Earthquake triggering

From aftershocks to induced seismicity

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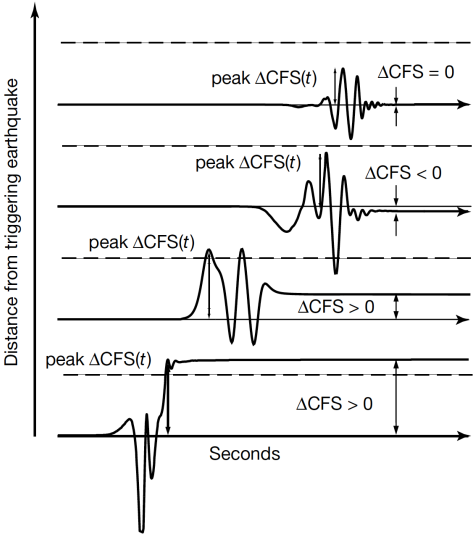
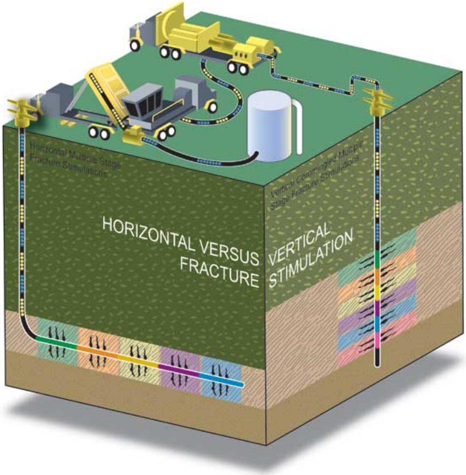
Outline

1. Definition of aftershocks and how to identify them
2. Temporal characteristics of (induced) seismicity
3. Statistical properties of aftershocks and underlying physics
4. Summary & Discussion

Earthquake-earthquake triggering (Kilb '00)



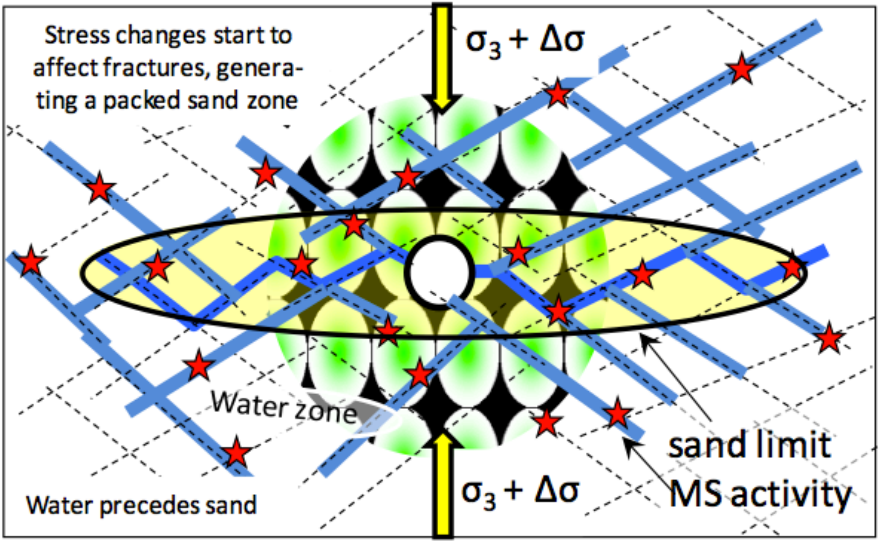
Example of induced seismicity: hydraulic fracturing



Fact

- *In order to enhance permeability, high pressure fluids are injected to activate (or create) fractures*
- *Proppant (e.g. sand) is typically mixed into the injected slurry, to hold fractures open*

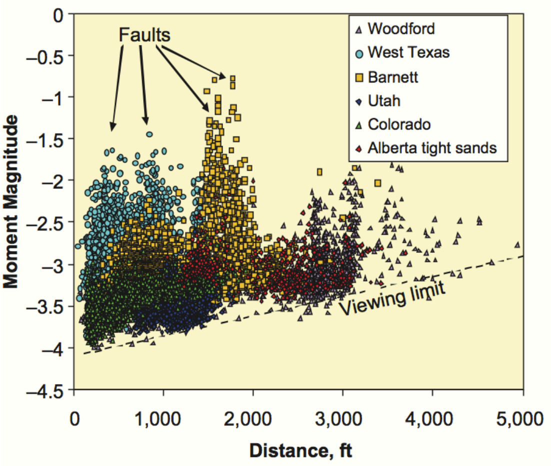
Induced microseismicity (Dusseault & McLennan ’11)



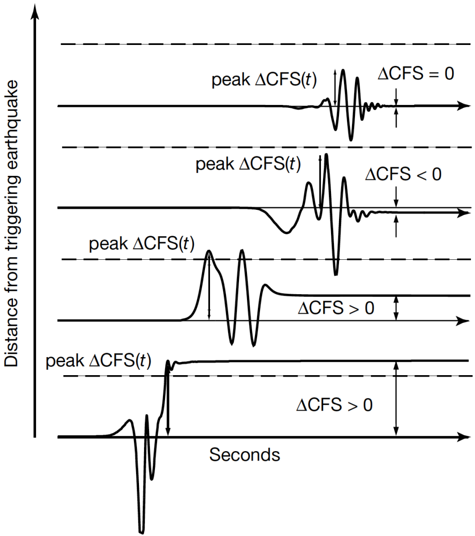
Triggering slip on existing faults (Warpinski '09)

Definitions

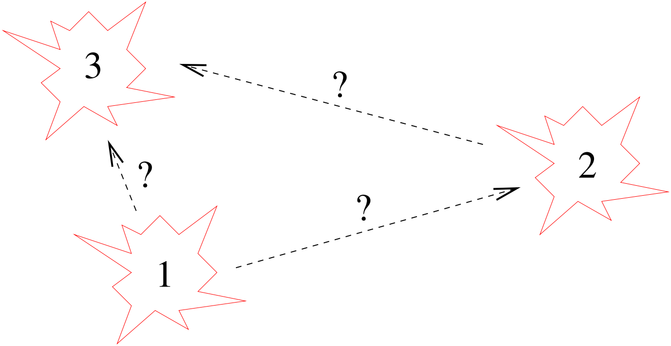
- Induced: Seismic event directly caused by human activities
- Triggered: Failure of a pre-existing zone of weakness due to a perturbation in state (may be natural or artificial)



Earthquake-earthquake triggering (Kilb ’00)

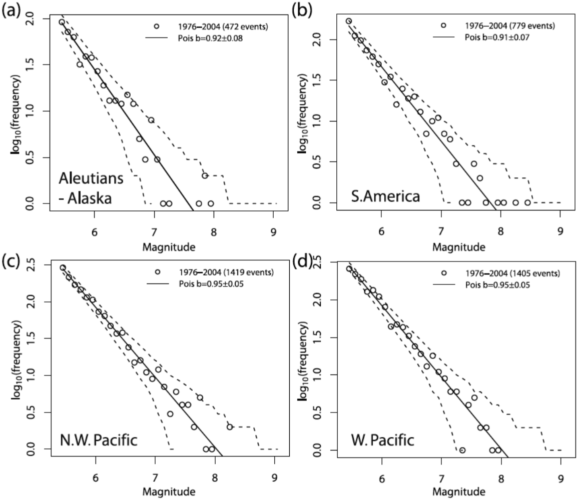


Spatiotemporal clustering & triggering



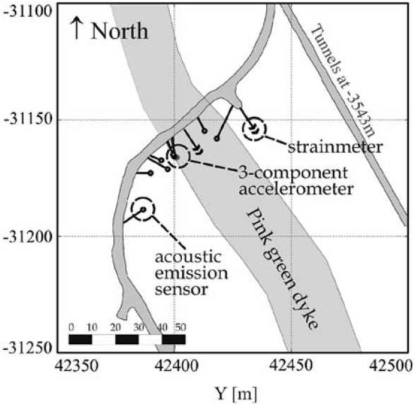
- Underlying microscopic dynamics is typically not observable
- Challenge: Infer triggering cascade and define “aftershocks”
- Need to identify suitable null model of uncorrelated events

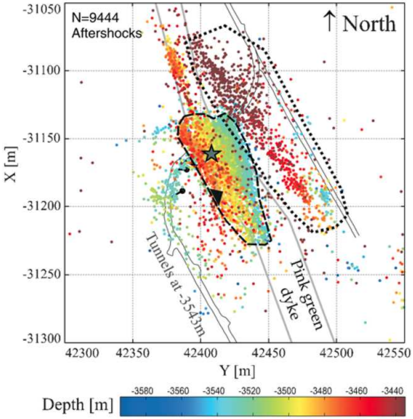
Gutenberg-Richter law: scale-free & universal



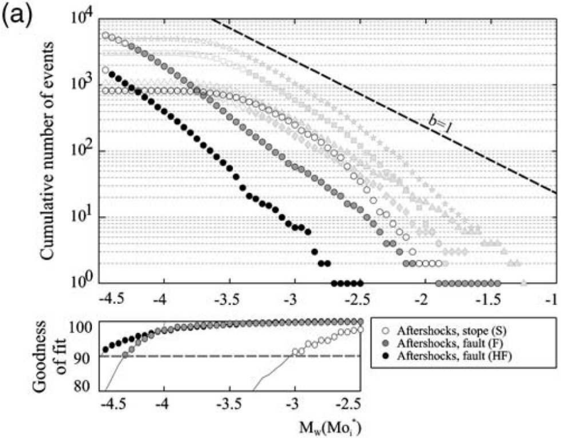
$$\log_{10} N(m' > m) = a(\Delta t, \mathrm{area}) - b\, m \Longrightarrow N(M' > M) \propto M^{-b/c}$$

JAGUARS: “Aftershock” sequence of $M_W = 1.9$ event



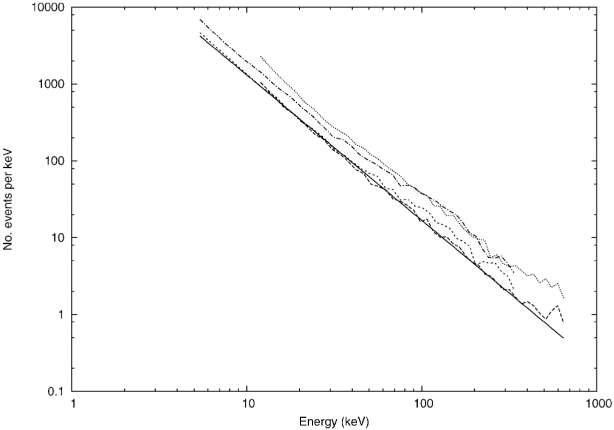


JAGUARS: Gutenberg-Richter law (Kwiatek '10)



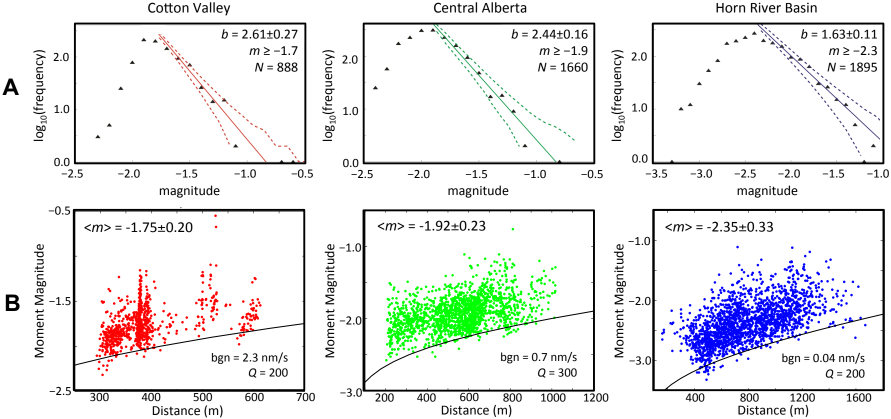
$$\log_{10} N(m' > m) = a(\Delta t, \mathrm{area}) - b\, m \Longrightarrow N(M' > M) \propto M^{-b/c}$$

CRESST: Fracture of sapphire crystal (Åström ’06)

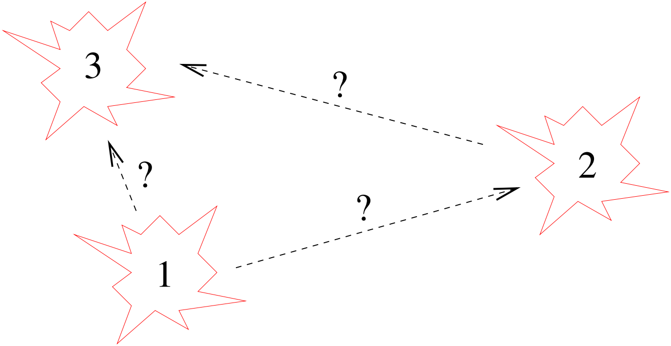


Assuming $E \propto M$: $b = c\,(\beta - 1) \in [1.0; 1.4]$

BUT: Hydraulic fracturing (Eaton et al. ’14)



Spatiotemporal clustering & triggering



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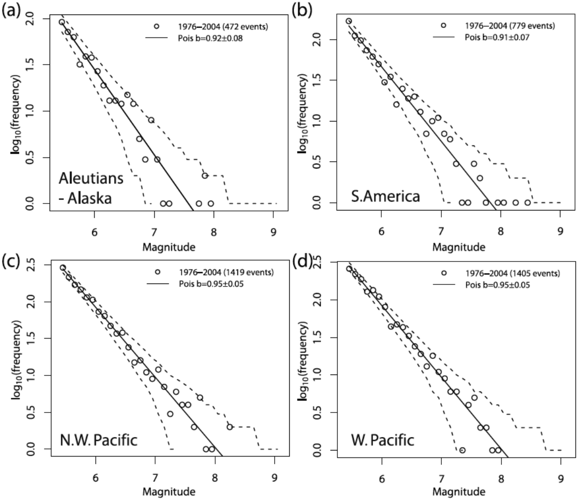
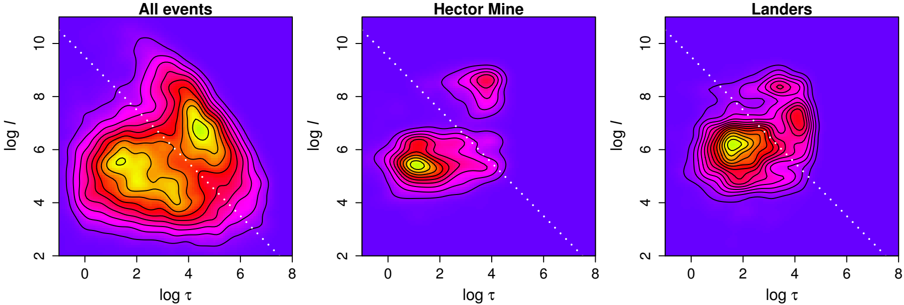
Null model: Poisson process with GR rate



$$\log_{10} N(m' > m) = a(\Delta t, \mathrm{area}) - b\, m \Longrightarrow N(M' > M) \propto M^{-b/c}$$

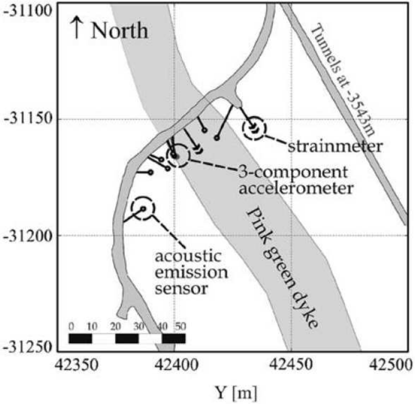
Identifying aftershocks (Baiesi'04, Zaliapin'08, Gu'13)

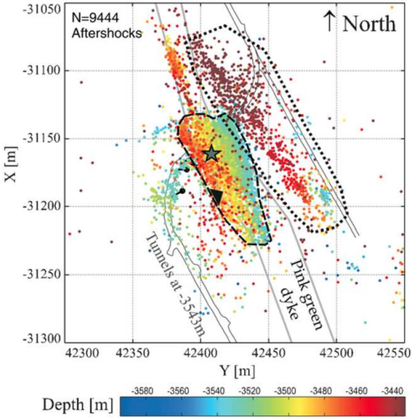
$$n_{ij} = c \cdot (r_{ij})^{D_f}\, t_{ij} 10^{-b\, m_i} \qquad n^*_j \equiv \min_{i<j}\{n_{ij}\}$$



$$\tau_{*j} = t_{*j} 10^{-b\, m_*/2} \qquad l_{*j} = (r_{*j})^{D_f}\, 10^{-b\, m_*/2}$$

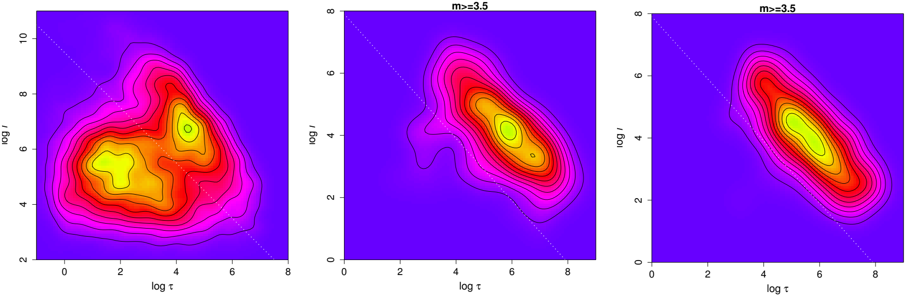
JAGUARS: “Aftershock” sequence of $M_W = 1.9$ event





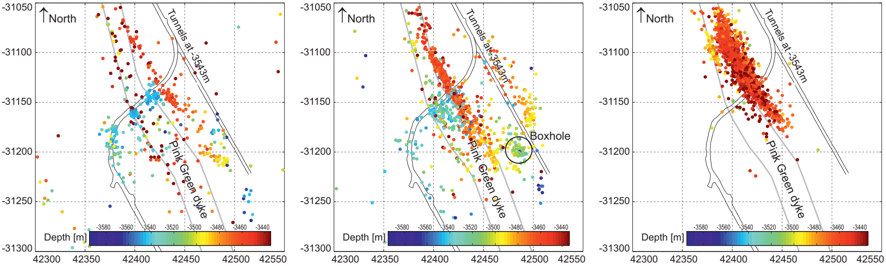
Secondary aftershocks in the $M_W = 1.9$ sequence

$$n_{ij} = c \cdot (r_{ij})^{D_f}\, t_{ij} 10^{-b\, m_i} \qquad n_j^* = \min_{i<j}\{n_{ij}\}$$

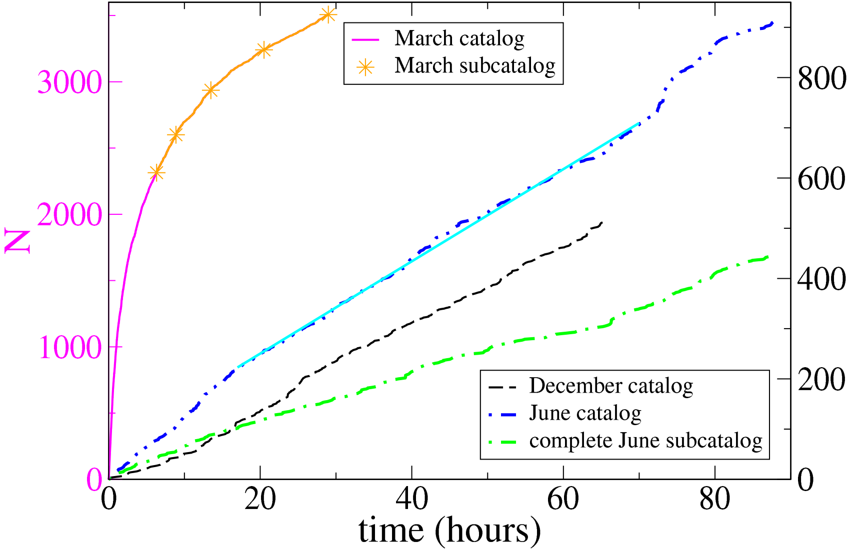


$$\tau_{*j} = t_{*j} 10^{-b\, m_*/2} \qquad l_{*j} = (r_{*j})^{D_f}\, 10^{-b\, m_*/2}$$

JAGUARS project: (Induced) Micro, nano- and picoseismicty (Davidsen et al. ’13)

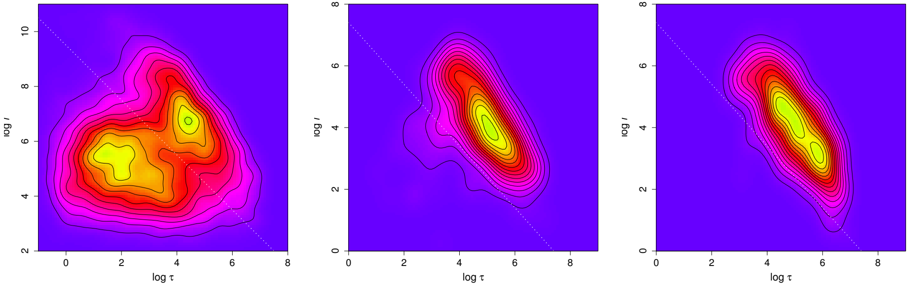


JAGUARS project: Seismic activity



Identifying aftershocks in the complete June catalog

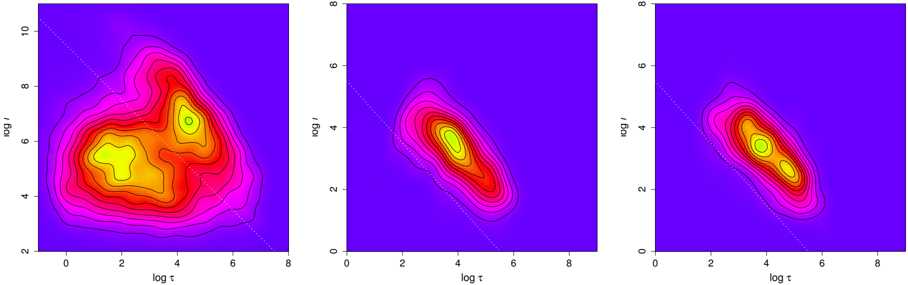
$$n_{ij} = c \cdot (r_{ij})^{D_f}\, t_{ij} 10^{-b\, m_i} \qquad n_j^* \equiv \min_{i<j}\{n_{ij}\}$$



$$\tau_{*j} = t_{*j} 10^{-b\, m_*/2} \qquad l_{*j} = (r_{*j})^{D_f}\, 10^{-b\, m_*/2}$$

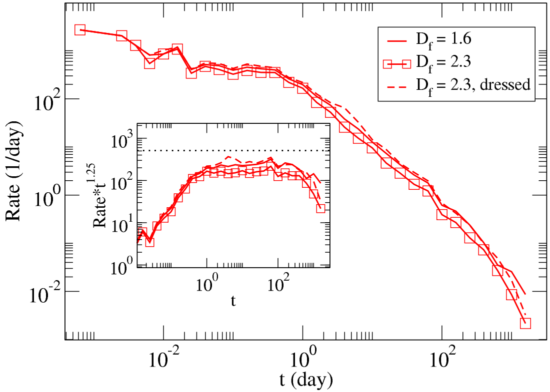
Secondary aftershocks in a blasting catalog

$$n_{ij} = c \cdot (r_{ij})^{D_f}\, t_{ij} 10^{-b\,m_i} \qquad n_j^* \equiv \min_{i<j}\{n_{ij}\}$$



$$\tau_{*j} = t_{*j} 10^{-b\,m_*/2} \qquad l_{*j} = (r_{*j})^{D_f}\, 10^{-b\,m_*/2}$$

Omori-Utsu law: Hector Mine (Gu'13)



$$\lambda(t, m > m_c|M) = \frac{\chi(m_c,M)}{(t+c(m_c,M))^p} \text{ with } p \approx 1$$

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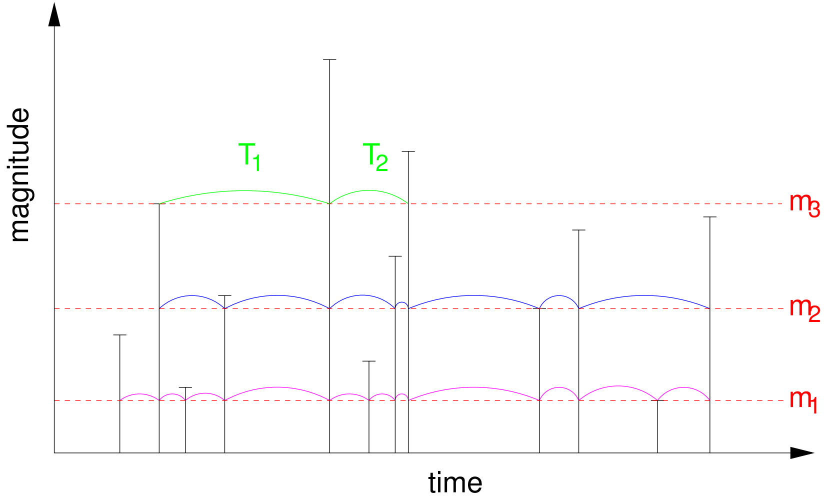
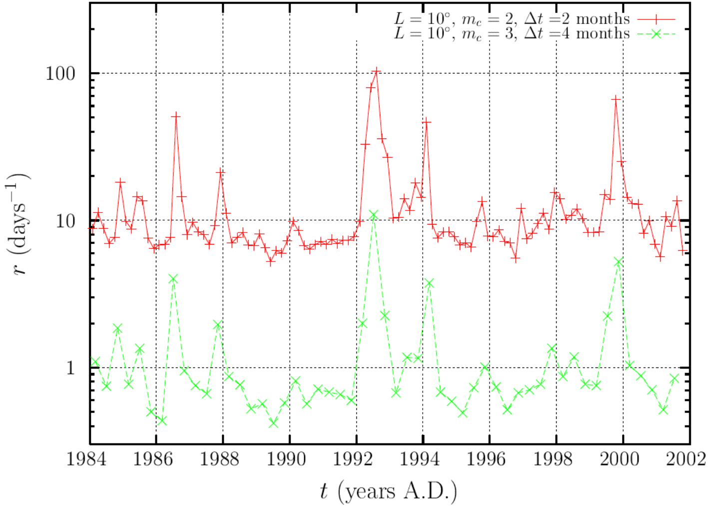
Interevent times & temporal clustering

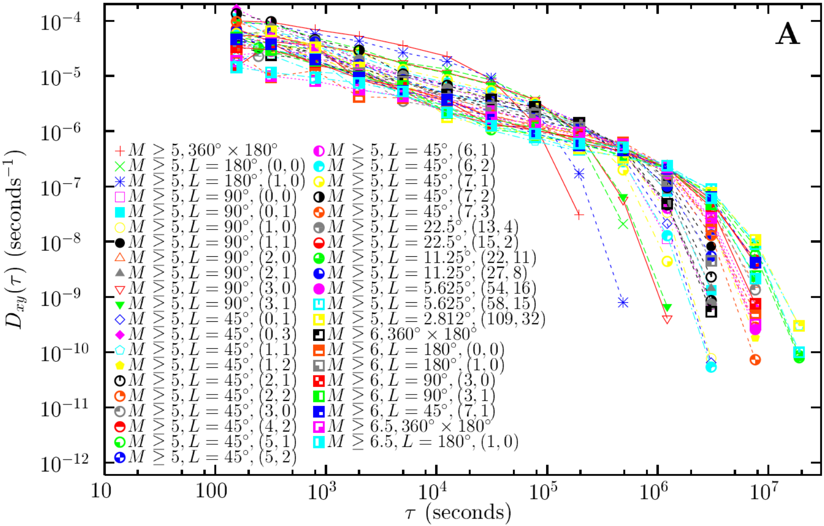


Interevent time distribution depends on *m* and *L*, e.g.: $\langle T \rangle = \frac{\Delta t}{N-1}$

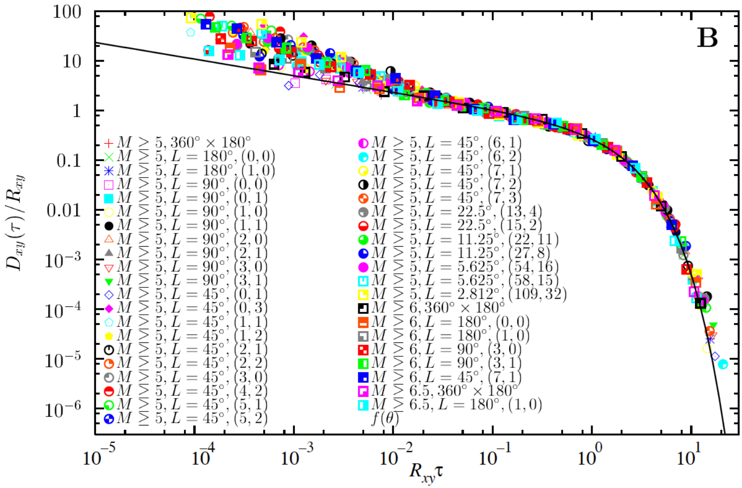
Rate of earthquake occurrence: California (Corral ’03)



“Stationary” interevent time distributions (Corral ’04)

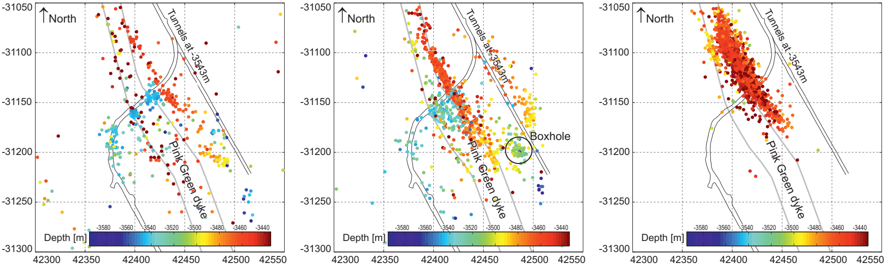


Rescaled interevent time distributions (Corral ’04)

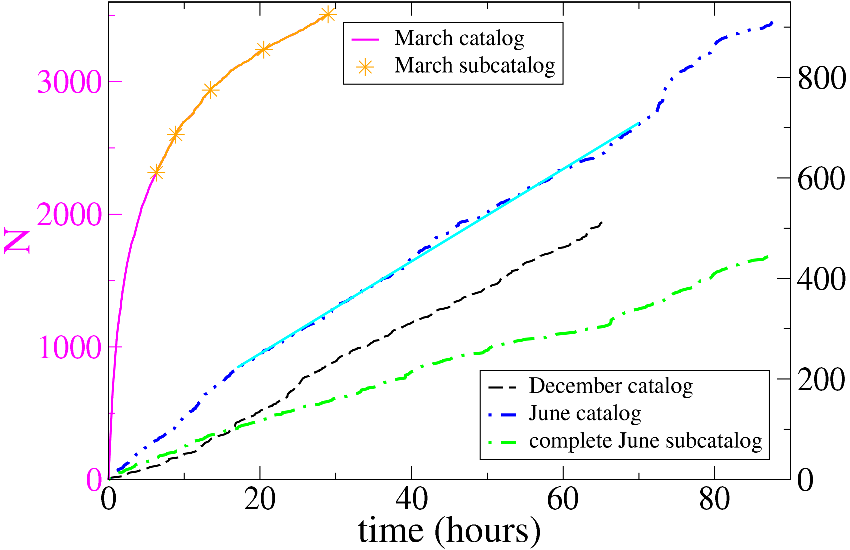


$$D_{xy}(\tau) = R_{xy}\, f(R_{xy}\tau) \qquad f(x) = \frac{0.50}{x^{0.33}} \exp^{(-x^{0.98}/1.58)}$$

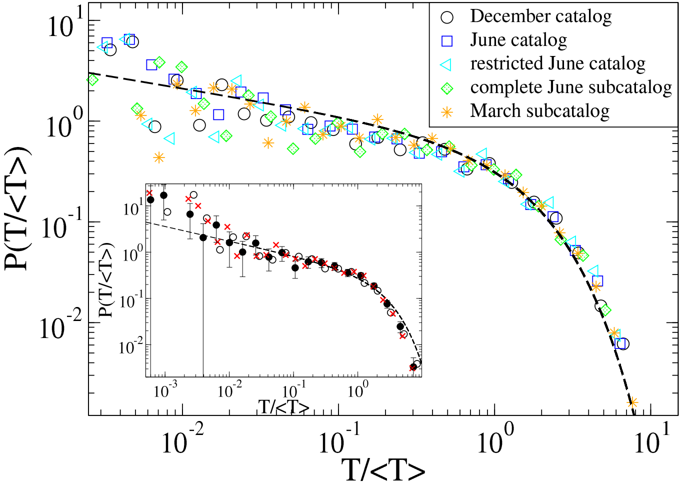
JAGUARS project: (Induced) Micro, nano- and picoseismicty (Davidsen et al. ’13)



JAGUARS project: Seismic activity

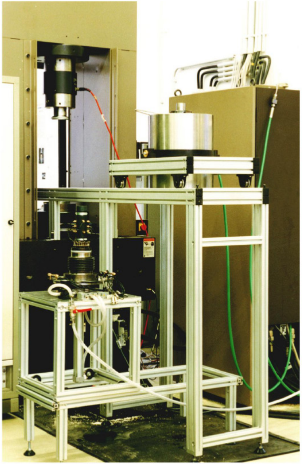


JAGUARS project: Interevent time distributions



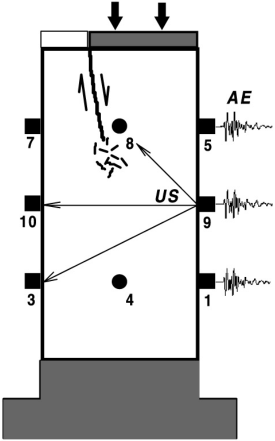
$P_C(T) = P(T/\langle T\rangle_C)/\langle T\rangle_C$ $\quad P(\theta) \propto \theta^{-0.32}\ \exp^{(-\theta/1.47)}$

Rock fracture and acoustic emissions



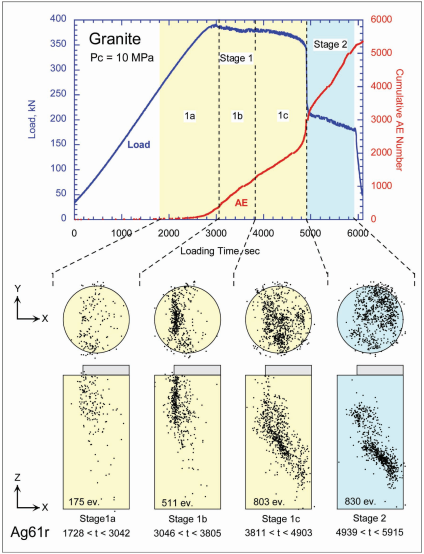
(a)

(b)

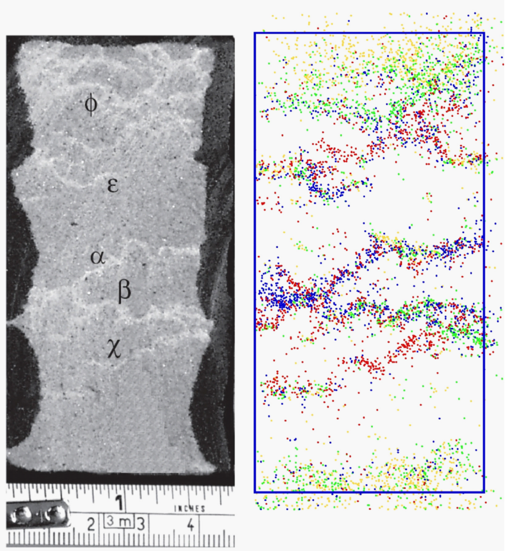


(c)

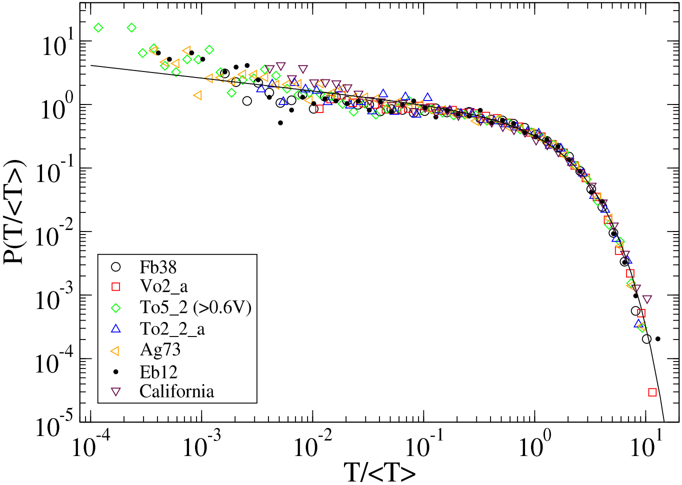
Example: AFC loading curve



Compaction bands in sandstone

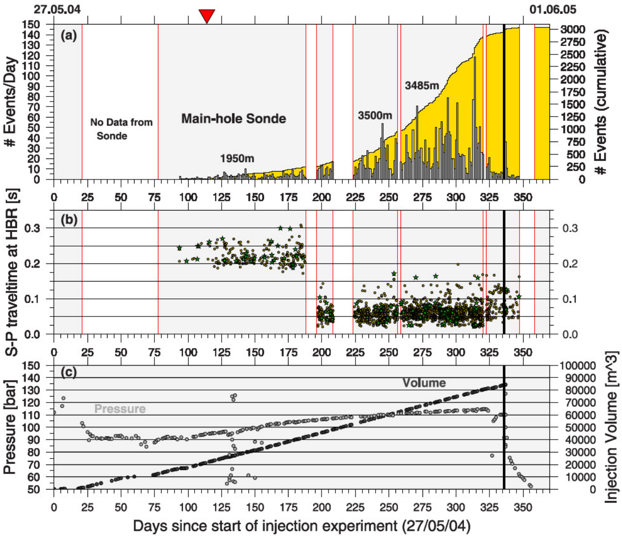


Rescaled interevent time distributions (Davidsen ’07)

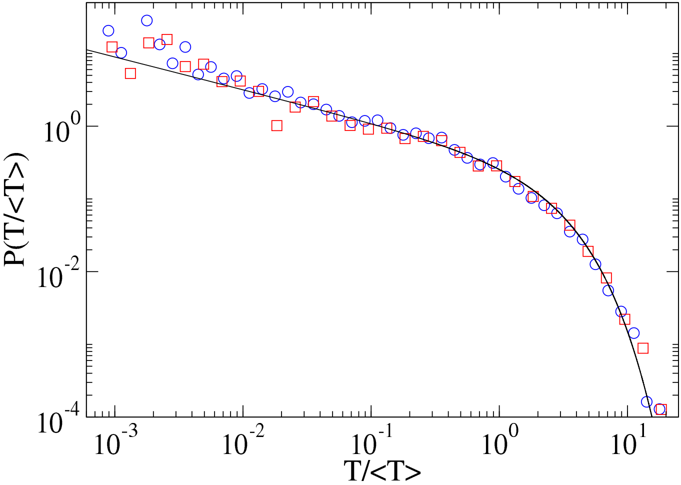


$P_E(T) = P(T/\langle T\rangle_E)/\langle T\rangle_E$ $\qquad$ $P(\theta) \propto \theta^{-0.2}\ \exp^{(-\theta/1.4)}$

Induced seismicty: 2004/05 KTB project (Shaprio ’06)

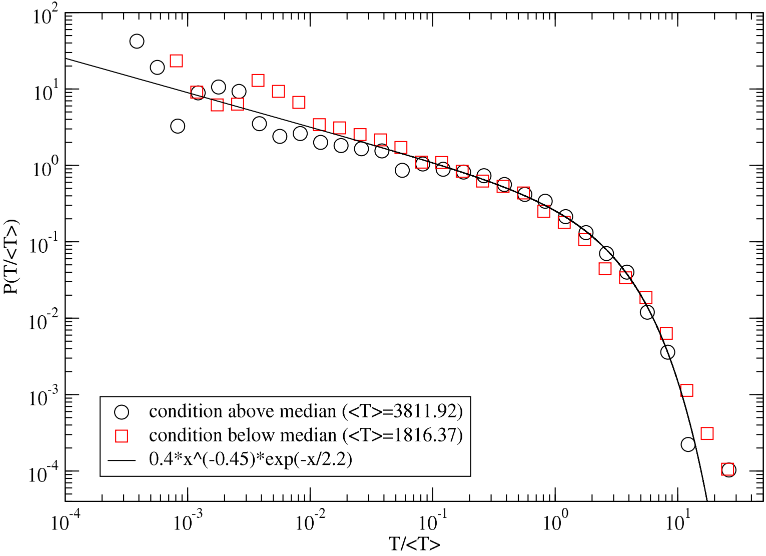


KTB: Interevent time distribution (Davidsen et al. ’13)

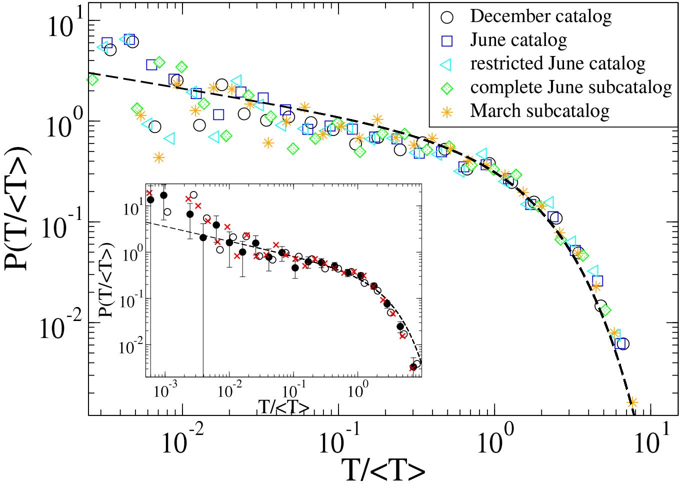


$P_C(T) = P(T/\langle T\rangle_C)/\langle T\rangle_C \qquad P(\theta) \propto \theta^{-0.45}\ \exp^{(-\theta/2.2)}$

KTB project: Conditional interevent time distribution

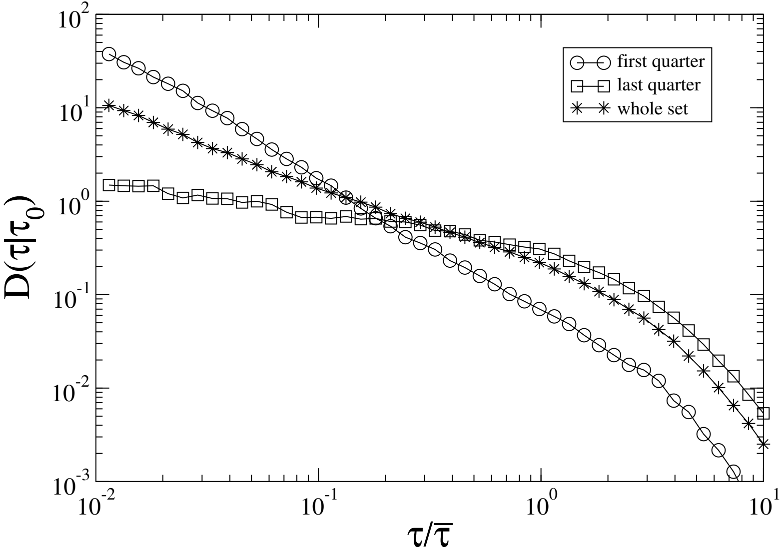


JAGUARS: Conditional interevent time distributions



$$P_C(T) = P(T/\langle T\rangle_C)/\langle T\rangle_C \qquad P(\theta) \propto \theta^{-0.32}\ \exp^{(-\theta/1.47)}$$

California: Conditional interevent time distributions (Livina '05)



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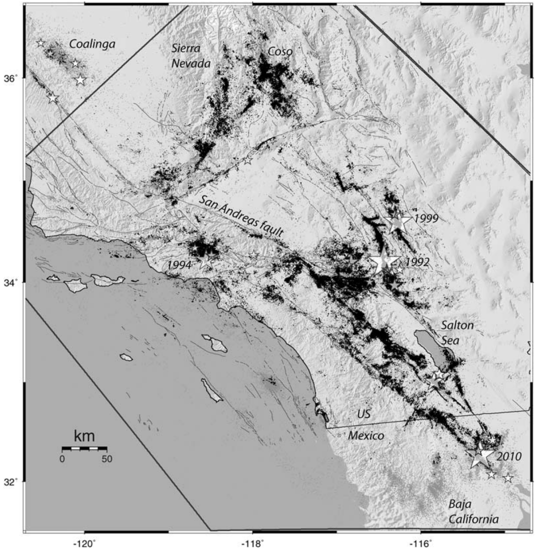
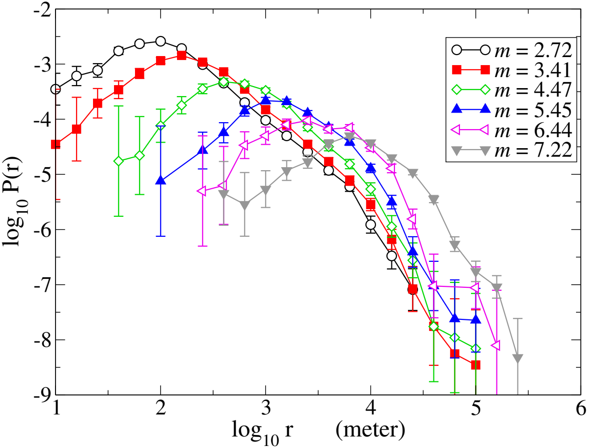
Relocated catalog for S. California (Hauksson '12)

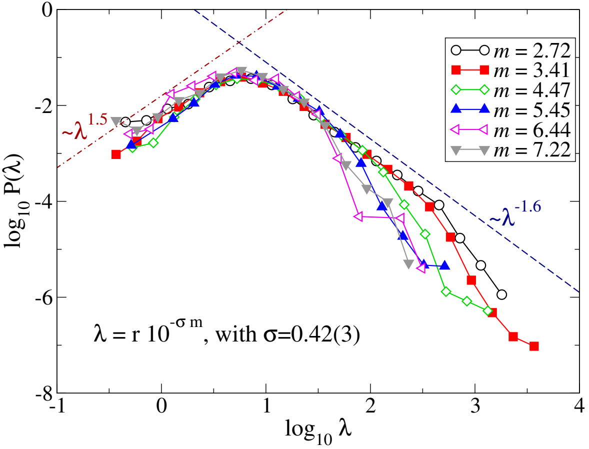


Aftershock density in space (Gu’13, Moradpour’14)



$$P_m(r) = \frac{q r^{\gamma}}{L_m^{\gamma+1}\left(\frac{r^{\gamma+1}}{L_m^{\gamma+1}} + 1\right)^{1+\frac{q}{\gamma+1}}}$$

Self-consistency & importance of rupture length (3D)



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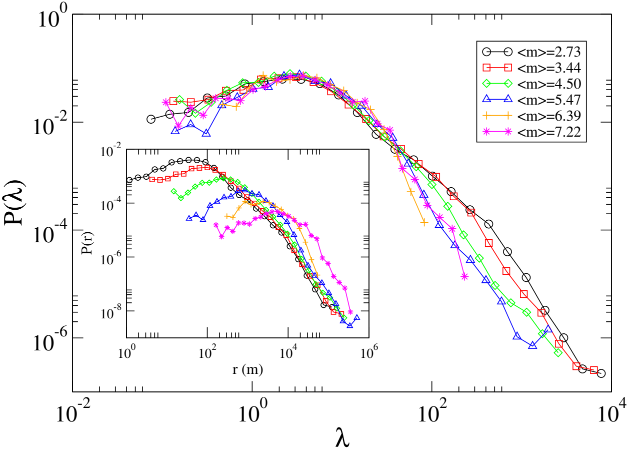
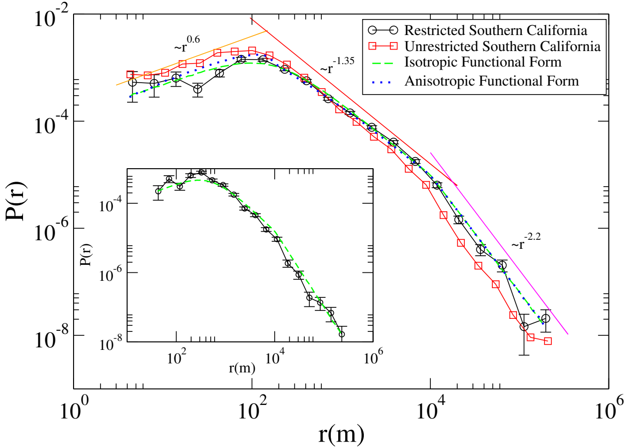
Self-consistency & importance of rupture length (2D)



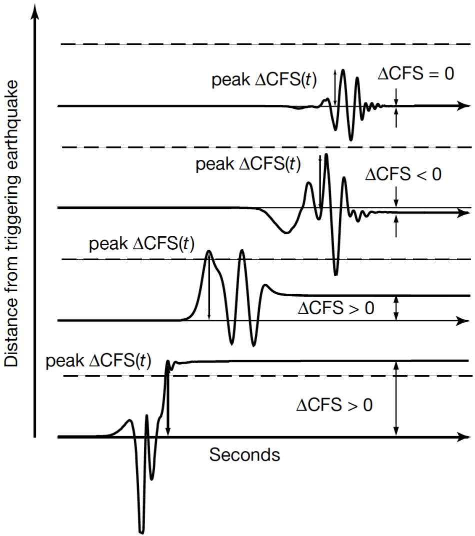
$$P_m(r) = \frac{q r^\gamma}{L_m^{\gamma+1}\left(\frac{r^{\gamma+1}}{L_m^{\gamma+1}} + 1\right)^{1+\frac{q}{\gamma+1}}}$$

Importance for identification of triggering mechanism

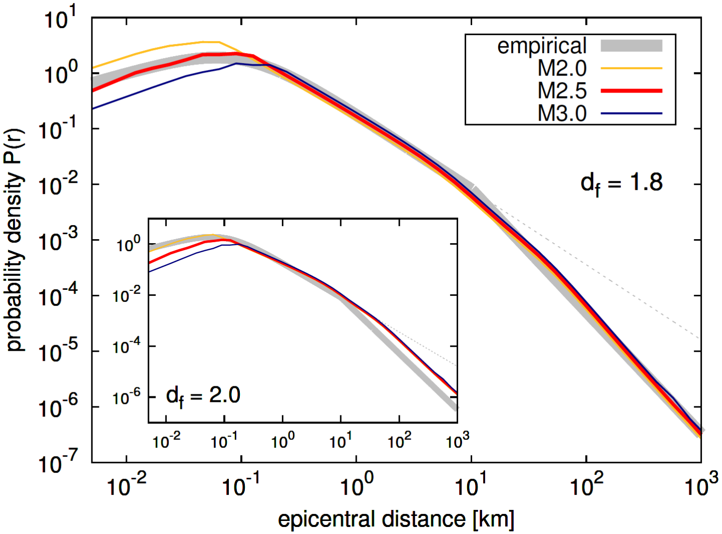


$$P_m(r_{<10km}) = \alpha \frac{q r^\gamma}{L_m^{\gamma+1} \left(\frac{r^{\gamma+1}}{L_m^{\gamma+1}} + 1\right)^{1+\frac{q}{\gamma+1}}}, \quad P_m(r_{>10km}) = \beta \frac{d r^\gamma}{L_m^{\gamma+1} \left(\frac{r^{\gamma+1}}{L_m^{\gamma+1}} + 1\right)^{1+\frac{d}{\gamma+1}}}$$

Static vs. dynamic stress triggering in nature (Kilb '00)



Modeling static stress triggering in Southern California



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- Interevent time distribution is form-invariant with respect to the energy scale and underlying cause
- Role of aftershocks for interevent time distribution?

Thanks!

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Geophys. Prospecting 62, 806 (2014)
J. Geophys. Res. 119, 5518 (2014)
J. Geophys. Res. 118, 4278 (2013)
Phys. Rev. Lett. 110, 068501 (2013)
Phys. Rev. Lett. 98, 125502 (2007)

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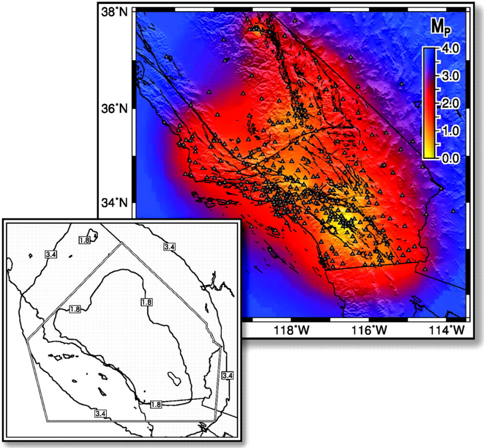
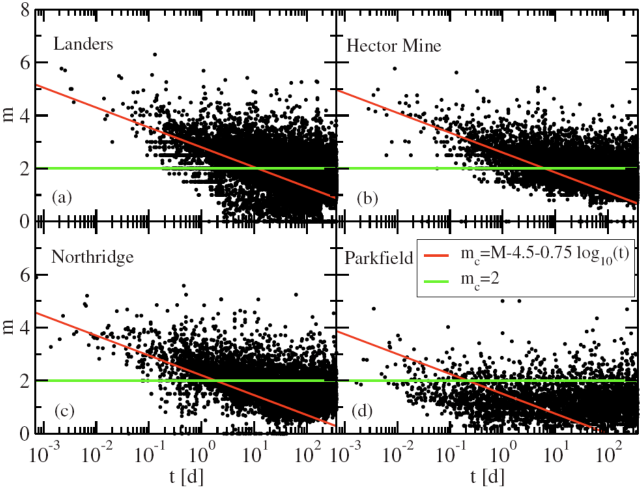
CALGARY, AB

Map of probabilistic magnitude of completeness

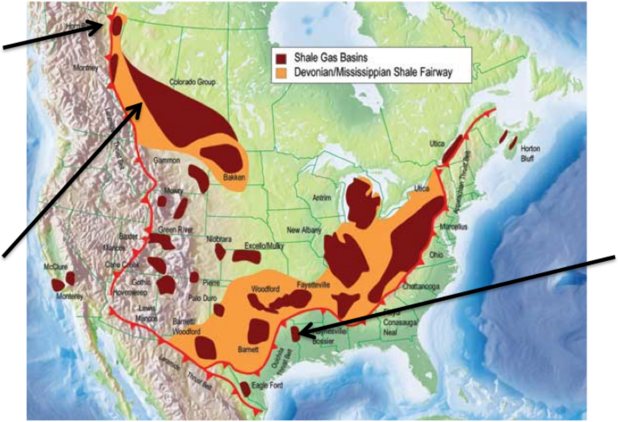


The completeness of SCSN is $M_P \geq 3.4$ for the authoritative region ignoring offshore areas. (BSSA 98, 2103)

Short-term aftershock incompleteness (Helmstetter'06)



Case study of fracking: 3 microseismic catalogs



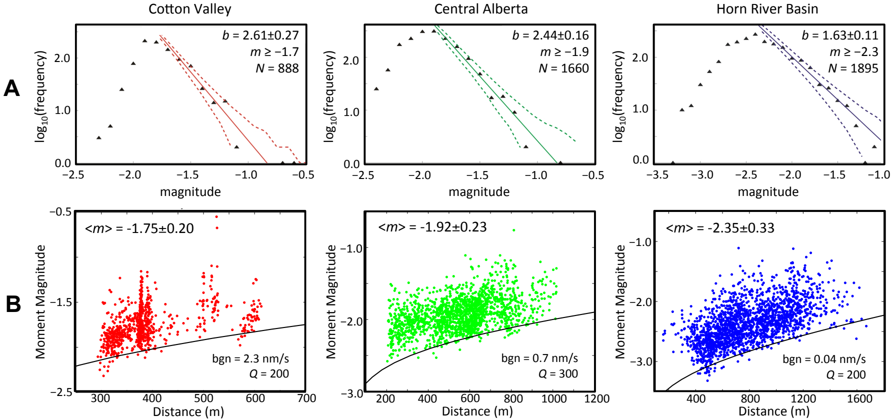
Horn River Basin
(courtesy EOG Resources)

Central Alberta
(Eaton et al. 2013; courtesy ConocoPhillips Canada)

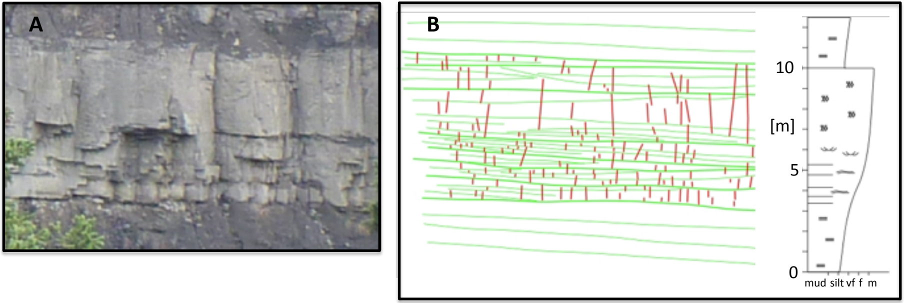
Cotton Valley
(Walker et al., 1997; Rutledge et al., 2004)

National Energy Board (2009), A Primer for Understanding Canadian Shale Gas

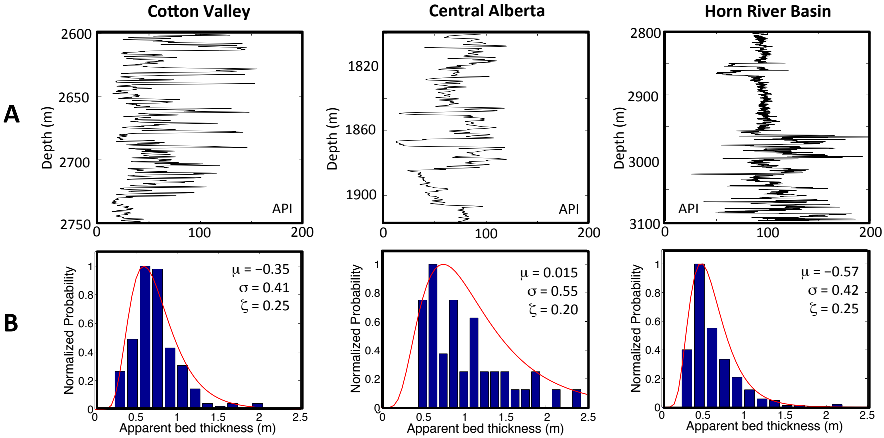
Frequency-magnitude distributions (Eaton et al. ’14)



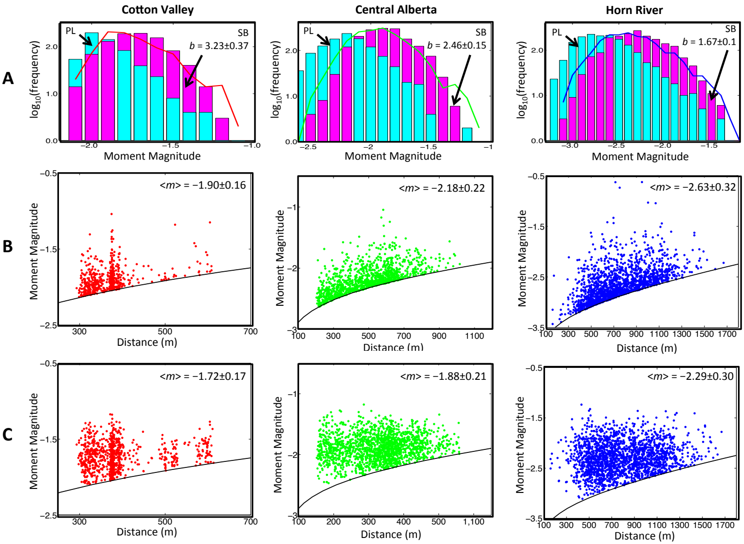
Central Alberta: Natural fractures



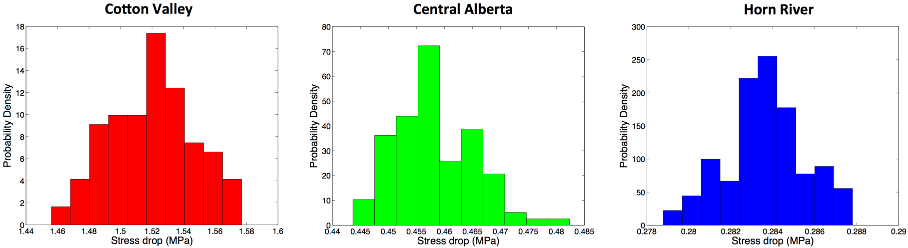
Mechanical bed thickness from borehole γ-ray logs



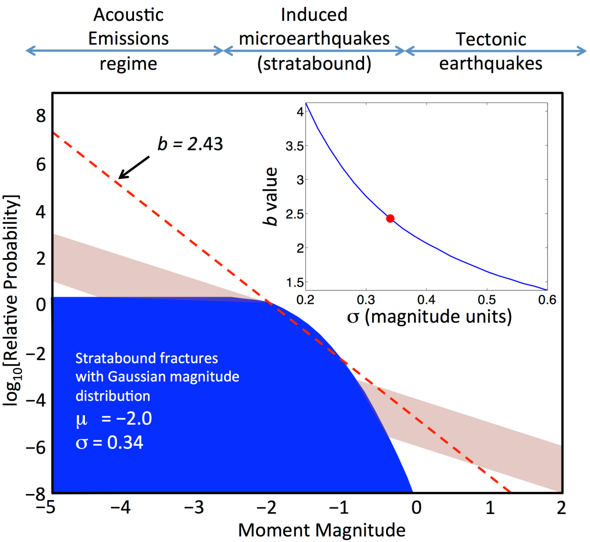
Stratabound model vs. power-law model



Estimated stress drop for stratabound model



Implications for hazard assessment



Conclusions: Fracking-induced seismicity

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- A lognormal bed thickness distribution was found for 3 reservoirs investigated here. Combining the stratabound hypothesis with the Brune source model, this fracture height predicts a Gaussian decay in the magnitude distribution
- This model suggests that the *b* value derived from induced microseismic catalogs significantly underestimates the hazard for triggering of larger seismic events by hydraulic fracturing