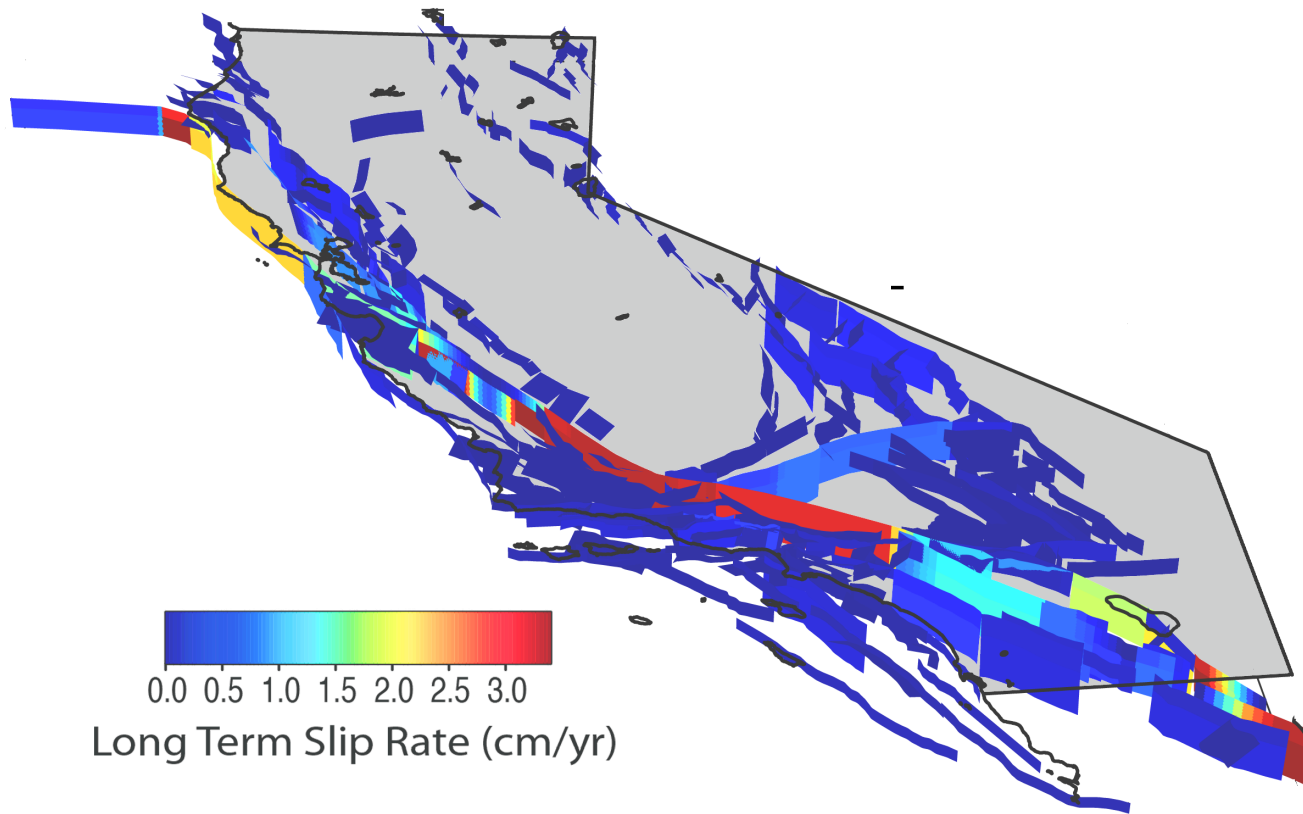


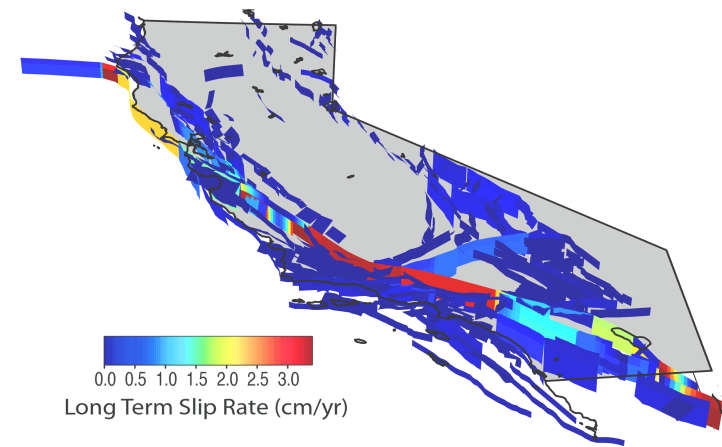
Earthquake Forecasting Using RSQSim Earthquake Simulations

Jim Dieterich, UC Riverside
Keith Richards-Dinger, UC Riverside
Jacqui Gilchrist, USC

Tom Jordan - USC
Kevin Milner - USC
Christine Goulet - USC
Phil Maechling - USC
Ned Field-USGS
Yifeng Cui - UCSD
Dmitry Pekurovsky - UCSD
Bruce Shaw - Columbia



RSQSim (Rate-State earthquake Simulator)



- **Capabilities**

- Quasi-dynamic rupture propagation
- Comprehensive simulations of fault slip phenomena:
 - earthquakes, continuous creep, slow slip events, afterslip
- Implement rate- and state-dependent friction effects
 - Short-term earthquake clustering effects
- Highly efficient simulation algorithm enables simulation of $>10^6$ earthquakes with models consisting of up to 500,000 elements
- Complex 3D fault geometry with rectangular or triangular boundary elements

- **Applications**

- Experimental tool to investigate the physics of fault and earthquake phenomena
- **Earthquake forecasting and assessment of earthquake probabilities**
- Stress evolution in fault systems and initial conditions for rupture simulations and ground motions
- Induced seismicity

Inputs to Simulations

- ❖ Fault system model
 - Fault system geometry
 - Rake angles
 - Fault slip rates
 - Mode of slip of each fault element (seismic, creep, SSE)
 - Elastic constants

- ❖ Mean recurrence times at fault sections

- ❖ Simulation parameters
 - dynamic overshoot
 - α -reduction
 - EQ slip speed (based on stress drop and shear impedance)

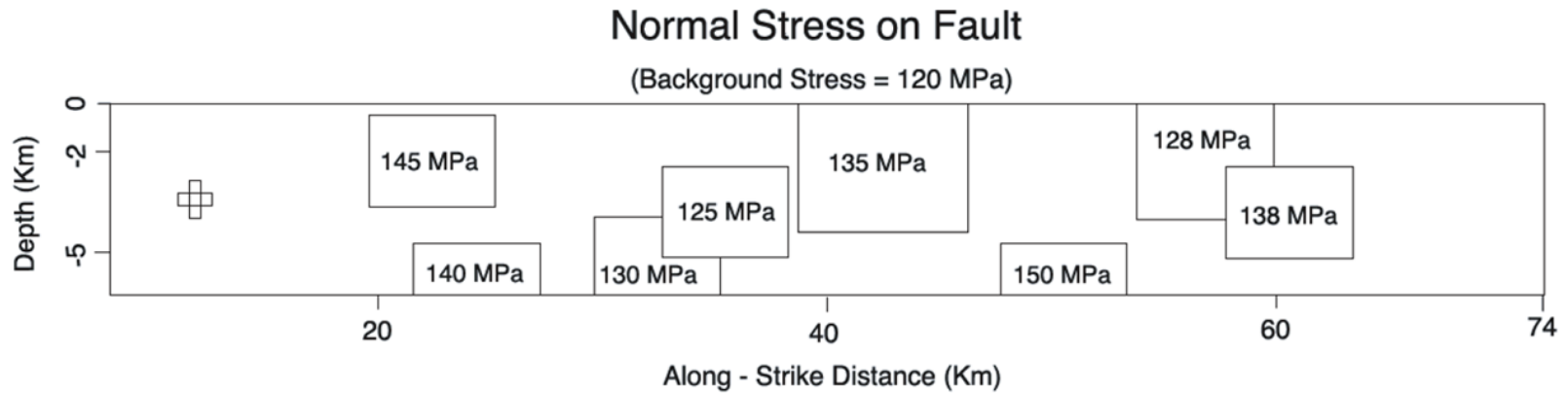
- ❖ Rate-state constitutive parameters (based on lab values)

- ❖ Normal stress acting on each element

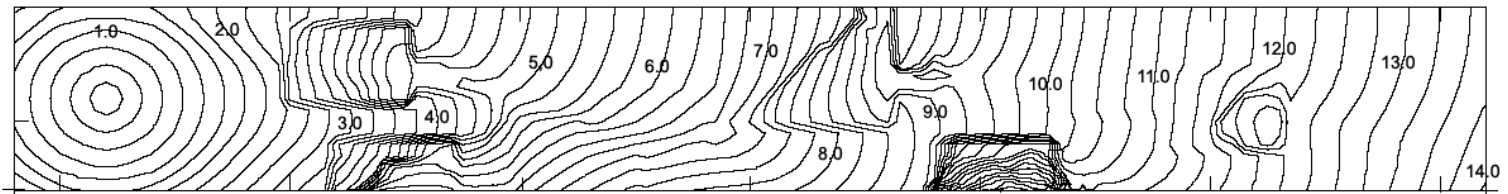
Validation of Earthquake Forecasts

	<i>Simulator-based</i>	<i>Statistics-based</i>
1) Simulator physics	x	na
2) Model consistent with observations? <ul style="list-style-type: none">• Earthquake statistics, scaling relations• Rupture dynamics• Geologic observations	x x x	x — x
3) Probabilistic methodology <ul style="list-style-type: none">• Short-term forecasts• Long-term large-earthquake forecasts	x x	x —

RSQsim – DYNA3D Comparison

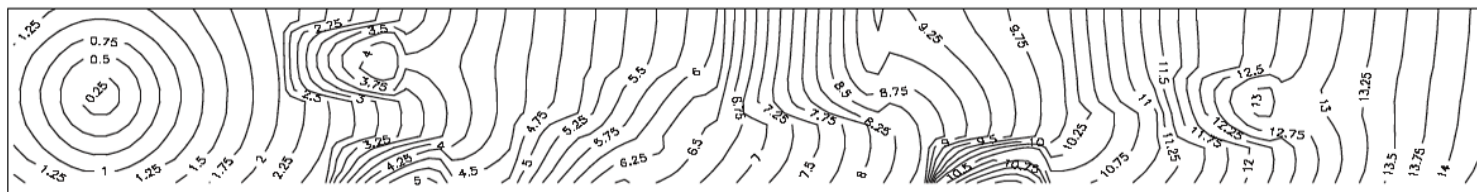


DYNA3D – Fully dynamic finite element simulation



Propagation time 14.0 s

RSQsim – Fast simulation

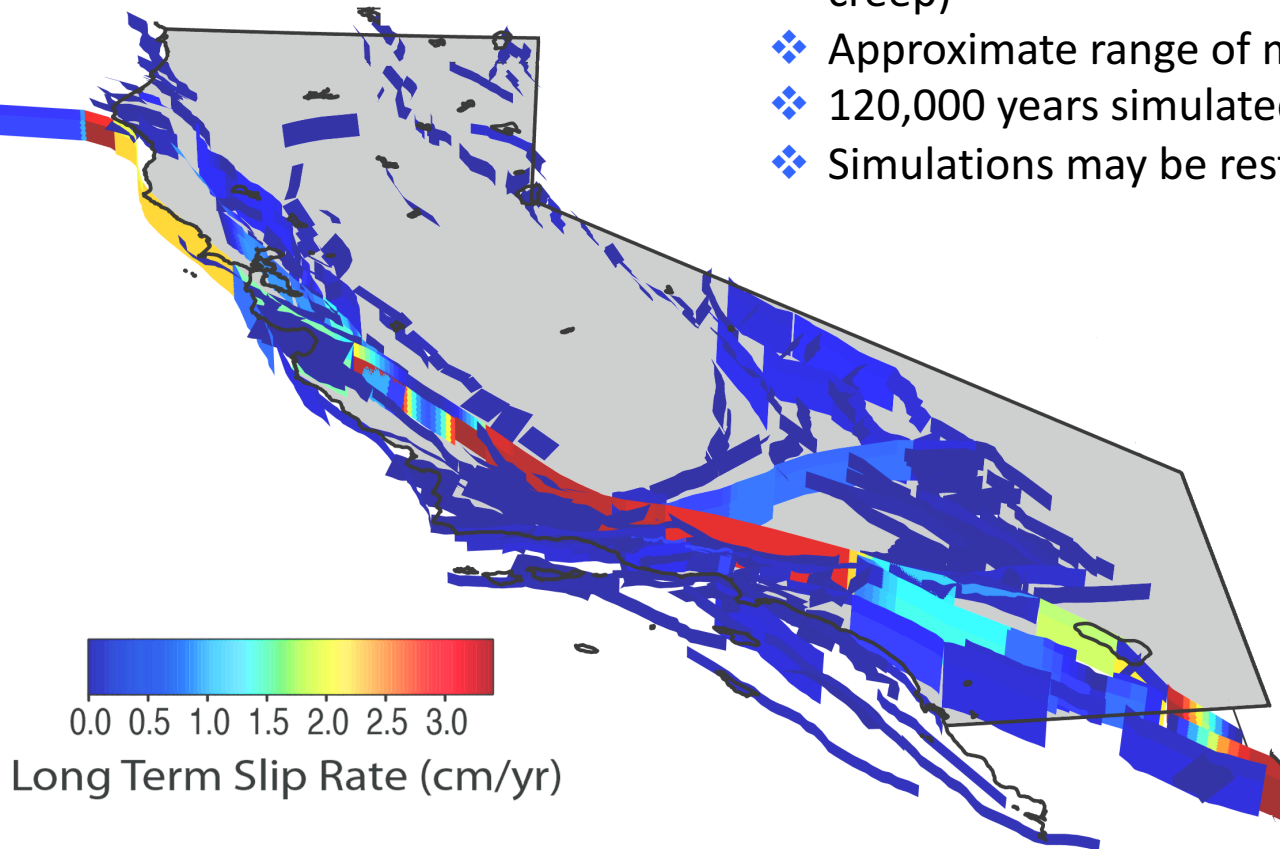


Propagation time 14.3 s

UCERF3 Fault Model and Slip Rates

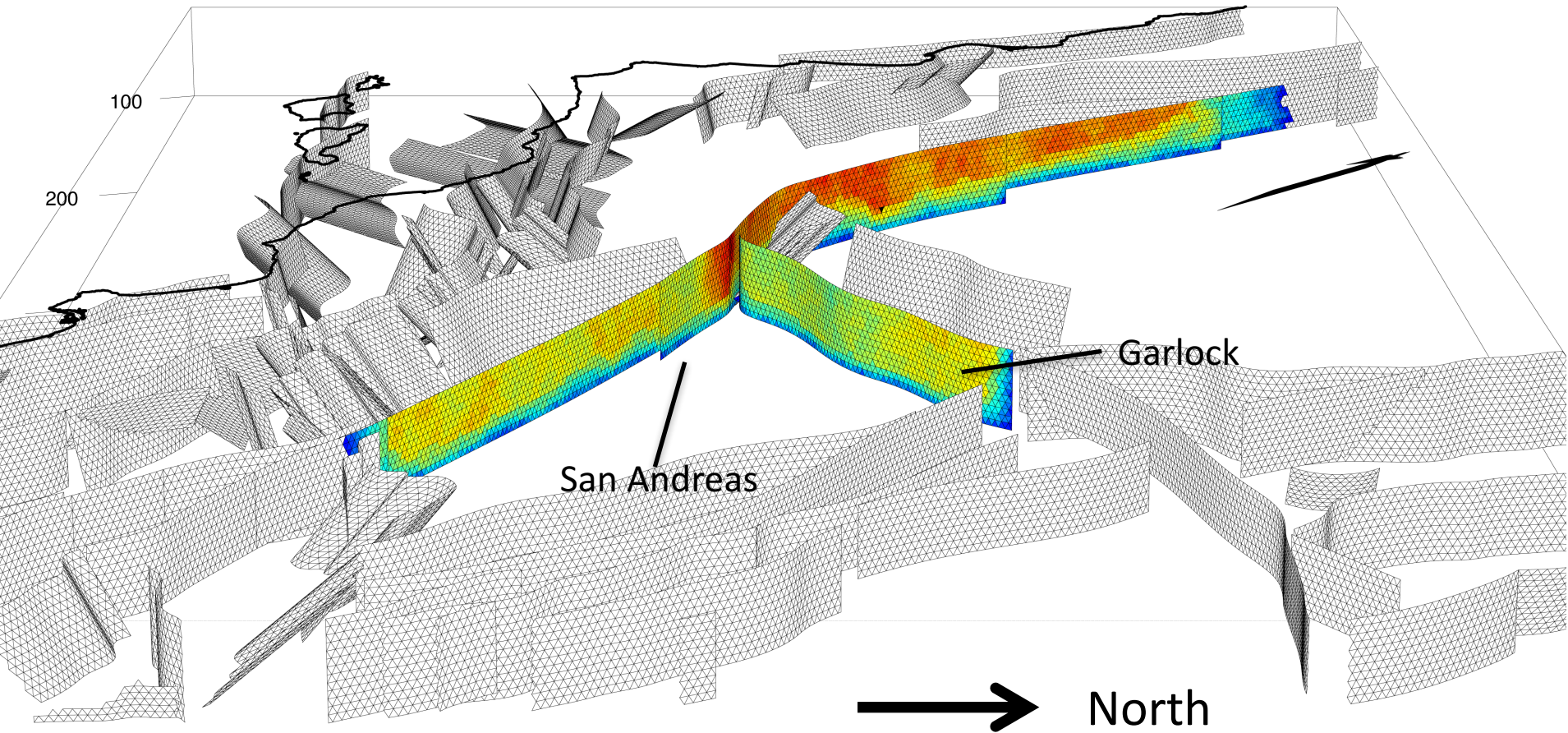
Simulations with UCERF3 fault model

- ❖ ~ 290,000 triangular elements ($\sim 1\text{km}^2$) in simulations with deep fault creep ($\sim 260,000$ no creep)
- ❖ Approximate range of magnitudes $M_w=4$ to $M_w=8$
- ❖ 120,000 years simulated time $\sim 16 \times 10^6$ events
- ❖ Simulations may be restarted to span 10^6 years

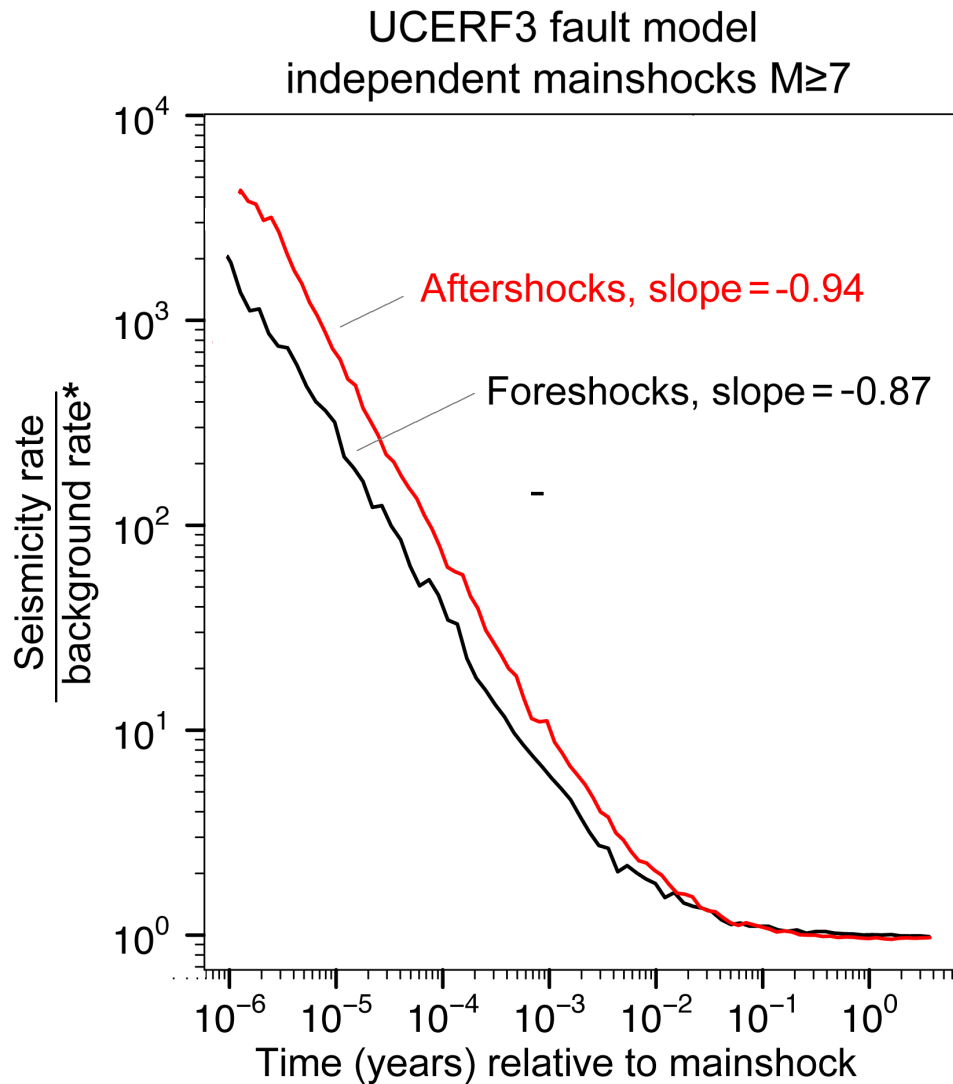


Detail of UCERF3 fault model

SAF Rupture Branching at Garlock Fault



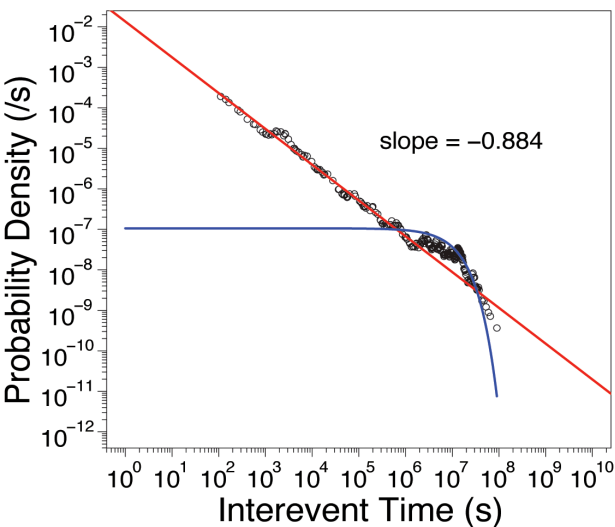
RSQSim – Foreshocks and aftershocks



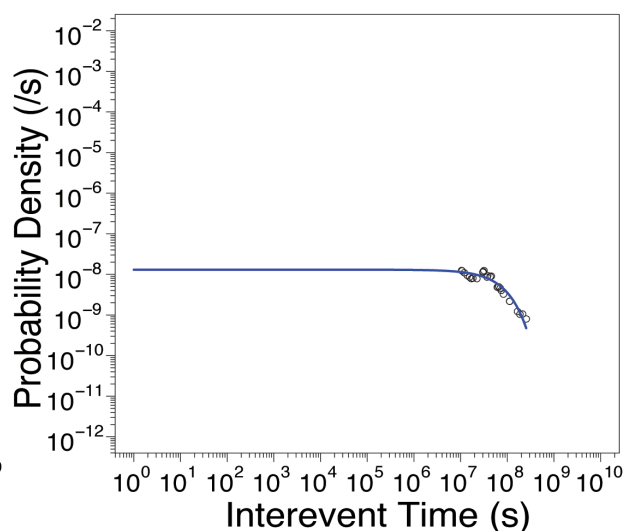
* Background seismicity rate is global average, not local to mainshock

Inter-event Waiting Time Distributions

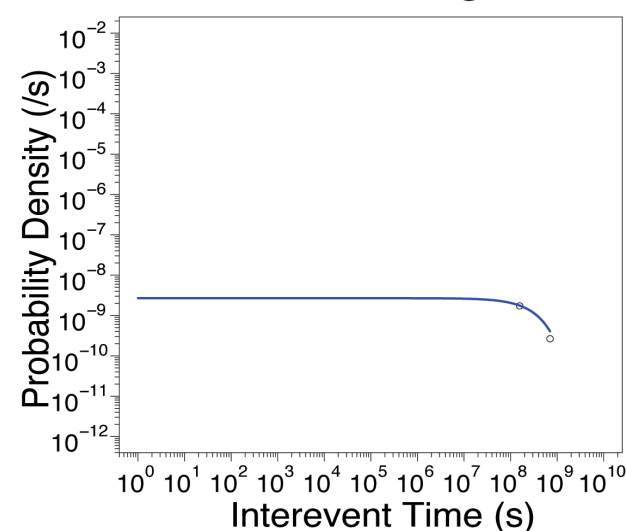
California Catalog: M5 to M6



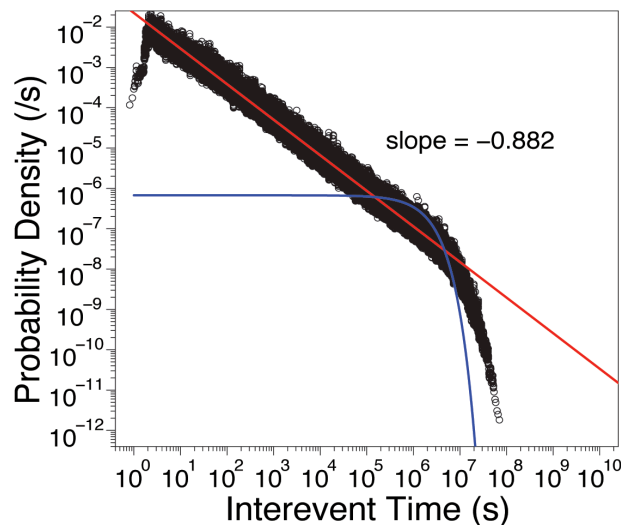
California Catalog: M6 to M7



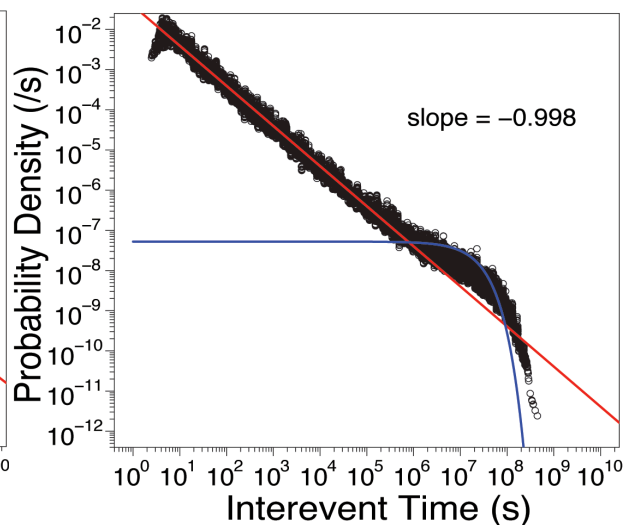
California Catalog: M7+



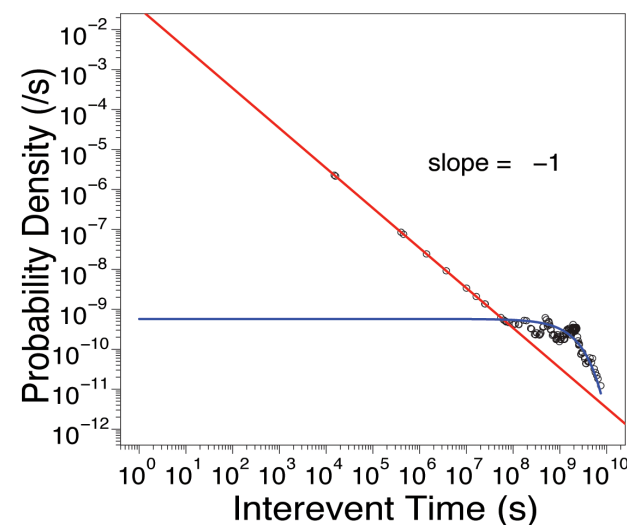
RSQSim Catalog: M5-M6



RSQSim Catalog: M6-M7

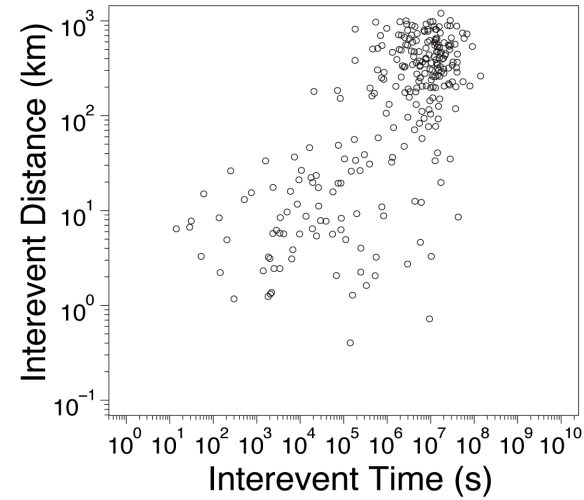


RSQSim Catalog: M7+

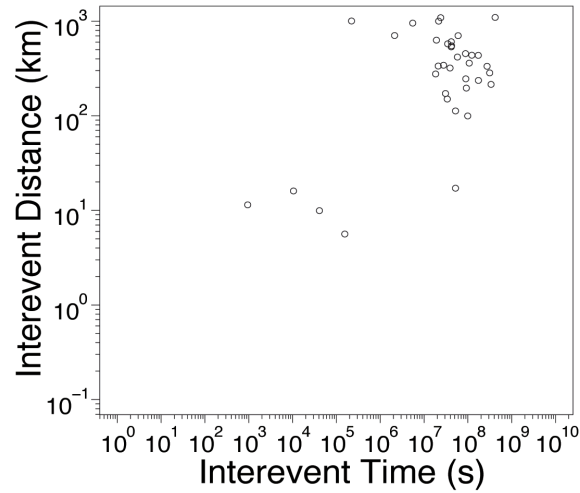


Space – Time Distributions

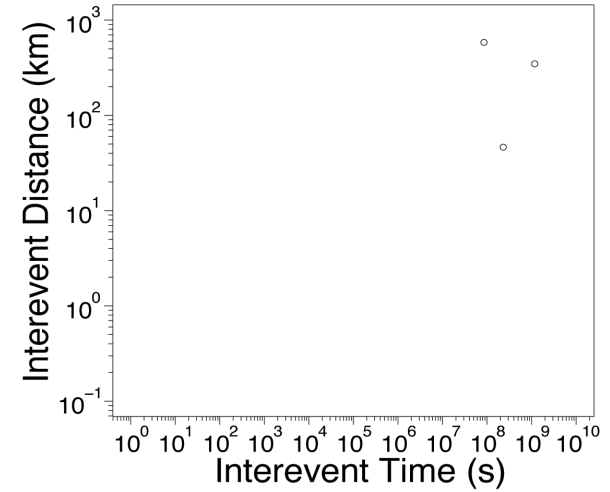
California Catalog: M5–M6



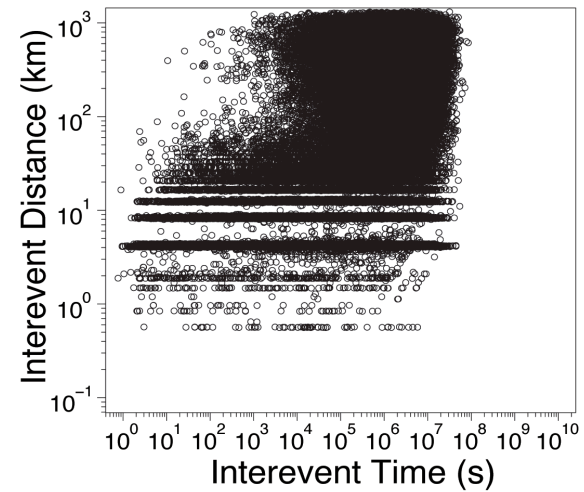
California Catalog: M6–M7



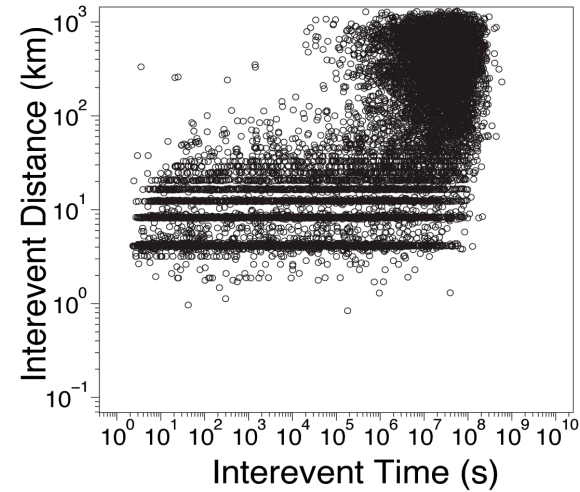
California Catalog: M7+



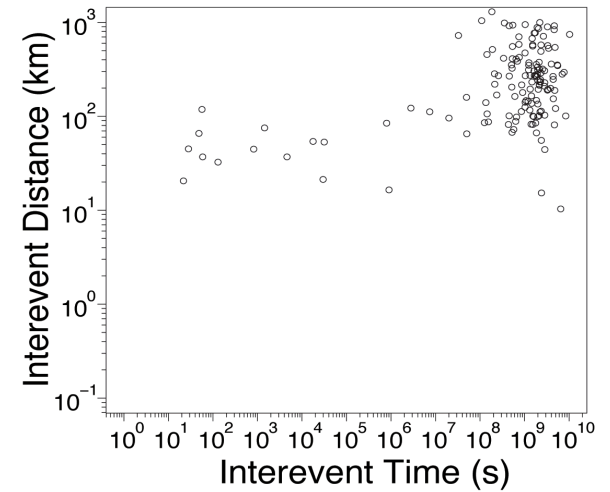
RSQSim Catalog: M5–M6



RSQSim Catalog: M6–M7

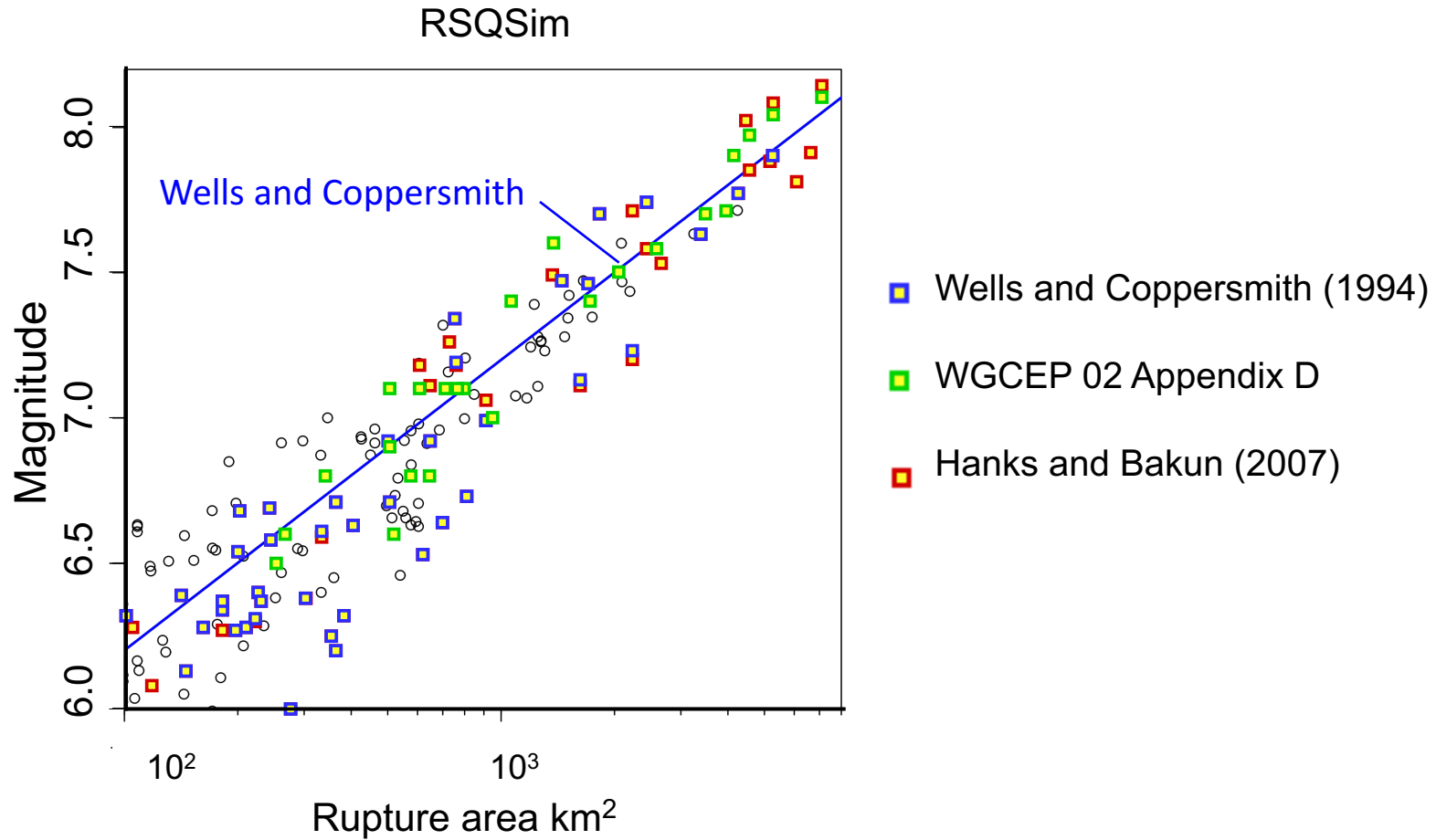


RSQSim Catalog: M7+



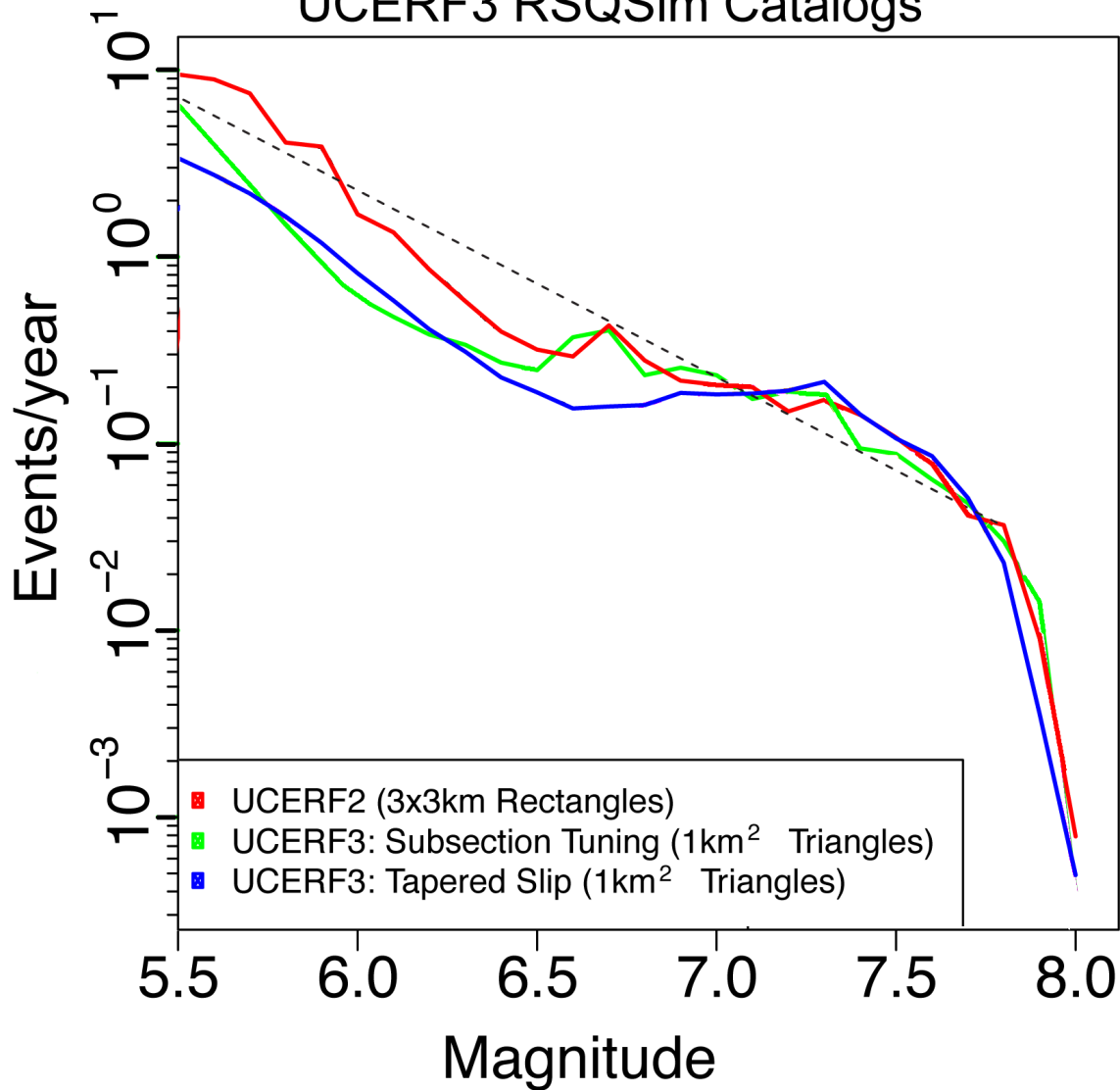
Magnitude-area Scaling

Showing only 200 years of simulated events



California fault system simulations

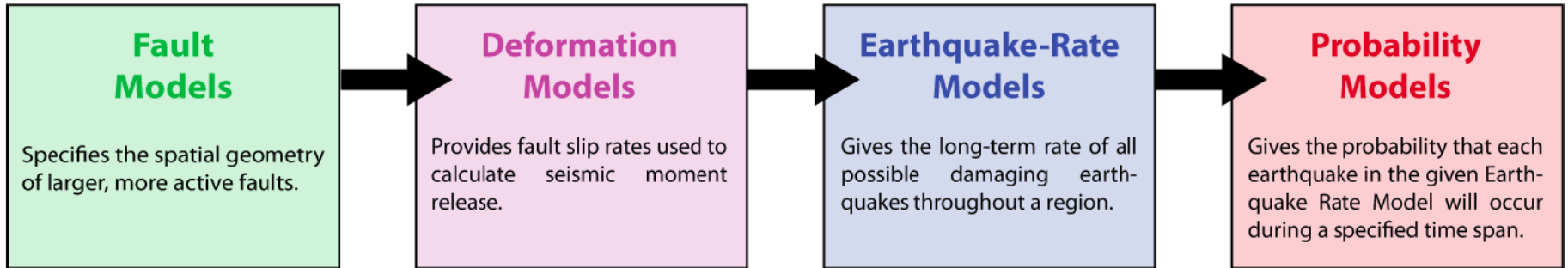
MFD Comparisons UCERF2 and UCERF3 RSQSim Catalogs



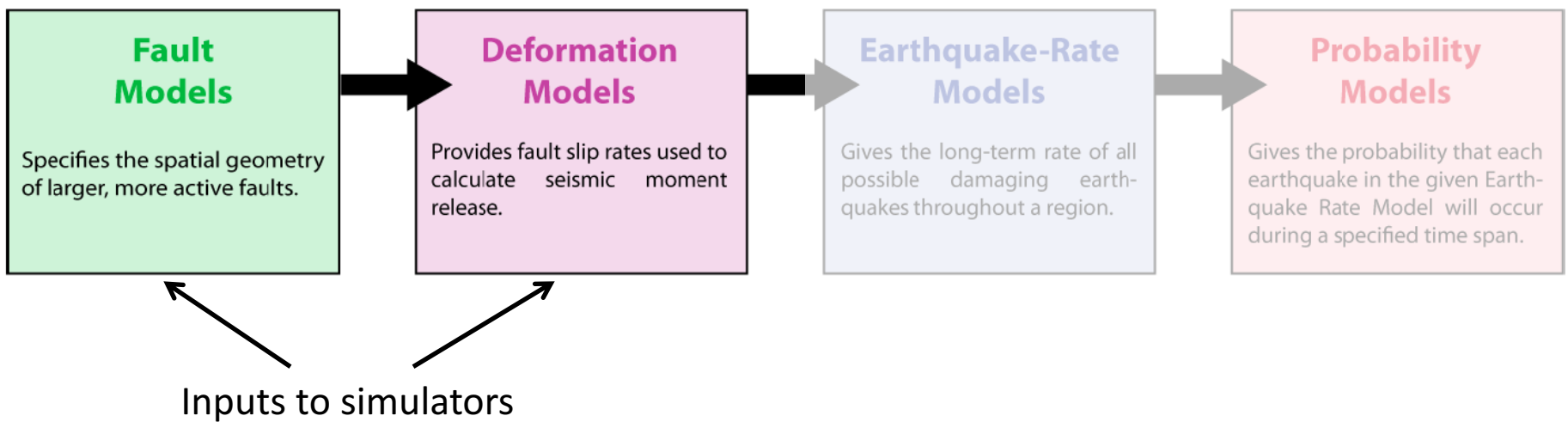
Possible Applications of Simulations to Earthquake Forecasts

- 1) Regional time-dependent probabilistic assessments of earthquakes on mapped faults
- 2) Applications based on space-time clustering of events
- 3) “Off-fault” seismicity (short- and long-term forecasts of earthquake rates)

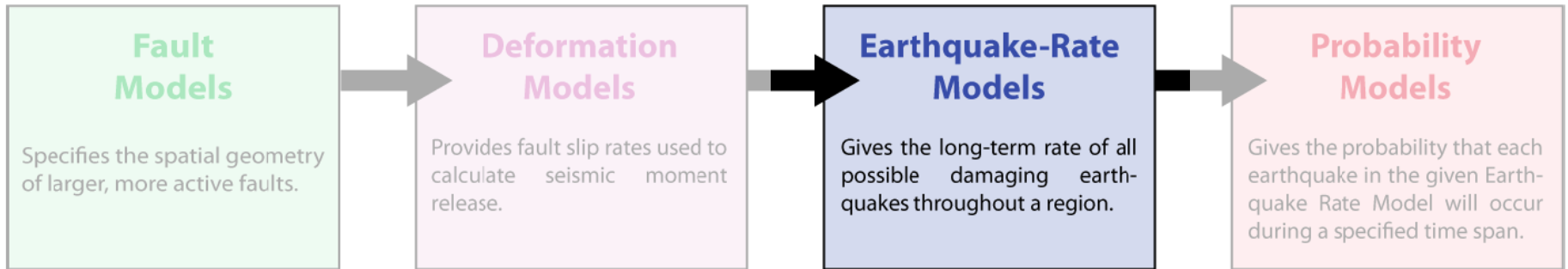
Components of the Uniform California Earthquake Rupture Forecast



Components of the Uniform California Earthquake Rupture Forecast



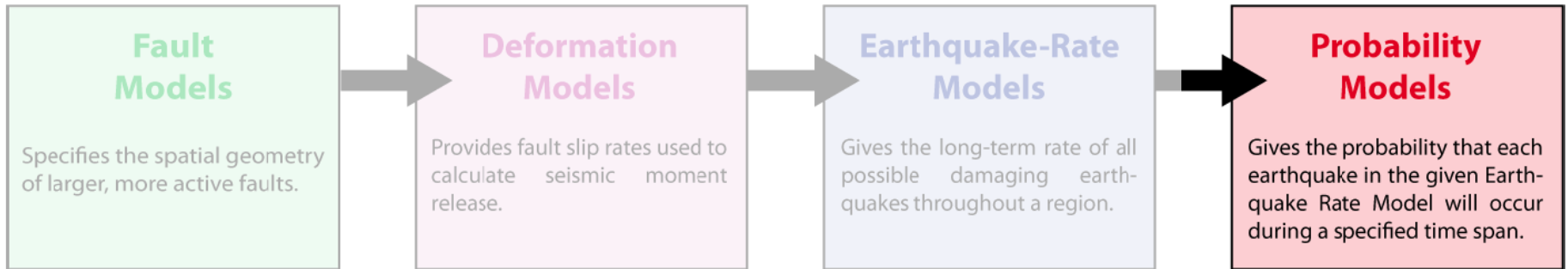
Components of the Uniform California Earthquake Rupture Forecast



Simulators directly produce earthquake rate models – Catalogs $\geq 10^6$ events.

- Uncertainties in moment balancing are avoided
- Segmentation is not assumed or enforced
- Multiple realizations → effect of parameter uncertainties
- Tuned to be consistent with paleoseismic recurrence
- Rupture jumps and branching
- Space-time clustering effects

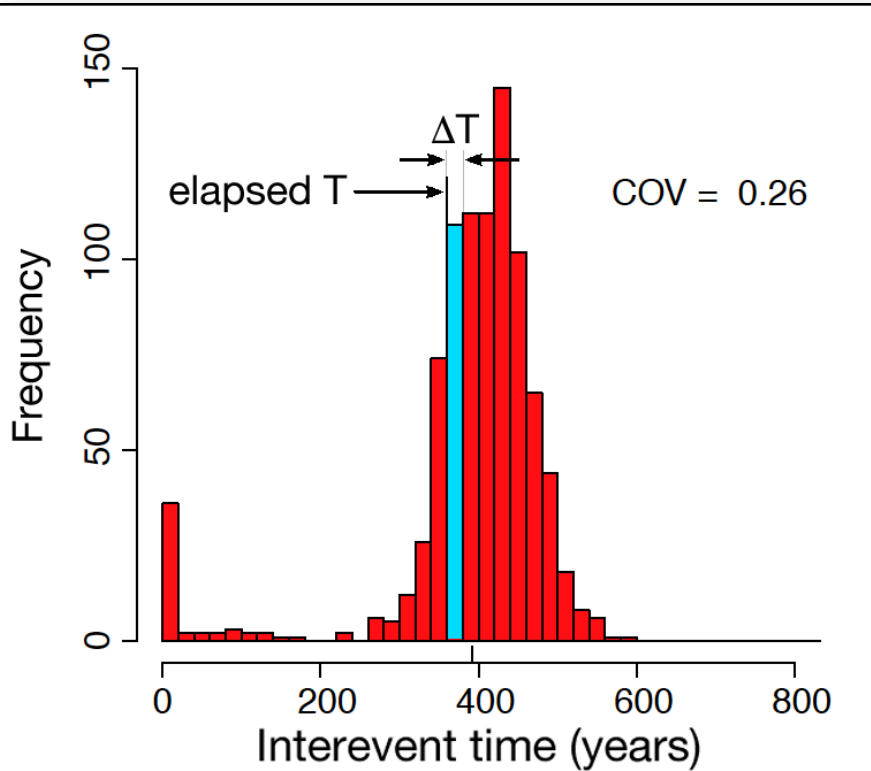
Components of the Uniform California Earthquake Rupture Forecast



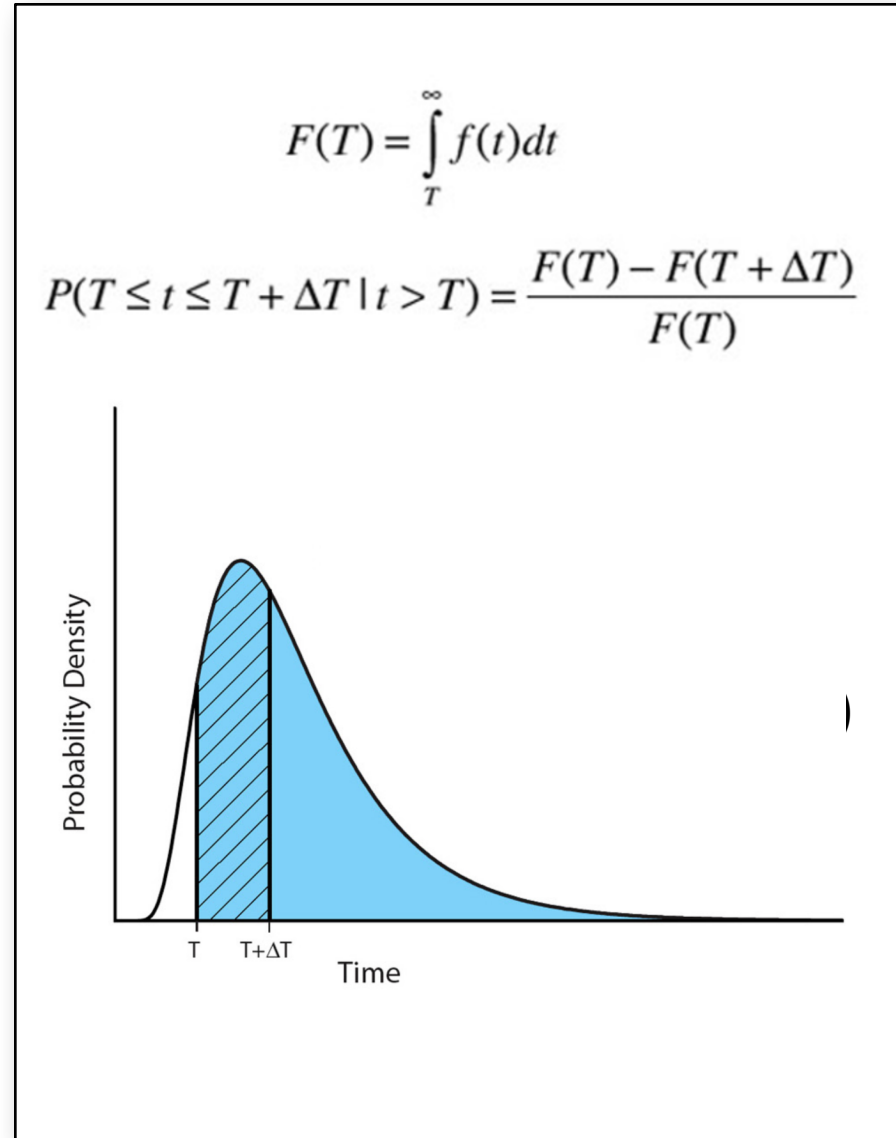
Estimation of conditional probabilities

- Sufficient number of events in catalogs to generate empirical probability density distributions for all fault sections
- No *a priori* assumptions about clustering vs Poisson vs quasi-periodic

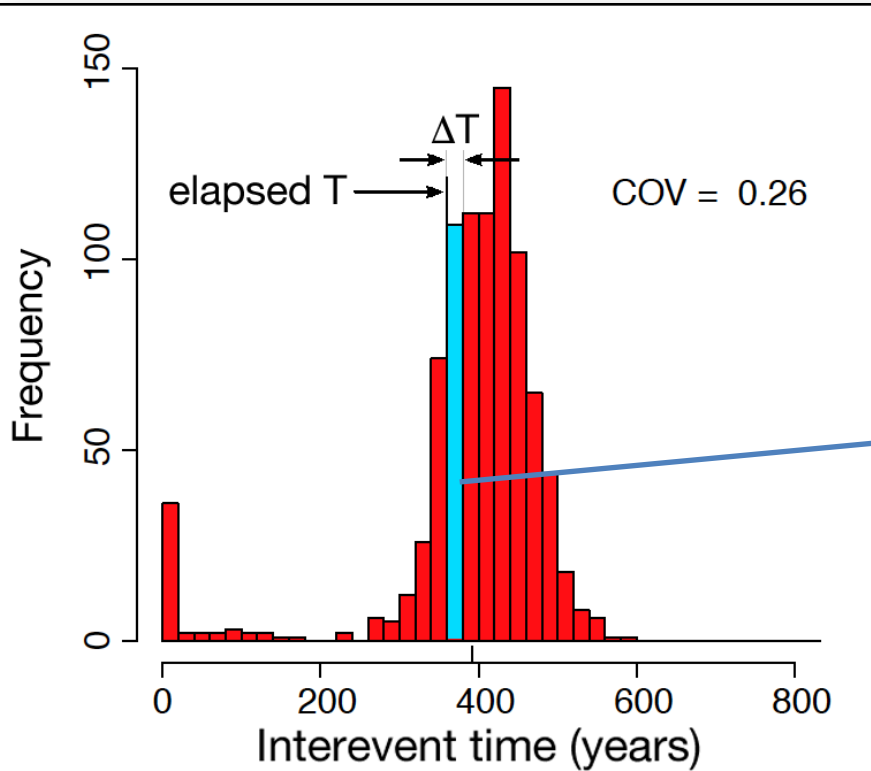
Conditional probabilities at fault section i



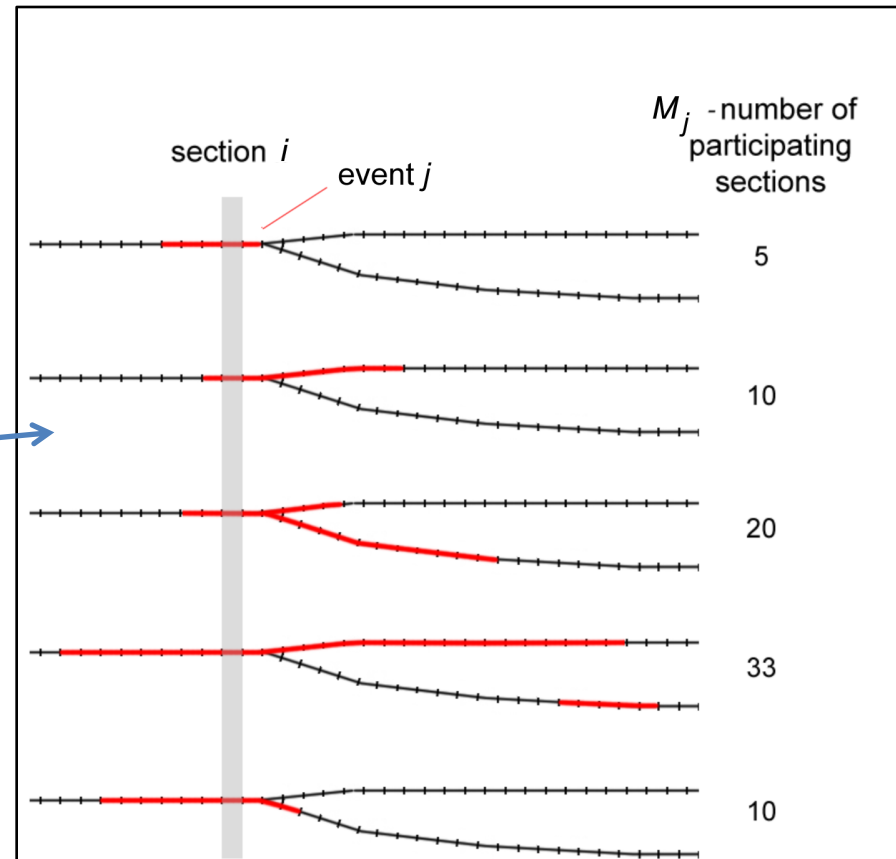
CP_i = conditional probability of event $M \geq M_{min}$ in interval ΔT on section i , given elapsed time T_i



The events in the interval ΔT of the pdf provide a sample of possible events that may occur in the future.



CP_i = conditional probability of event $M \geq M_{min}$ in interval ΔT on section i , given elapsed time T_i



Sub-catalog of n events for a section that occur in the interval ΔT used to determine CP_i

Inversion for event probabilities p_j

Section probabilities

Event probabilities

$$CP_i = \sum_{j=1} \delta_{ij} p_j$$

i – index on fault sections

j – index on earthquake events that appear in the Δt sub-catalogs

δ_{ij} – participation matrix. Takes value of 1 for section numbers i that participate in earthquake j . Otherwise value = 0.

The inversions are underdetermined

Inversion for event probabilities p_j

Goal is to minimize misfit for inversion for unknown event probabilities p_j

$$CP_i = \sum_j \delta_{ij} p_j$$

Misfit for section some section i

$$E_i = CP_i - \sum_j \delta_{ij} p_j$$

Minimize the sum of the squares for all sections

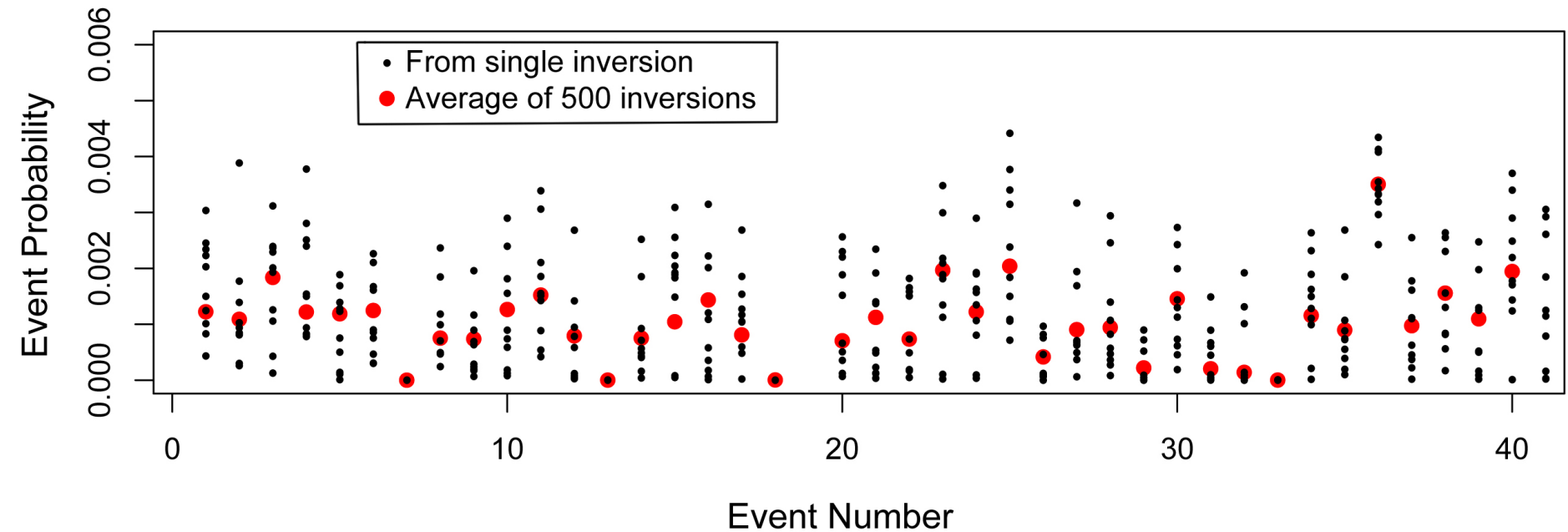
$$\{E_i\}^2 = \sum_i \left\{ CP_i - \sum_j \delta_{ij} p_j \right\}^2$$

Optimization based on non-negative least squares (Lawson, 1995) is very efficient. Specifically we use bounded-value least squares (BVLS) constrained to be positive, and within prescribed intervals (0 to 1).

30-year time-dependent event probabilities $M \geq 6.7$, Northern California faults

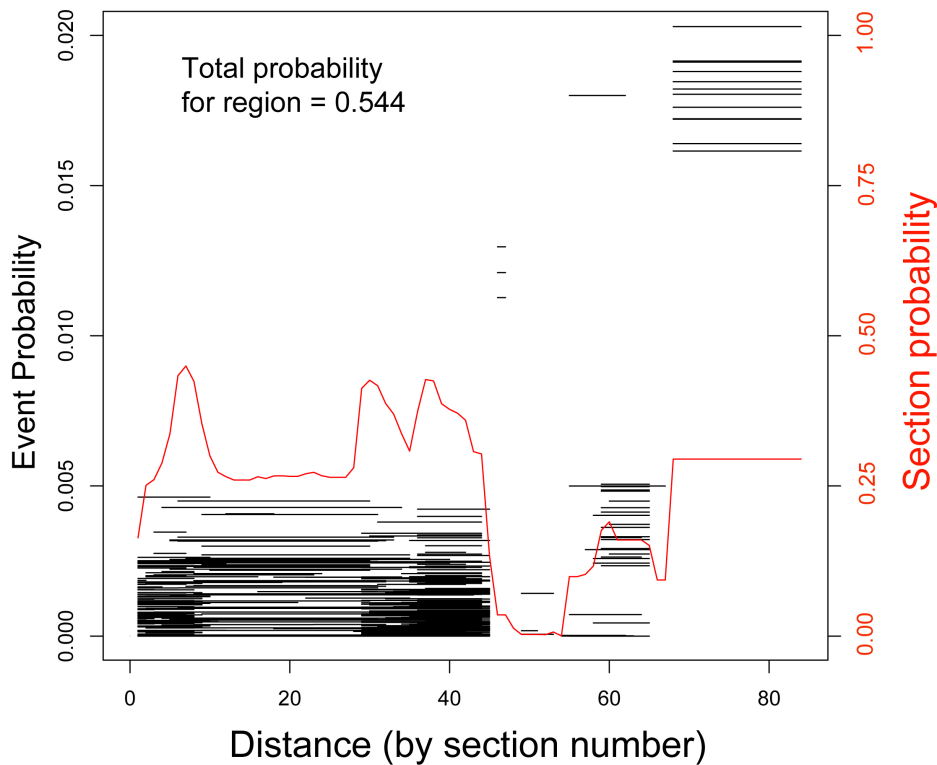
Inversion at set maximum misfit error using simulated annealing

Sample of event probabilities (from 469 events in sub-catalog)

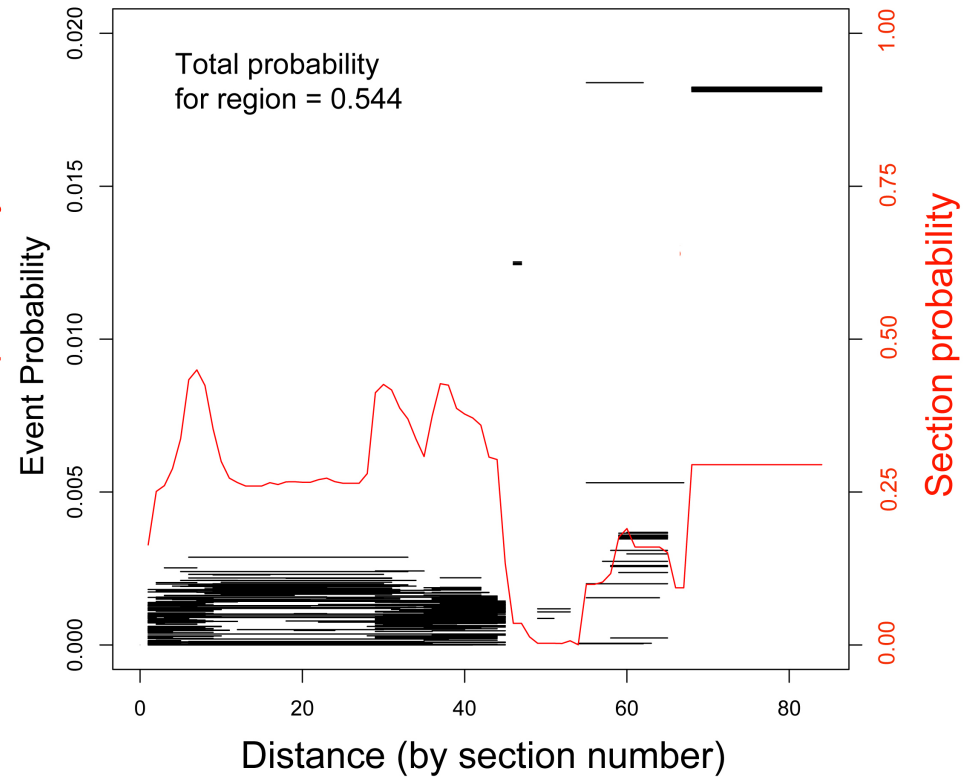


Example of 30-yr conditional event probabilities by position in fault system

Northern California faults, single inversion



Northern California faults, average of 500 inversions



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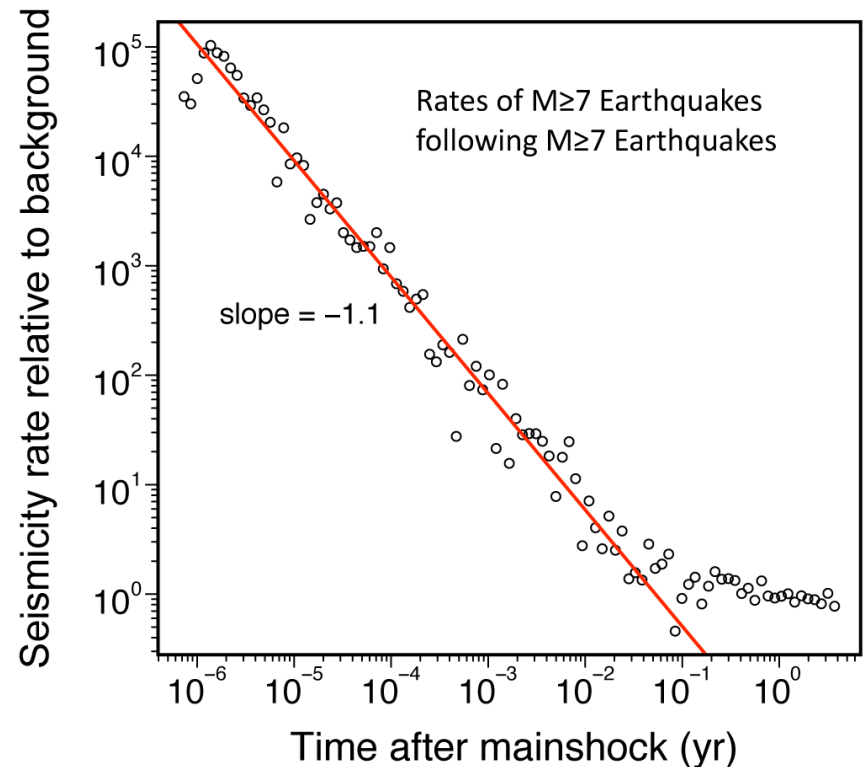
Clusters of Large Earthquakes

F_{cluster} is the fraction of $M \geq 7$ events that occur within 4 years of other $M \geq 7$ events (in excess of that predicted by a Poisson model)

All Cal model – effect of a	F_{cluster} $M \geq 7$
All-Cal, $a = 0.008$	0.124
All-Cal, $a = 0.009$	0.117
All-Cal, $a = 0.010$	0.145
All-Cal, $a = 0.012$	0.171

California Catalog 1911-2010.5, $M=6$ to $M=7$	F_{cluster}
	0.14

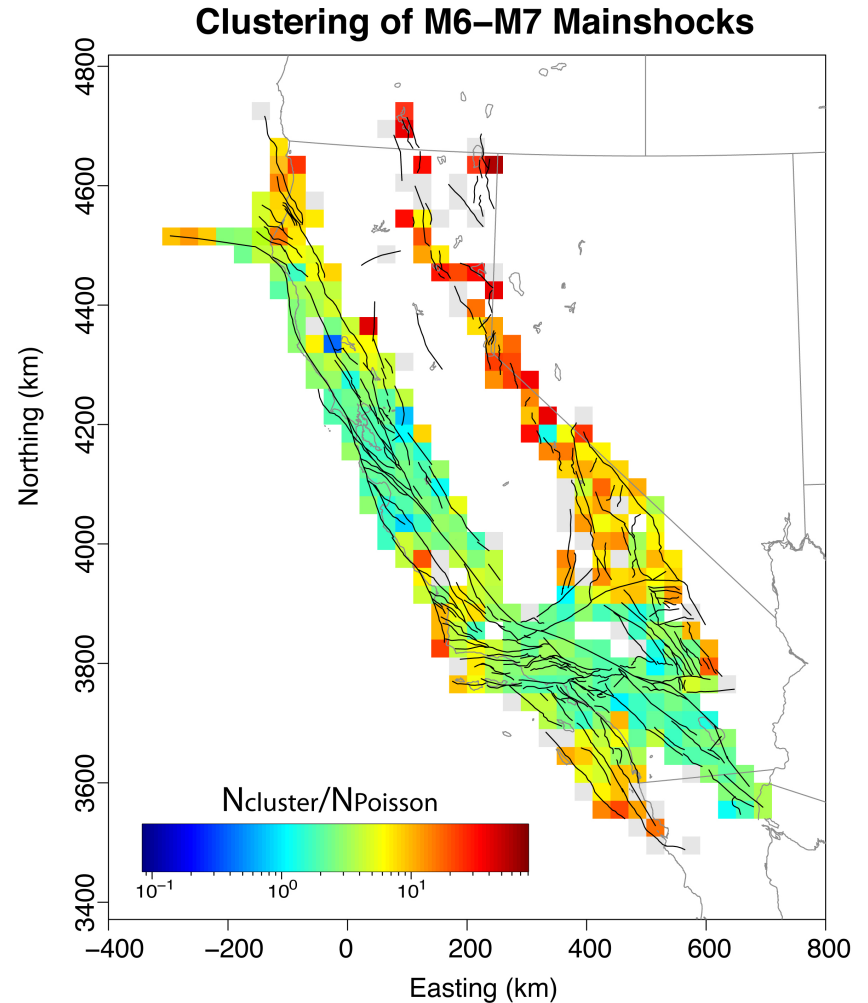
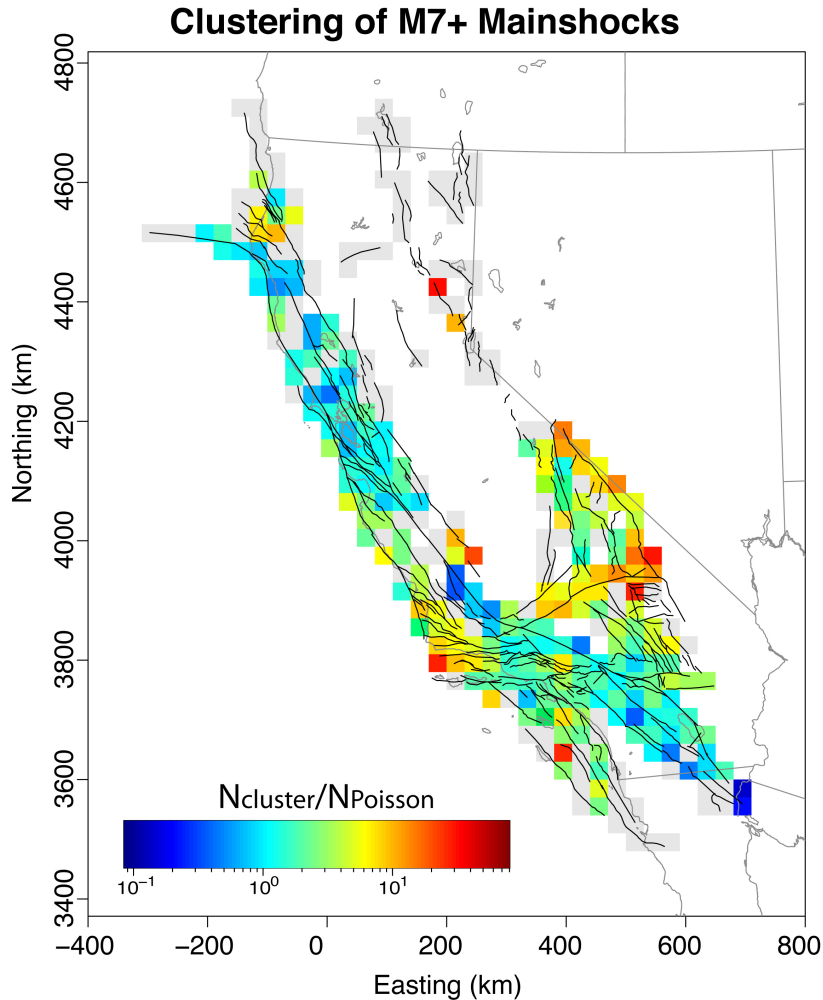
All Cal Simulation



Spatial variations of large event clusters

N_{cluster} – number of events in $\Delta t = 4$ years and within 100km of prior event

N_{poisson} – number of events expected in $\Delta t = 4$ years and within 100km assuming Poisson rate rate of occurrence

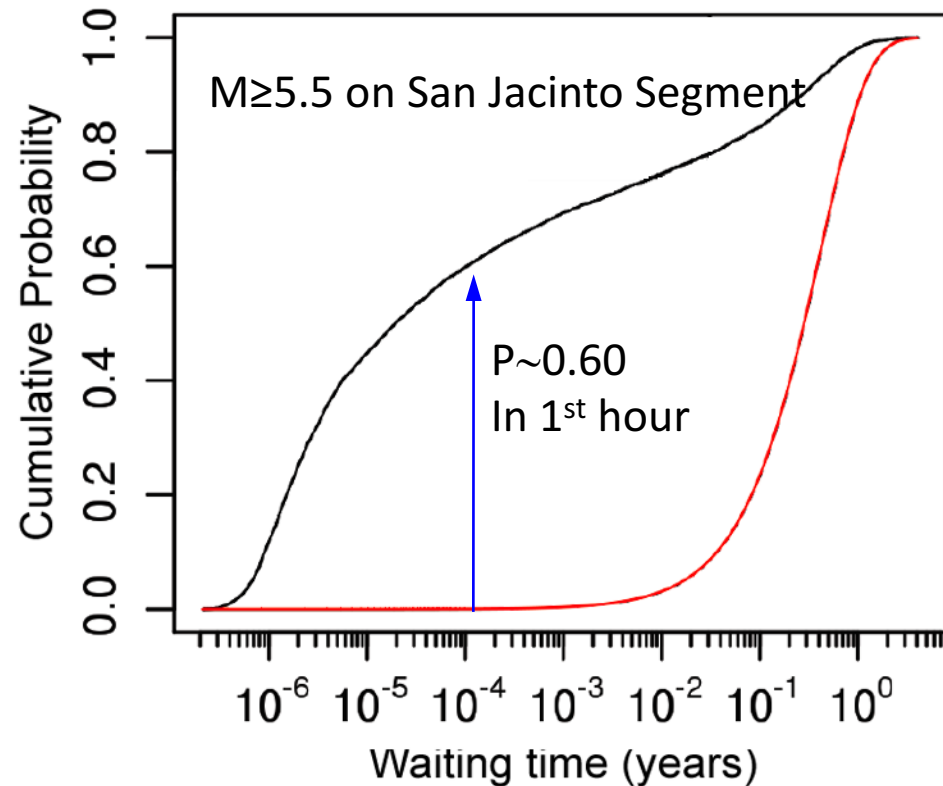
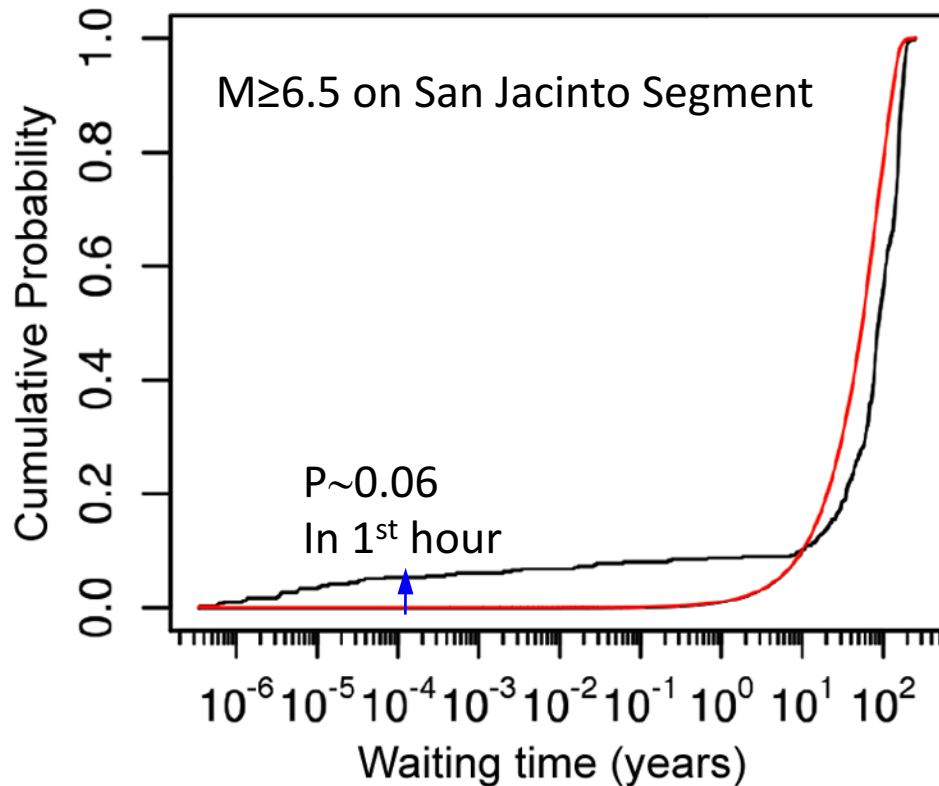


Linking short-term and long-term forecasts

Cumulative probability of earthquakes (on San Jacinto fault segment of the San Jacinto fault)

— From random time
— From time of $M \geq 6.5$ on adjacent Anza segment

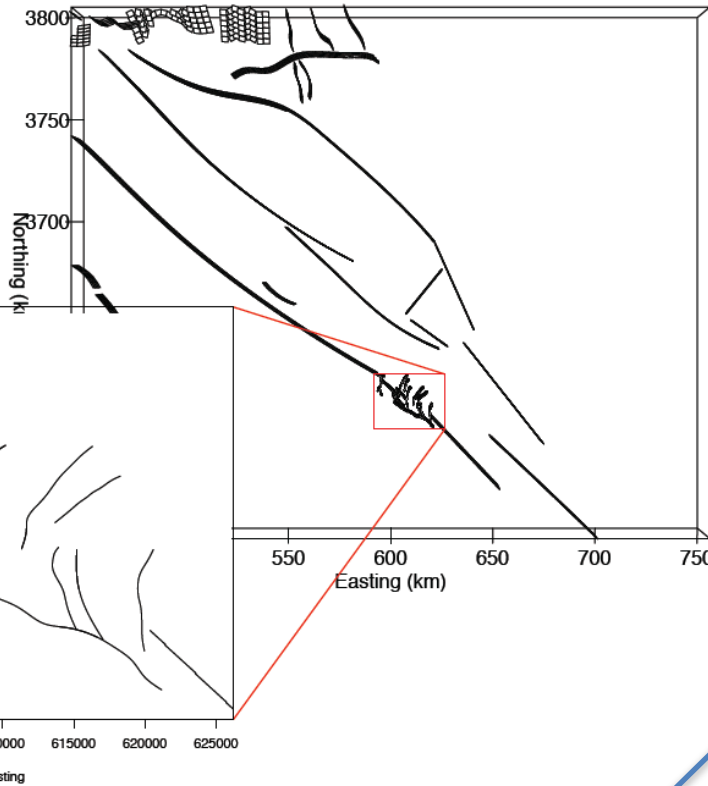
— From random time
— From time of $M \geq 6.5$ on adjacent Anza segment



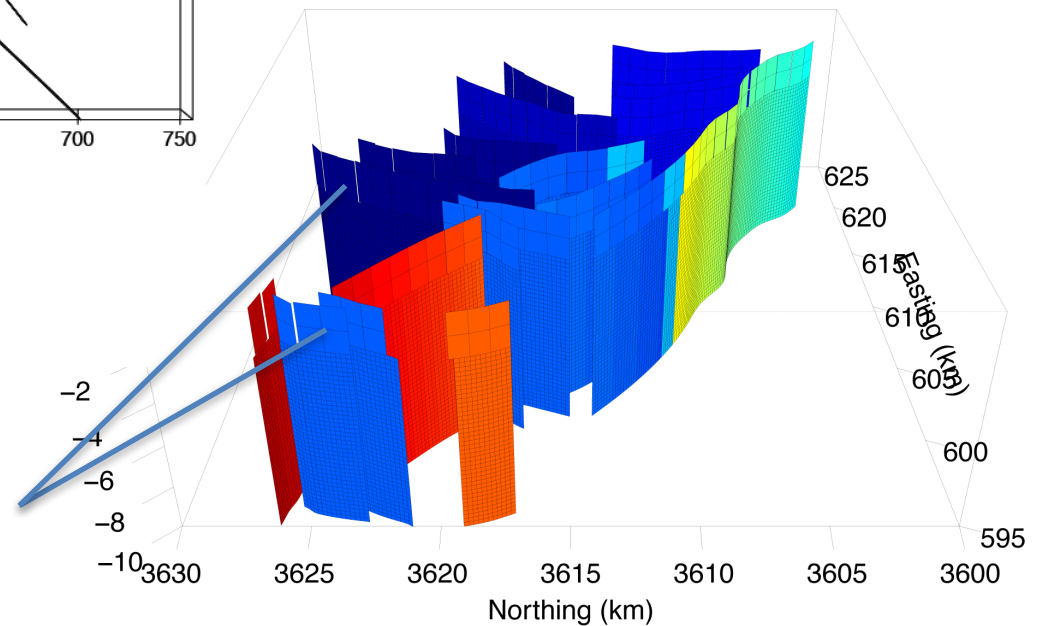
Possible Applications of Simulations to Earthquake Forecasts

- 1) Regional time-dependent probabilistic assessments of earthquakes on mapped faults
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- 3) “Off-fault” seismicity (short- and long-term forecasts of earthquake rates)

Complex fault geometry in area of step-over



Model detail in area of step-over



Fault creep in upper 2 km results in co-seismic slip at time of large earthquakes on Laguna Salada and Elsinore faults

Simulated RSQSim and Off-Fault Seismicity

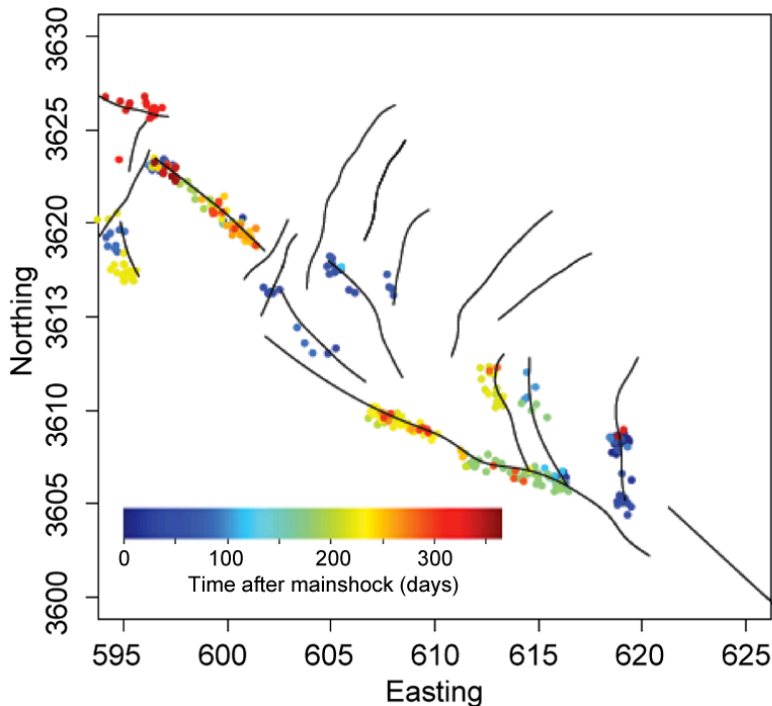
Detailed high-resolution fault model embedded in the California fault model

Seismicity rate (Dieterich, 1994)

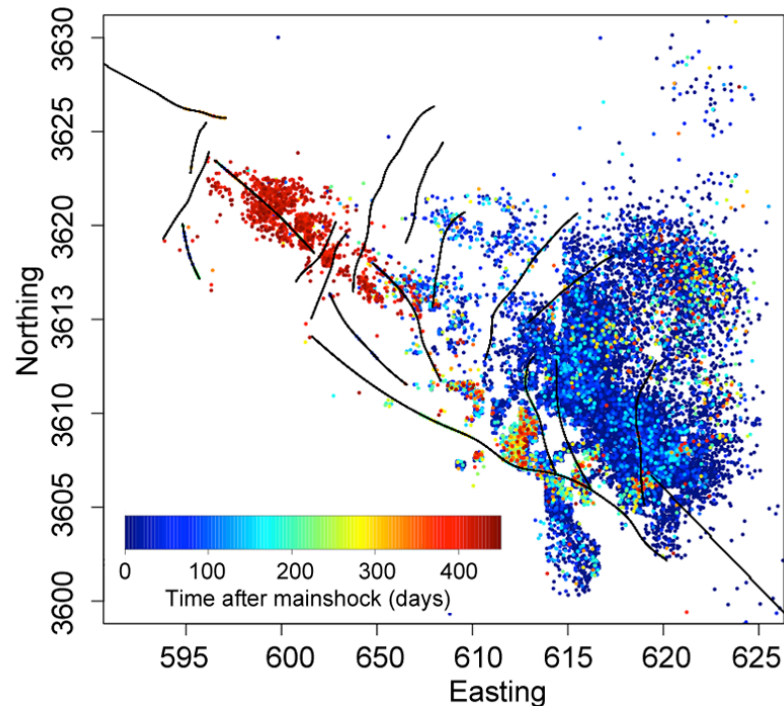
$$R = \frac{r}{\dot{S}_r \gamma} \quad d\gamma = \frac{1}{a\sigma} (dt - \gamma ds)$$

Off-fault stresses from RSQSim, plus tectonic stressing, drive off-fault seismicity. Magnitudes are drawn from Gutenberg-Richter distribution with upper and lower cutoffs

RSQSim aftershocks following
M7.04 Laguna Salada Mainshock



Off-fault aftershocks following
M7.04 Laguna Salada Mainshock



Possible advantages in using earthquake simulations for probabilistic forecasts

- ❖ Direct computation of the set of “all possible” earthquakes and their rates
- ❖ Obtain magnitude- and position-dependence of MRI distributions used in computing time-dependent conditional probabilities of fault sections
 - Additionally within a magnitude range, event magnitude with elapsed time
- ❖ No *a priori* assumptions concerning PDFs for clustering vs Poisson vs quasi-periodic density functions
- ❖ Space-time clustering is included in long-term probabilistic forecasts
 - Span the range from short- to long-term forecast with single model

Current issues

- ❖ **Mismatch of paleo MRIs with current (last 100 yrs) seismicity**
- ❖ **Representation of discontinuities in California fault model**
 - Fault discontinuities have strong effect on simulations. Explore alternatives to current representation of gaps as undamaged intact elastic material (Idealized connecting faults?)
- ❖ **MFD's have a possible deficit of events around M6.5 in current test simulations**
- ❖ **Current test simulations have small COVs, which result in unacceptably high probabilities for sections at or past their MRI**

