

Porosity evolution within the active Alpine Fault zone, New Zealand. Implications for fault zone rheology.

**Martina Kirilova¹, Virginia Toy^{1,2}, Katrina Sauer¹, François Renard^{3,4}, Klaus Gessner^{5,6}, Richard Wirth⁷,
Xianghui Xiao^{8,9}, Risa Matsumura², David Prior², Francesco Cappuccio², and Soltice Morrison².**

¹Institut für Geowissenschaften, Johannes Gutenberg Universität-Mainz, Germany

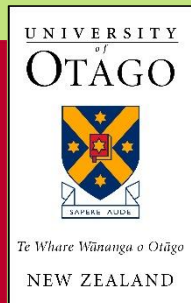
²Department of Geology, University of Otago, New Zealand

³Department of Geosciences, University of Oslo, Norway. ⁴Université Grenoble Alpes, France.

⁵Geological Survey of Western Australia, Australia. ⁶School of Earth Sciences, The University of Western Australia, Australia

⁷Helmholtz-Zentrum Potsdam, GFZ, Germany ⁸Advanced Photon Source, Argonne National Laboratory, USA

⁹National Synchrotron Light Source II, Brookhaven National Laboratory, USA



UiO : **University of Oslo**



**Geological Survey of
Western Australia**

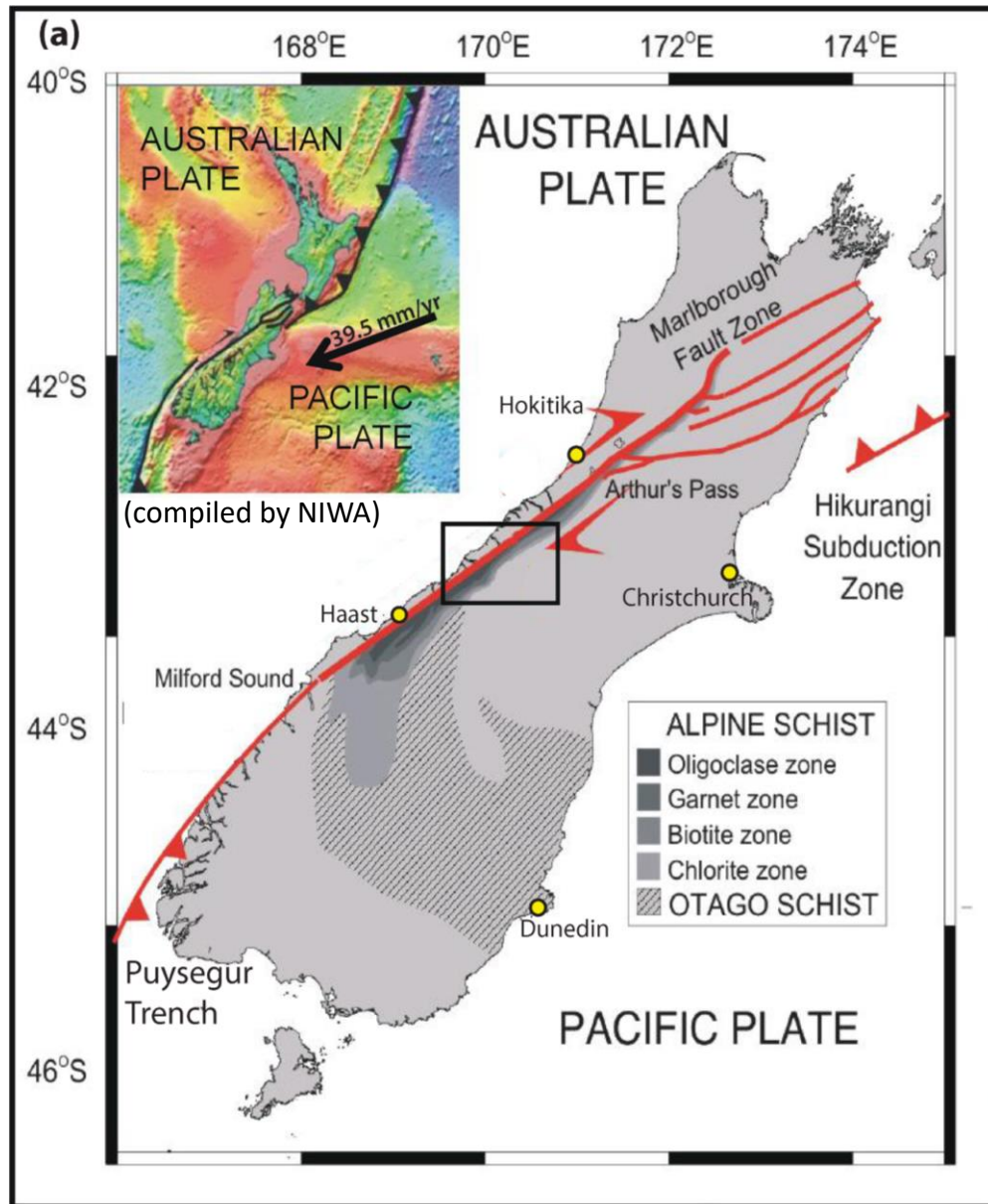


Why is porosity in fault rocks important?

- Porosity reduction can lead to **pore fluid overspressure**, and hence cause friction failure and earthquake nucleation.
- Pores represent open spaces where **weak phases may precipitate** and then lubricate the fault.
- Can **facilitate fluid flow**, formation of mineral and geothermal resources, and can **promote strain localization**

The state of porosity in rocks comprising the active fault zones may shed profound insights in fault mechanics.

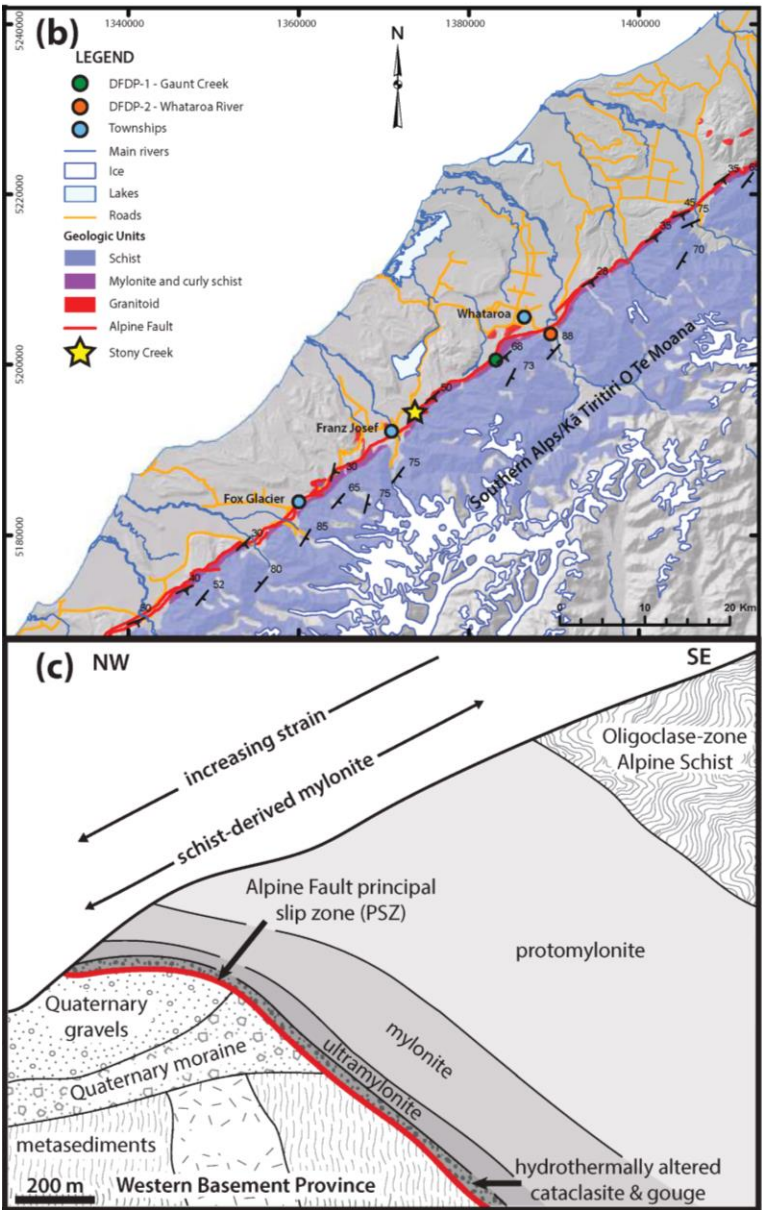
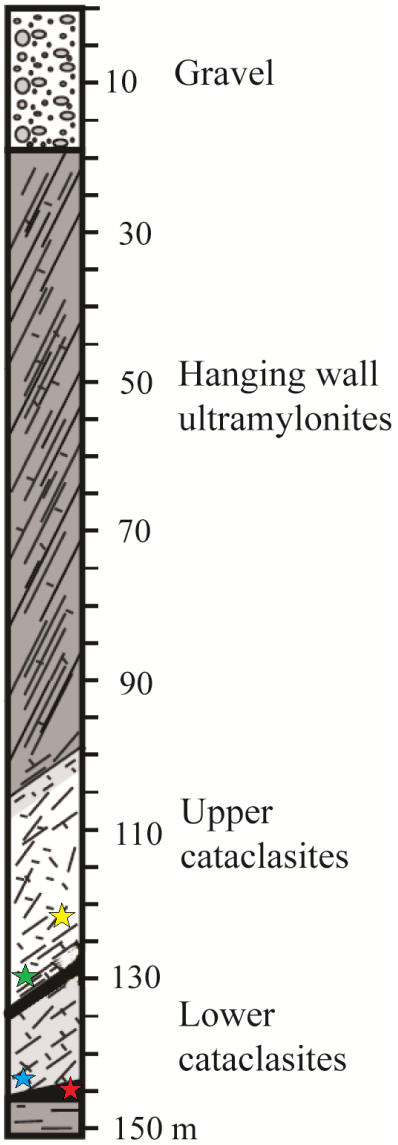
We investigated and compared the porosity distribution in cataclasites and mylonites comprising the Alpine Fault zone by using X-ray computed tomography scanning and transmission electron microscopy.



The Alpine Fault, New Zealand

- a dextral reverse fault that accommodates 75% of the 37 mm/y relative motion along the Australian-Pacific plate boundary
- responsible for large earthquakes every 300-400 years the last one of which ruptured in 1717
- 75% chance of a rupture in the next 50 years
- two phases of the Deep Fault Drilling Projects at Gaunt Creek (February 2011) -DFDP-1A (100.6 m) and DFDP-1B (151.4 m), and Whataroa (December 2014) – DFDP-2B (< 800 m)

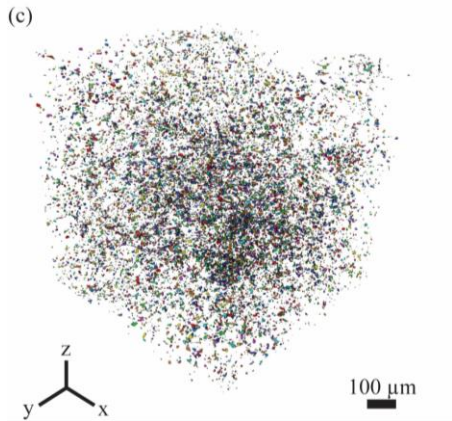
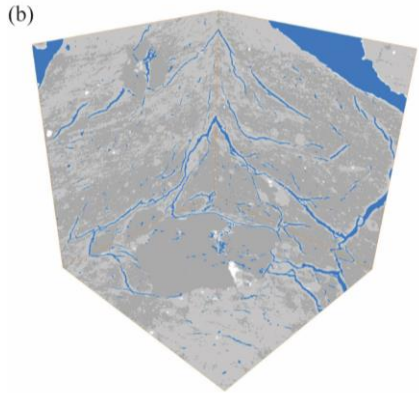
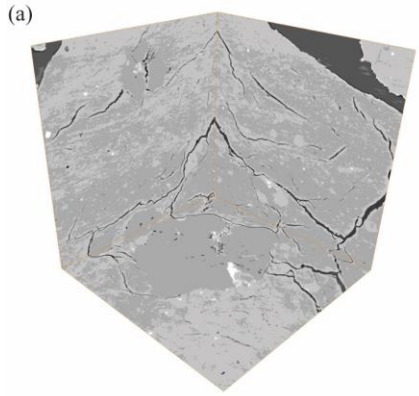
DFDP-1B borehole



(after Norris & Cooper, 2007)

Sample #	Dep/dist	Lithology
DFDP-1B 58-1.9	126.94 m	Upper foliated cataclasite with gouge-filled shears
DFDP-1B 69-2.48	143.82 m	Upper foliated cataclasite with gouge-filled shears
DFDP-1B 69-2.54	143.88 m	PSZ-2 gouge layer
DFDP-1B 69-2.57	143.91 m	Lower cataclasite
SC15-006	~15 mff	Ultramyl
SC15-007	~40 mff	Myl
SC15-012	~65 mff	Myl
SC15-016	~200 mff	Protom

DFDP - 1B 69-2.57



X-ray computed tomography (XCT)

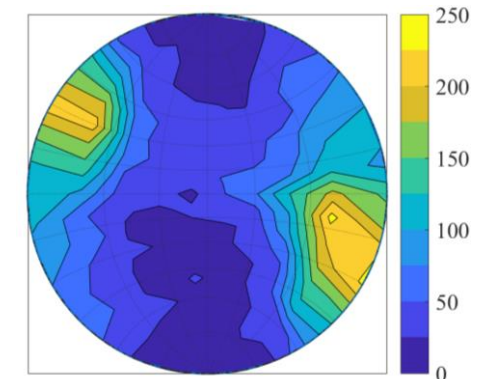
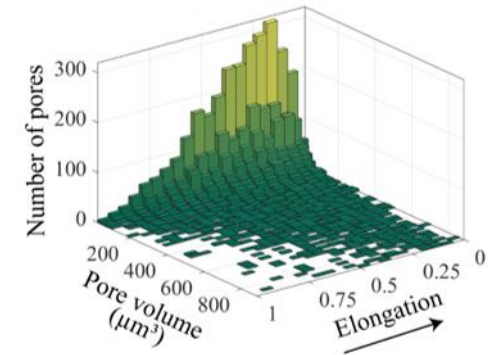
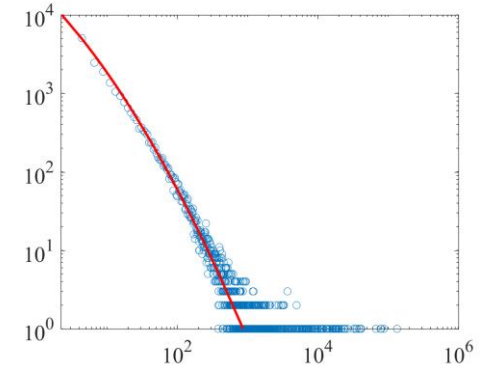
- Alpine Fault samples – Advanced Photon Source (APS), Chicago in 2012 (voxel size $1.3\text{ }\mu\text{m}$)
- JFAST samples – Super Photon Ring – 8 GeV (Spring-8) in 2018 (voxel size $0.524\text{ }\mu\text{m}$ and $0.0304\text{ }\mu\text{m}$).

Transmission electron microscopy (TEM)

- FEI Tecnai G2 F20 X-Twin with a Gatan double-tilt holder, 200 kV, at German Research Center for Geosciences (GFZ).

XCT analyses

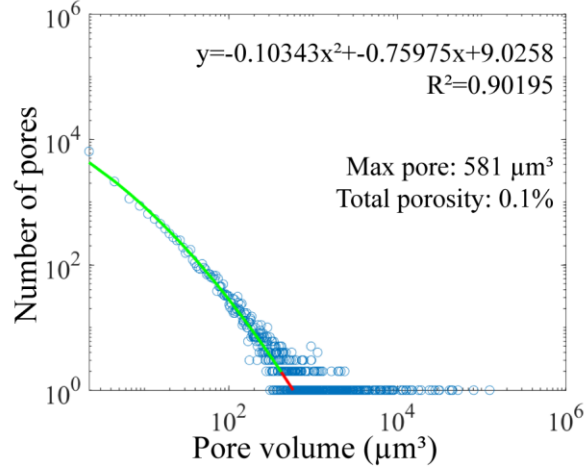
- image processing and visualization on Avizo software
- quantitative analyses on Matlab
- total porosities: estimated by fitting the data to a polyfit curve
- elongation of individual pores: plotted on bivariate histograms
- distribution of pore unit orientations: displayed on a lower hemisphere equal area stereographic projection with a probability density contour.



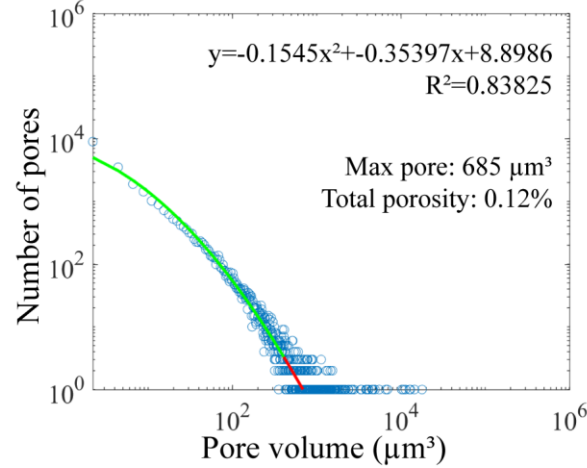
Minimum total porosity

Cataclasites (1.3 voxel size)

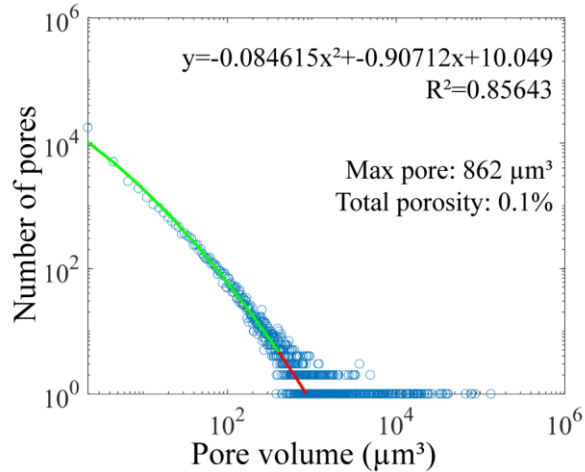
(a) DFDP-1B 58-1.9 (upper foliated ccl)



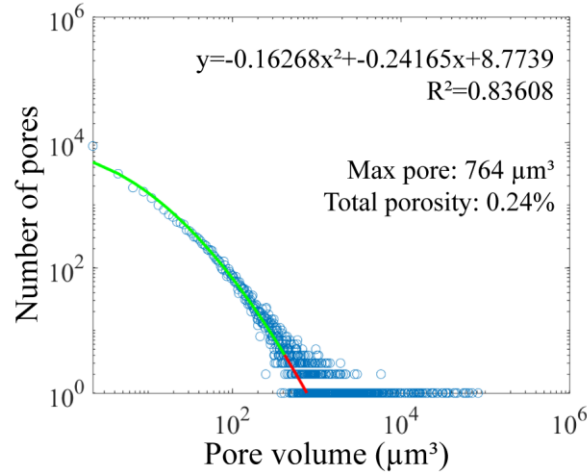
(b) DFDP-1B 69-2.48 (upper foliated ccl)



(c) DFDP-1B 69-2.54 (PSZ-2)

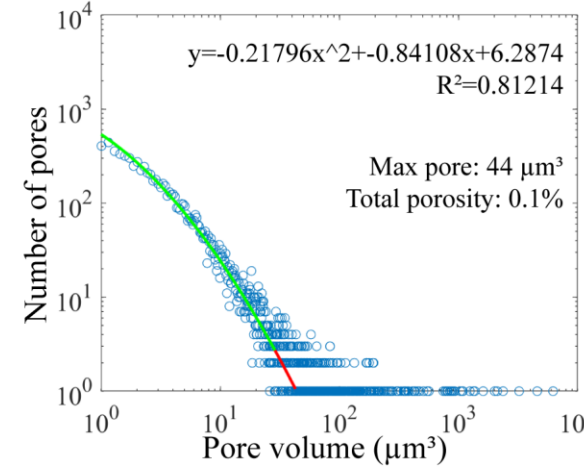


(d) DFDP-1B 69-2.57 (lower ccl)

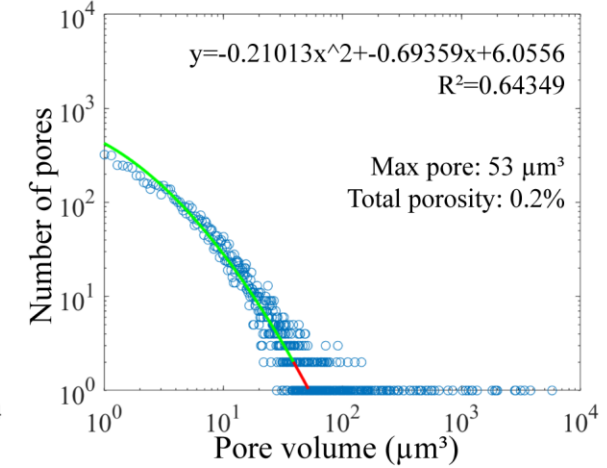


Mylonites (0.524 voxel size)

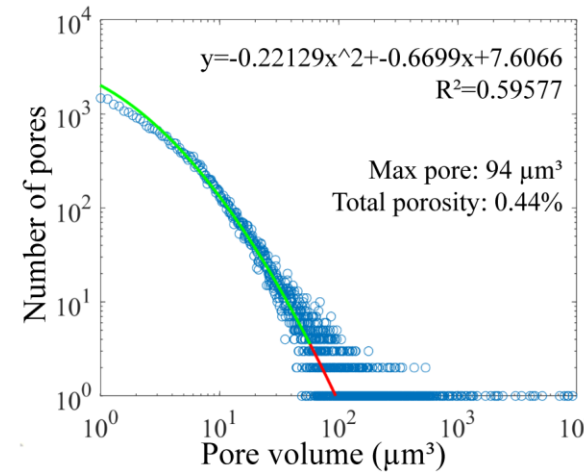
(a) SC15-006 (ultramyl, 15/20 m dff)



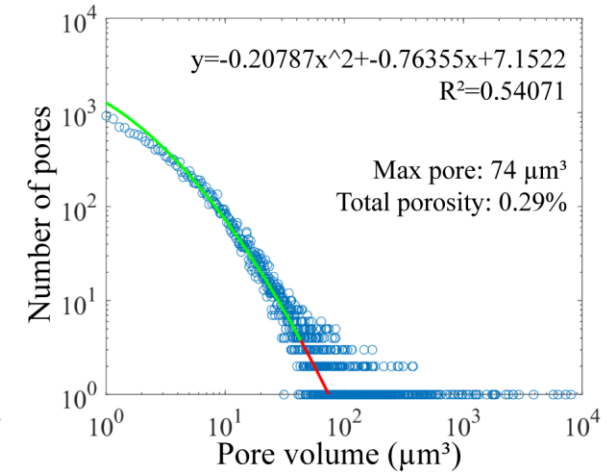
(b) SC15-007 (myl, 40/55 m dff)



(c) SC15-012 (myl, 65/90 m dff)



(d) SC15-016 (protomyl, 200/285 m dff)

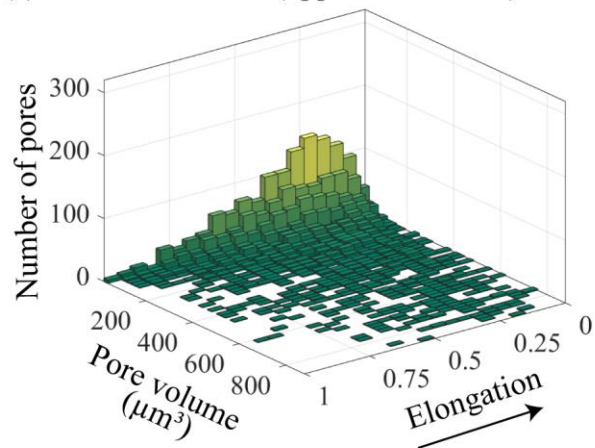


Minimum total porosity

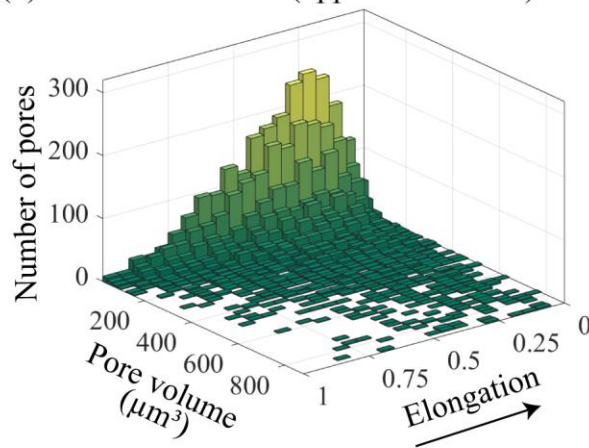
Sample	Lithology	Total porosity %			
		Macro CT 1.3 voxel size	Macro CT 0.524 voxel size	Nano CT 0.0304 voxel size	Micro & nano
DFDP-1B 69-2.57	lower ccl	0.24%	n/a	n/a	n/a
DFDP-1B 69-2.54	PSZ	0.1%	n/a	n/a	n/a
DFDP-1B 69-2.48	upper foliated ccl	0.1%	n/a	n/a	n/a
DFDP-1B 58-1.9	upper foliated ccl	0.1%	n/a	n/a	n/a
SC15-006	ultramyl	0.10%	0.10%	0.07%	0.17%
SC15-007	mylonite	0.18%	0.20 %	0.19 %	0.38 %
SC15-012	mylonite	0.40%	0.44 %	0.08 %	0.53 %
SC15-016	protomyl	0.25%	0.29 %	0.03%	0.32 %

Cataclasites

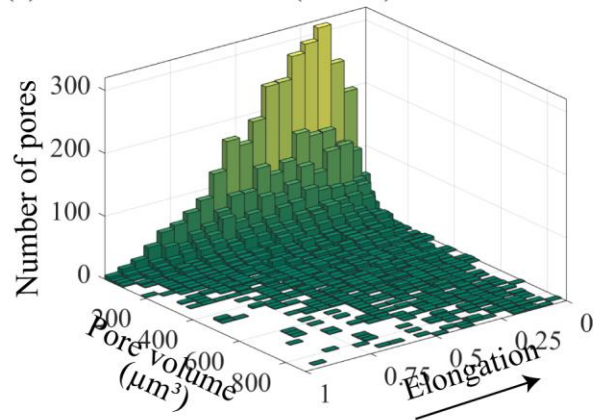
(a) DFDP-1B 58-1.9 (upper foliated ccl)



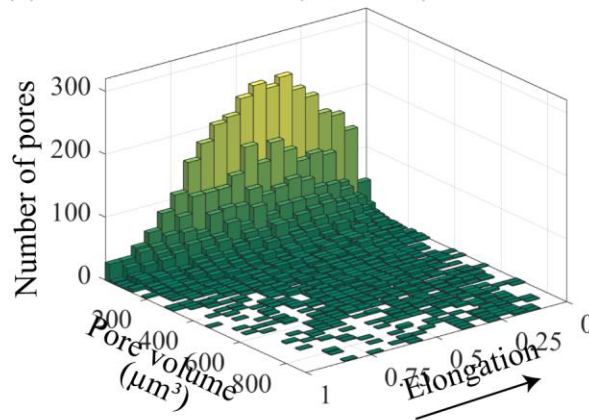
(b) DFDP-1B 69-2.48 (upper foliated ccl)



(c) DFDP-1B 69-2.54 (PSZ-2)

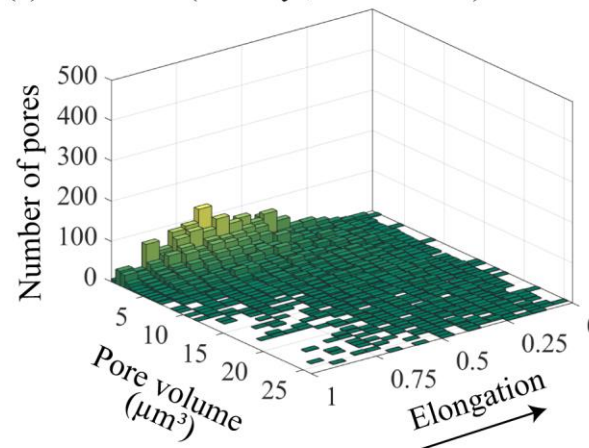


(d) DFDP-1B 69-2.57 (lower ccl)

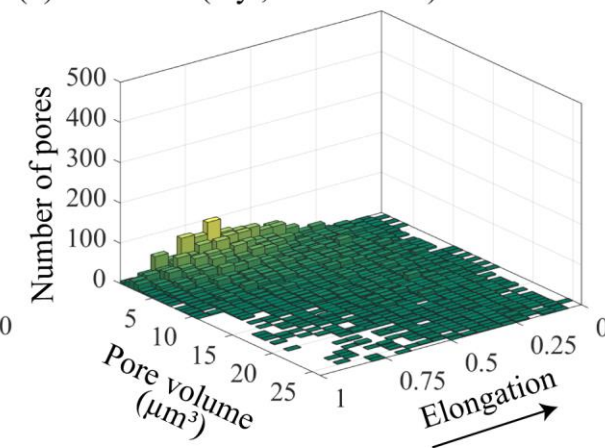


Mylonites

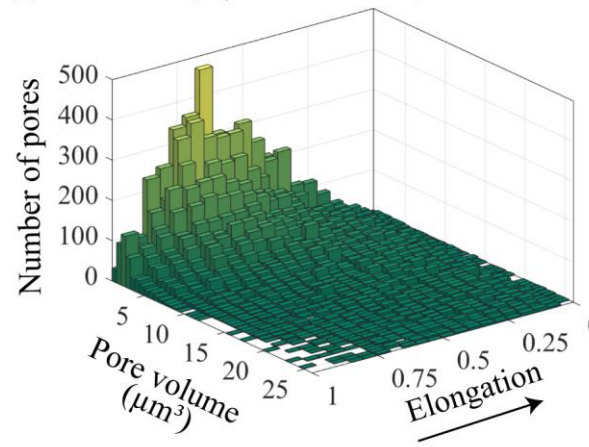
(a) SC15-006 (ultramyl, 15/20 m dff)



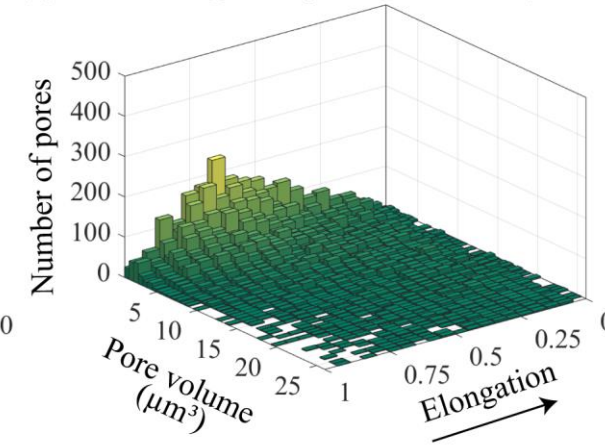
(b) SC15-007 (myl, 40/55 m dff)



(c) SC15-012 (myl, 65/90 m dff)

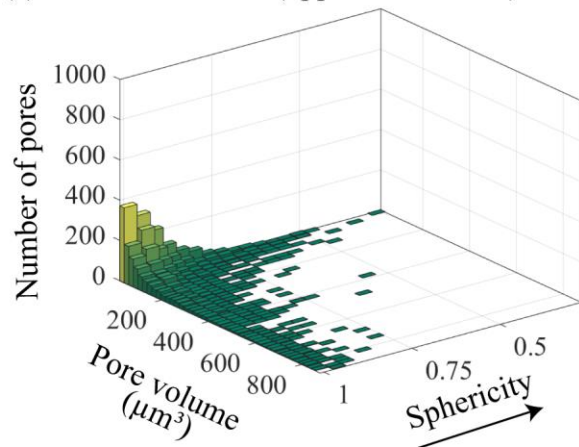


(d) SC15-016 (protomyl, 200/285 m dff)

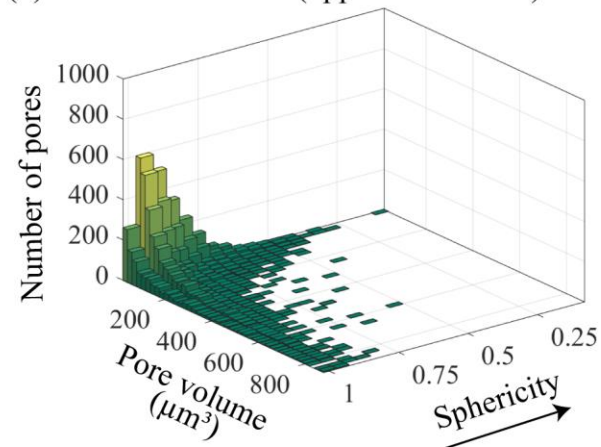


Cataclasites

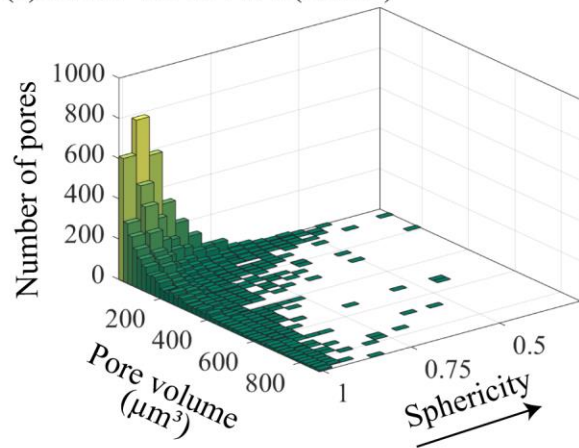
(a) DFDP-1B 58-1.9 (upper foliated ccl)



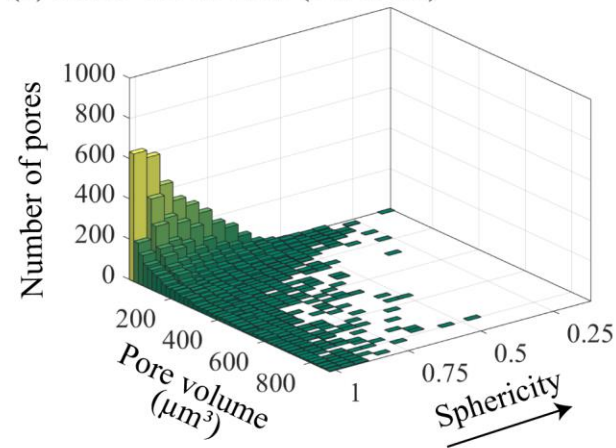
(b) DFDP-1B 69-2.48 (upper foliated ccl)



(c) DFDP-1B 69-2.54 (PSZ-2)

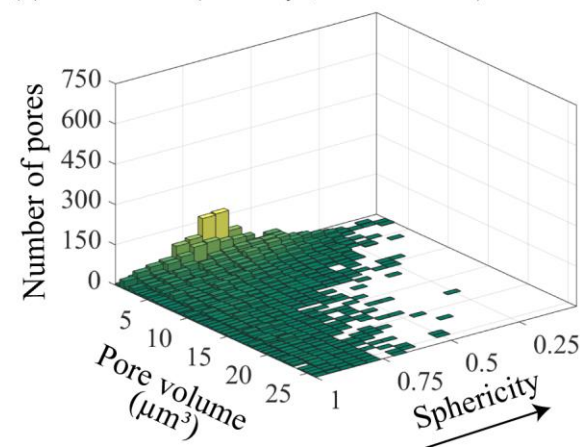


(d) DFDP-1B 69-2.57 (lower ccl)

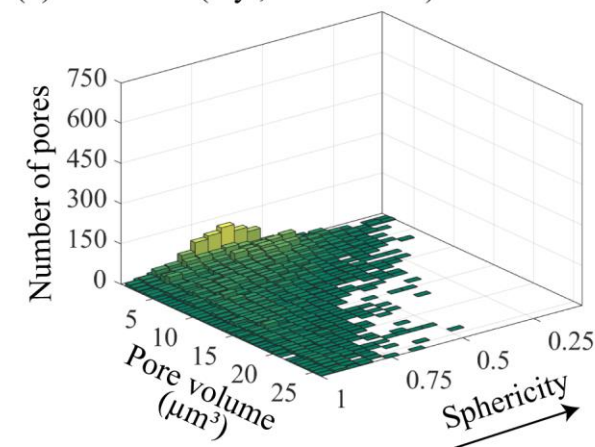


Mylonites

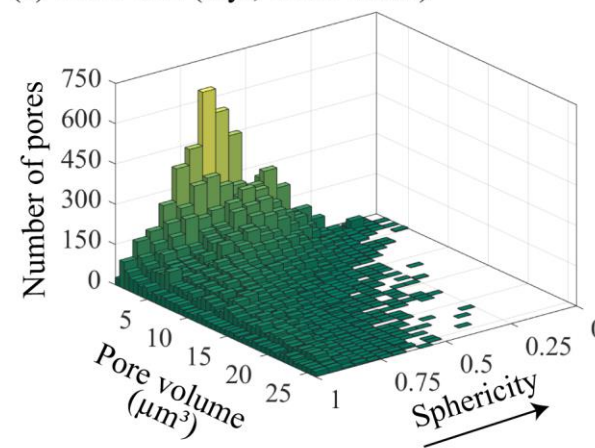
(a) SC15-006 (ultramyl, 15/20 m dff)



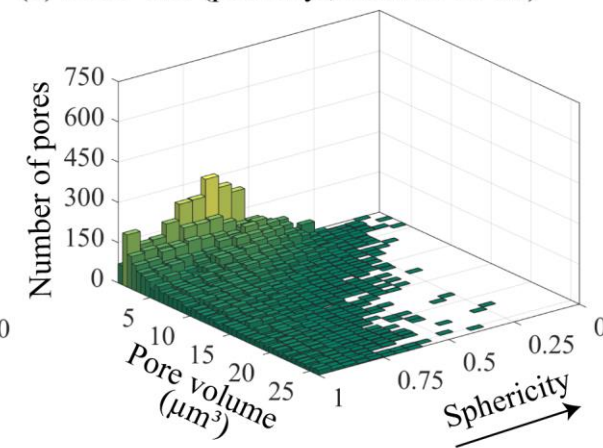
(b) SC15-007 (myl, 40/55 m dff)



(c) SC15-012 (myl, 60/90 m dff)

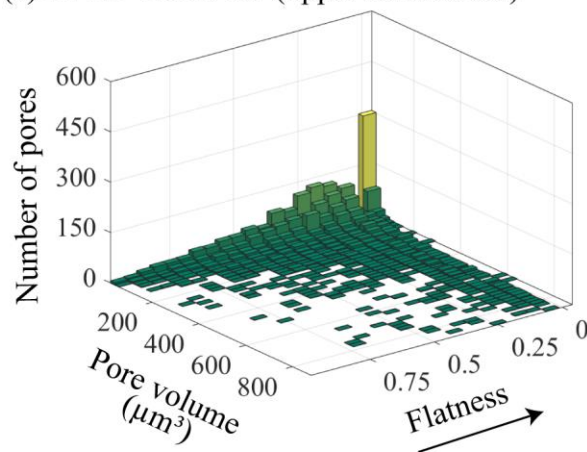


(d) SC15-016 (protomyl, 200/285 m dff)

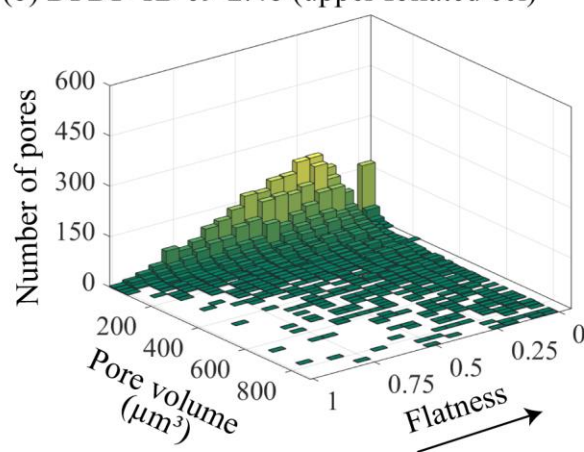


Cataclasites

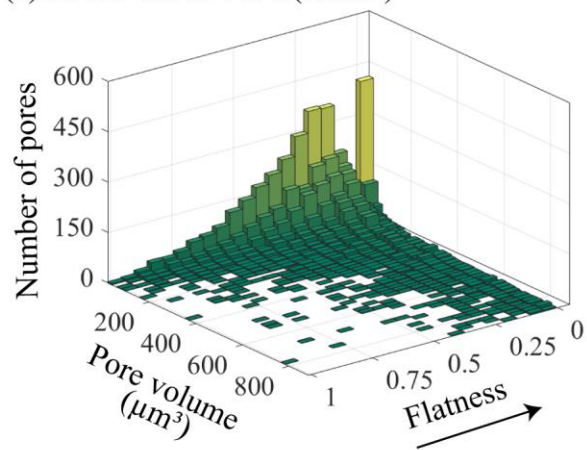
(a) DFDP-1B 58-1.9 (upper foliated ccl)



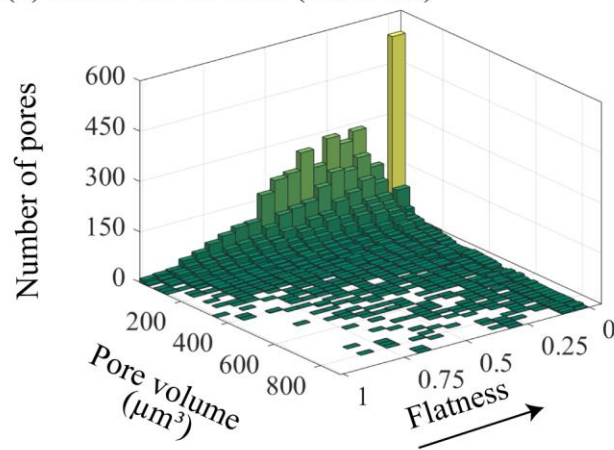
(b) DFDP-1B 69-2.48 (upper foliated ccl)



(c) DFDP-1B 69-2.54 (PSZ-2)

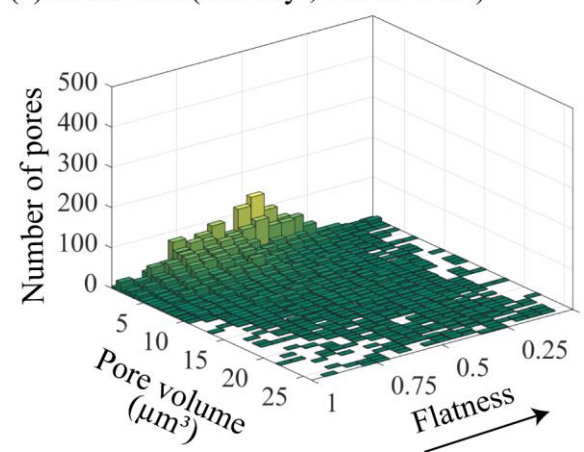


(d) DFDP-1B 69-2.57 (lower ccl)

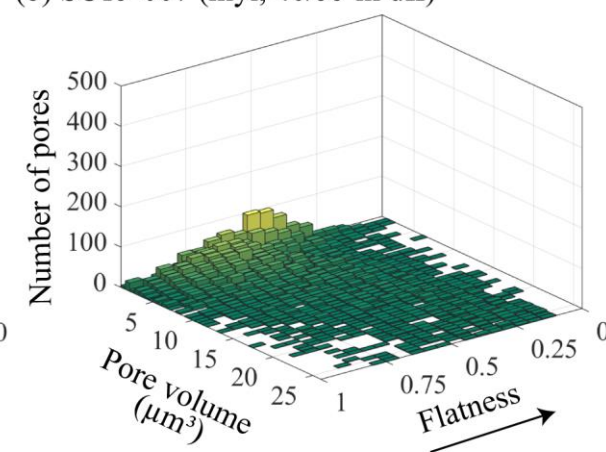


Mylonites

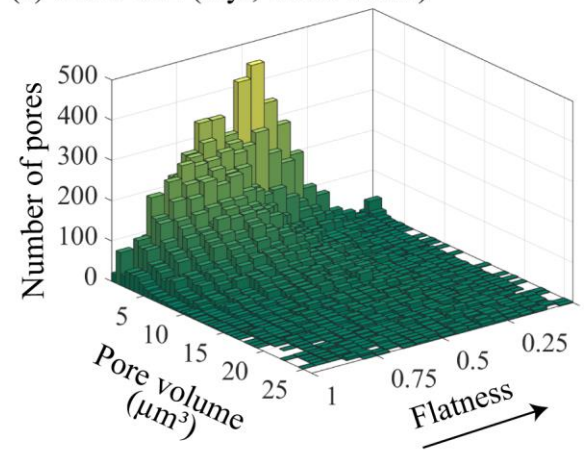
(a) SC15-006 (ultramyl, 15/20 m dff)



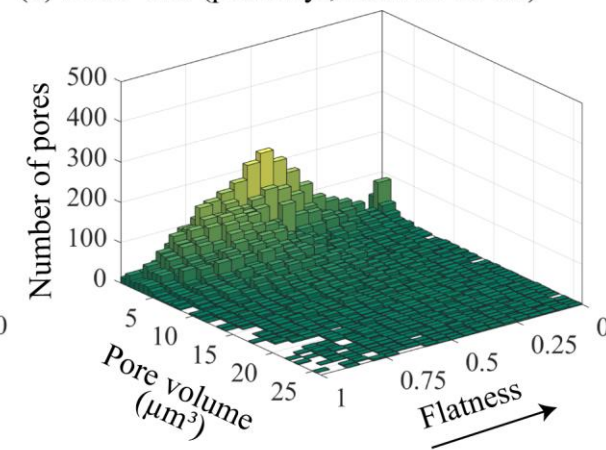
(b) SC15-007 (myl, 40/55 m dff)



(c) SC15-012 (myl, 65/90 m dff)

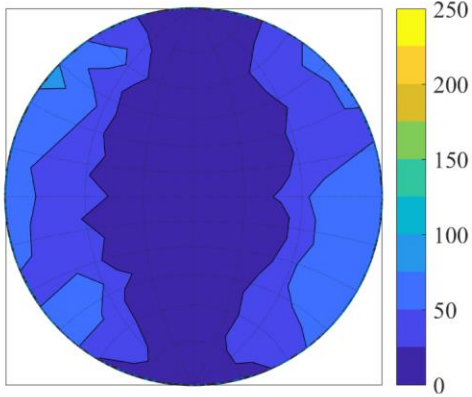


(d) SC15-016 (protomyl, 200/285 m dff)

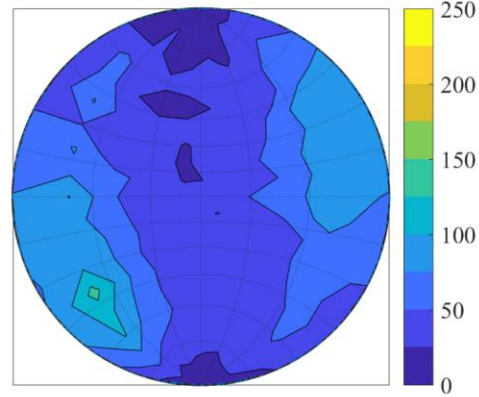


Cataclasites

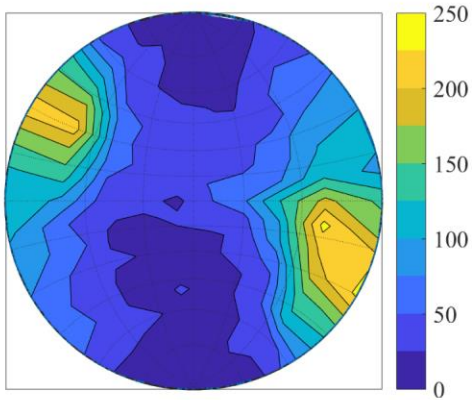
(a) DFDP-1B 58-1.9 (upper foliated ccl)



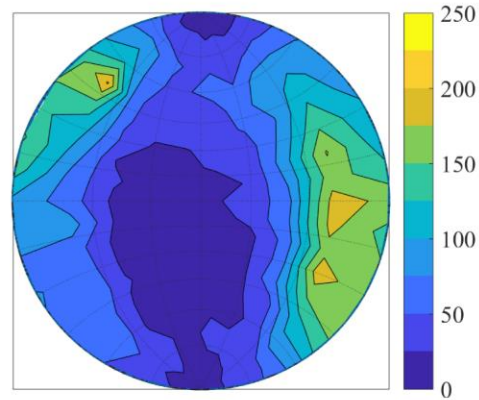
(b) DFDP-1B 69-2.48 (upper foliated ccl)



(c) DFDP-1B 69-2.54 (PSZ-2)

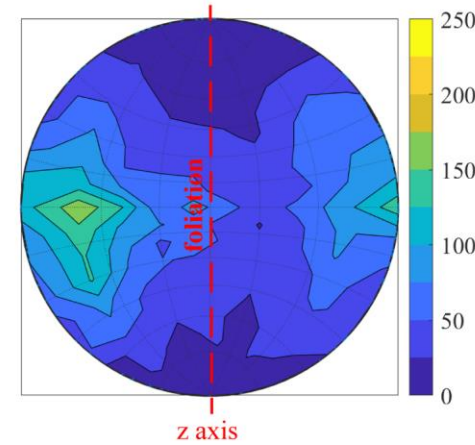


(d) DFDP-1B 69-2.57 (lower ccl)

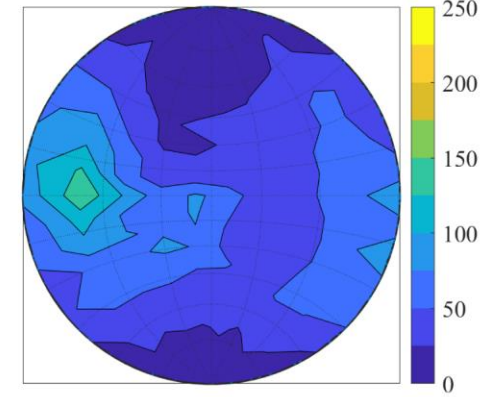


Mylonites

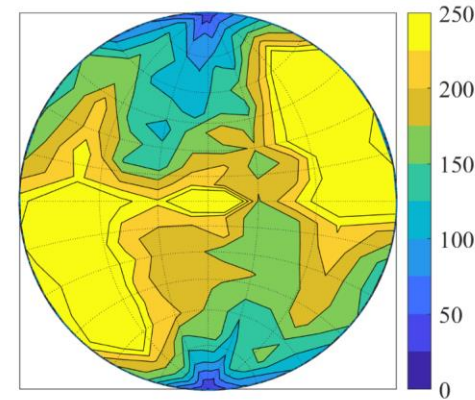
(a) SC15-006 (ultramyl, 15/20 m dff)



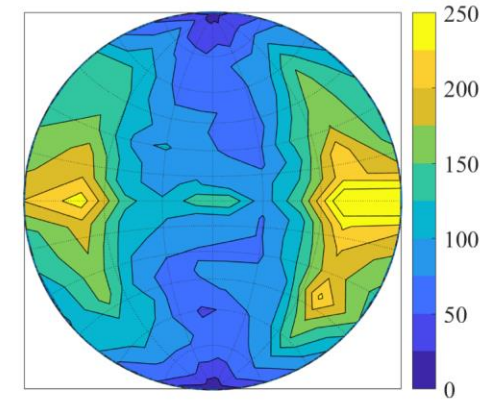
(b) SC15-007 (myl, 40/55 m dff)



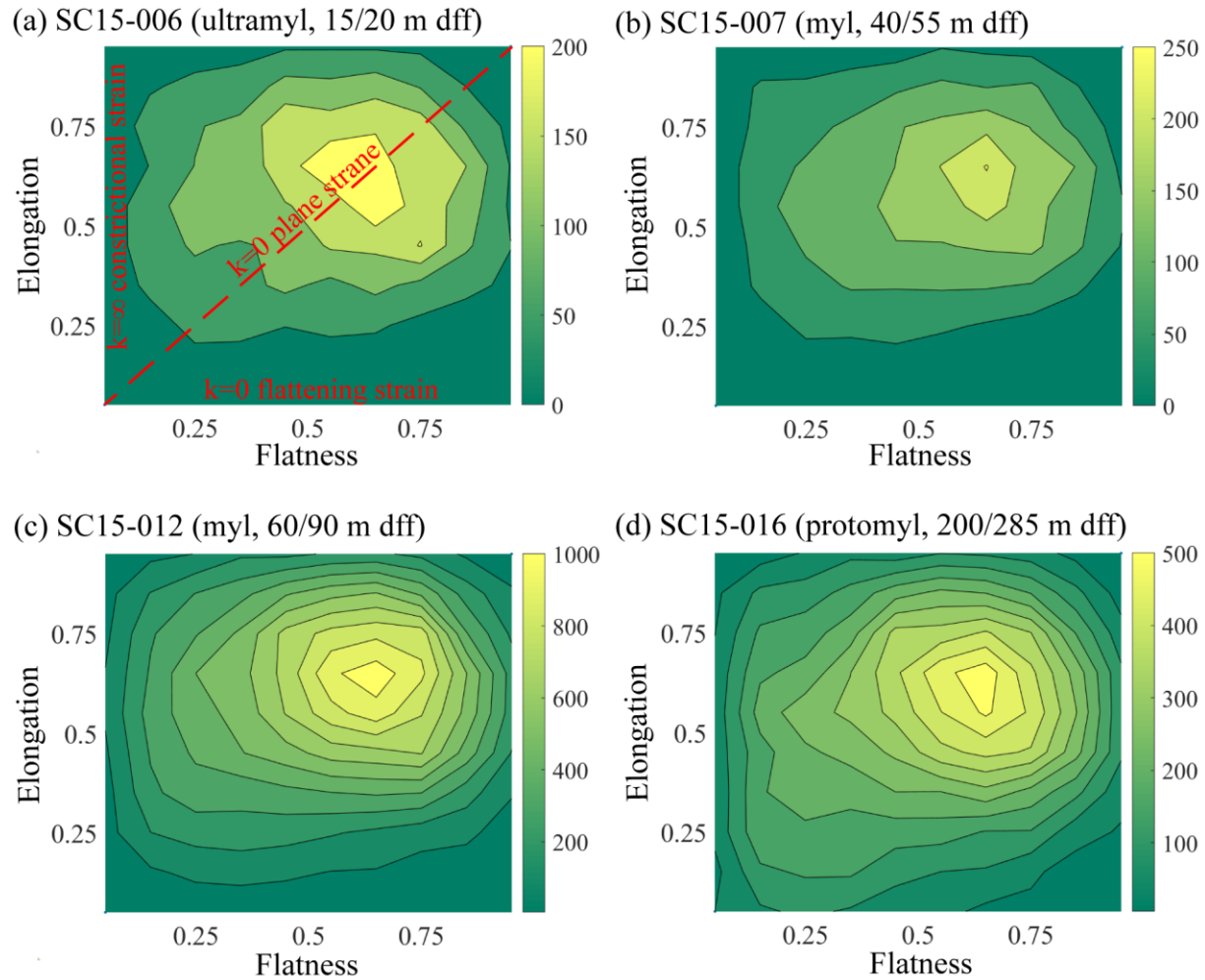
(c) SC15-012 (myl, 65/90 m dff)



(d) SC15-016 (protomyl 200/285 m dff)



Pore orientations



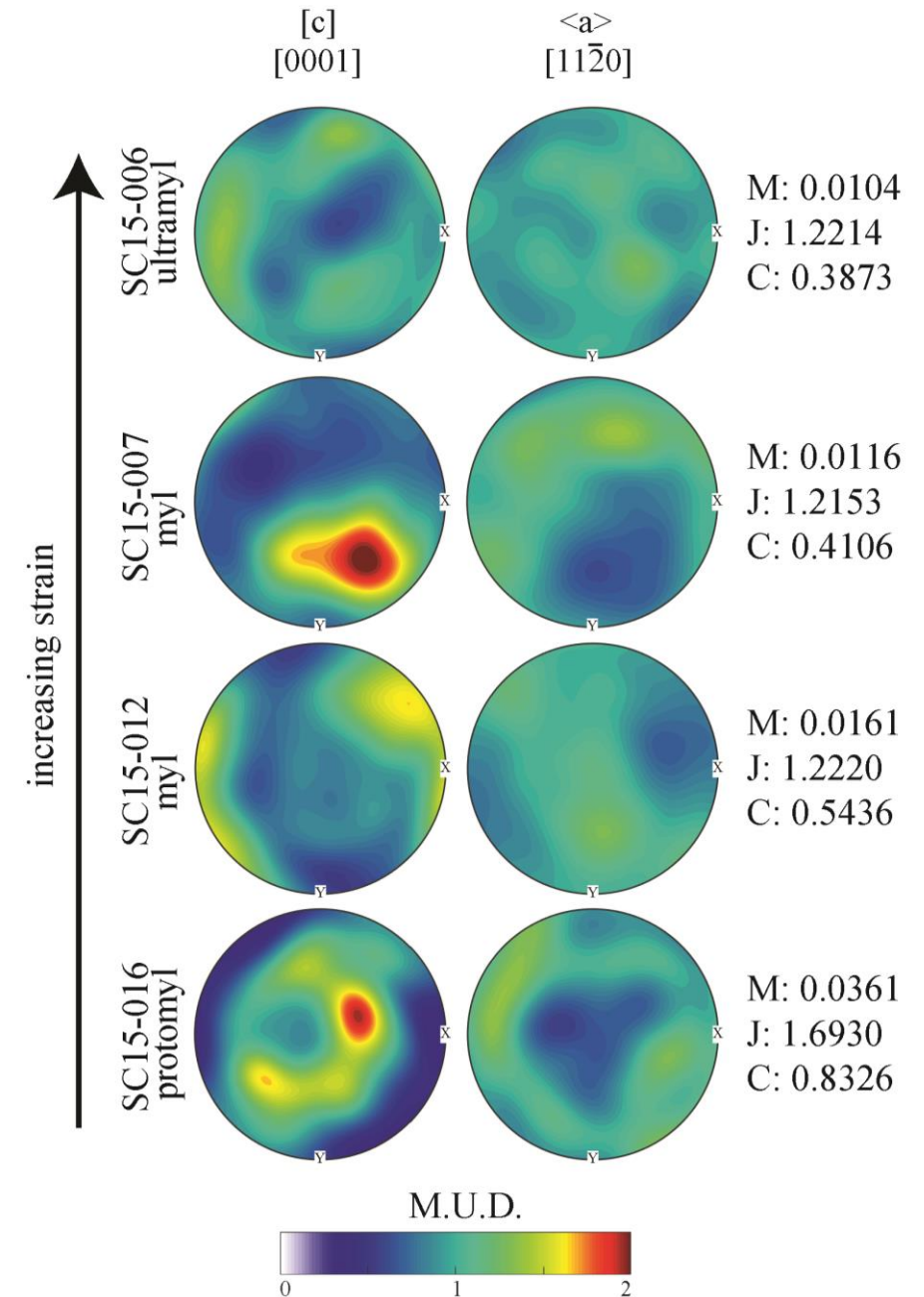
Plots of flatness vs. elongation presented in the context of Flynn diagram show pore shape clusters with average k value ~ 0 .

Pore orientations

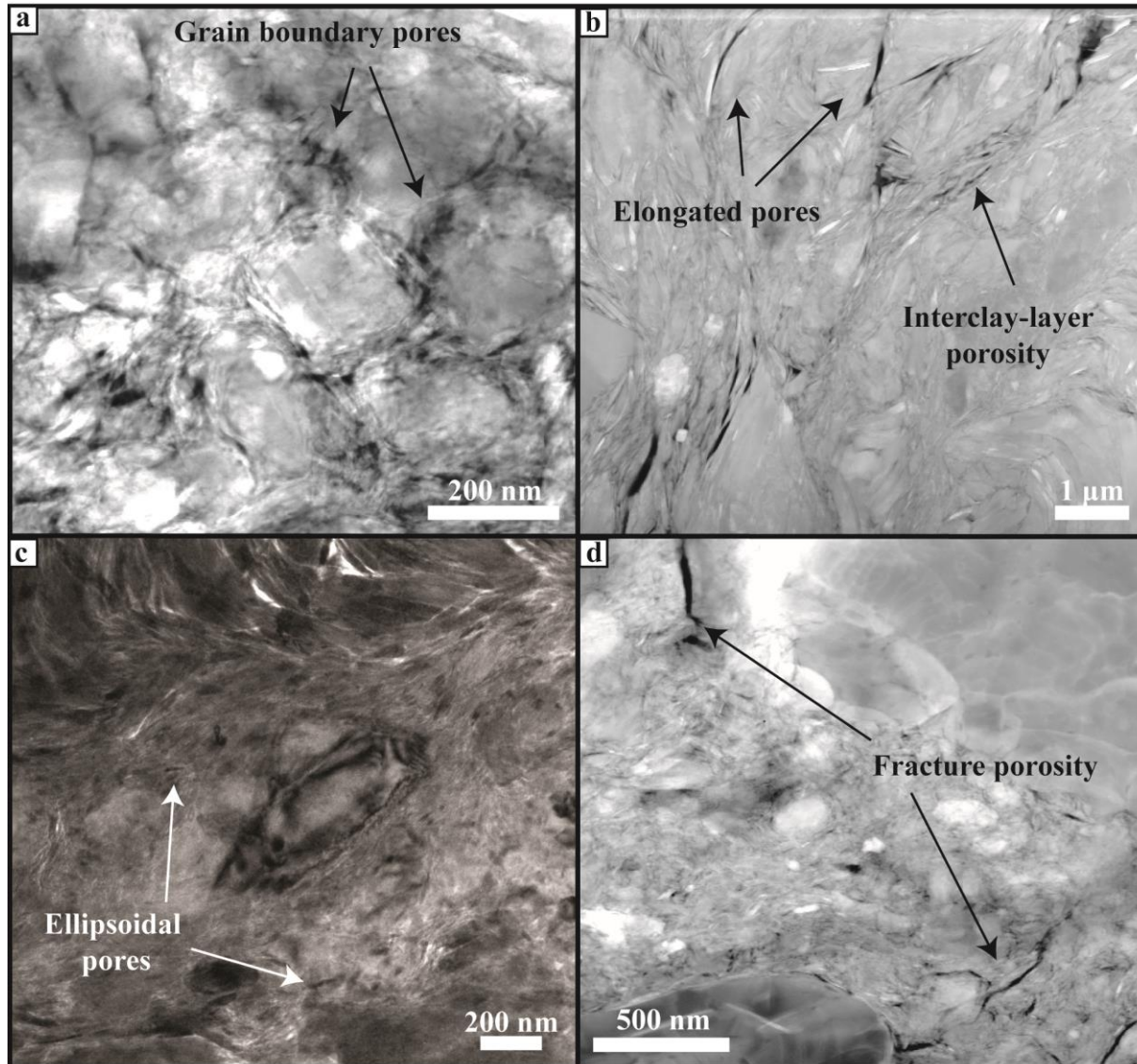
The LPO strength measures demonstrate that the protomylonite sample (SC15-16) has significantly higher M, J and C-indexes (0.0361, 1.6930 and 0.8326 respectively) than the higher strained mylonites

The symmetries and shapes of quartz LPOs demonstrate predominantly weak fabric development.

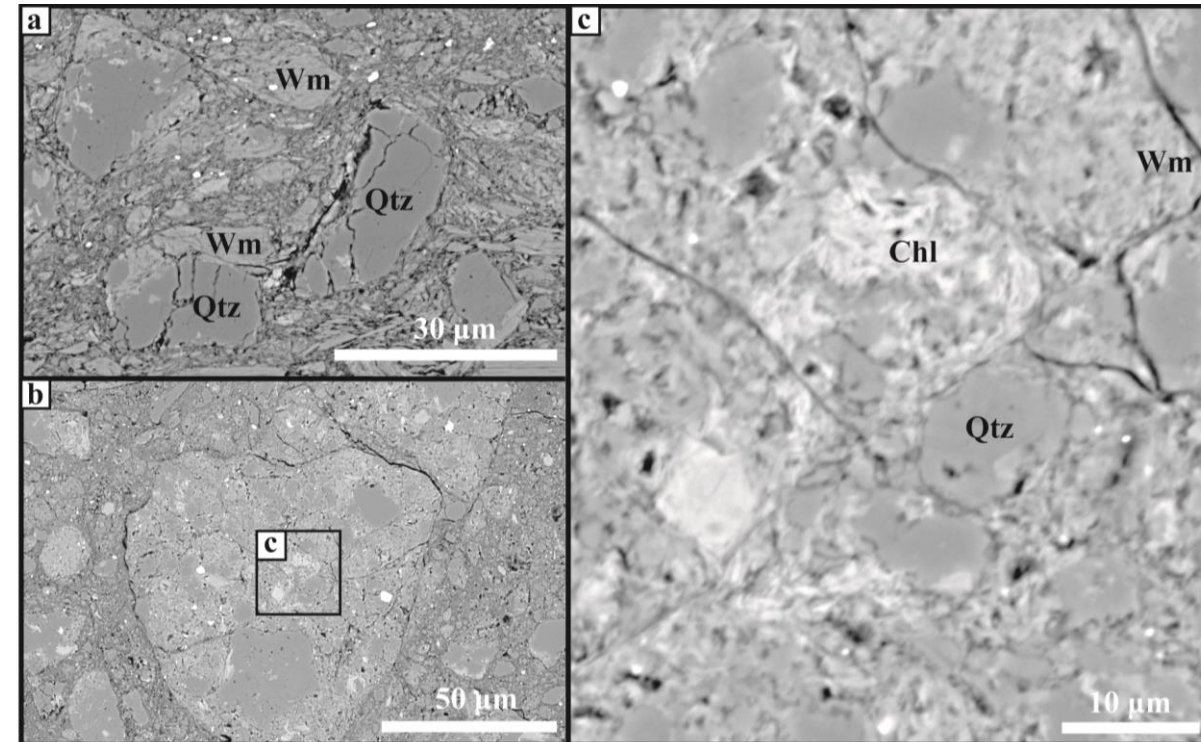
Strong quartz LPOs are demonstrated only by the $\langle c \rangle$ axis in samples SC15-016 and SC15-007 where they form asymmetrical single girdles. Sample SC15-012 shows weaker LPO development with $\langle c \rangle$ maxima on the perimeter of the pole figure on either side of the X plane. The remainder of the pole figures indicates only very weak quartz fabrics.



Alpine Fault: DFDP-1B 69-2.54 (PSZ-2)



SEM images reveal rounded to sub-rounded crystalline clasts up to 100 μm in diameter which consist of $\sim 50\%$ plagioclase, $\sim 40\%$ K-feldspar, and $\sim 10\%$ quartz and are elongated at angles of $0\text{--}30^\circ$ to the foliation. The surrounding matrix material is composed of finer grains ($< 30\ \mu\text{m}$ in diameter) of white micas, chlorite, K-feldspar, calcite and Ti-oxide. Numerous quartz clasts contain microfractures, filled by calcite and/or chlorite.



Rocks from the Alpine Fault zone contain

- extremely low total porosities – 0.1 to 0.24% in the cataclasites
- up to 0.5% in the mylonites – typical low values for mylonitic rocks

Cataclasites:

- The distribution of pores along grain boundaries controls both their shape and orientation.

Evidence for **pressure solution processes** within the Alpine Fault core:

- Abundant precipitation of alteration minerals (Sutherland et al., 2012)
- Calcite filled intragranular and cross-cutting veins (Williams et al., 2017)
- Newly formed smectite clays (Schleicher et al., 2015)
- Hydrothermal graphite precipitation (Kirilova et al., 2017)

These small volumes of open spaces may:

- Represent areas where pore fluid overpressure occurs
- Facilitate deposition of weak mineral phases

Mylonites:

- In the mylonitic samples, pores are sub-parallel to the foliation, and often associated with C'-type shear bands, indicating formation during creep cavitation.
- Facilitate propagation of fluids triggered by cavity formation in the ductile regime is likely to cause further mineral precipitation in fluid filled pores within the fault zone.
- Such precipitation can affect the mechanical behavior of the Alpine Fault by decreasing the already critically low total porosity of the fault core, causing elevated pore fluid pressures, and/or introducing weak mineral phases, and thus lowering the overall fault frictional strength.

- The state of porosity in mylonites from the Alpine Fault zone facilitates fluid circulation, and thus enhances fluid-rock reactions and contributes to mineral deposition.
- The state of porosity in cataclasites from the Alpine Fault core is likely to affect the mechanical behavior of the Alpine Fault, because it promotes:
 - (i) generation of pore fluid overpressure
and
 - (ii) precipitation of weak mineral phases within open pore spaces.

We conclude that the current state of porosity in the Alpine Fault zone is likely to play a key role in the initiation of the next fault rupture.

Thank you!