The nature and properties of fracture damage surrounding faults

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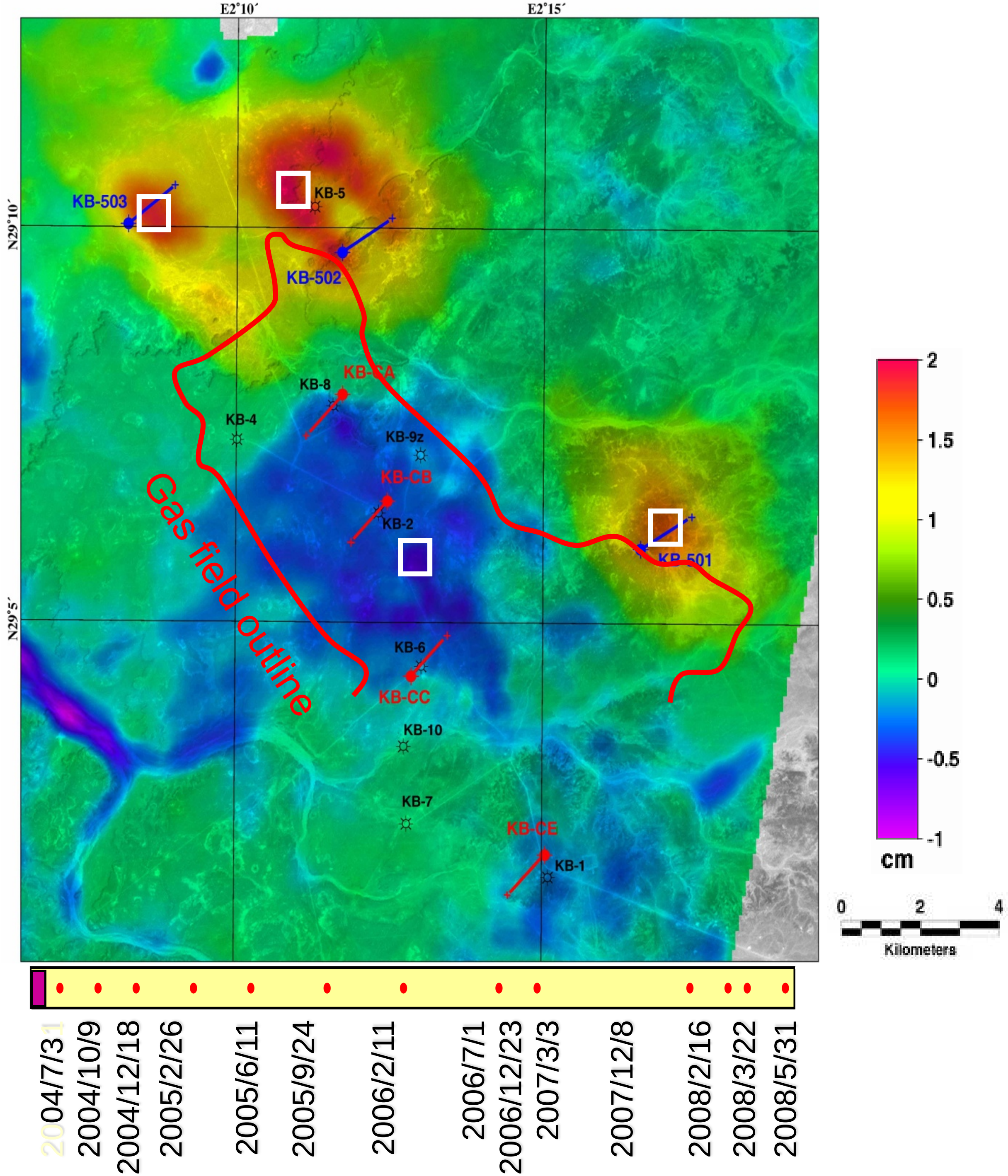
Francois Passelegue
Alex Schubnel
Jerome Fortin

Where does the fluid go during injection?

- Faults
  - Occupy only a small fraction of the crust, but exert a disproportionate influence on its properties – including permeability

In Salah -Injection of CO_2

- Active monitoring ongoing – satellite and tiltmeters
- Permanent Scatterer Interferometry (PSInSAR™)
- Pinnacle, Lawrence Berkeley (US) and TRE (Milan, Italy)



In Salah Surface Deformation Time Series from 2004/7/31 to 2008/5/31

Crustal permeability

- Field studies showing the distribution of fractures surrounding faults
  - What is the physical nature of faults?
- Laboratory studies of elastic anisotropy development
  - Permeability
  - P and S wave velocity
- Development of permeability during deformation in different tectonic regimes

102 F. M. Chester and J. M. Logan PAGEOPH,

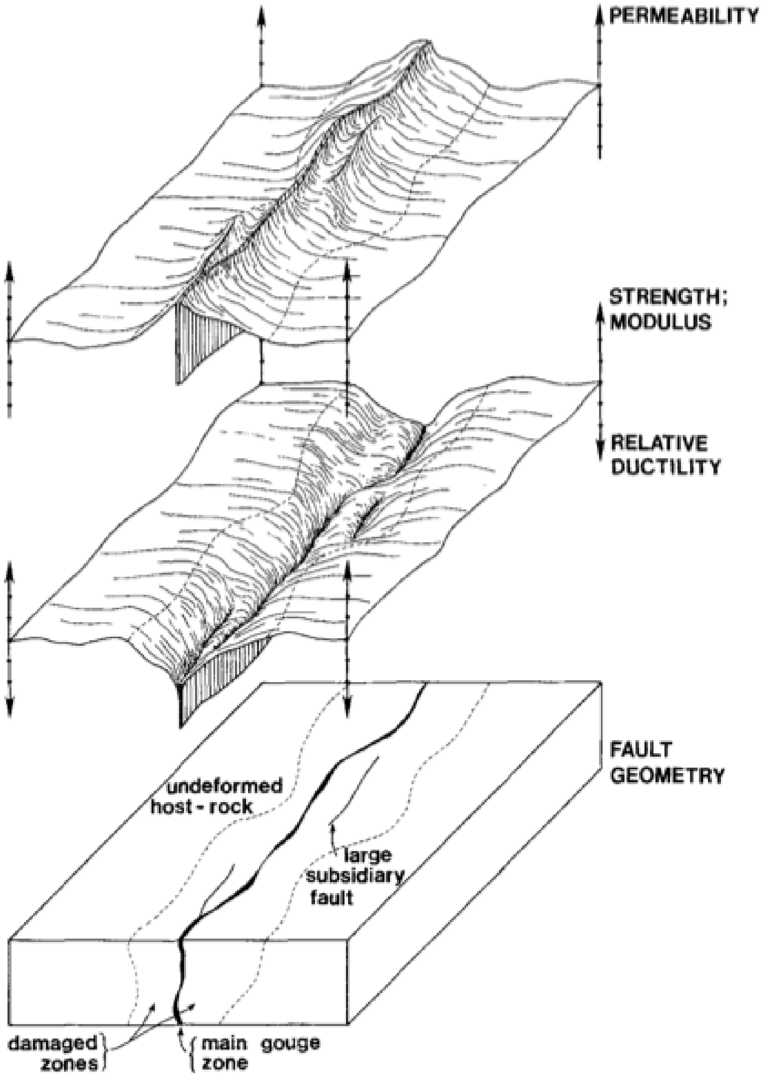
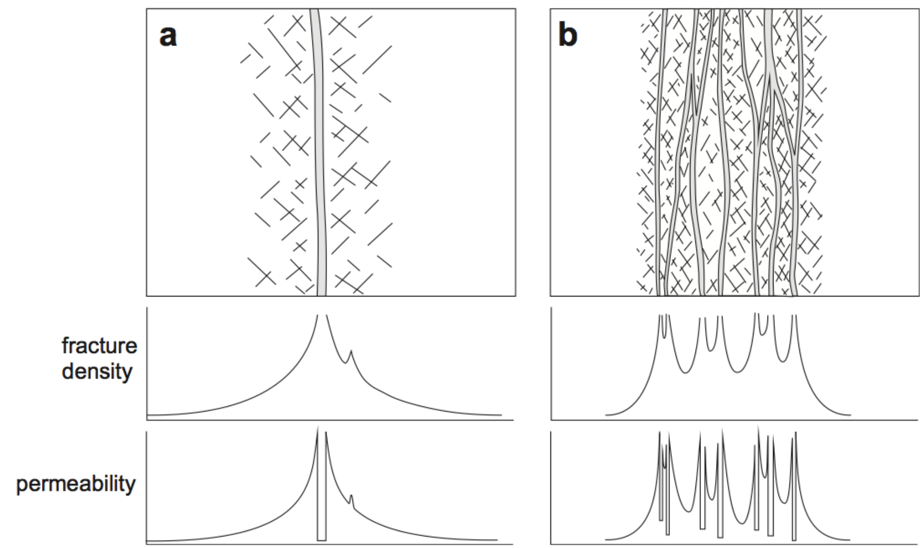
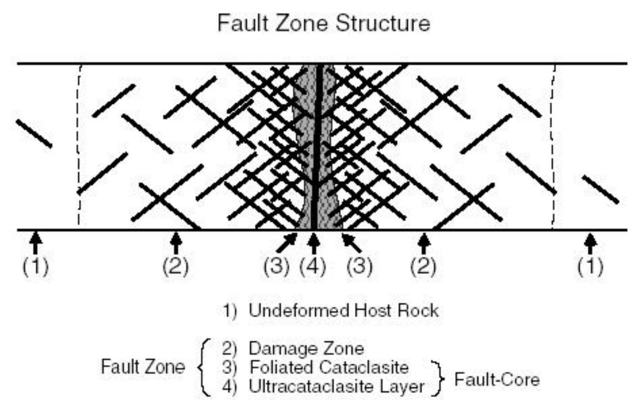


Figure 15
Schematic diagram of structure and relative properties of idealized brittle fault zone based on observations of Punchbowl fault. Block diagram indicates structural-mechanical units of fault. Surfaces indicate relative variation in properties along and across fault. Note that increasing direction of particular properties may be up or down, as shown on axes. Mesoscopic or macroscopic scale intended.

Chester and Logan, 1986

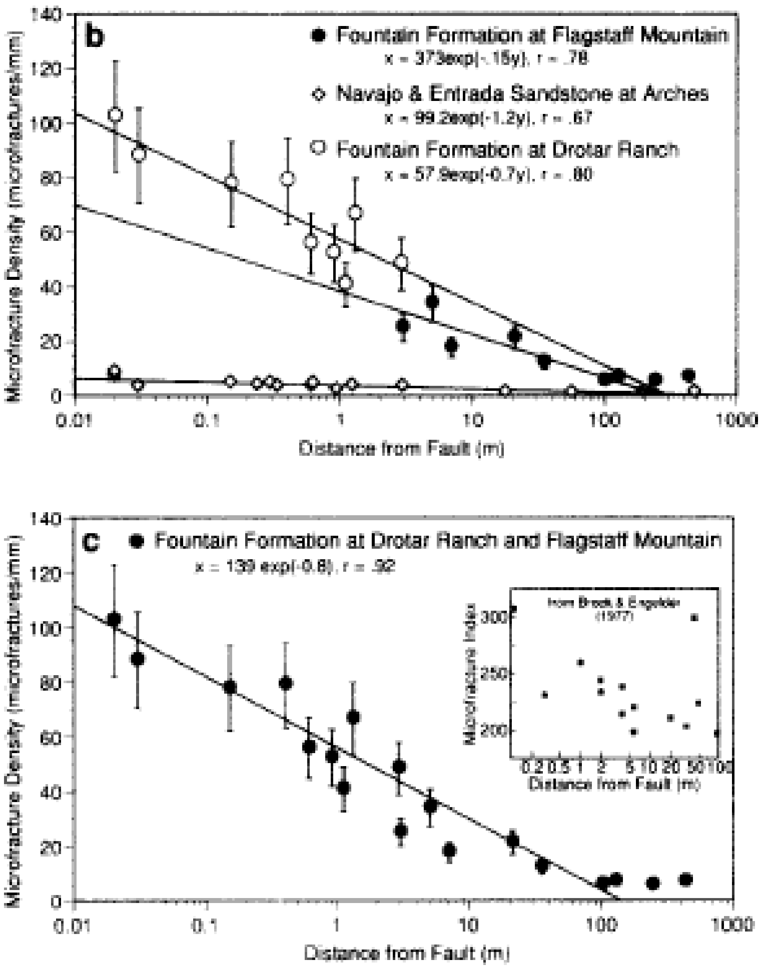


Faulkner et al. 2010 JSG



Chester et al. 2004

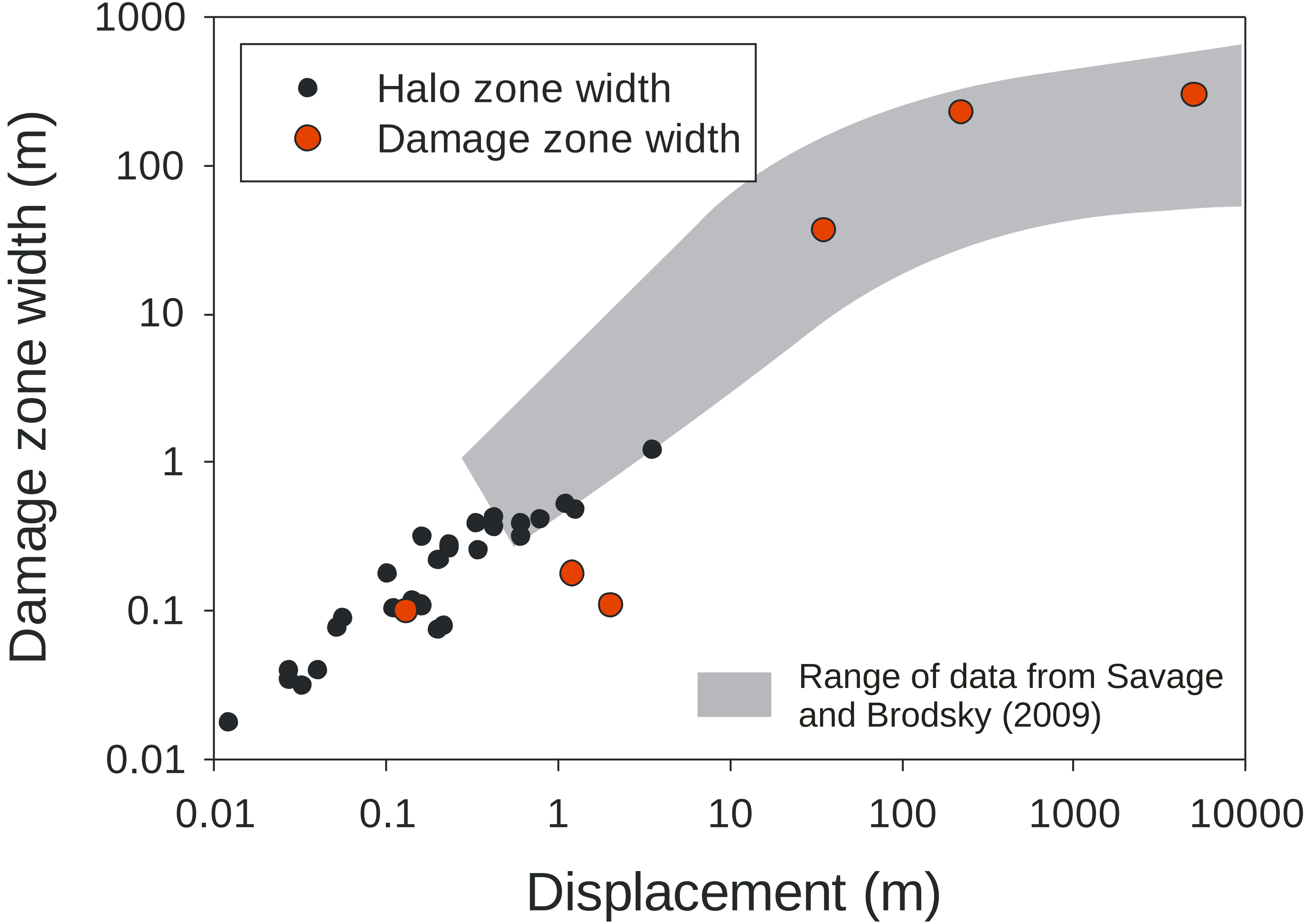
Distribution of fractures around faults



Anders and Wiltschko, 1994, JSG

$$F = F_0 \exp(-x/\beta)$$

F = fracture density (no./mm)
F_0 = max F (at fault)
x = distance (m)
β = characteristic distance (m)
(Mitchell and Faulkner, 2012 EPSL)



Faulkner et al. 2011 JGR

So, we know the distribution of damage surrounding faults, what about the permeability?

- Depends on:
  - tectonic environment
  - depth
  - $\boldsymbol{k}_{ij} = f(\boldsymbol{F}_{ij}, \boldsymbol{\sigma}_{ij}, \varepsilon_{ijkl})$

  stress field that produced the crack network and the stress field acting on the crack network
  - we can explore these concepts experimentally…

Experiments

Permeability measurements at three different effective pressures:

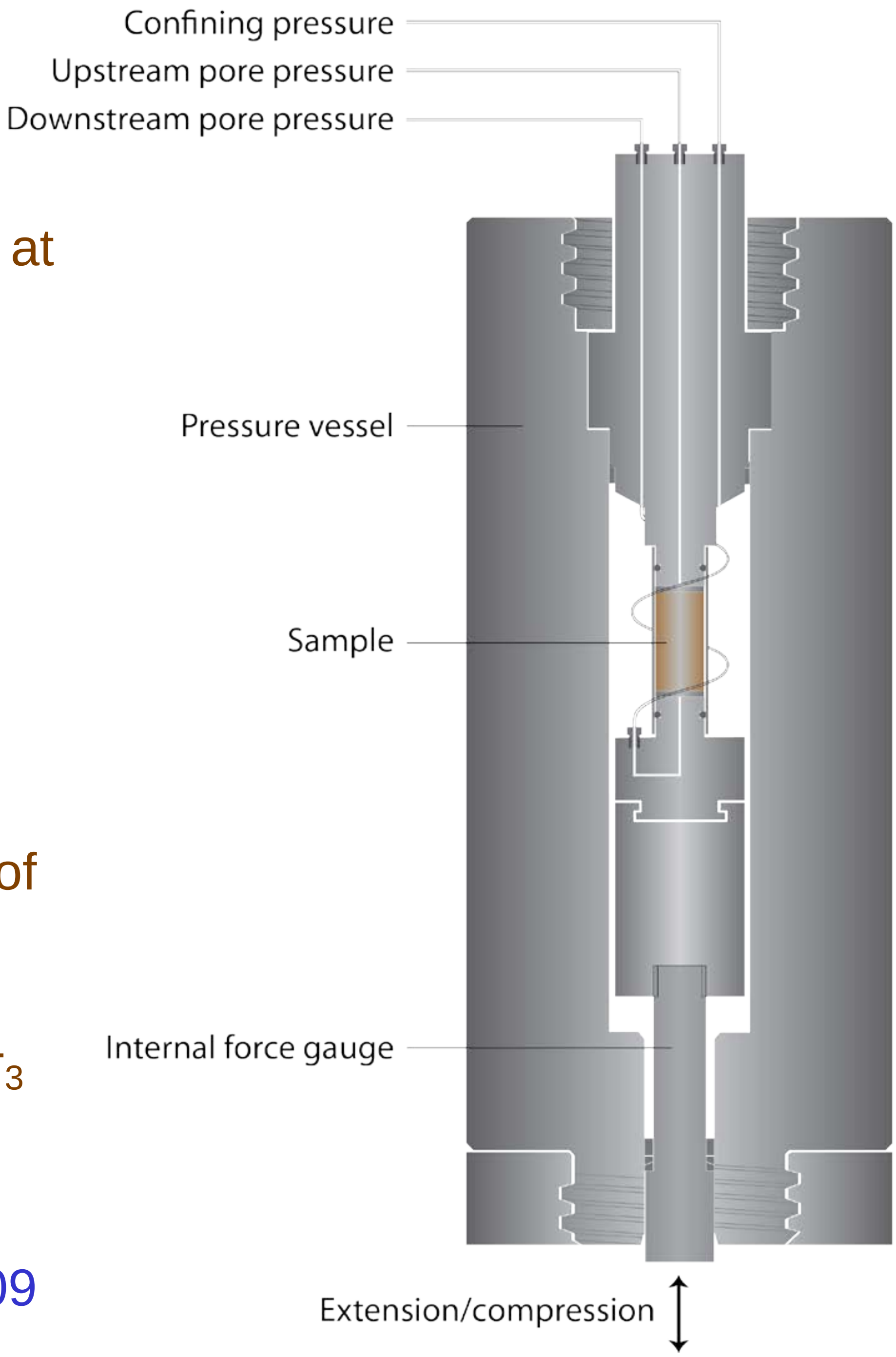
- 10 MPa
- 30 MPa
- 50 MPa

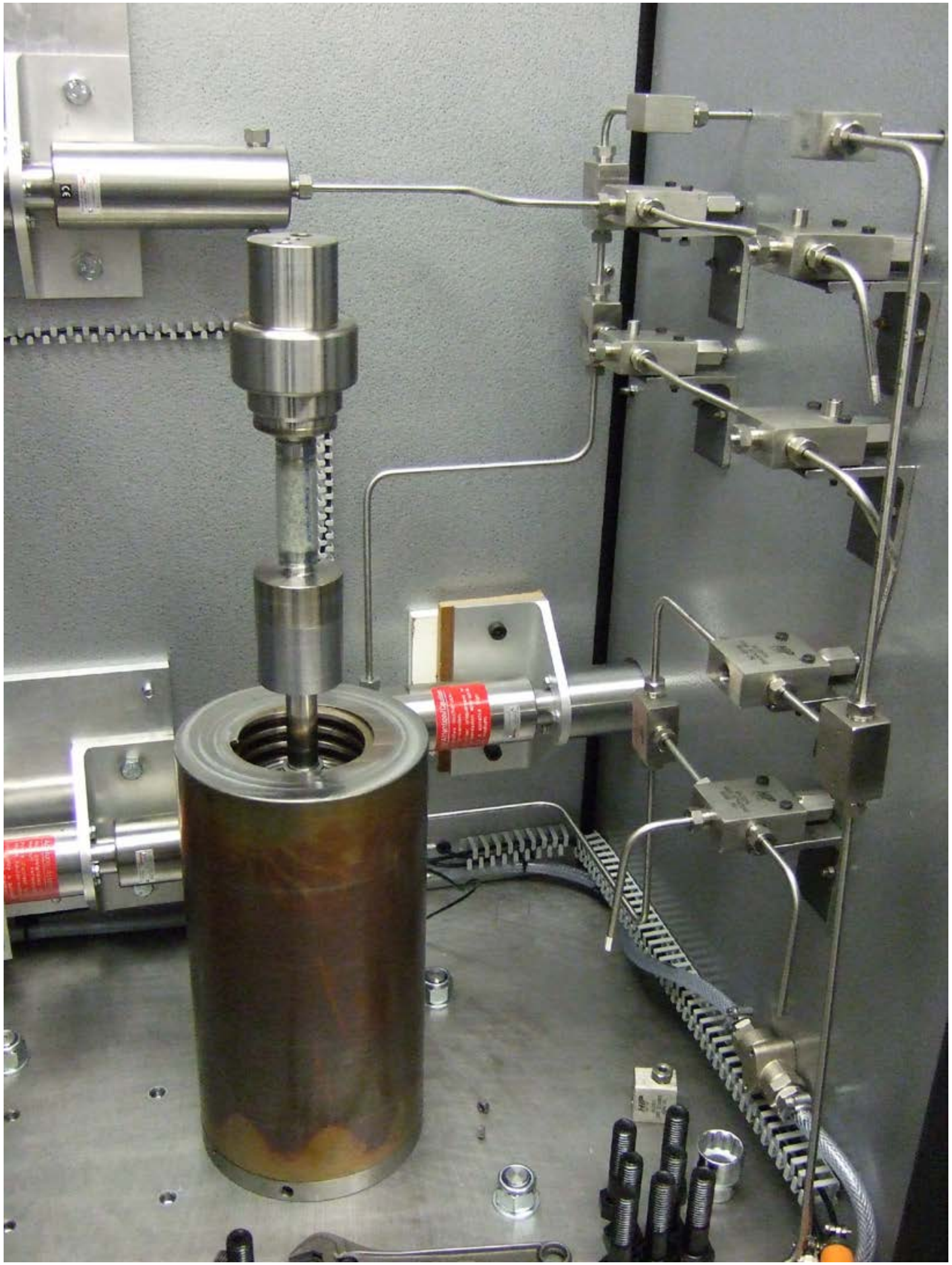
Samples loaded to <25% of failure stress

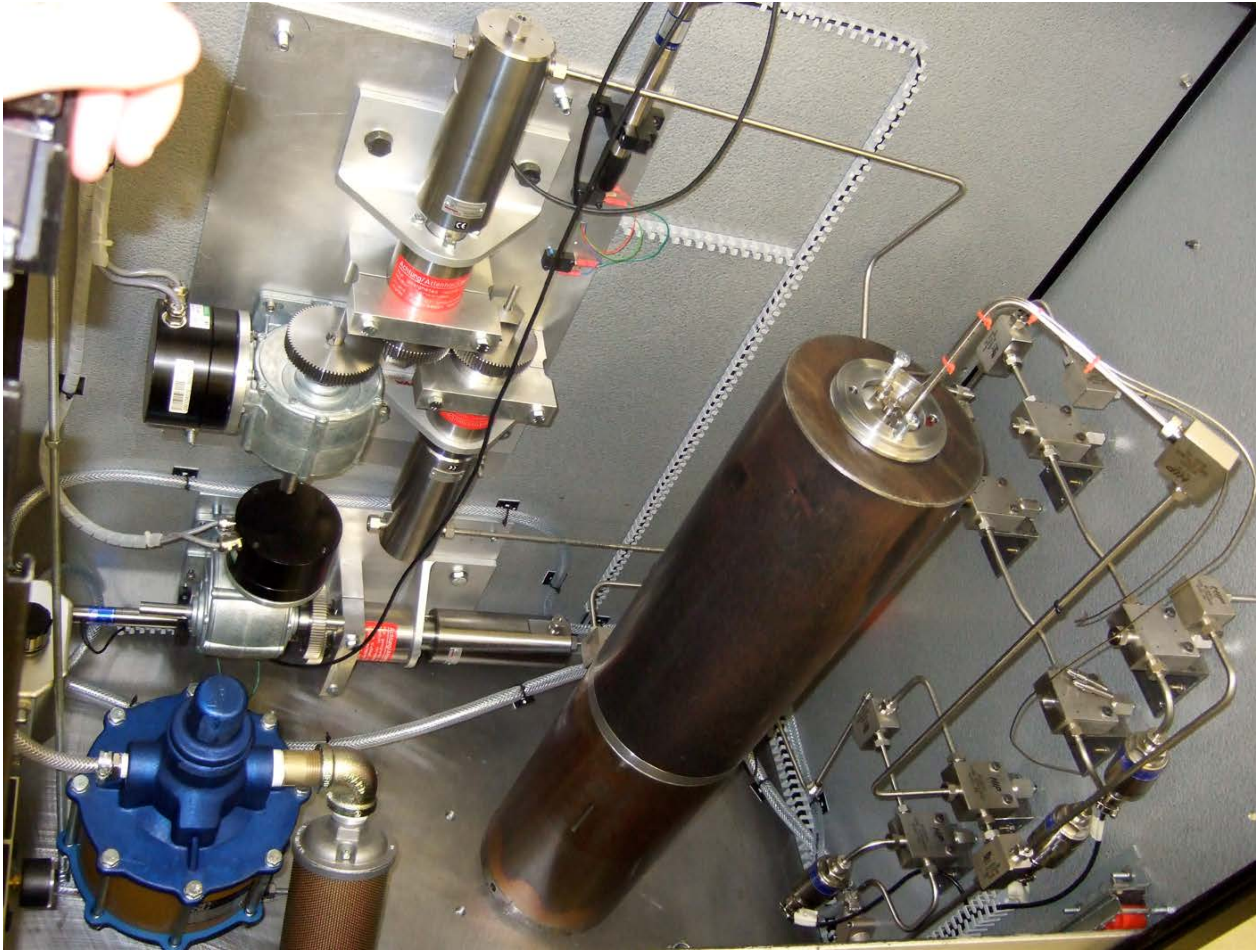
Compression: *k* in direction of σ_1

Extension: *k* in direction of σ_3

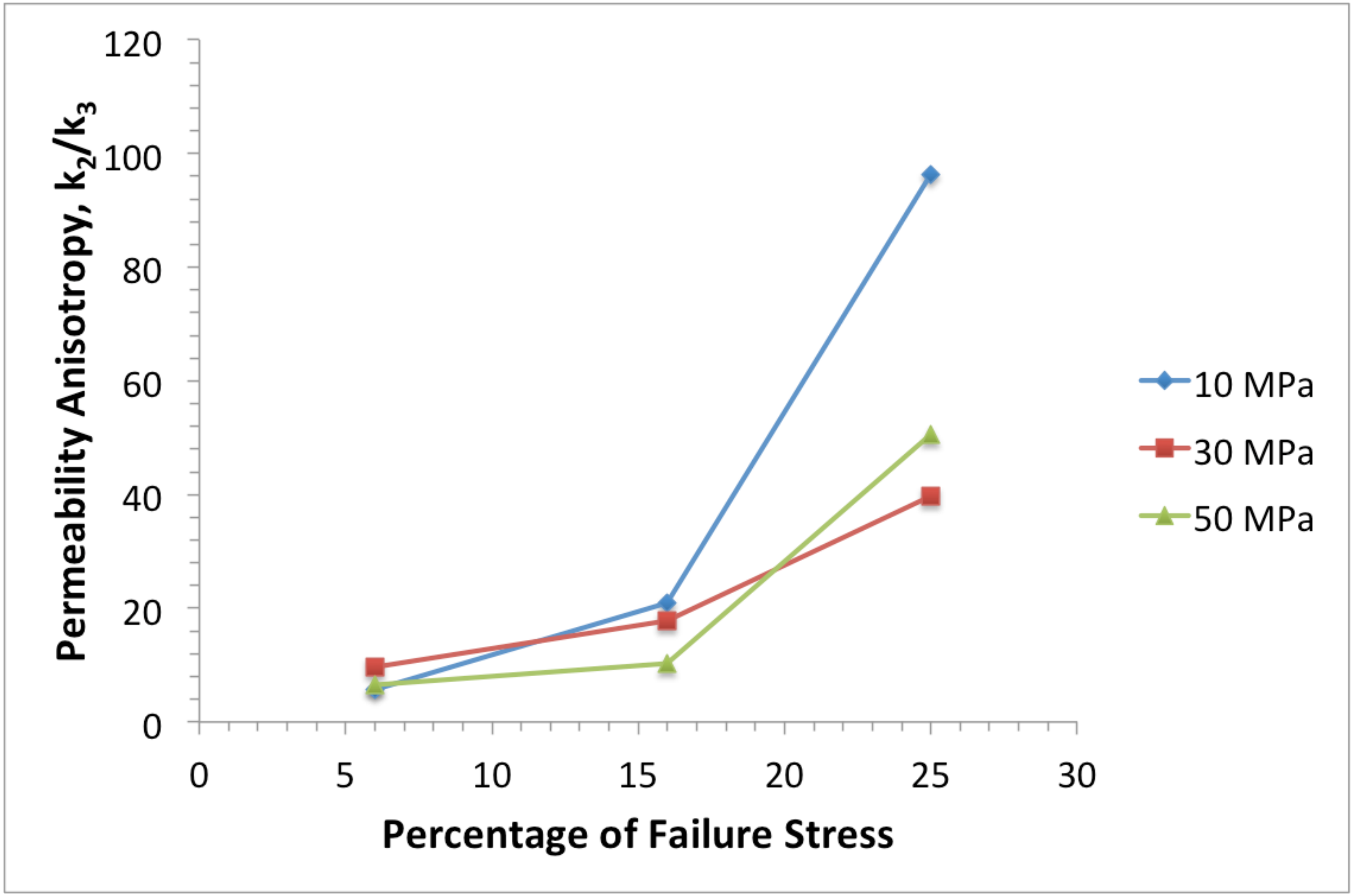
cf. Zhu et al., 1997;
Zhu and Wong, 1999
See also Daudriat et al., 2009



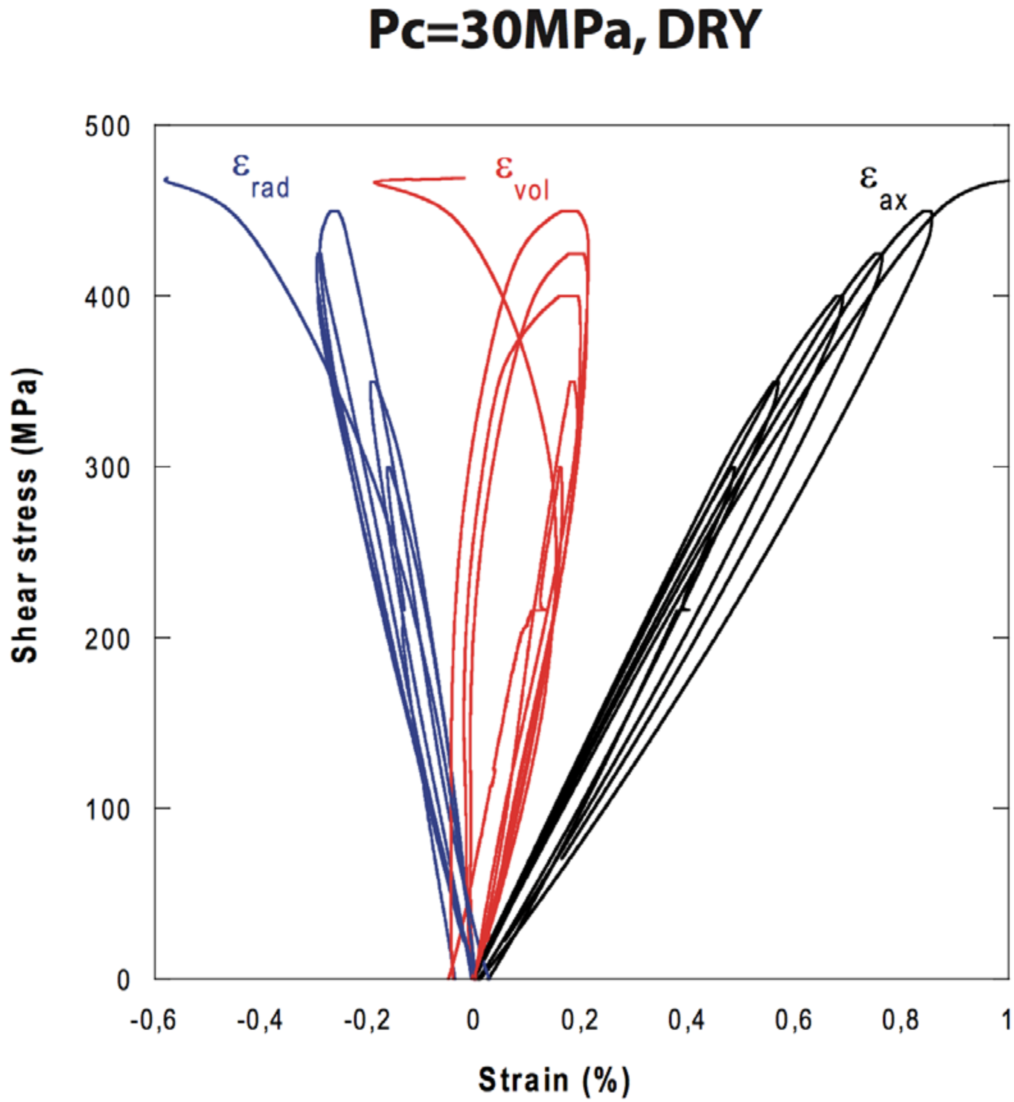


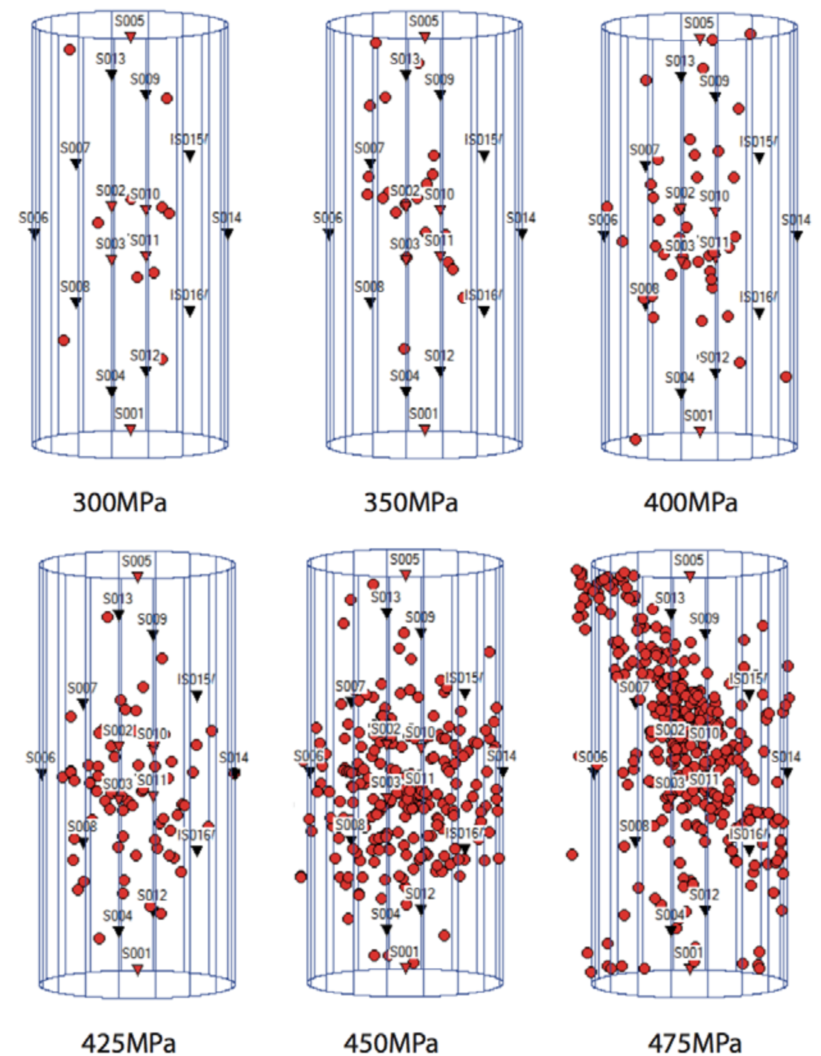


Stress-induced permeability anisotropy in isotropically fractured Westerly Granite



Faulkner and Blake, 2014, Unpublished data

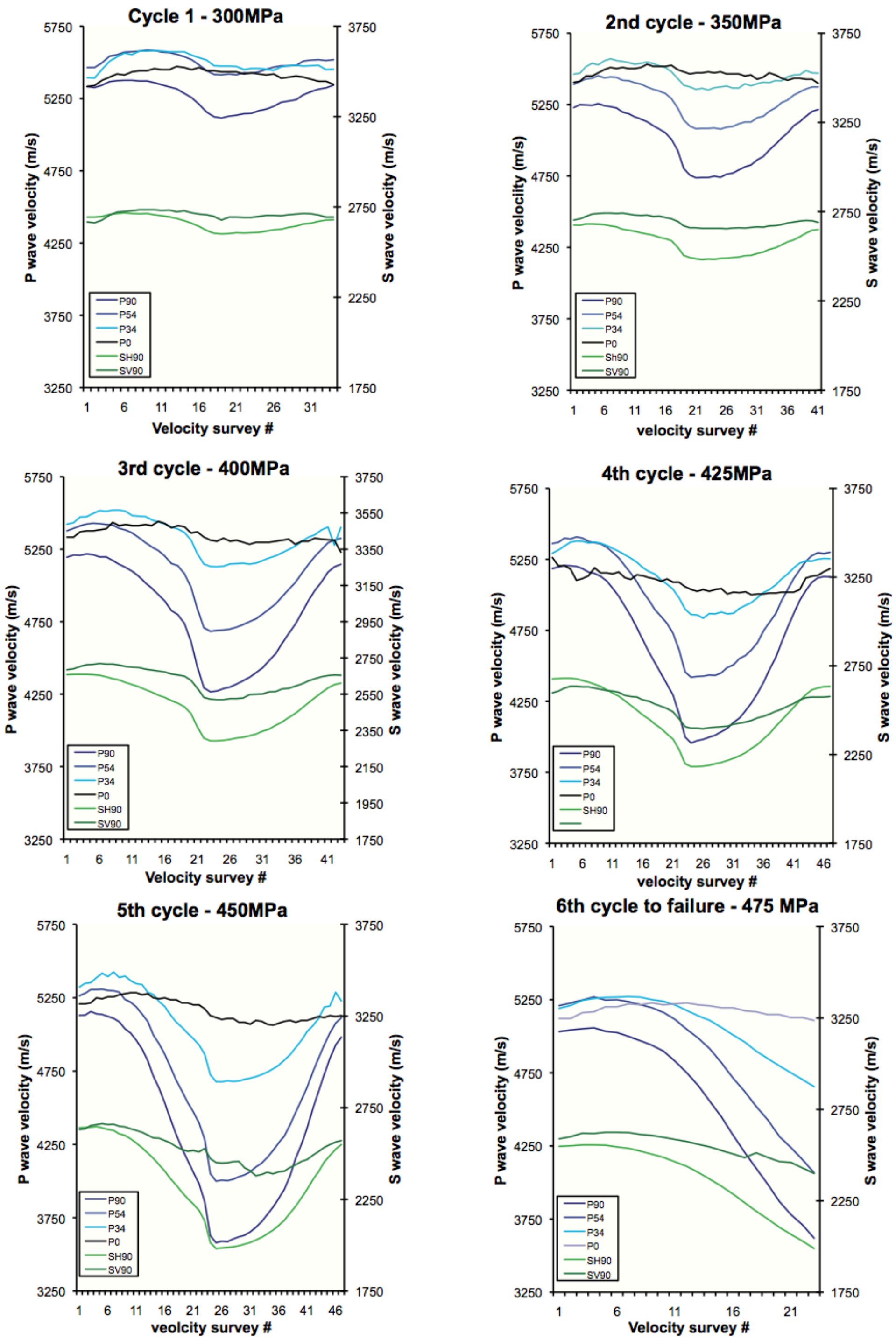


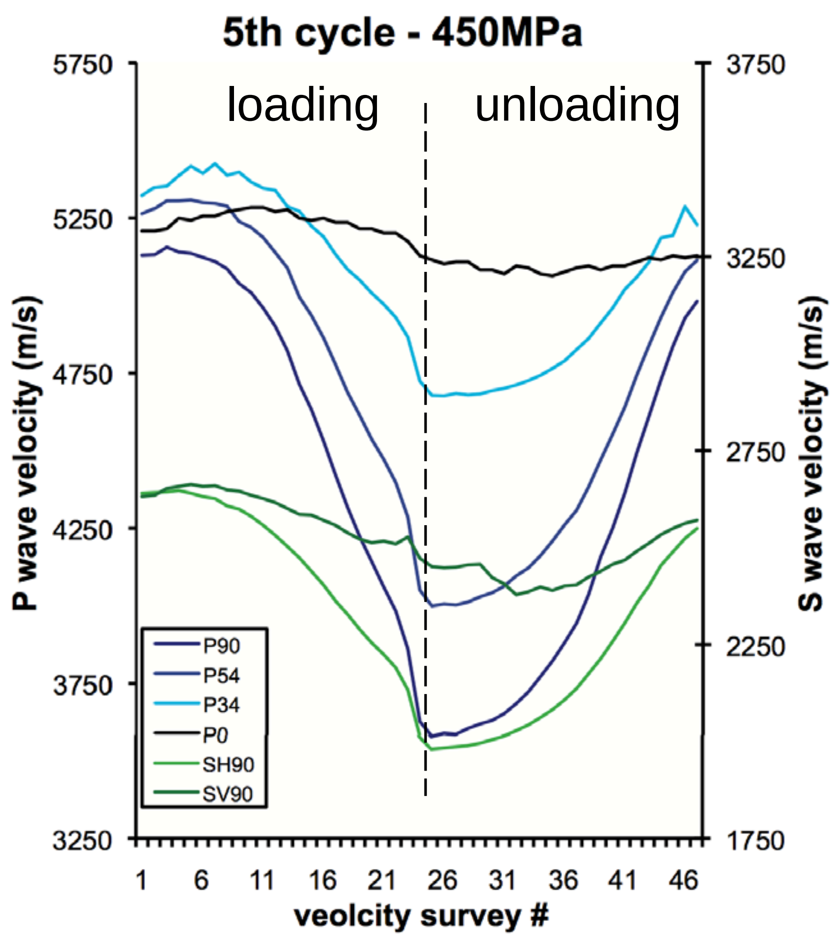


Cyclic loading of Westerly granite – elastic anisotropy

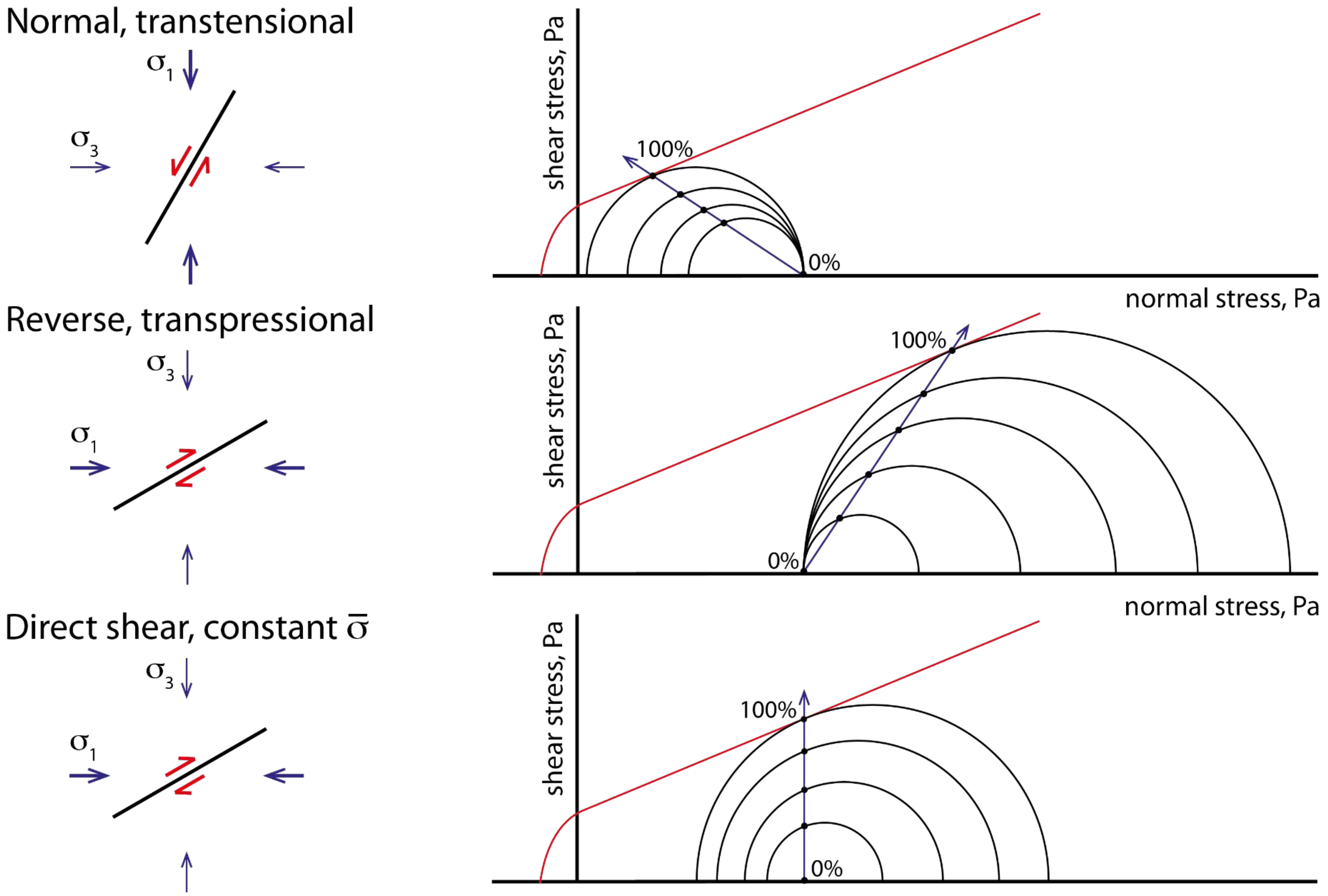
ENS Paris with Alex Schubnel, Francois Passelegue and Jerome Fortin

Recovery of elastic wave speeds also indicates the influence of stress-induced anisotropy in fractured samples

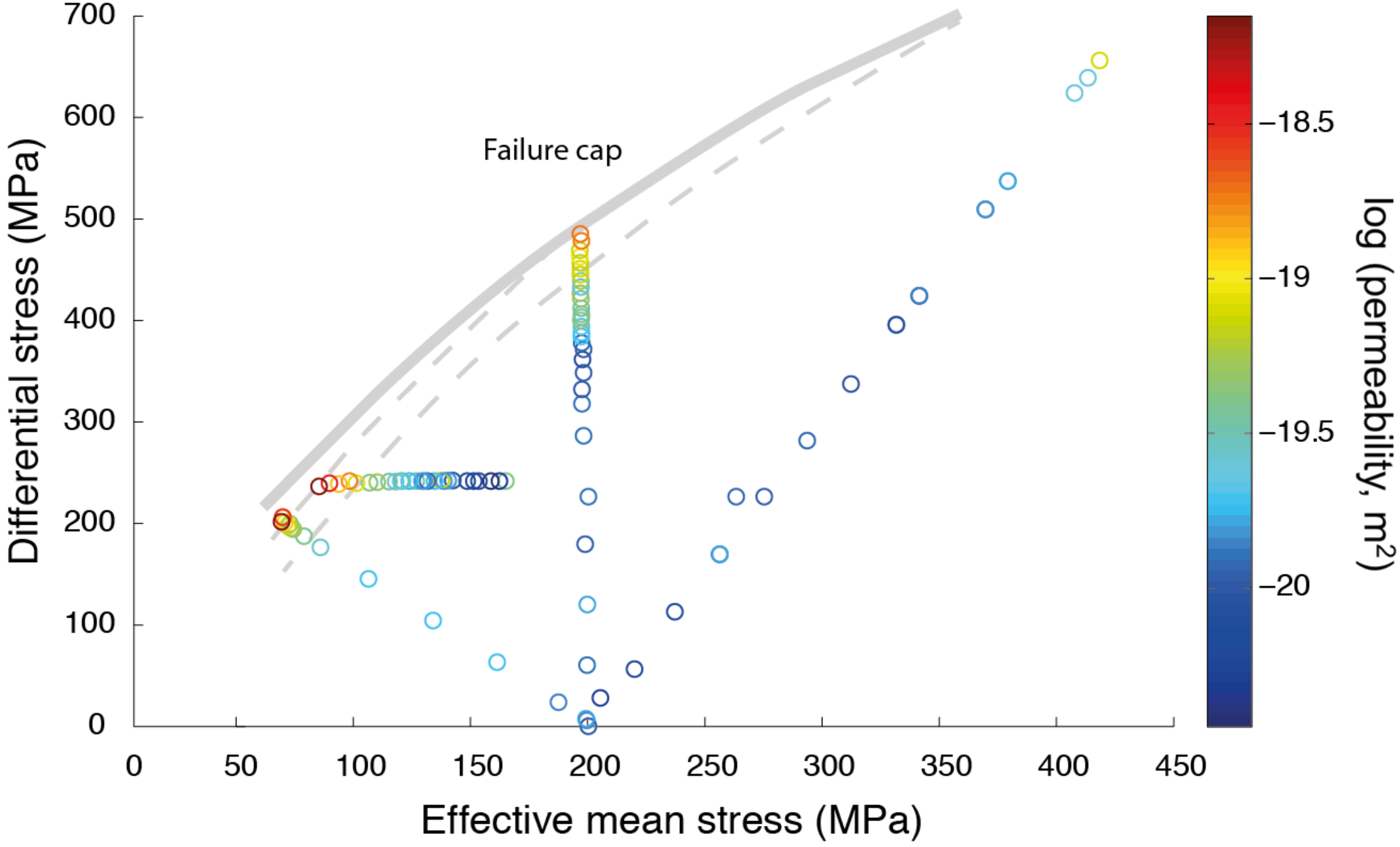




How does permeability change with stress path?



cf. Sibson, 1993

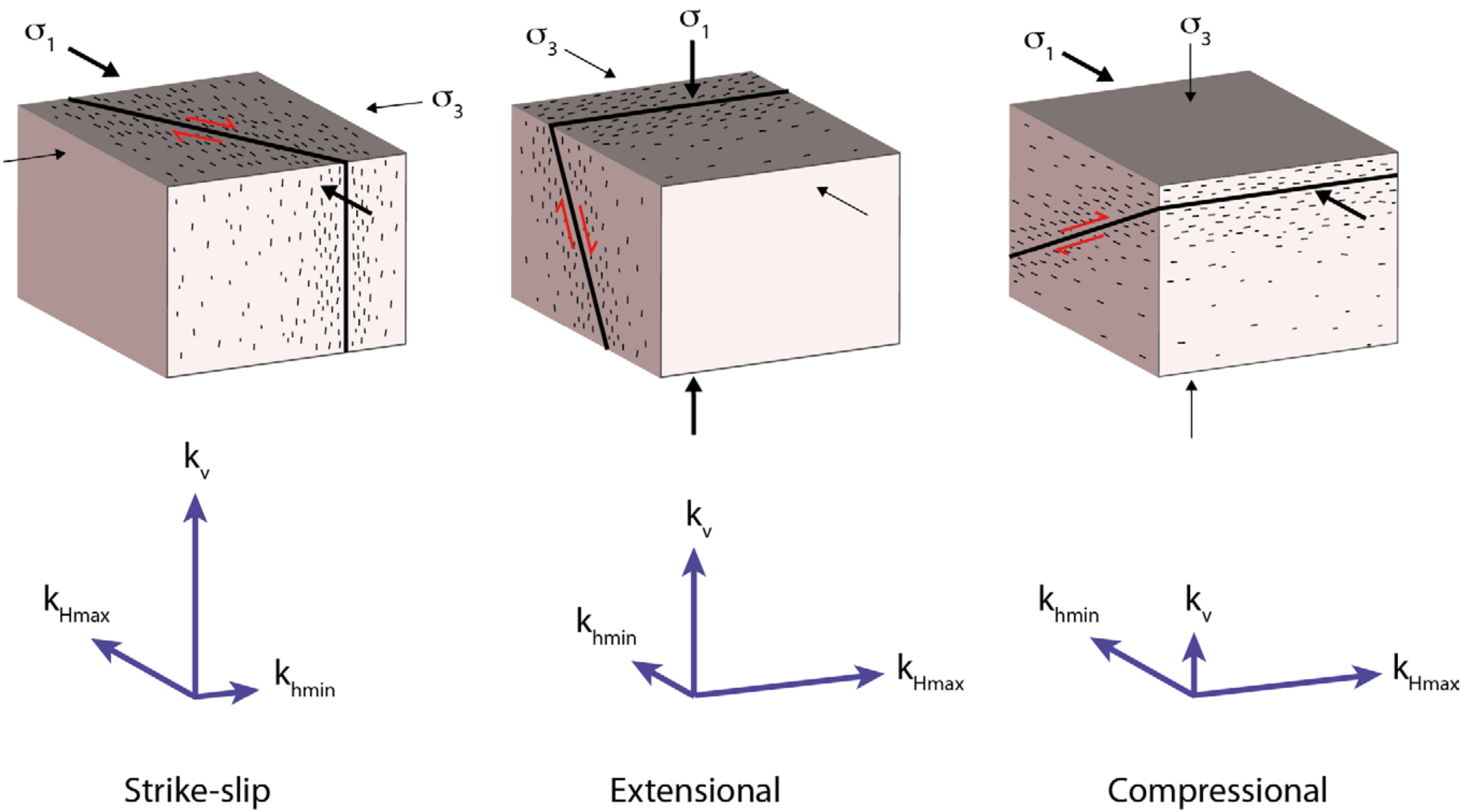


Faulkner and Armitage, 2013, EPSL

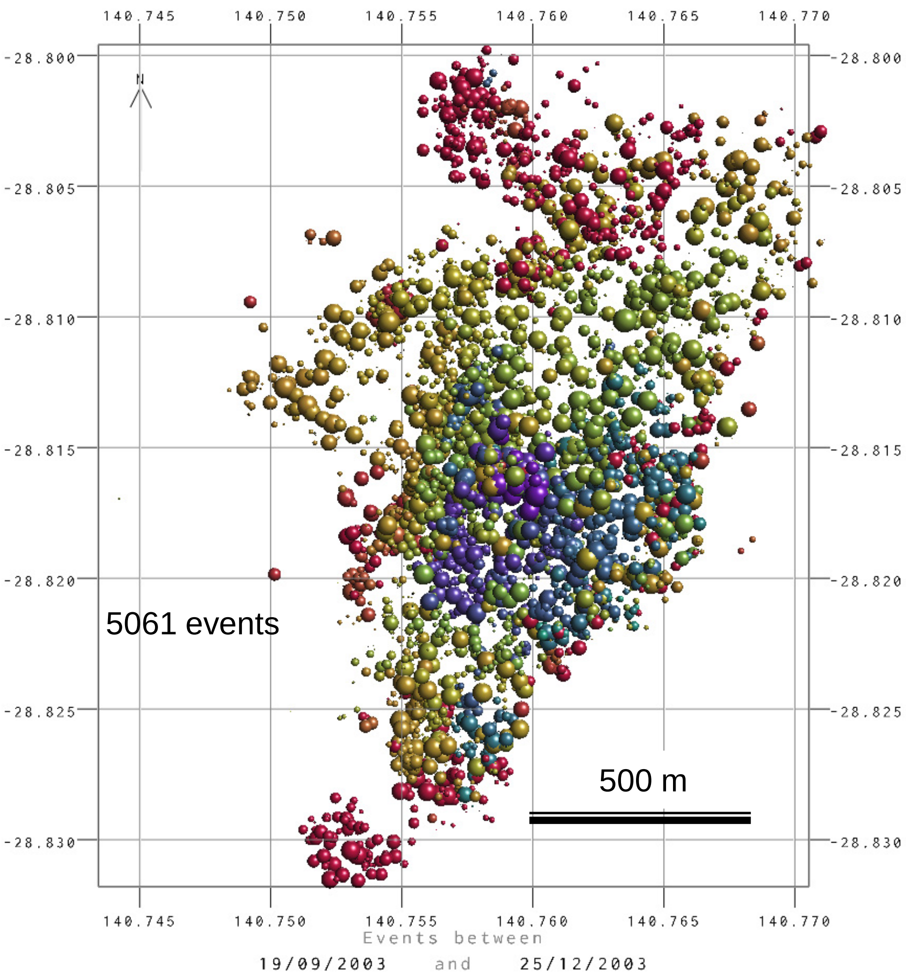
Development of permeability is different in different tectonic regimes

- But can it wholly be explained by the applied stress?
- Is there any difference in the crack network?

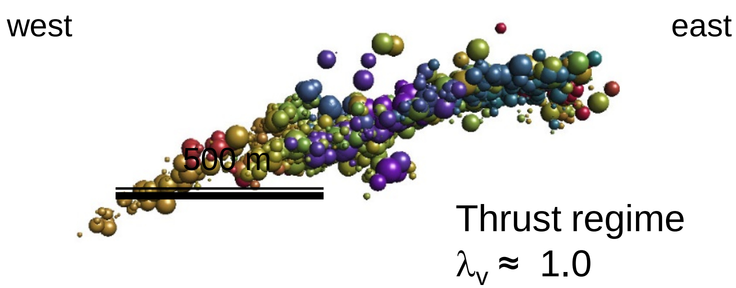
Permeability anisotropy in the crust



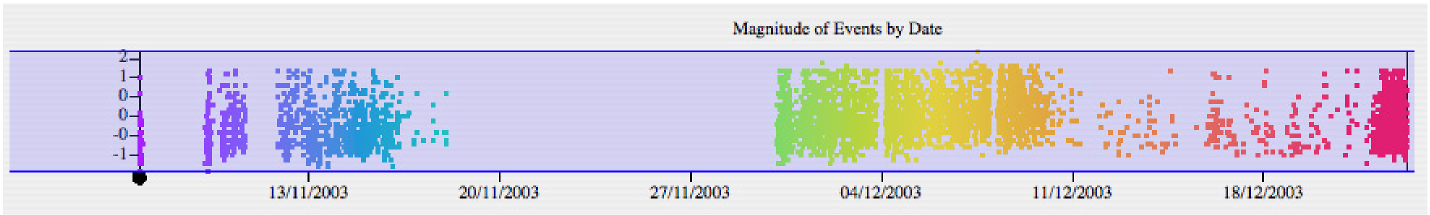
2003 Cooper Basin Fluid Injection Experiment - thrust



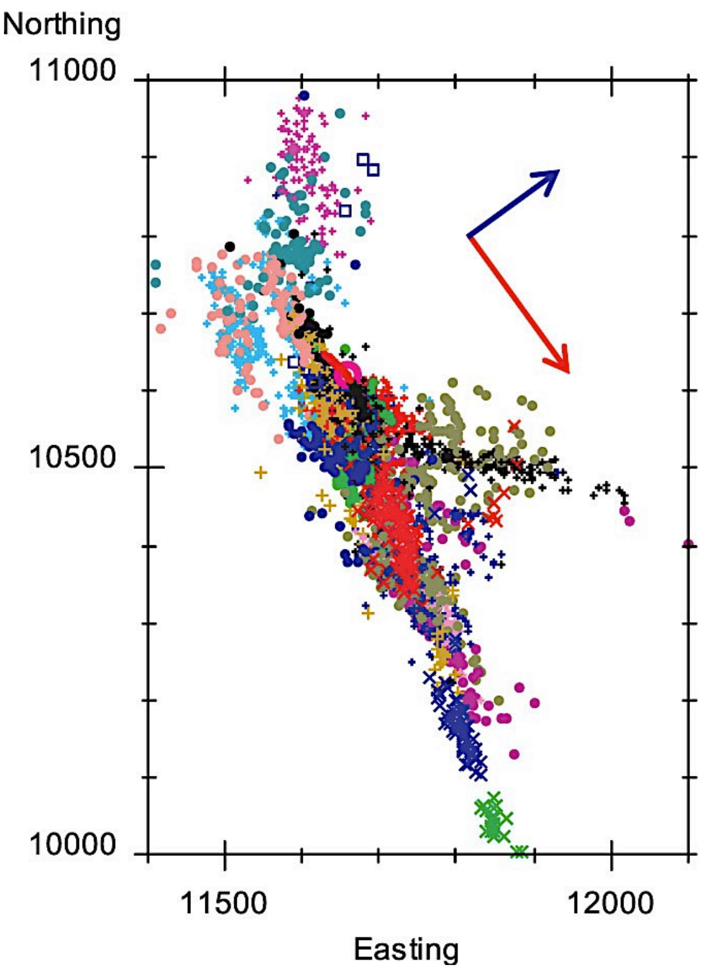
hypocentres:
Geodynamics Ltd



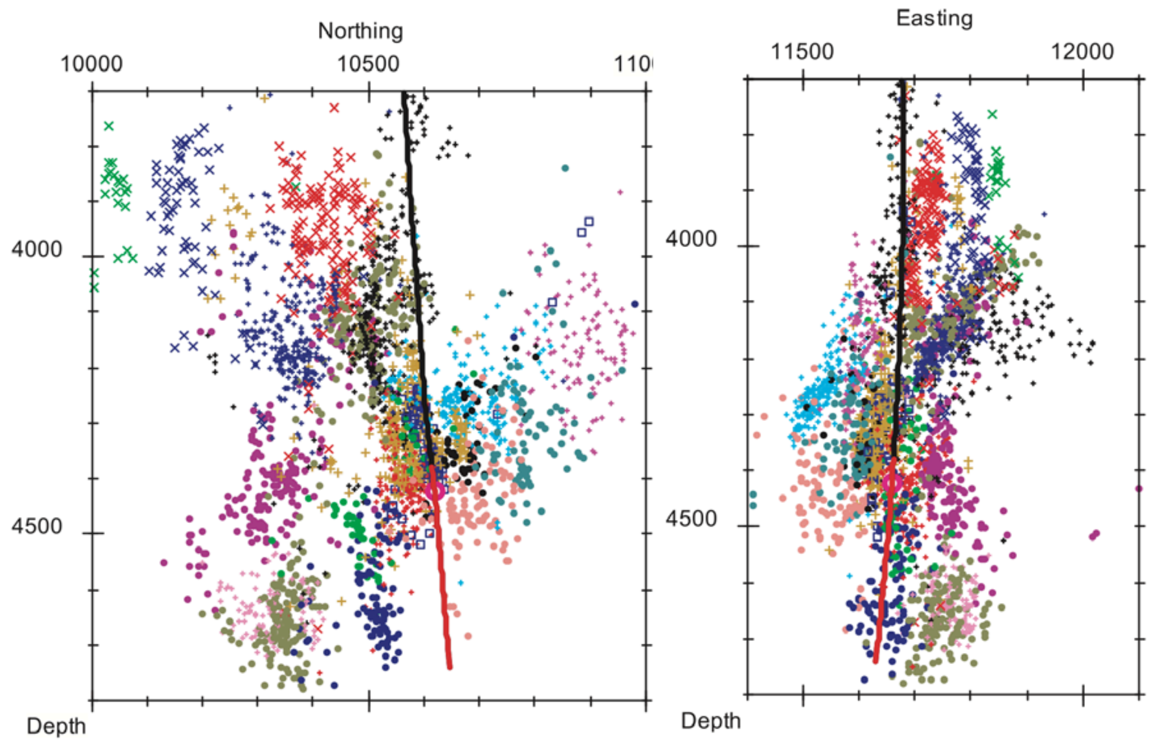
- max. cumulative slip: several 10s cm
- migration of seismicity with time
- anisotropy of migration rate



Induced seismicity, 2006 Basel fluid injection experiment - SS



- diffusive time migration of front of seismicity “cloud”
- migration of fluid pressure front



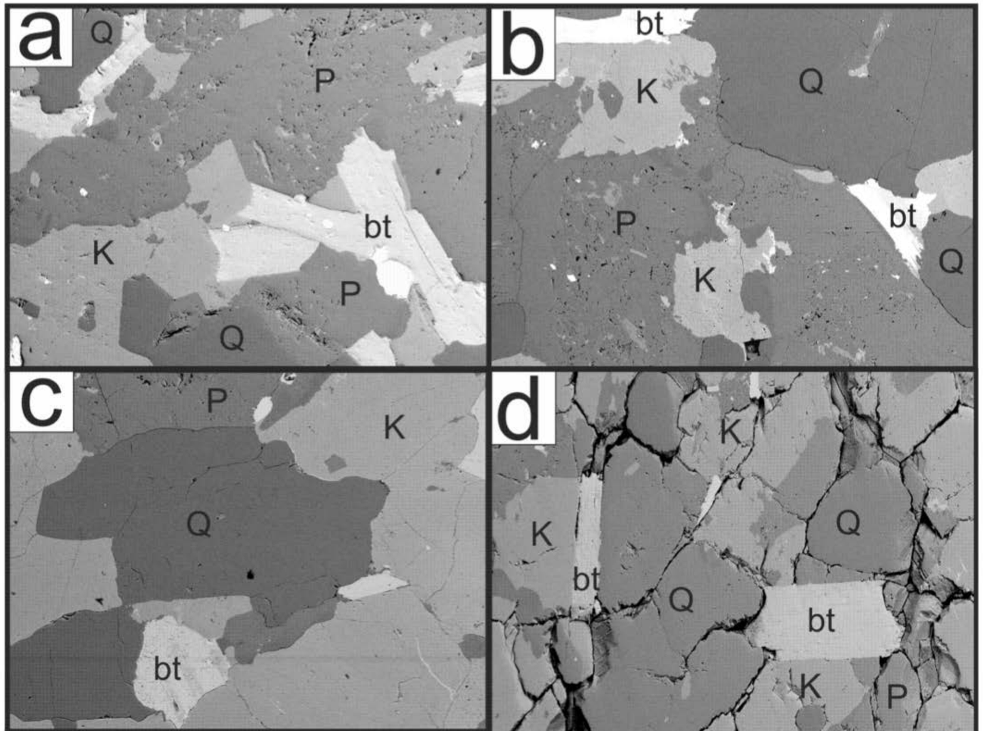
Dyer et al (2010)

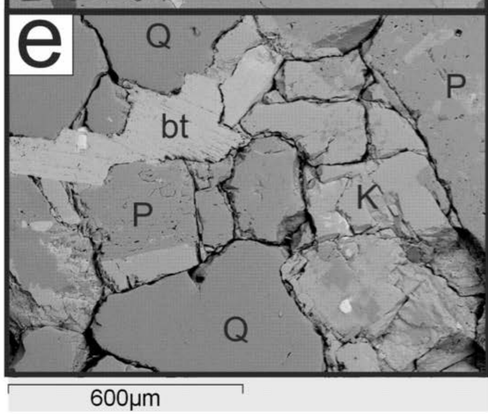
Conclusions

- Fracture damage is predictable for faults in crystalline rock (within bounds)
- Significant permeability and elastic anisotropy can develop with differential stress – this will control where injected fluid goes, but also can be measured
- Permeability development depends on the tectonic environment (stress path)

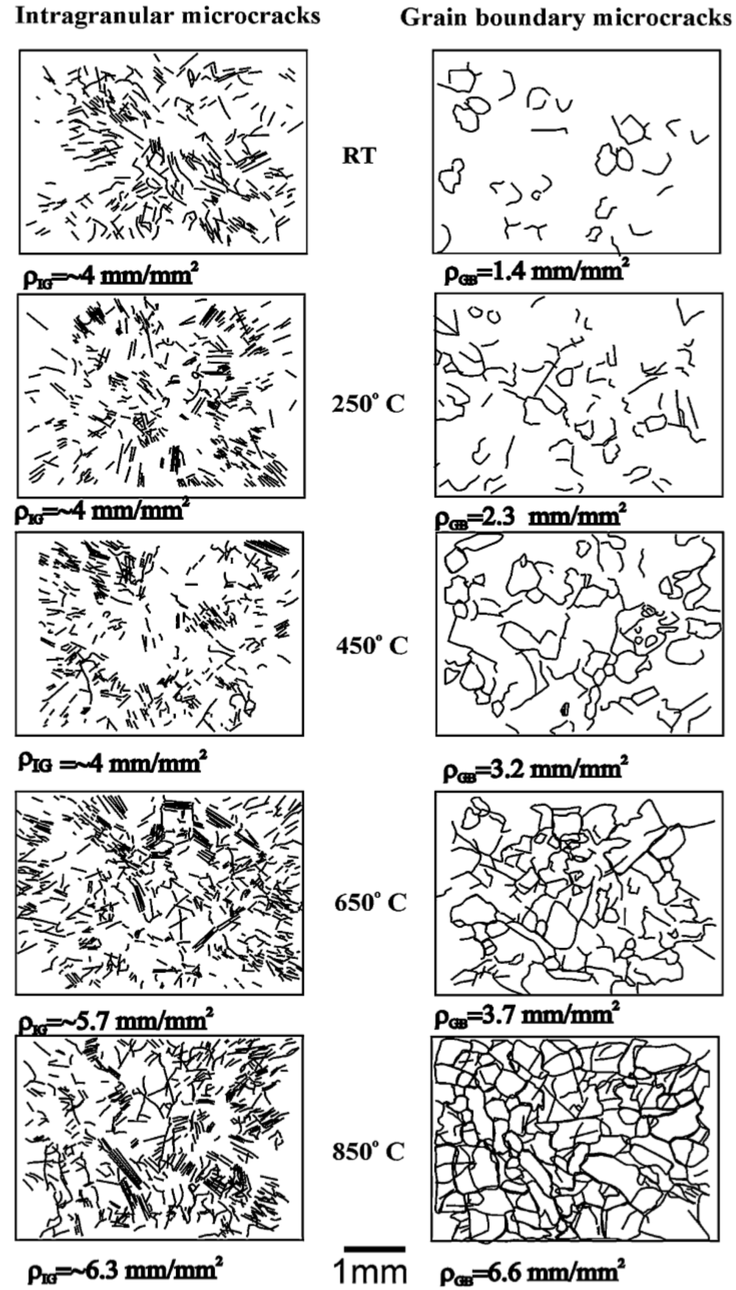
Limitations and future work…

- What is the role of macrofractures?
  - Evans et al. 1995 JGR
  - Nara et al. 2011 Tectonophys.
- Lithology?
- Hydrothermal conditions
  - Morrow et al. 2001 JGR
  - Polak et al. 2003 GRL





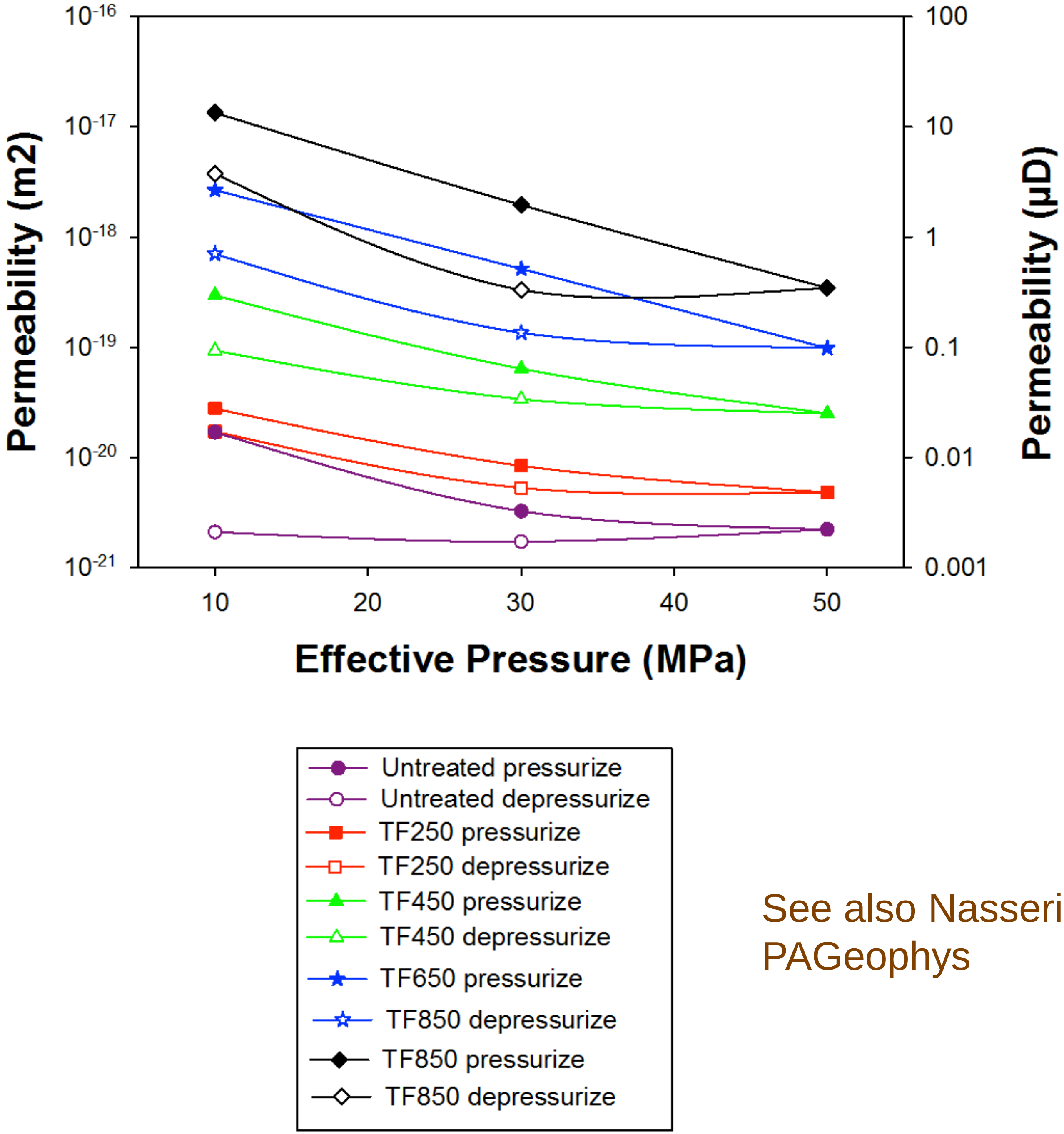
Q = Quartz
P = Plagioclase
K = K-feldspar
bt = Biotite.



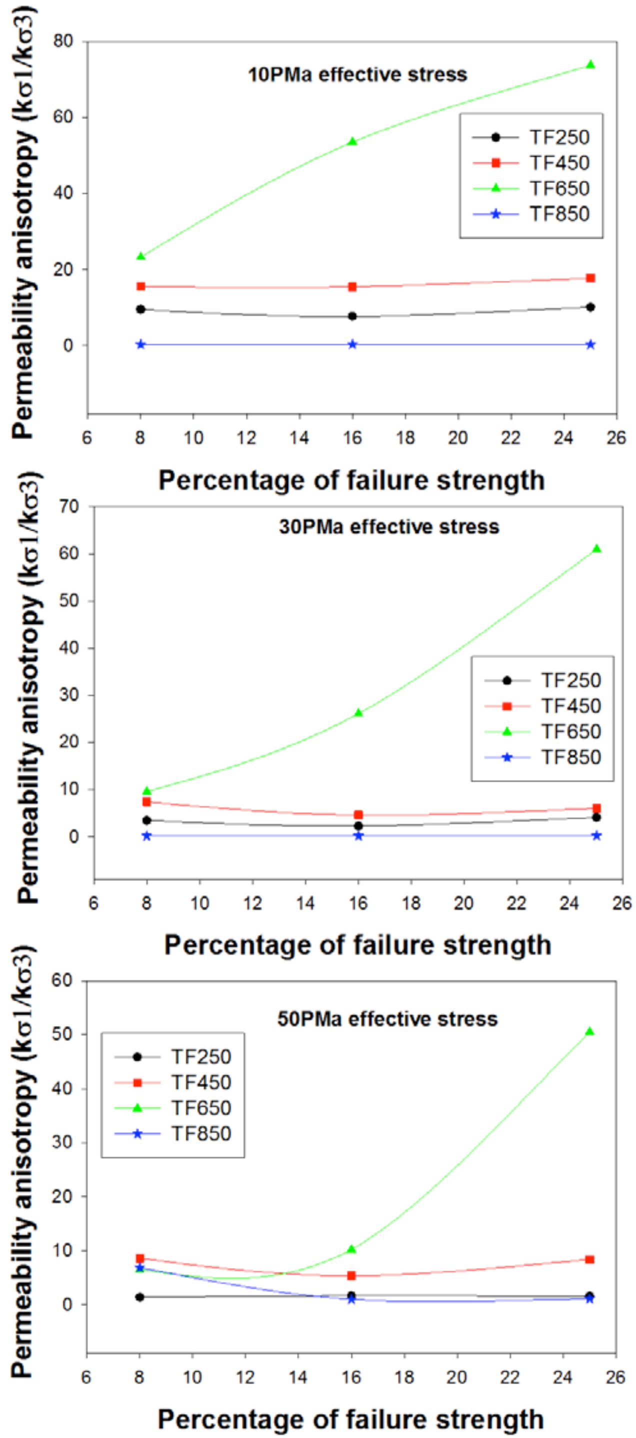
Thermally fractured Westerly granite

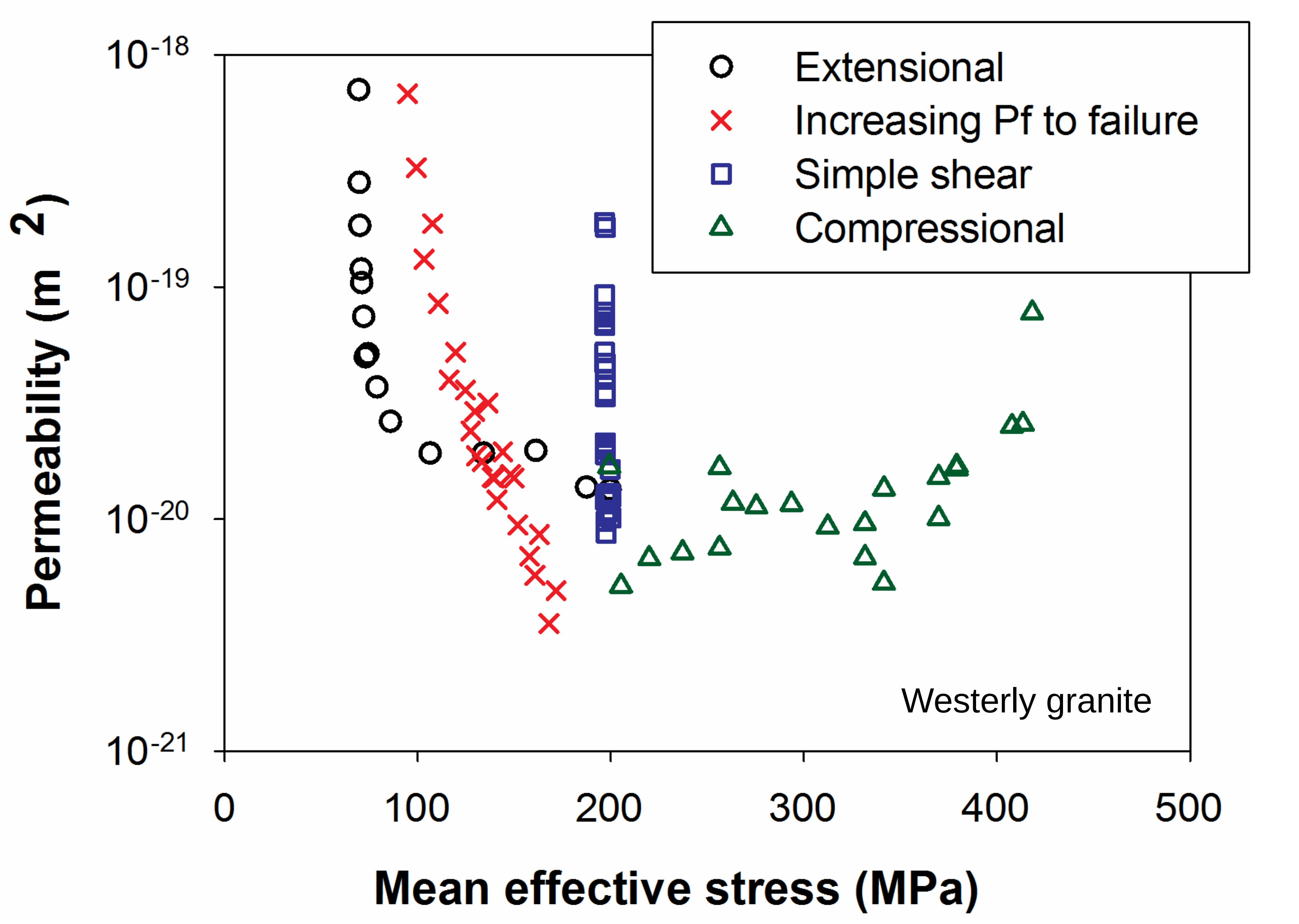
a = room temperature
b = 250°C
c = 450°C
d = 650°C
e = 850°C
Heating rate of 0.25°C per minute under ambient pressure

Nasseri et al. 2009 PAGeophys

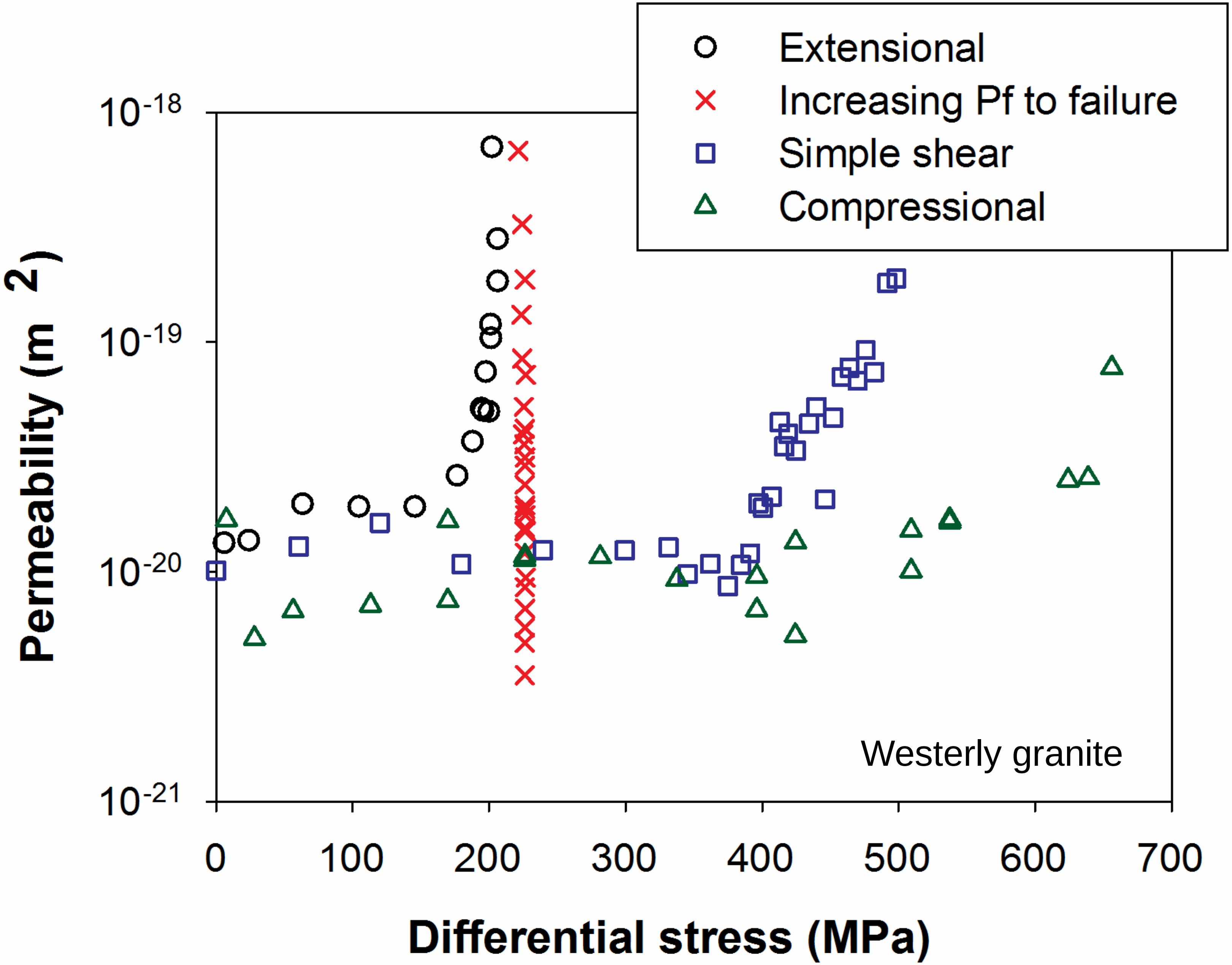


See also Nasseri et al. 2009 PAGeophys

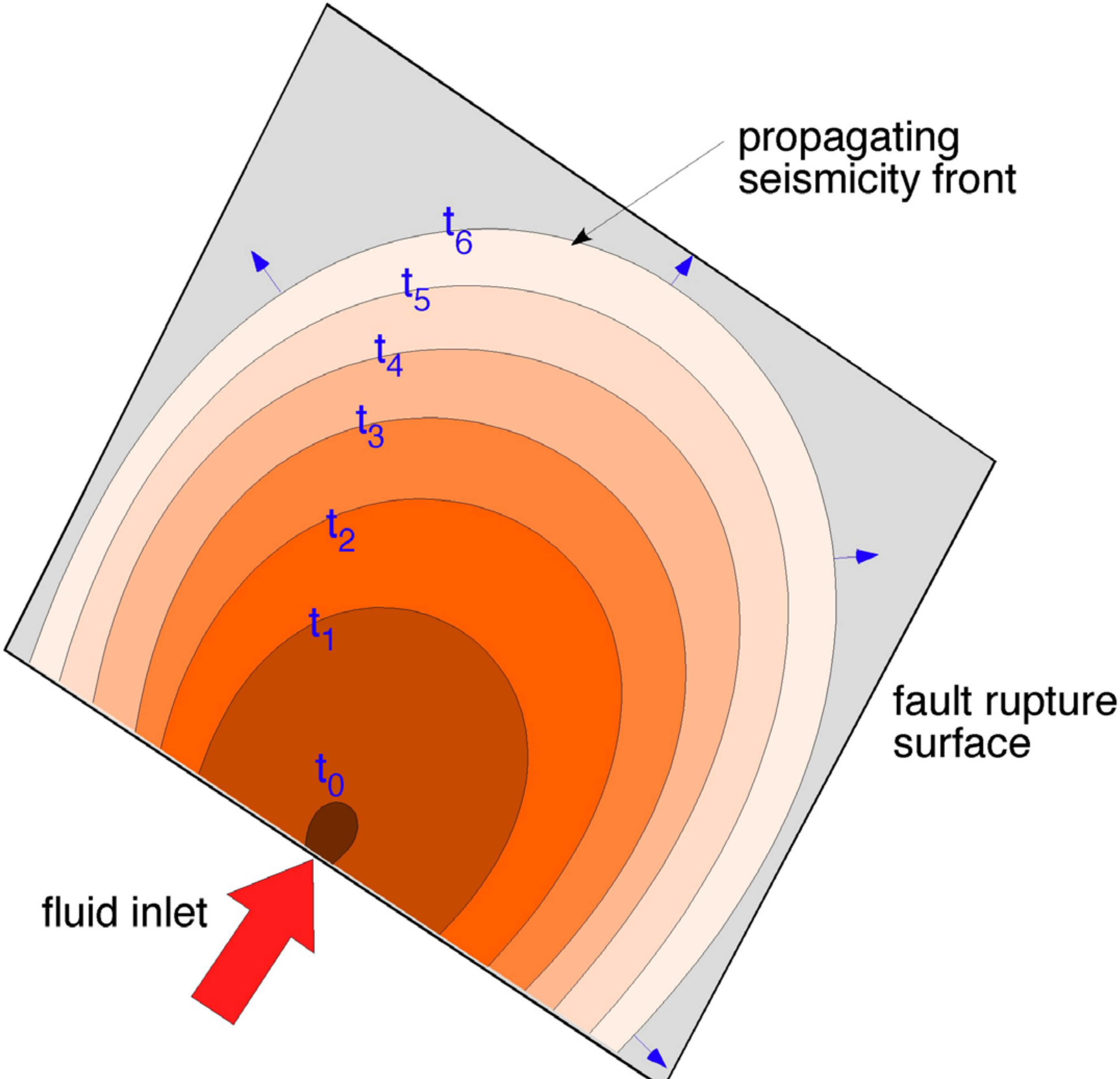

10PMa effective stress
30PMa effective stress
50PMa effective stress
Permeability anisotropy (kσ1/kσ3)
Percentage of failure strength
TF250
TF450
TF650
TF850
80
70
60
50
40
30
20
10
0
6
8
10
12
14
16
18
20
22
24
26



Faulkner and Armitage 2013 EPSL



Faulkner and Armitage 2013 EPSL

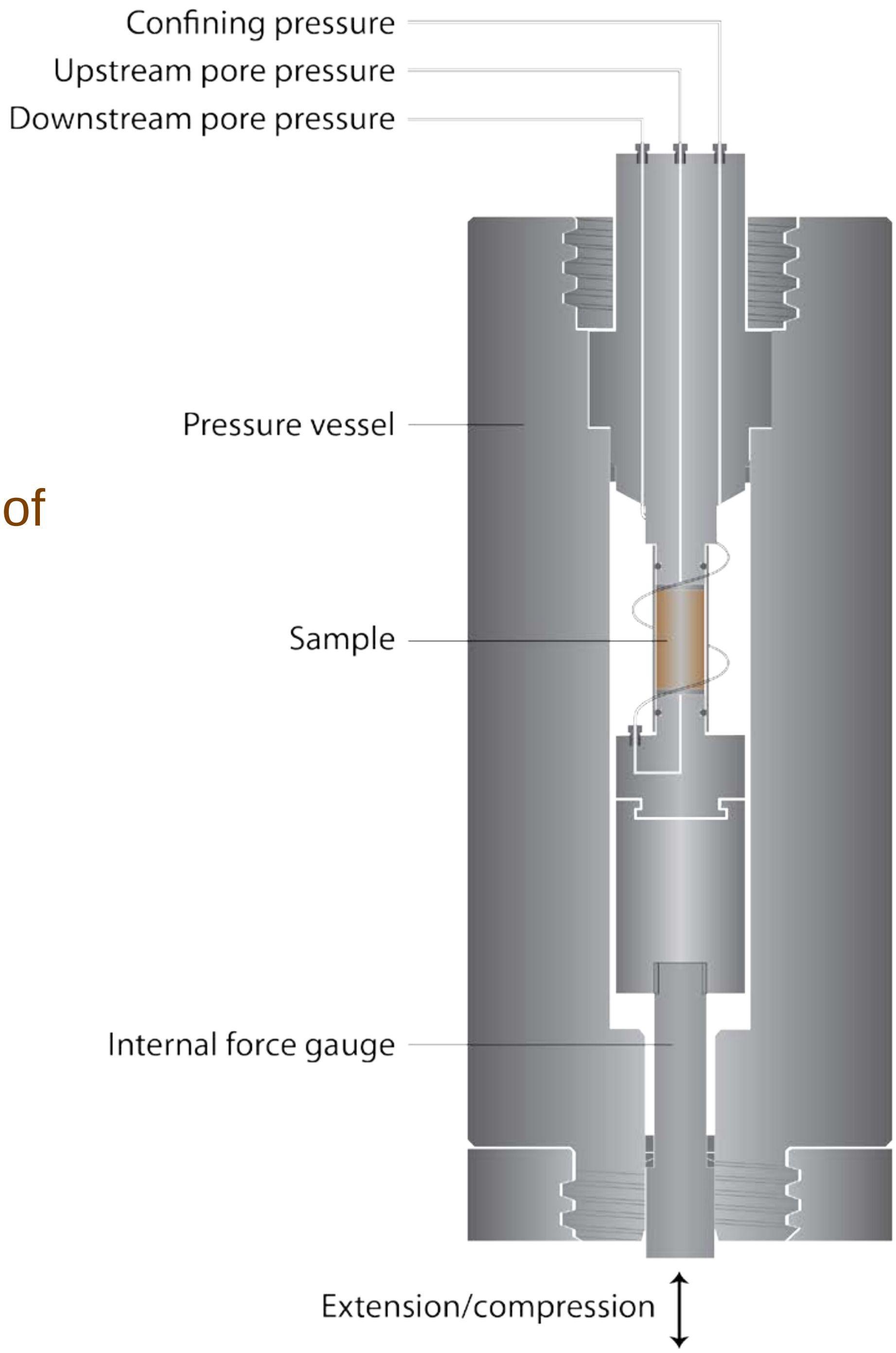

propagating
seismicity front
t_6
t_5
t_4
t_3
t_2
t_1
t_0
fault rupture
surface
fluid inlet

Experiments

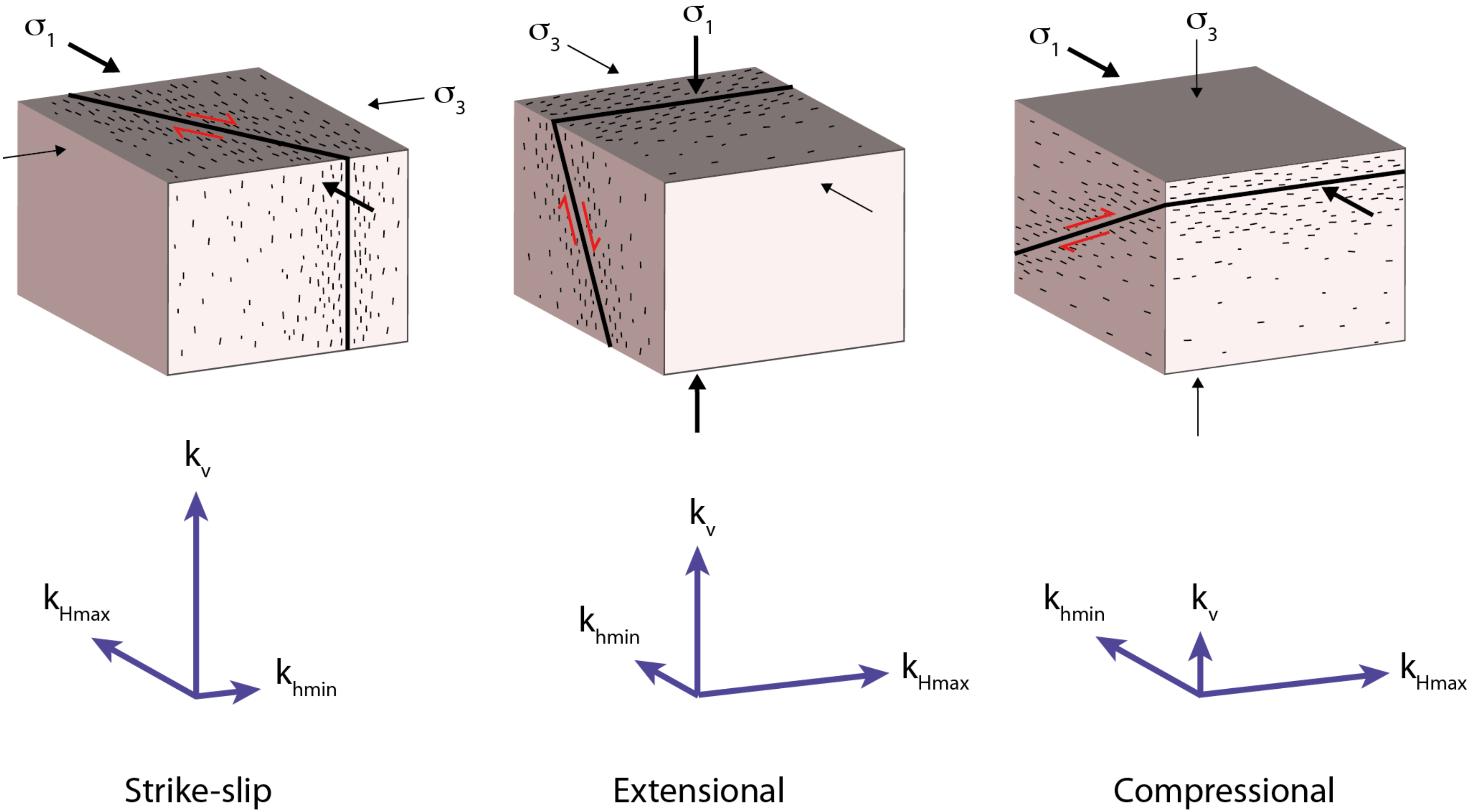
In experiments we typically measure
permeability in the direction of σ_1

e.g. Zoback and Byerlee, 1975
Mitchell and Faulkner, 2008

Is σ_1 the most appropriate direction to measure permeability?



Permeability anisotropy



Faulkner and Armitage 2013 EPSL