Partitioning of seismic and aseismic strain

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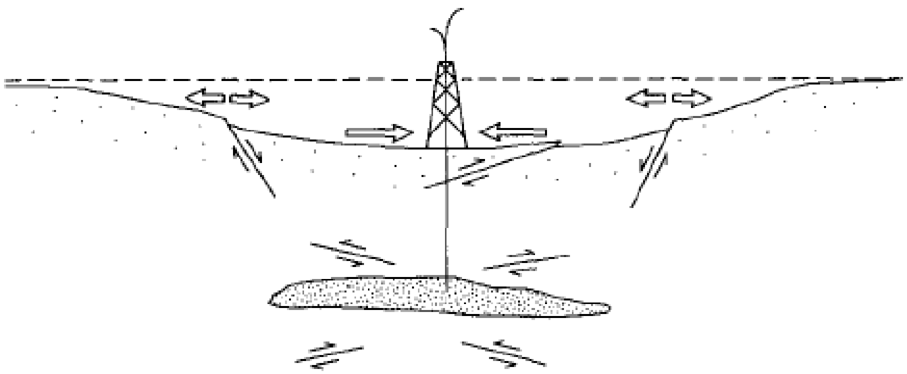
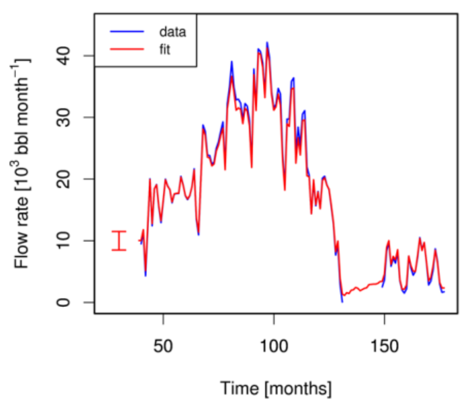
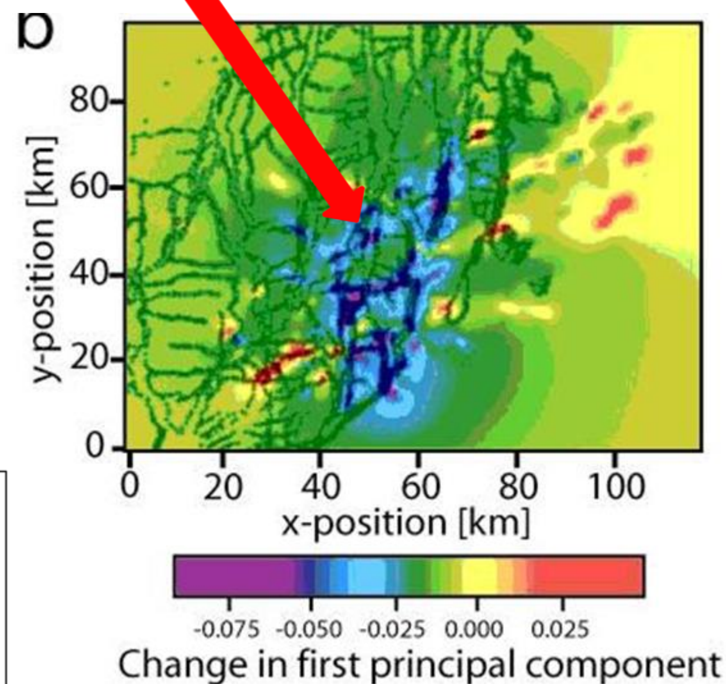
Partition of Scalar Strain

Total Strain = (Poro-elastic + Seismic + Silent permanent) strain



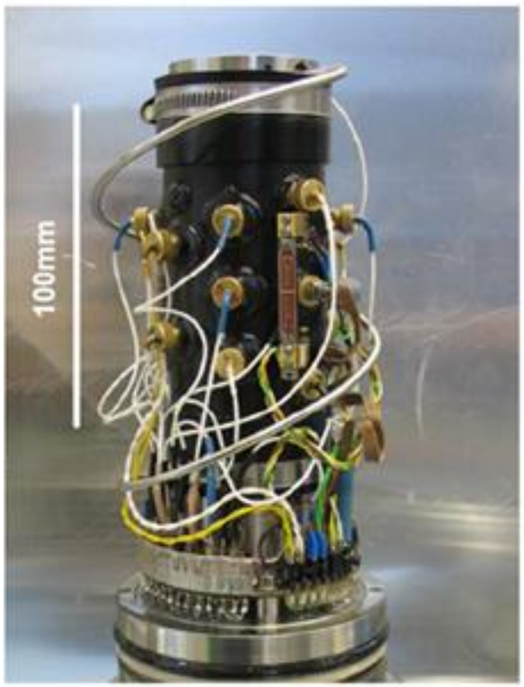
Segall, 1989

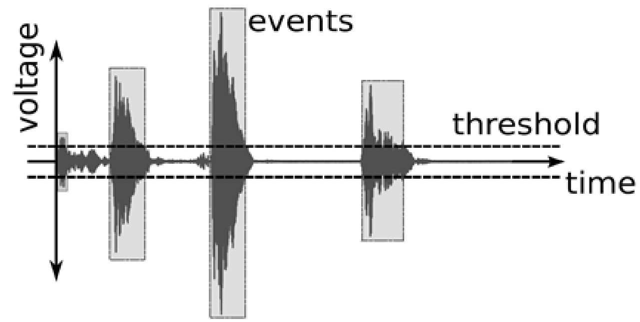


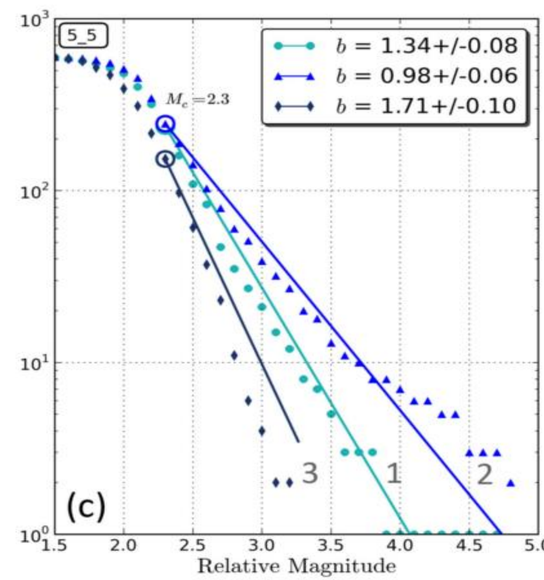


Main et al., GRL, 2006

Learning from the lab
Acoustic Emissions (AE)



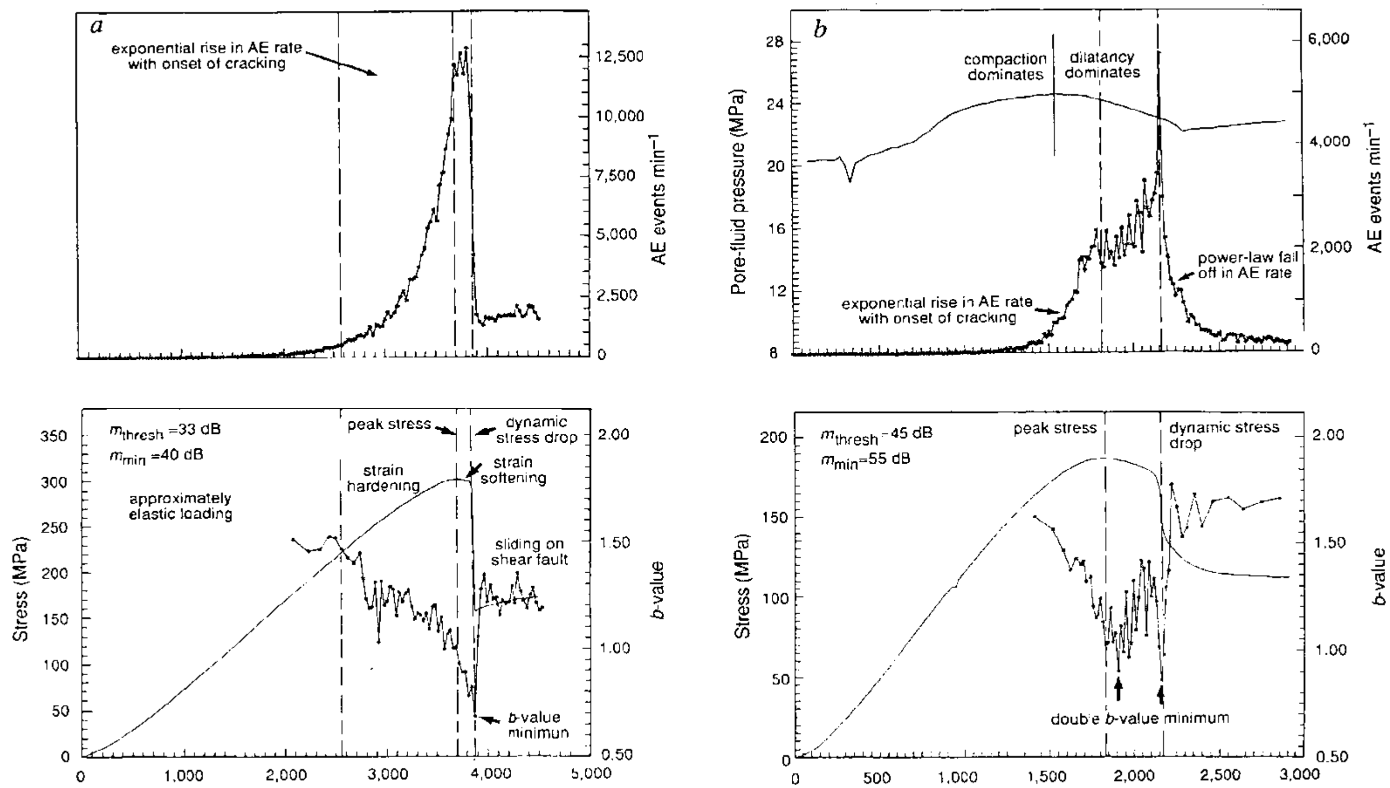




Graham et al., IJRM 2010

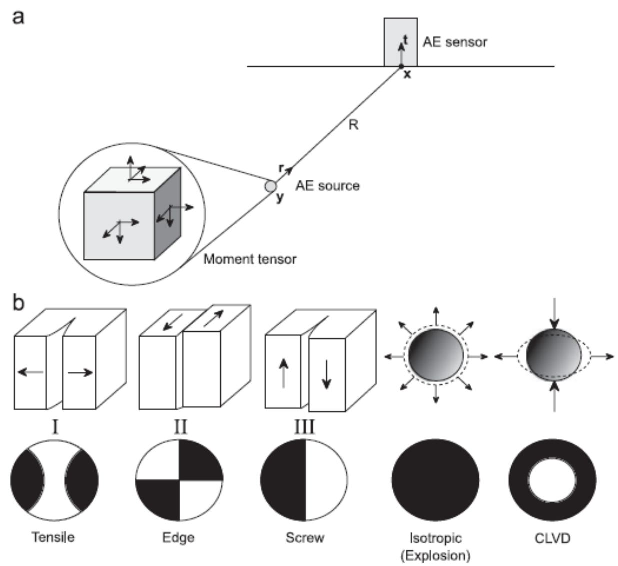
Gutenberg-Richter law: log(N)=a–bm
Scaling exponent is the "b-value"

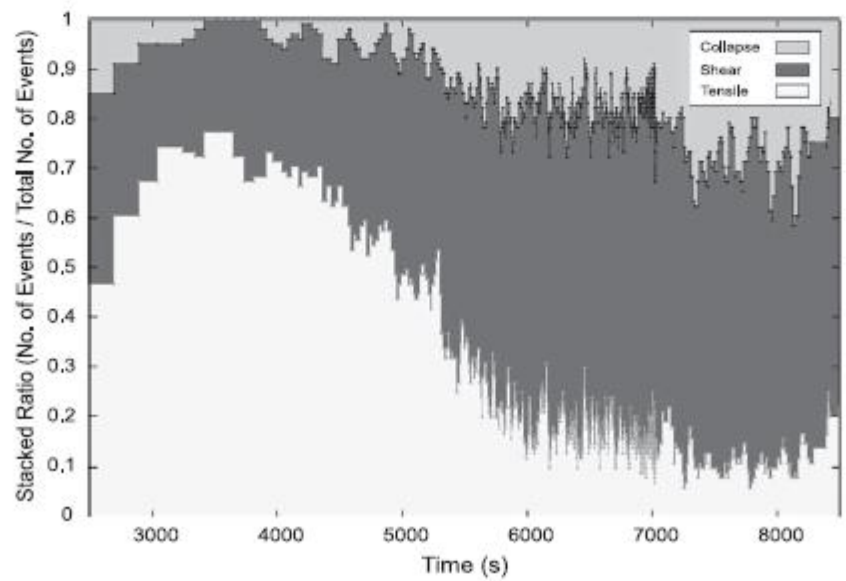
Acoustic emission event rate and b-value evolution (Sammonds et al, Nature, 1994)



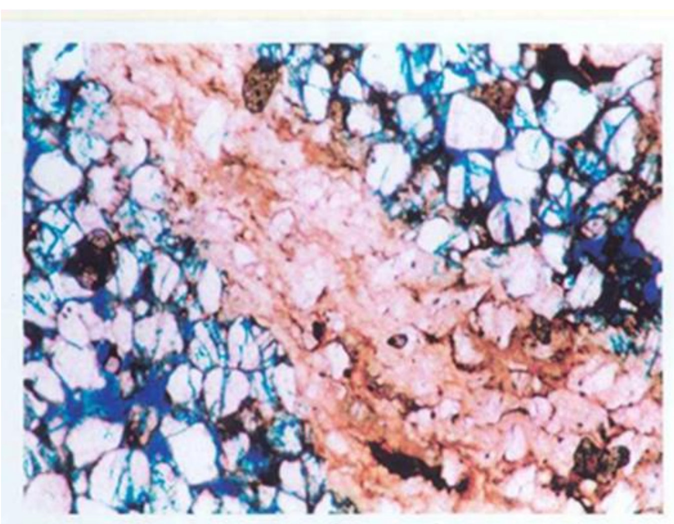
Drained test: Event rate increases exponentially or as inverse power law; *b*-value drops
Undrained: Produces hiatus due to poro-elastic dilatant hardening

Partition of Tensor Strain





Graham, Stanchits, Main, Dresen IJRM, 2010

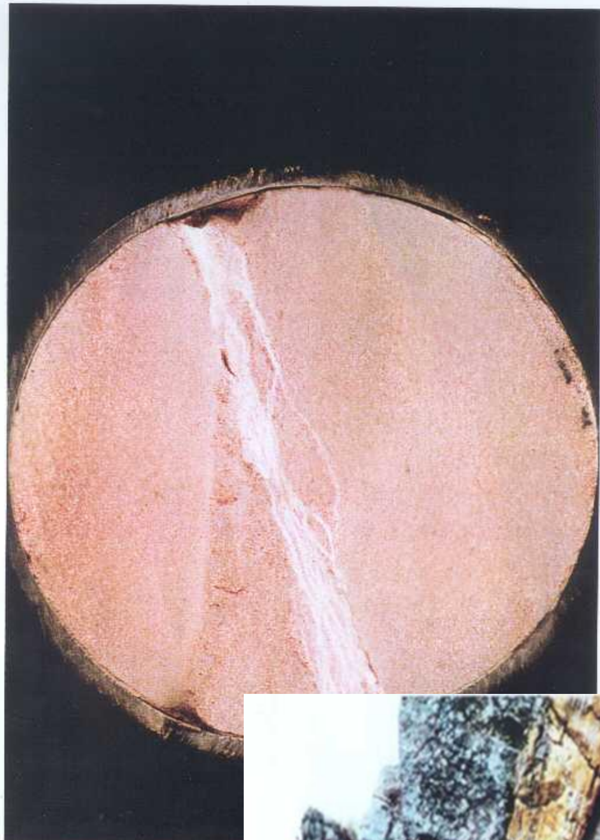


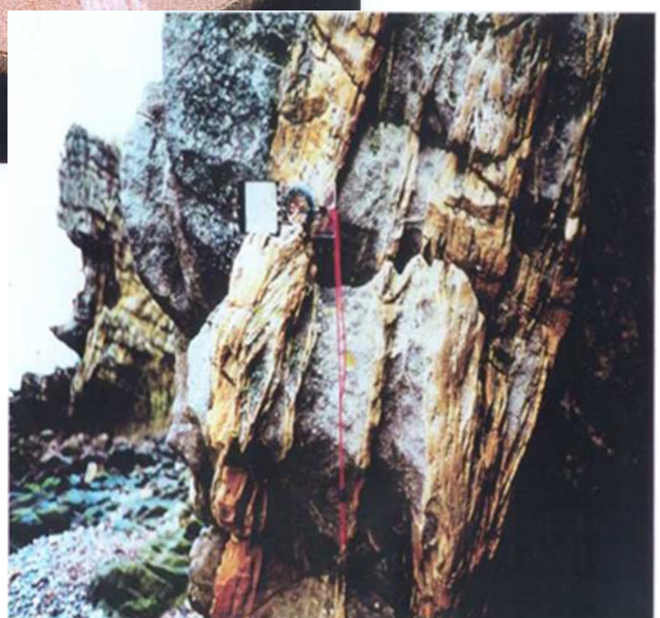
Mair et al., JSG, 2000

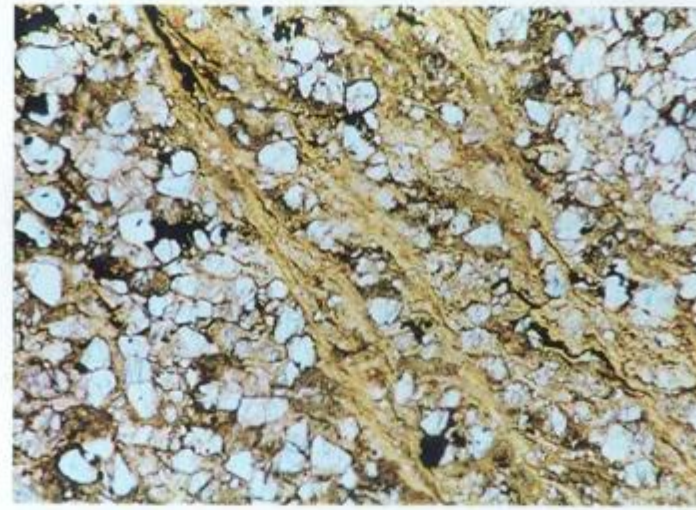
All focal mechanism types occur at all times, consistent with post-test microstructure

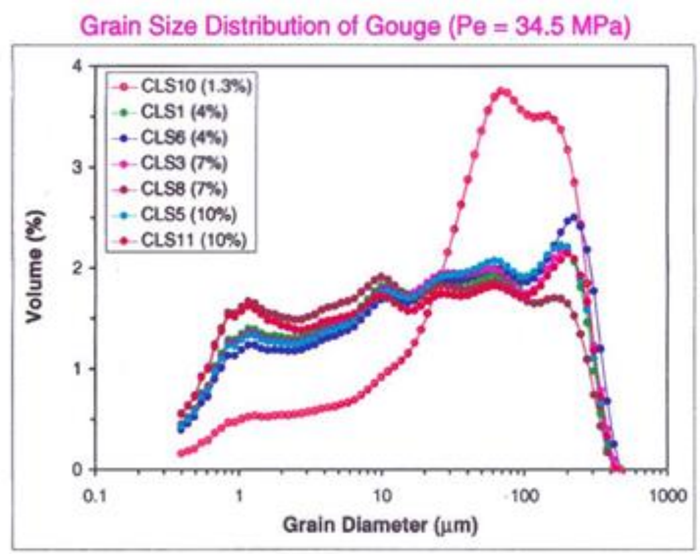
Tensor strain partitions increasingly to shear

Microstructures

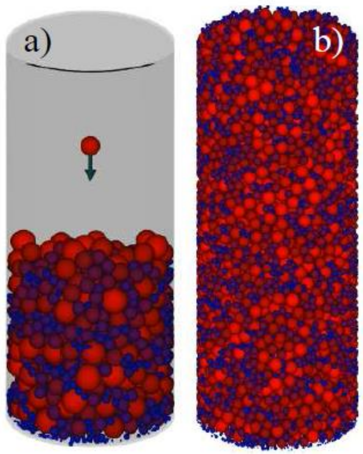








Mair et al., JSG 2000



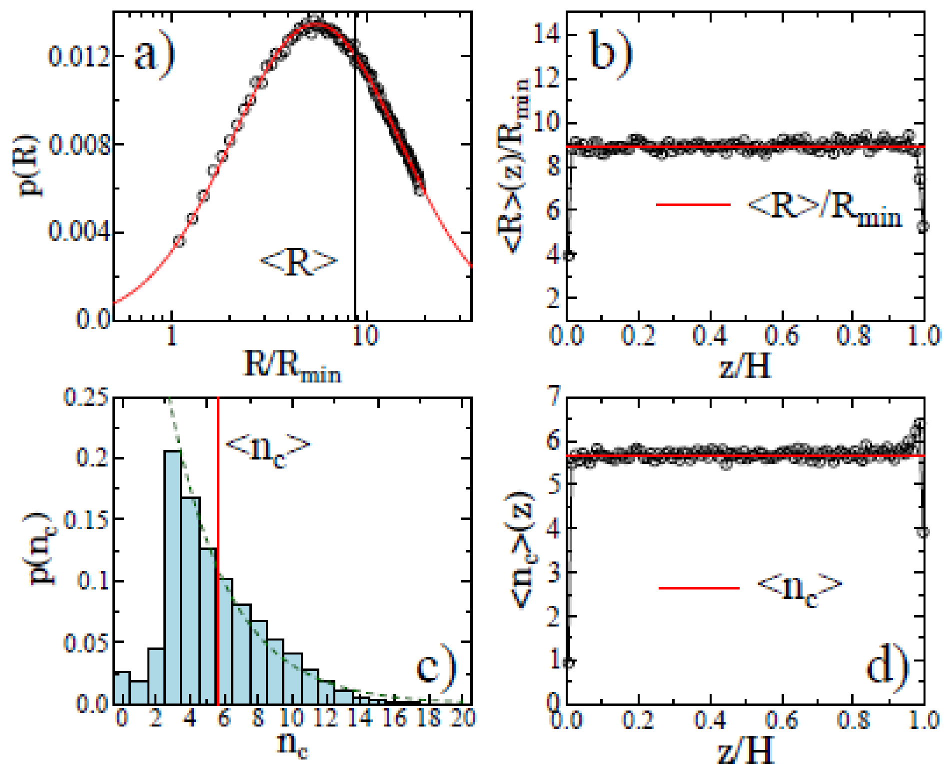
Making a discrete element model

Kun et al., PRE 2013, PRL 2014

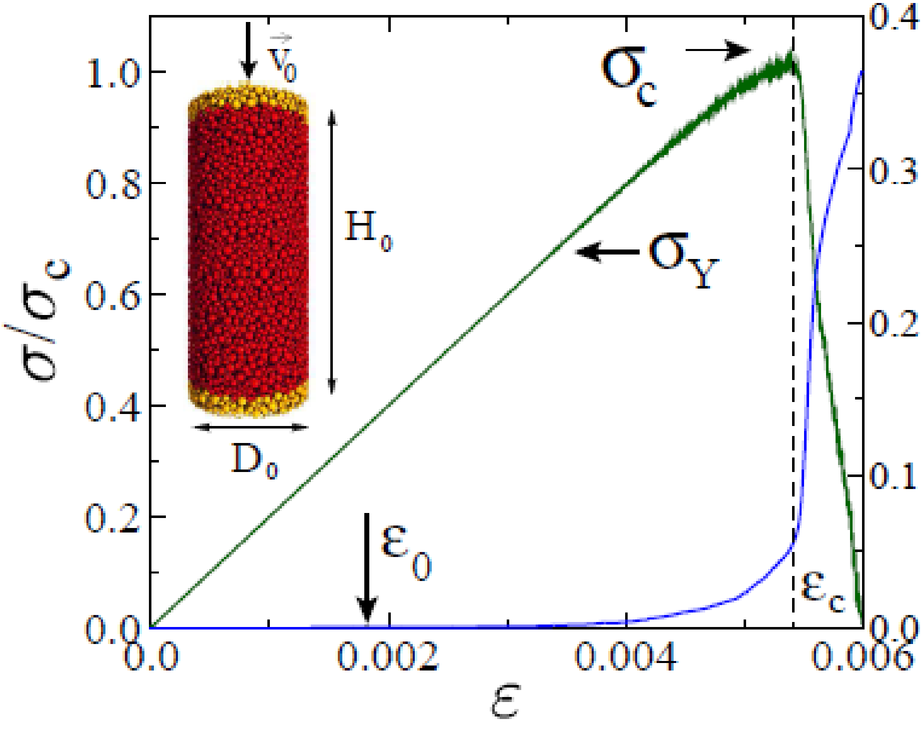
Sedimentation under gravity

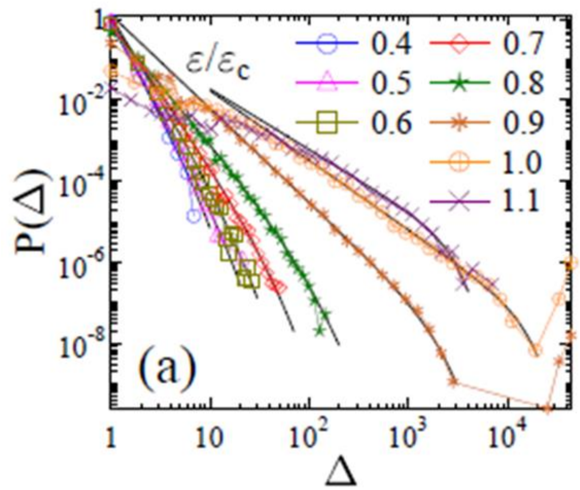
(a) Particle size distribution
(b) Average grain size vs. vertical position
(c) Co-ordination number
(d) Average co-ordination no. vs. depth

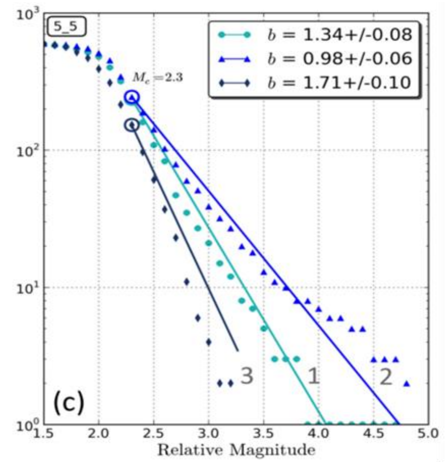
- Discrete elements are unbreakable
- Cemented by bonds that deform in tension, compression, shear and bending
- The only disorder is structural
- **No power-laws are put in at step 1**



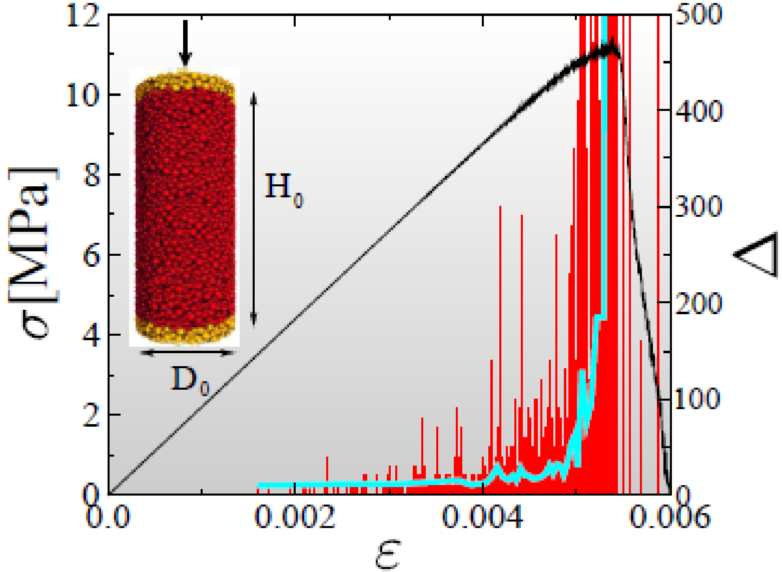
Squashing the digital rock



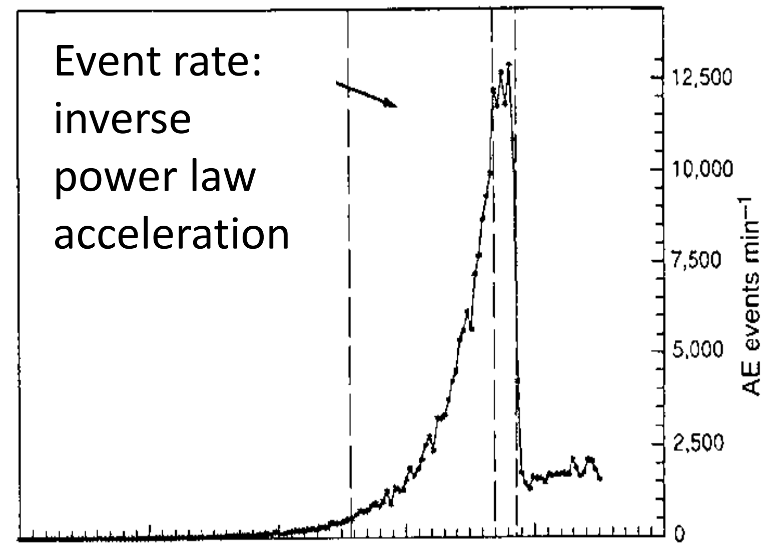




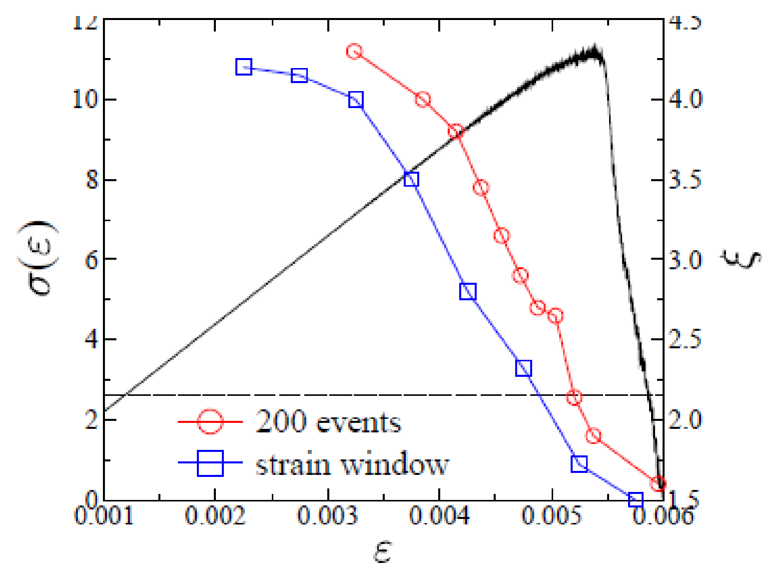
$$\dot{N} = A(1 - t/t_f)^{-p}$$



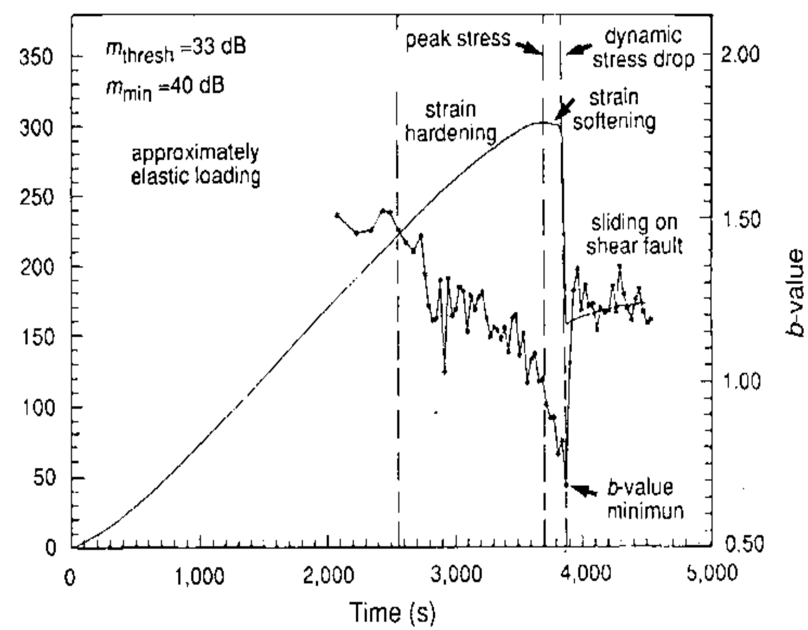
σ[MPa]
H_0
D_0
Δ
ε



Event rate:
inverse
power law
acceleration
AE events min^-1



σ(ε)
ξ
200 events
strain window
ε

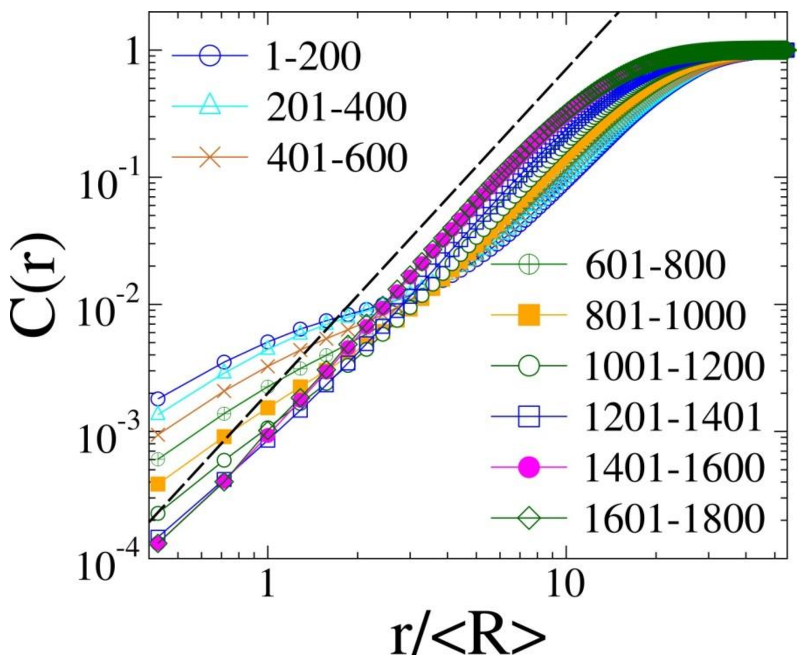


m_thresh =33 dB
m_min =40 dB
peak stress
dynamic stress drop
strain hardening
strain softening
approximately elastic loading
sliding on shear fault
b-value minimun
b-value
Time (s)

Approach to failure – spatial localization

Model: Pair correlation function

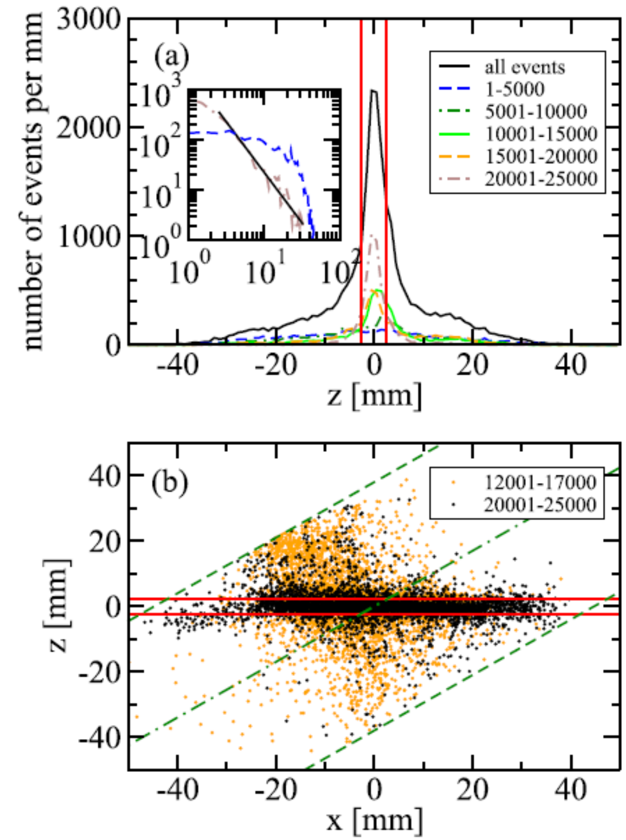
$$C(r) = N(<r)/N_p$$



$C(r) \sim r^{D_2}$ $\qquad$ $D_2 = 2.55$

Real Data

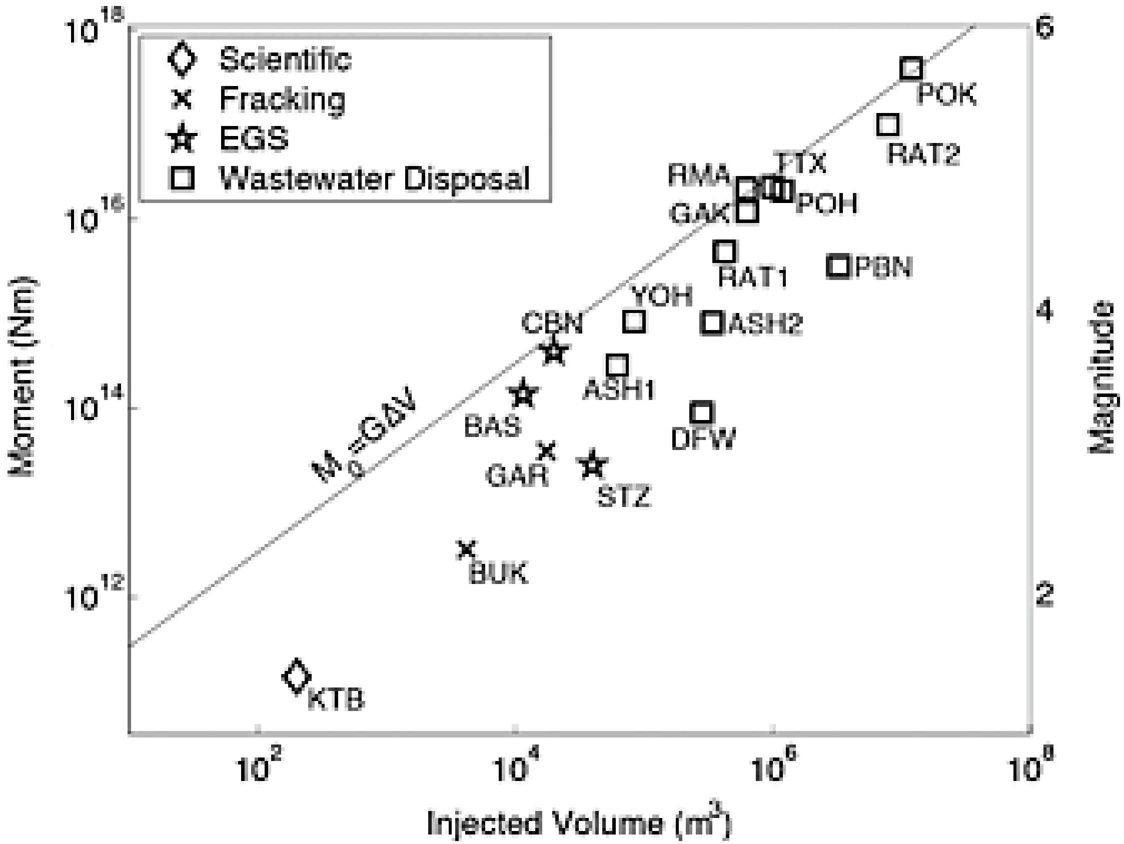
(Lennartz-Sassinek et al., PRE, 2014)



c.f. **2.25**<D_2<**2.75** (Hirata et al., 1987)

Some published data

Maximum magnitude earthquakes induced by fluid injection (McGarr, 2014)
Note biased sample: "most do not produce earthquakes"



$$F(M) = AM^{-B}$$

$$B = 2b/3$$

For $b \cong 1$; $B \cong 2/3$

$$\sum M_i = \left(\frac{B}{1-B}\right) M_{min} N^{\frac{1}{B}}$$

or $\boxed{\sum M_i \cong 2M_{max}}$

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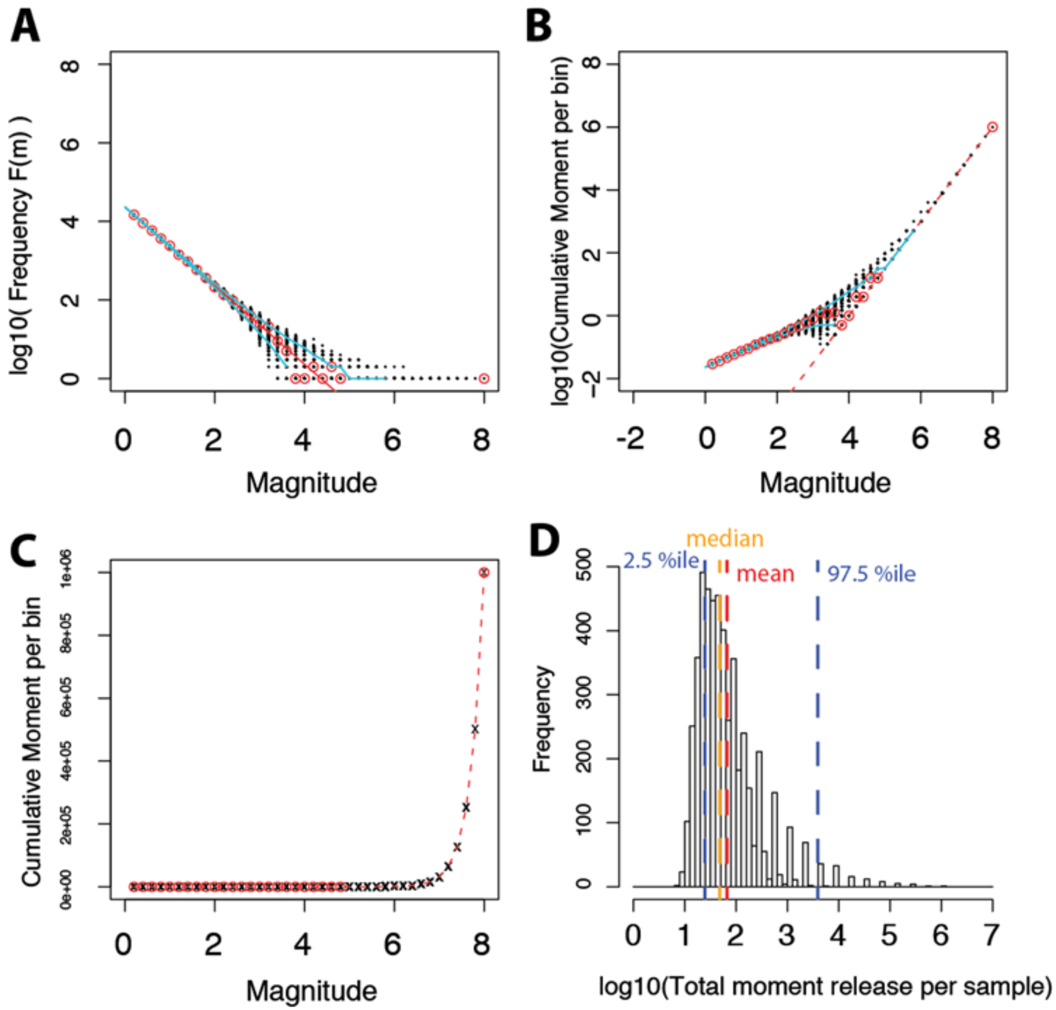
2013JB010597, 4 FEB 2014 DOI: 10.1002/2013JB010597
http://onlinelibrary.wiley.com/doi/10.1002/2013JB010597/full#jgrb50496-fig-0002

Finite sampling issues

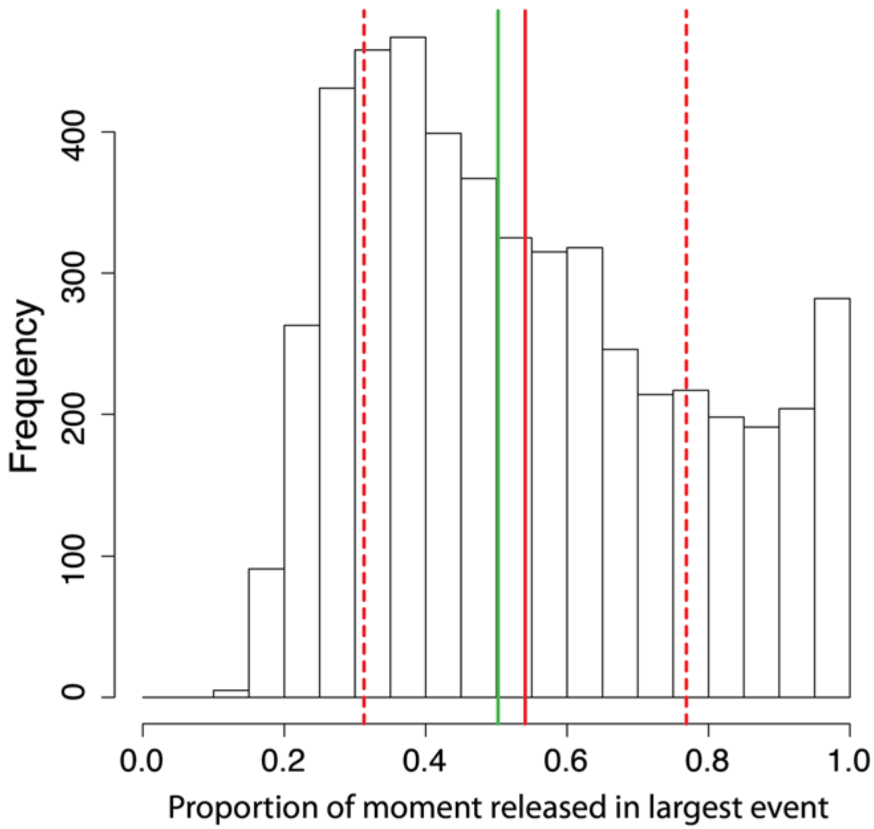


Poisson counting errors propagate into **2 orders of magnitude fluctuations** in total seismic moment released in a given time

Moment release totally dominated by largest events

Main & Naylor EPJ (2012)

Uncertainty in assuming $\sum M_i \cong 2M_{max}$



Red lines: Mean and standard deviations 0.54±0.22

Green line: $\sum M_i \cong 2M_{max}$

Evolution of partition factor

We know

$$\sum M_i = \left(\frac{B}{1-B}\right) M_{min} N^{\frac{1}{B}}$$

After yield at *t*=0, the partition factor $= X(t) = \varepsilon^S/\varepsilon^T$ evolves for linear strain rates as

$$X(t) = \frac{\sum M_i\,(t)}{2\mu V(\varepsilon_0^T + \dot{\varepsilon} t)} = \frac{\left(\frac{B}{1-B}\right)\left(\frac{M_{min}}{2\mu V \varepsilon_0^T}\right) N^{1/B}}{(1 + \dot{\varepsilon} t/\varepsilon_0^T)}$$

For a **transient power-law model** (Main, 2000) $N(t) = N_0(1 + t/\tau)^{\alpha};\ \alpha > 0$

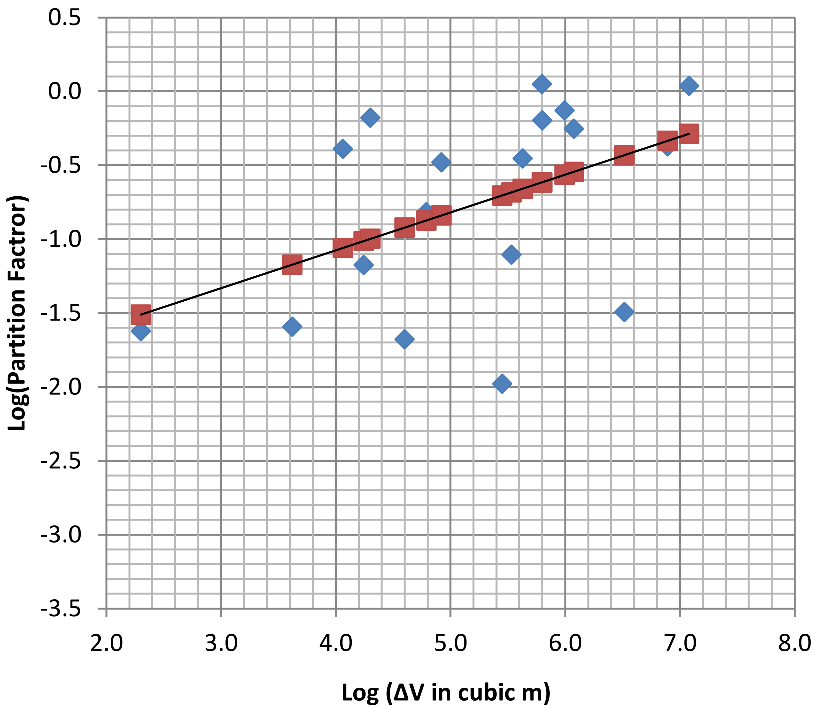
At large strains

$$\boxed{X(t) = A t^{\left(\frac{\alpha}{B}-1\right)}}$$

For **inverse power-law growth**, after integration

$$\boxed{X(t) = A\,\frac{\left[1-(1-t/tf)^{\frac{1-p}{B}}\right]}{t}}$$

Implied Partition Factor



$$\log(Y) = 0.25(\pm 0.23)\log(\Delta V) - 2.10(\pm 1.26)$$

r^2=0.217

Partition factor increases slowly with strain, as a power law of exponent ~1/4

$$\frac{\alpha}{B} - 1 \cong \frac{1}{4}$$

$$\alpha \cong 5/6$$

implies near-linear, slowly decelerating event rate

Large scatter dominates, roughly similar to the finite sampling error – low correlation coefficient

Assumes $\Delta V = \nabla \dot{V} t$

Conclusions

- Total strain = elastic + seismic + silent damage or creep
- The location of silent damage can be inferred from changes in hydraulic properties (flow rate), as well as geodetic data
- Discrete element models can now reproduce lab observations, inc. evolution of stress, event rate and *b*-value
- (More needs to be done on coupling to pore fluid pressure and add time-dependent weakening)
- In a spatial sample, field data for fluid injection strain partition is consistent with a transient power-law even rate model with *b*~1, but
- The transient power-law model is only marginally preferred over one where strain partition is invariant of strain (ΔBIC~2)
- Fluctuations in strain partition for real data (not just the biased sample) exceed finite sampling errors