Interphase misorientation as a tool to study metamorphic and magmatic processes

Interphase boundaries

Upscaling from TEM to thin-section

Interphase misorientation boundaries

Example 3 – Atlantis bank gabbros

Example 2 – calcite-aragonite

Example 1 – olivine - antigorite

Conclusions

One of the quickest talks you will ever see in your life

ScopeM

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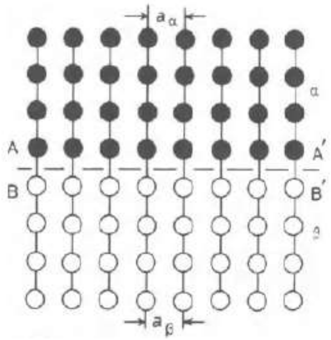
Interphase Boundaries

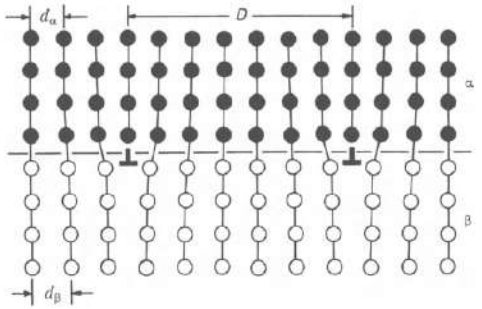
Separates two different phases which may have different composition, crystal structure and/or lattice parameters

- **Coherent interface** → two crystals match perfectly at the interface plane (small lattice mismatch can be accommodated by elastic strain in the adjacent crystals)
- **Semi-coherent interface** → lattice mismatch is accommodated by periodic array of misfit dislocations
- **Incoherent interface** → disordered atomic structure of the interface

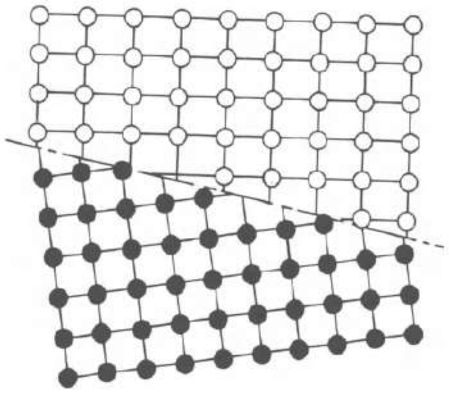
Coherent



Semi-coherent



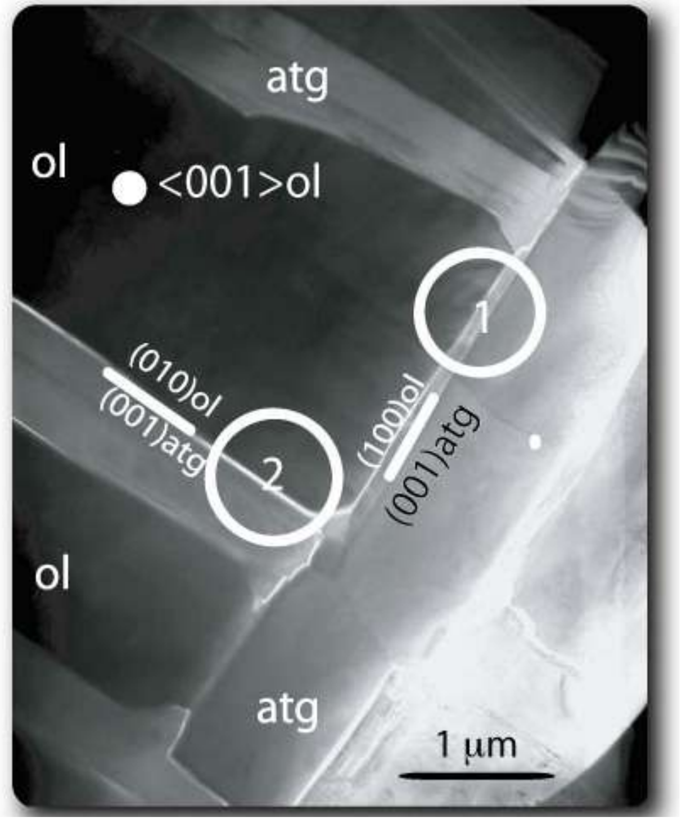
Incoherent



Porter & Easterling 1997 - Phase Transformations in Metals and Alloys

However…

- Geometry of interphase boundaries has received much less attention than grain boundaries in monomineralic aggregates
- Studies of metamorphic reactions have shown that nucleation and growth of new phases can be controlled by the crystallography of parent mineral
- Important to understand mineral reactions
- Interphase boundaries may influence interface diffusion (metamorphic processes) and rheology (e.g. phase mixing – deformation processes)



relation 1
$(100)_{Olivine}$ || $(001)_{Antigorite}$
$[001]_{Olivine}$ || $[010]_{Antigorite}$

relation 2
$(010)_{Olivine}$ || $(001)_{Antigorite}$
$[001]_{Olivine}$ || $[010]_{Antigorite}$

Boudier et al. 2010 – Journal of Petrology

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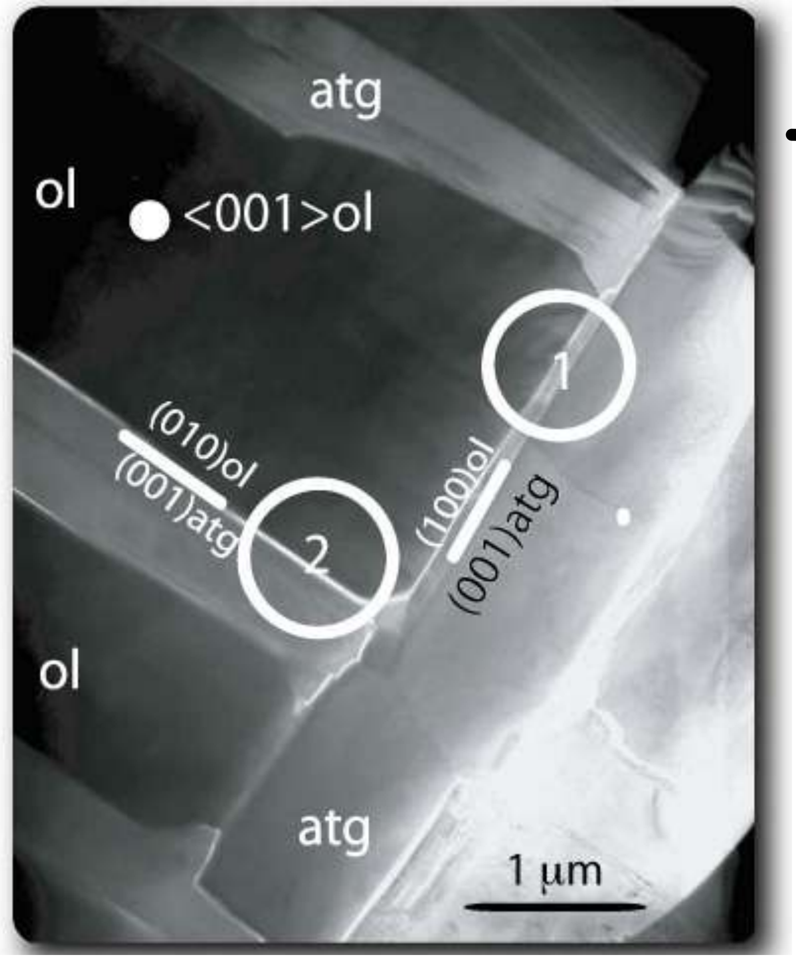
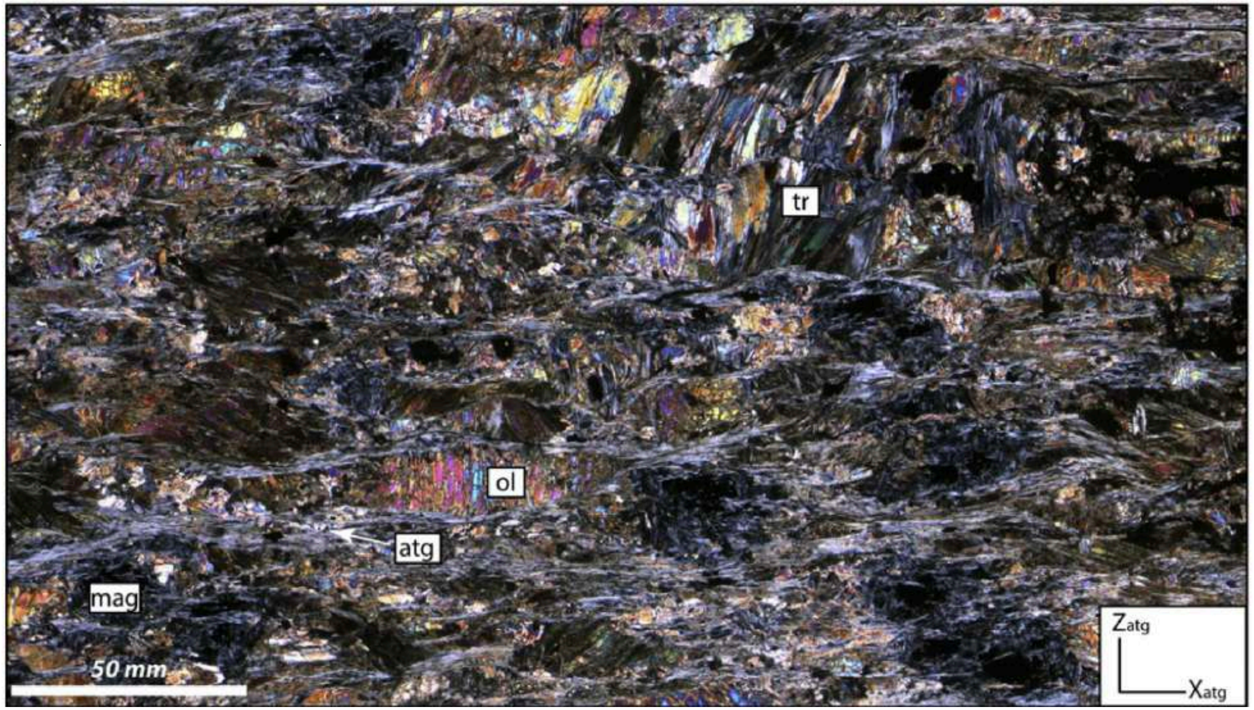
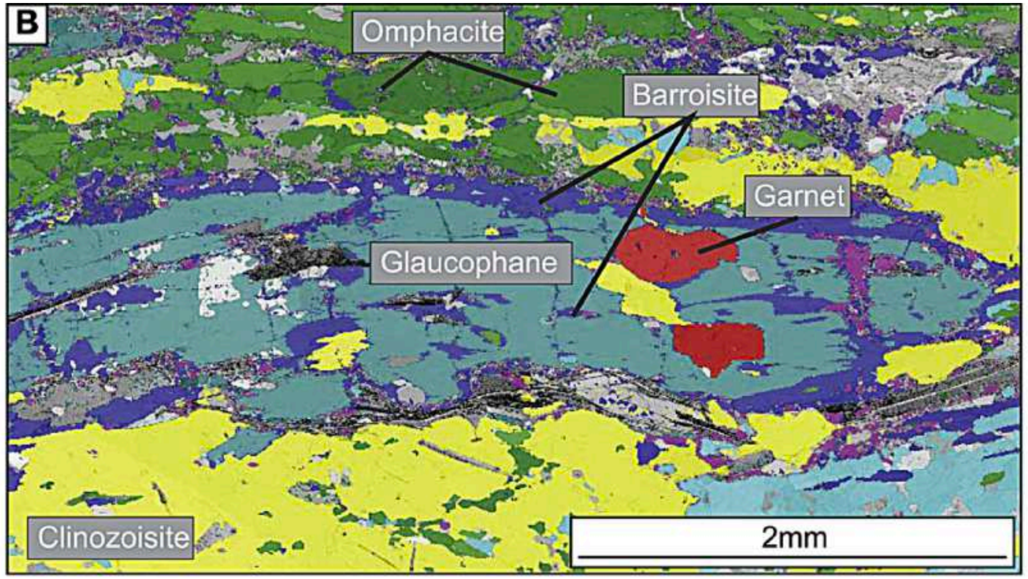
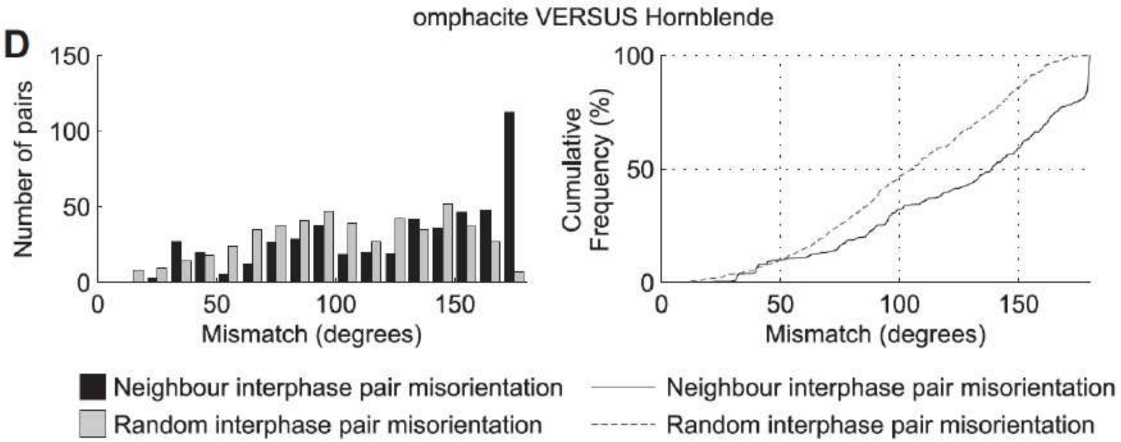
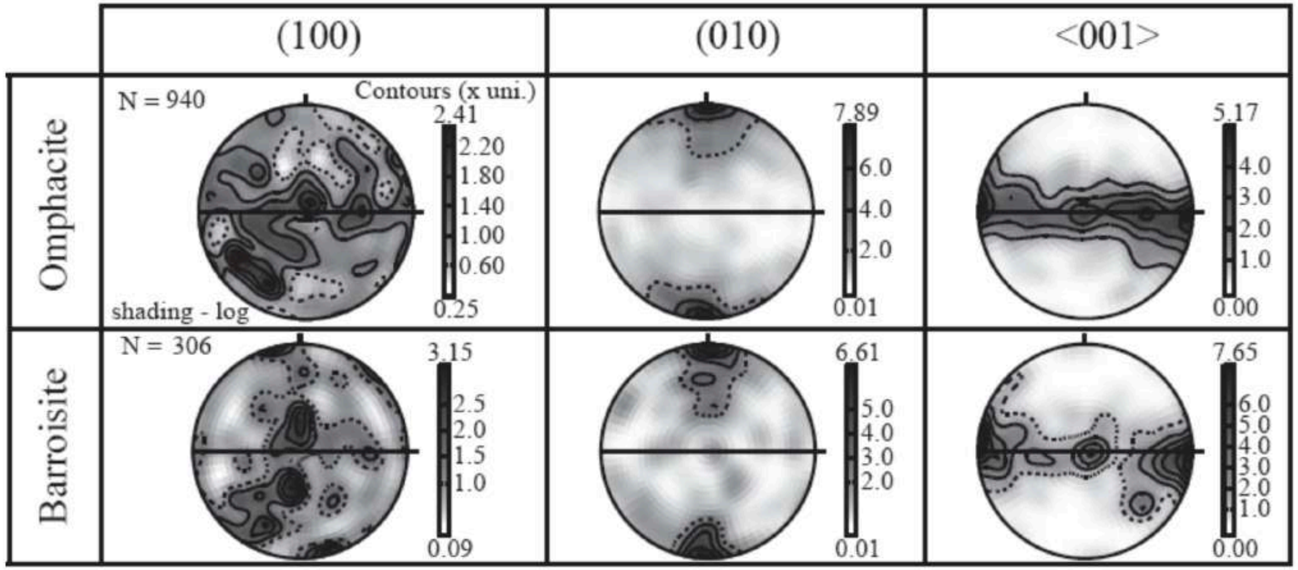
Can we extrapolate these observations to larger scales?











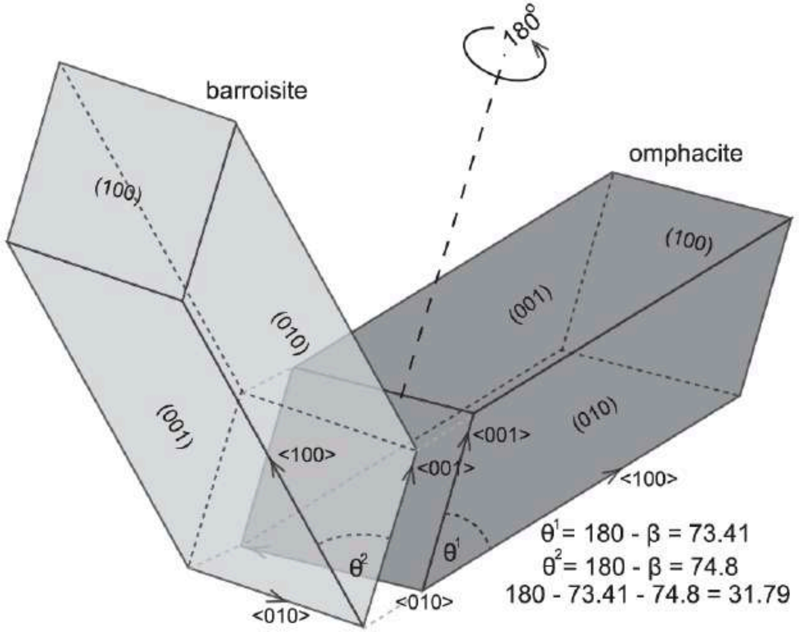


Fig. 6. Diagrammatical representation of the 'special orientation relationship' that barroisite employs to replace omphacite and the 180° rotation axis about <001>.

McNamara et al. 2012 - JSG

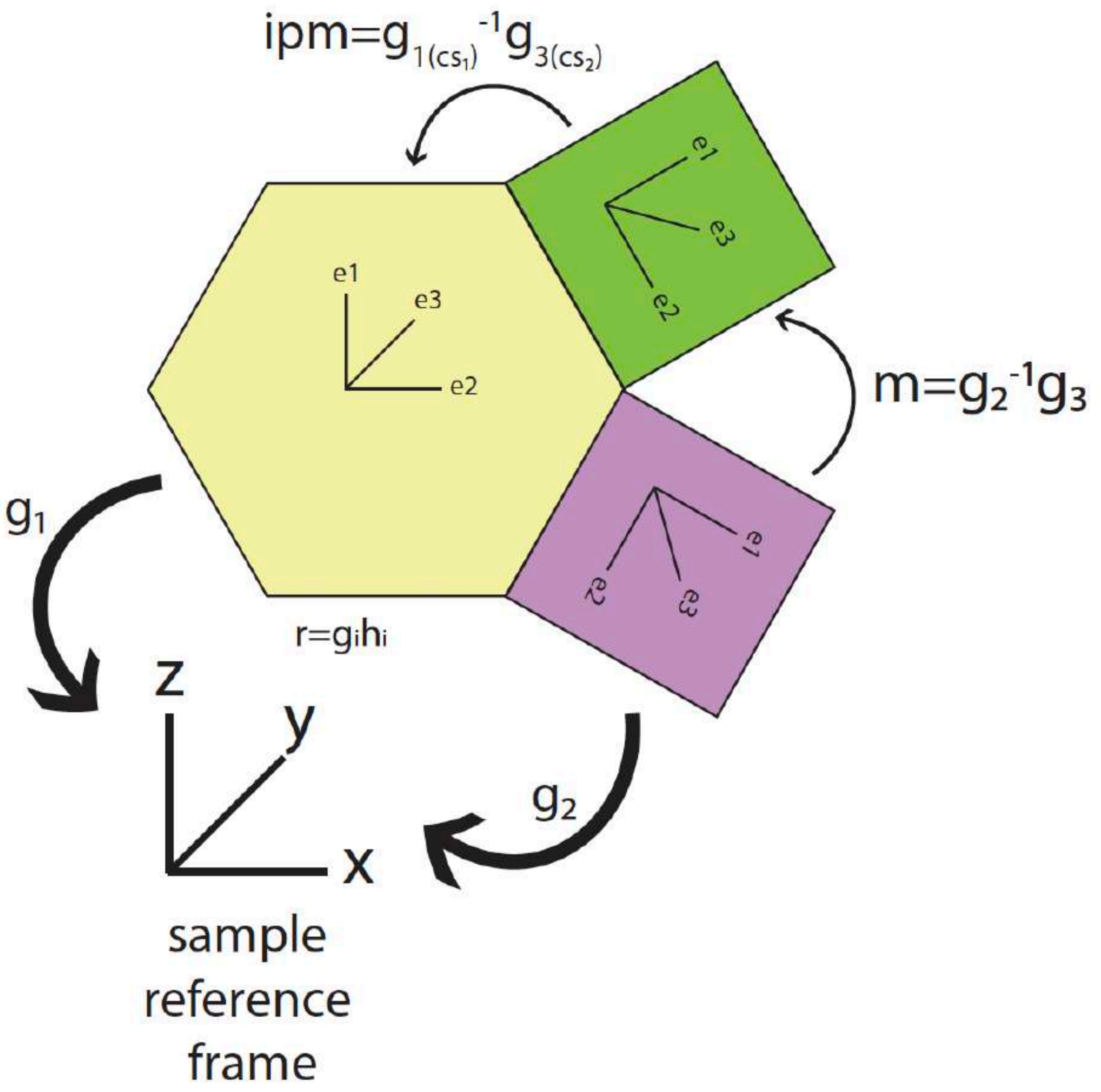
Interphase misorientations

To study the phase transformation between phase A and phase B

- We calculated the misorientation function (MDF) along grain boundaries between phase A and phase B;
- 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 relations such as (100)pA || (001)pB & [001]pA || [010]pB in Burgers vector notation
- Those relations are geometrical and do not imply in a specific mechanism

Interphase misorientations - complications

- The distribution's fundamental region requires an entire upper hemisphere due to the combination of the orthorhombic symmetry of olivine and the monoclinic symmetry of antigorite.
- In addition, there is the constraint that grain 1 cannot be exchanged with grain 2 because they are clearly different physical entities.
- Therefore, there is no exchange symmetry across a phase boundary

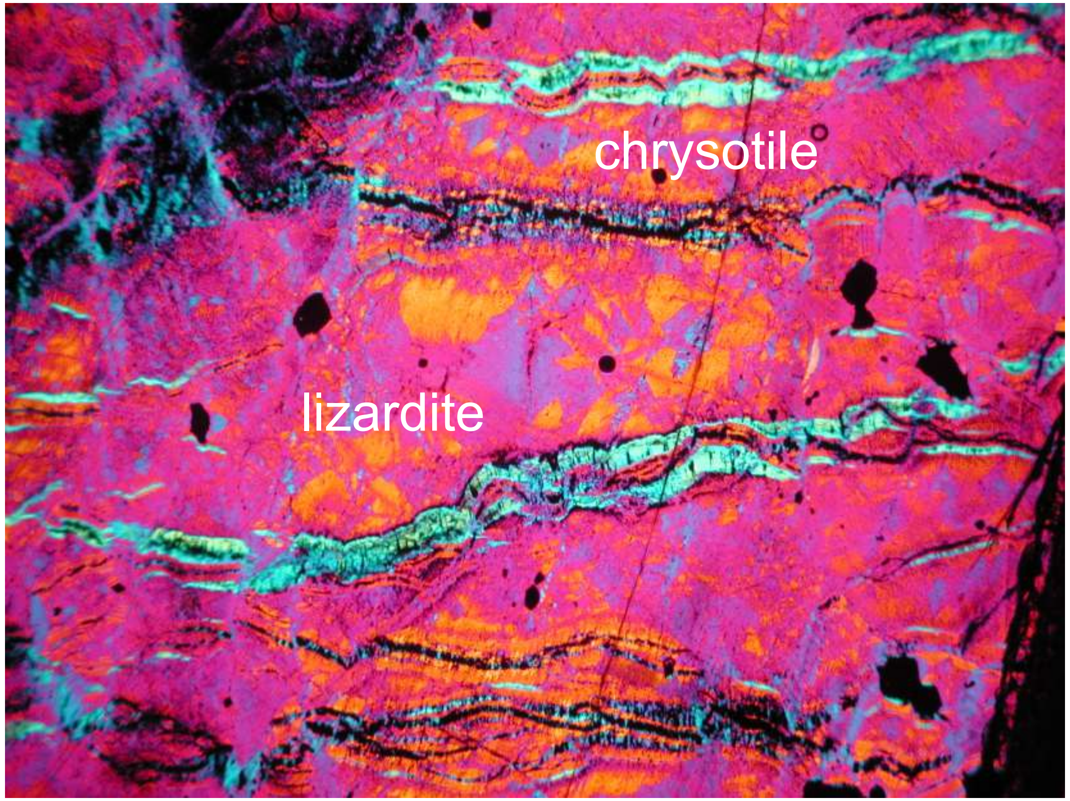


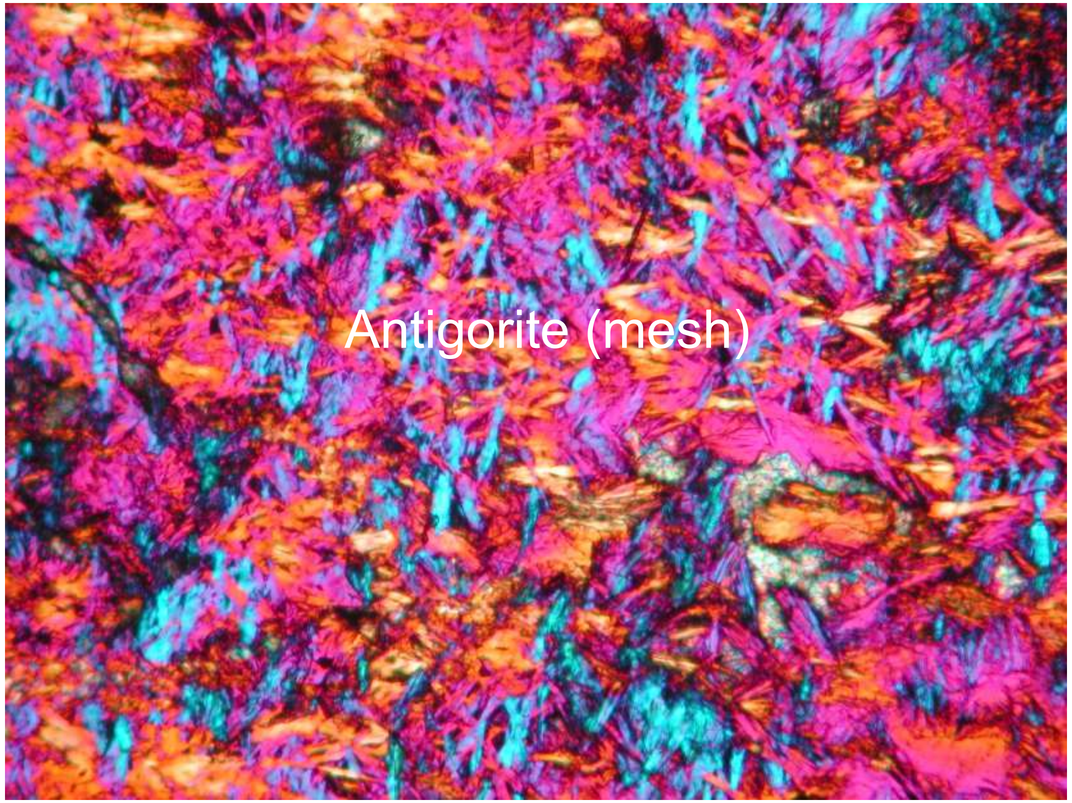
EXAMPLE 1 – olivine → antigorite

Olivine – Antigorite

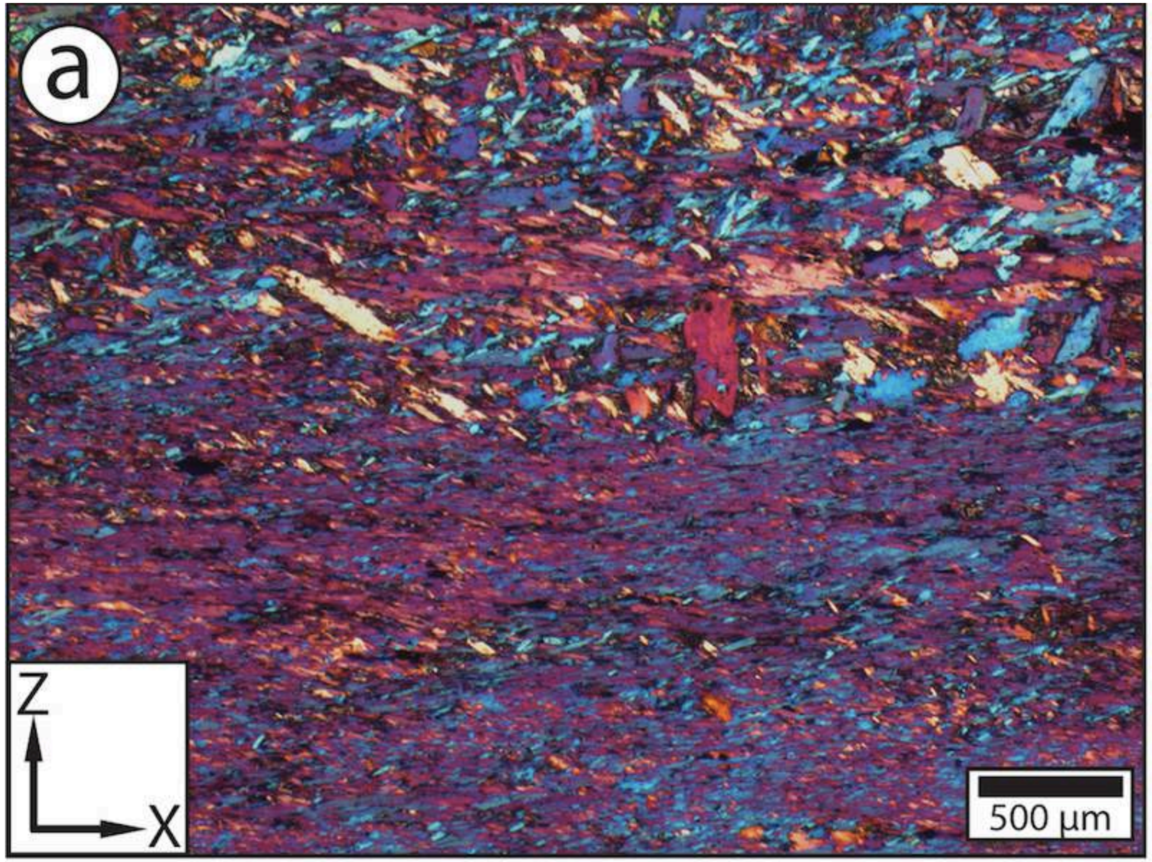
- **Olivine to Serpentine (+ Brucite):**

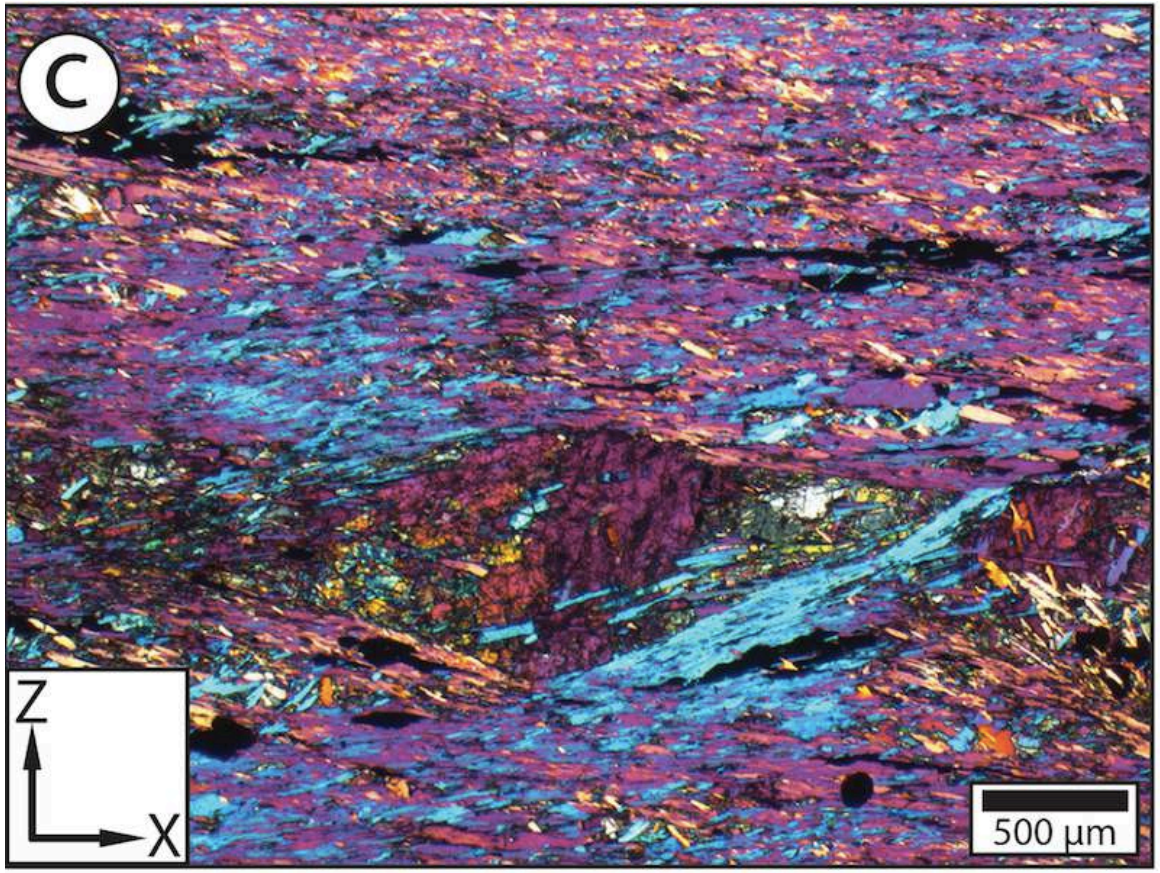
  $2Mg_2SiO_4 + 3H_2O = Mg_3Si_2O_5(OH)_4 + Mg(OH)_2$



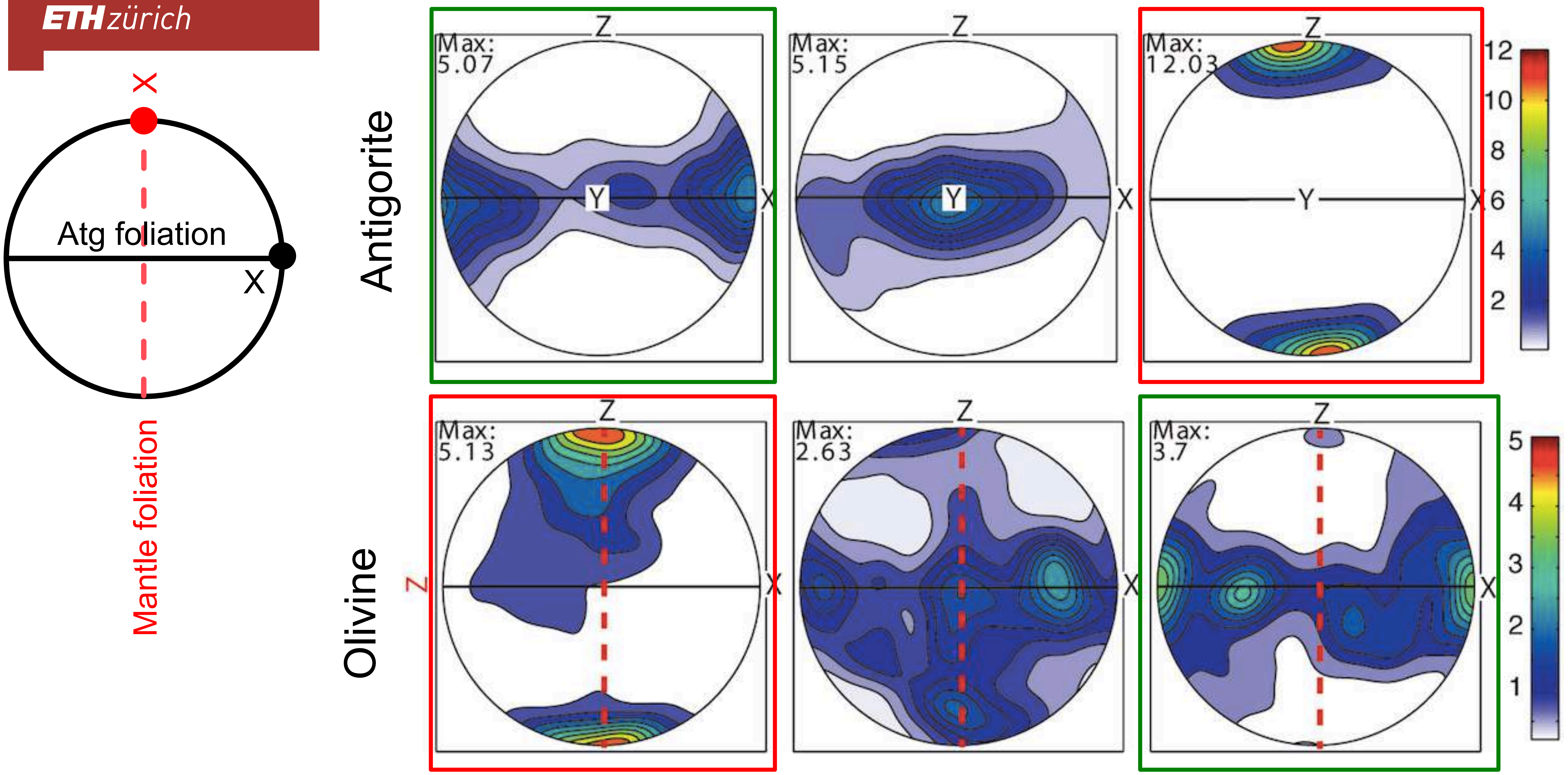


Olivine-antigorite schist from Val Malenco

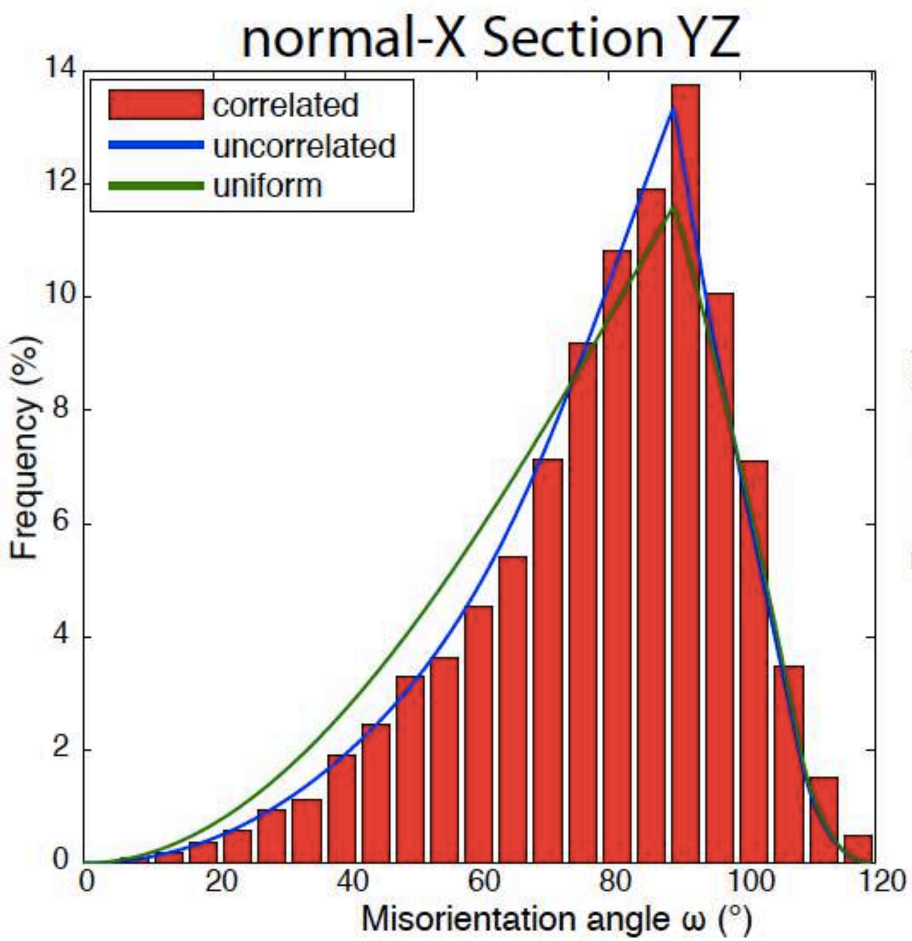


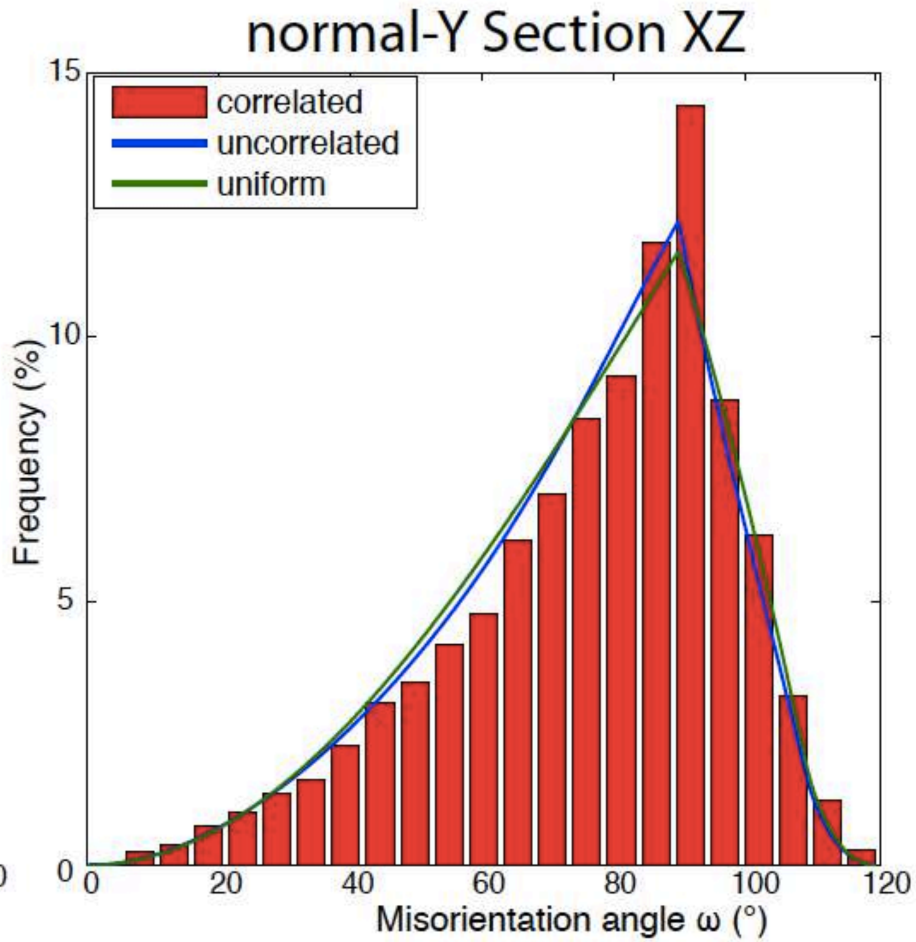


Morales et al. 2018 (Tectonophysics)


X
Atg foliation
X
Mantle foliation
Antigorite
Olivine
Z
Max: 5.07
Max: 5.15
Max: 12.03
Y
X
12
10
8
6
4
2
Max: 5.13
Max: 2.63
Max: 3.7
5
4
3
2
1

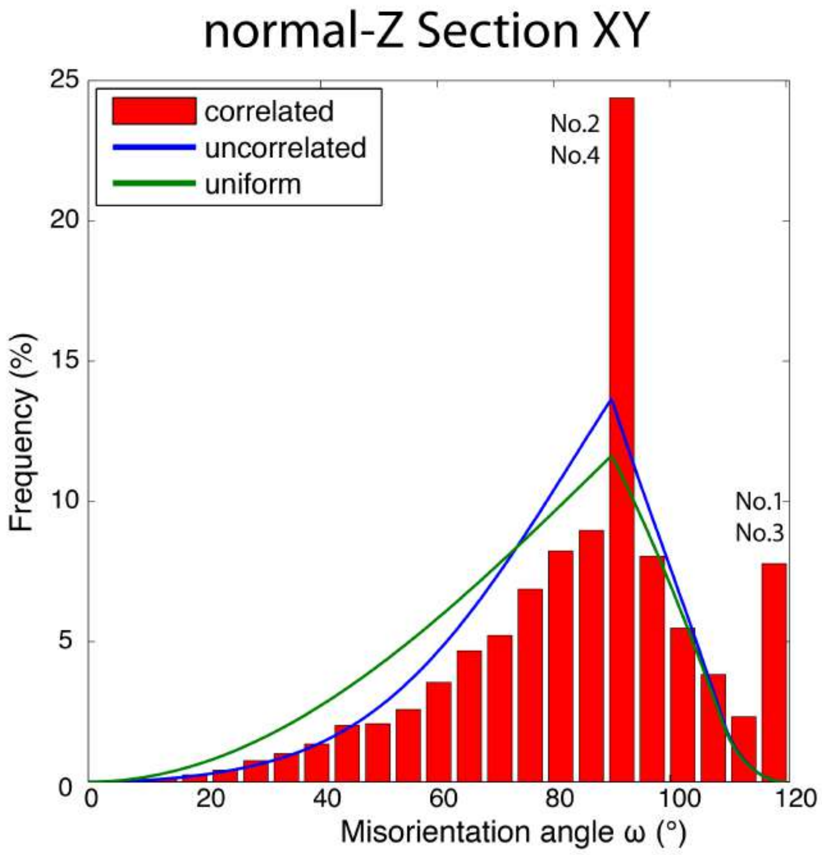
Olivine-Antigorite misorientation angles for correlated, uncorrelated and uniform distributions



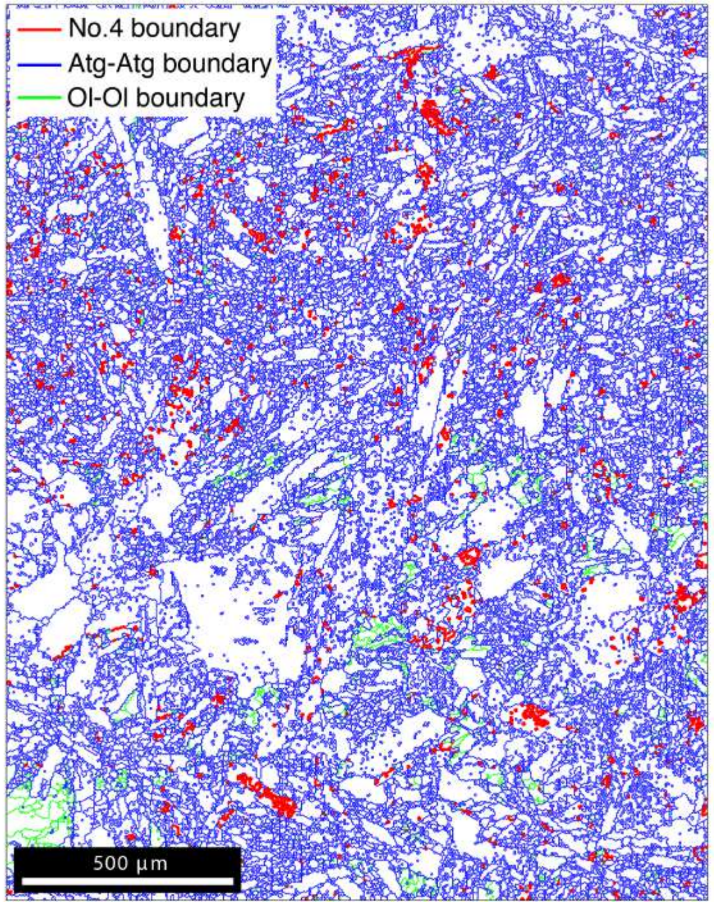


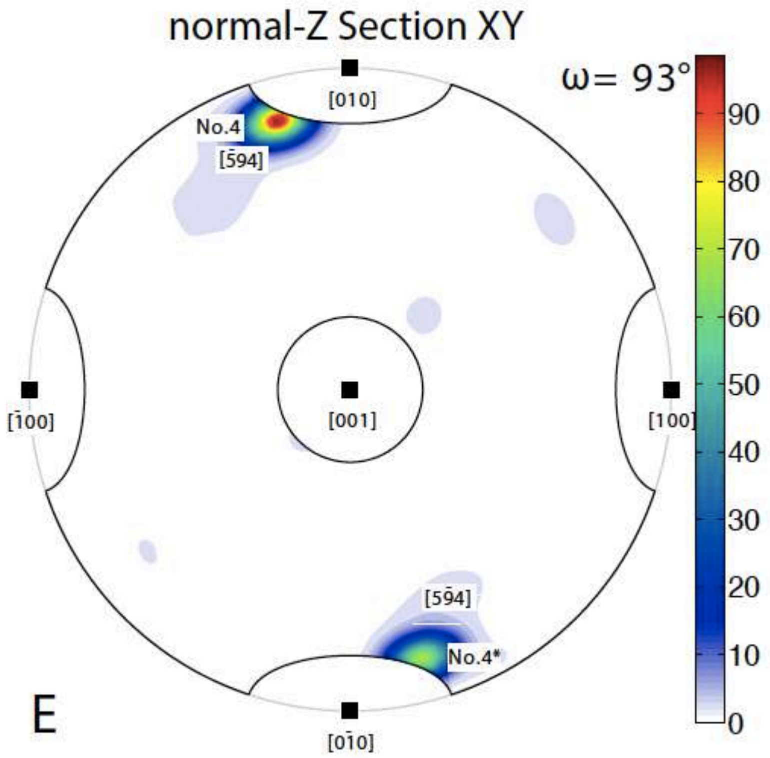
Morales et al. 2018 (Tectonophysics)

Interphase misorientation plots and maps



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

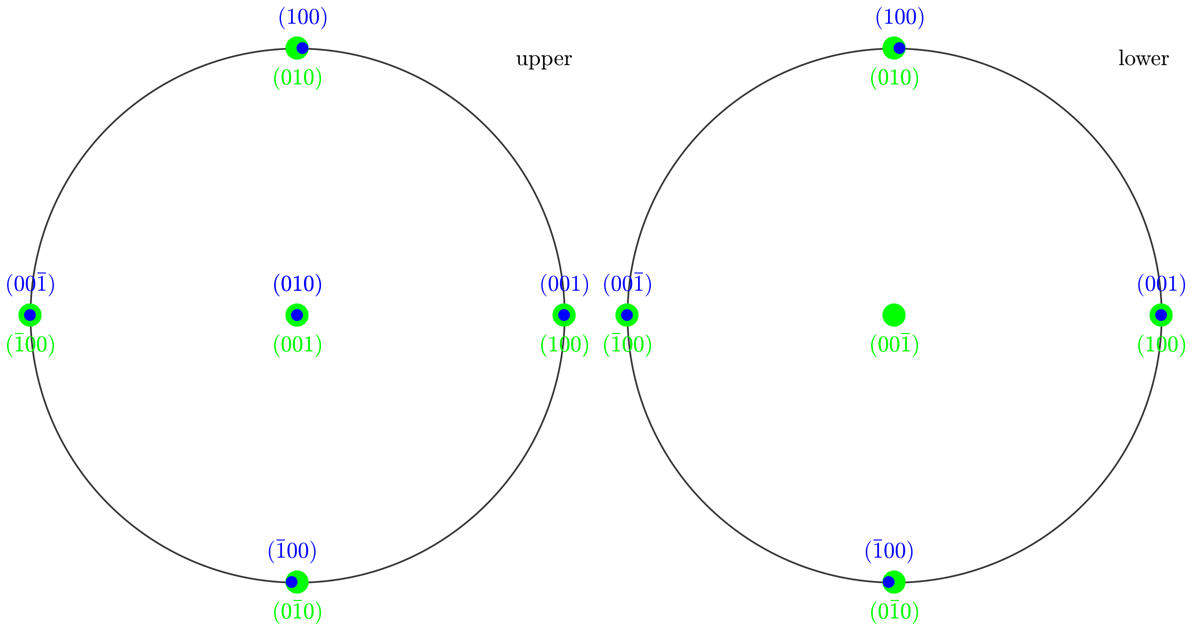




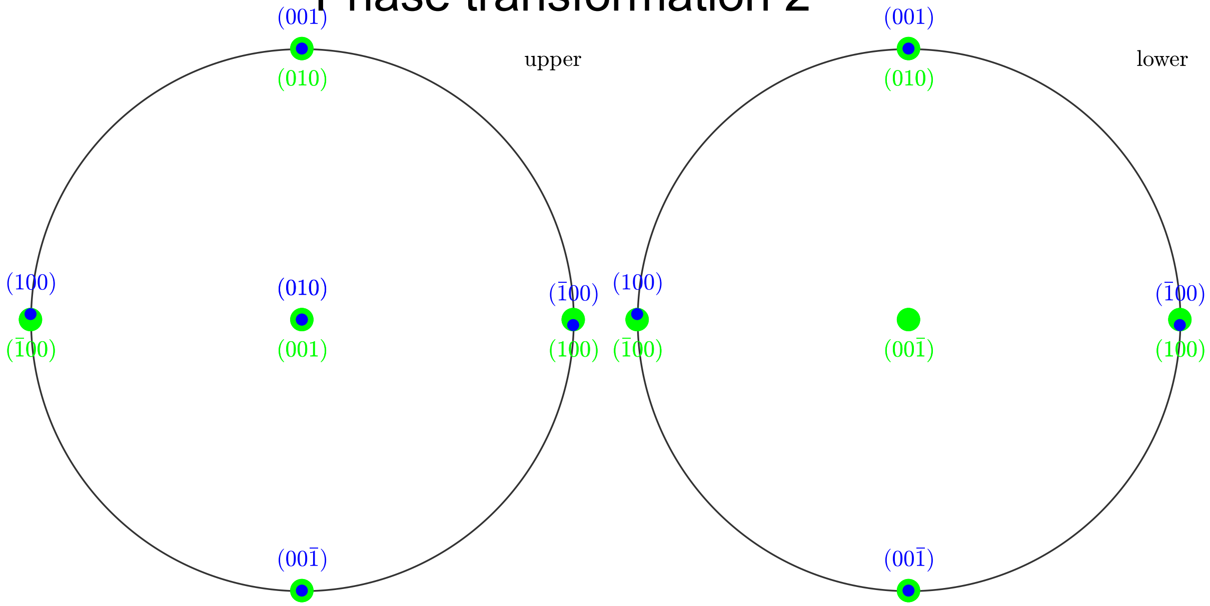
Morales et al. 2018 (Tectonophysics)

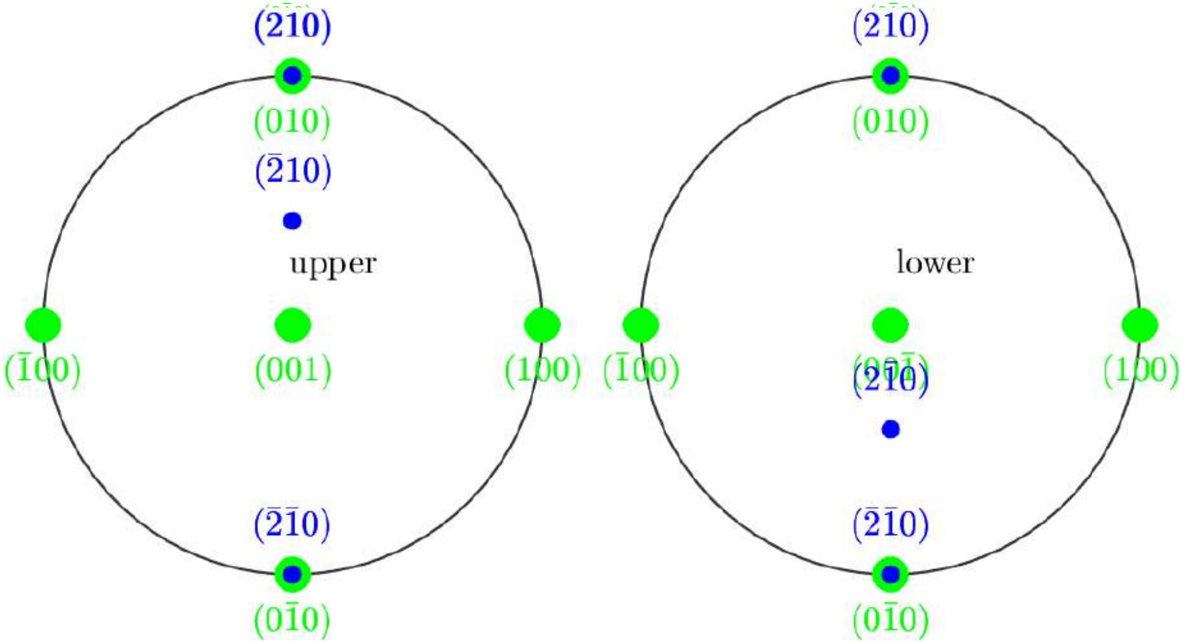
Observed interphase relationships

Phase transformation 1



Phase transformation 2



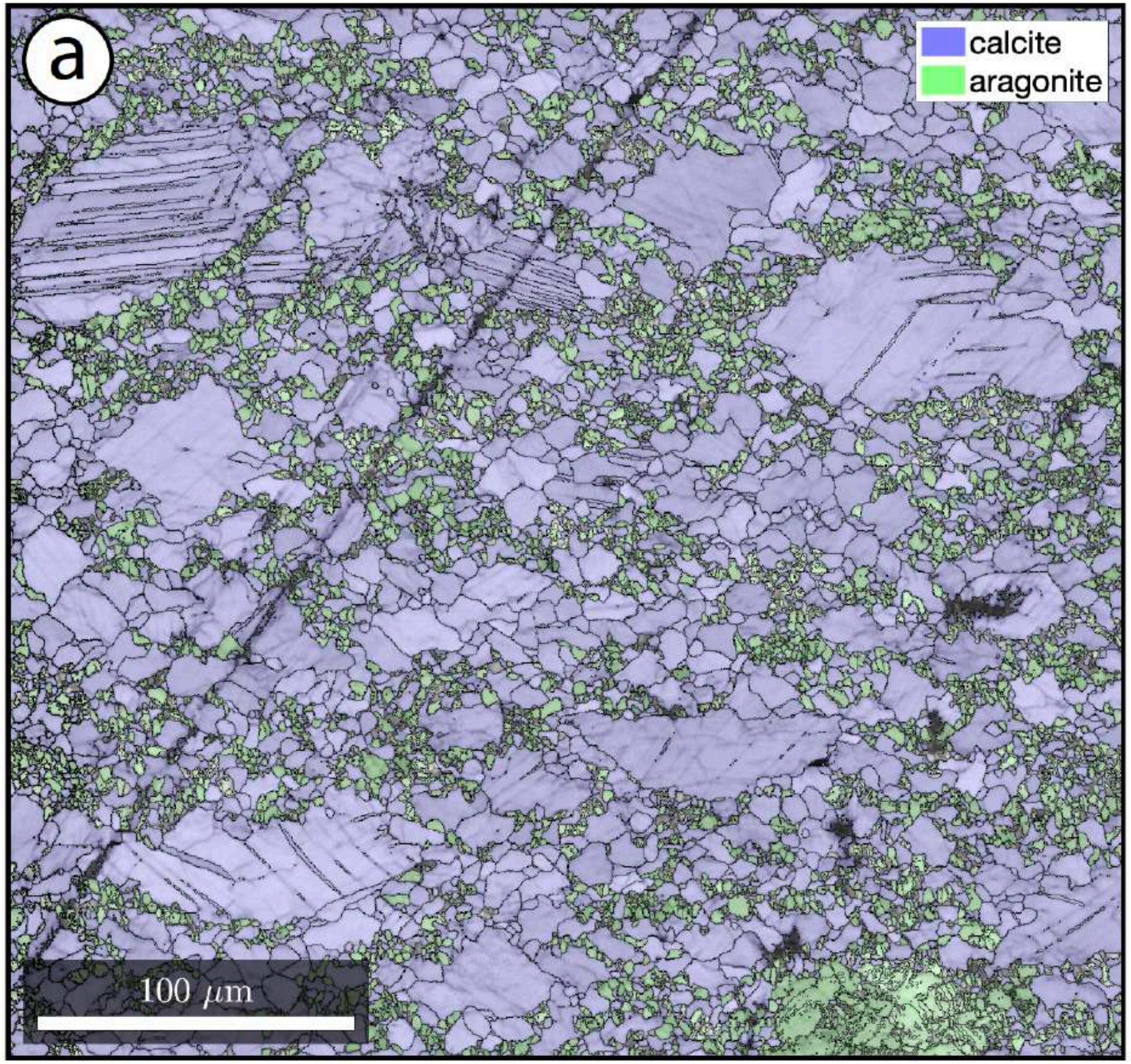


Phase transformation 4

EXAMPLE 2 – calcite-aragonite

Calcite-aragonite

- Heterogenenous nucleation and topotactic growth
- Metastable aragonite-rich mylonites can be found in areas that experienced high P-low T metamorphism (bluschists)
- Orientation relations described in the literature
- $(11\text{-}20)_{cal}$ || $[100]_{ar}$
- $[0001]_{cal}$ || $[110]_{ar}$
- Results presented here from hydrostatic experiment in a Griggs apparatus operating at



Calcite-aragonite definition on MTEX

```
Cal2Ara_No1 = orientation('map',...
  Miller(1,1,-2,0,ebsd('calcite').CS,'hkl'),Miller(1,0,0,ebsd('aragonite').CS,'hkl'),...
  Miller(0,0,0,1,ebsd('calcite').CS,'uvw'),Miller(0,1,1,ebsd('aragonite').CS,'uvw'))
%
% check angles between hkl and uvw of parent and daughter to be 90 degrees
angle_hkl_uvw_parent = angle(Miller(1,1,-2,0,ebsd('calcite').CS,'hkl'),...
                             Miller(0,0,0,1,ebsd('calcite').CS,'uvw'))/degree
angle_hkl_uvw_daughter = angle(Miller(1,0,0,ebsd('aragonite').CS,'hkl')...
                              ,Miller(0,1,1,ebsd('aragonite').CS,'uvw'))/degree
% axis vector3d
axis_No1 = vector3d(axis(Cal2Ara_No1))
% axis Aragonite
axis_No1_Ara = axis(Cal2Ara_No1)
% axis Calcite
axis_No1_Cal = Miller(axis_No1,ebsd('calcite').CS,'hkl')
% rotation angle
angle_No1 = angle(Cal2Ara_No1)/degree
% Euler angles
f1Ff2_No1 = Euler(Cal2Ara_No1)/degree
% Olivine reference orientation Euler (0,0,0)
ori_cal = orientation('Euler',0,0,0,ebsd('calcite').CS)
% Calculate all Daughter (Aragonite) variants
% by using all crystalloraphically equivalent orientations
% of Parent (Calcite)
ori_Ara_No1 = symmetrise(ori_cal) * inv(Cal2Ara_No1)
```

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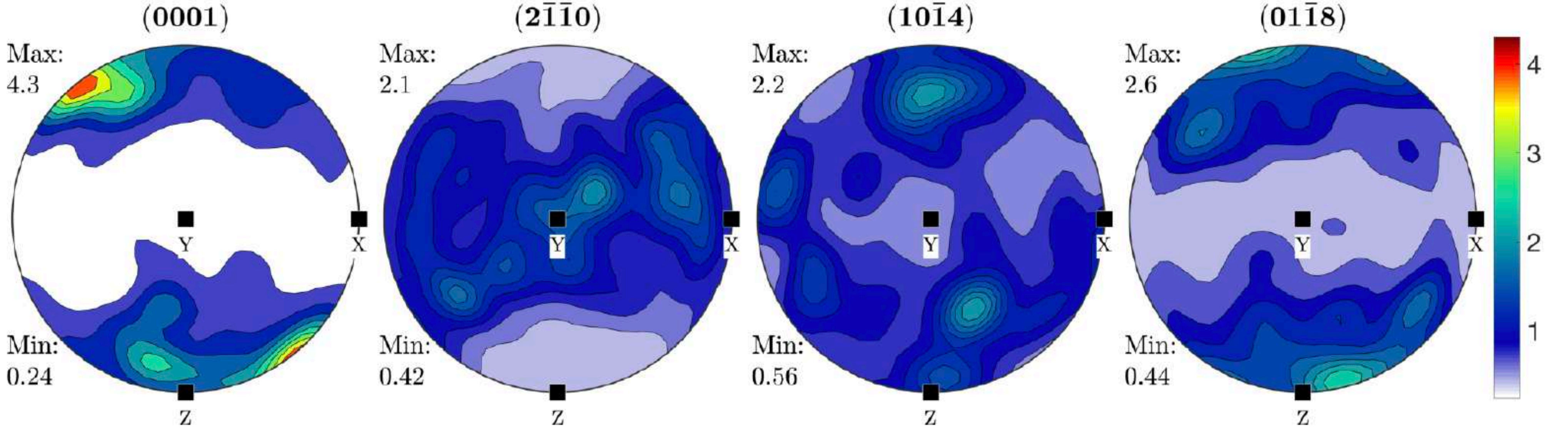
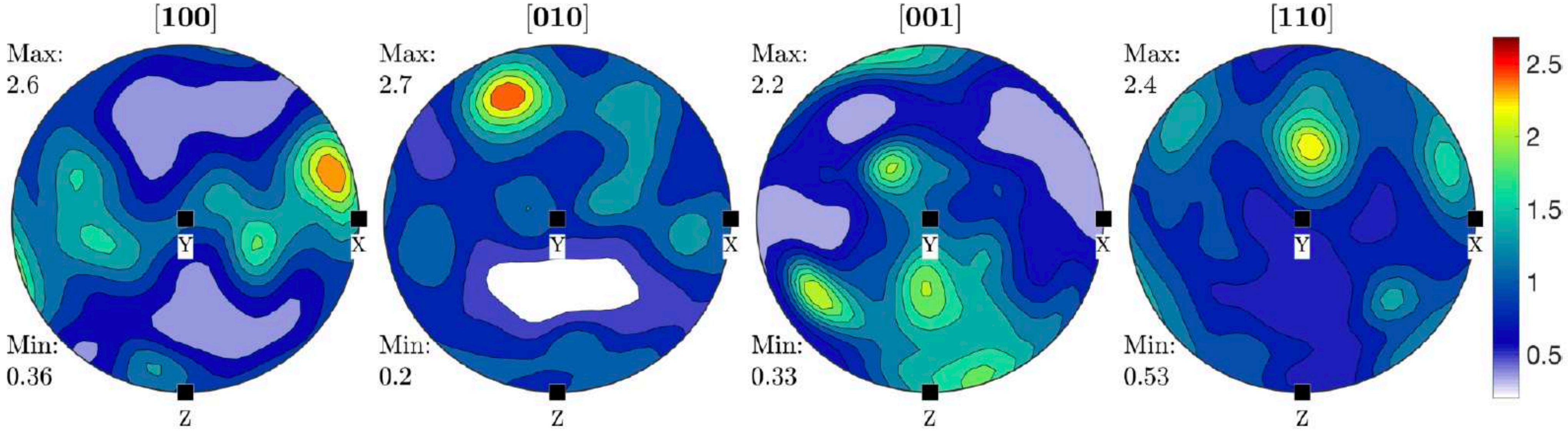
Calcite pole figures

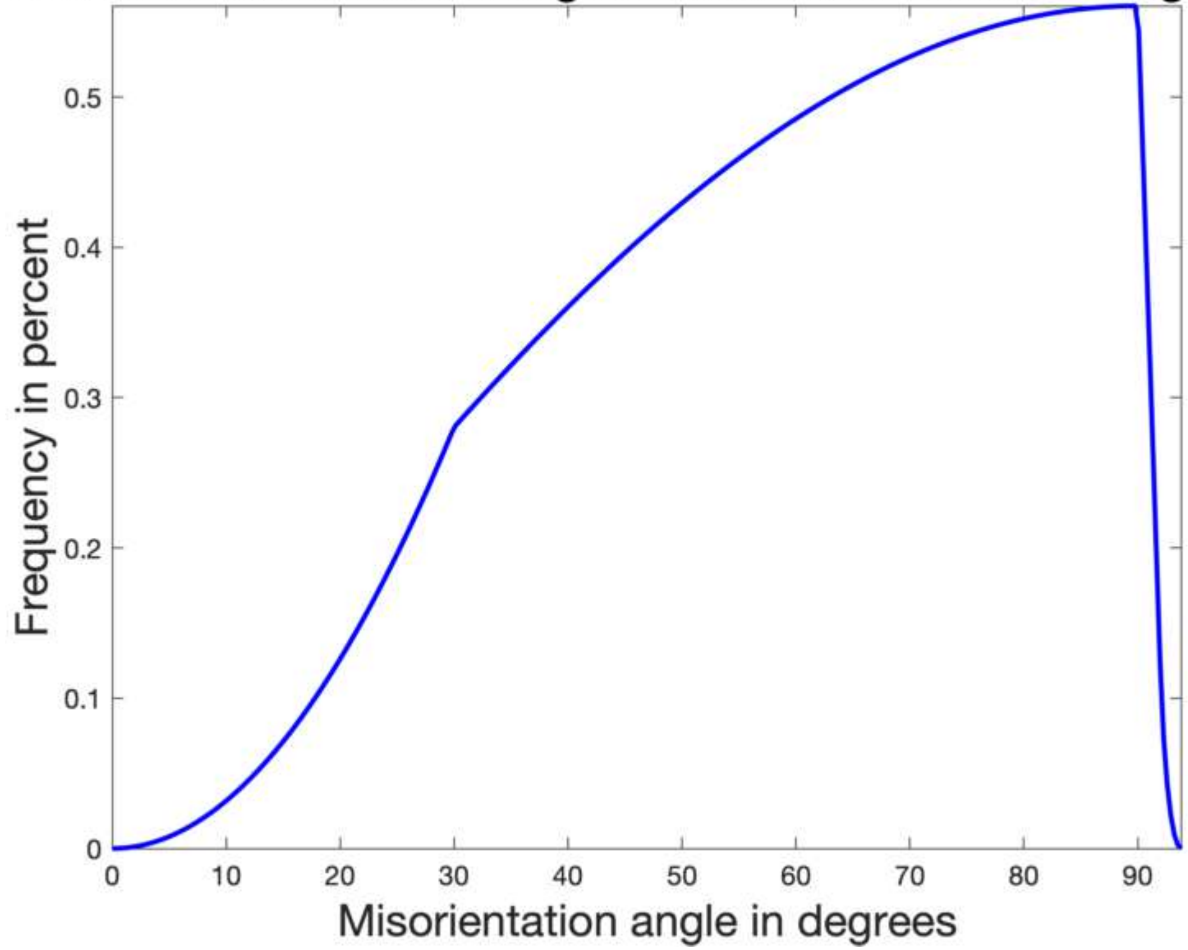


Aragonite pole figures

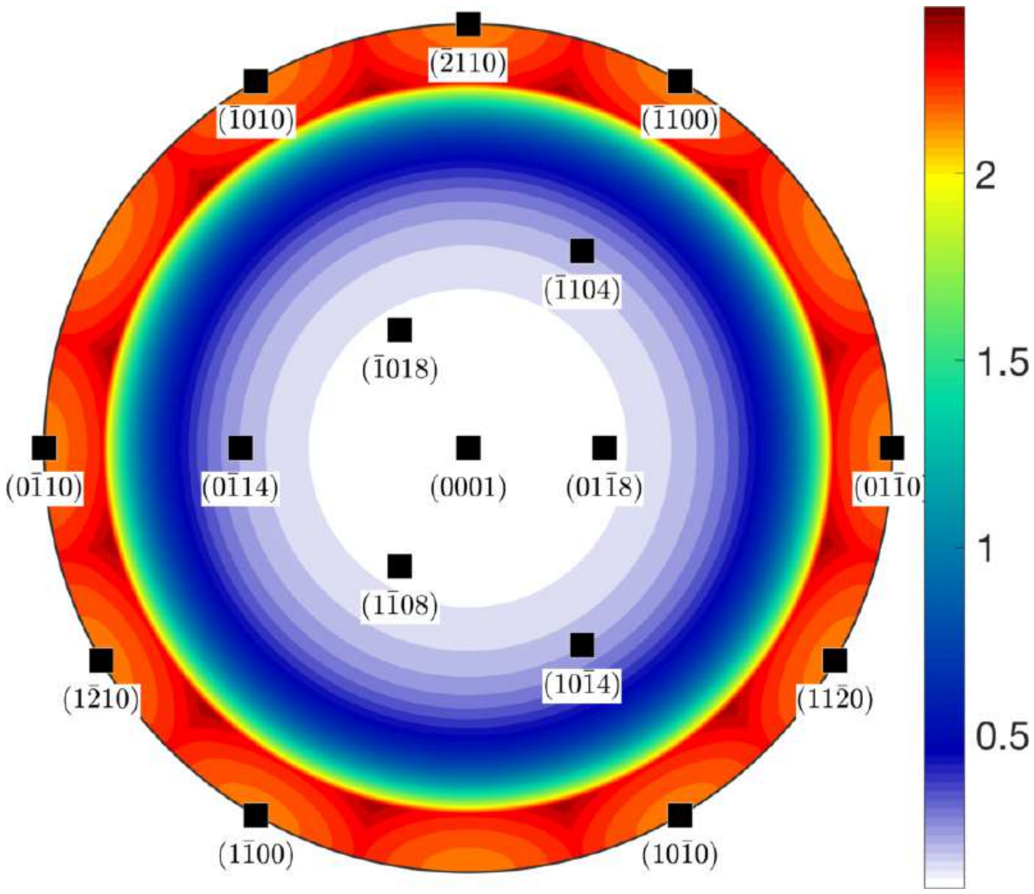


Uniform MDF calcite-aragonite

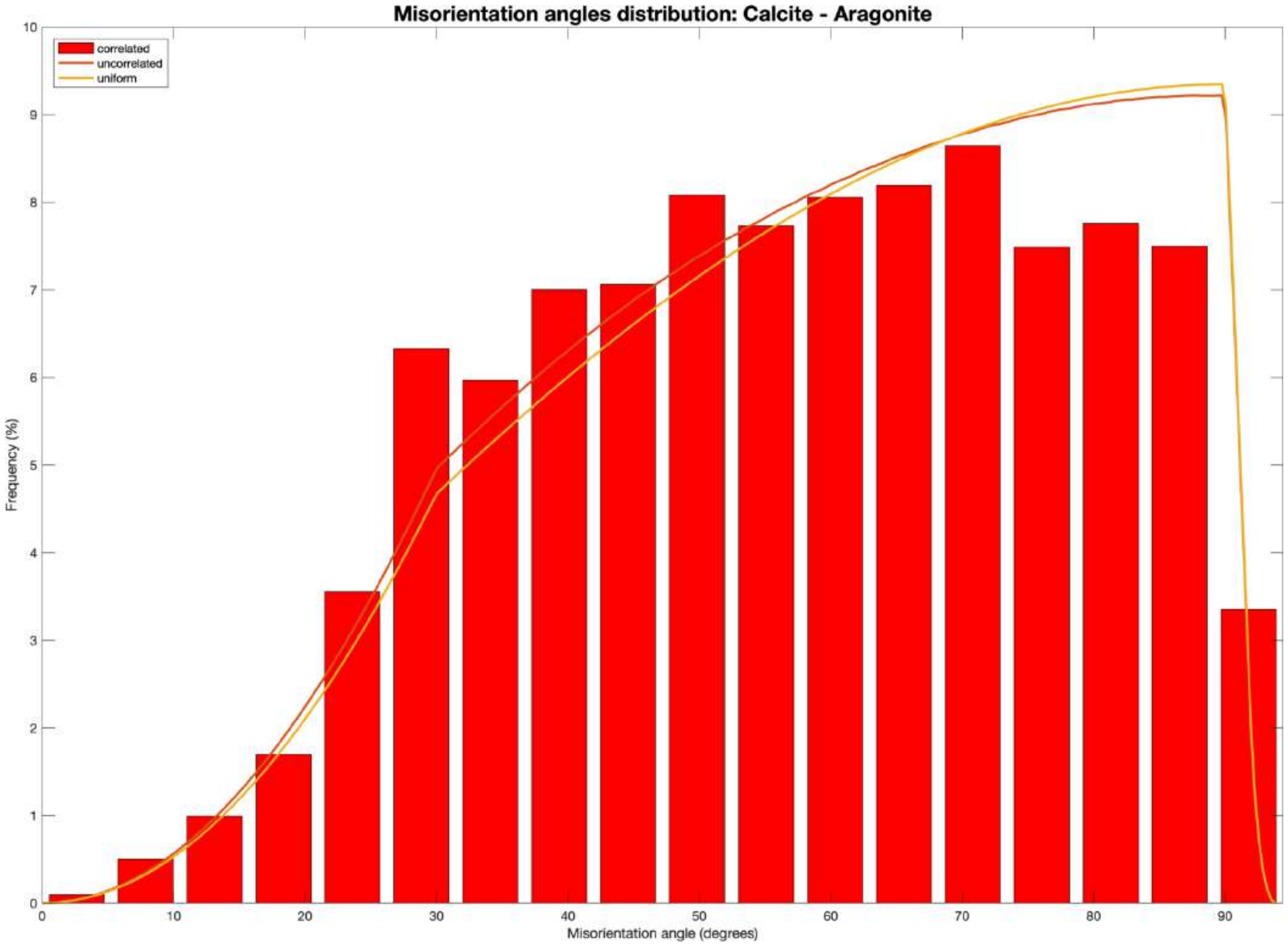
Uniform misorientation angle distribution: Calcite - Aragonite

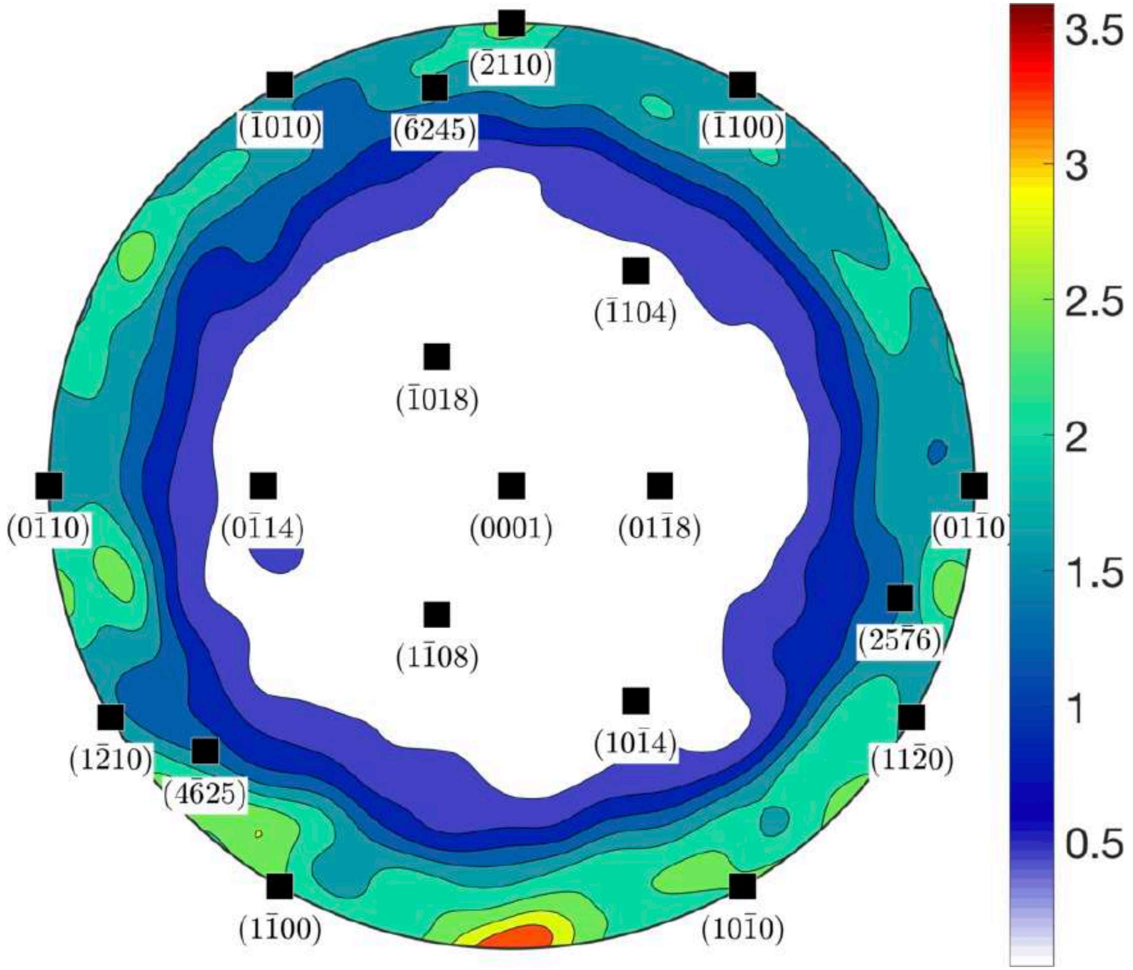


Uniform MDF axis distribution

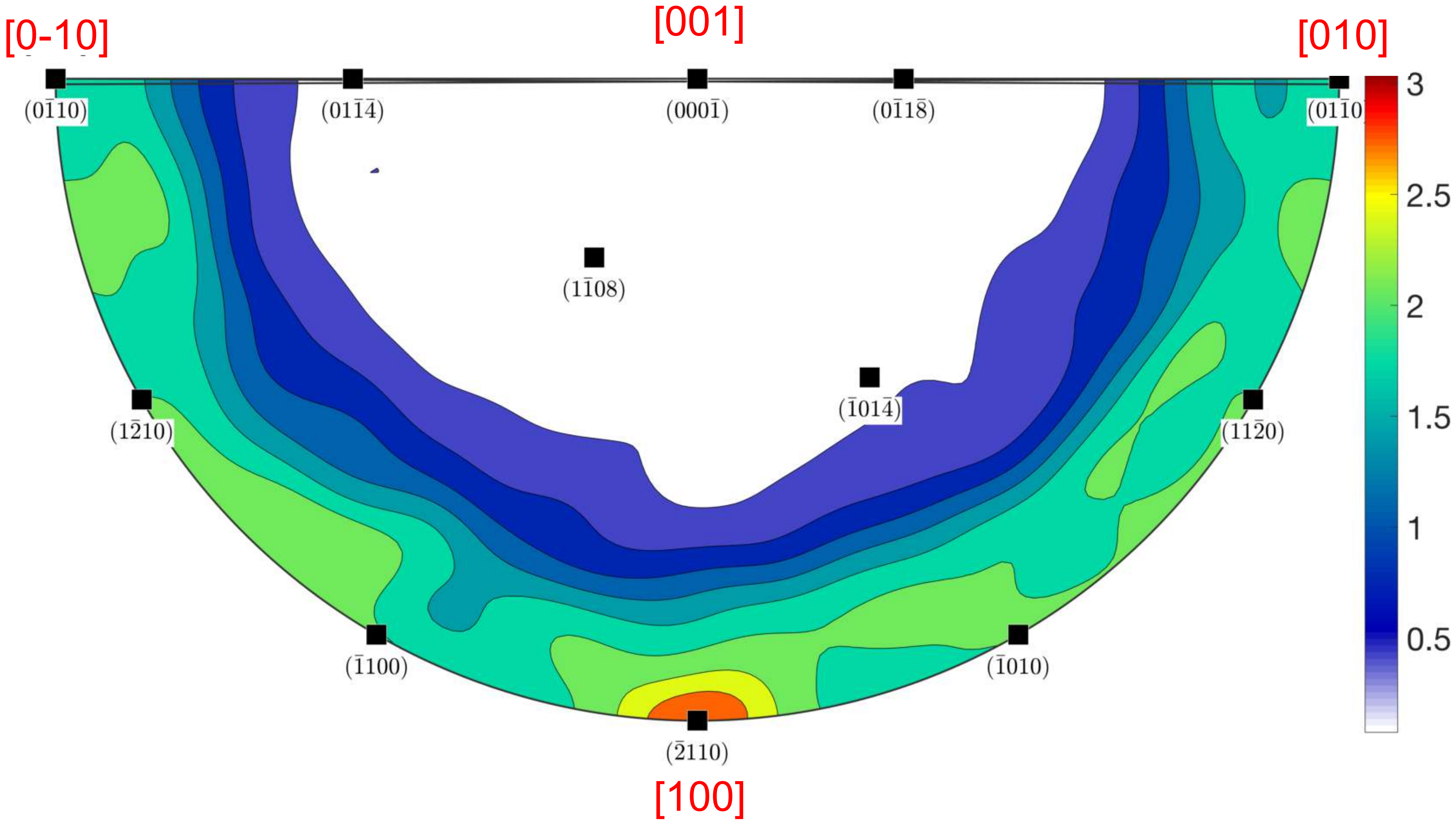


Correlated MDF – calcite-aragonite





Correlated MDF – calcite-aragonite



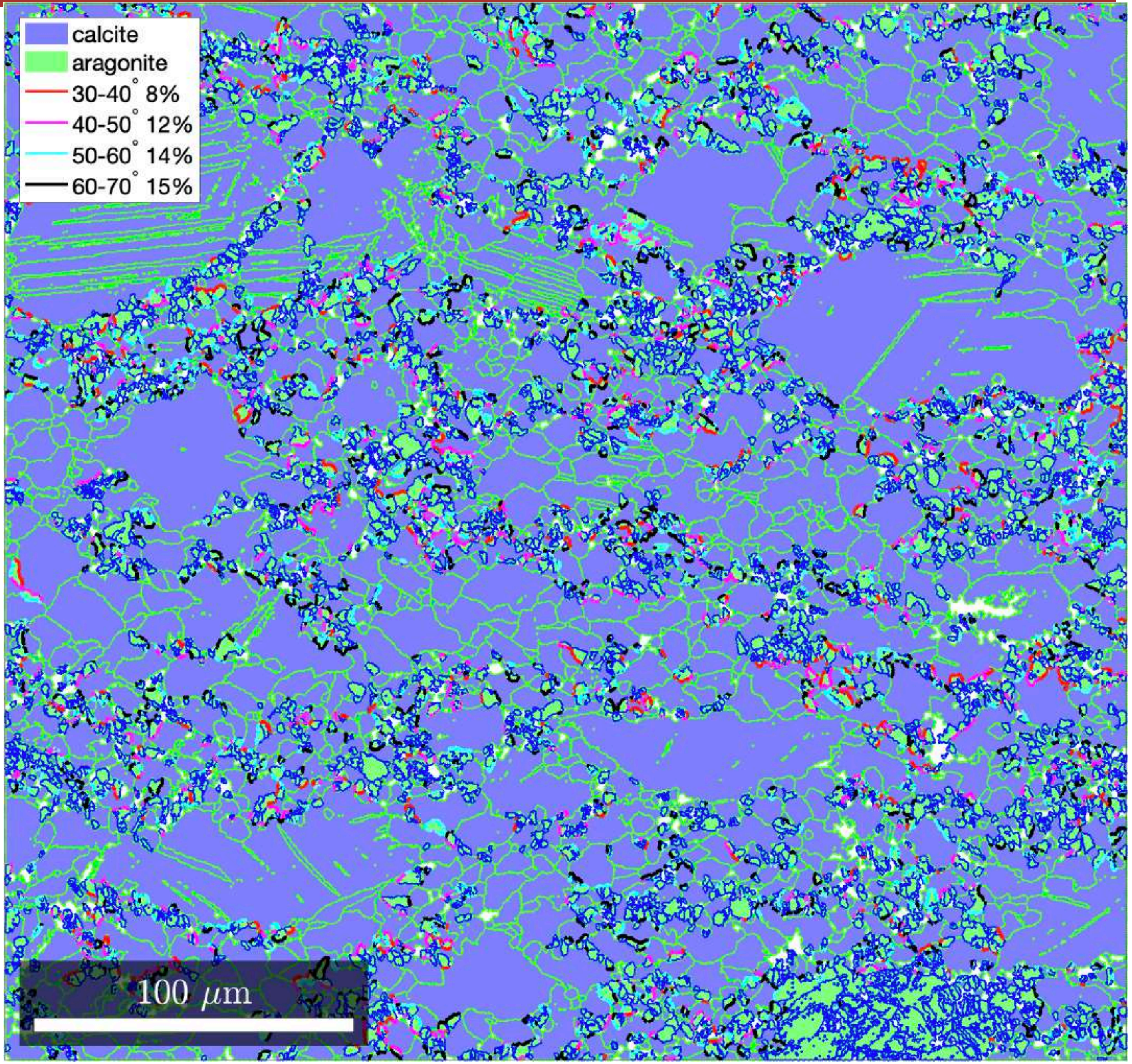
Search for boundaries with specific angles

```
%% Create search structure for boundary lengths per misorientation angle interval
% N.B. With this method you select using uniquely the misorientation angle
%      so if you have several different misorienation axes in a given
%      angle interval they will be added together
% minimum:interval:maximum with interval = 5,10,15... etc try several

gb_m_axis_cor = axis(gB_c_a_mis.project2FundamentalRegion);
gb_m_angle_cor = angle(gB_c_a_mis.project2FundamentalRegion)./ degree;
min_angle = 10;
interval_angle = 10;
maximum_angle = 120;
[segments_per_interval,interval_id] = histc(gb_m_angle_cor,min_angle:interval_angle:maximum_angle);
x_bar=min_angle:interval_angle:maximum_angle;
width=1;
clear percent_boundary_length n_percent angle_scale;
percent_boundary_length = zeros(length(segments_per_interval));
% total boundary length
total_boundary_length = sum(gB_c_a.segLength);
% total number
total_number = sum(segments_per_interval);
%
for i=1:length(segments_per_interval)-1;
% calculate boundary length in map units
boundary_length = sum(gB_c_a(interval_id==i).segLength);
% Percent boundary length
percent_boundary_length(i,1) = 100 * boundary_length / total_boundary_length;
% Percent number
n_percent(i,1) = 100 * segments_per_interval(i) / total_number;
    fprintf(' %3i %3i %s %3i %17.2f %12.2f %17.2f %12.2f \n',...
      i,x_bar(i),'-
',x_bar(i+1),boundary_length,percent_boundary_length(i),segments_per_interval(i),n_percent(i))
  angle_scale(i,1) = x_bar(i);
end
```

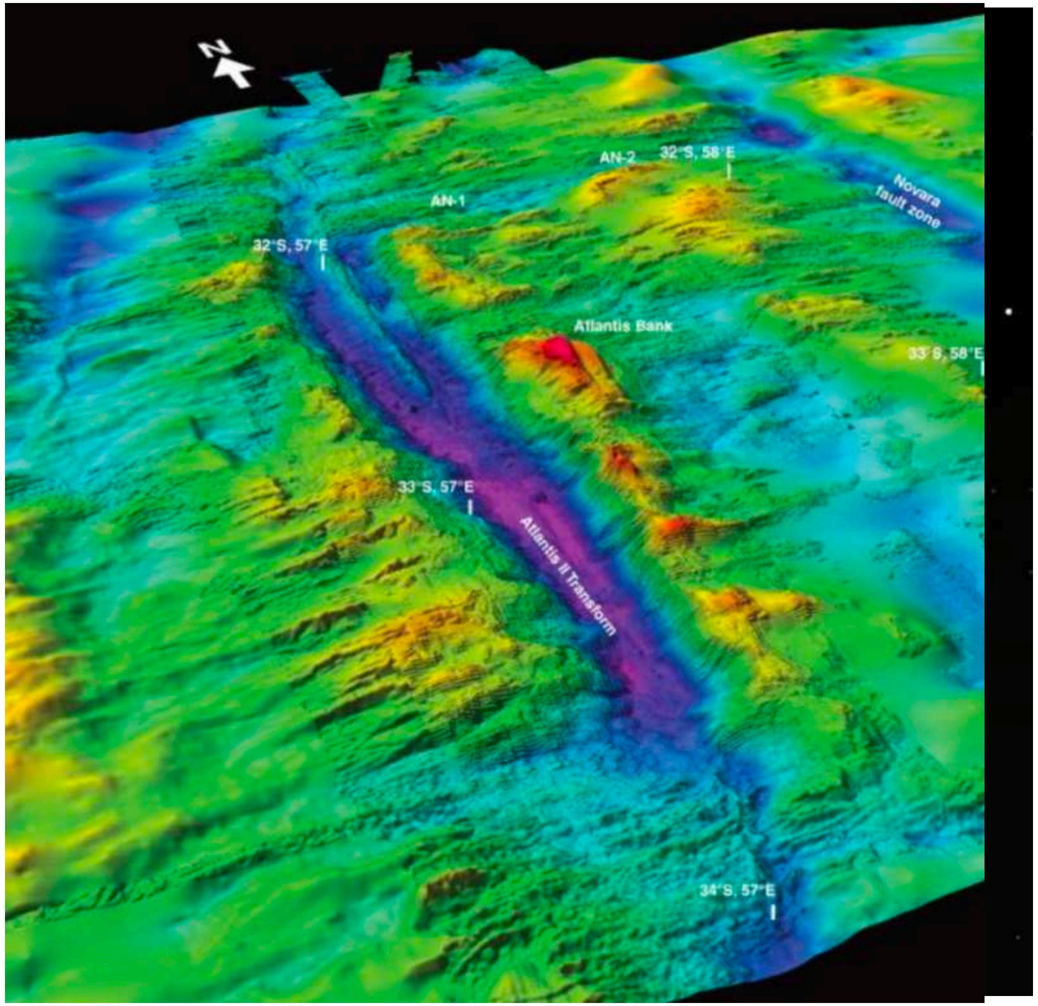
Boundaries calcite-aragonite – mis=30-70°

```
plot(ebsd)
hold on
plot(grains('c').boundary,'linecolor','k','li
newidth',1)
plot(grains('a').boundary,'linecolor','k','li
newidth',1)
plot(gB_c_a(interval_id==2),'linecolor','r','
linewidth',2,'displayName','20-30^\circ
8%','figSize','large')
plot(gB_c_a(interval_id==3),'linecolor','m','
linewidth',2,'displayName','30-40^\circ
12%','figSize','large')
plot(gB_c_a(interval_id==4),'linecolor','c','
linewidth',2,'displayName','40-50^\circ
14%','figSize','large')
plot(gB_c_a(interval_id==5),'linecolor','k','
linewidth',2,'displayName','50-60^\circ
15%','figSize','large')
hold off
```



EXAMPLE 3 – gabbro from Atlantis Bank

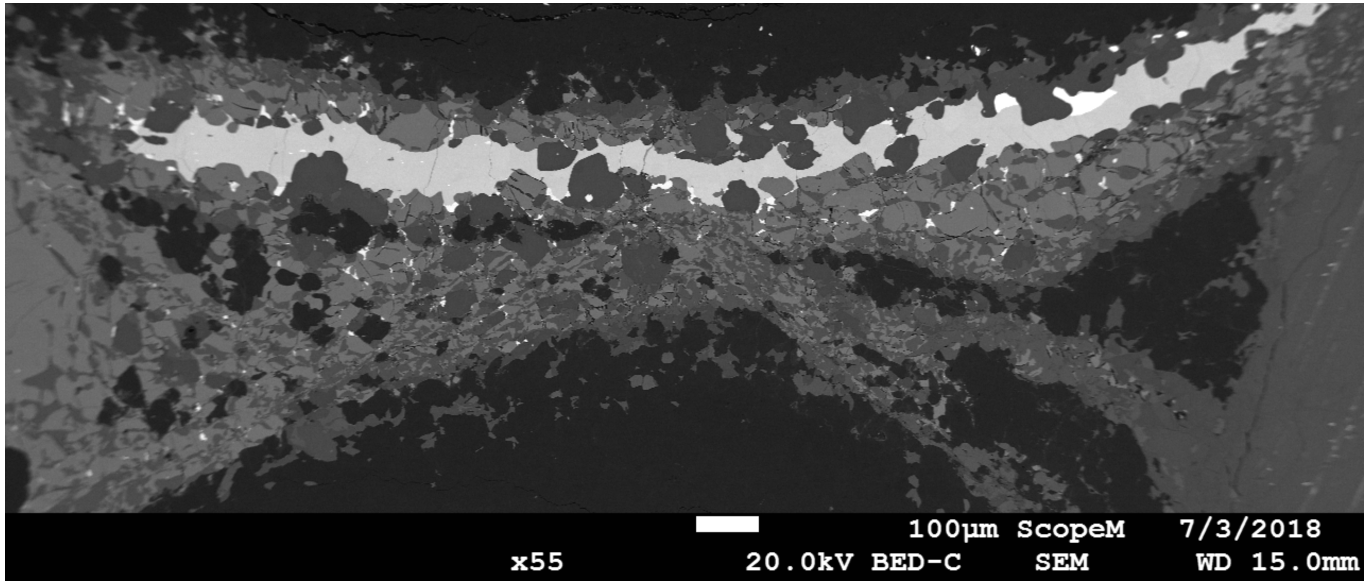
What is the Atlantis Bank?

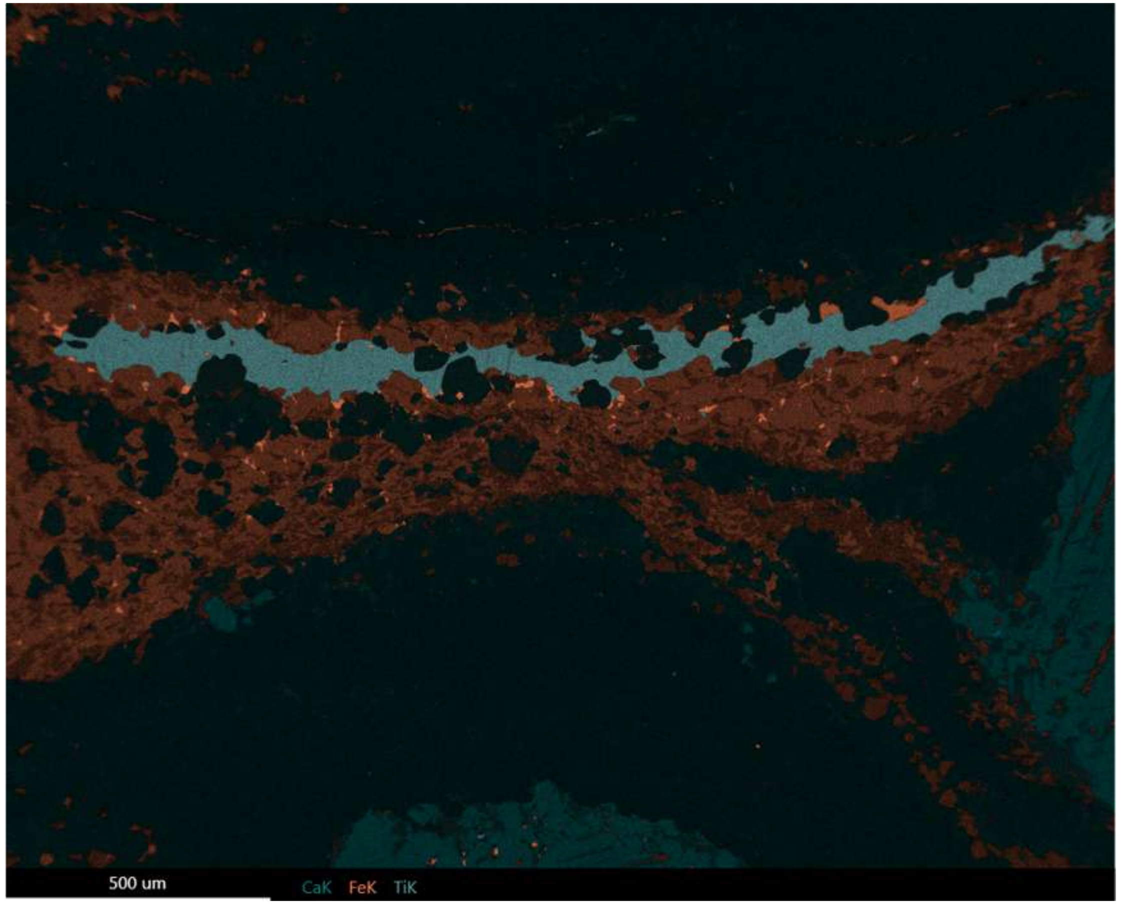


- Undersea mountain, named after the lost city of Atlantis;
- Middle of the ultra-slow spreading southwest Indian Ridge, southwest of Madagascar
- About 700 m below the sea level, approximately 1000 m height
- Result from the uplift along the Atlantis II transform faults, one of the biggest faults seen on Earth
- See presentation from Maël Allard this afternoon

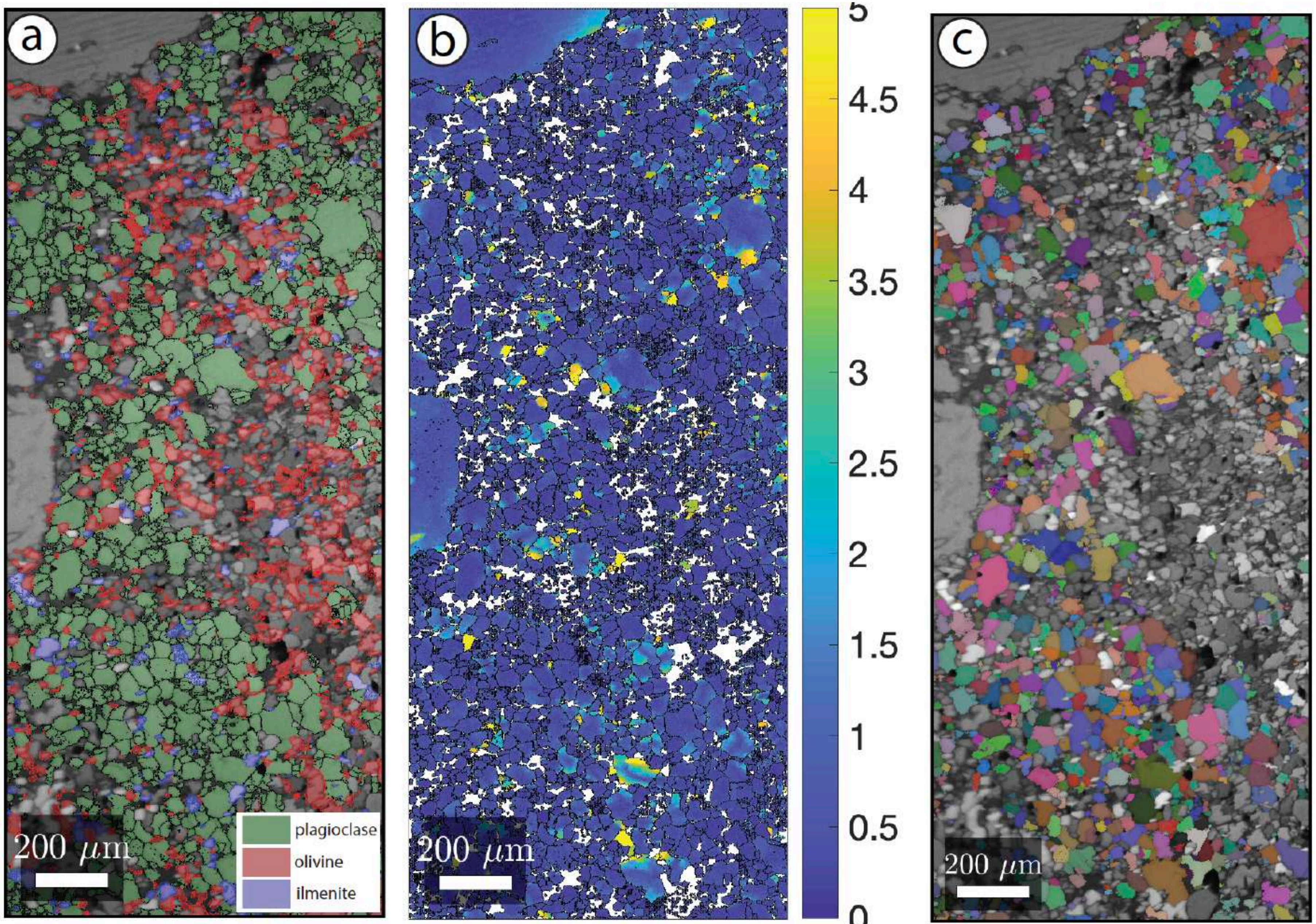
http://joidesresolution.org/atlantis-bank-a-mountain-under-the-sea/

”Squeezed melt” microstructures



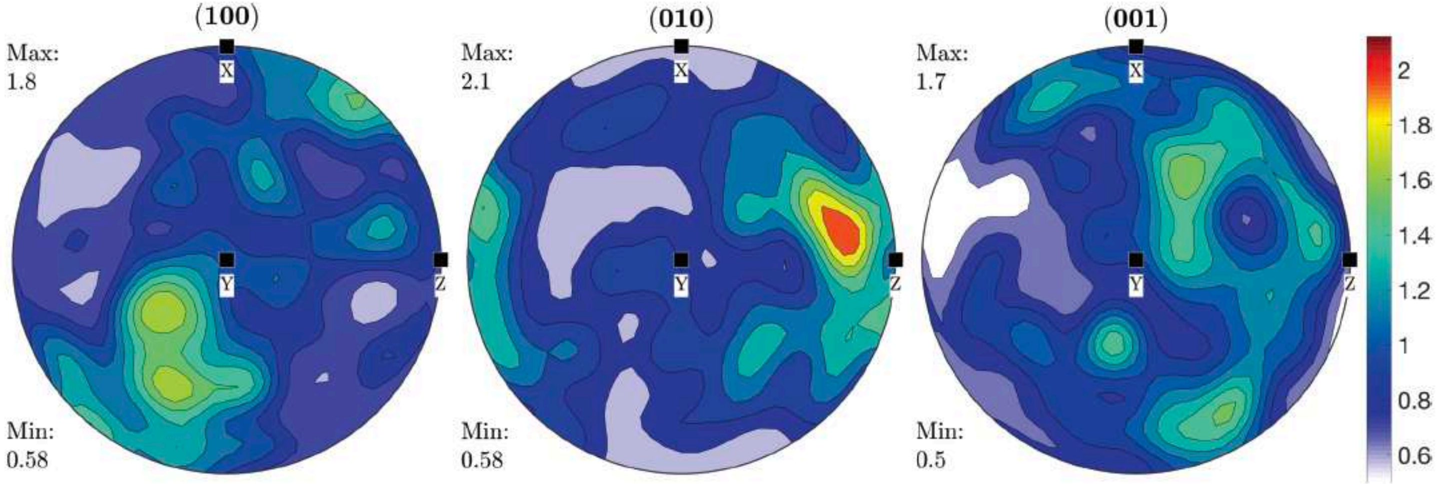


Sample 118-56R - oxide-rich gabbro

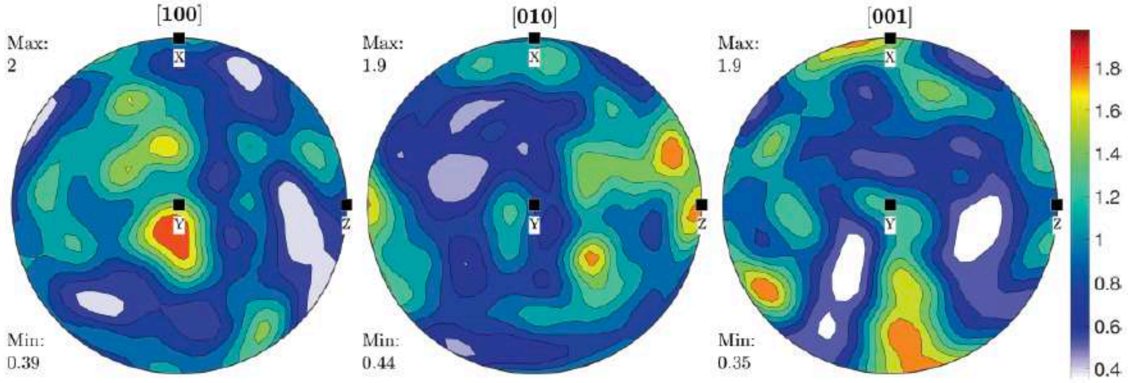


Pole figures – plagioclase, olivine and ilmenite

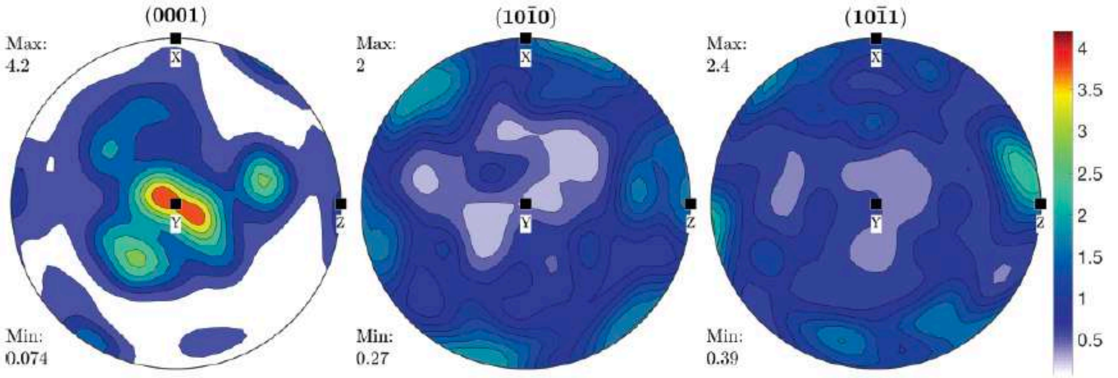
Plagioclase pole figures



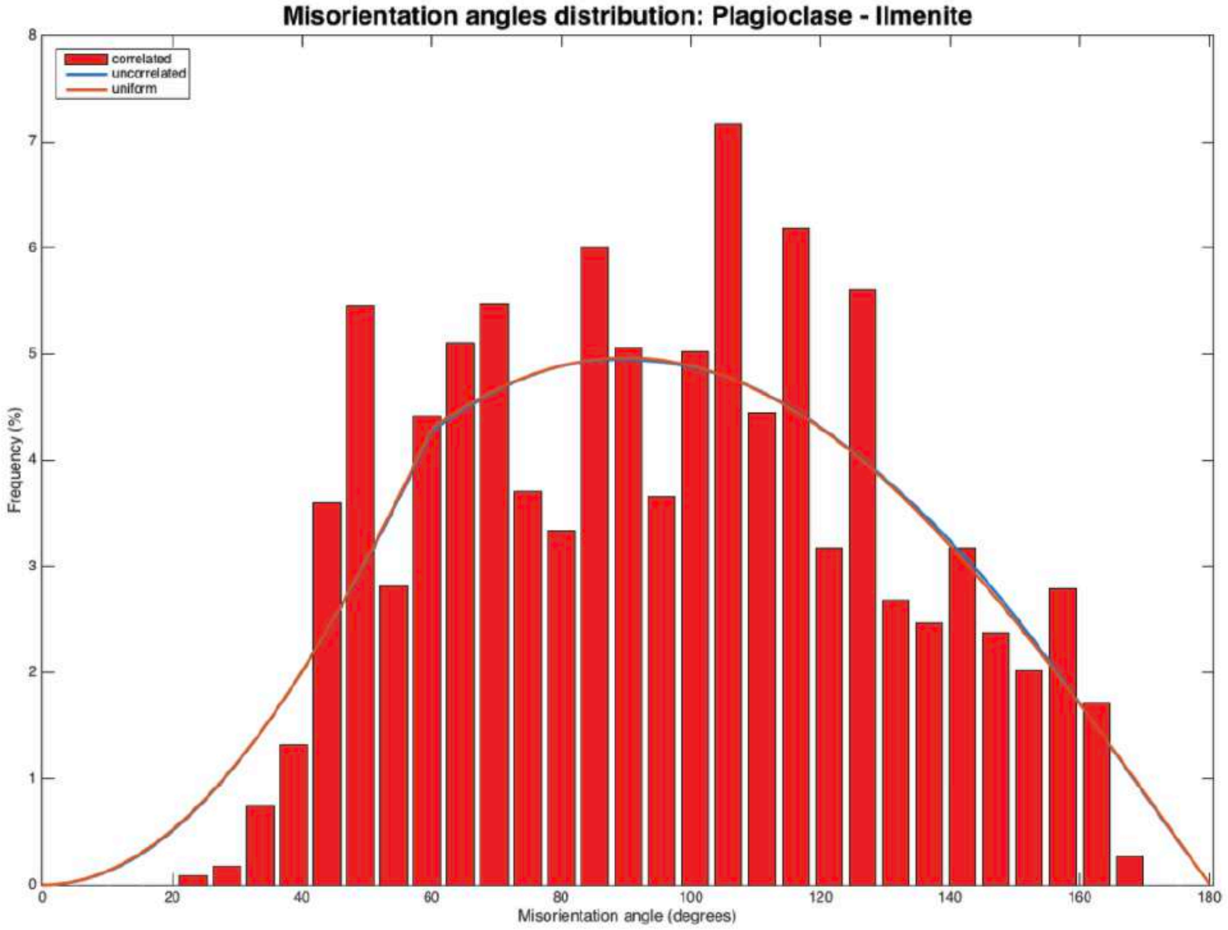
Olivine pole figures

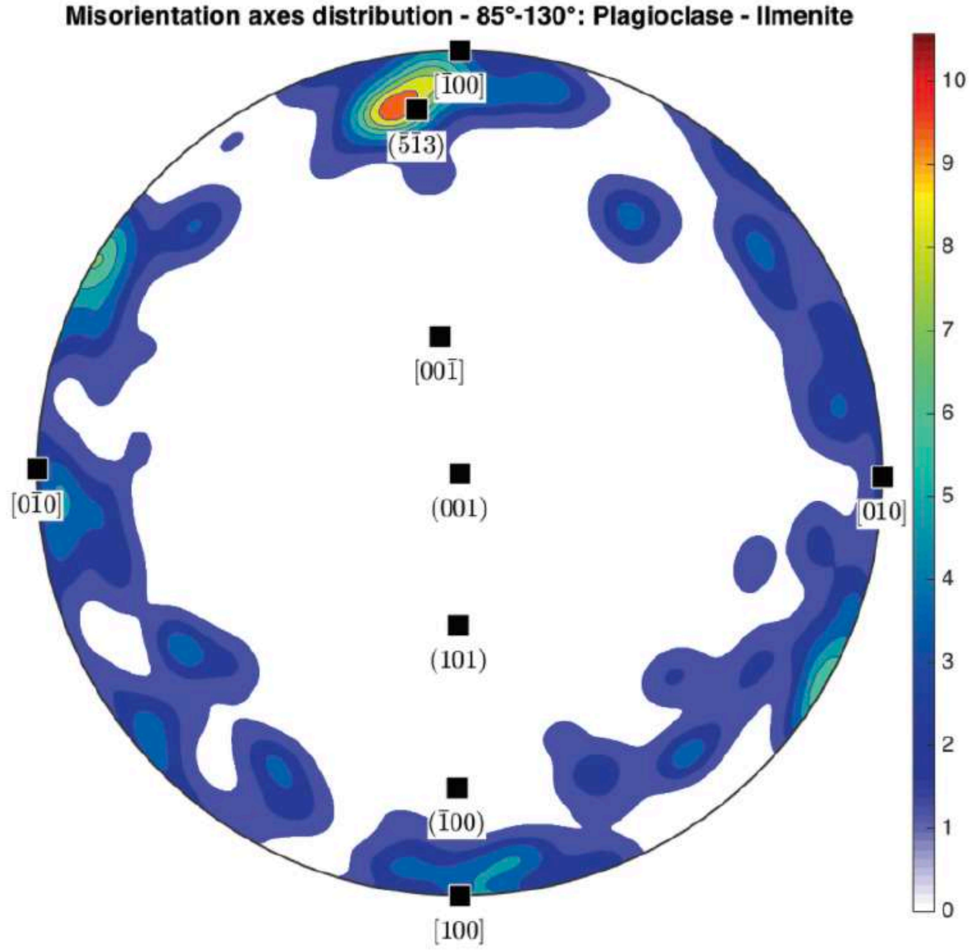


Ilmenite pole figures

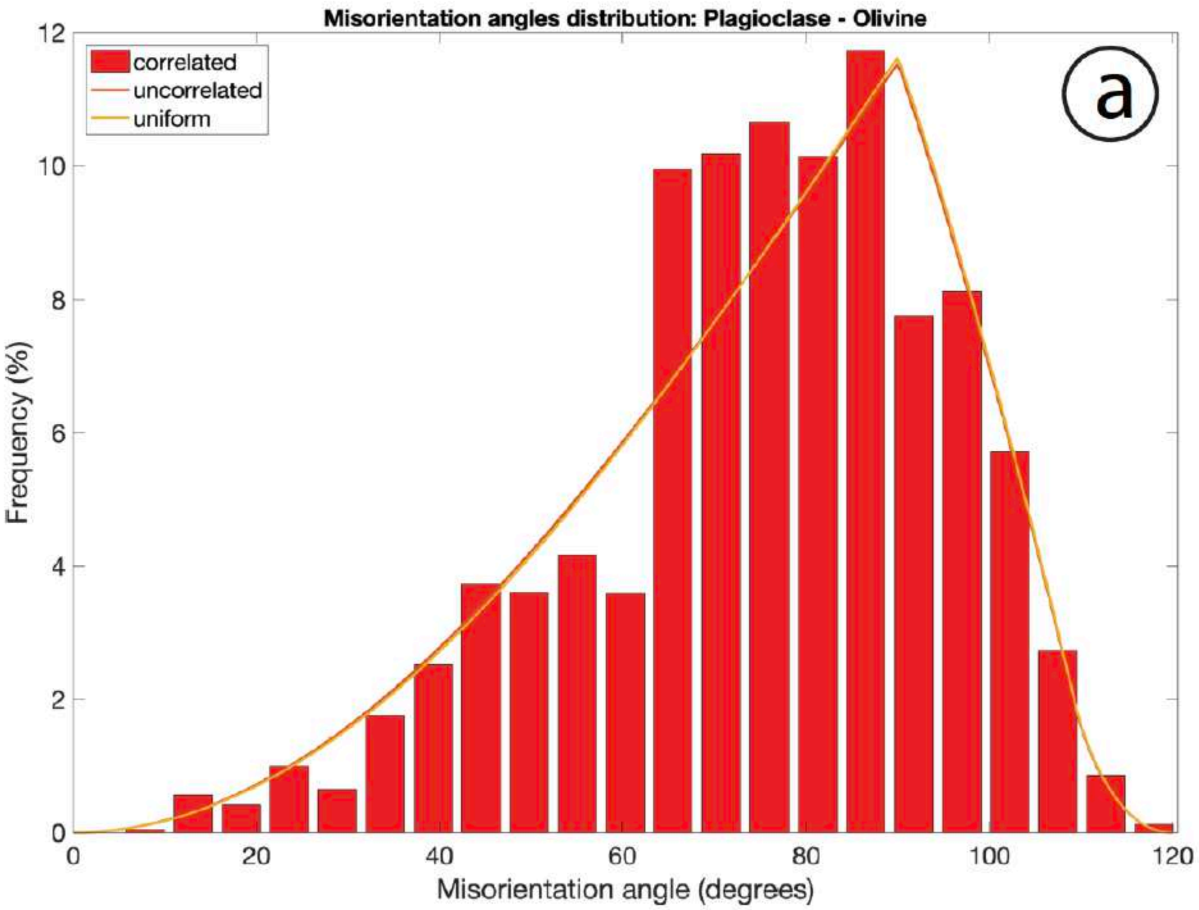


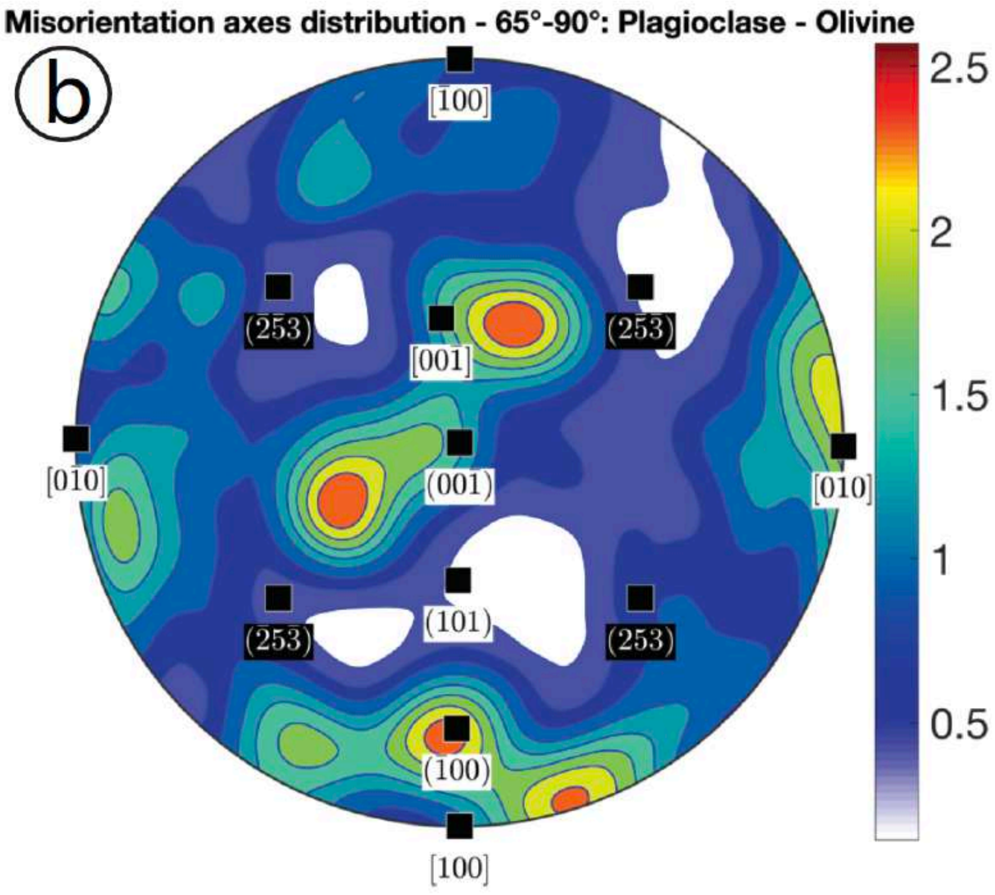
Interphase misorientation plagioclase →ilmenite





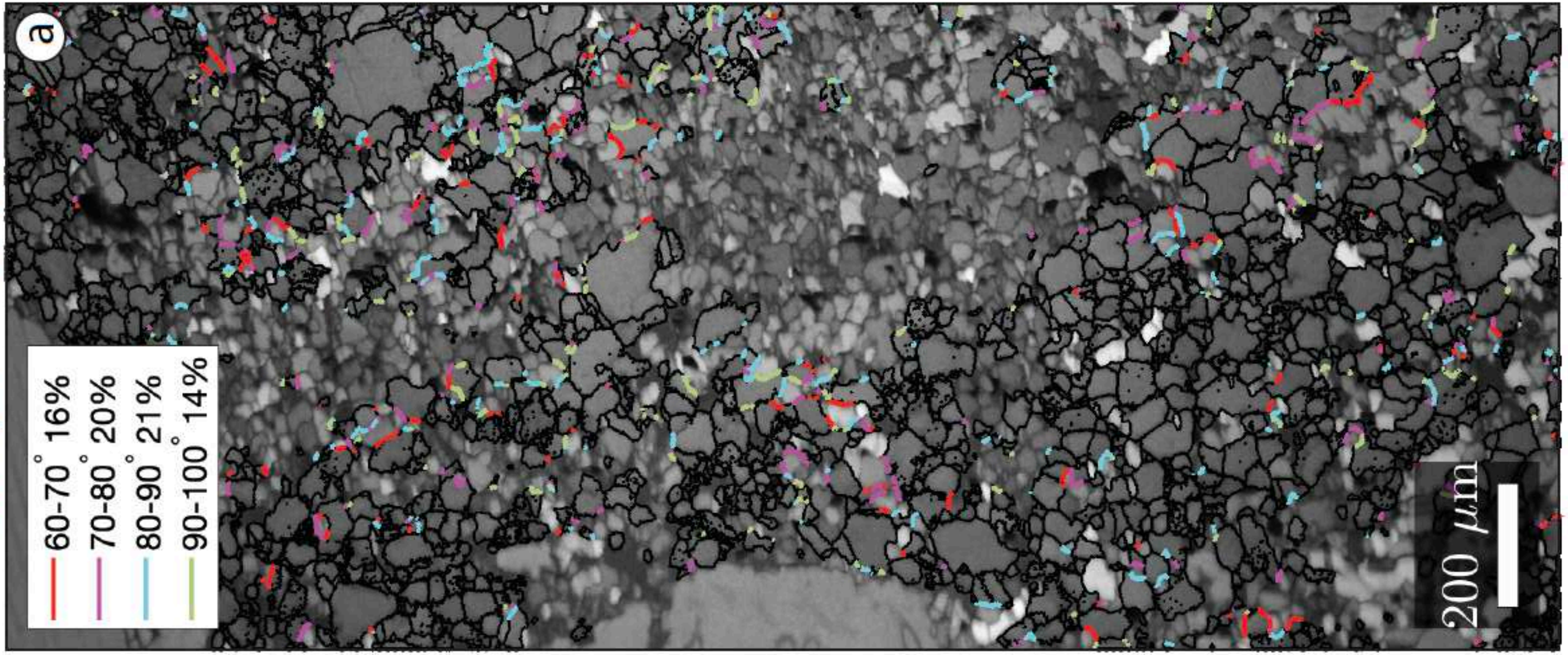
Interphase misorientation plagioclase →olivine



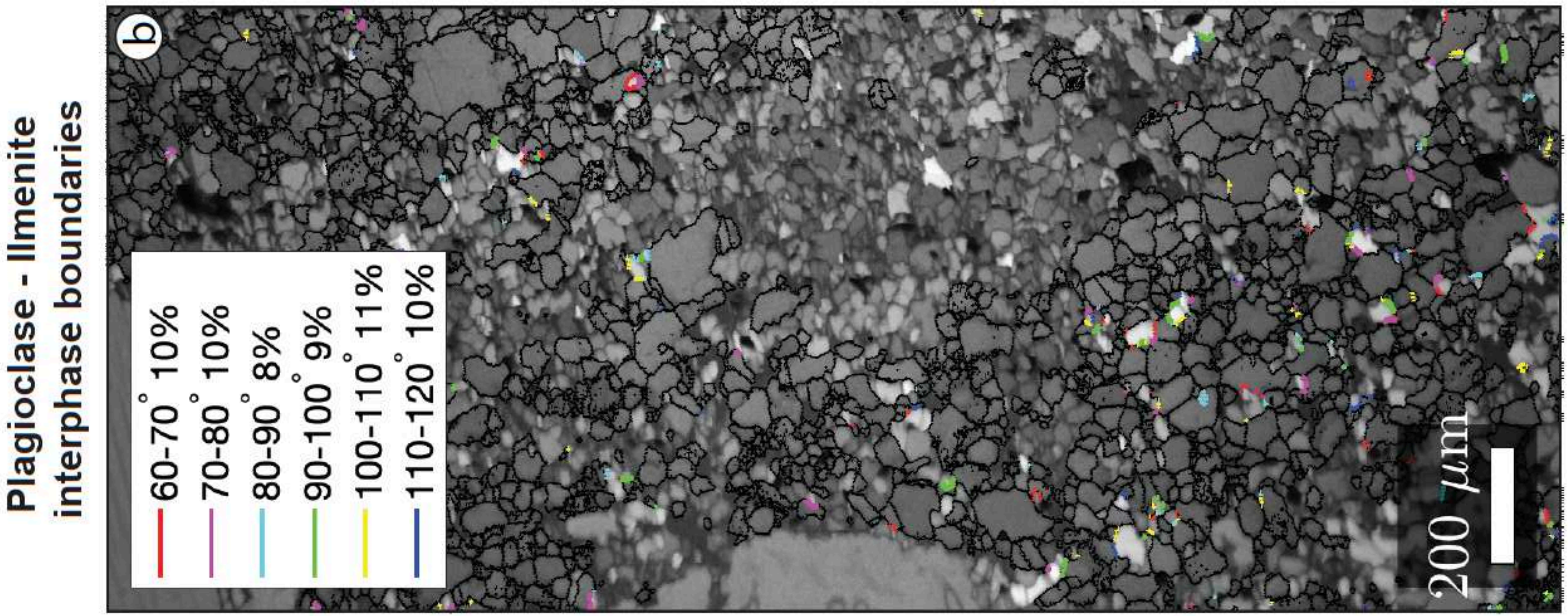


Interphase misorientation plagioclase →olivine

Plagioclase - Olivine
interphase boundaries



Interphase misorientation plagioclase →ilmenite



Take home message…

- Interphase boundary misorientation in EBSD maps is powerful method to understand orientation relationships between different phases in a statistically representative way;
- One can study the orientation relationships between two different phases whose orientation relationship is known, and in principle calculate other possible orientation relationships
- The advantage of this approach is that one can explore possible orientation relationships between any phase present in the map. Most of them won't show anything meaningful, but some pairs may show potential relationships
- The processes of course that lead to those are another business
- From this approach, one can precisely mark the interphase boundaries of interest, than bring the sample to the FIB, make TEM lamellae in the exact phase boundary you want to study (not "shooting in the dark")