Field and experimental evidence of frictional melting in fluid-rich faults

Giulio Di Toro, M. Fondriest, T. Mitchell, R. Gomila, E. Jensen, S. Masoch, A. Bistacchi, G. Magnarini, D. Faulkner, J. Cembrano, S. Mittempergher, E. Spagnuolo

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For any info regarding this contribution to EGU 2020 virtual General Assembly, please contact

Giulio Di Toro

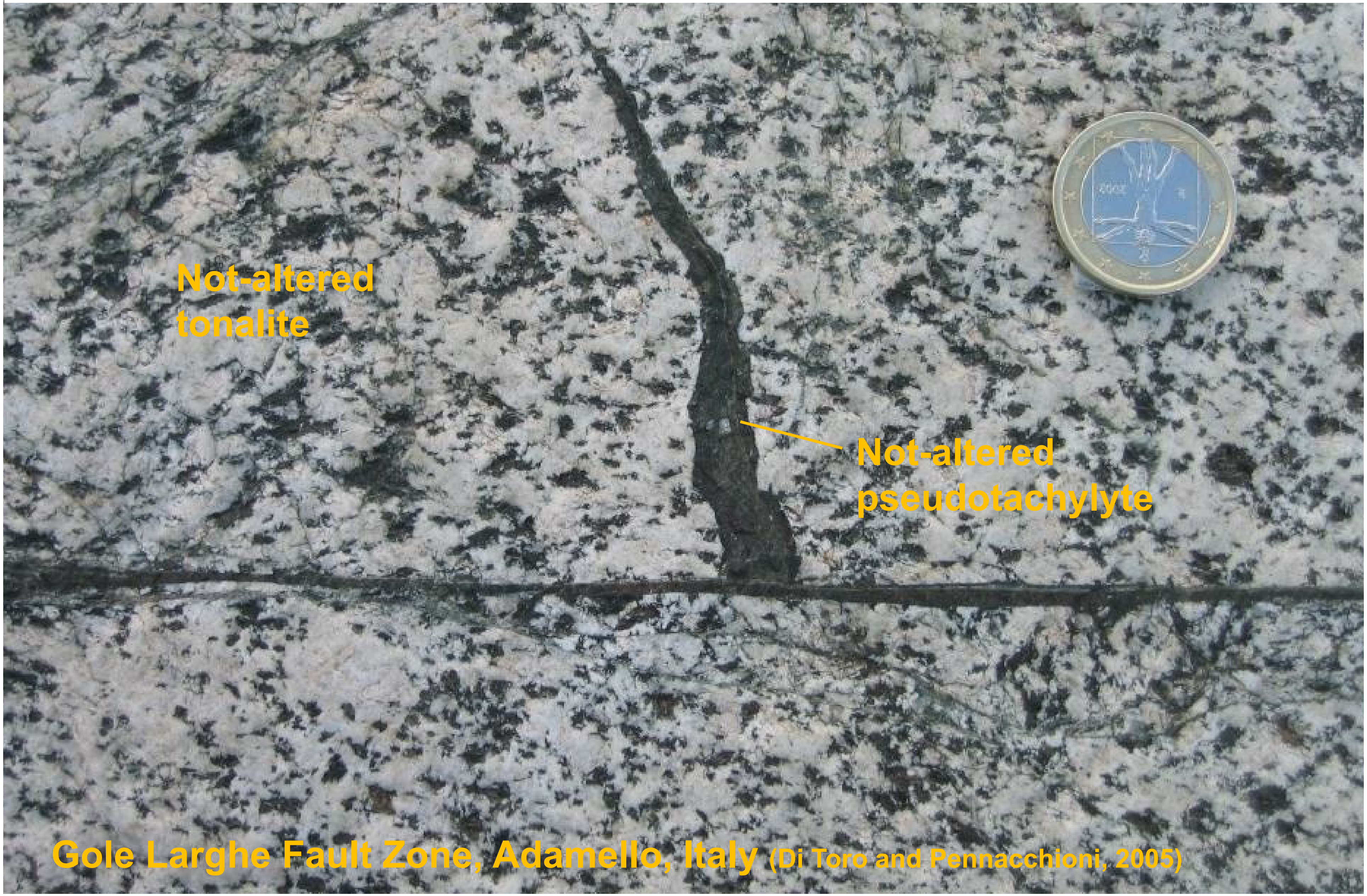
giulio.ditoro@unipd.it

or

Rodrigo Gomila:

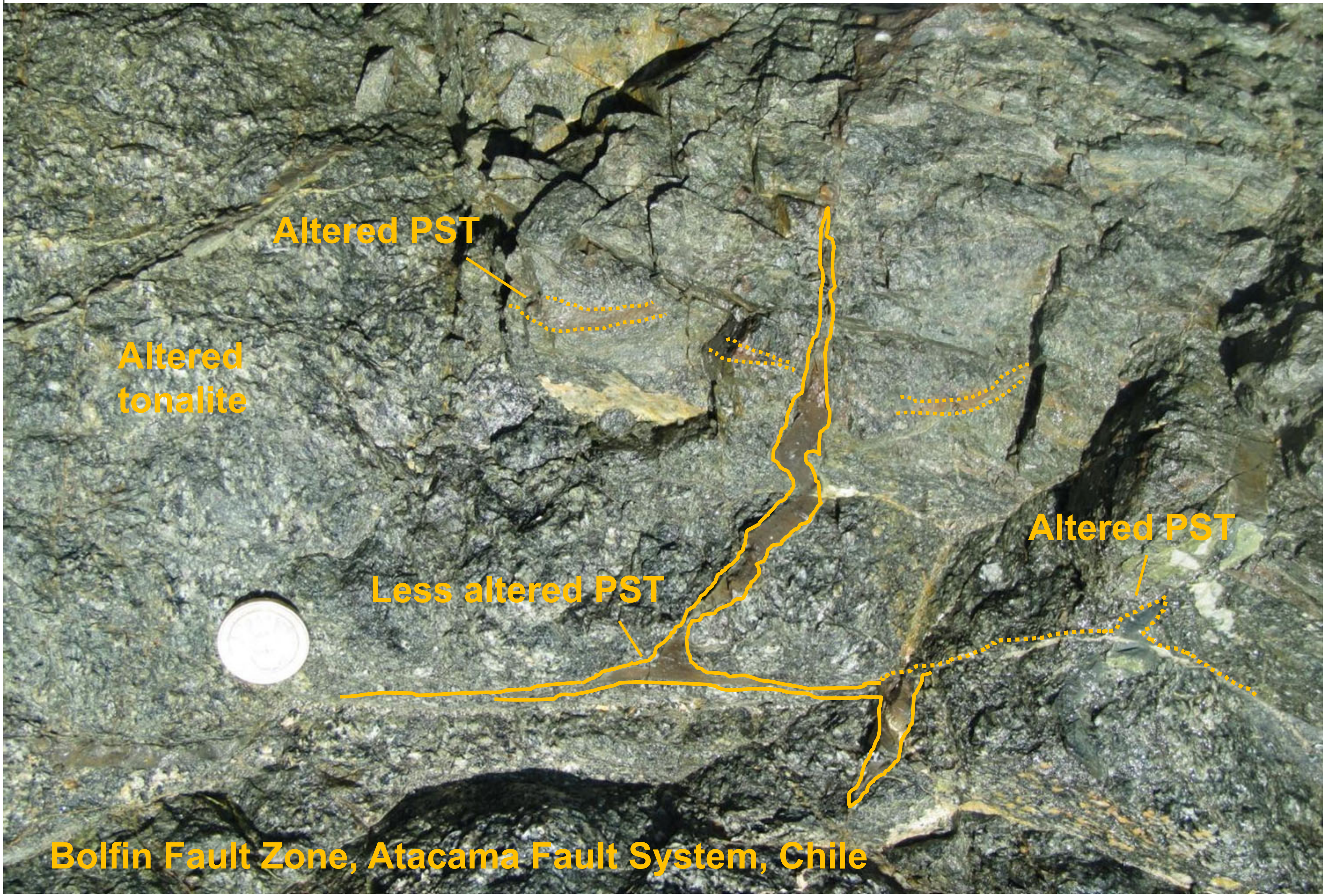
r.gomilaolmosdeaguilera@unipd.it

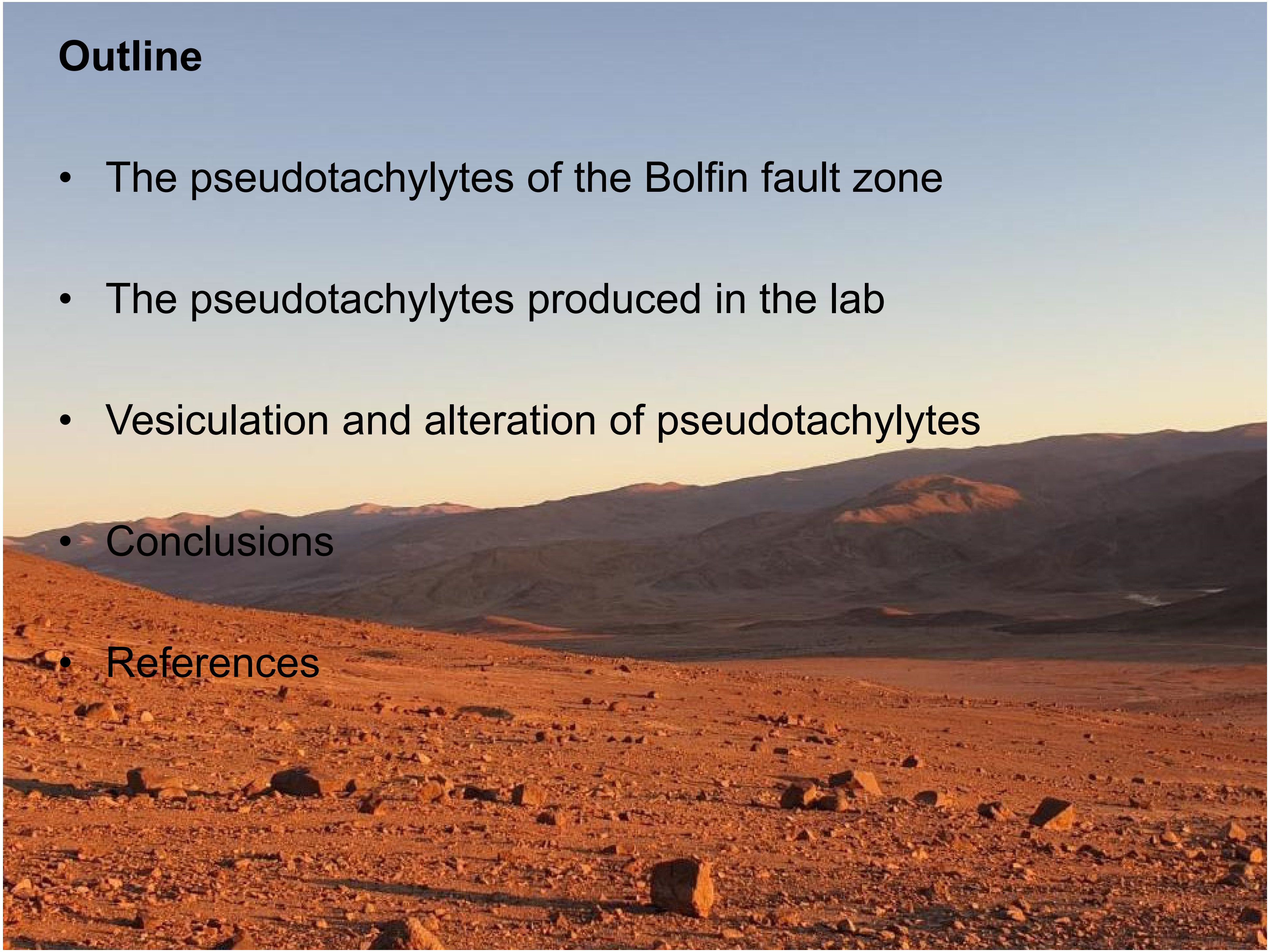
Pseudotachylyte are thought to be associated to seismic ruptures propagating in **immature and dry faults** hosted in cohesive rocks of the continental crust (Sibson and Toy, 2006)



But could PST be also produced in **mature and fluid-rich faults**? And because of this, prone to alteration and lost from the geological record?

If yes, PST might be **more common** than believed. Would not be this relevant for earthquake mechanics? (rise time, rupture mode, co-seismic and post-seismic fault healing, etc.)

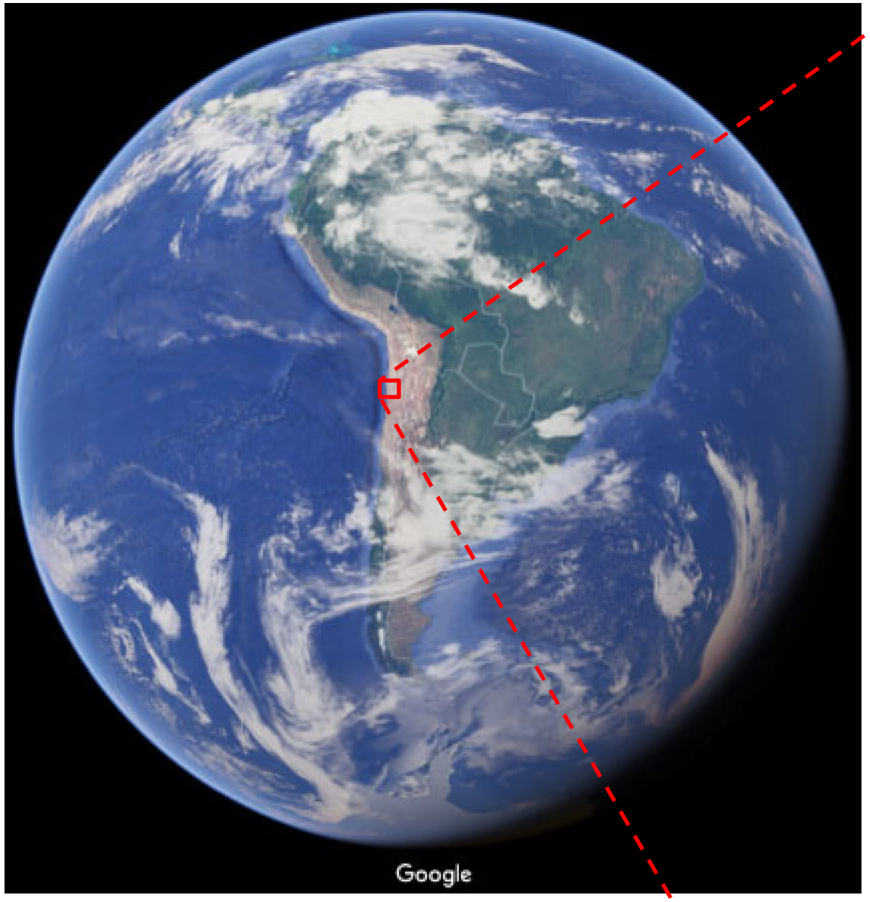


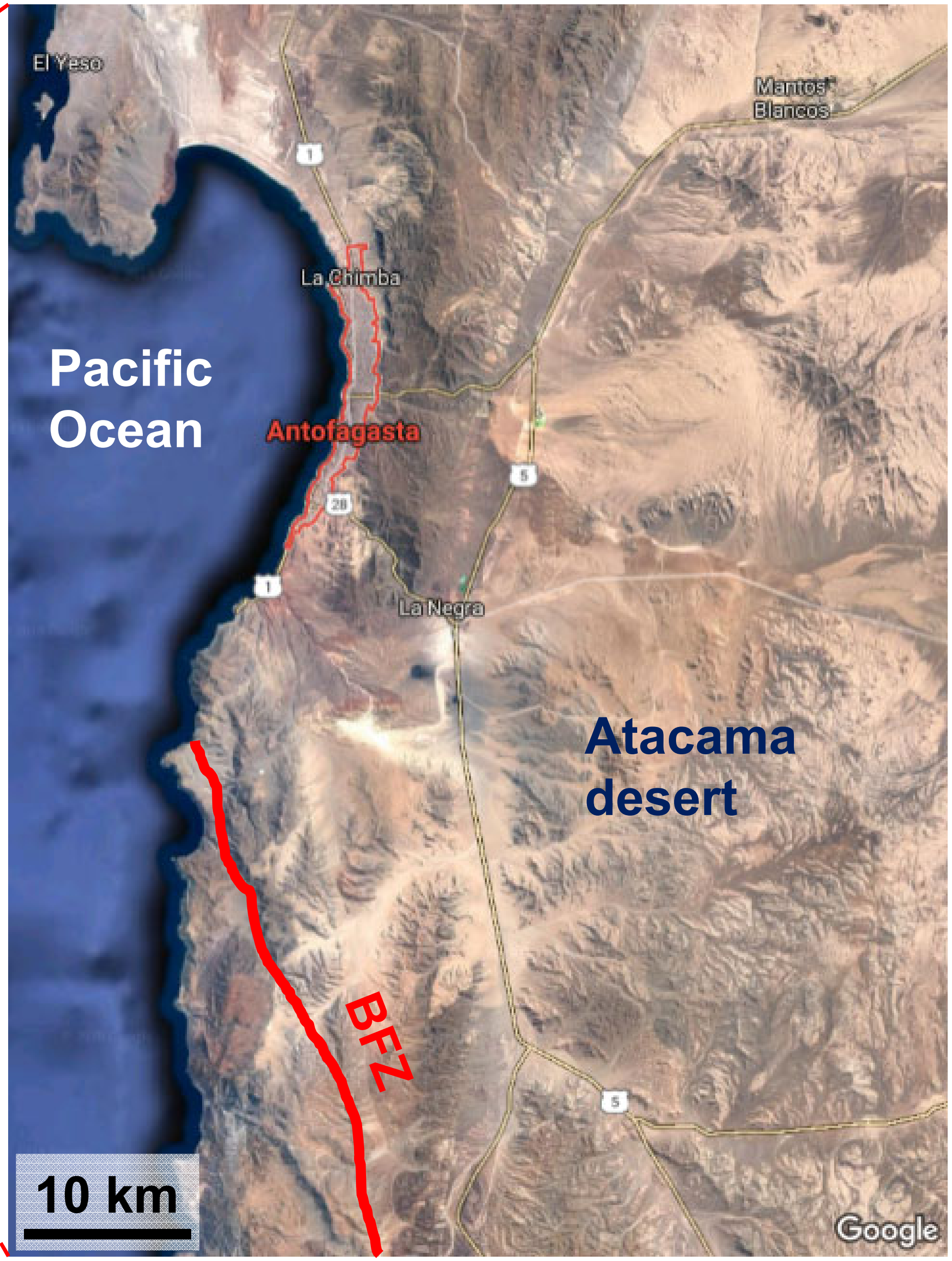


Outline

- The pseudotachylytes of the Bolfin fault zone
- The pseudotachylytes produced in the lab
- Vesiculation and alteration of pseudotachylytes
- Conclusions
- References

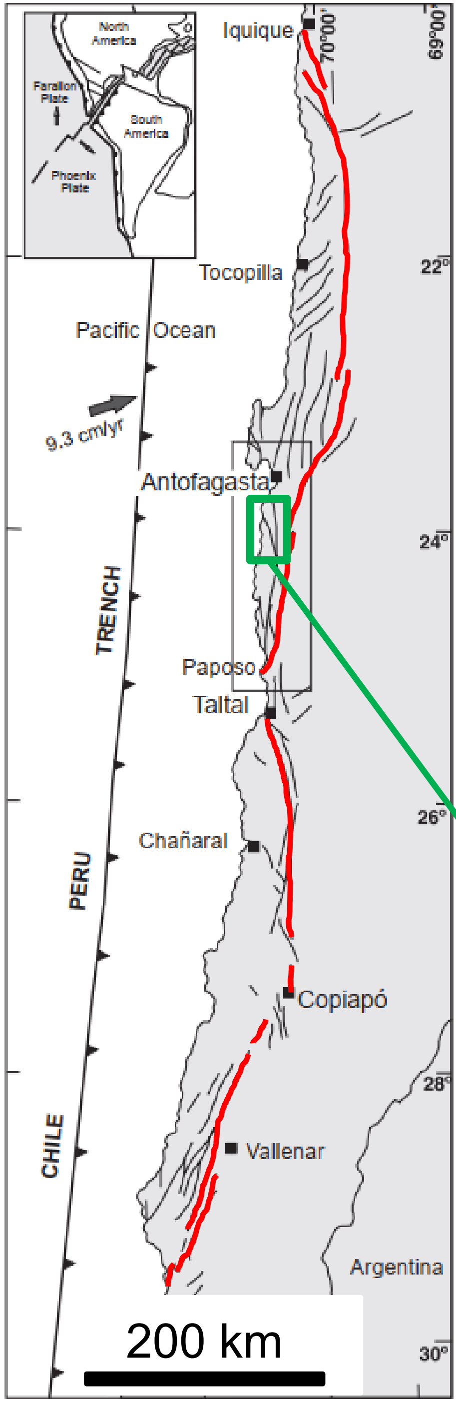
The 60 km long strike slip Bolfin Fault Zone (BFZ)





Beautifully exposed in the Atacama desert in Northern Chile

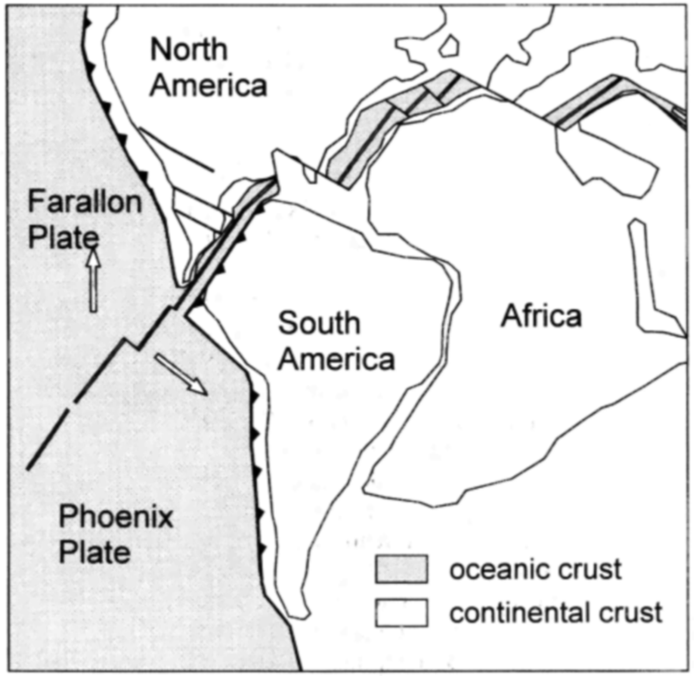
Scheuber and Gonzalez (1999)

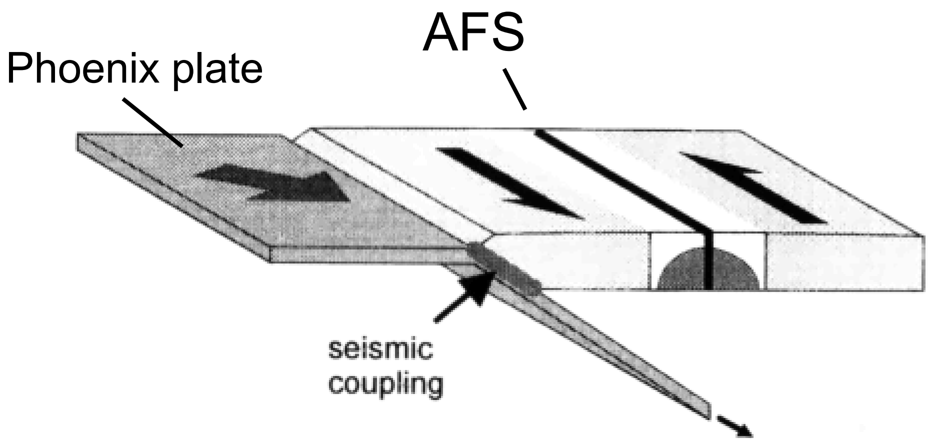


The "brittle" Atacama Fault System (AFS)

- Lower Cretaceous
- Oblique subduction
- Sinistral strike-slip
- 1000 km long and 60 km in width
- Cuts a magmatic arc

Next slide

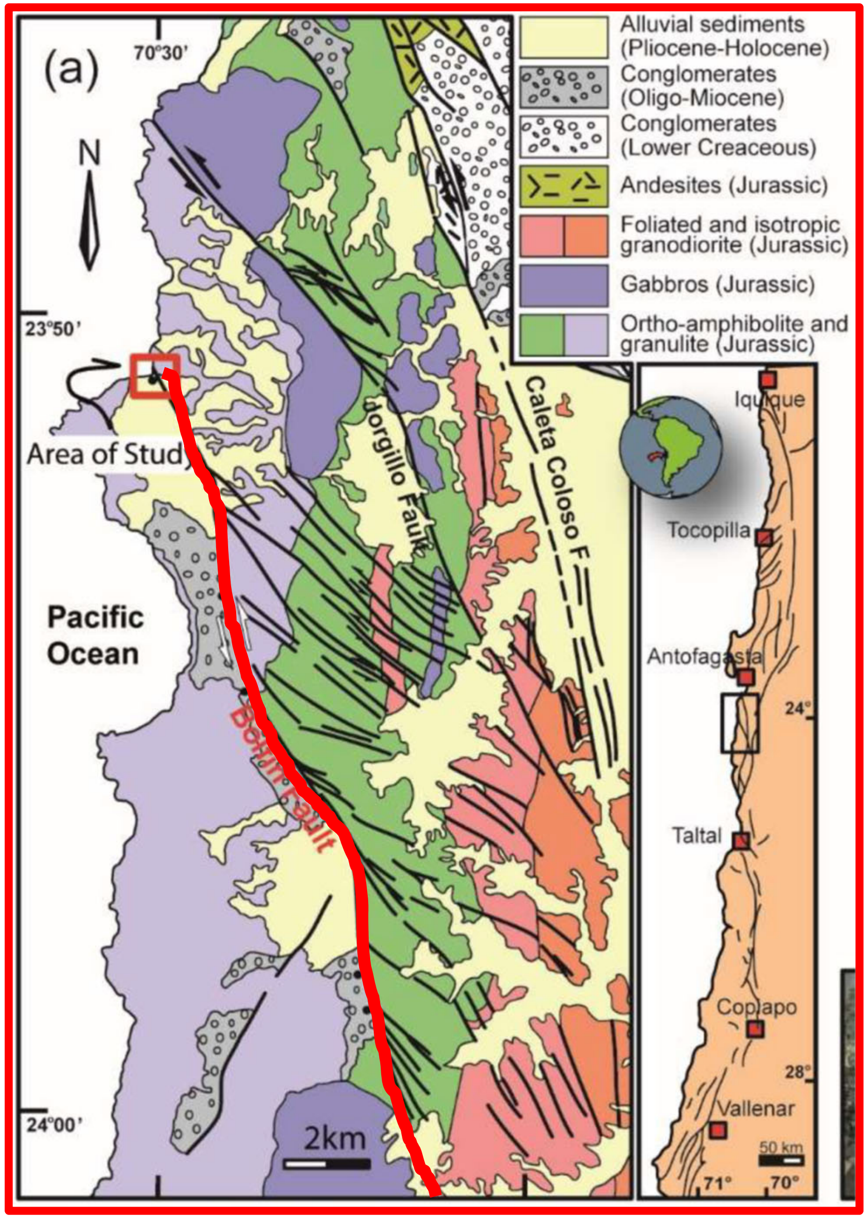


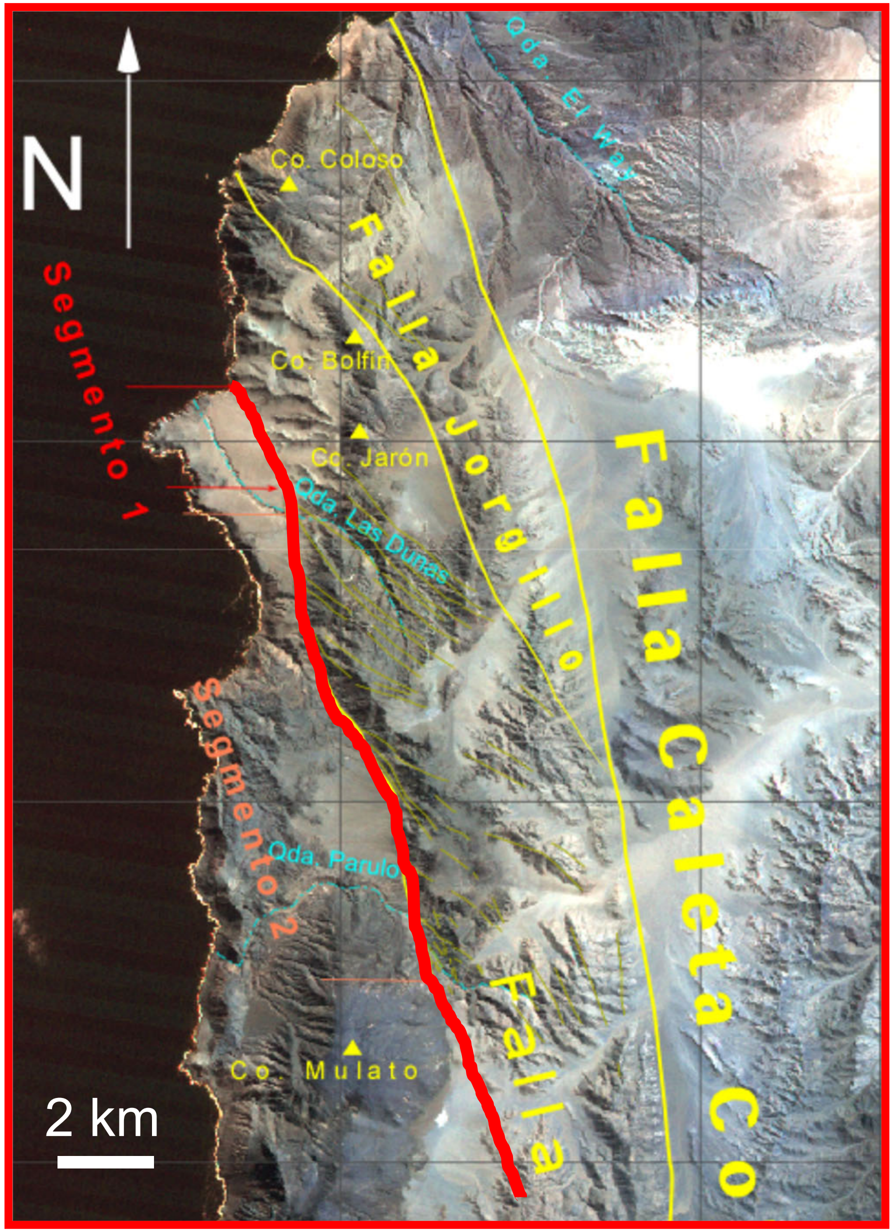


Scheuber and Gonzalez (1999): Cembrano et al. (2005)

The Bolfin Fault Zone accommodated > 4-5 km of sinistral strike slip movement and cuts tonalites, diorites, etc.

Cembrano et al. (2005)

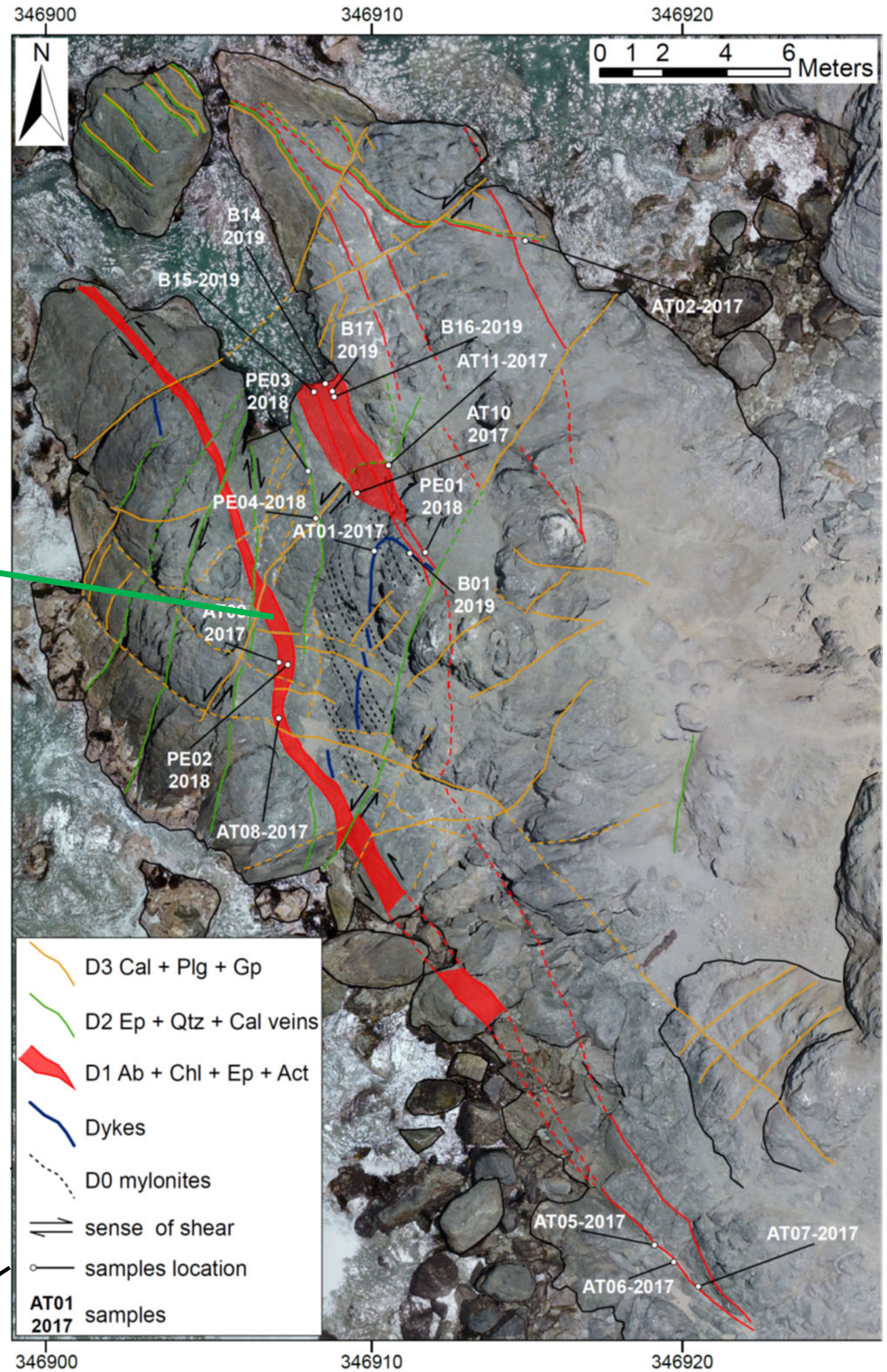




The Bolfin FZ's pseudotachylytes at Playa Escondida

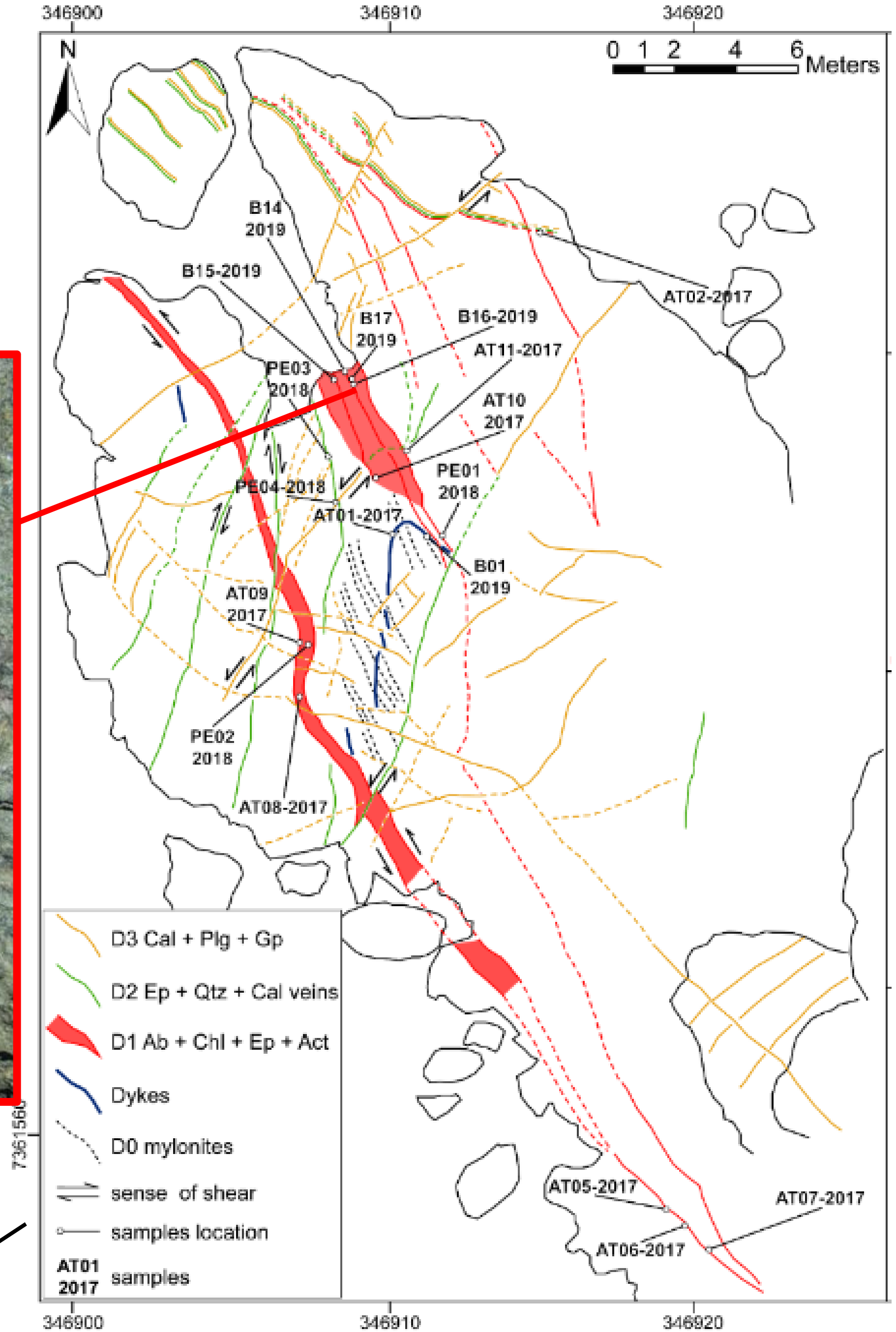
Foliated cataclasites in hydrothermally altered main fault cores sheared at T= 250-300 °C and at 4-8 km depth.

Mitchell et al., 2009 JSG
Jensen et al., 2011 JSG
Faulkner et al., 2011 JGR
Arancibia et al., 2014 Tectonophysics
Gomila et al., 2016 JSG



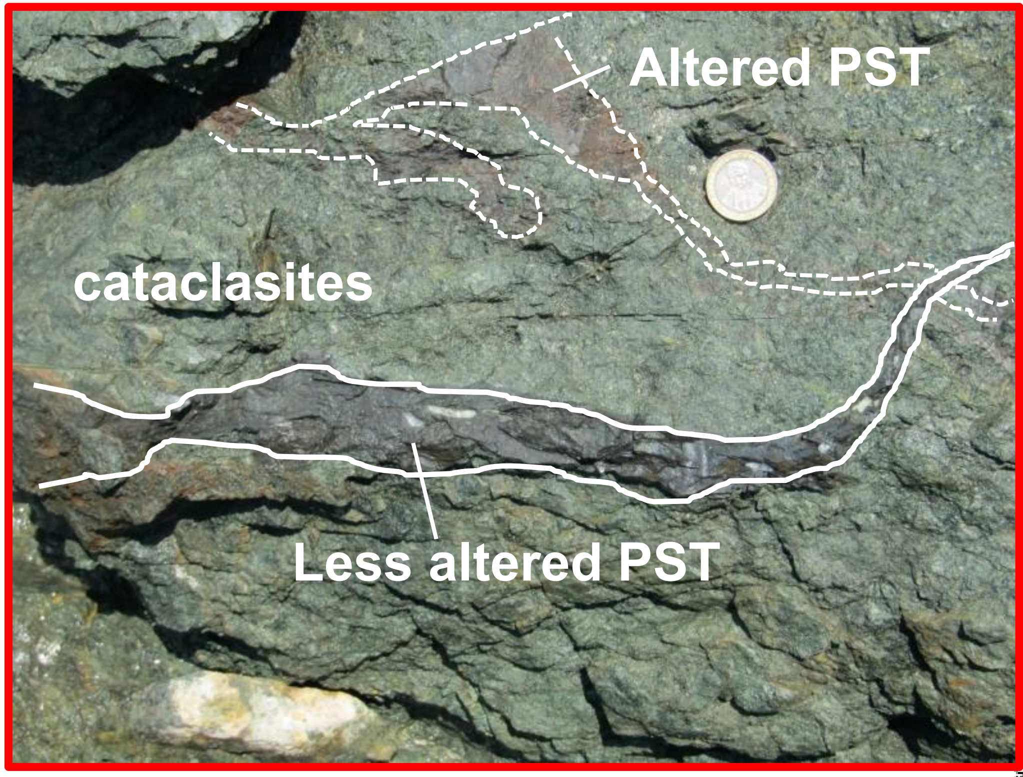
Surface map from drone images

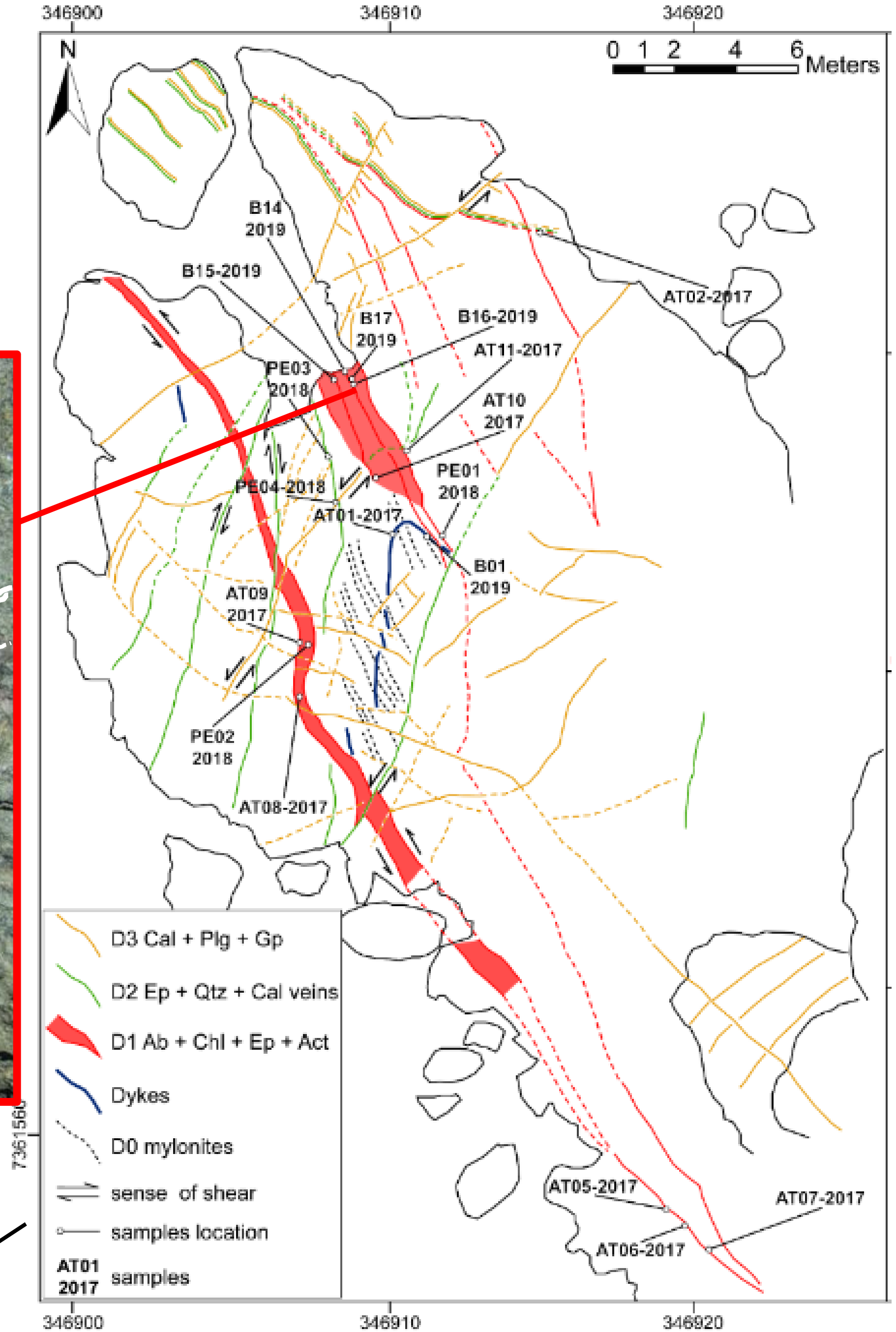
Multiple generations of pseudotachylytes cutting cataclasites and altered tonalites



Surface map from drone images

Multiple generations of pseudotachylytes cutting cataclasites and altered tonalites

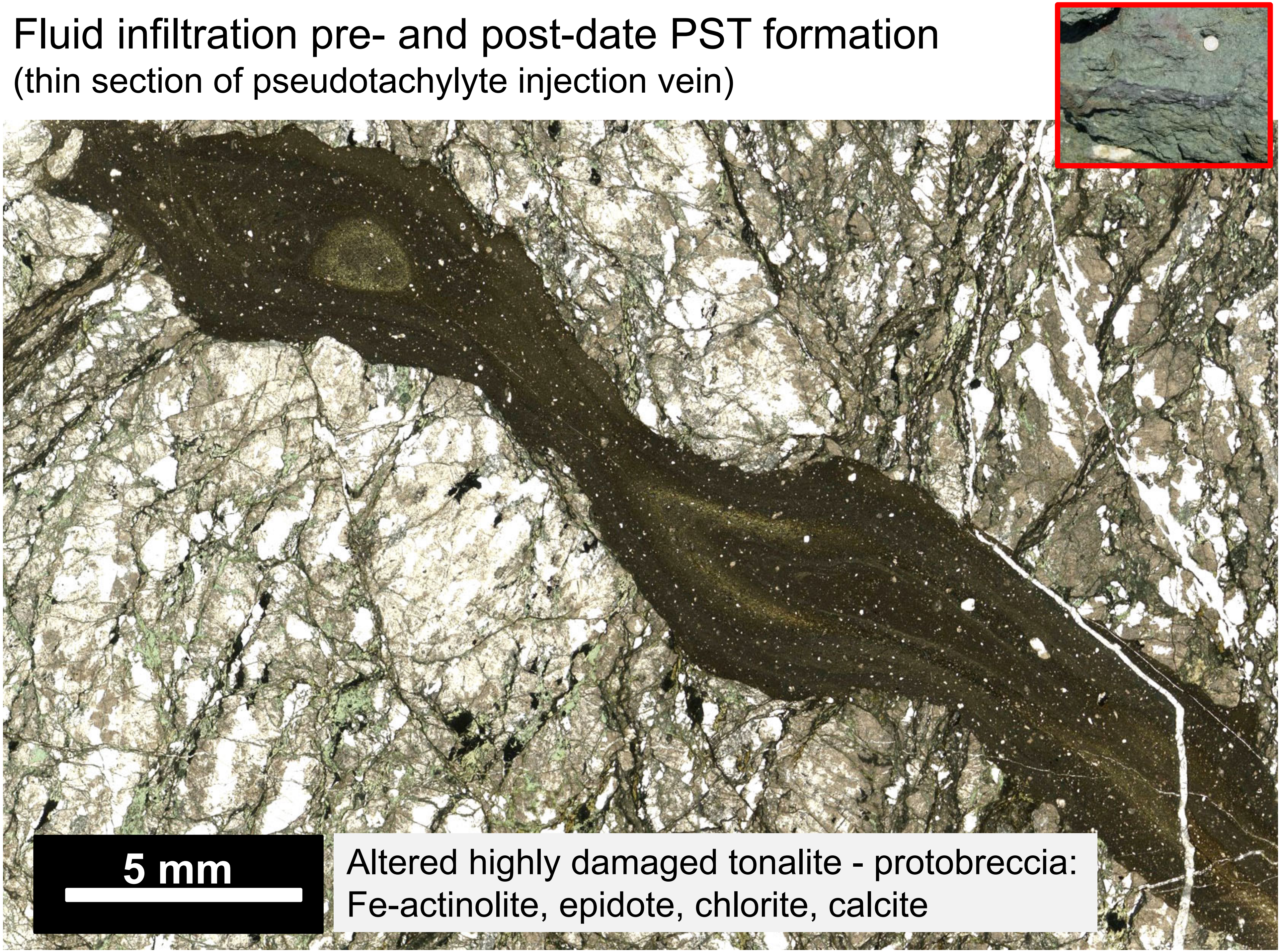




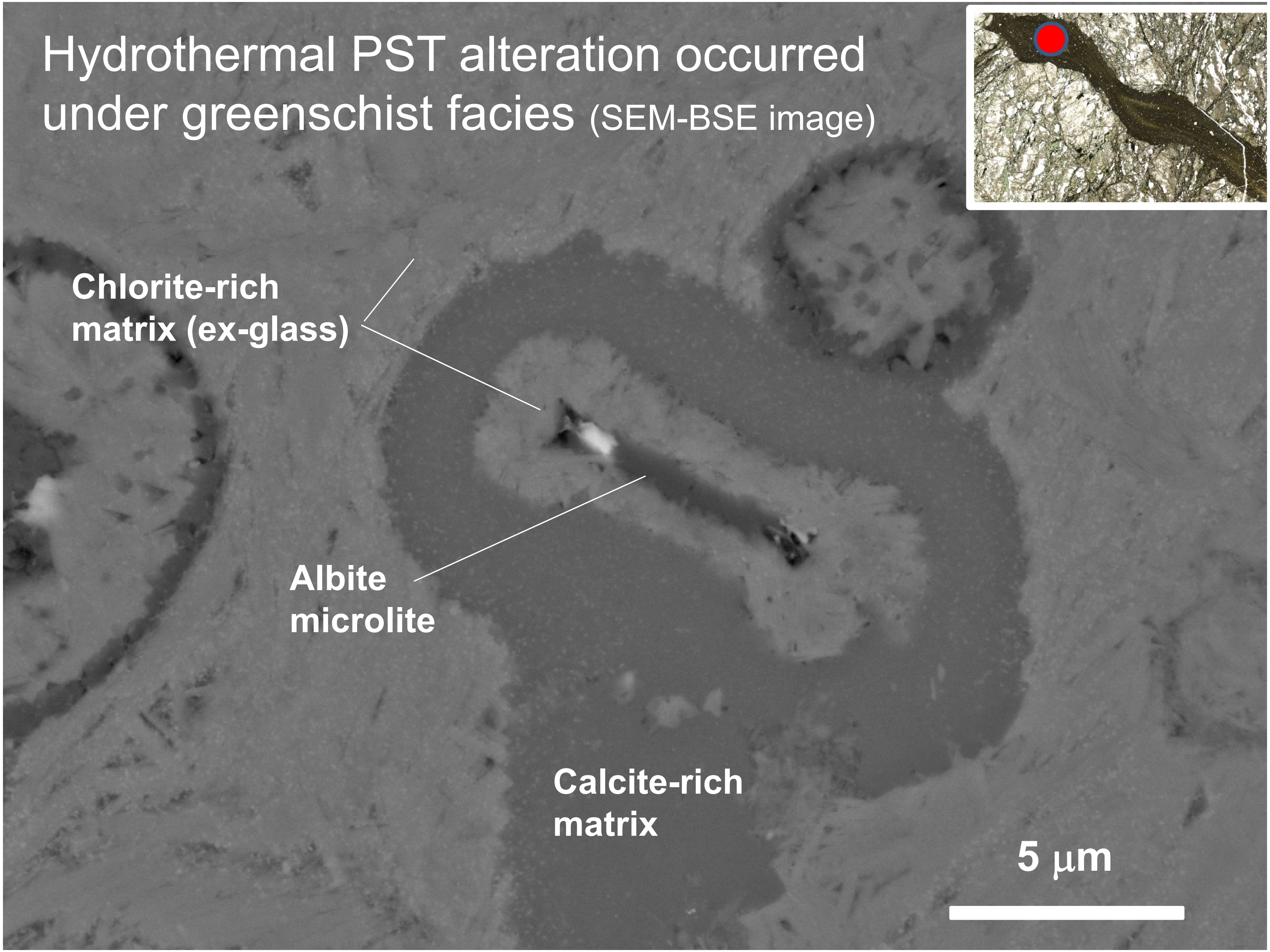
Surface map from drone images

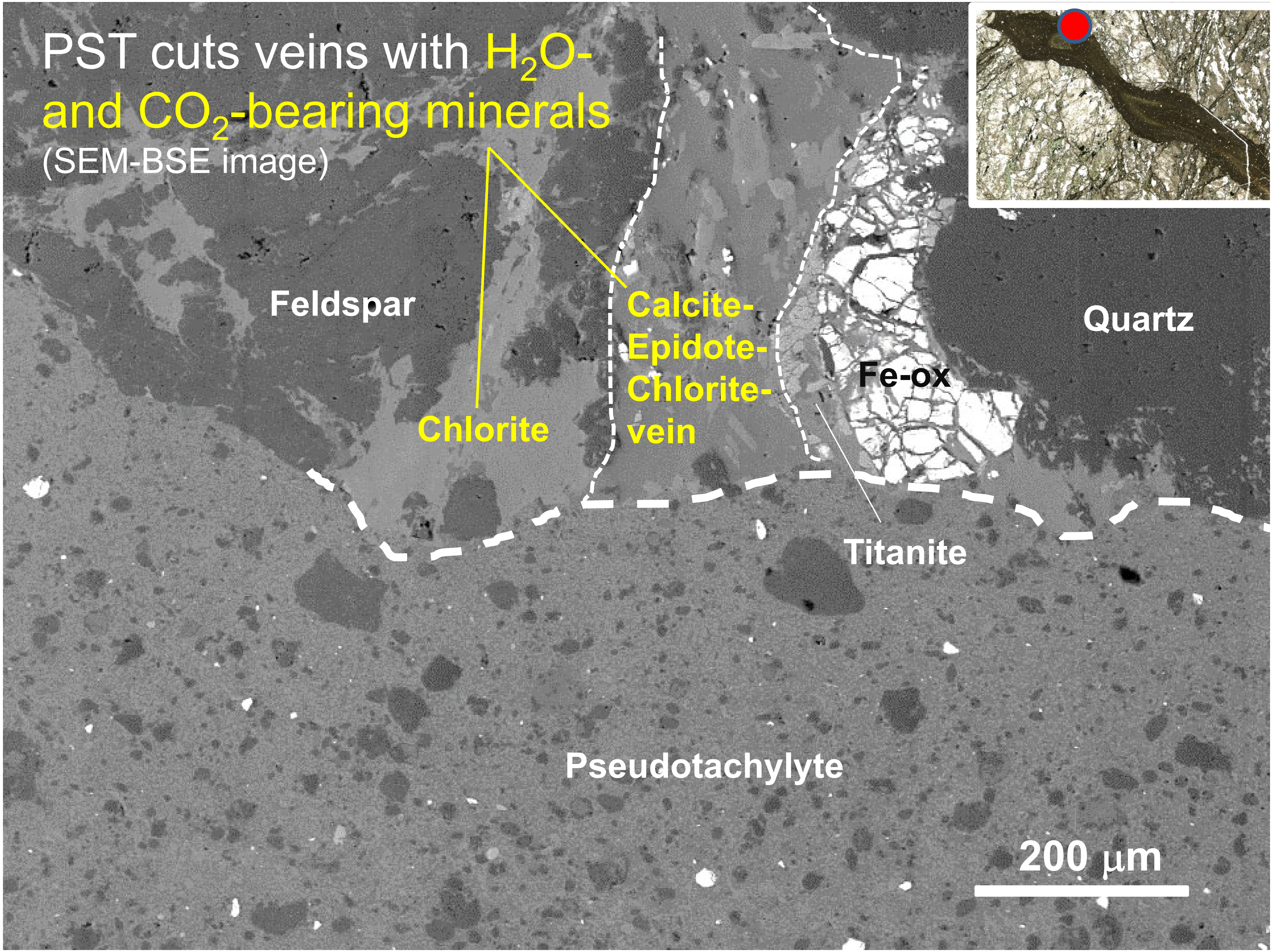
Fluid infiltration pre- and post-date PST formation

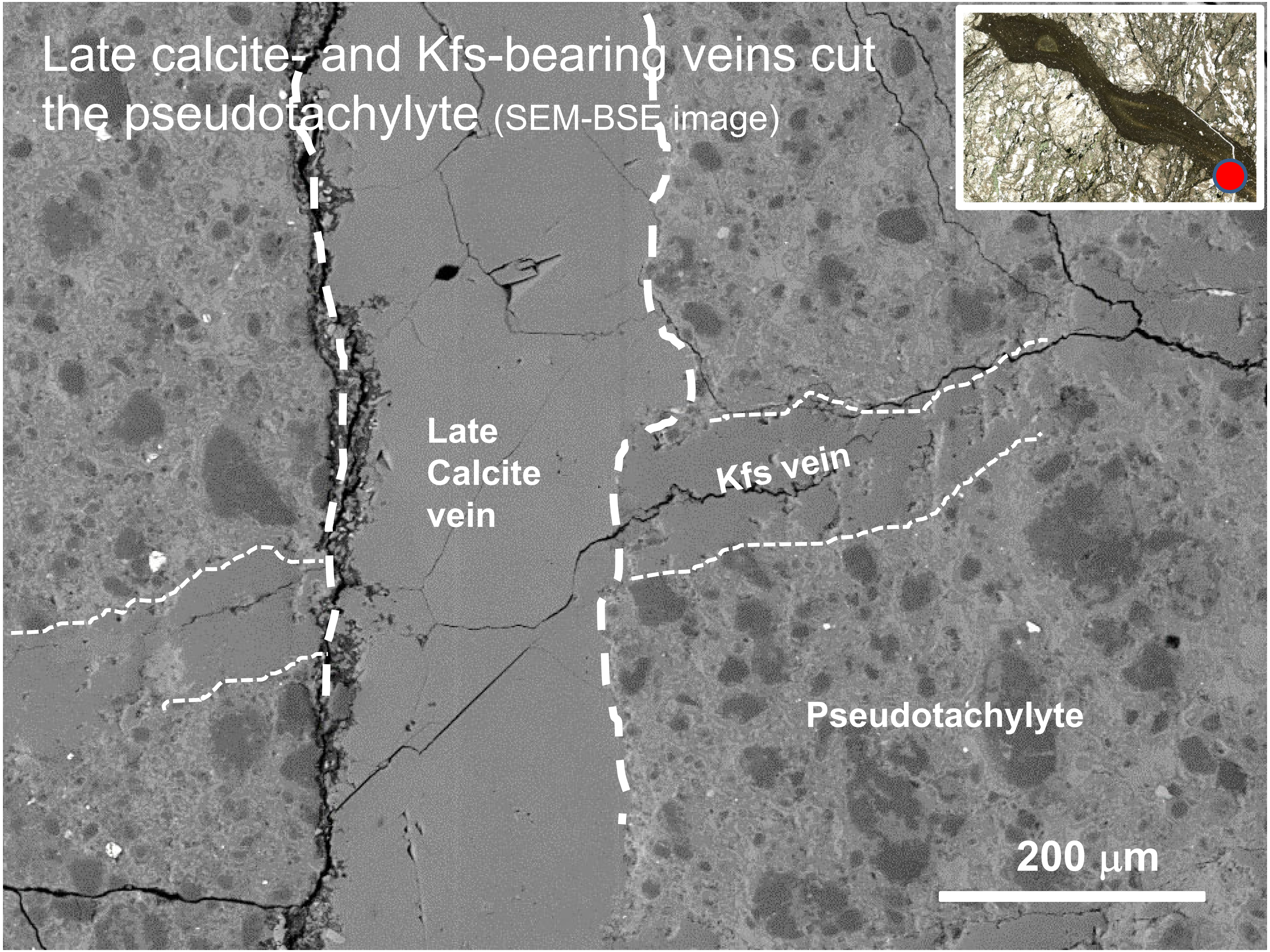
(thin section of pseudotachylyte injection vein)



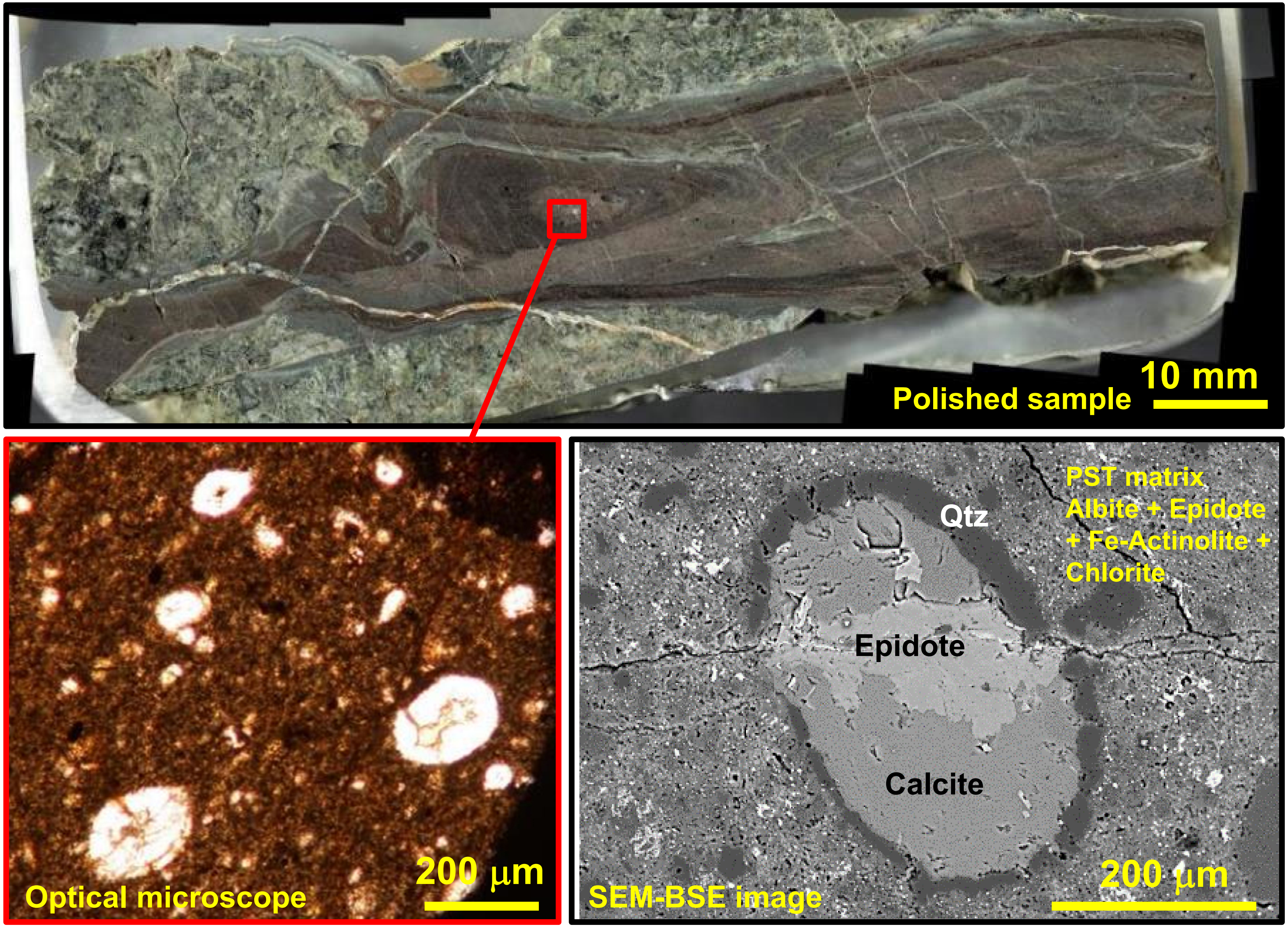
Hydrothermal PST alteration occurred under greenschist facies (SEM-BSE image)




PST cuts veins with H_2O-
and CO_2-bearing minerals
(SEM-BSE image)
Feldspar
Chlorite
Calcite-
Epidote-
Chlorite-
vein
Fe-ox
Quartz
Titanite
Pseudotachylyte
200 μm


Late calcite- and Kfs-bearing veins cut the pseudotachylyte (SEM-BSE image)
Late Calcite vein
Kfs vein
Pseudotachylyte
200 μm

Flow structures and mineral-filled vesicles in PSTs (e.g., Magloughlin, 2011)

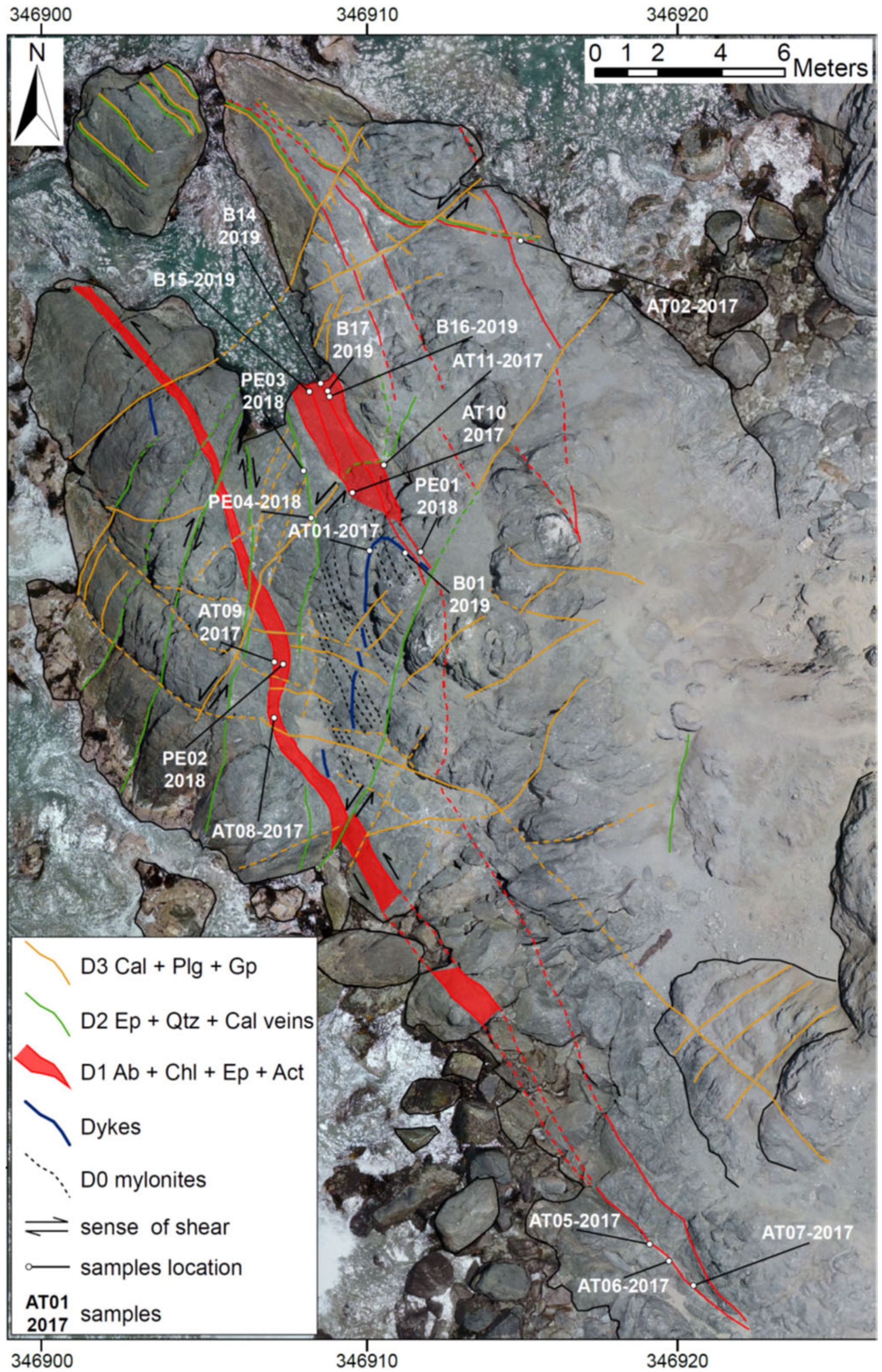


Bolfin Fault Zone Pseudotachylytes

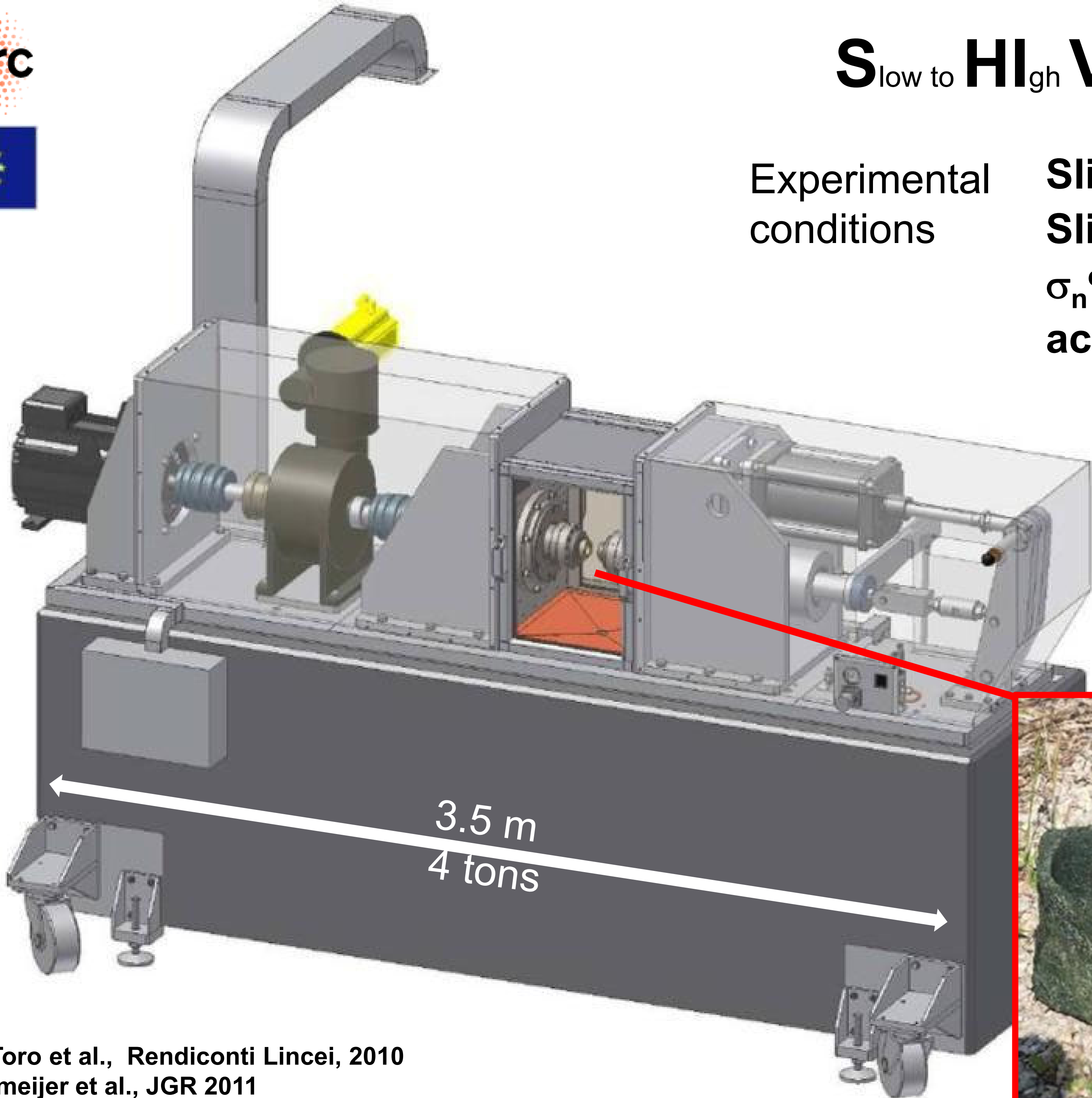
- found in **large slip and mature seismogenic faults** (> 4 km slip)
- produced **under hydrothermal conditions** (250< T< 300 °C and 4-8 km depth)
- record **multiple** seismic ruptures
- produced **in the presence of fluids** before and after seismic faulting
- prone to **alteration**

But can PST be produced in the presence of free pore fluids? And why the vesicles?

Let's produce PST in the lab



Slow to **HI**gh **V**elocity **A**pparatus

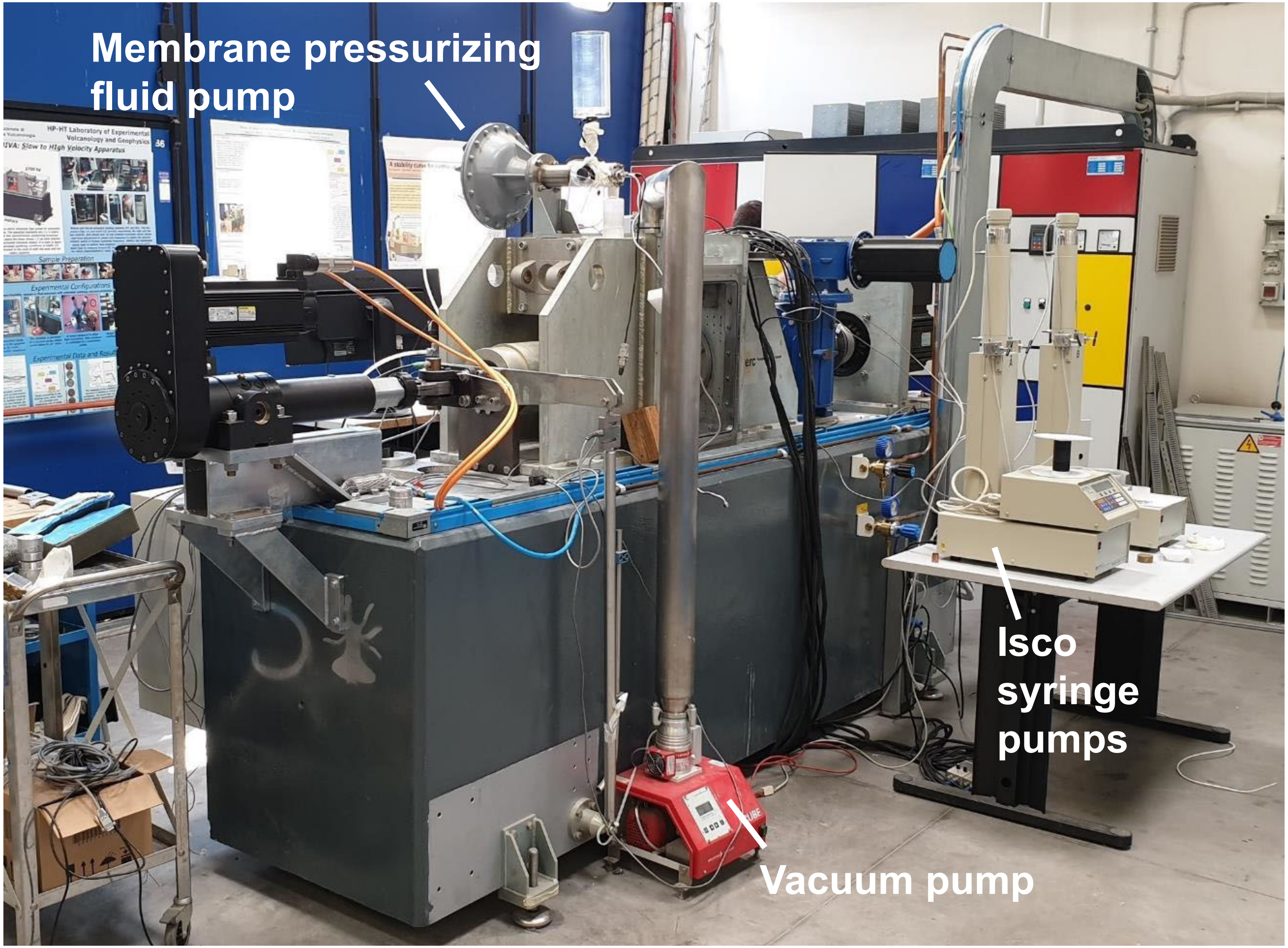


Experimental conditions

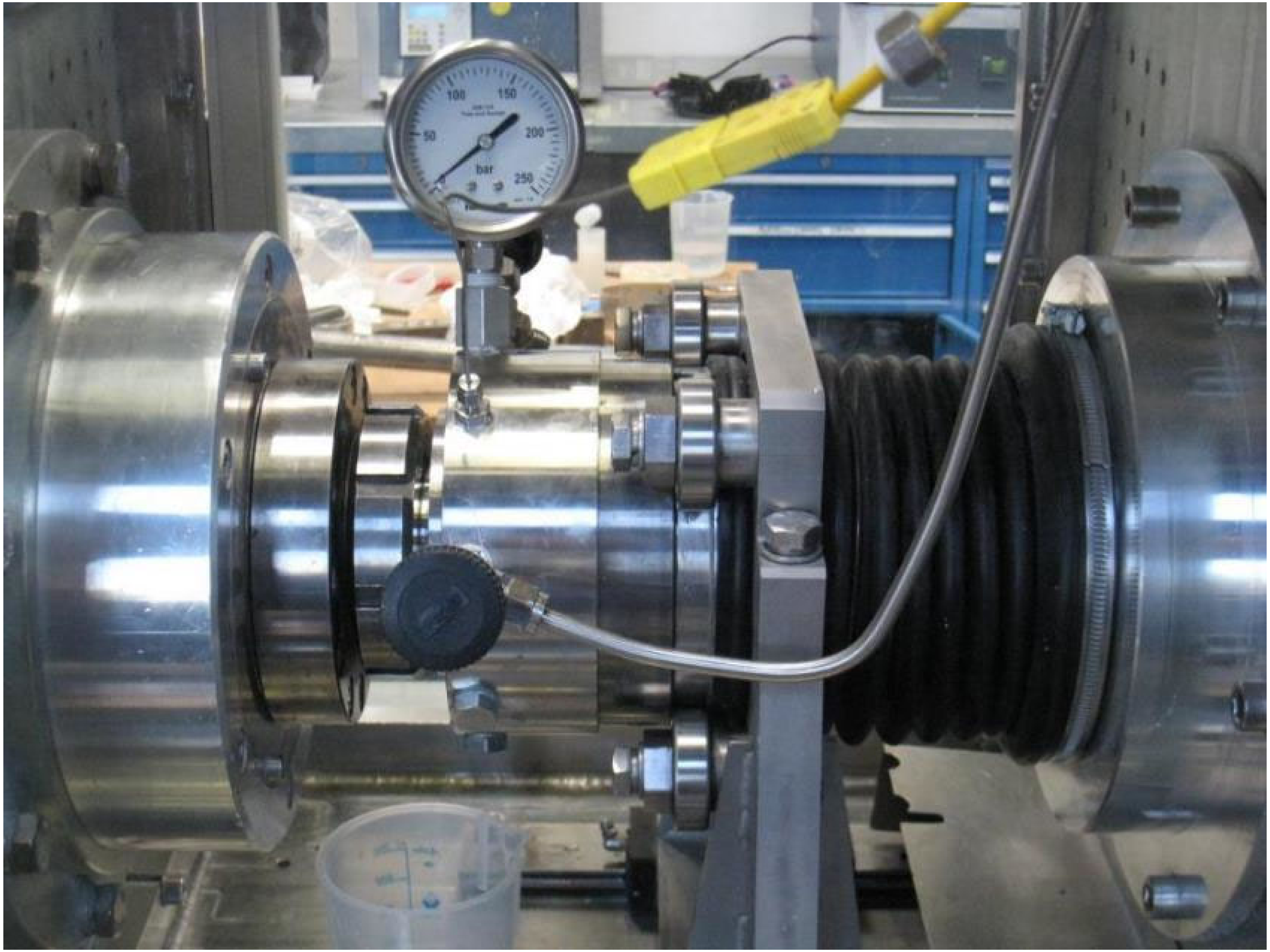
Slip rate = 3 m/s,
Slip = 1 m
σ_n^{eff} = 20 MPa
acc. = 24 m s^{-2}

Di Toro et al., Rendiconti Lincei, 2010
Niemeijer et al., JGR 2011

Environmental conditions: **room humidity, pressurized water (Pp = 5 MPa), vacuum (10^{-4} mbar)**

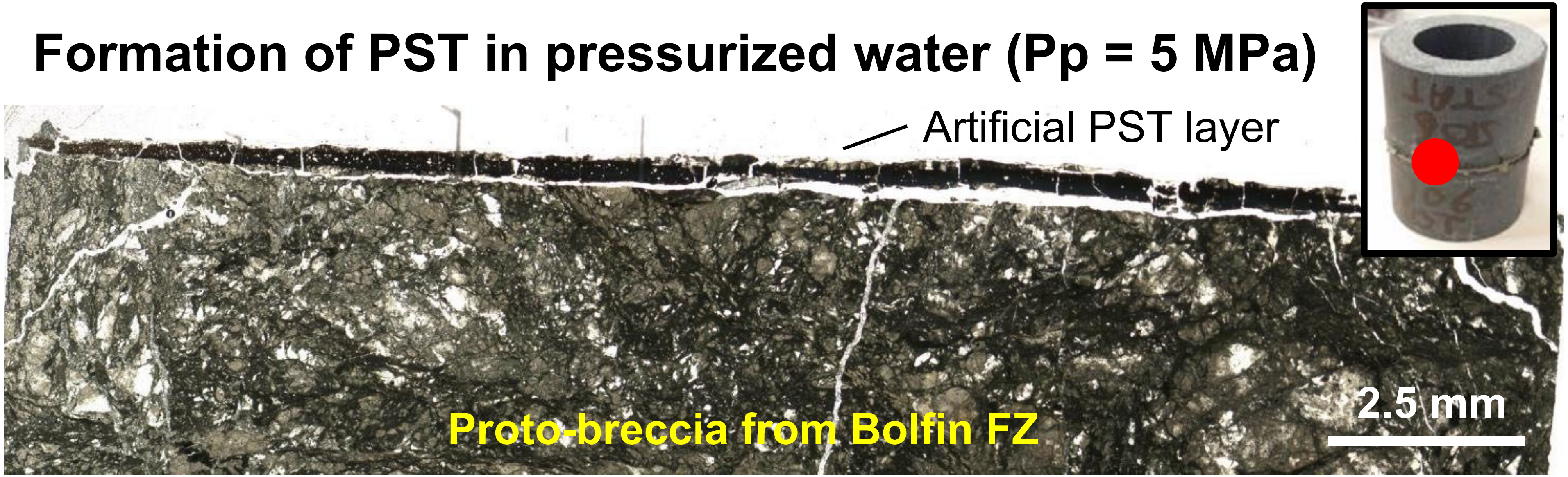


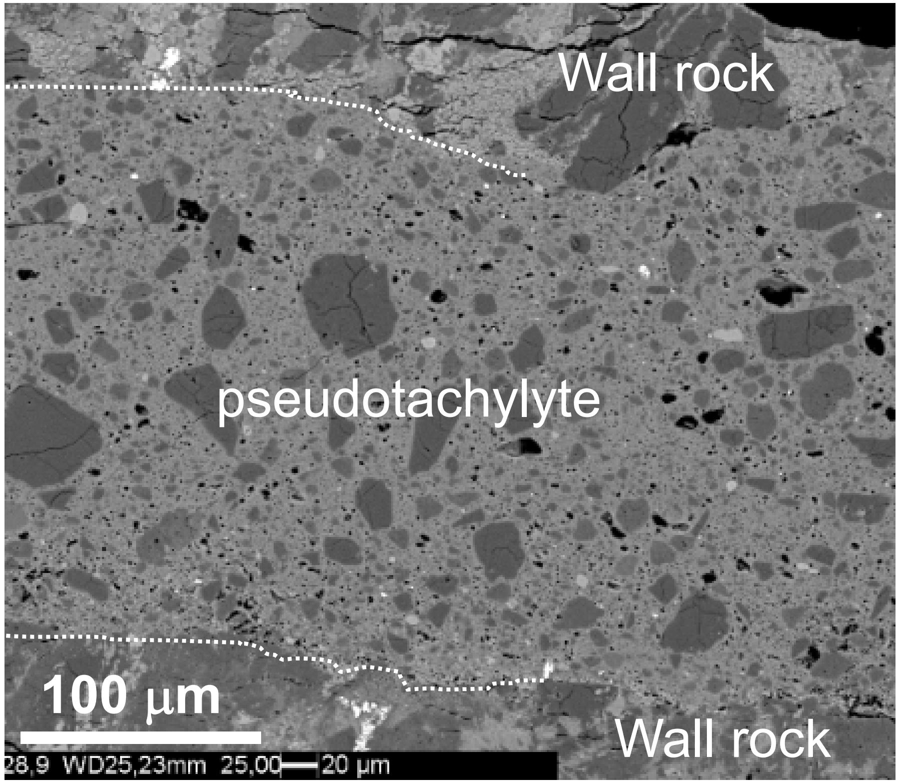
Rotary shear experiments in pressurized fluids

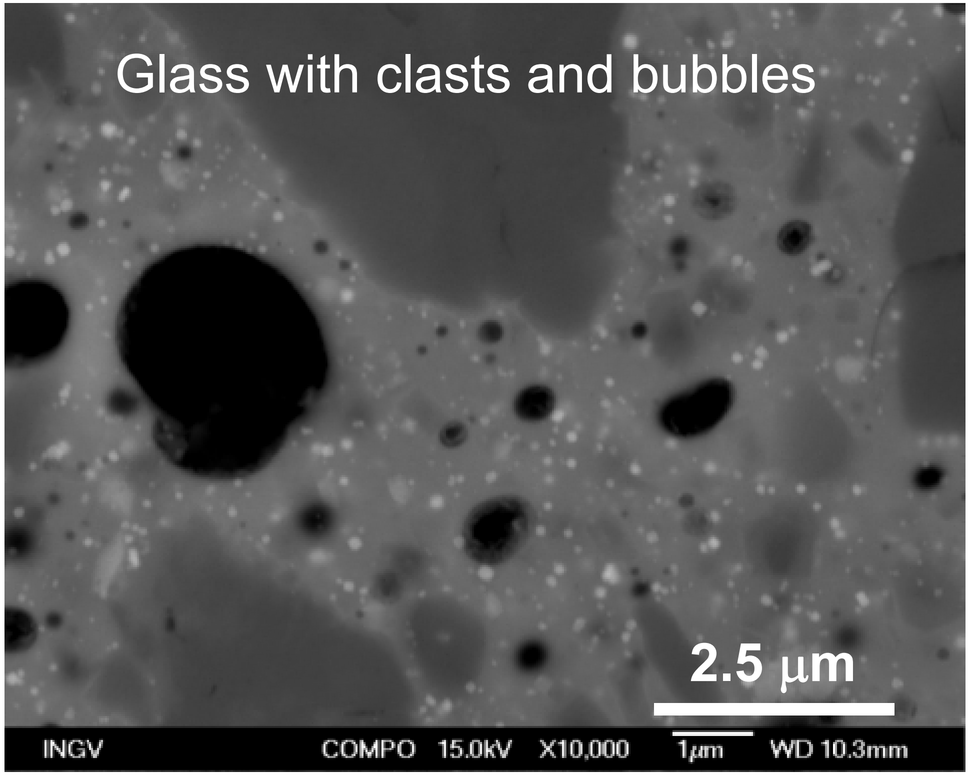


Violay et al., EPSL 2013; Geology, 2014; EPSL 2015

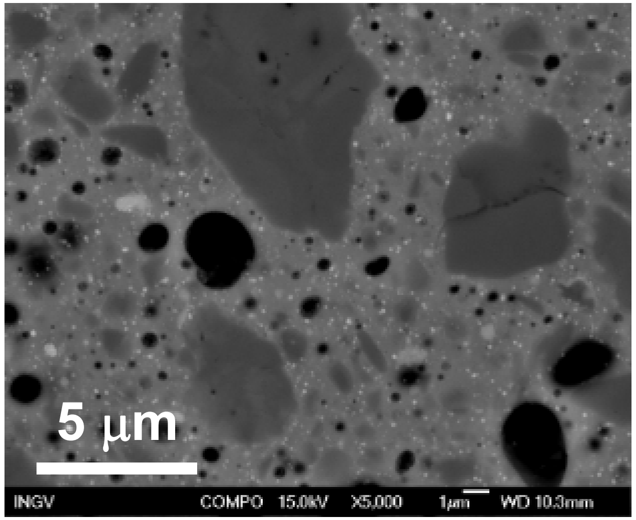
Formation of PST in pressurized water (Pp = 5 MPa)



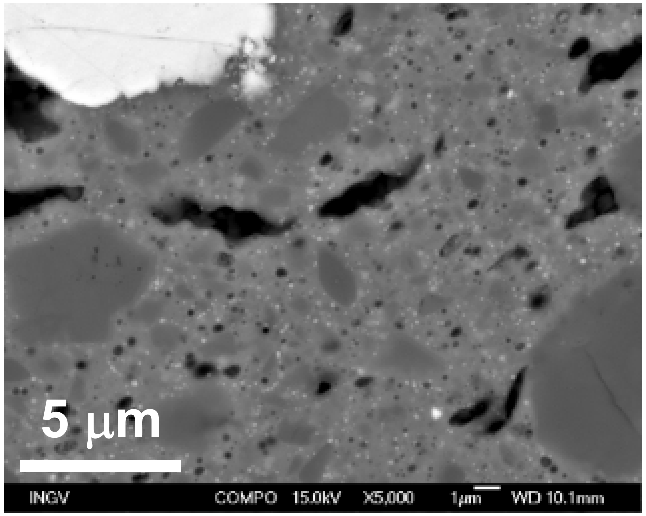




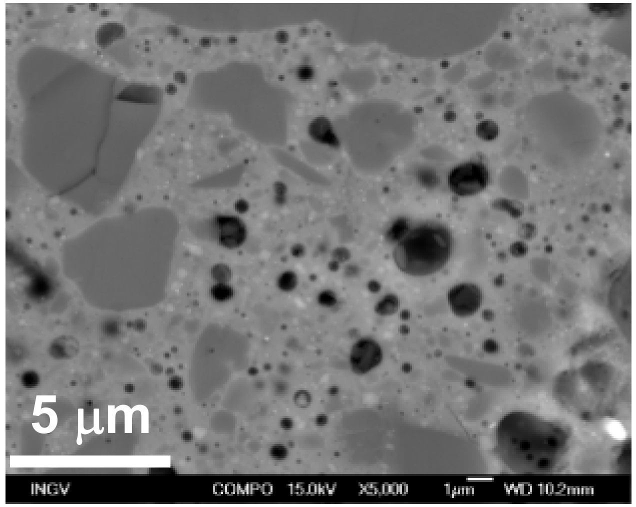
Pressurized water



Room humidity



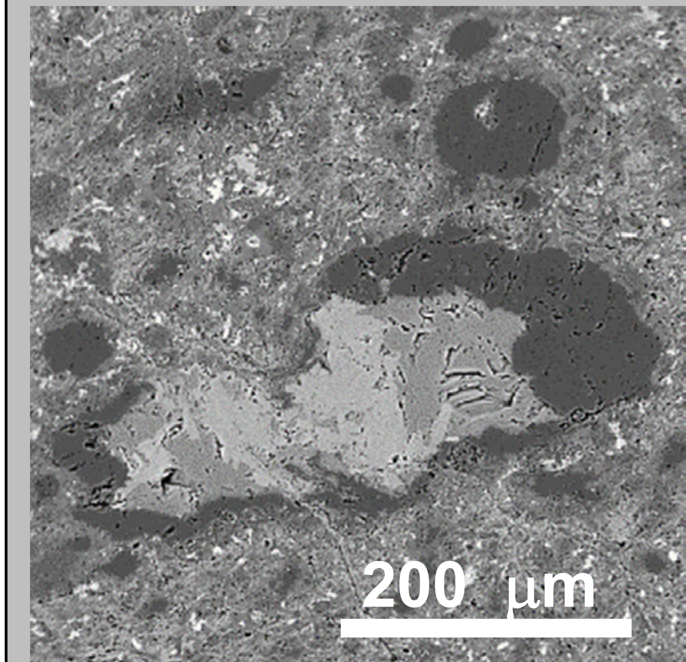
Vacuum (10^{-4} mbar)

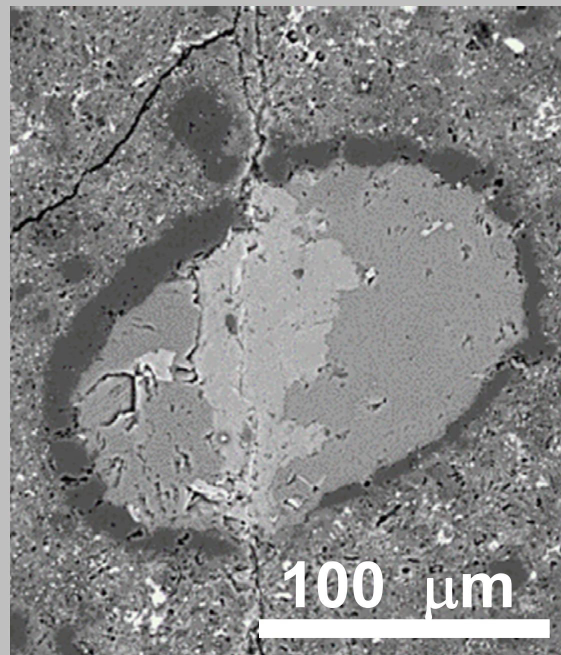


Experimental PST vesicles:

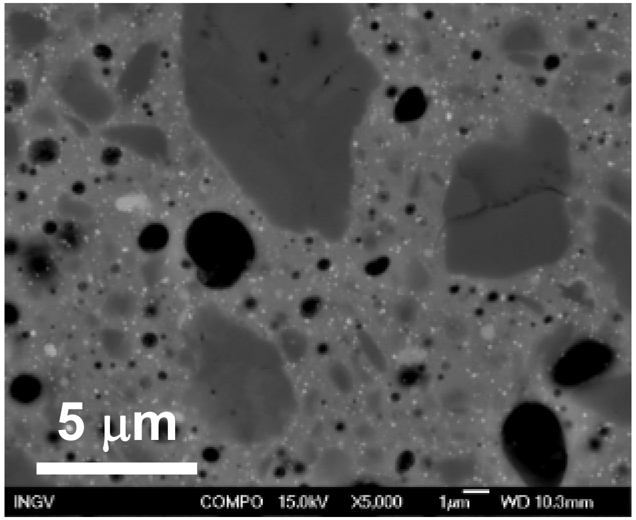
- found independently of ambient conditions
- similar to mineral-filled vesicles of natural PST.

Natural pseudotachylytes from BFZ

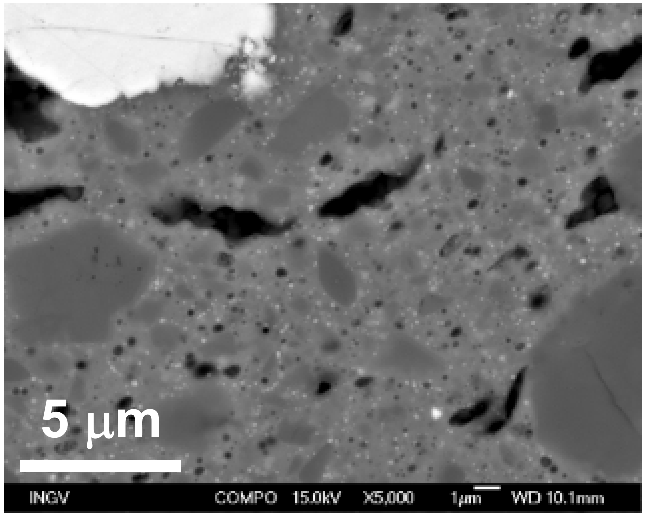




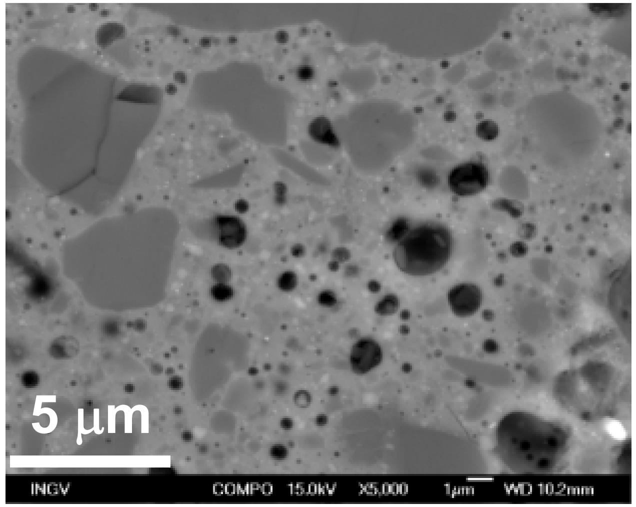
Pressurized water



Room humidity

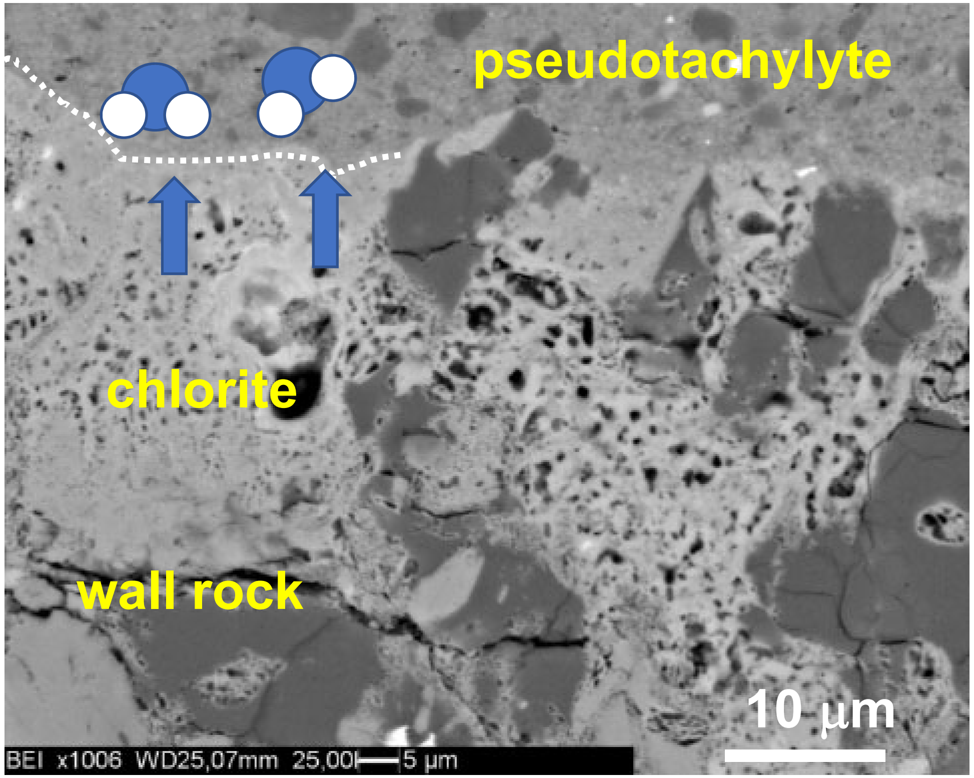


Vacuum (10^{-4} mbar)



Experimental PST bubble formation (al low confining pressure):

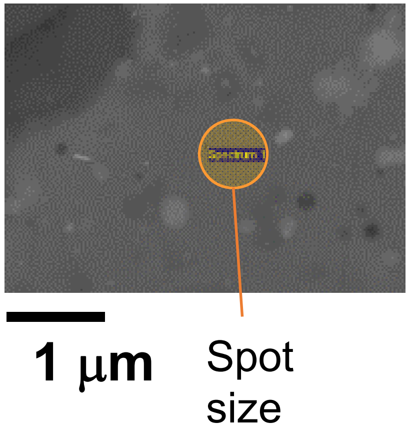
- fluid cavitation?
- H_2O & CO_2 release from the breakdown of wall rock fluid-rich minerals (calcite, chlorite, Fe-actinolite and epidote).

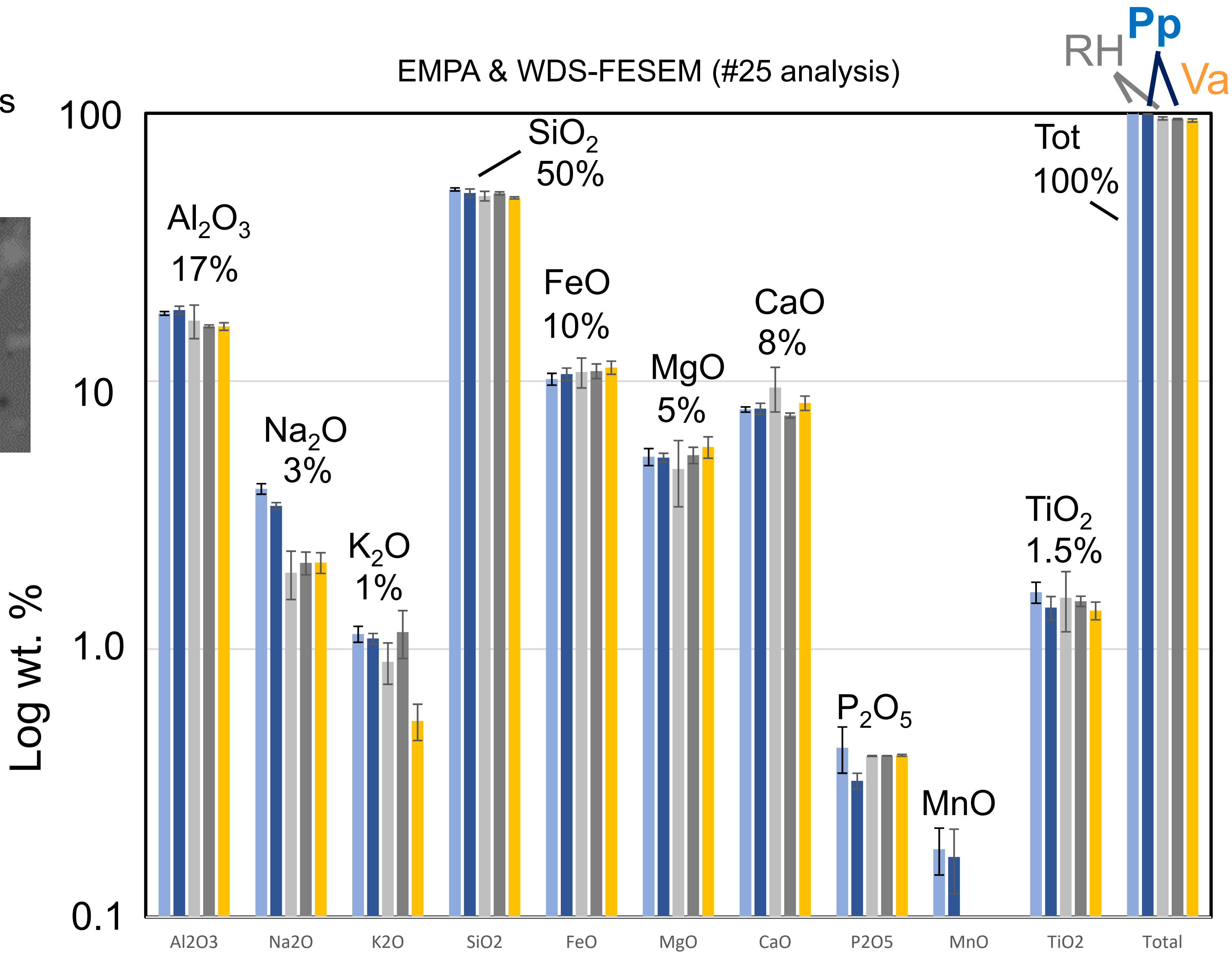


Experimental **PST matrix**: chemically similar and volatile free* **basaltic in composition glass** independently of ambient conditions.

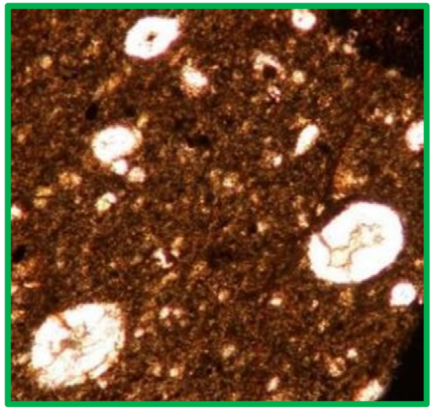
*limited confinement also in the pressurized experiments

Example of analysis of the PST matrix from vacuum exp.





Why vesiculation in natural PST?



Estimate of total H_2O and CO_2 produced by frictional melting of altered host rocks

Volatile-bearing minerals (EMPA & XRD analysis)

Mineral	wt.% $[H_2O]_{min}$	wt.% $[CO_2]_{min}$	wt. % of mineral in host rock $[Min]_{HR}$
Chlorite	12.0	---	8 - 15
Epidote	3.4	---	2 - 15
Fe-actinol.	2.4	---	8 - 9
Calcite	----	43.4	4 - 7

$$H_2O_{tot} = \frac{1}{100} \sum_{min\_1}^{min\_i} [H_2O]_{min\_i} \, [Min]_{HR}$$

$$CO_{2\,tot} = \frac{1}{100} [CO_2]_{Calcite} \, [Calc]_{HR}$$

H_2O_{tot} = 1.7-2.1 wt.%

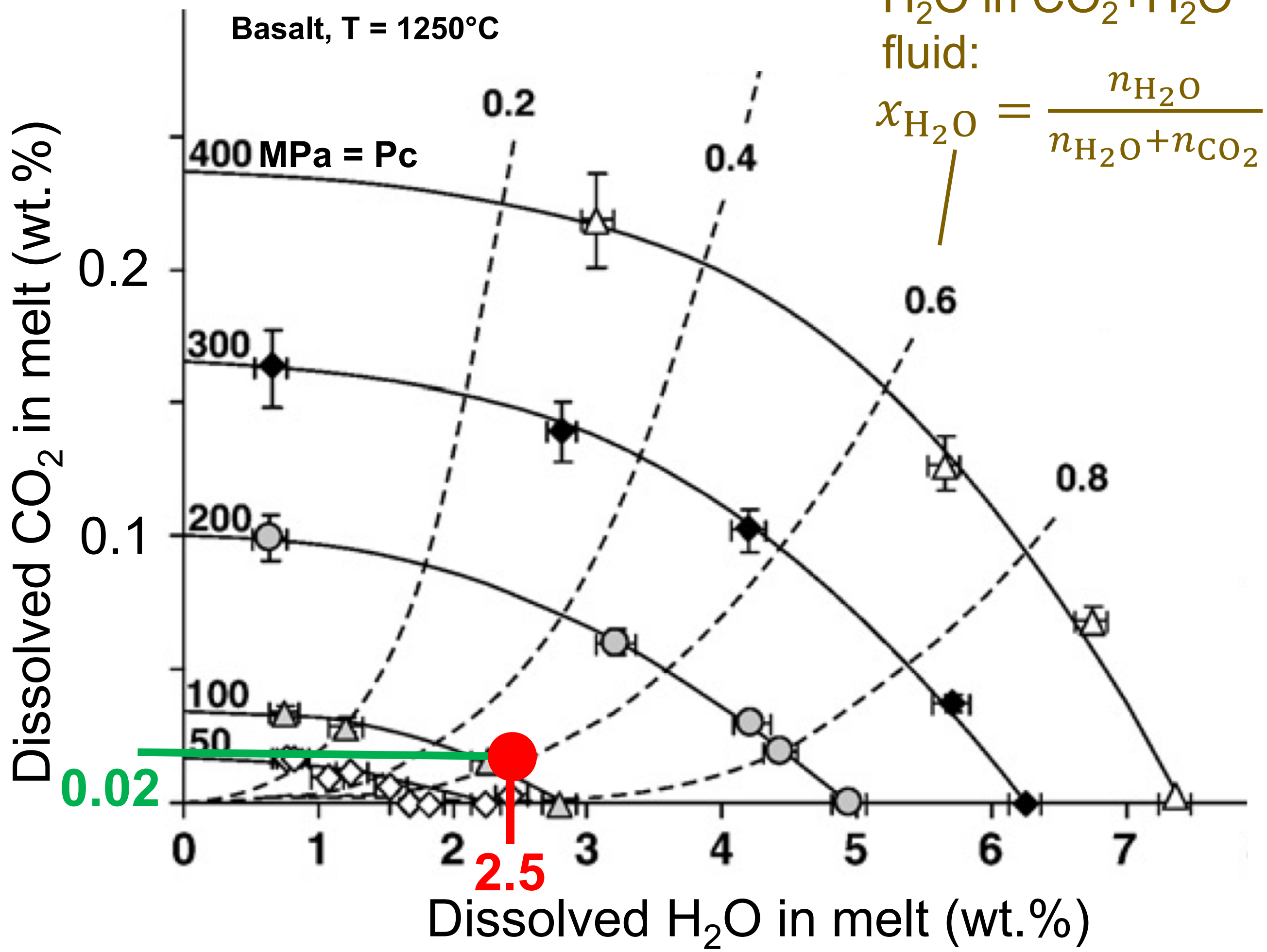
$CO_{2\ tot}$= 1.7-3.0 wt.%

Solubility of a two component $H_2O + CO_2$ fluid in basaltic melt **increases with depth** (= confining pressure Pc).

Assumptions:

- **matrix of natural PST** before alteration is **basaltic in composition** like experimental PST
- thermodynamic equilibrium
- constant fluid composition
- constant temperature

Experimental data



Molar fraction of H_2O in CO_2+H_2O fluid:

$$x_{H_2O} = \frac{n_{H_2O}}{n_{H_2O}+n_{CO_2}}$$

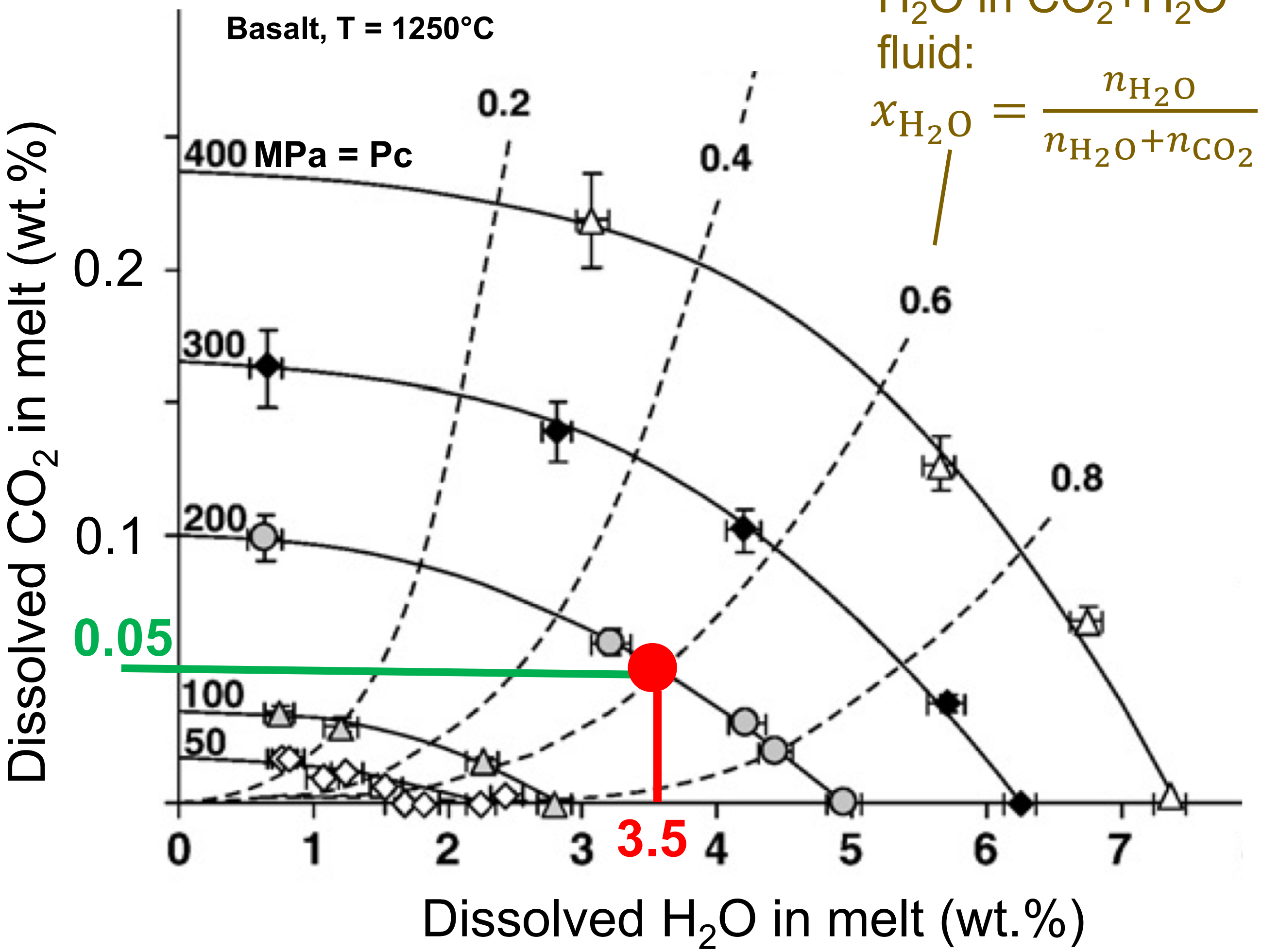
Shishkina et al., Chem. Geol., 2010

H_2O is 50-100 times more soluble than CO_2 in basaltic melts

Assumptions:

- **matrix of natural PST** before alteration is **basaltic in composition** like experimental PST
- thermodynamic equilibrium
- constant fluid composition
- constant temperature

Experimental data



Molar fraction of H_2O in CO_2+H_2O fluid:

$$x_{H_2O} = \frac{n_{H_2O}}{n_{H_2O}+n_{CO_2}}$$

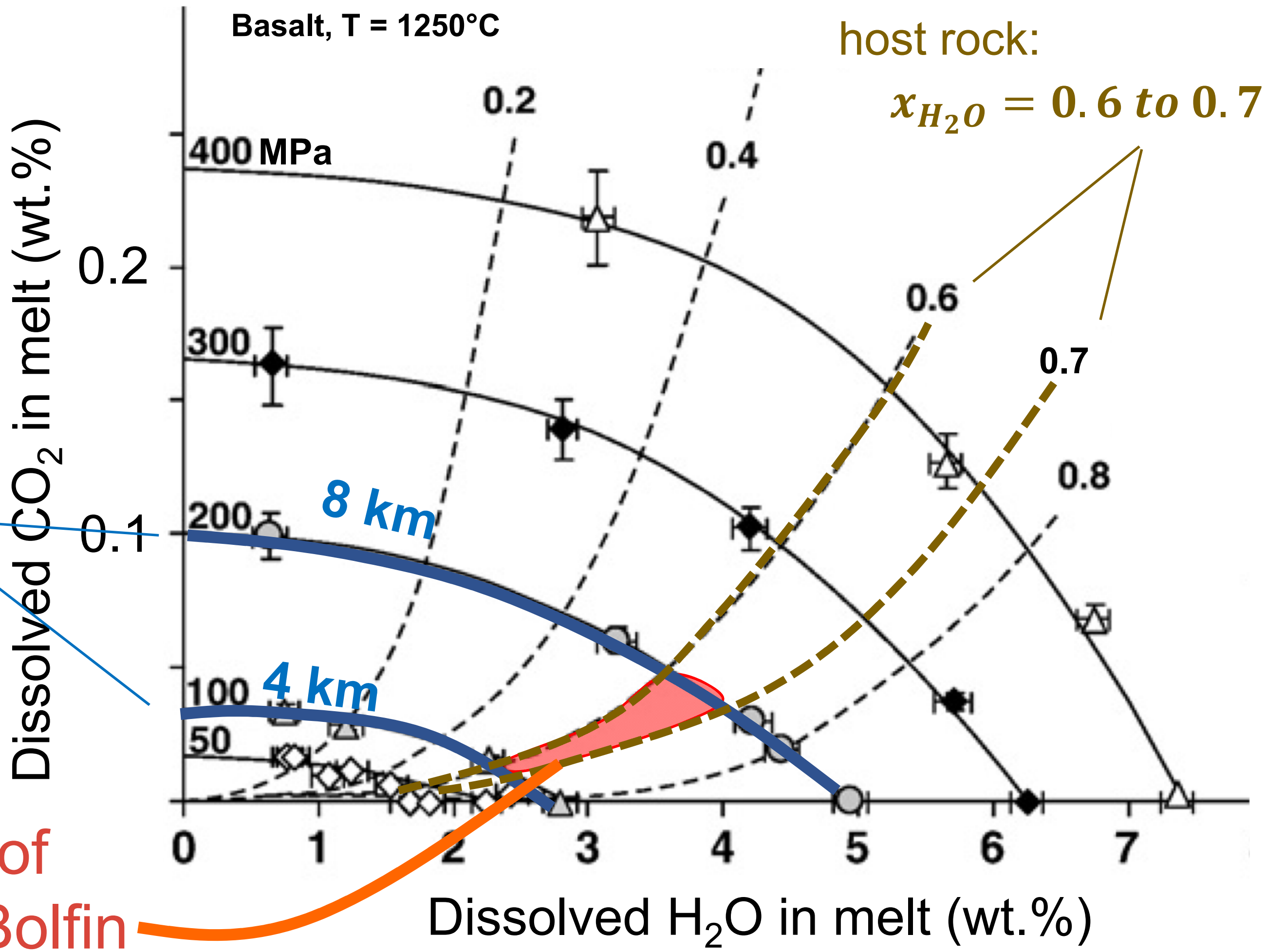
Shishkina et al., Chem. Geol., 2010

Solubility of a two component $H_2O + CO_2$ fluid in basaltic melts at 1250°C between 4 and 8 km depth for χ_{H2O} = 0.6-0.7.

Experimental data

Molar fraction of H_2O in volatiles from melted host rock:

$x_{H_2O} = 0.6\ to\ 0.7$



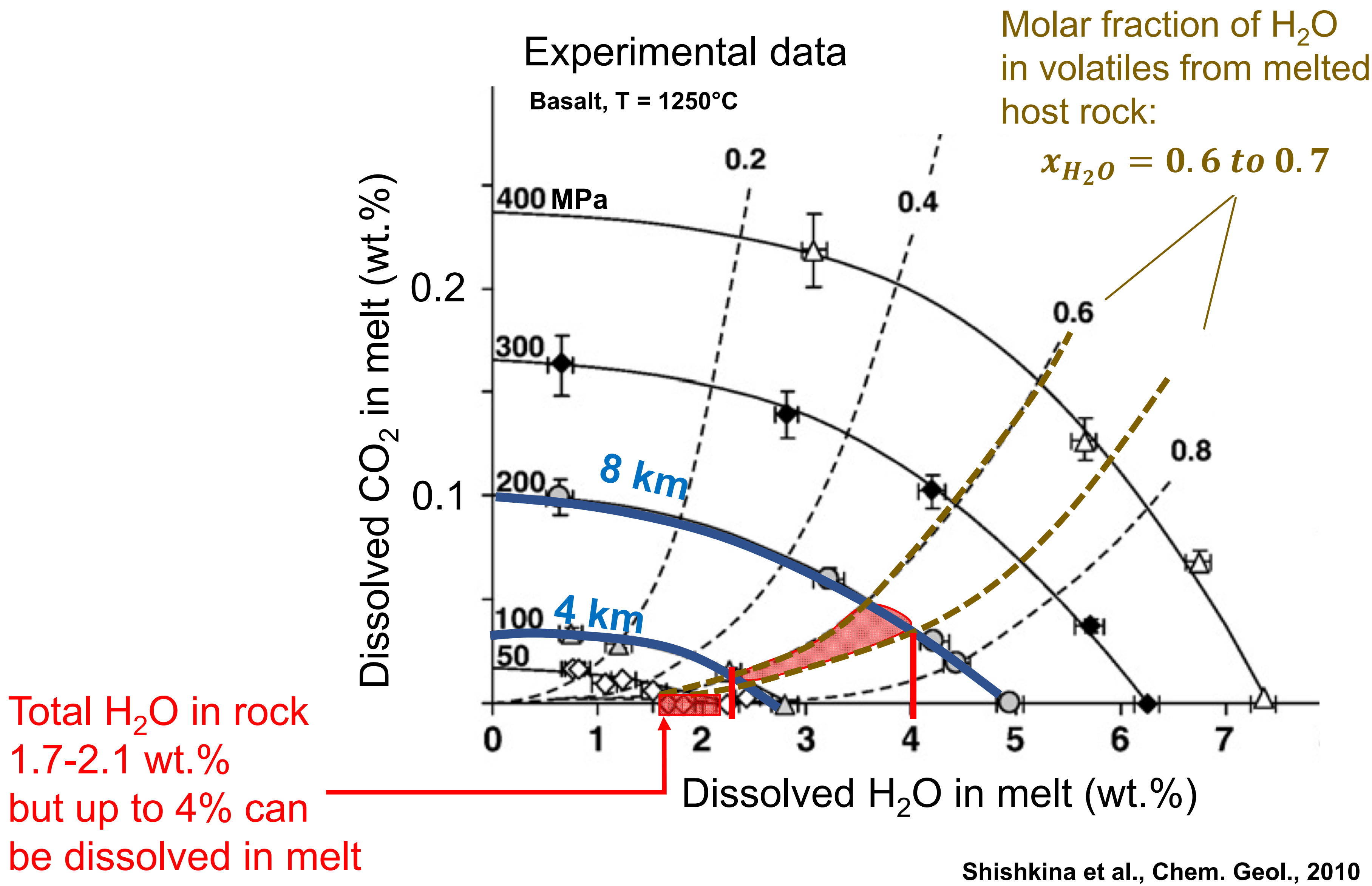
Depth of formation for Bolfin PST

Solubilty window of H_2O and CO_2 in Bolfin friction melts

Shishkina et al., Chem. Geol., 2010

Between 4 and 8 km depth

- H_2O might be dissolved in the friction melt

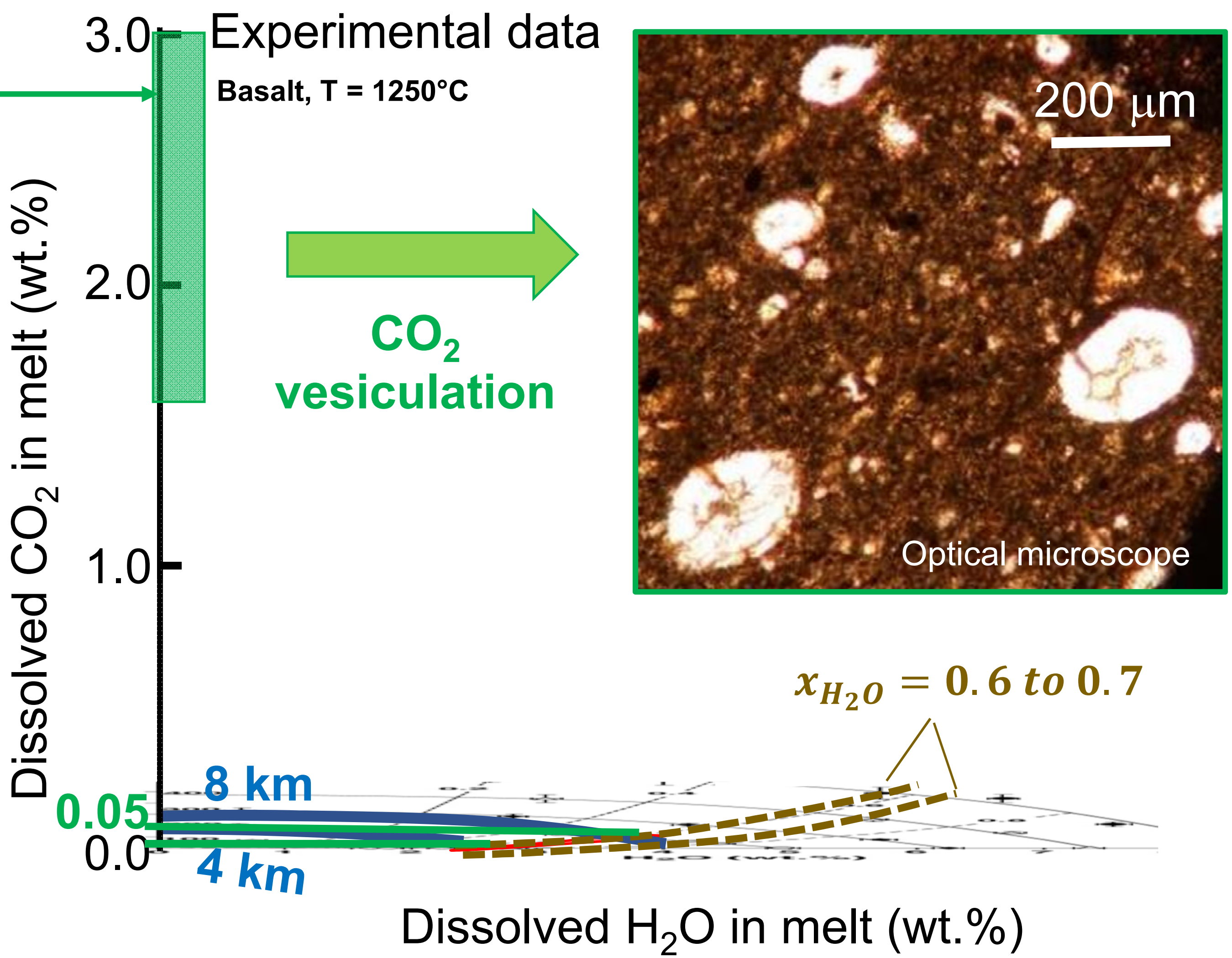


Shishkina et al., Chem. Geol., 2010

Between 4 and 8 km depth

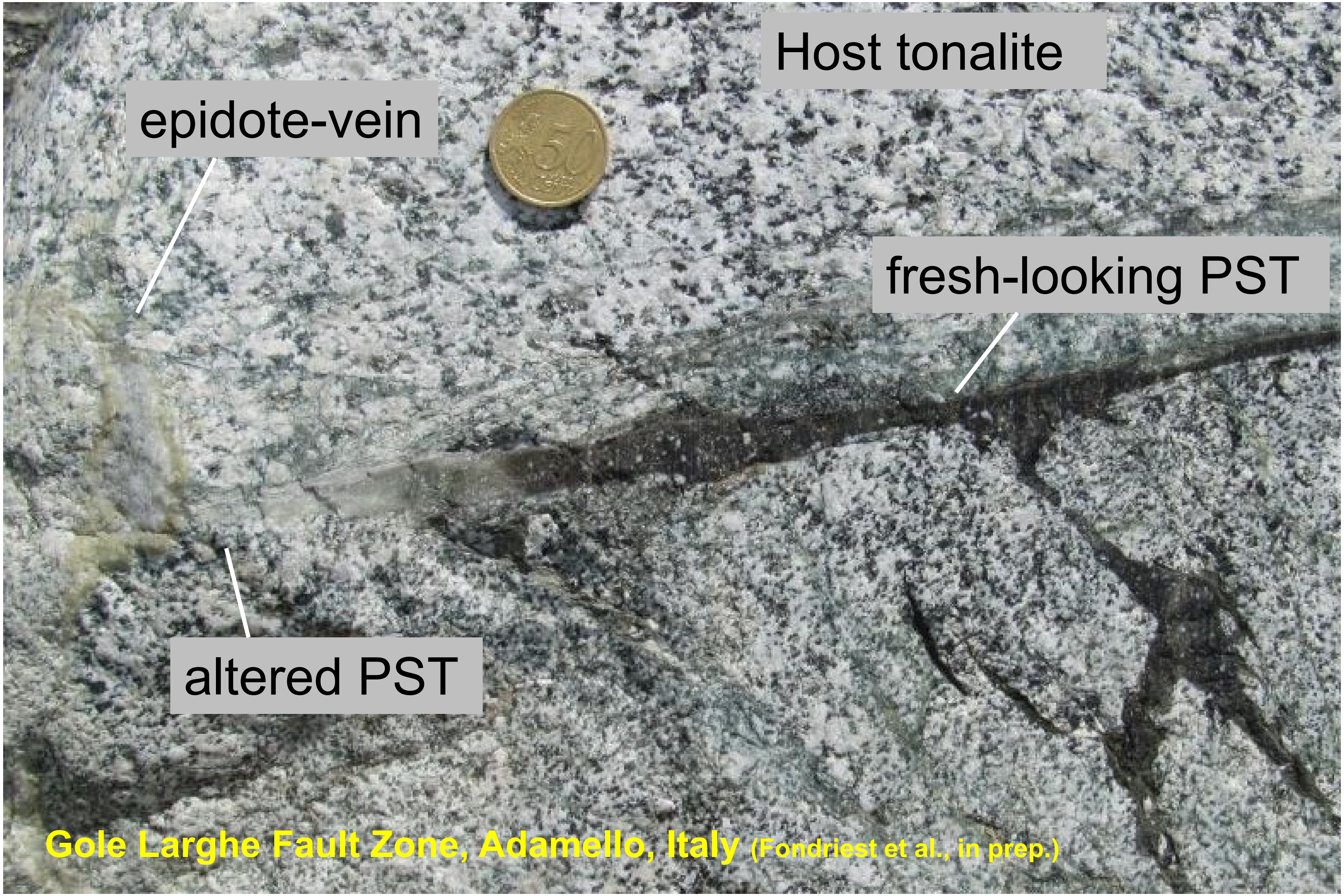
- H_2O might be dissolved in the friction melt
- CO_2 is oversaturated in the melt and forms vesicles

Total CO_2 in rock 1.7-3.0 wt.% but only < 0.05 wt.% can be dissolved in melt



Shishkina et al., Chem. Geol., 2010

In experiments at 300°C ambient T in presence of pore H_2O, PST alter into cataclasite-looking rocks in < 30 days and disappear from the geological record.



Conclusions

- Tectonic pseudotachylytes (PST) are thought to be rare in the geological record because rarely produced or preserved.
- The > 60 km long Bolfin Fault Zone hosts PST produced in a fluid-rich environment (alteration, vesiculation, etc.).
- Experiments show that PST may form in pressurized water.
- In nature, it was not possible to discern if there were pore-fluids at the time of seismic faulting. Vesicles in natural PST were probably due to calcite breakdown and CO_2 release.
- In fluid-rich environments, PST are prone to alteration and easily lost from the geological record.
- Frictional melting during earthquakes might be more common than believed.

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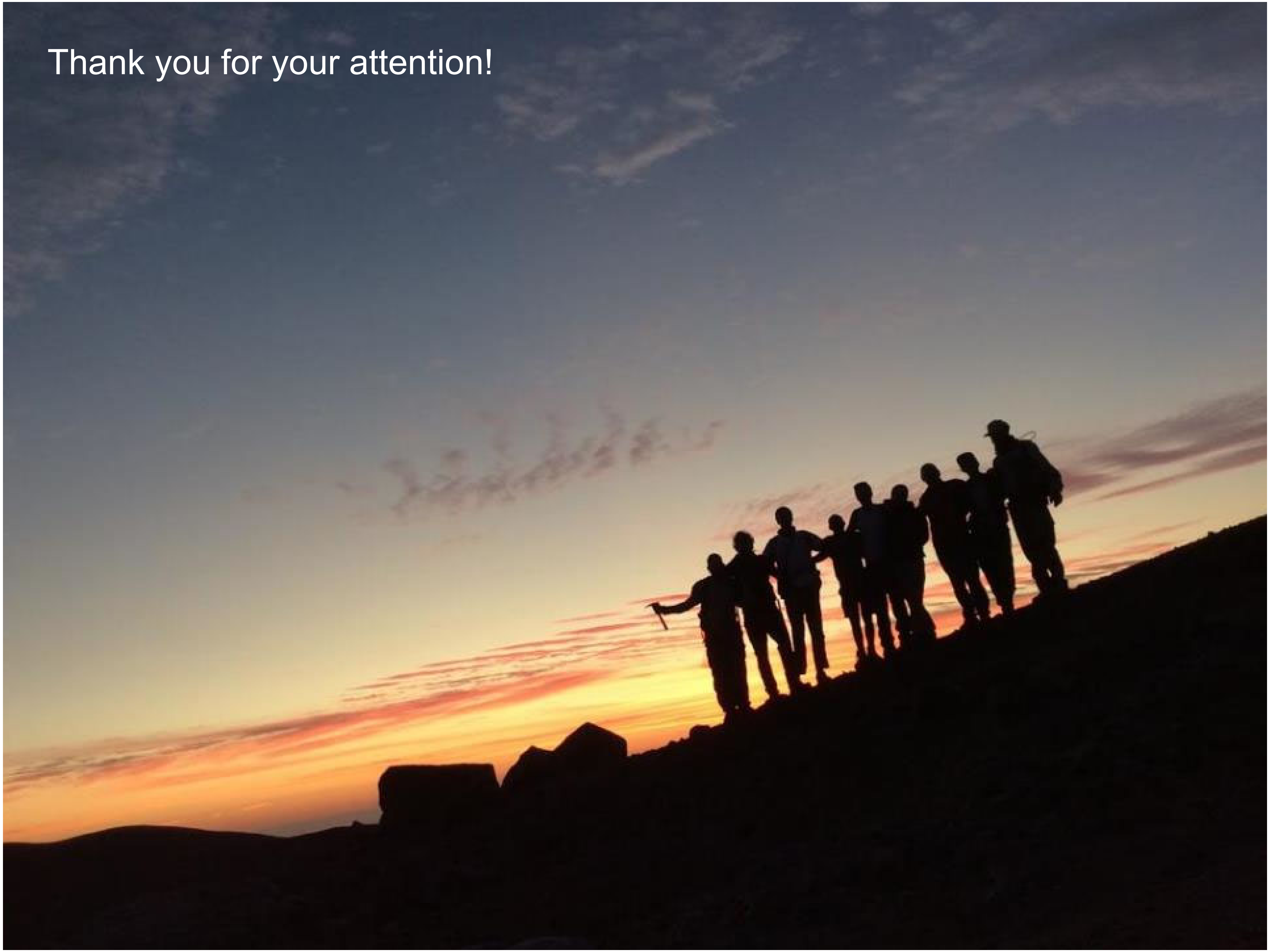
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