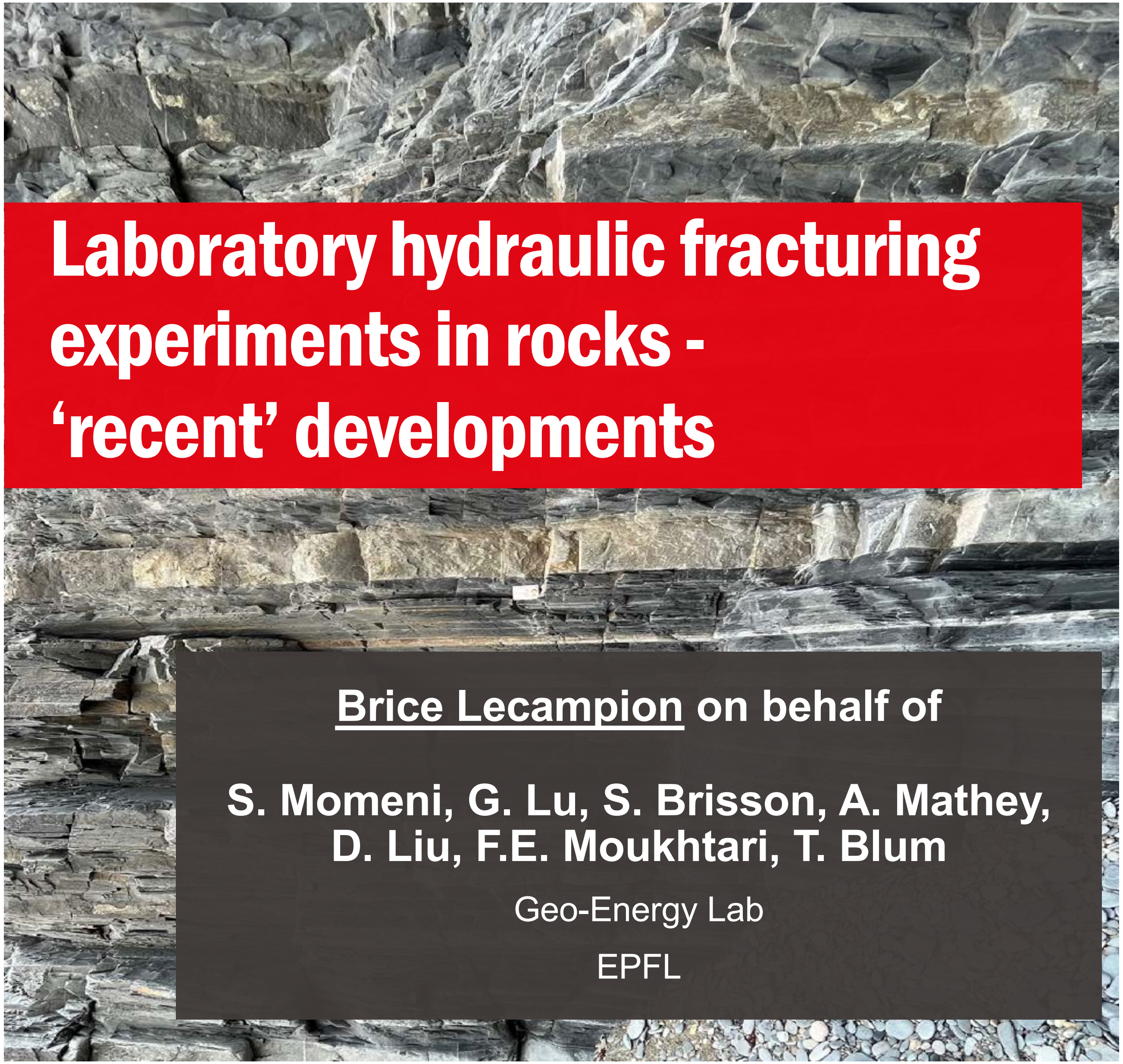


Laboratory hydraulic fracturing experiments in rocks - ‘recent’ developments

Brice Lecampion on behalf of

S. Momeni, G. Lu, S. Brisson, A. Mathey, D. Liu, F.E. Moukhtari, T. Blum

Geo-Energy Lab

EPFL

EPFL

GeoEnergyLab

gaz nat

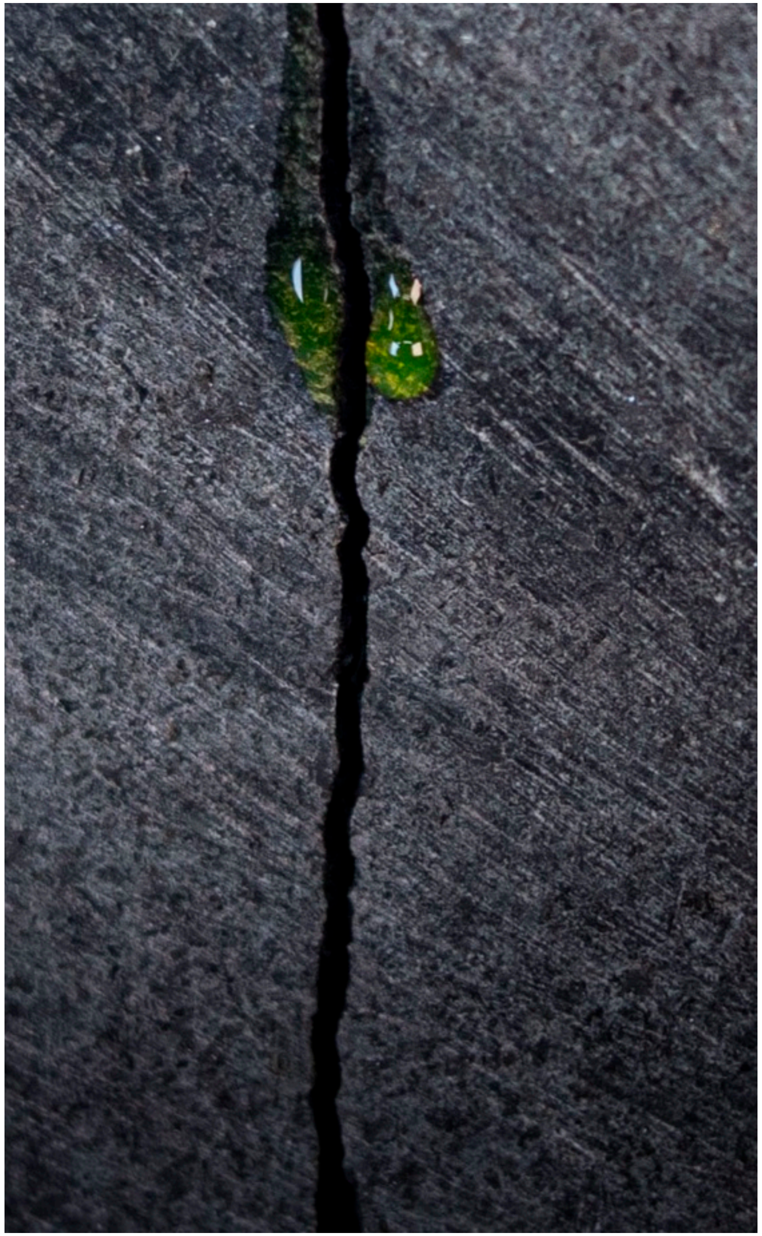
Swiss National Science Foundation

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Bundesamt für Energie BFE
Office fédéral de l’énergie OFEN

ARMA 2025
Santa Fe, June 8, 2025

EPFL



Value of large block HF experiments ?

- Validate / invalidate theory

  Hubert & Willis (1957), Haimson & Fairhust (1969), Daneshy (1973), Warpinski & Teufel (1987), El-Raaba (1987), Weijers & de Pater (1992, 99), Jeffrey & Bunger (2007, 2009), Bunger *et al.* (2008, 2013), Xing *et al* (2017), Lu *et al* (2024) …

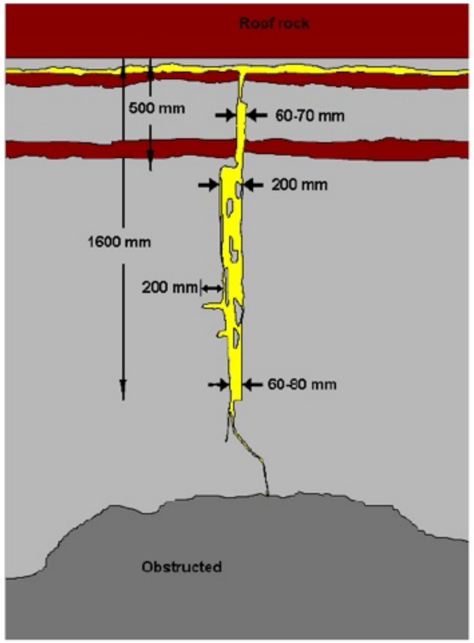
- Explore Hydraulic Fracturing behavior
  - In a particular rock
  - Under specific conditions

- Re-assure stakeholders

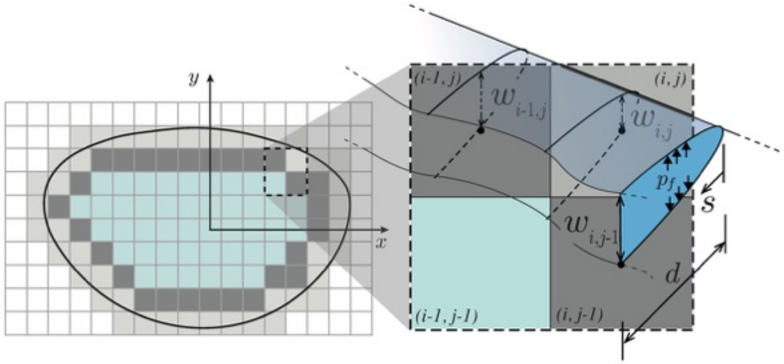
- Lab experiments

- In-situ observations

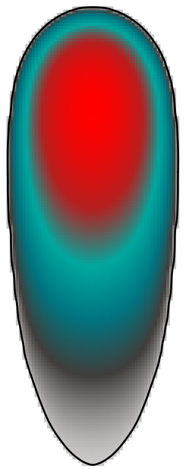
Elder (1977), Warpinski (1985),
Warpinski & Teufel (1987),
Jeffrey *et al.* (1992),
M-site (1990s)
Jeffrey *et al* (2009)
HF Test site
EGS Collab
Utah Forge
…



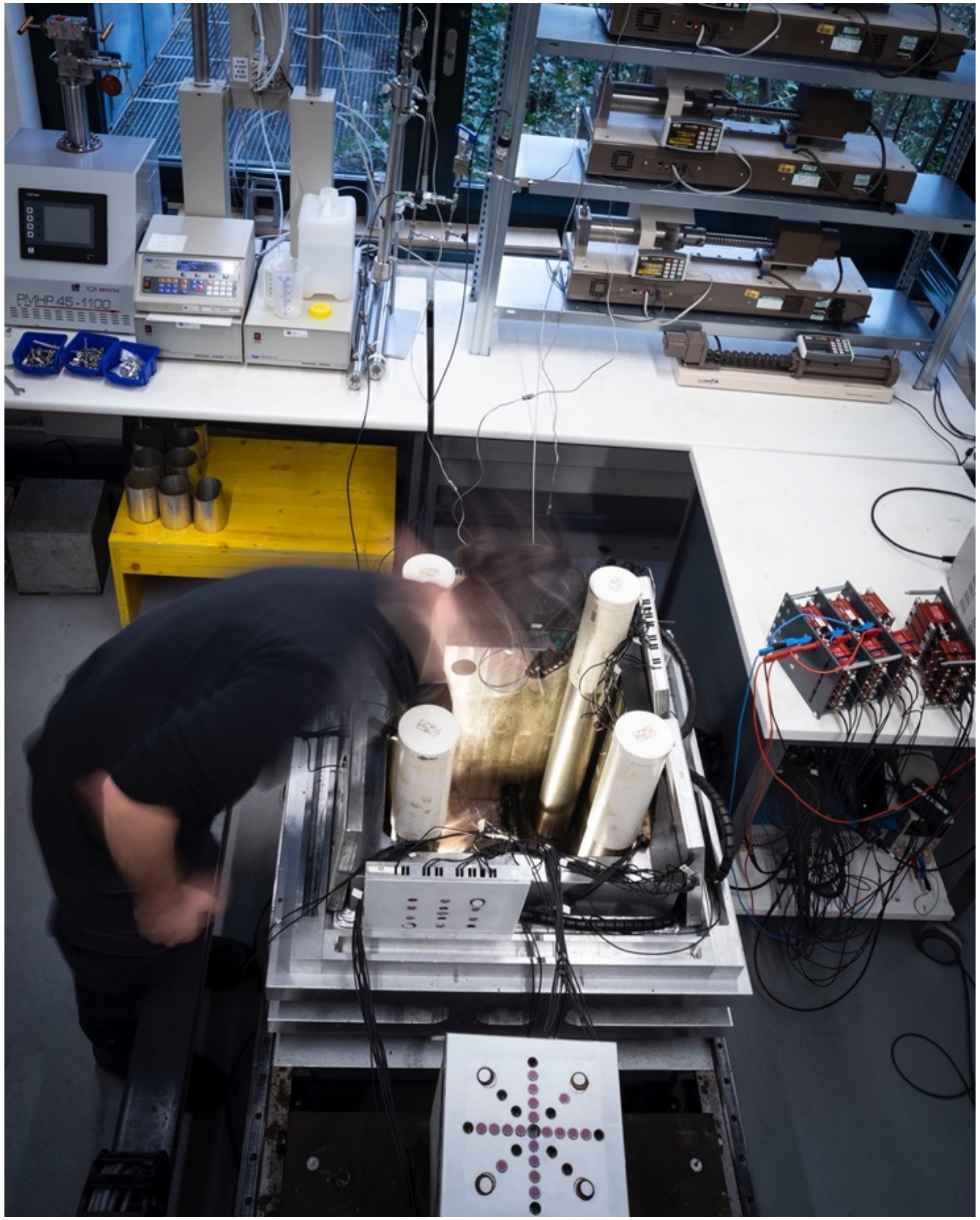
- Theoretical / numerical modeling



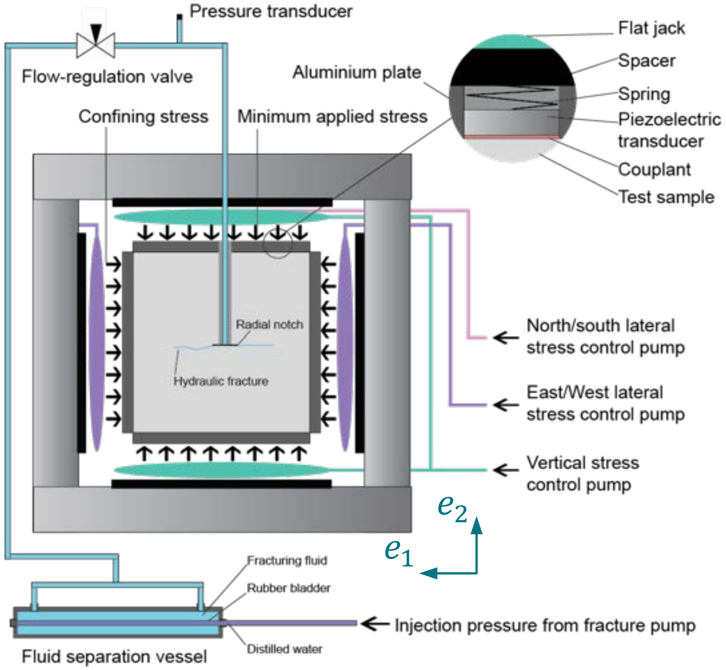
Kristianovic & zheltov (1955),Geerstma & de Klerk (1969), Nordgren (1972), Simonson et al (1978), Nolte & Smith (1981), Spence & Sharp (1983), Lister (1991), SCR (1993) …

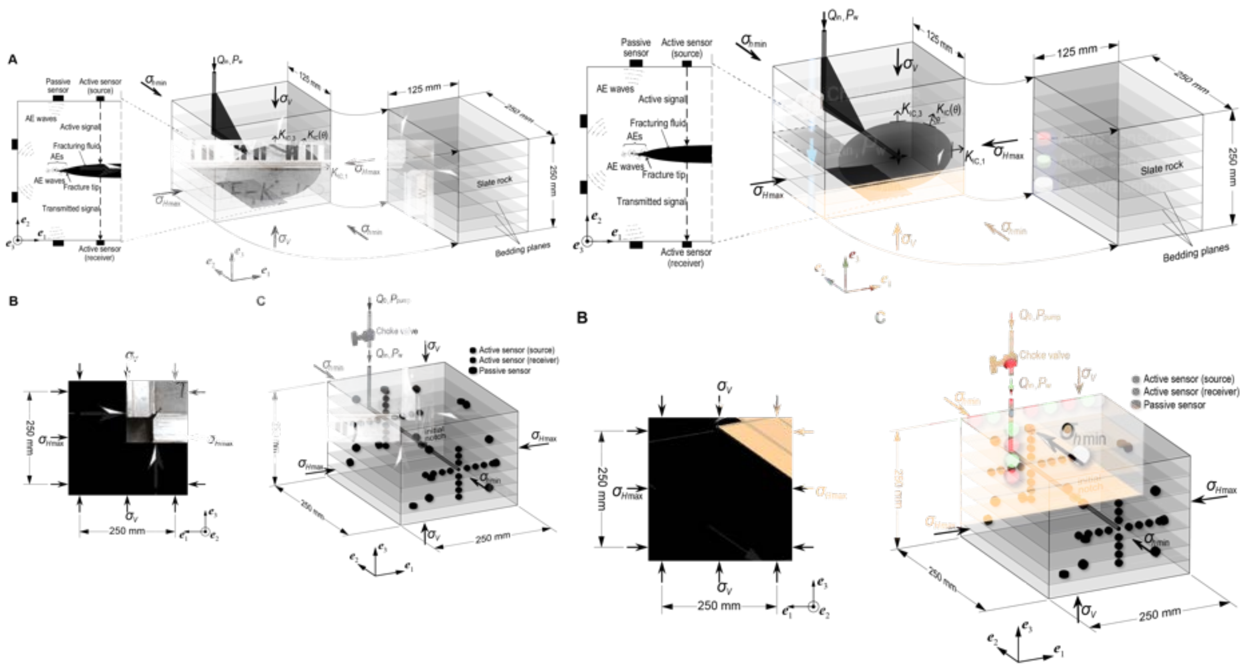


In the lab, we *can* control



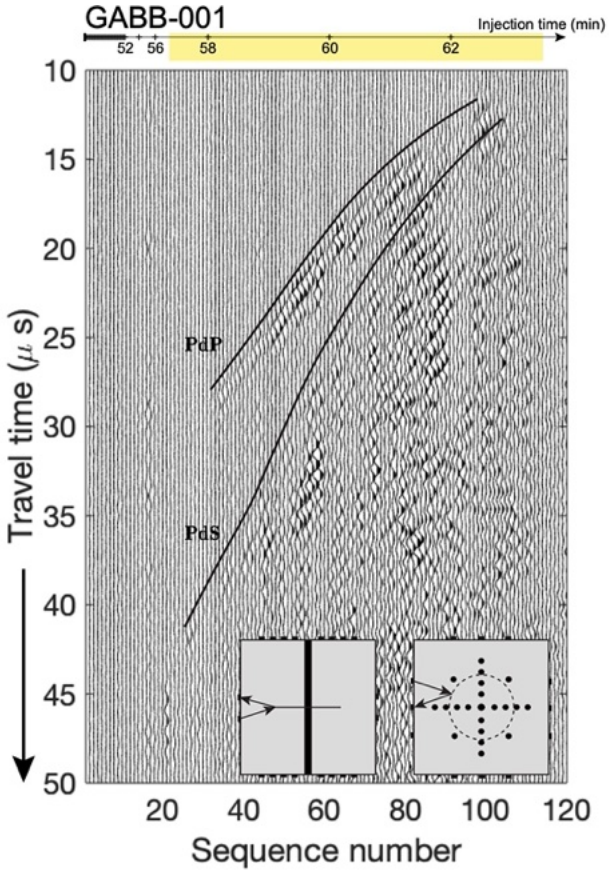
Experimental setup at EPFL





- 3 axis with separate confining stresses (0 - 20MPa)
- 250×250×250 mm blocks, completion with radial notch, epoxied well
- Acoustic monitoring: 16 passive acoustic sensors & 32 active acoustic sensor pairs

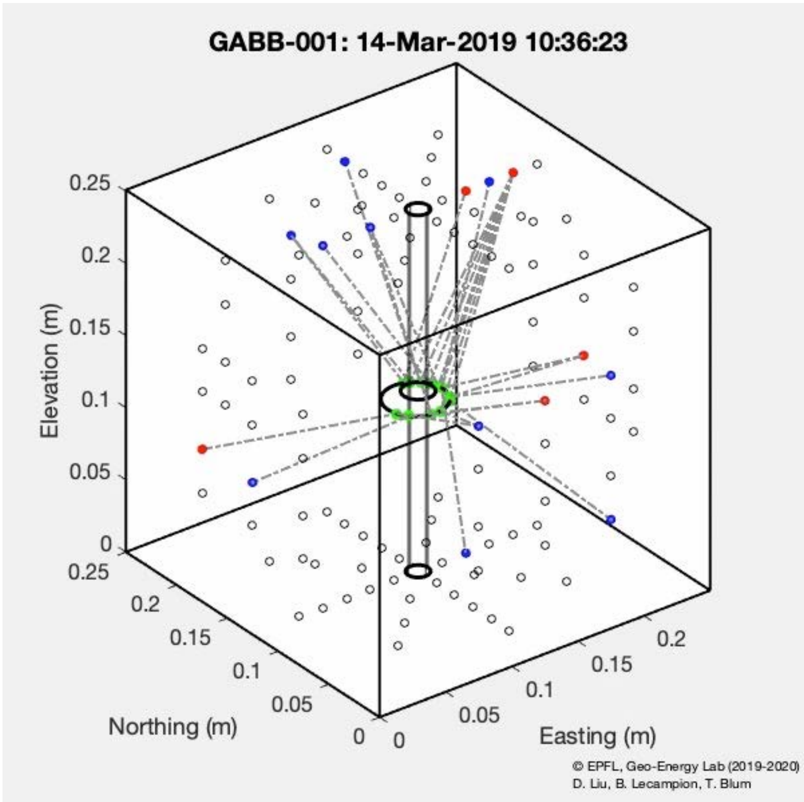
Fracture front evolution from diffracted waves



Experimental time

Different diffracted waves pattern in GABB-001

Toughness dominated HF in gabbro



Source

Receiver

Groenenboom (1998-2000)
D. Liu *et al. Geophys. J. Int.* (2020)
D. Liu & BL, *J. Geophys. Res.* (2022)

B. Lecampion

Passive acoustic monitoring

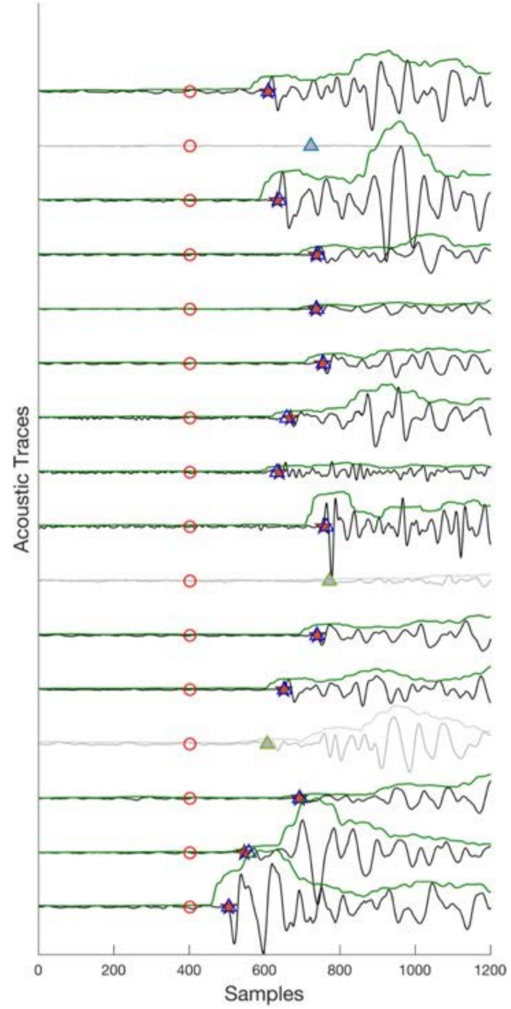
16 passive sensors

- 150kHz central frequency / now all broadband (25-500kHz)
- Continuous recording @ 10Mhz

Semi-automated processing

S. Momeni *et al*, (2022, 2023, 2024)

Simorgh



What is needed to perform a ‘good’ HF experiment ?

1. Have a properly defined question

2. Understand hydraulic fracturing scaling (& its restrictions)

   Detournay (2004, 2016), Bunger *et al.* (2005), Lecampion *et al.* (2017)

3. Have accurate and robust experimental facility & protocol

4. Use precise measurements to monitor fracture growth

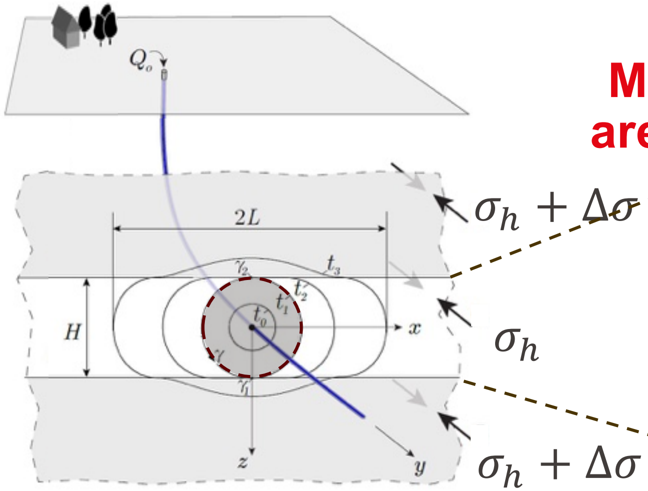
   Medlin & Masse (1984), Groenenboom et al. (1996-99), Bunger (2006), Rodriguez *et al* (2017), Hampton et al. (2013-17)…

5. Be resilient & tenacious

Some questions that we have investigated / are exploring

- Effect of the pervasive nature of rock anisotropy on HF growth
- Scale dependence of fracture energy / quasi-brittle failure
- HF growth in permeable rocks (leak-off, poroelasticity …)
- HF closure
- Fluid-induced fault slip

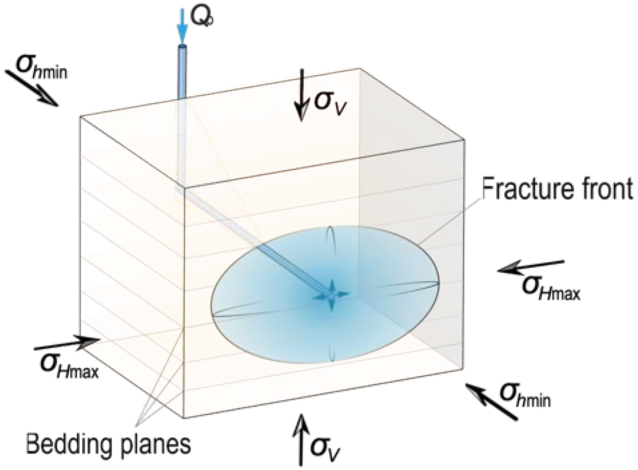
Fracture containment in anisotropic rocks



Modified from Peruzzo (2024)

Most sedimentary rocks are transversely isotropic

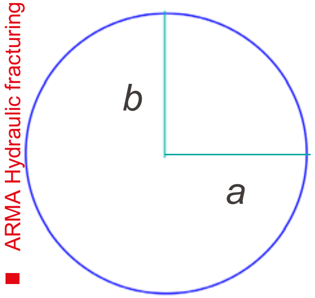
Shale outcrop

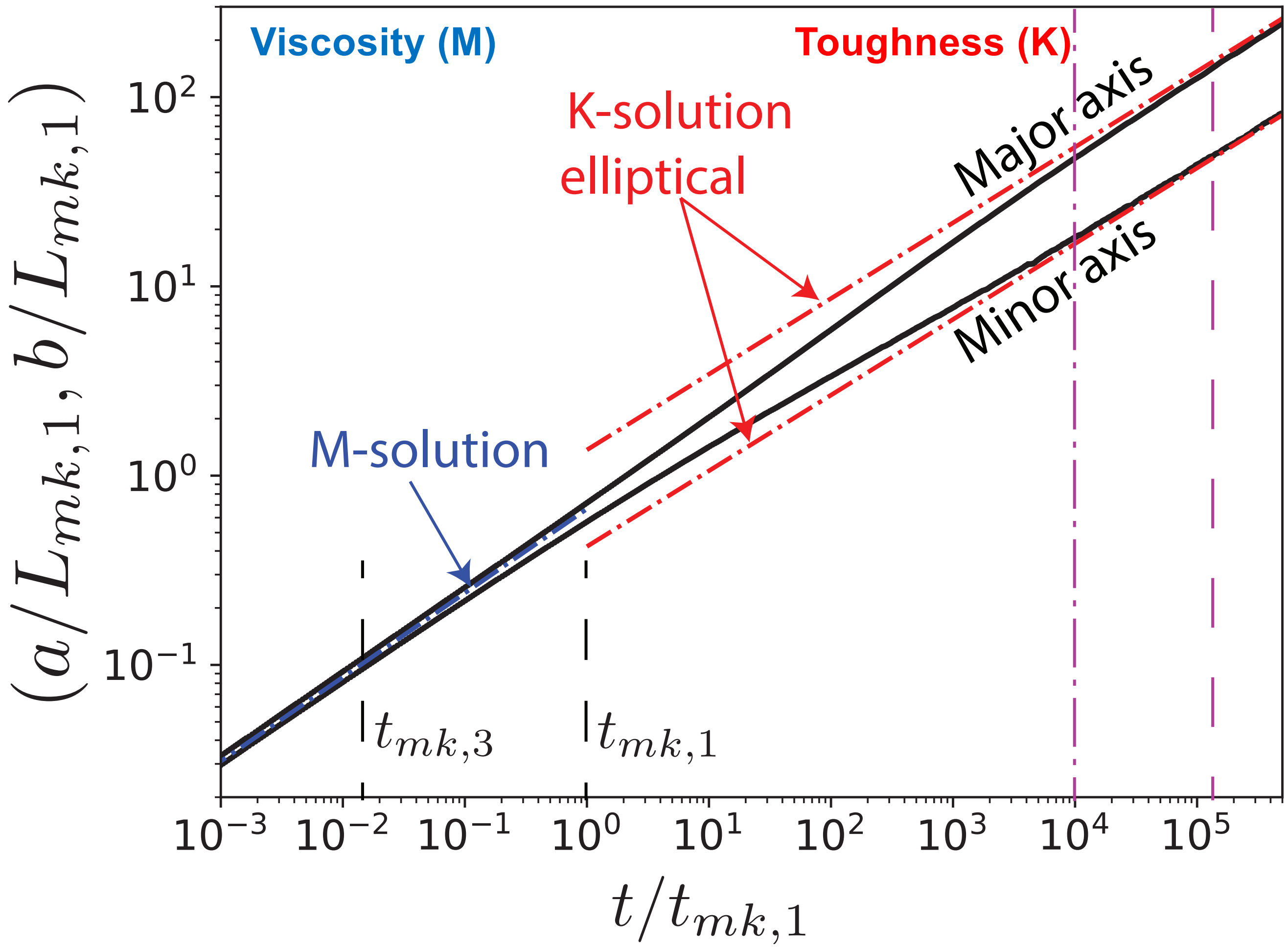


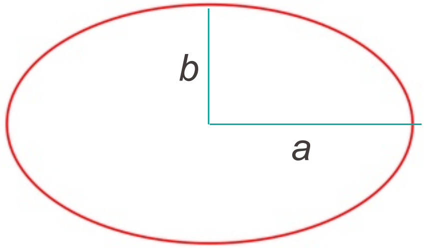
EPFL

From radial (M) to elongated (K)

TI elasticity & toughness

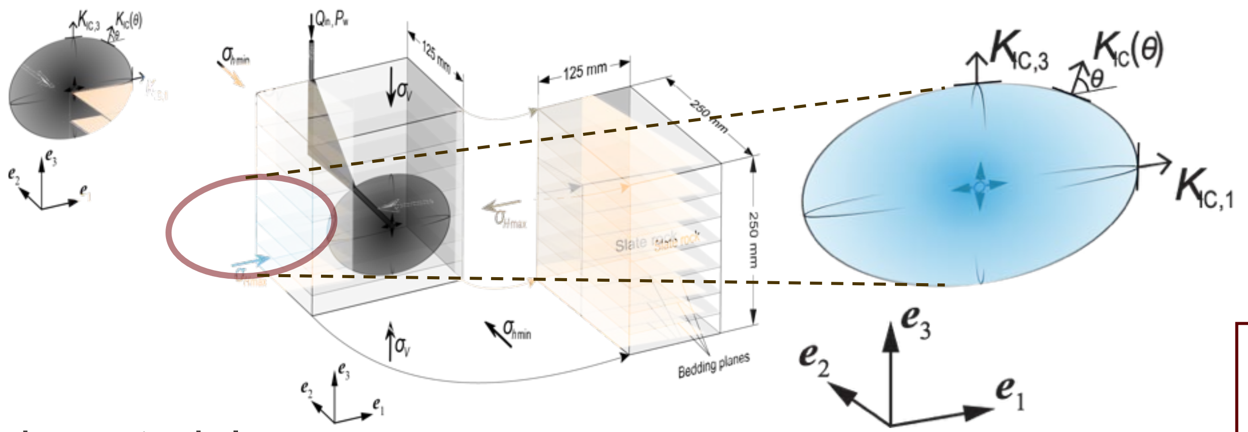






Dontsov (2019)
Moukhtari *et al.* (2020)

Rock anisotropy



- Isotropic materials:

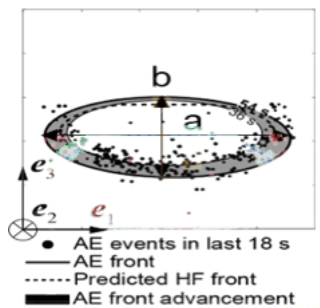
$$G = K_I^2/E$$

- Transversely isotropic materials:

$$G = K_I^2(\theta)/E(\theta) \begin{cases} K_{Ic,1} \le K_{Ic}(\theta) \le K_{Ic,3} \\ E_1' \ge E'(\theta) \ge E_3' \end{cases}$$

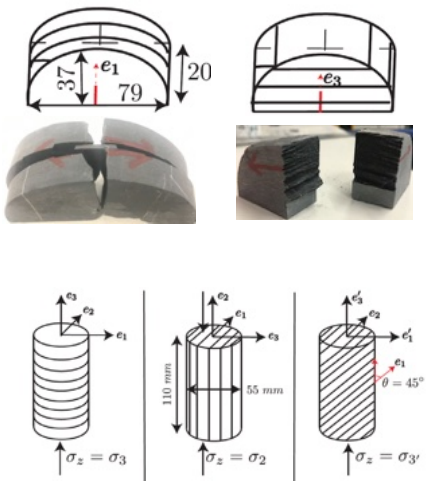
$$\Rightarrow \quad G_{c,1} \le G_c(\theta) \le G_{c,3}$$

K_{Ic}: fracture toughness; E': plane-strain elastic modulus.



$$a/b = \left(\frac{K_{Ic,3} \cdot E_1'}{K_{Ic,1} \cdot E_3'}\right)^2$$

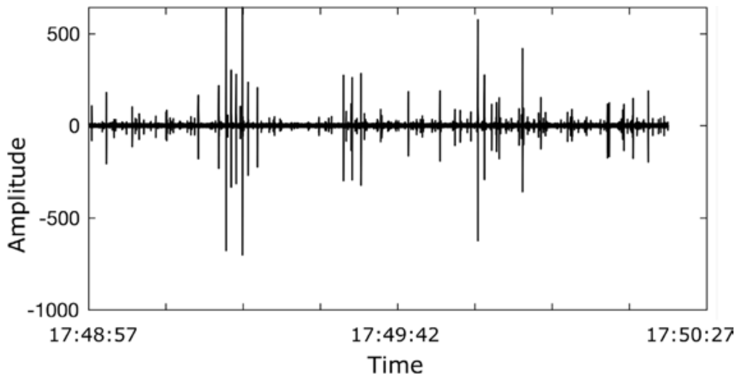
$K_{Ic,1} = 2.5\ \mathrm{MPa}\sqrt{\mathrm{m}}$;
$K_{Ic,3} = 3.5\ \mathrm{MPa}\sqrt{\mathrm{m}}$

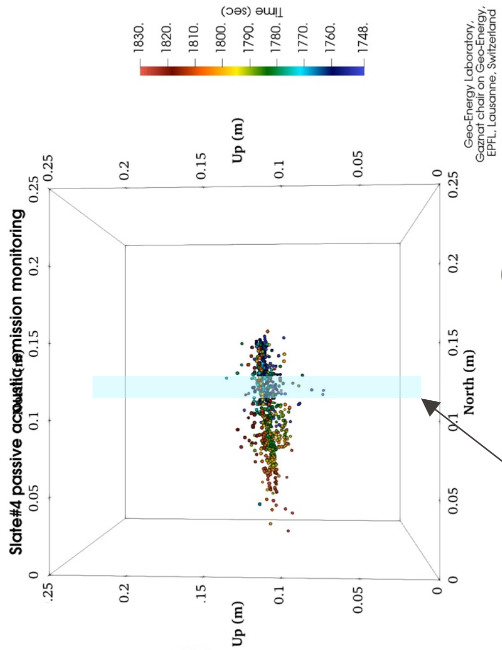


Moukhtari *et al.* (2020). *JMPS*

Lu *et al.* (2024). *JGR Solid Earth*

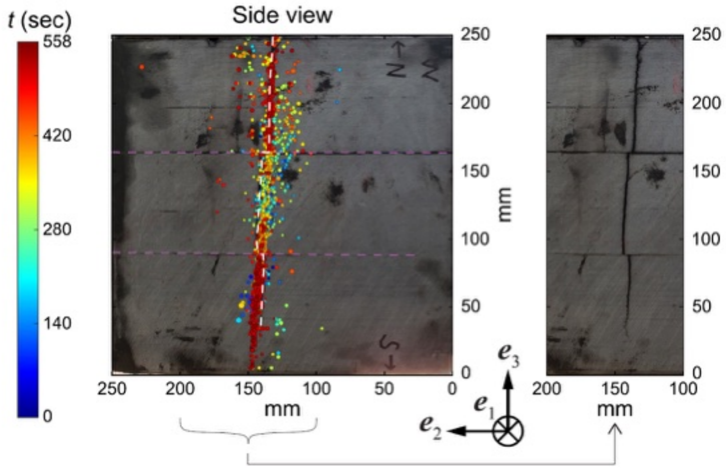
Acoustic emission





Acoustic emission (AE) event location

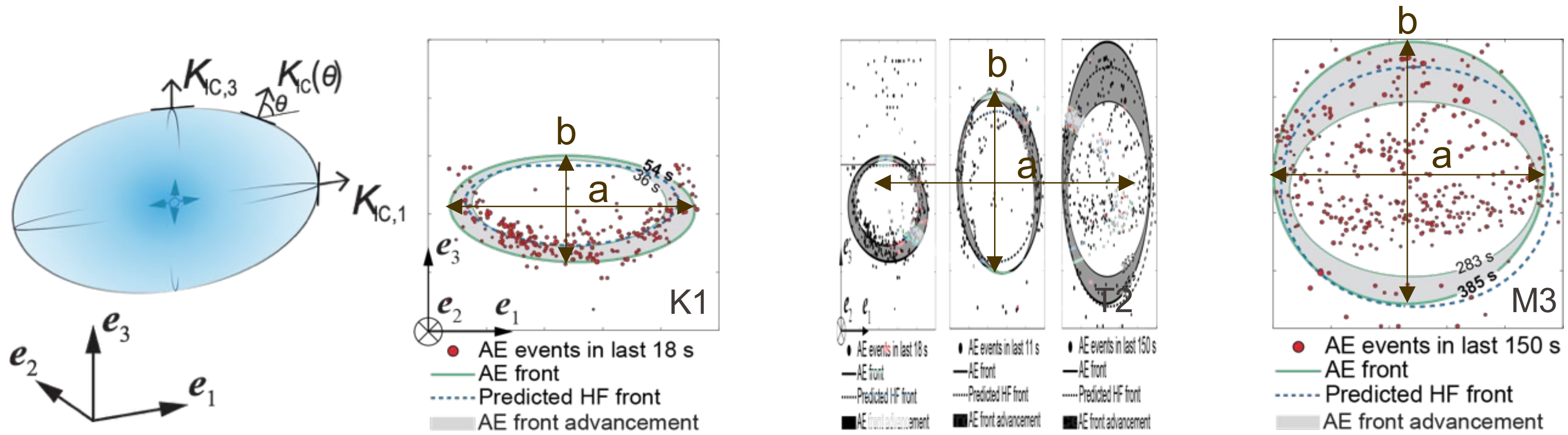
Wellbore



Simorgh

Momeni, *et al.* (2021, 2022, 2023)
Lu *et al*. (2024). *JGR Solid Earth*;

Hydraulic fracture elongation



$$a/b = \left(\frac{K_{\mathrm{Ic},3} \cdot E_1'}{K_{\mathrm{Ic},1} \cdot E_3'}\right)^2 \approx 2.4$$

$$(a/b)_{\mathrm{K1}} > (a/b)_{\mathrm{T2}} > (a/b)_{\mathrm{M3}}$$

Lu et al. (2024). *JGR Solid Earth*

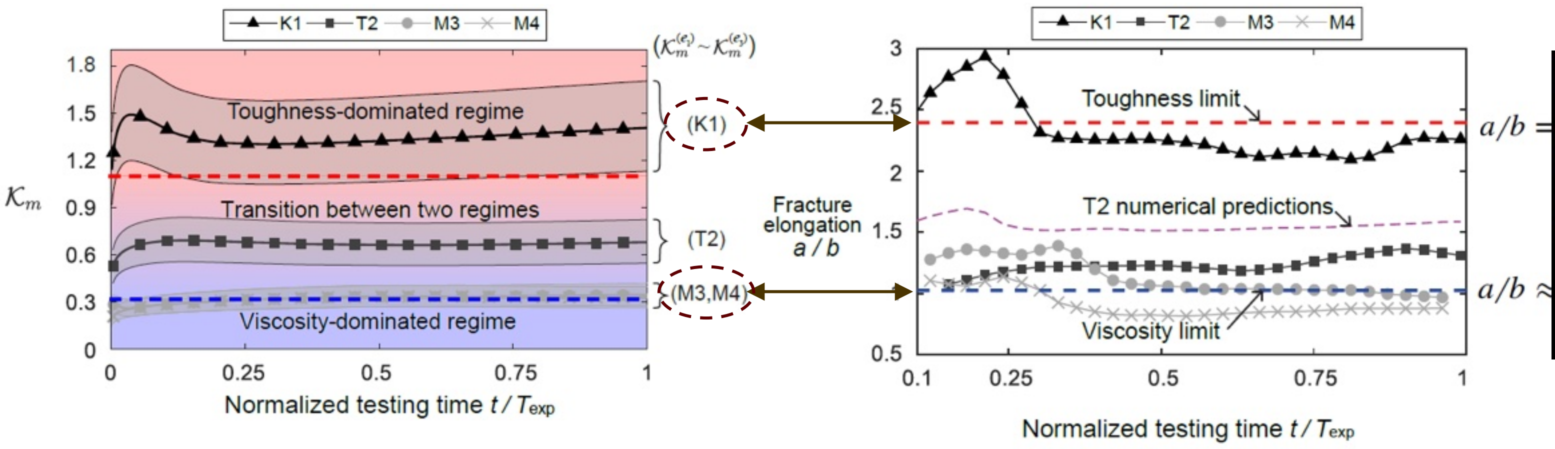
Viscous vs toughness dominated growth regimes

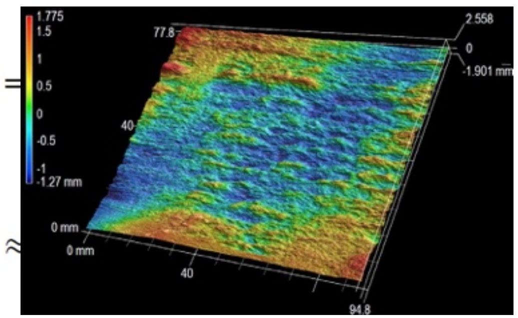
$$\mathcal{K}_m(t) = \frac{K_{\text{Ic}} t^{5/18}}{E'^{13/18} \mu'^{5/18} V_{\text{in}}(t)^{1/6}}$$

Savitski & Detournay, (2002)
Garagash, (2009)

$\mathcal{K}_m$: 0.32, 1.1

Viscosity-dominated | Transition | Toughness-dominated



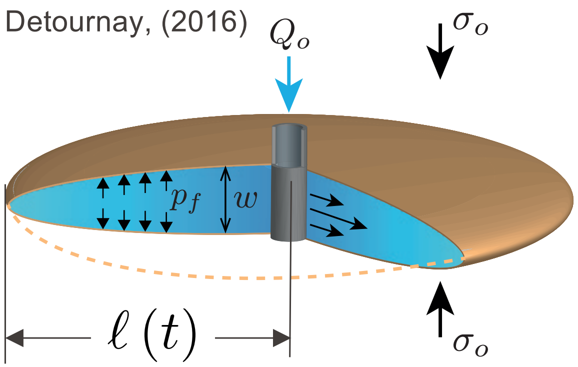


K_{Ic}: average fracture toughness; E': average plane-strain elastic modulus; μ: dynamic fluid viscosity; V_{in}: injection volume.

Lu et al. (2024). *JGR Solid Earth*

HF energy budget

Detournay, (2016)



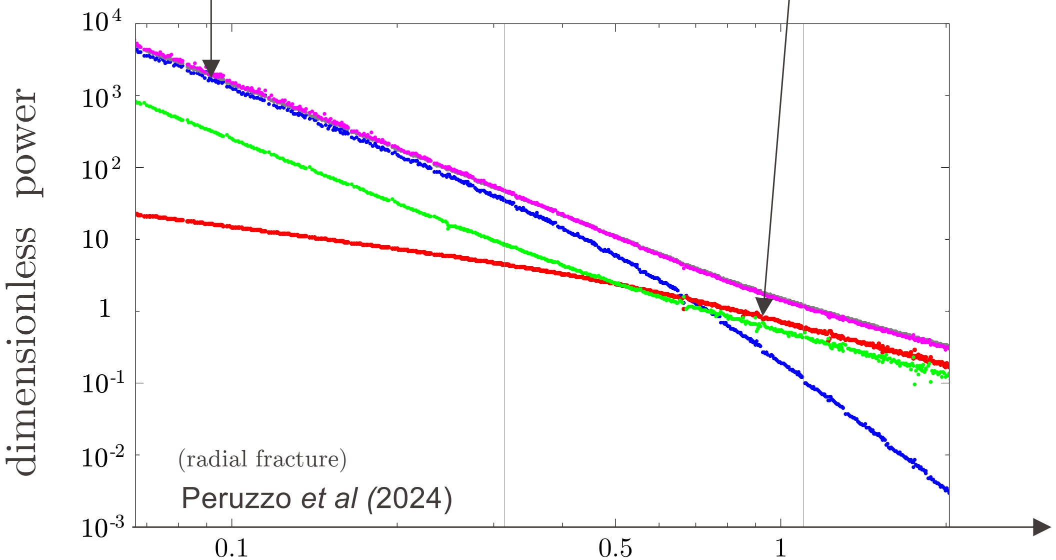
$$\mathcal{K}_m(t) = K_{Ic}\frac{t^{1/9}}{E'^{13/18}\mu'^{5/18}Q_o^{1/6}}$$

$$\propto \frac{\text{fracture en. dissipation}}{\text{viscous en. dissipation}}$$

$$\mathcal{K}(t) > 1 \rightarrow \text{"K or K-regime"}$$

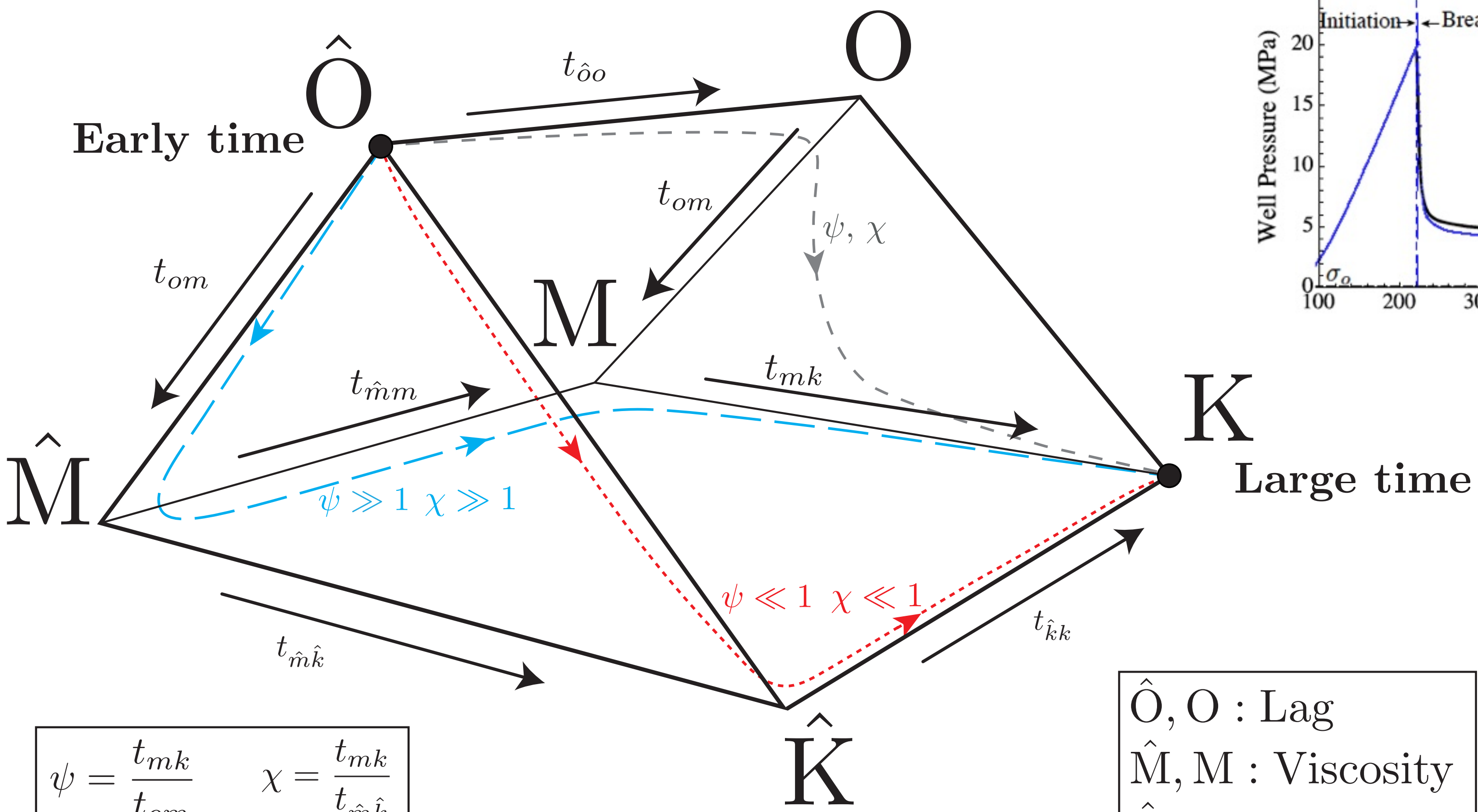
$$\mathcal{K}(t) < 1 \rightarrow \text{"M or M-regime"}$$

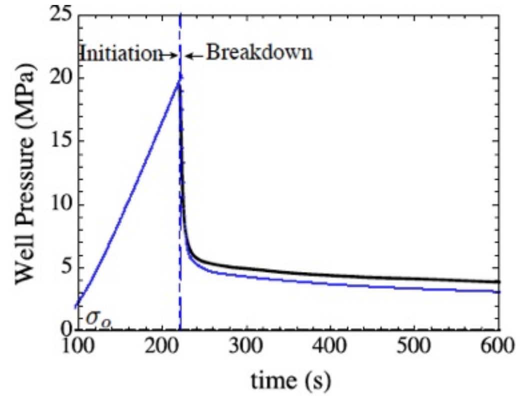
$$\overbrace{\underbrace{12\mu\int_{\partial\Omega_F}\frac{\mathbf{v}^2}{w}\mathrm{d}s}_{\text{dissipated by viscous fluid flow}} + \underbrace{\int_{\partial\Omega_{F-S}}\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{1}{2}w\,p\right)\mathrm{d}s}_{\text{stored as elastic deformation of the solid medium}} + \underbrace{\int_{\Gamma}G_c\mathbf{v}\,\mathbf{n}\mathrm{d}\gamma}_{\text{dissipated to create new fracture surfaces}}}^{\text{Internal power}} = \underbrace{Q_o p_o}_{\text{External power}}$$



$$\mathcal{K}(t) = K_{Ic}\frac{t^{1/9}}{E'^{13/18}\mu'^{5/18}Q_o^{1/6}}$$

On the importance of scaling for lab exp.



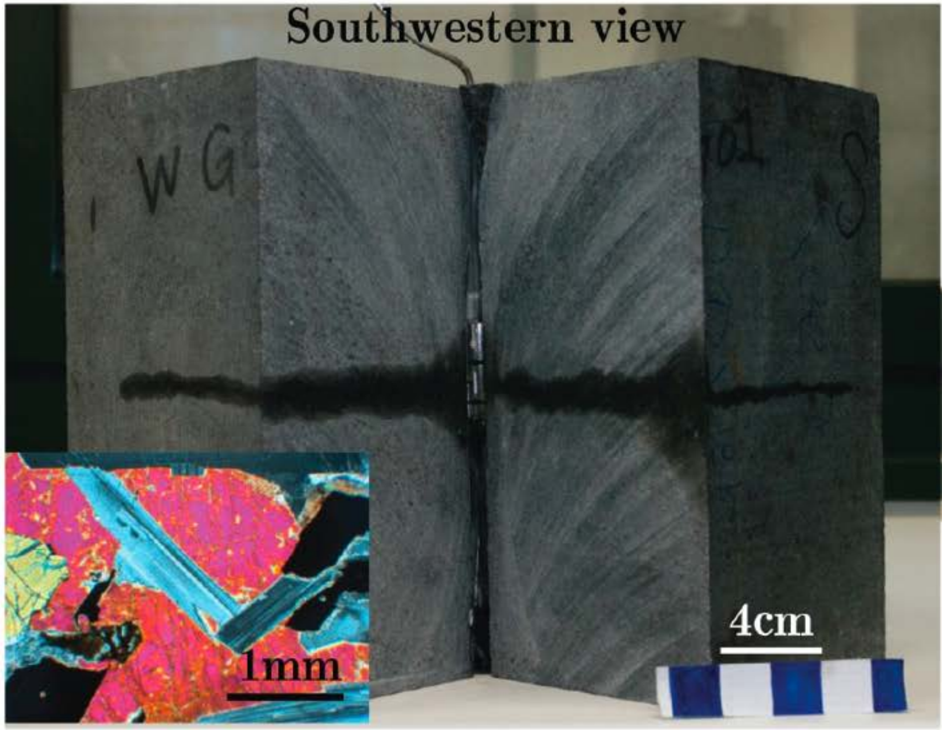


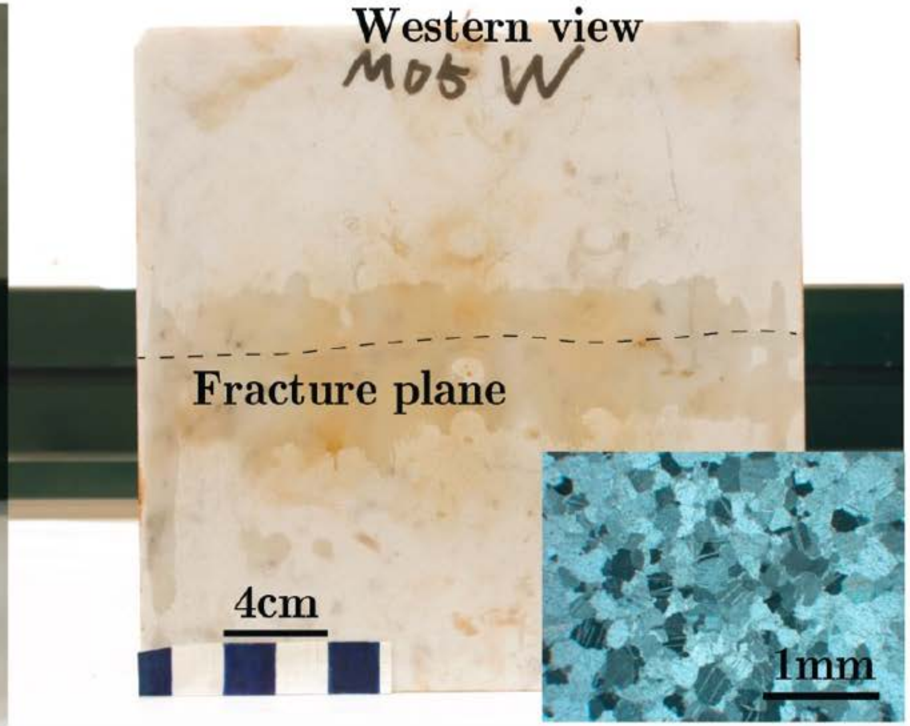
$$\psi = \frac{t_{mk}}{t_{om}} \qquad \chi = \frac{t_{mk}}{t_{\hat{m}\hat{k}}}$$

$\hat{\mathrm{O}}, \mathrm{O}$: Lag
$\hat{\mathrm{M}}, \mathrm{M}$: Viscosity
$\hat{\mathrm{K}}, \mathrm{K}$: Toughness

Lecampion *et al* (2017)

Separability of scales ?

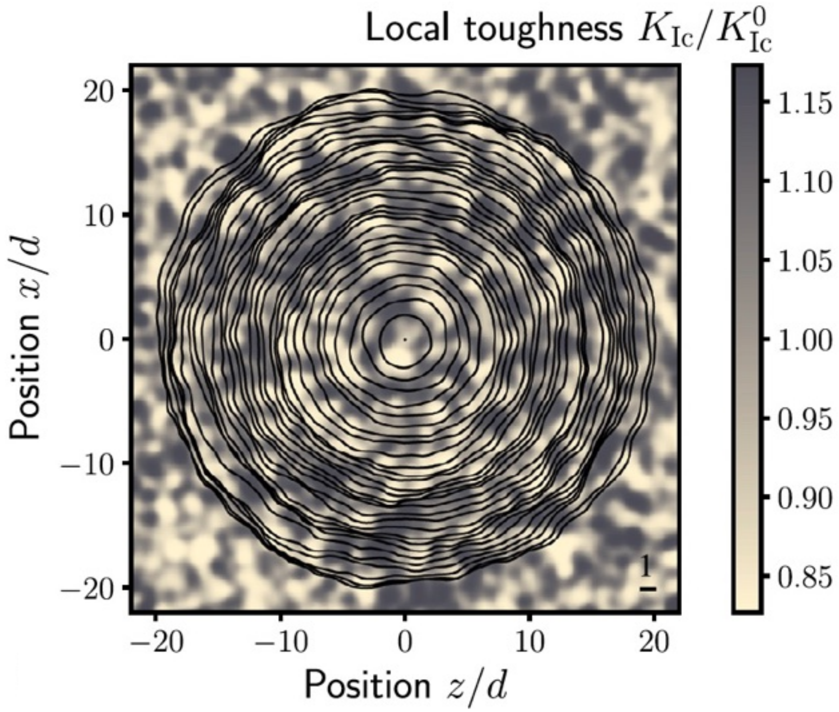




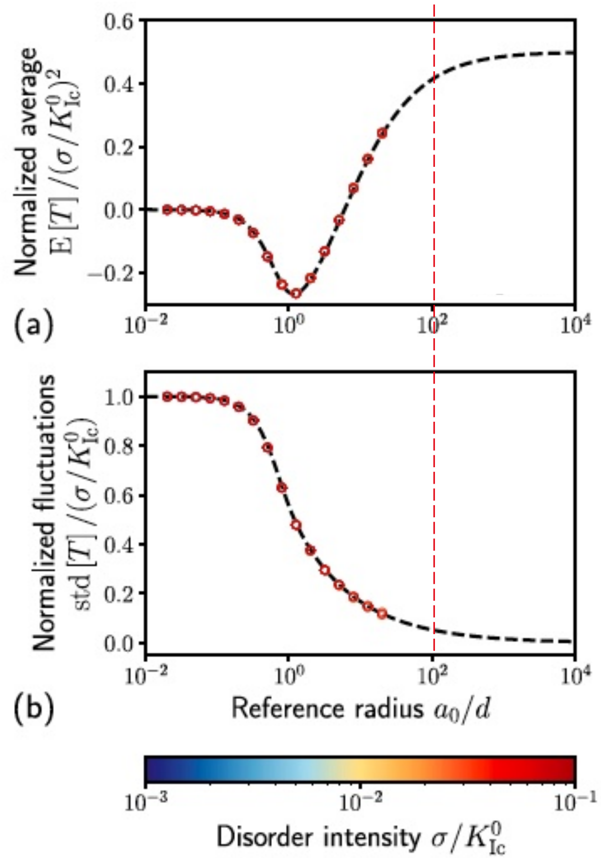
Liu *et al.* (2020)

$$d \ll L_{RVE} \ll L_{sample}$$

In most rocks ... we must be careful

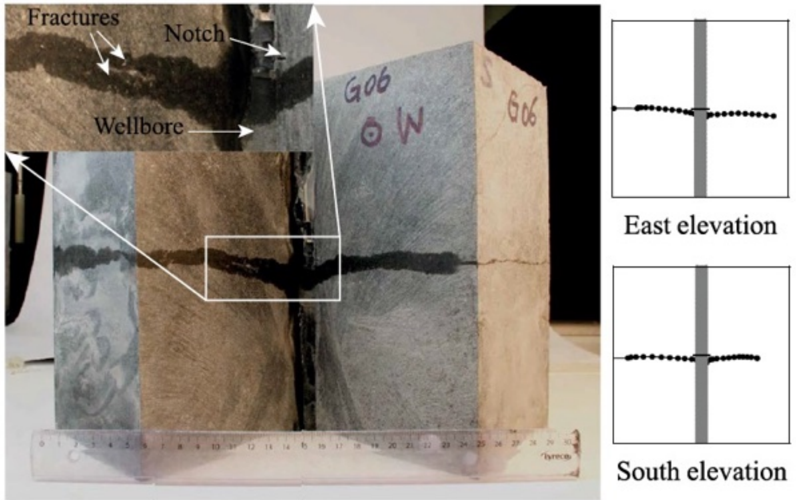


Lebihain *et al* (2023)



$$L_{sample} > 10^2 - 10^3 d$$

Zimbabwe Gabbro



d) GABB-006

Table 1
Zimbabwe Gabbro Properties

Bulk density ρ ($\times 10^3$ kg/m^3)	Porosity (%)	Grain size (mm)	E (GPa)	ν $(\cdot)$	K_{Ic} (MPa $\cdot$ m$^{1/2}$)
3.00	0.32	1–3	99.7	0.29	2.79 ± 0.11

Taken from Liu & Lecampion (2022)

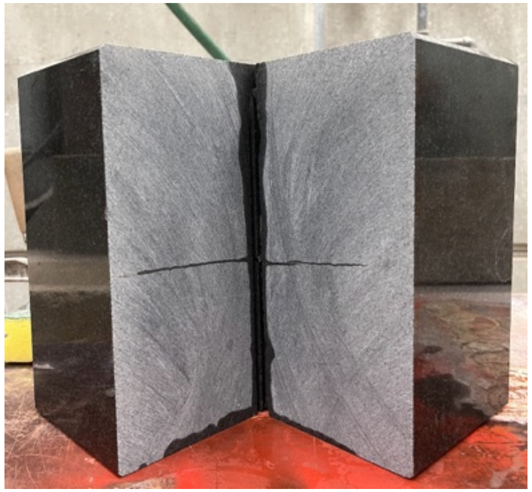
	Confining stresses	Fluid viscosity	Injection rate	Propagation duration
GABB-006	20-20-10 MPa	Glycerol (0.6Pa.s)	0.04 mL/min	~120 s
GABB-007	20-15-5 MPa	Glycerol (0.6Pa.s)	0.08 mL/min	~65 s

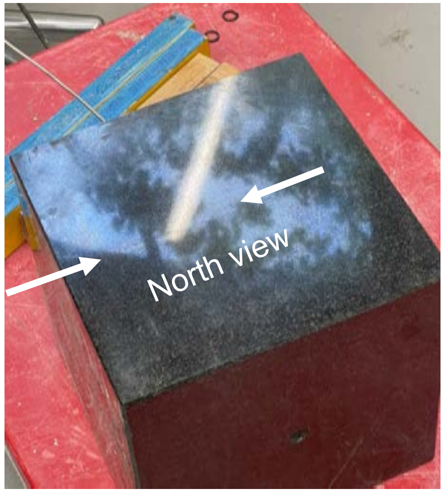
+ 2 additional injection phases

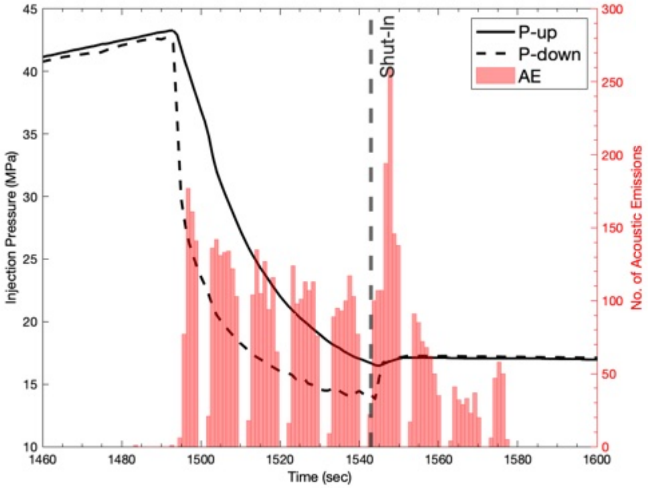
Gabbro-007 experiment

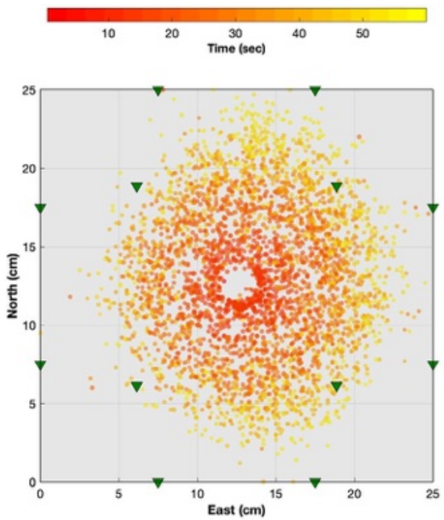
B. Lecampion

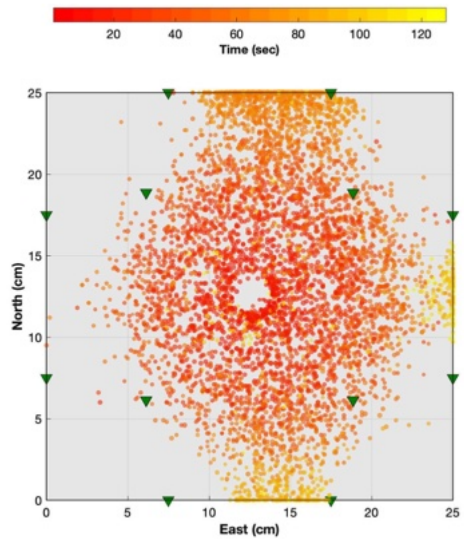
- Toughness-dominated HF
- Fluid: Glycerol
- Injection rate: 0.08 ml/min
- Confining stresses:
  TB: 5 Mpa
  EW:10 Mpa
  NS: 15 Mpa
- Shut-in after 60s





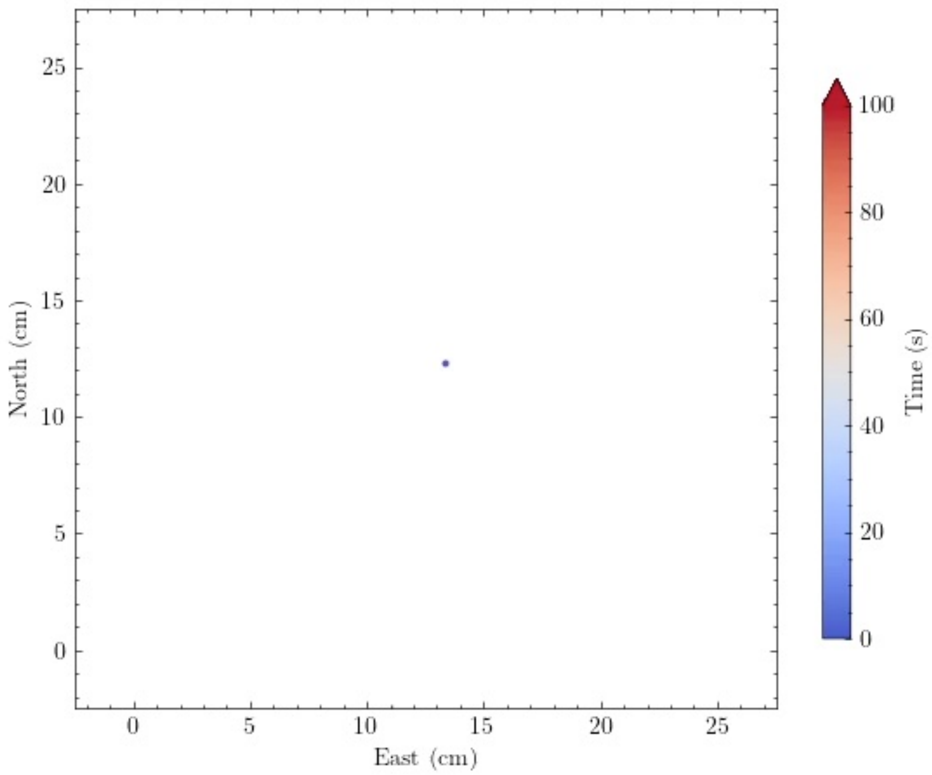




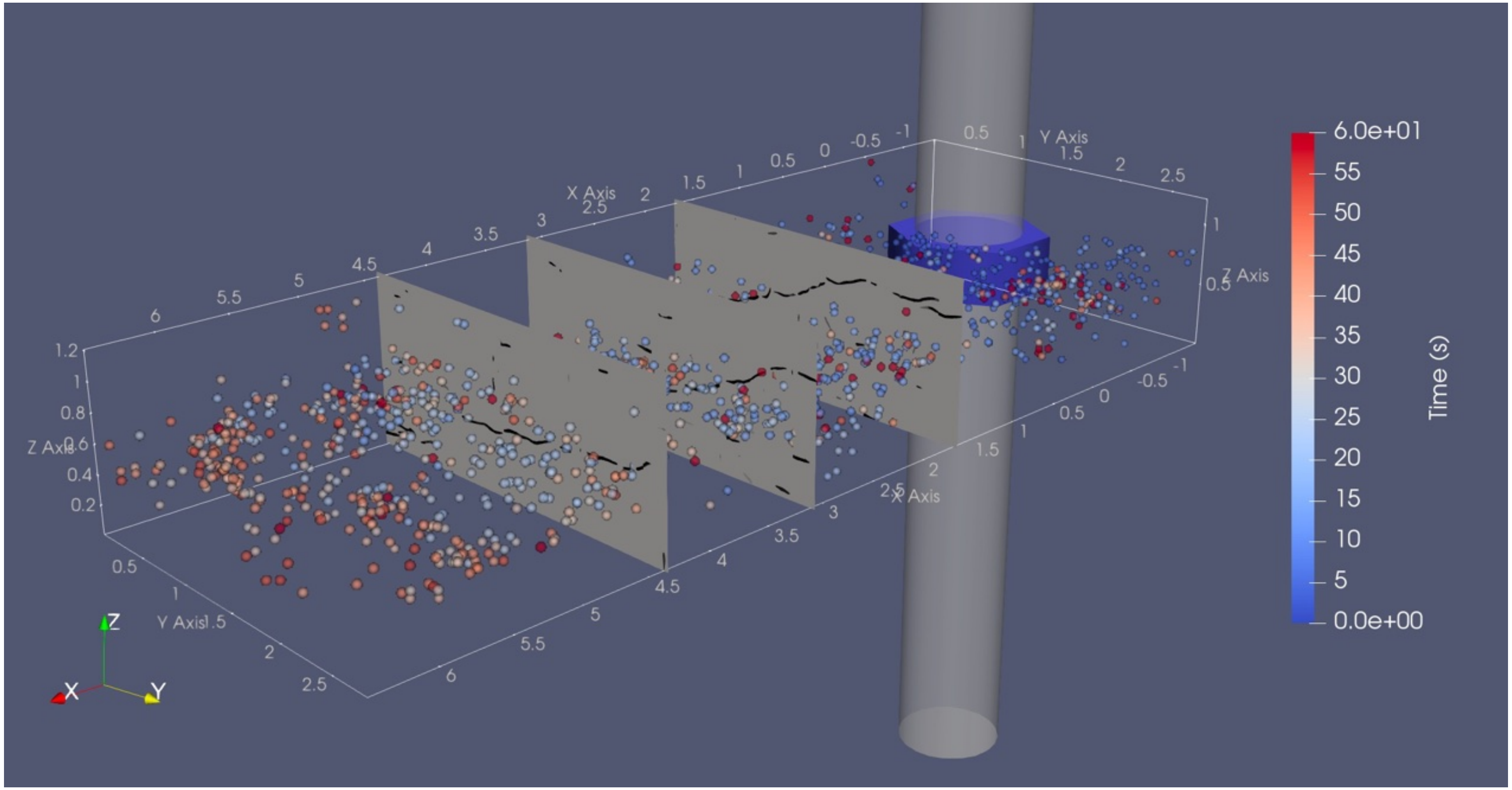


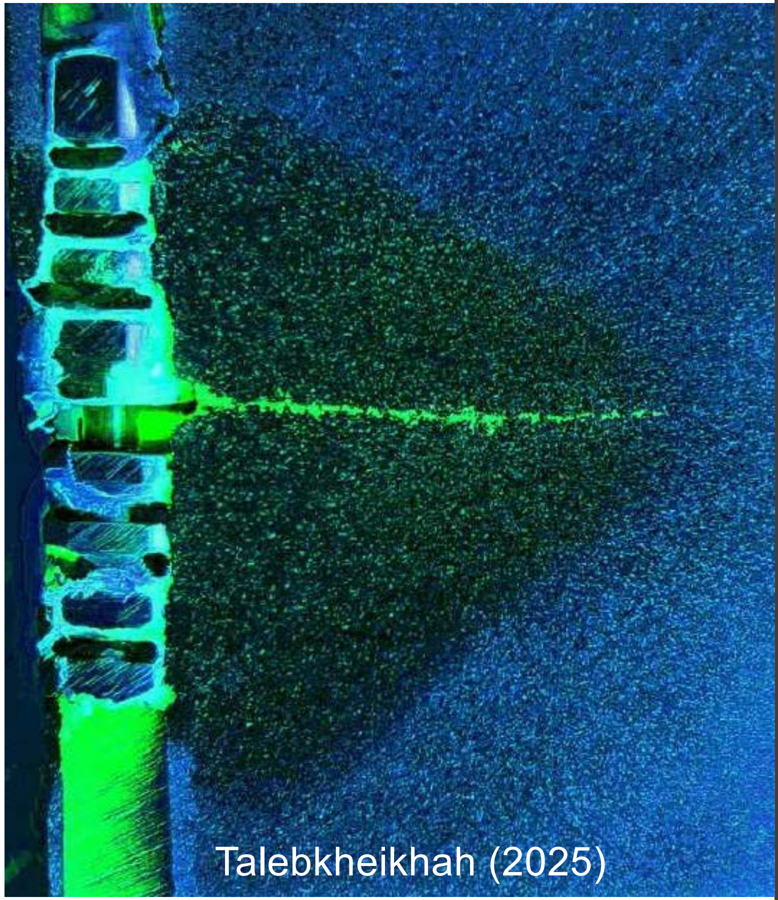
Gabbro 7

Initial catalog: 6’150
With template matching: 25’230



Along a sub-cores CT-scan

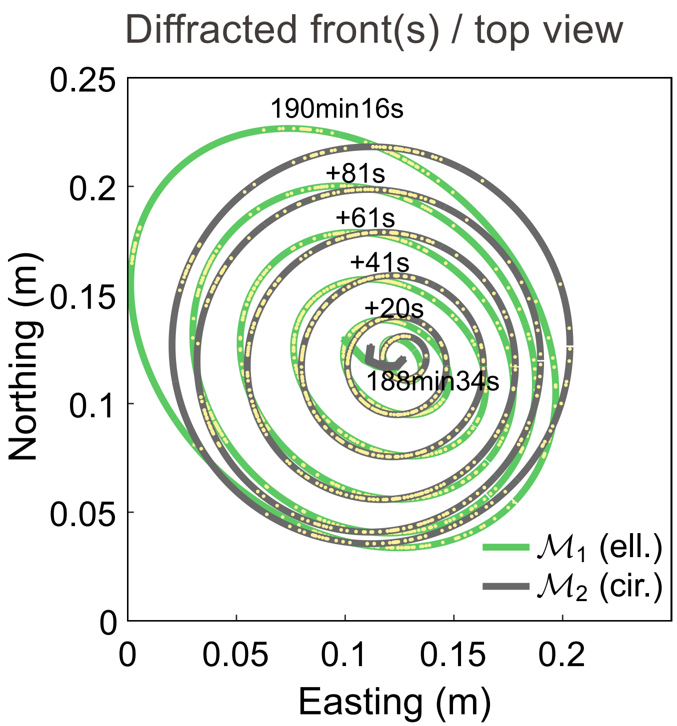


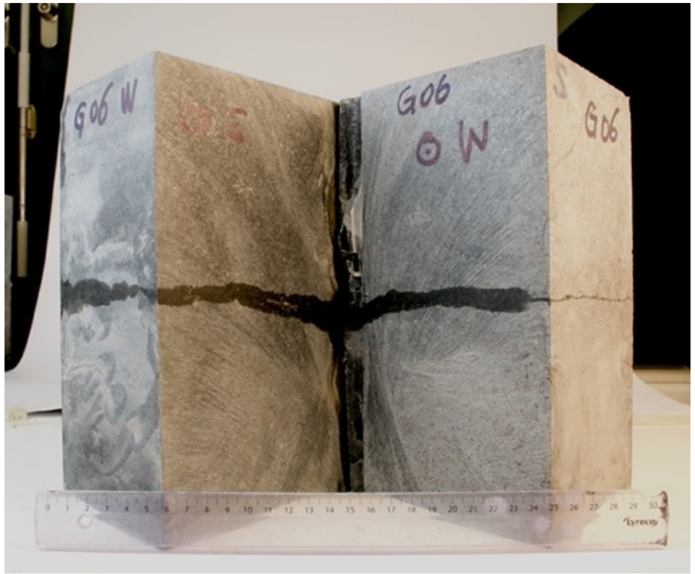


Conclusions

- Lab experiments must be thought holistic (with field & theory in mind)
- LHFM theory provide ”guidelines” to explore further
- Precise monitoring must be continuously advanced
- As a community, we must promote open data set

Gabbro-006 experiment





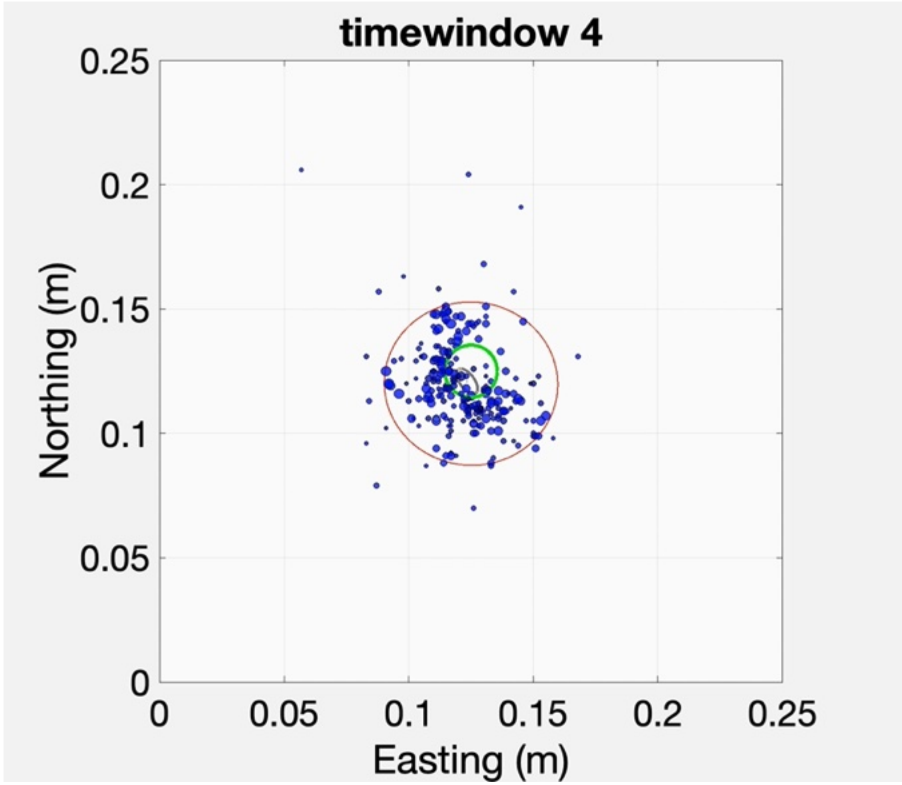
Adapted from Liu & Lecampion (2022)

Gabbro-006 experiment

Each time window is 10 seconds
Reference time is when we observed the first AE

Red: passive front
Black: active front
Green: notch

Top view

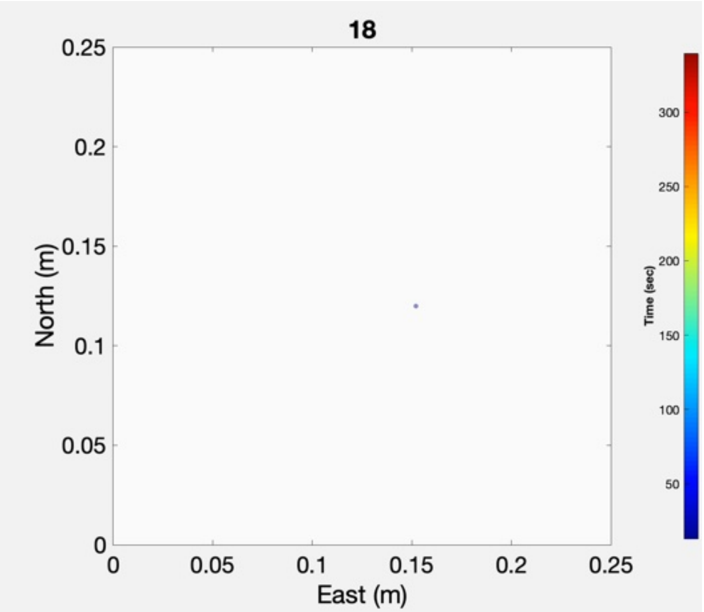


Gabbro-006 AEs

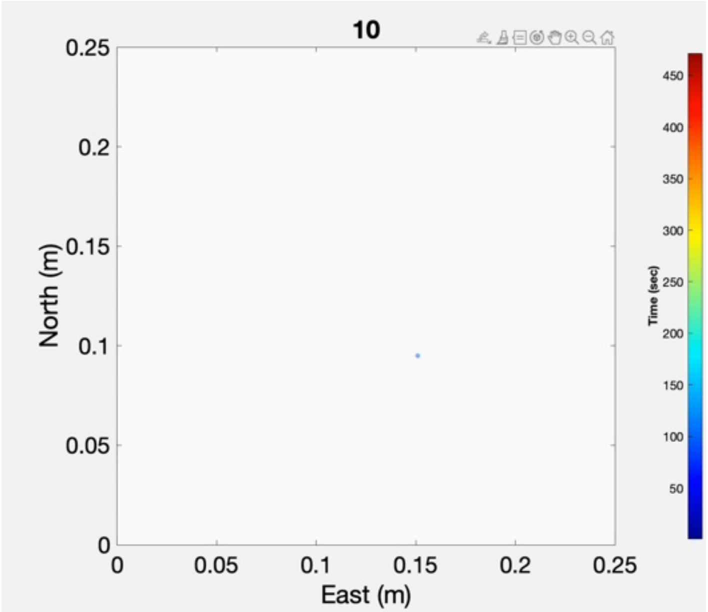
>33,000 AEs in total
>8,000 precisely located AEs

B. Lecampion

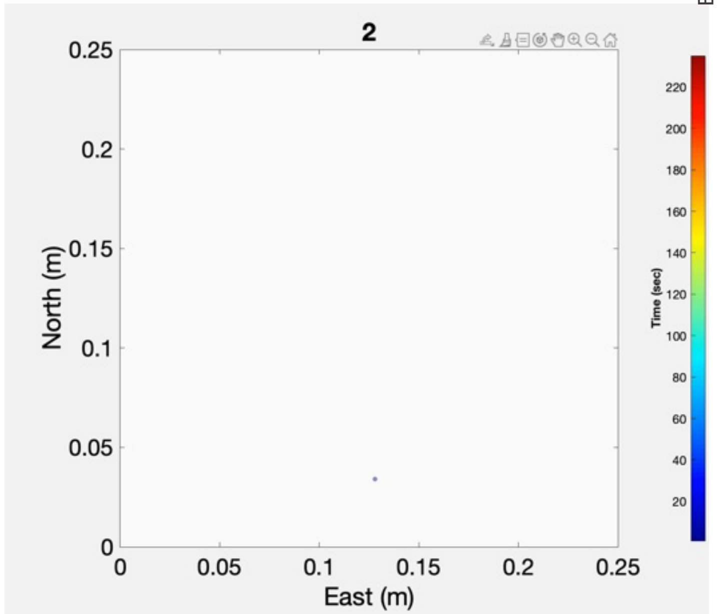
Phase1 (0.04 mL/min)

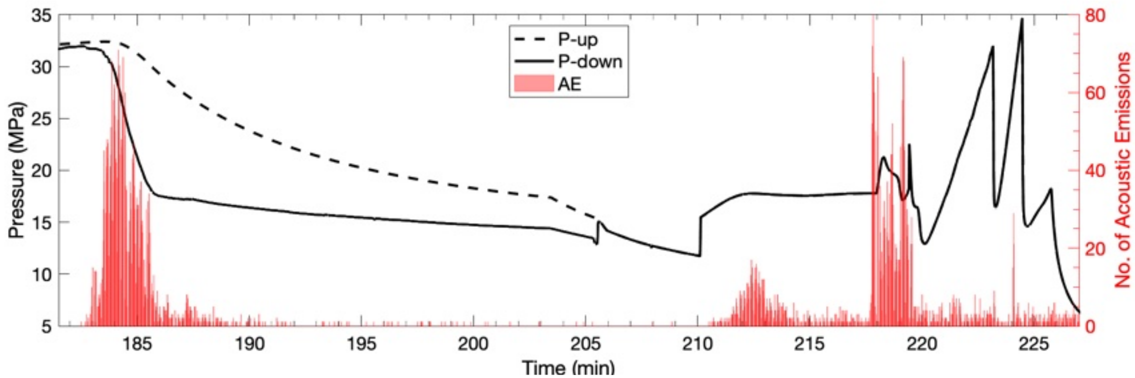


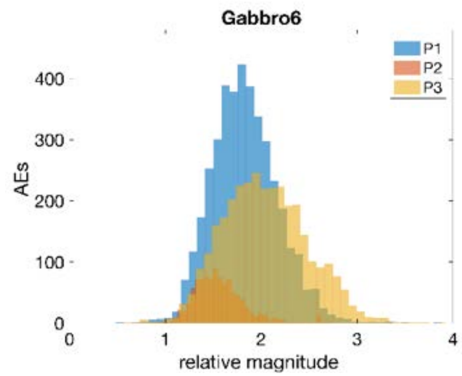
Phase 2 (0.12 ml/min)



Phase 3 (0.4 ml/min)

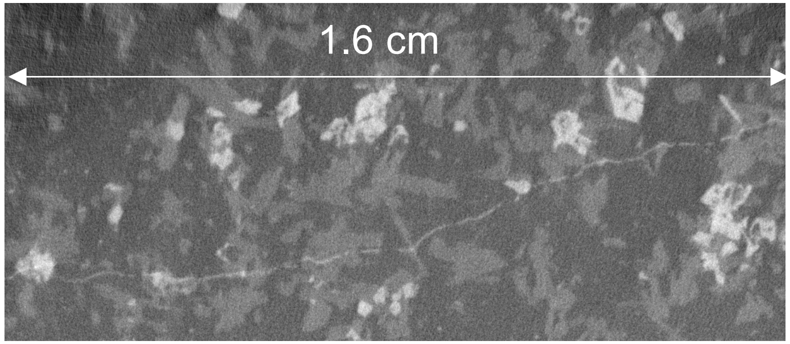


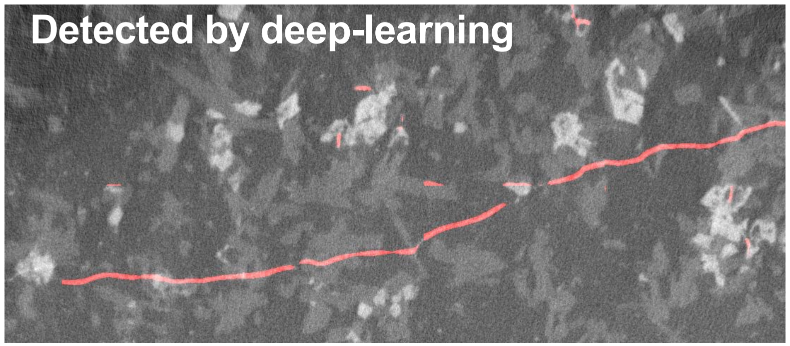




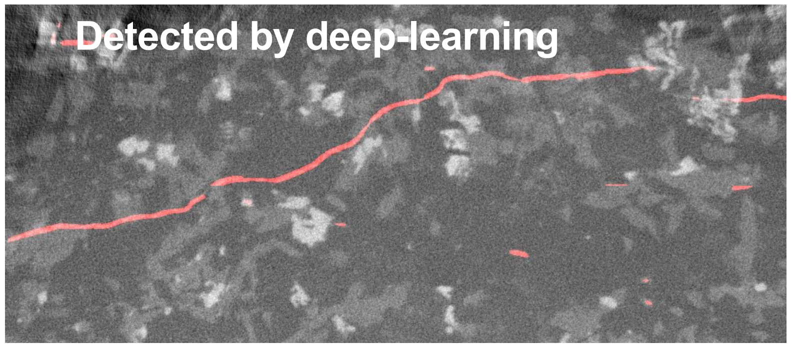
Gabbro-007 core 2

1.5 cm from notch



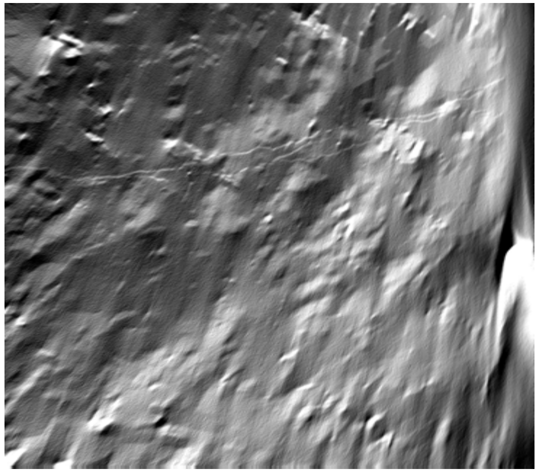


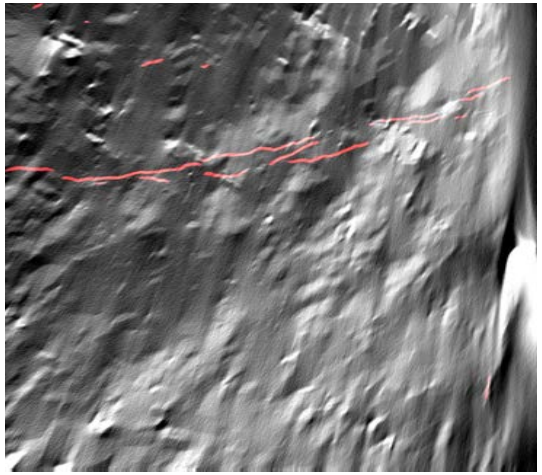
3.3 cm from notch



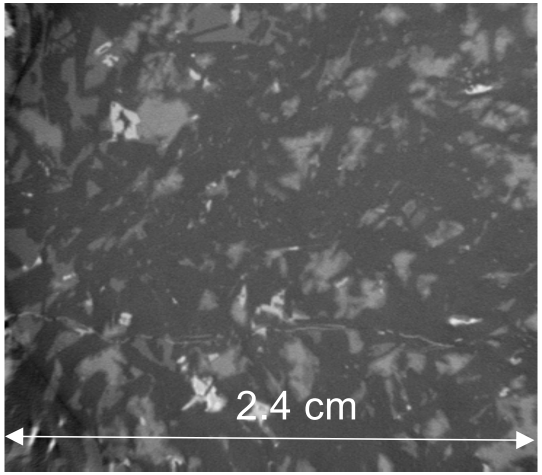
Gabbro-007 core 3

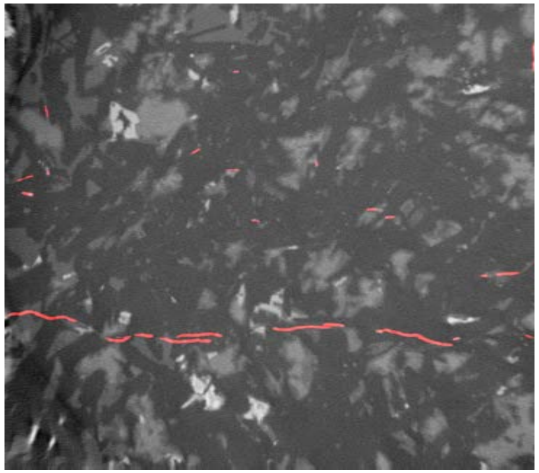
1 cm from notch



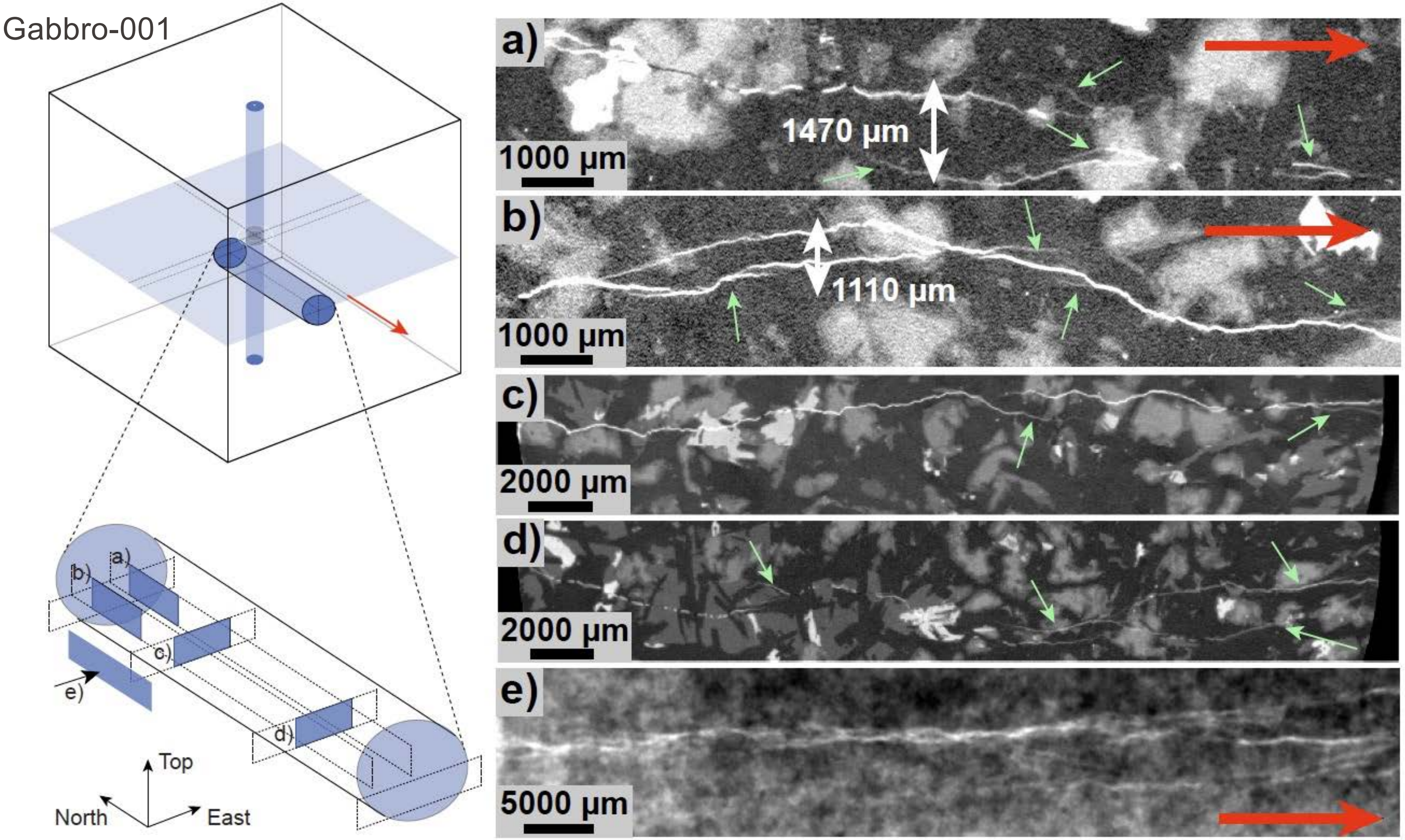


4.7 cm from notch





Another example of micro-scale complexity



Some Recent papers

- G. Lu, S. Momeni, C. Peruzzo, F.-E. Moukhtari, and B. Lecampion. Rock anisotropy promotes hydraulic fracture containment at depth. *J. Geophys. Res. Solid Earth*, 129(4):e2023JB028011, 2024.
- A. Möri, C. Peruzzo, D. I. Garagash, and B. Lecampion. How stress barriers and fracture toughness heterogeneities arrest buoyant hydraulic fractures. *Rock Mechanics and Rock Engineering*, 2024.
- A. Sáez and B. Lecampion. Fluid-driven slow slip and earthquake nucleation on a slip-weakening circular fault. *J. Mech. Phys. Sol.*, page 105506, 2024.
- A. Sáez and B. Lecampion. Post-injection aseismic slip as a mechanism for the delayed triggering of seismicity. *Proceedings of the Royal Society A*, 479(2273):20220810, 2023.
- A. Möri and B. Lecampion. Three-dimensional buoyant hydraulic fracture growth: finite volume release. *J. Fluid Mech.*, 972(A20), 2023.
- A. Möri and B. Lecampion. Three-dimensional buoyant hydraulic fracture growth: constant release from a point source. *J. Fluid Mech.*, 950(A12), 2022.
- A. Sáez, B. Lecampion, P. Bhattacharya, and R. Viesca. Three-dimensional fluid-driven stable frictional ruptures. *J. Mech. Phys. Sol.*, 160:104754, 2022.
- D. Liu and B. Lecampion. Laboratory investigation of hydraulic fracture growth in zimbabwe gabbro. *Journal of Geophysical Research: Solid Earth*, 127(11):e2022JB025678, 2022.
- A. Möri and B. Lecampion. Arrest of a radial hydraulic fracture upon shut-in of the injection. *Interna- tional Journal of Solids and Structures*, 219:151–165, 2021.
- D. Liu and B. Lecampion. Propagation of a plane-strain hydraulic fracture accounting for a rough cohesive zone. *J. Mech. Phys. Solids*, 149:104322, 2021.
- H. Zia and B. Lecampion. PyFrac: a planar 3D hydraulic fracturing simulator. *Comp. Phys. Comm.*, 255:107368, 2020.
- D. Liu, B. Lecampion, and T. Blum. Time-lapse reconstruction of the fracture front from diffracted waves arrivals in laboratory hydraulic fracture experiments. *Geophys. J. Int.*, 223:180–196, 2020.