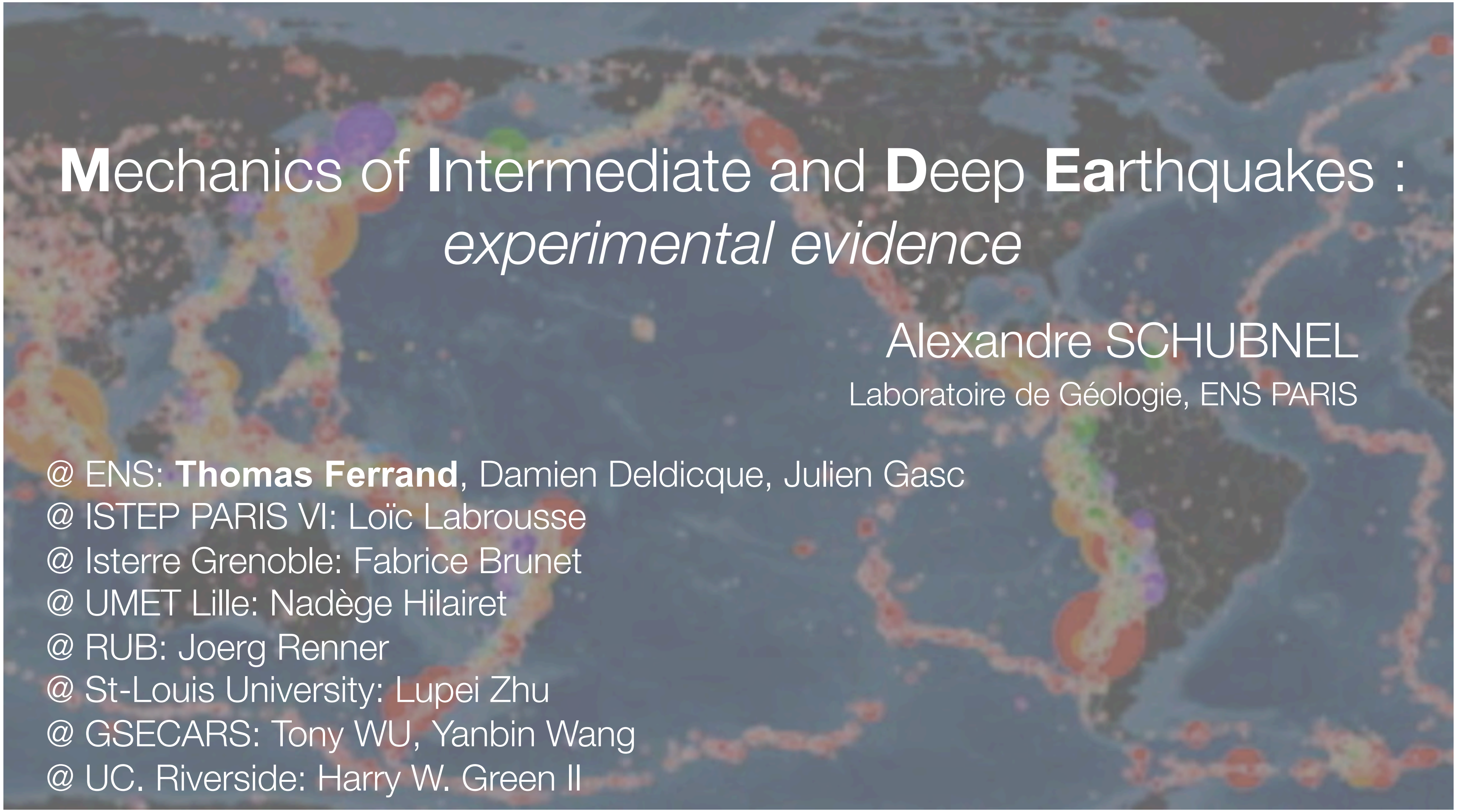

Mechanics of **I**ntermediate and **D**eep **Ea**rthquakes : *experimental evidence*

Alexandre SCHUBNEL
Laboratoire de Géologie, ENS PARIS

@ ENS: **Thomas Ferrand**, Damien Deldicque, Julien Gasc
@ ISTEP PARIS VI: Loïc Labrousse
@ Isterre Grenoble: Fabrice Brunet
@ UMET Lille: Nadège Hilairet
@ RUB: Joerg Renner
@ St-Louis University: Lupei Zhu
@ GSECARS: Tony WU, Yanbin Wang
@ UC. Riverside: Harry W. Green II

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1794
ENS

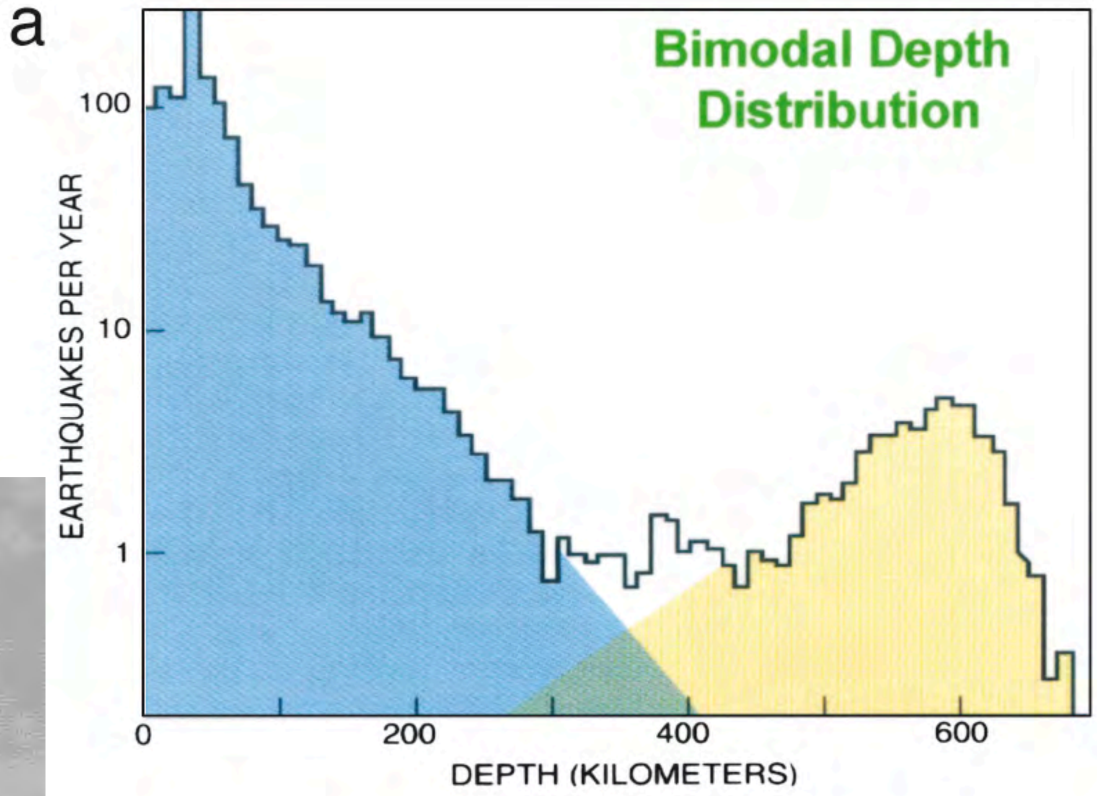
cnrs dépasser les frontières
INSU
Observer & comprendre

AGENCE NATIONALE DE LA RECHERCHE
ANR

MARIE CURIE ACTIONS

MOTIVATION

Herbert Hall Turner, 1861- 1930



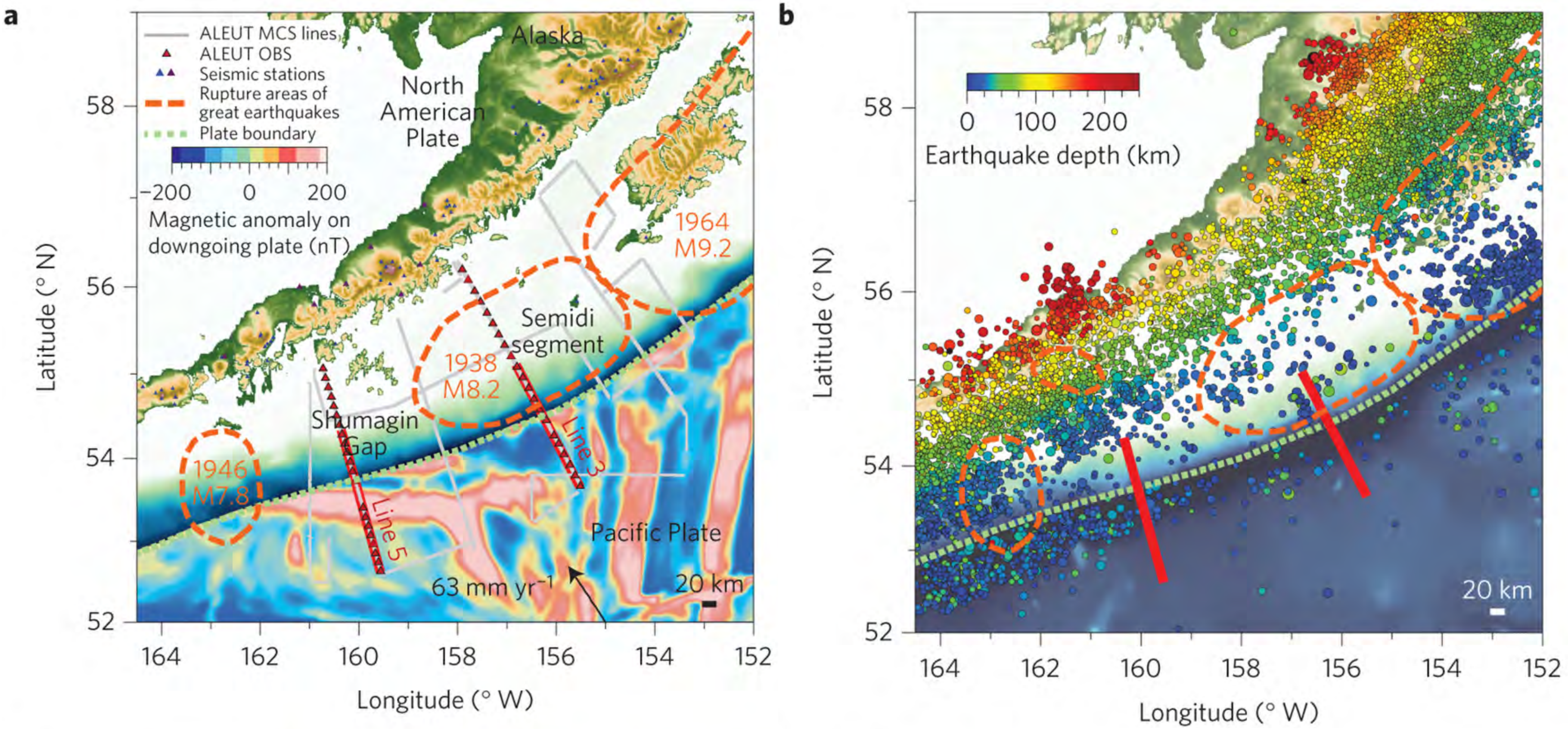
Frohlich 1987

Kiyoo Wadati, 1902 - 1995

Hugo Benioff, 1889-1968

MOTIVATION

Intermediate seismicity and slab hydration



Shillington et al. Ngeo 2015

MOTIVATION

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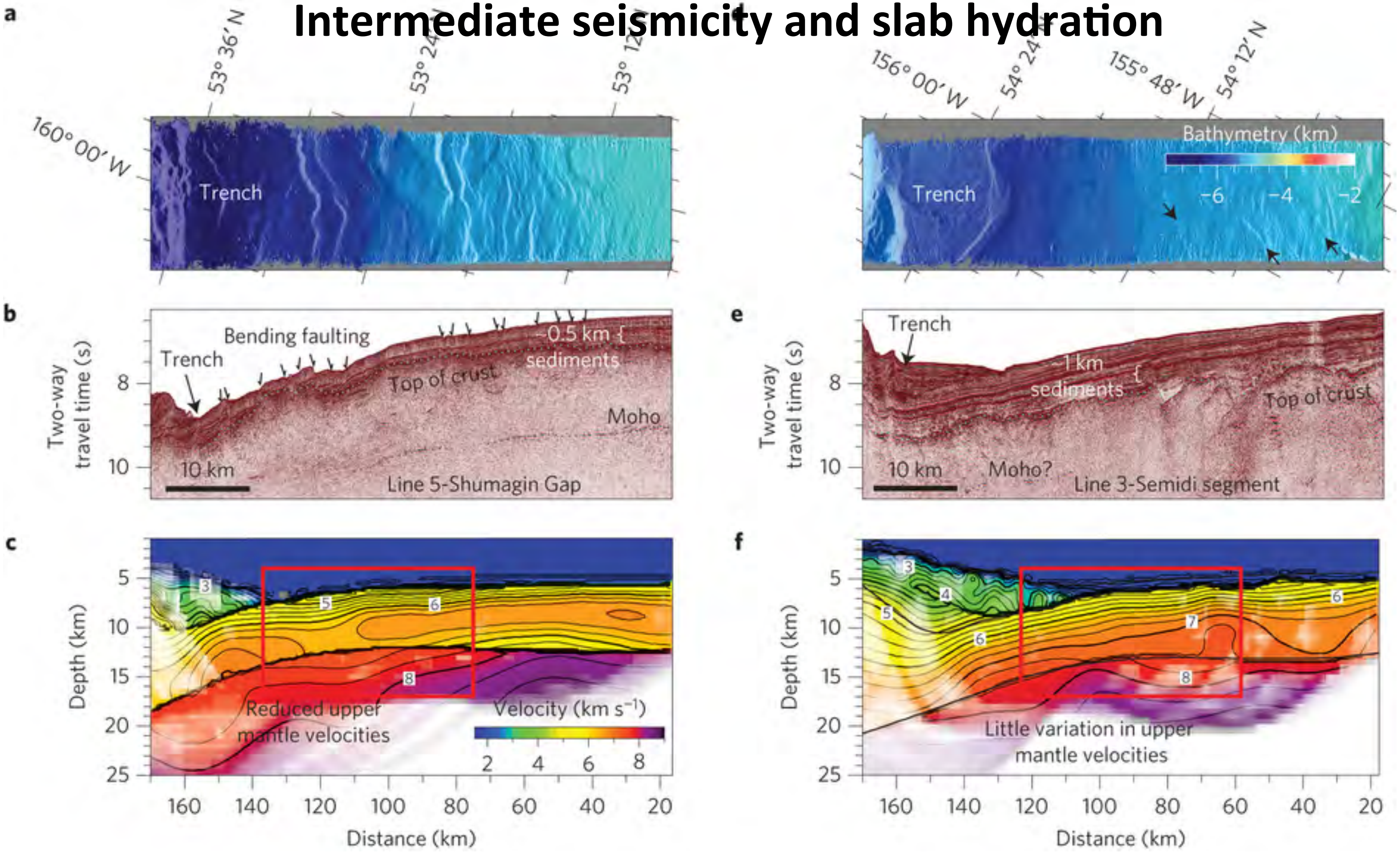
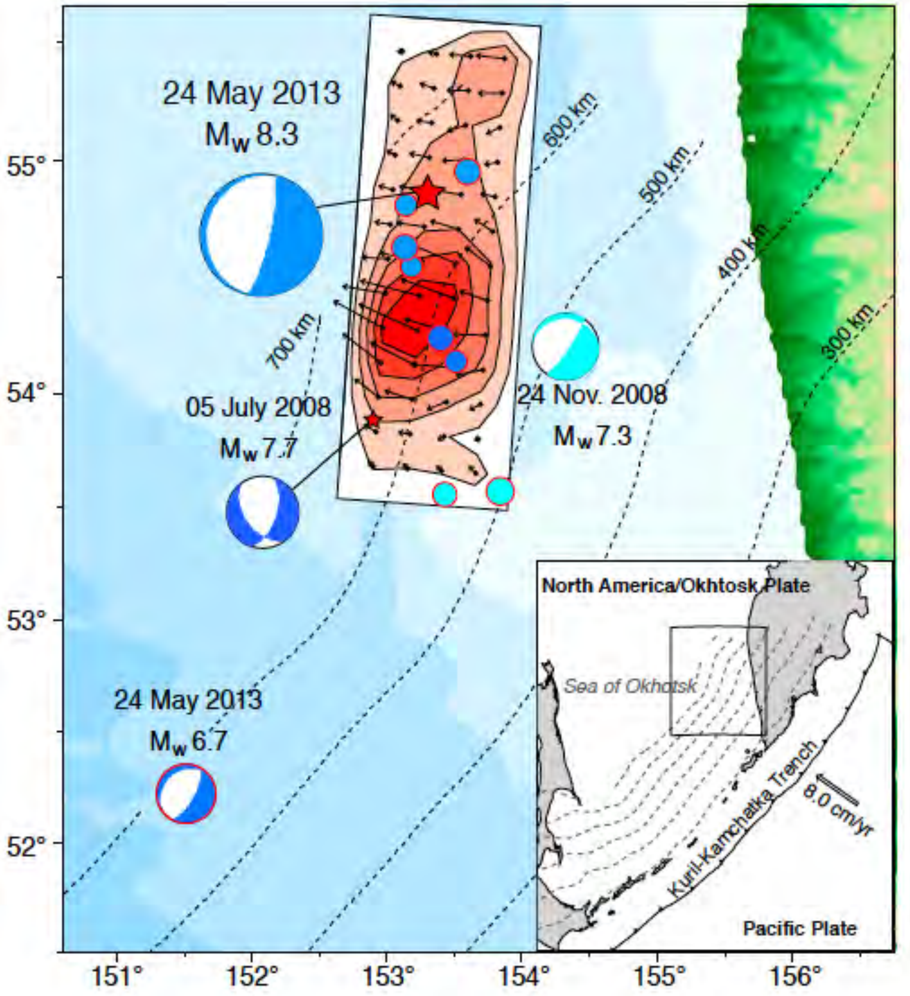


Shillington et al. Ngeo 2015

MOTIVATION

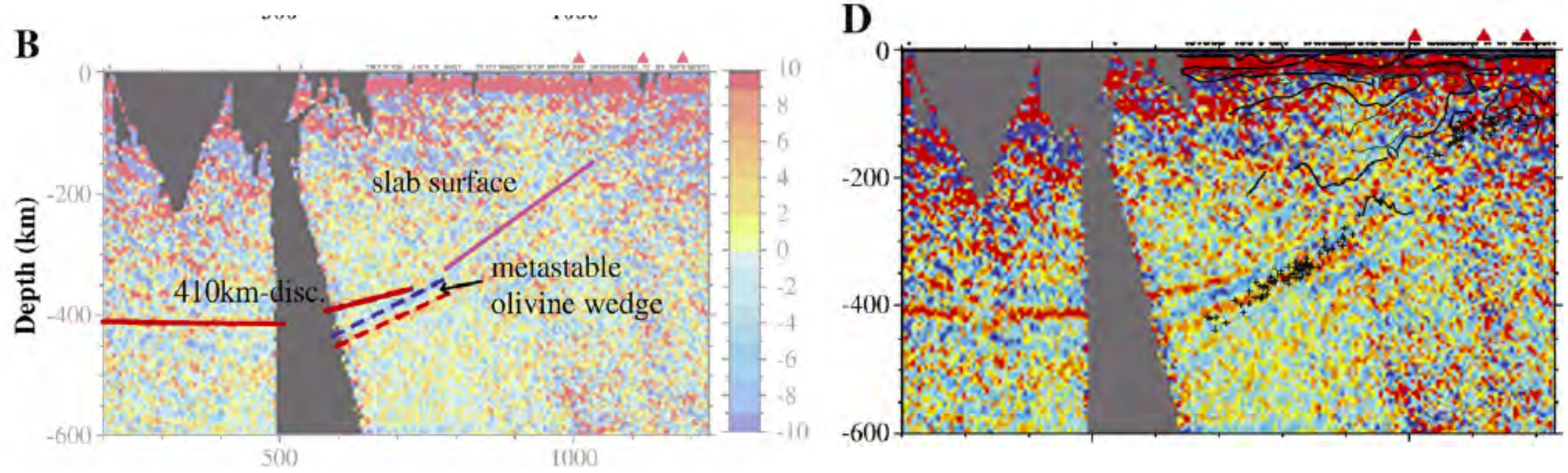
The Okhotsk, May 24th 2013, Mw=8.3, 620km deep EQ



Ye et al. Science 2013

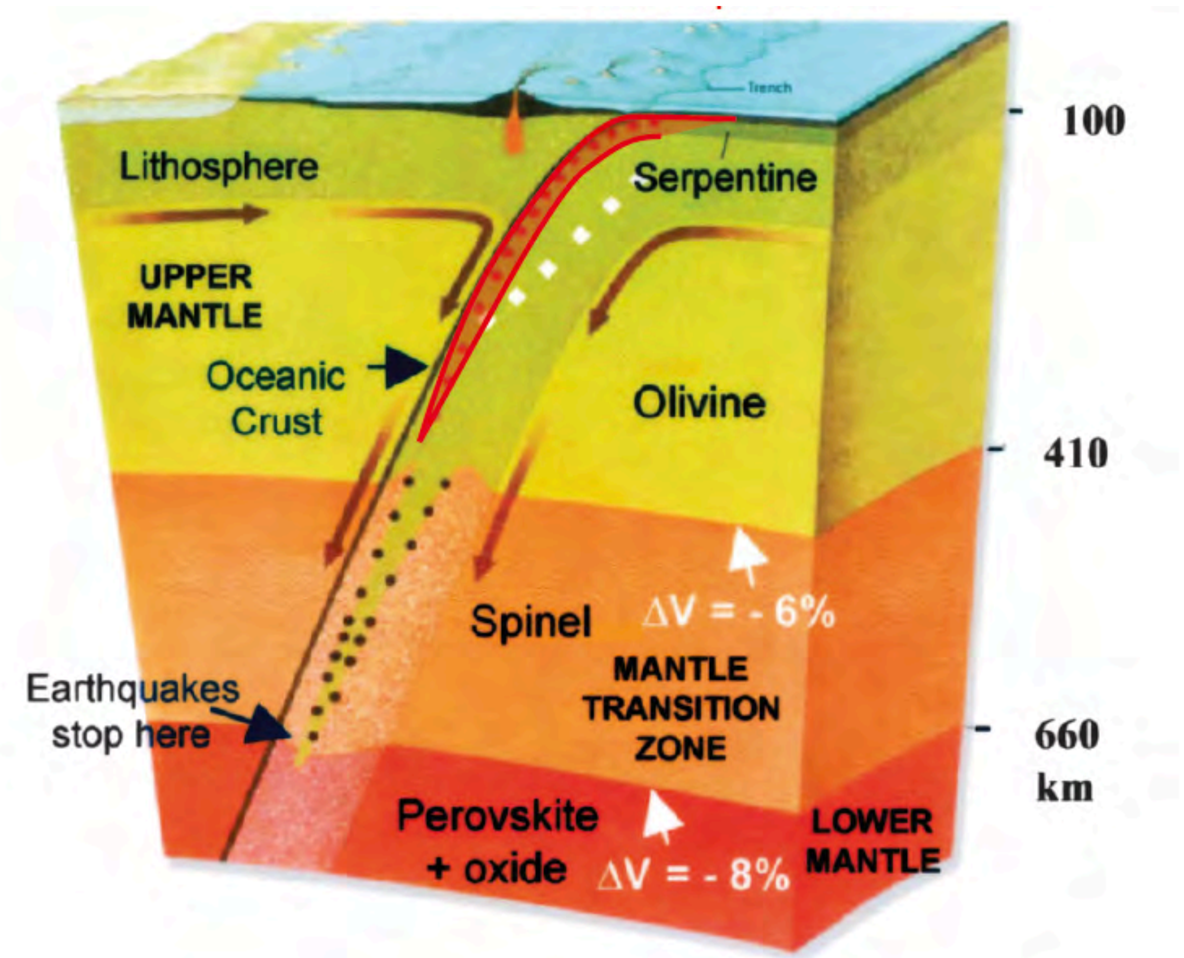
MOTIVATION

Deep focus seismicity and metastable olivine



Kawakatsu and Yoshioka 2012

Earthquakes at depth: *mineralogy at play*



(Green, 2007)

Mechanical role played by **M**INERAL transformations?

Deformation experiments

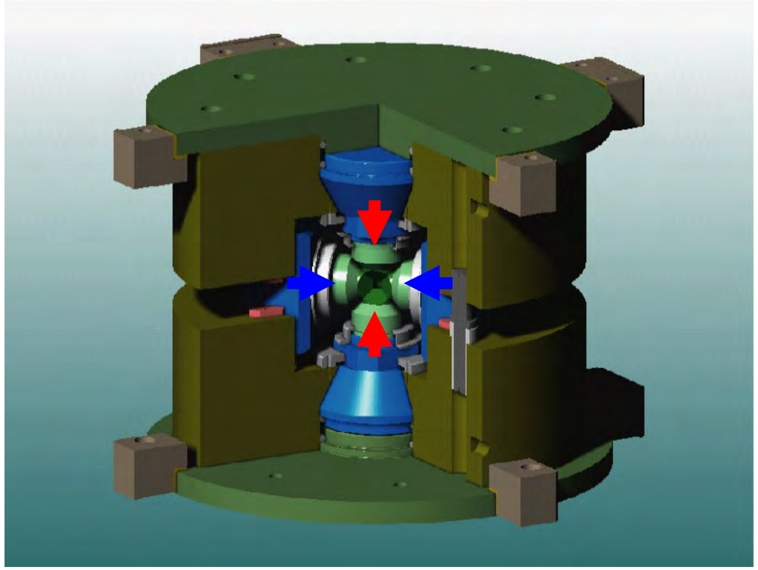
at in-situ mantle (σ,P,T) conditions

(transformation under stress)

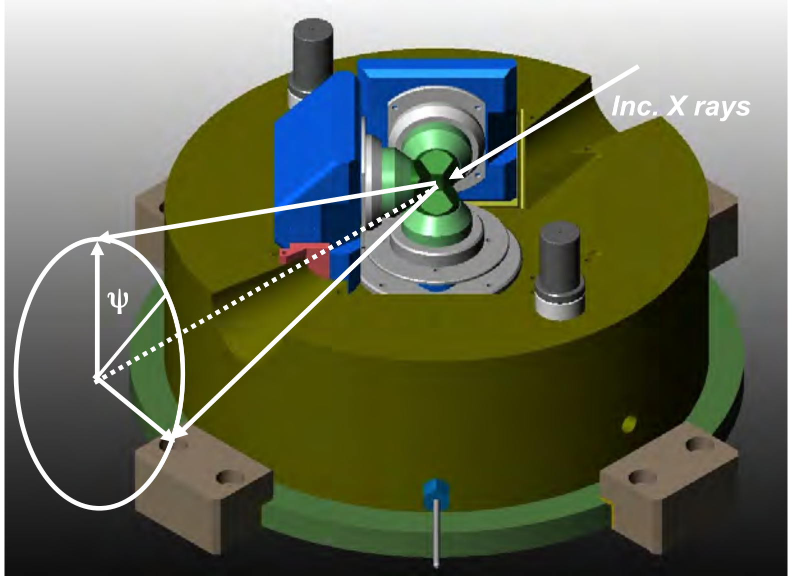
Experimental set-up

The DDIA – controlled pressure, stress and strain under HP-HT conditions

D-DIA
HP-HT + deviatoric stress



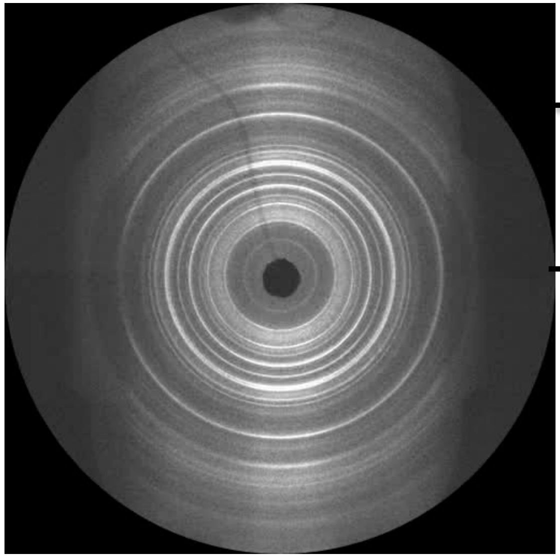
Sintered diamond rear-anvils (Debye rings)

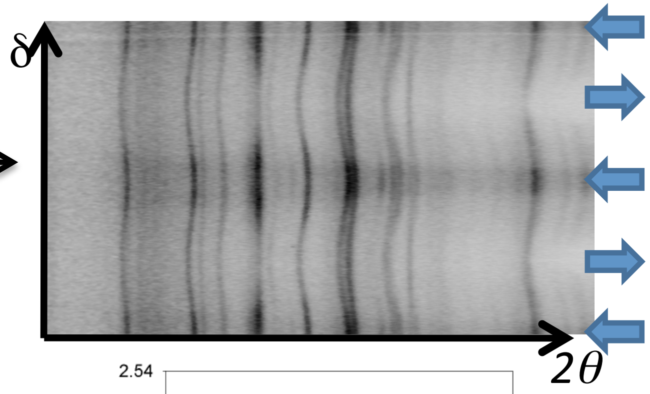


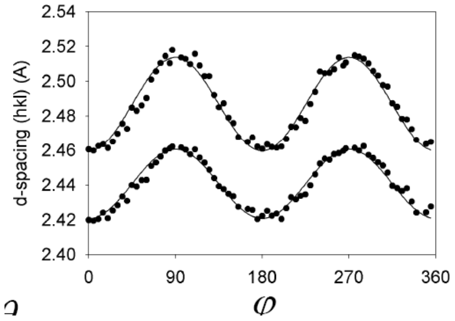
Durham et al, 2002, Wang et al, 2003

Experimental set-up

X-Ray Diffraction







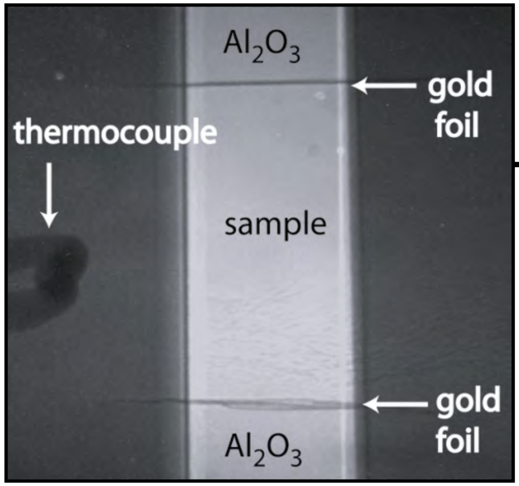
$$\varepsilon_{(hkl)} = \frac{d_{\varepsilon} - d_{p}}{d_{p}} = \frac{t}{3}(1 - 3\cos^{2}\psi)\frac{1}{2G_{(hkl)}}$$

e.g. Singh et al, 1998, Uchida et al, 1996

STRESS

REACTION PROGRESS

X-Ray Radiography



STRAIN + STRAIN RATE

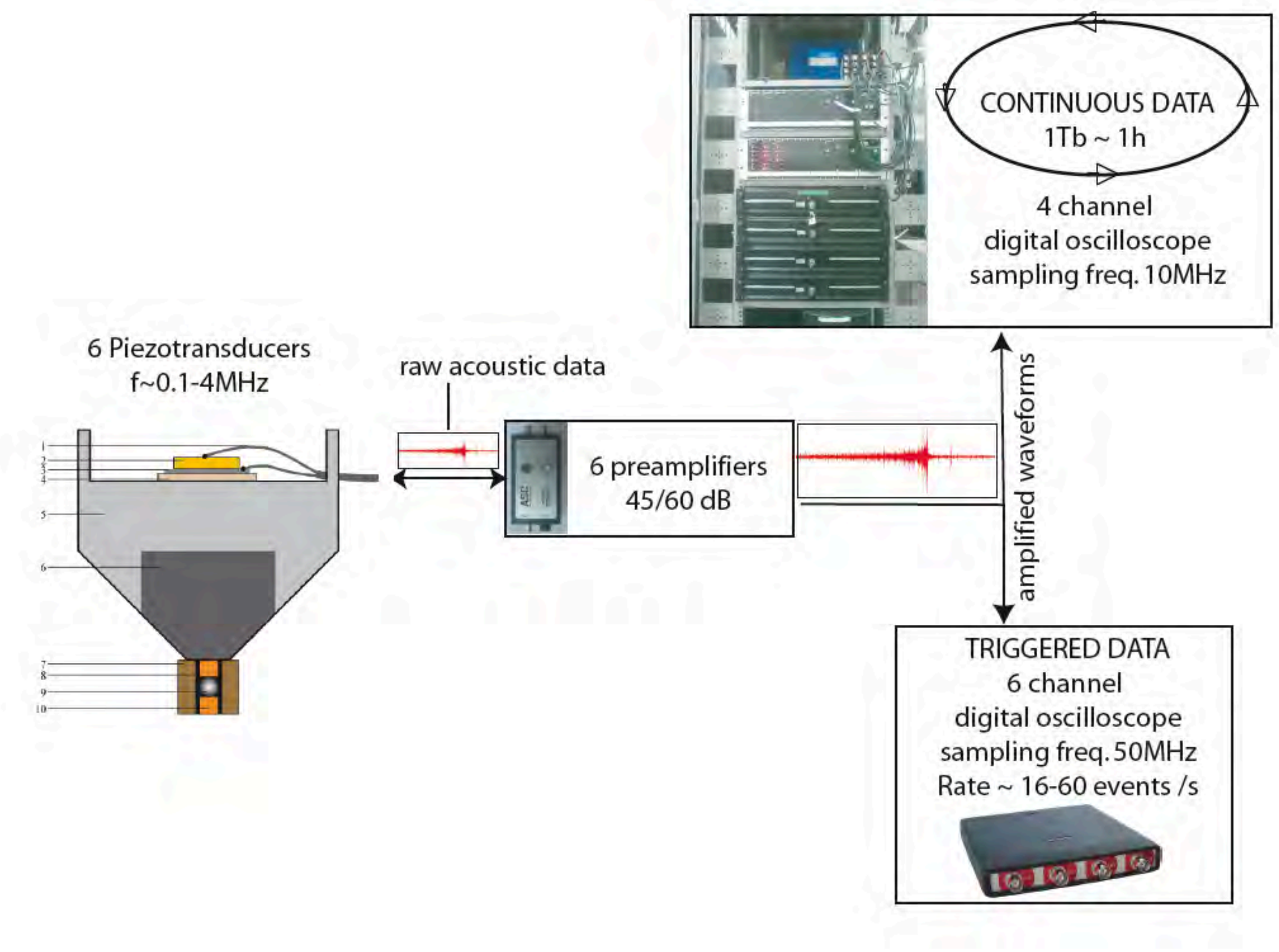
Experimental set-up

The Richter **continuous acoustic recording system**

6 sensors in total (One behind each anvil - Possibility of AE location)

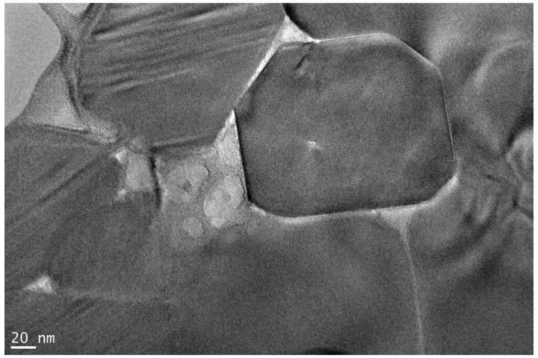
Continuous acoustic recording (ie complete AE catalogue) + Triggered systems

Focal mechanisms inversion

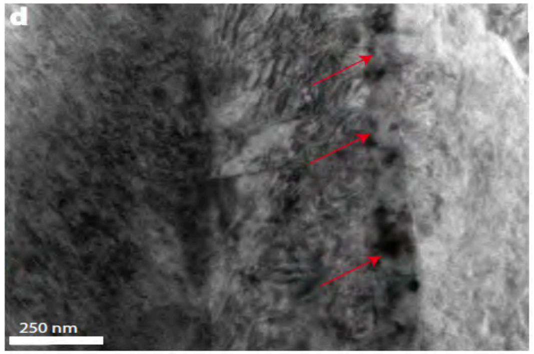


OUTLINE

1.Serpentinized peridotites dehyd.



2. (Ge-)Olivine to spinel transf.



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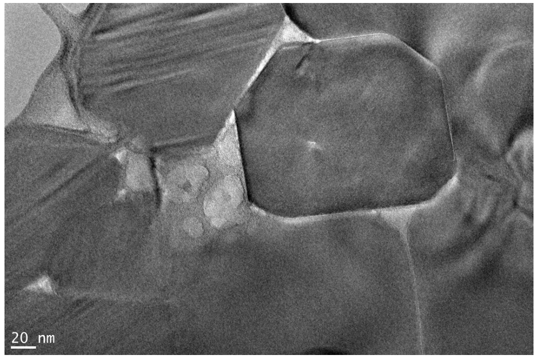
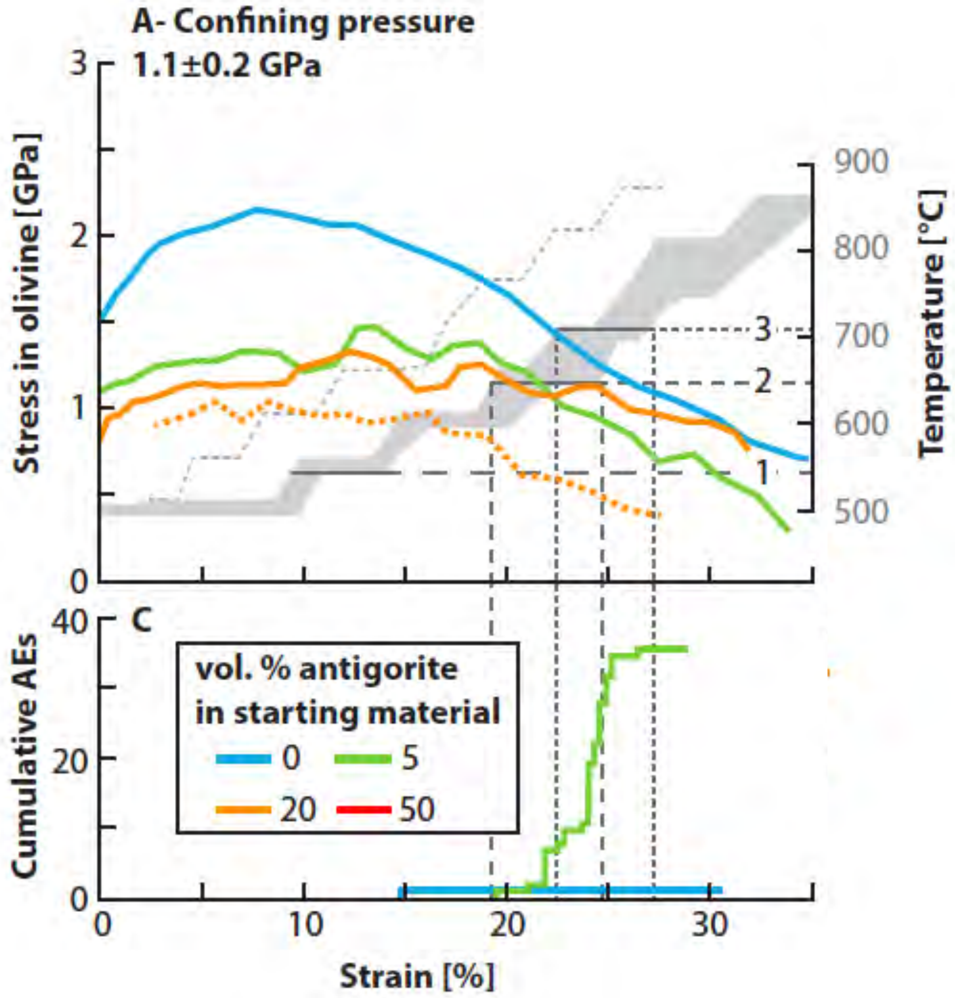


Serp. peridotite dehydration under stress

Hot pressed San Carlos olivine + 5, 10, 20, 50 vol% Antigorite (Corsica)

Strain rate = 5×10^{-5}/s; dT/de ≈1000



AEs, even for 5-20% serp.

Ferrand et al., Nat. Comm 2017

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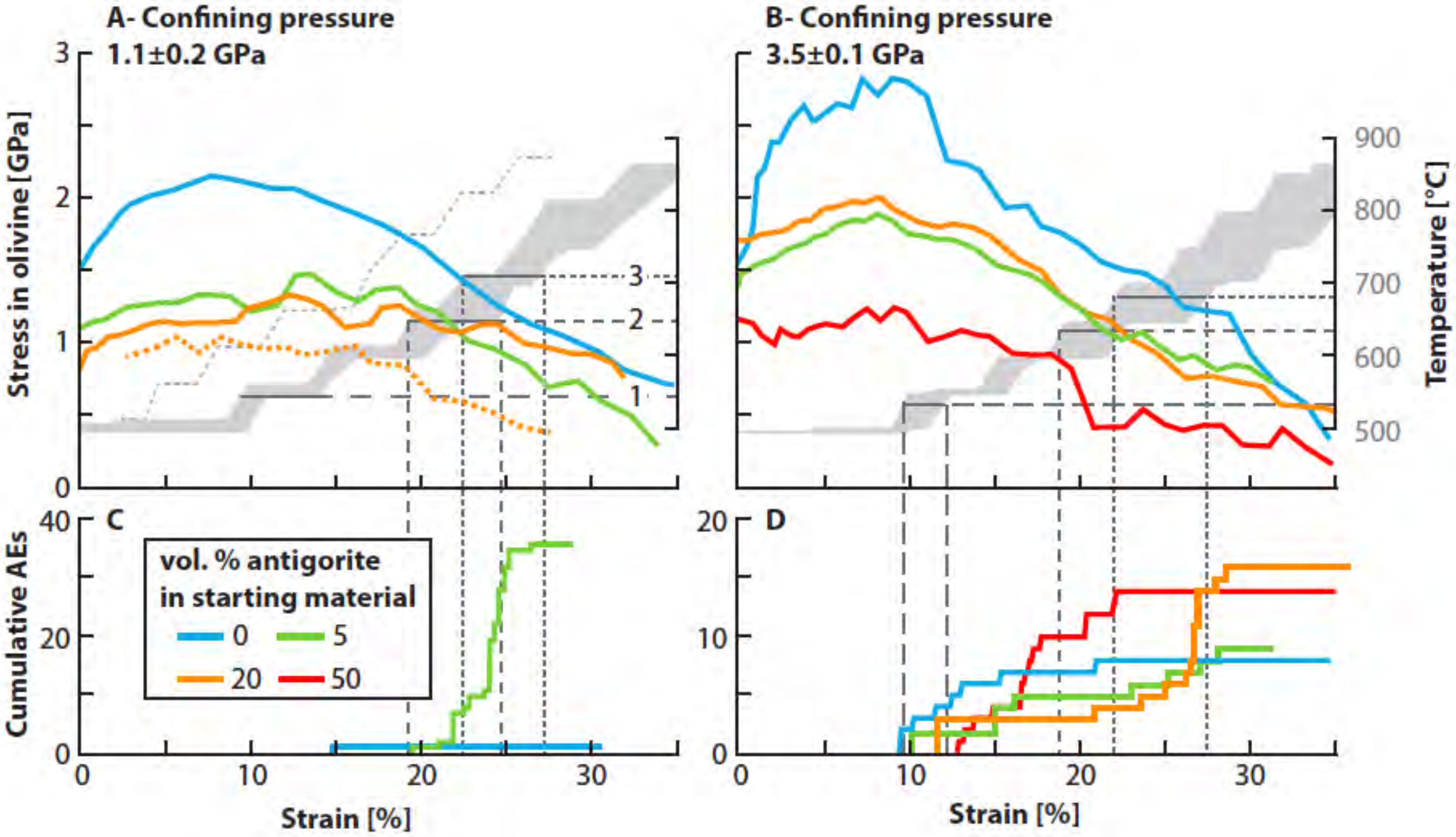

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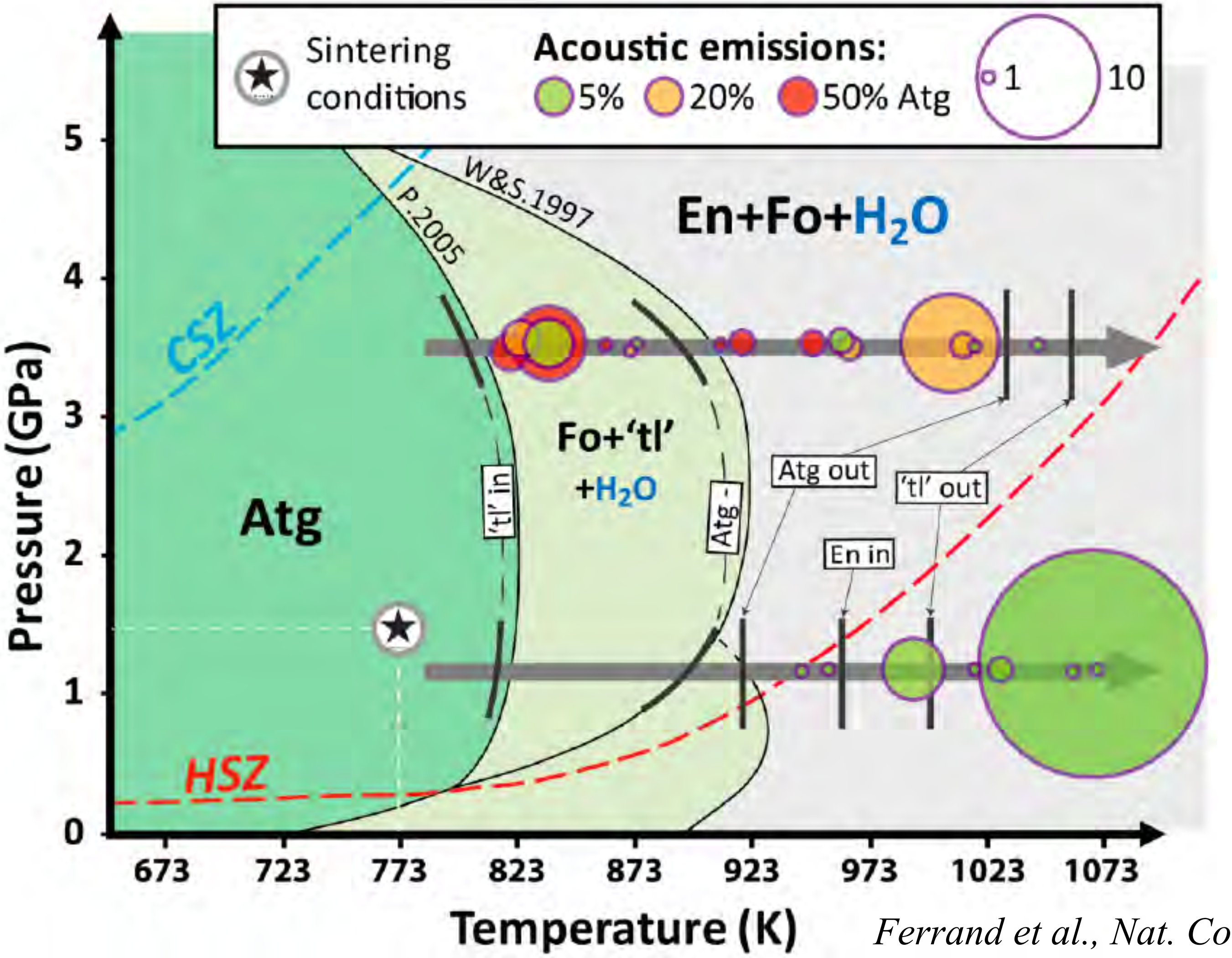
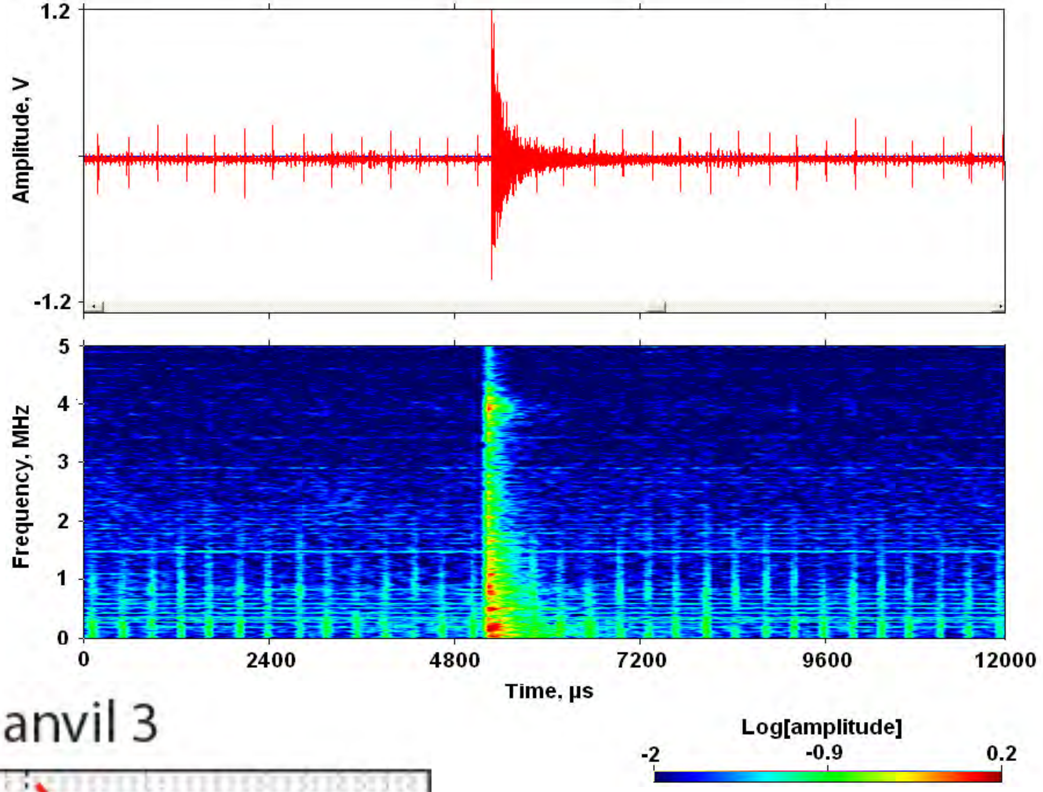
Strain rate = 5x10^{-5}/s; dT/de ≈1000 **PT-AE diagram**

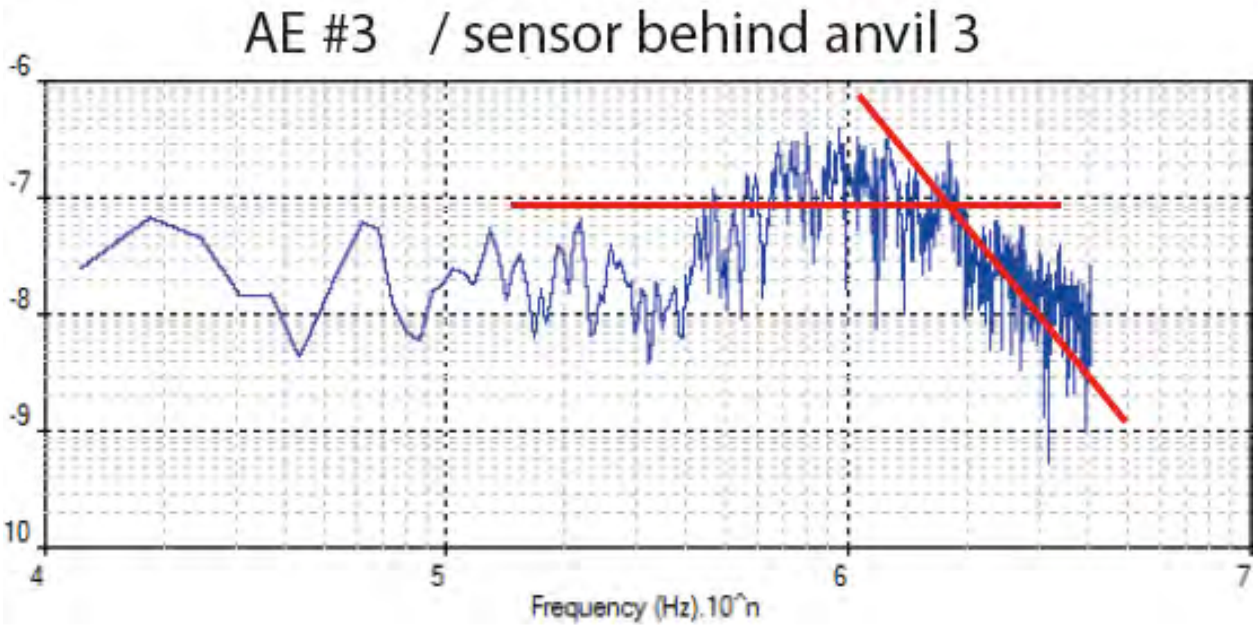


Ferrand et al., Nat. Comm 2017

Serp. peridotite dehydration under stress

Corner frequency fc ≈ Vr/L



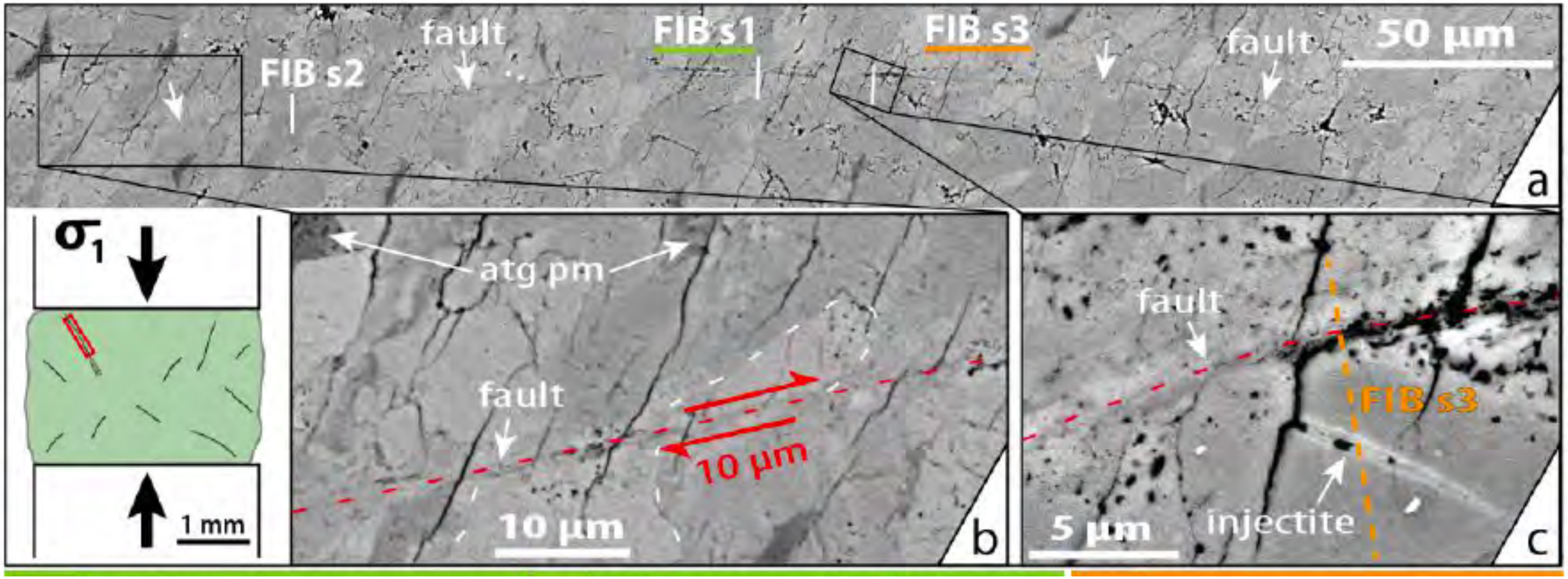


Vr ≈ 4km/s

=> L ≈ 2mm

Serp. peridotite dehydration under stress

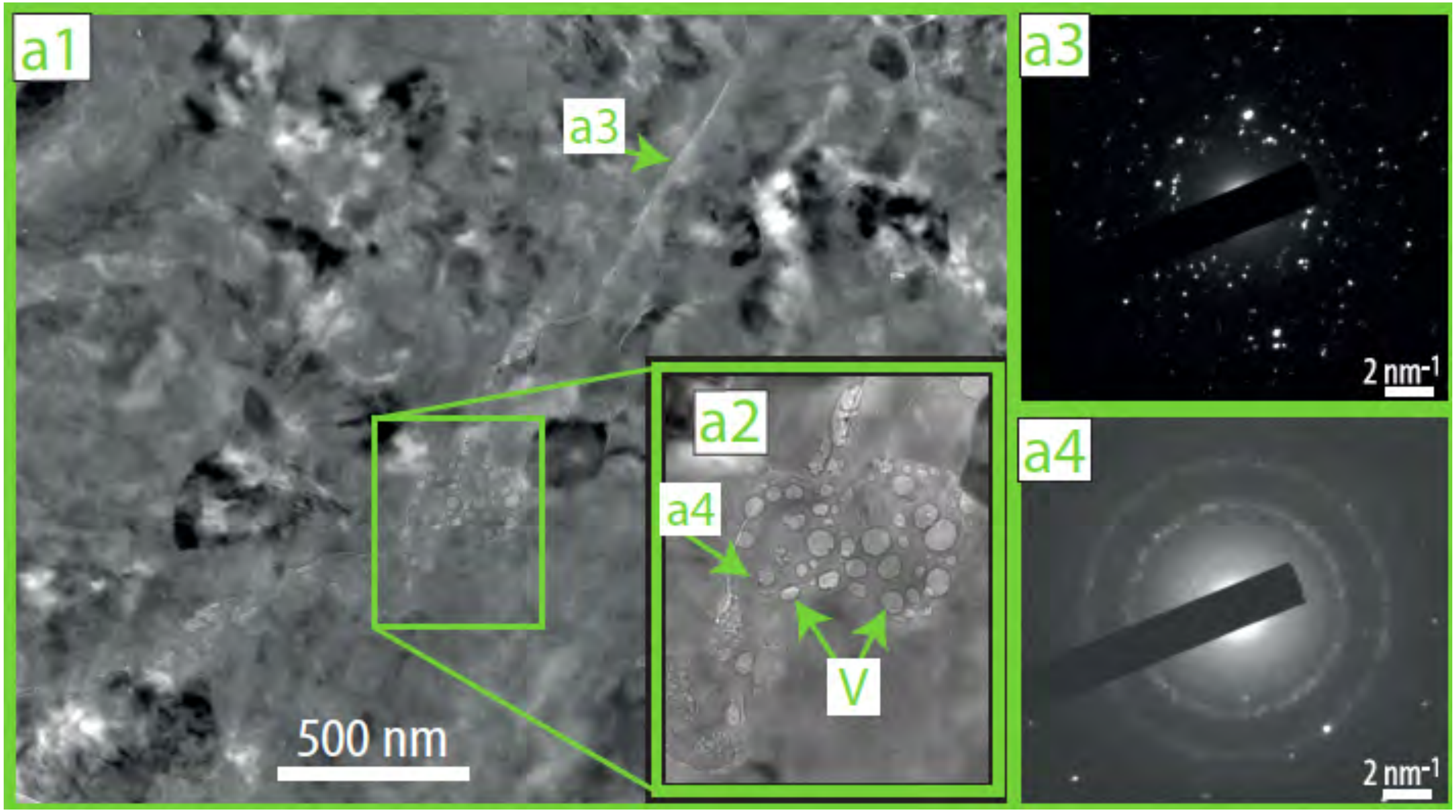
SEM (Backscattered) evidence of HP-faulting



Ferrand et al., Nat. Comm 2017

Serp. peridotite dehydration under stress

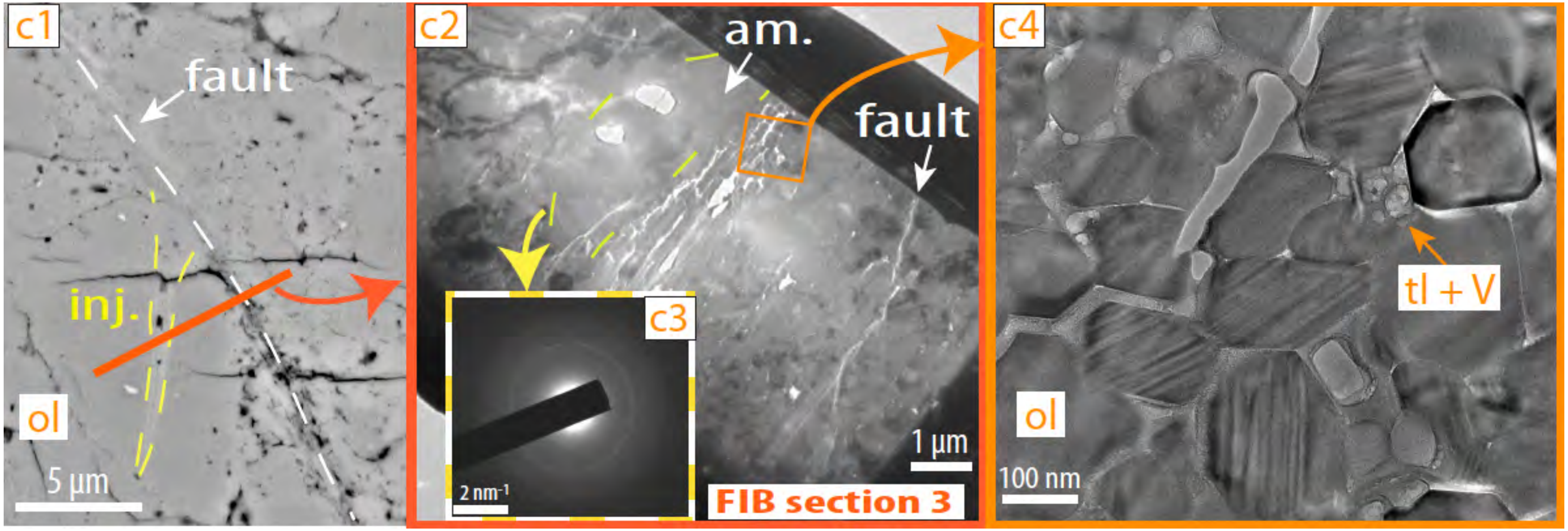
TEM – fault zone nanostructure



Ferrand et al., Nat. Comm 2017

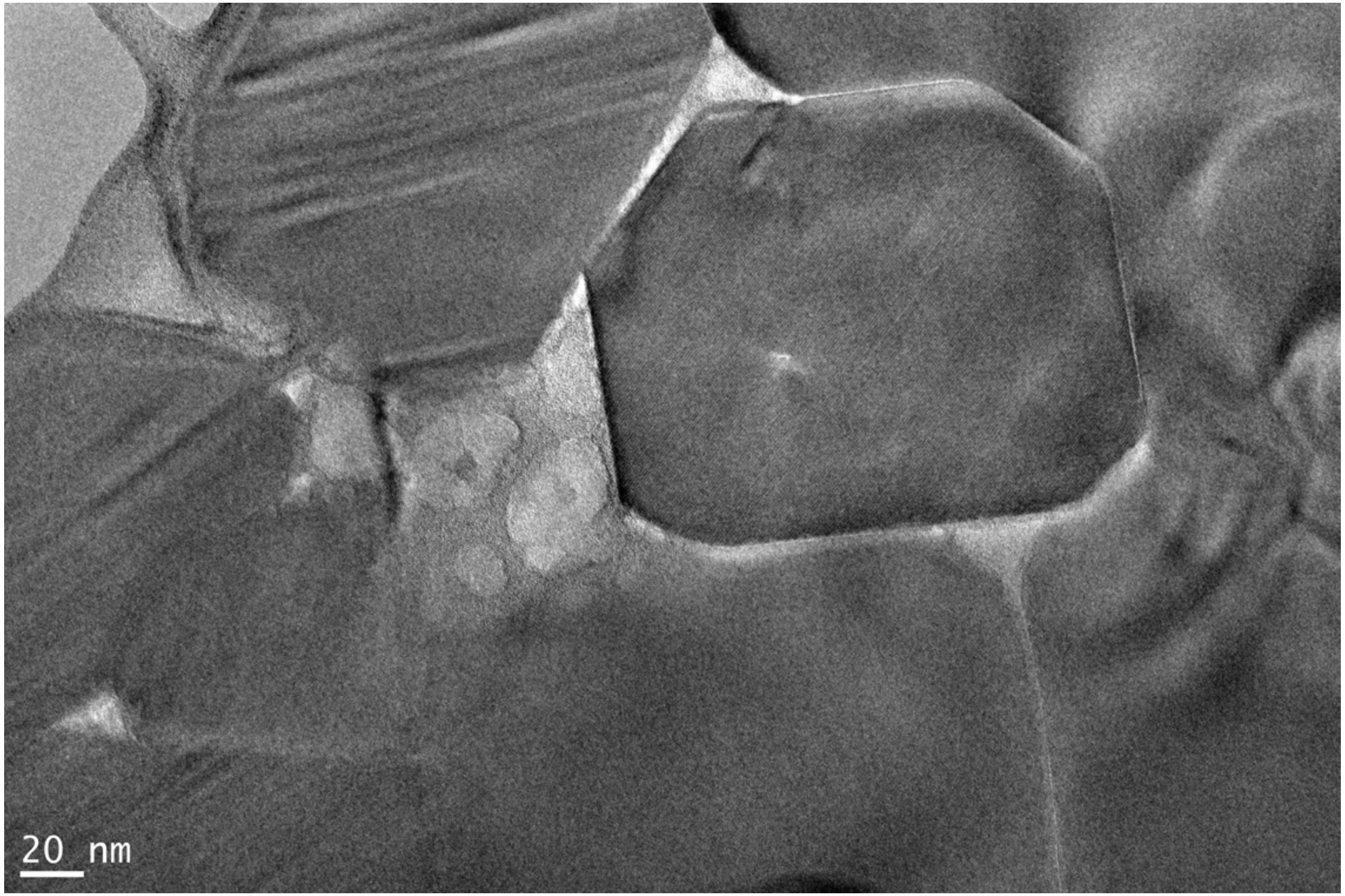
Serp. peridotite dehydration under stress

TEM – fault zone nanostructure



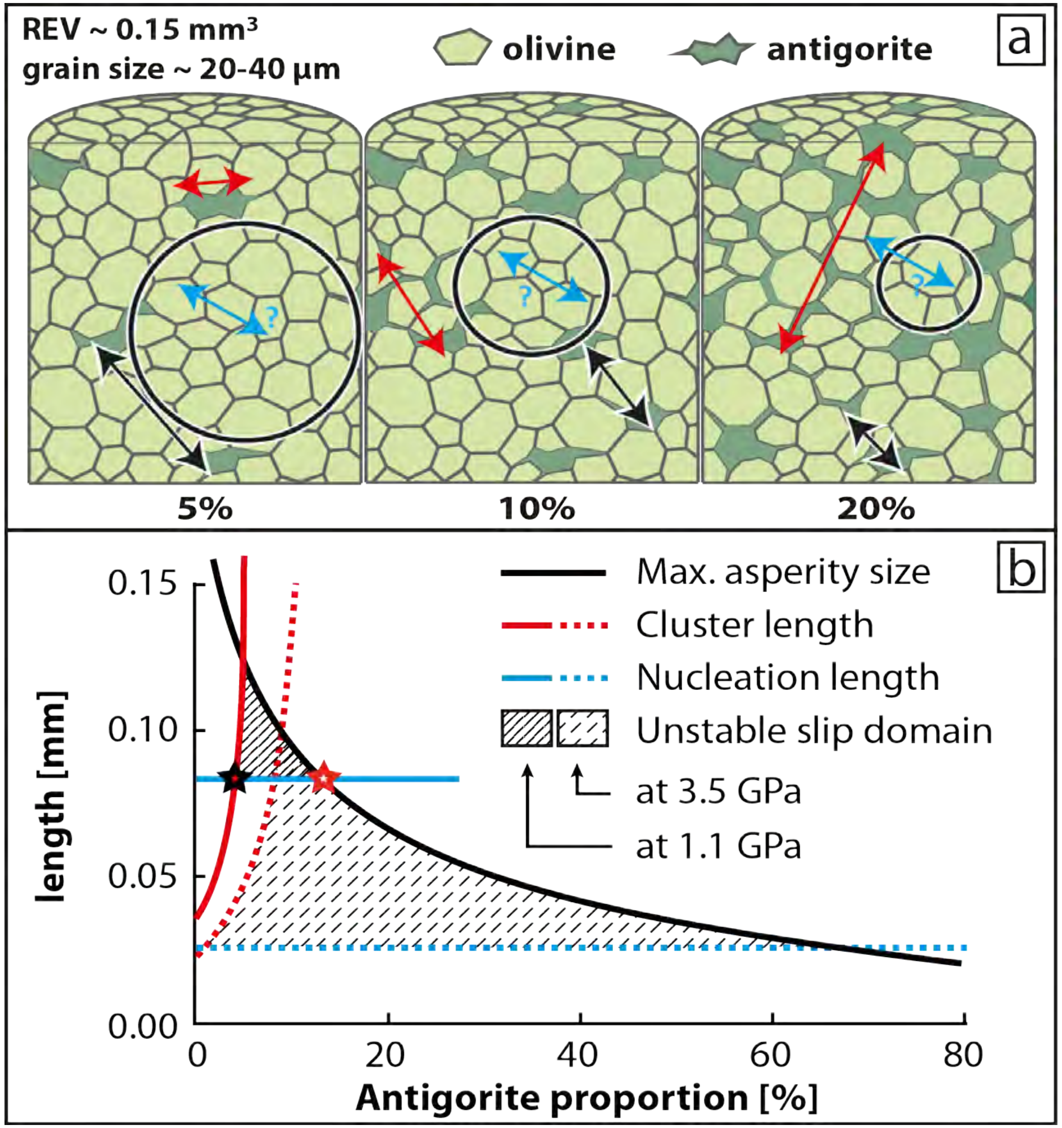
Serp. peridotite dehydration under stress

TEM – evidence of melting?



Serp. peridotite dehydration

Dehydration stress transfer model



Ferrand et al., Nat. Comm 2017

OUTLINE

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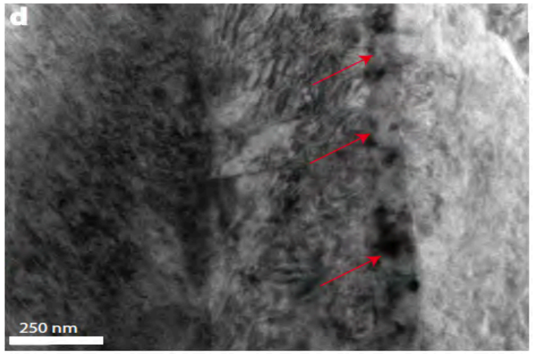


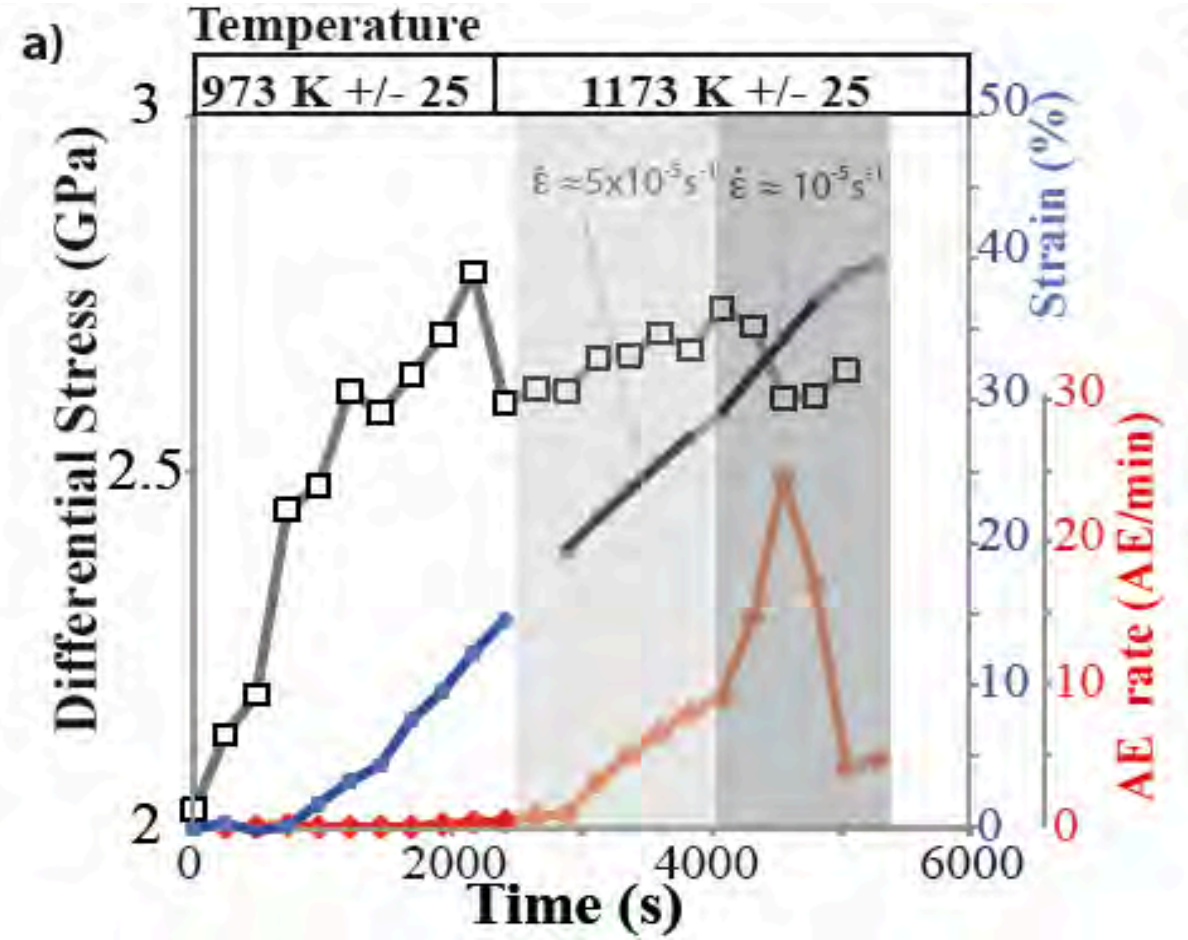
Ge-olivine-spinel transition

Sintered Mg_2GeO_4 – 30µm grain size

Effective mean stress $(\sigma_1+2\sigma_3)/3$ = 4GPa +/-0,25

Strain rate = 10^{-4}/s

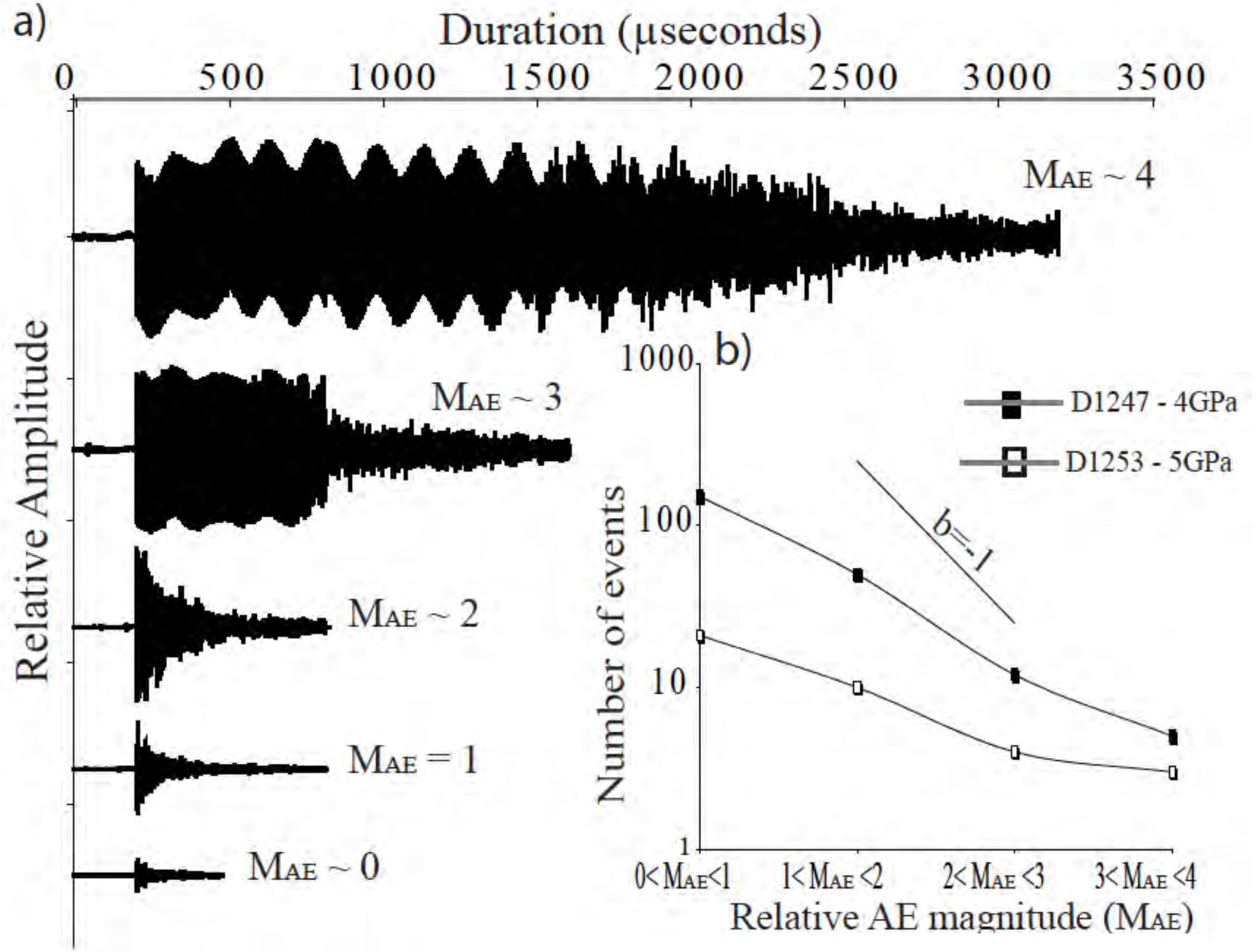
Stress – strain curve



Schubnel et al. Science 2013

Ge-olivine-spinel transition

Two complete AE catalogues
D1247 Effective mean stress $(\sigma_1+2\sigma_3)/3$ = 4GPa +/-0,25
D1253 Effective mean stress $(\sigma_1+2\sigma_3)/3$ = 5GPa +/-0,25
Strain rate = 10^{-4}/s



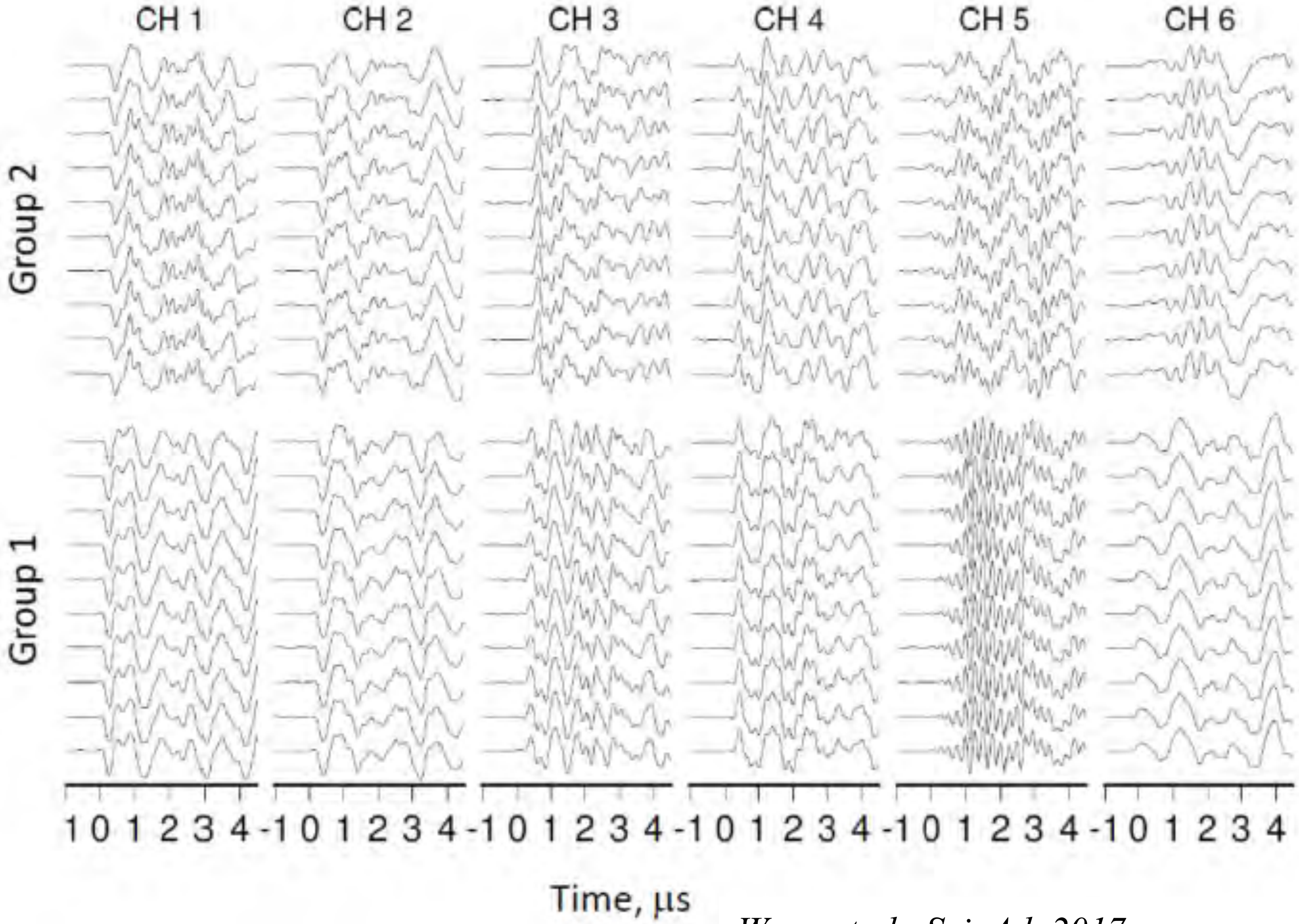
Schubnel et al. Science 2013

Sonification:
courtesy to Ben Holtzman
LDEO, U. Columbia NY
Visiting prof. ENS 2015

Ge-olivine-spinel transition

Correlating X-ray tomography and AE locations

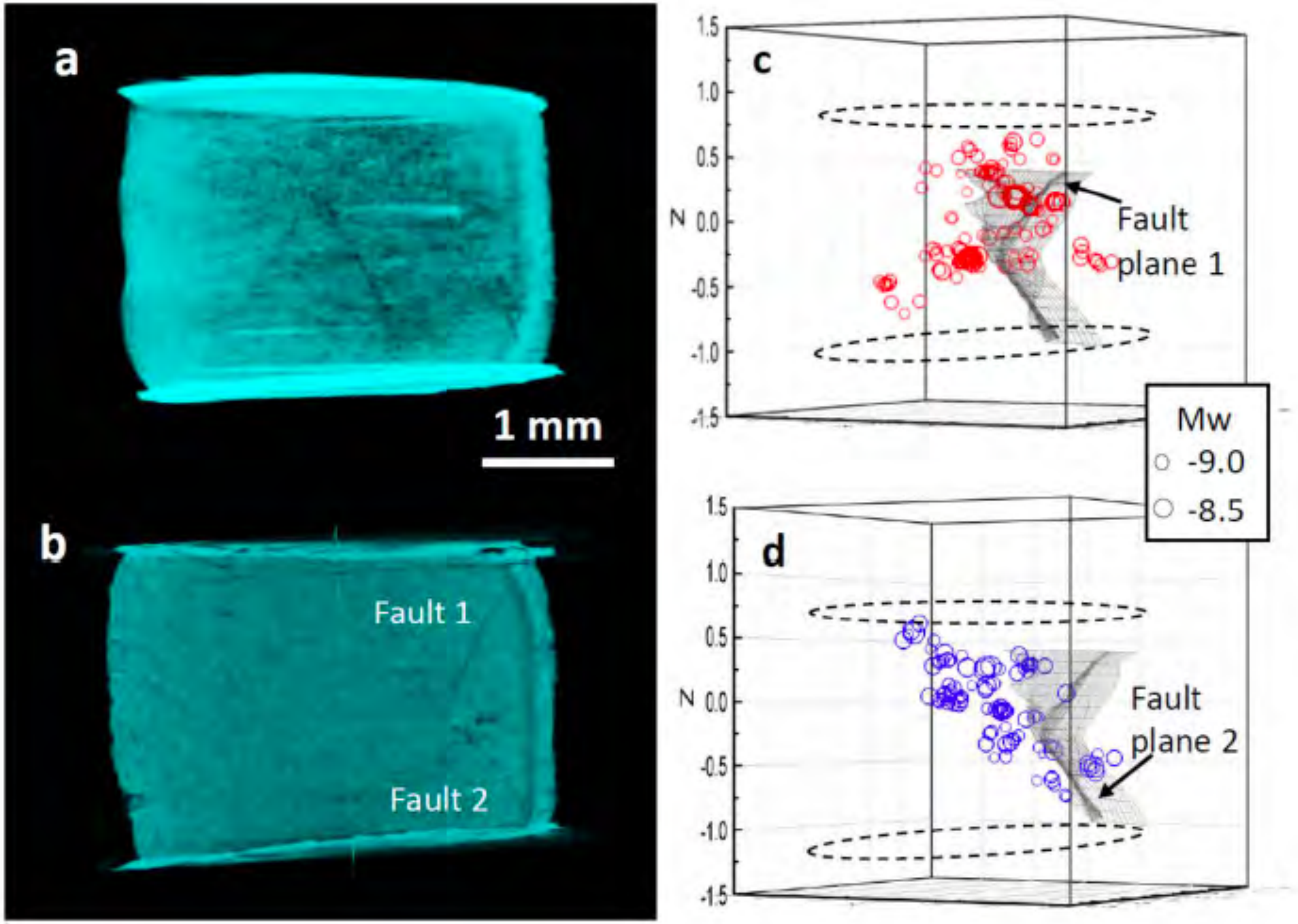
Double difference relocation (Waldhauser and Ellsworth 2000)



Wang et al., Sci. Ad. 2017

Ge-olivine-spinel transition

Correlating X-ray tomography and AE locations

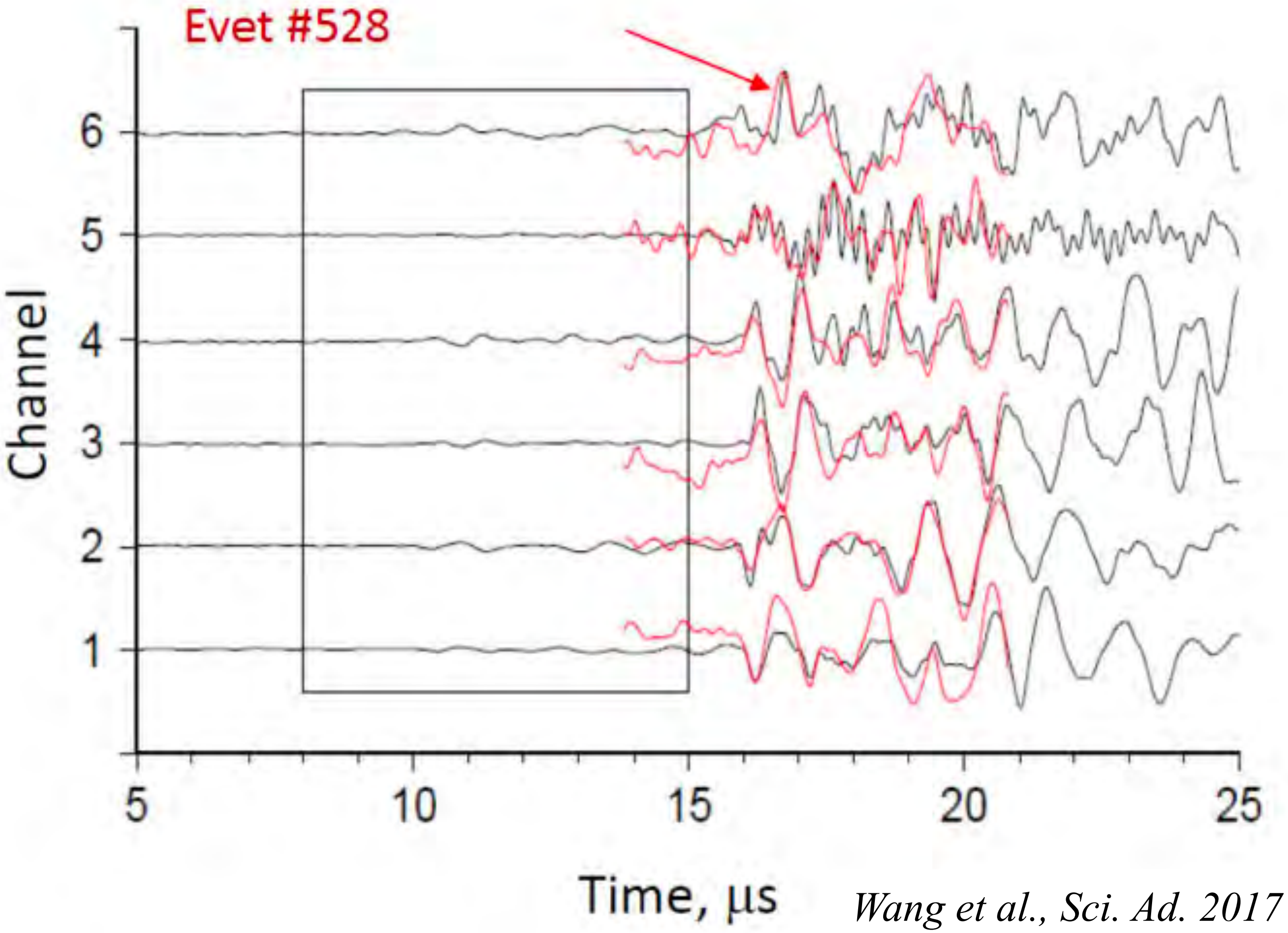


Wang et al., Sci. Ad. 2017

Ge-olivine-spinel transition

Nano-seismicity time-series analysis

(template matching of continuous wfms)



Wang et al., Sci. Ad. 2017

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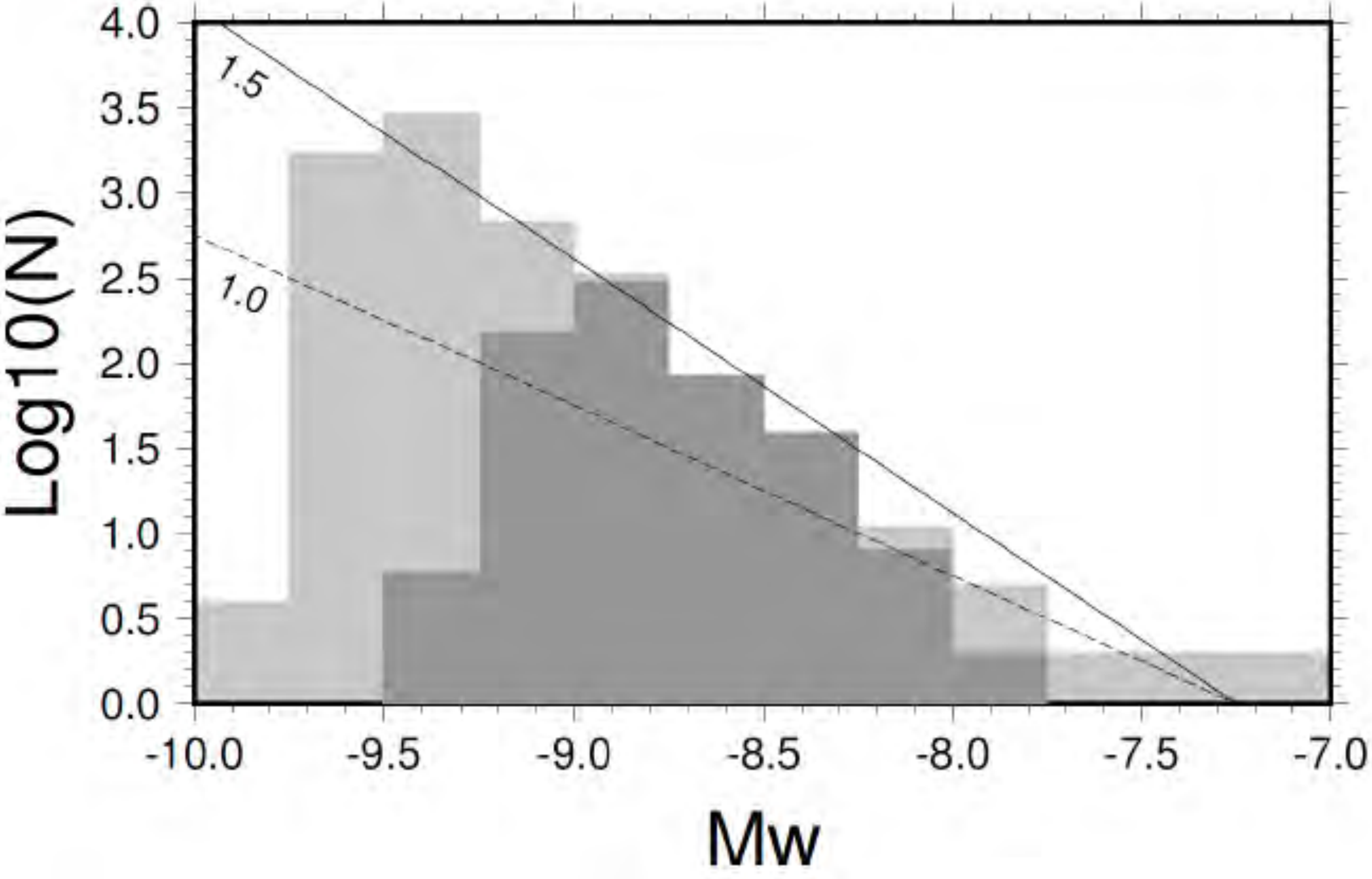

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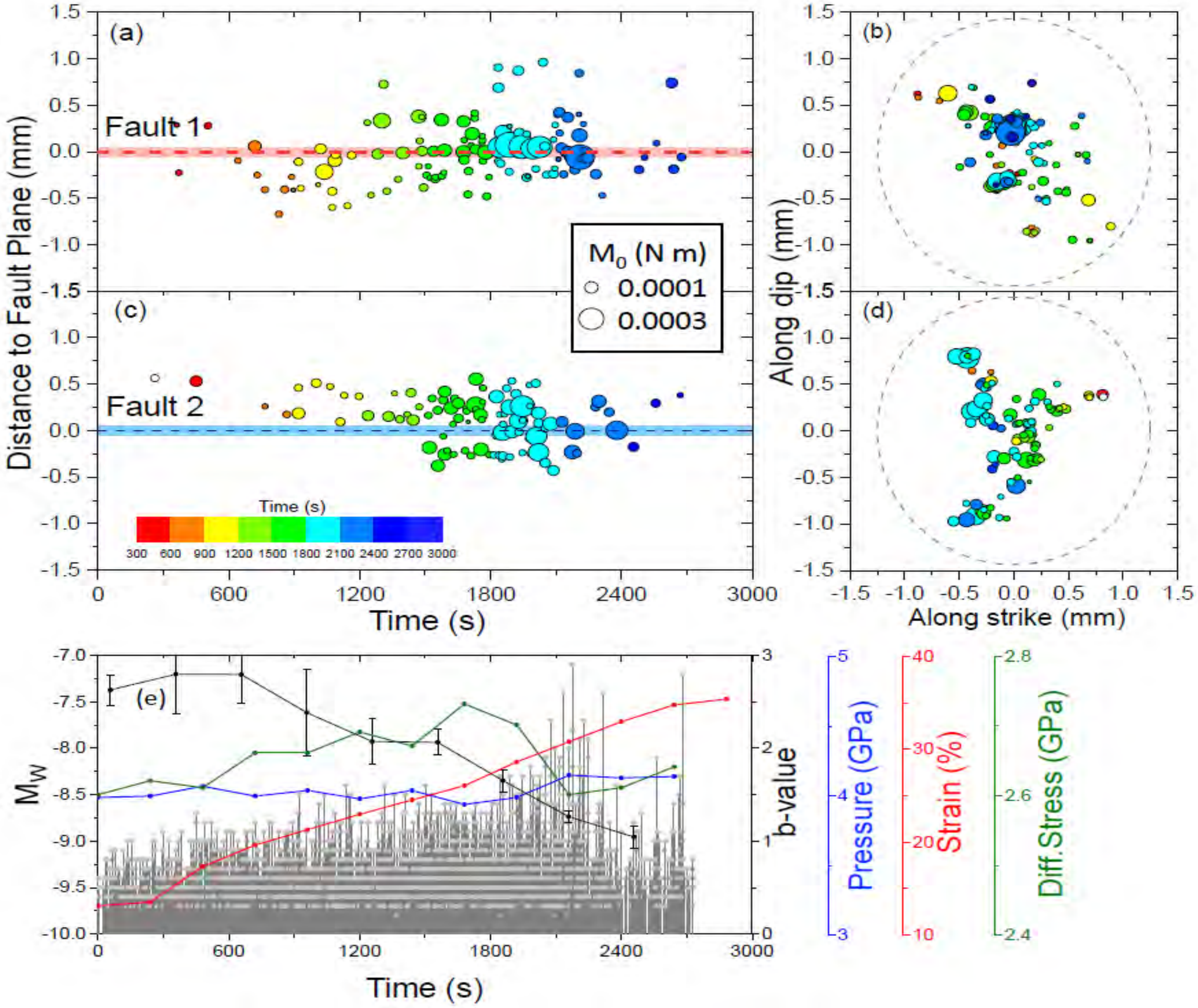
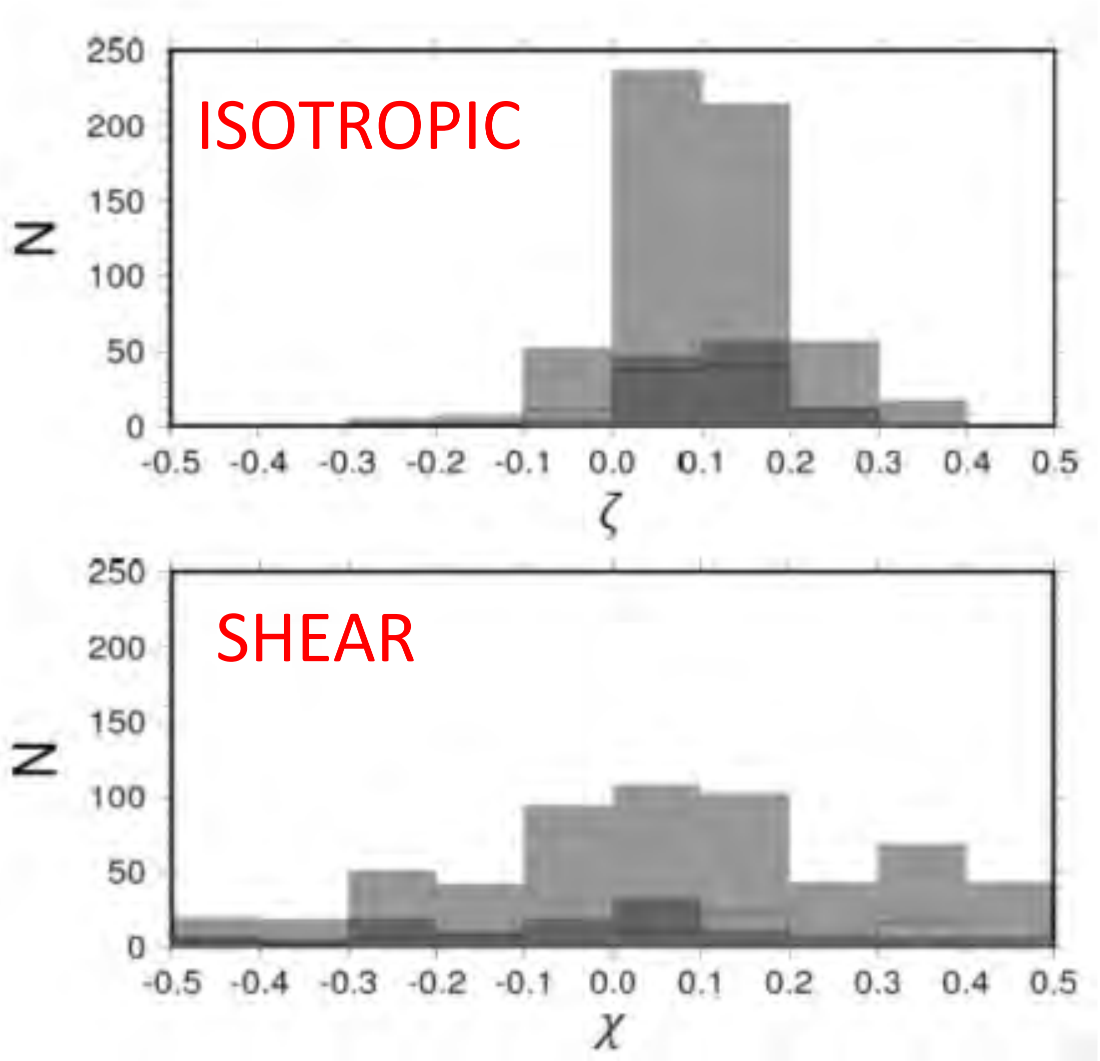


Wang et al., Sci. Ad. 2017

Ge-olivine-spinel transition

Moment Tensor inversion

- 90 % Shear, i.e. less than 10% volumetric component
- Up to 50%CLVD (compensated linear vector dipole)



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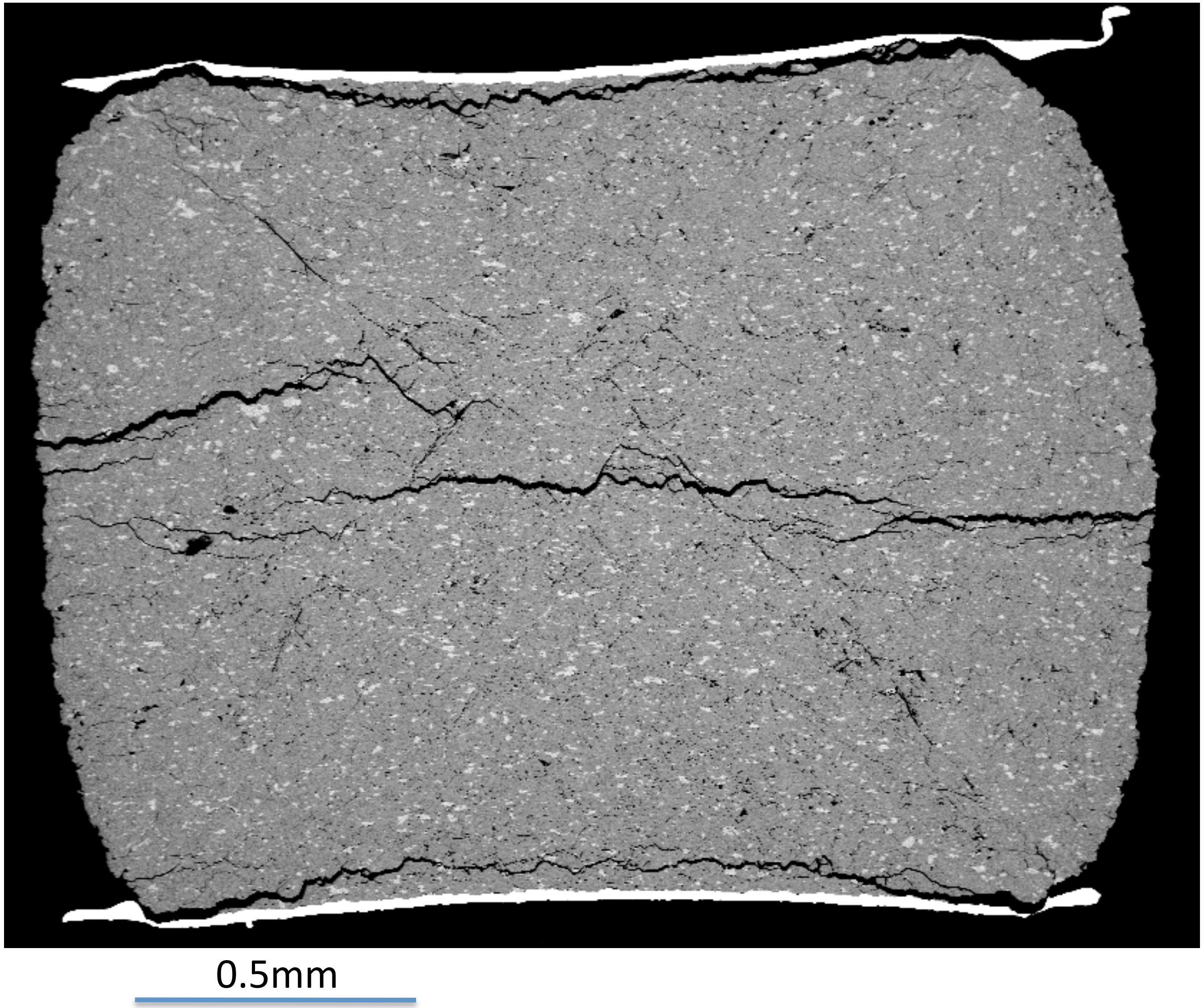

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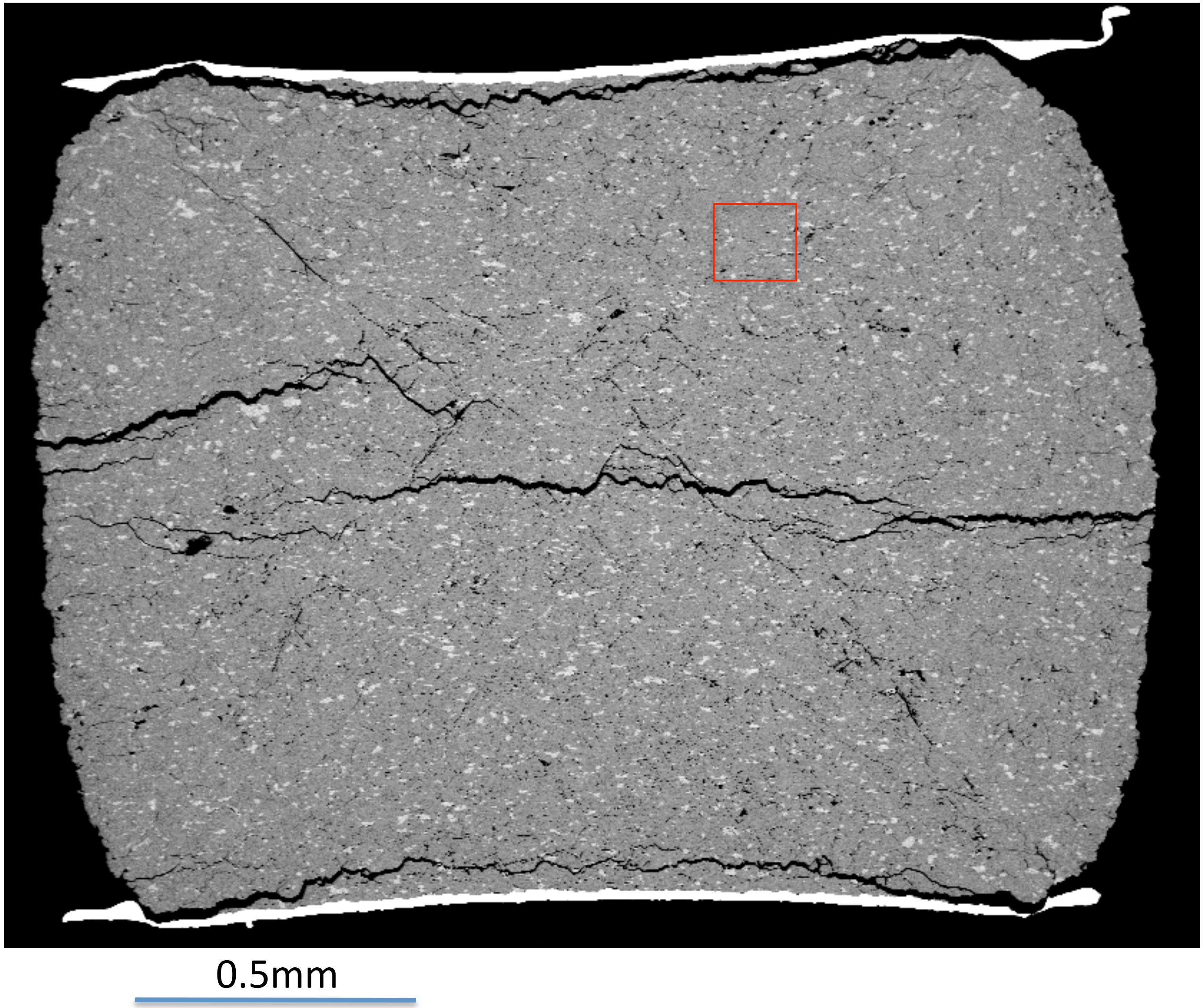

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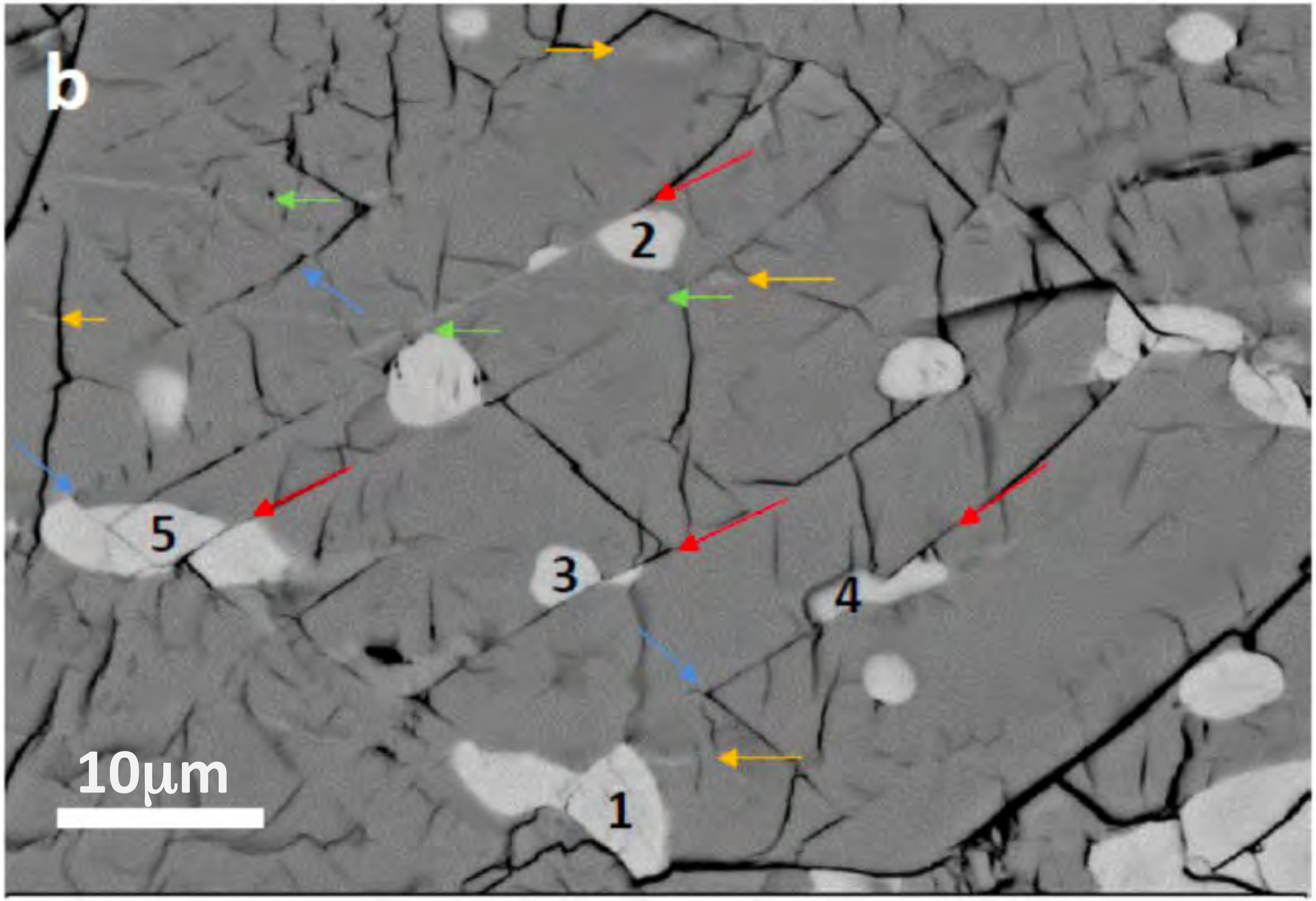

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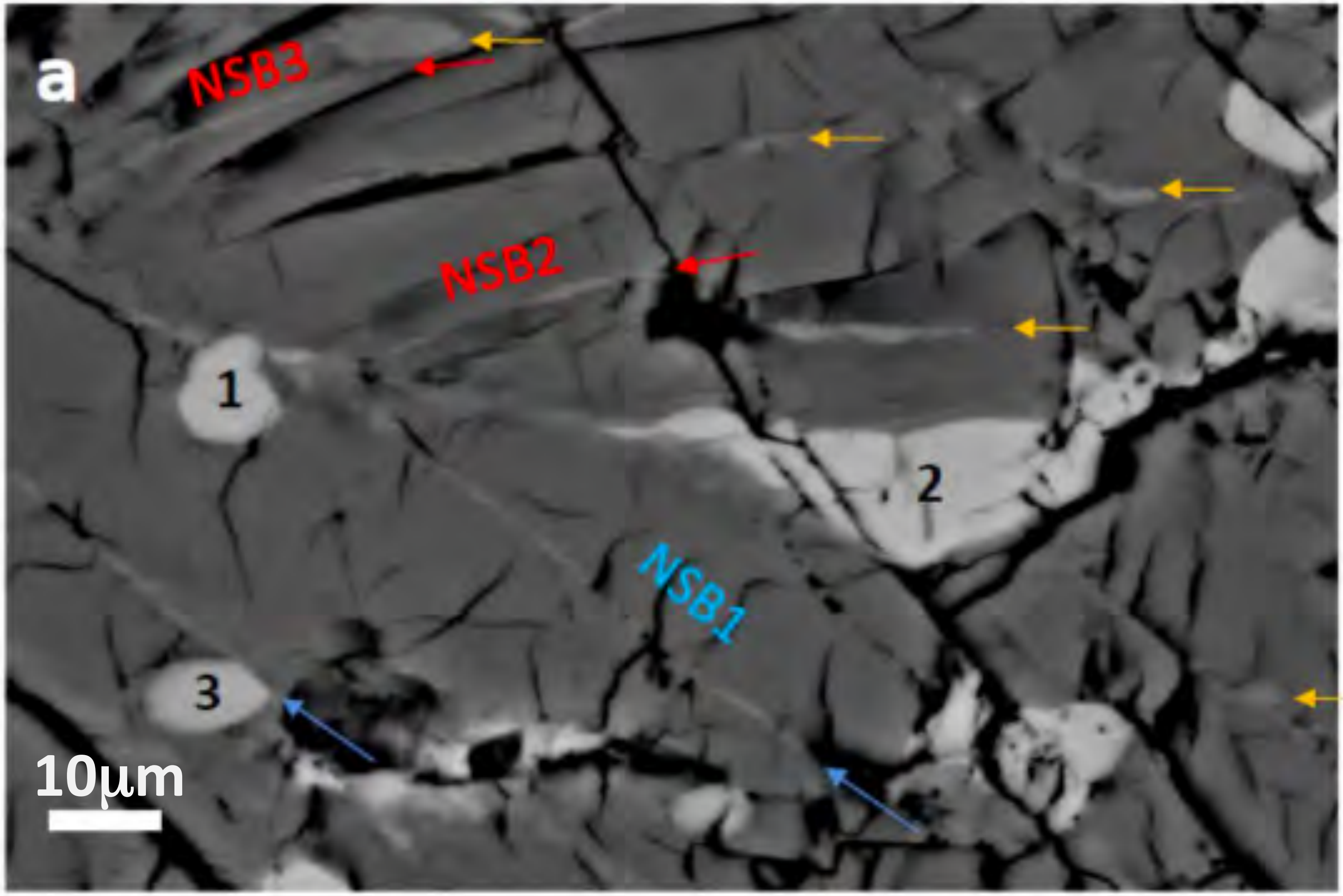

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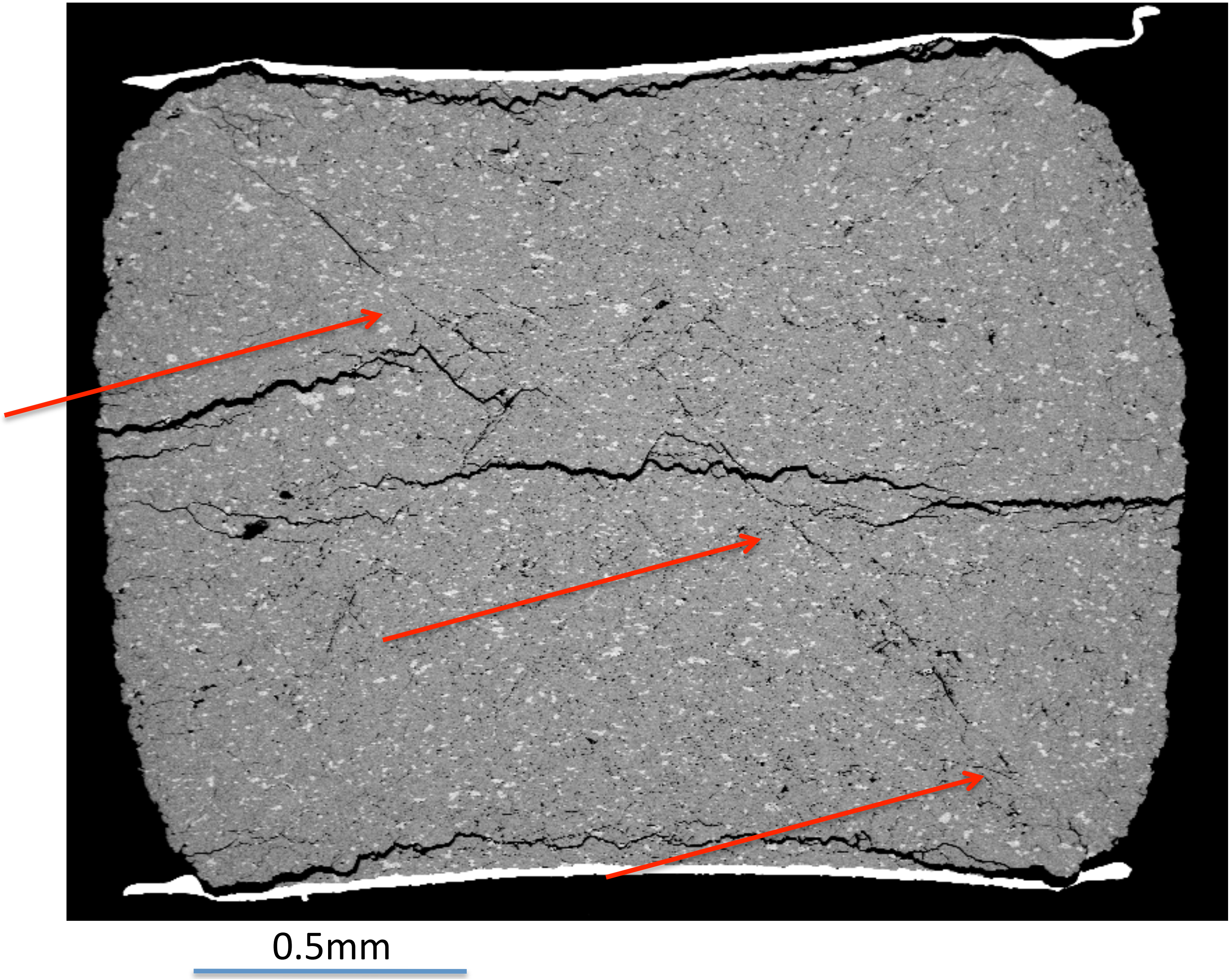

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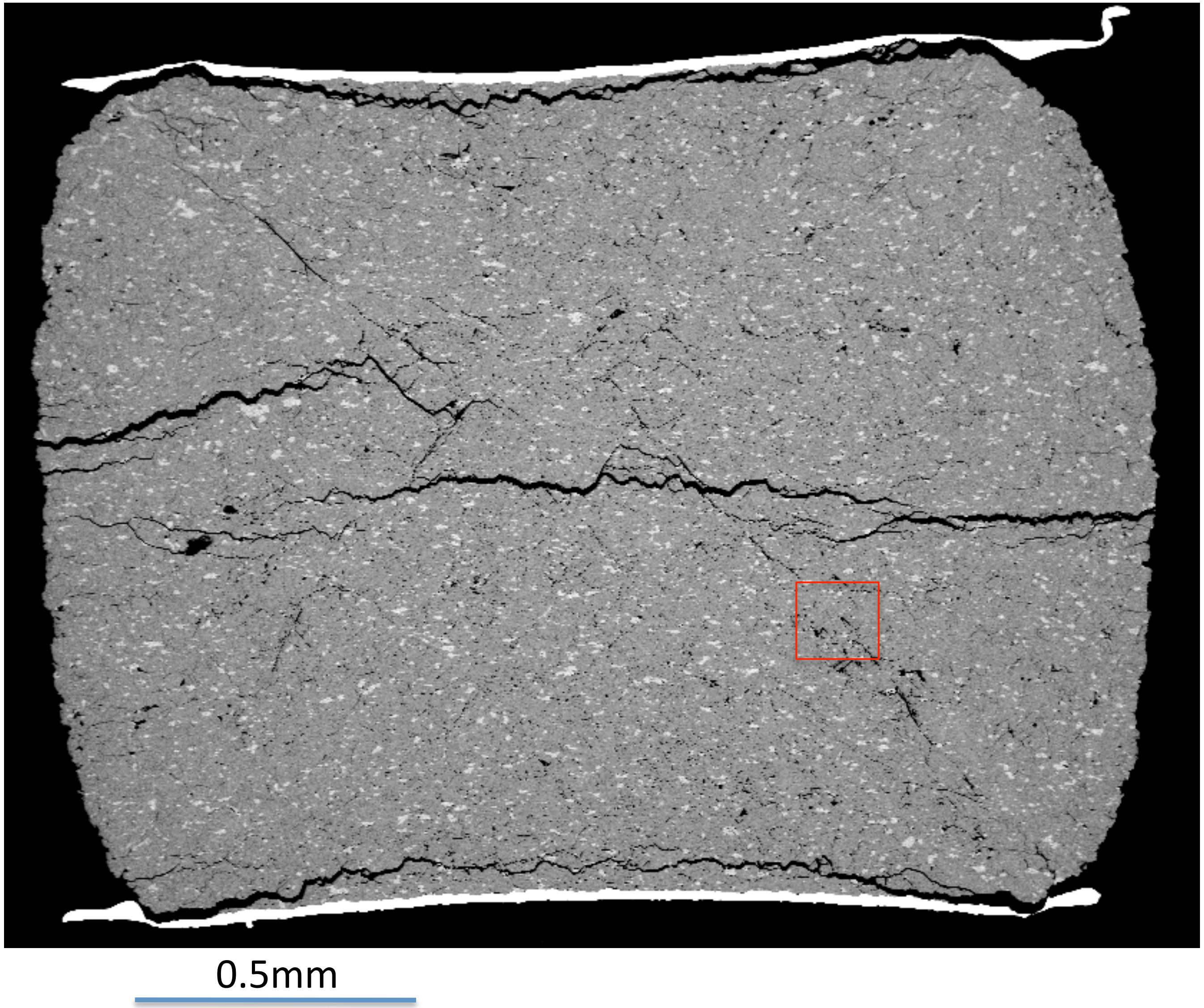

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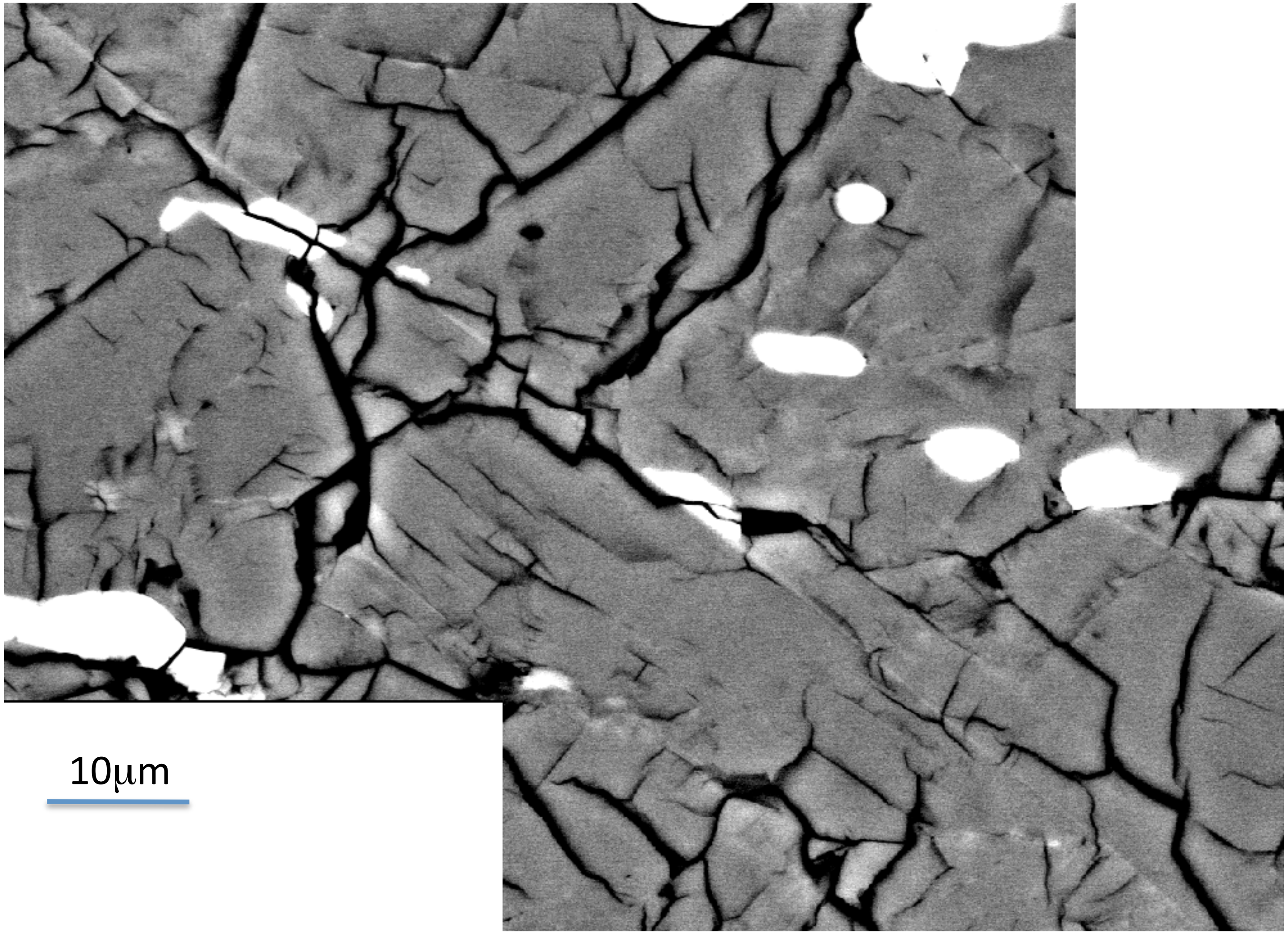

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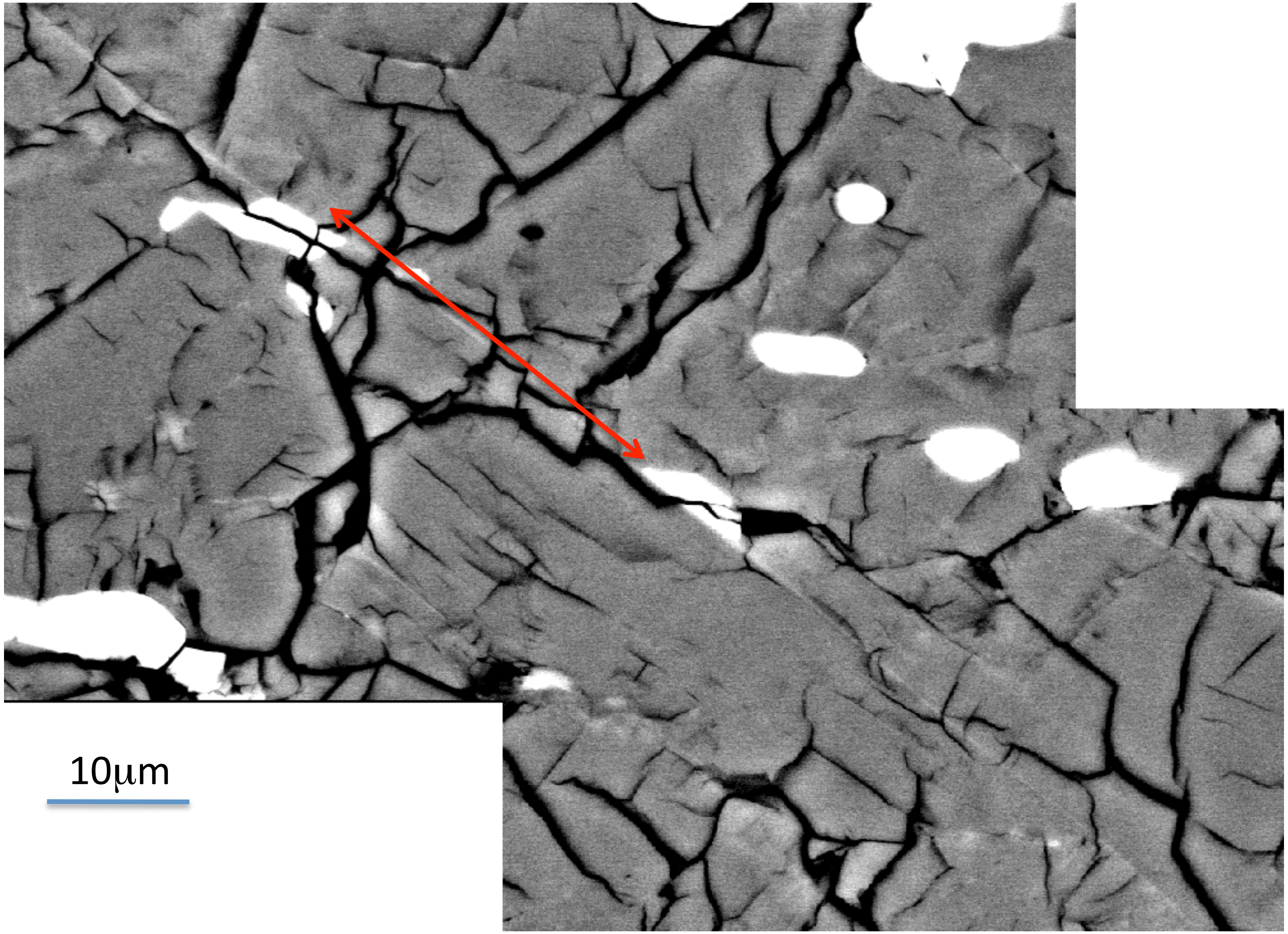

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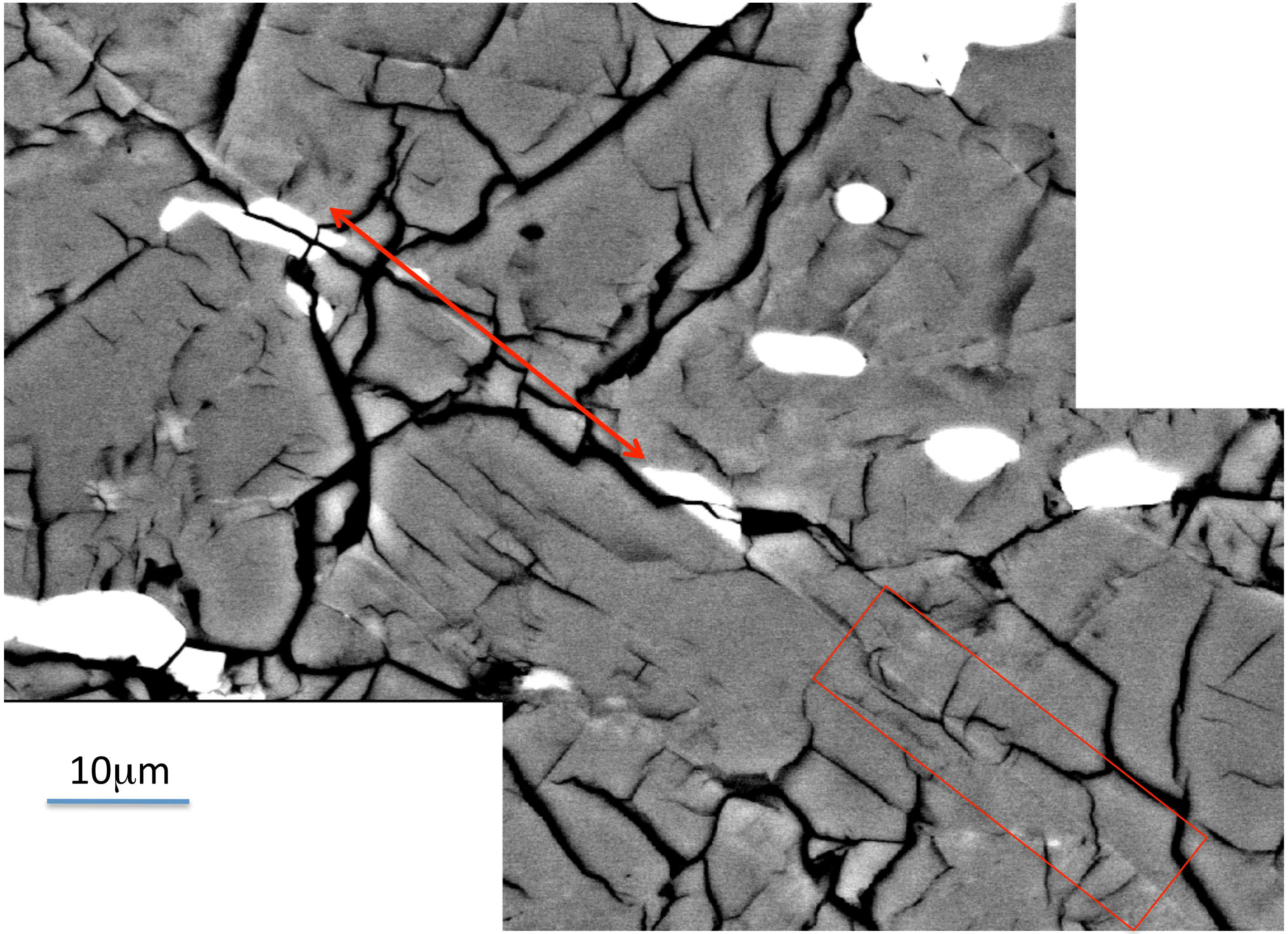

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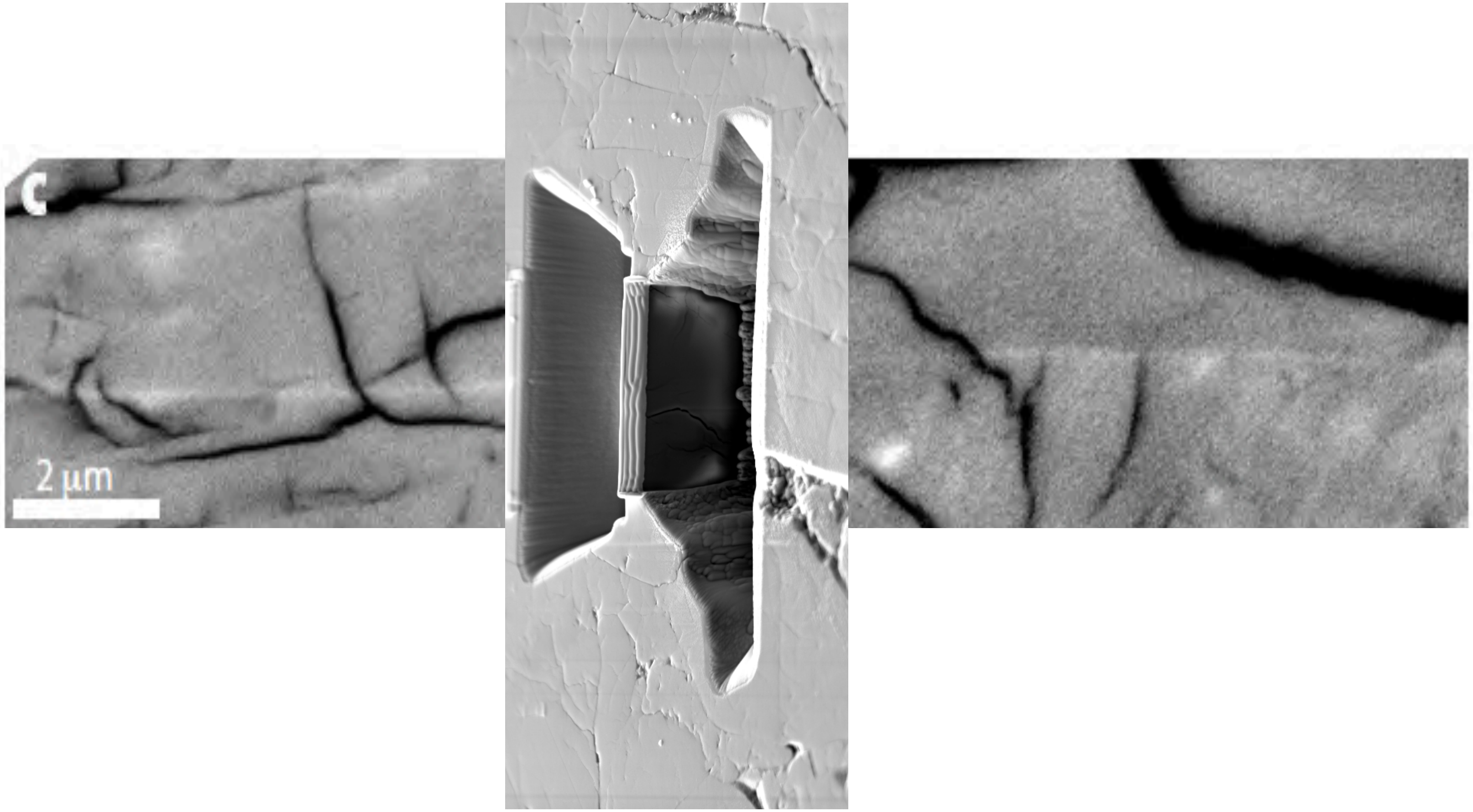

FIB Section

Ge-olivine-spinel transition

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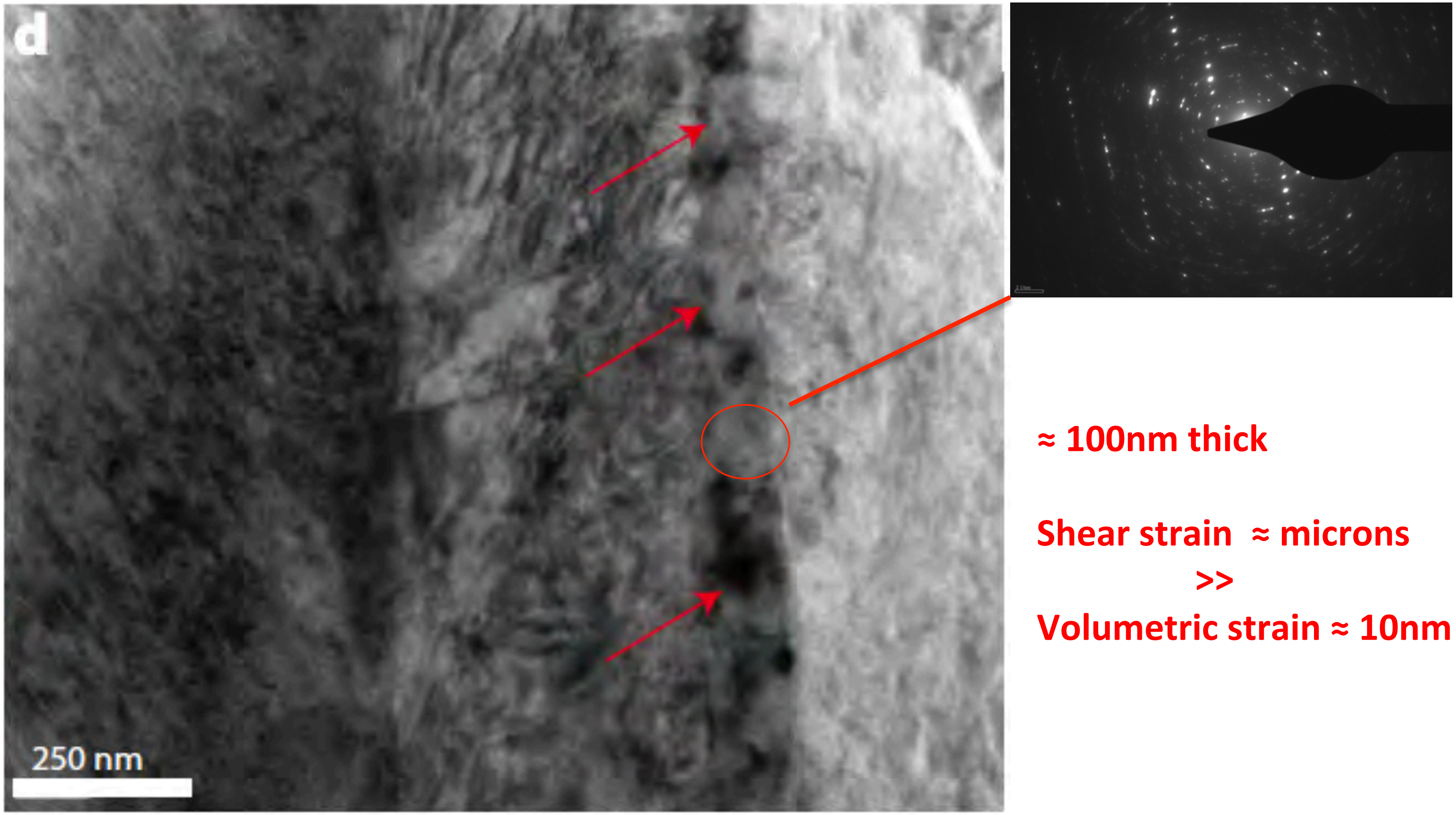

≈ XRPD of spinel phase

≈ 100nm thick

Shear strain ≈ microns
>>
Volumetric strain ≈ 10nm

Ge-olivine-spinel transition

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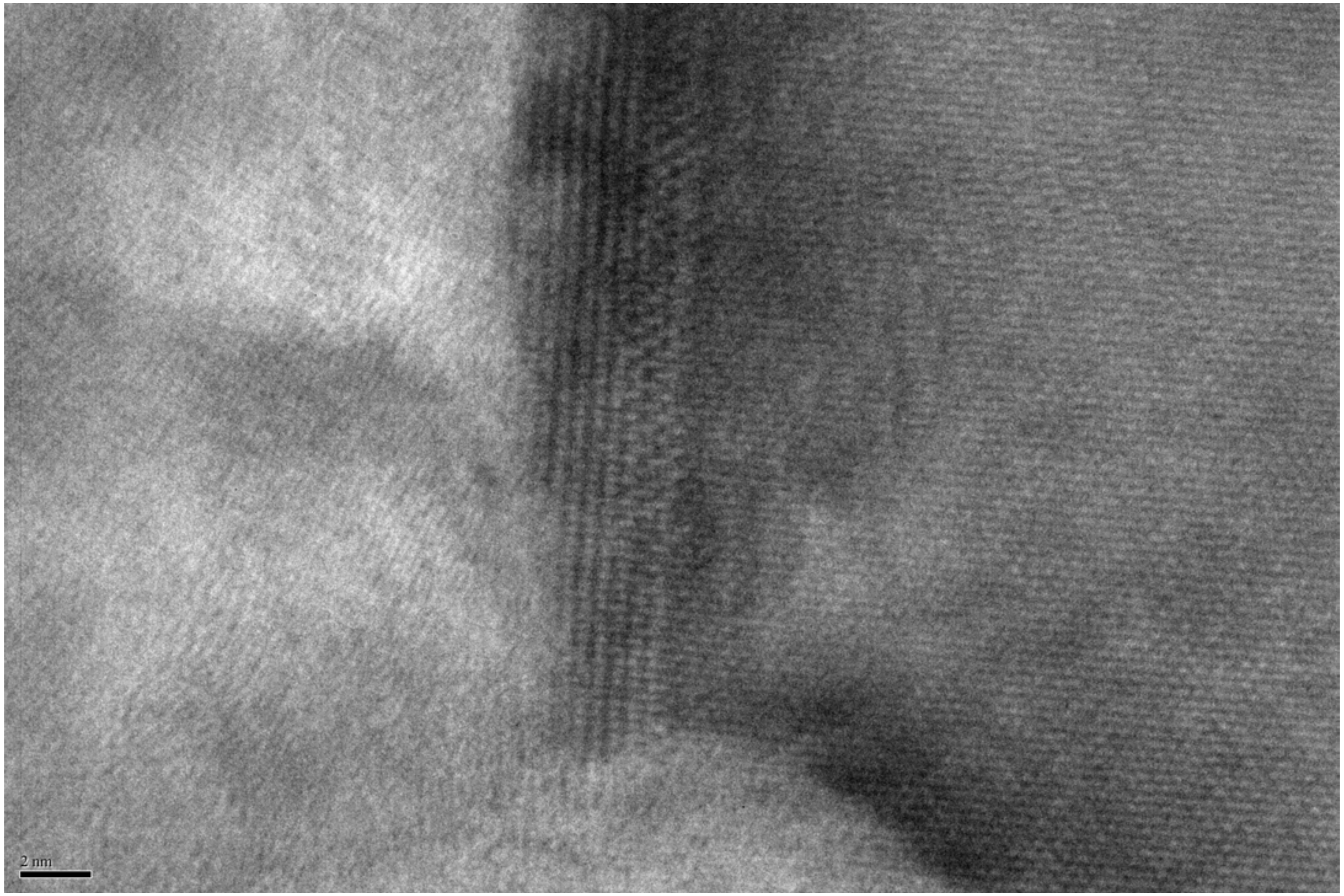
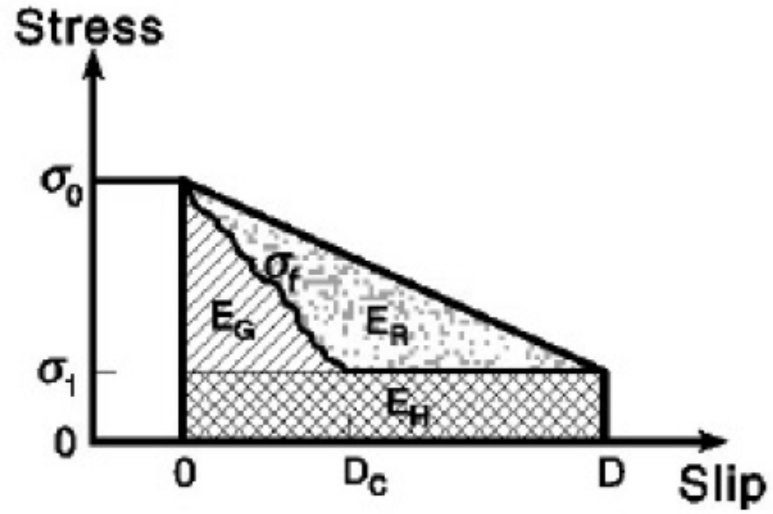
Effective mean stress = 5GPa +/-0.25, Strain rate = 10^{-4}/s

Fully crystalline, no melt!



4nm

Discussion: Energy balance *during EQ*



E_G = Fracture energy
E_R = Radiated energy, into seismic waves
E_H = Frictional heat

Energy balance

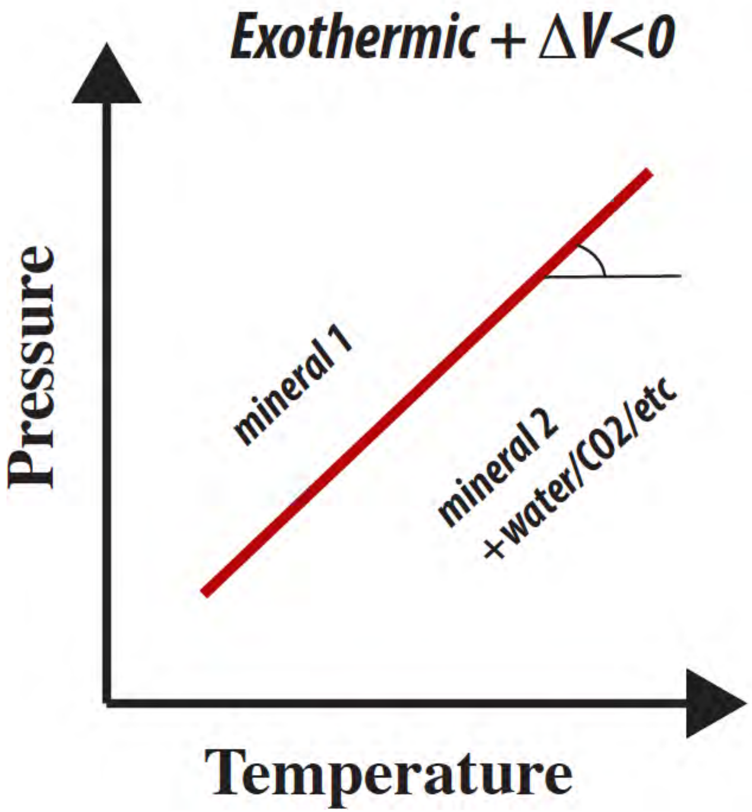
But what becomes that energy budget, if above a given pressure or temperature (that of the reaction) the system liberates / consumes

mineral

HEAT or WORK?

Gln -> Omp+tlc; Ab-> Jd+ Qz; Olivine $\alpha \rightarrow \gamma$

$\Delta rH \approx -$ 50-500 MJ/m^3



A self-sustained thermo-mechanical instability?

For comparison, the fracture energy of Tohoku EQ ≈ 30-60 MJ/m^2 ***Fulton et al. 2014***

Conclusions

- During **dehydration of partially serpentinized San Carlos olivine under stress**, "dehydration embrittlement" was observed for serpentine ratio as low as 5% (@ 1 GPa), and as high as 50% (@ 3 GPa), including within ΔV<0. Dehydration stress transfer model (Ferrand et al. Nat. Com., 2017)

- During **Ge-olivine – spinel phase transformation under stress**, faults propagate dynamically (rapid enough to radiate AEs) ***– NO FLUIDS! Applying modern seismology techniques, we see clear evidence of a nucleation phase*** (Wang et al. Sci. Ad, 2017)!

- *Similar experimental observations during:*
  - ***Eclogitization of CO and CC:***
    - ***Blueschist under stress*** *: glaucophane breakdown → Omphacite (Incel et al. EPSL 2017)*
    - ***Dry granulites*** *: Ab-An breakdown (Shi et al., sub. & Incel et al., in prep)! UWP and deep continental Eqs.*
  - ***OPx – HP-CPx*** *(Shi et al., AGU 2018), EQs nests at 200-300km depth like Bucaramanga?*

Conclusions

- During **dehydration of partially serpentinized San Carlos olivine under stress**, “dehydration embrittlement” was observed for serpentine ratio as low as 5% (@ 1 GPa), and as high as 50% (@ 3 GPa), including within $\Delta V<0$. Dehydration stress transfer model (Ferrand et al. Nat. Com., 2017)

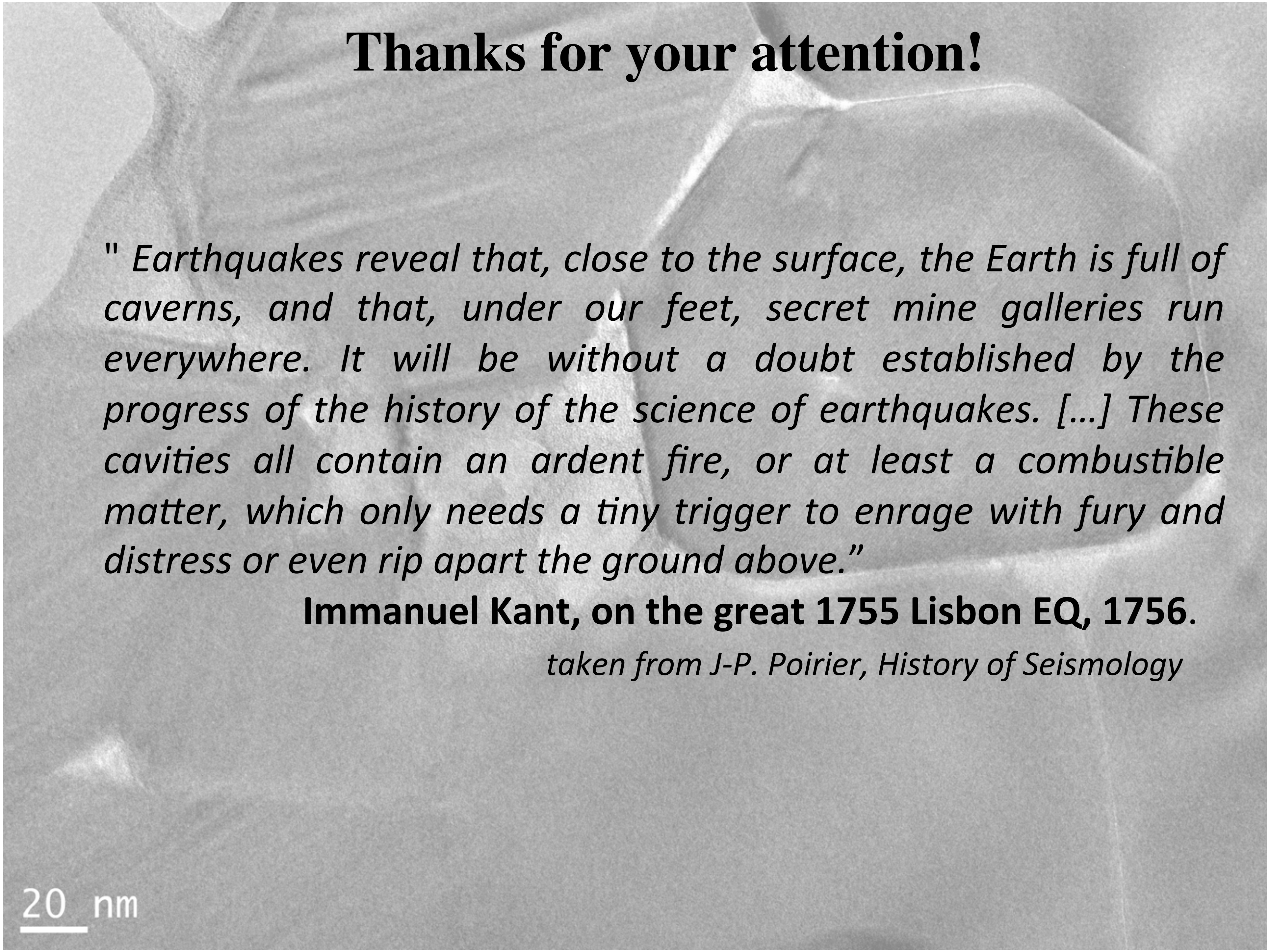
- During **Ge-olivine – spinel phase transformation under stress**, faults propagate dynamically (rapid enough to radiate AEs) ***– NO FLUIDS! Applying modern seismology techniques, we see clear evidence of a nucleation phase*** (Wang et al. Sci. Ad, 2017)!

Mineral transformation not to be neglected:
- **during EQ nucleation**
- **the overall energy balance,**

because reactions are: 1) highly exothermic, 2) produce extremely fine grain-size material 3) and possible stress transfer

(LARGE AMOUNTS OF) FLUIDS ARE NOT NEEDED!

Thanks for your attention!



" *Earthquakes reveal that, close to the surface, the Earth is full of caverns, and that, under our feet, secret mine galleries run everywhere. It will be without a doubt established by the progress of the history of the science of earthquakes. […] These cavities all contain an ardent fire, or at least a combustible matter, which only needs a tiny trigger to enrage with fury and distress or even rip apart the ground above.”*

Immanuel Kant, on the great 1755 Lisbon EQ, 1756.

taken from J-P. Poirier, History of Seismology