Societa Italiana di Fisica, Enrico Fermi school, Varenna, July 2018

Mechanics of intermediate and deep earthquakes:
field and experimental evidences

Alexandre SCHUBNEL
Laboratoire de Géologie, ENS PARIS

Thanks to:
@ ENS: **Sarah Incel (U. Oslo), Thomas Ferrand (ERI), Julien Gasc,** Damien Deldicque
@ Isterre Grenoble: Fabrice Brunet
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@ GSECARS, Argonne Il.: Feng Shi; Yanbin Wang
@ UC. Riverside: Harry W. Green II

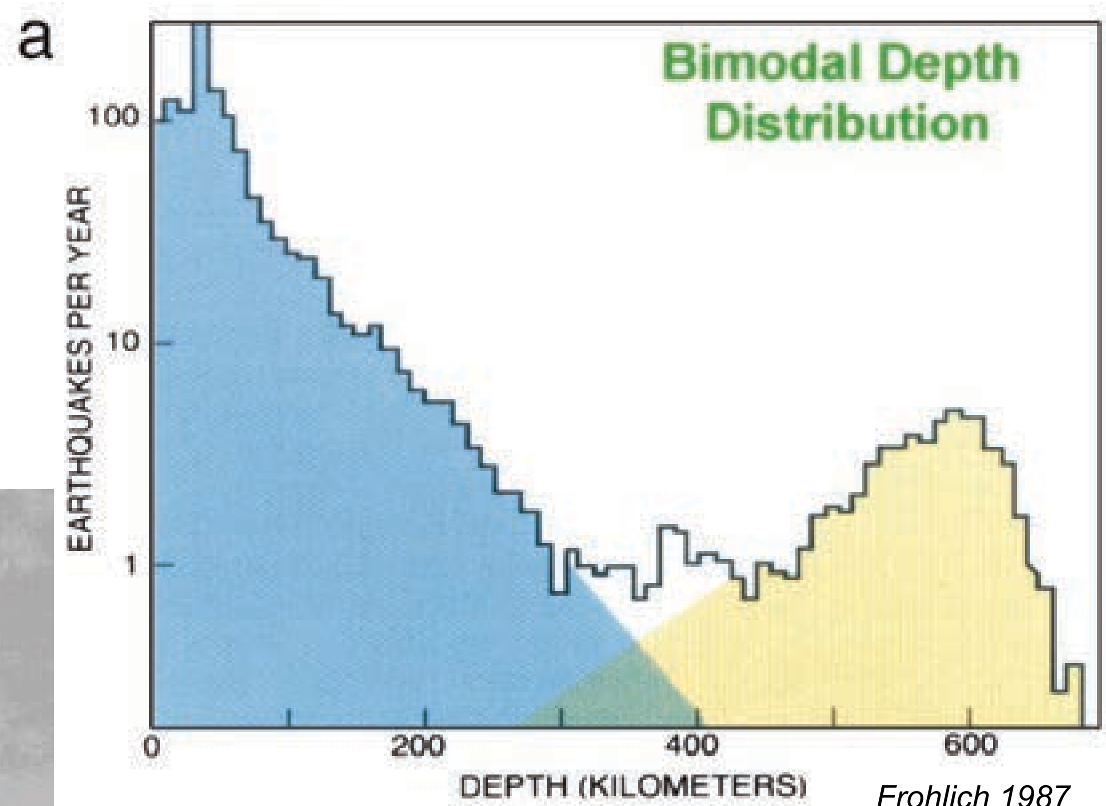
European Research Council
Established by the European Commission

Earthquakes at depth

Herbert Hall Turner, 1861- 1930

Kiyoo Wadati, 1902 - 1995

Hugo Benioff, 1889-1968



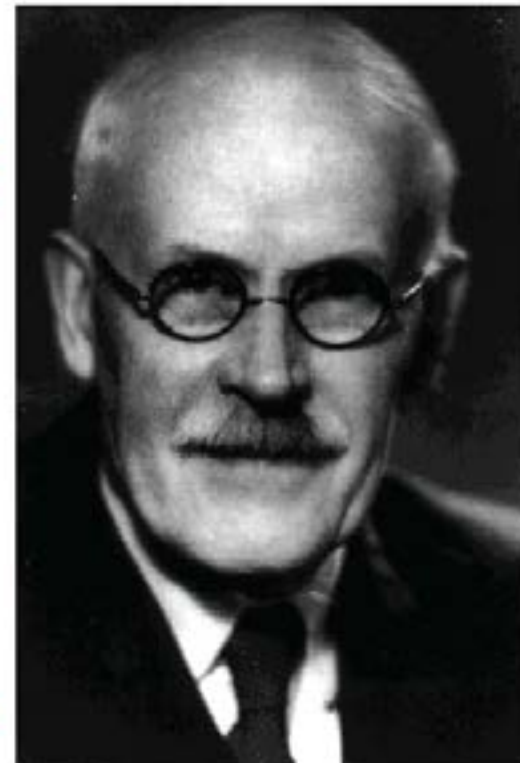
Frohlich 1987

Earthquakes at depth

The Times of Transmission and Focal Depths of Large Earthquakes.
By Harold Jeffreys, M.A., D.Sc., F.R.S.

(*Received* 1927 *September* 17.)

8.1. First, we know definitely that the upper layers of the earth are strong enough to support the weight of the Himalayas and other great mountain ranges. On the other hand, the evidence of isostasy is clear that this strength is confined to a comparatively thin layer, and that at some distance down the materials are too weak to resist the stress-difference due to the weight of about 200 metres of uncompensated material. Barrell, when he put this view forward originally, suggested that the transition took place at a depth of about 300 km., and I was originally prepared on this ground to entertain Prof. Turner's theory.† But further work on the mechanism of isostasy has led me to the conclusion that Barrell's estimate was much too great. Difficulties about the production of compensation within a mountain range ‡ made me consider a lithosphere only 100 km. thick, and later one of 70 km.§ A recent attempt ‖ to use the conventional depth of compensation of geodesists to determine the thickness of the strong layer has shown that it is most probably about 30 km., agreeing with the thickness of the two upper layers of seismology. Thus if the focal depth exceeded this amount the focus would be in the asthenosphere.

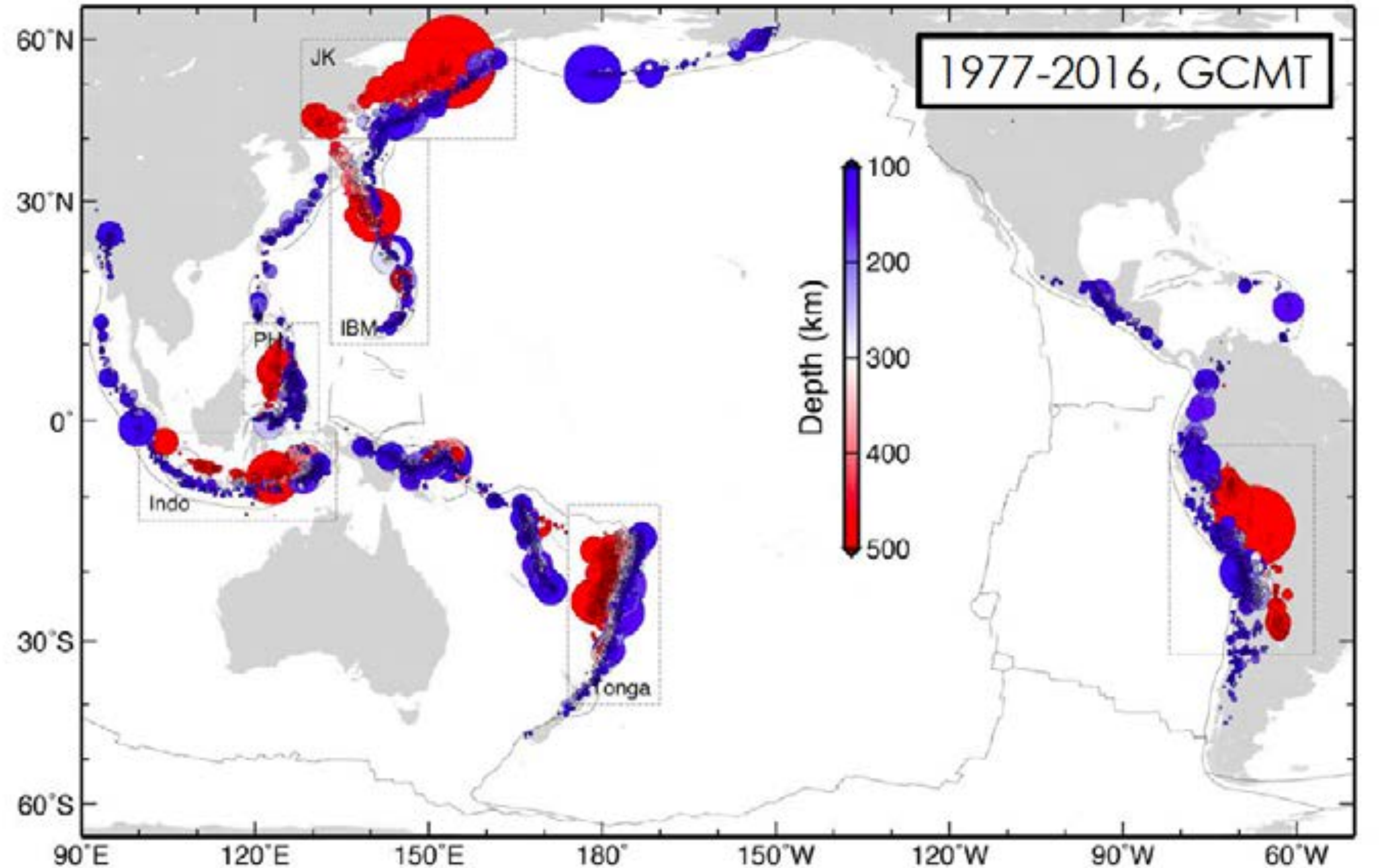


PHASE TRANSITION MODEL

Suggested as early as 1945 by Piercy Bridgman

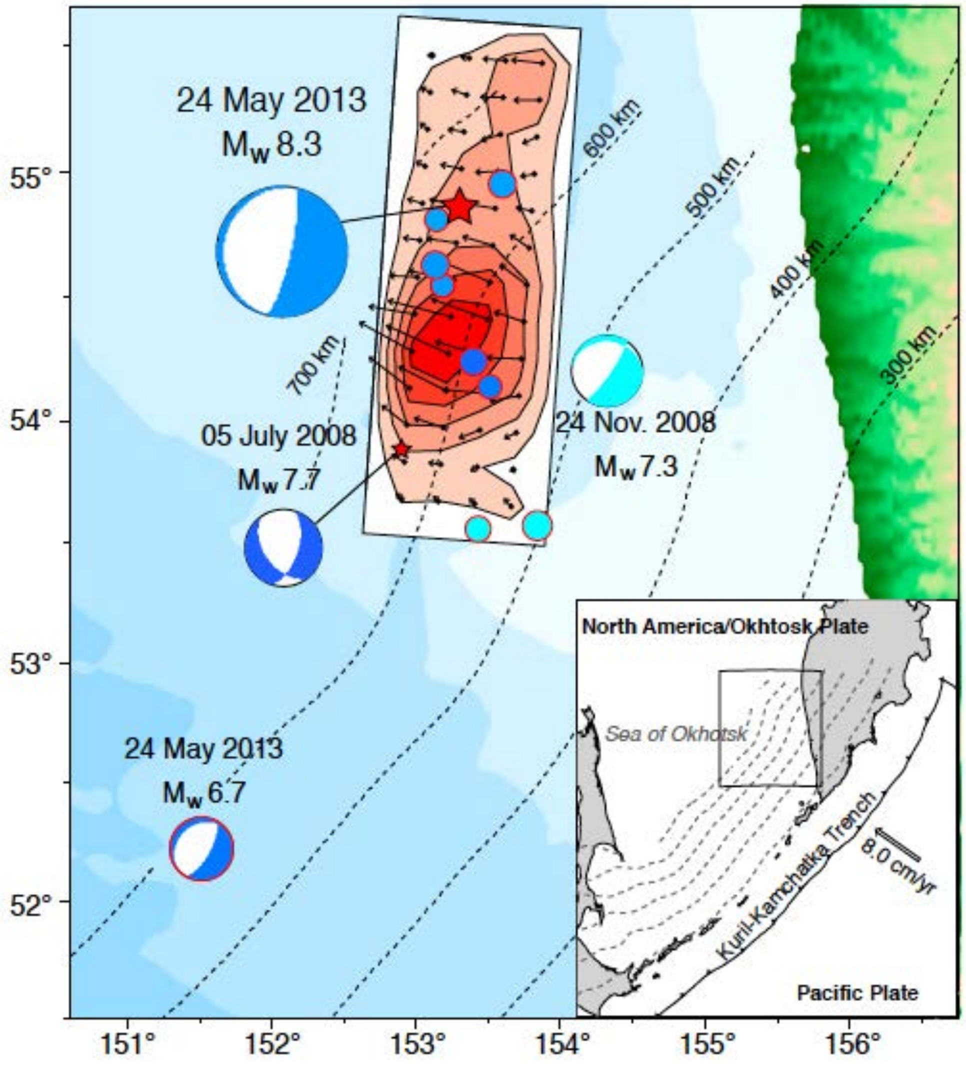
There is a theoretical possibility which should be kept in mind. There is no thermodynamic reason why [polymorphic] transitions should not occur under shearing stress ... No examples of phenomena which have been positively identified as being of this character have yet been found . . .

Earthquakes at depth



MOTIVATION

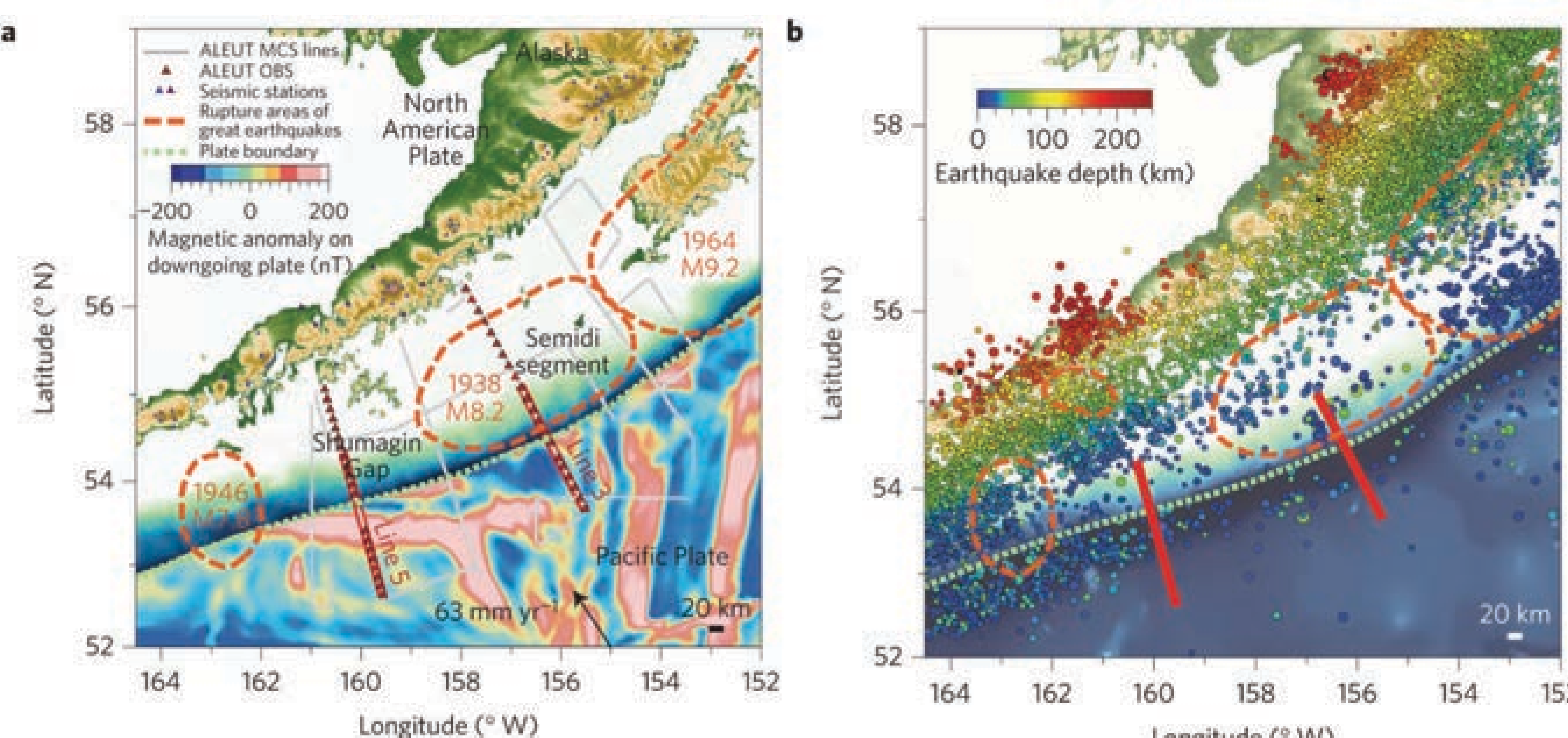
The Okhotsk, May 24th 2013, Mw=8.3, 620km deep EQ



Ye et al. Science 2013

MOTIVATION

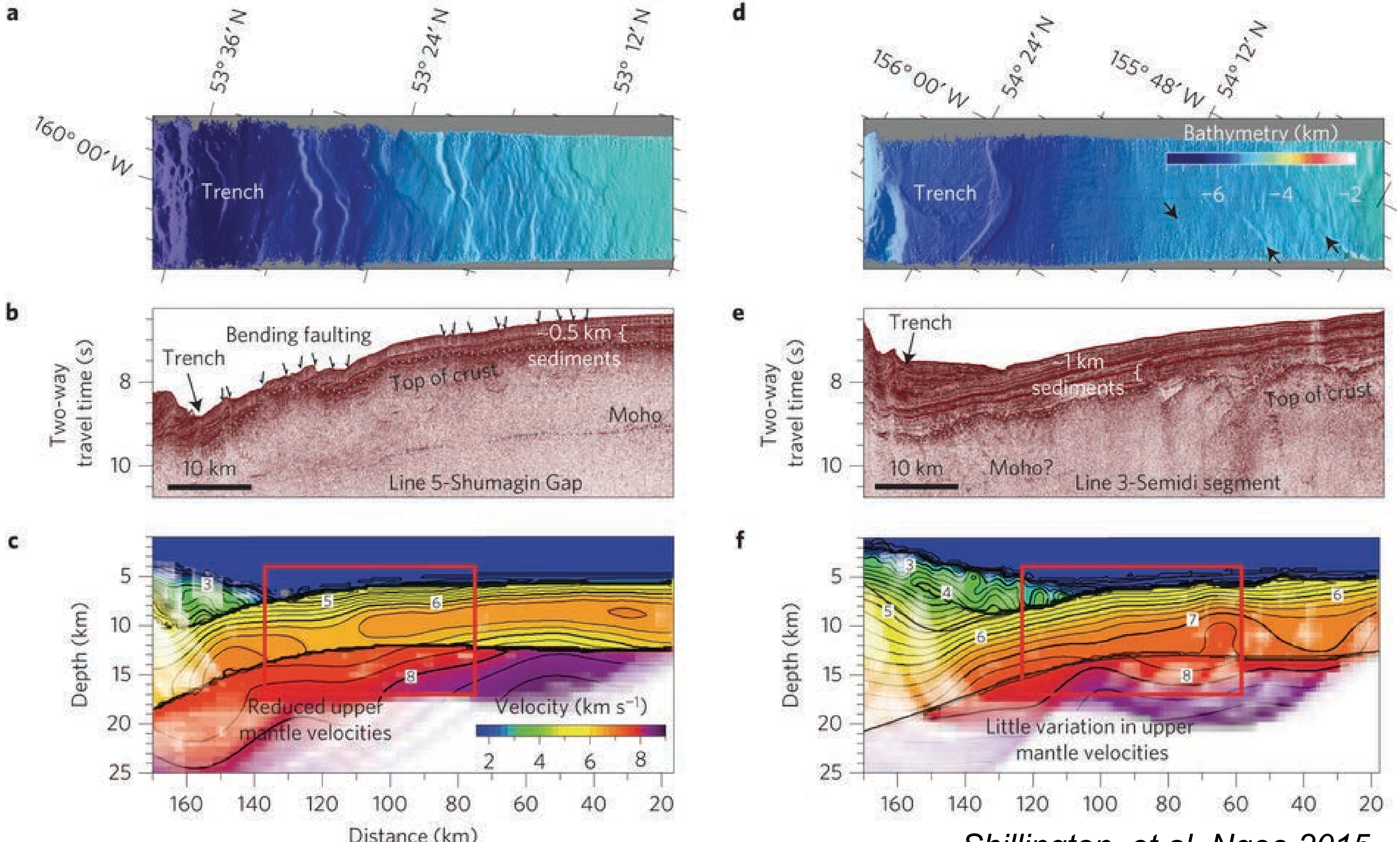
Link between Intermediate seismicity and slab hydration



Shillington et al. Ngeo 2015

MOTIVATION

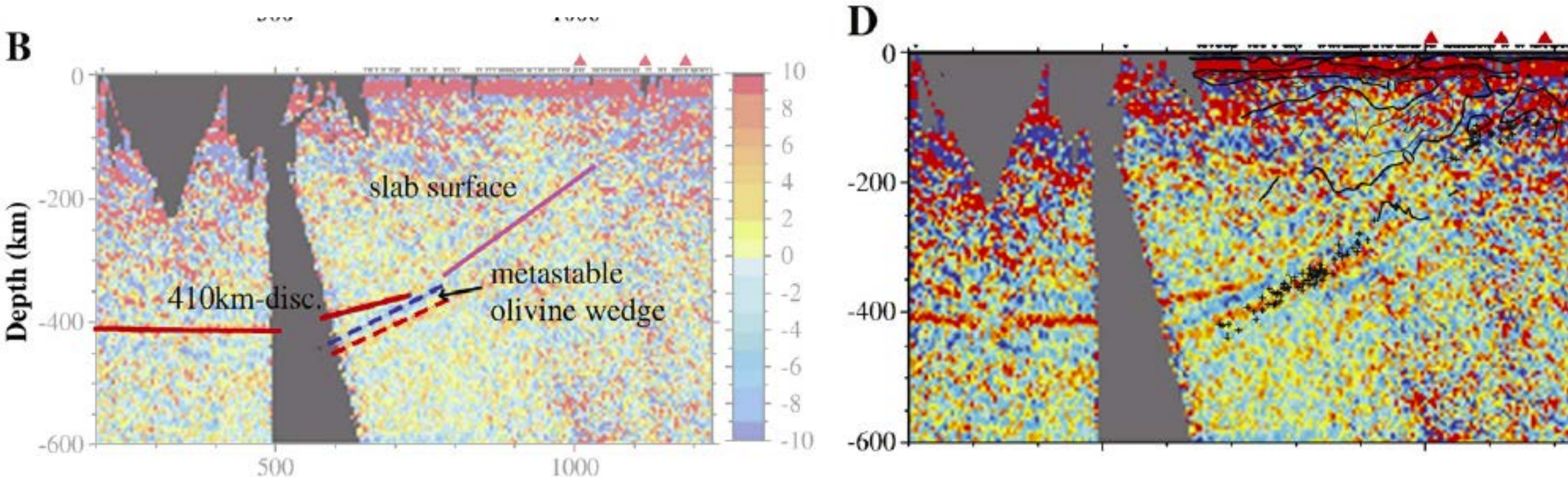
Intermediate seismicity and slab hydration



Shillington et al. Ngeo 2015

MOTIVATION

Deep focus seismicity and metastable olivine



Kawakatsu and Yoshioka 2012

OLIVINE PHASE TRANSITIONS
in the mantle transition zone

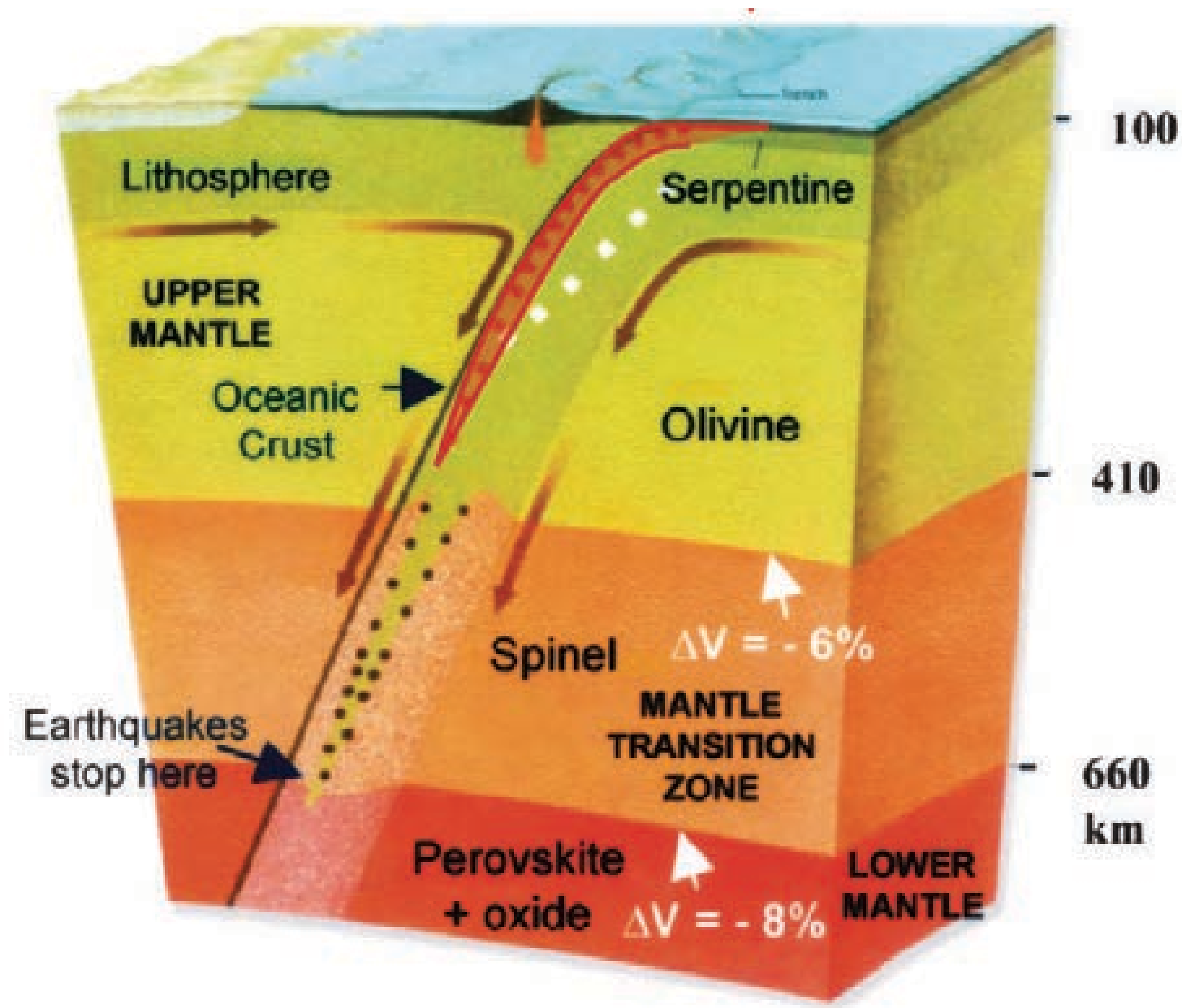
OLIVINE : Mg_2SiO_4
orthorhombic

And its high pressure form
RINGWOODITE: Mg_2SiO_4
cubic

PHASE TRANSITION MODEL

The Green model

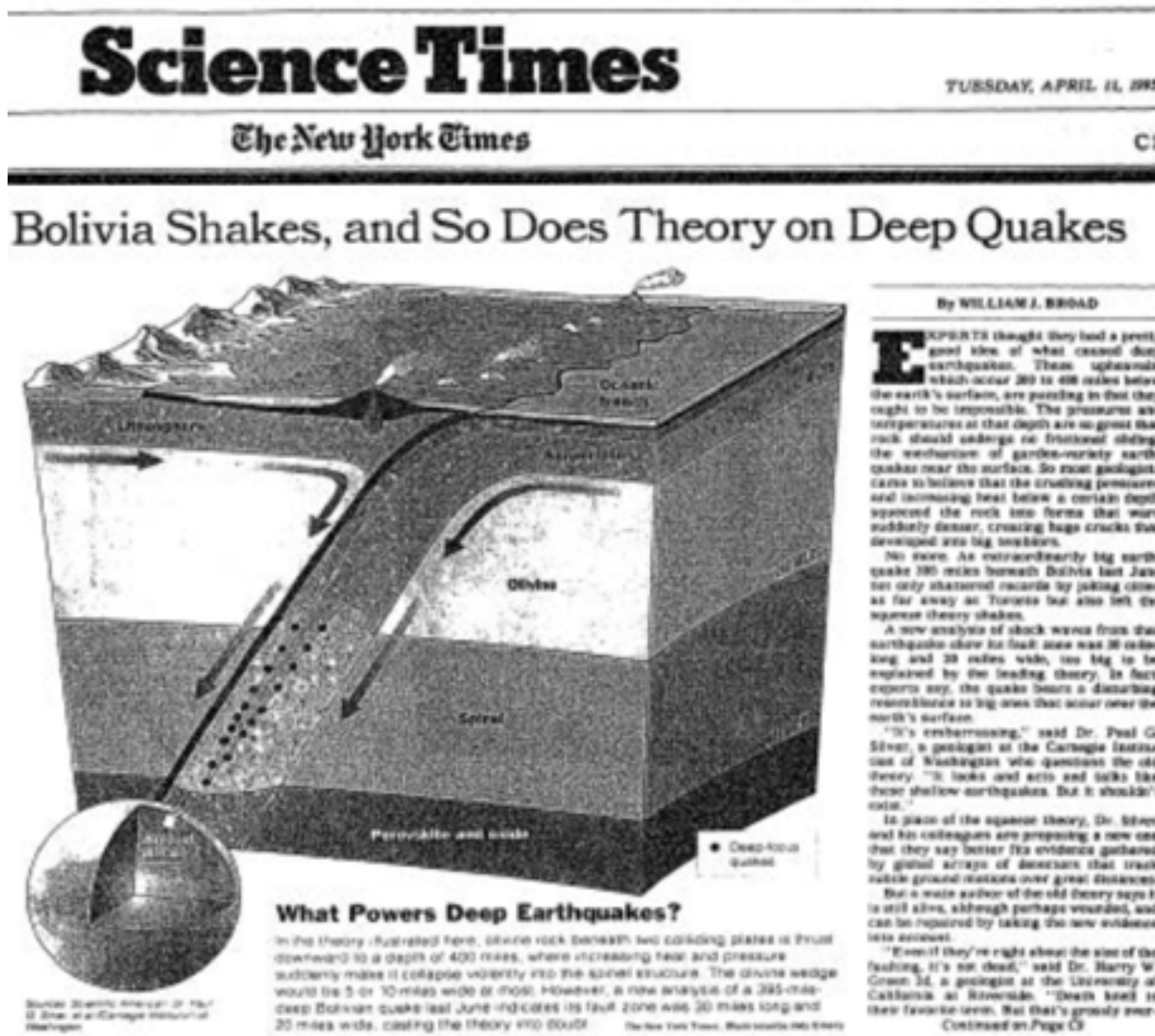
Harry W. Green *1940-2017*



PHASE TRANSITION MODEL

The Green model

Harry W. Green *1940-2017*



Science Times

TUESDAY, APRIL 11, 1995

The New York Times

C1

Bolivia Shakes, and So Does Theory on Deep Quakes

What Powers Deep Earthquakes?

In the theory illustrated here, olivine rock beneath two colliding plates is thrust downward to a depth of 400 miles, where increasing heat and pressure suddenly make it collapse violently into the spinel structure. The olivine wedge would be 5 or 10 miles wide at most. However, a new analysis of a 395-mile-deep Bolivian quake last June indicates its fault zone was 30 miles long and 20 miles wide, casting the theory into doubt.

By WILLIAM J. BROAD

EXPERTS thought they had a pretty good idea of what caused deep earthquakes. These upheavals, which occur 200 to 400 miles below the earth's surface, are puzzling in that they ought to be impossible. The pressures and temperatures at that depth are so great that rock should undergo no frictional sliding, the mechanism of garden-variety earthquakes near the surface. So most geologists came to believe that the crushing pressures and increasing heat below a certain depth squeezed the rock into forms that were suddenly denser, creating huge cracks that developed into big temblors.

No more. An extraordinarily big earthquake 395 miles beneath Bolivia last June not only shattered records by jolting cities as far away as Toronto but also left the squeeze theory shaken.

A new analysis of shock waves from that earthquake show its fault zone was 30 miles long and 20 miles wide, too big to be explained by the leading theory. In fact, experts say, the quake bears a disturbing resemblance to big ones that occur near the earth's surface.

"It's embarrassing," said Dr. Paul G. Silver, a geologist at the Carnegie Institution of Washington who questions the old theory. "It looks and acts and talks like these shallow earthquakes. But it shouldn't exist."

In place of the squeeze theory, Dr. Silver and his colleagues are proposing a new one that they say better fits evidence gathered by global arrays of detectors that track subtle ground motions over great distances.

But a main author of the old theory says it is still alive, although perhaps wounded, and can be repaired by taking the new evidence into account.

"Even if they're right about the size of the faulting, it's not dead," said Dr. Harry W. Green 2d, a geologist at the University of California at Riverside. "Death knell is their favorite term. But that's grossly over-

Continued on Page C8

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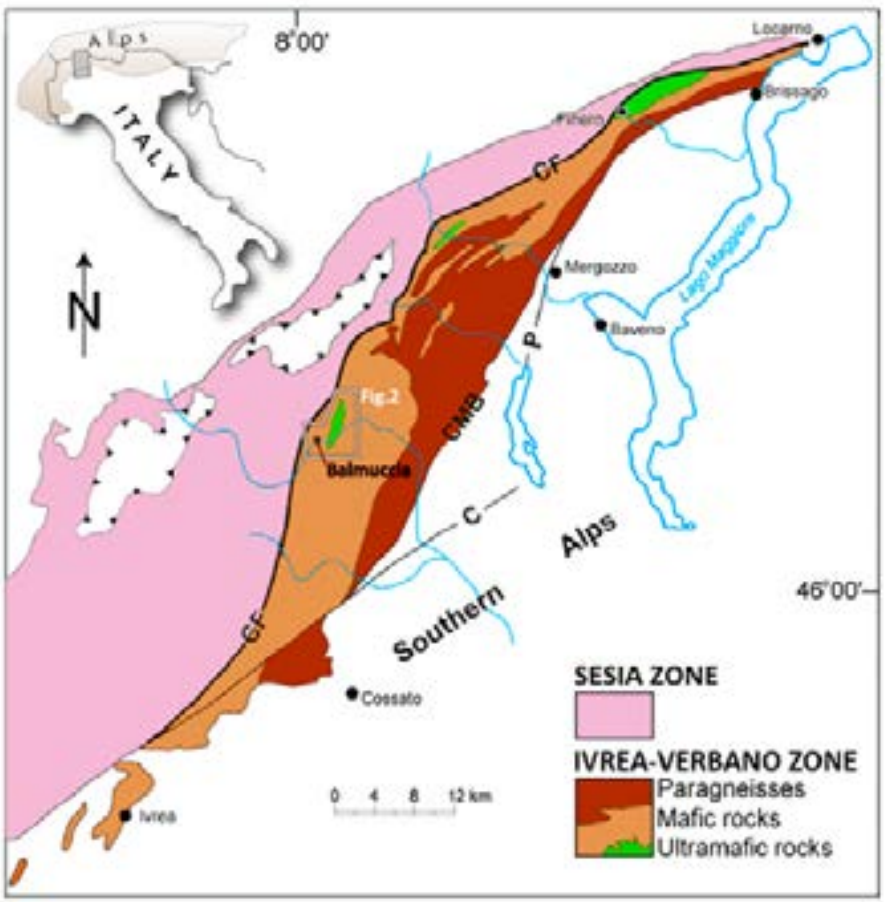
A frozen mantle EQ in Balmuccia, It.

Peridotite body exhumed along the Insubric line



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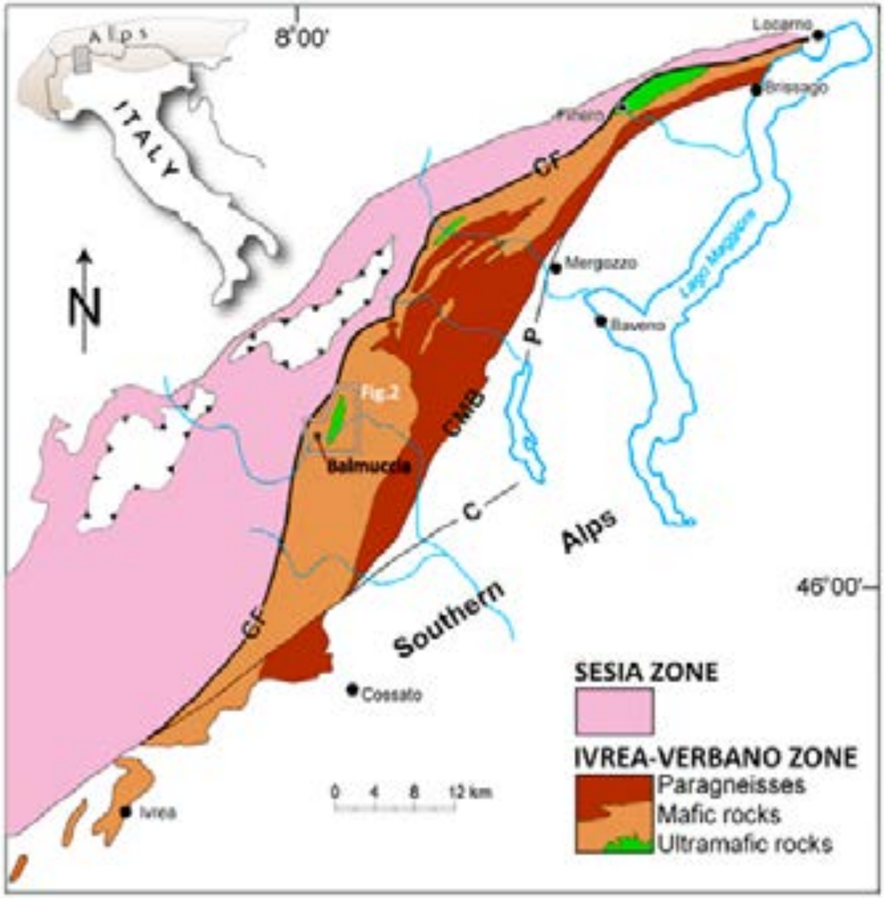
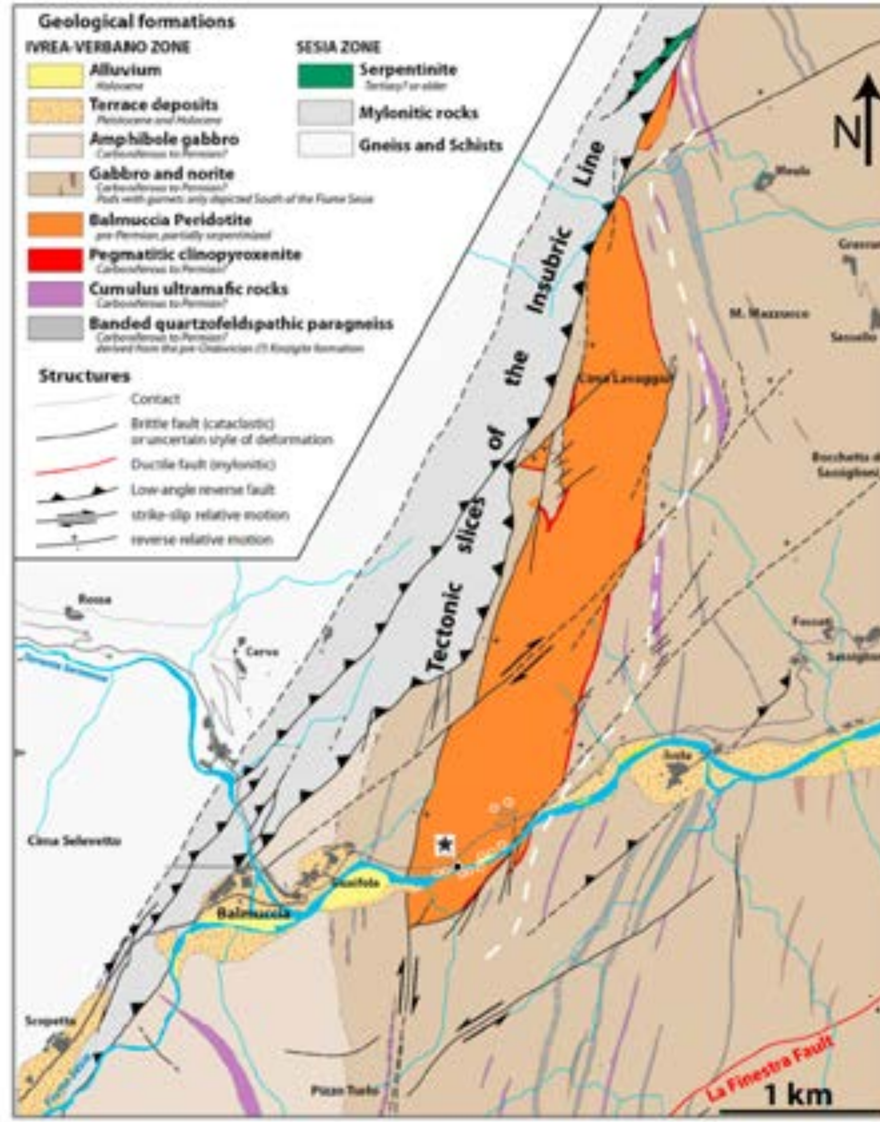
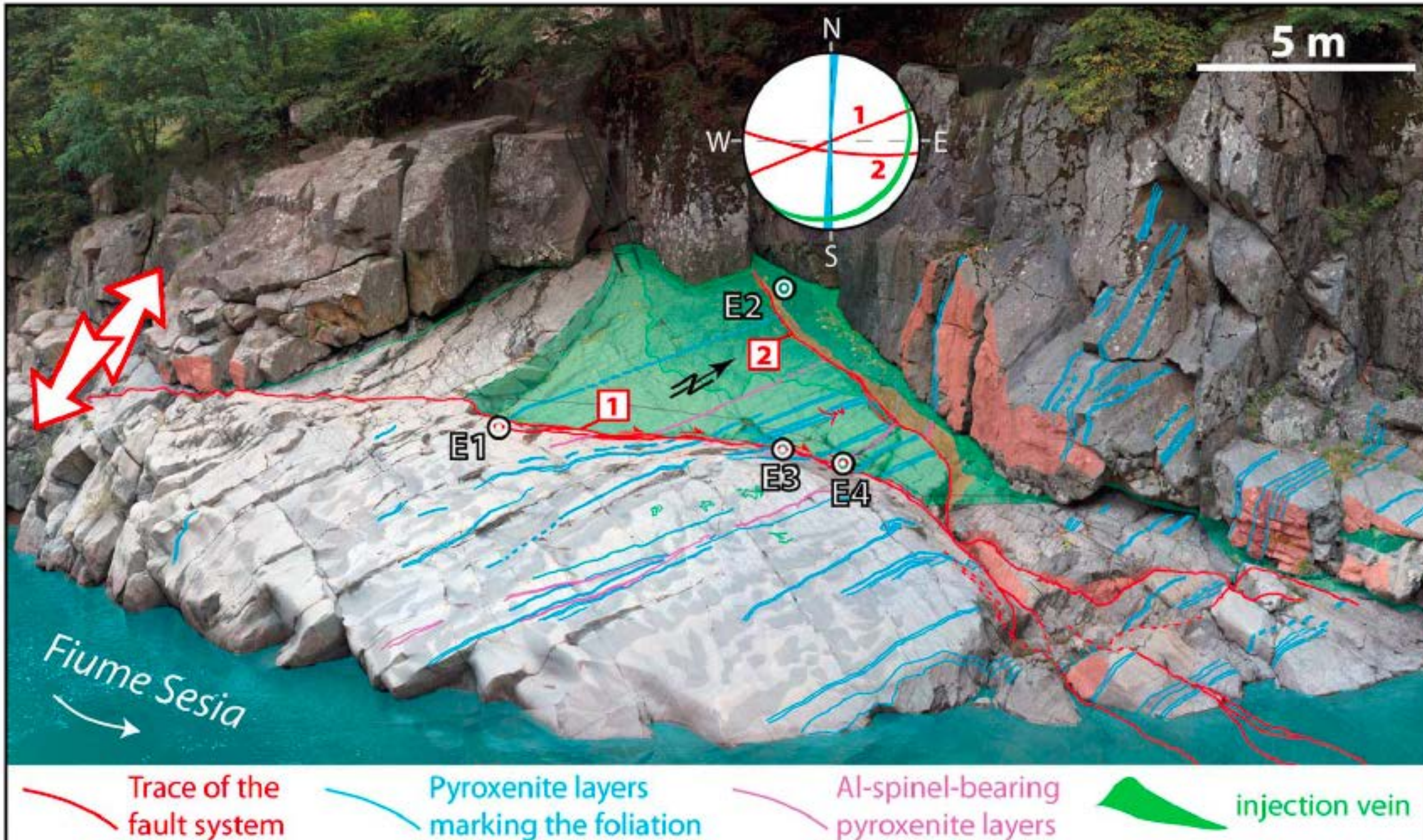




Modified from Quick et al. 2003

A frozen mantle EQ in Balmuccia, It.

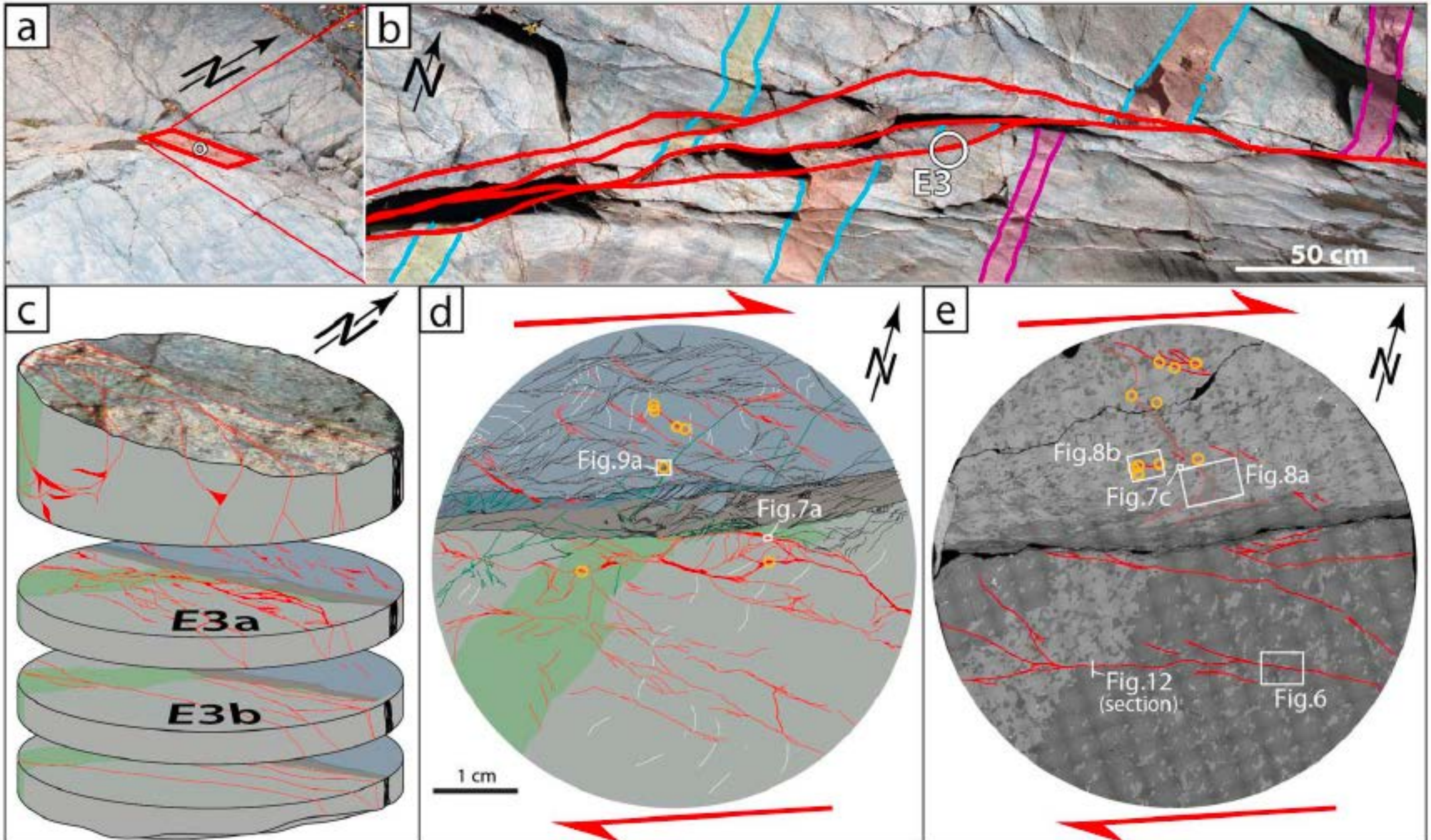
Fault trace // to Insubric line, along the river, approx. 100m long



Ferrand et al., JGR 2018

A frozen mantle EQ in Balmuccia, It.

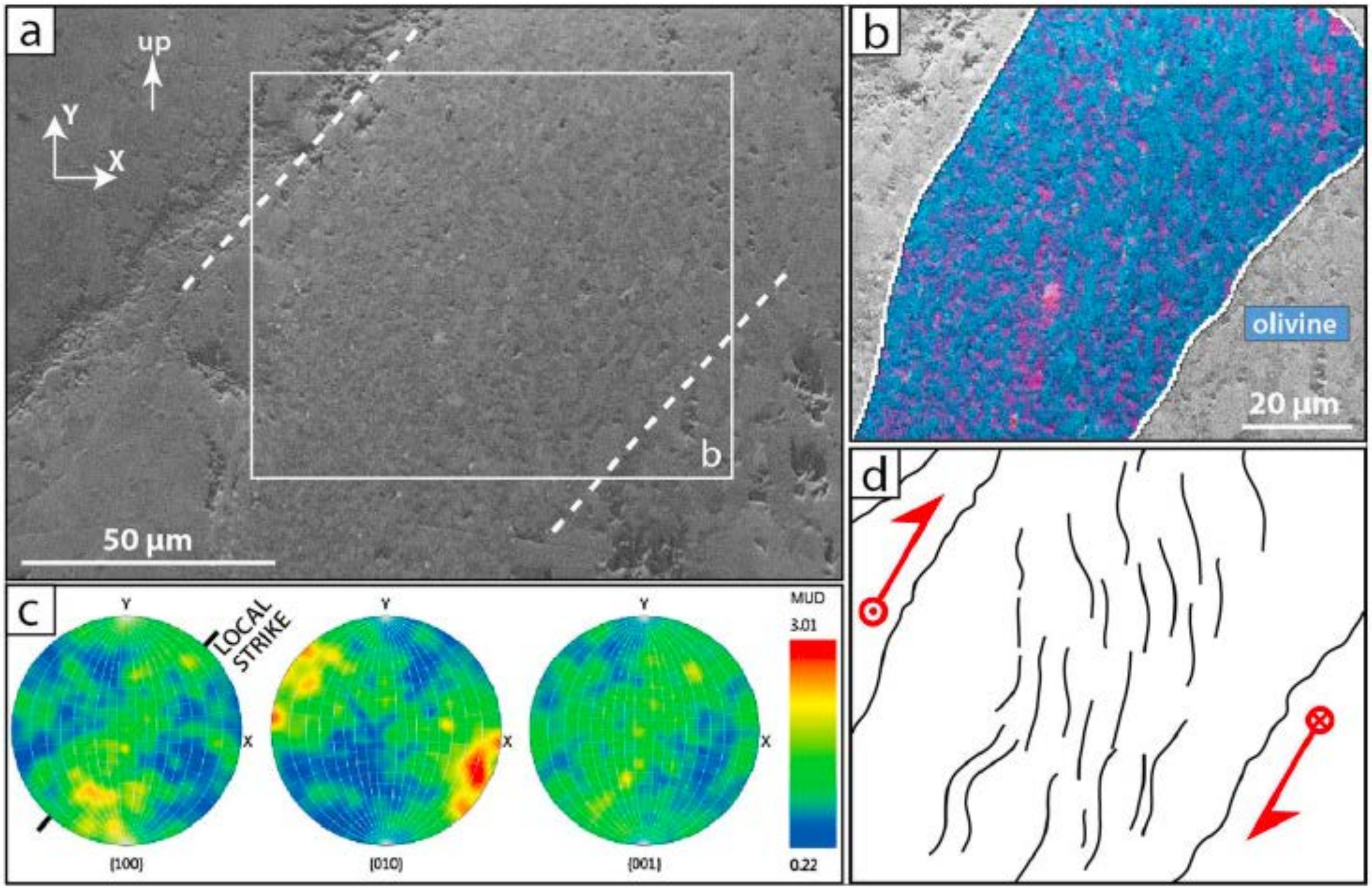
1.2m horizontal offset, 5mm wide



Ferrand et al., JGR 2018

A frozen mantle EQ in Balmuccia, It.

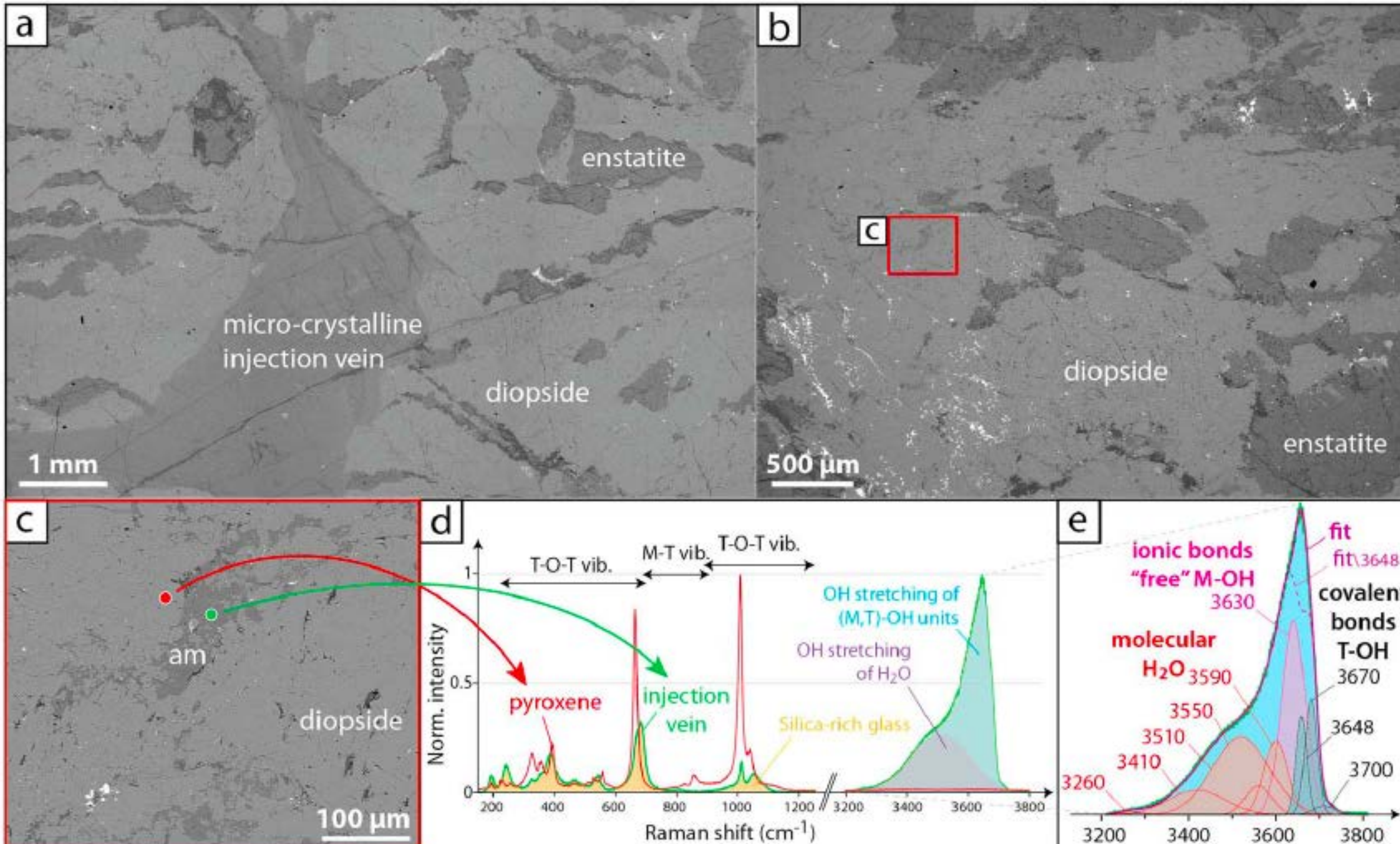
PSZ − recrystallized olivine, but HT (>1200°C) fabric
Alumina spinel stable P>1.2GPa
Updip component to slip



Ferrand et al., JGR 2018

A frozen mantle EQ in Balmuccia, It.

Presence of fossil (hydrated) glass at the tip of injection veins
Close to 2w% H20 in the glass - Origin of water?



Ferrand et al., JGR 2018

A frozen mantle EQ in Balmuccia, It.

Energy balance reconstruction (from melt production and displacement)
Dynamic friction << 0.1, Mw 6+

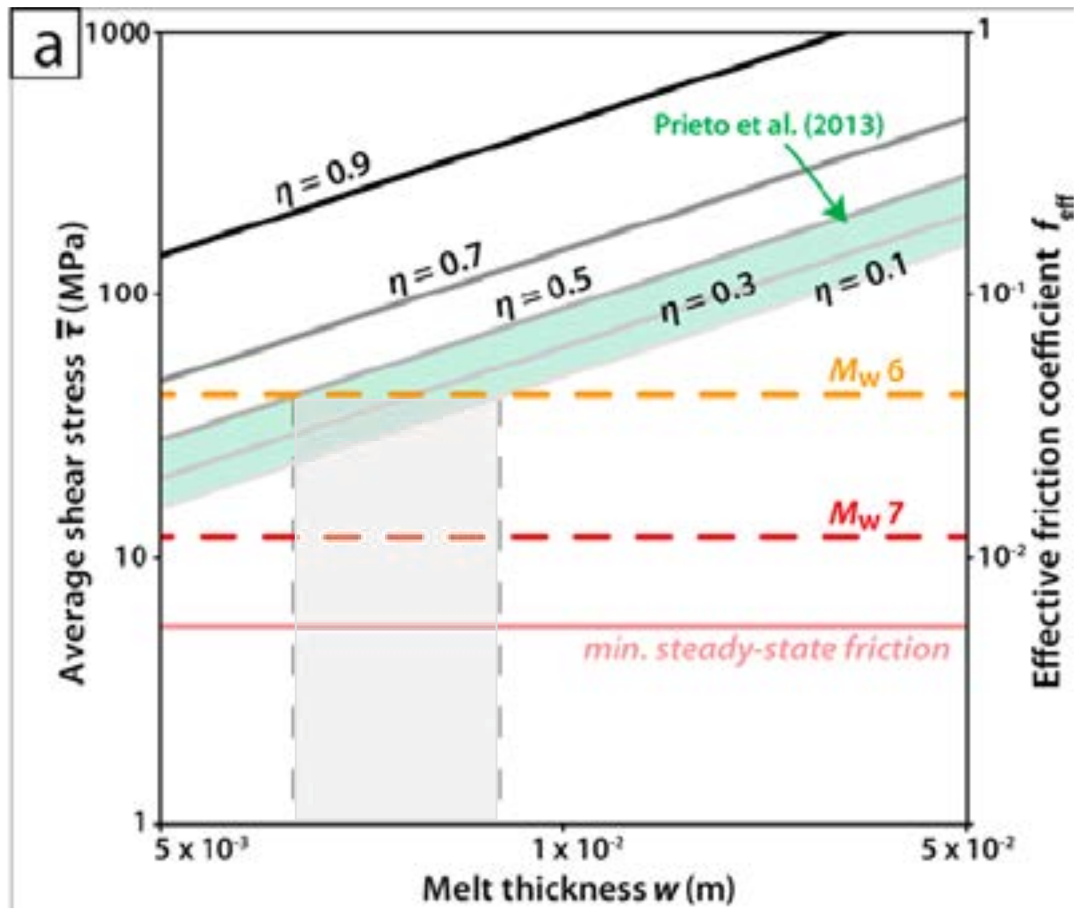
$$\eta = E_R/E_{tot} \approx 1 - Q_f/E_{tot}$$

$$\downarrow$$

$$\overline{\tau} = \frac{\rho \cdot [H + C_p \cdot \Delta T] \cdot w}{(1 - \eta) D}$$

and

$$\Delta\tau \approx (GD)^{3/2}/Mo^{1/2}$$



Ferrand et al., JGR 2018

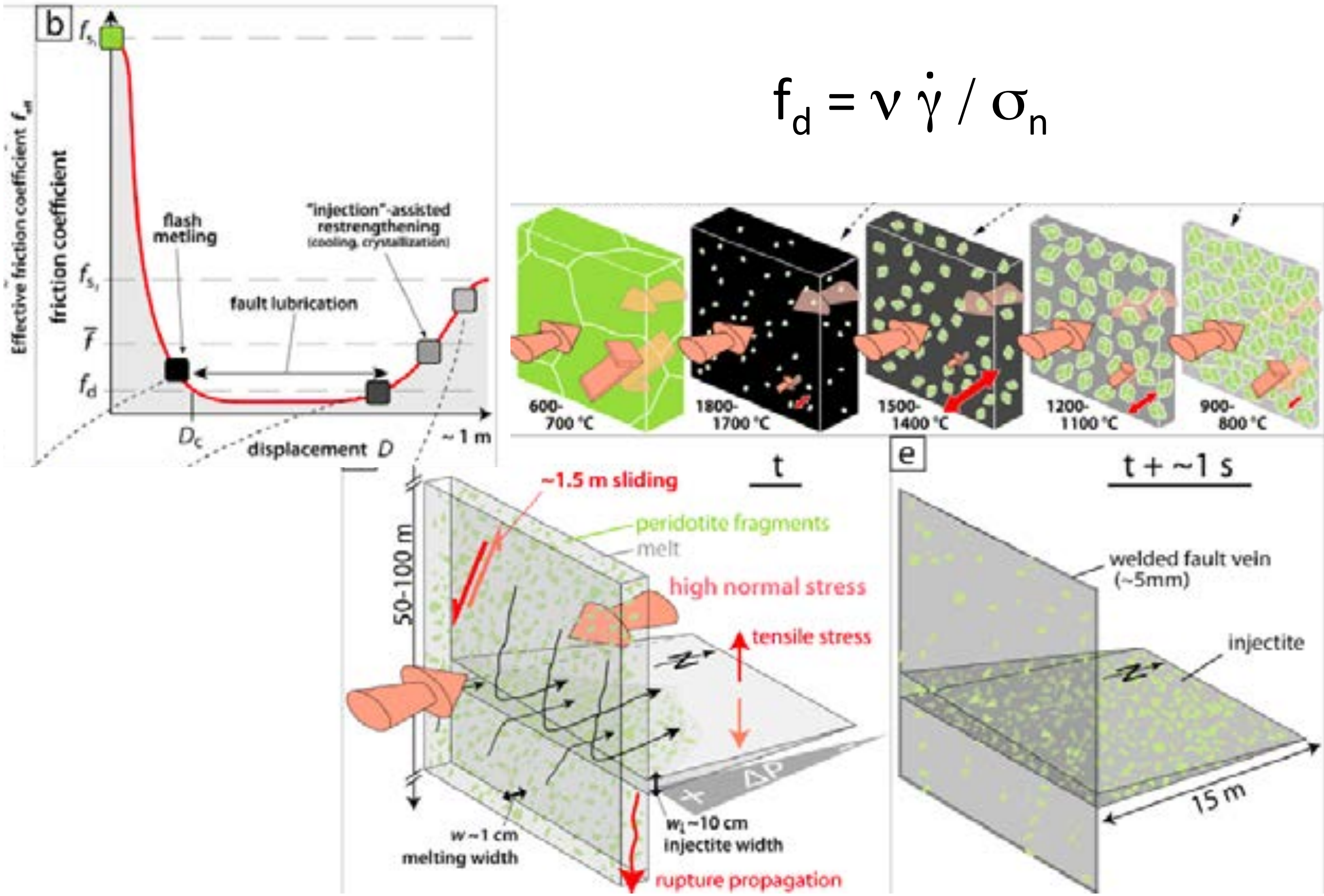
A frozen mantle EQ in Balmuccia, It.

low viscosity (<10 Pa.s) melt

→ High strain rates and possible ultralocalization (Platt, Rudnicki and Rice, 2014)

-->melt injection may induce restrengthening

$$f_d = \nu \, \dot{\gamma} \, / \, \sigma_n$$



Ferrand et al., JGR 2018

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- A frozen mantle EQ in the field
- HP experimental set-up
- Dehydrations and intermediate depth seismicity
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What is the role played by **M**INERAL transformations?

Increasing depth

SHALLOW → DEEP

friction

Increasing pressure/temperature

Mineral Transformations?

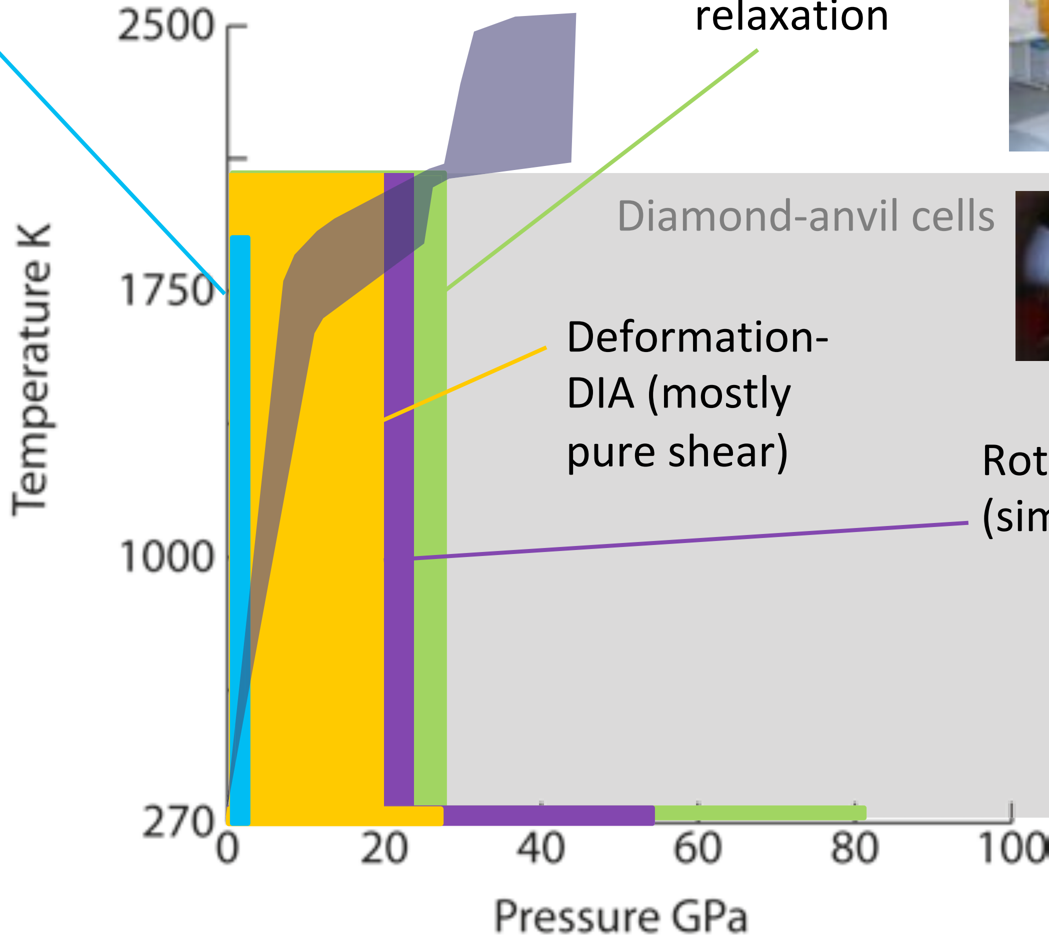
Deformation experiments

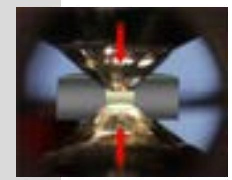
at in-situ PT conditions

HP Deformation devices

Griggs, Heard, Paterson…

Multi-anvils in relaxation





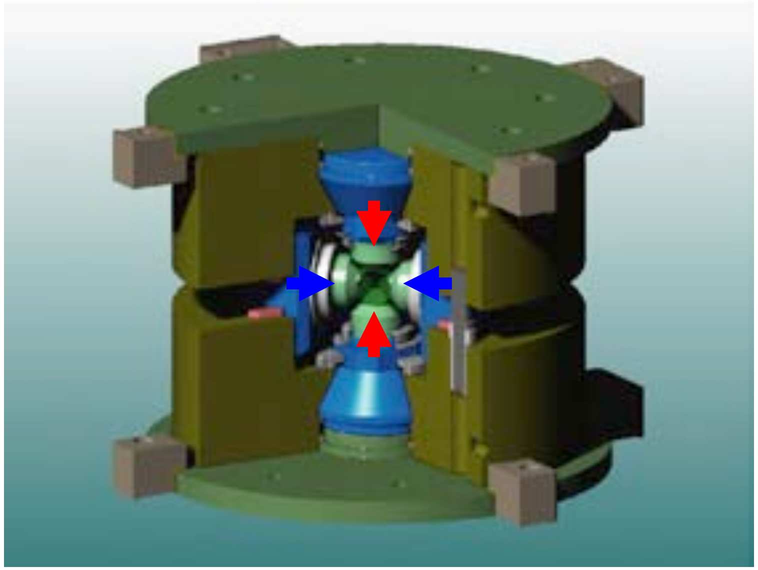
Deformation-DIA (mostly pure shear)

Rotational Drickamer (simple shear)

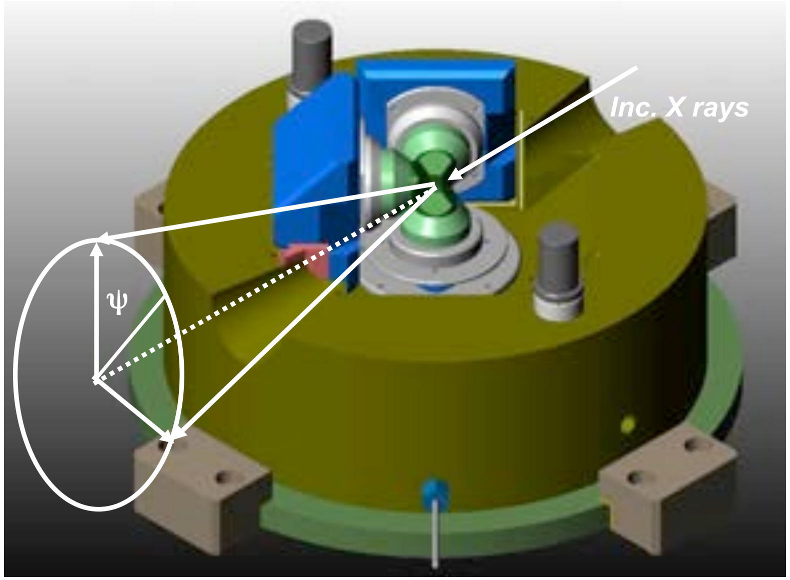
Experimental set-up

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

D-DIA
HP-HT + deviatoric stress



Sintered diamond rear-anvils (Debye rings)

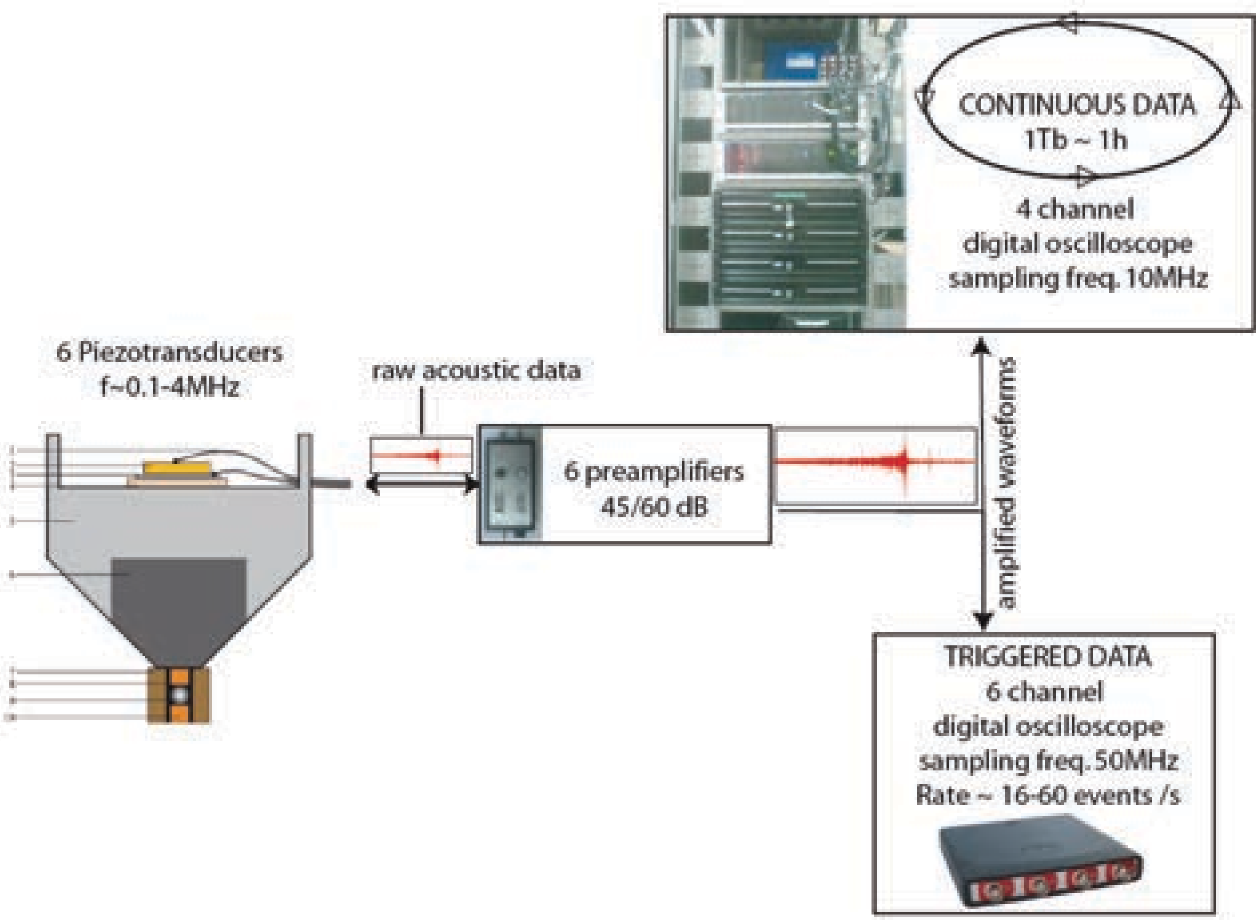


Durham et al, 2002, Wang et al, 2003

Experimental set-up

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



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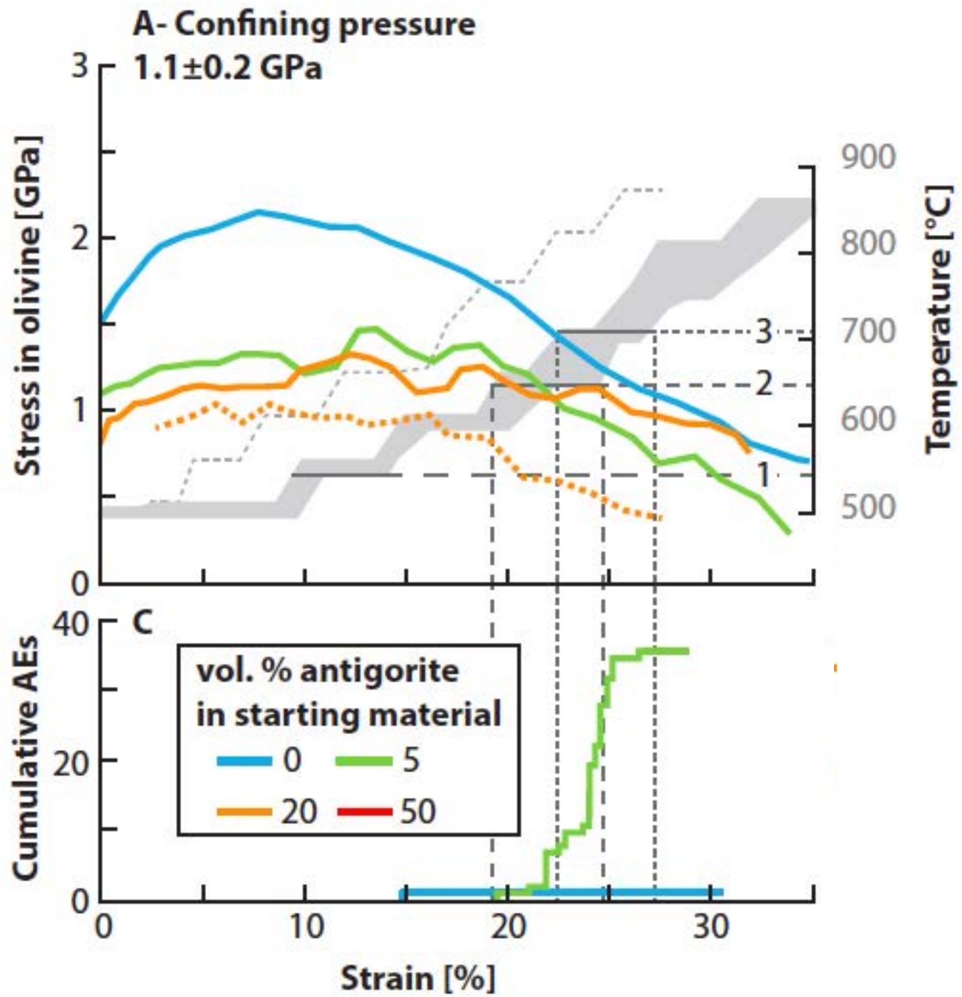
Serp. peridotite dehydration under stress

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

Strain rate = $5x10^{-5}$/s; dT/de ≈1000 **AEs, even for 5% serp.**



Ferrand et al., Nat. Comm 2017

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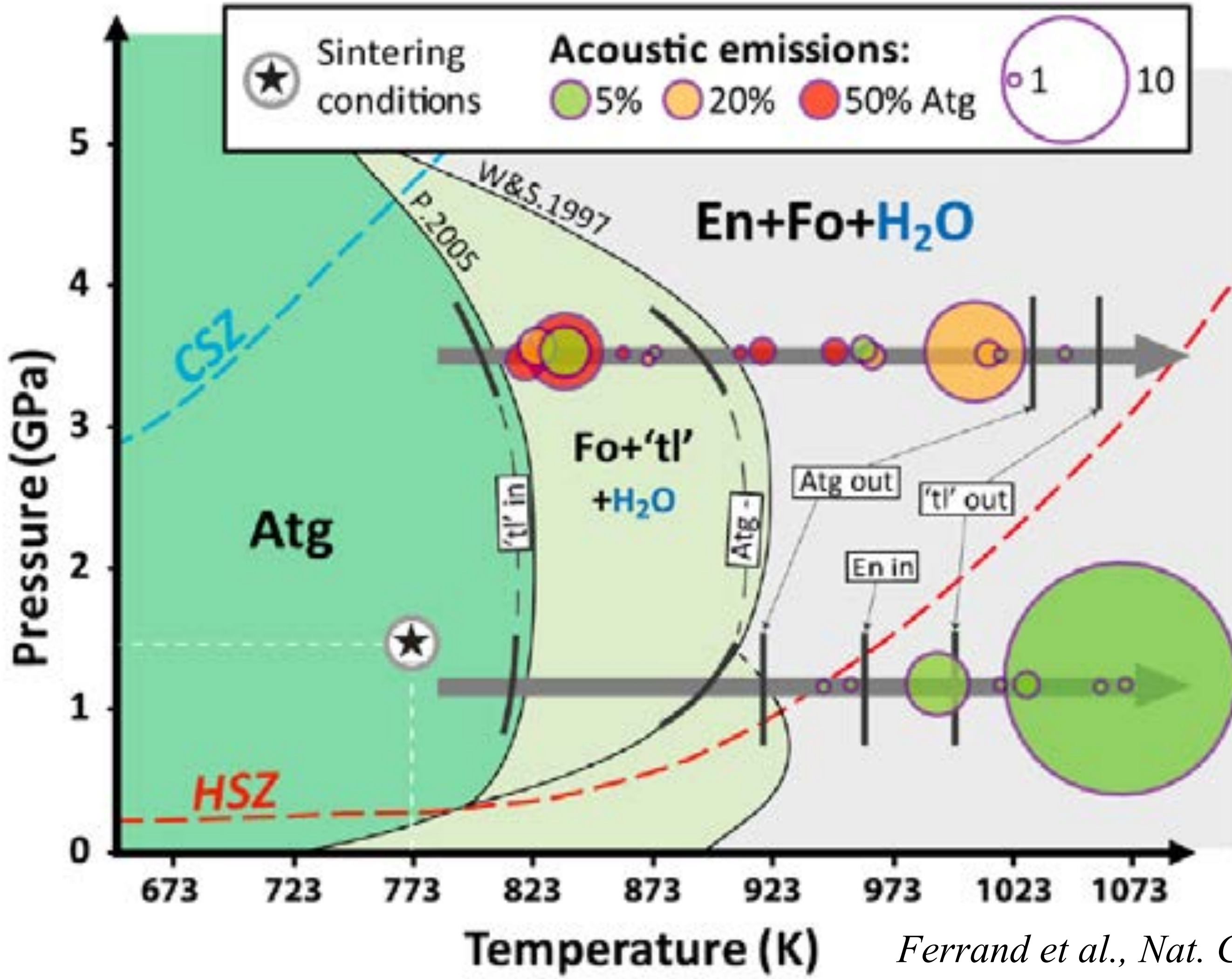
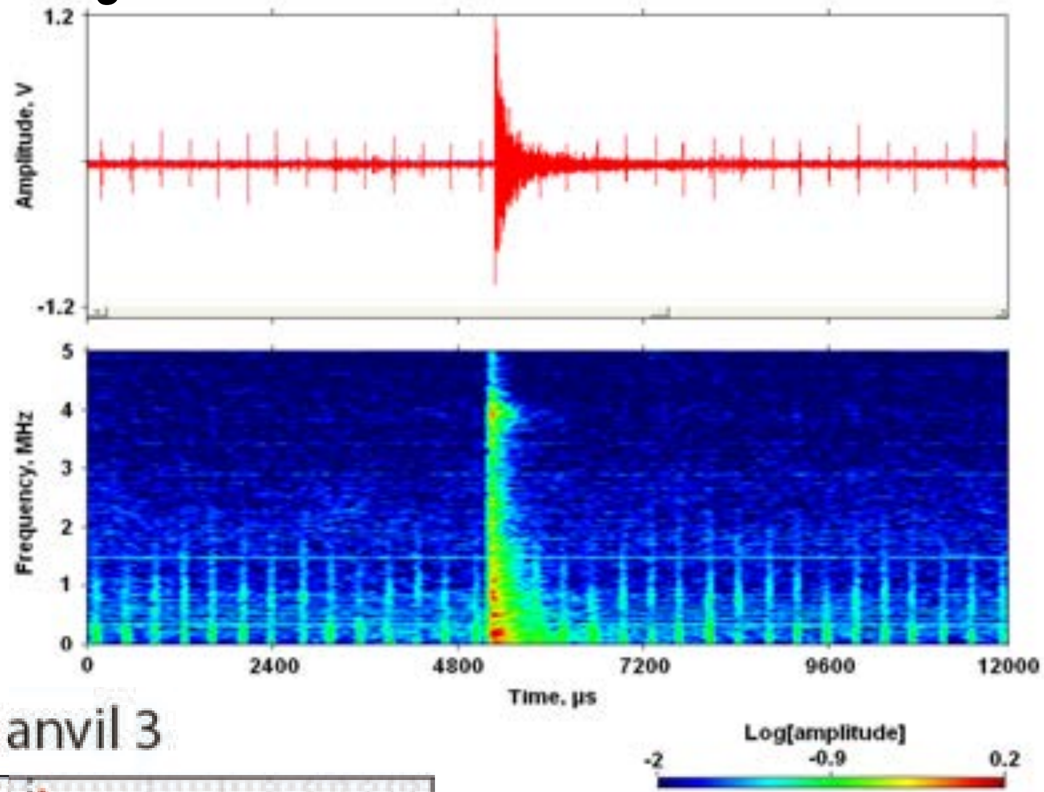


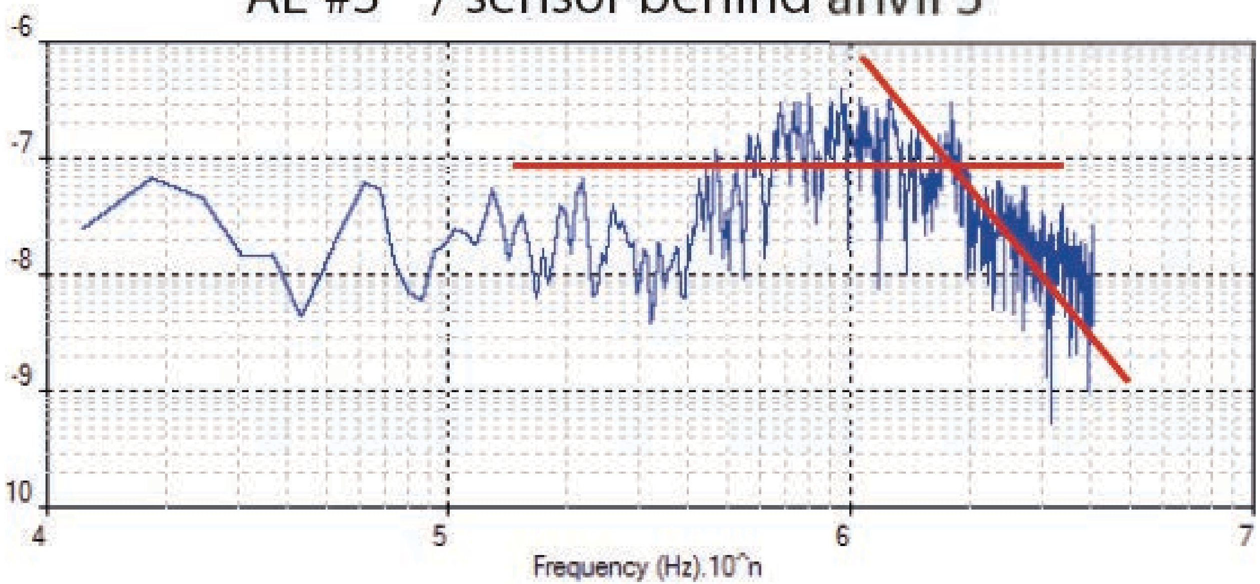
Ferrand et al., Nat. Comm 2017

Serp. peridotite dehydration under stress

Corner frequency fc ≈ Vr/L



AE #3 / sensor behind anvil 3

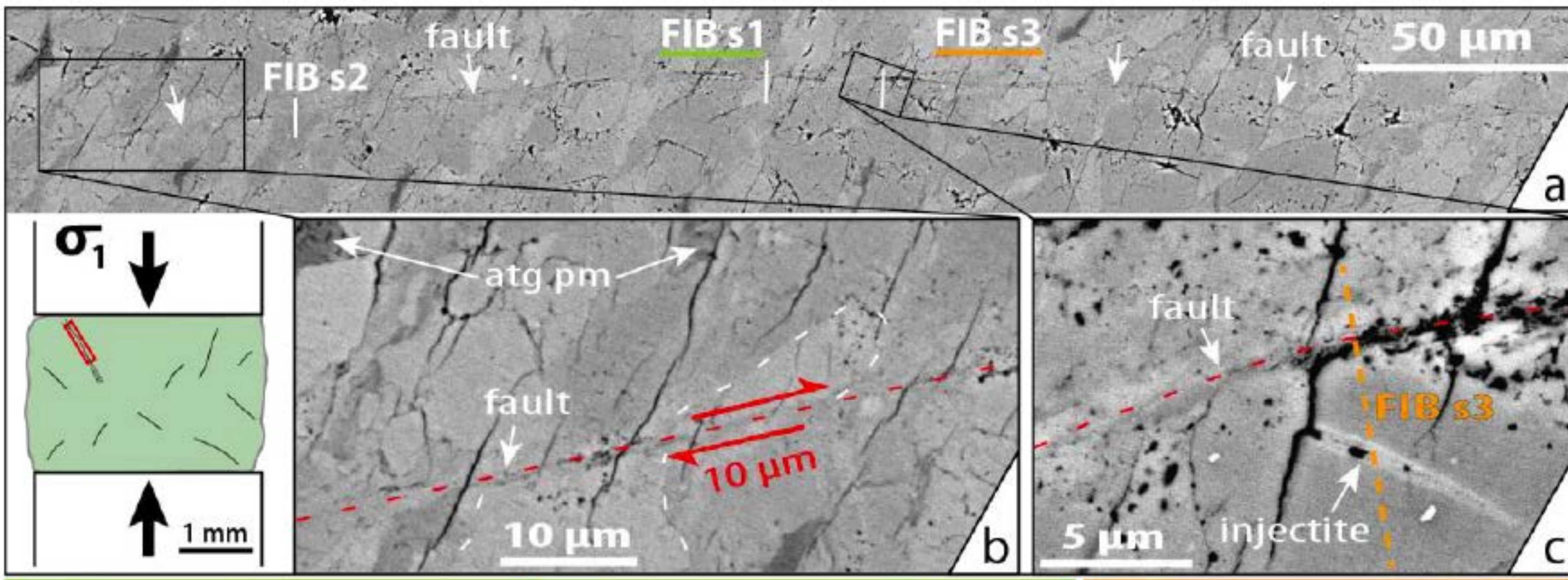


Vr ≈ 4km/s

=> L ≈ 2mm

Serp. peridotite dehydration under stress

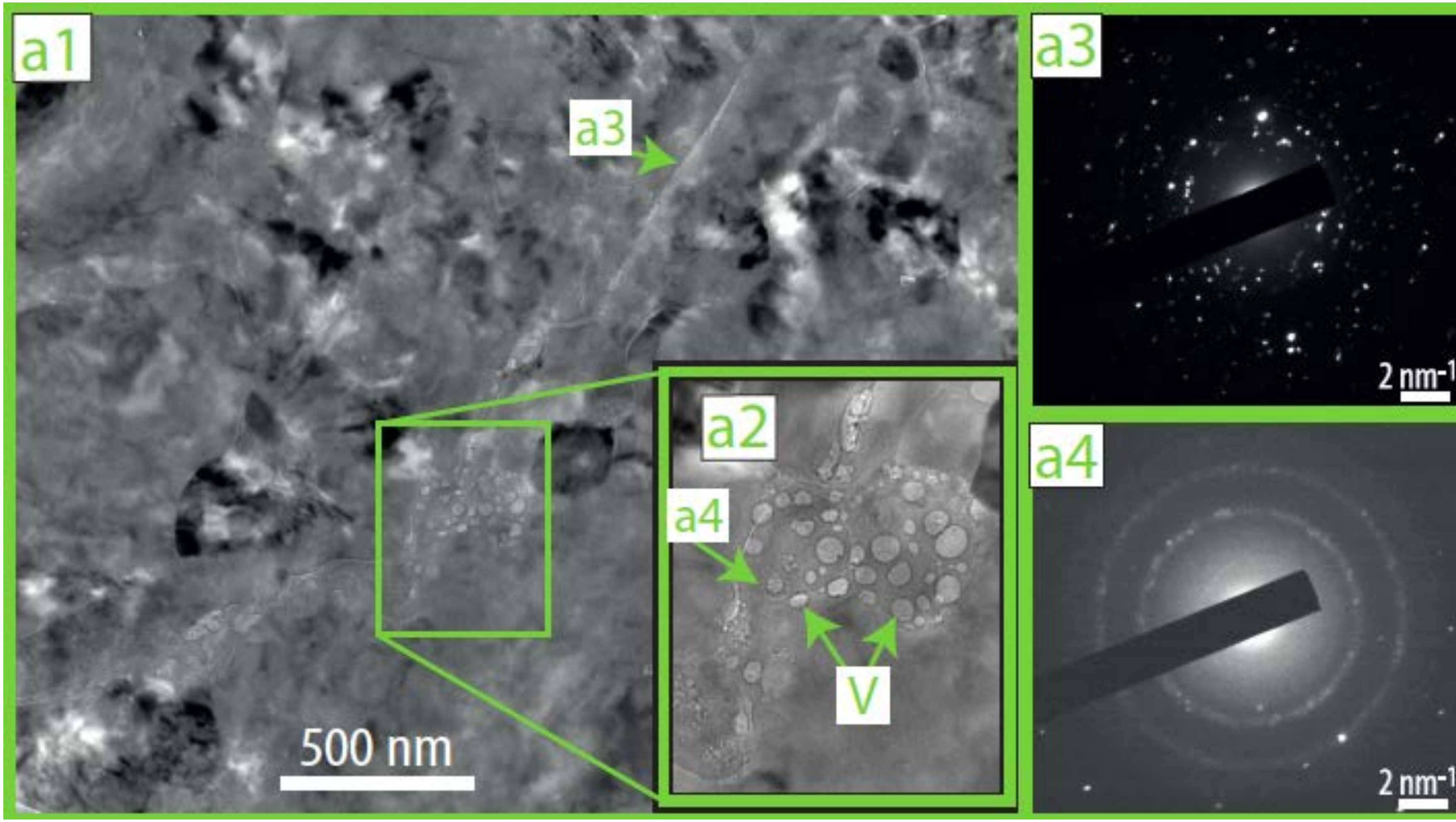
SEM (Backscattered) evidence of HP-faulting



Ferrand et al., Nat. Comm 2017

Serp. peridotite dehydration under stress

TEM – fault zone nanostructure



Ferrand et al., Nat. Comm 2017

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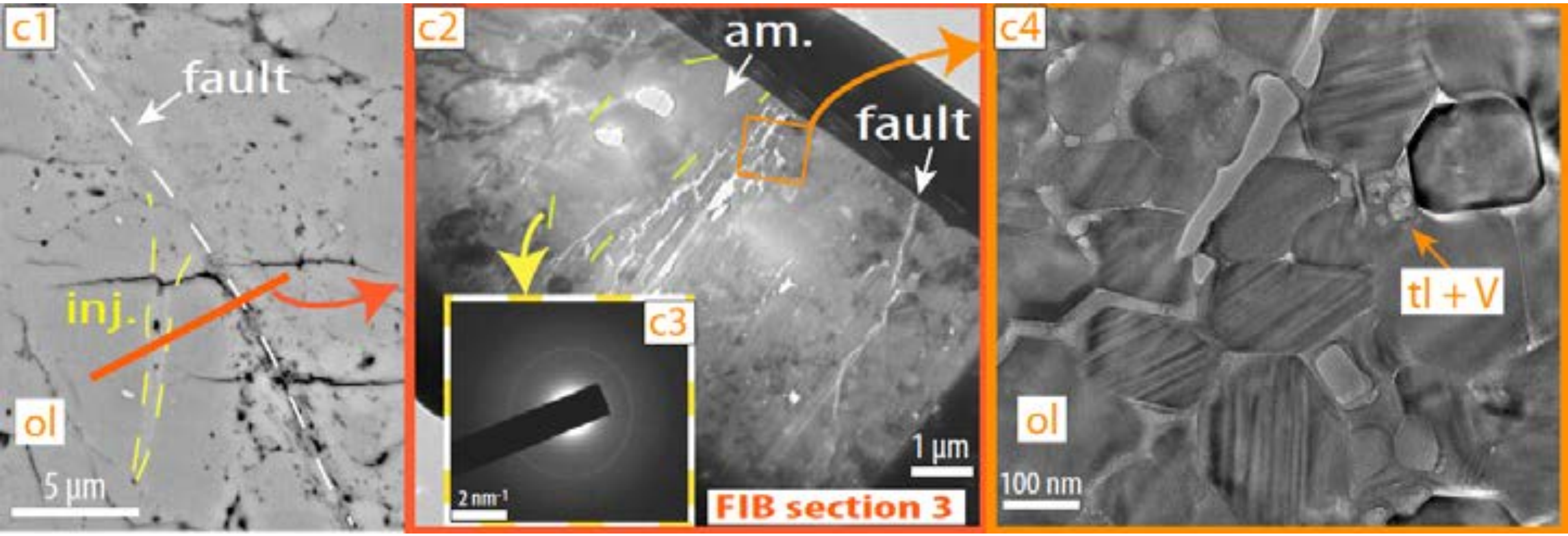
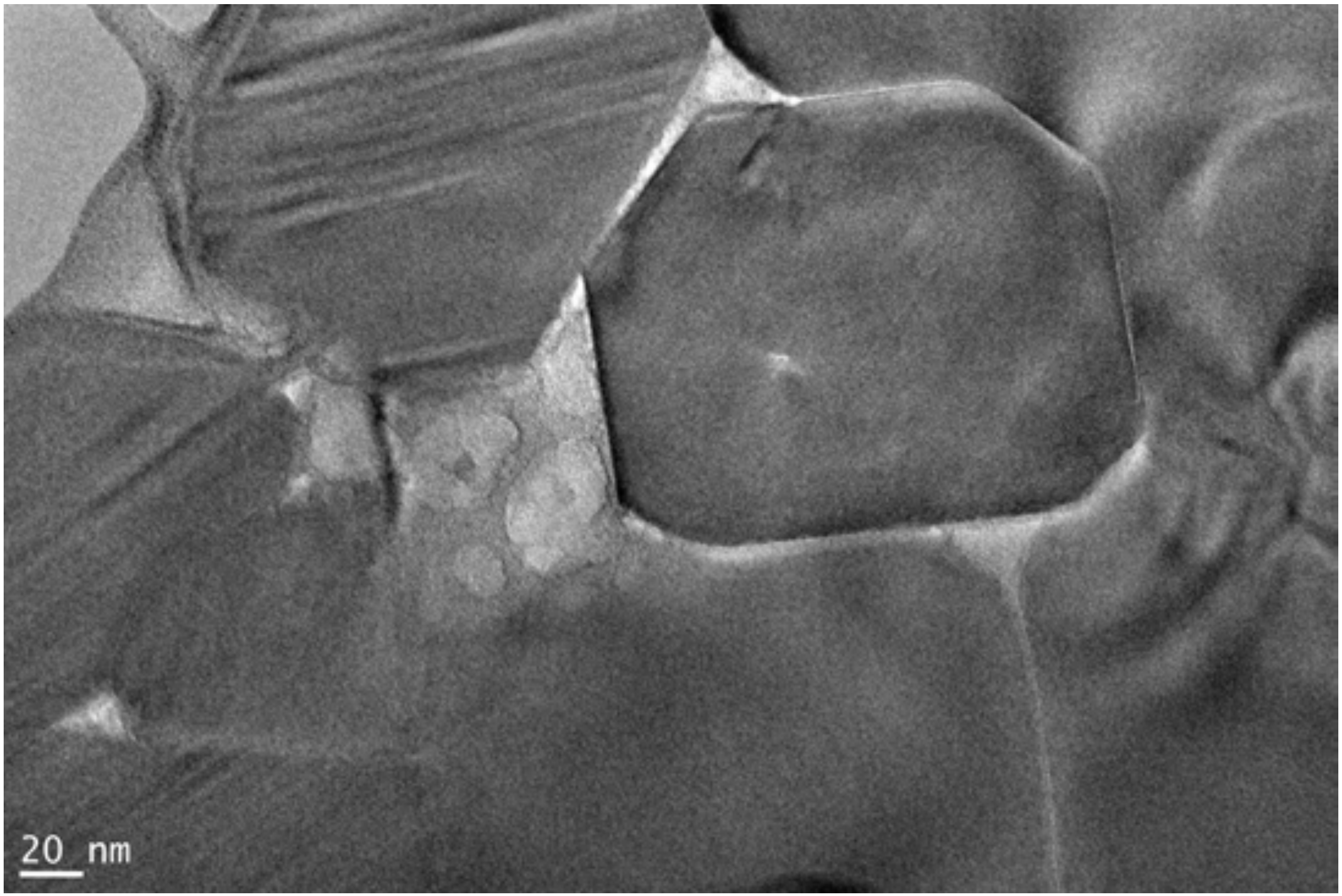


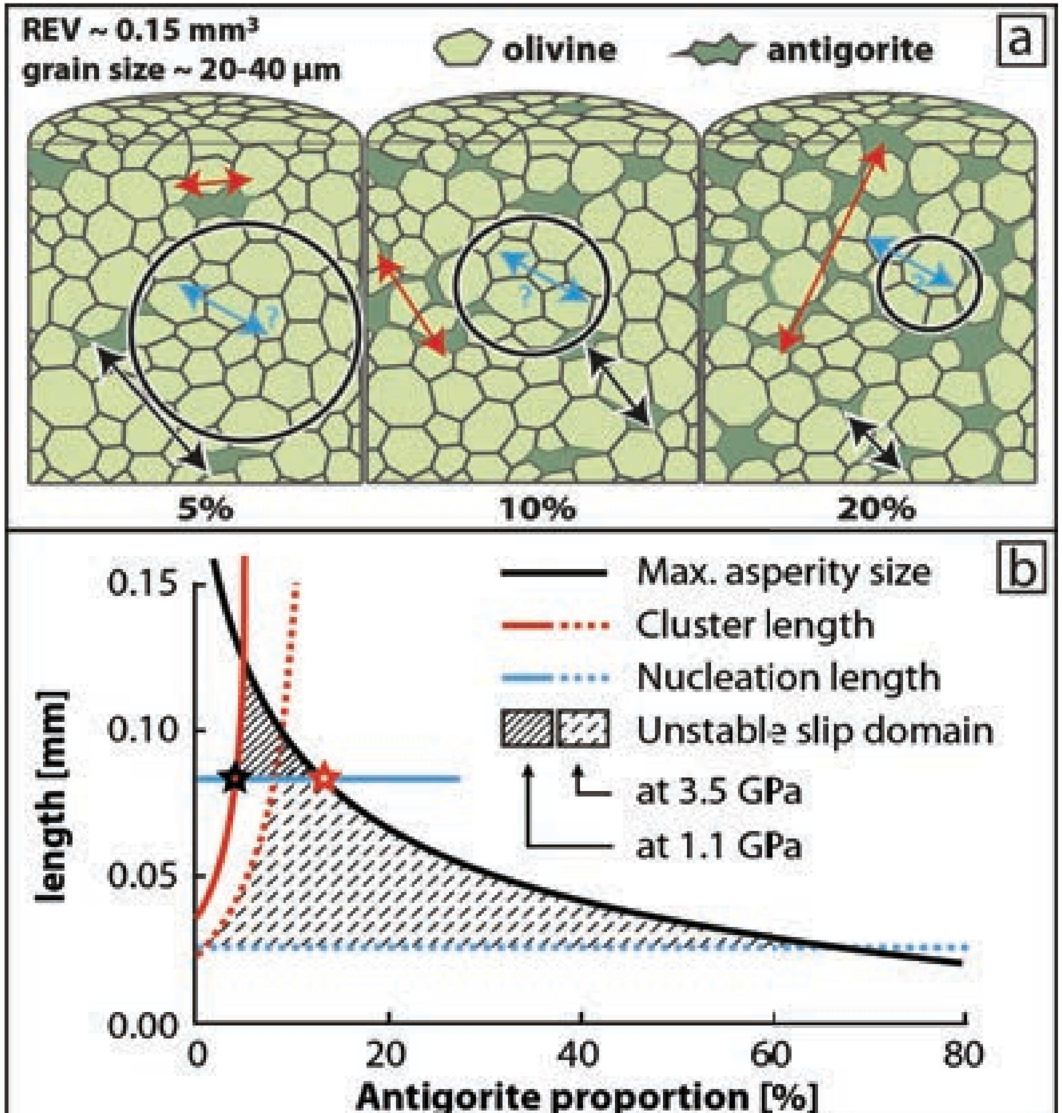
Serp. peridotite dehydration under stress

TEM – evidence of melting?



Serp. peridotite dehydration

Dehydration stress transfer model



Ferrand et al., Nat. Comm 2017

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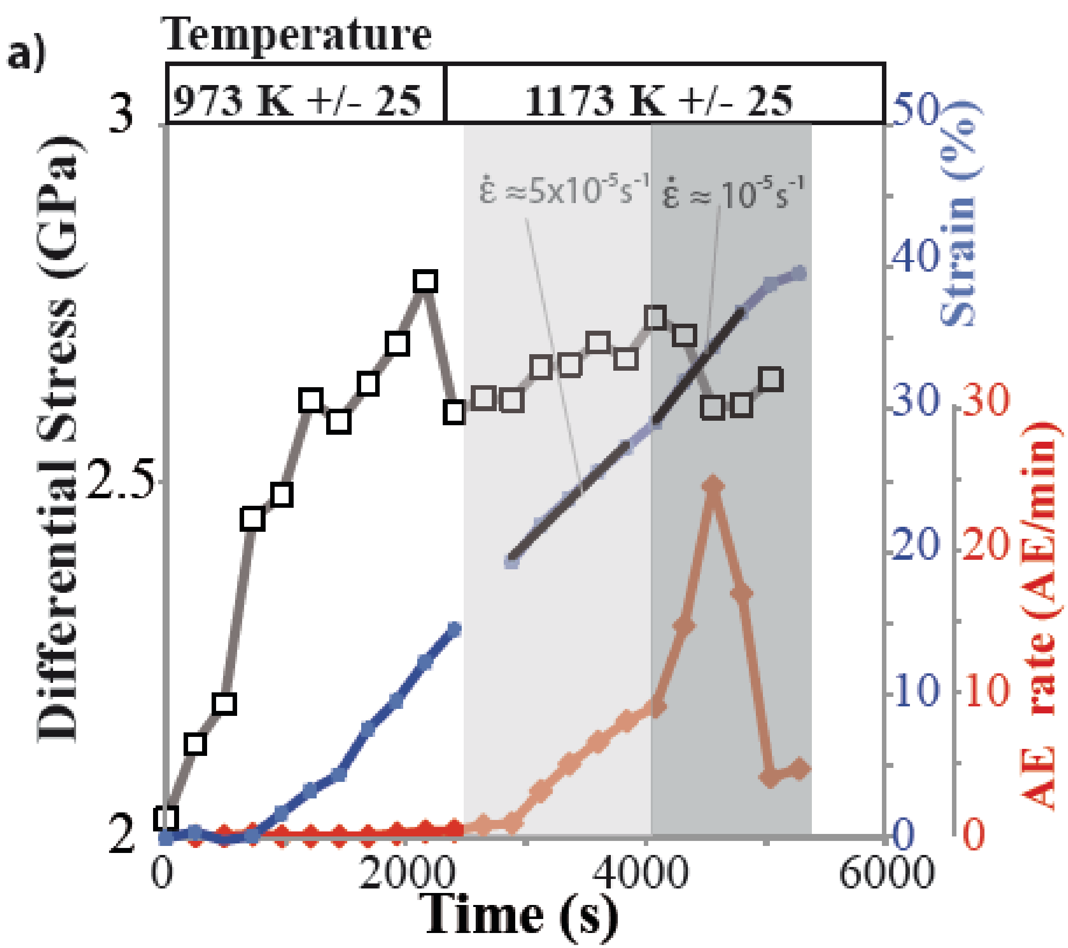
Ge-olivine-spinel transition

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

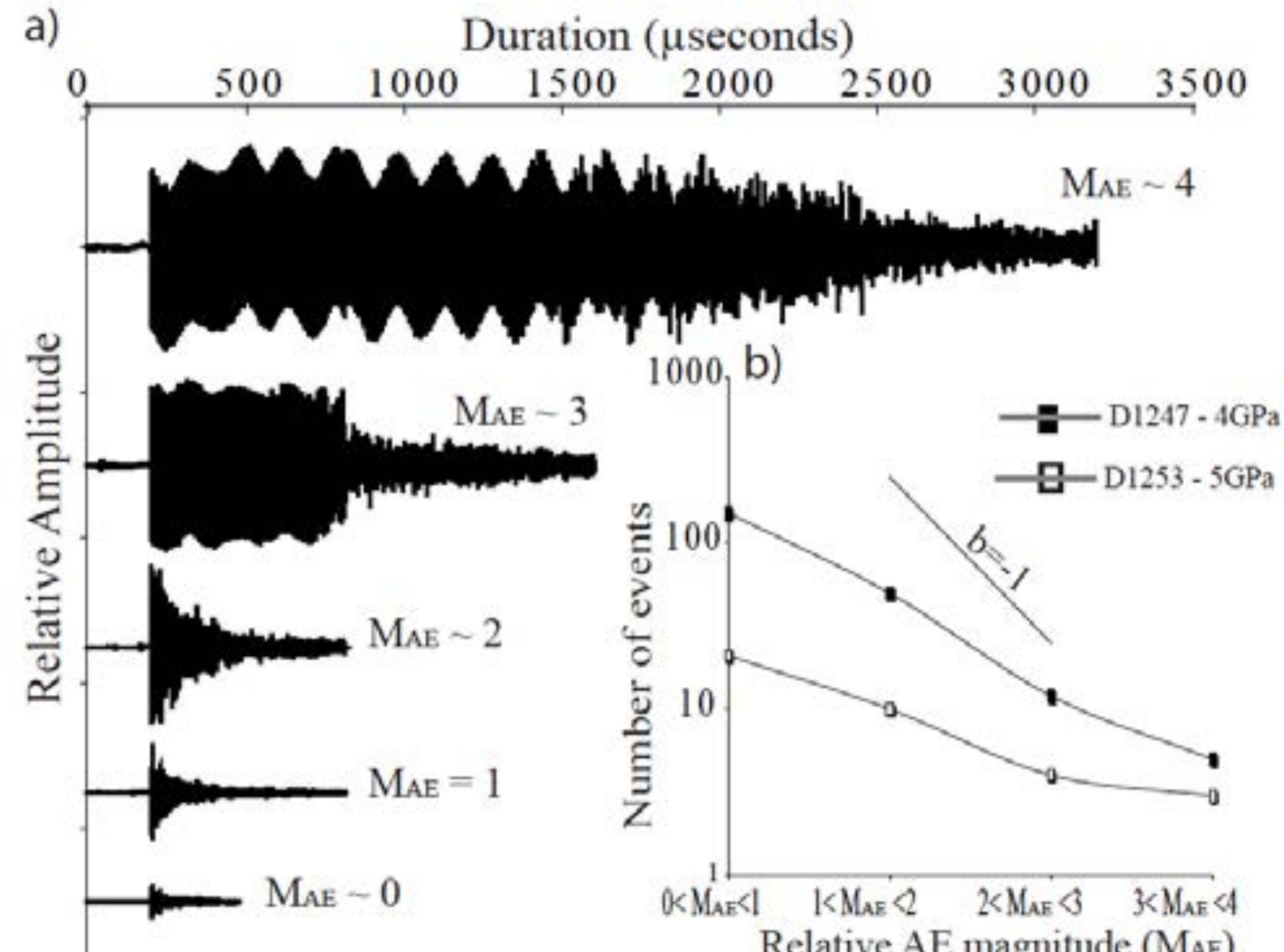


Schubnel et al. Science 2013

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

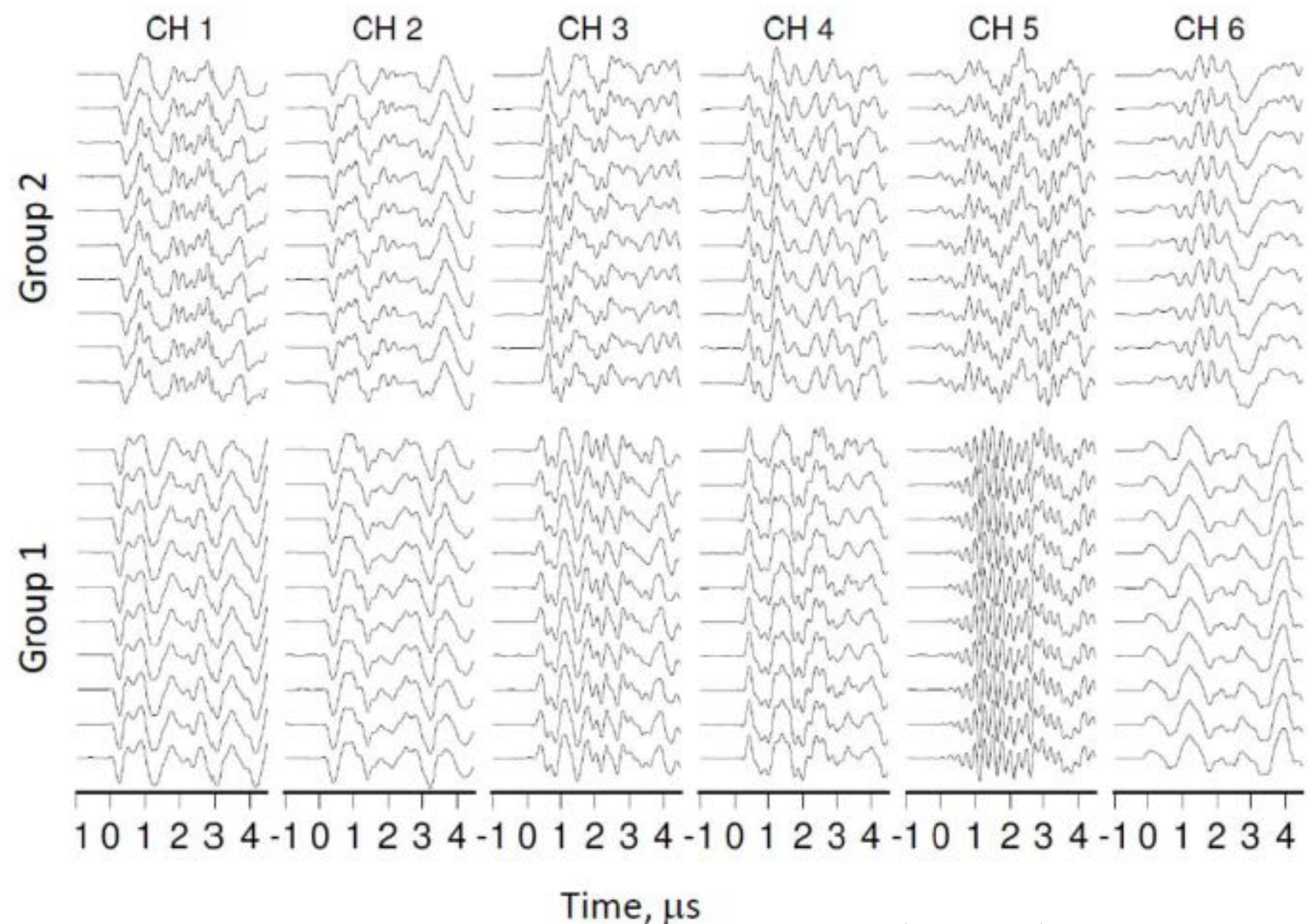
Sonification:
courtesy to Ben Holtzman
LDEO, U. Columbia NY
Visiting prof. ENS 2015



Schubnel et al. Science 2013

Ge-olivine-spinel transition
Correlating X-ray tomography and AE locations

Double difference relocation (Waldhauser and Ellsworth 2000)



Wang et al., Sci. Ad. 2017

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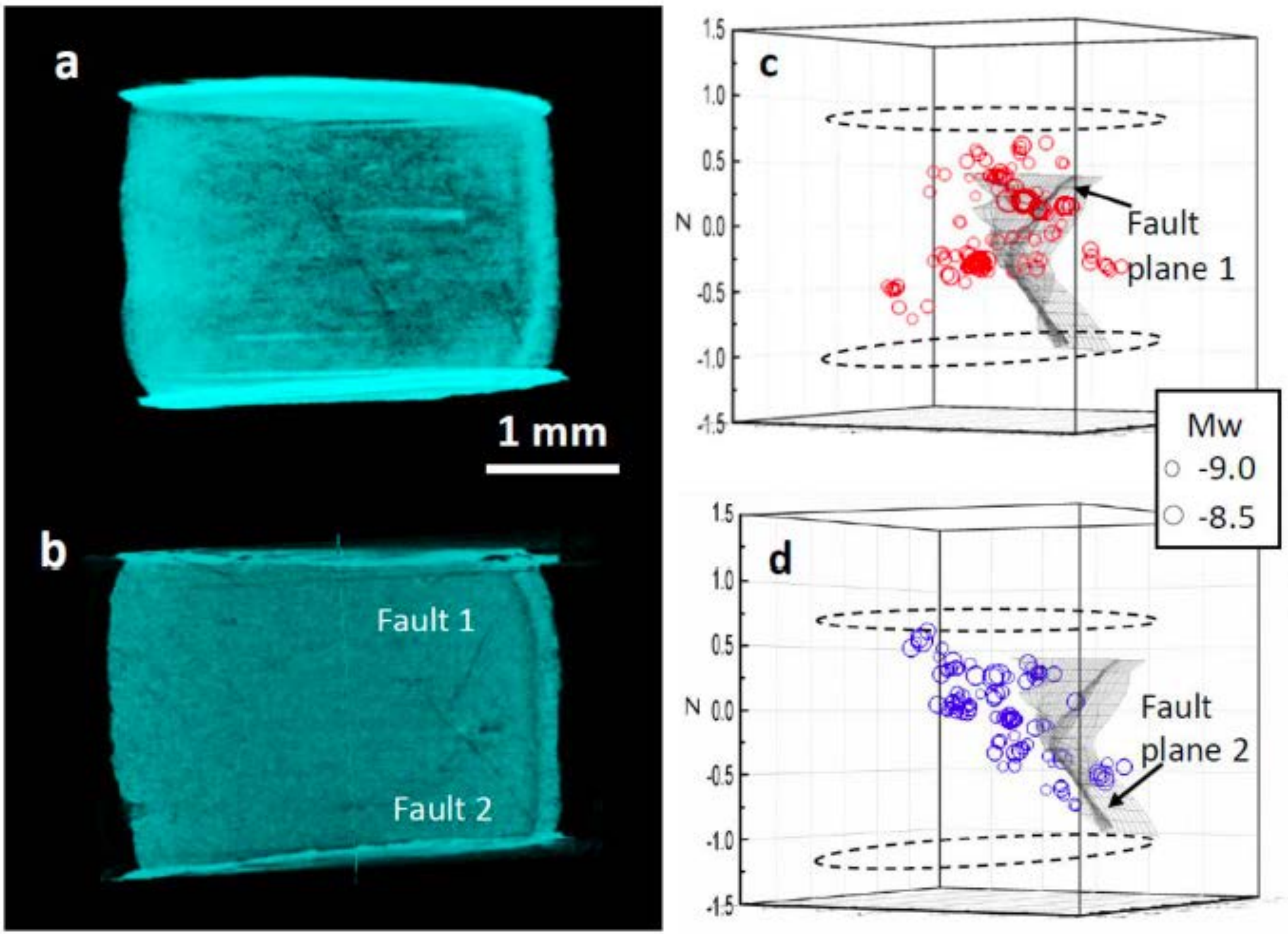
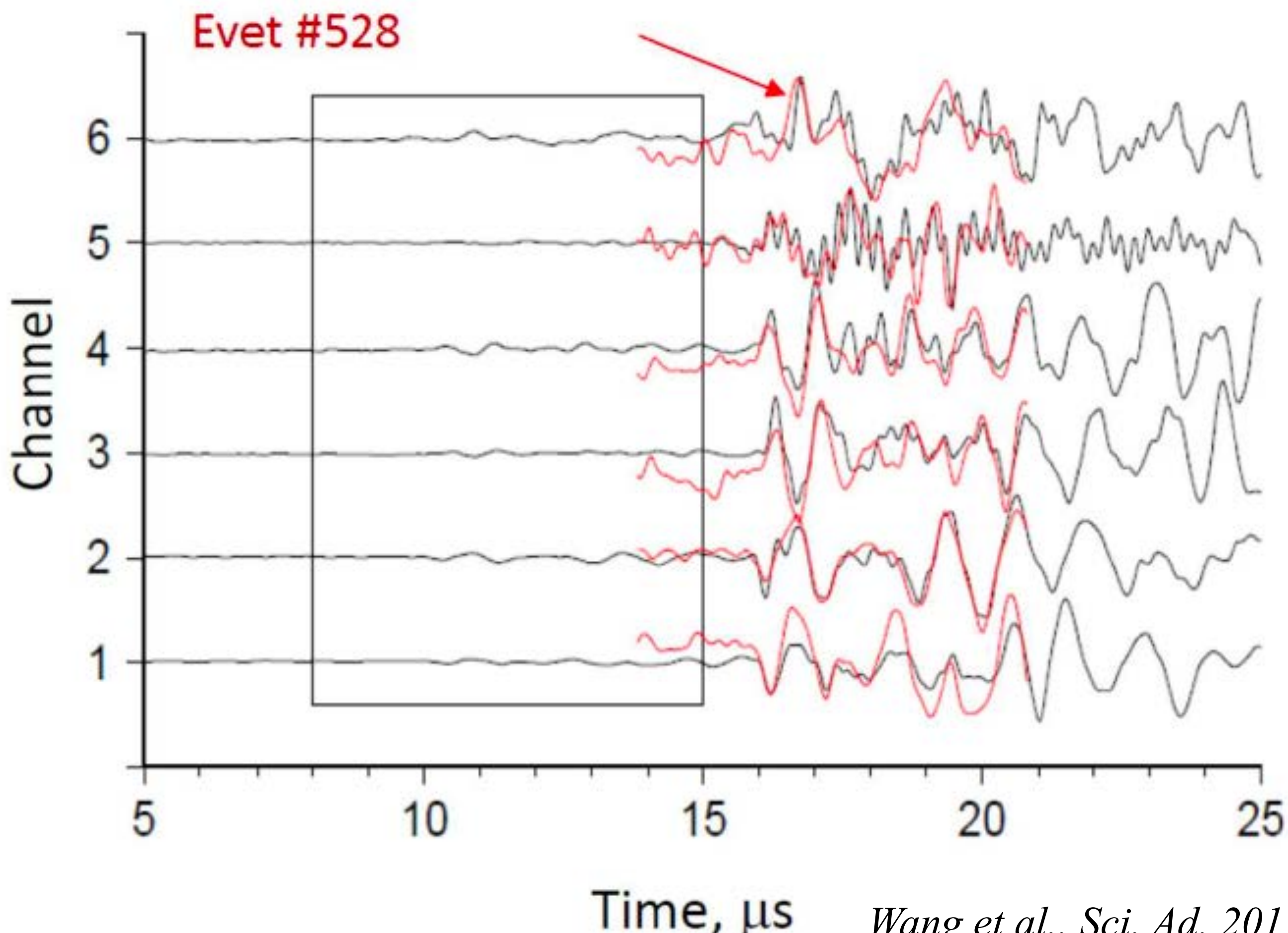


Wang et al., Sci. Ad. 2017

Ge-olivine-spinel transition

Nano-seismicity time-series analysis
(template matching of continuous wfms)



Wang et al., Sci. Ad. 2017

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Nano-seismicity time-series analysis

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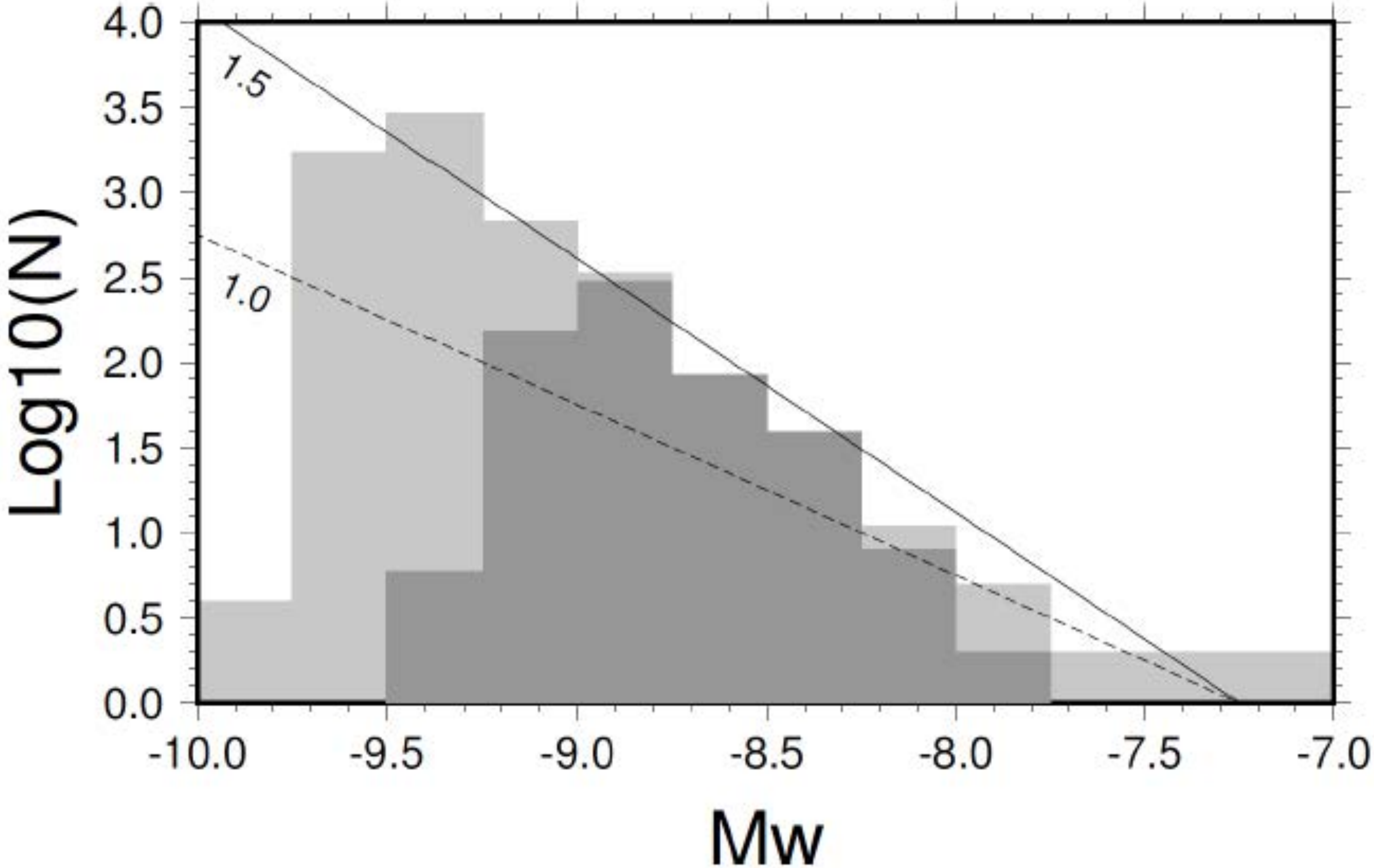

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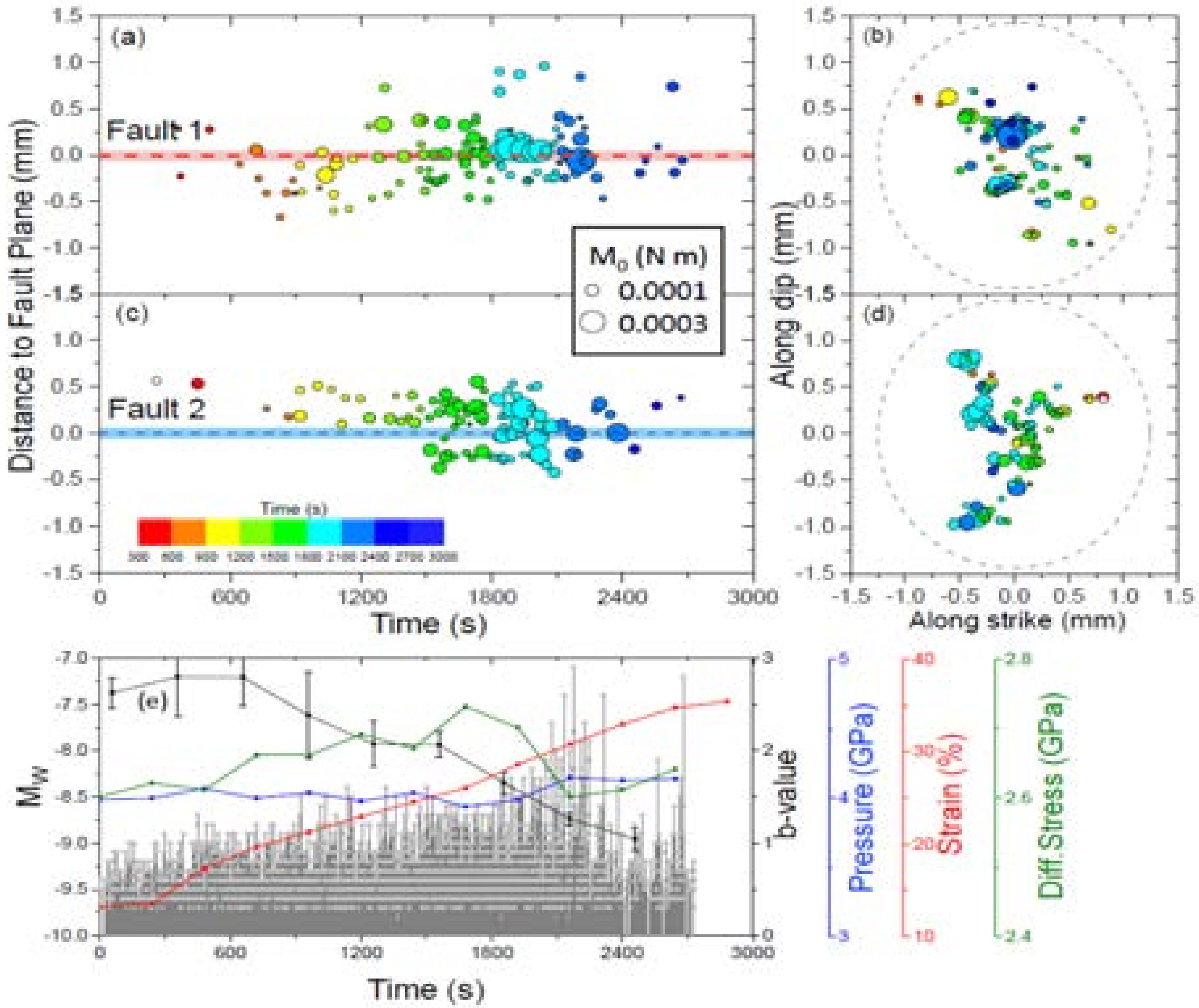
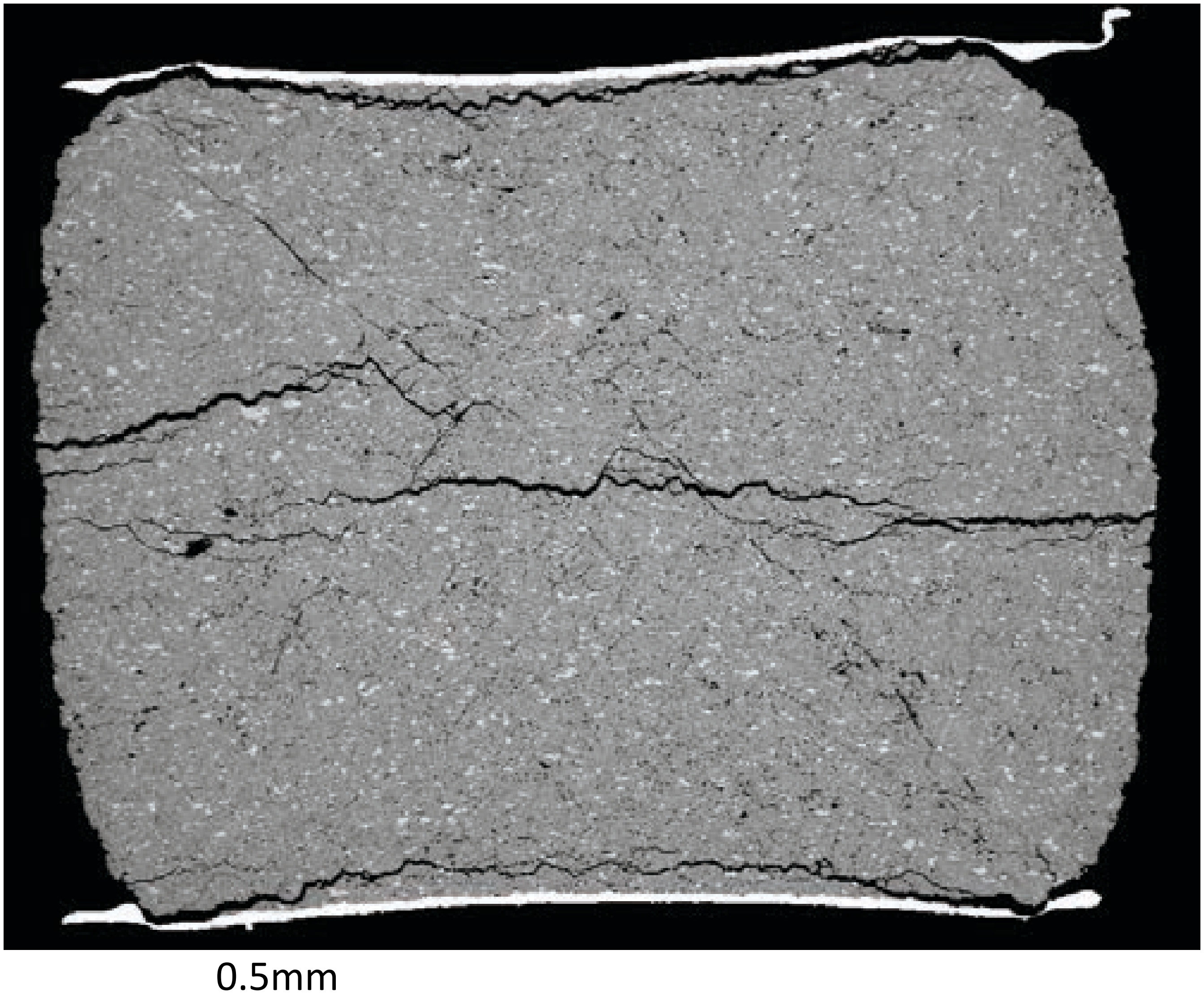


Wang et al., Sci. Ad. 2017

Ge-olivine-spinel transition

Microstructure - Sintered Mg_2GeO_4 – 30µm initial grain size
Effective mean stress = 5GPa +/-0.25, Strain rate = 10^{-4}/s



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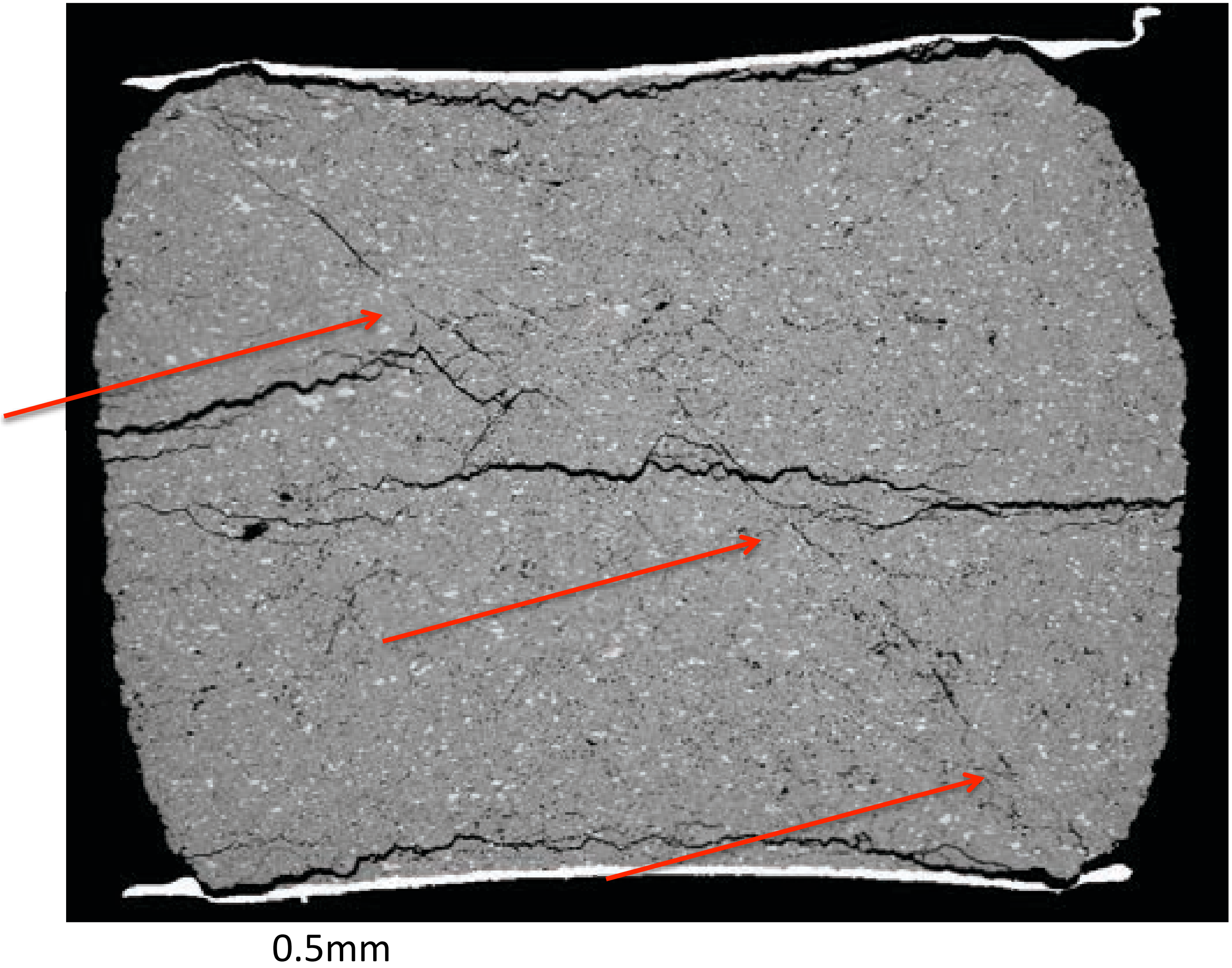

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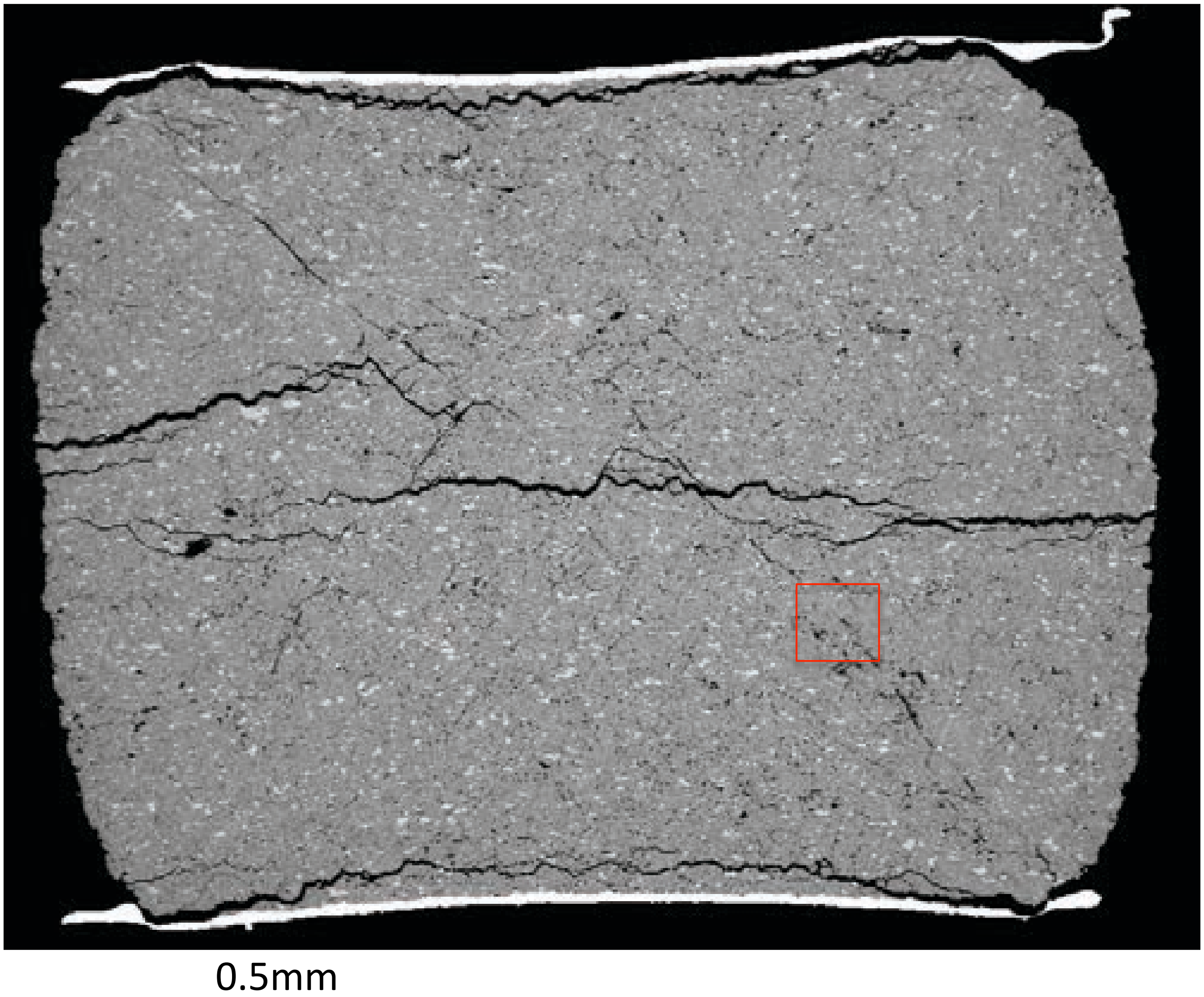

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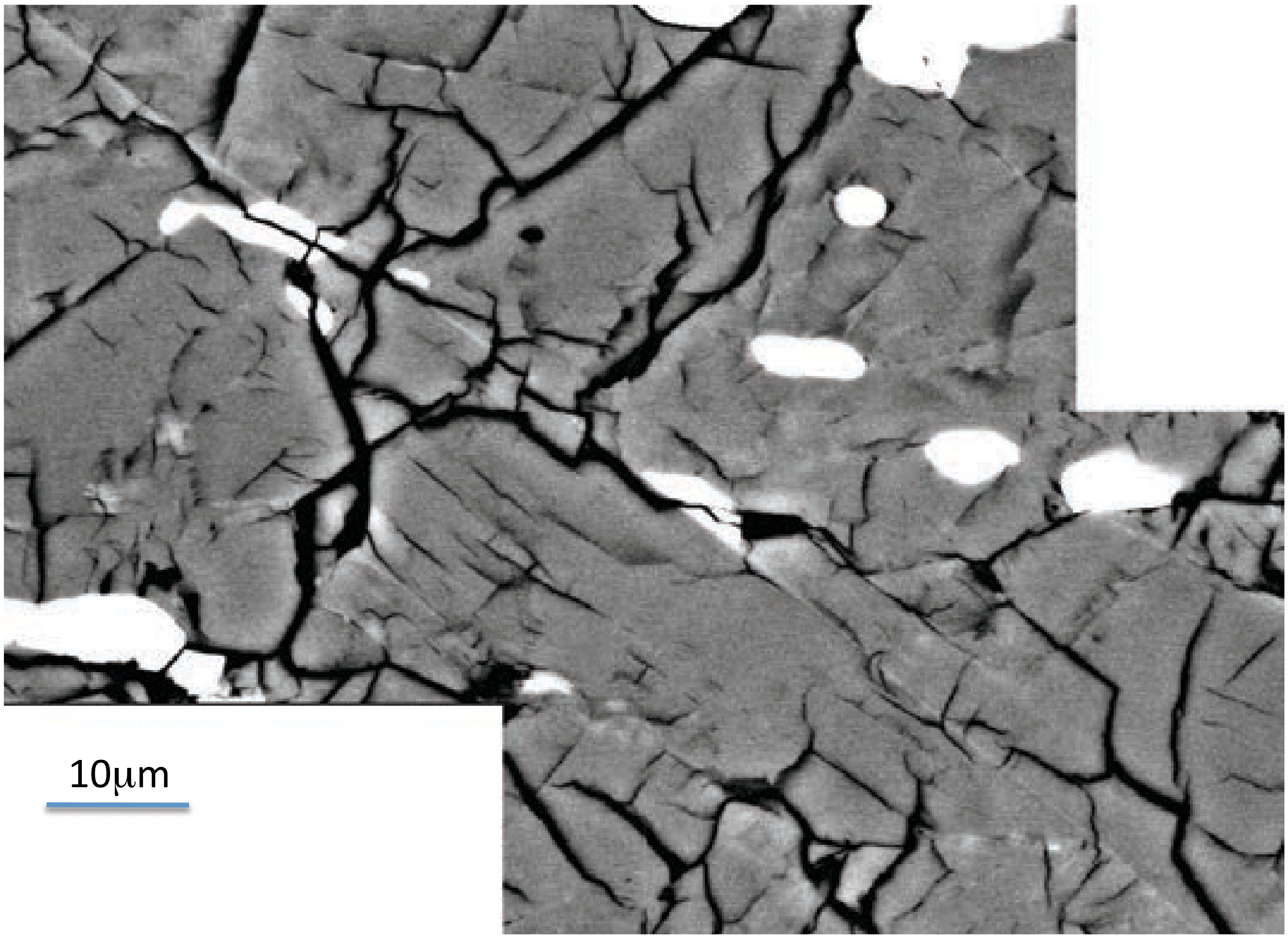

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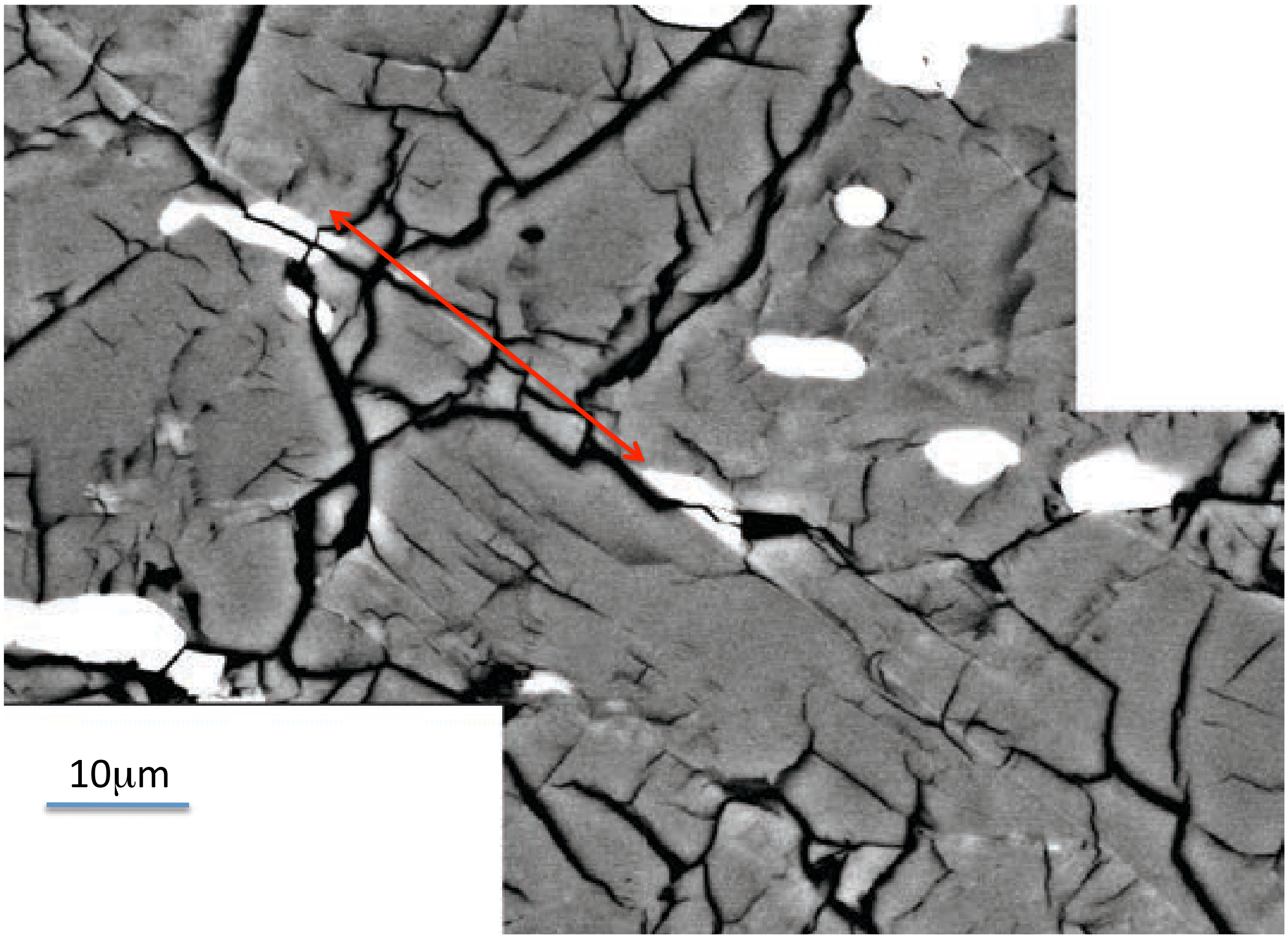

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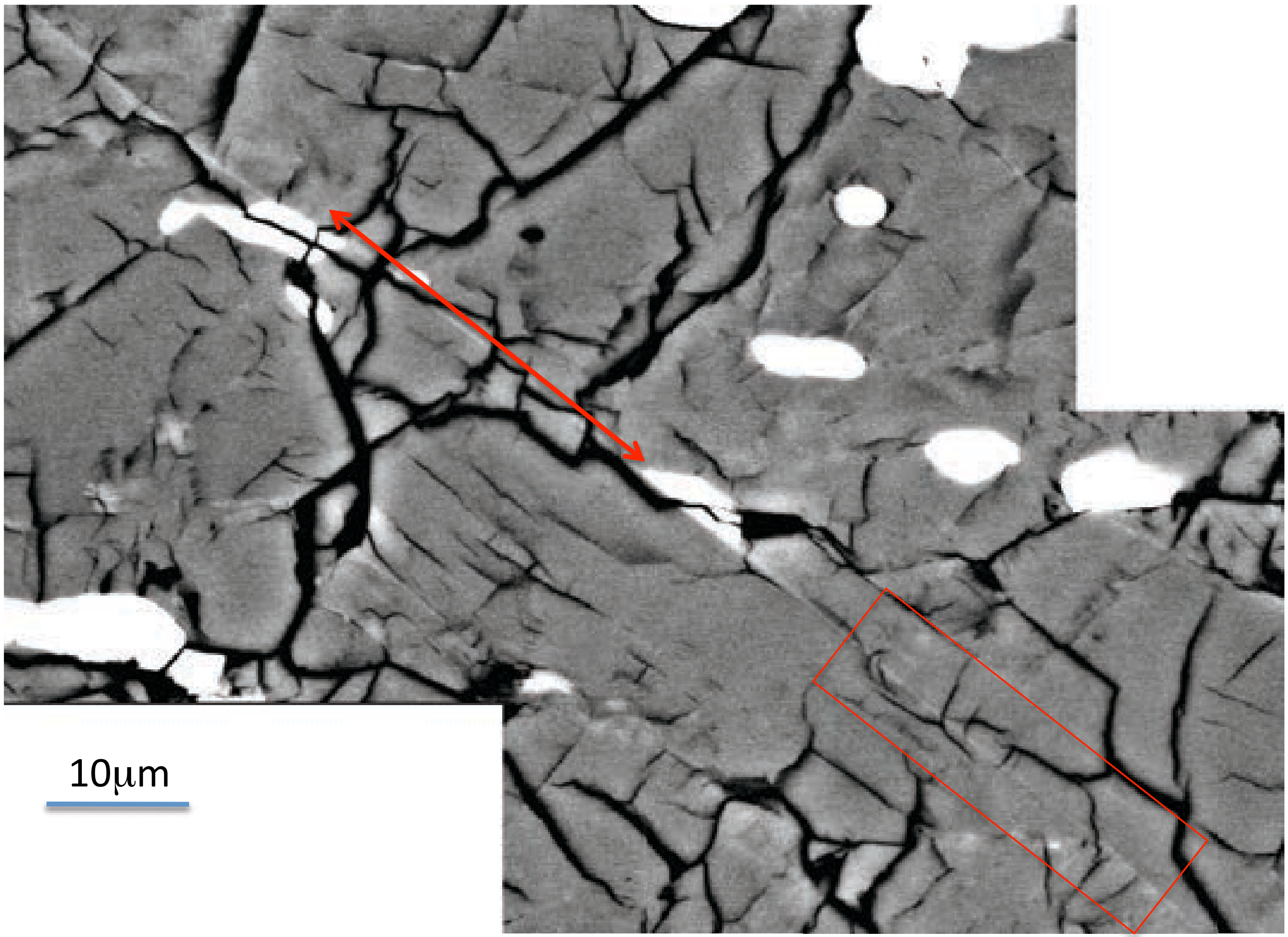

Ge-olivine-spinel transition

Microstructure - Sintered Mg_2GeO_4 – 30µm initial grain size

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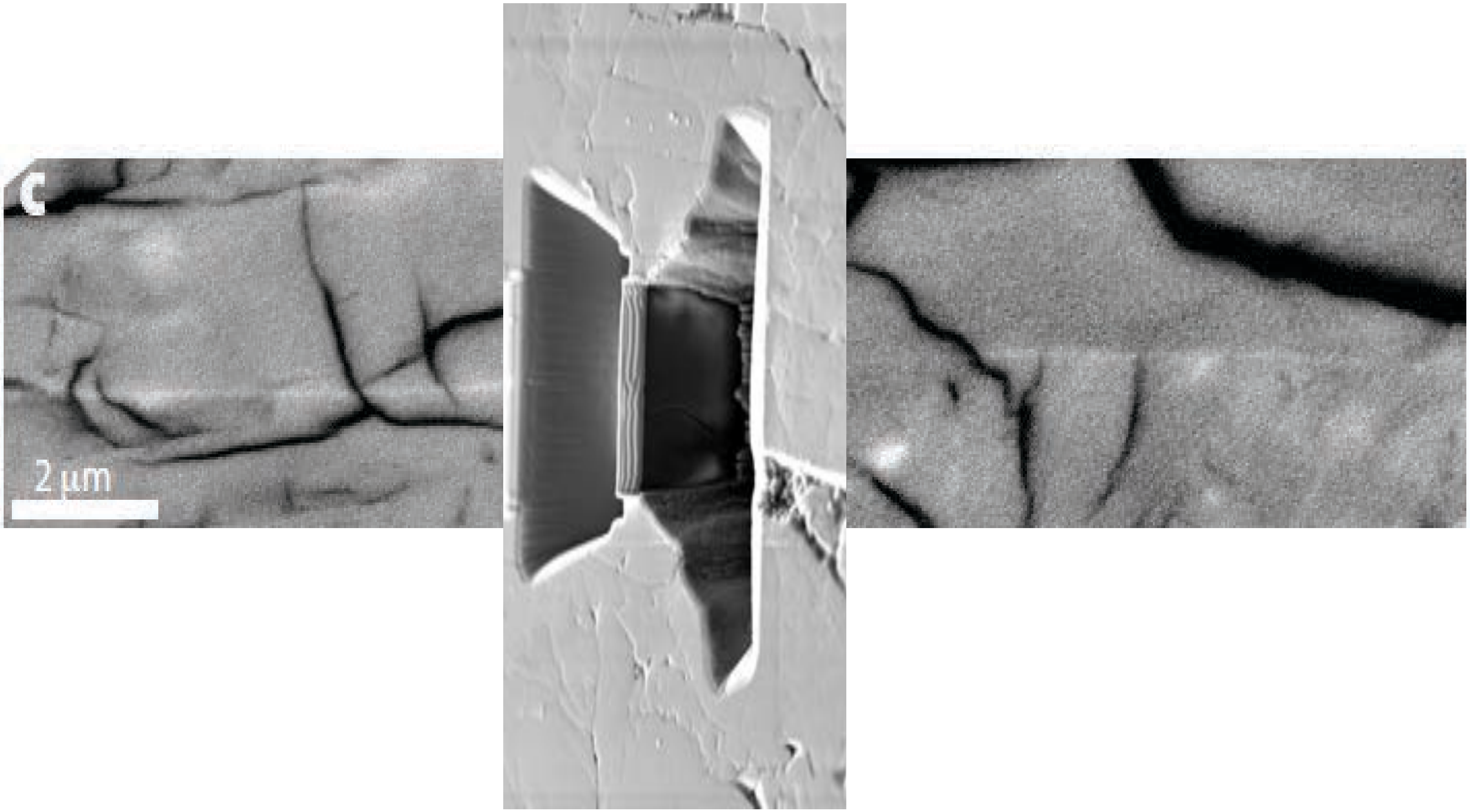
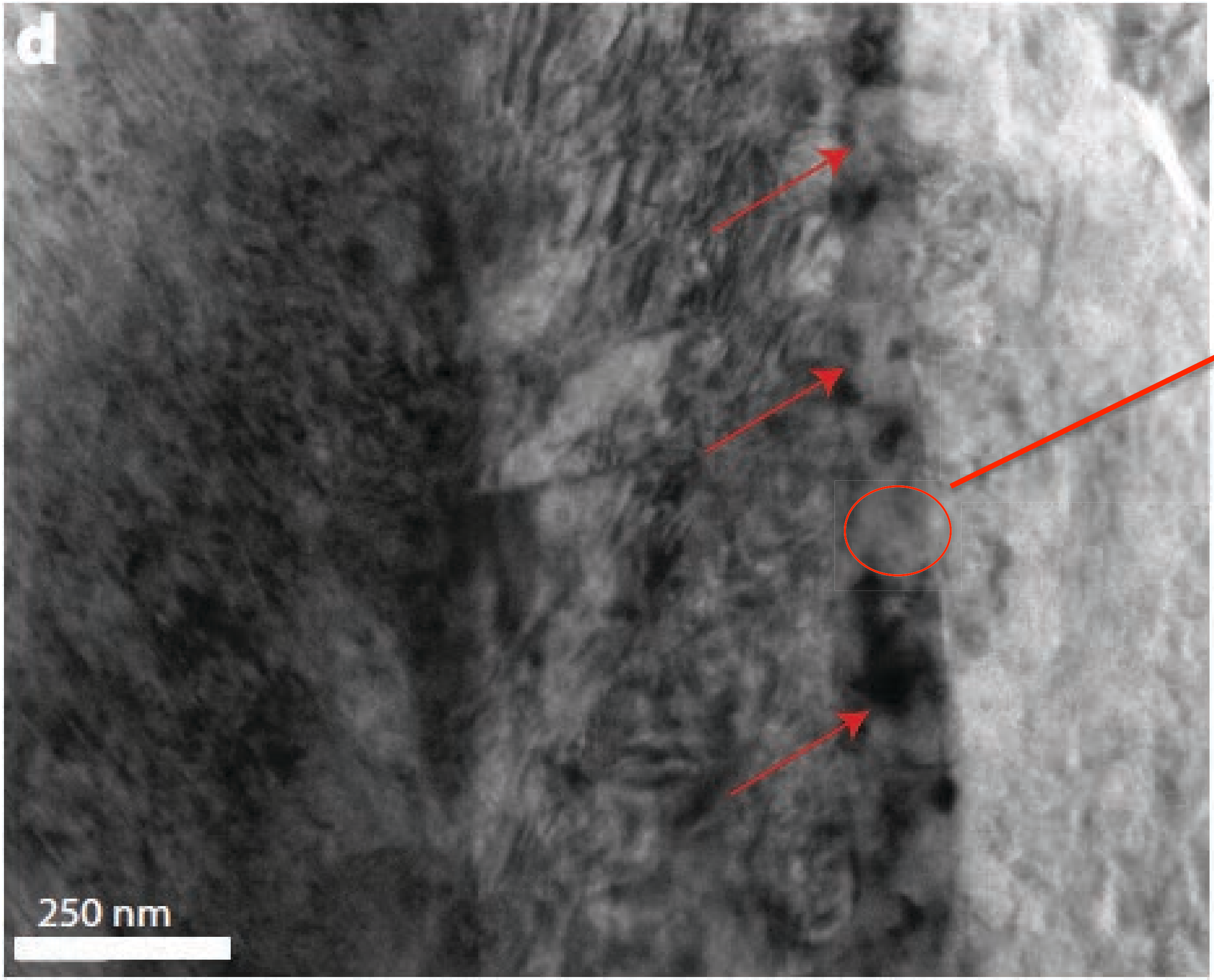
FIB Section

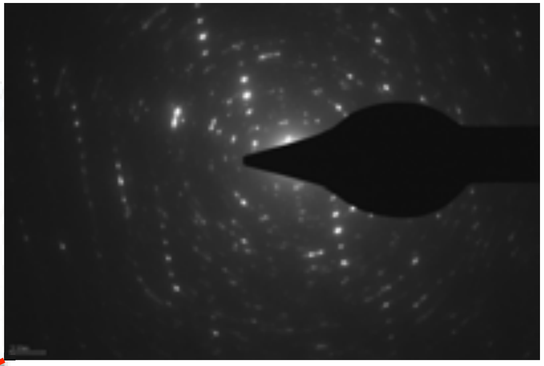


Ge-olivine-spinel transition

Microstructure - Sintered Mg_2GeO_4 – 30µm initial grain size
Effective mean stress = 5GPa +/-0.25, Strain rate = 10^{-4}/s

≈ XRPD of spinel phase





≈ 100nm thick

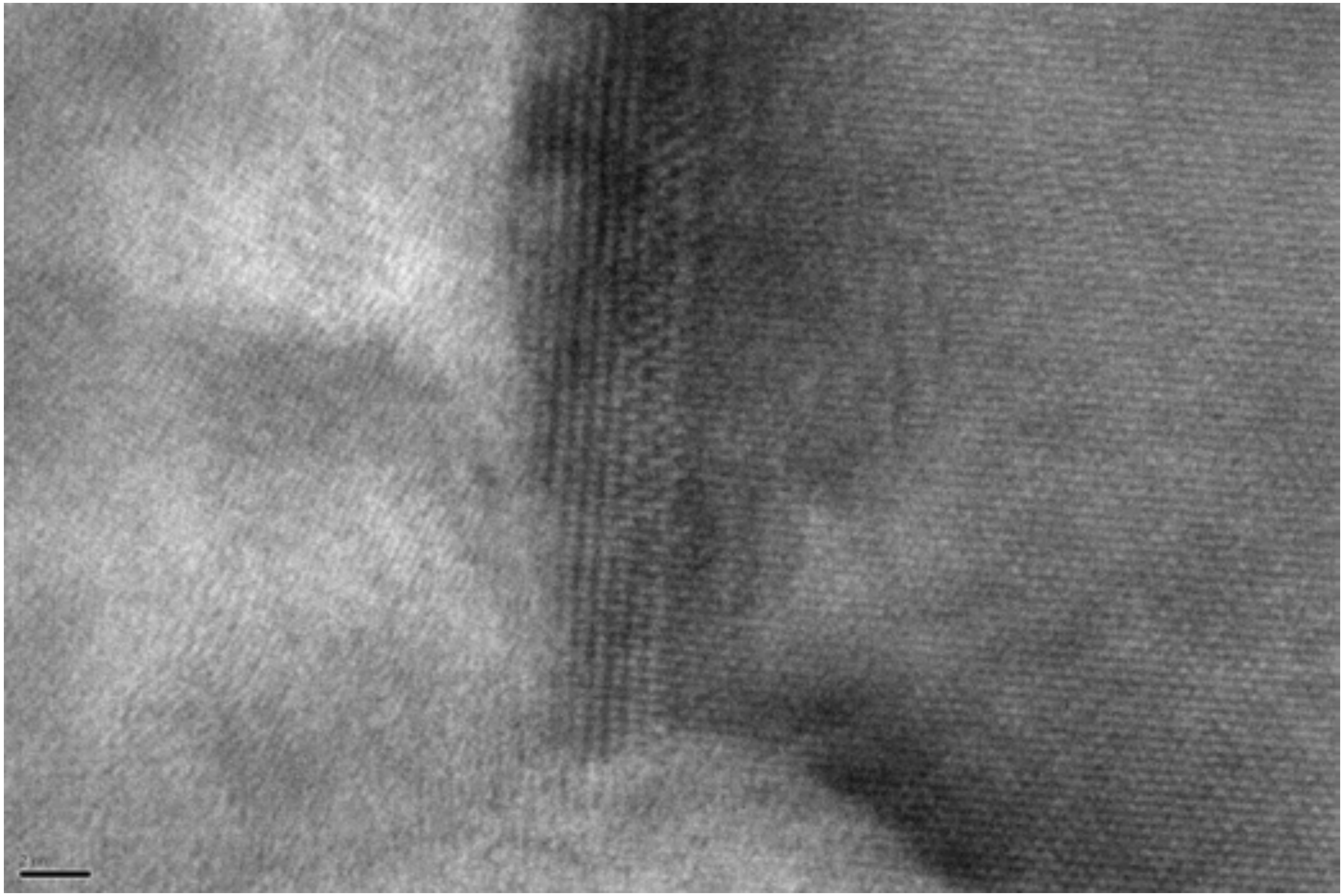
Shear strain ≈ microns
>>
Volumetric strain ≈ 10nm

Ge-olivine-spinel transition

Microstructure - Sintered Mg_2GeO_4 – 30μm initial grain size

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

Fully crystalline, no melt!



4nm

Ge-olivine-spinel transition

Frictional sliding?

Shear heating: w/o diffusion :

$$\Delta T = f\sigma_n D/(h\rho c)$$

σ_n: 5.10^9Pa; D: 30.10^{-6}m; h: 100.10^{-9}m; ρc: 3.10^6Pa/K

f≈0.01, ΔT= 6000°C

Shear heating: w diffusion :

$$\Delta T = f\sigma_n D/(\rho c\sqrt{\pi\kappa t})$$

t: 10^{-6}s; κ: $10^{-6}m^2/s$

f≈0.1, ΔT= 6000°C

This is neglecting latent heat ΔrH (transformation is exothermic)

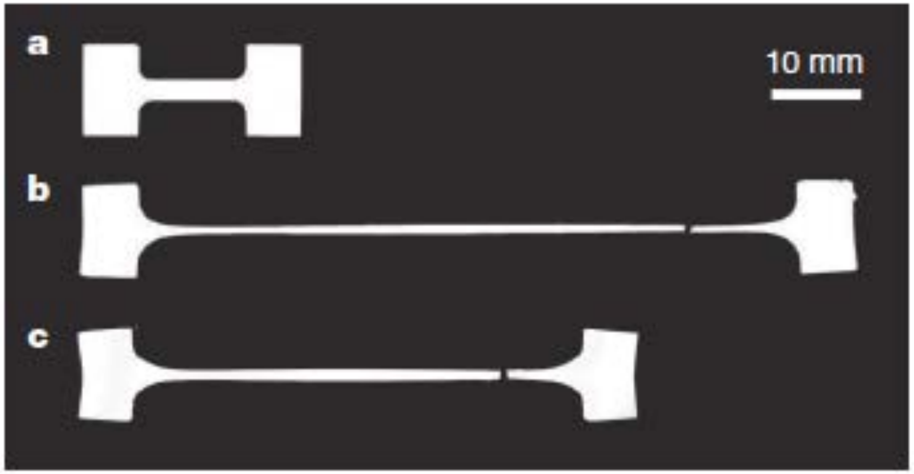
Ge-olivine-spinel transition

So what mechanism? **Superplastic flow for olivine?**

$$\dot{\varepsilon} = \Lambda \sigma^n d^p$$

$n \approx 2.3$ and $p \approx -1.5$

$10^{-5} s^{-1}$ at 1500 K and 20 MPa

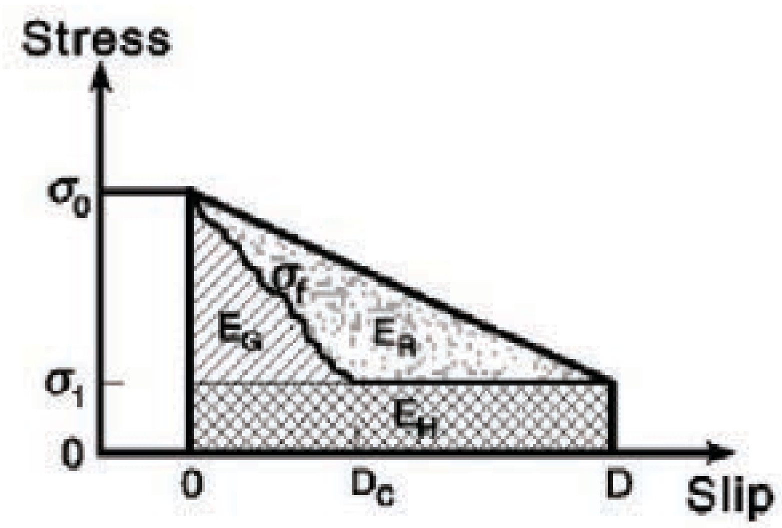


Hiraga et al, Nature 2010

In our experimental conditions,

$\sigma \approx 5.10^9$Pa, $d \approx 10$nm yields $\dot{\varepsilon} \approx 10^4 s^{-1}$

Discussion: Energy balance *during EQ*



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

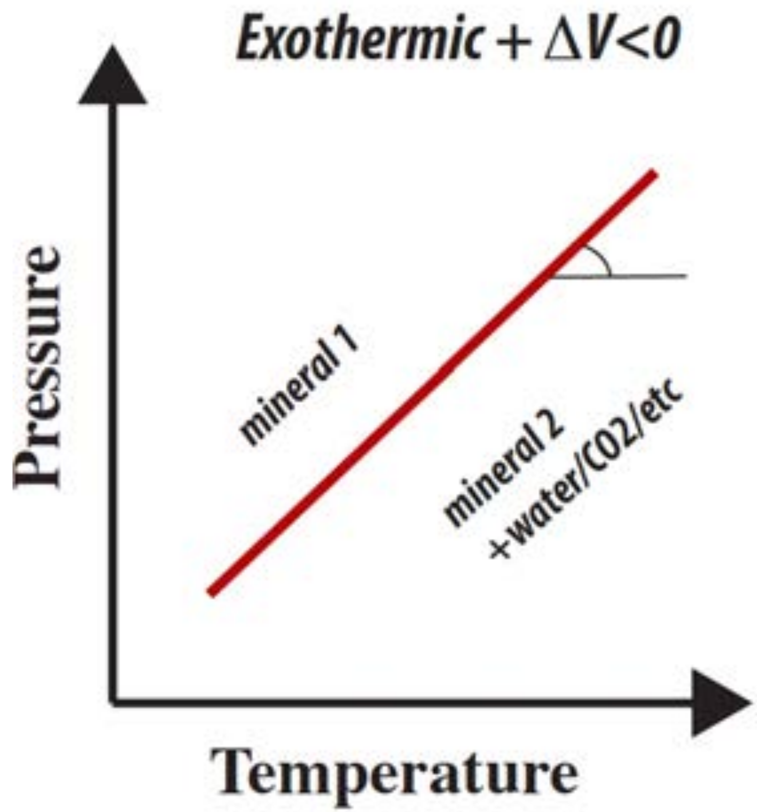
Energy balance

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?

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

- **Energy balance of a deep lithospheric EQ (Mw 6+) can be unraveled in Balmuccia, It.** Dynamic friction <<0.1, role of injection veins in re-strengthening. Recrystallized ol. is a marker of the afterslip (*Ferrand et al. JGR 2018*).

- 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! Evidence of a nucleation phase*** (*Wang et al. Sci. Ad, 2017*)

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

Conclusions

Mineral transformation not to be neglected in the overall energy balance, because reactions are:

1) **heat sinks or source**
2) **pressure sink or source**
3) **produce extremely fine grain-size – weak- material and**
4) **possible stress transfer**

(LARGE AMOUNTS OF) FLUIDS ARE NOT NEEDED!