

A Physicist's View of Earthquakes: What can we learn from Simple Models?

W. Klein

Collaborators

C. Serino-BU, K. Tiampo-UWO,
J. B. Rundle-UC Davis, H. Gould -
Clark University

March 2013

Outline

- ▶ Background
- ▶ Motivation
- ▶ Single fault scaling
- ▶ Fault system scaling
- ▶ Summary and conclusions
- ▶ Future work

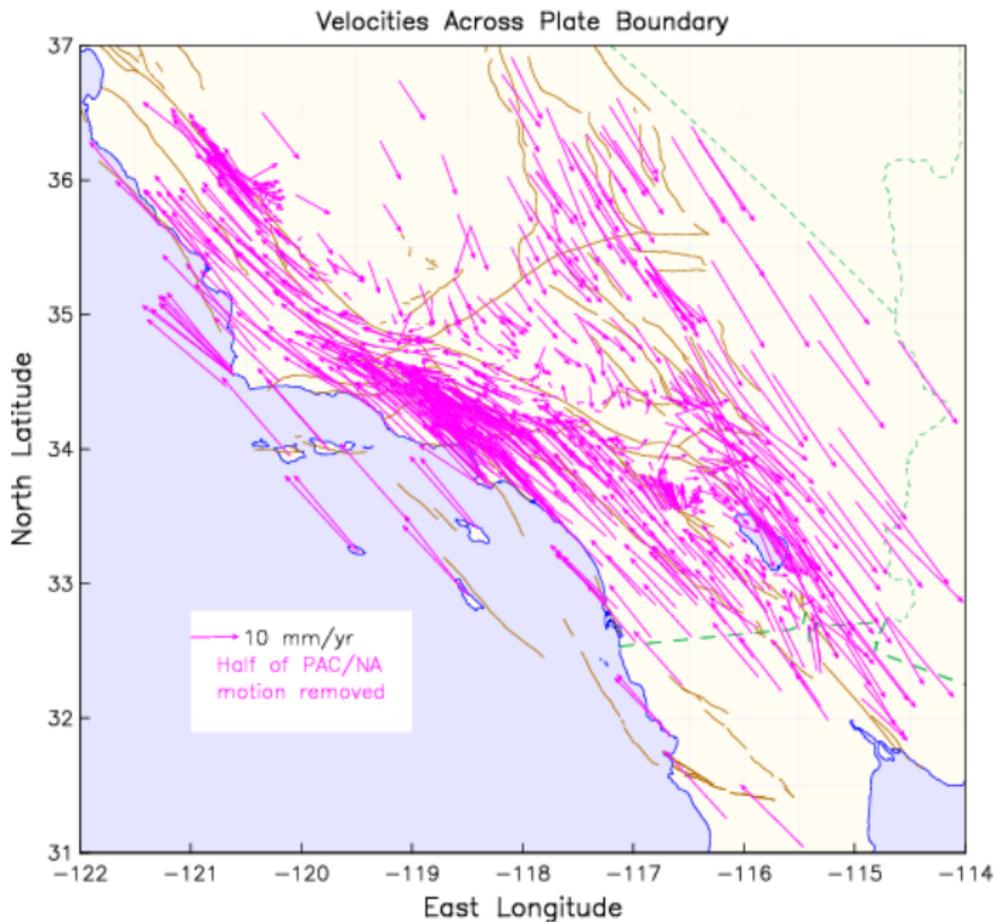
Background

Why study earthquakes?

- ▶ Obvious reason: Prediction
- ▶ Earthquakes cause billions of dollars of property damage and significant loss of life every year.
- ▶ Economic disruption can be serious (Kobe, Sendai).
- ▶ Present potential danger to reactors, dams and waste disposal sites; important consideration in placement.
- ▶ No area is safe (New Madrid, New England).

- ▶ More subtle reasons – statistical mechanics (connected)
- ▶ Earthquakes are a cooperative phenomenon and exhibit scaling, metastability and nucleation, chaos, self-organization, temporal clustering and limit cycles. Phase Transitions!
- ▶ The role of fault structure versus cooperative behavior is not understood.

Earthquake Phenomenology: What we know



- ▶ Most earthquakes occur on pre-existing faults.
- ▶ Faults occur in networks.
- ▶ Energy provided by plate tectonics. Plates (fault surfaces) move $\sim 1\text{--}3\text{ cm/year}$.
- ▶ *Most* earthquakes occur at or near a plate boundary.
- ▶ Majority of earthquakes occur in the outer layer of the earth's crust called the Lithosphere – sustain shear.
- ▶ Stick-slip mechanism. Areas of fault become locked until a critical stress is reached (elastic rebound).

Energy (ergs)	Richter Mag.	Equivalent/Comment
2×10^{25}	9	~ 9 Anch., Sendai
6×10^{23}	8	1000 megatons
2×10^{22}	7	
6×10^{20}	6	6.6 LA quake, 1 megaton
2×10^{19}	5	
6×10^{17}	4	
2×10^{16}	3	smallest felt
6×10^{14}	2	
2×10^{13}	1	
6×10^{11}	0	
2×10^{10}	-1	
6×10^8	-2	100 Watt bulb

What do we need to explain

- ▶ Somewhat periodic behavior.

Magnitude ~ 6 earthquake every 22 ± 3 years for 150 years.

- ▶ Parkfield: Last interval was 38 years.
- ▶ San Andreas near SF – magnitude ~ 8 every 80 years. Last event 1906.
- ▶ Do faults change character with time?
- ▶ Temporal clustering (aftershocks follow large quakes).

$$n(t) = \frac{c}{(1+t)^p}$$

▶ SCALING

- ▶ Gutenberg - Richter (GR) noted

$$N_M \sim M^{-\beta}$$

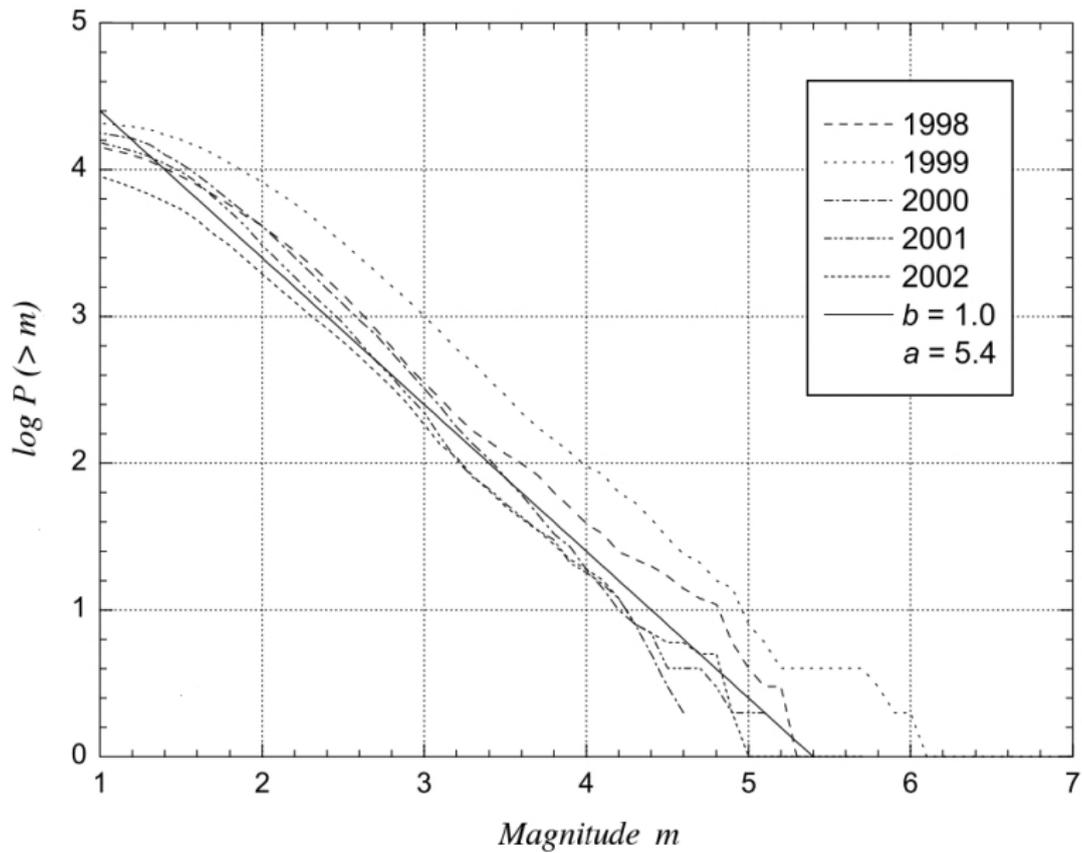
where M is the earthquake moment. (power law)

- ▶ β (exponent) is related to the so called b value

$$\beta = \frac{2}{3}b$$

$$N_m \sim 10^{-bm}$$

where m is the magnitude. (cumulative)



- ▶ Fault system exponents appear to vary over seismic regions

J. B. Rundle *et al* Rev. of Geophys. **41**, 1019 (2003)

L. Gulia and S. Wiener, Geophys. Res. Lett. **37**, L10305 (2010)

- ▶ Not all faults have GR scaling. Controversial - discuss below.

R. B. Hofman, Eng. Geol. **43**, 5 (1996)

Y. Ben-Zion, JGR **101**, 5677 (1996)

- ▶ Fault system scaling - larger range - different exponent than single faults

- ▶ Many researchers relate GR scaling to critical phenomena. Critical points $N_S \sim S^{-\tau}$

P. Bak *et al* *PRL* **59**, 381 (1987)

Feder and Feder, *PRL* **66**, 2669 (1991)

W. Klein *et al* in *Complexity and the Physics of Earthquakes*, Am. Geophysical Union (2000)

- ▶ **Question** - Mechanism for GR scaling on single faults? How is it related to fault system GR scaling? How do we account for differences between faults and differences between single faults and systems? Forecasting.

Motivation

- ▶ **Simple Model** Paradigm for understanding the underlying mechanisms - without complications.
- ▶ Many simple models of earthquake faults have GR scaling e.g.

R. Burridge and L. Knopoff, *Bull. Seis. Soc. Am.*, **57** 341 (1967)

J. B. Rundle and D. D. Jackson, *B. Seismol. Soc. Am.* **67**, 1363 (1977)

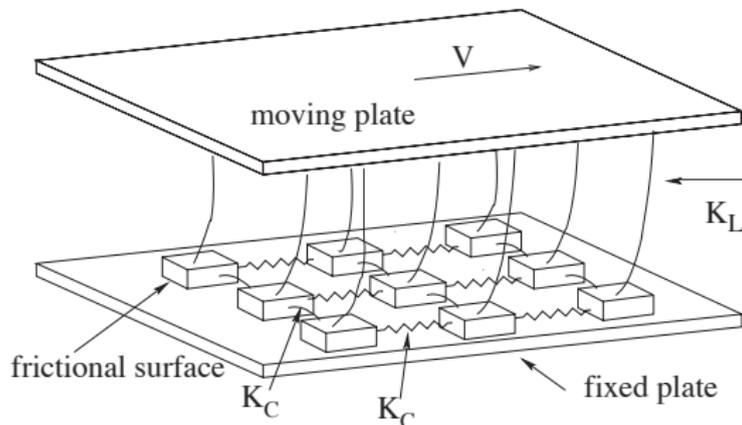
Z. Olami *et al.*, *PRL*, **68**, 1244 (1988)

D. S. Fisher *et al.*, *PRL*, **78** 4885 (1997)

Problems

- ▶ Models of faults - not fault systems.(entire earth)
- ▶ Models are (generally) homogeneous unlike real faults.
- ▶ In a fault system faults differ in their properties. Some faults appear to be nearer to a CP(better scaling) and others farther away. Models do not account for this.
- ▶ Want to build a simple model that addresses these problems.

2D Nearest-Neighbor Burridge-Knopoff Model



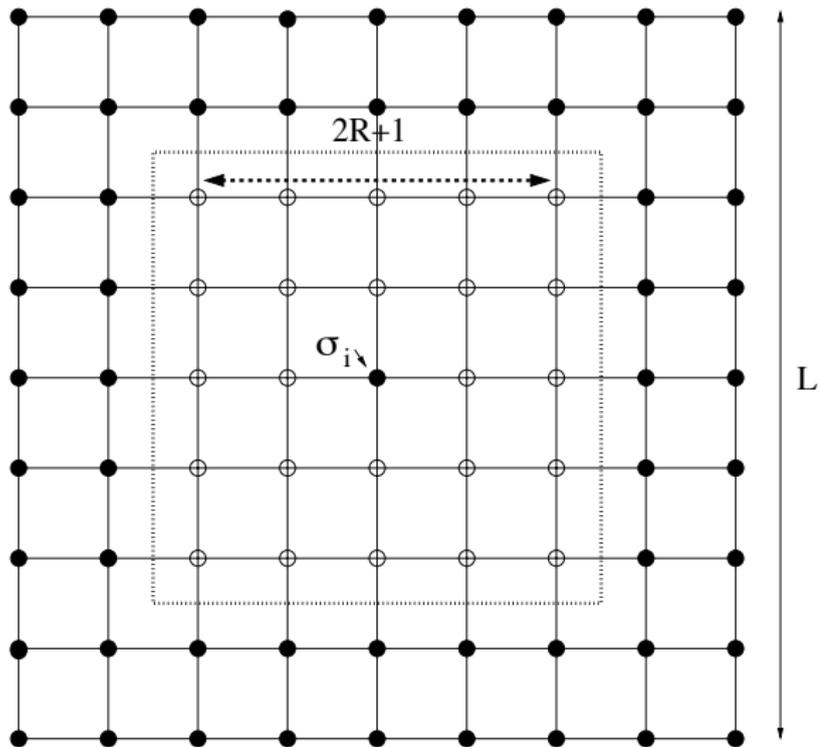
RJ Cellular Automaton Model

- ▶ Each block assigned a failure threshold σ_F and a residual stress σ_R .
- ▶ Blocks are distributed at random. Stress on block $\sigma_j \geq \sigma_F$

$$\Delta x = \frac{\sigma_j - \sigma_R}{K_L + qK_C} + \eta$$

where η is a noise with zero mean.

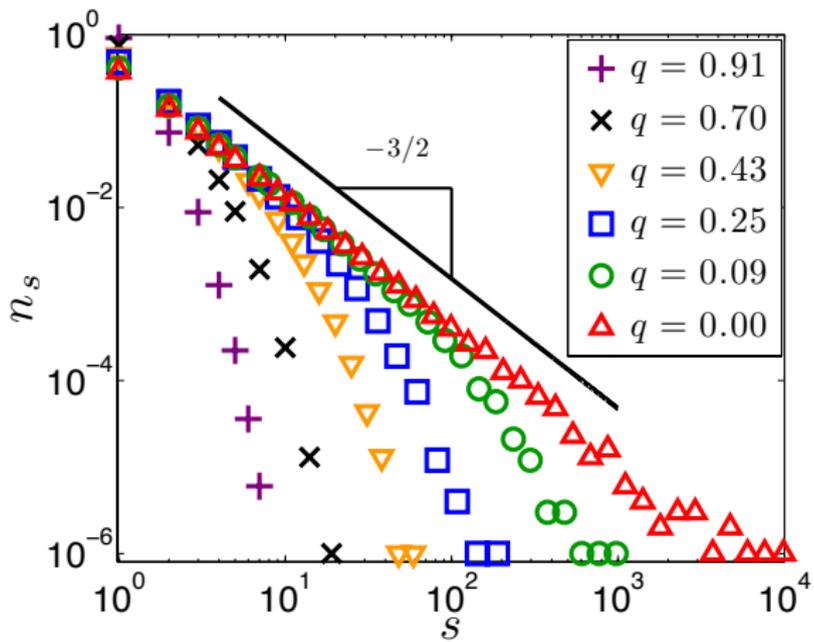
- ▶ Continues until all blocks have $\sigma_j < \sigma_F$. Reload by moving plate.(zero velocity limit)



- ▶ OFC model: Z. Olami, H. J. S. Feder, and K. Christensen, Phys. Rev. A **46**, 1829 (1992) (identical to RJ model, easier to simulate).
- ▶ Square lattice with stress on each site. Assign failure threshold σ^F and residual stress σ^R to each site. Choose dissipation coefficient α and stress transfer range $R \gg 1$.
- ▶ $R \gg 1$ mimics elastic force in real faults
- ▶ Initially distribute stress at random. If $\sigma_j < \sigma^F$ skip.
- ▶ If $\sigma_j \geq \sigma^F$, set stress $\sigma_j = \sigma^R + \eta$ and distribute $(1 - \alpha)(\sigma_j - \sigma^R - \eta)$ to the $(2R + 1)^d$ neighbors.

- ▶ η is a flat random noise.
- ▶ Continue until $\sigma_j < \sigma^F \forall j$. Count s (number of failed sites) for “earthquake”
- ▶ Find site with largest stress – add stress to bring this site to failure. (Add same stress to each site.) and repeat.
- ▶ Many variations (vary α , lower failure threshold).
- ▶ Scaling: Number of events N_s vs s where s is number of failed sites.
- ▶ As $R \rightarrow \infty$ sites all fail at failure threshold. Implies that for $R \gg 1$ s scales as the moment.

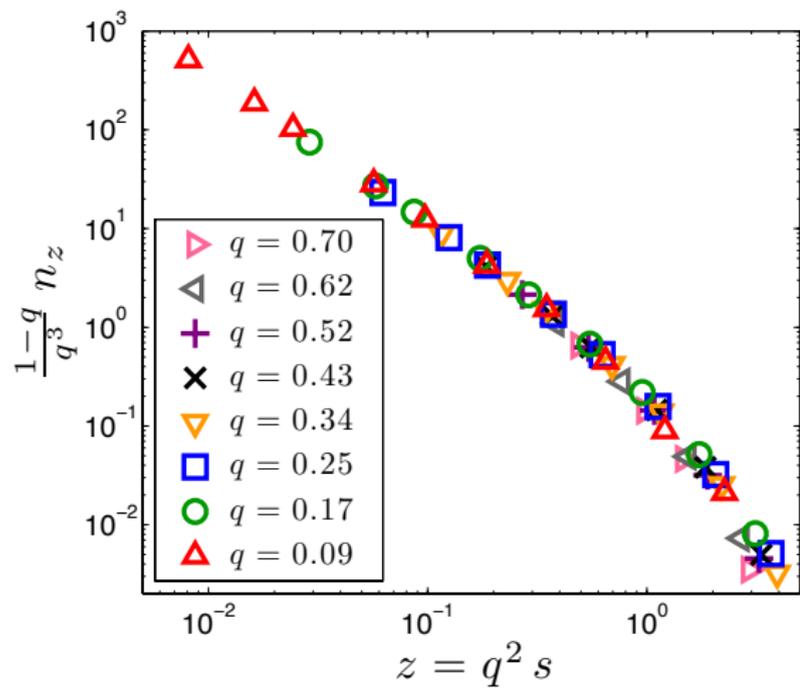
- ▶ Damage the model by removing fraction q of the sites.
- ▶ When stress is transferred to an empty site it is dissipated.
- ▶ Caused in real faults by small cracks.
- ▶ Increased $q \rightarrow$ higher dissipation.
- ▶ For $q = 0$ theory (W. Klein *et al* in *Complexity and the Physics of Earthquakes*, Am. Geophysical Union (2000)) predicts that the non-cumulative exponent is $3/2$



- ▶ The curves can be fit by

$$N_s(q) = \frac{1}{1-q} \frac{\exp[-q^2 s]}{s^{3/2}} \quad (1)$$

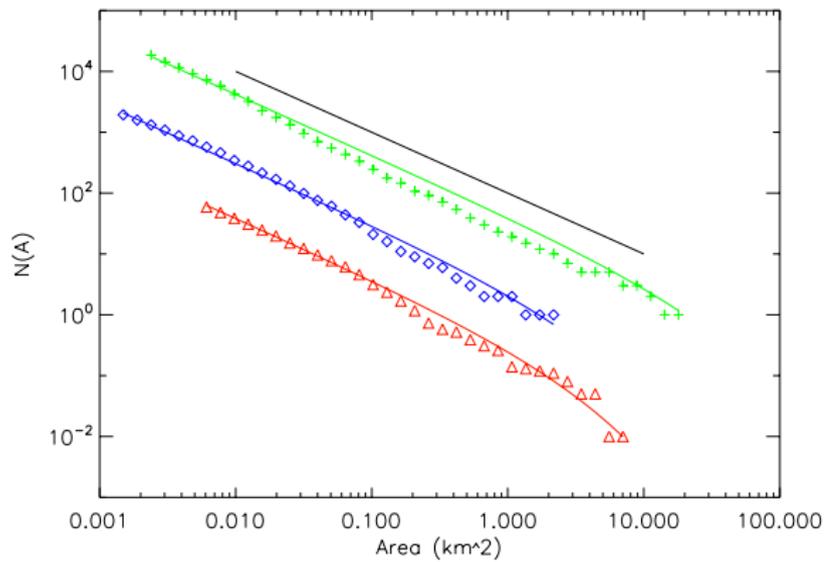
- ▶ This implies that the right choice of variables leads to data collapse. Data for all values of q lie on a master curve.



- ▶ Using the theory of spinodals this corresponds to

$$N_A = A_o \frac{\exp \left[\Delta h A^{2/3} \right]}{A} \quad (2)$$

- ▶ The area $A \propto \xi^2$ where ξ is the correlation length.
- ▶ This can be tested on real faults (Δh fit parameter)



- ▶ San Jacinto (green crosses) - Fort Tejon segment of San Andreas (blue diamonds) - Creeping section of San Andreas (red triangles)
- ▶ Solid colored lines are the least squares fit
- ▶ Straight line (black) is $1/A$.
- ▶ Data is consistent with scaling hypothesis $N_A \sim e^{-\Delta h A^{2/3}} / A$ discussed on previous slide.

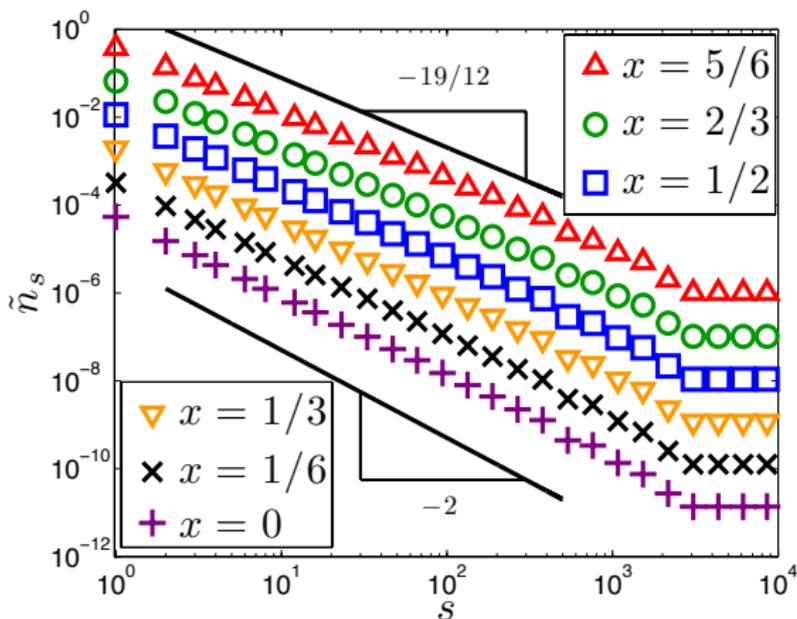
Fault System Scaling

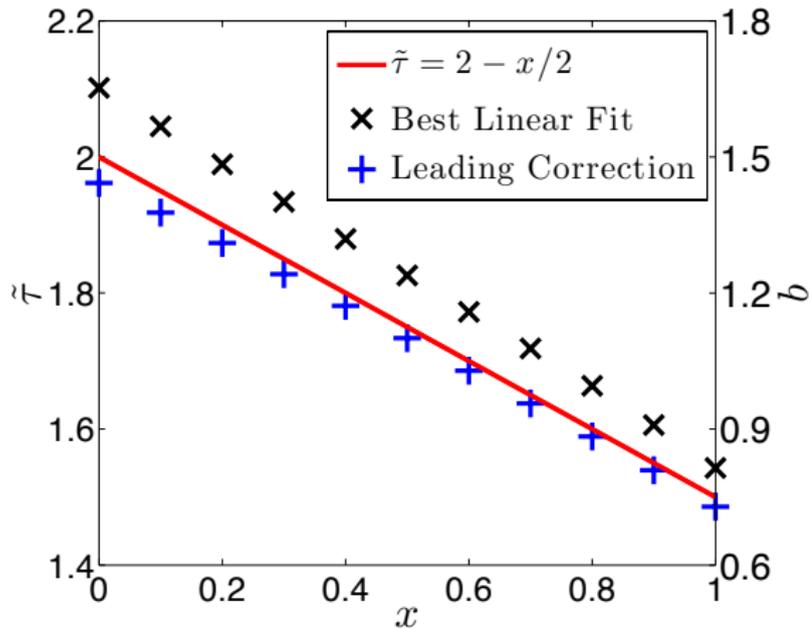
- ▶ How does the scaling of single faults relate to scaling of a fault system?
- ▶ GR statistics of a fault system (entire earth) are the sum of events on individual faults.

$$\bar{N}_s \sim \int_0^1 dq \frac{D(q)}{1-q} \frac{\exp[-q^2 s]}{s^{3/2}} \quad (3)$$

- ▶ $D(q)$ is the density of faults with damage fraction q .
- ▶ In real fault systems we don't know $D(q)$.
- ▶ Small cracks have a fractal distribution. M. Sahimi et al Physica A **191**, 57 (1992) reasonable assumption $D(q) = 1/q^x$
- ▶ With integral $\rightarrow \bar{N}_s \sim 1/s^{2-x/2}$

- CA Model - \bar{N}_s vs s for different values of x





- ▶ Results are consistent with theory.
- ▶ Cumulative b value range $0.75 \leq b \leq 1.5$

Summary and Conclusions

- ▶ Single fault scaling is consistent with a spinodal critical point.(data)
- ▶ Fault system scaling can be viewed as a sum over non-interacting faults.
- ▶ The paradigm allows scaling world wide when all faults do not scale and with fault system scaling exponents different than the scaling on a single fault.
- ▶ Also explains how system scaling can change from one system to another. ($D(q)$)

C. A. Serino, W. Klein, and J. B. Rundle, Phys. Rev. E **81**, 106105 (2010).

C. A. Serino, K. Tiampo and W. Klein Physical Review Letters **106**, 108501 (2011)

Future Research

- ▶ Include different types of damage in CA model.
- ▶ Add dynamics and real friction - damage in BK model.
- ▶ Determine the affect of interaction of faults.
- ▶ Investigate foreshocks(AMR) and aftershocks(Omori) in models .