Olivine-antigorite phase transformation: microstructures, phase boundary misorientation and seismic properties

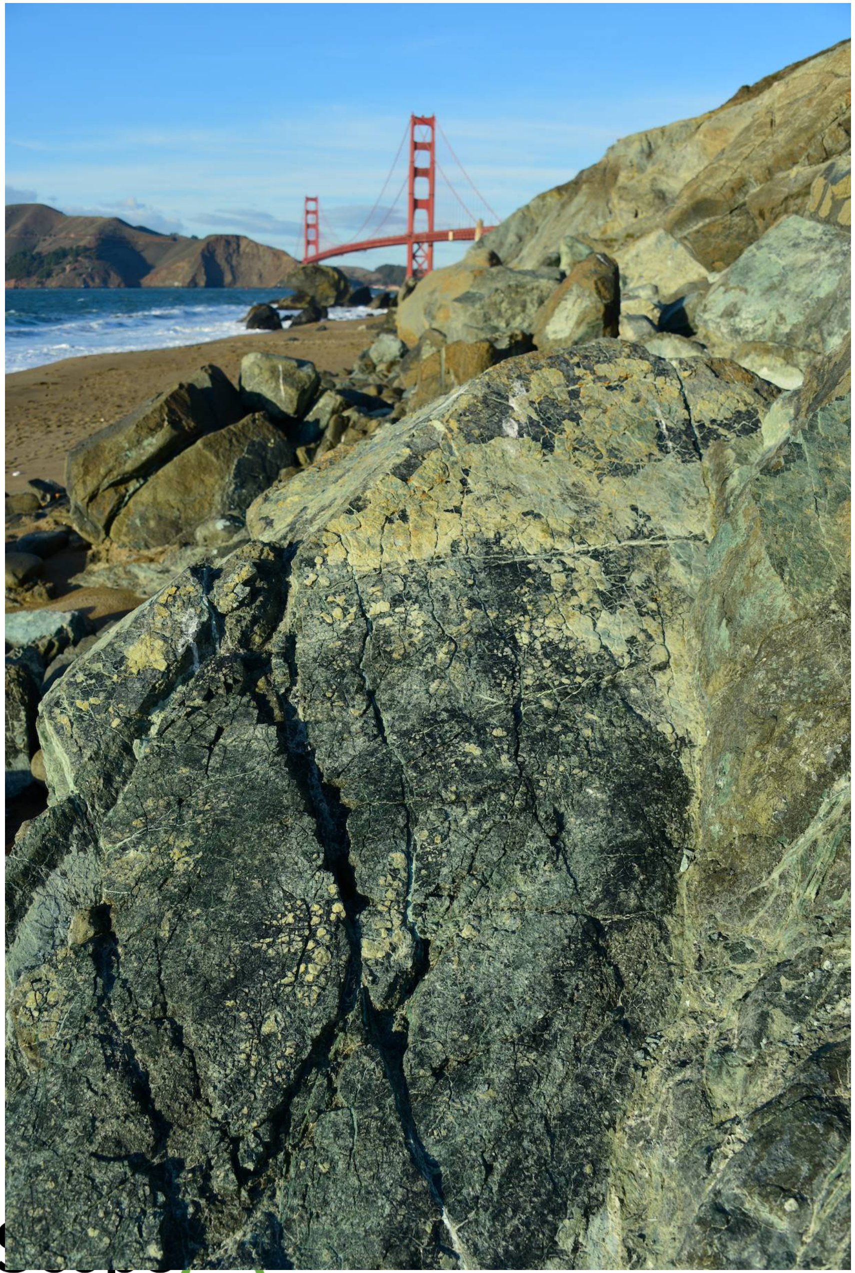
Luiz F. G. Morales (ScopeM – ETHZ),
David Mainprice (Geosciences Montpellier)
Hartmut Kern (Universität Kiel)

Why serpentinites?

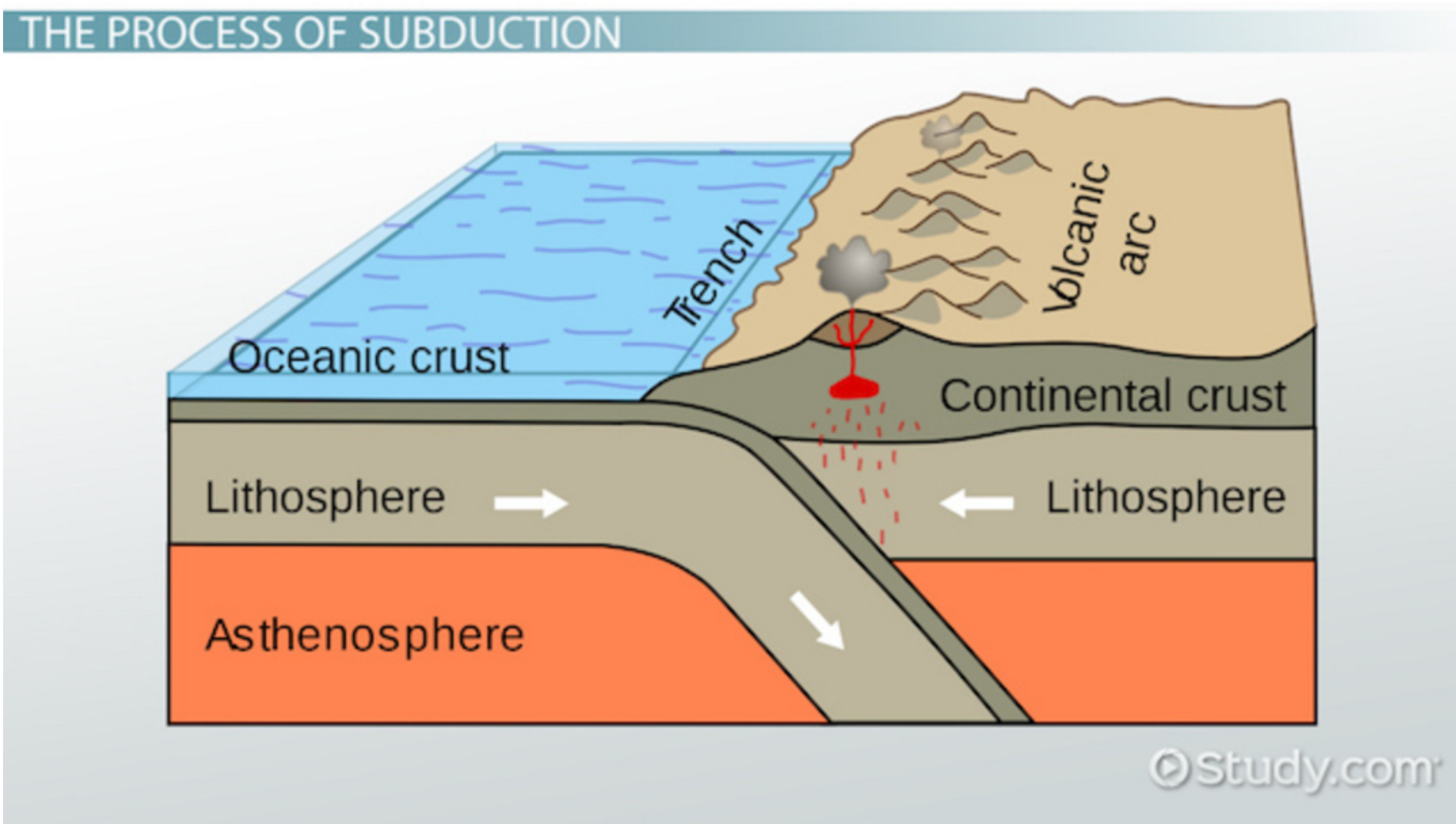
- The presence of different types of serpentine at different crustal levels in subduction zones is the direct expression of the mantle wedge hydration;
- Have a very important role on the subduction geodynamics;
- Contains relatively high amounts of water that is released during dehydration and have an important role on the partial melt of the mantle wedge;

Some basic information

What is a serpentinite?



- Serpentinite is a (normally) olive green rock (when fresh) to red when weathered;
- Glossy/soapy to touch, it's easy to spot when you're out in the field.
- Hydration / alteration of mantle rocks and prograde metamorphism of preexisting serpentinites


THE PROCESS OF SUBDUCTION
Trench
Volcanic arc
Oceanic crust
Continental crust
Lithosphere
Lithosphere
Asthenosphere
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What is serpentine?

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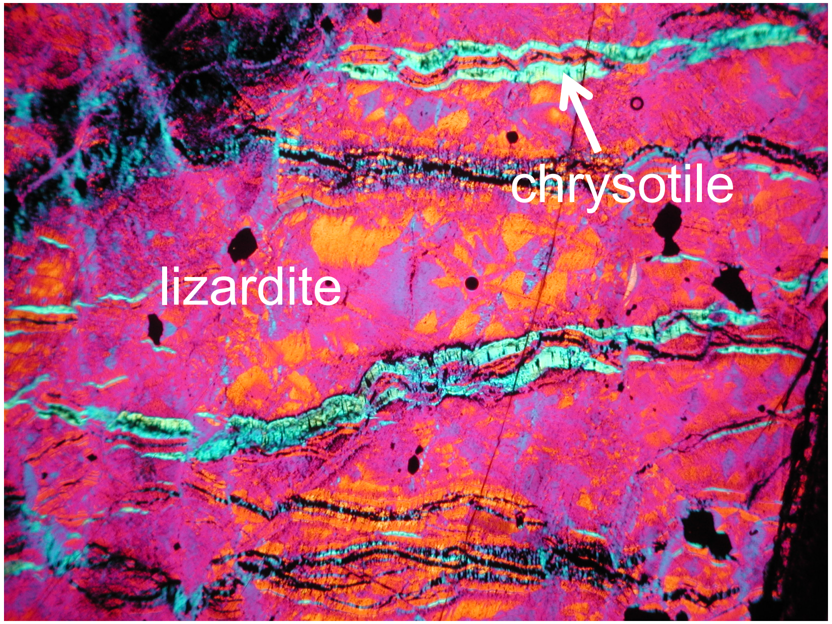
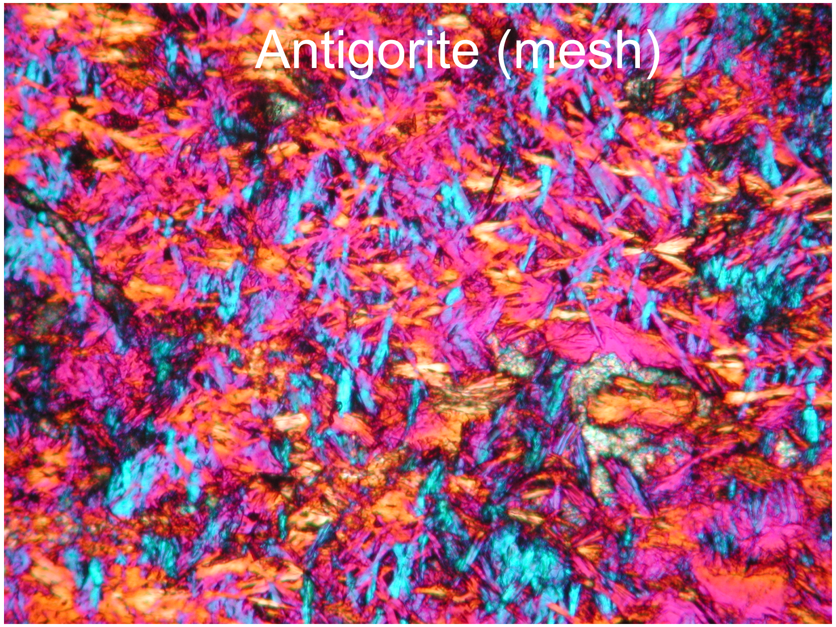
- Group of common rock forming hydrous magnesium iron phyllossilicate;
- **Olivine to Serpentine (+ Brucite):**
  $2Mg_2SiO_4 + 3H_2O = Mg_3Si_2O_5(OH)_4 + Mg(OH)_2$
- Three main polymorphs – lizardite, chrysotile and antigorite
- Lizardite and antigorite have platy habit, chrysotile is fibrous (one of the asbestos);
- Density around 2.6 g/cm^3





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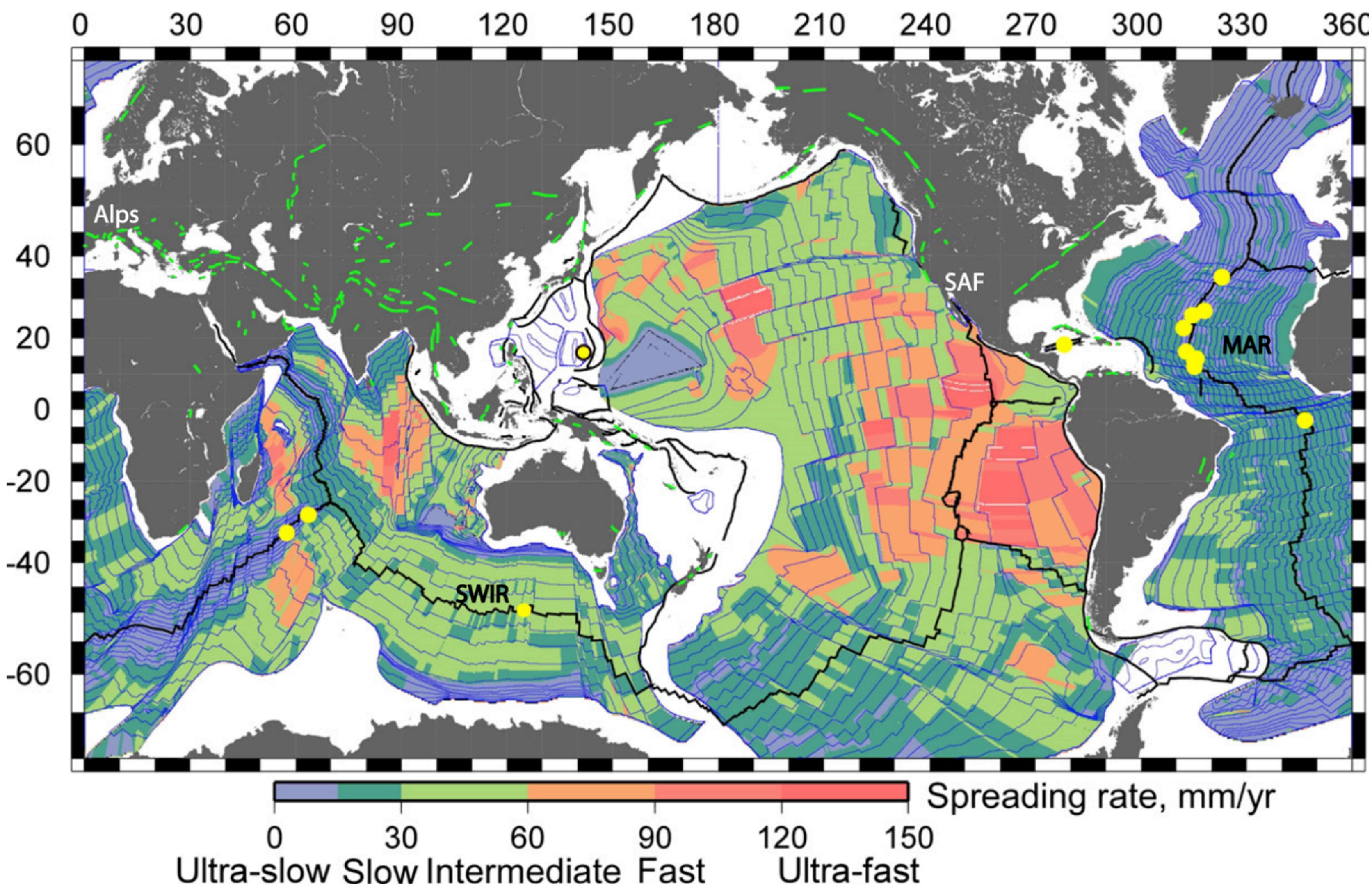
Global distribution of serpentinites



Guillot et al., 2015 - Tectonophysics

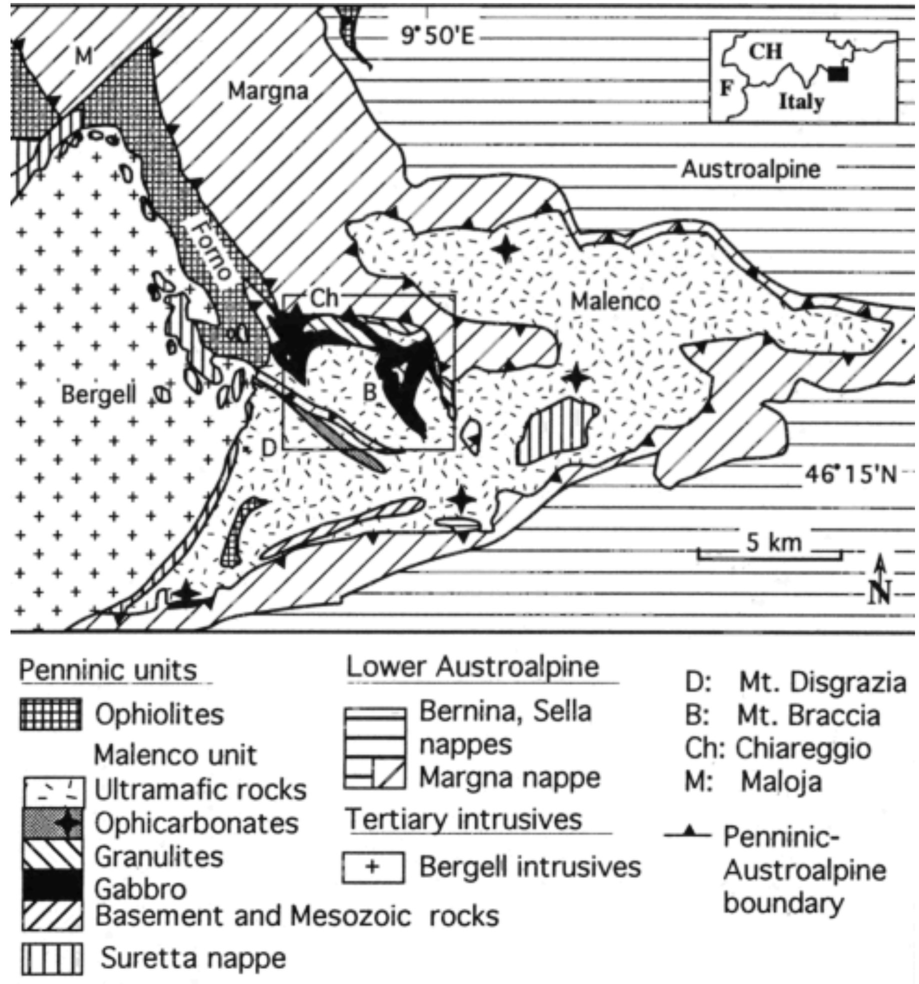
What we want?

- Better understand microstructures and CPOs in antigorite rich rocks;
- Calculated seismic properties of these rocks and compare with results published in the literature

Results & Interpretation – microstructures & CPO

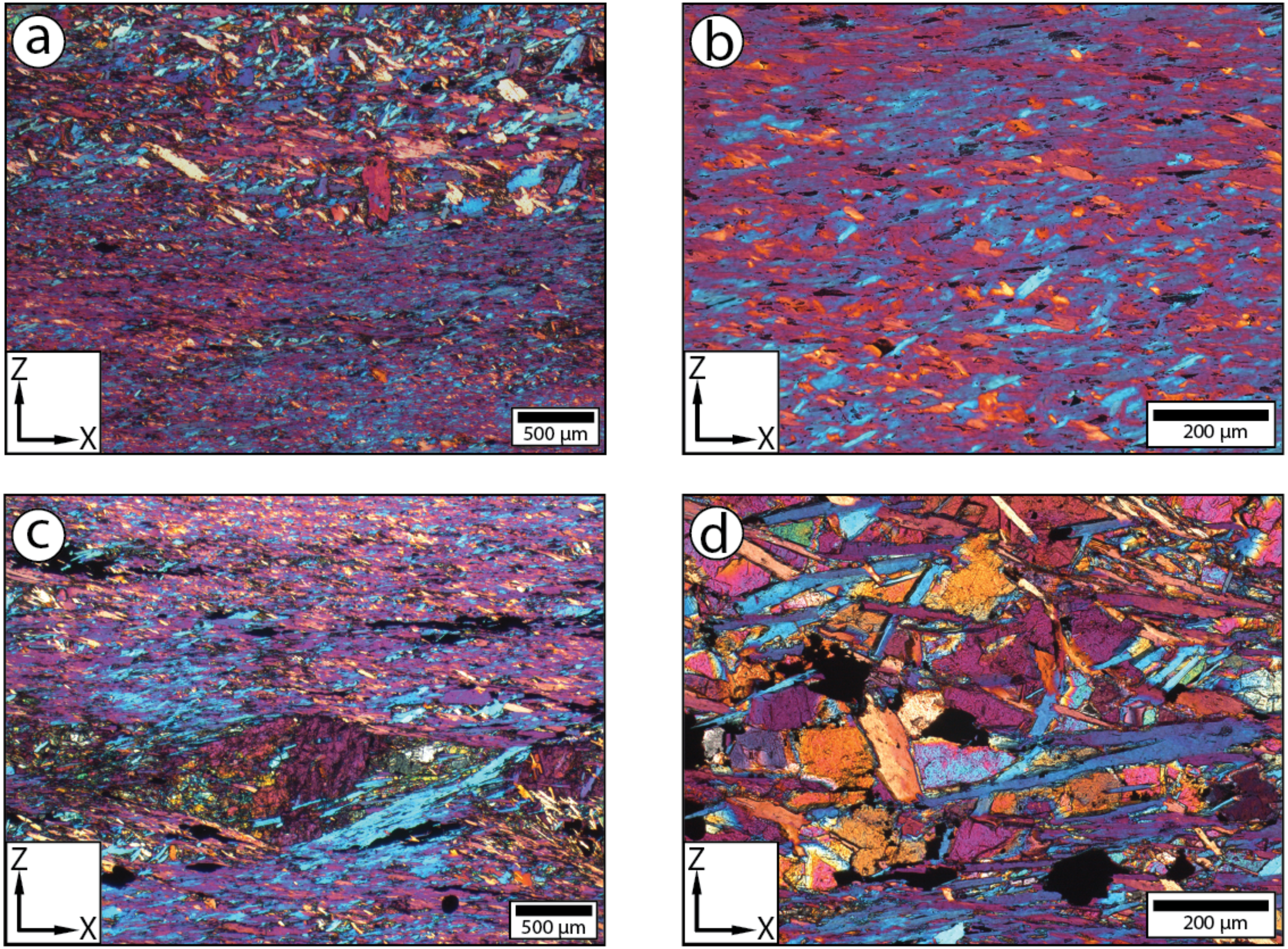
Hartmut Kern's Sample 987

- High-temperature antigorite **a**-axis length = 35Å from Val Malenco (Western Alps, Northern Italy);
- Seismic anisotropy measured at Temperature and Pressure in 1993 (PEPI) and 1997 (JGR)
- CPO measured by X-ray and Neutron diffraction and compared with experiemental seismic measurements in 2015 (JGR)



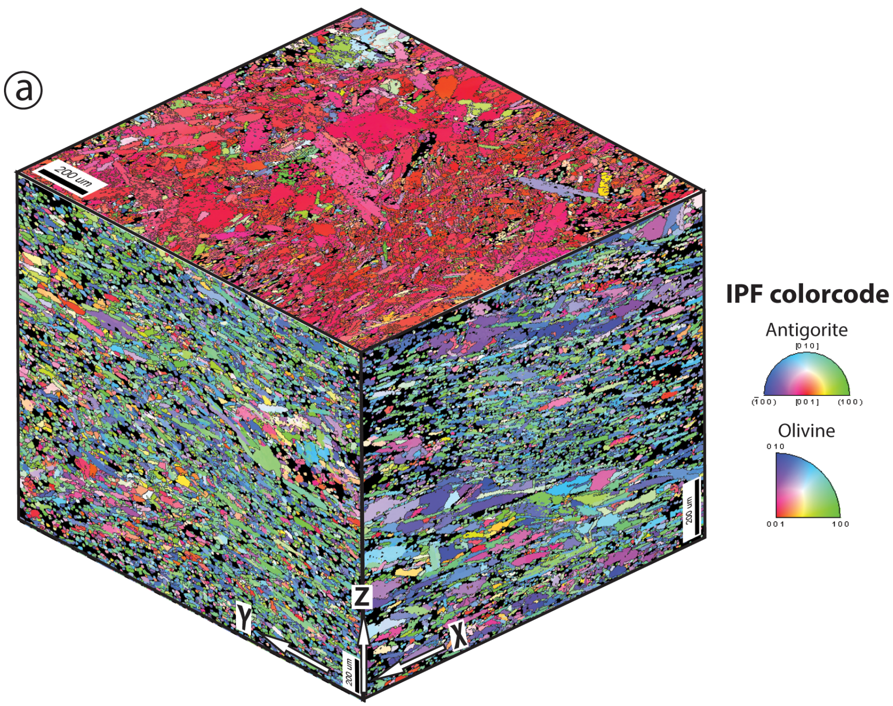
Hermann et al., 1997 - JGR

Sample 987 - microstructures

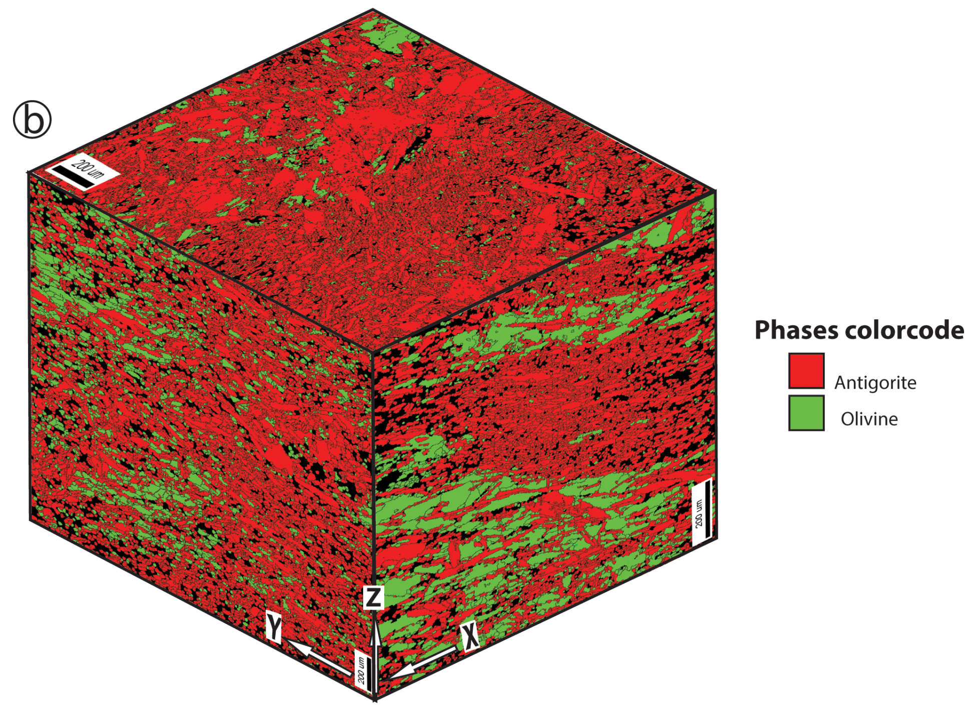


Orientation maps in three orthogonal sections XZ, YZ and XY

Orientation map



Phase map



- Some technical details – 20 kV, 8 nA, stepsize 0.5 µm, binning 2x2, resulting in 2 days of measurements for each map

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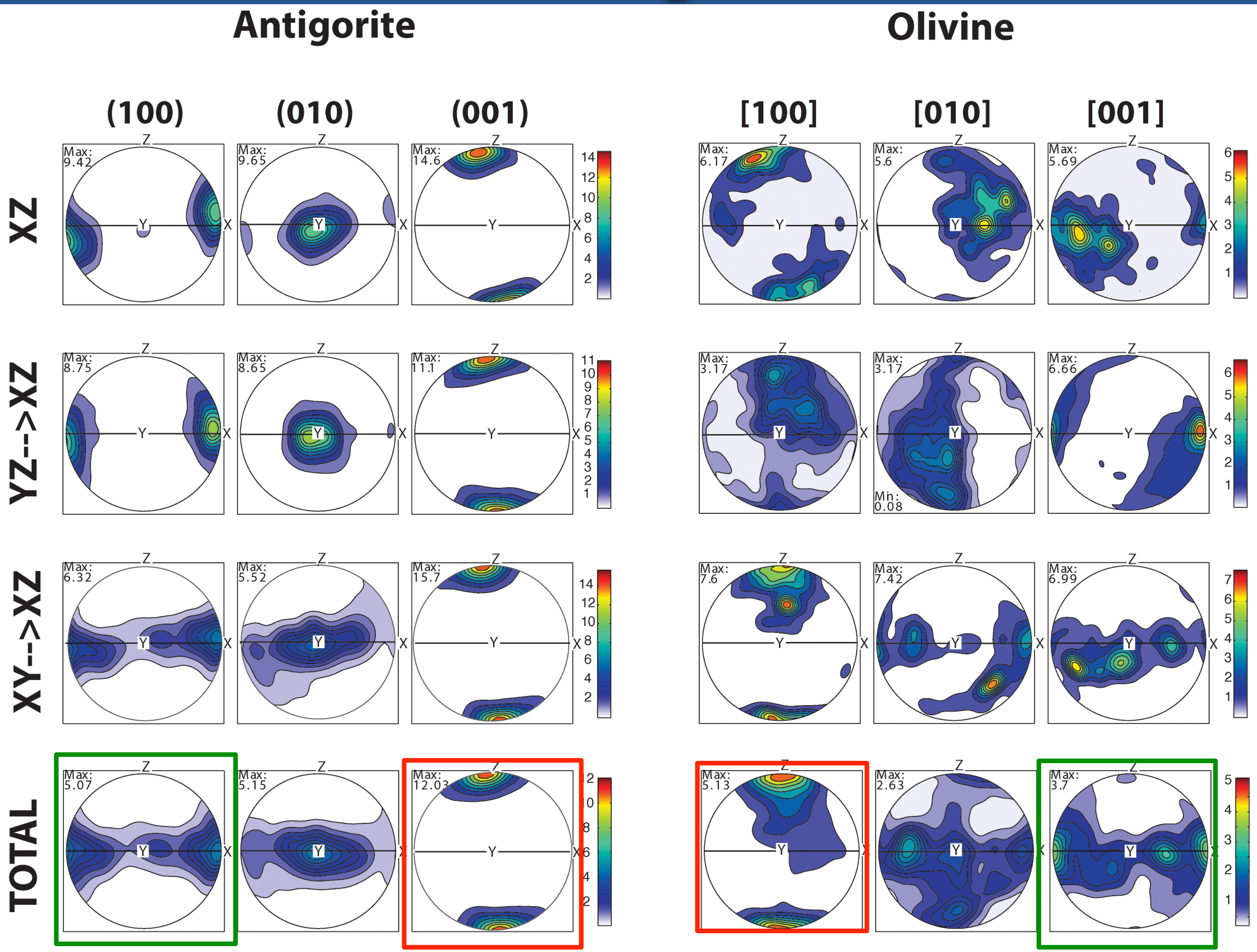
Pole Figures



To study the phase transformation olivine to antigorite using EBSD

- We calculated the misorientation function (MDF) along grain boundaries between olivine and antigorite;
- The MDF can be plotted as specific misorientation angles sections showing misorientation axes distribution in crystallographic coordinates;
- The MDF can be represented by misorientation angle histograms for all axes;
- Misorientation axes and angles corresponds to the Burger transformation relations e.g. (100)ol || (001)atg & [001]ol || [010]atg

Burger phase relationships

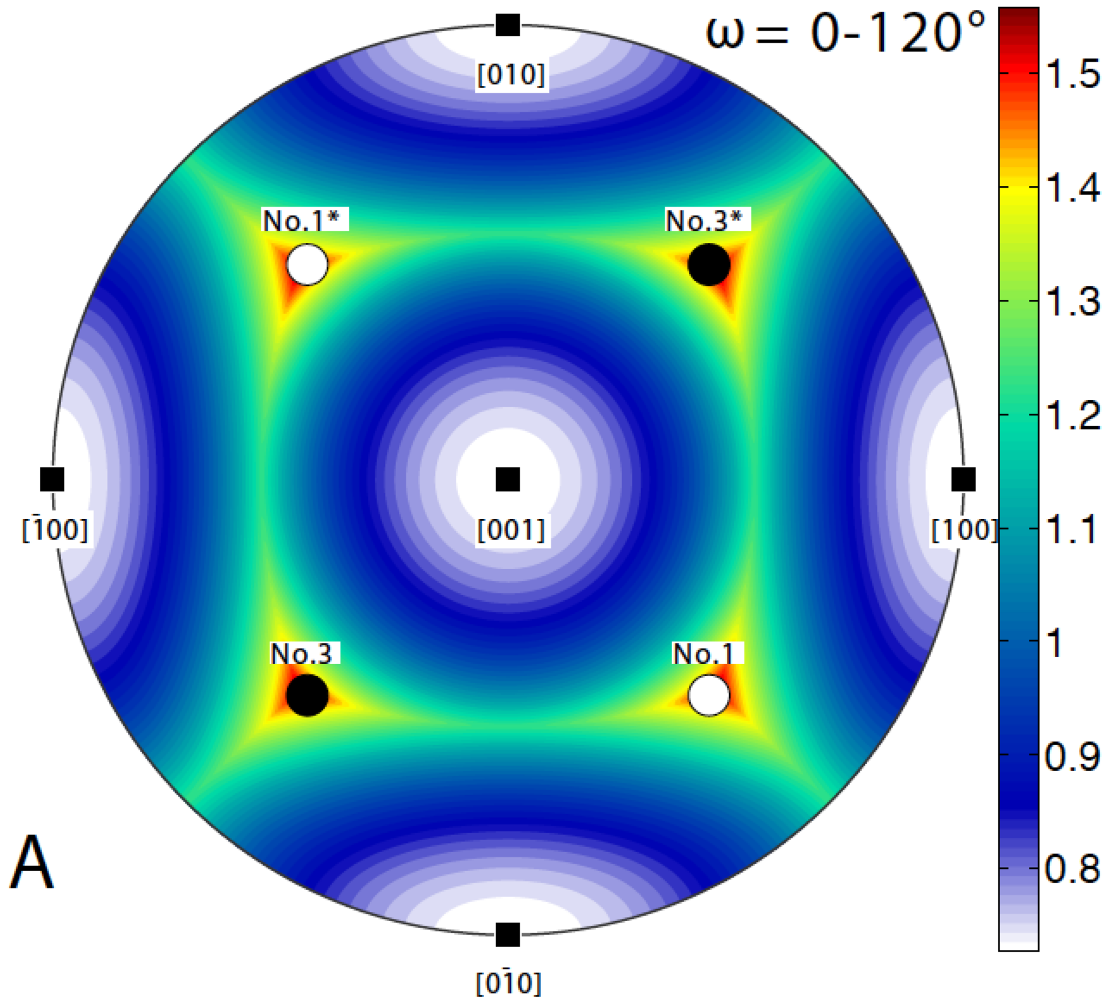
Number	Olivine		Antigorite	axis/angle
No.1	(100)ol	||	(001)atg	[12 -6 10]/119.33°
	[001]ol	||	[001]atg	* [-12 6 0]/120.67°
No.2	(010)ol	||	(001)atg	[-1 0 0]/90.01°
	[001]ol	||	[010]atg	*none
No.3**	(100)ol	||	(010)atg	[-12 -6 0]/119.33°
	[001]ol	||	[010]atg	*[-12 -6 0]/120.67°
No.4**	(010)ol	||	{210}atg	[-5 9 0]/93.00°
	[100]ol	||	[001]atg	* [5 -9 0]/94.13°

*Equivalent by symmetry for orthorhombic-monoclinic symmetry of olivine to antigorite phase transition.

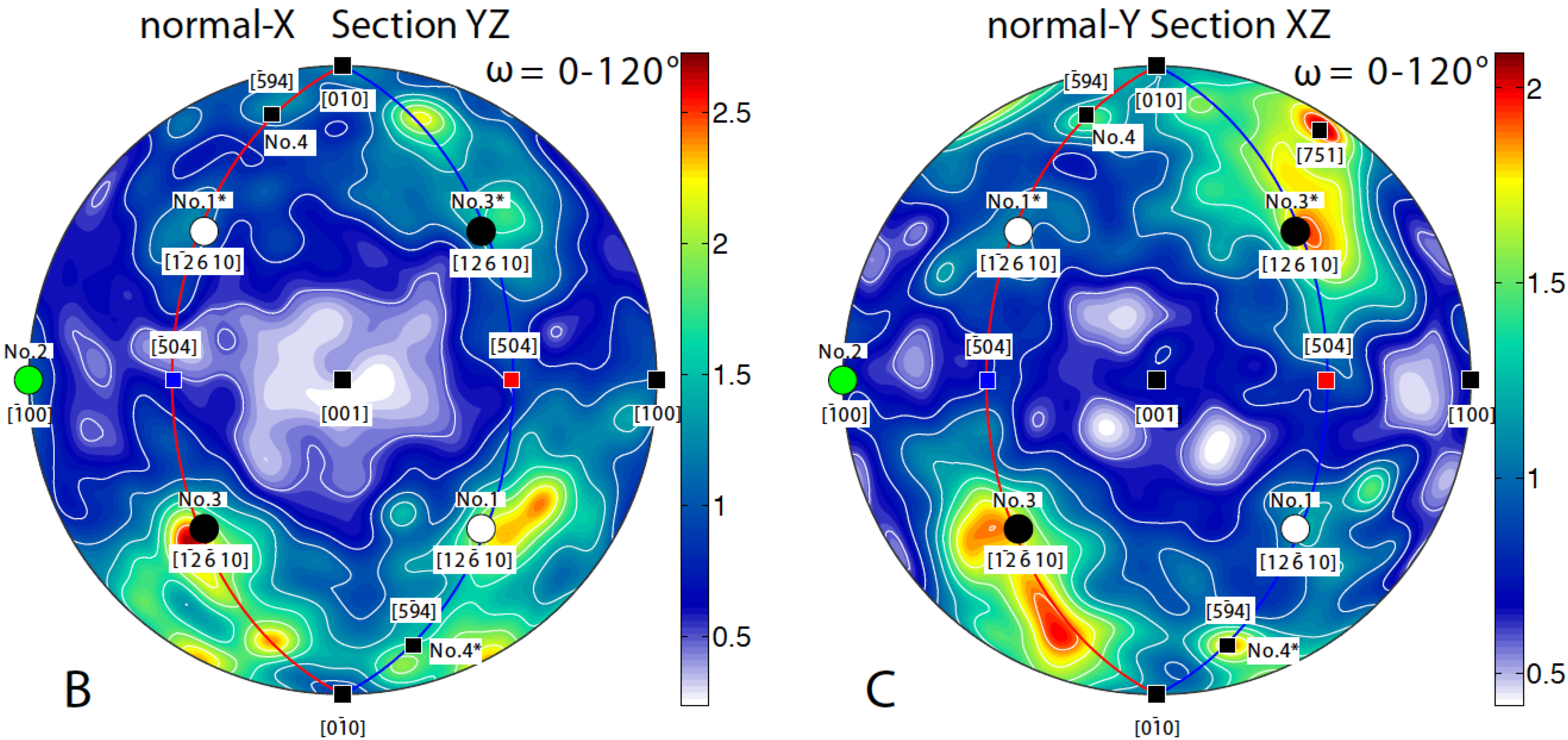
** Not previously reported by Boudier et al. [2009]

Uniform distribution of axes for ω=0° to 120°

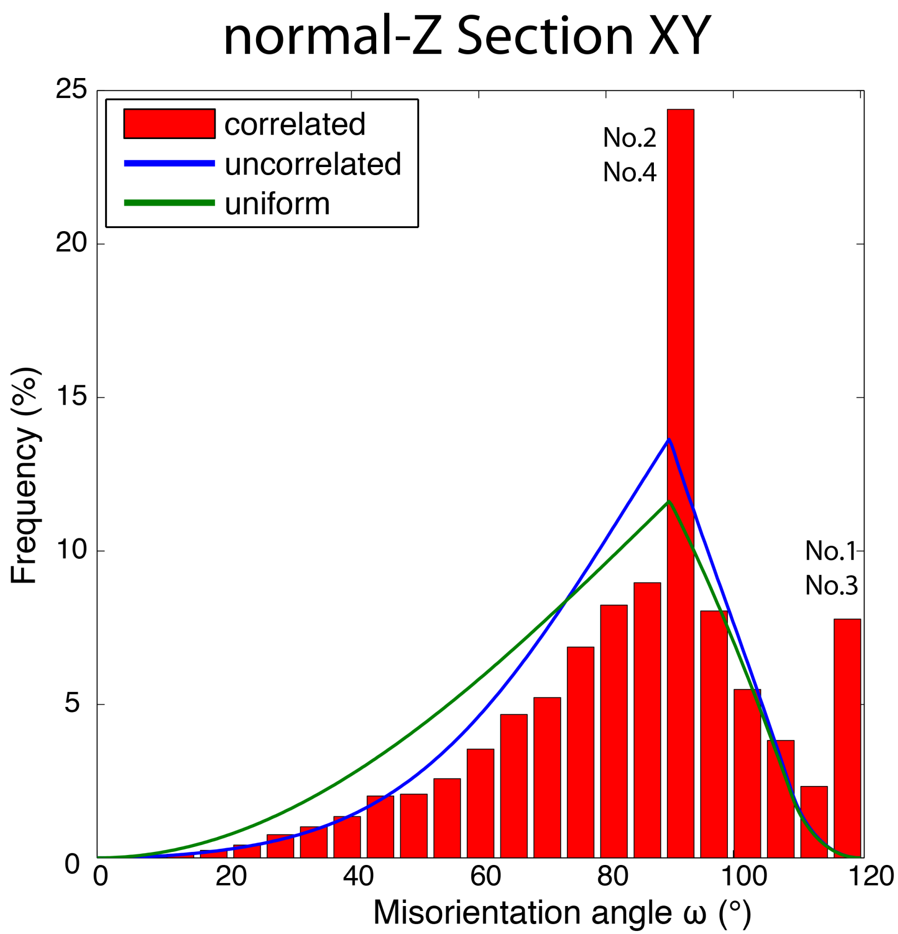
Olivine – Antigorite uniform
misorientation axes distribution

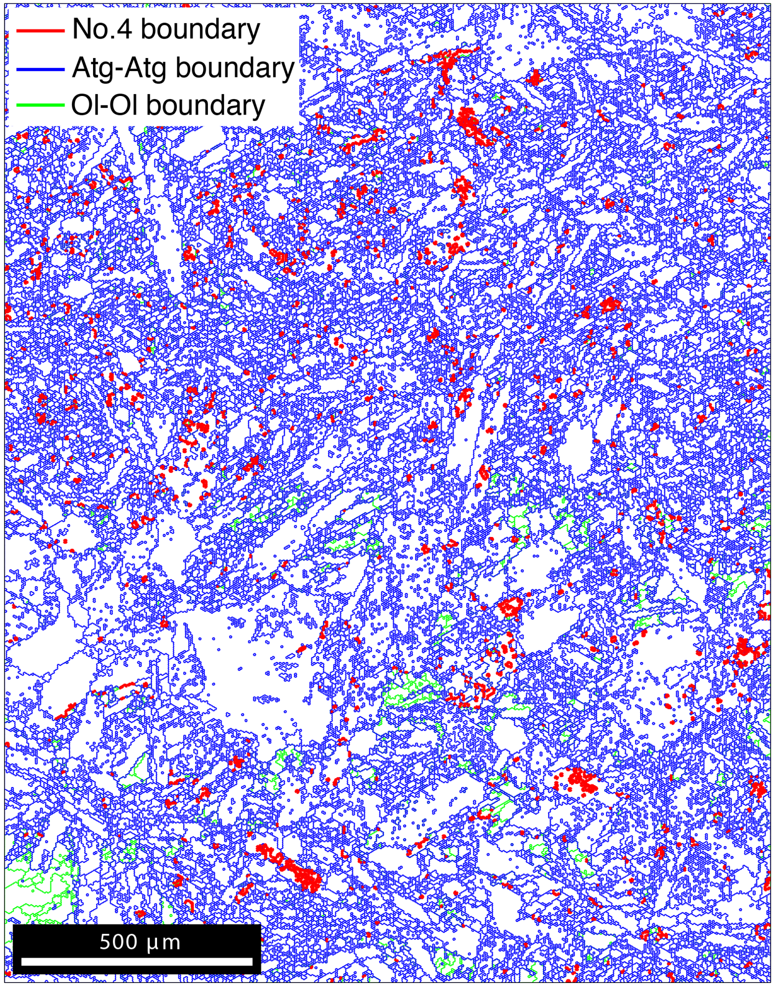


MDF axes for all angles ω = 0 to 120°

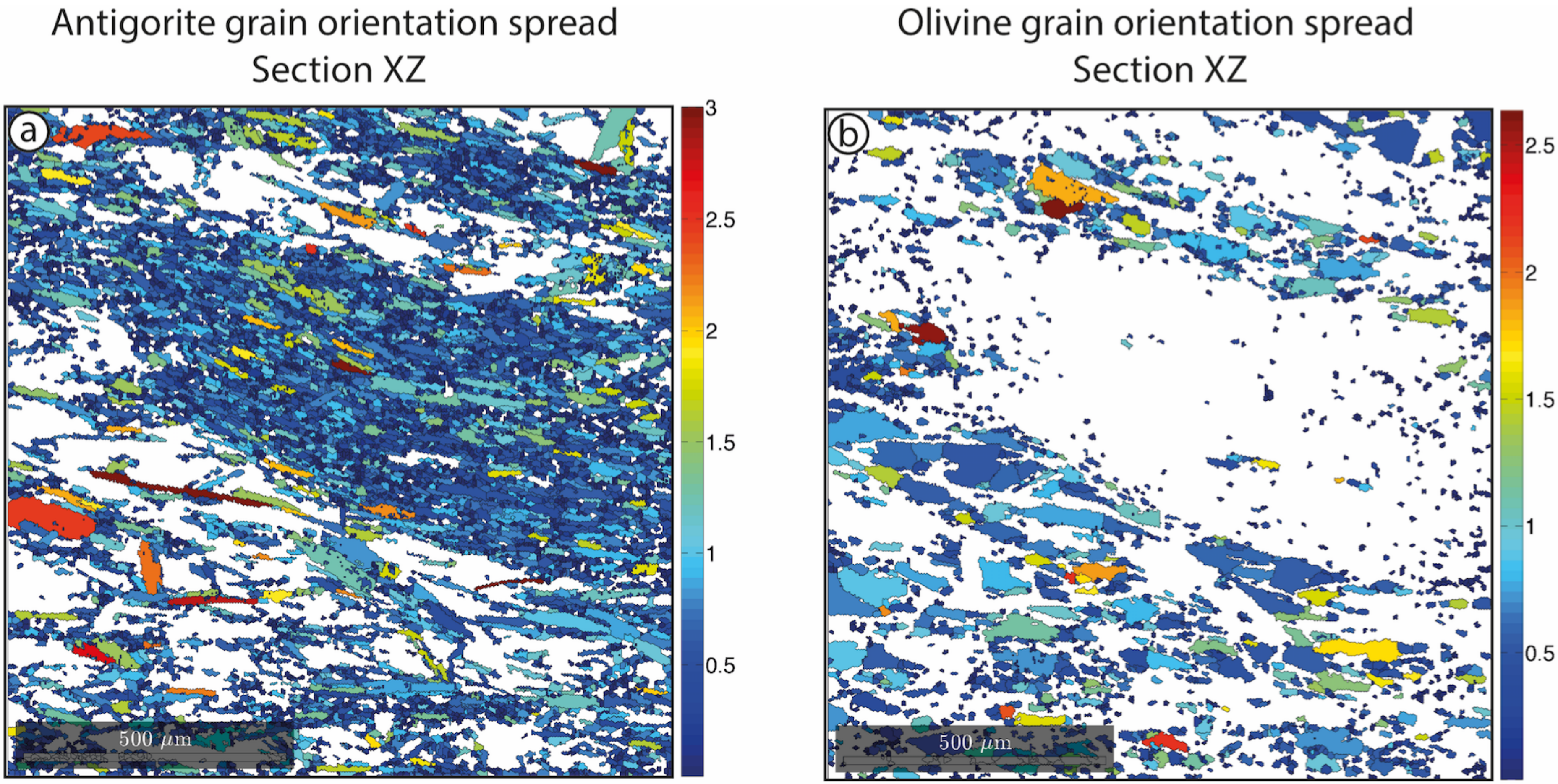


EBSD map of Section XY of olivine-antigorite boundaries with Burger relation No.4





Small variation of orientation within grains



GOS = Grain Orientation Spread in degrees

ETH zürich Summary for Sample 987 - microstructures

•Using EBSD on 3 orthogonal thin sections provides a CPO in agreement with volume diffraction X-ray and Neutron determinations.
Using a single section will not allow a complete CPO determination;

• The CPO of antigorite is a c-axis fibre texture, which is compatible with the conjugate slip systems reported by *Amiguet et al*. [2014] [101](10-1) and [10-1](101). However these slip systems are not sufficient to achieve strain compatibility of general deformation, other mechanisms must operate;

•CPO strength increases with grain size in the range 5 to 45 μm, further suggesting dislocations are active;

•Two new phase transformation Burger relations (No.3,No.4) have been detected, We find that No.3 and No.1 are most frequent misorientations, which are clearly favoured as they both involve the [100]ol and [001]atg the two directions with highest alignment in both phases

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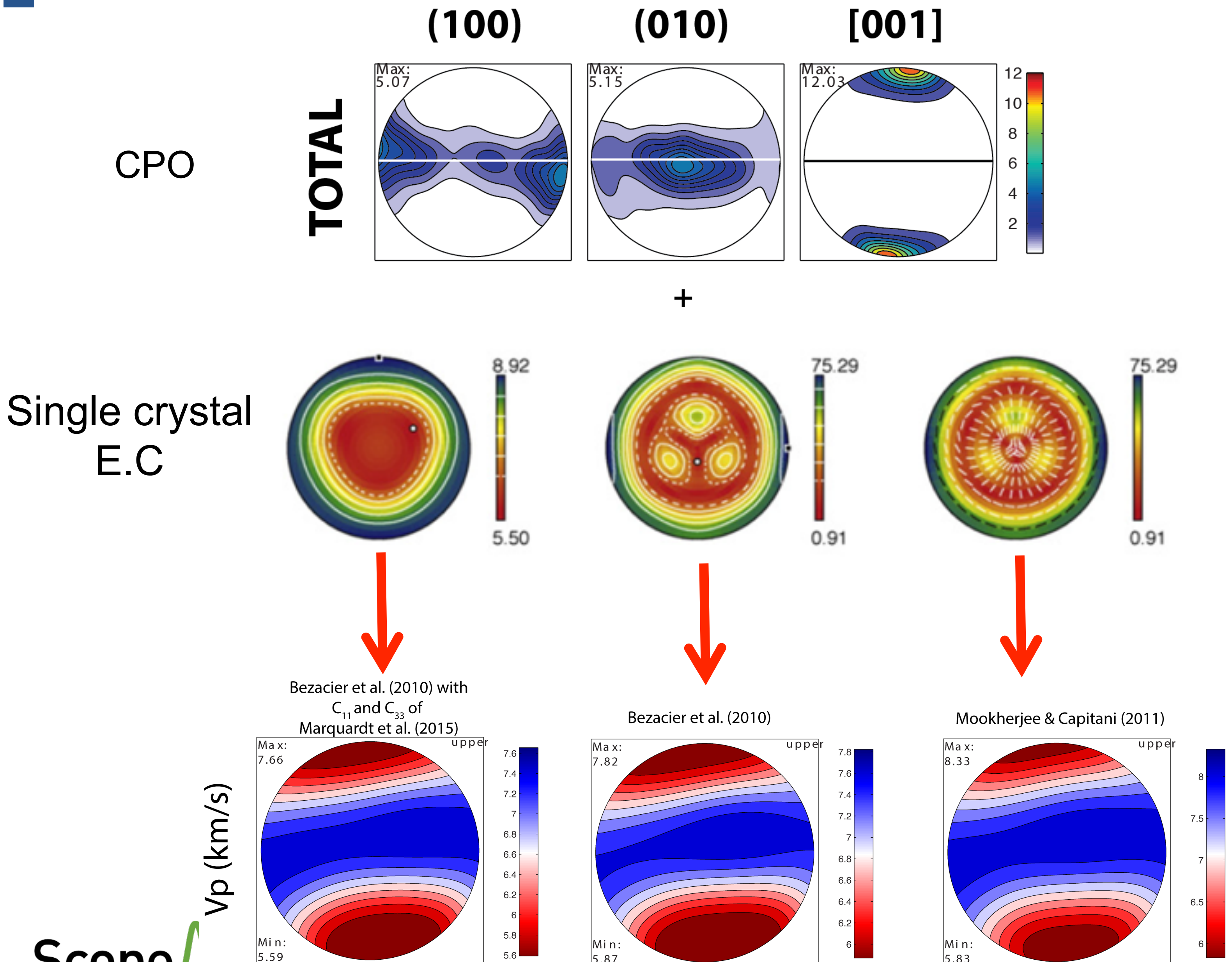
Results & Interpretation – seismic properties



(100)
(010)
[001]
CPO
TOTAL
Max: 5.07
Max: 5.15
Max: 12.03
12
10
8
6
4
2
+
Single crystal
E.C
8.92
5.50
75.29
0.91
75.29
0.91
Bezacier et al. (2010) with
C_{11} and C_{33} of
Marquardt et al. (2015)
Bezacier et al. (2010)
Mookherjee & Capitani (2011)
Vp (km/s)
Max: 7.66
Min: 5.59
upper
Max: 7.82
Min: 5.87
upper
Max: 8.33
Min: 5.83
upper

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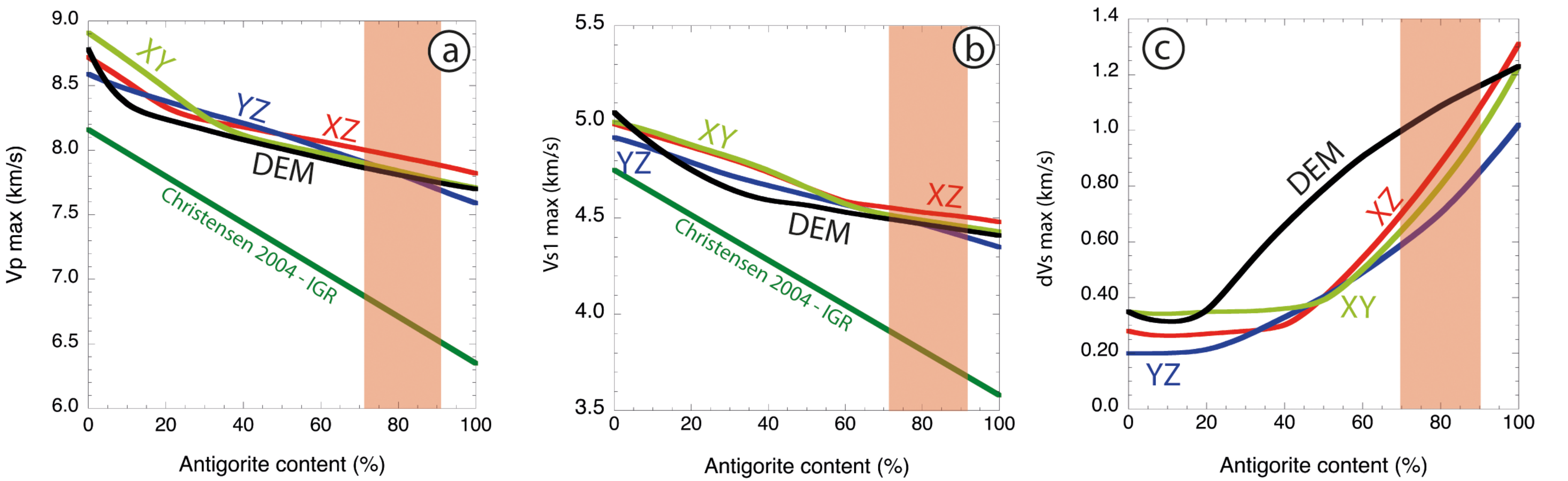
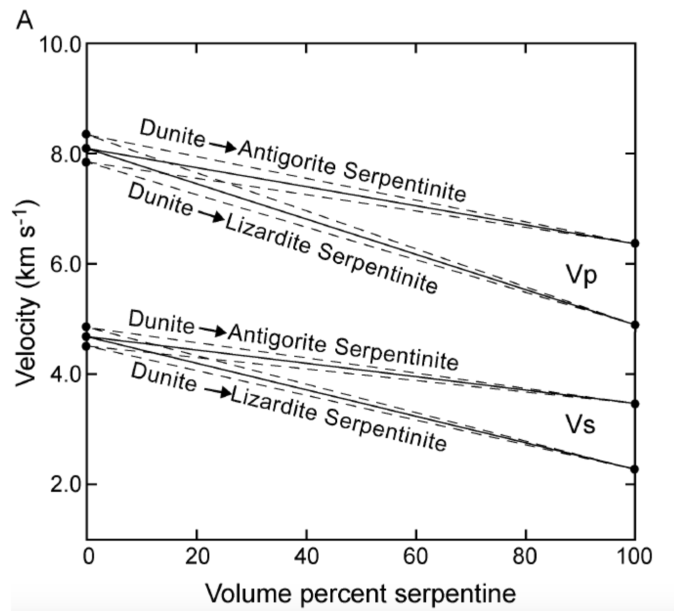
Seismic velocities with increasing antigorite %



Isotropic model from Lab data Christensen(2004): linear



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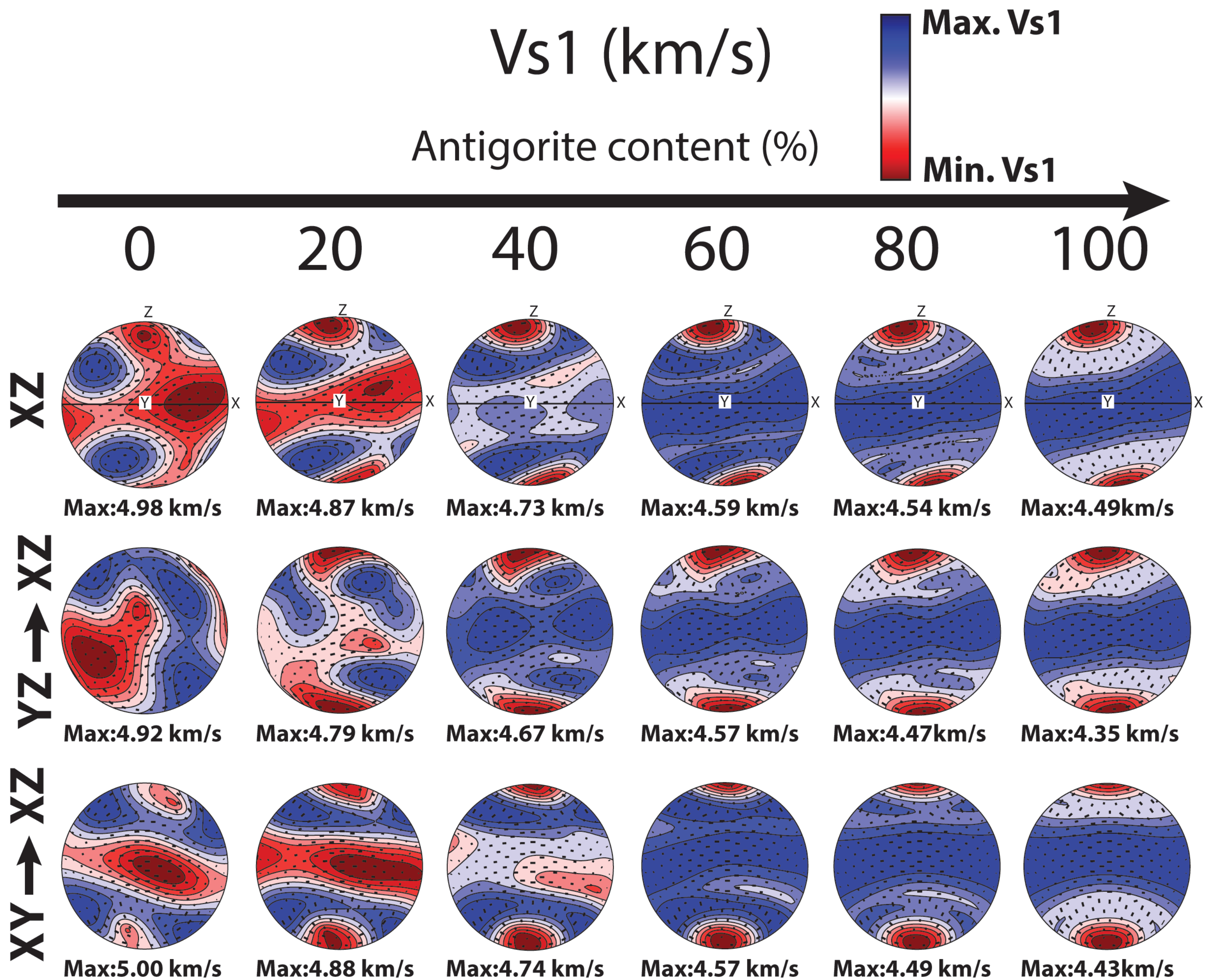
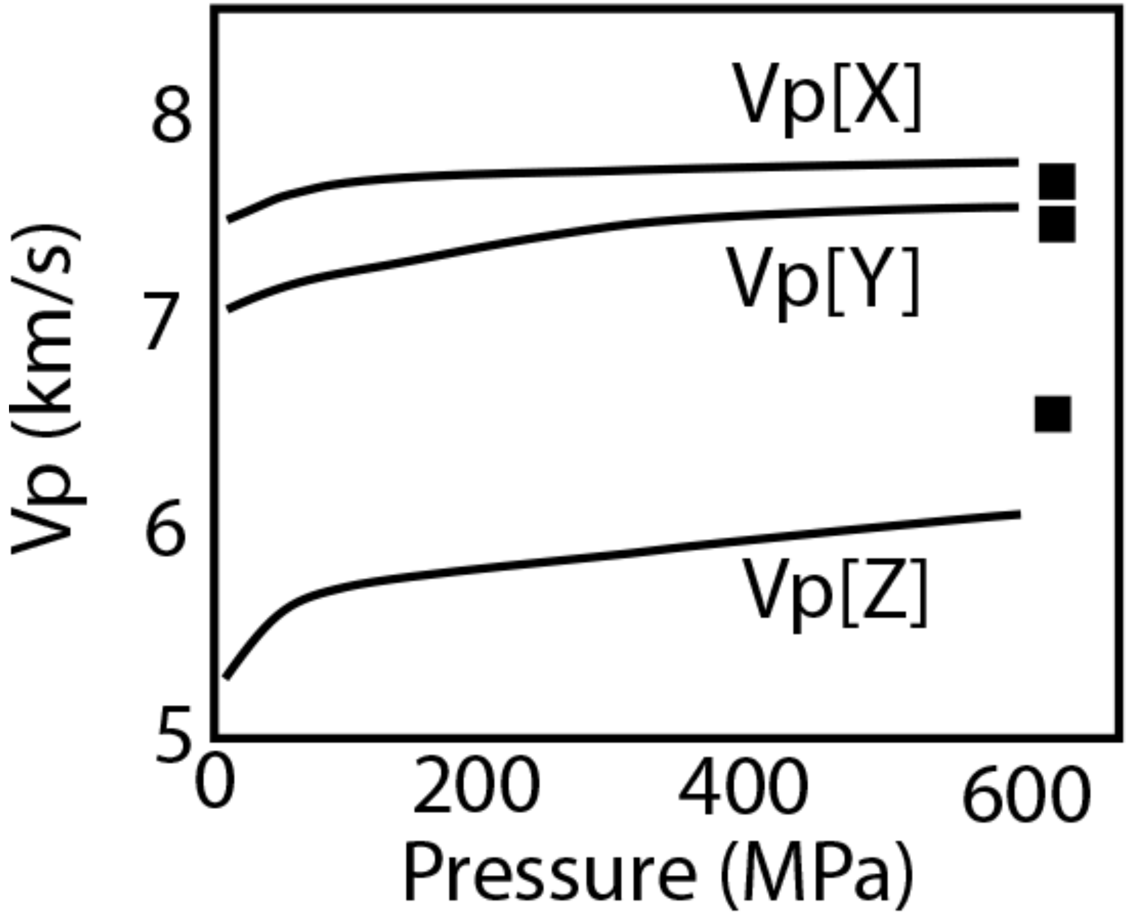
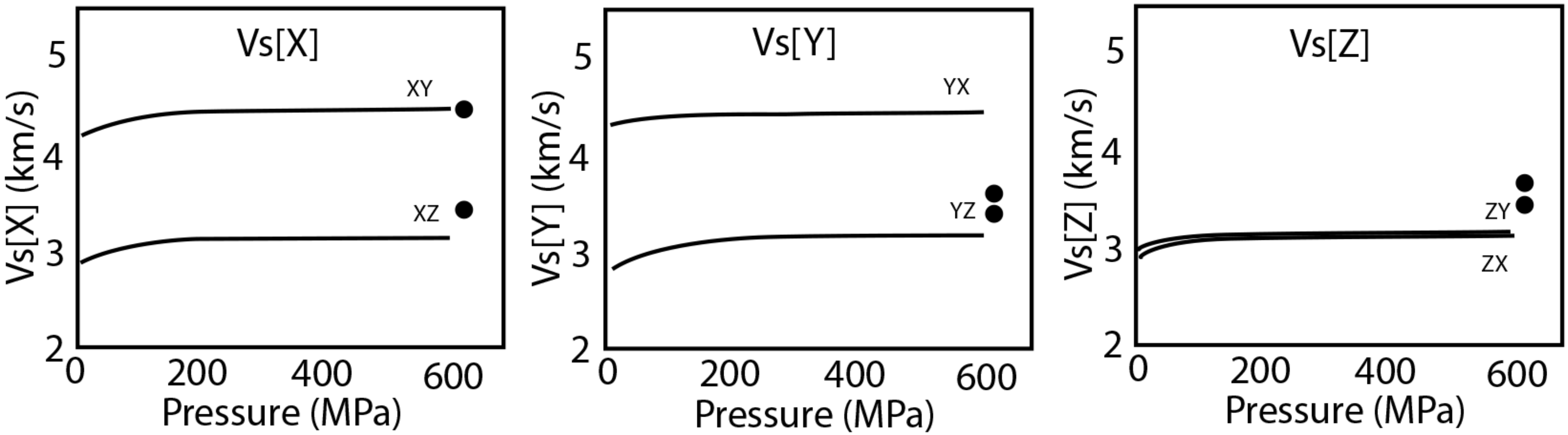
Fast shear waves (Vs1)



Ultrasonic Vp measurements at different P (Kern et al., 1997) and CPO-derived Vp



Ultrasonic Vs measurements at different P and sections (Kern et al., 1997) and CPO-derived Vs1



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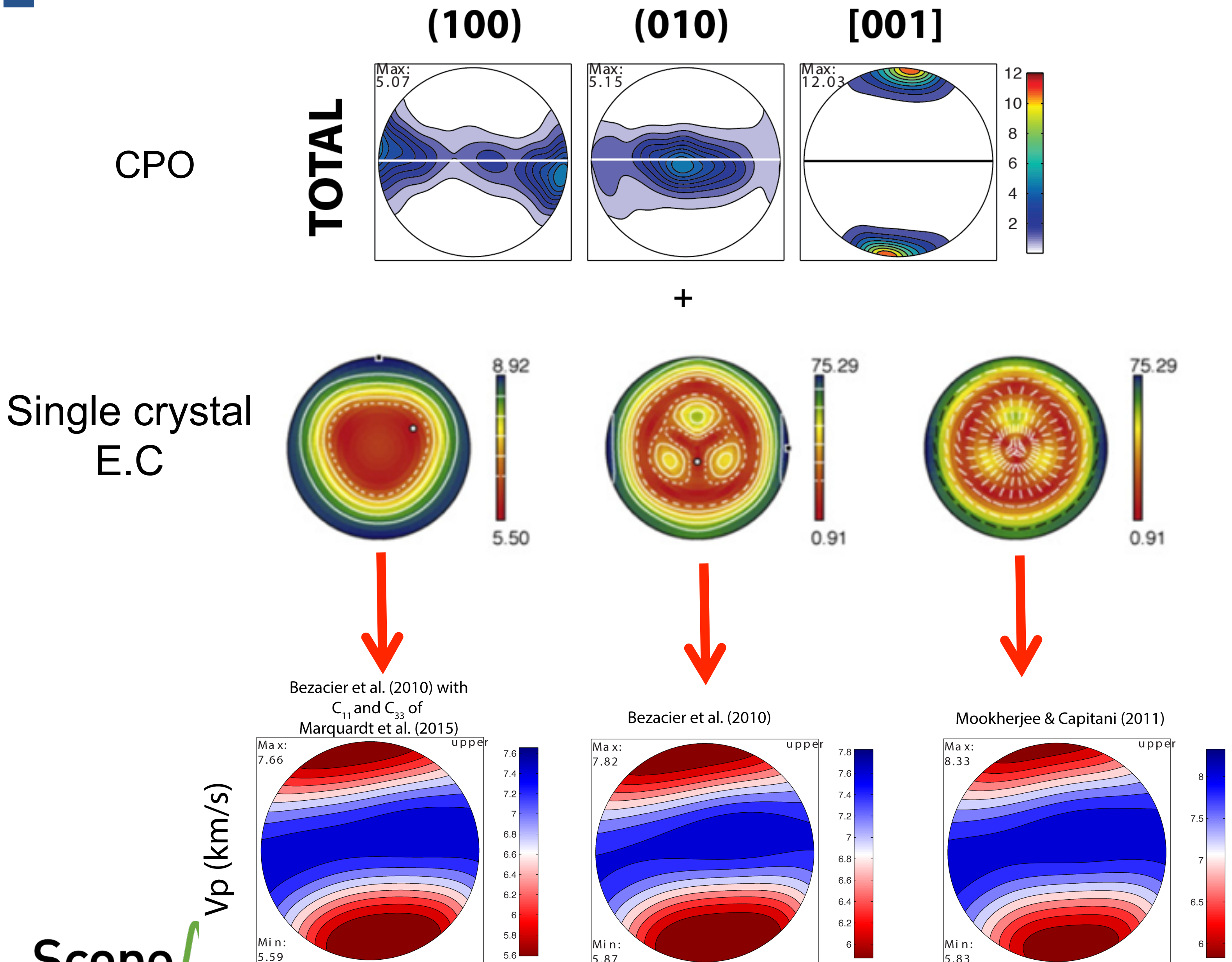
Why the velocities are different?



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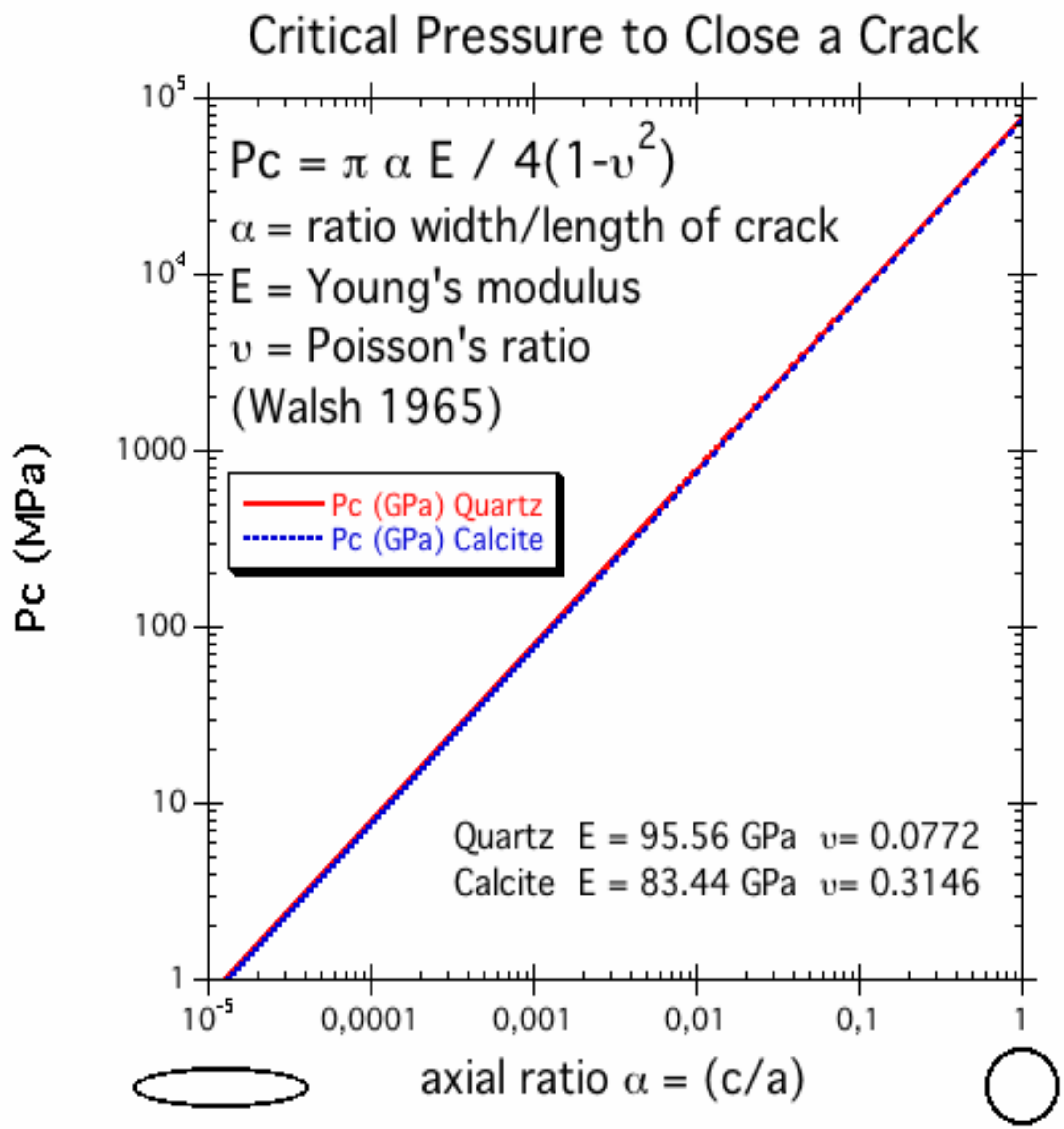
Influence of crack shape

- With increasing pressure, oriented grain boundaries of the platy antigorite are progressively closed, increasing contact areas, leading to an increase of velocities. However, due to asperities on the surfaces these boundaries, the closure of a long flat crack results in a line of a number of low-aspect pores, which are not completely closed even at pressures > 600 MPa (see *Christensen*, [1974]);



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Summary – seismic properties

- Calculations of EBSD-derived seismic properties using 3 orthogonal thin sections are in agreement with X-ray/Neutron diffraction based calculations;

- There is a good agreement between the CPO-derived seismic velocities and ultrasonic methods in directions parallel to the foliation (XY);

- The calculated velocities are between 0.2-1.0 km/s faster than ultrasonic velocities measured normal to the foliation (Z), even for measurements at a pressure of 600 MPa. Such a difference is probably caused by cracks, cleavage and grain aligned grain boundaries;

- It is likely that not all pores, micro-cracks, cleavages and grain boundaries are closed [*Christensen* 1974], which would explain the slower ultrasonic velocities if the open defects are mainly aligned with antigorite foliation plane

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Thank you for your attention!!!

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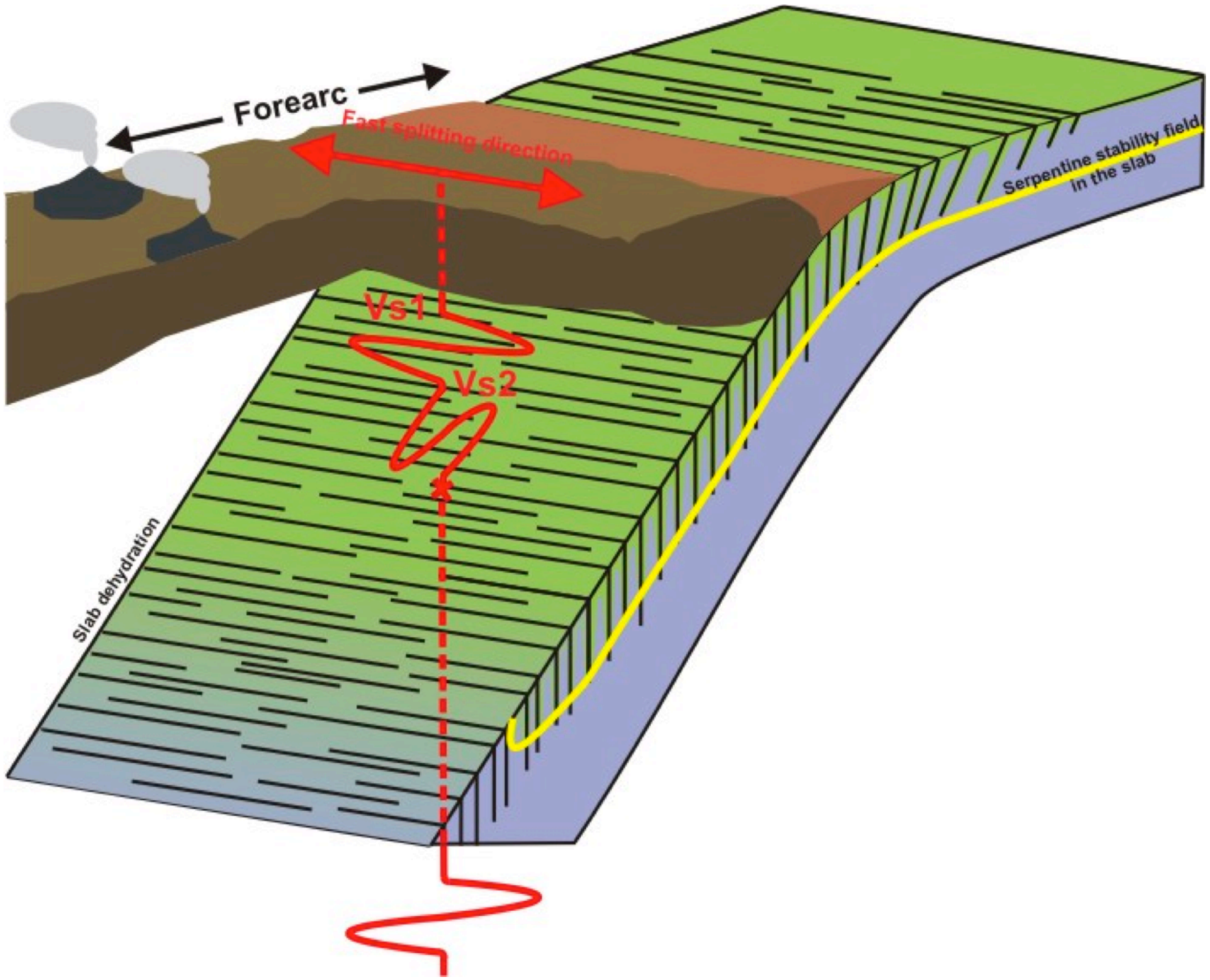
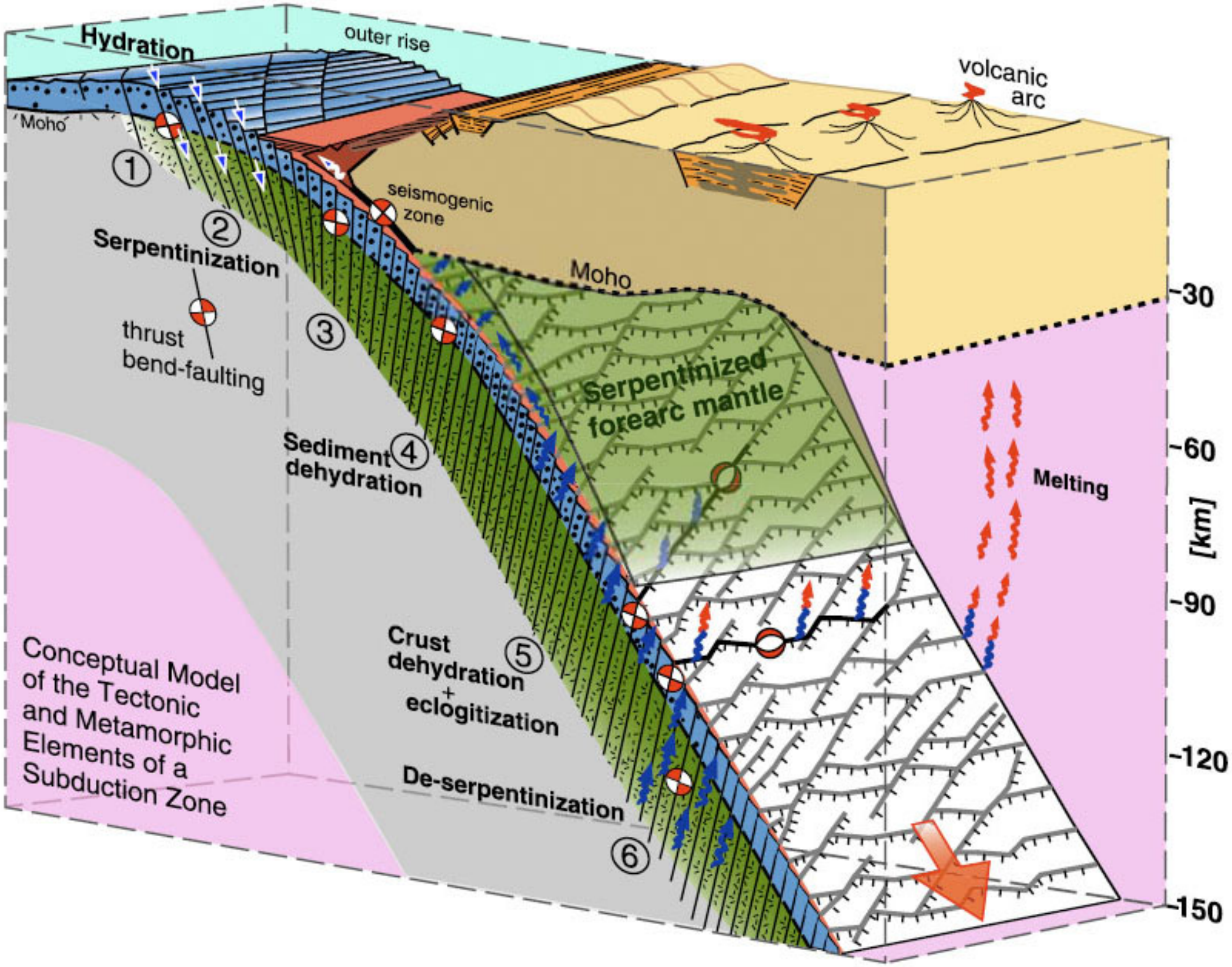
Trench parallel Vs1 polarization



Faccenda et al 2008 Nature

Fracturing of the slab



Ranero et al.(2005) G3

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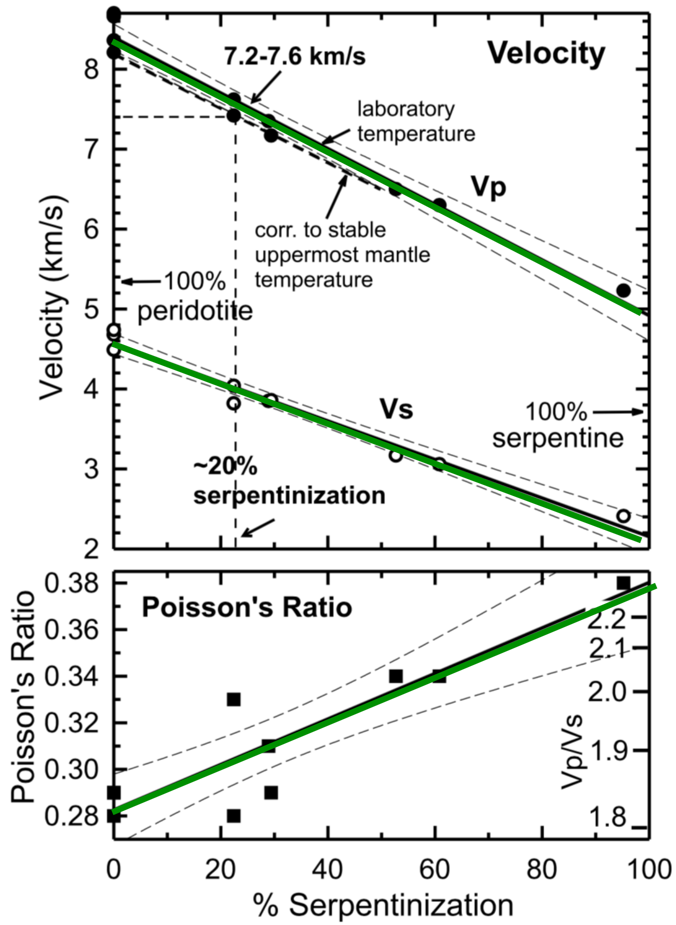
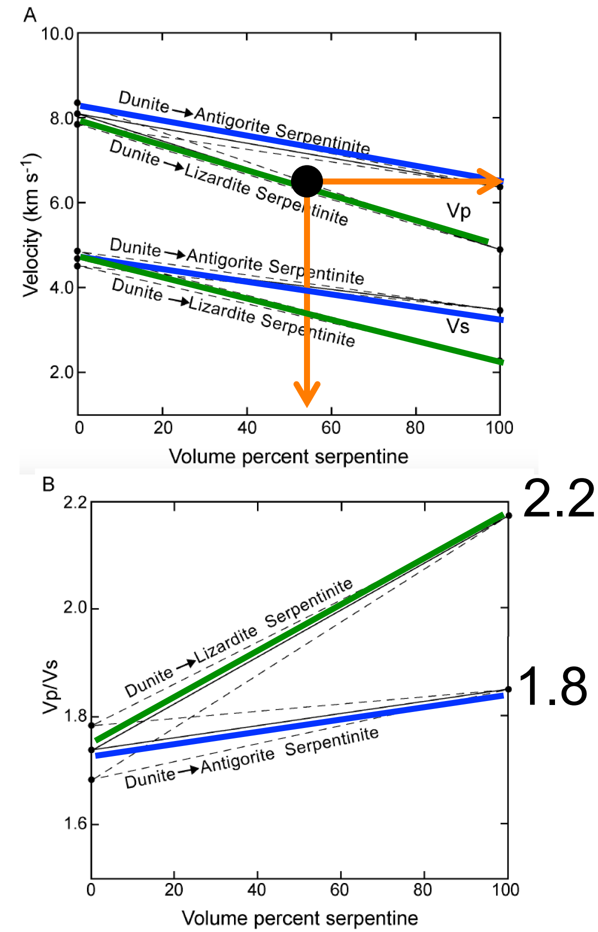
Lizardite (LT/LP) and Antigorite (HT/HP)



All of Christensen's samples are isotropic !

However many antigorite samples are highly deformed and a strong CPO and are anisotropic



Antigorite has higher velocities & lower Vp/Vs ratios than lizardite and chrysotile

R. D. Hyndman & S. M. Peacock(2003) EPSL
"Serpentinization of the forearc mantle"
Serpentine = Lizardite !!!

N.I. Christensen (2004)
Int. Geol. Review. 46,795-816.

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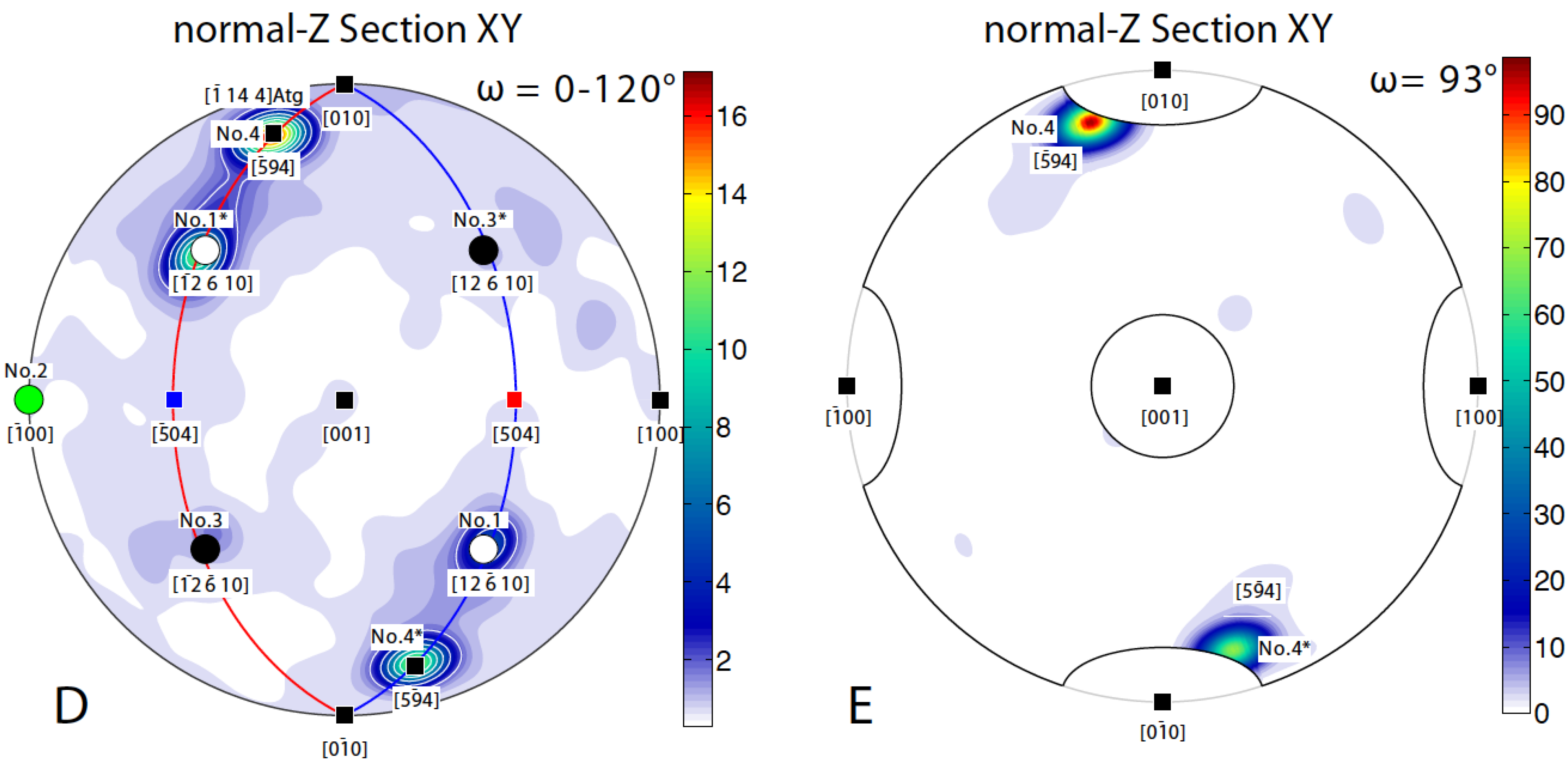
MDF axes for all angles ω = 0 to 120° & section at ω = 93°



- Antigorite in faults or antigorite topotactic relationships with olivine produces TRENCH PARALLEL anisotropy for "A-type" olivine CPO, with the correct order of magnitude to explain seismic delay times of 1s in the Mantle wedge. In this case no need for abundant B- or C-type olivine CPOs.

- The anisotropy of the majority of hydrous phases is very pressure sensitive – hence more anisotropic at shallower depths

- The depth range of anisotropy needs to be better defined.