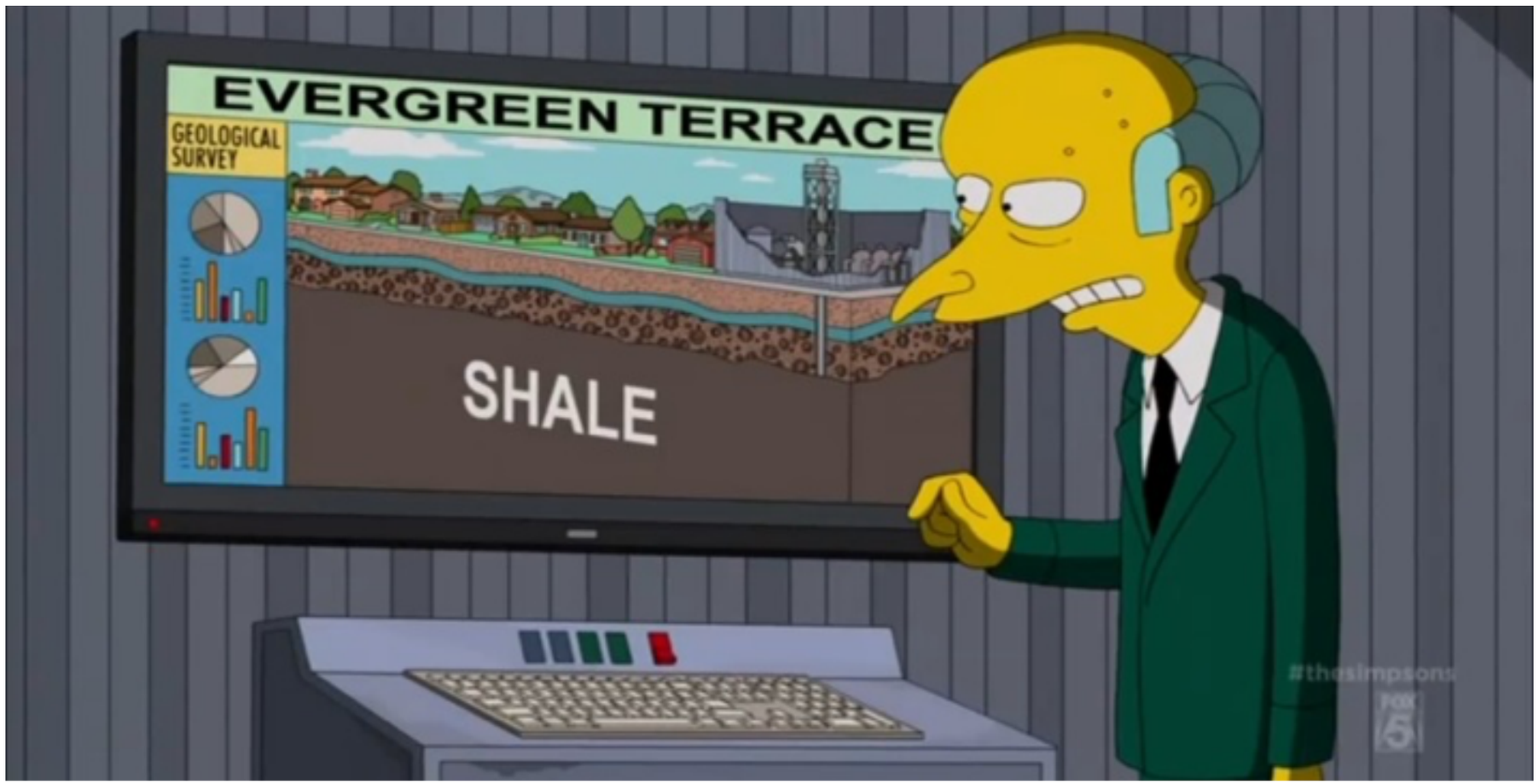
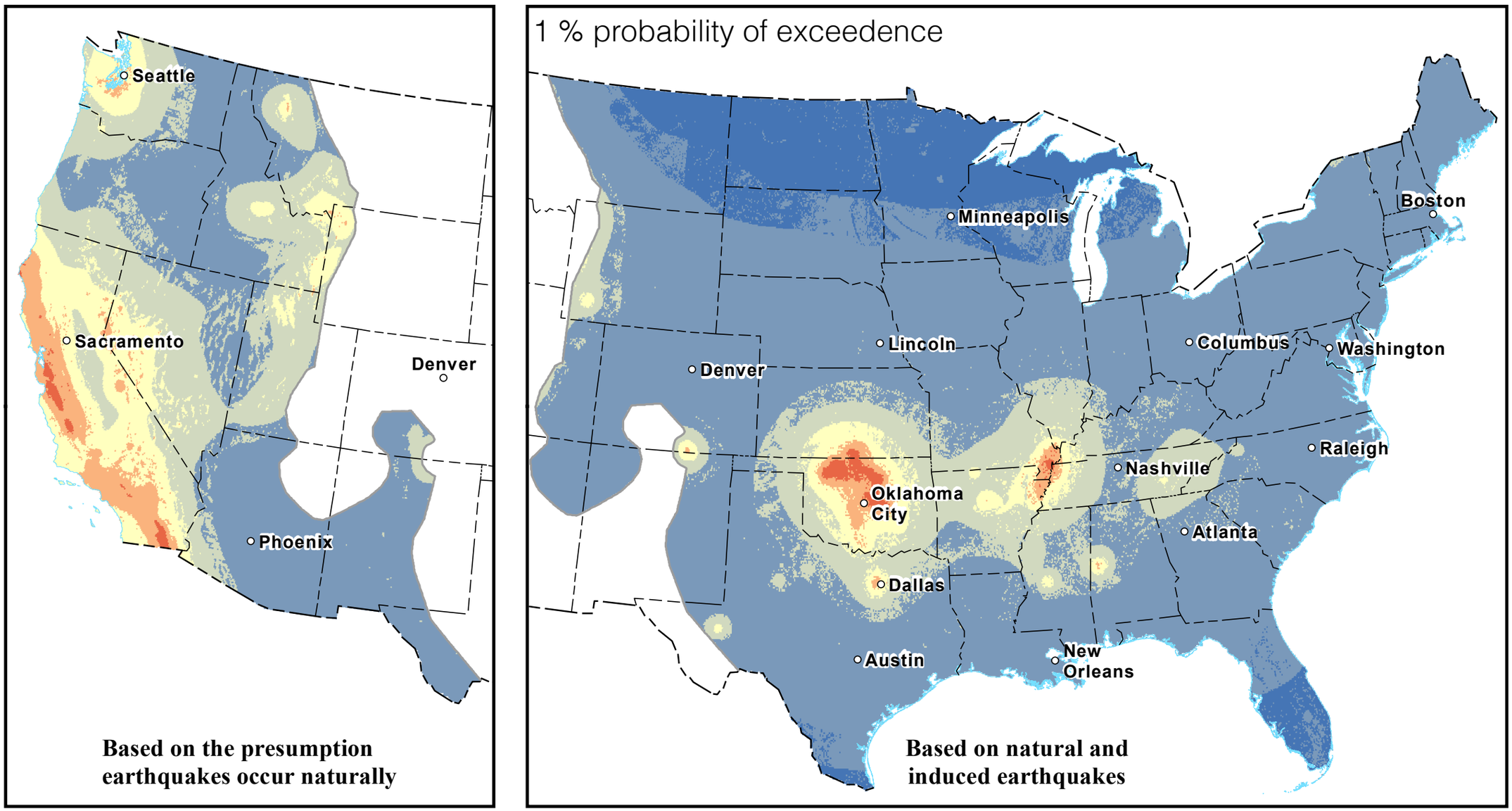
Induced earthquake magnitudes are as large as (statistically) expected.

Nicholas van der Elst, U.S. Geological Survey
Morgan Page, U.S. Geological Survey
Thomas Goebel, UC Santa Cruz and Caltech
Deborah Weiser, USGS and UCLA
S. Mehran Hosseini, USC



Proto-OEF: one-year shaking forecast, including induced seismicity

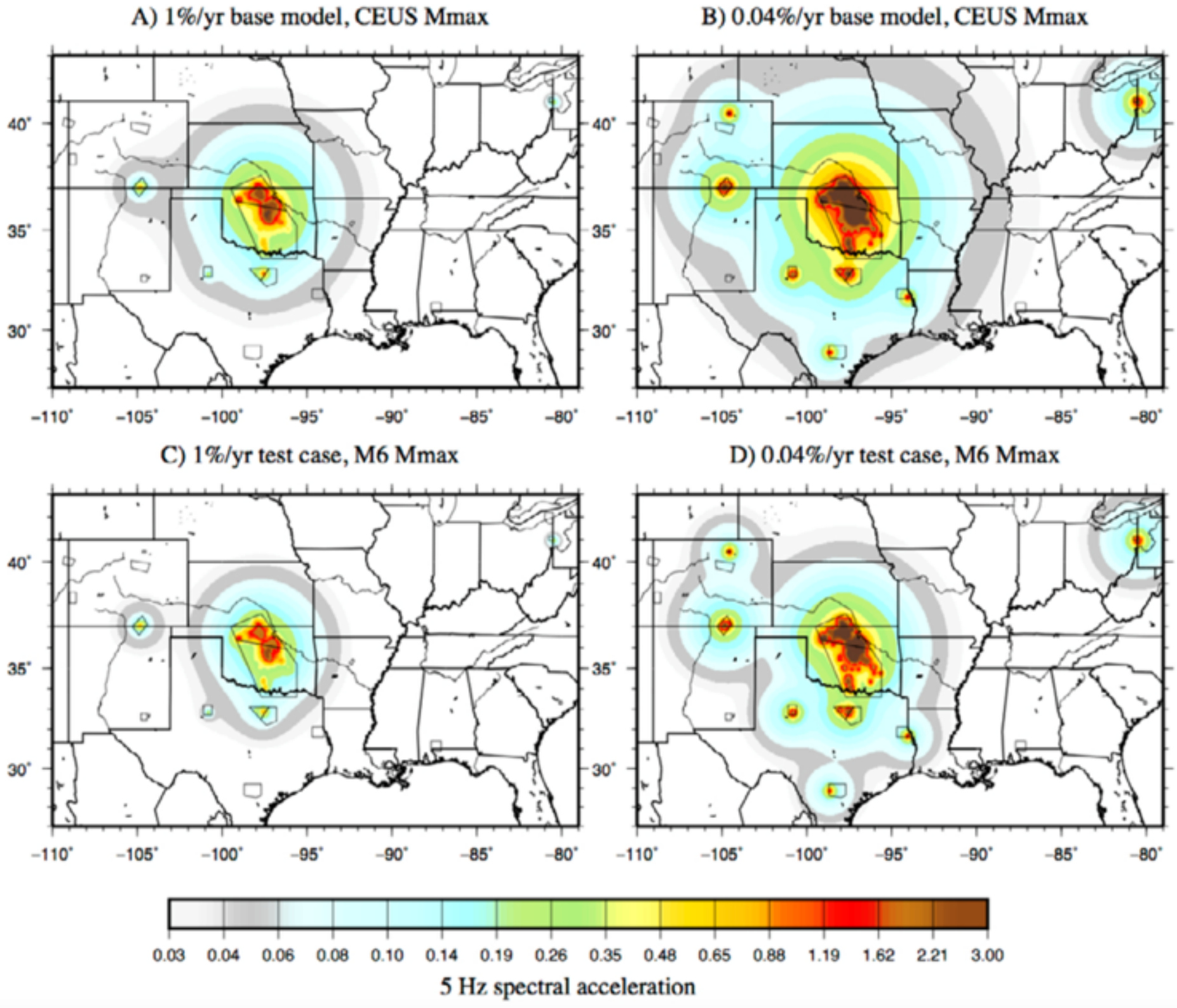


Petersen et al., 2015

Dependence on maximum magnitude

$M_{max} \approx 7$

$M_{max} = 6$



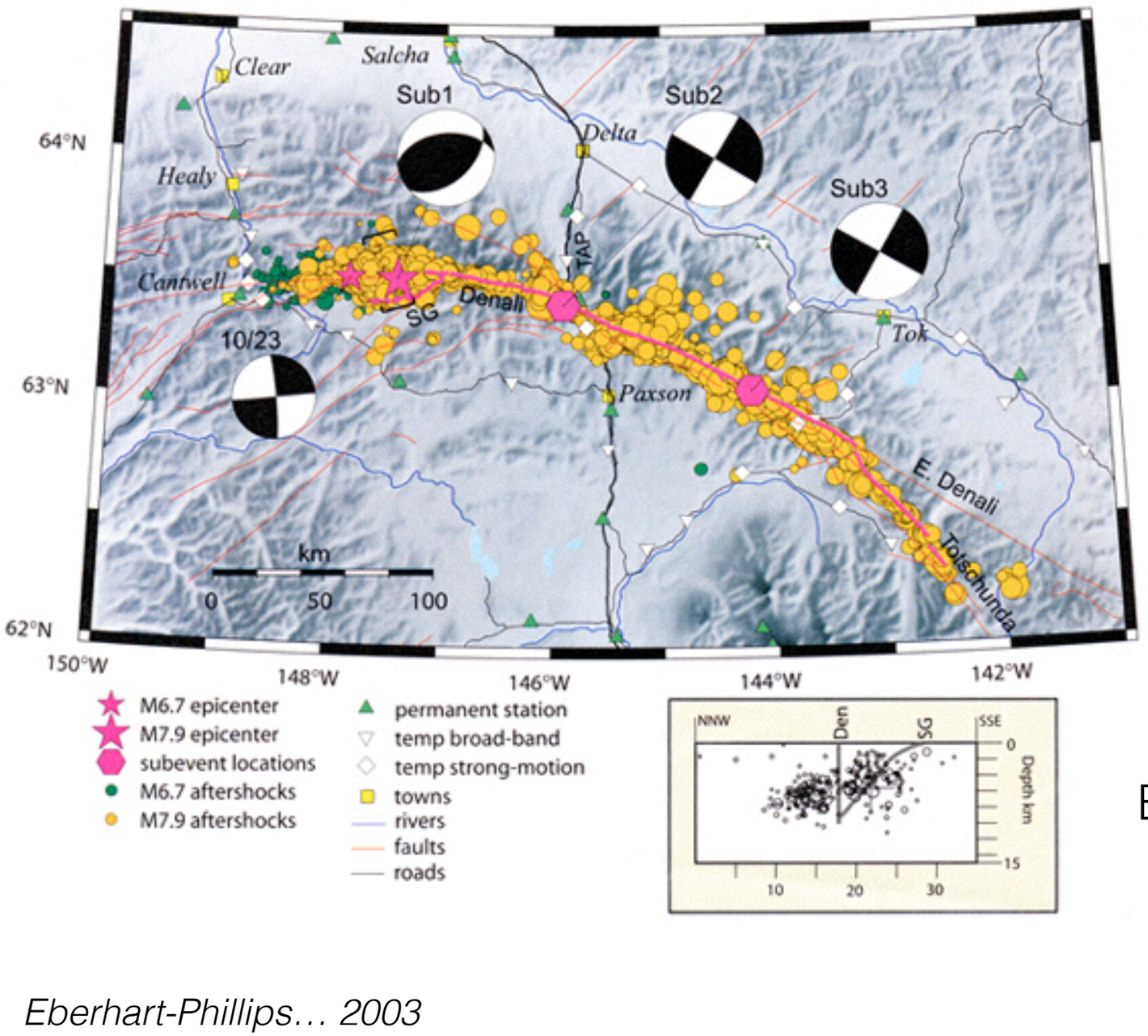
Is there evidence that induced earthquakes are smaller than tectonic?

- Are induced earthquake magnitudes restricted by injection volume?
- Or, are induced earthquake magnitudes determined by the pre-stress and connectivity of the fault network?

- are the observed sizes of induced earthquakes just a consequence of sampling the GR distribution?

Tectonic earthquakes are not confined to the structure on which they initiate

2002 M7.9 Denali Earthquake



Eberhart-Phillips… 2003

<u>A classic question:</u>

Does Gutenberg-Richter reflect the distribution of fault sizes, or the *statistics of earthquake growth and arrest on a complex, inter-connected fault network?*

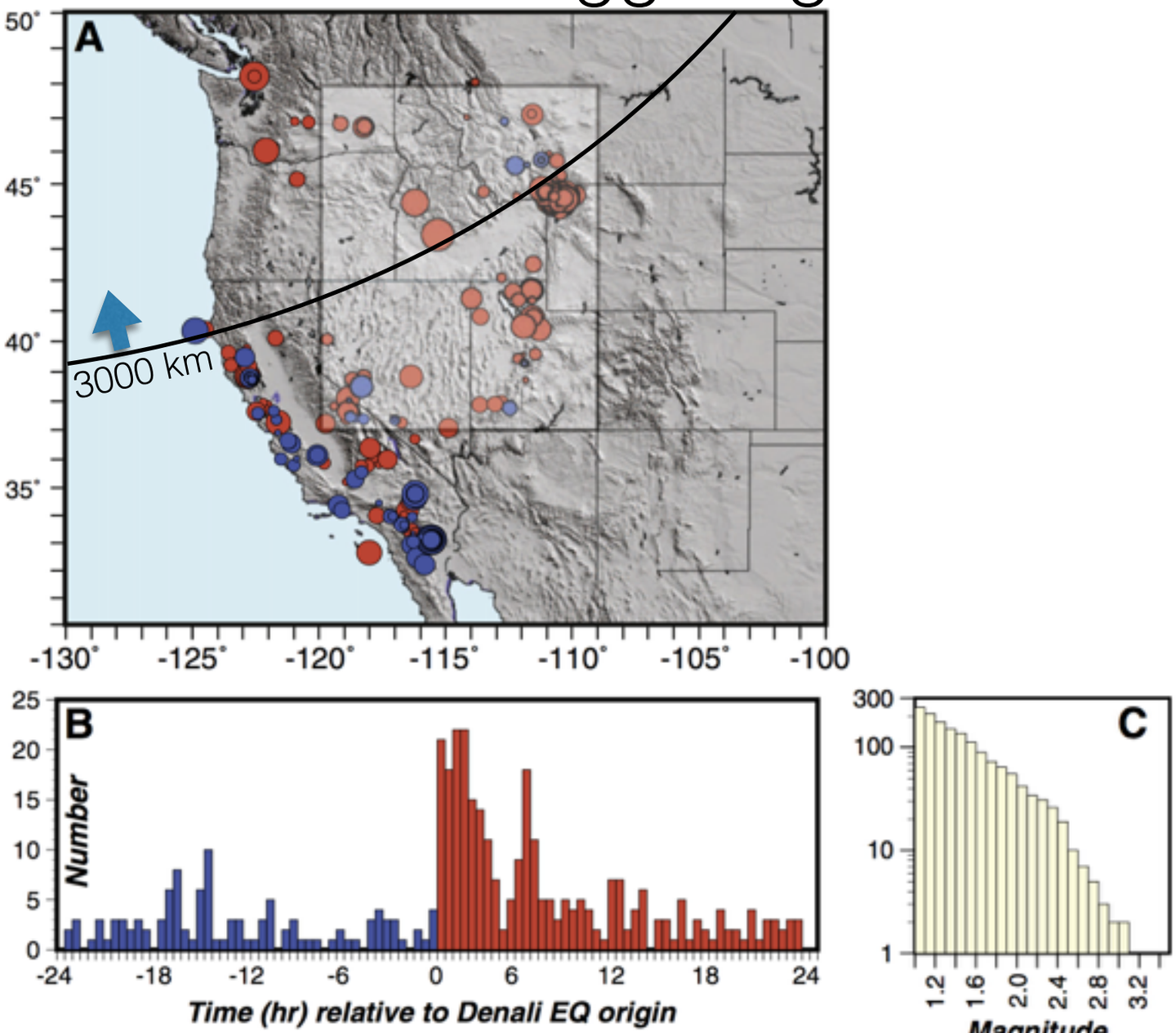
<u>Other examples:</u>

El Mayor-Cucapah

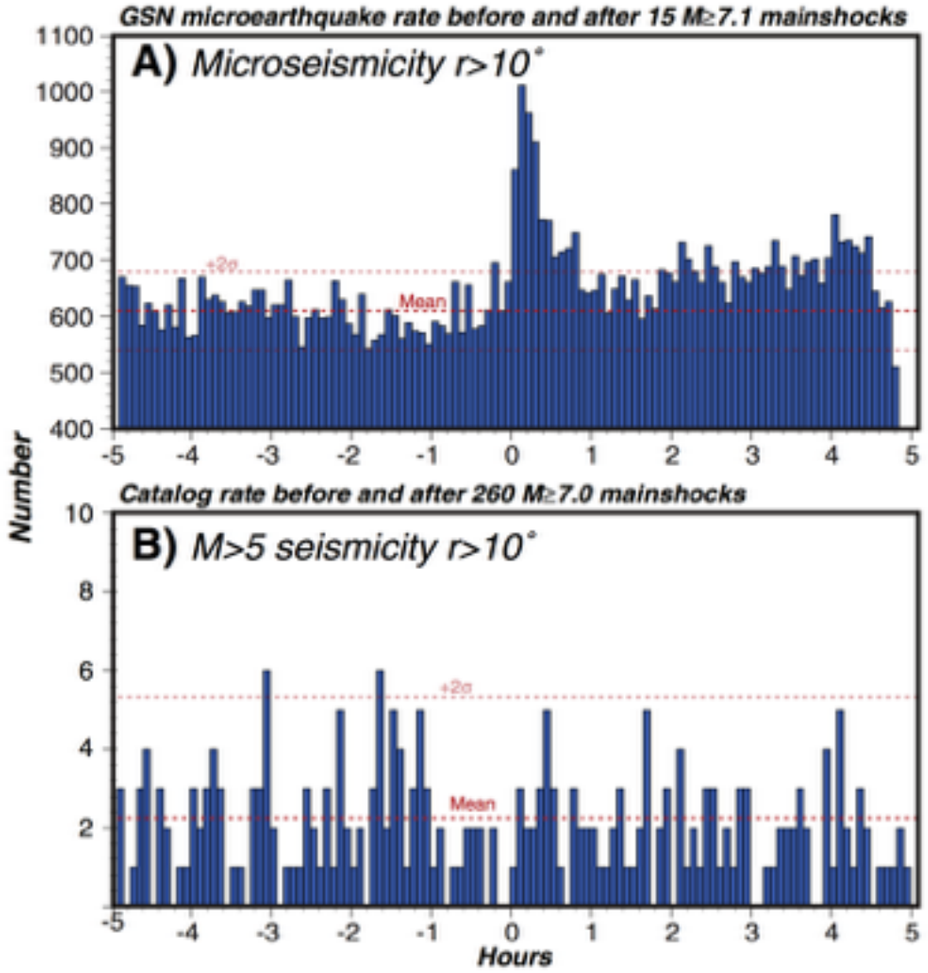
Landers

Cautionary Tale: Remote triggering

Denali remote triggering

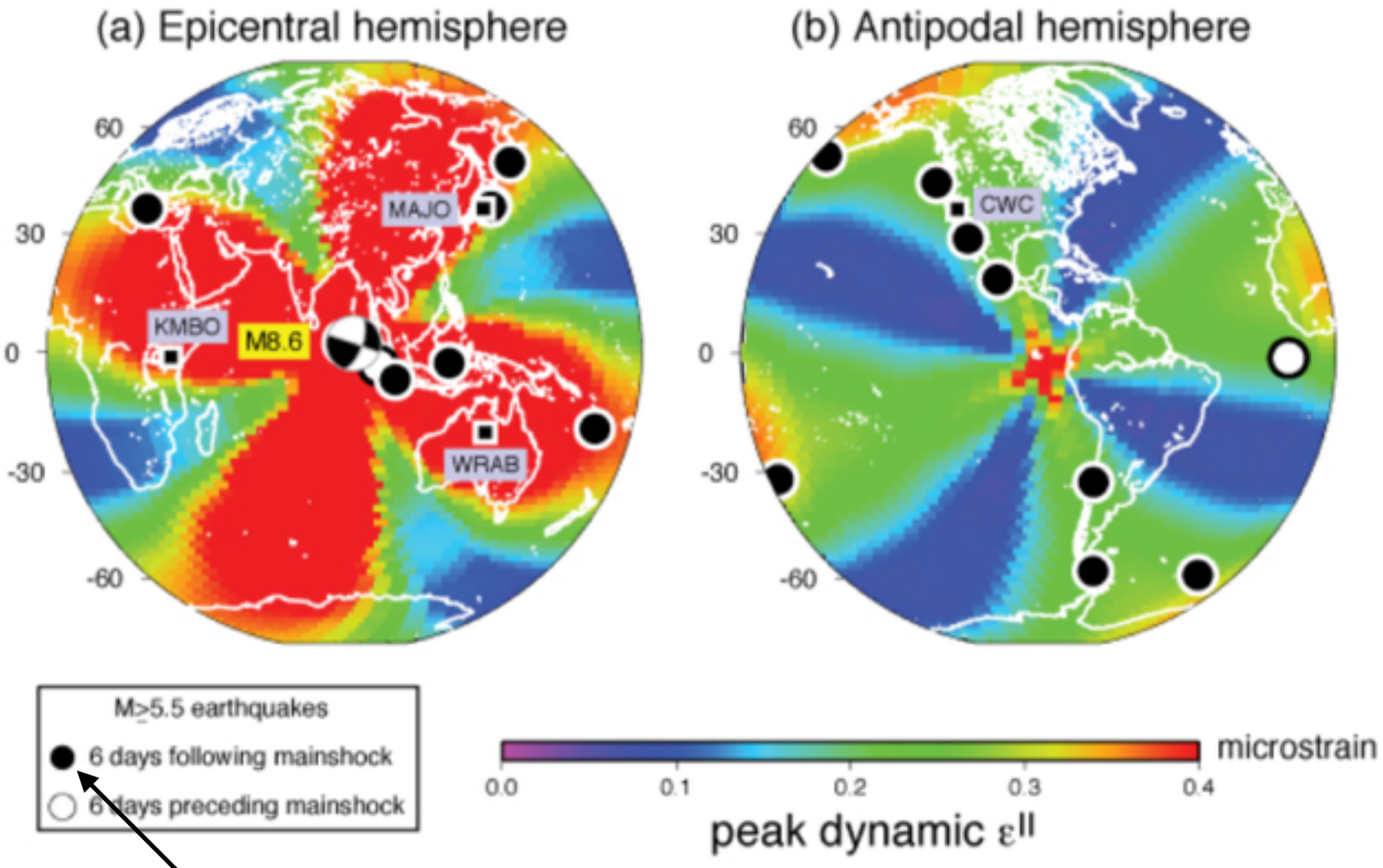


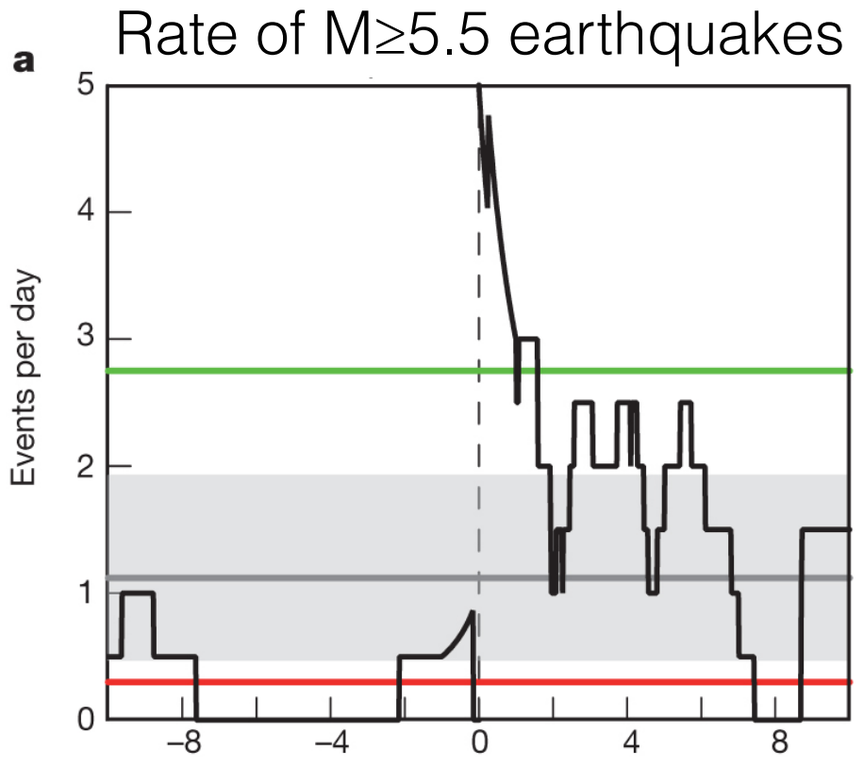
Global stack



Velasco… 2008, Parsons… 2014

But then: 2012 M8.6 East-Indian Ocean



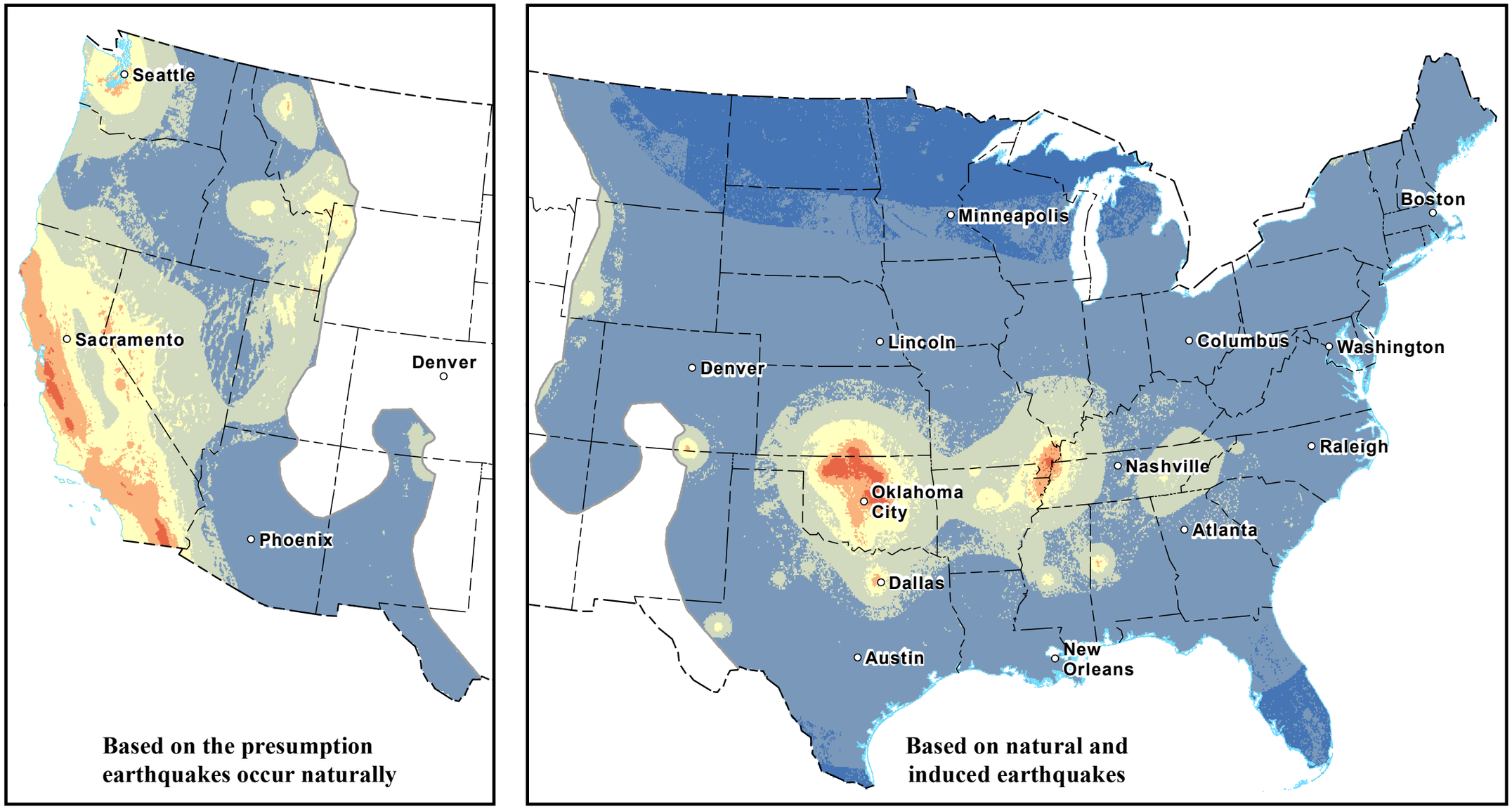


remotely triggered
M≥5.5 earthquakes

Pollitz…, 2012

Could we make the same mistake with induced earthquakes?

USGS Forecast for Ground Shaking Intensity from Natural and Induced Earthquakes in 2016



USGS

Is there evidence that induced earthquakes are smaller than tectonic?

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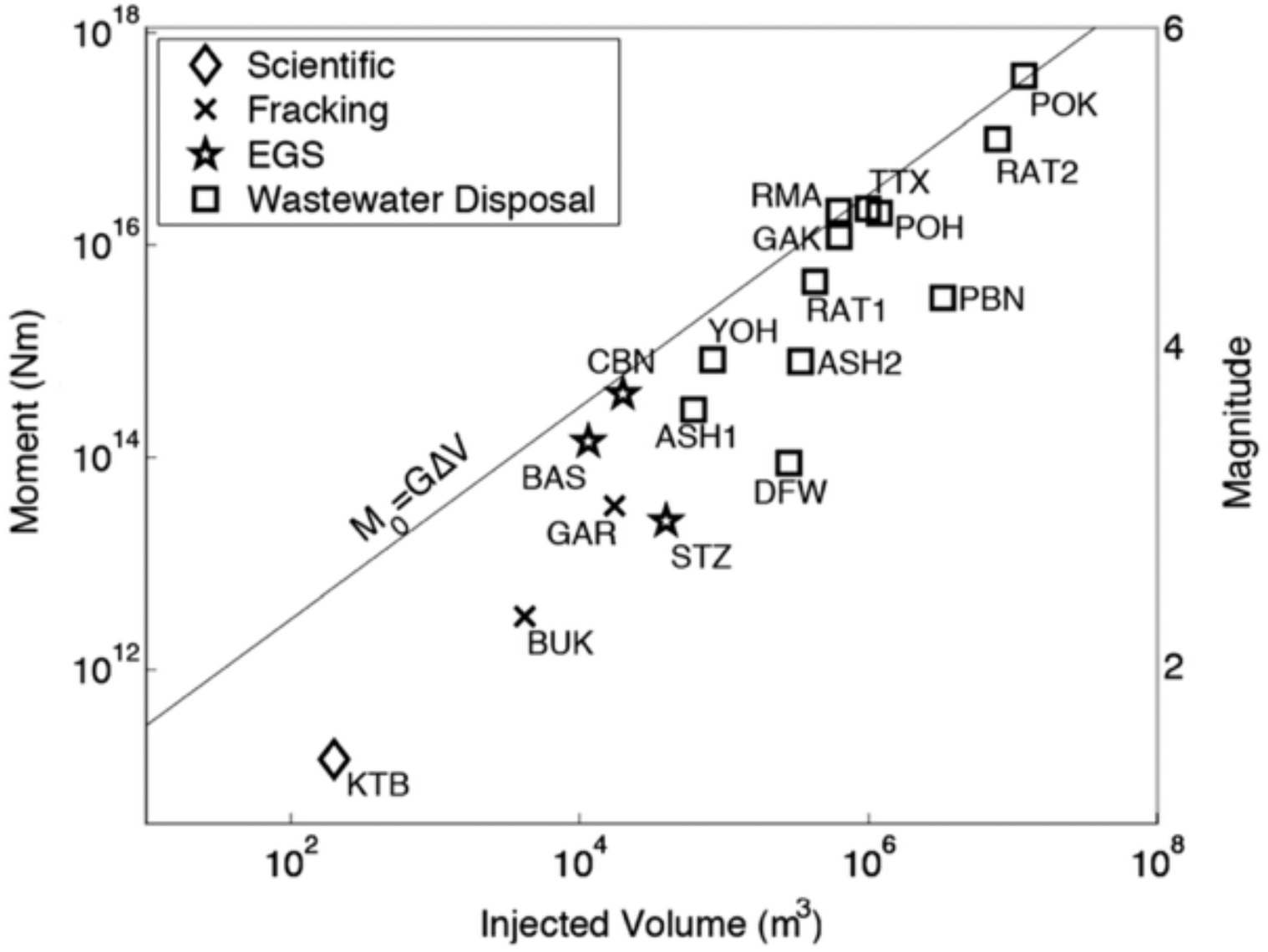
- are the observed sizes of induced earthquakes just a consequence of sampling the GR distribution?

Re-evaluating the limit* on the magnitudes of induced earthquakes.



(*Other than the tectonic limit)

McGarr, 2014

basic assumptions

1. There are faults nearby
2. faults are stressed within one stress drop of failure
3. formation already saturated ($\Delta P \sim \Delta V$)
4. Gutenberg-Richter
5. Earthquakes are confined to the fluid perturbation

An analogy with aftershocks (triggered earthquakes)

- Suppose the total moment of an aftershock sequence were limited to the moment of the mainshock.

- Deterministic application of G-R implies that the largest aftershock should have 1/2 the moment of the mainshock.

- In magnitude: $M_{ms} - M_{as}^{(1)} = \frac{2}{3}\log_{10}\left(\frac{M_0}{\frac{1}{2}M_0}\right) \approx 0.2$

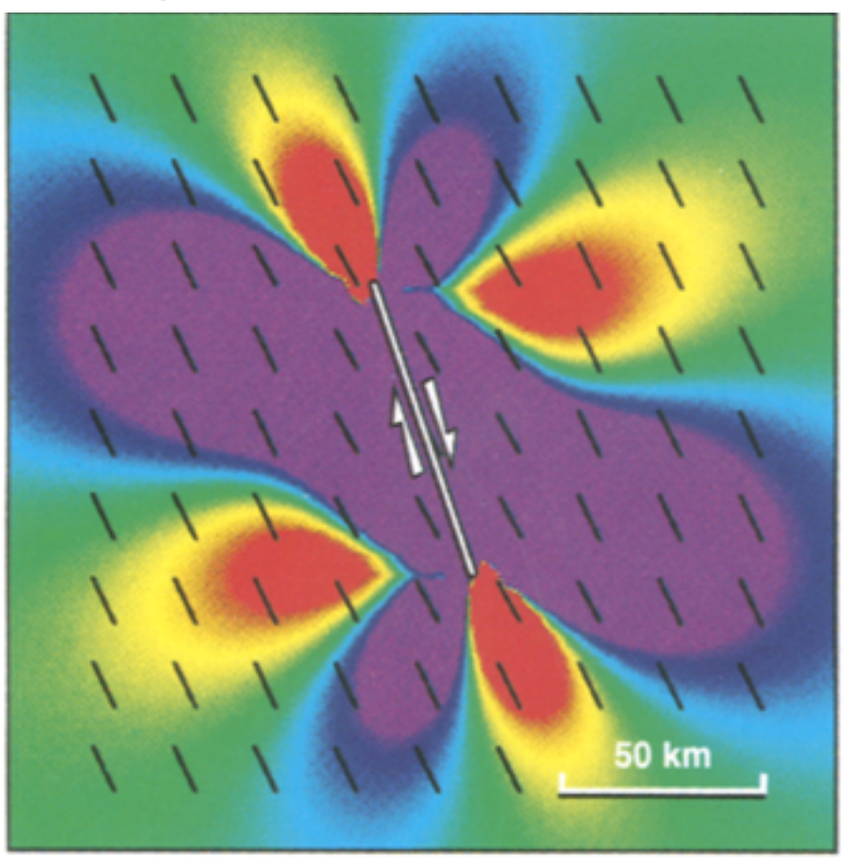
  1) $\Delta M_{as} = 0.2$ is not consistent with Båth's law (too large in the expectation).

  2) $\Delta M_{as} = 0.2$ is regularly exceeded (too small in the limit).

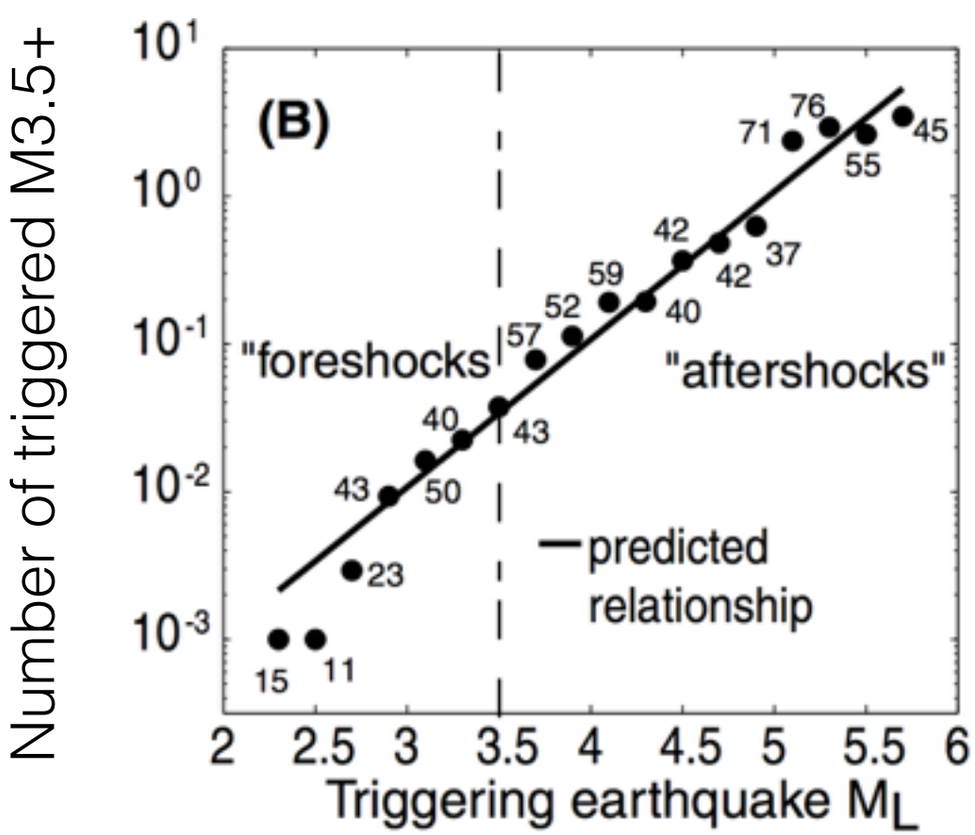
what went wrong?

- Gutenberg-Richter is probabilistic. The *number* of aftershocks nucleated scales with the mainshock stress perturbation

- But the sizes of the aftershocks are determined by the pre-stress and the tectonics (or whatever), not the size of the triggering perturbation.



King…, 1994



Felzer…, 2006

the moment-cap hypothesis

1. There are faults nearby
2. faults are stressed within one stress drop of failure
3. formation already saturated ($\Delta P \sim \Delta V$)
4. Gutenberg-Richter
5. Earthquakes are confined to the fluid perturbation

the sample-size hypothesis

1. There are faults nearby
2. faults are stressed within one stress drop of failure
3. formation already saturated ($\Delta P \sim \Delta V$)
4. Gutenberg-Richter (probabilistic)
5. ~~Earthquakes are confined to the fluid perturbation~~

Tests of the sample size hypothesis

1. The maximum observed magnitude is proportional to the log of the number of prior induced events.

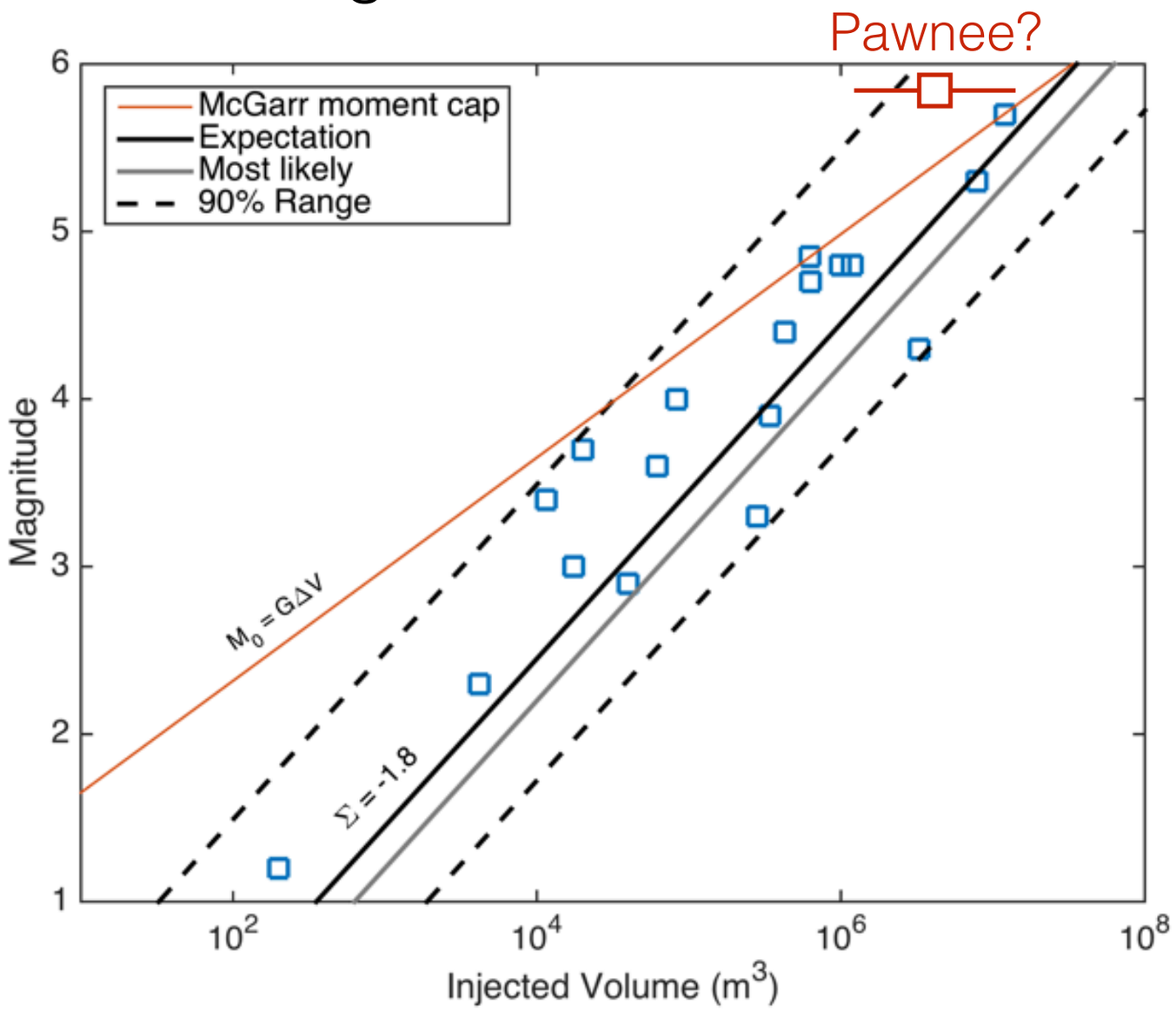
2. The order of occurrence of the largest earthquake is random within the sequence.

3. Bonus test: injected volume controls *number* not *moment* of induced eathquakes.

Quick sanity check

1. Magnitudes are distributed Gutenberg-Richter.
2. No upper limit.
3. Number is proportional to volume injected.

$$\hat{M}_{\max} = \frac{1}{b}\left(\Sigma + \log_{10} V\right)$$



expected distribution of M_{max}

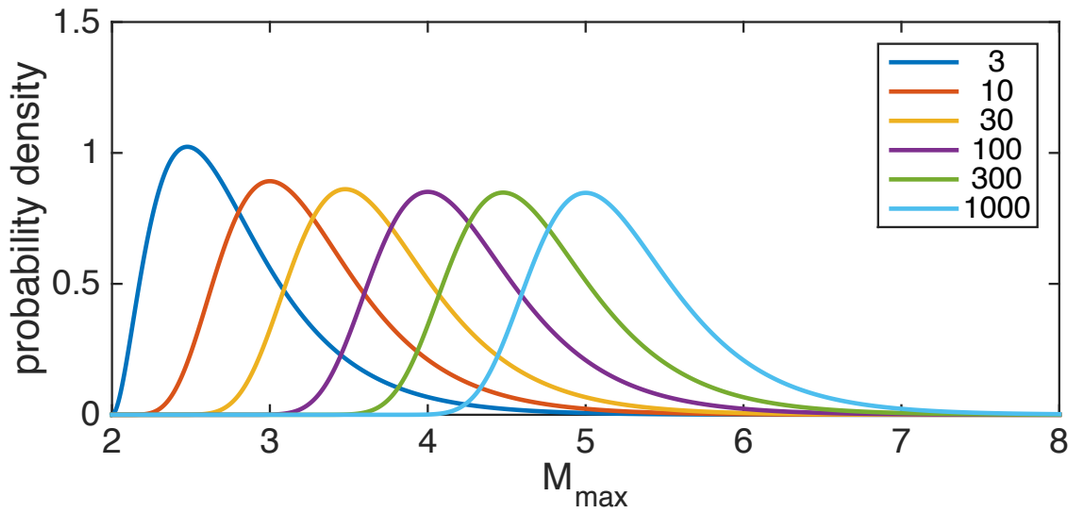
1) Gutenberg Richter

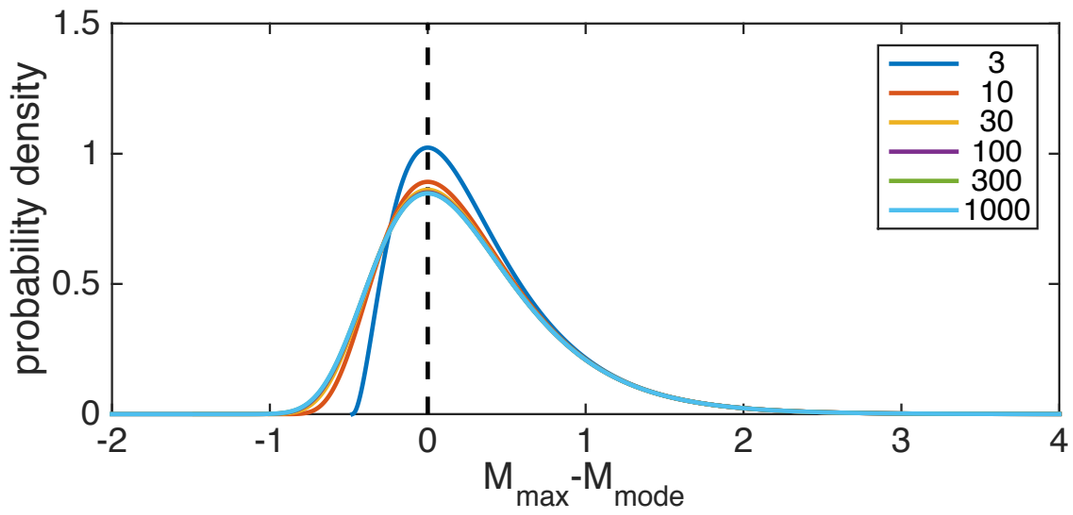
$$N(M) = N10^{-b(M-M_c)}$$

2) N =1 for M_{max} (the mode)

$$\hat{M}_{\max} = M_c + \frac{1}{b}\log_{10} N$$

Probability densities (cdf)





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1) Gutenberg Richter

$$N(M) = N10^{-b(M-M_c)}$$

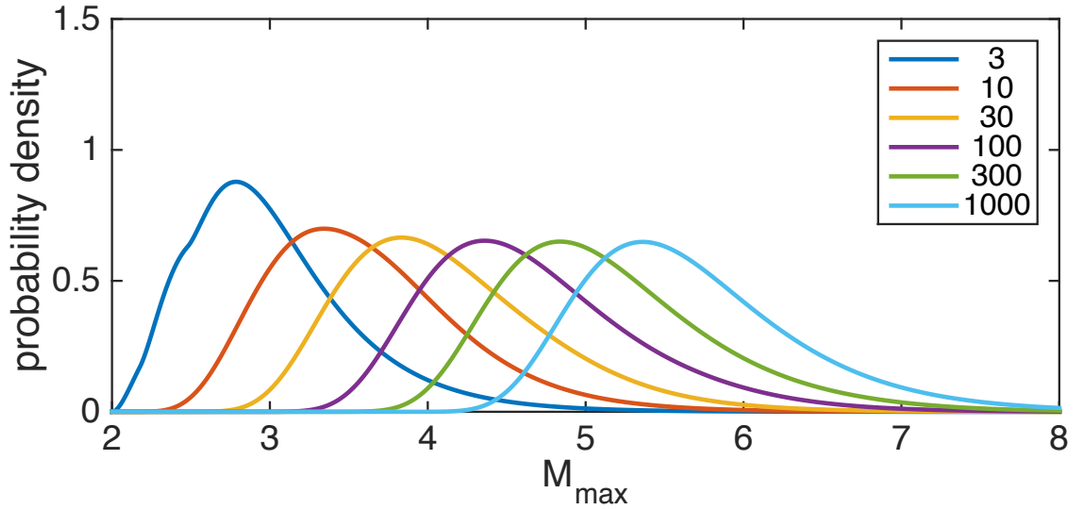
2) $N=1$ for M_{max} (the mode)

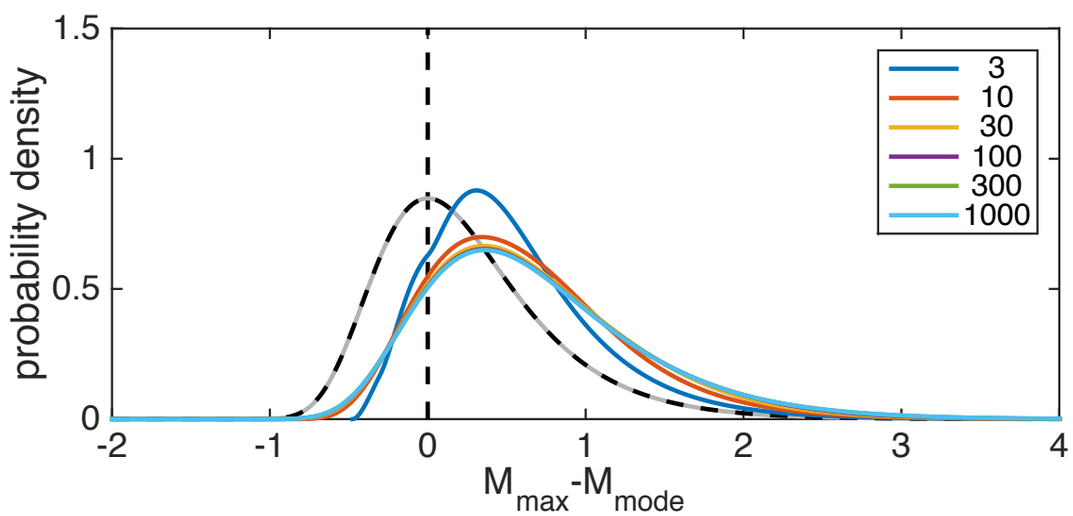
$$\hat{M}_{\max} = M_c + \frac{1}{b}\log_{10} N$$

3) correction for using N *prior* to M_{max}

$$\left\langle \hat{M}'_{\max} \right\rangle = \hat{M}_{max} + \log_{10}(e)$$

Probability densities (cdf)

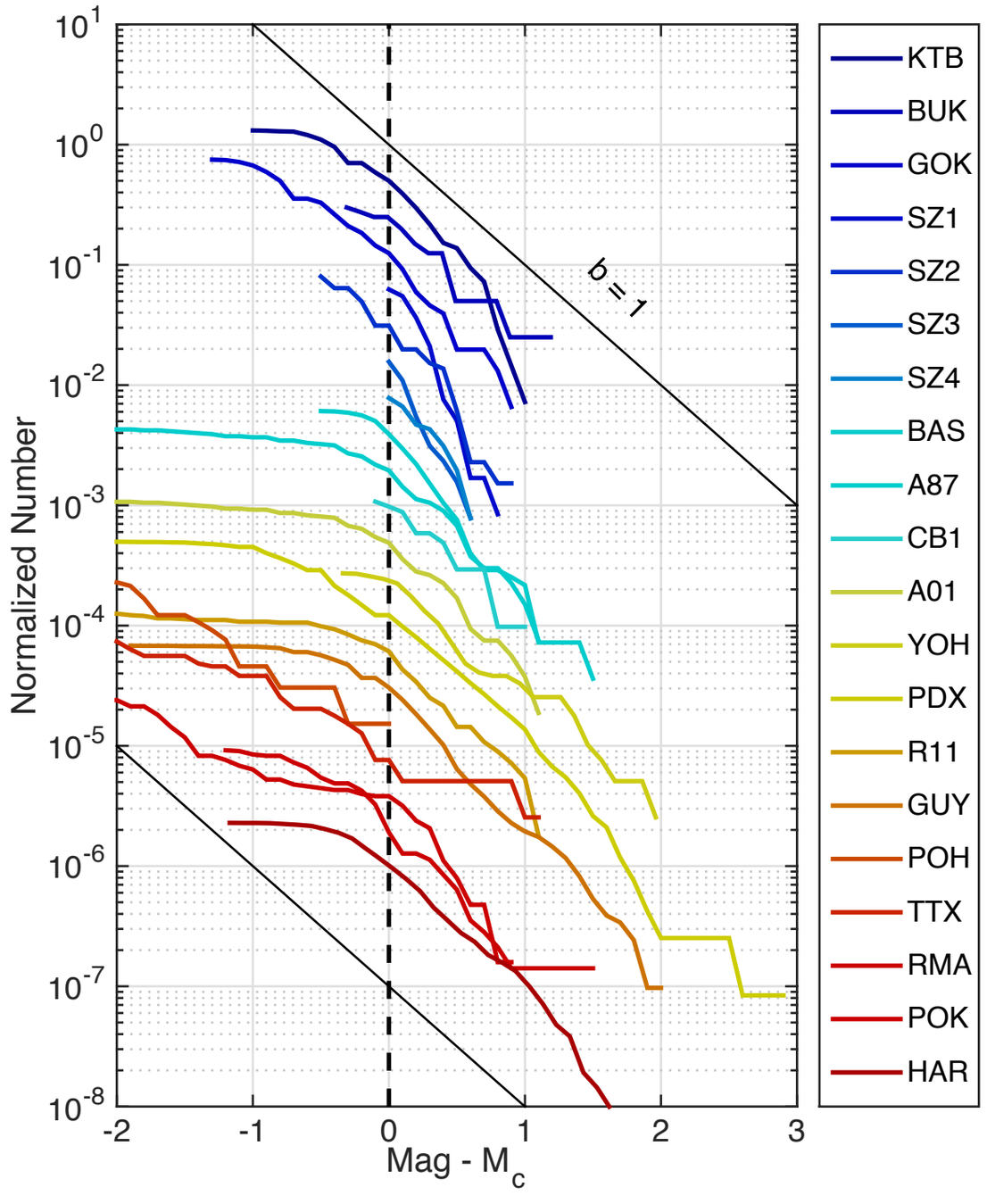




GR statistics of each sequence

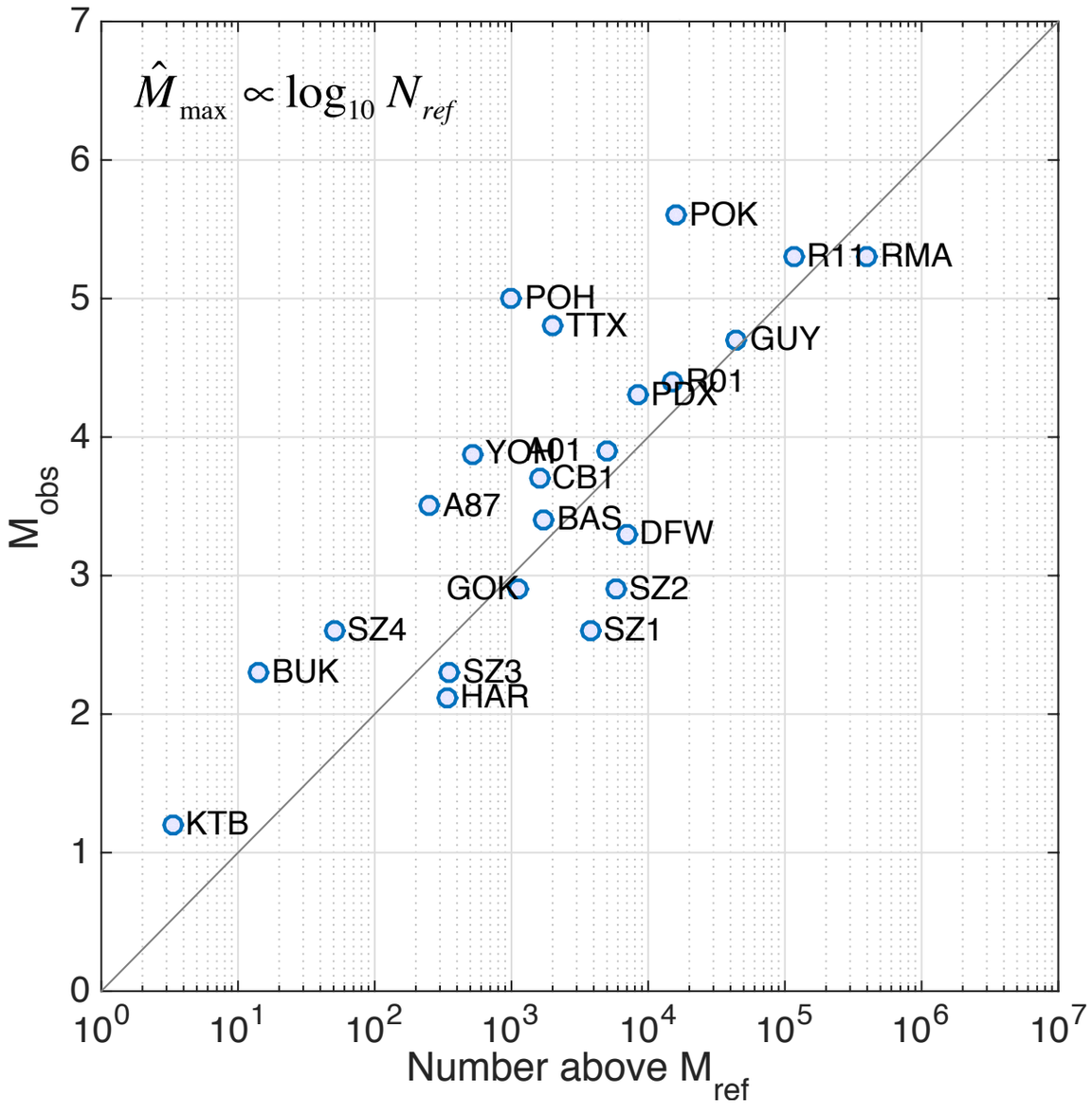
- Magnitude of completeness M_C
- b-value (excluding largest event)
- Number above M_C

$$\hat{M}_{\max} = M_c + \frac{1}{b}\log_{10} N$$



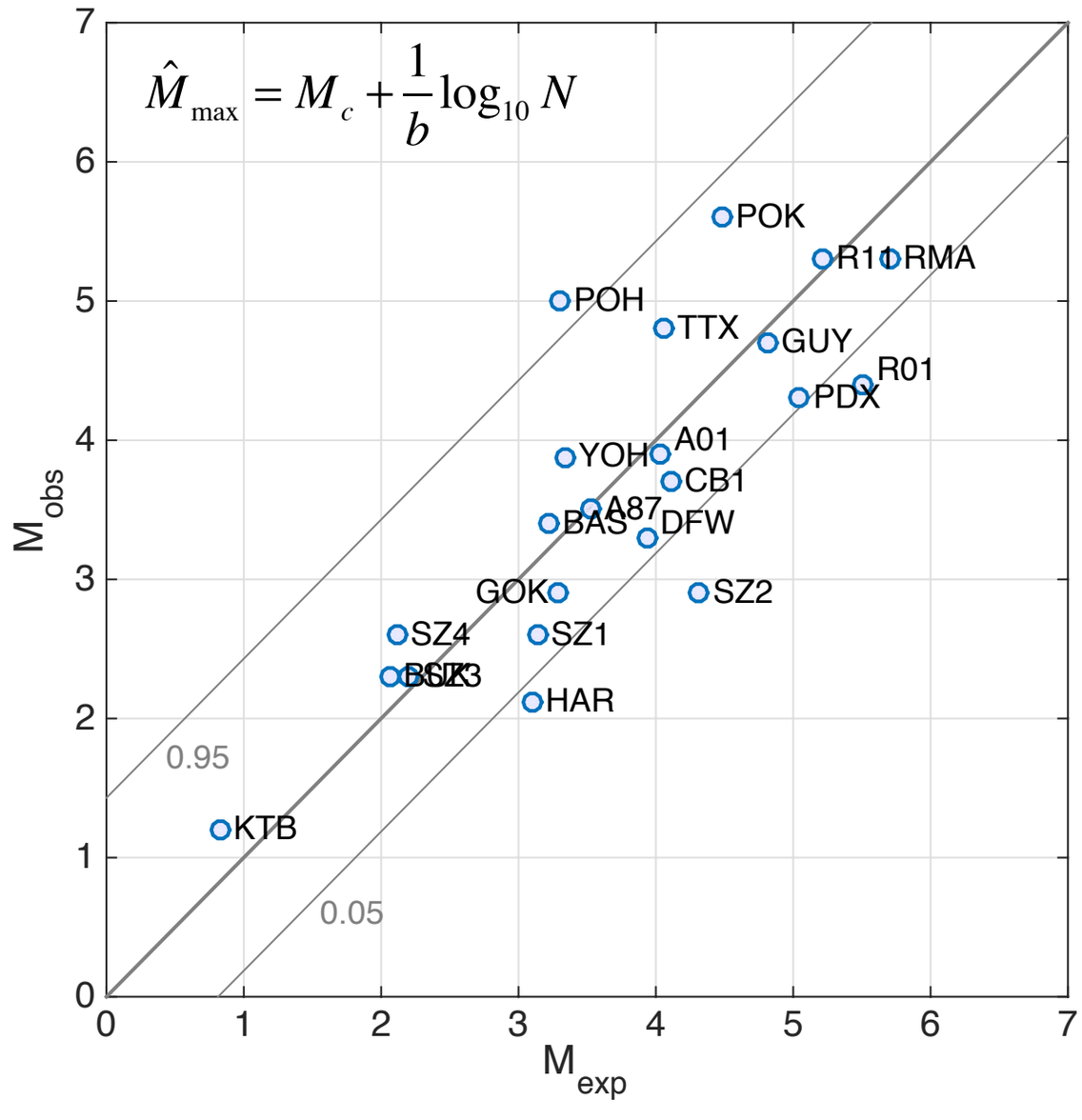
Observed vs. expected magnitudes

M_{max} vs. N_{prior}



Taking into account M_c only

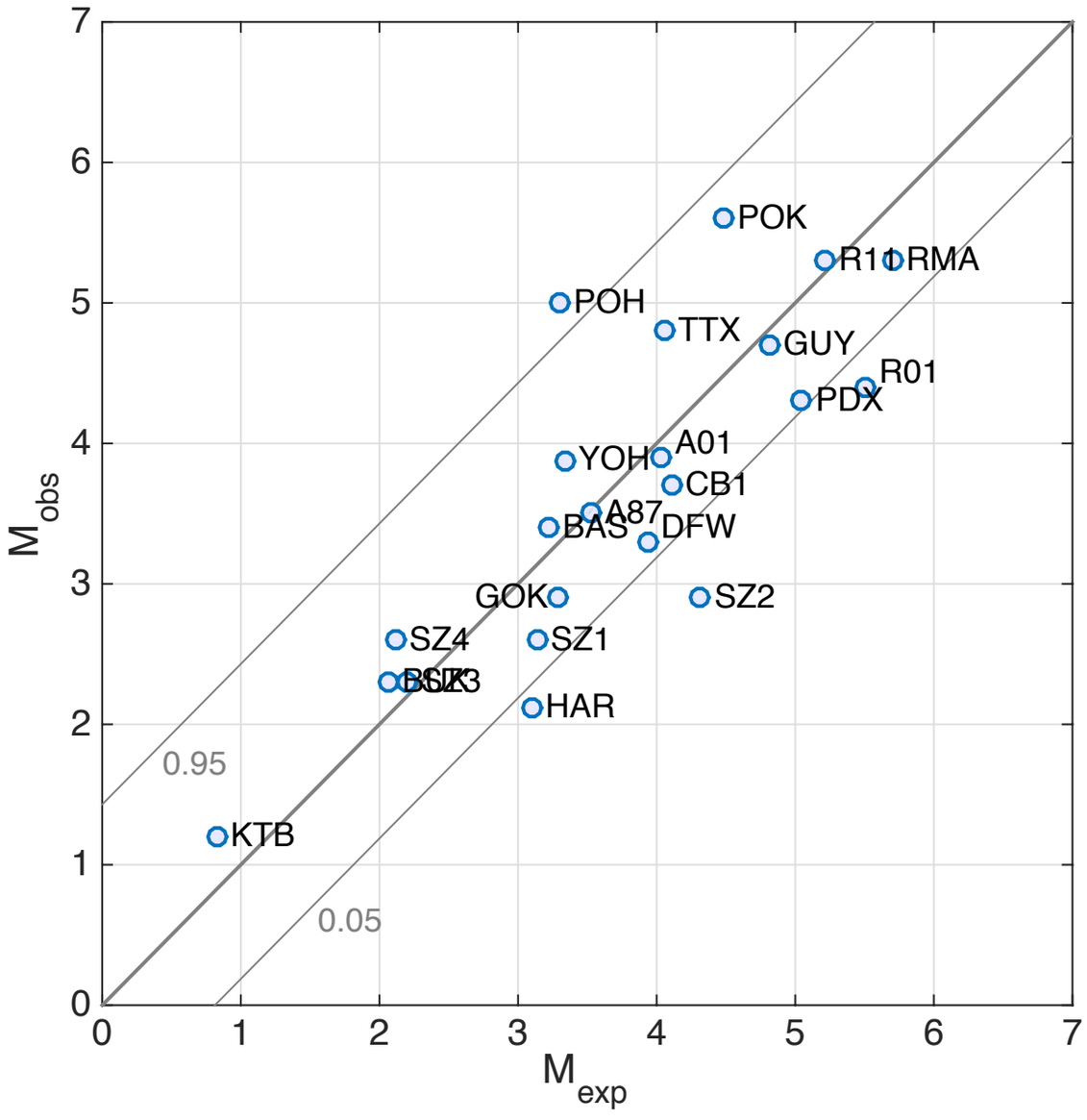
M_{max} vs. $M_{expected}$



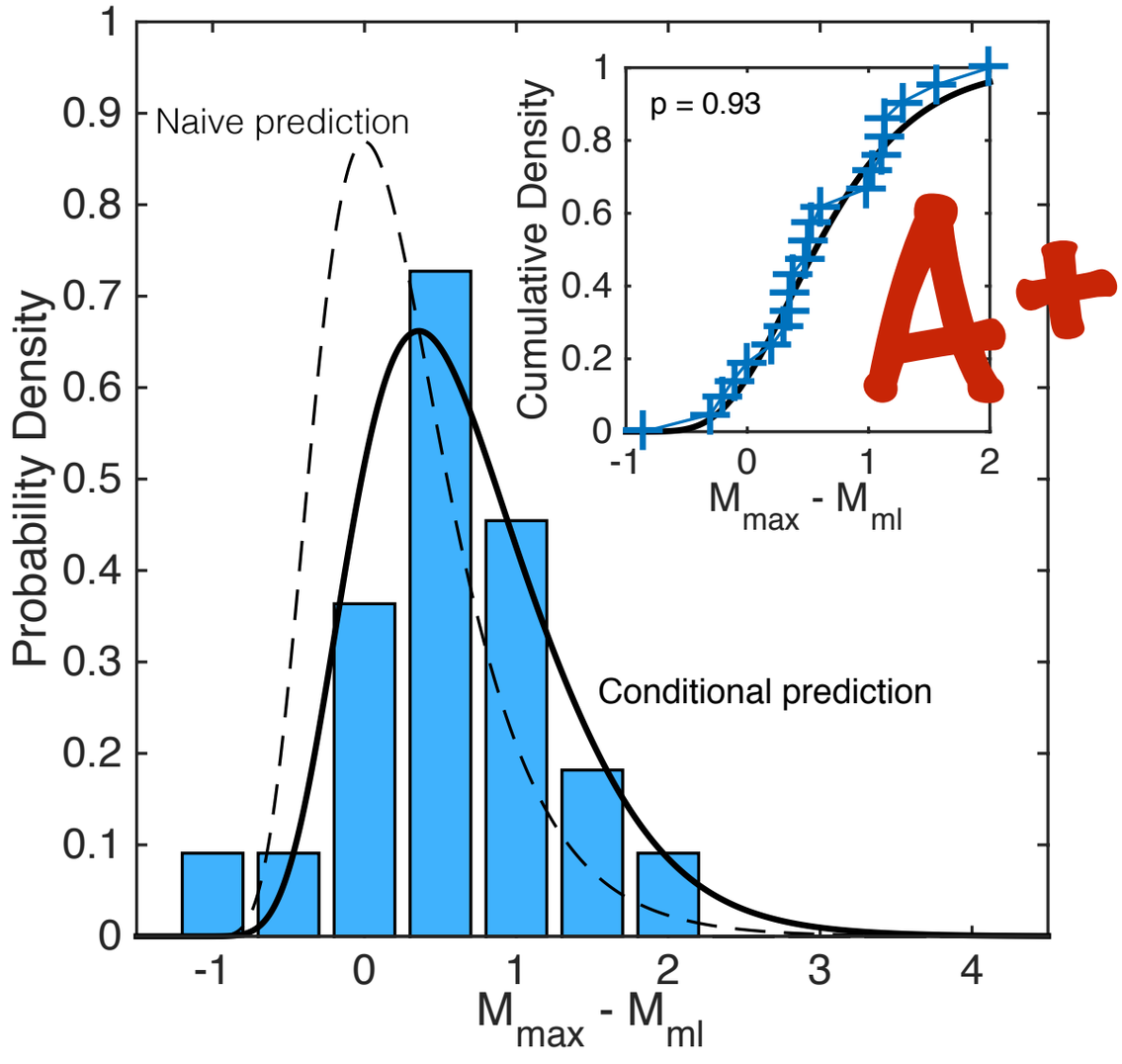
Taking into account Mc, b, N_{prior}

Test #1: M_{max} is consistent with N_{prior}

M_{max} vs. $M_{expected}$

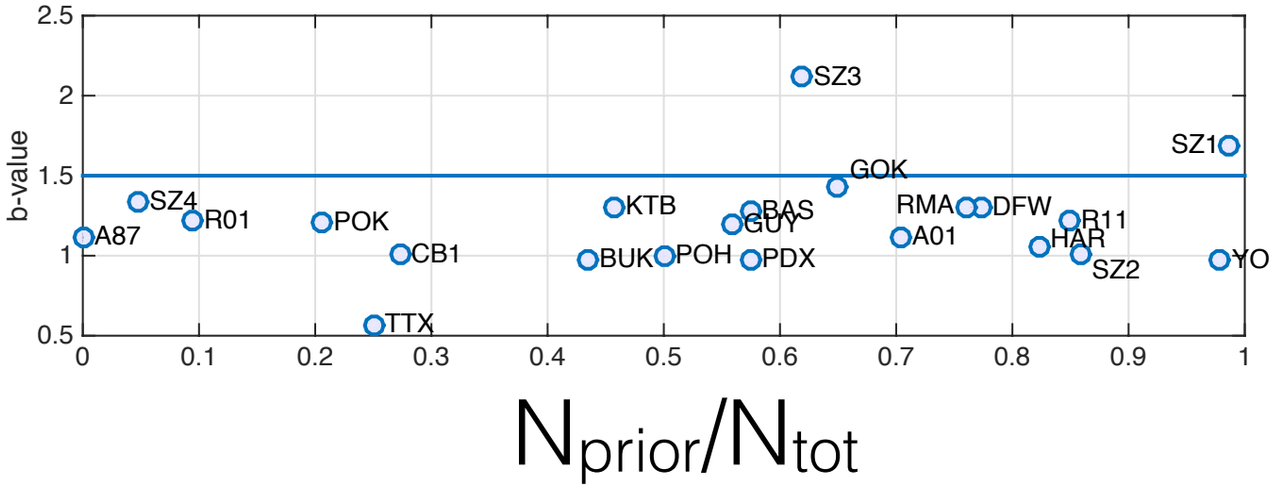


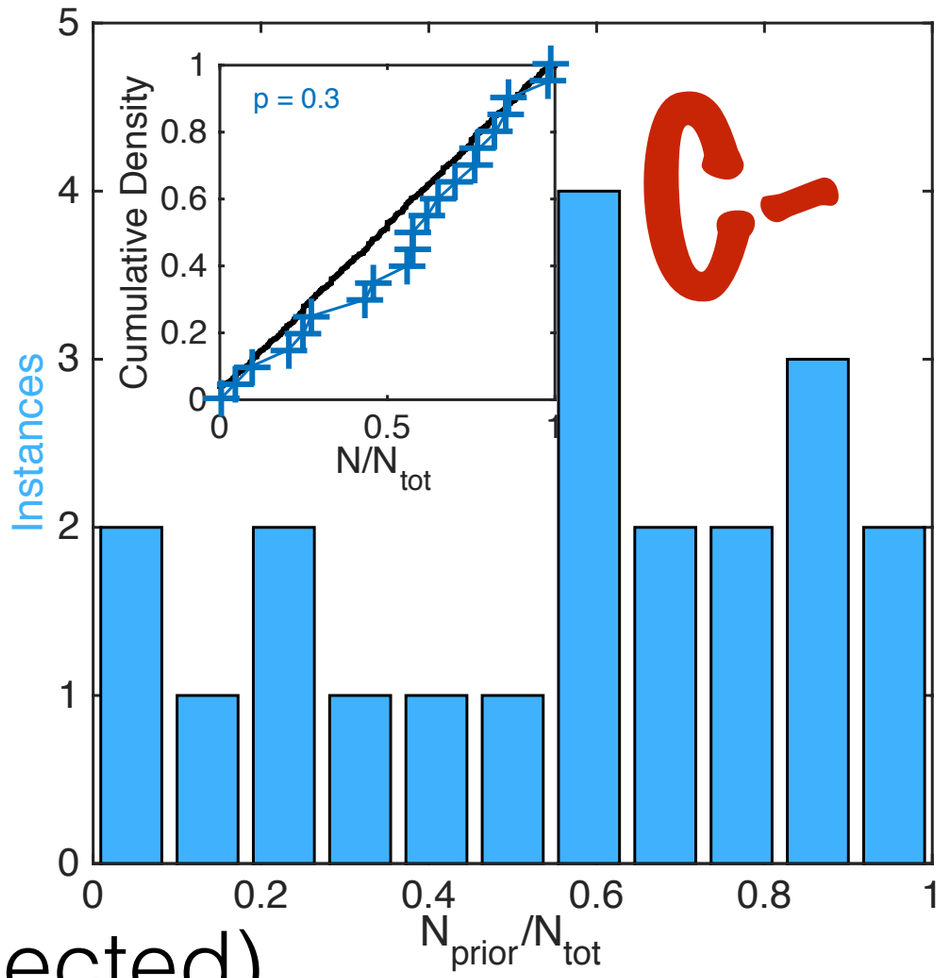
Distribution of difference between M_{obs} and $M_{predicted}$



Taking into account Mc, b, N_{prior}

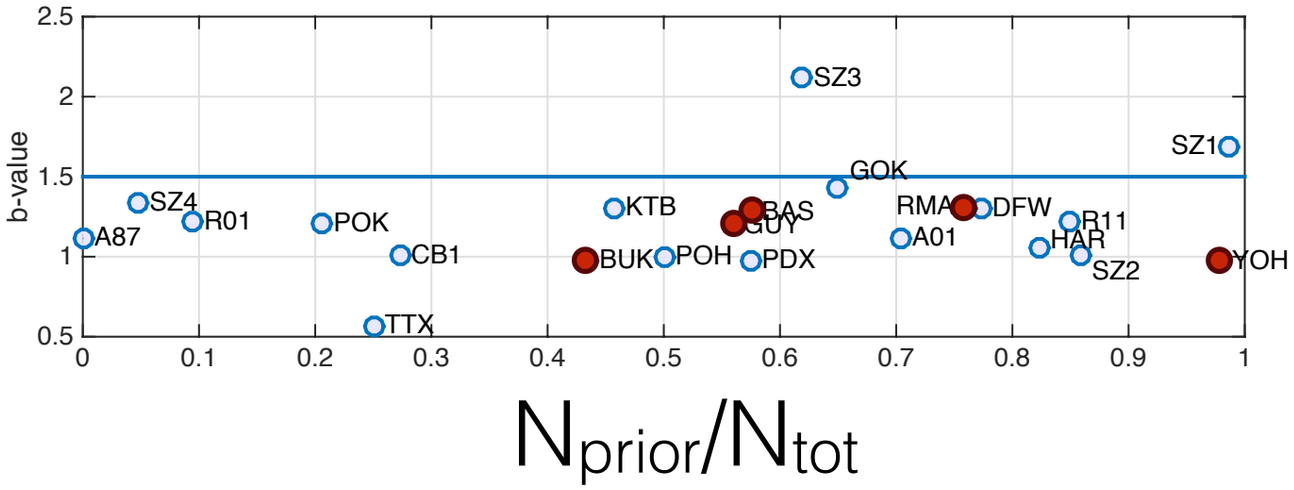
Test #2: order of occurrence is random

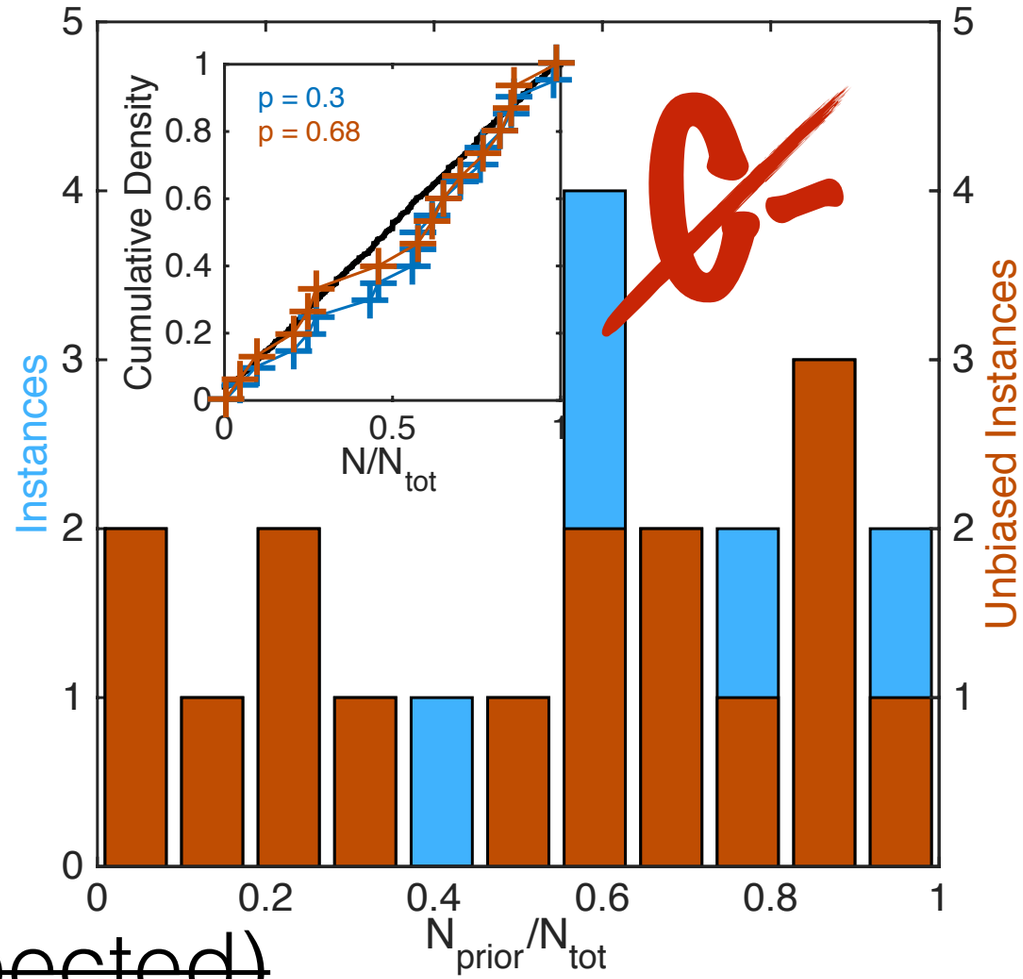




13 out of 21 in latter half (10.5 expected)

Test #2: order of occurrence is random





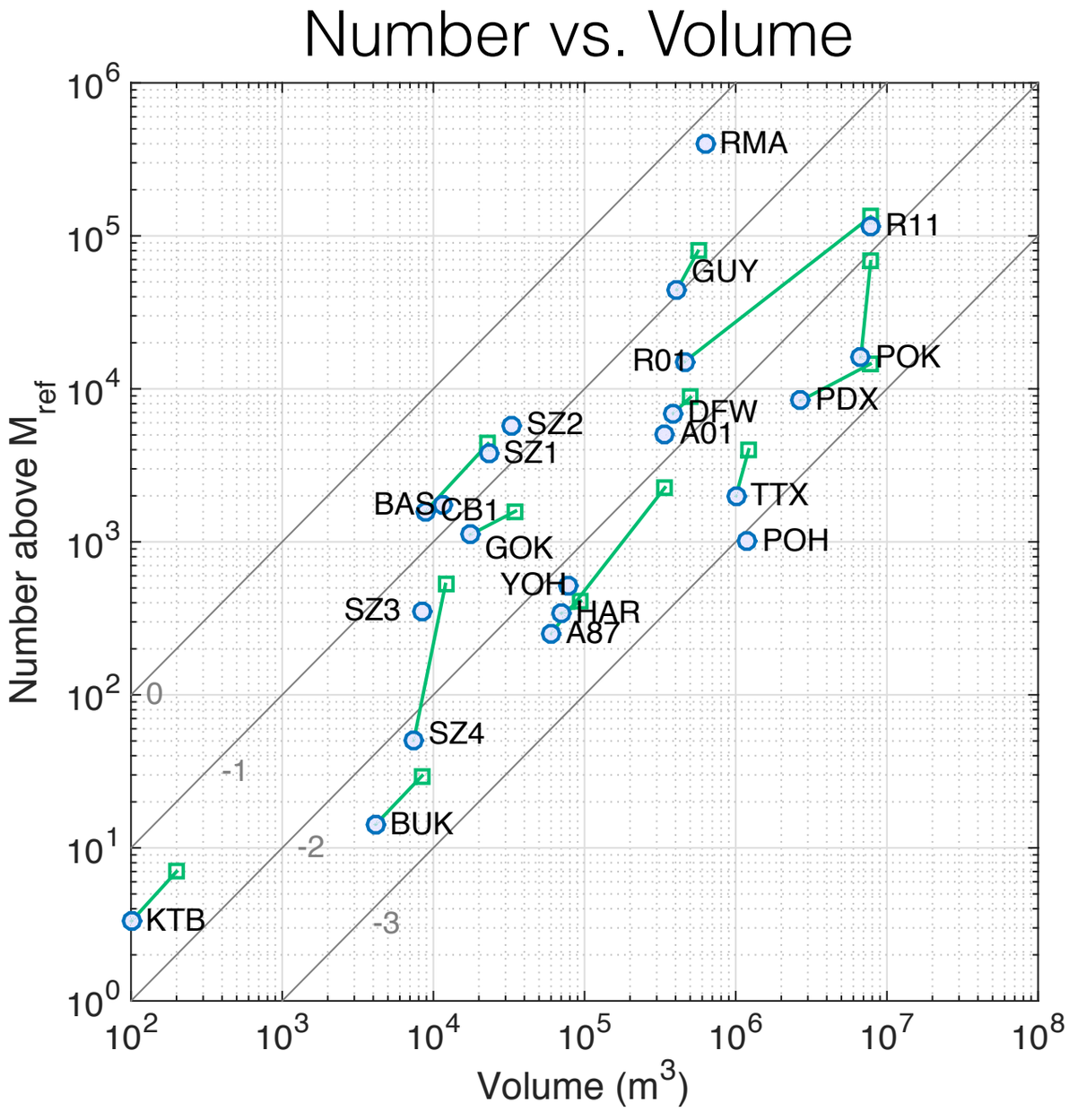
~~13 out of 21 in latter half (10.5 expected)~~

excluding cases shut down *because* of large quakes:

9 out of 16 in latter half (8 expected)

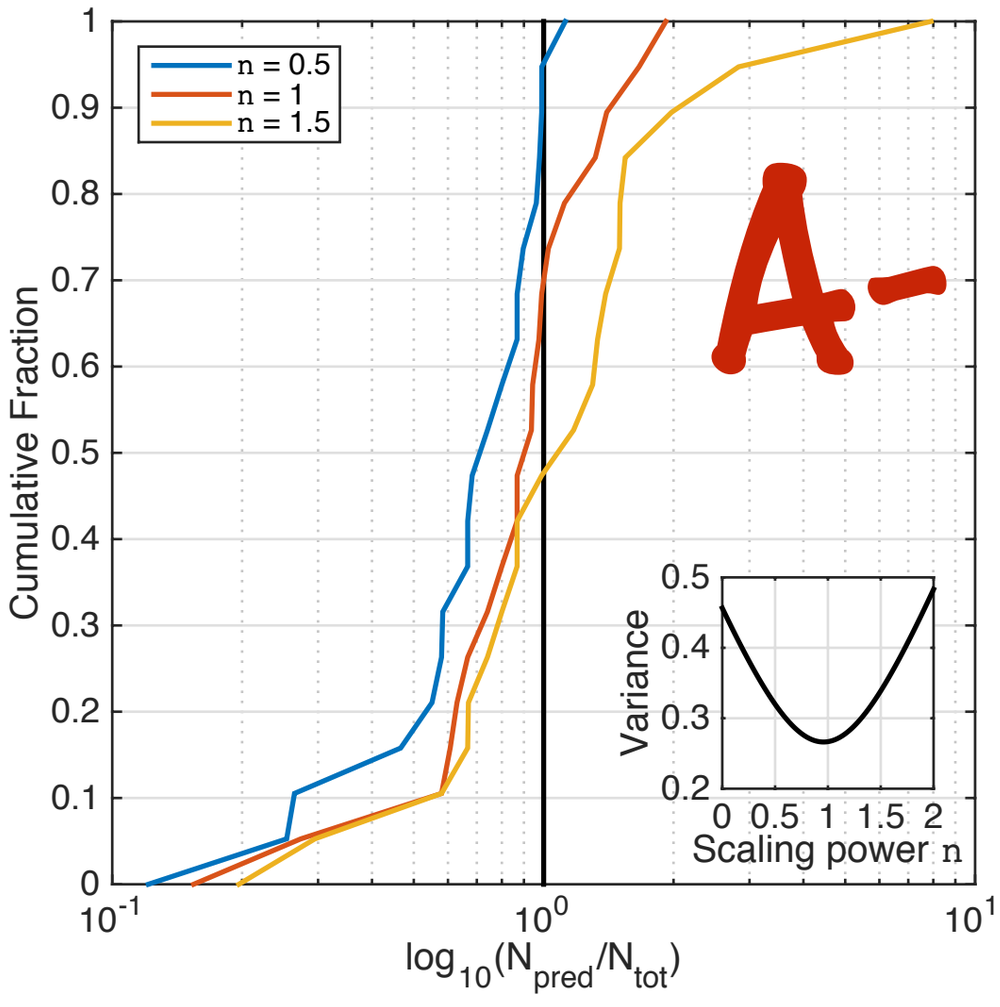
A-

Test #3: Number proportional to volume



Taking into account Mc

$$\frac{N_{tot}}{N_0} = \left(\frac{V_{tot}}{V_0}\right)^n \qquad n=1$$

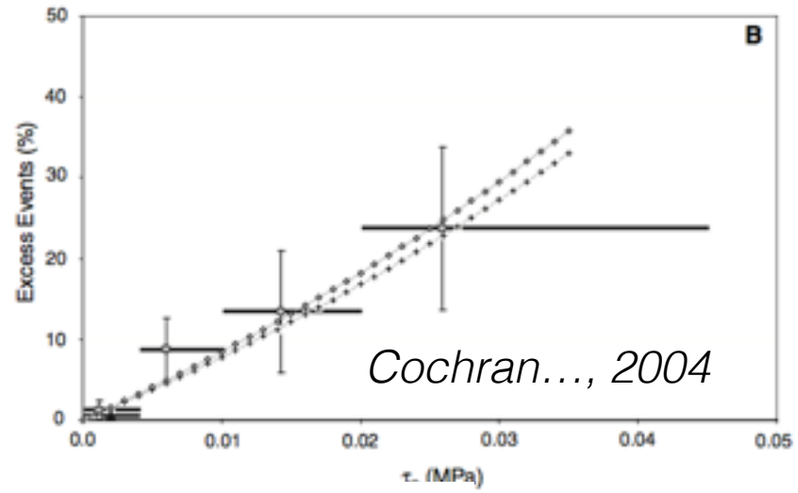


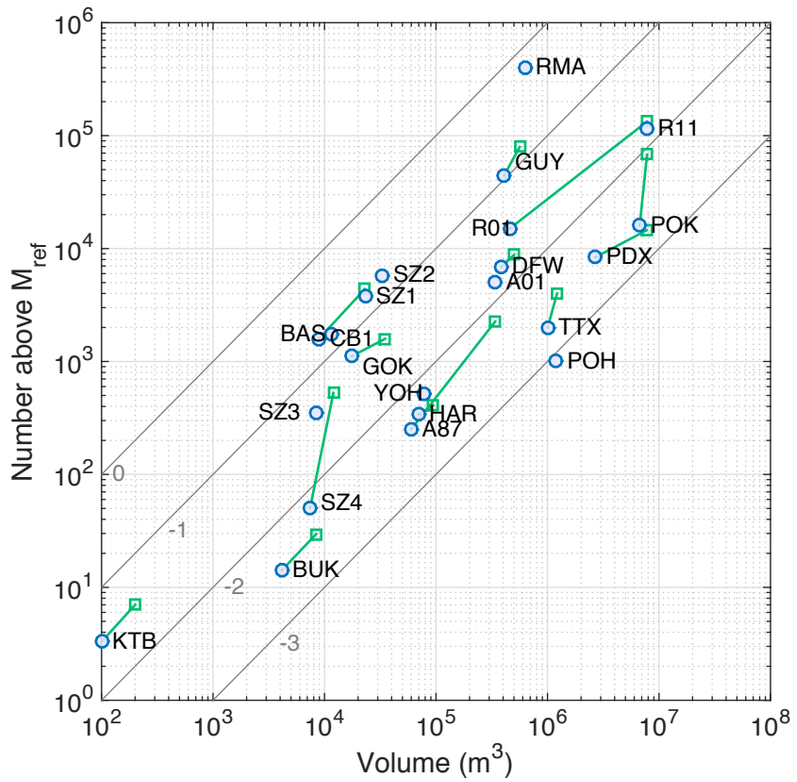
Why should *number* of triggered earthquakes scale with volume?

1. faults are distributed *uniformly* over one stress drop from failure.

$$N \propto \Delta P$$

Consistent with tidal triggering of earthquakes





Why should *number* of triggered earthquakes scale with volume?

1. faults are distributed ~*uniformly* over one stress drop from failure.

$$N \propto \Delta P$$

2. nucleation sites are distributed ~uniformly over the volume.

$$N \propto \Delta PV$$

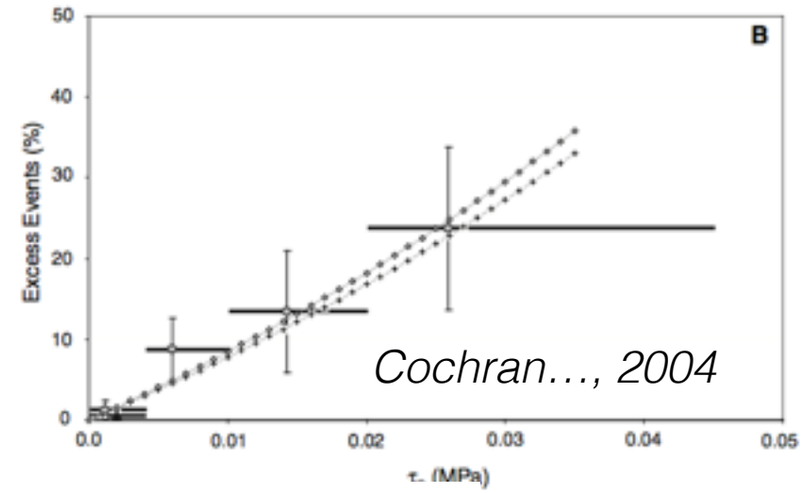
3. Pressure proportional to injection volume over reservoir volume.

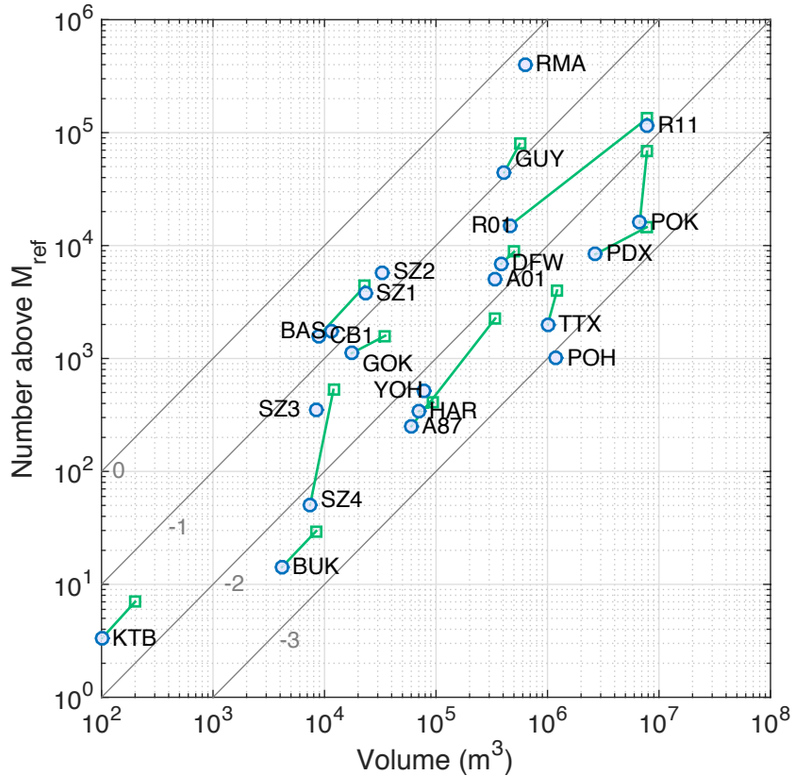
$$\Delta P \propto \Delta V/V$$

$$N \propto \Delta V$$

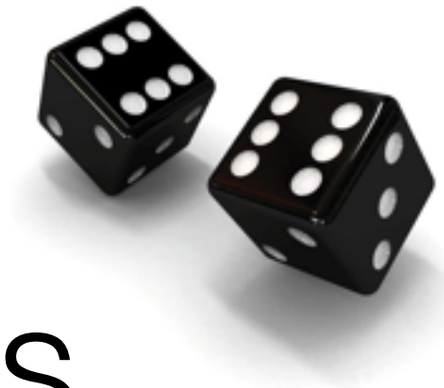
Shapiro…, 2007,2010,2011

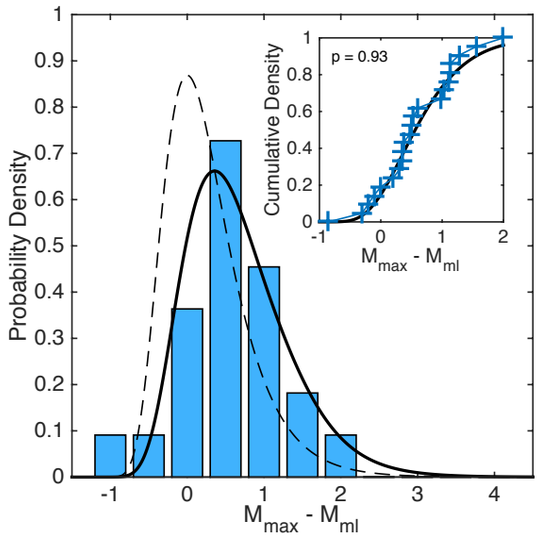
Consistent with tidal triggering of earthquakes





Confirmation of the sample size hypothesis



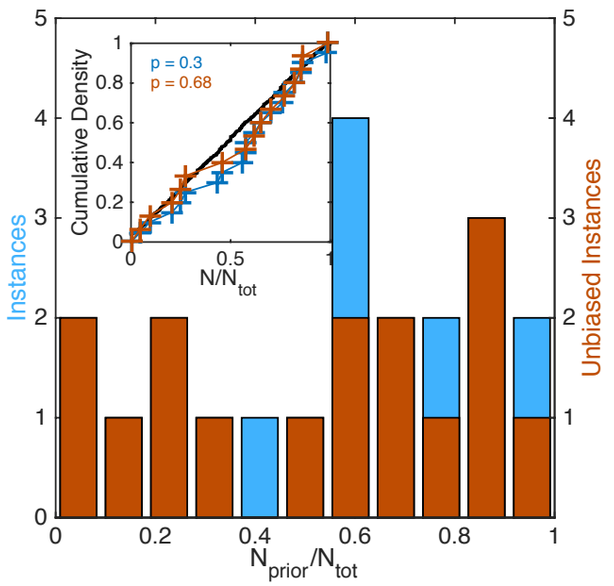


1. The maximum observed magnitude is predicted by the number of prior events

A+

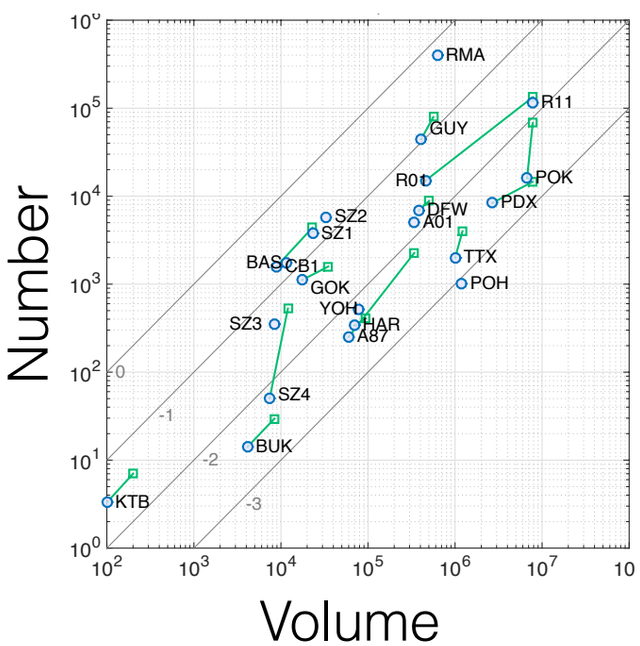
2. The order of occurrence of the largest earthquake is random within the sequence.

A-

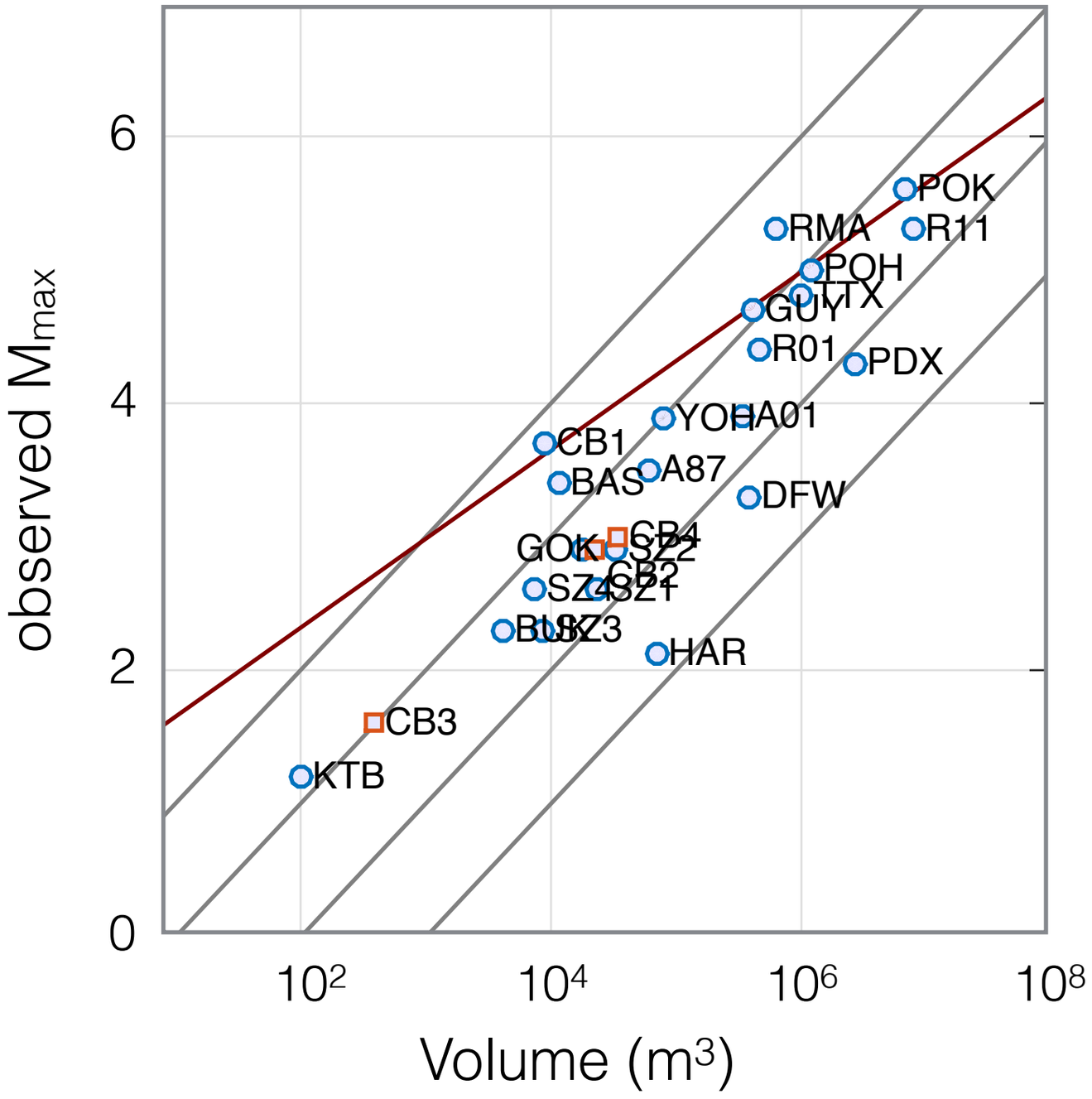


3. The number of induced earthquakes is proportional to injected volume.

A-



evidence from lab triggering

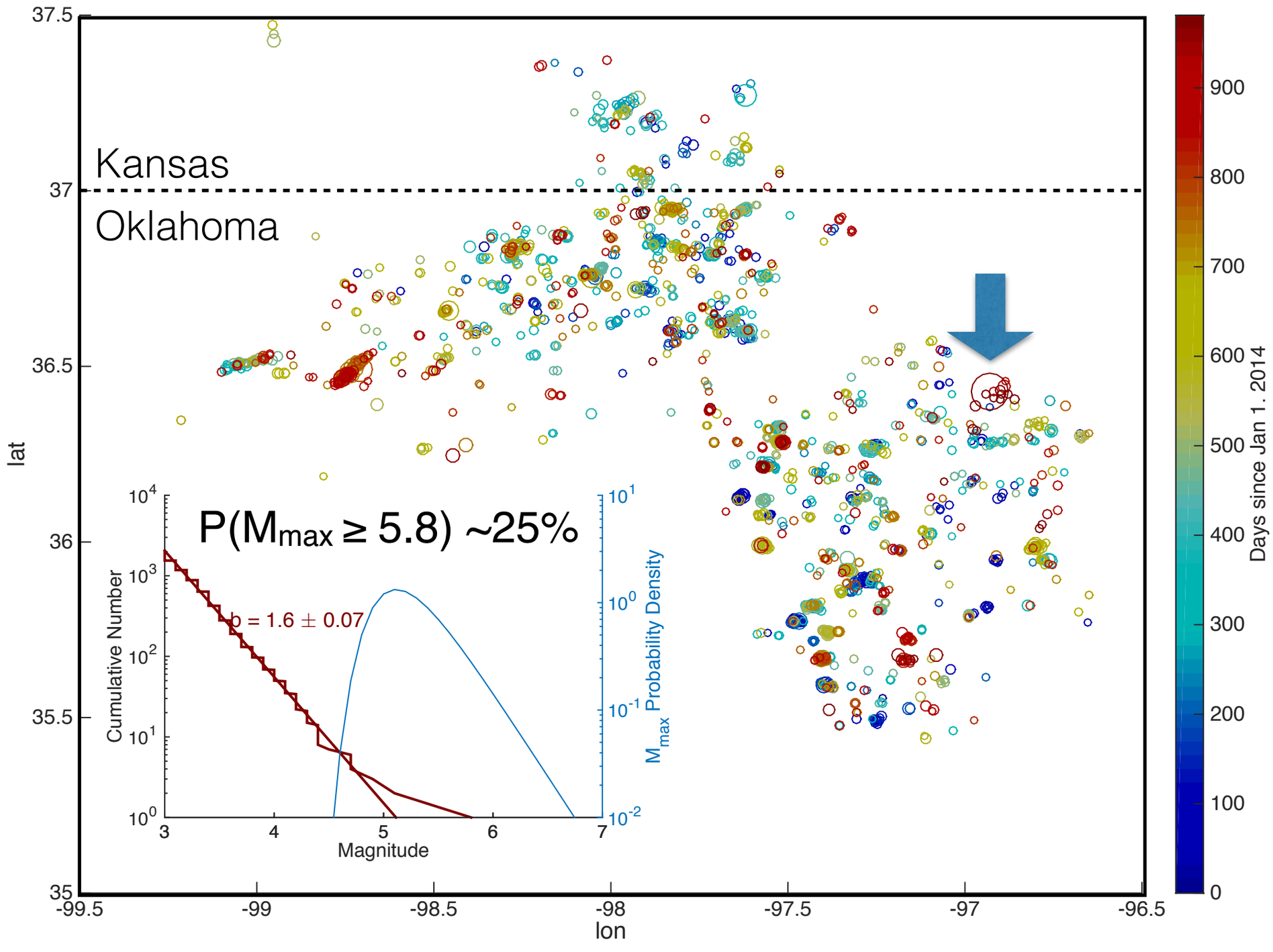


- Need a wider range of volumes
- All Cooper Basin stims
- Lab hydrofrack: (4 ml, M_{max} -7)

M_{max} vs. $\log_{10}(V)$

Goodfellow…, 2015

Was the M5.8 Pawnee earthquake expected?



Conclusion

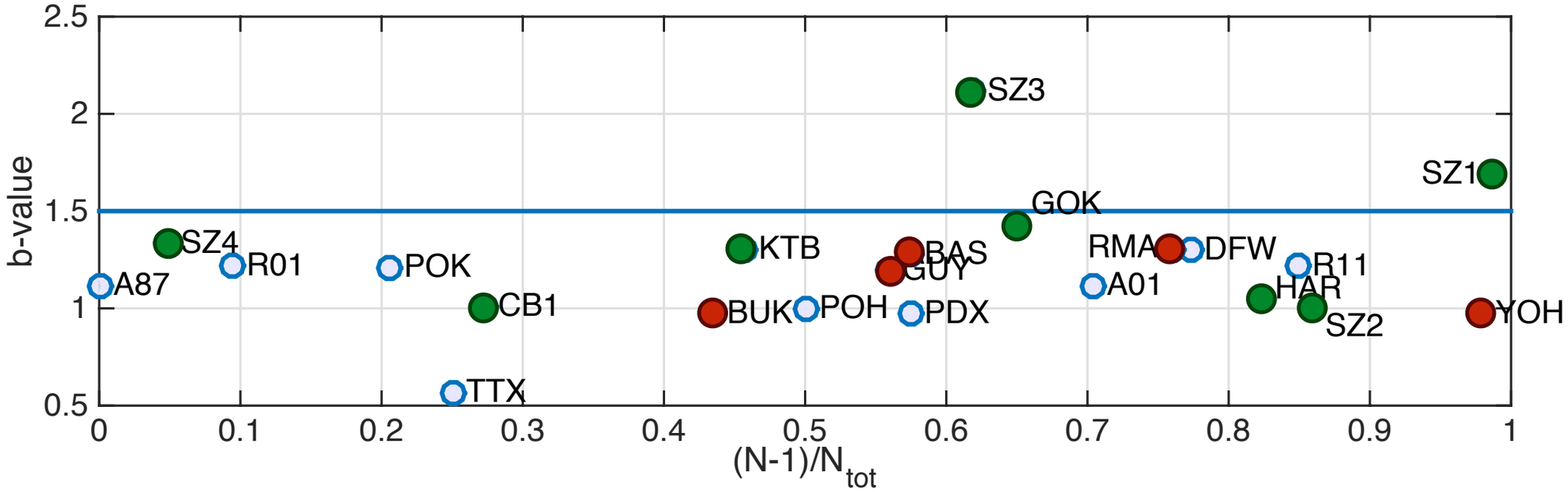
- Induced earthquakes are as large as expected (they are triggered tectonic earthquakes).

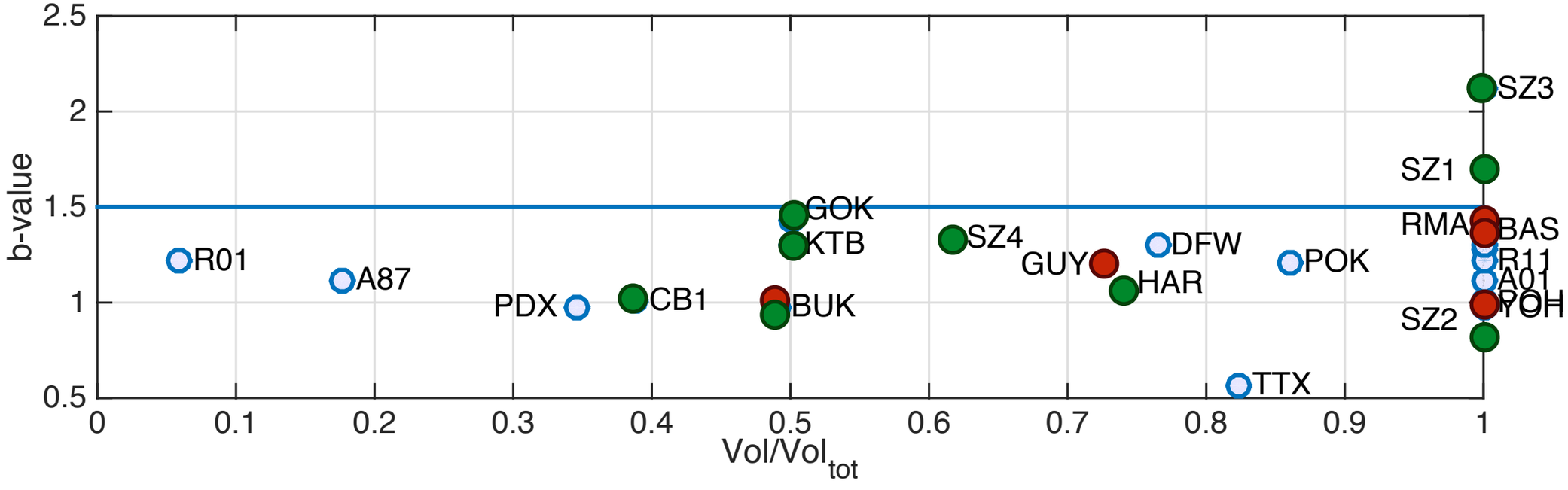
- The NSHM map should probably use the same magnitude limit for induced and tectonic earthquakes.

- Good news: the probability of a large earthquake can be estimated. Best predictor: $M_{max} \sim \Sigma \log_{10} V$

- Bad news: there are no absolutes.

Are EGS wells different?





Northern OK post-2014