Fossil earthquake formation at shallow depths: Evidence of natural and experimental fault rock record

Li-Wei Kuo

5th Feb, 2015 at NCU

Outline

Fossil earthquake formation at shallow depths: Evidence of natural and experimental fault rock record

Fossil earthquake

Fig. 1.1. Cartoon image from the Japanese science fiction movie *Ultraman-daina* showing a monster bird from Chinese mythology fighting Ultraman (inside the shuttle plane) with the aid of the immense seismic energy of pseudotachylyte sourced from a large earthquake that occurred within the Chinese continent. Pt: Pseudotachylyte, W: seismic wave. Image courtesy Y. Lin

Lin, 2007

Fossil earthquake

The processes occurred during individual seismic event and associated products!!

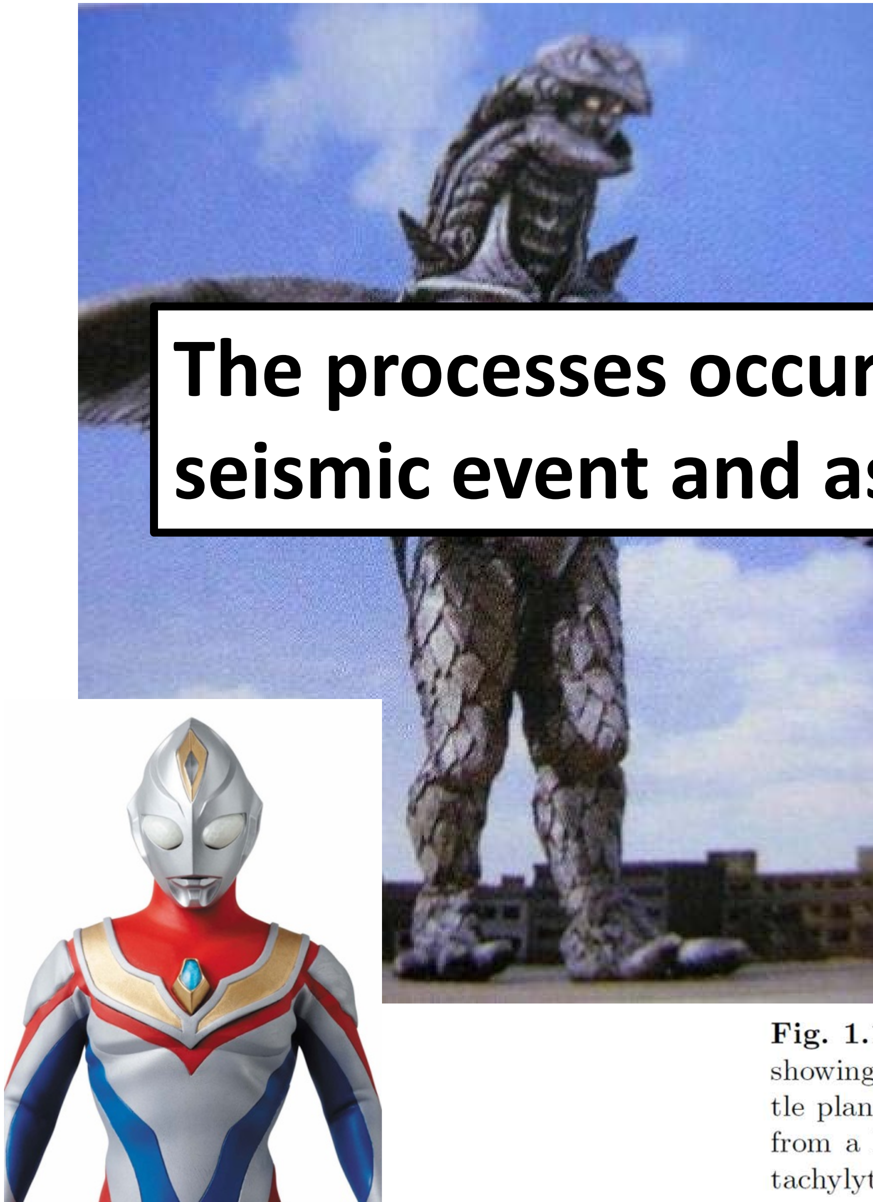


Fig. 1.1. Cartoon image from the Japanese science fiction movie *Ultraman-daina* showing a monster bird from Chinese mythology fighting Ultraman (inside the shuttle plane) with the aid of the immense seismic energy of pseudotachylyte sourced from a large earthquake that occurred within the Chinese continent. Pt: Pseudotachylyte, W: seismic wave. Image courtesy Y. Lin

Lin, 2007

Fossil earthquake

- **Pseudotachylyte**

Shand, 1916

(meteorite impact)

Fossil earthquake

basaltic opaque glass

- Pseudo-tachylyte

Shand, 1916

(meteorite impact)

basaltic transparent glass
=> sideromelane

Fossil earthquake

- **Pseudotachylyte**

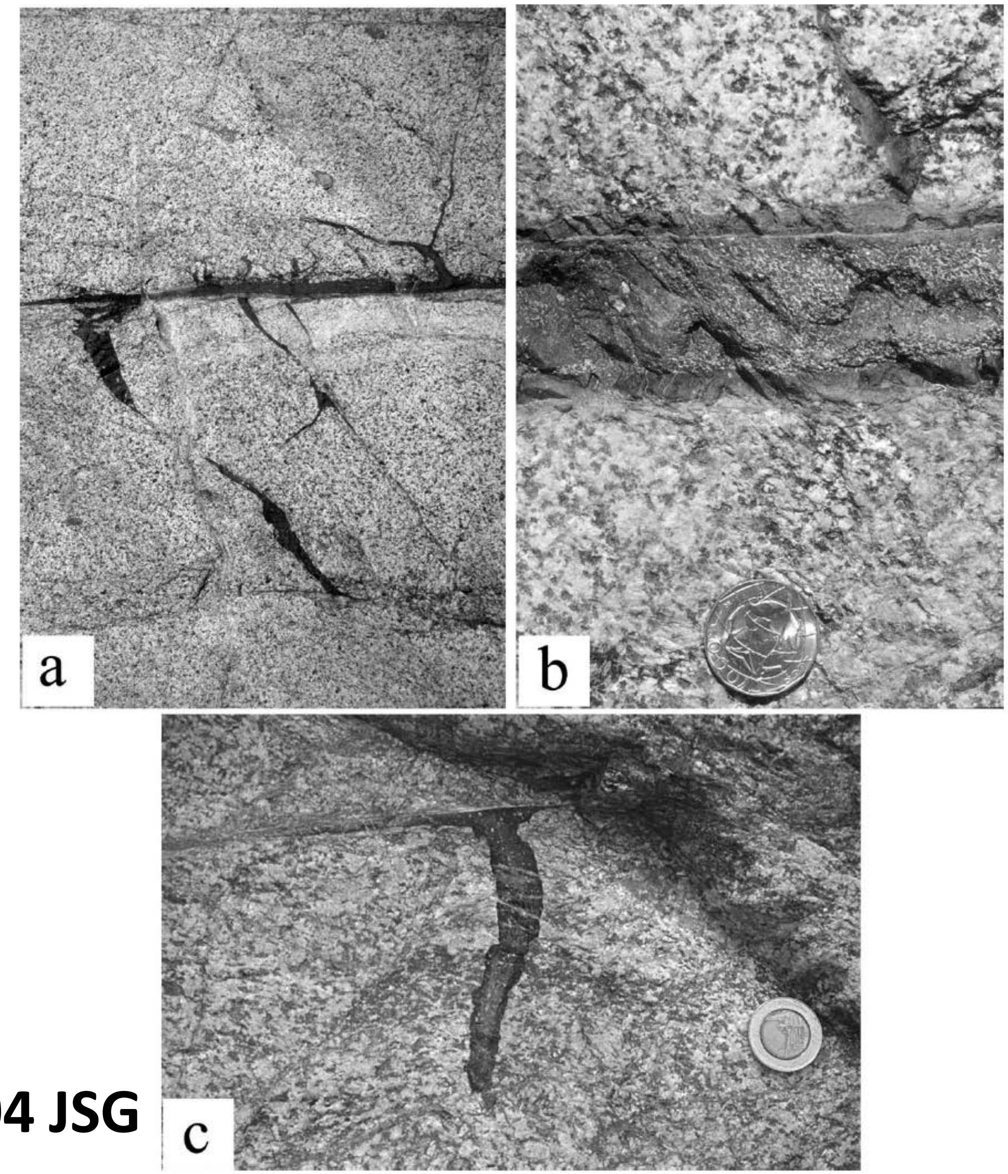
Shand, 1916

(meteorite impact)

Sibson, 1975 GJR

More than 400 papers in 40 years

Prante et al., 2014 EPSL



Di Toro et al., 2004 JSG

Fossil earthquake

e.g., Pseudotachylyte (fault origin)

Presence	Temperature estimate	Process
↓	↓	↓
Seismic activity	Frictional energy	Fault strength
↓	↓	↓
Rupture dynamics	Energy budget	Weakening mechanism

of **Earthquakes**

Fossil earthquake **formation**

- Decarbonation (Rowe et al., 2012 EPSL)
- Dehydration and dehydroxylation (Kuo et al., 2009 GRL)
- Demagnetization (Chou et al., 2012 Geology)
- Graphitization (Kuo et al., 2014 Geology)
- Flash heating and weakening (Goldsby and Tullis, 2011 Science)
- *Nanoscale smoothing (Chen et al., 2013 Geology)*
- Thermal pressurization (Brantut et al., 2008 JGR)
- *Silica gel formation (Di Toro et al., 2004 Nature)*
- Thermal decomposition (Han et al., 2010 JGR)
- Powder lubrication (Han et al., 2007 Science)
- Recrystallization (Smith et al., 2013 Geology)
- Melt lubrication (Di Toro et al., 2006 Science)
- *Fluidization (Anders et al., 2012)*

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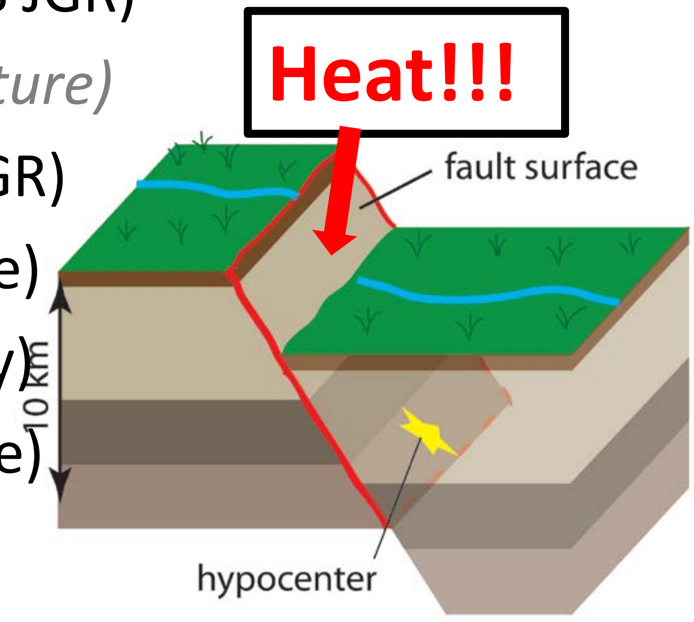


Fossil earthquake formation
at shallow depths

Catastrophic phenomena caused by ***active faulting***, such as major ***earthquakes***, ***landslides***, and ***tsunamis***, have a huge impact on the environment and society.

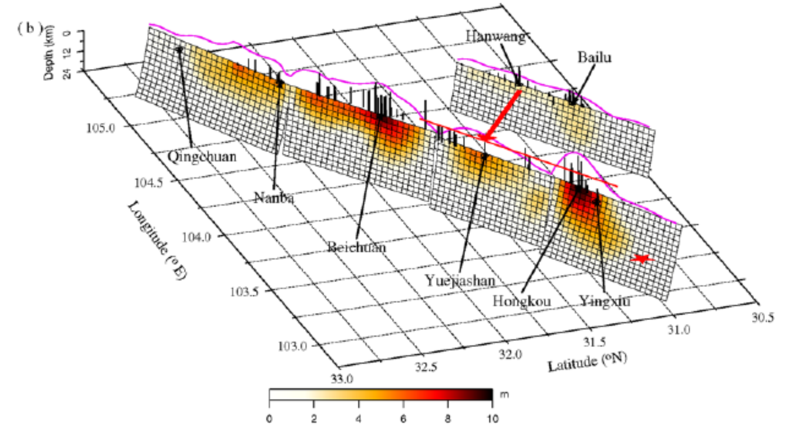
2008 Mw 7.9 Wenchuan EQ

1999 Mw 7.6 Chi-Chi EQ

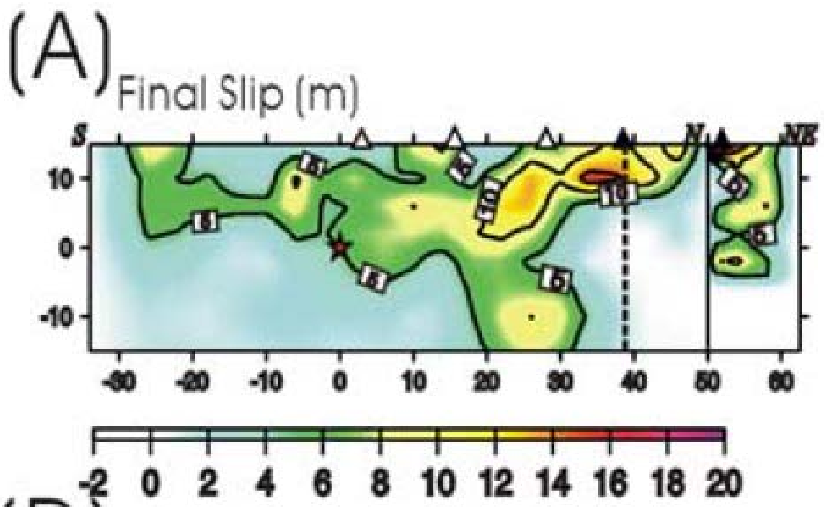
2011 Mw 9.0 Tohoku-Oki EQ

Fossil earthquake formation **at shallow depths**

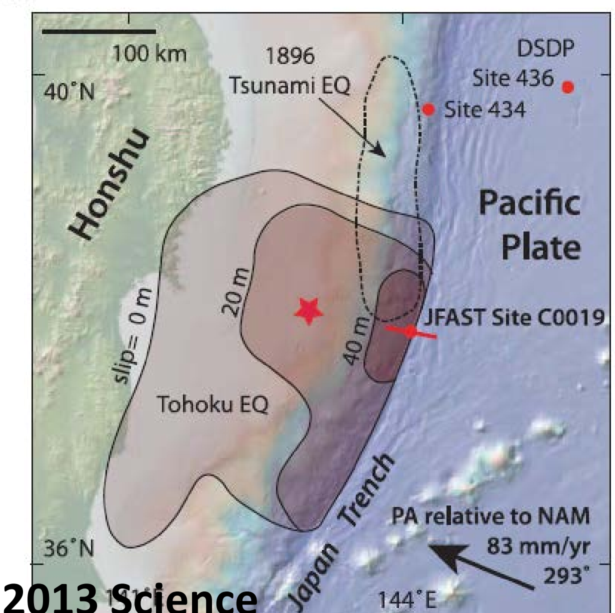
Xu et al., 2010 BSSA



Presence of fossil earthquake can be used to assess **seismic hazards** in areas.



Ma et al., 2003 GRL

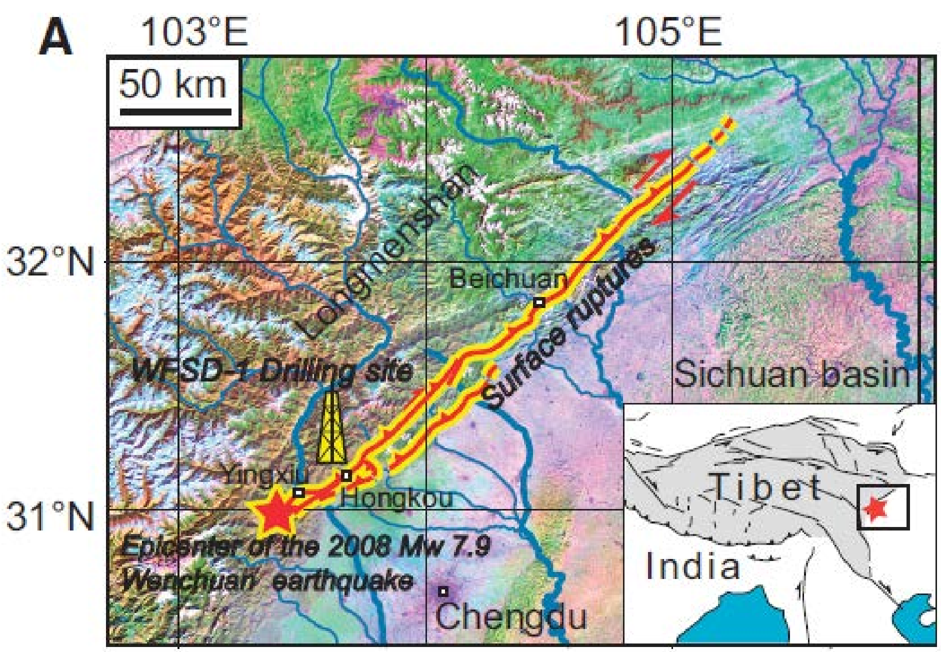


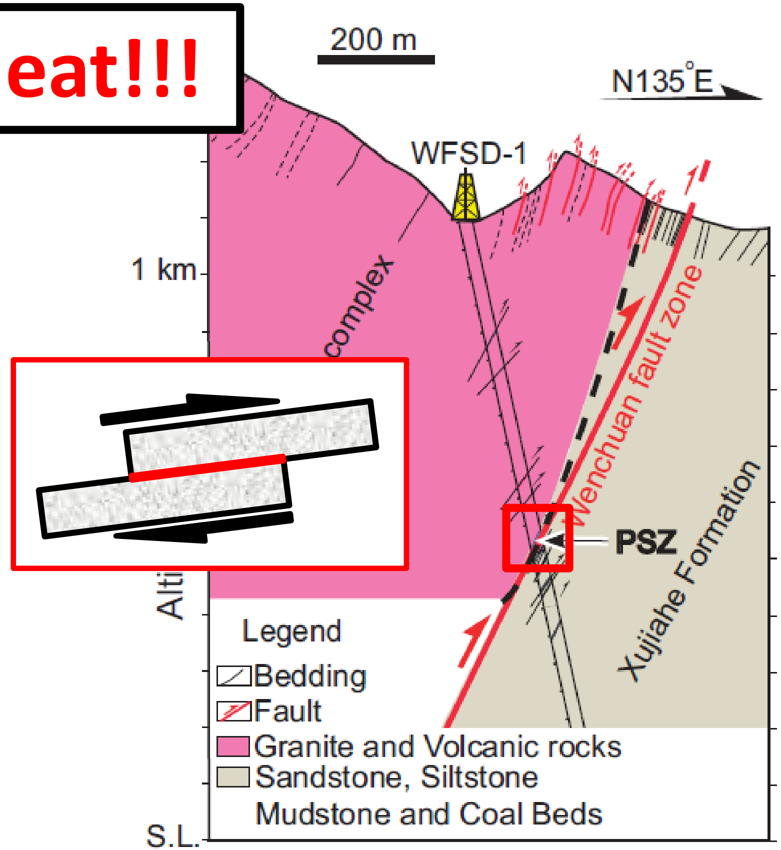
Chester et al., 2013 Science

Fossil earthquake formation at shallow depths:

Evidence of natural and experimental fault rock record

Signature of Heat!!!



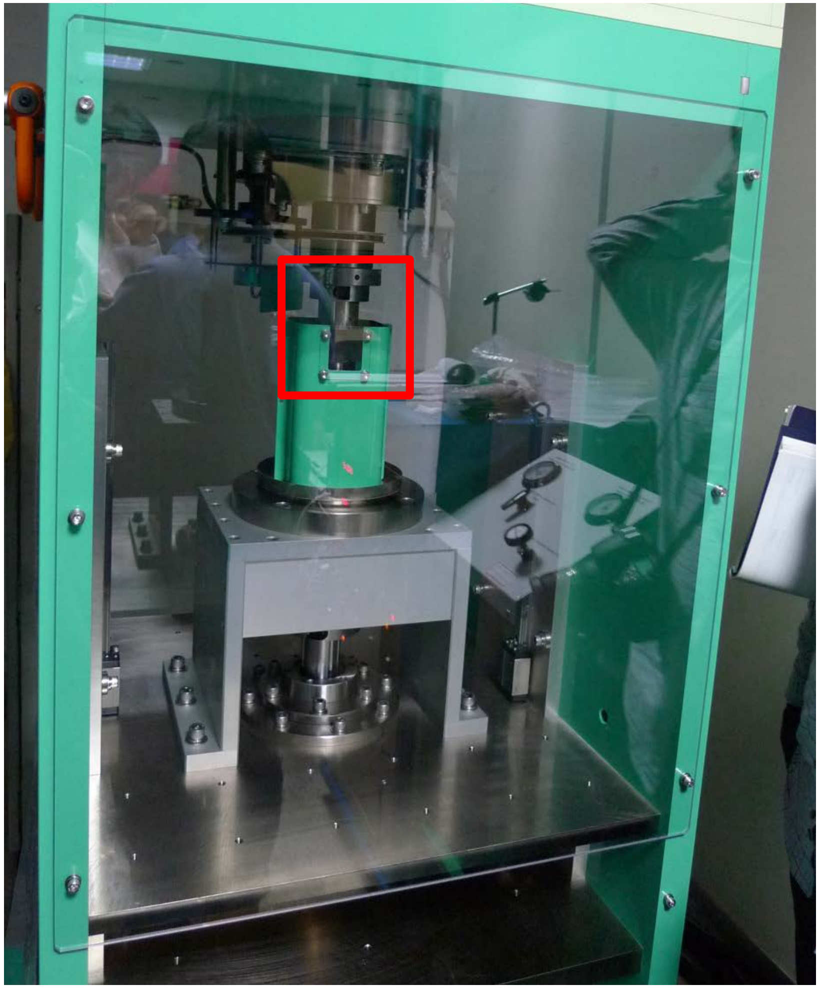


Fossil earthquake formation at shallow depths: Evidence of natural and experimental fault rock record

from

1. **Taiwan Chelungpu fault Drilling Project (TCDP)**
2. **Wenchuan earthquake Fault Scientific Drilling (WFSD)**
3. **A shallow borehole in Miaoli area *(if time is available)***

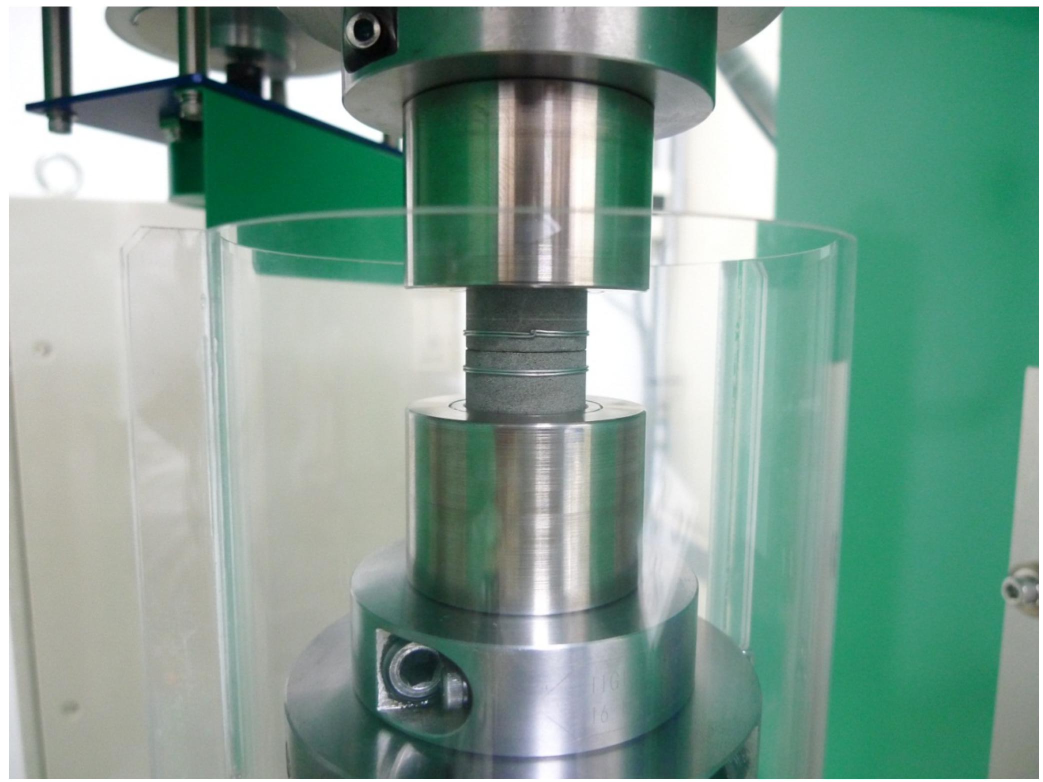
High Velocity Rock Friction Experiments (HVRFE) are conducted in **rotary shears**



$\sigma_n < 25$ MPa

v = 50 µm/s – 1.3 m/s

d = infinite



Low to High velocity friction Apparatus at NCU

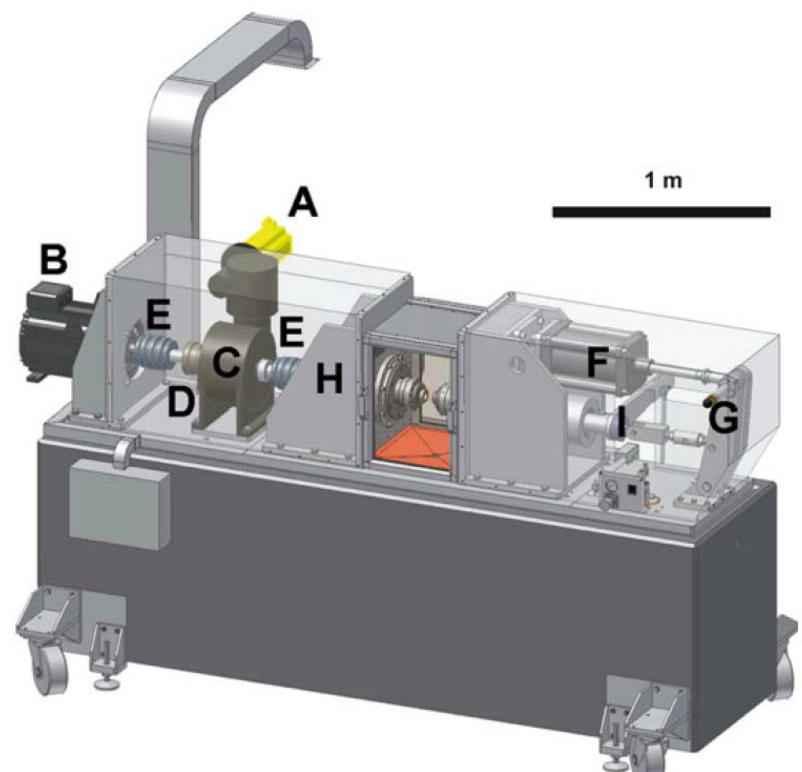
High Velocity Rock Friction Experiments (HVRFE) are conducted in rotary shears

$\sigma_n < 60$ MPa

v = 1 μm/s – 9 m/s

d = infinite

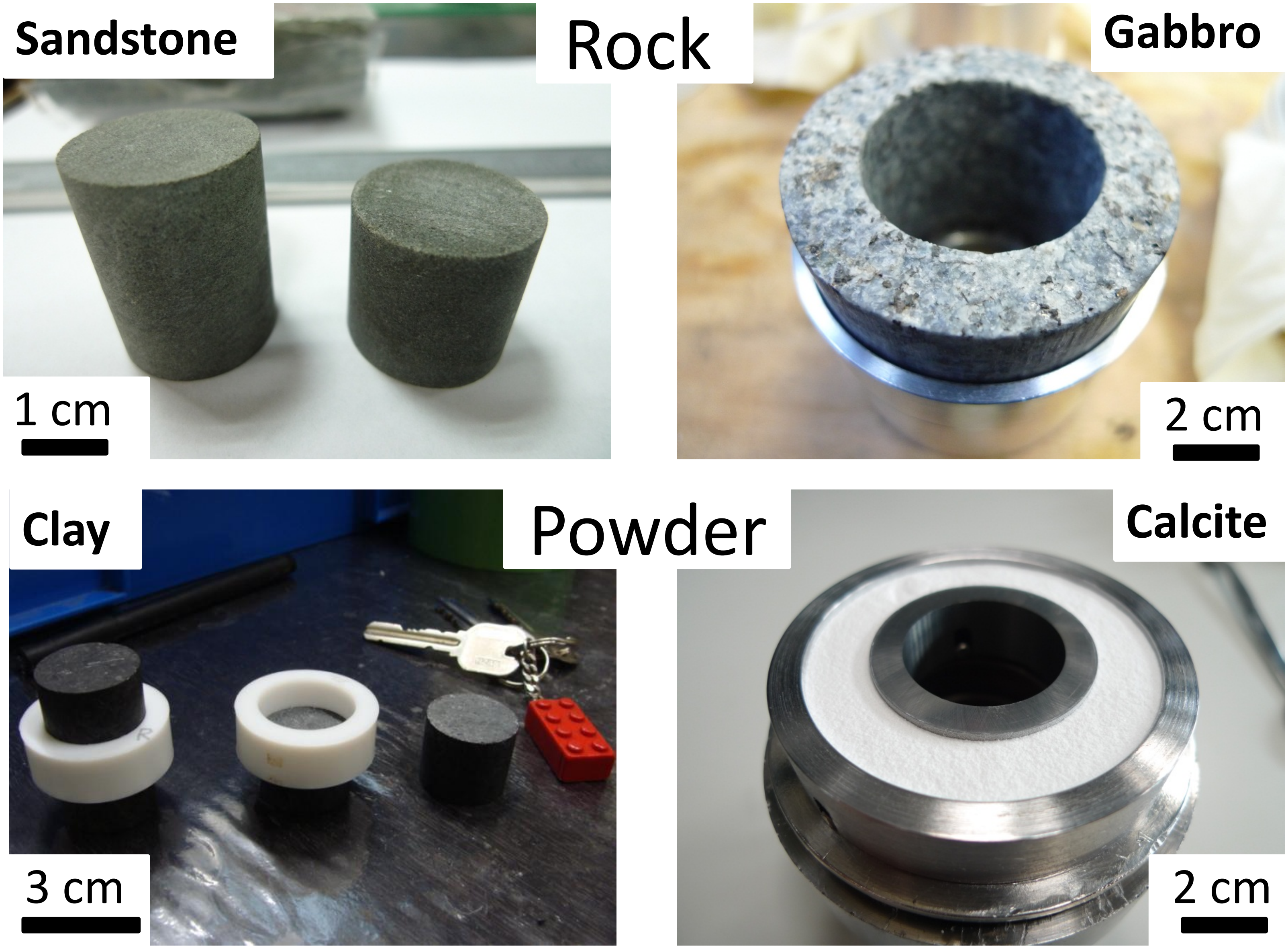
acceleration < 80 m/s^2



Slow to **Hi**gh **V**elocity **A**pparatus (SHIVA) at INGV

Di Toro et al., 2010

HVRFE are performed on **cohesive and non-cohesive** rocks.

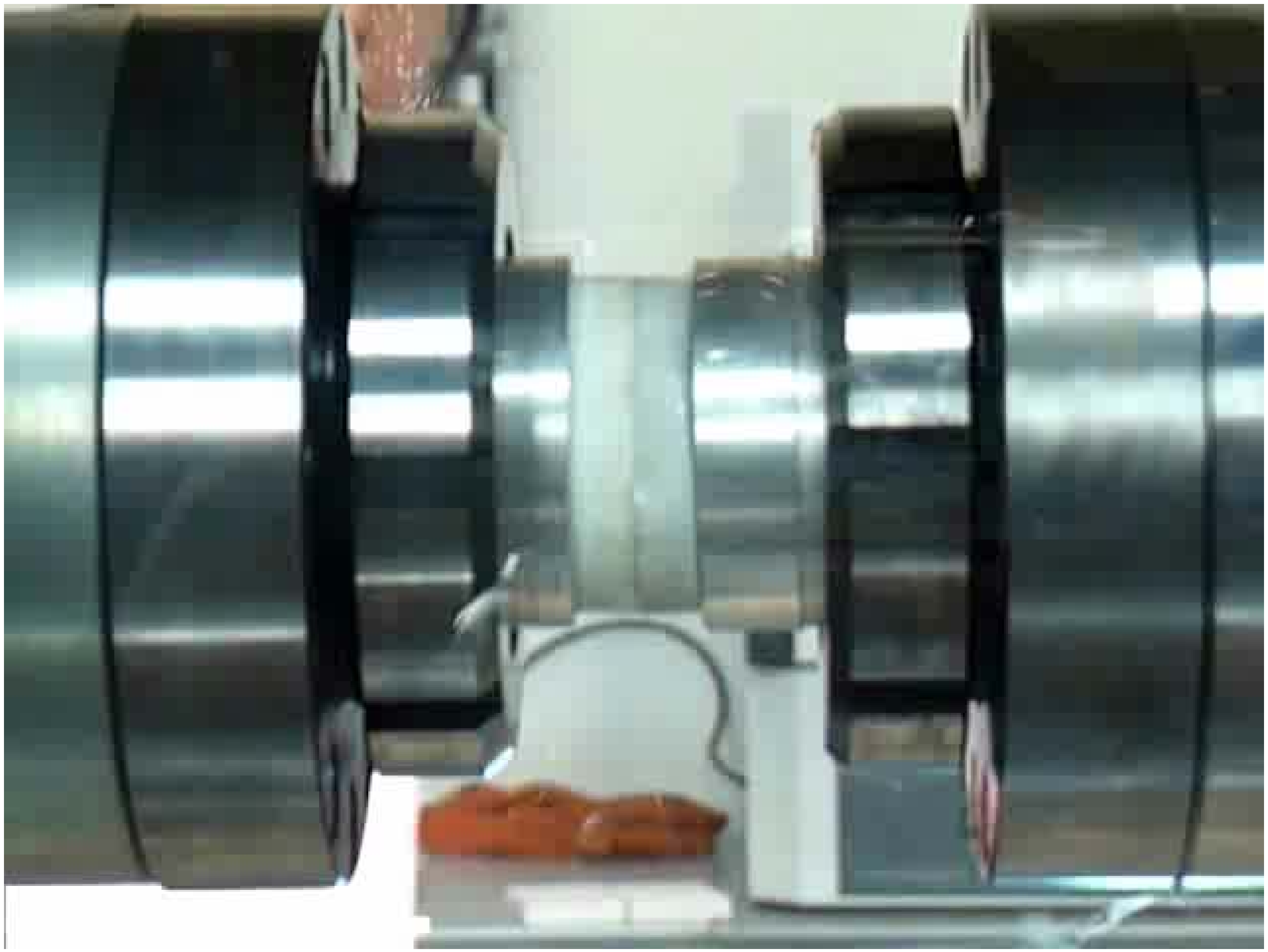


SHIVA: gabbro at $v = 5$ m/s, $\sigma_n = 25$ MPa, 0 to 5 m/s in 0.1 s

50 mm

http://www.youtube.com/watch?v=YTfwJ3Elw5s

SHIVA: marble at v = 5 m/s, σ_n = 10 MPa

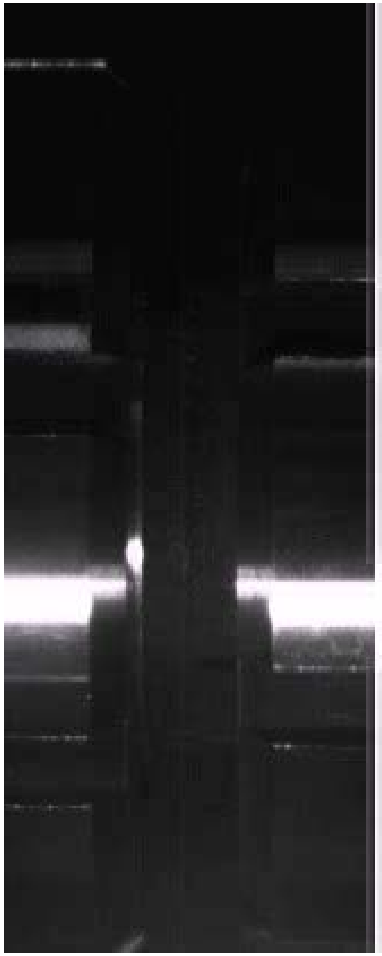


50 mm

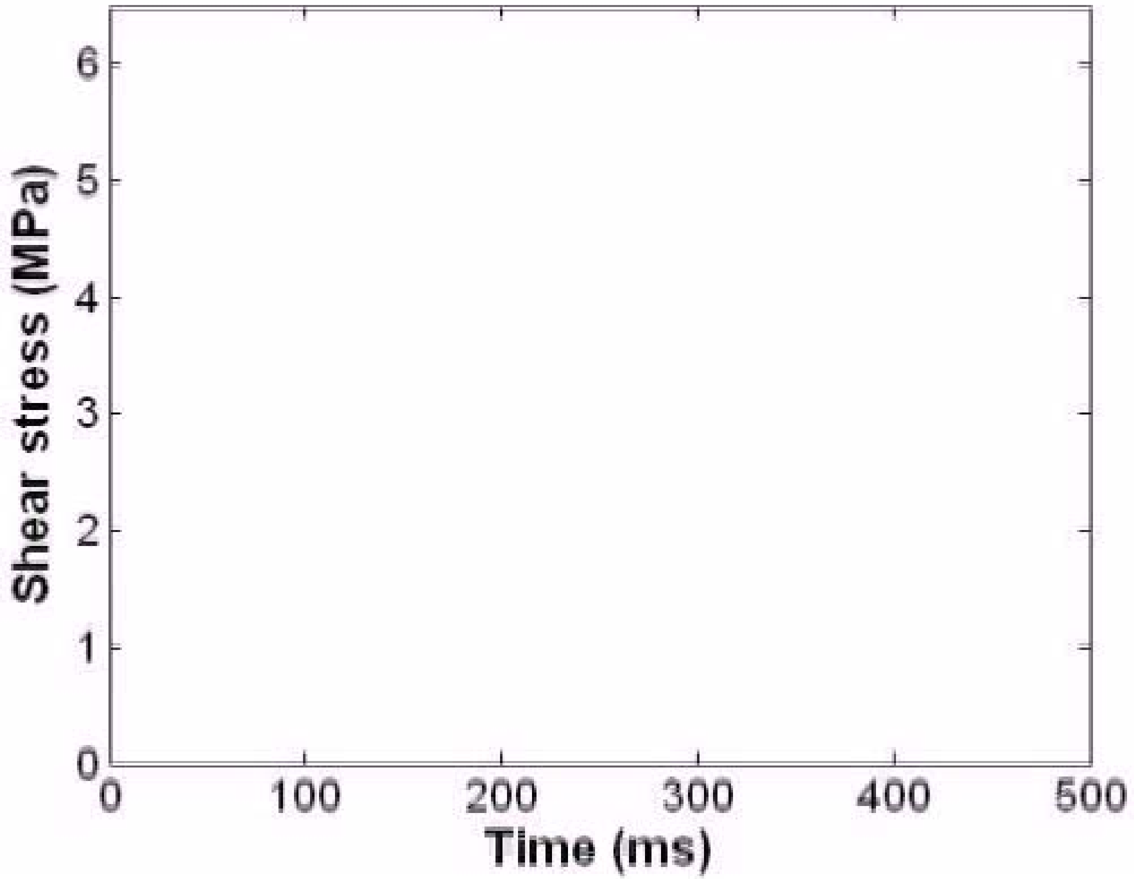
Spagnuolo et al., poster EGU2011-12748

SHIVA: gabbro at v = 3 m/s, σ_n = 20 MPa, 0 to 3 m/s in 0.5 s

High speed camera allows to investigate fault dynamic weakening mechanisms in detail



20 mm

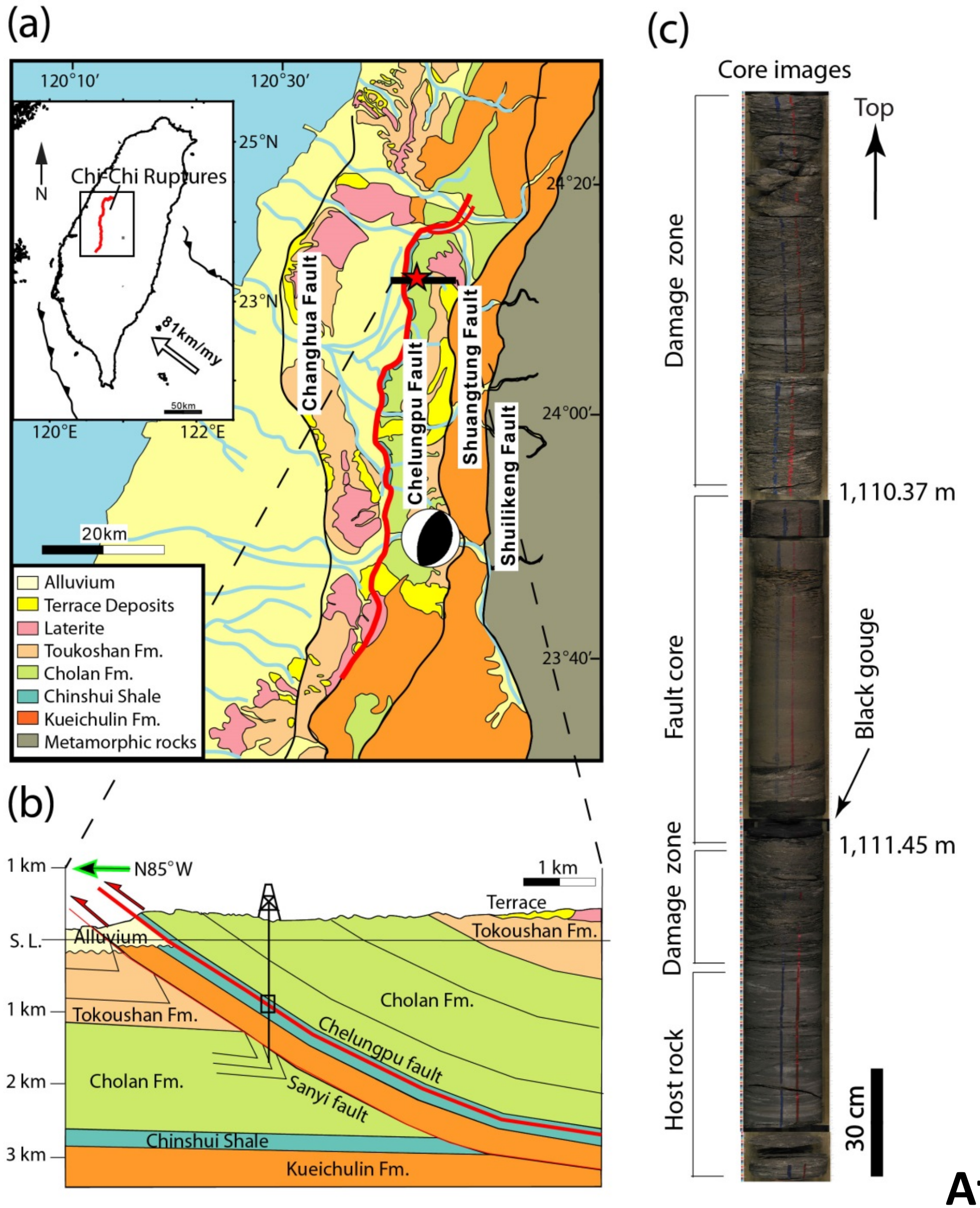


Niemeijer et al., in preparation

High Velocity Rock Friction Experiments (HVRFE) performed at seismic slip rates (**0.1-10 m/s**) may allow the:

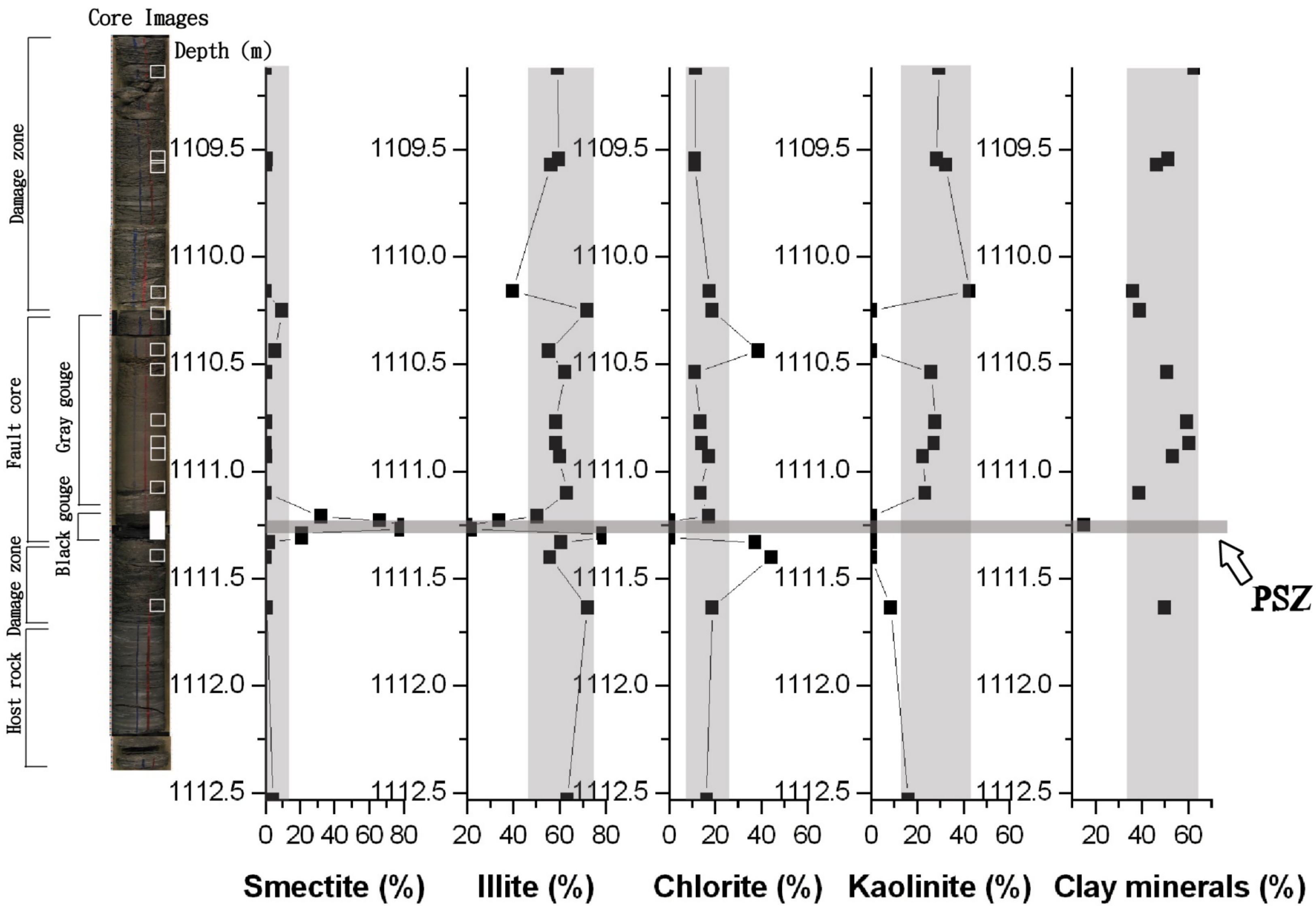
- Determination of dynamic friction (and its evolution) during seismic slip (friction energy, fracture energy and associated energy budget of EQ)
- Investigation of the processes occurred during simulated faulting
- Recognition of mineralogical and microstructural indicators within exhumed (or active) fault zones

1. Natural observation (TCDP)



After Hung et al., 2007 TAO

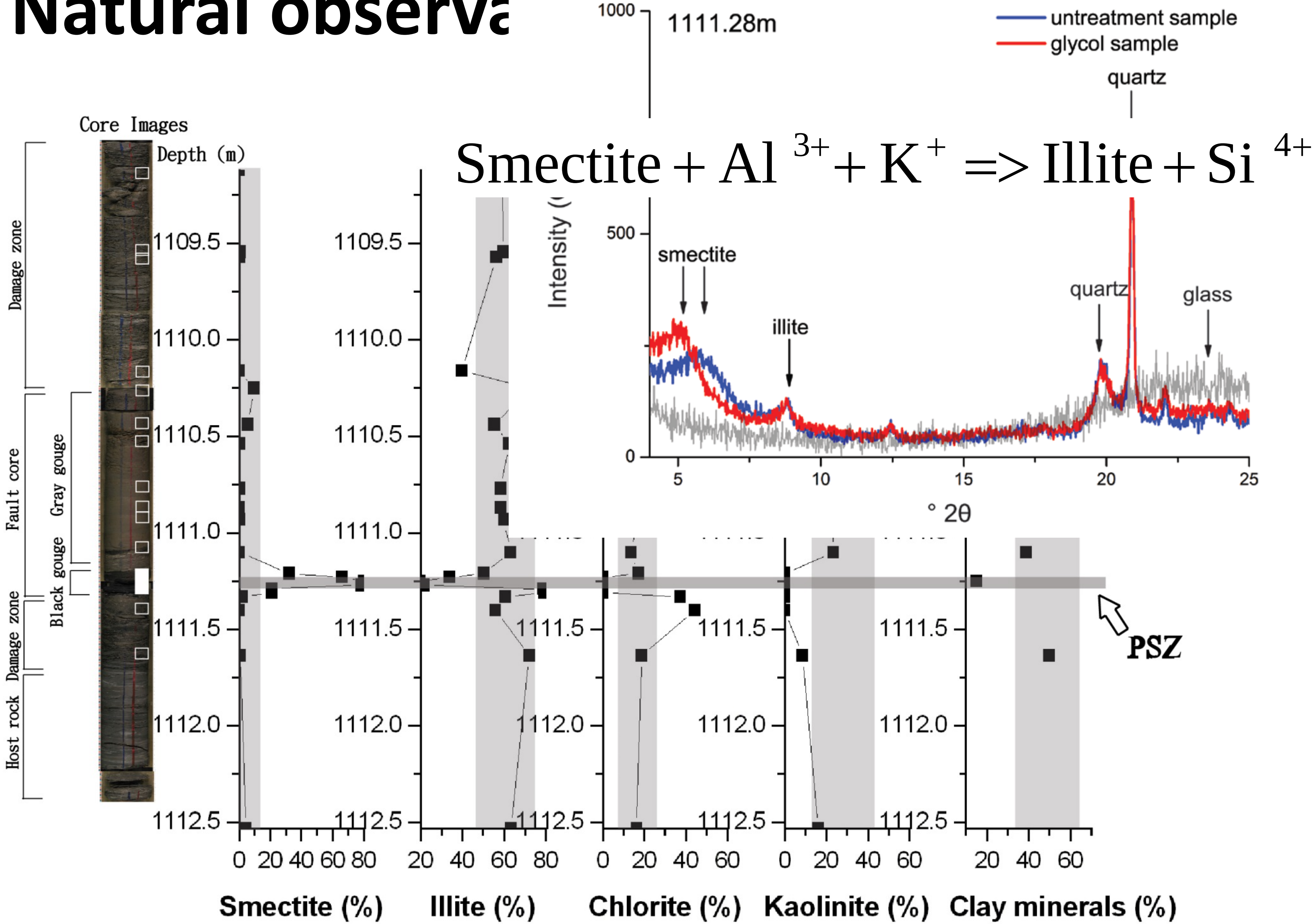
1. Natural observation (TCDP)



Kuo et al., 2009 GRL

1. Natural observa

$$Smectite + Al^{3+} + K^{+} \Rightarrow Illite + Si^{4+}$$



Kuo et al., 2009 GRL

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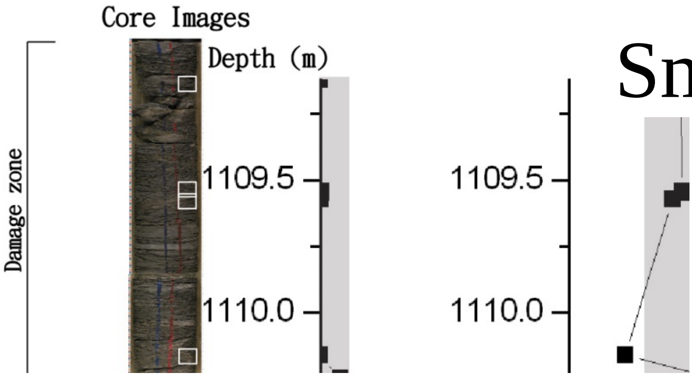

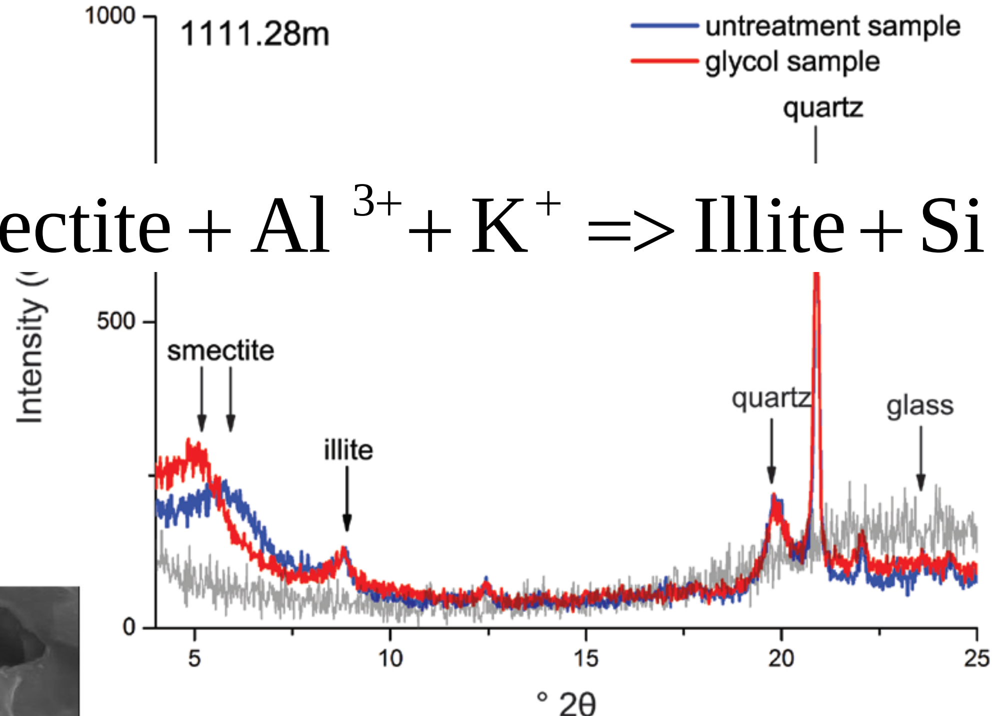

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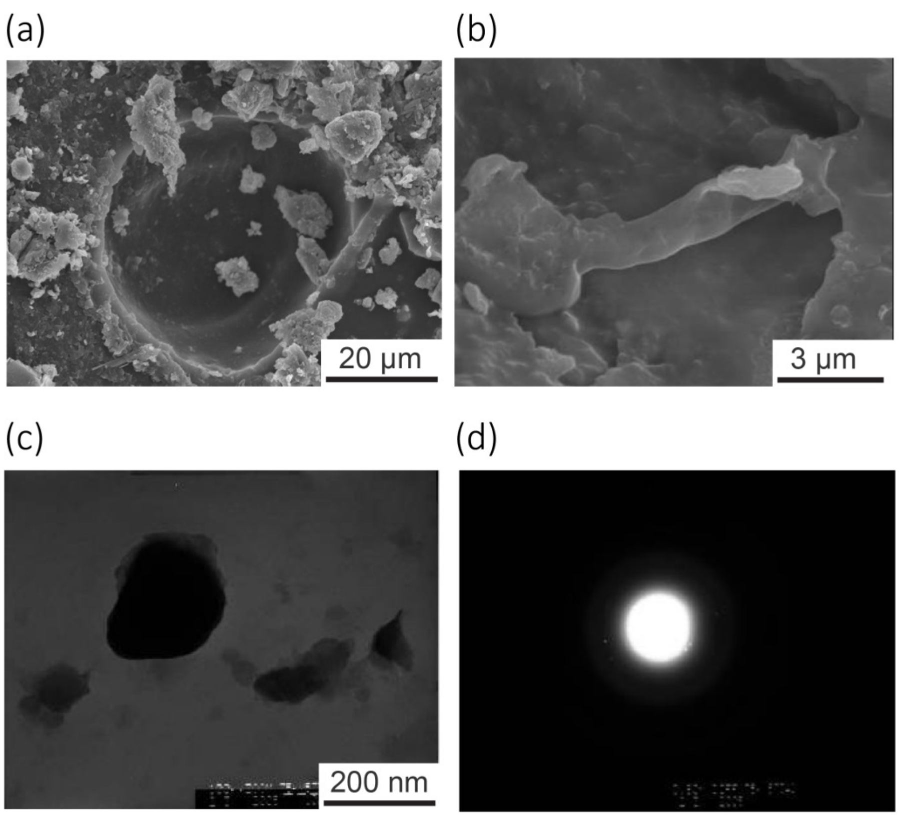
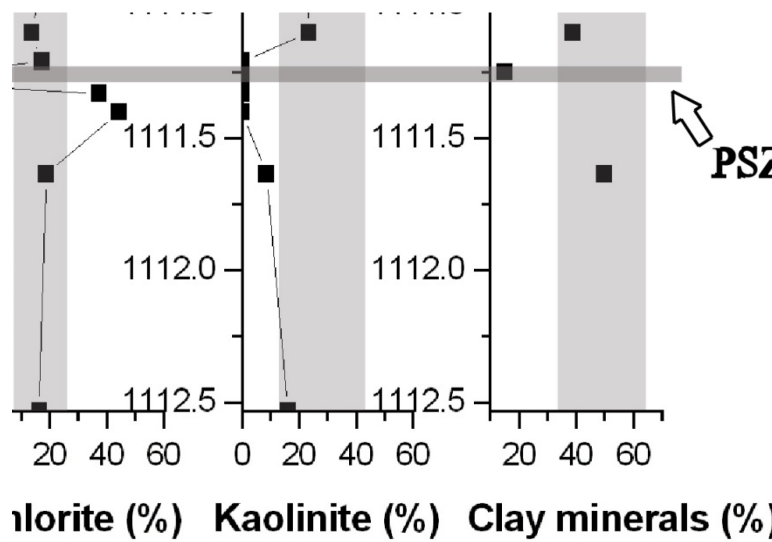




Kuo et al., 2009 GRL

1. Natural observa

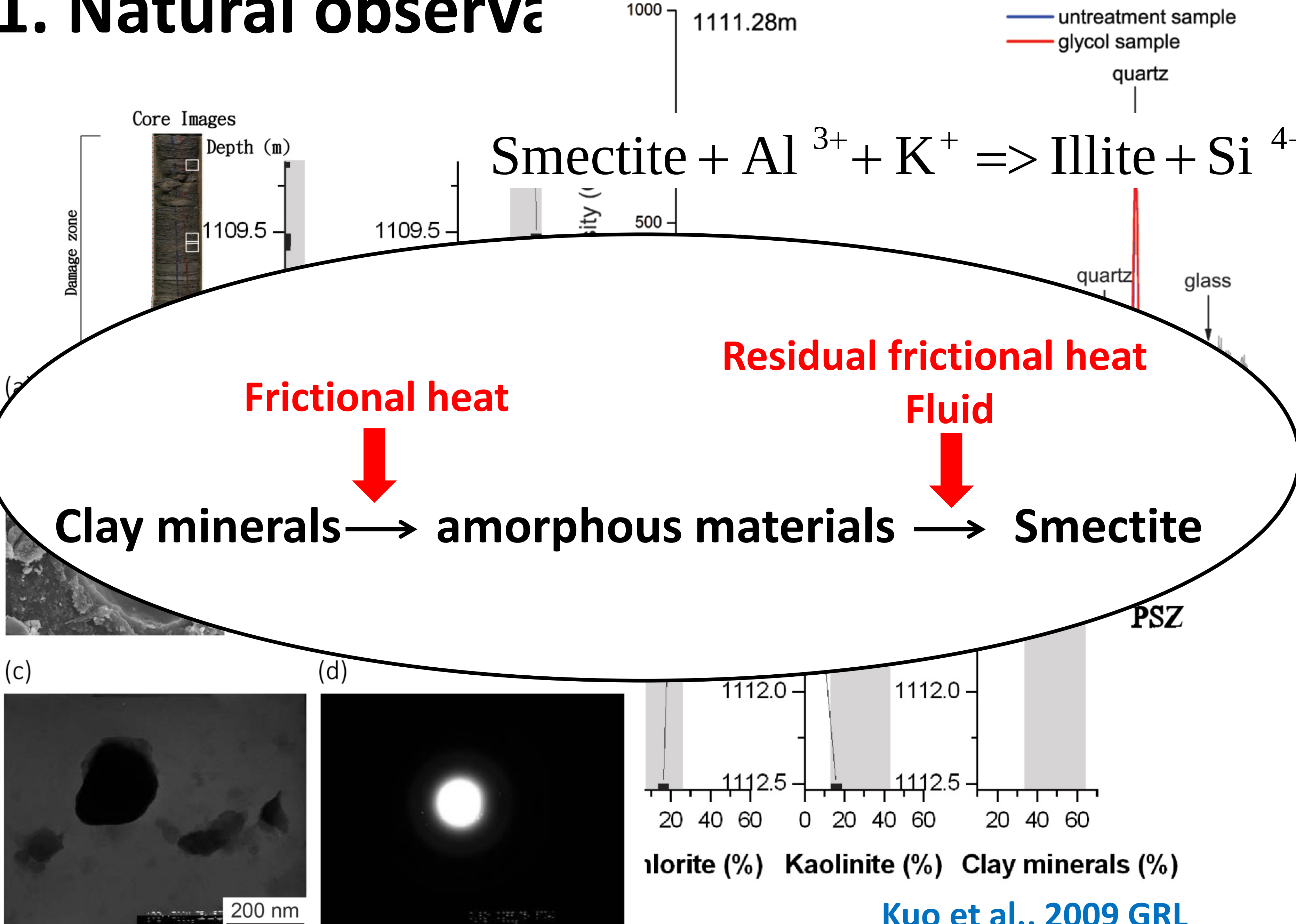
$$Smectite + Al^{3+} + K^{+} => Illite + Si^{4+}$$

Frictional heat

Residual frictional heat

Fluid

Clay minerals ⟶ amorphous materials ⟶ Smectite



Kuo et al., 2009 GRL

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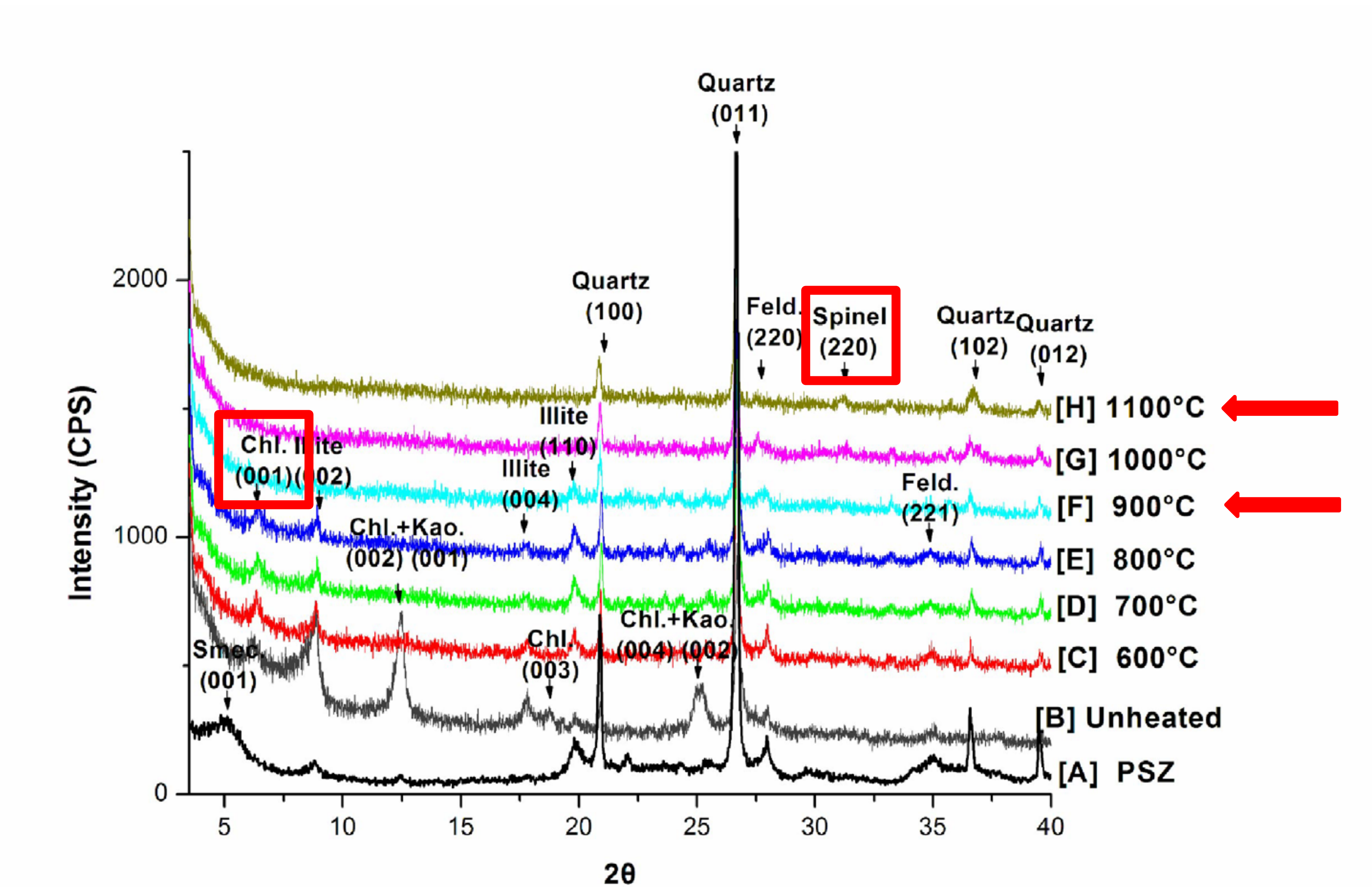
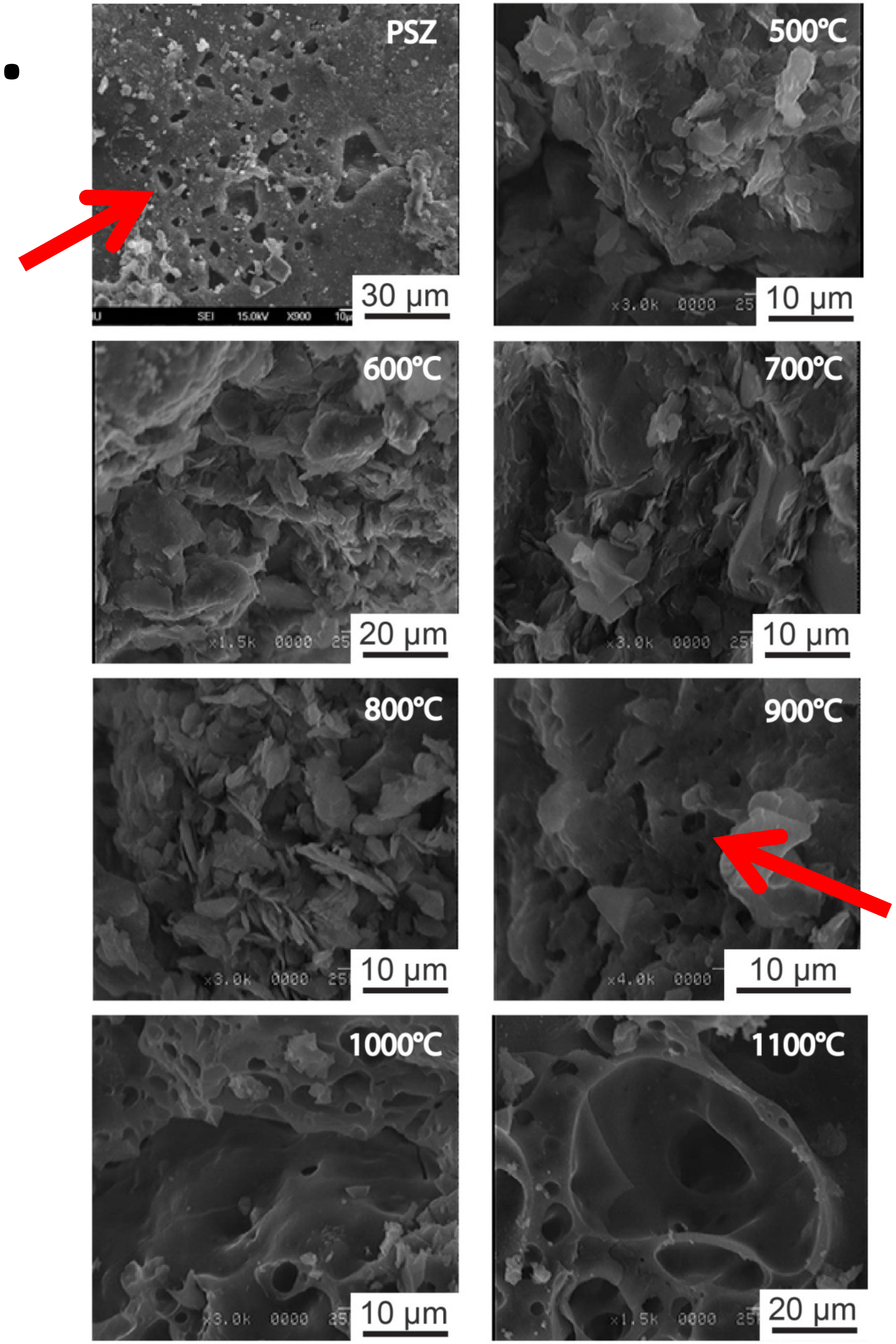


Kuo et al., 2011 Tectonophysics

1.



(TCDP)

Kuo et al., 2011 Tectonophysics

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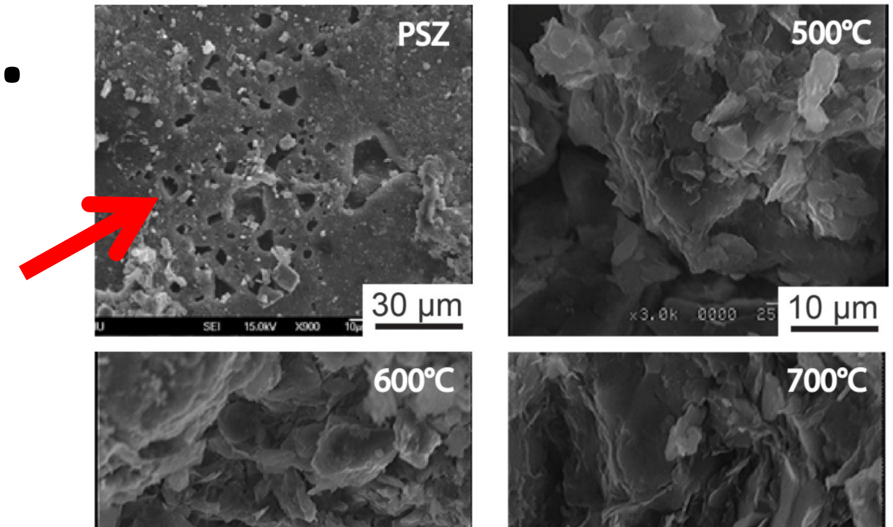
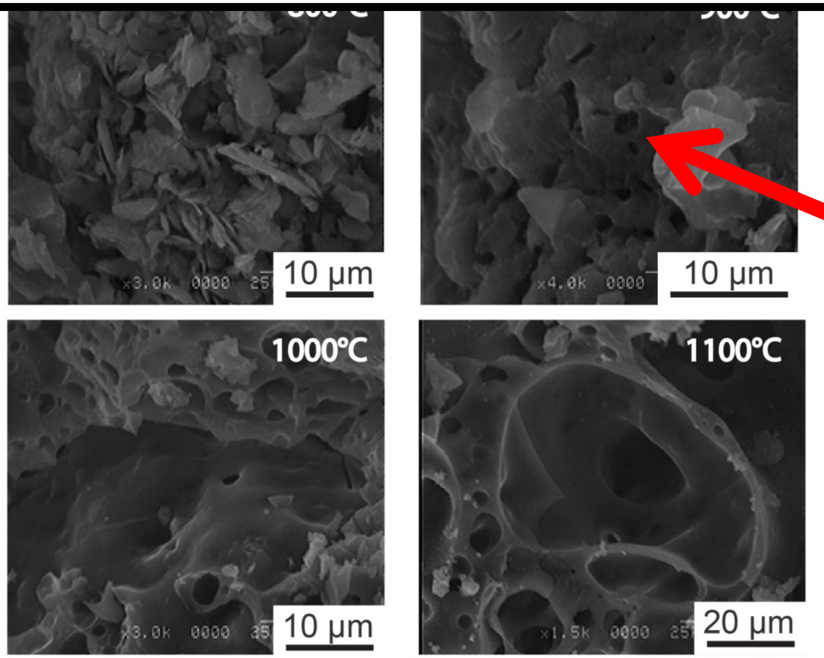
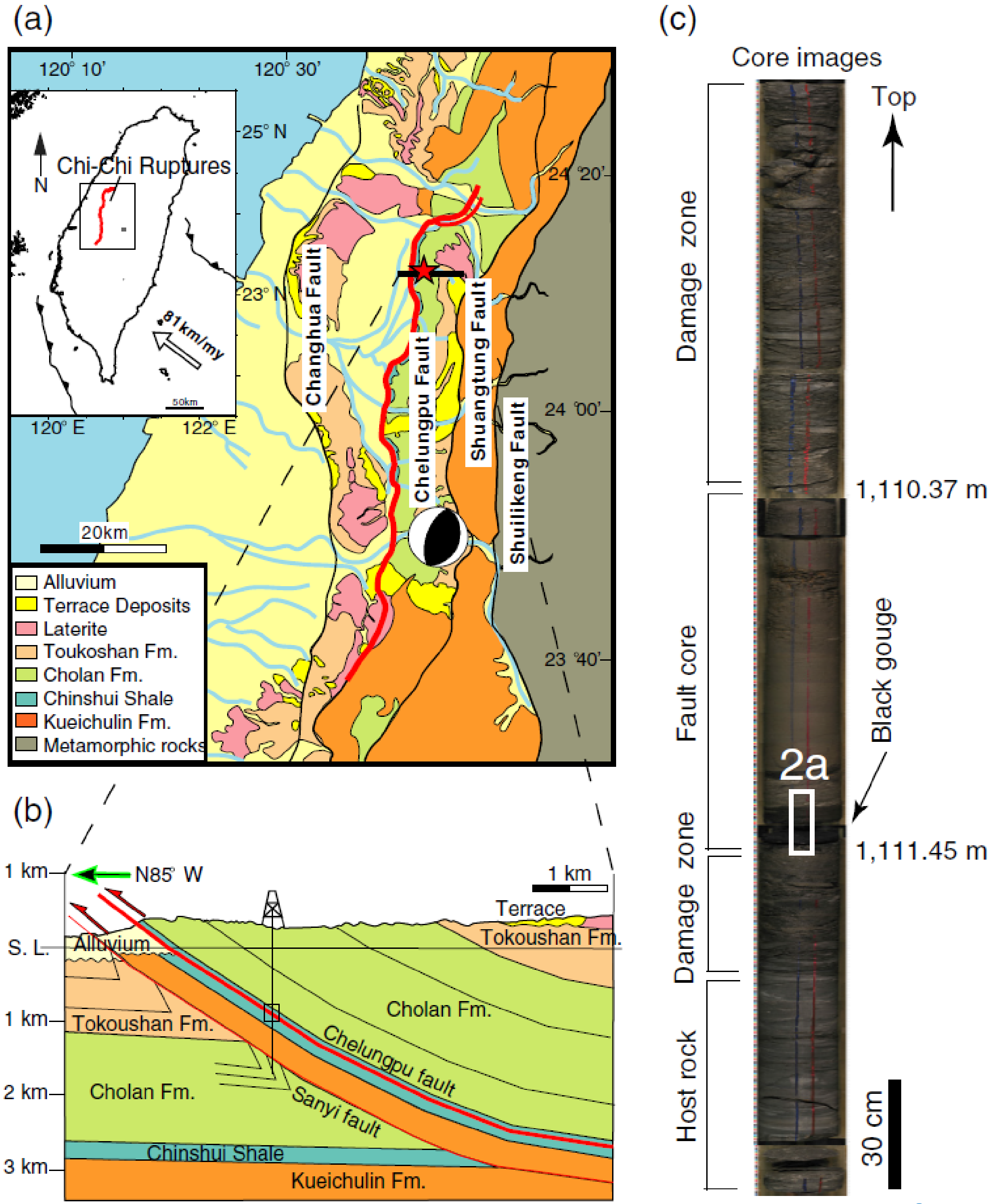


- Estimated **temperature** generated by faulting within the PSZ is **900-1100°C**



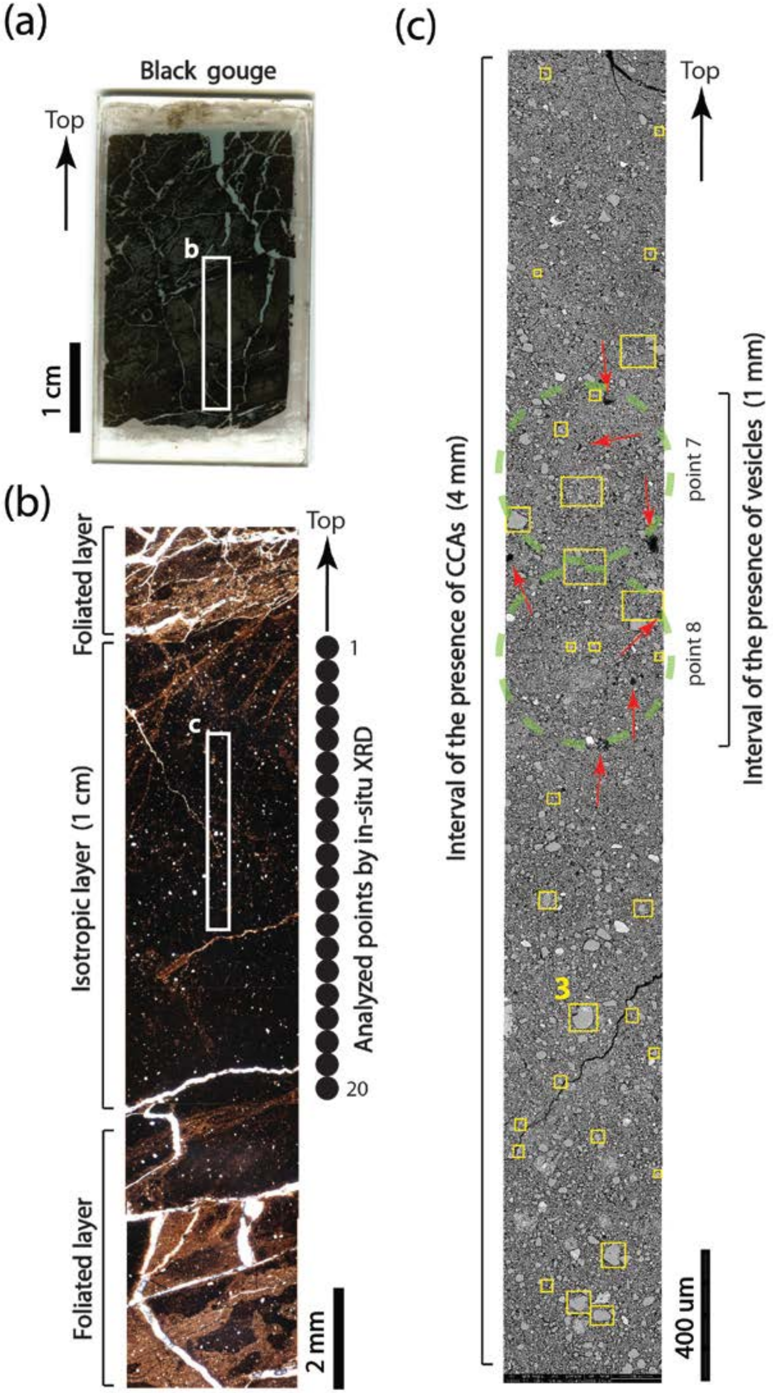
Kuo et al., 2011 Tectonophysics

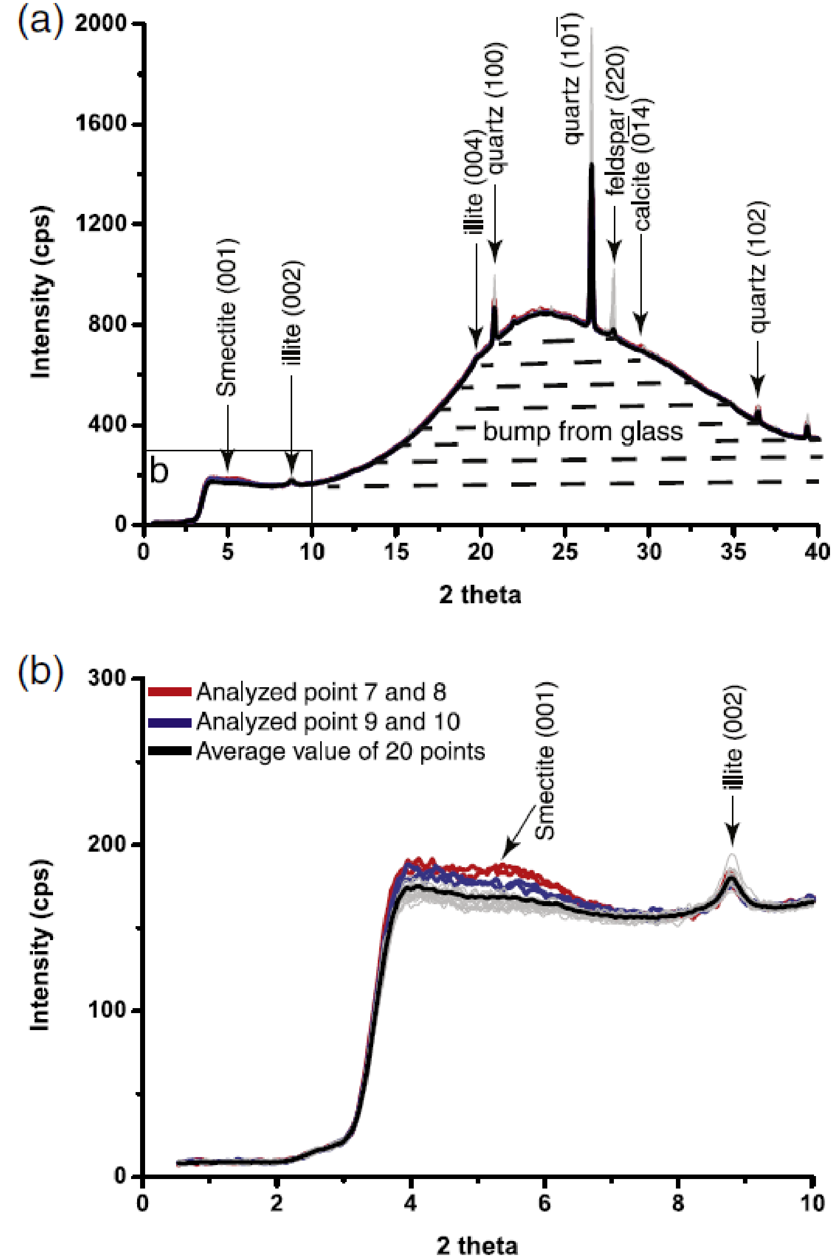
1. Natu



Kuo et al., 2014 Tectonophysics

1

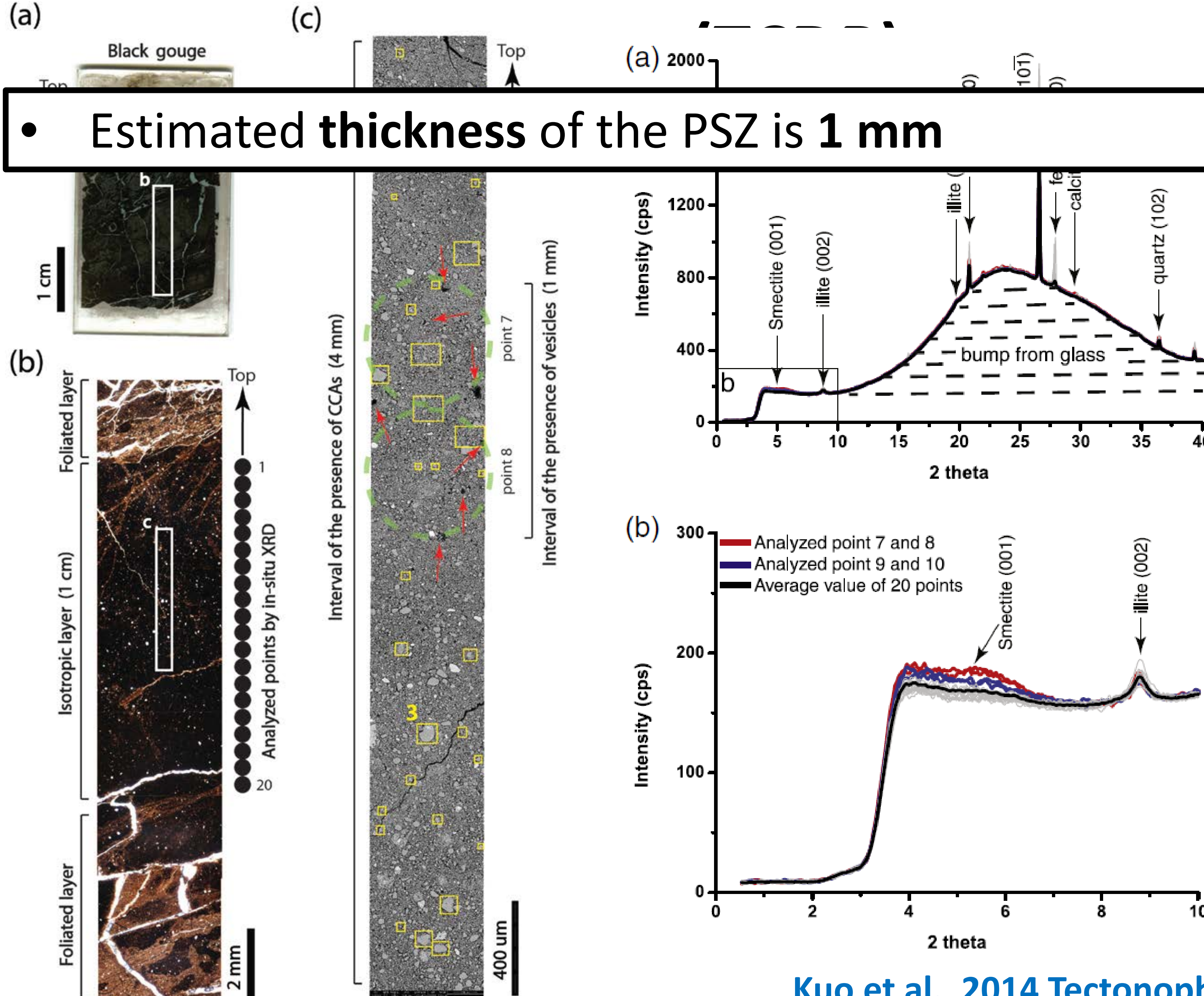




Kuo et al., 2014 Tectonophysics

1

- Estimated **thickness** of the PSZ is **1 mm**



Kuo et al., 2014 Tectonophysics

1

- Estimated **thickness** of the PSZ is **1 mm**

- **Surface fracture energy (0.22 MJ m-2)** is **1.9%** of the breakdown work (11.6 MJ m-2)
- **Frictional energy** is estimated about **3.24 MJ m-2**

$E_H = [(1-\phi)H + C_p (T_m - T_{hr})]\rho t$ (Di Toro et al., 2005 Tectonophysics)

ϕ = ratio of clasts/pt matrix (0.5)

H = latent heat of fusion (3.28×10^5 Jkg^{-1})

C_p = the specific heat (1277 $Jkg^{-1}K^{-1}$)

T_m = initial friction melt temperature (1273°K)

T_{hr} = host rock temperature (320°K)

ρ = melt density (2350 kgm^{-3})

t = average pseudotachylyte thickness (1×10^{-4} m)

$G_{msz} = S_{msz}\lambda G_c$ (Scholz, 2002; Ma et al., 2006 Nature)

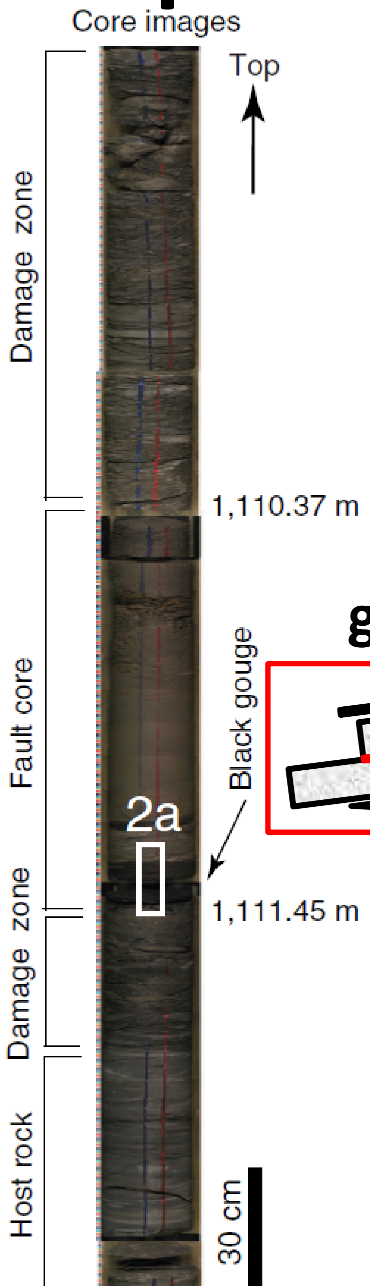
S_{msz} = particle surface area (3.23×10 m^2 per metre squared area)

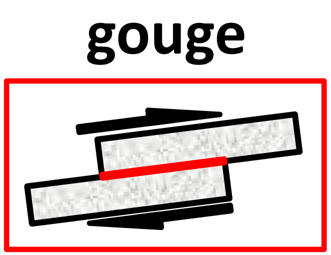
λ = grain roughness (0.66)

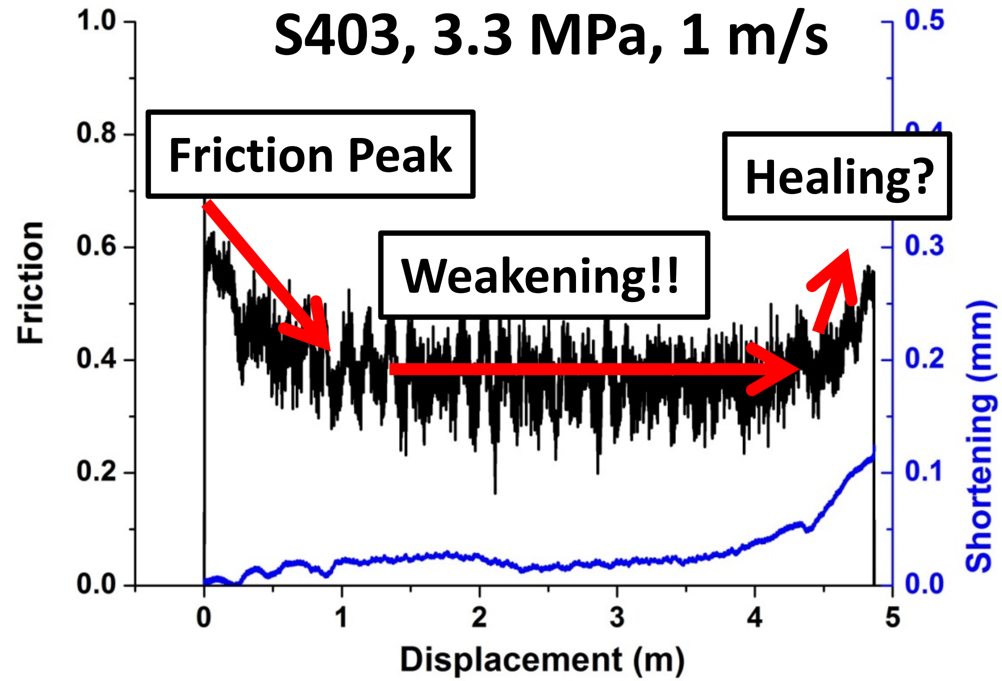
G_c = specific fracture energy (1 Jm^{-1})

Kuo et al., 2014 Tectonophysics

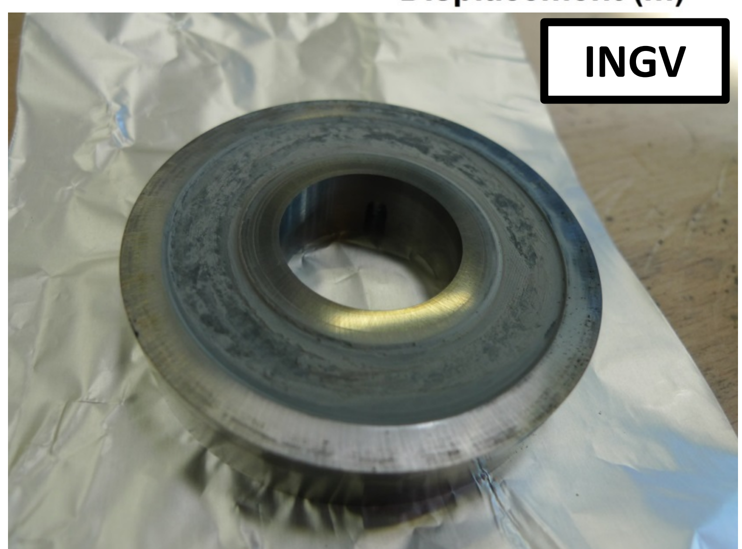
1. Experimental results (TCDP)





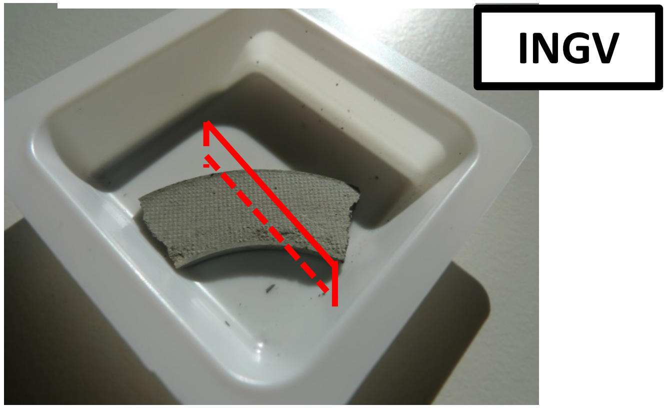


20 mm

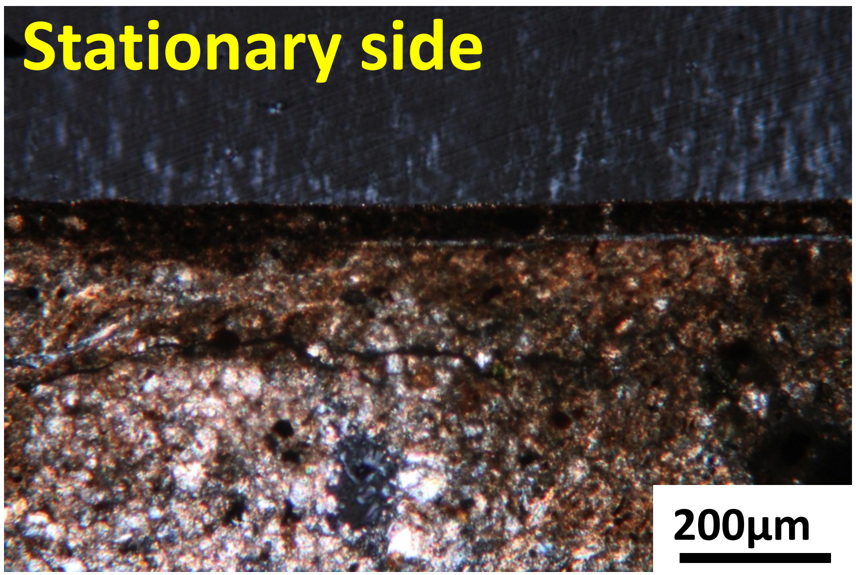


Kuo et al., 2012 EGU

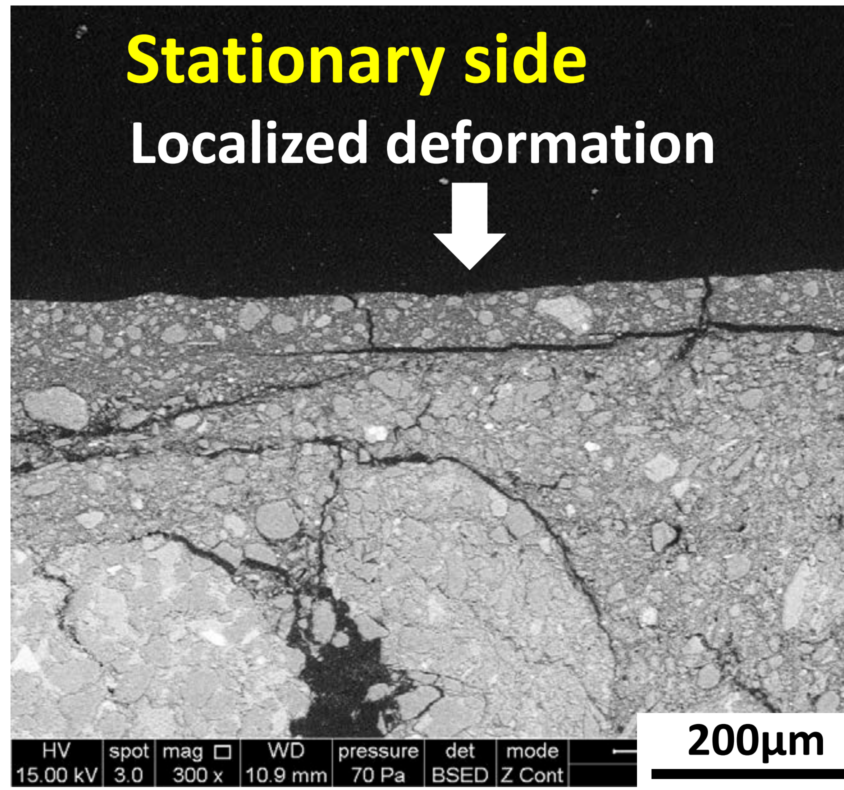
Thin section



Change in deformation mechanism close to **slip surface**

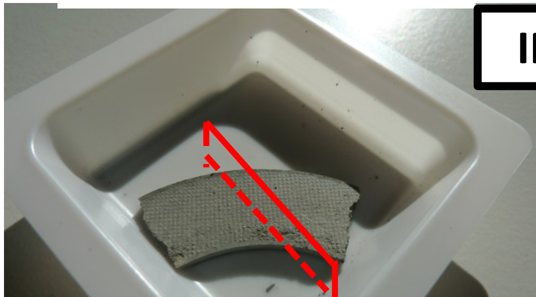


S403, 2.3 MPa, 4.4 m/s



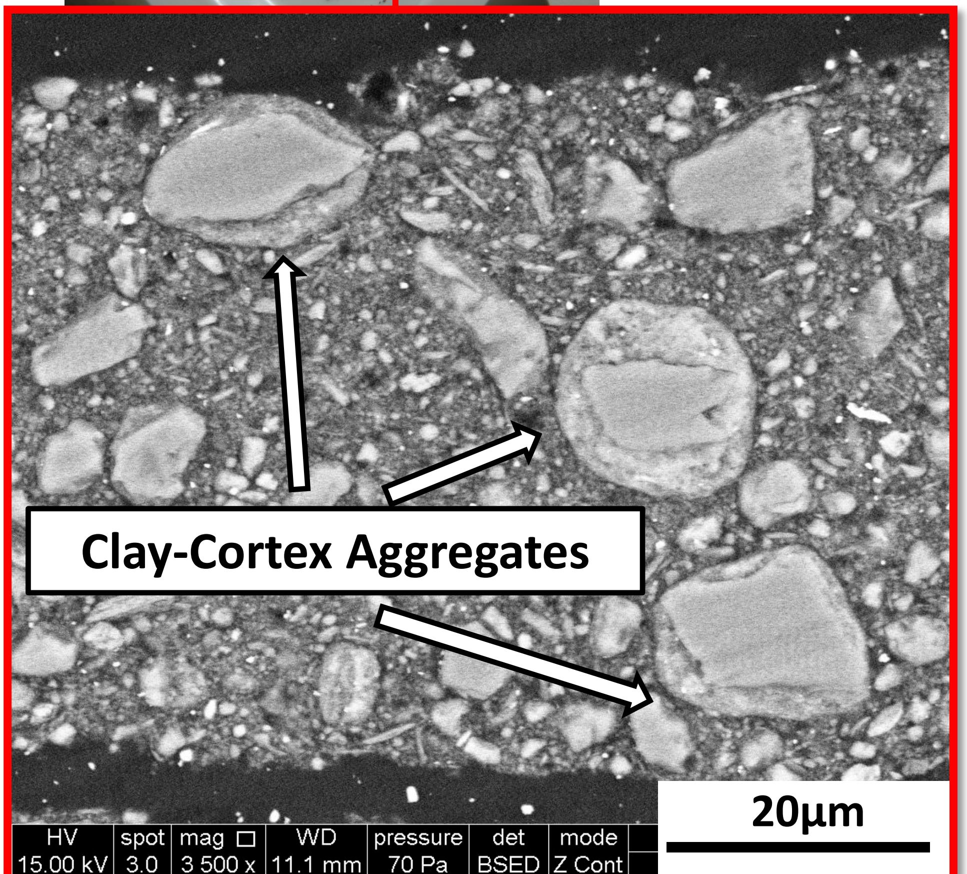
Kuo et al., 2012 EGU

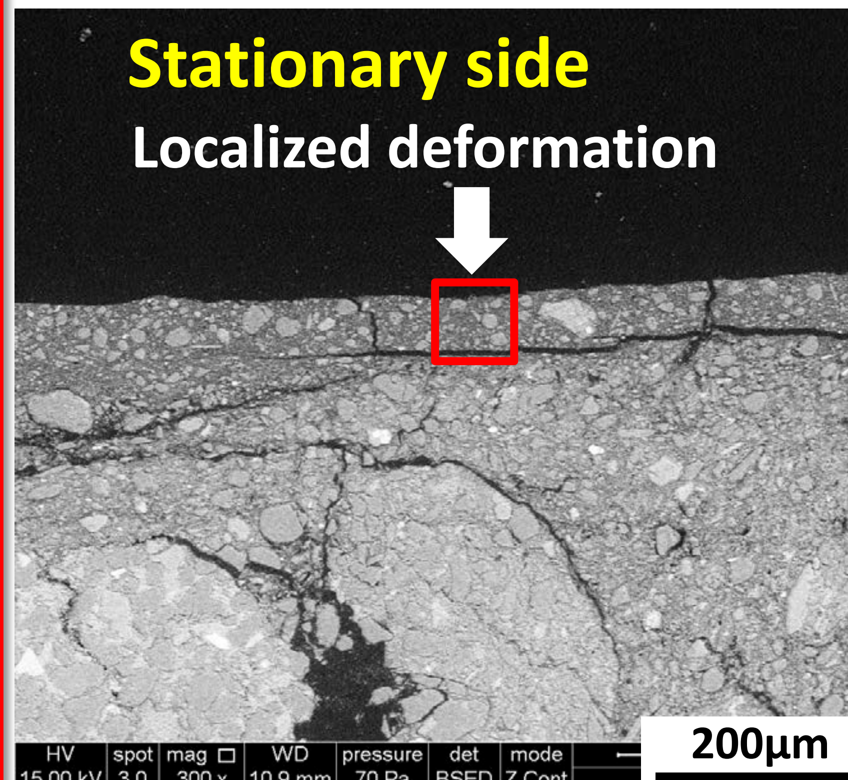
Thin section



INGV

Change in deformation mechanism close to **slip surface**

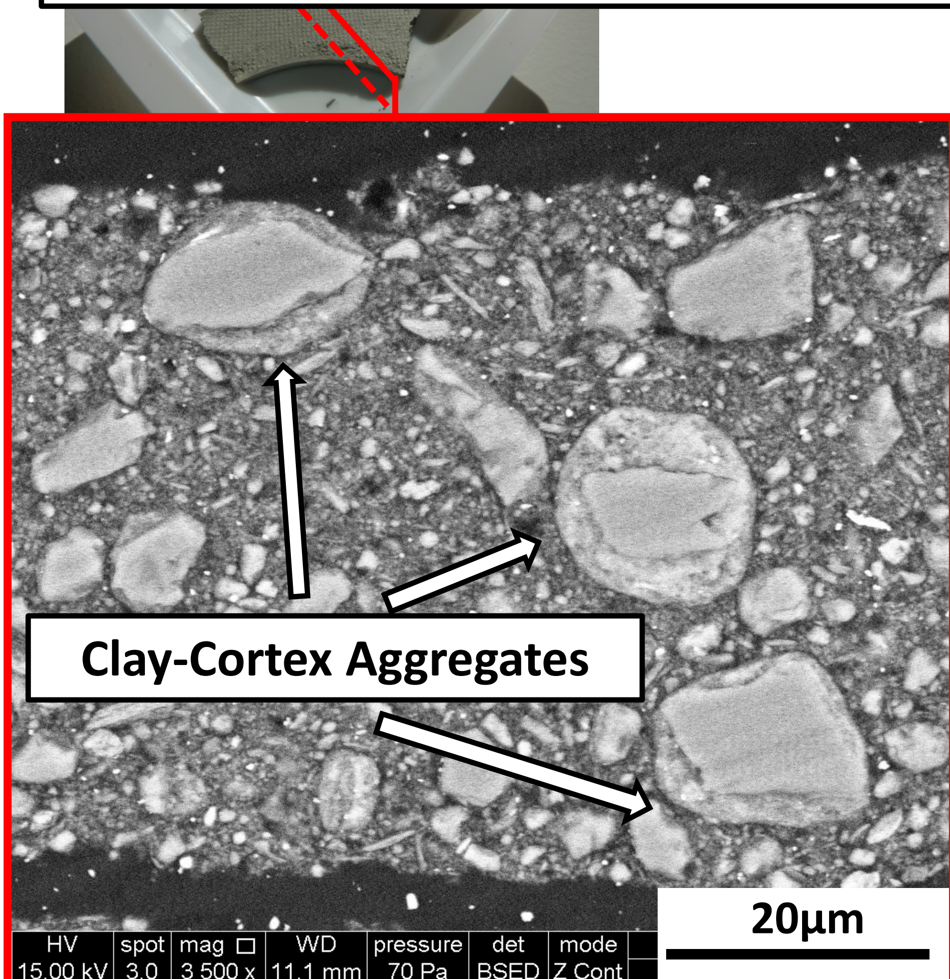




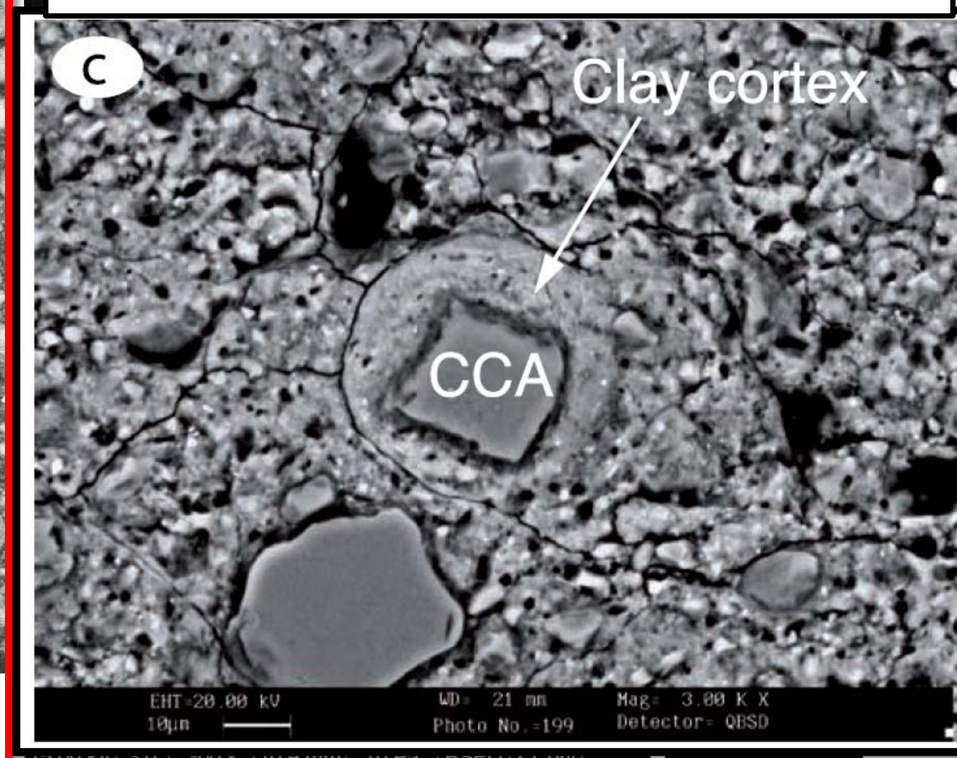
Kuo et al., 2012 EGU

Are experimental products similar to natural ones?

Yes (example for clay-rich gouge).



Natural observation in the PSZ

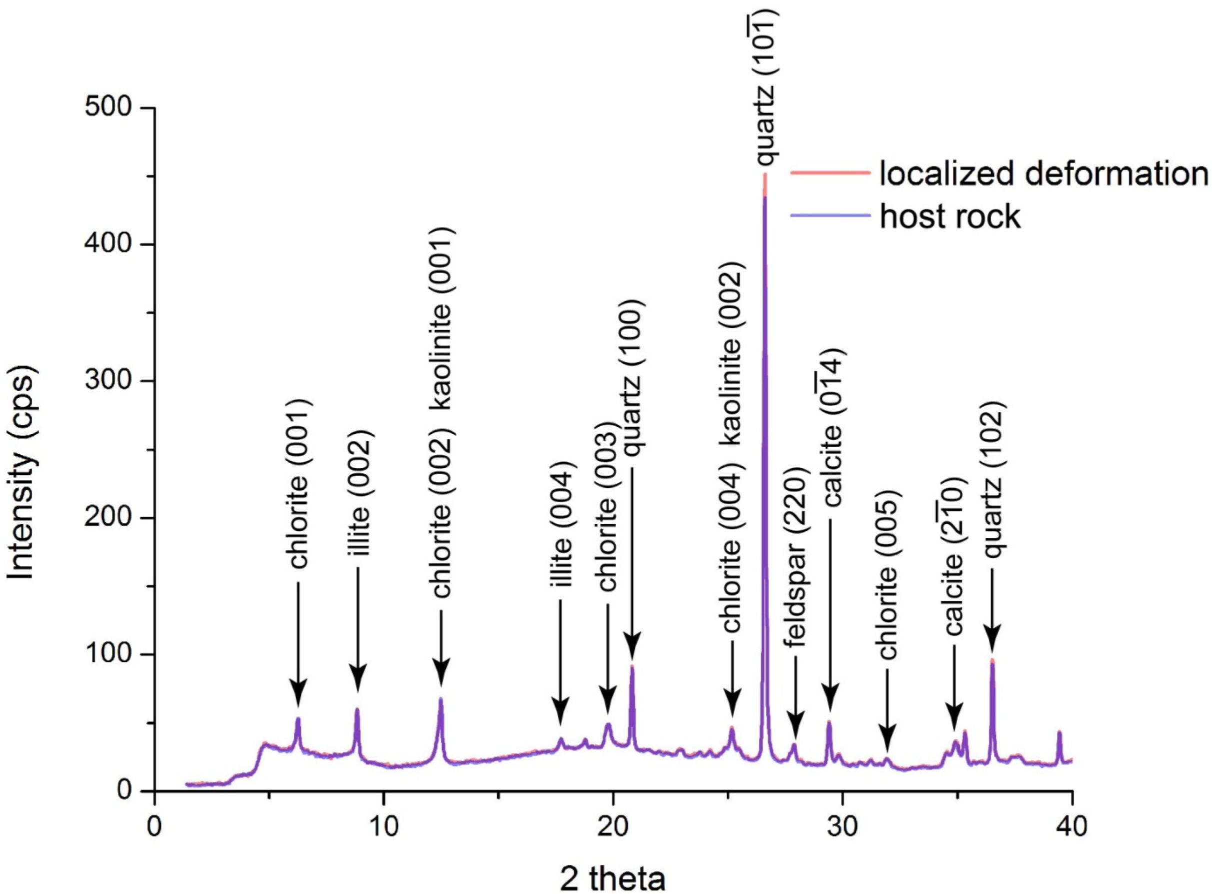


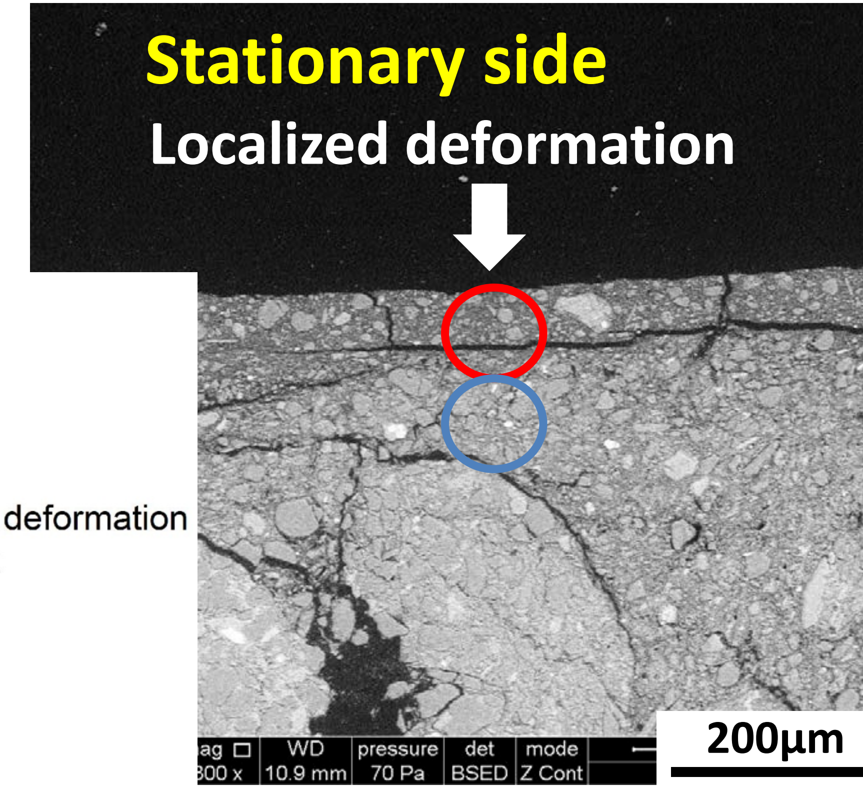
Boullier et al., 2009 G cube

Kuo et al., 2012 EGU

1. Experimental results (TCDP)

No mineral phase change!!

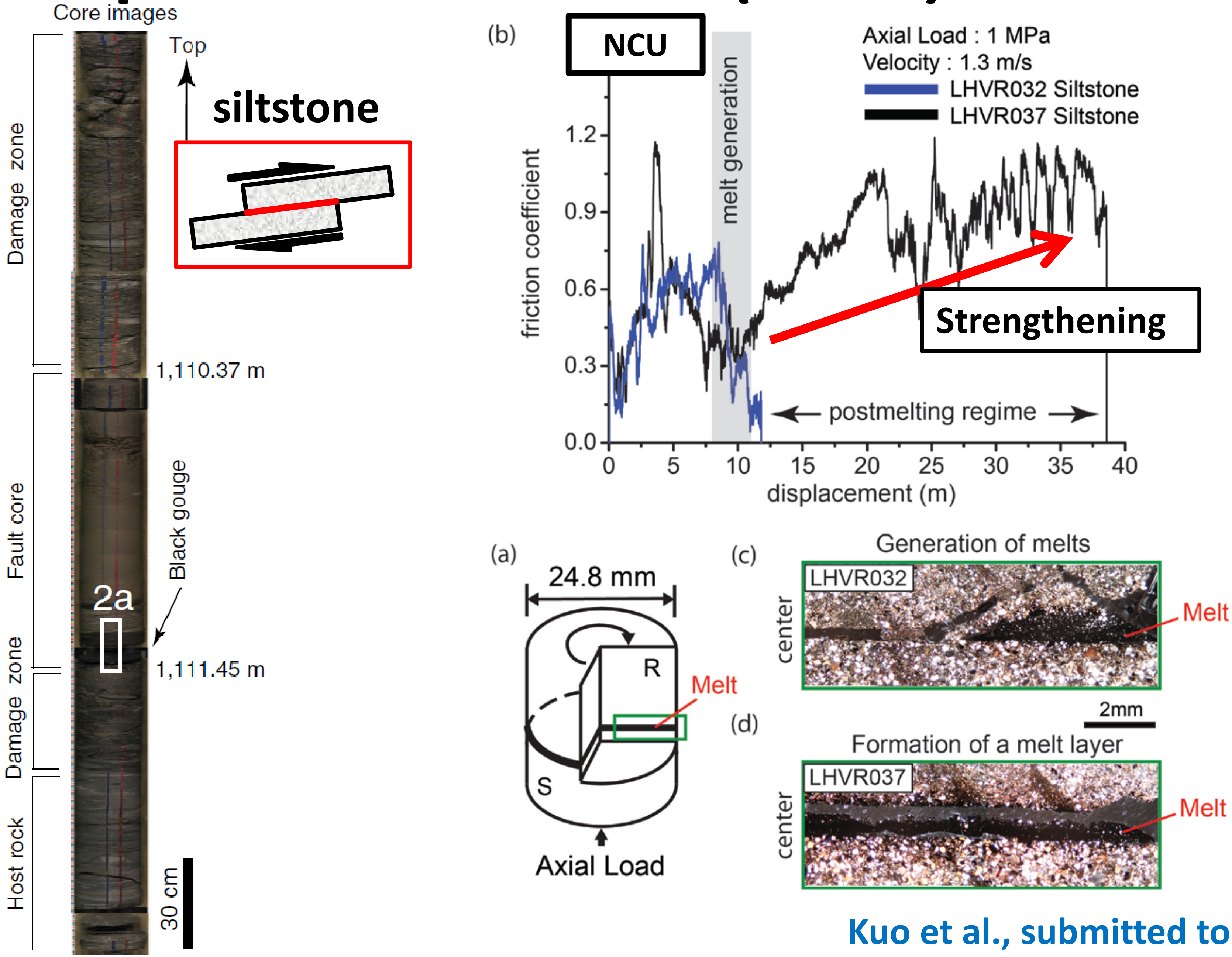




S403

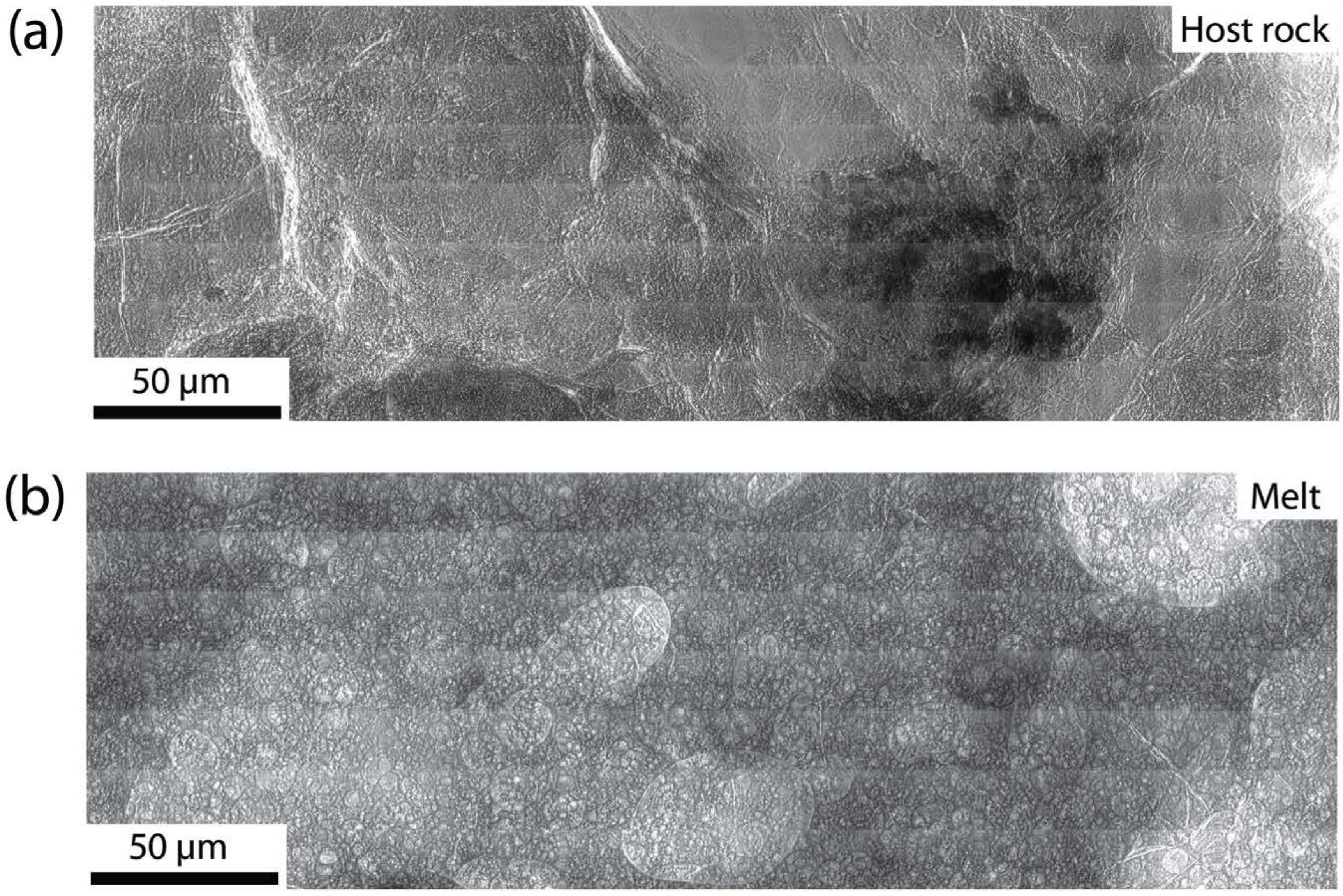
Kuo et al., 2012 EGU

1. Experimental results (TCDP)



Kuo et al., submitted to JGR

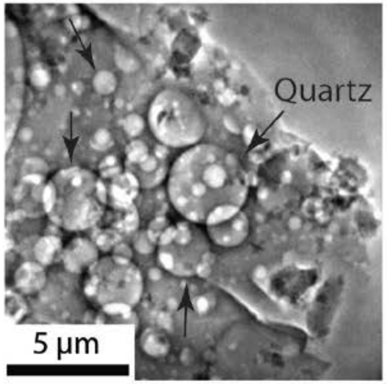
1. Experimental results (TCDP)



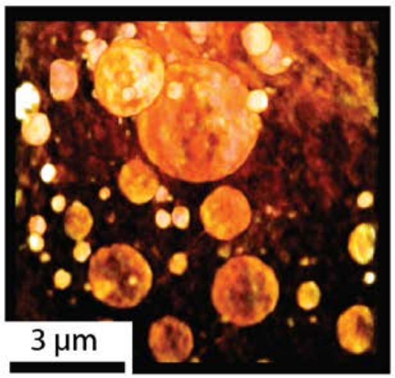
Kuo et al., submitted to JGR

1. Experimental results (TCDP)

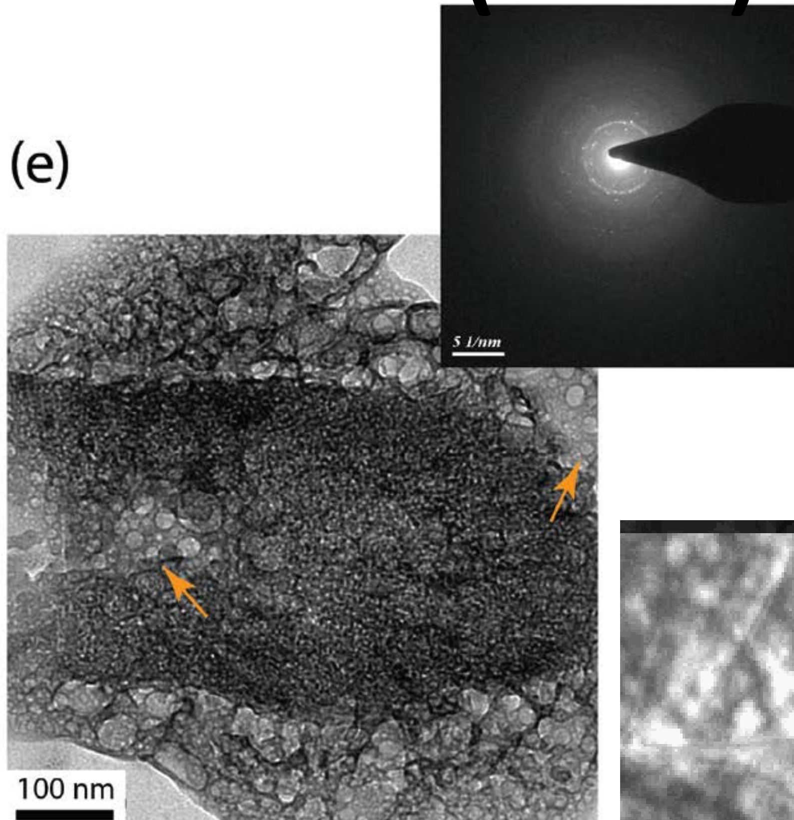
(c)

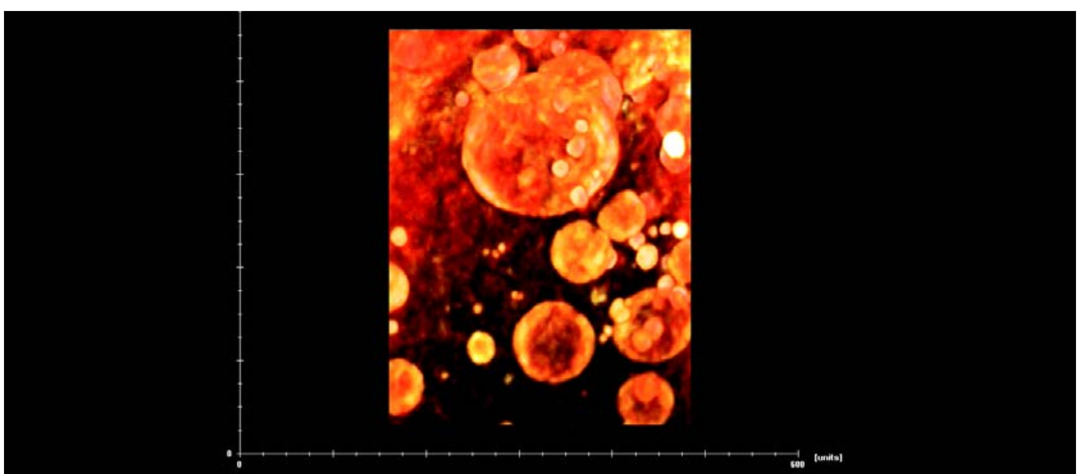


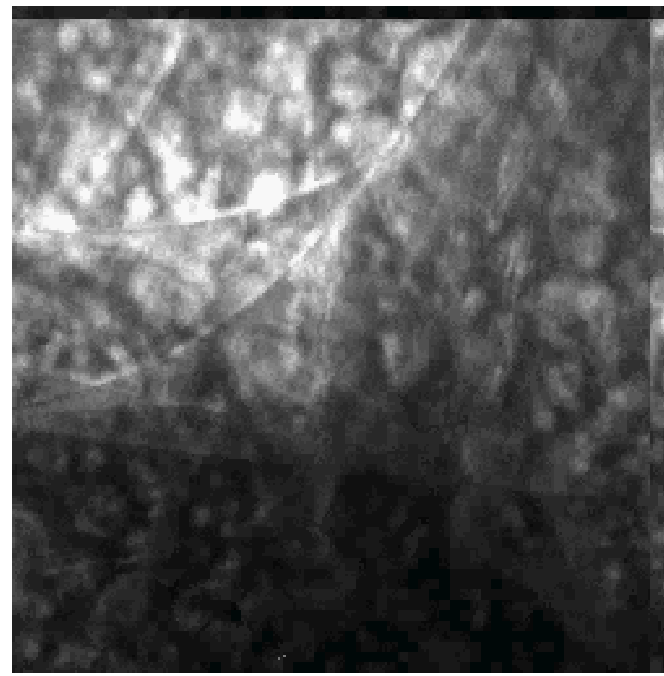
(d)



(e)



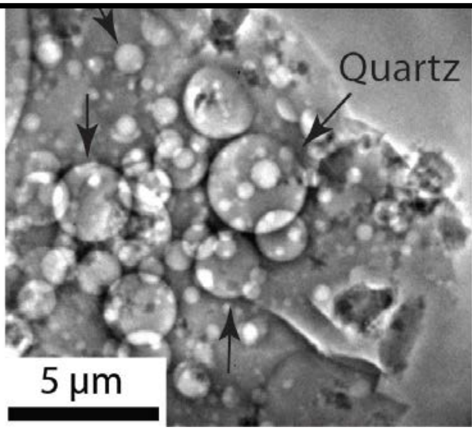




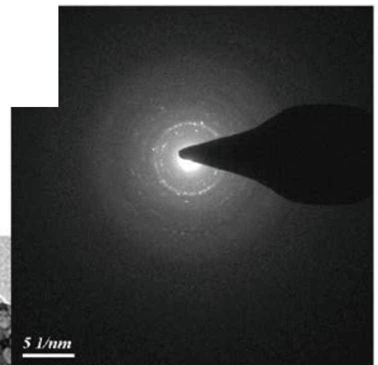
Kuo et al., submitted to JGR

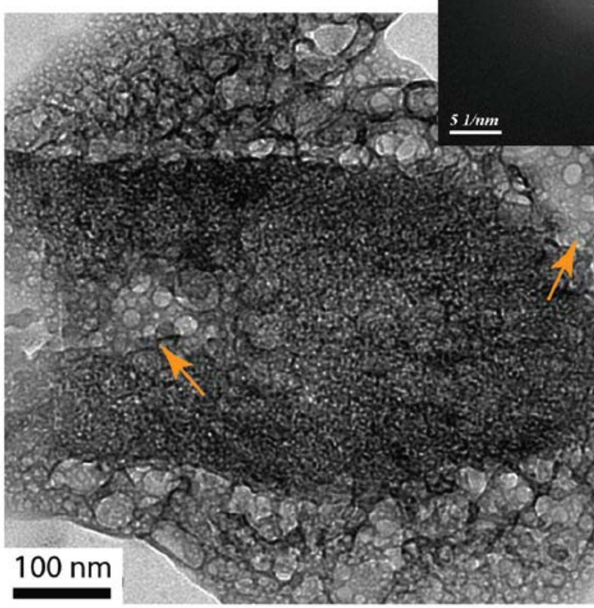
Are experimental products similar to natural ones?

Yes (example for solid host rock).

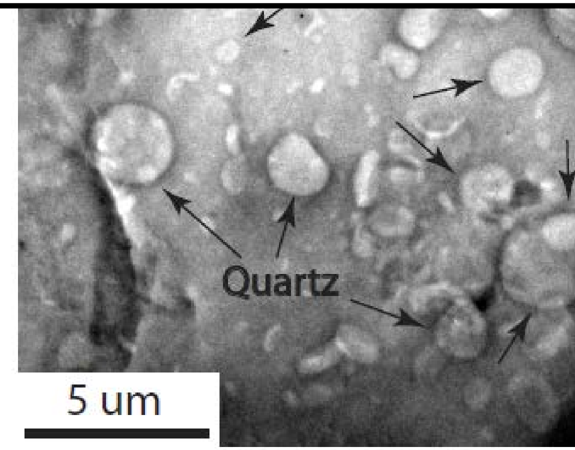


(e)

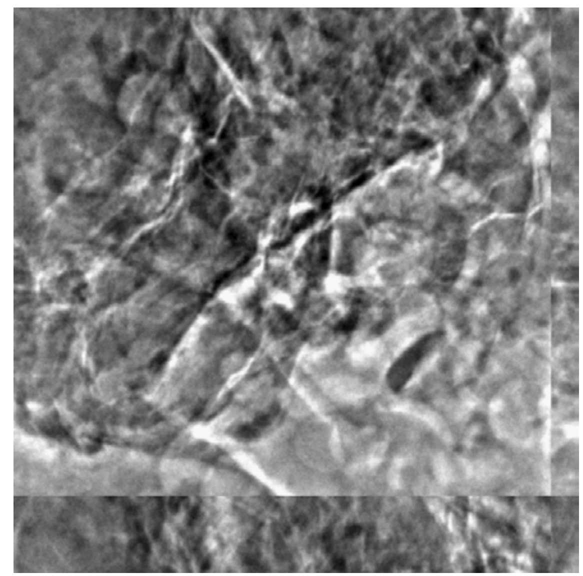




Natural observation in the PSZ

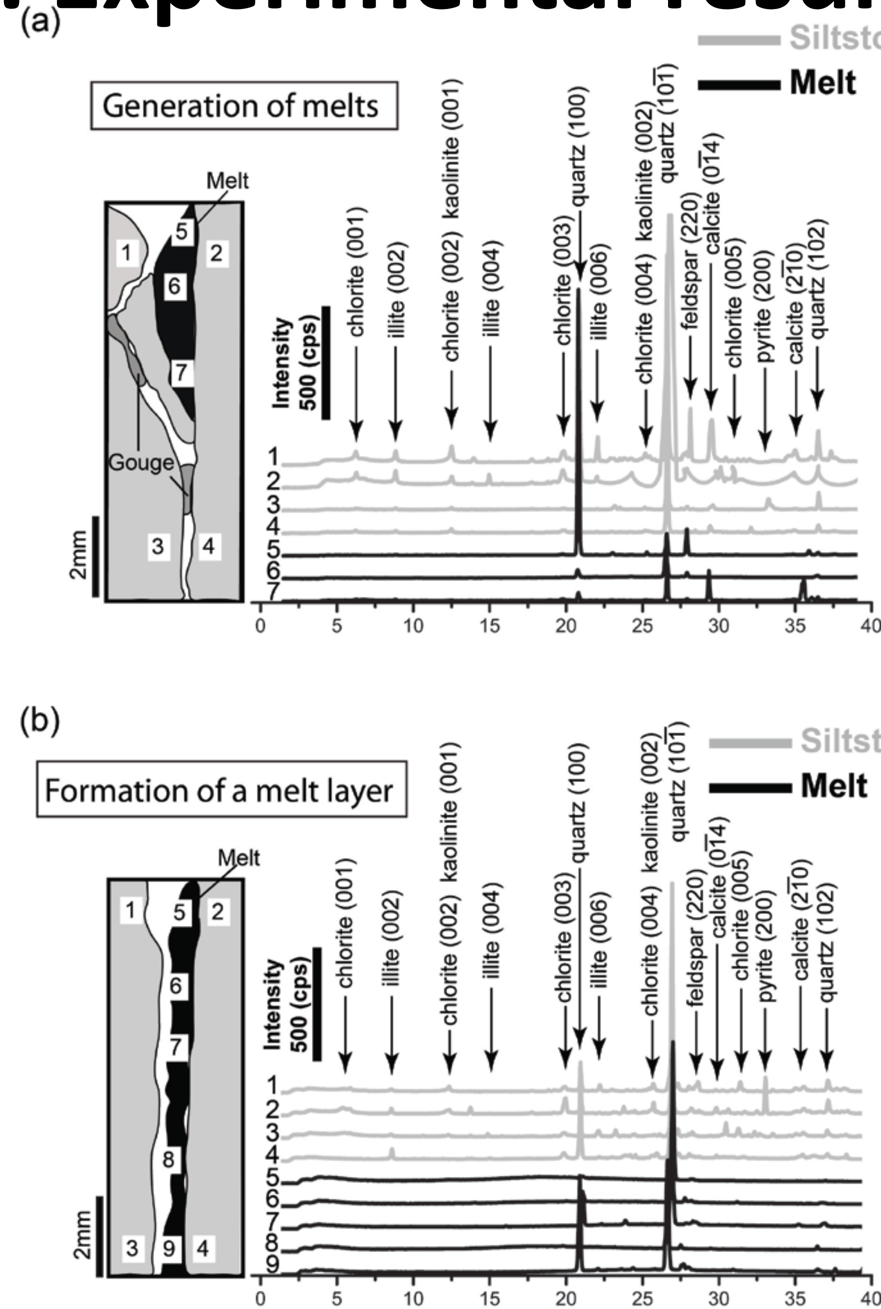


Ma et al., 2006 Nature



Kuo et al., submitted to JGR

1. Experimental results (TCDP)



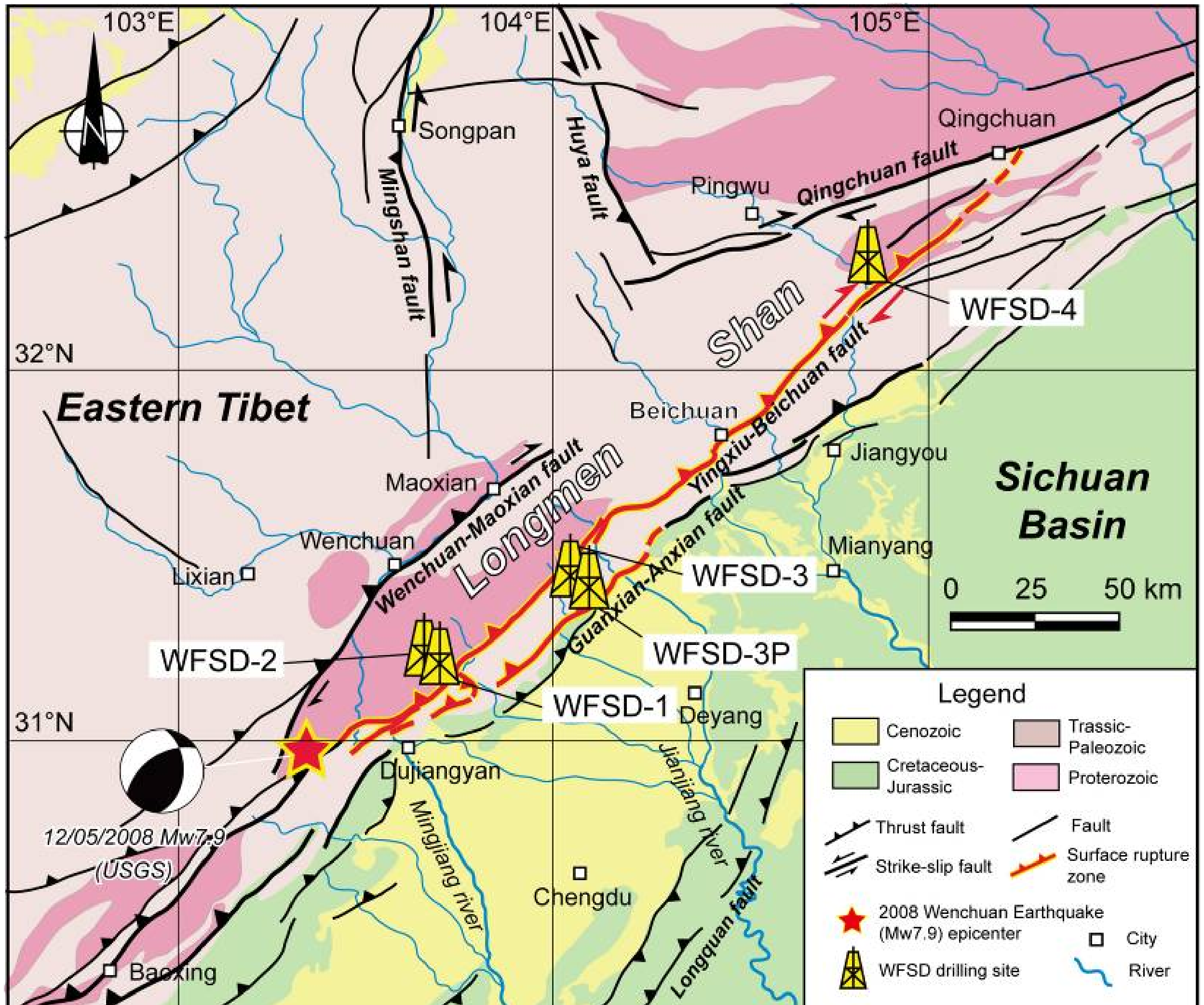
(1) the **ultrafine spherical quartz** grains (USQ) were discovered in **PSZ** of the Chelungpu fault
(2) rock friction experiments **on siltstone** generated **USQ** in the matrix of pseudotachylyte,
(3) **slip strengthening** was presumably resulted from the **dehydration of pseudotachylyte**,
(4) similarity to experimentally friction formed products, the USQ in the PSZ was plausibly the result of seismic slip on siltstone,
(5) the **presence of USQ** represent an **indicator for the slip zone of the most recent seismic event**.

Kuo et al., submitted to JGR

Summary

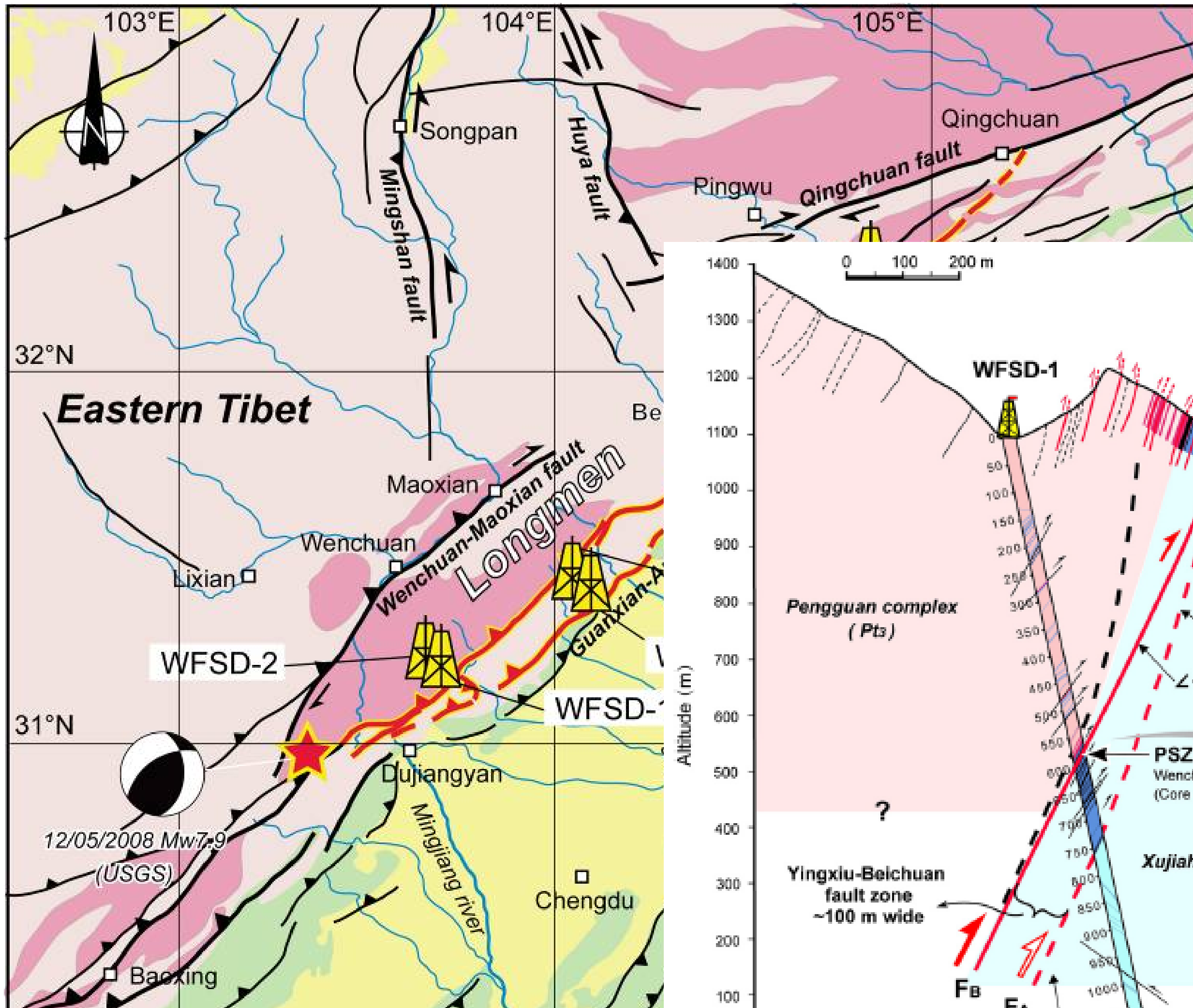
- The **PSZ** corresponding to the 1999 Mw7.6 Chi-Chi earthquake was recognized at the depth of 1,111m.
- **Frictional melting occurred** (on solid host rock and/or clay-rich gouge) during the EQ.
- **Earthquake source parameters** were estimated.
- **Multi-fault zone processes** occurred simultaneously during the earthquake because of **heterogeneous physical properties and geometry along the fault**.

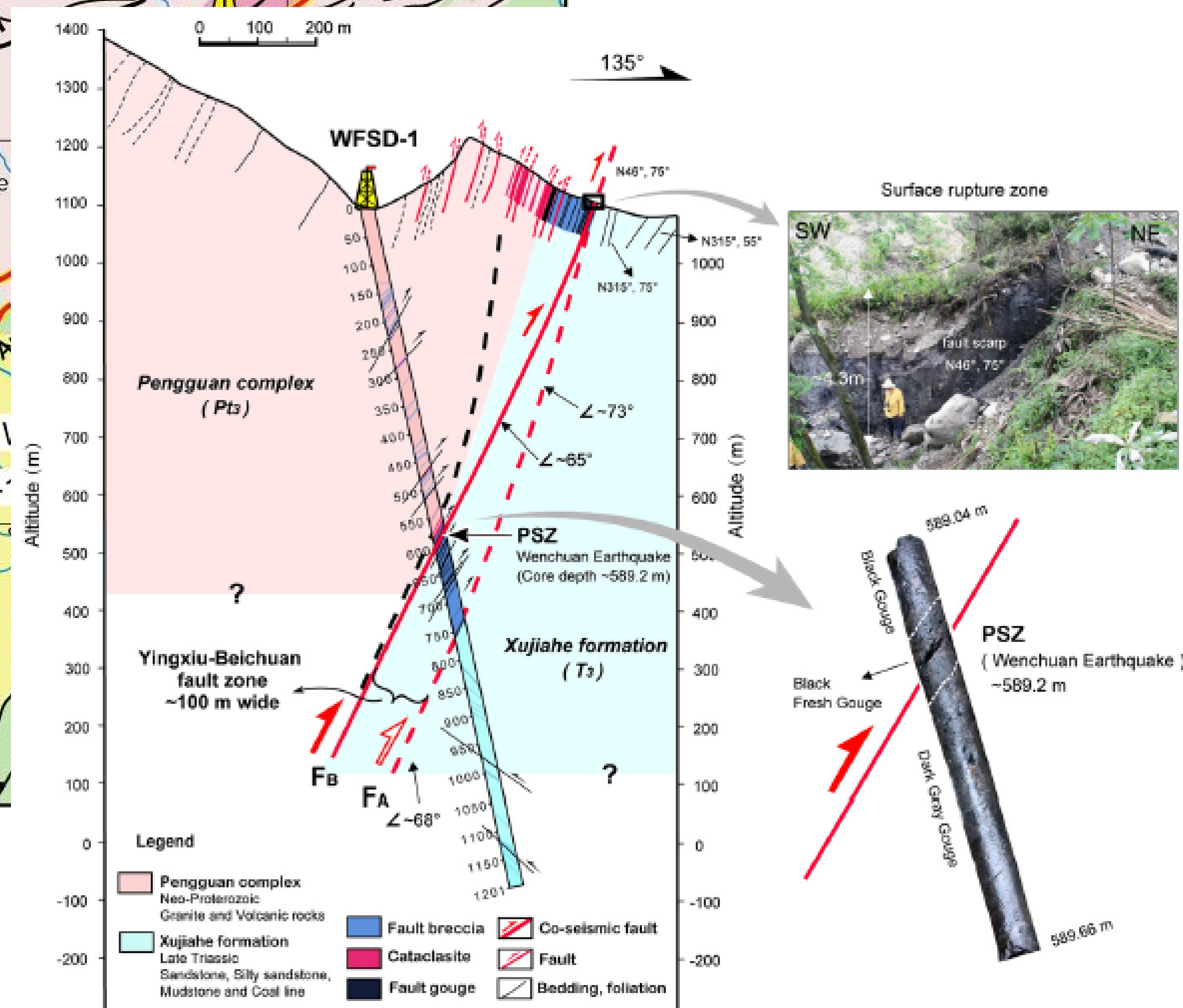
2. Natural observation (WFSD-1)



Li et al., 2013 Tectonophysics

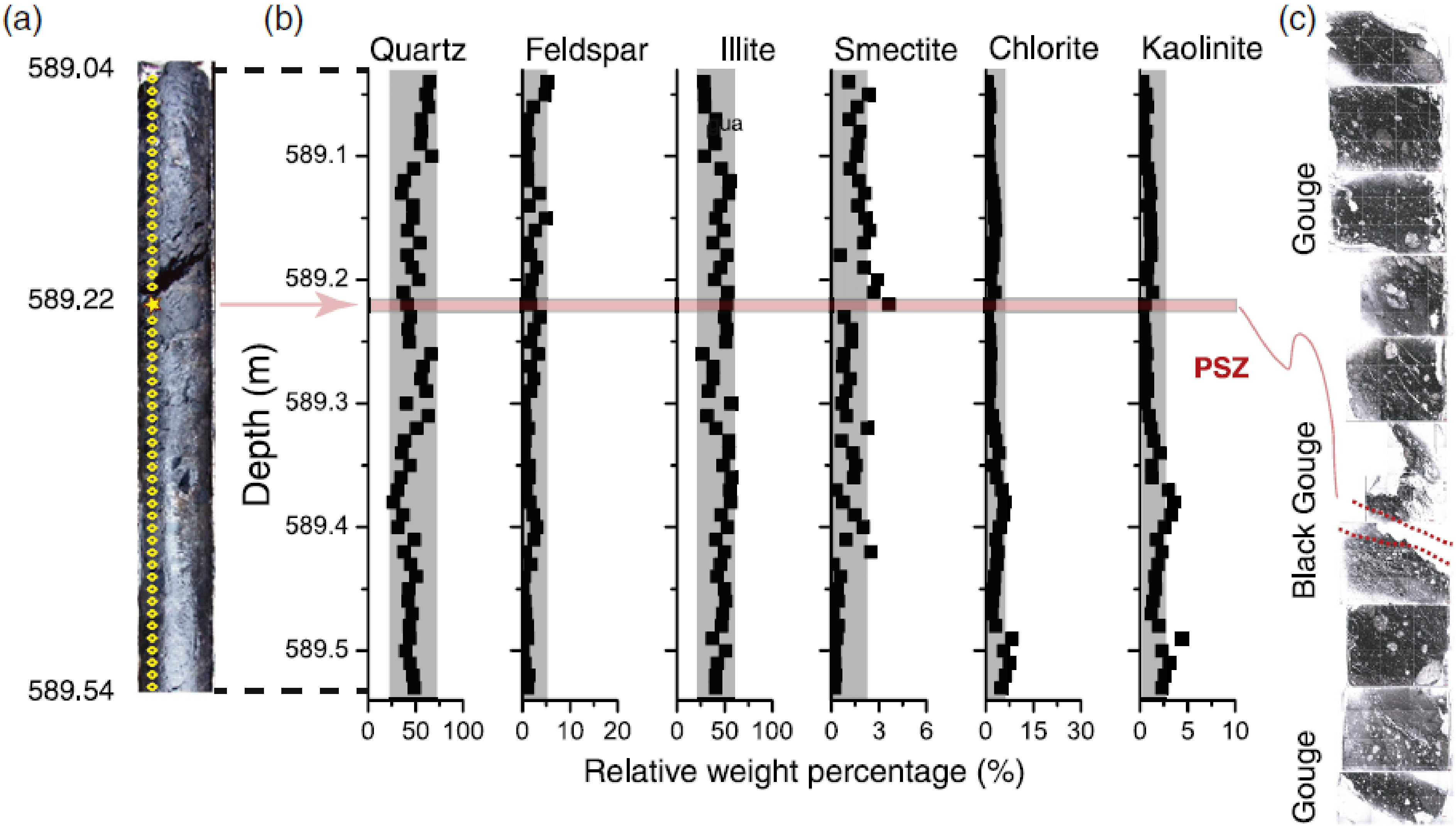
2. Natural observation (WFSD-1)





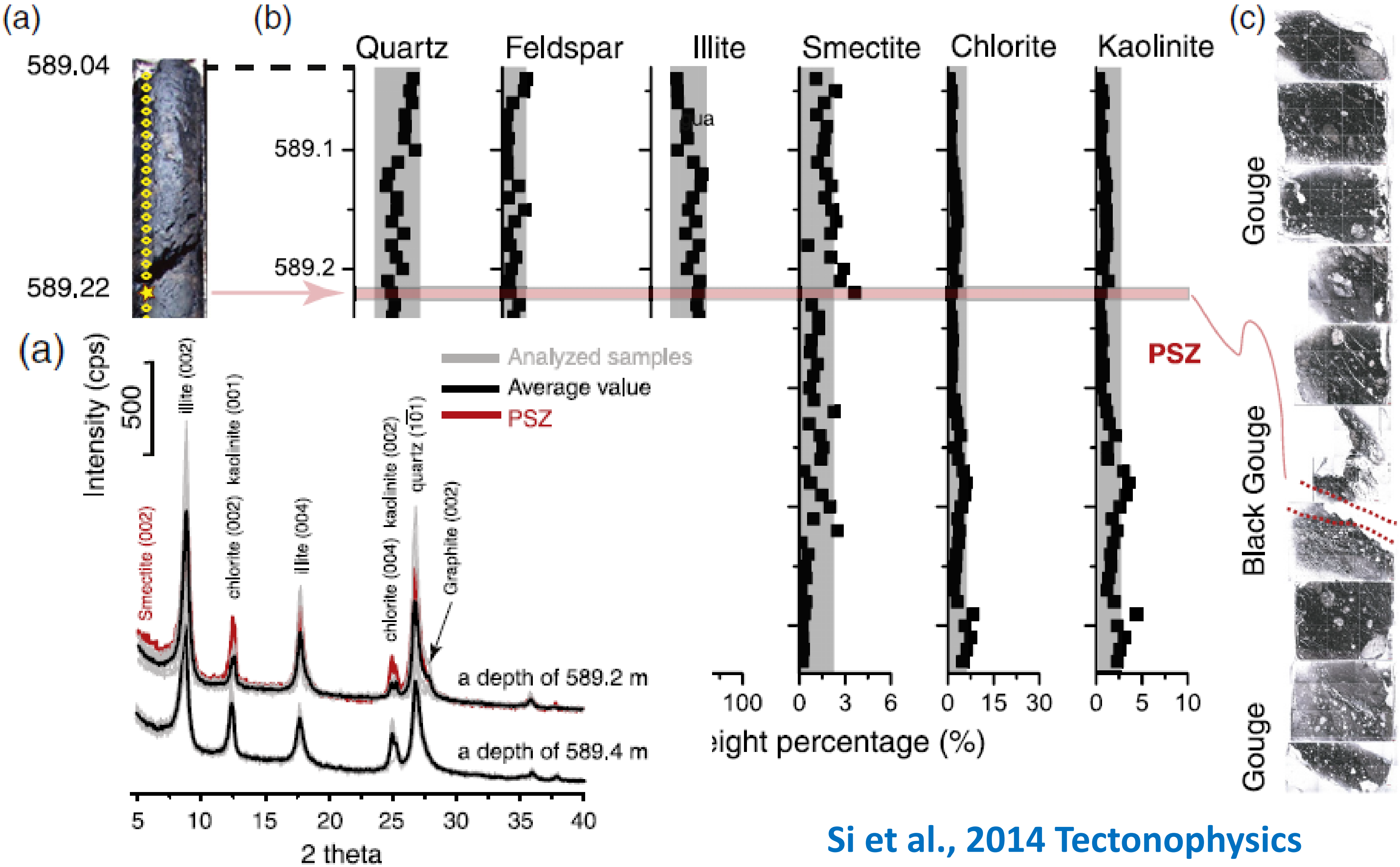
Li et al., 2013 Tectonophysics

2. Natural observation (WFSD-1)



Si et al., 2014 Tectonophysics

2. Natural observation (WFSD-1)



Si et al., 2014 Tectonophysics

2. Natural observation (WFSD-1)

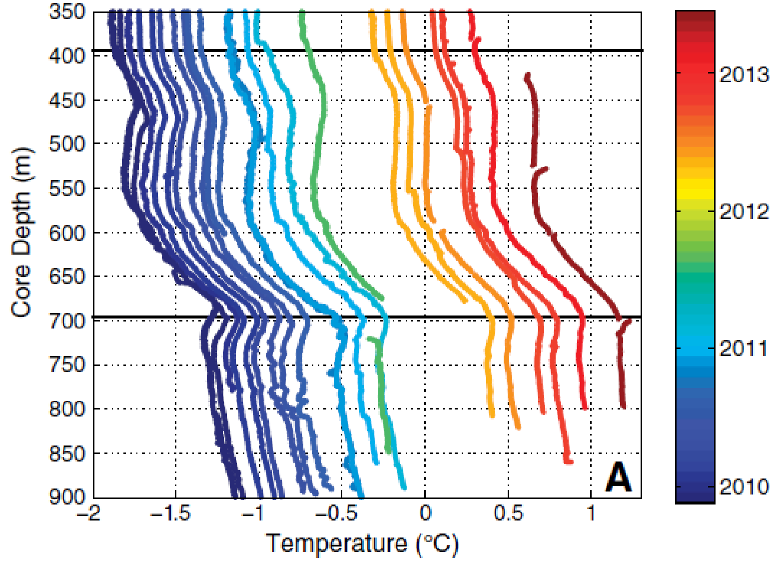
Li et al., 2015 Geology

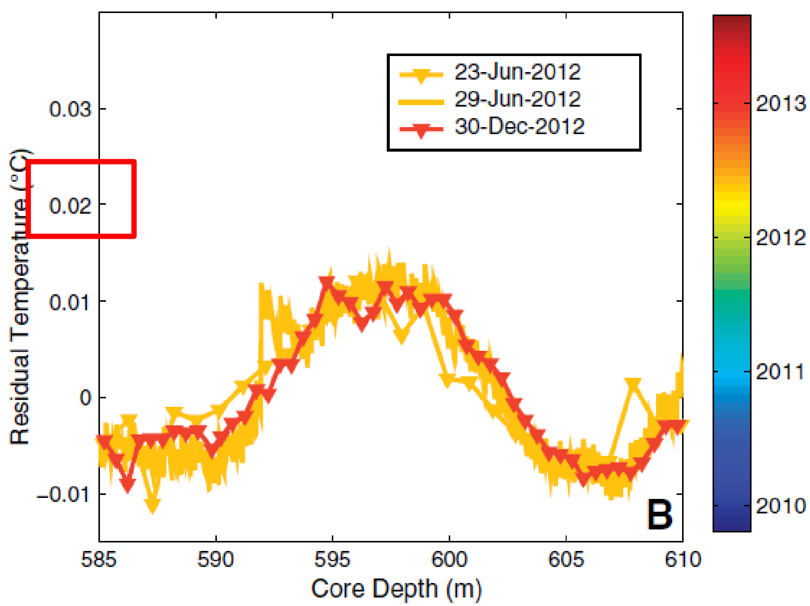
(a)

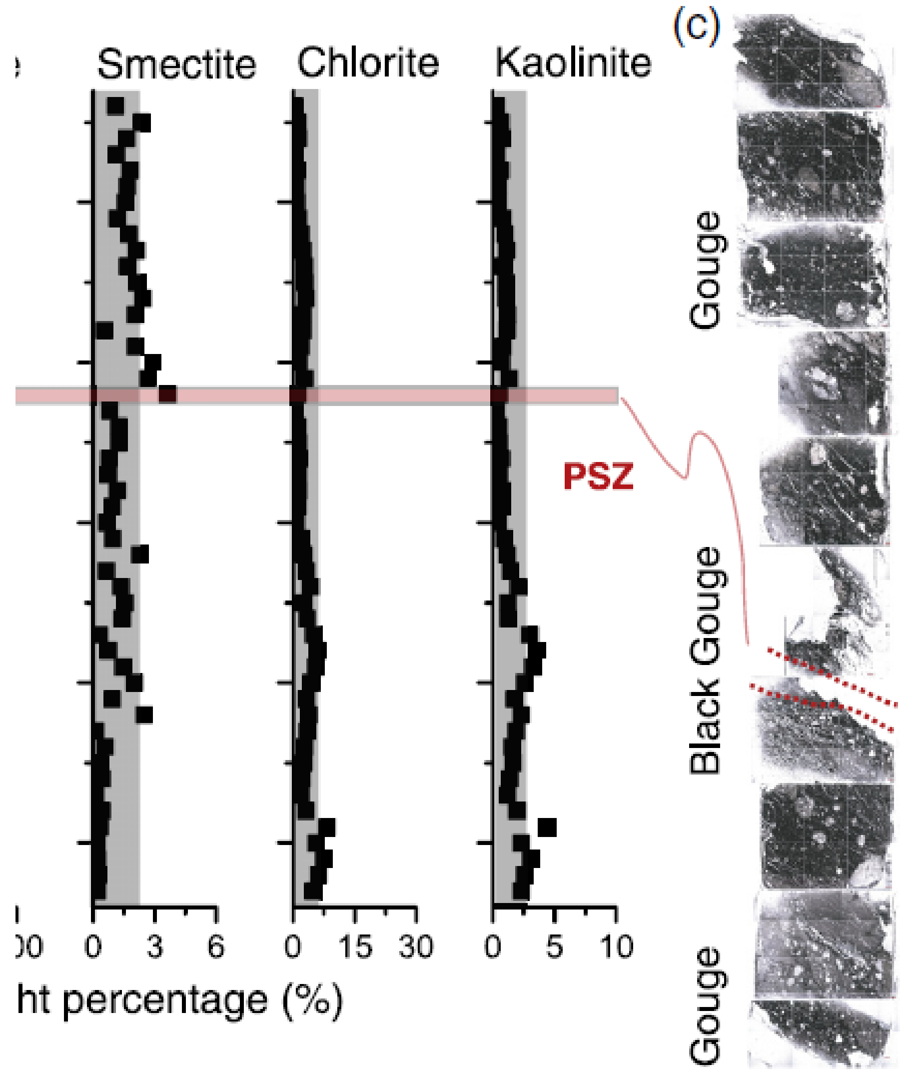
589

589

(a)



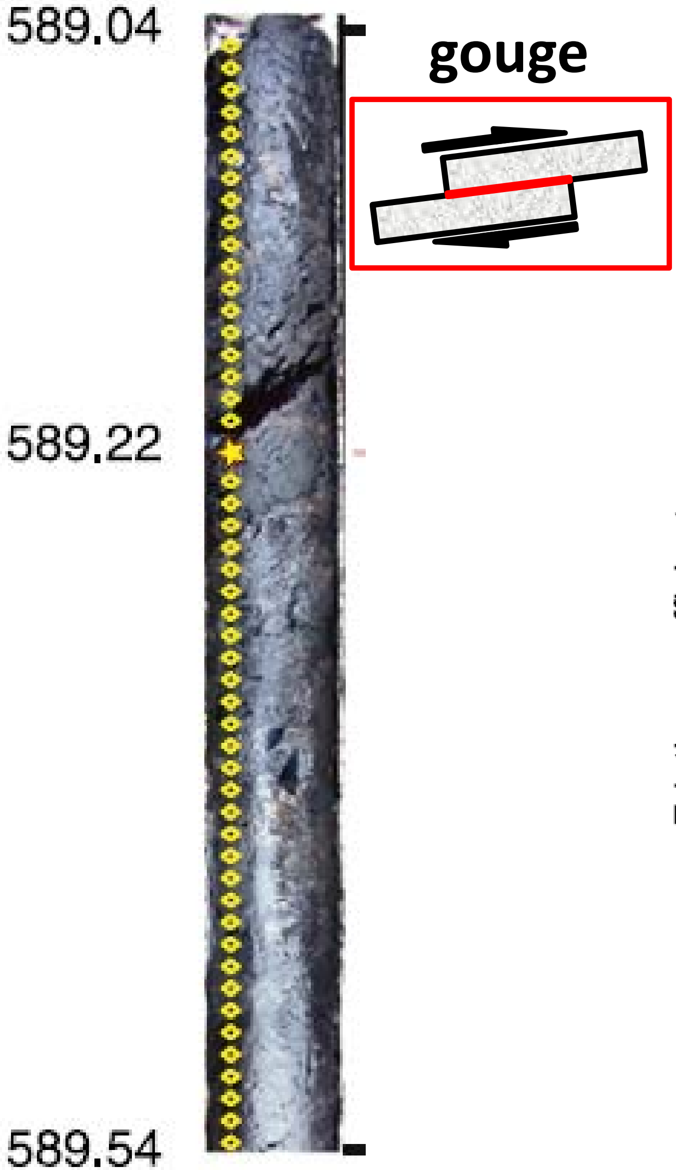




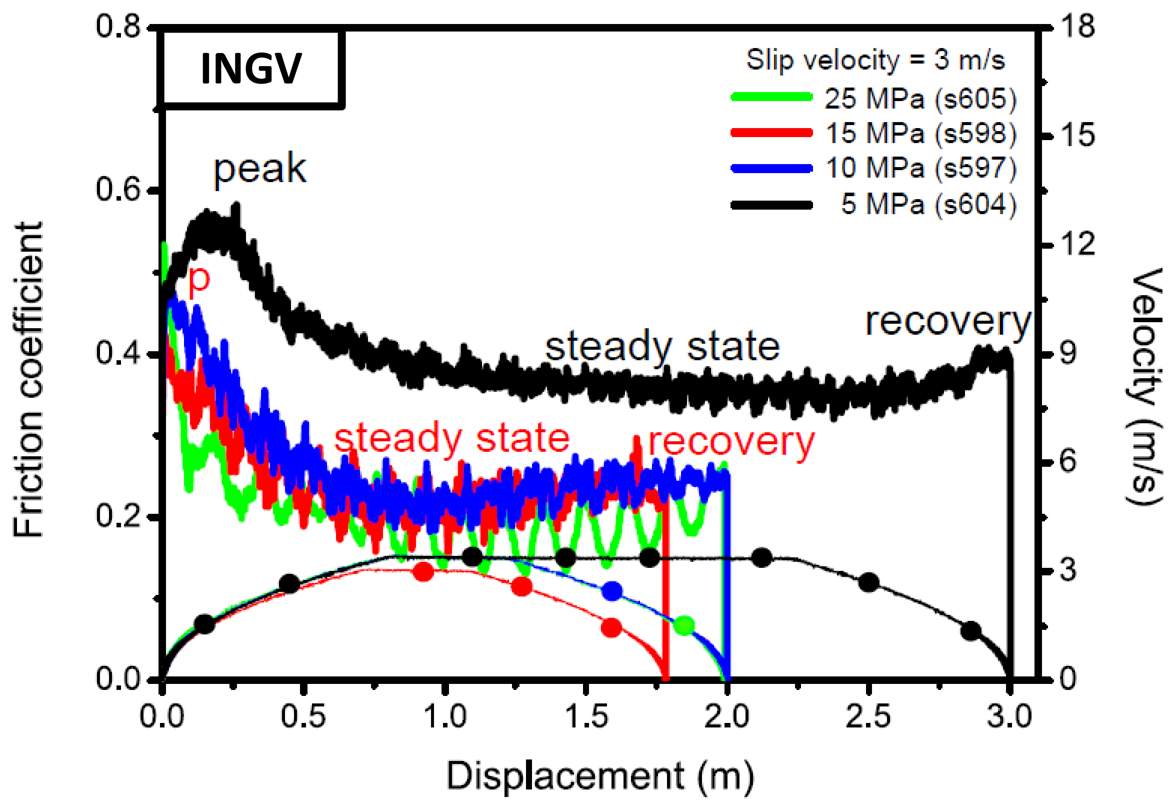
Si et al., 2014 Tectonophysics

2. Experimental results (WFSD-1)

a)

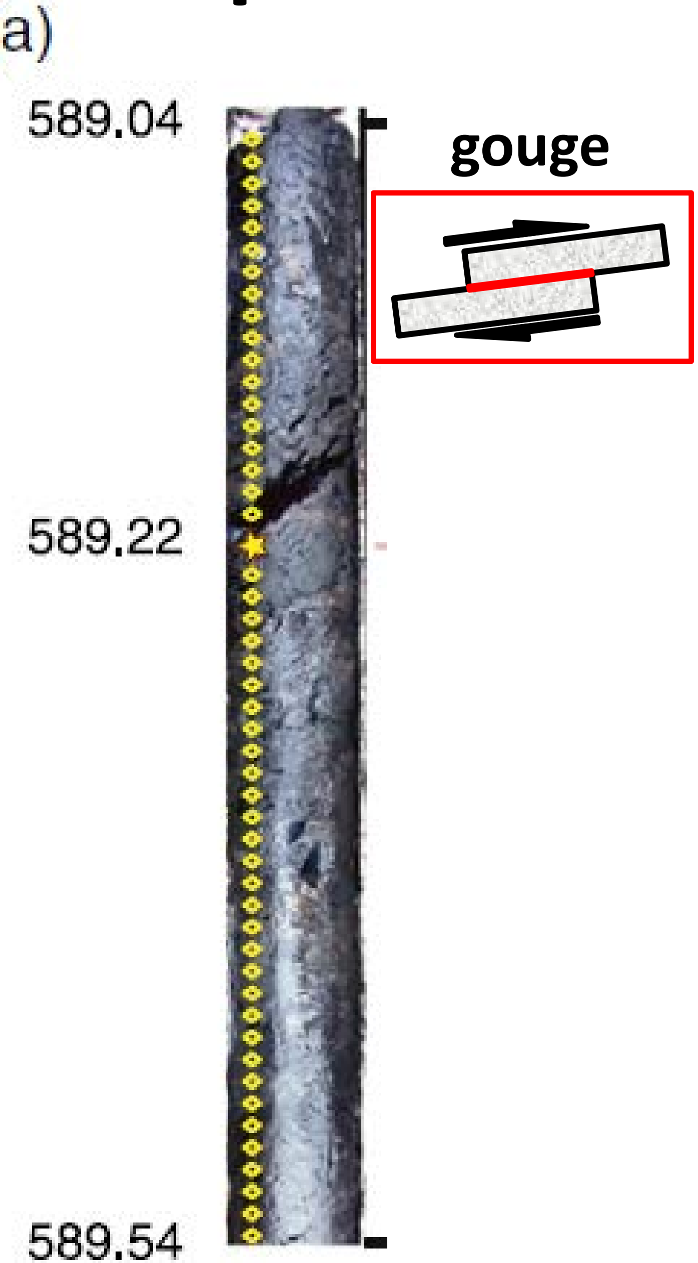


Evolution of friction during “realistic” co-seismic slip pulses

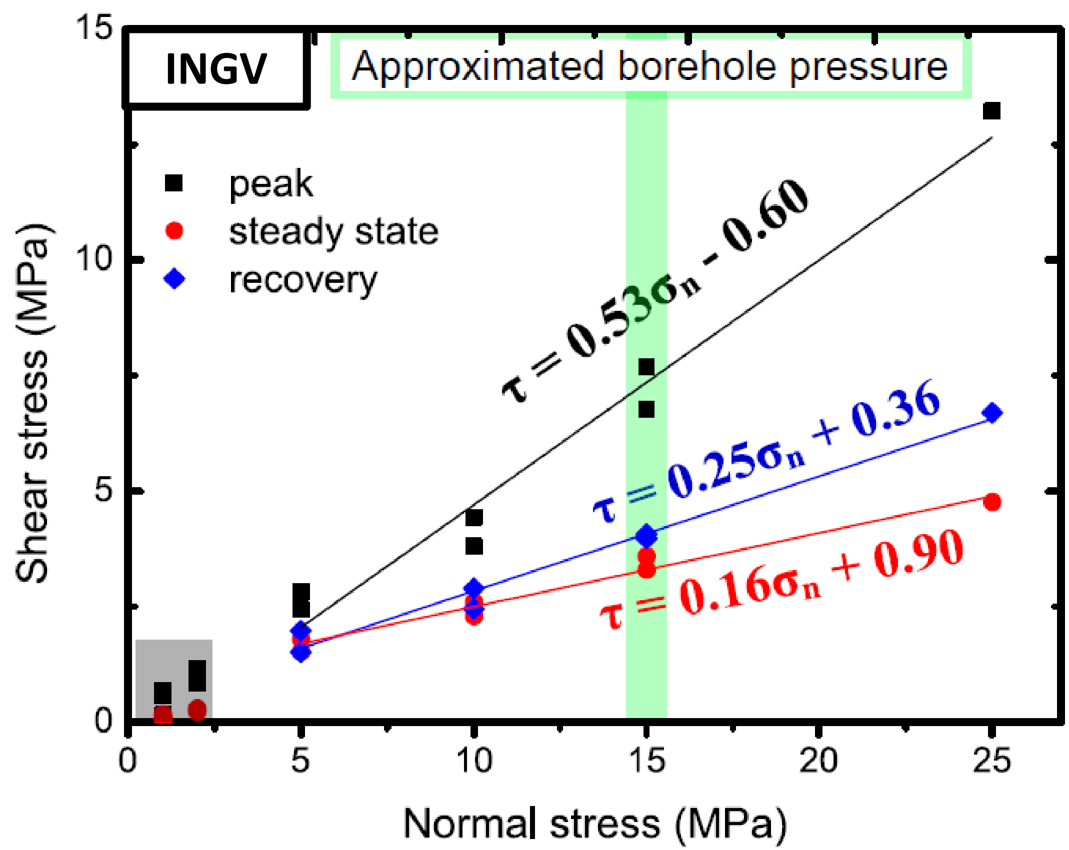


Kuo et al., 2014 Geology

2. Experimental results (WFSD-1)

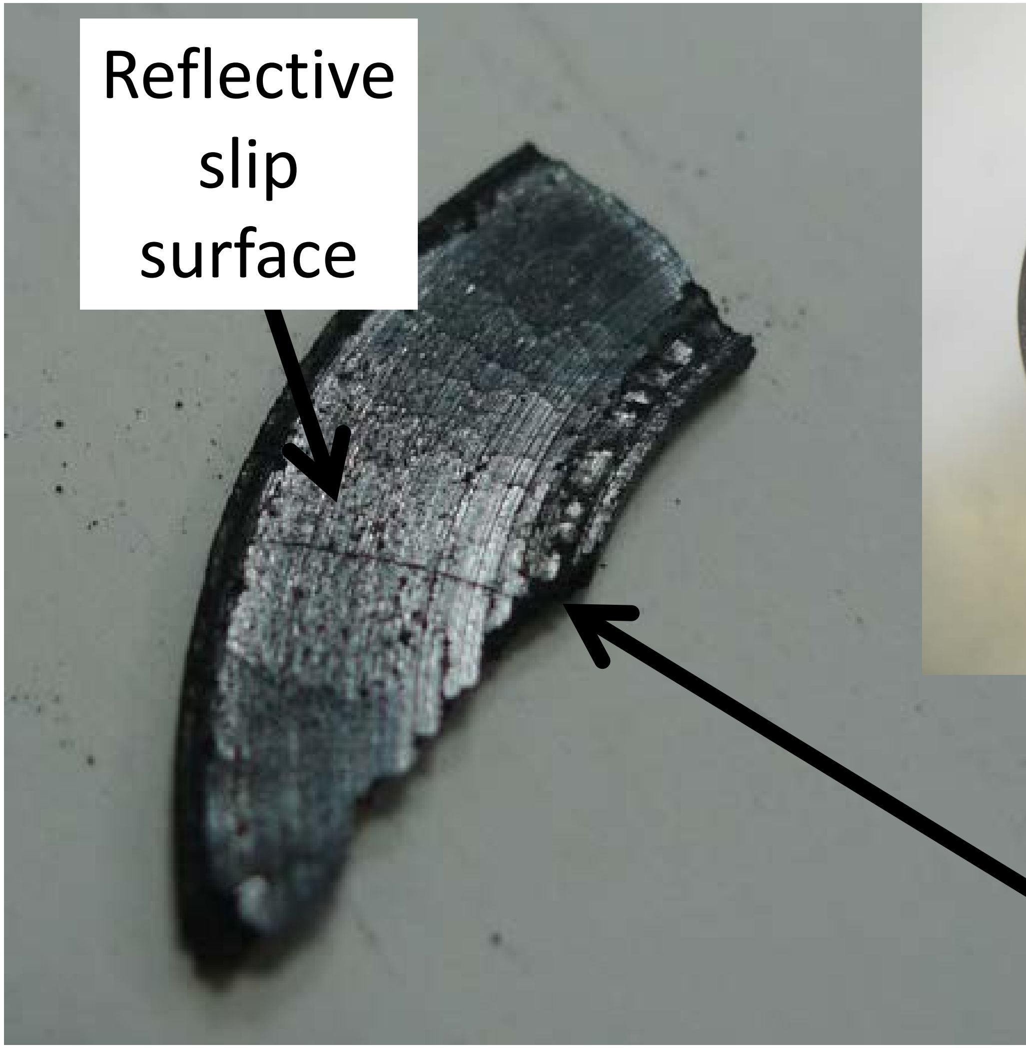


Fault gouges are dynamically weakened at **high normal stress** and **co-seismic slip velocities**



Kuo et al., 2014 Geology

Fault gouges deformed at **co-seismic slip velocities** are cut by highly **reflective slip surfaces**



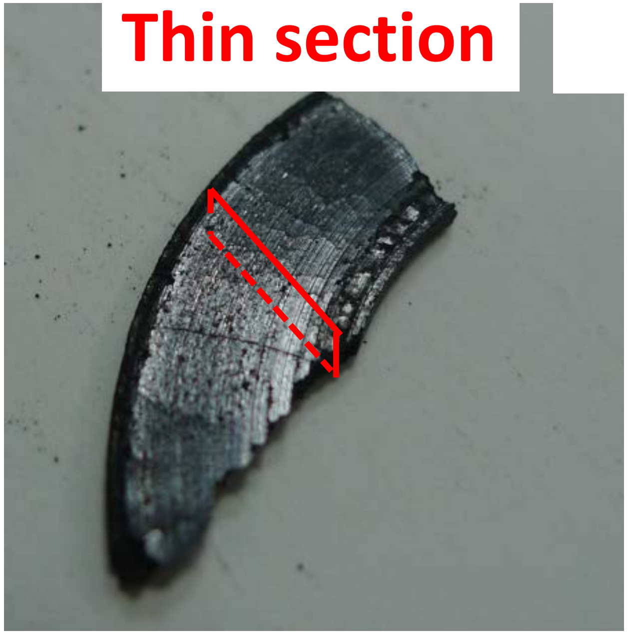
10 mm

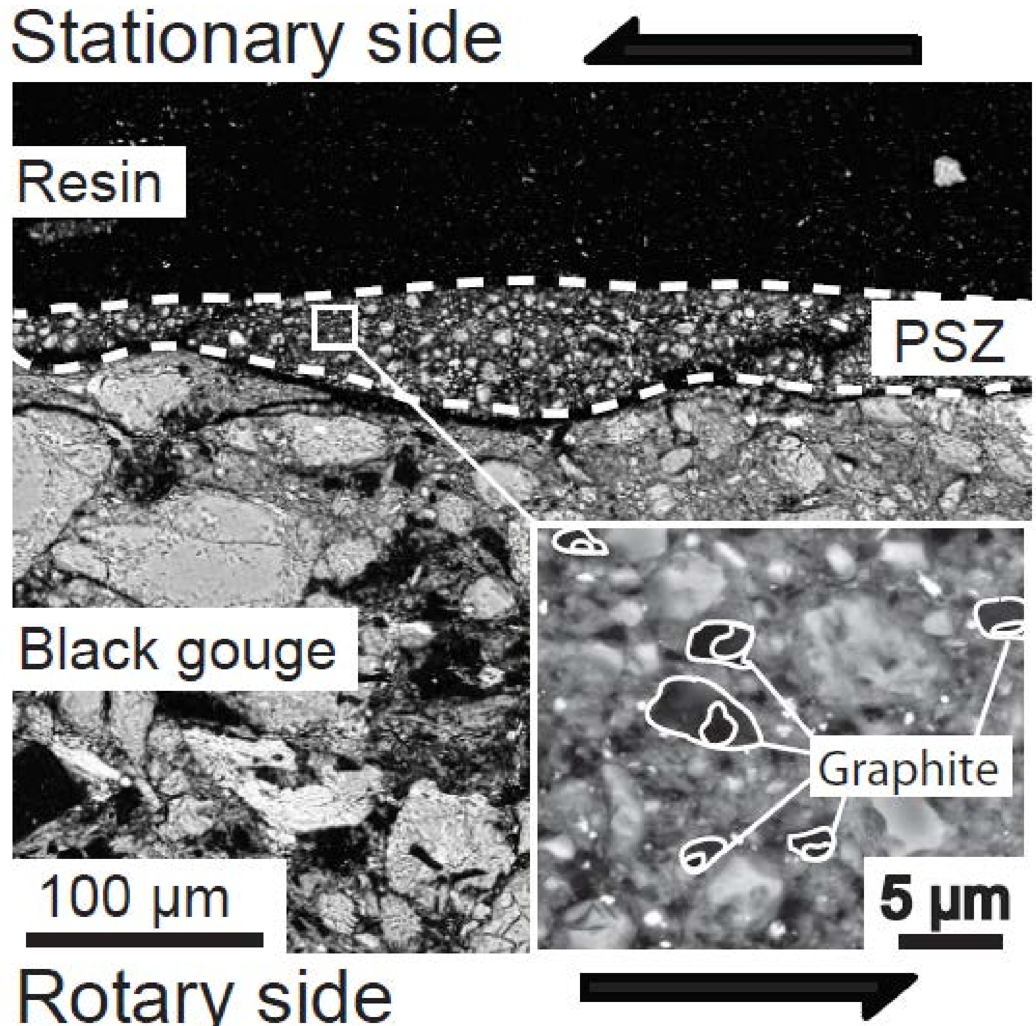
Starting material

Gouge layer underneath slip surface

Kuo et al., 2014 Geology

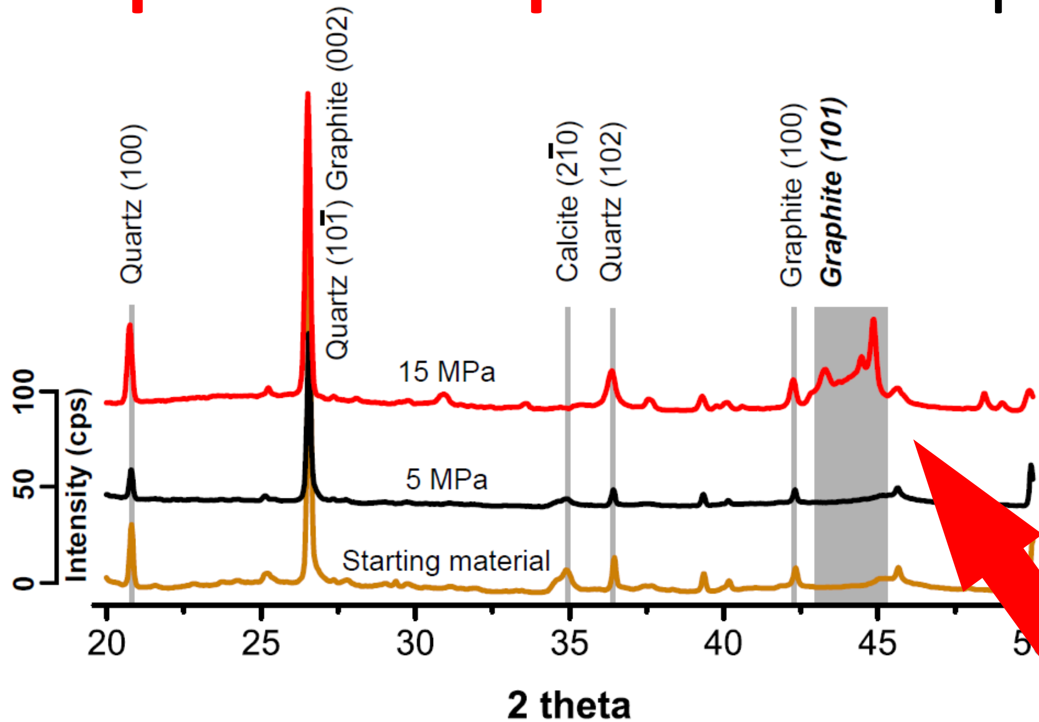
Change in deformation mechanism close to **slip surface**



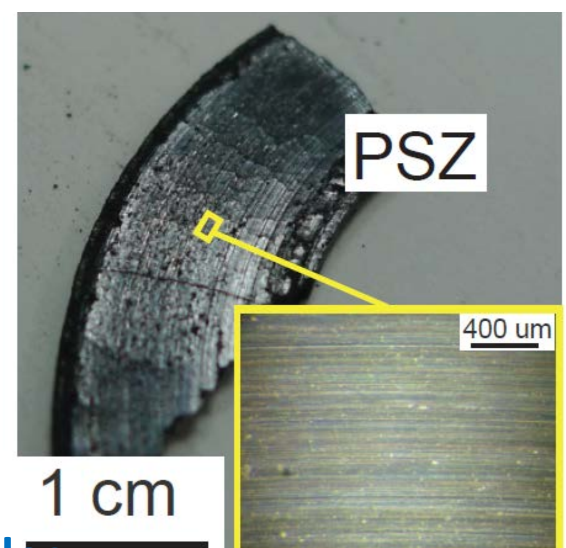


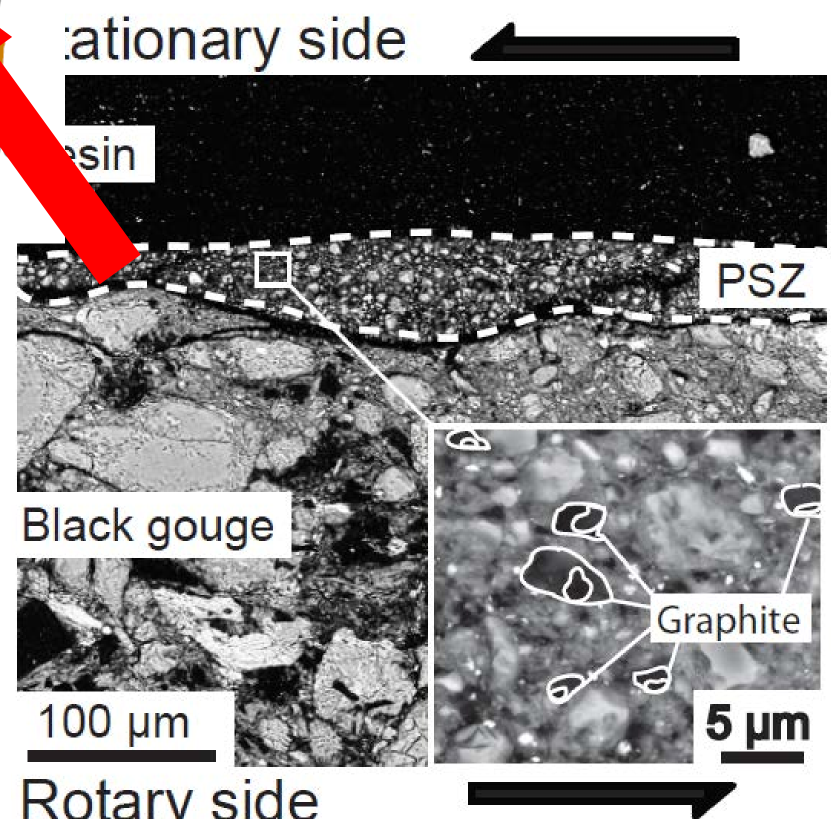
Kuo et al., 2014 Geology

Graphitization process took place during EQs!!



Experiment





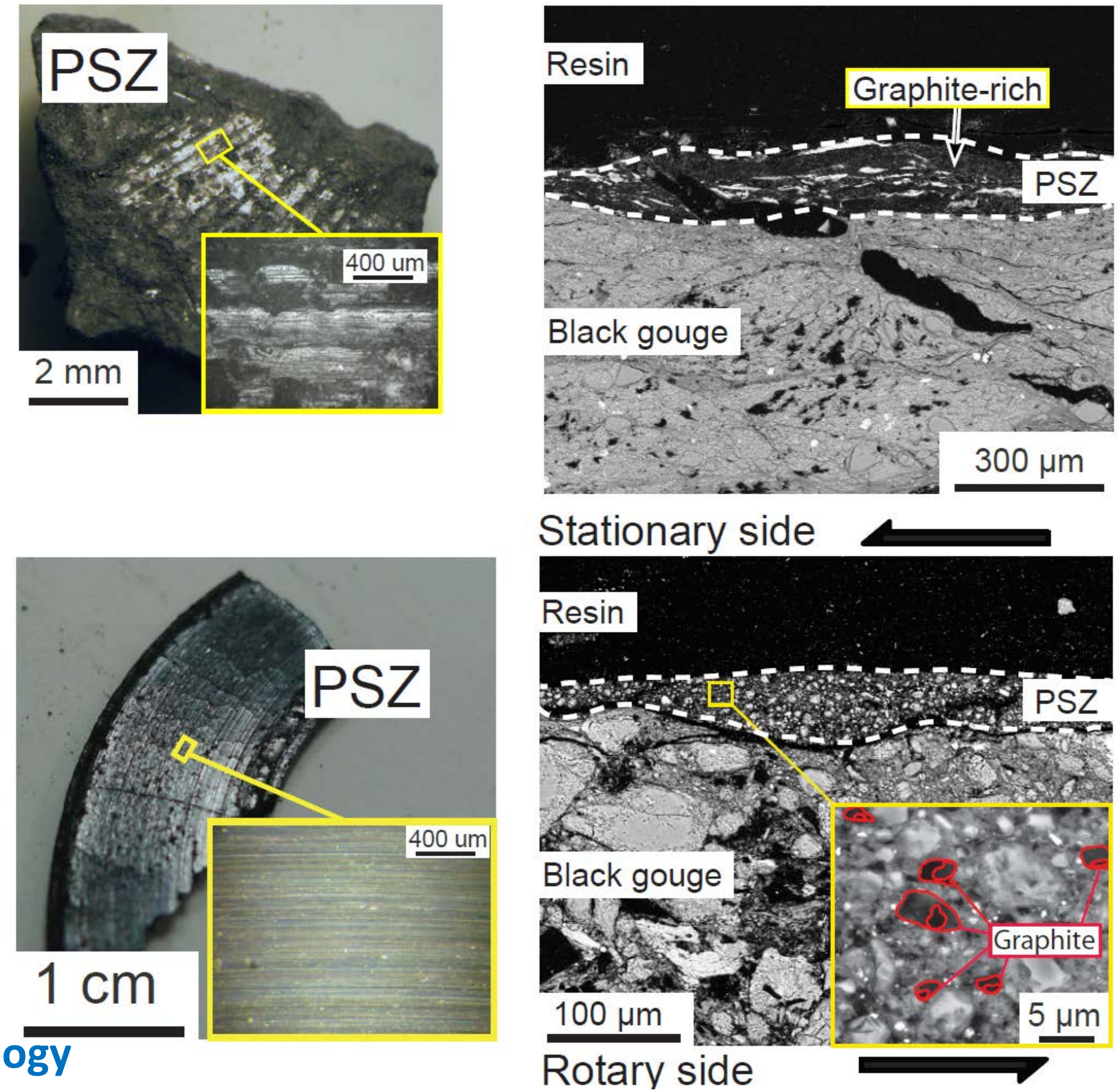
Kuo et al., 2014 Geology

Are experimental products similar to natural ones?

Yes (example for carbonaceous gouge).

Nature

Experiment



Kuo et al., 2014 Geology

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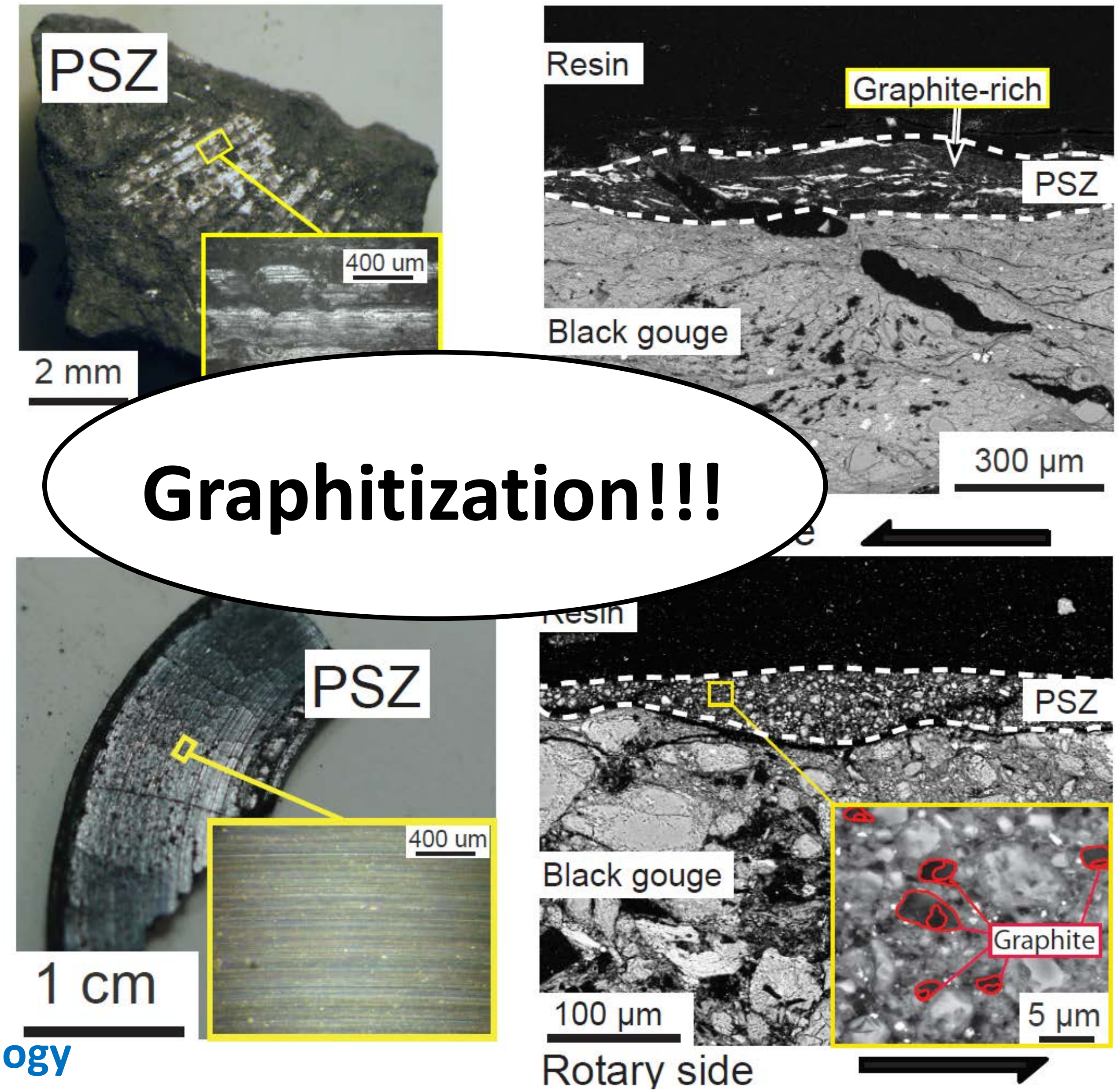
Nature

Experiment

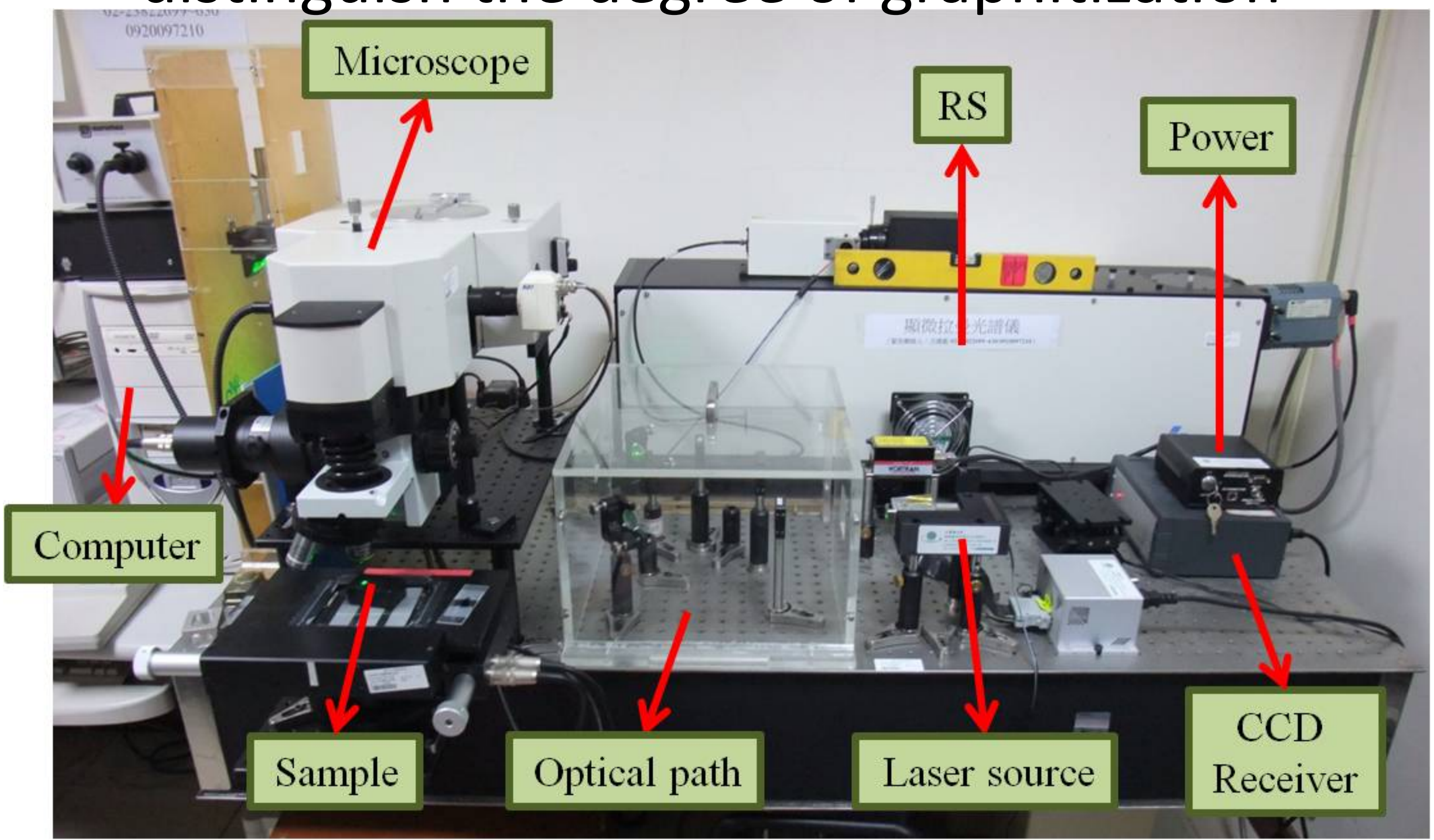


Kuo et al., 2014 Geology

Raman spectrometer (RS)

★ Instrument: *UV-VIS LABRAM HR* Raman Spectrometer (at the National Taiwan Museum)

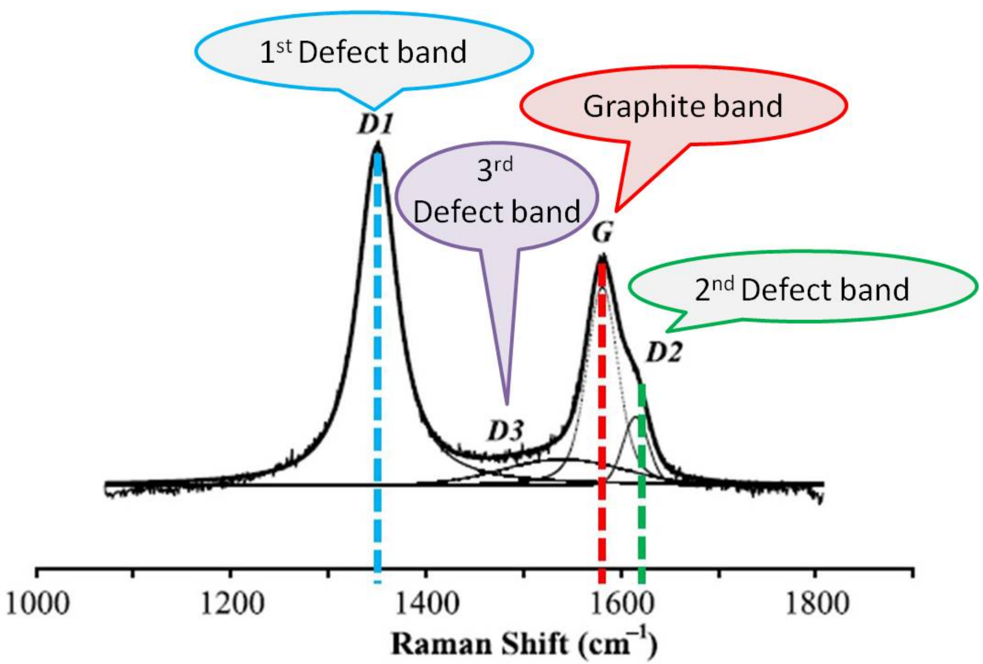
★ Benefit: High-resolution, short analysis time, easy to distinguish the degree of graphitization



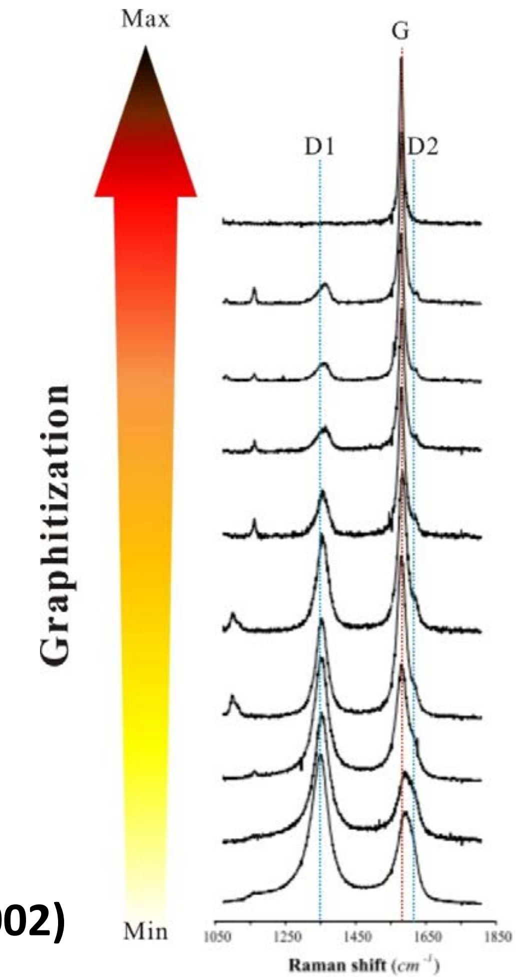
Raman Spectra of Carbonaceous Material (RSCM)

★ RSCM geothermometer: 100~700 °C (Beyssac et al., 2002; Jeffrey M.Rahl et al., 2005)

G band ： 1580 cm^{-1}	D2 band ： 1620 cm^{-1}
D1 band ： 1350 cm^{-1}	D3 band ： 1500 cm^{-1}



(Beyssac et al., 2002)



Raman Spectra of Carbonaceous Material (RSCM)

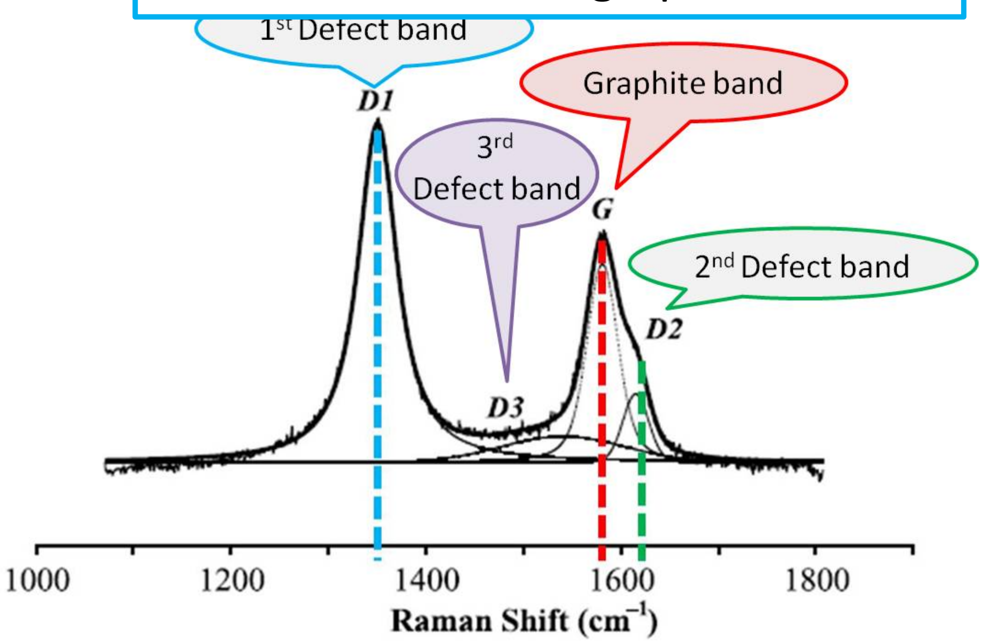
★ RSCM geothermometer: 100~700 °C (Beyssac et al., 2002; Jeffrey M.Rahl et al., 2005)

G b ... 0 cm^{-1}

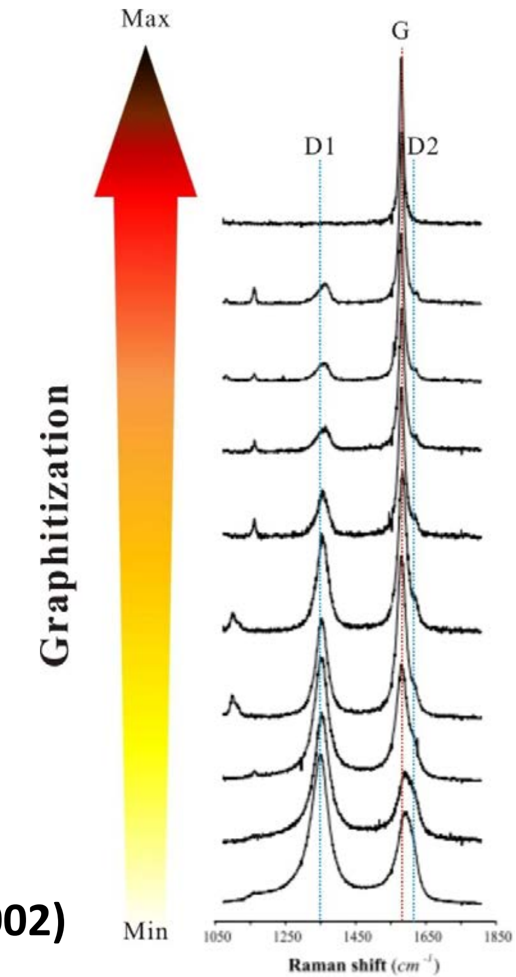
D1 ... 0 cm^{-1}

$$\text{R1 ratio} = \frac{\text{D1 Intensity}}{\text{G Intensity}}$$

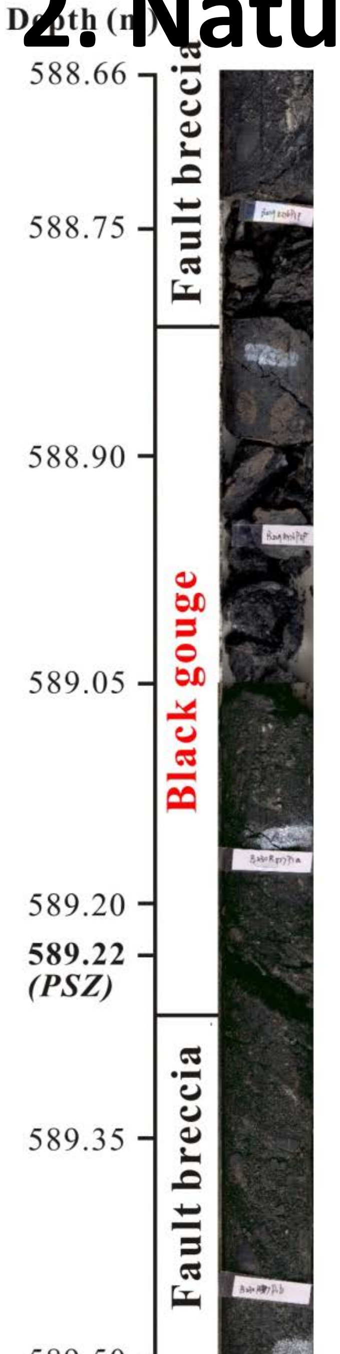
※ R1 ratio: value↓, graphitization ↑

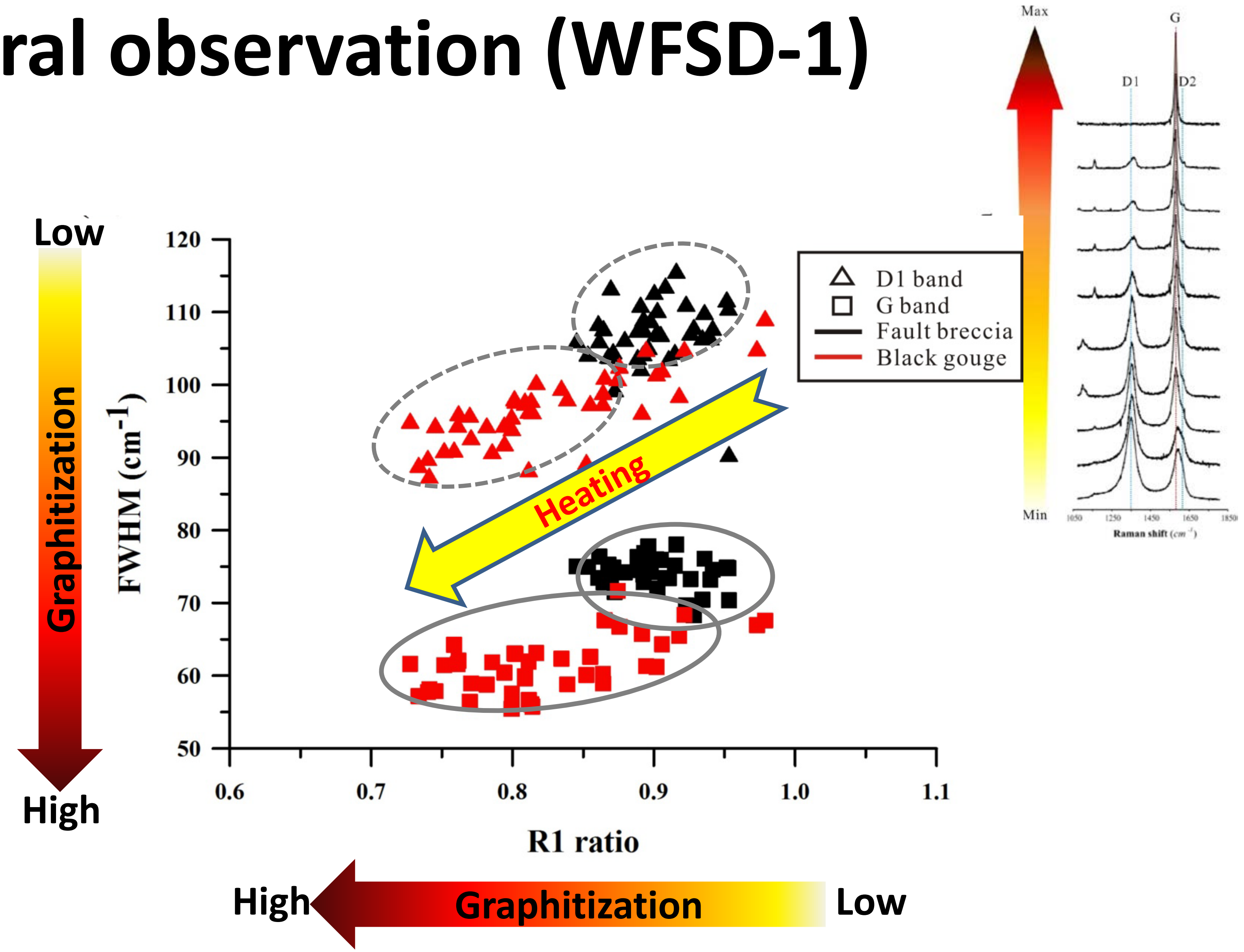


(Beyssac et al., 2002)

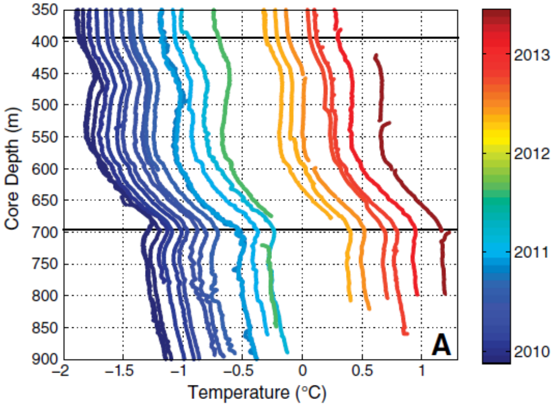


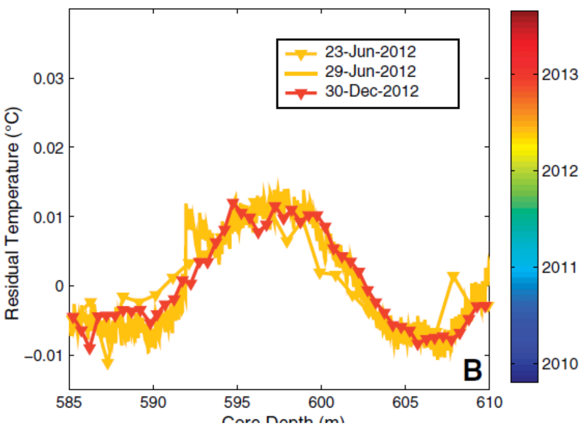
2. Natural observation (WFSD-1)





Huang et al., 2014, AGU T33A-4652





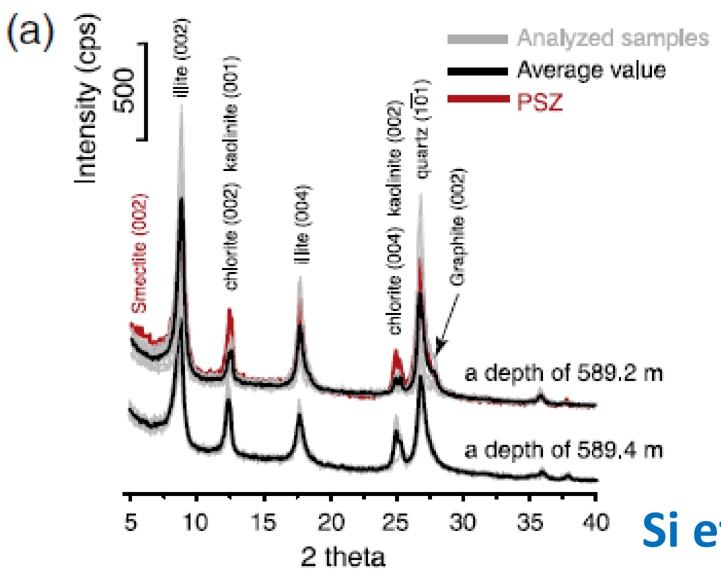
Li et al., 2015 Geology

The role of strain energy in creep graphitization of anthracite

J. V. Ross & R. M. Bustin **(1990, Nature)**

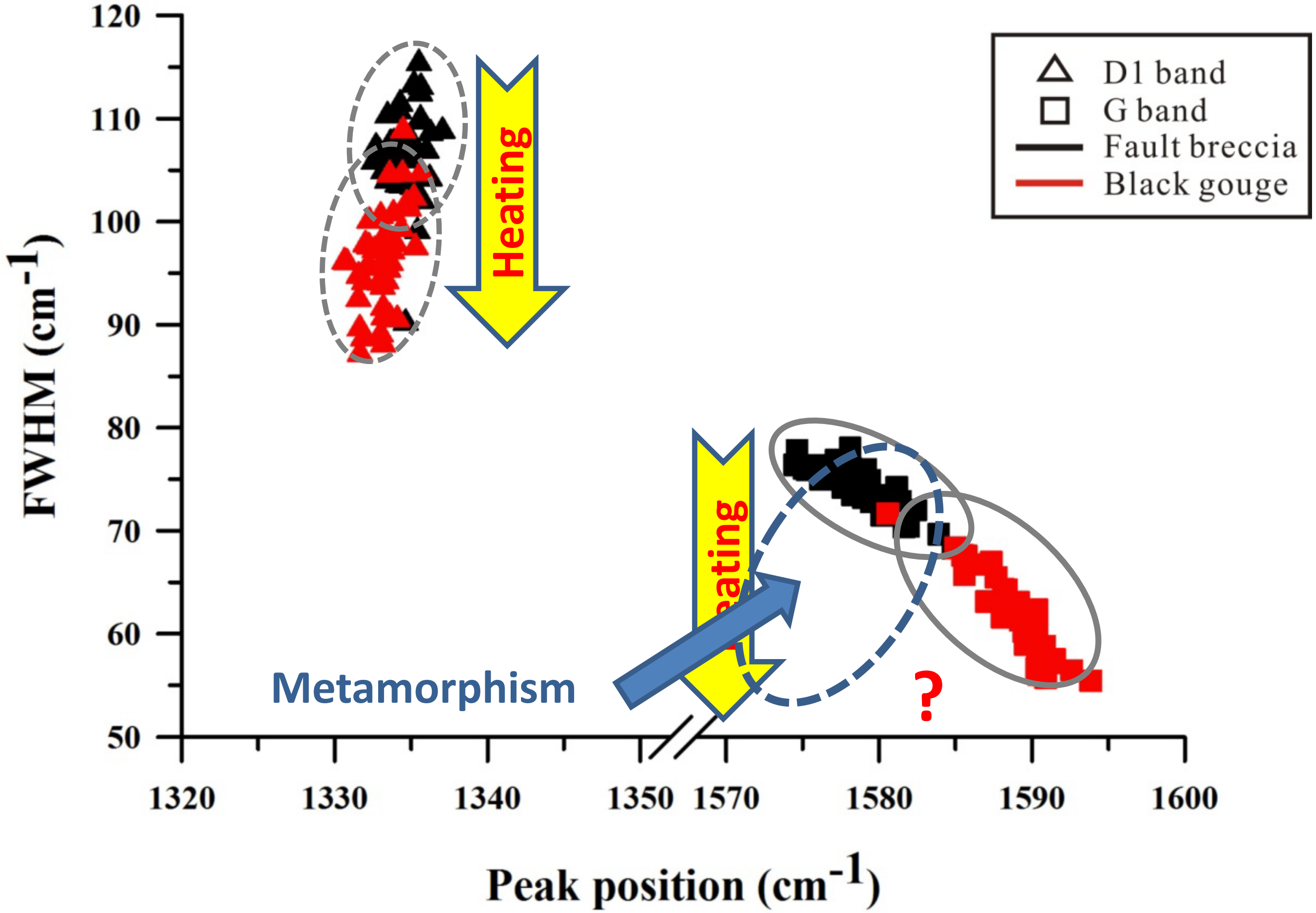
Department of Geological Sciences, The University of British Columbia, Vancouver, Canada, V6T 2B4

RECENT research on ceramics and natural minerals has demonstrated that non-hydrostatic stress can affect some polymorphic transitions and can increase reaction rates[1,2]. One such example is the graphitization of anthracite. Under natural conditions graphite forms at temperatures of 300–500 °C and confining pressures of ~500 MPa (refs 3–9). But in simple heating experiments at ambient pressure and high confining pressure (up to 1 GPa), temperatures of ~2,000 °C are required for graphite formation[10–13]. Here we report creep experiments on natural anthracite



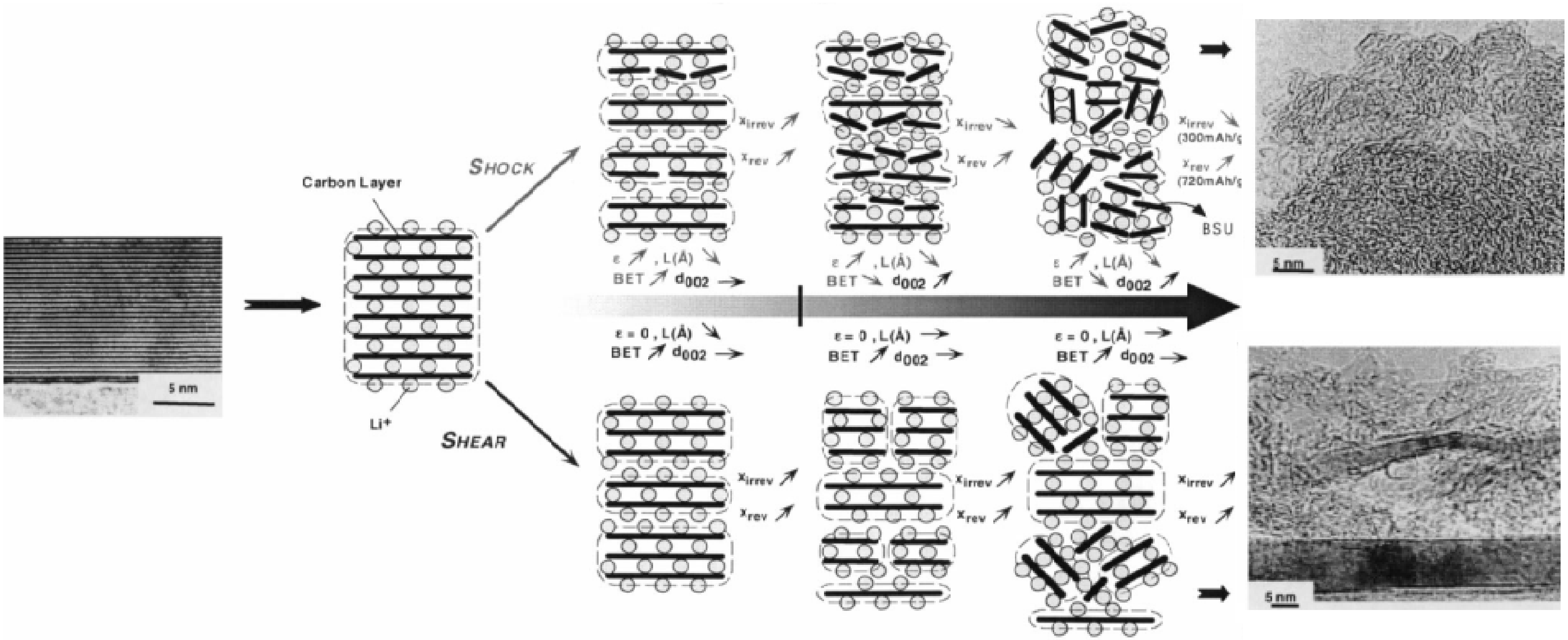
Si et al., 2014 Tectonophysics

2. Natural observation (WFSD-1)



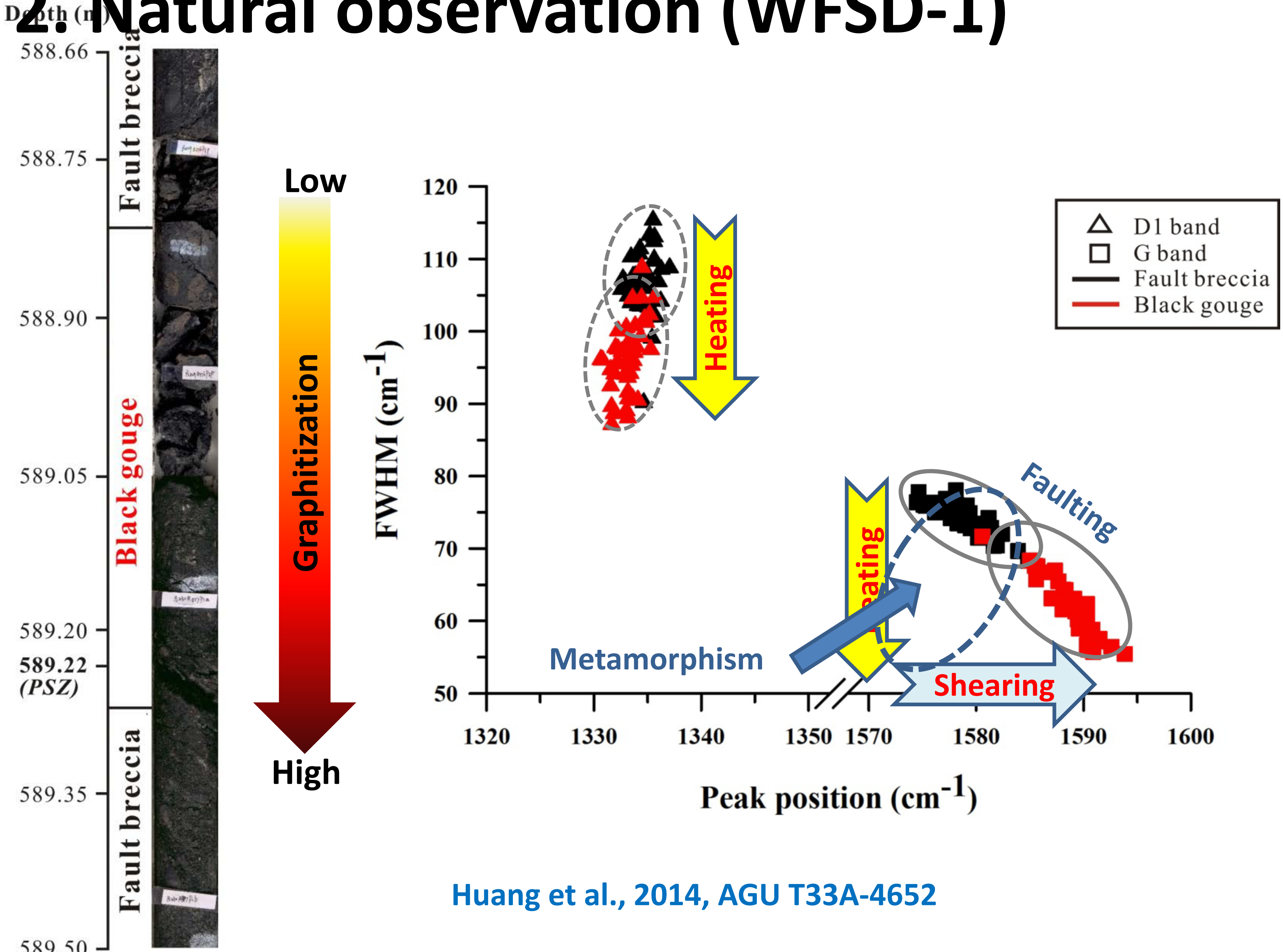
Huang et al., 2014, AGU T33A-4652

The grinding effect on carbon



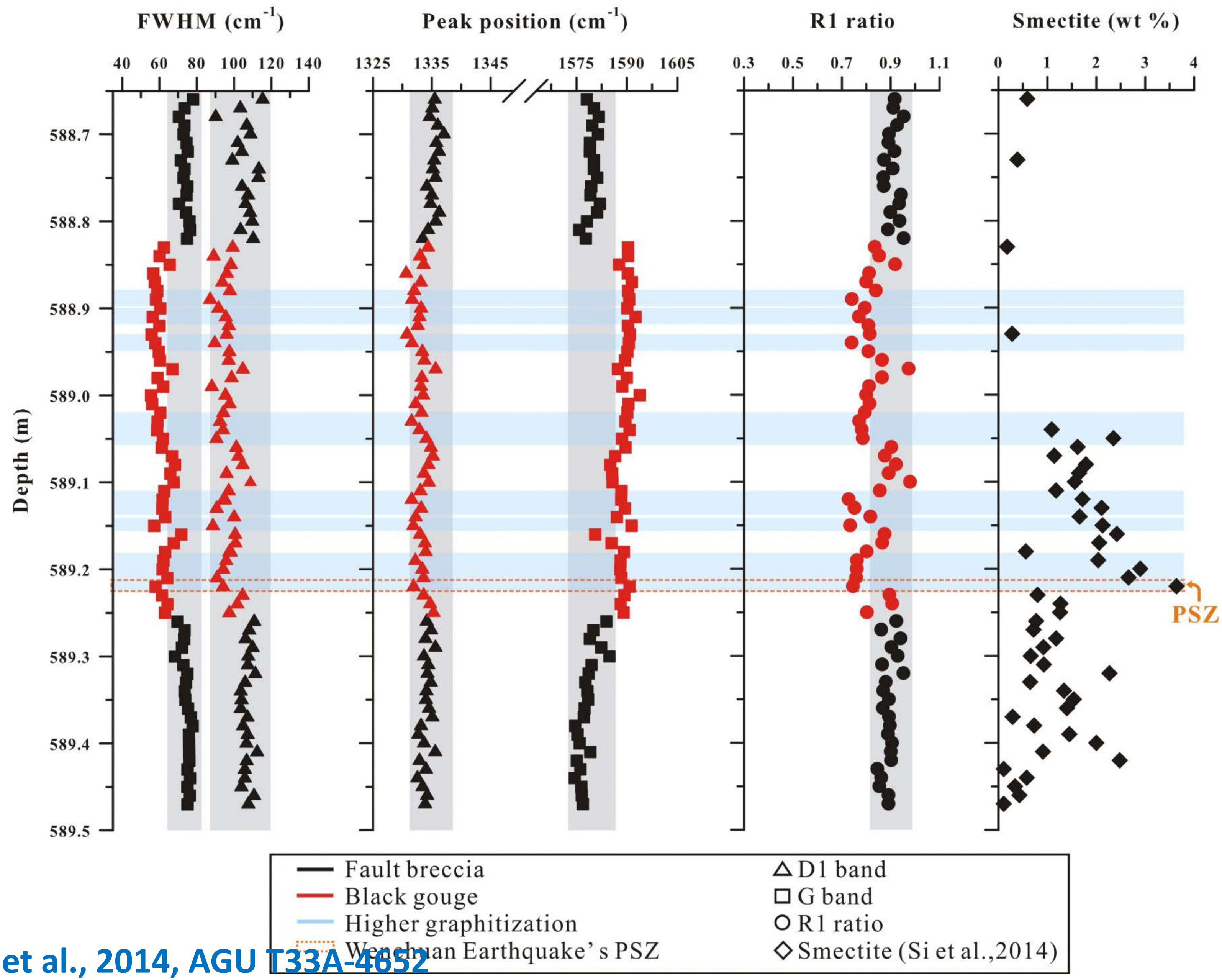
(Salver-Disma et al., 1999)

2. Natural observation (WFSD-1)



Huang et al., 2014, AGU T33A-4652

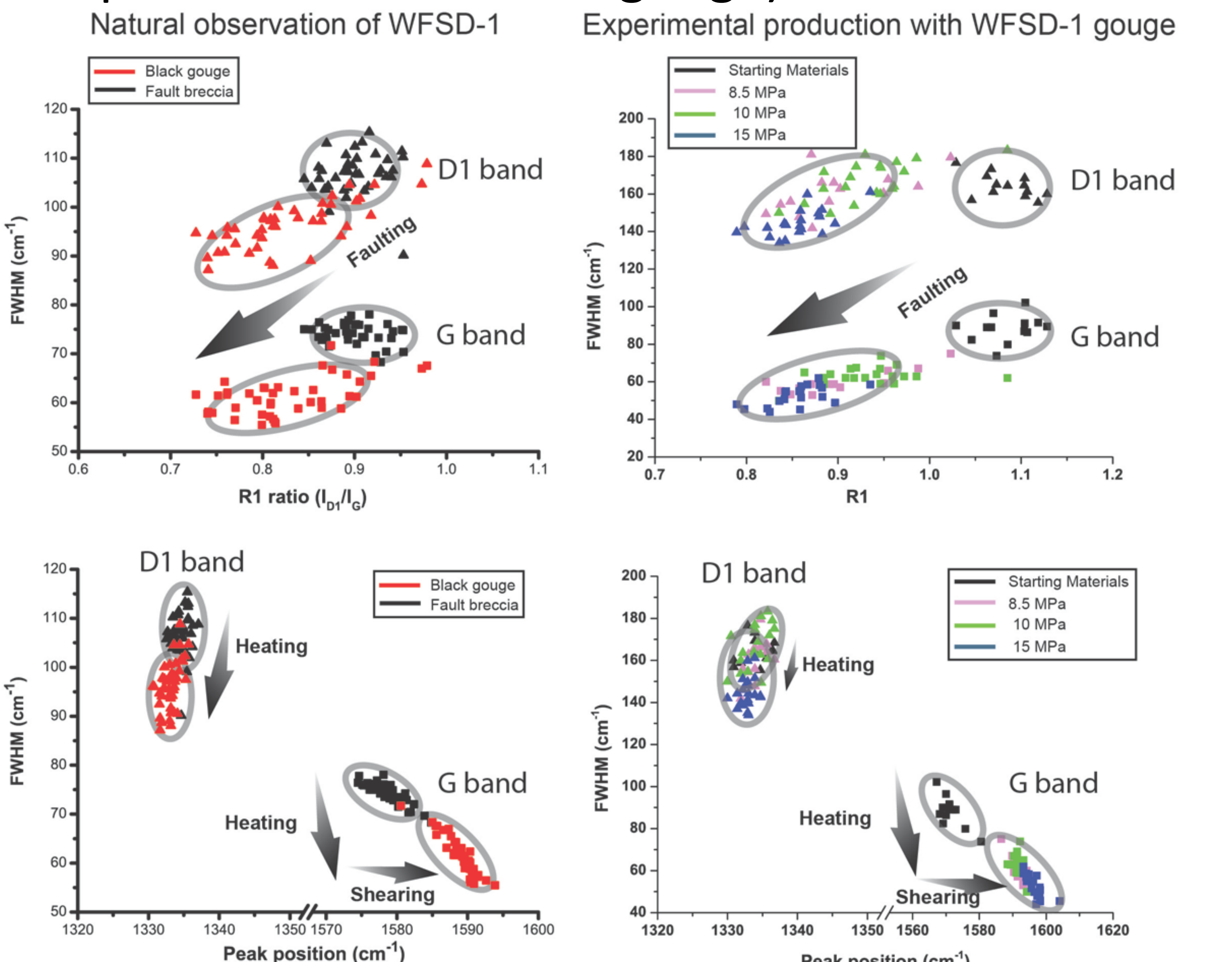
2. Natural observation (WFSD-1)



Huang et al., 2014, AGU T33A-4652

Are experimental products similar to natural ones?

Yes (example for carbonaceous gouge).



Huang et al., 2014, AGU T33A-4652

Di Toro et al., 2014, AGU T33A-4638

Summary

- The **PSZ** corresponding to the 2008 Mw7.9 Wenchuan earthquake was recognized at the depth of 590 m.
- **Graphitization process occurred** (on carbonaceous gouge) during the EQ.
- **Earthquake source parameters** could be obtained.
- And more……

Conclusion

- **Characterization of clay mineralogy** within active fault zones
- **Recognition of the PSZ** within the active fault zone(s)
- **Investigation of the processes** occurred during seismic slip and plausible slip weakening mechanism operated at seismic rates
- **Determination of dynamic friction** (and its evolution) during seismic slip (friction energy, fracture energy and associated energy budget of EQ)
- **Recognition of mineralogical and microstructural indicators** within exhumed (or active) fault zones
- **Estimation of earthquake source parameters** (e.g., estimate of **temperature** for calculating associated **frictional energy** and **thickness** of the PSZ for calculating associated **surface fracture energy**)

Conclusion

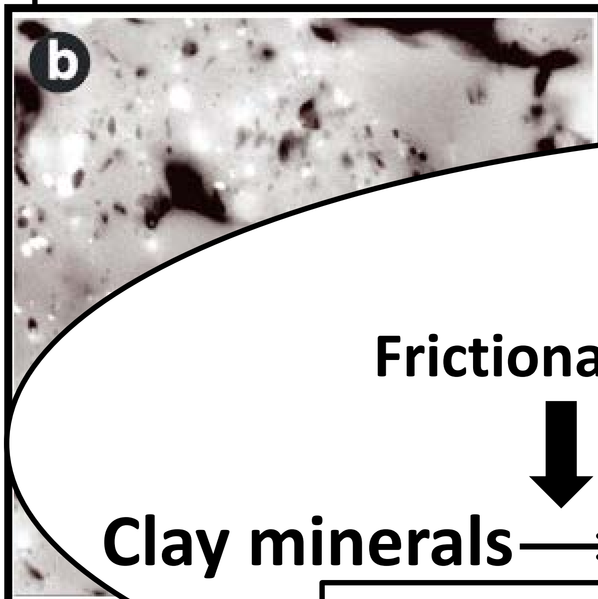
- **Characterization of clay mineralogy** within active fault zones
- **Recognition of the PSZ** within the active fault zone(s)
- **Investigation of the processes** occurred during seismic slip and
  plausible
  ates
- **Determi**
  ng seismic
  slip (frict
  budget of
  EQ)
- **Recognit**
  rs within
  exhumed (or active) fault zones
- **Estimation of earthquake source parameters** (e.g., estimate of **temperature** for calculating associated **frictional energy** and **thickness** of the PSZ for calculating associated **surface fracture energy**)

To better address **earthquake mechanics** it is necessary to integrate **field geology** and **laboratory rock experiments**!!

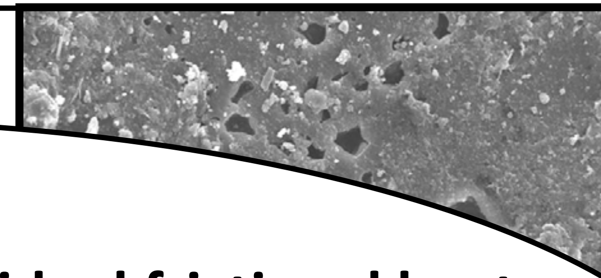
Thank you for your listening!!

Are experimental products similar to natural ones?

Yes (example for clay-rich gouge).



5 MPa, 1.3 m/s



Frictional heat

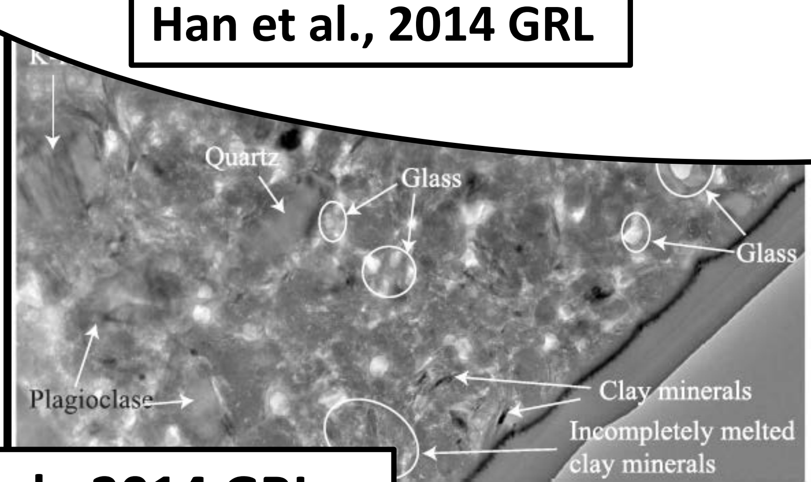
Residual frictional heat

Fluid

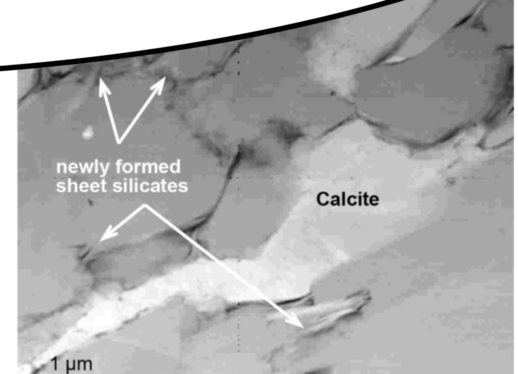
Clay minerals ⟶ amorphous materials ⟶ Smectite

Han et al., 2014 GRL

Janssen et al., 2014 JSG

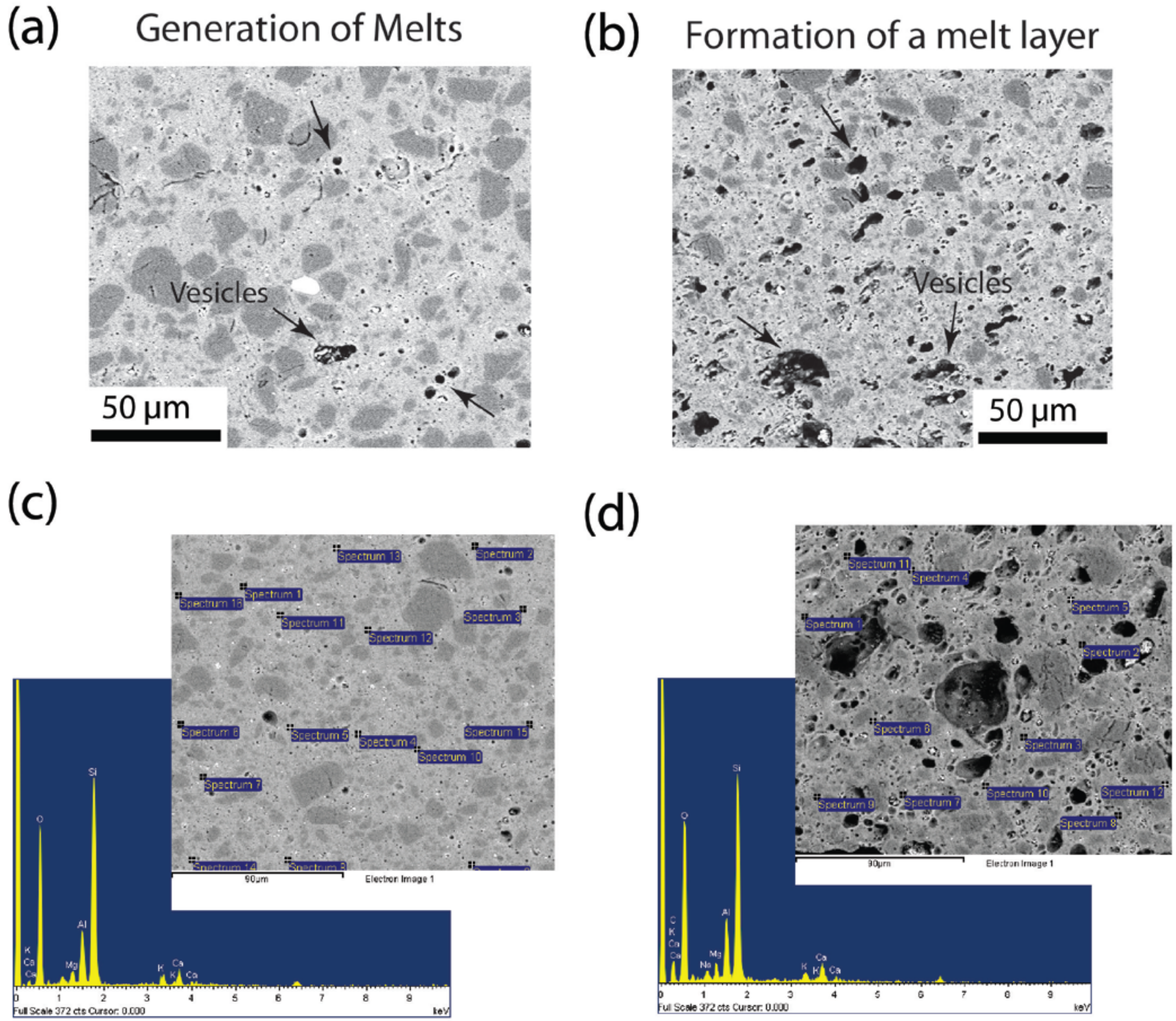


Han et al., 2014 GRL



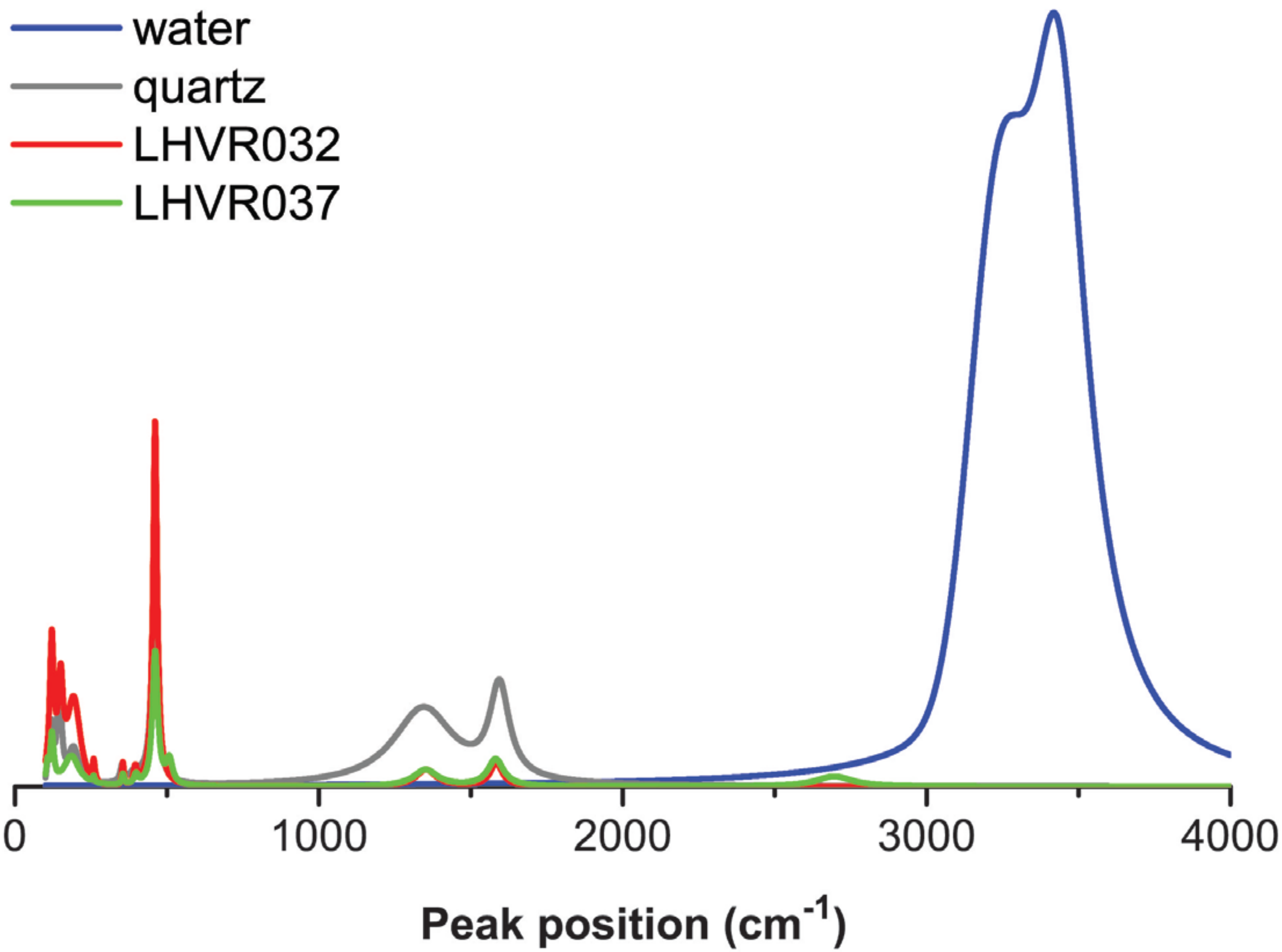
Janssen et al., 2014 JSG

Melt viscosity



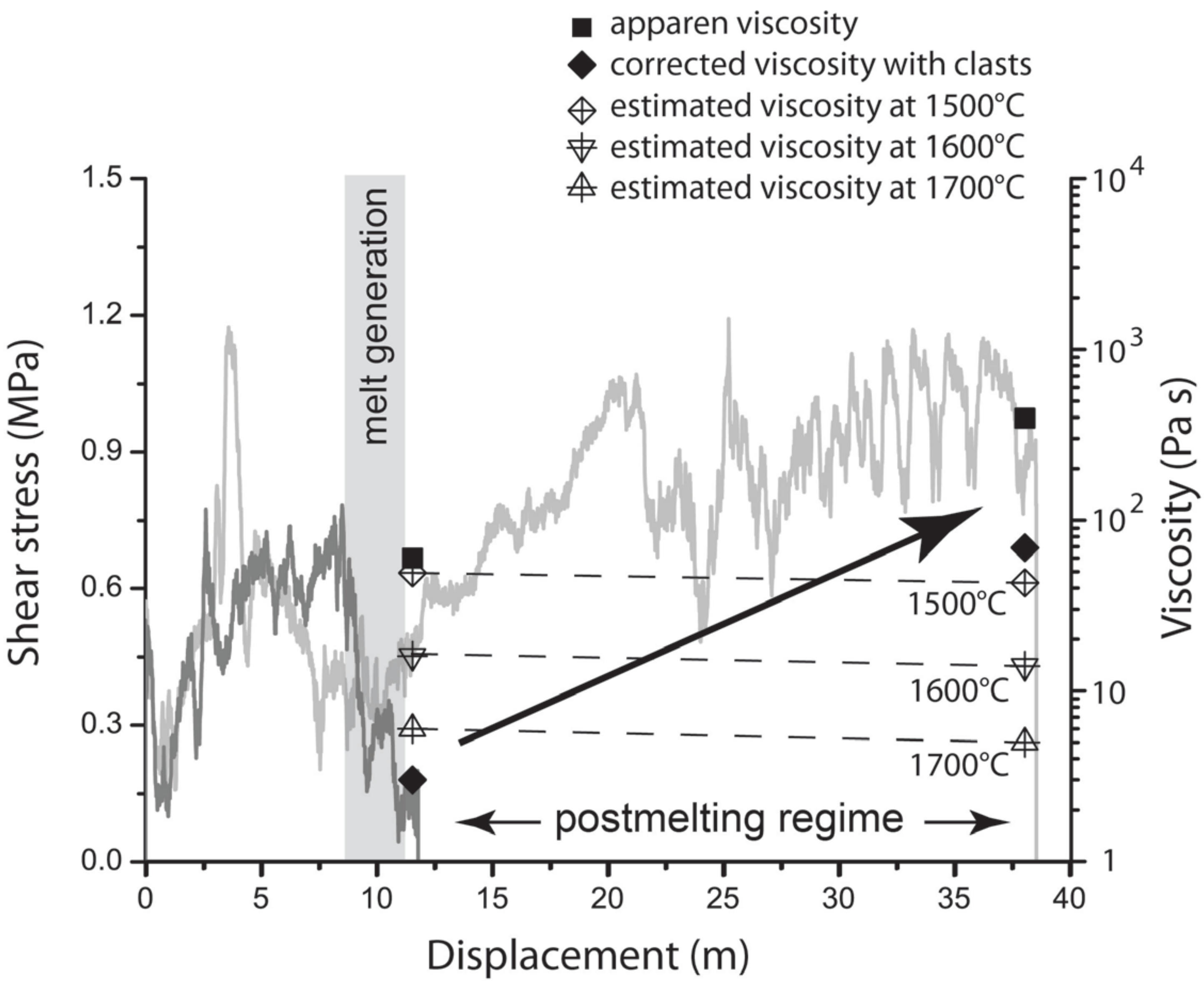
Kuo et al., submitted to JGR

Melt viscosity

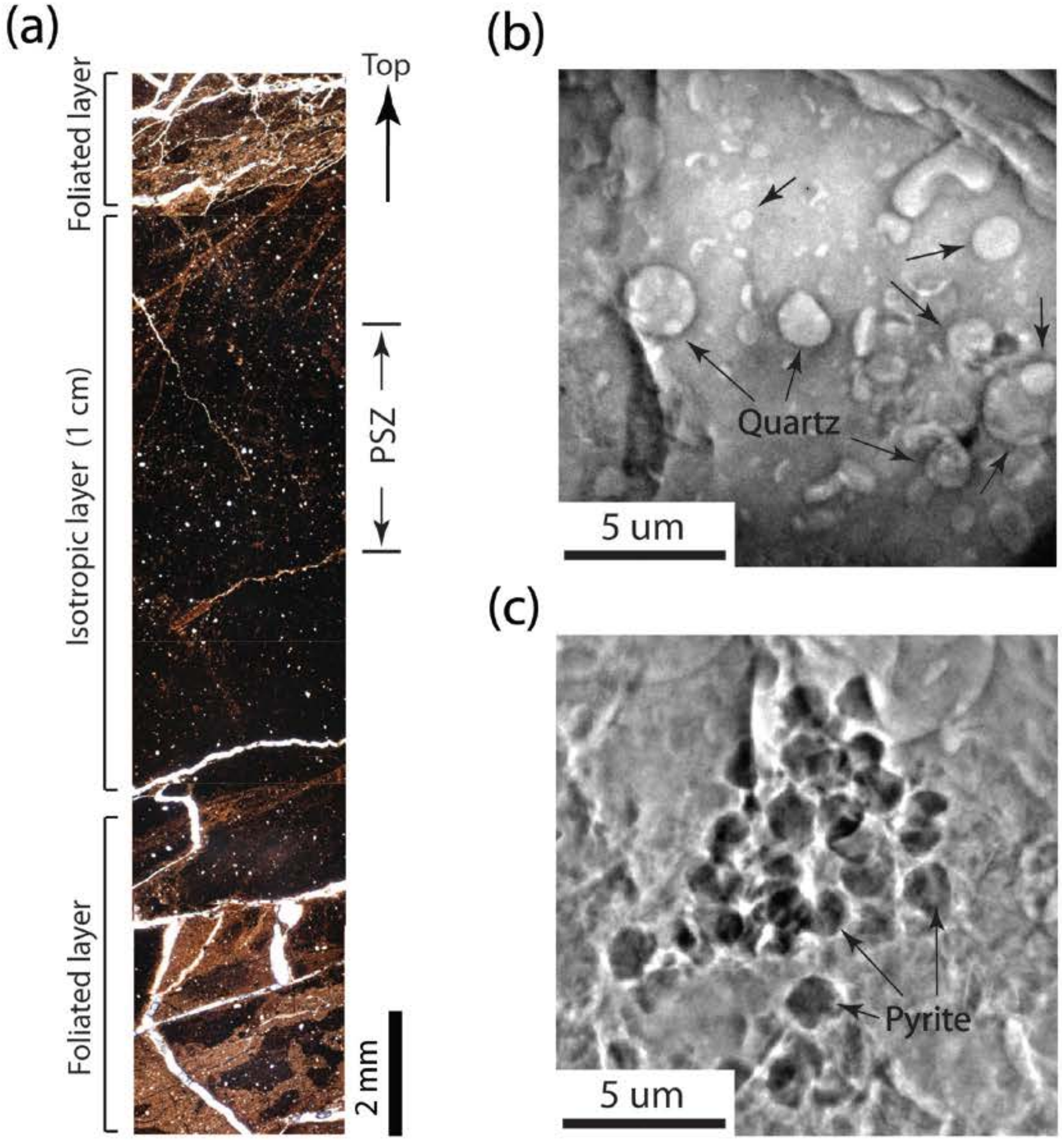


Kuo et al., submitted to JGR

Melt viscosity



Kuo et al., submitted to JGR


(a)
Top
Foliated layer
Isotropic layer (1 cm)
PSZ
Foliated layer
2 mm
(b)
Quartz
5 um
(c)
Pyrite
5 um