Fault rock injections record paleo-earthquakes

Christie.Rowe@mcgill.ca
James D. Kirkpatrick
Emily E. Brodsky

UCSC
McGill

Injections record pressure

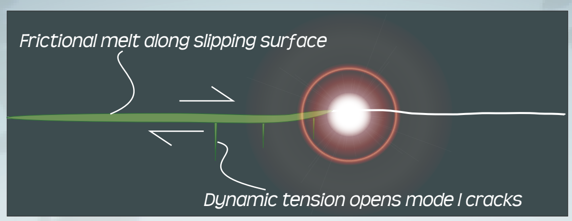
◈ Many faults have off-fault injections of fault rock.

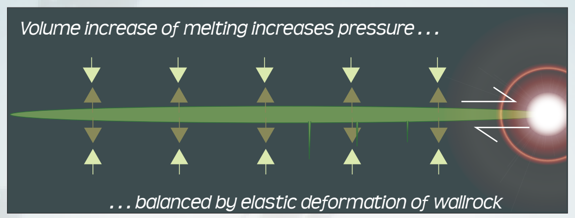
◈ These are evidence for mobilization and pressurization of fault rocks.

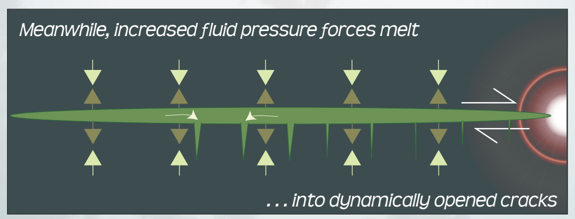
◈ Pressures are important for dynamic shear resistance.

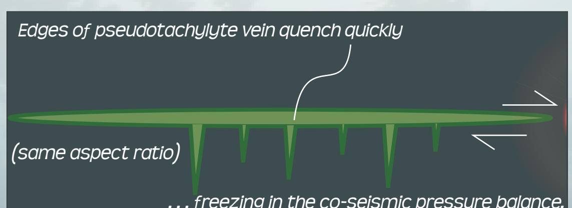
◈ ***Can injections be used to measure in-situ pressure during an earthquake?***

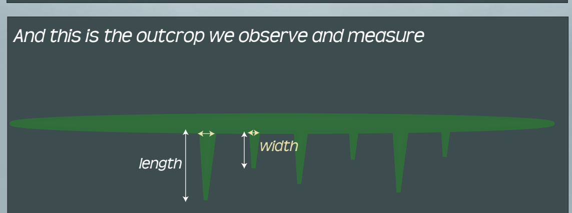
Cartoon Summary





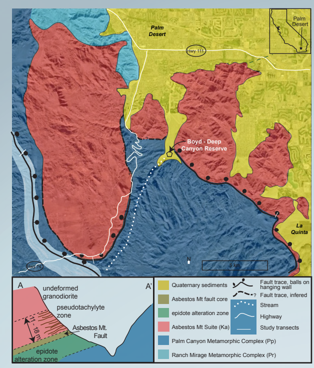






Motivating Observations

Injections of fault rock (pseudotachylyte and gouge) are found on many faults! They preserve a record of pressure in the fault. For pseudotachylytes, this pressure is locked in before the injection veins quench.



Asbestos Mountain Fault Zone

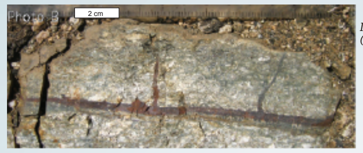
Near Palm Desert, California

Early Tertiary pseudotachylytes, dated and described by previous workers (Wenk et al. 2000)

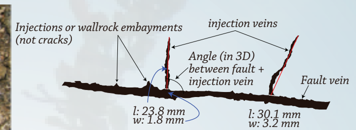
Hundreds of pseudotachylyte-bearing faults, most with multiple injection veins up and down section.

Host rock is variably foliated granodiorite and tonalite.

Pseudotachylytes:

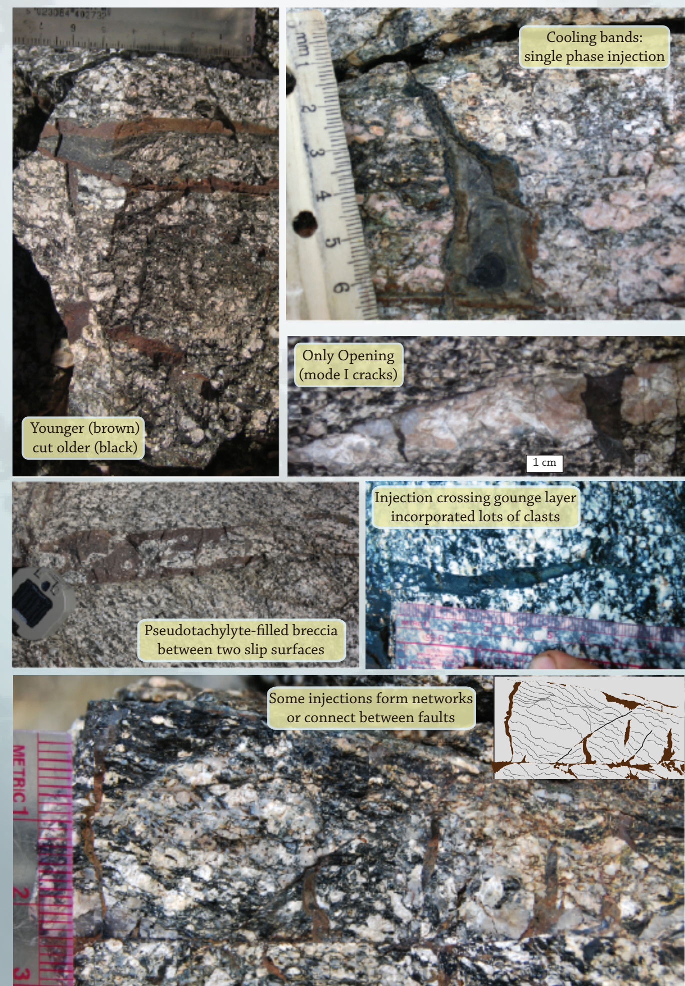


Measurements:



Selection Criteria:

1. Continuous connection from slip surface (source vein) to injection (injection vein).
2. Injection vein decreased in thickness from base to tip and we observed thickness decrease to zero.
3. Rejected veins which turned to follow host rock fabric or intersecting fractures.
4. Rejected veins which spanned two or more fault veins or formed breccias.
5. Rejected veins containing clasts or groups of clasts which appeared same width as injection
6. Rejected veins of same scale as local grain size in host rock
7. Only opening-mode offset across injection vein was observed.
8. Concentric cooling zonations demonstrate single-phase melt intrusion.



Gouge injections:

Top:
Badwater Detachment, active, Death Valley, CA.
Wallrock is unconsolidated alluvium.

Muddy Mountain Thrust, Jurassic, southern Nevada.
Wall rock is cemente dolomite breccia.

Bottom:
Naukluft Thrust, Cambrian, central Namibia. Subsidiary injections branch from main injection and follow foliation in limestone-mylonite wall rock.

Wall rock is chloritic phyllite

Wall rock is massive dolomite.

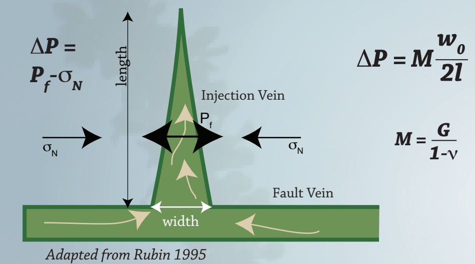
Estimating coseismic pressures

10^8 Pa < ΔP < 10^9 - 10^{10} Pa.

Injection vein is a simple opening-mode elastic crack.

Aspect ratio is linearly related to the net pressure (ΔP) inside the vein: the balance of fluid pressure pushing outward on crack walls, and wall rock stresses resisting crack opening, where w_0 / l is the aspect ratio of the vein (a measure of strain associated with vein opening), and M incorporates the shear modulus (G) and Poisson's ratio (ν).

$$\Delta P = P_f - \sigma_N$$

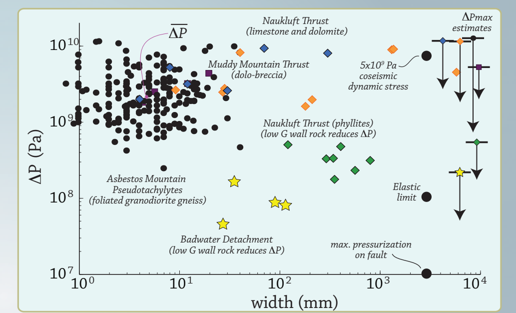


$$\Delta P = M\frac{w_0}{2l}$$

$$M = \frac{G}{1-\nu}$$

Adapted from Rubin 1995

Upper bound: fully elastic



Lower bound: elastic limit (must have been exceeded)

Laboratory limit on elastic shear strain ≈ 0.01; Multiplied by shear modulus gives ΔP ≈ 10^8 Pa

Wall rock deformation

We calculate, for reasonable fault rock expansion, the degree to which peak pressure is buffered by elastic deformation around the fault surface

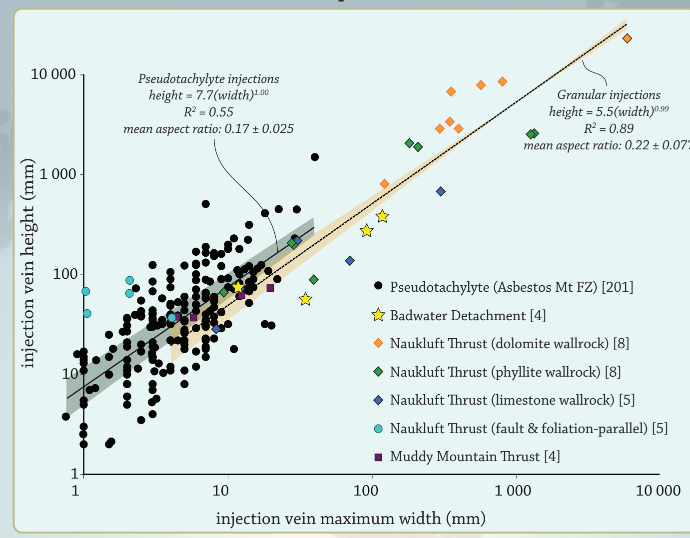
$$\Delta P = \frac{XK_{fluid}K_{rock}(w/l)}{(1+X)(K_{rock})(w/l)+K_{fluid}}$$

X = expansion of fault rock (=1.1 for melting)
K_{fluid} = compressibility of fault rock
K_{rock} = compressibility of wall rock
w/l = aspect ratio of fault rock layer

◈ The maximum likely pressurization along the fault is ≈ 10^7 Pa.

Pseudotachylyte and granular injection veins are the same shape.

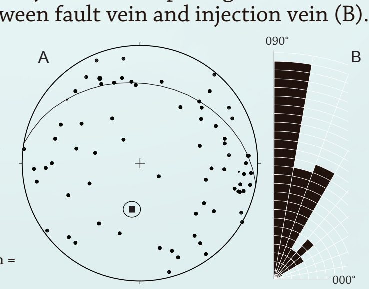
Aspect ratios of both sets are about 0.2



Pseudotachylyte injection veins are at high angles to the source fault but variable in strike.

No consistent injection vein opening direction (A).
Average ~ 70° angle between fault vein and injection vein (B).

A: Orientations of fault and injection pseudotachylyte veins. Injection veins are steeply dipping, but there is no apparent pattern in strike orientation. Mean plane of fault veins (parallel to the Asbestos Mountain Fault), 280/33N, n=65 (solid great circle) and mean pole (black square with 95% confidence circle). Poles to injection veins, n=71 (small black dots).
B: Rose diagram showing angle between fault vein and its own injection veins. N = 67. Mean =

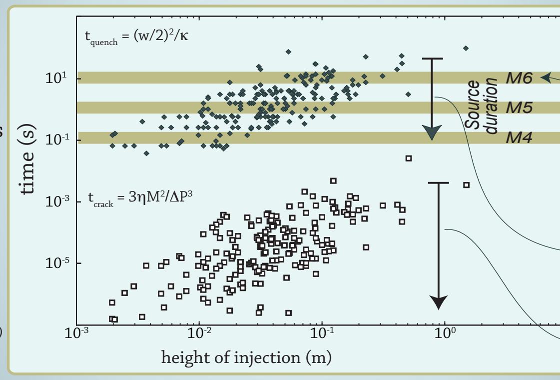


How does ΔP in the injections exceed 10^8 Pa?

Co-seismic transient tensile stresses up to 5*10^9 Pa.
(Reches & Dewers, 2005.)

Dynamic tensile stresses open Mode I cracks at a high angle to fault.
(Di Toro et al. 2005, Griffith et al. 2009.)

Timescales: Are we measuring CoSeismic Pressure?



η = *average melt viscosity (=* 10^4 *Pa*s)*
w/2 = injection vein half width
κ = *thermal diffusivity of melt (=* 10^{-6} m^2/s)
M = shear modulus/(1 - Poisson's ratio)
ΔP = fluid overpressure

How long do dynamic transient stresses last?

1-10s for M6
(rupture length ≈ shortest chord through mapped trace.)
(Kanamori and Brodsky, 2004)

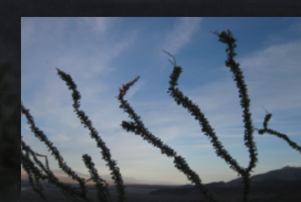
Can injection vein aspect ratios be locked in during that time?
YES.

Do crack growth rates limit injection size?
NO.

Conclusions

- 10^8 Pa < *Pressure inside injections* < 10^9 - 10^{10} Pa.
- Can't be produced by on-fault pressurization alone; *must preserve dynamic tension*
- ◈ **INJECTIONS ARE SEISMIC SIGNATURES** - pseudotachylyte (obviously) but *also* granular injections
- Co-seismic weakening mechanisms (frictional melting and thermal pressurization of pore water) produce pressures on par with overburden - we predict ***TOTAL STRESS DROP*** on affected parts of faults.

This work is in press in EPSL, for pdf file visit eps.mcgill.ca/~crowe/publications.html



Background photo: Ocatillo at sunset, Palm Desert, California, by Lia Lajoie

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