential for localizing strain far from plate boundaries***

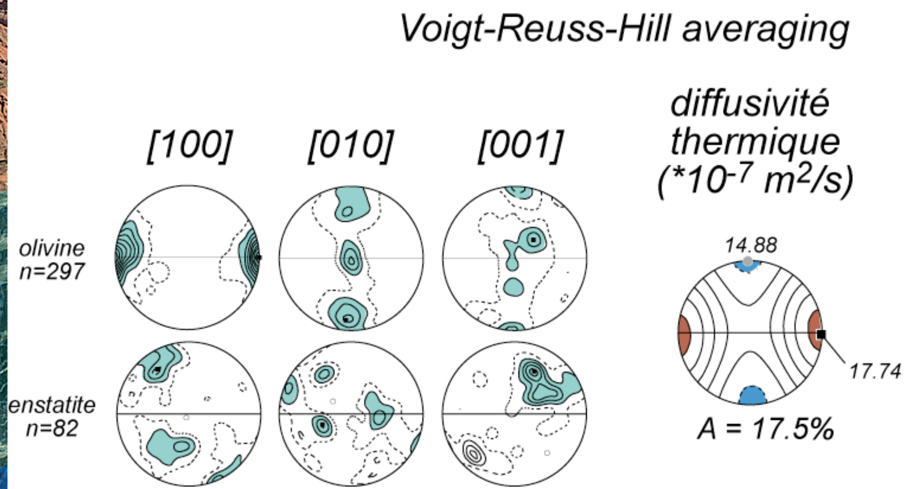
➔*additive contributions = often work together*

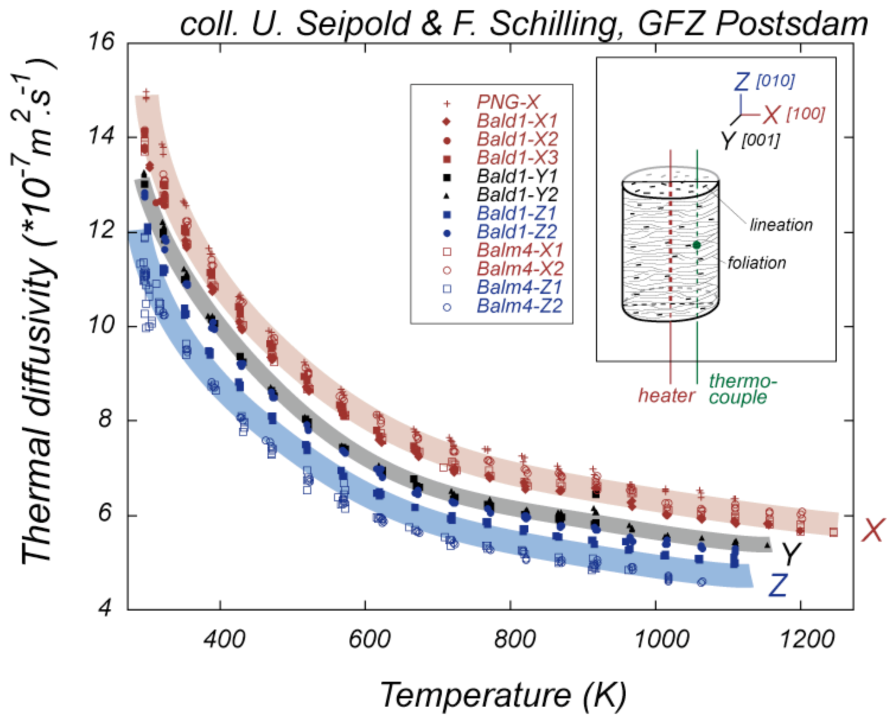
➔ *thermal gradients = highly effective to localize deformation*
but shorter lifetime (few 10s m.y. except cratons)
& no direct effect on strain regime

➔ *anisotropy = weaker strain localization (strain rates vary by a factor 2-5)*
but preserved for very long time spans & control strain regime
= shearing // to preexisting fabric

Anisotropic thermal diffusivity in the upper mantle







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

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