Earthquake and fault system dynamics – Putting the pieces together

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With Thanks to
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Kayla Kroll - LLNL
Jacqui Gilchrist - USC
Debbie Smith - USGS

Outline of topics

- Elements of earthquake and fault system dynamical models
- A few comparisons with observations and results from well-established computation models
- Earthquake rupture similarity
- Interactions between slow slip events and earthquakes
- Earthquake clustering
- Rupture propagation at fault complexities
- Future direction: earthquakes occurring off of explicitly modeled faults

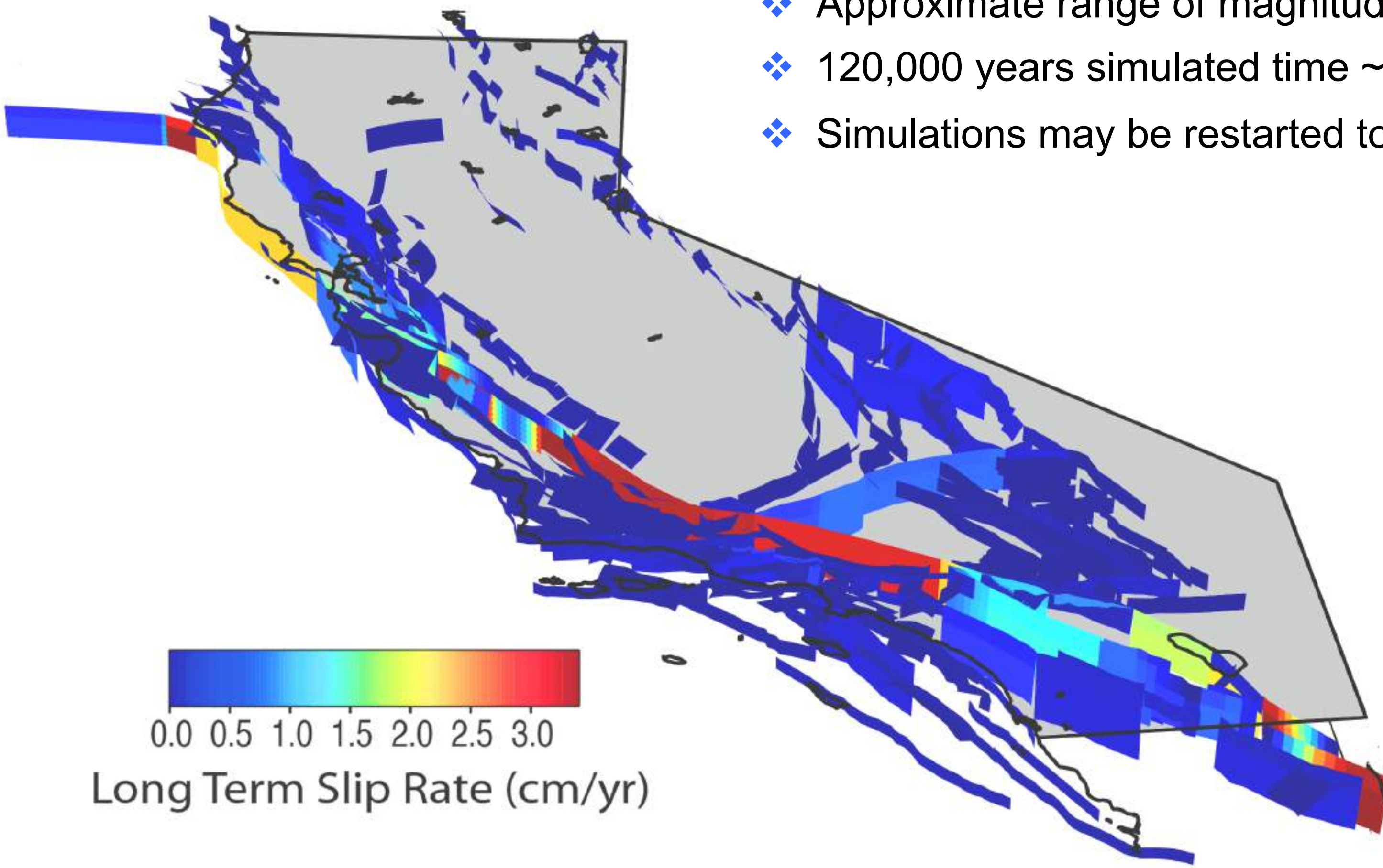
Modeling challenges – system dynamics

- *Extreme range of time and length scales→ <u>New approach to EQ modeling</u>*
  - *10^5 years and >10^6 earthquakes*
  - *High spatial resolution for range of earthquake magnitudes*
- *Space-time clustering of EQs → essential element of seismic activity*
  - *Added modeling complexity to incorporate time-dependent failure*
- *Fractal-like geometry of faults and fault systems → Geometric incompatibilities and modeling pathologies*
  - *<u>Uniform remote stressing does not work</u>*
  - *Finite strength requires off-fault failure (seismicity)*
    - → *Off-fault yielding alters slip processes on modeled faults*
    - → *Introduces additional time-dependencies*

Simulation ingredients – 1) Fault model

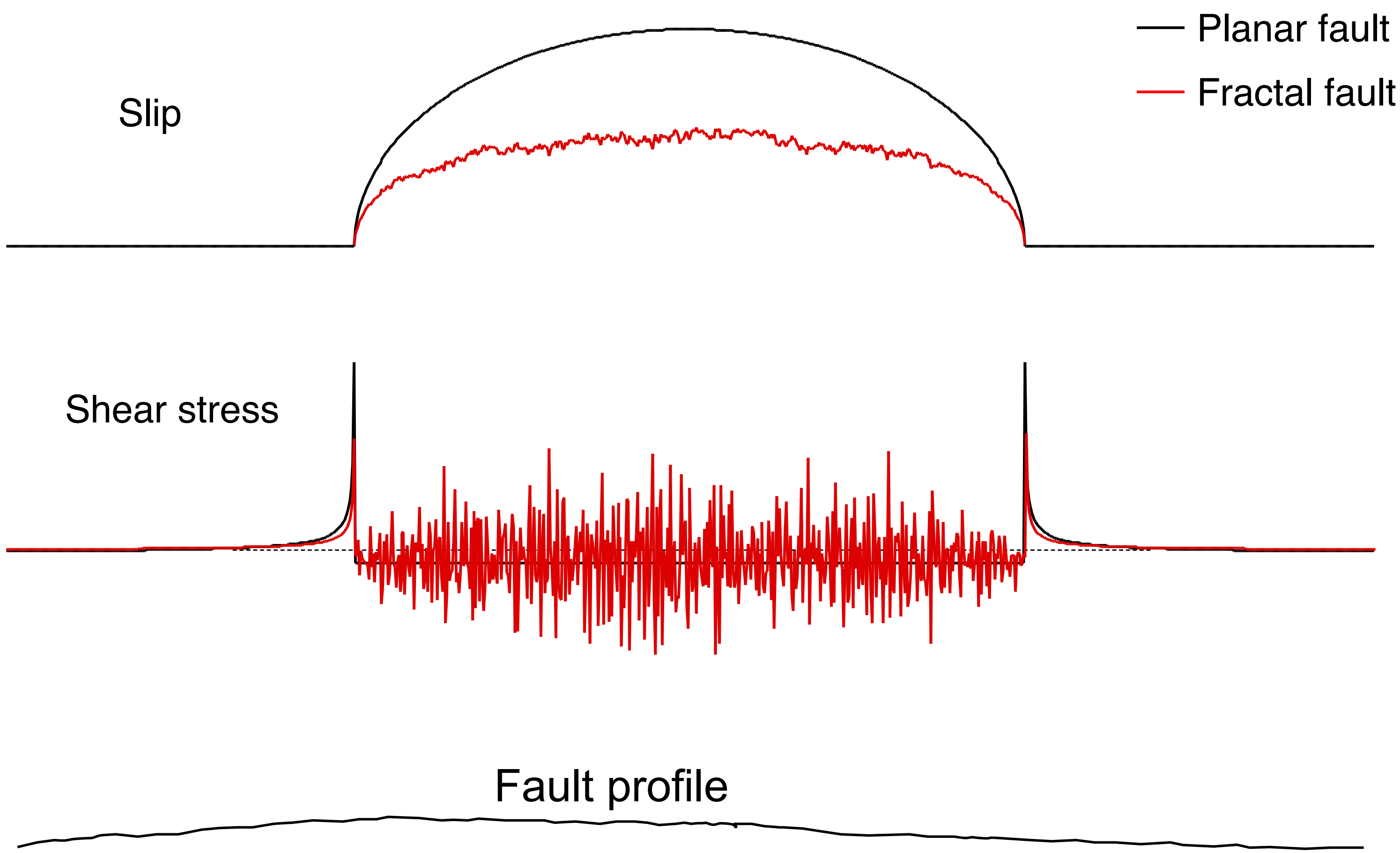
UCERF3 fault model and slip rates

- ~ 290,000 triangular elements (~1km^2) in simulations with deep fault creep (~ 260,000 no creep)
- Approximate range of magnitudes M_w= 4 to M_w= 8
- 120,000 years simulated time ~16x10^6 events
- Simulations may be restarted to span 10^6 years



Loading conditions in systems with geometric incompatibility – fault systems and non-planar faults

Slip in response to an applied uniform stress increment $\Delta\sigma_{xy}$

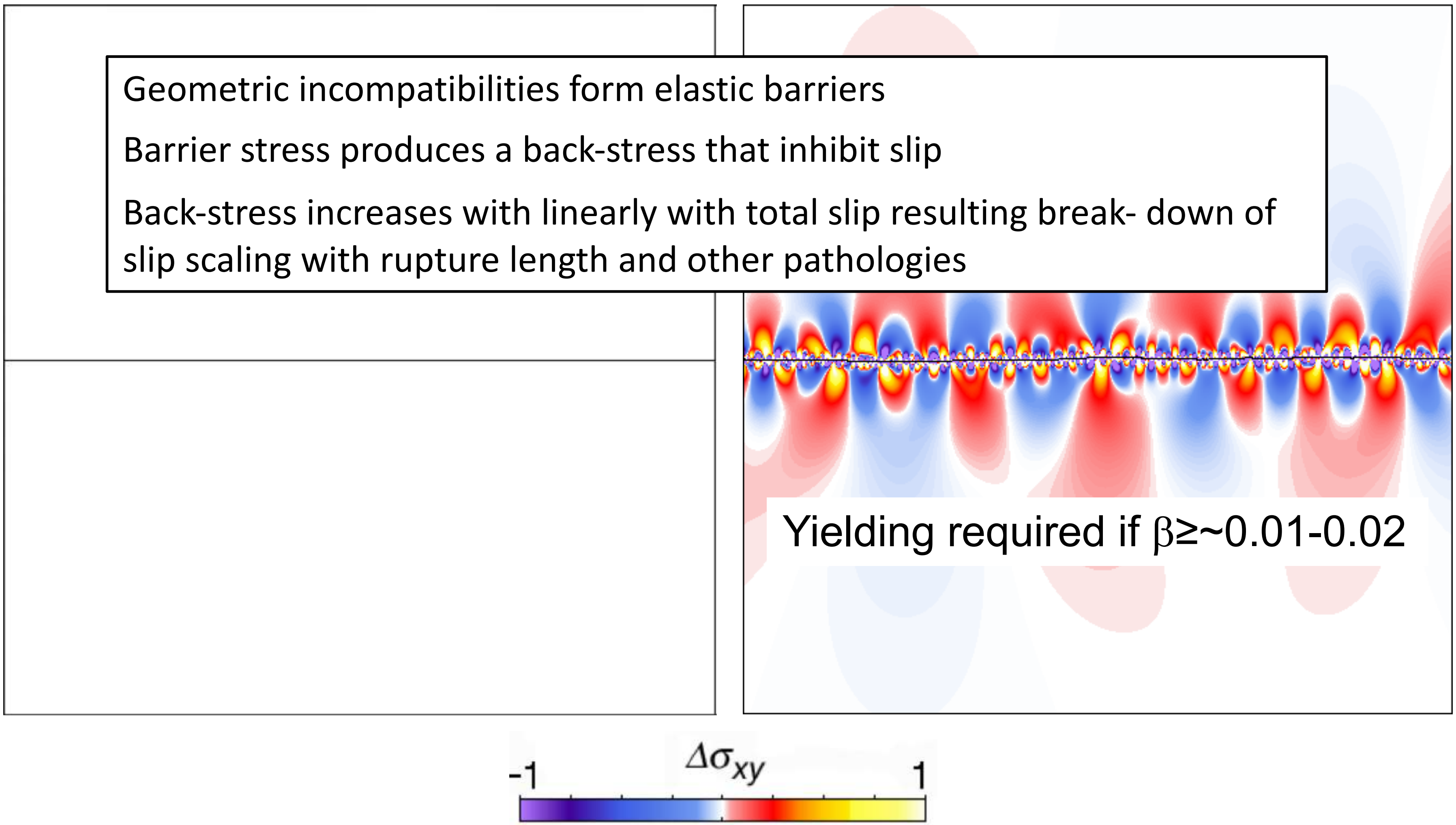


Dieterich and Smith (2009)

Fault slip and stress changes

Smooth fault

Fault with self-similar roughness



Geometric incompatibilities form elastic barriers

Barrier stress produces a back-stress that inhibit slip

Back-stress increases with linearly with total slip resulting break- down of slip scaling with rupture length and other pathologies

Dieterich and Smith (2009)

Simulation ingredients – 2) Loading conditions

To prevent long-term build-up of stresses resulting from geometric incompatibilies the following condition must be satisfied at each element *i* in the model

$$\dot{S}_i^T + \overline{\dot{S}}_i^R + \overline{\dot{S}}_i^F = 0$$

Direct tectonic stressing rate at element *i*

Average stressing rate from other sources (stress relaxation processes and slip of (unknown faults)

Long-term average stressing rate from interactions among the simulated fault elements

Simulation ingredients – 2) Loading conditions

External loading of modeled fault elements

Internal interactions

$$\dot{S}_i^T + \overline{\dot{S}}_i^R + \overline{\dot{S}}_i^F = 0$$

Direct tectonic stressing rate at element *i*

Average stressing rate from other sources (stress relaxation processes and slip of unknown faults)

Long-term average stressing rate from interactions among the simulated fault elements

In the simulations

$\overline{\dot{S}}_i^F = K_{ij}\overline{\dot{\delta}}_j$, where $\overline{\dot{\delta}}_j$ is the long-term fault slip rate

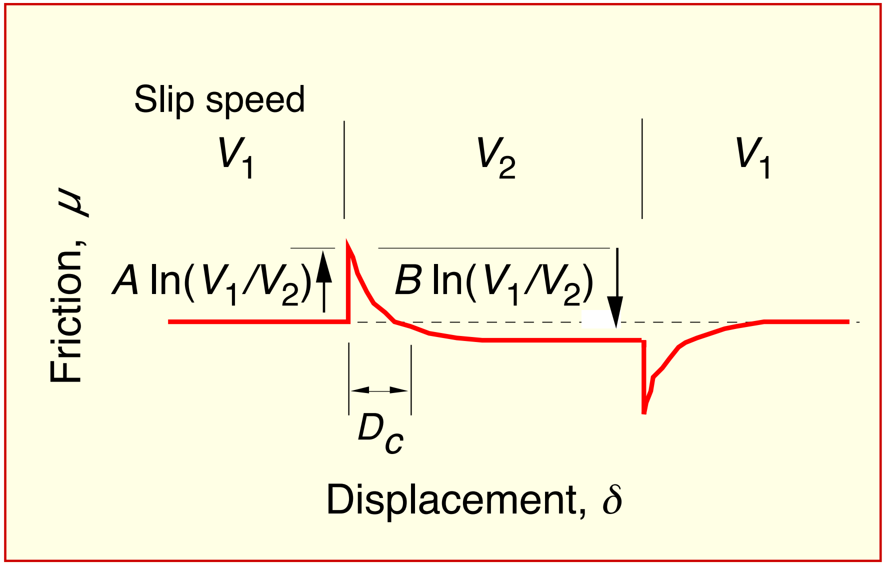
Hence, the the long-term average loading rate of the external loading sources is

$$\dot{S}_i^T + \overline{\dot{S}}_i^R = -\overline{\dot{S}}_i^F = K_{ij}\left(-\overline{\dot{\delta}}_j\right)$$

BACKSLIP LOADING

Simulation ingredients – 3) Constitutive Law for fault slip

Rate- and state-dependent friction



Coefficient of friction:

$$\frac{\tau}{\sigma} = \mu = \mu_0 + A \ln\left(\frac{V}{V^*}\right) + B \ln\left(\frac{\theta}{\theta^*}\right)$$

Evolution law for state:

$$d\theta = dt - \frac{\theta}{D_c} d\delta - \frac{\alpha\theta}{B\sigma} d\sigma$$

Stationary contact at constant normal stress, $\mathrm{d}\theta = \mathrm{d}t$
fault strengthens with $B \ln(\mathrm{time})$

At steady state, $\mathrm{d}\theta/\mathrm{d}t = 0$ and

$$\theta_{ss} = \frac{D_c}{V} \qquad \mu_{ss} = const. + (A - B) \ln V$$

Simulation ingredients – 4) Computational engine: RSQSim

- Boundary elements → faults are represented as arrays of rectangular or triangular elements
- Simulations avoid repeated solutions of a large system simultaneous equations → fast computation
- Event driven computations based on changes of fault sliding state. A fault element may be at one of three sliding states
  - 0 – Fault is essentially locked – aging by log time of stationary contact
  - 1 – Nucleating slip: Time- dependent accelerating slip to instability

    Analytic solutions with rate-state friction
  - 2 – Earthquake slip: quasi-dynamic – slip speed is specified as an input based on shear wave impedance.

$$\dot{\delta}_{EQ} = \frac{2\beta\Delta S}{G}$$

Estimate of EQ stress drop

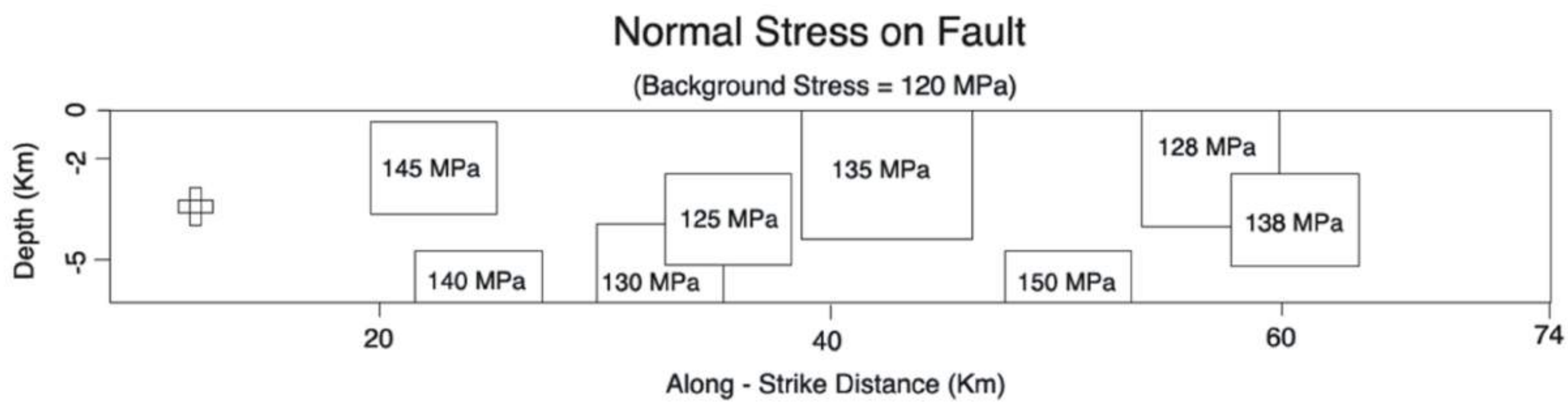
Simulation ingredients – 4) Computational Inputs

- Fault system model —— (e.g. SCEC community fault model)
- Long term slip rates
- Slip rake angles

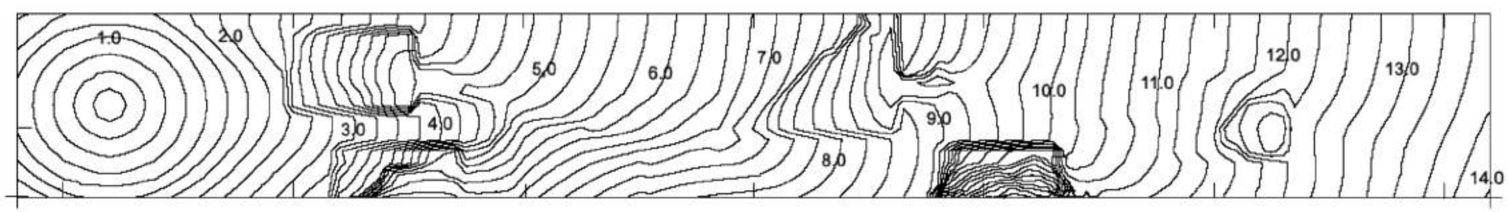
} — UCERF deformation model

- Fault-normal stresses acting on fault elements — locally tuned to given interevent recurrence times consistent with community paleoseismic results
- EQ slip speed (We typically use 1m/s, which is appropriate for stress drops of ~4-5MPa)
- Rate-state friction parameters (a, b, D_c) at each element
- Simulation parameters (dynamic overshoot, rupture tip parameters)

RSQsim – Dynamic finite element comparison

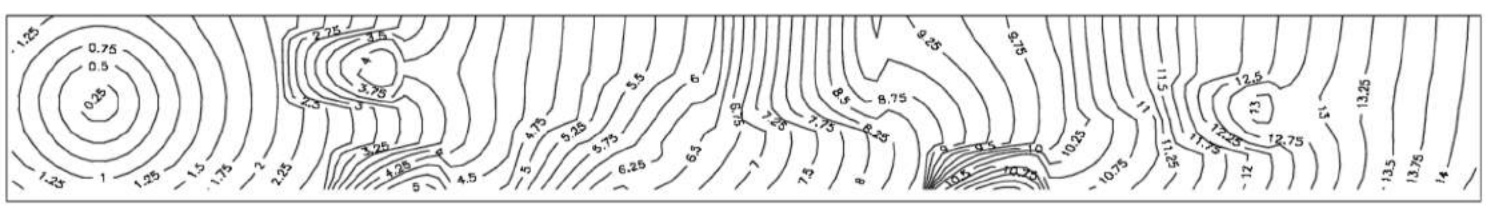


DYNA3D – Fully dynamic finite element simulation



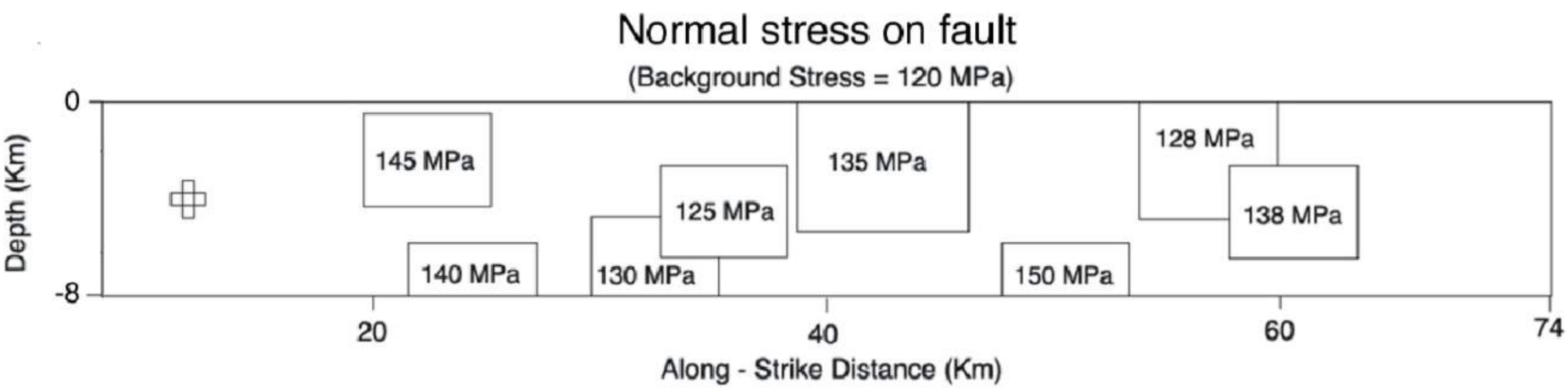
Propagation time 14.0 s

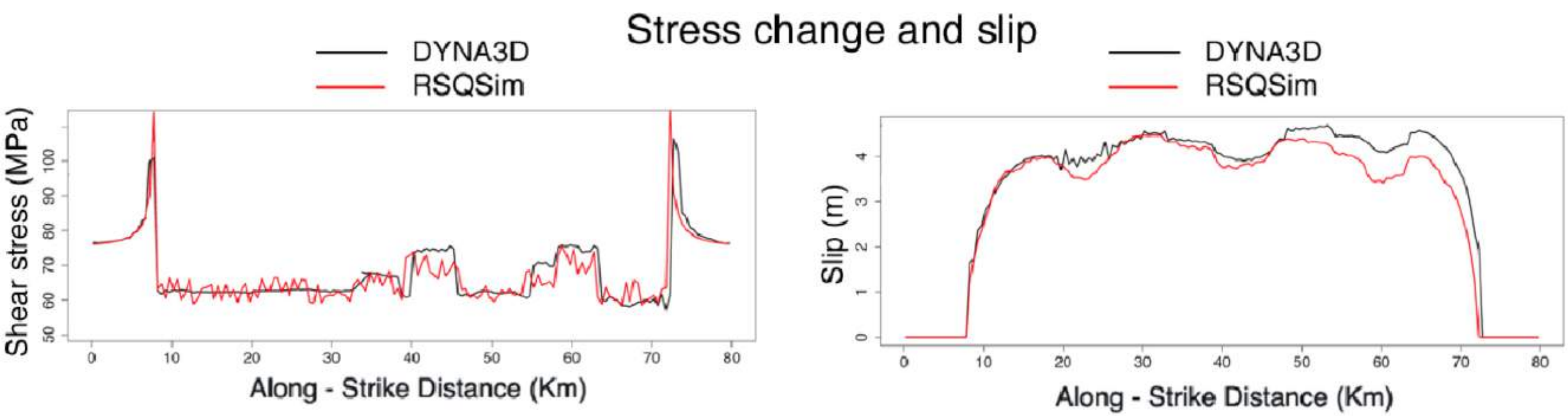
RSQsim – Fast simulation



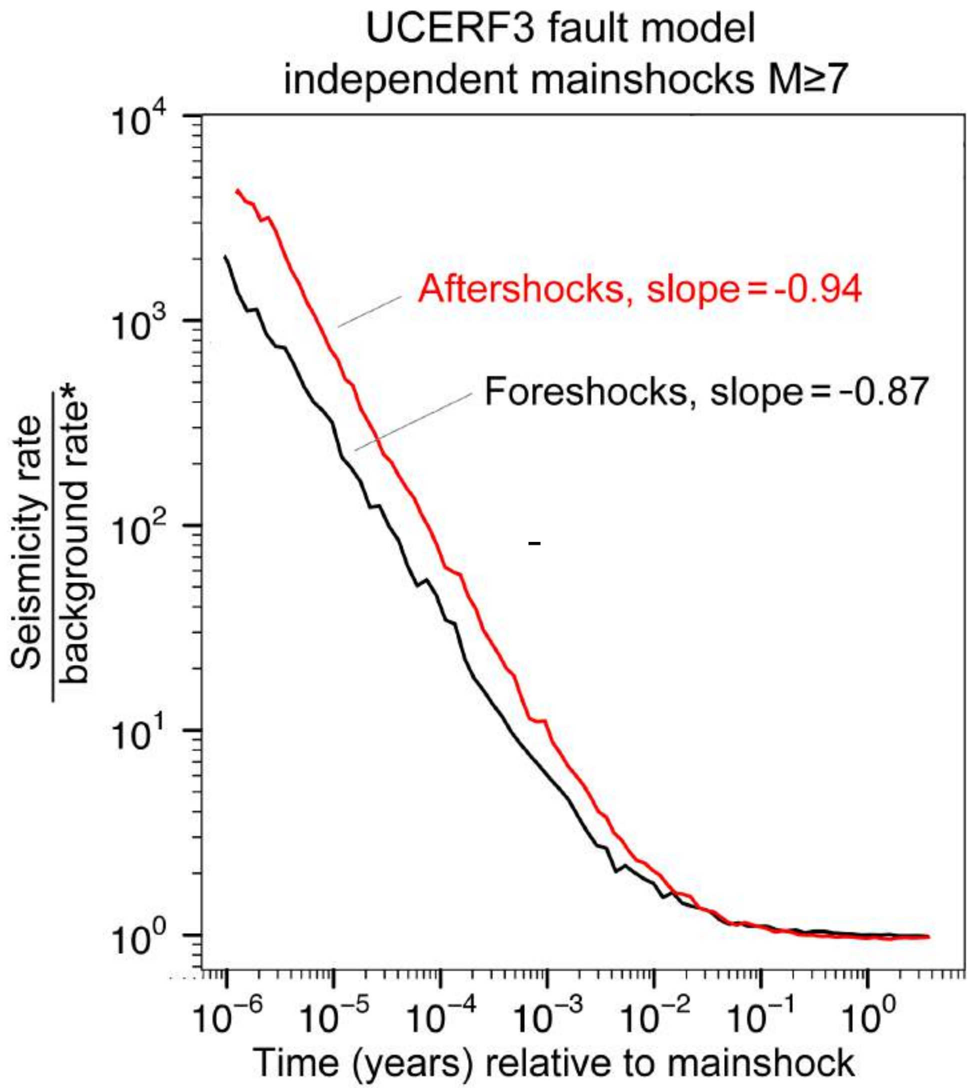
Propagation time 14.3 s

RSQSim – Fully Dynamic Finite Element Comparison



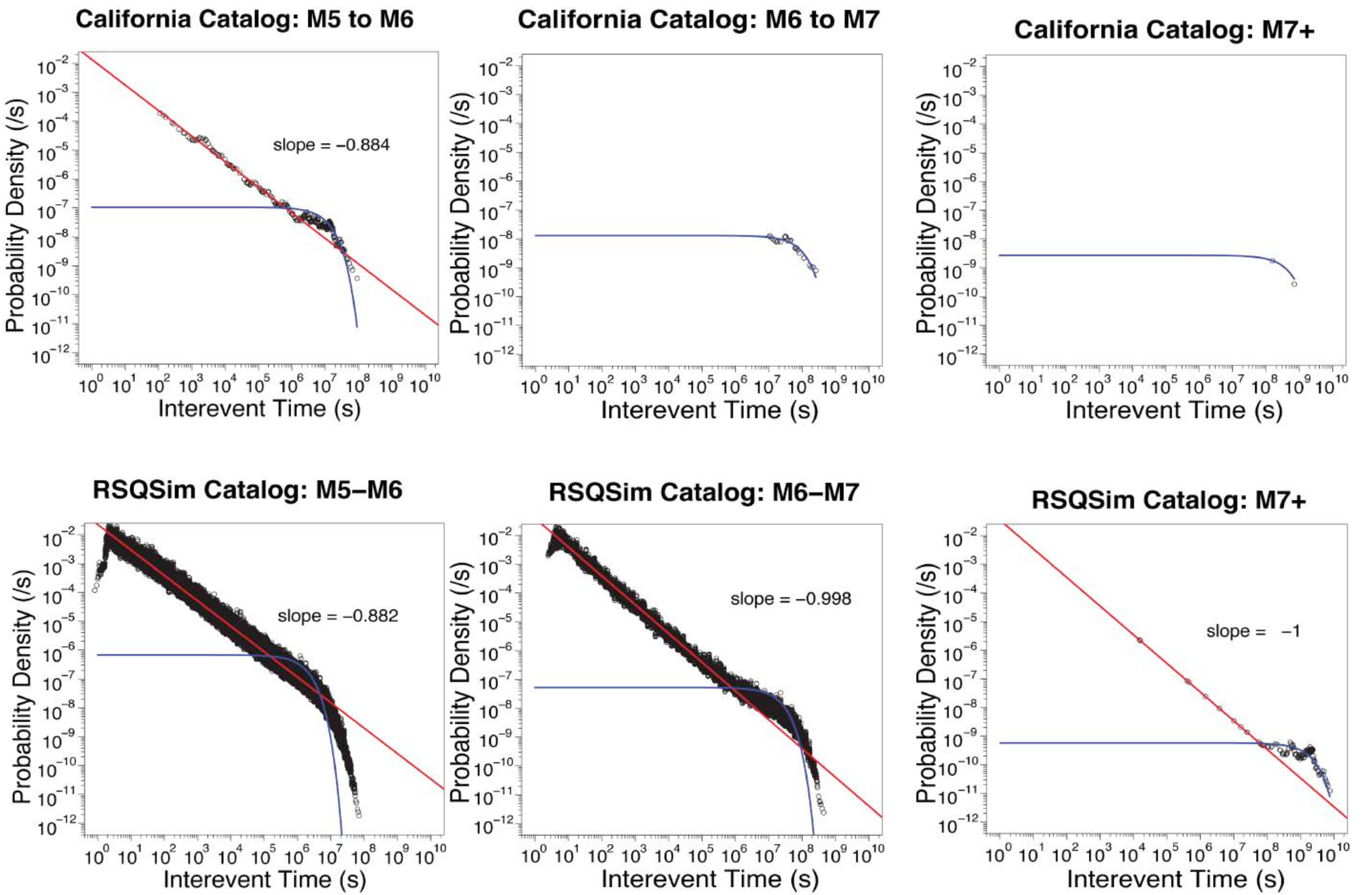


RSQSim – Foreshocks and aftershocks

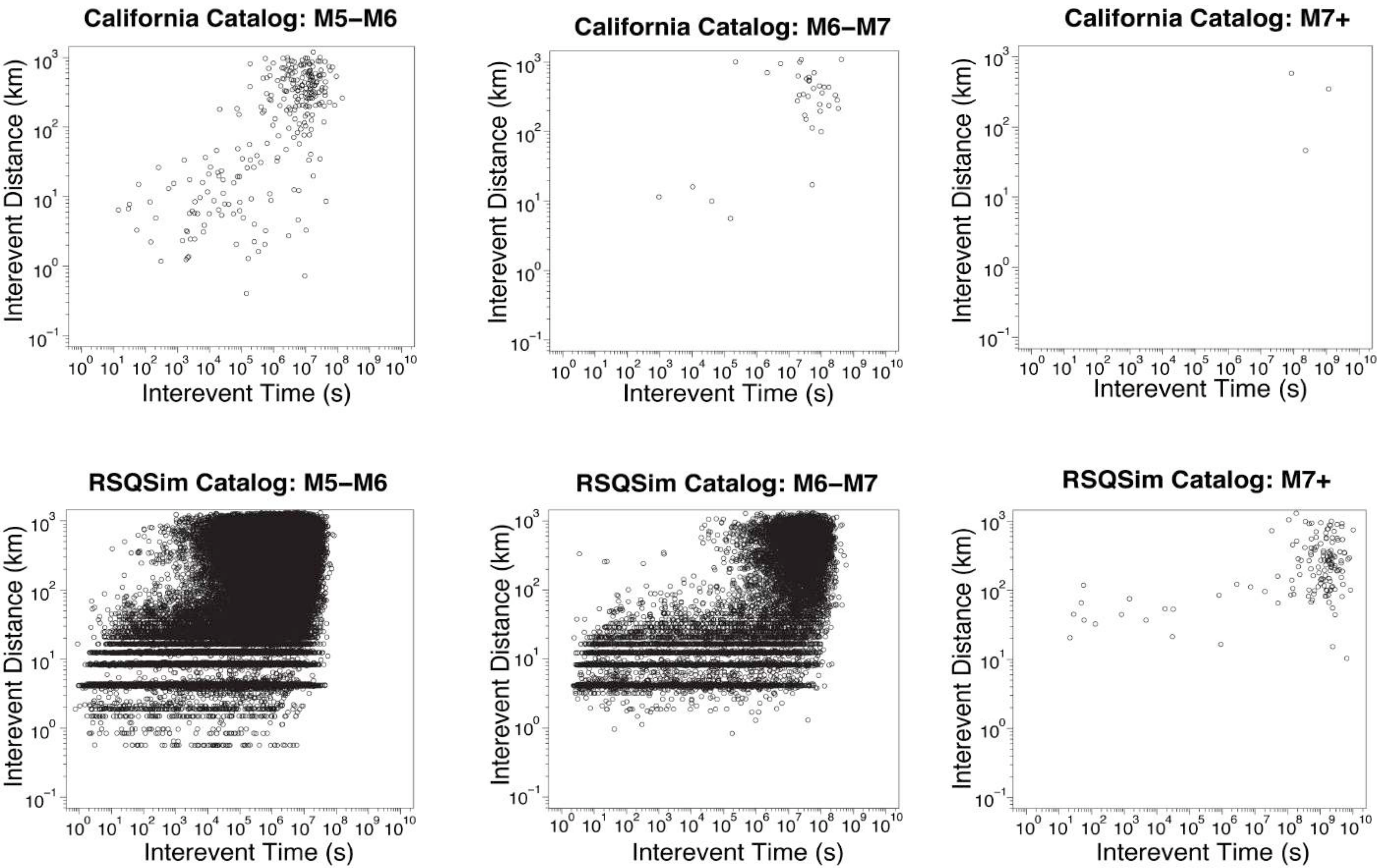


* Background seismicity rate is global average, not local to mainshock

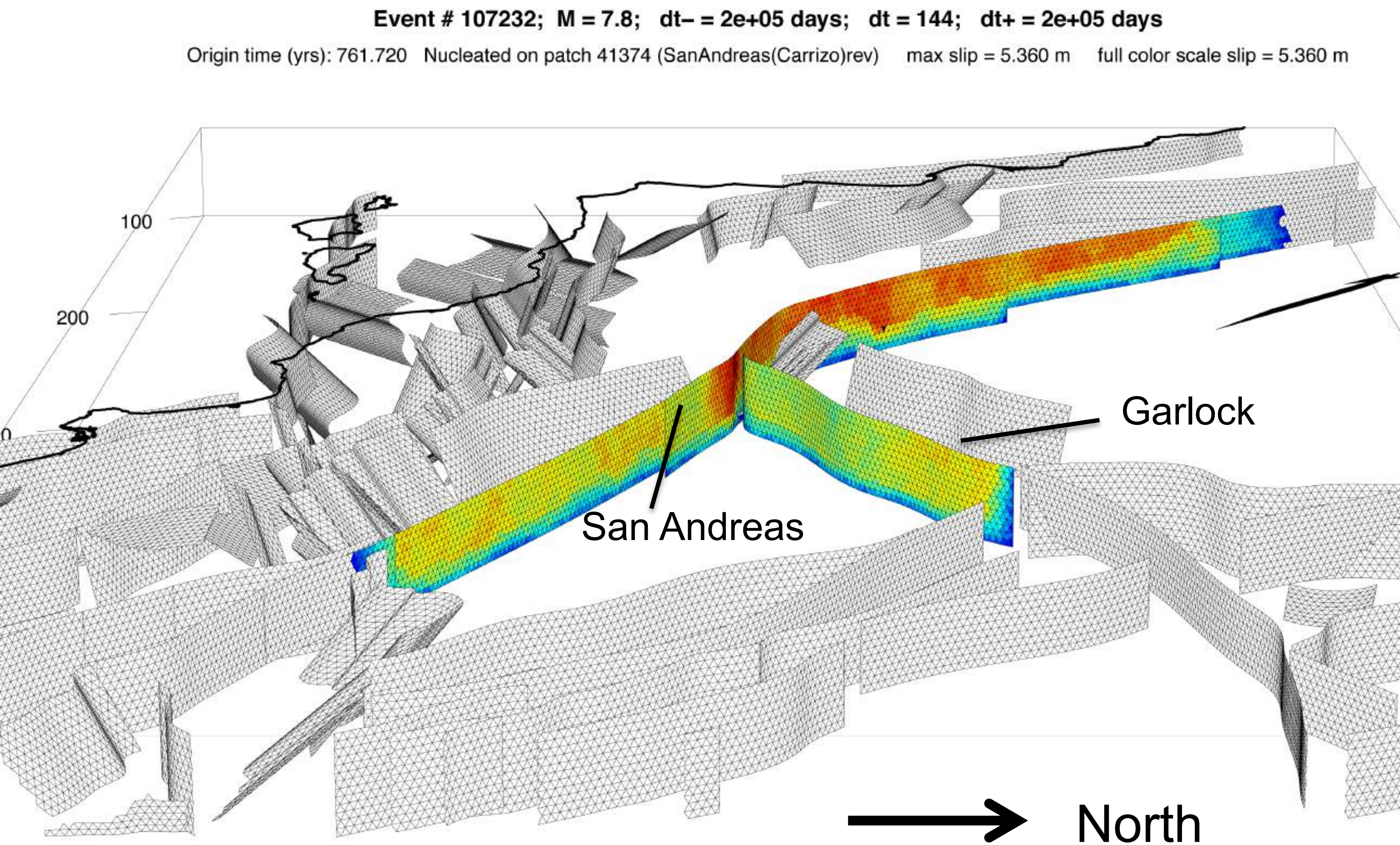
Interevent Waiting Time Distributions



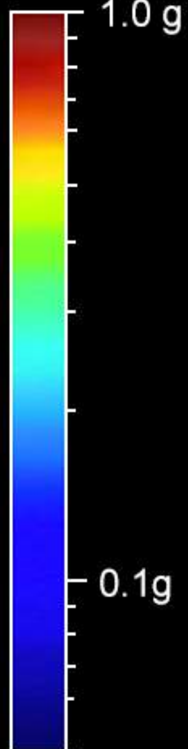
Space – Time Distributions

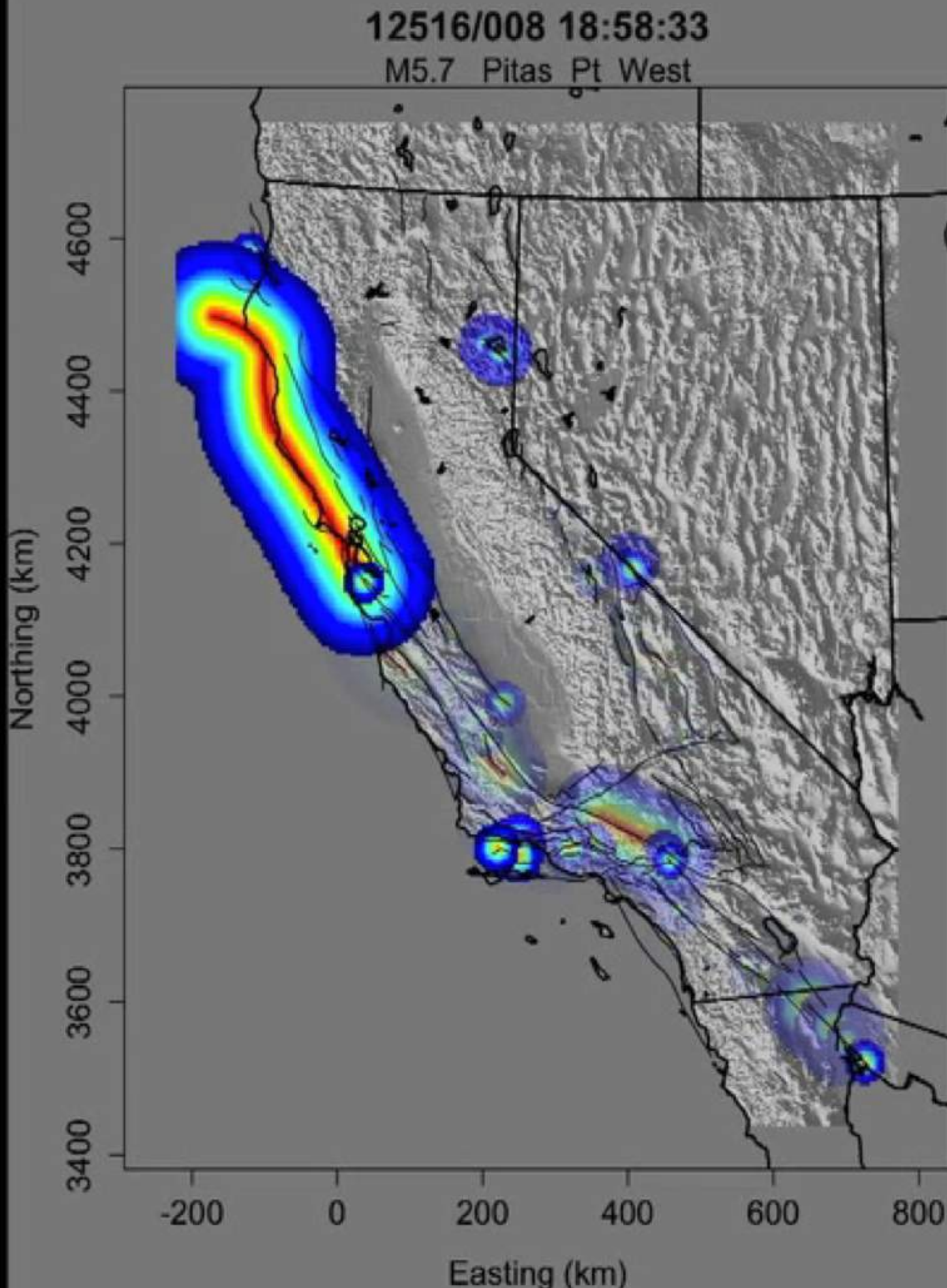


Rupture Branching



PGA (horizontal – bedrock)

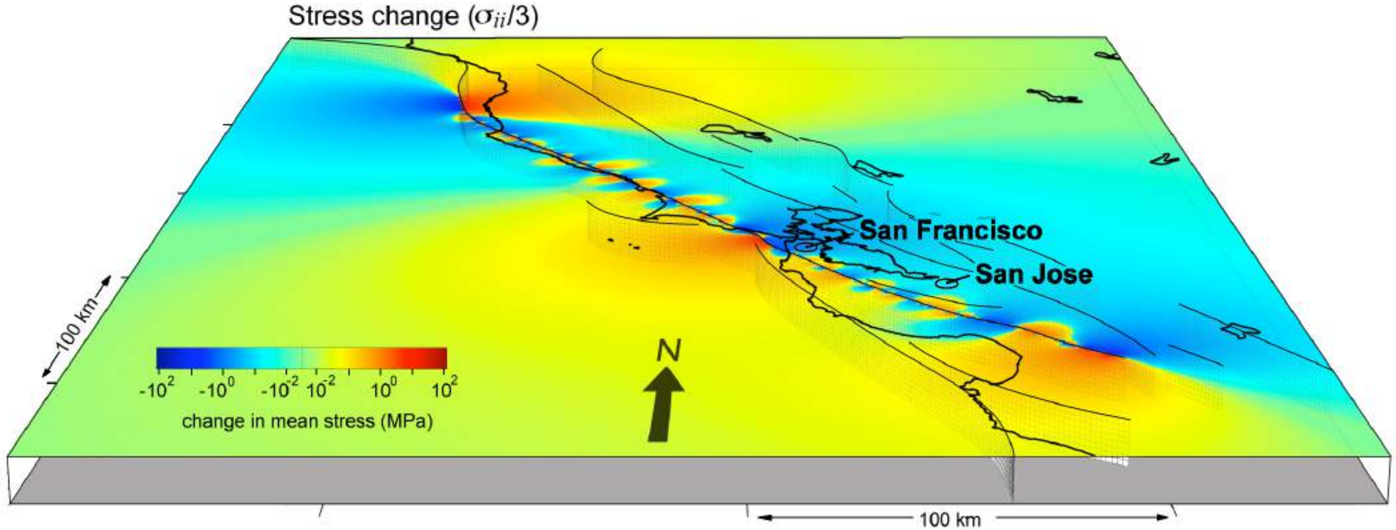


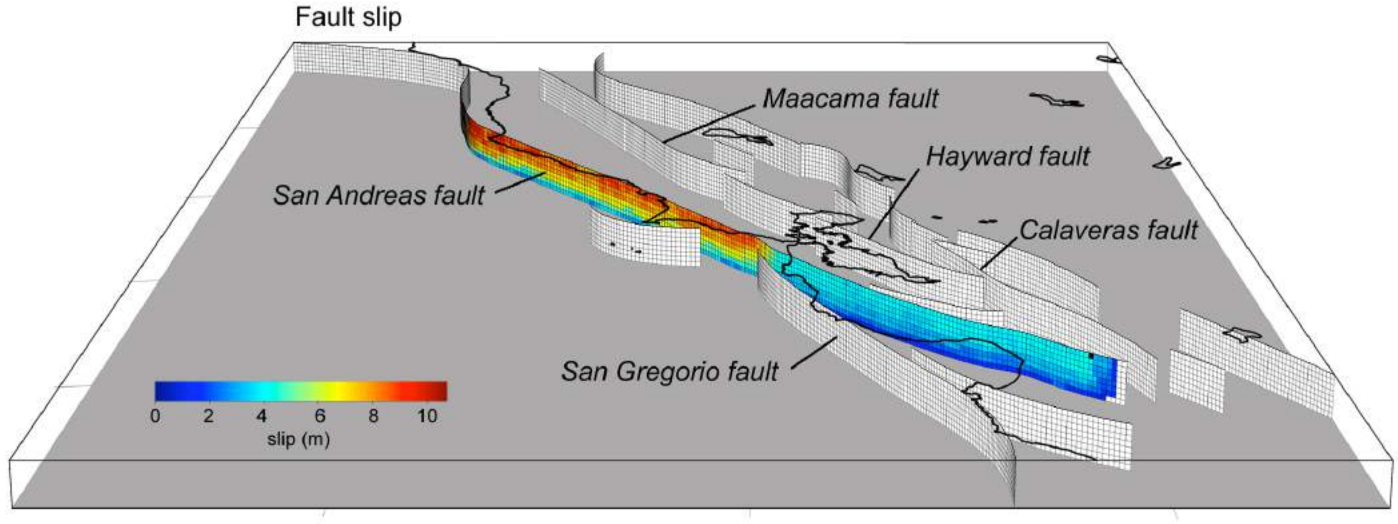


Sadigh et al. (1997)

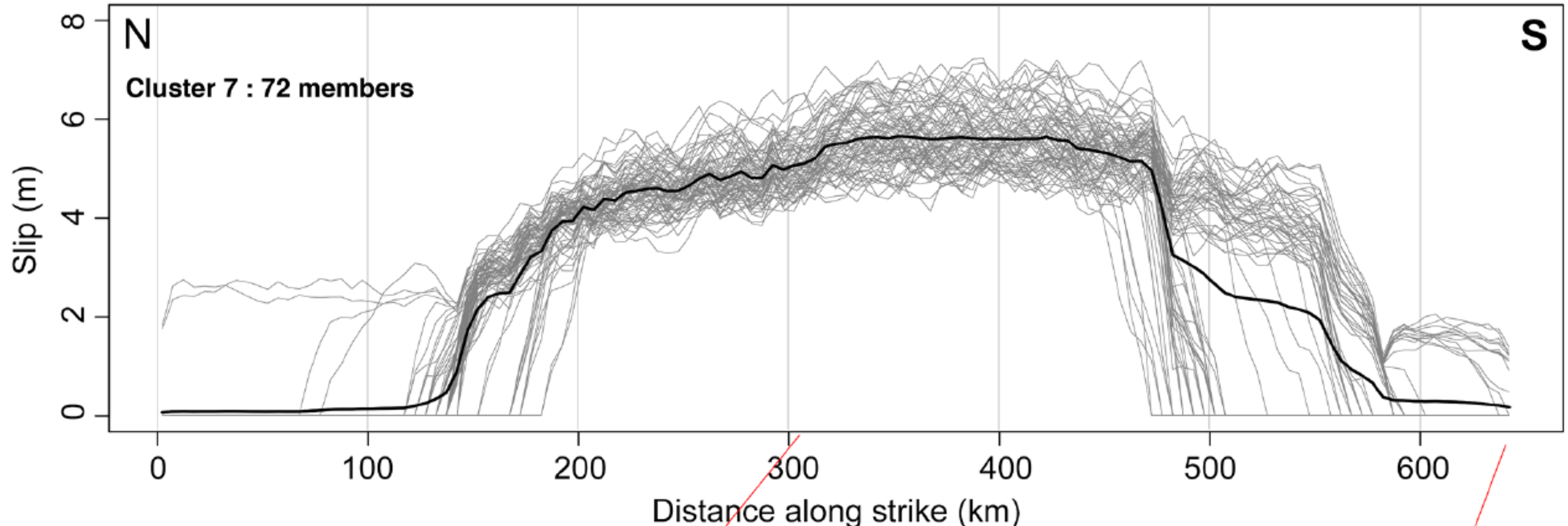
Rupture Similarity

Example of 1906-type earthquake on San Andreas Fault



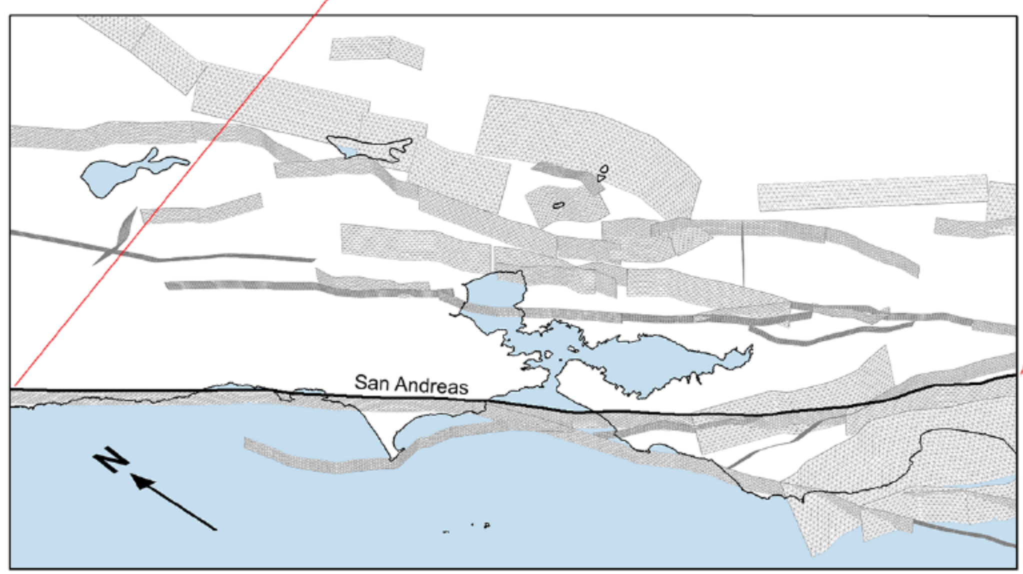


Event similarity – N. section of San Andreas

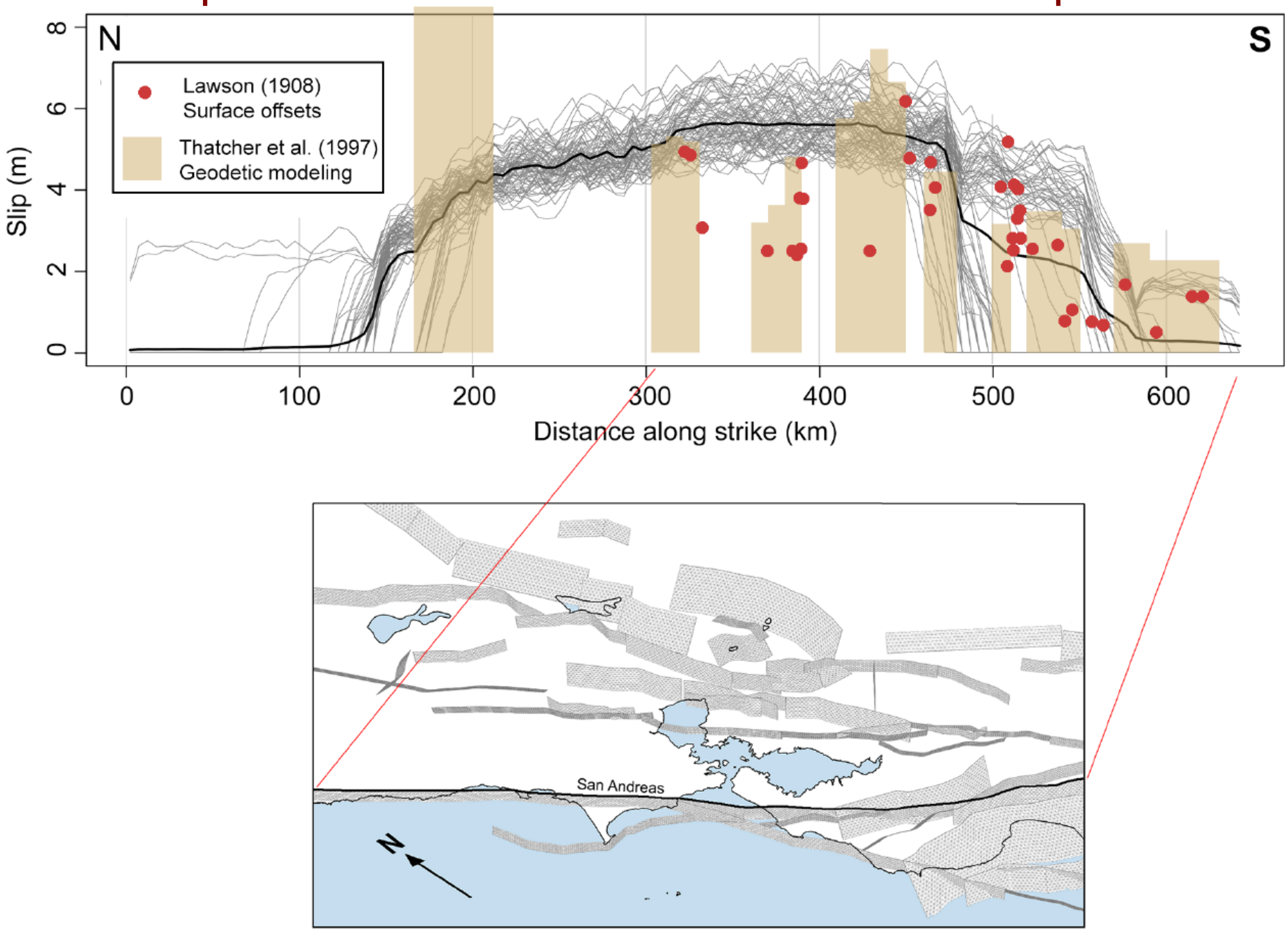


From an all-California simulation by J. Gilchrist, with cluster analysis on along-strike EQ slip by K. Richards-Dinger.

UCERF fault model and slip rates, tuned to paleoseismic recurrence intervals



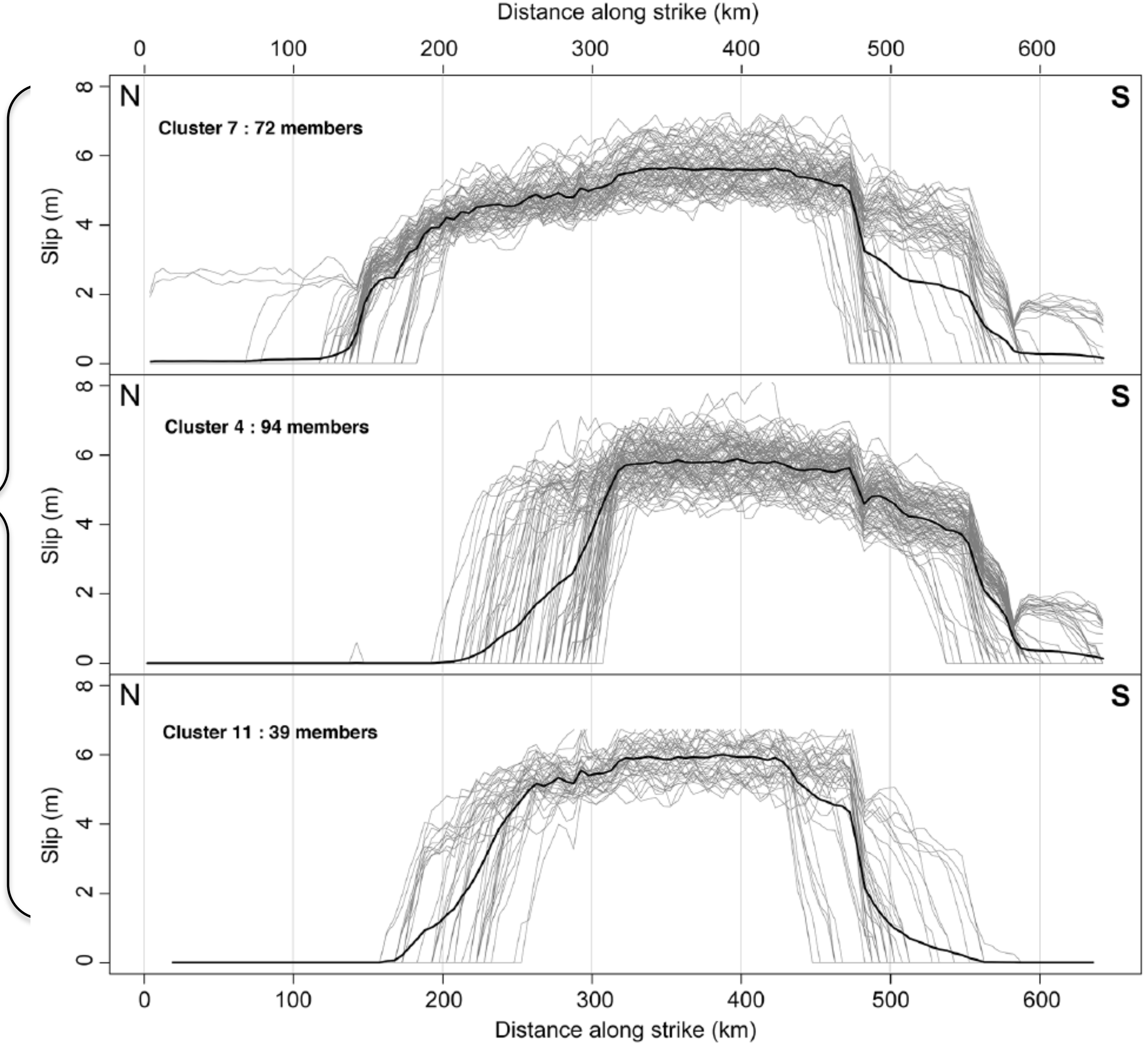
Event similarity – N. section of San Andreas
Comparison with 1906 San Francisco earthquake



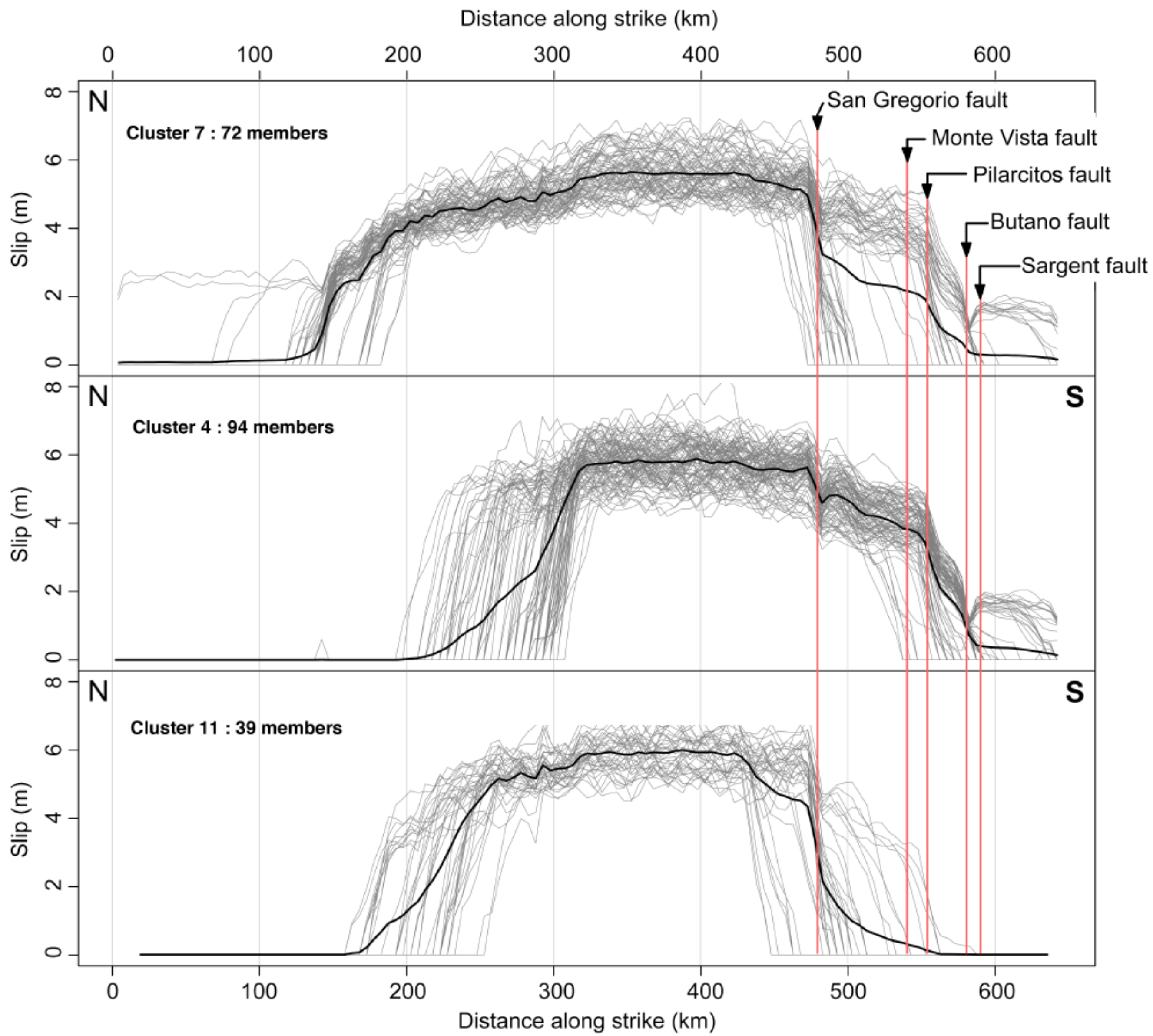
Event similarity – N. section of San Andreas

90% of all events L ≥ 290km (~M≥8) fall in one of these 3 clusters

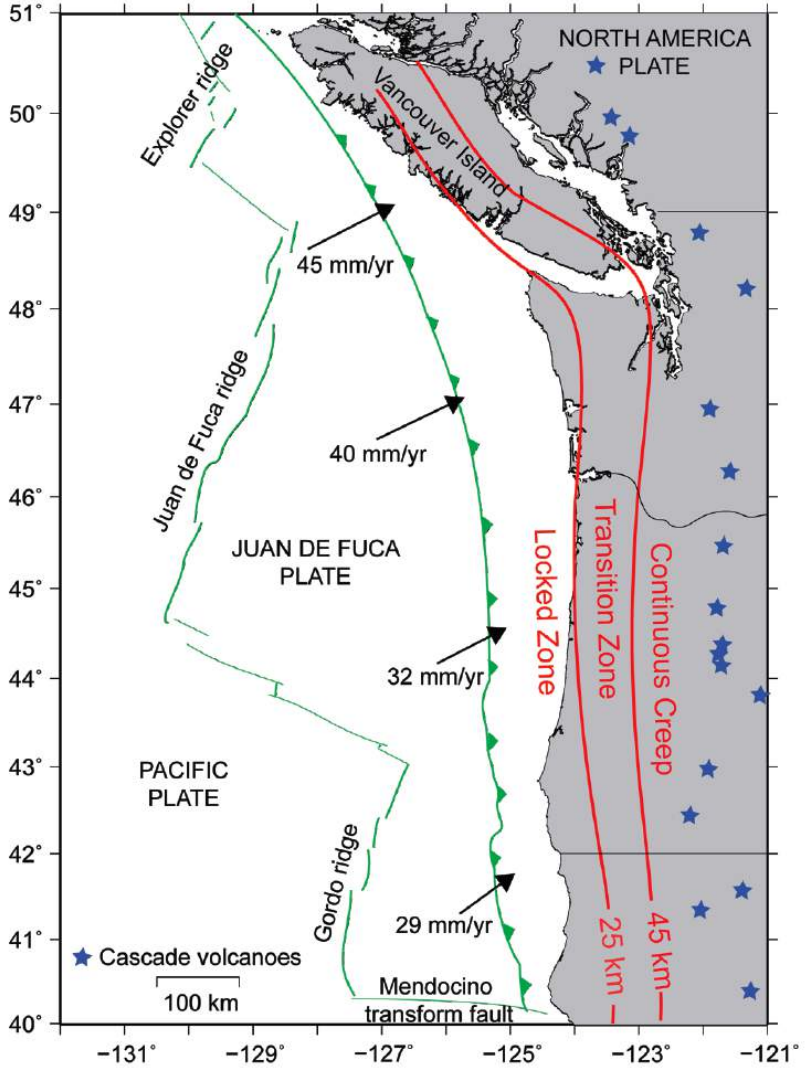
205 EQs

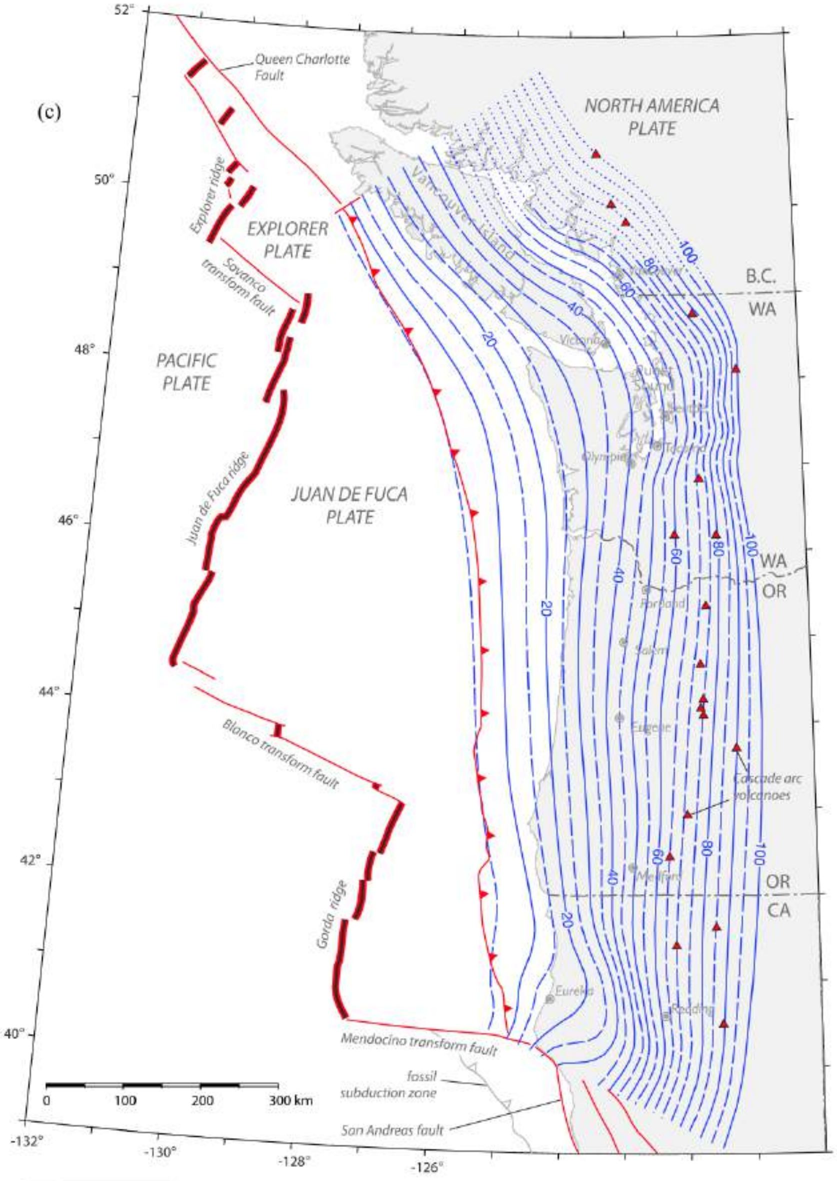


Event similarity – N. section of San Andreas

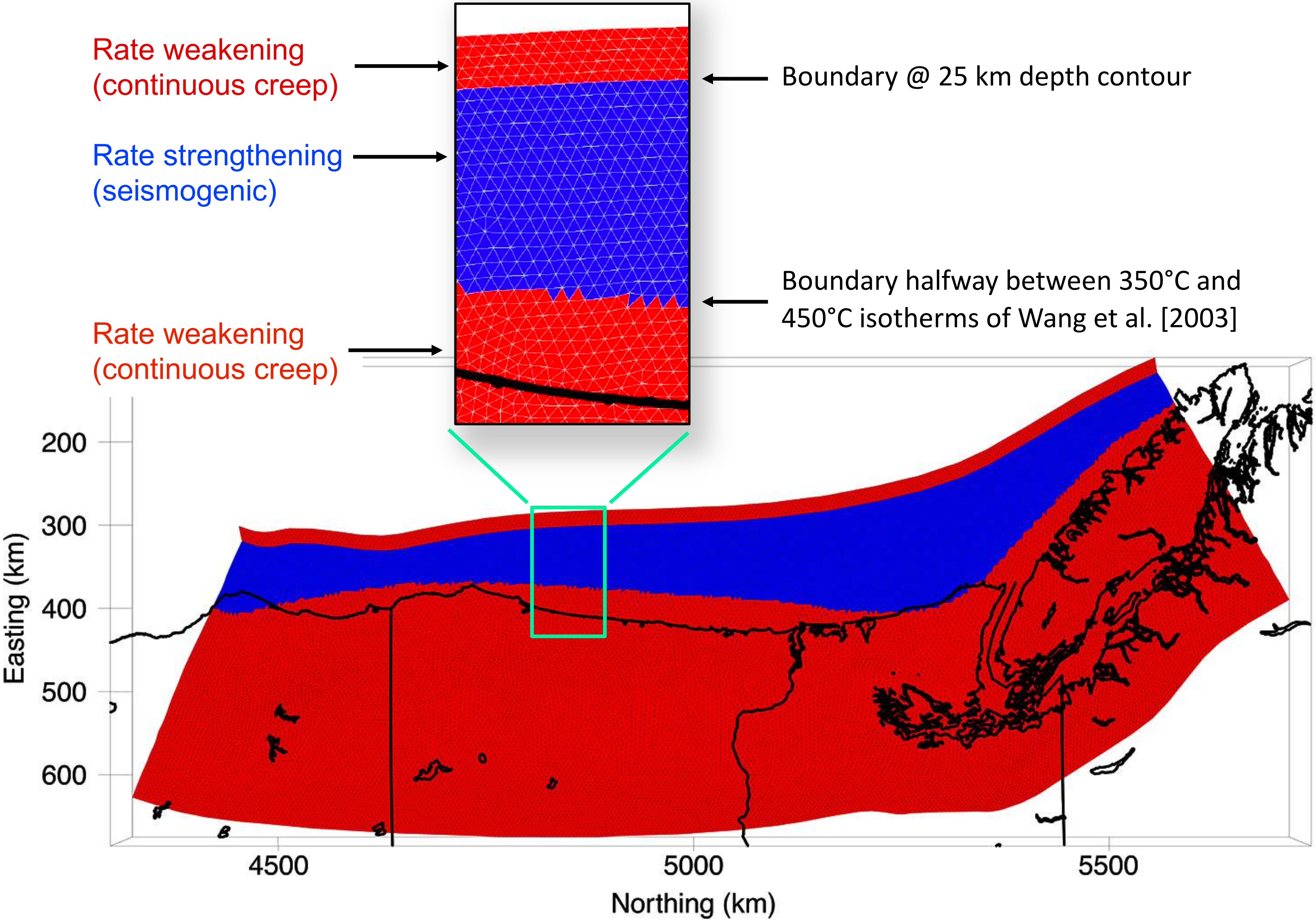


Rupture similarity – Cascadia



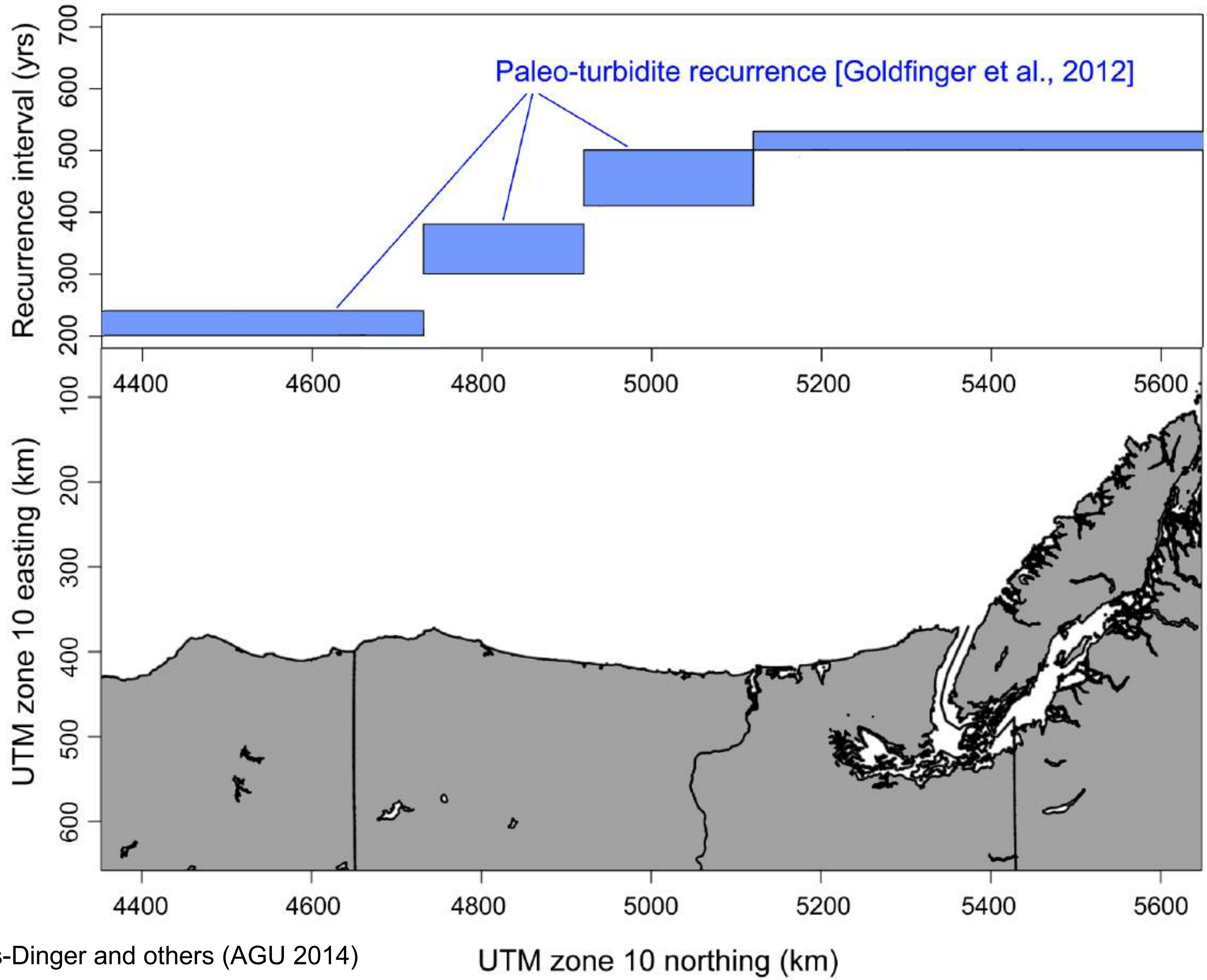


McCrory et al. [2012]



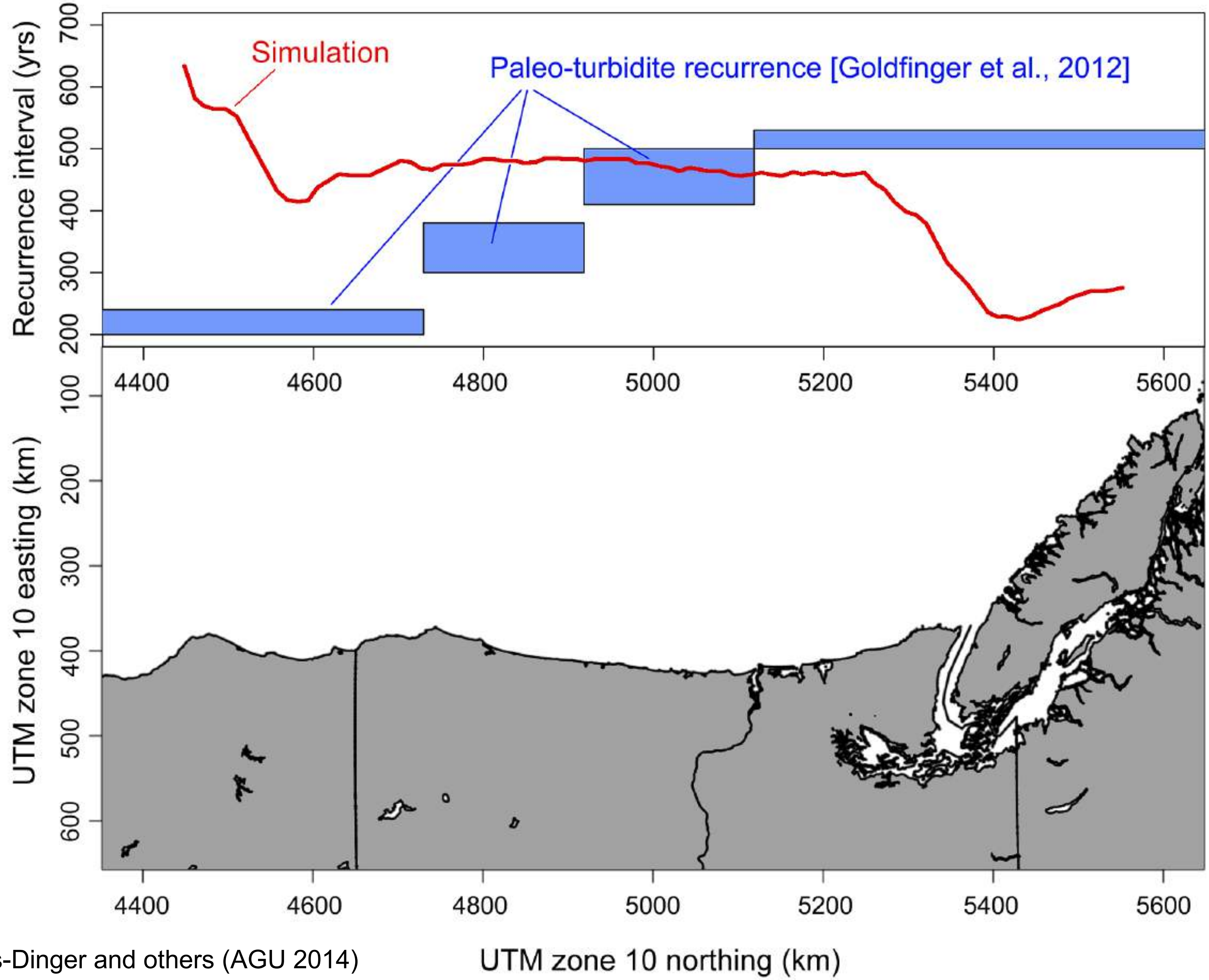
Richards-Dinger, Dieterich, Wells (AGU 2014)

Cascadia mean recurrence interval M>8



Richards-Dinger and others (AGU 2014)

Cascadia mean recurrence interval M>8



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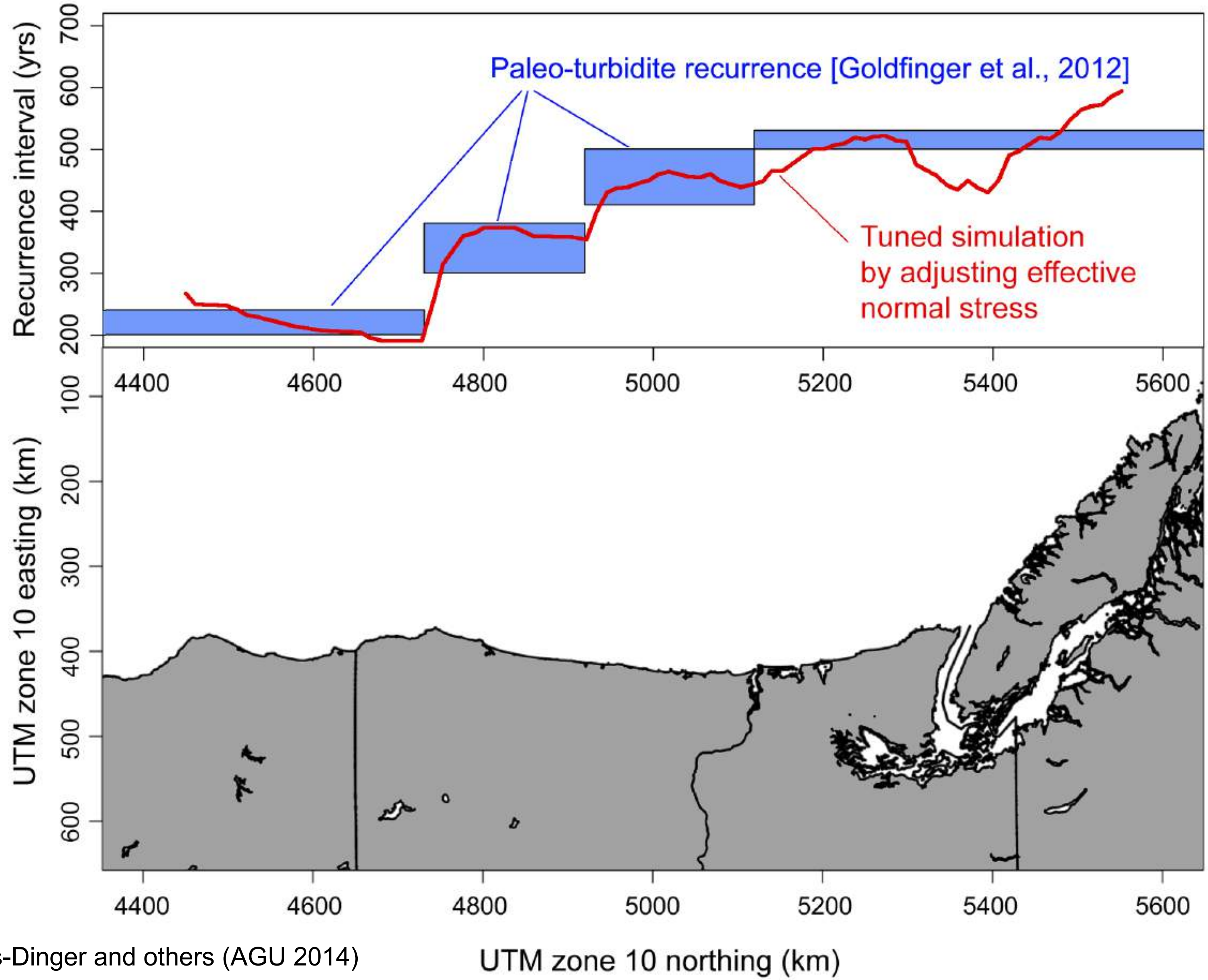
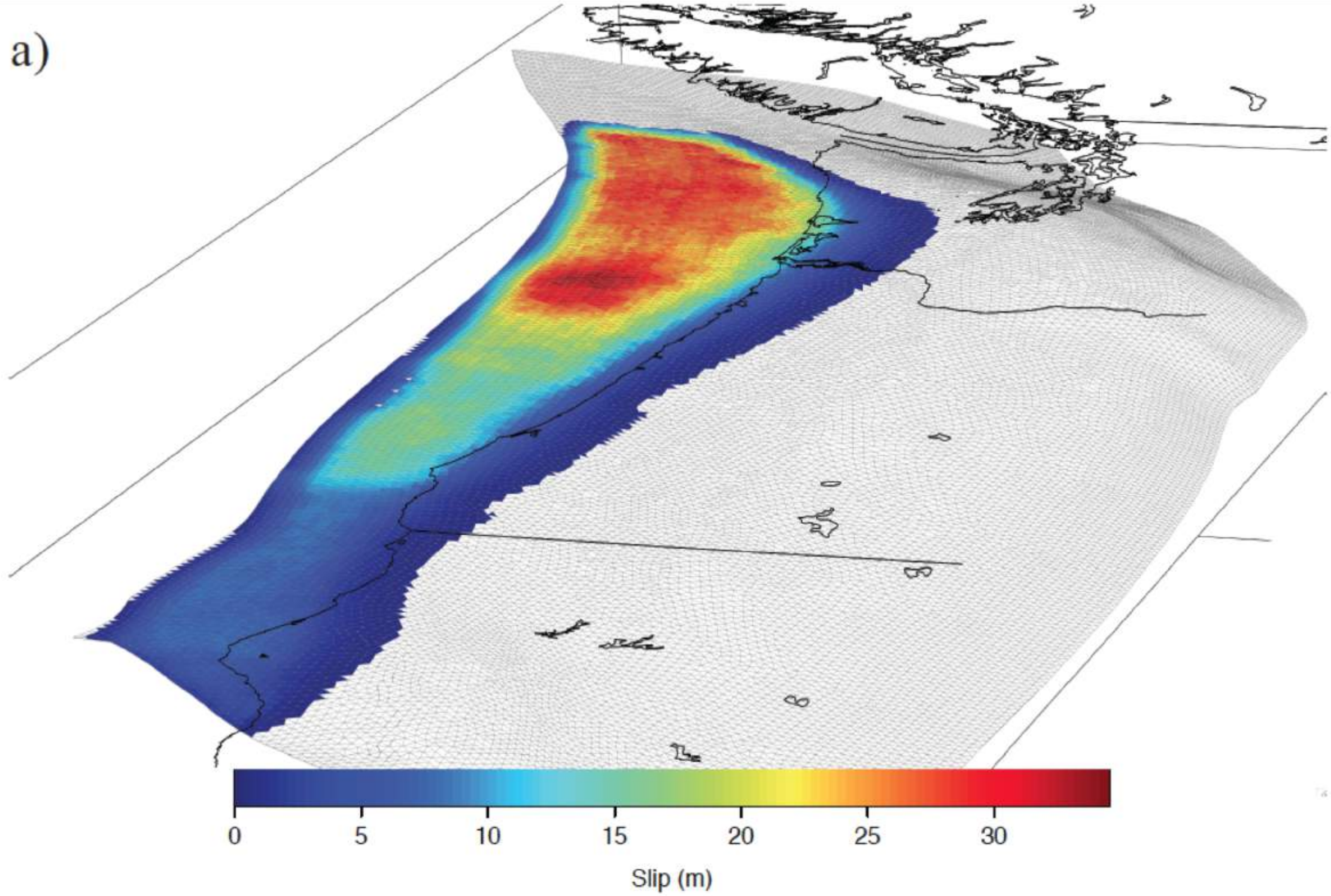
Cascadia mean recurrence interval M>8



Richards-Dinger and others (AGU 2014)

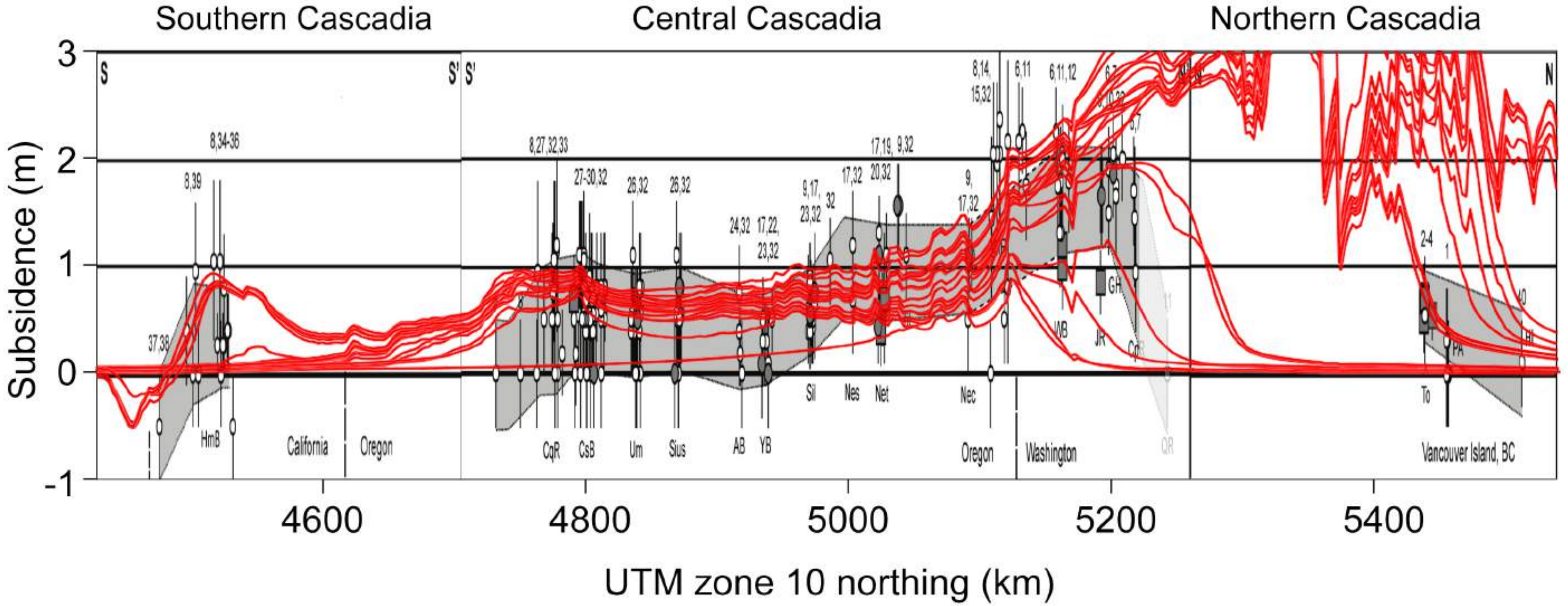
Slip and Coastal Subsidence in Great Cascadia Earthquakes



Richards-Dinger and others (AGU 2014)

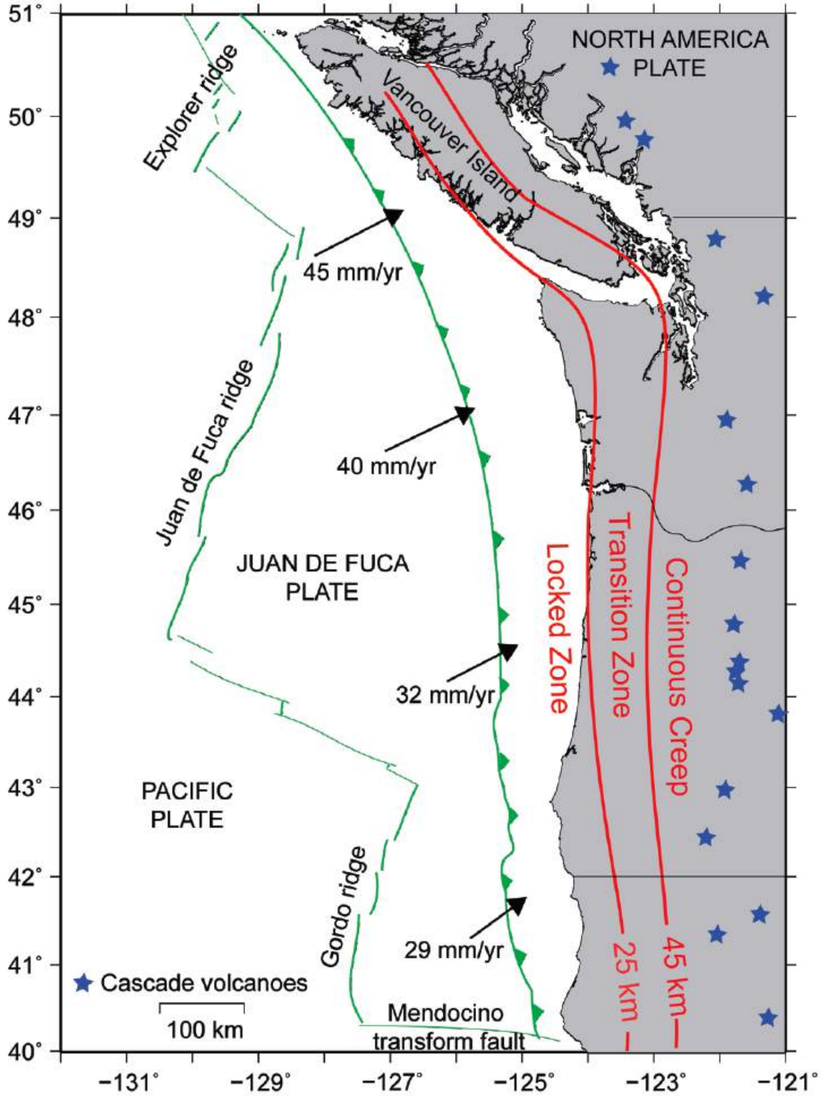
Vertical Deformation M>8

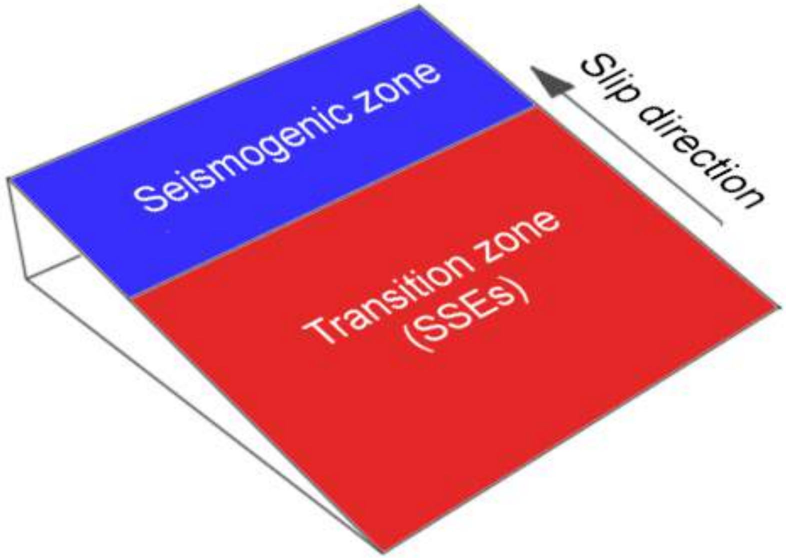
Comparison w/ data for the great earthquake of 1700
Leonard et al [2004]



Richards-Dinger and others (AGU 2014)

Exploratory model for coupled interactions between slow slip events and earthquakes





<u>Effective normal stress (MPa)</u>

seismogenic zone $\sigma = 100$

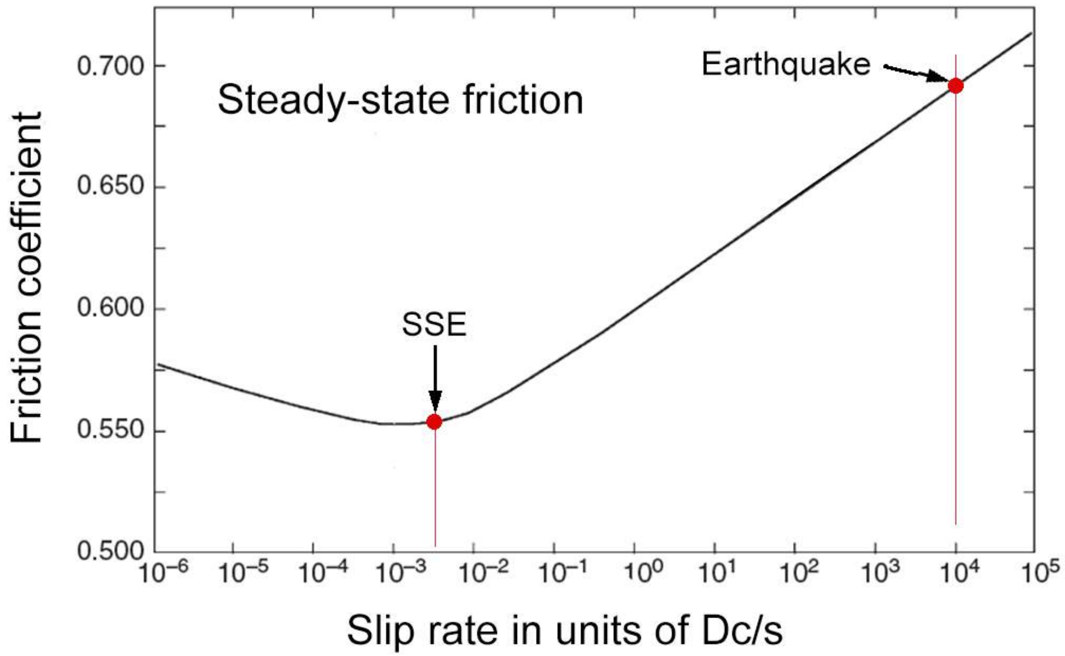
SSE zone (high P_f) $\sigma = 3$

Slow slip events

Necessary conditions:

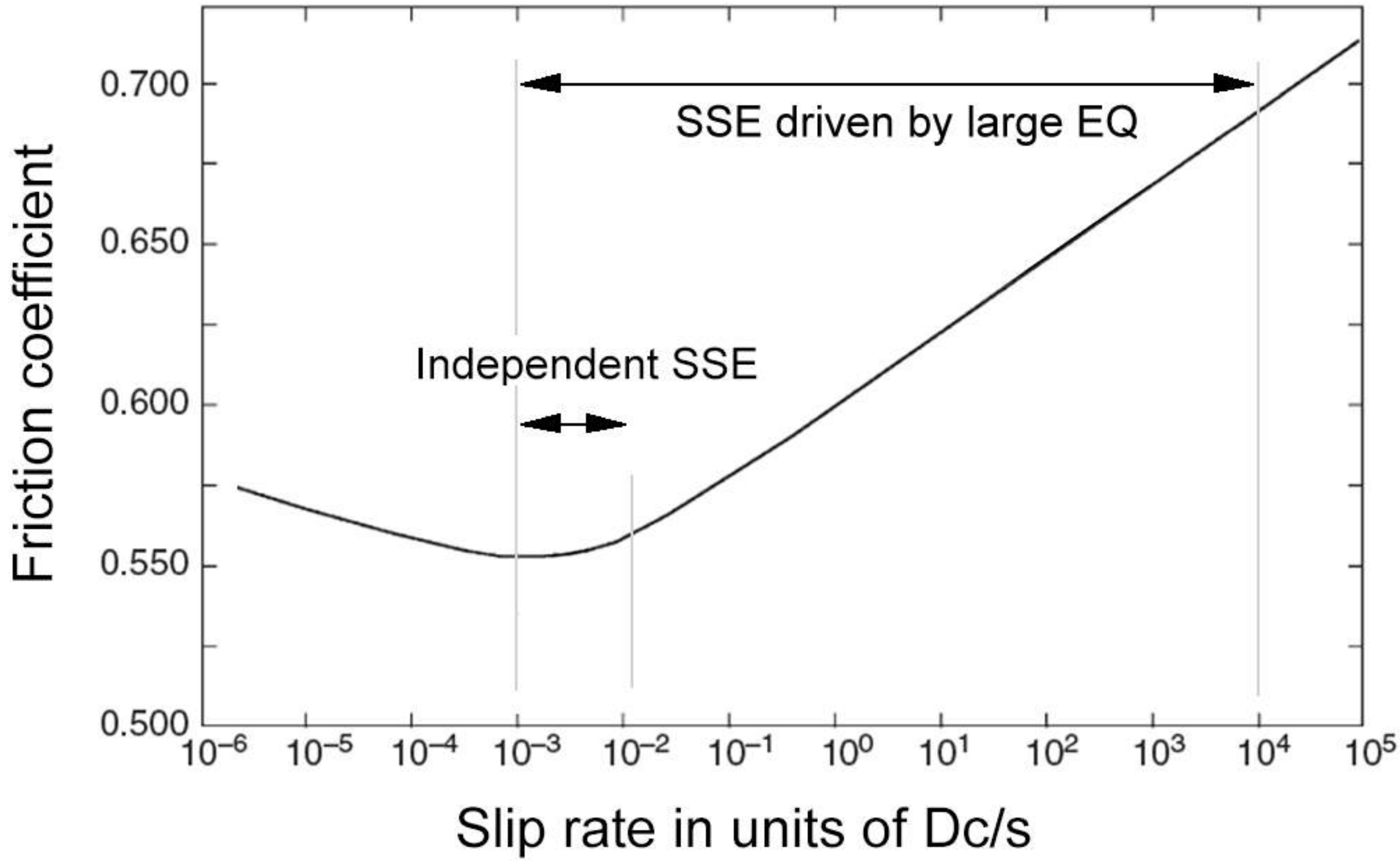
1) Slip-rate weakening (*b*>*a*) at slow slip speeds
2) Mechanism to quench acceleration of slip before reaching earthquake slip speeds
   - Cut-off of state term in constitutive law → reversal from rate weakening at low slip speeds to rate strengthening at higher speeds

$$\mu = \mu_0 + a ln\left(\frac{V}{V^*}\right) + b ln\left(\frac{\theta}{\theta^*} + c\right)$$

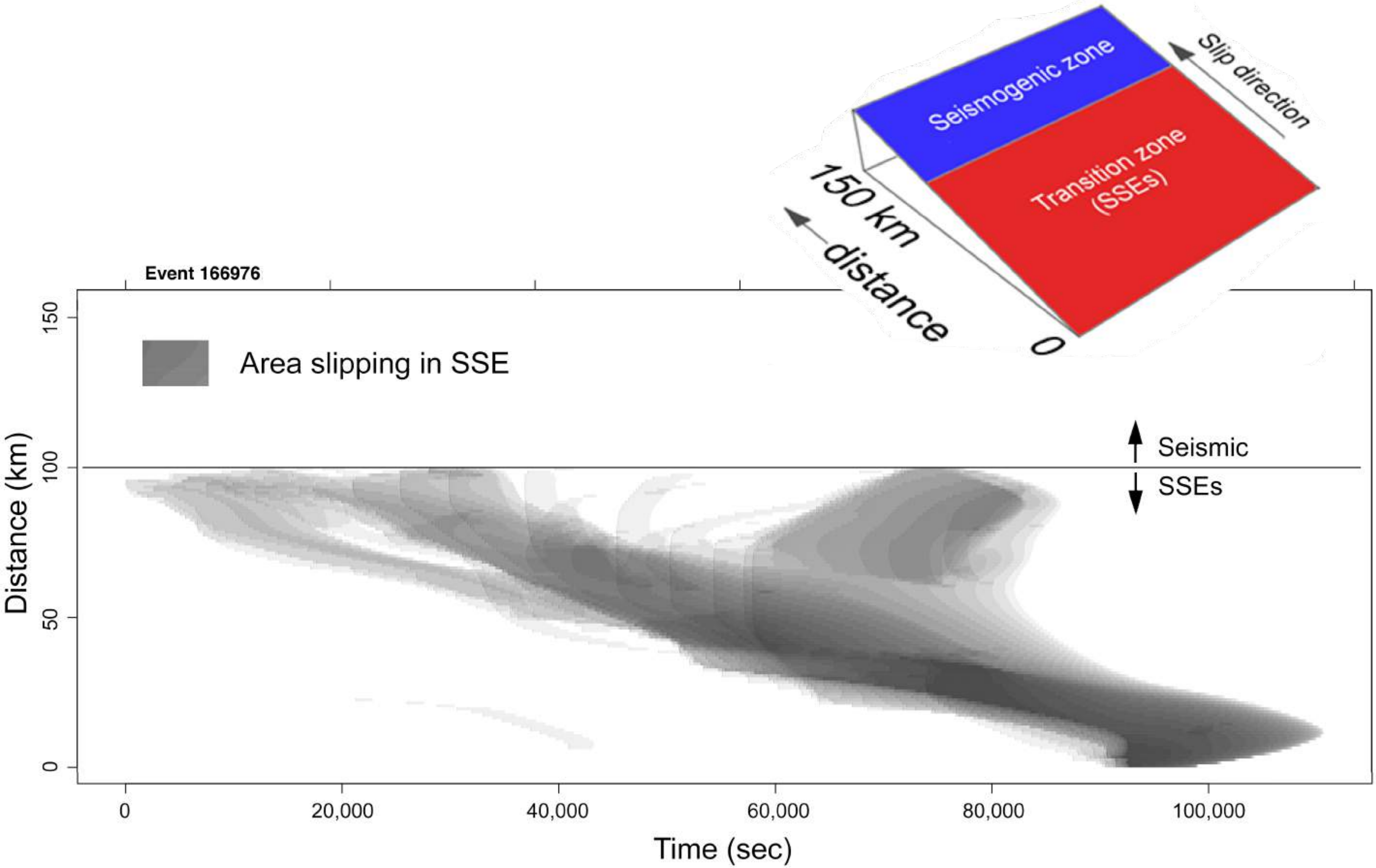


Range of slip speeds in SSEs

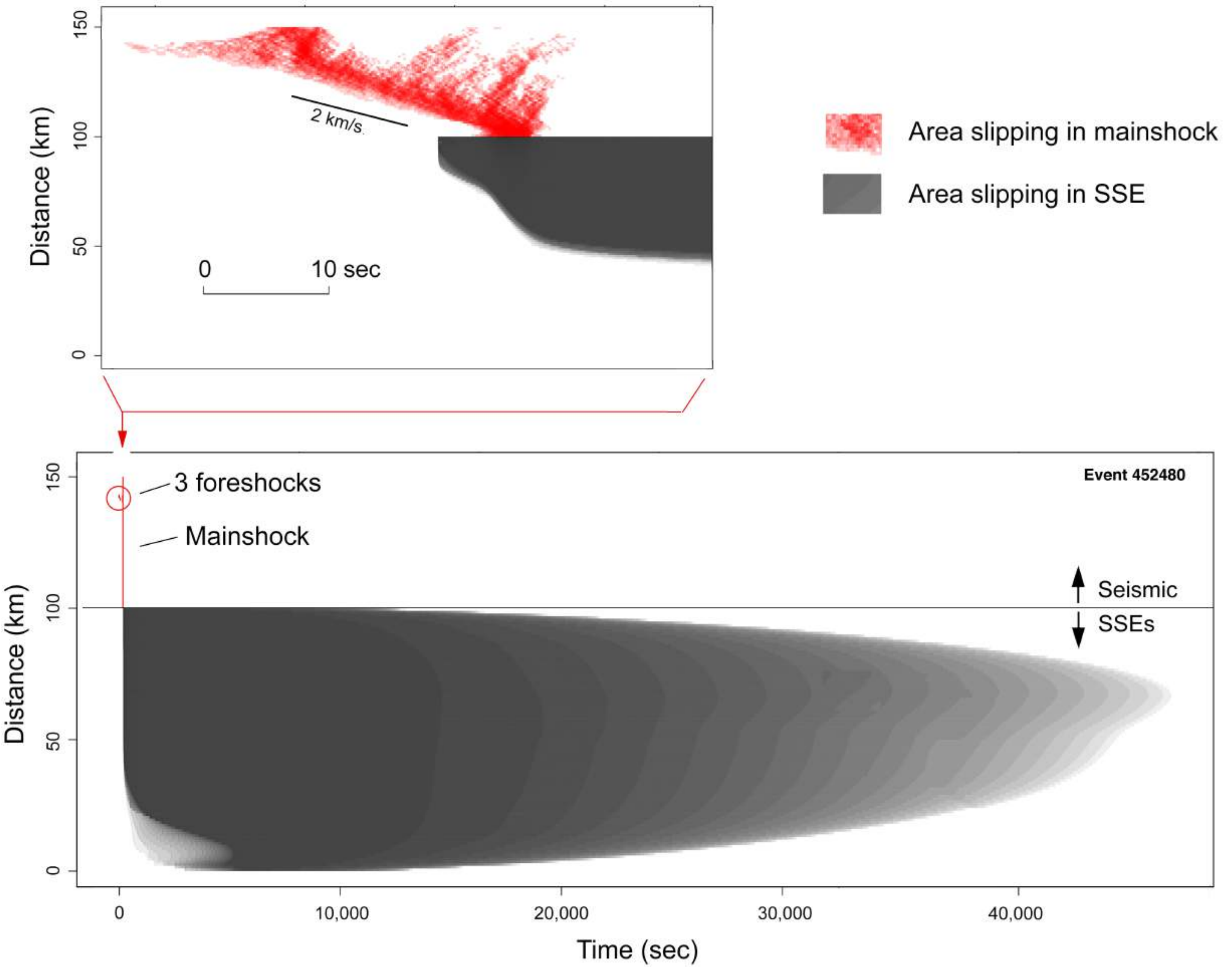
Effective normal stress conditions
Seismogenic sector σ = 100MPa
SSE sector σ = 3MPa



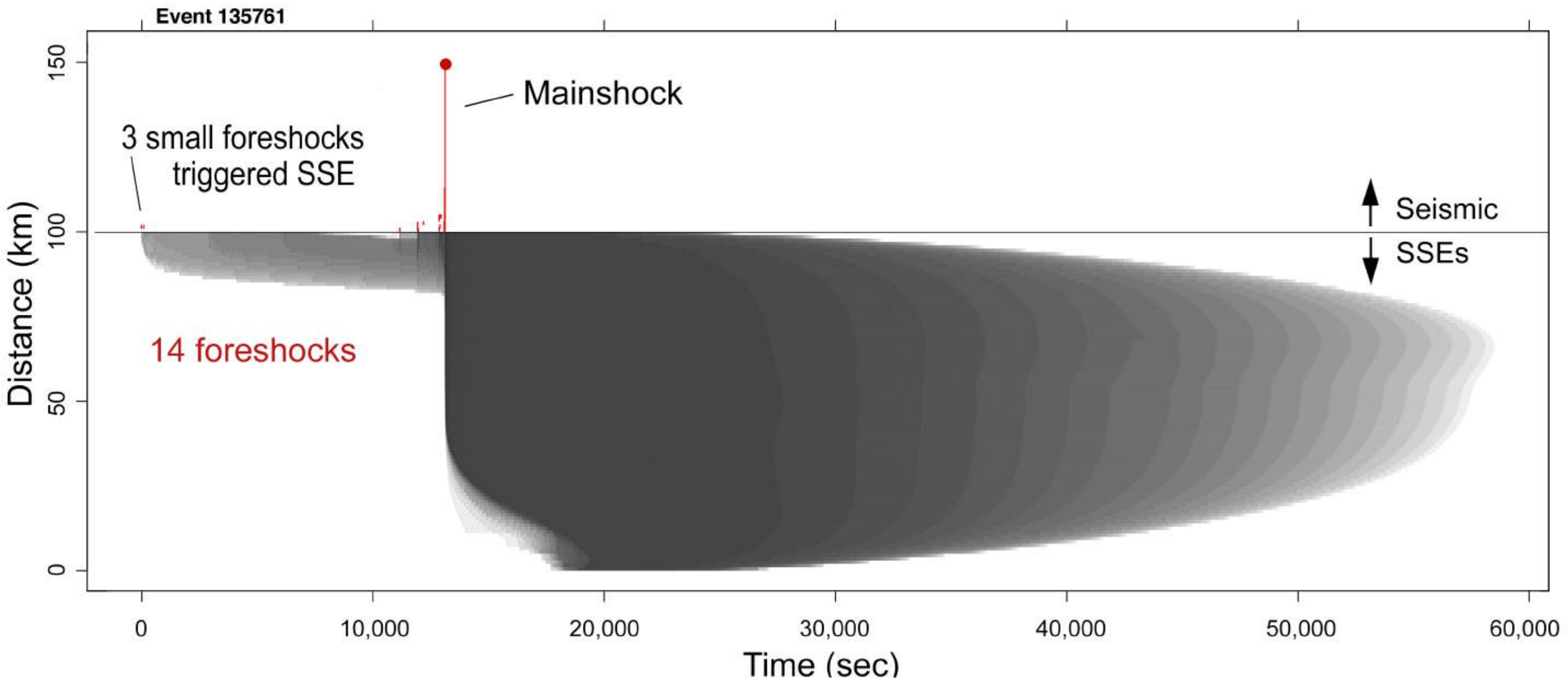
Space – time plot of SSE



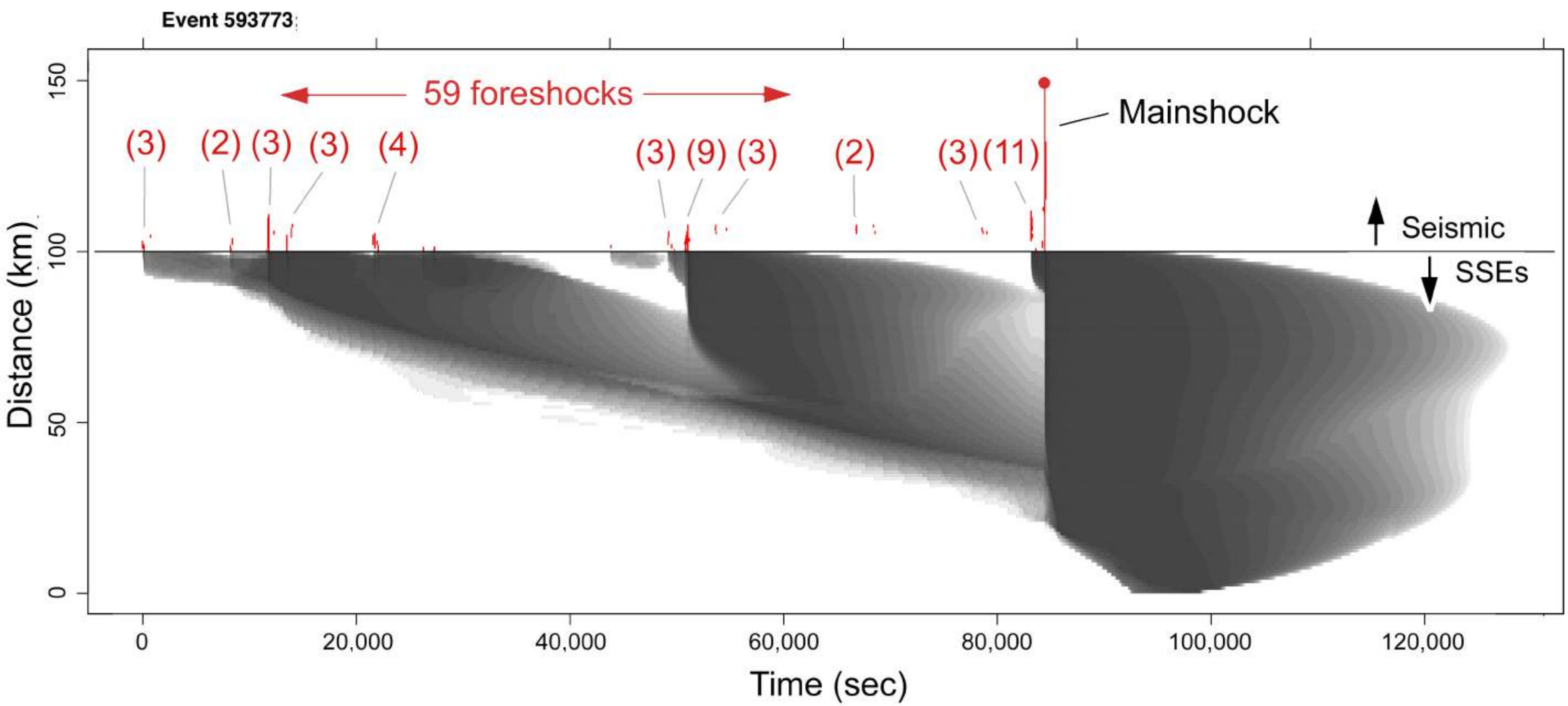
SSE triggered by mainshock



Space – time plot of SSE



Space – time plot of complex SSE with mainshock



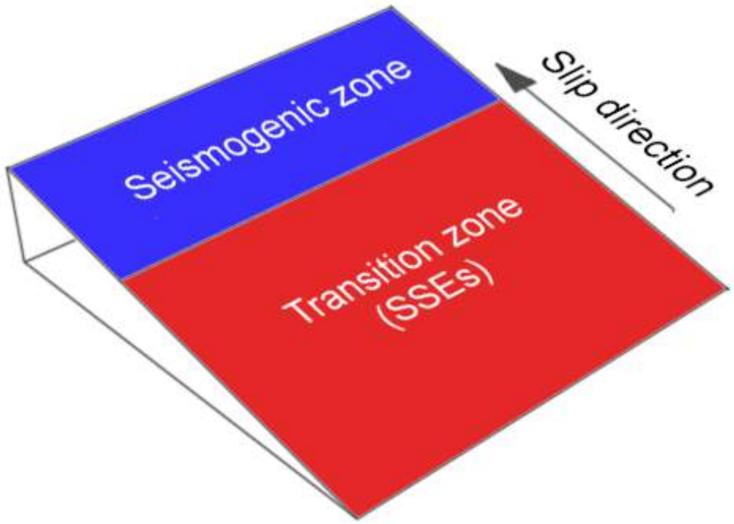
Summary

Definitions
Large SSE: slip area > 75% of transition zone
Large EQ: slip area> 75% of seismogenic zone

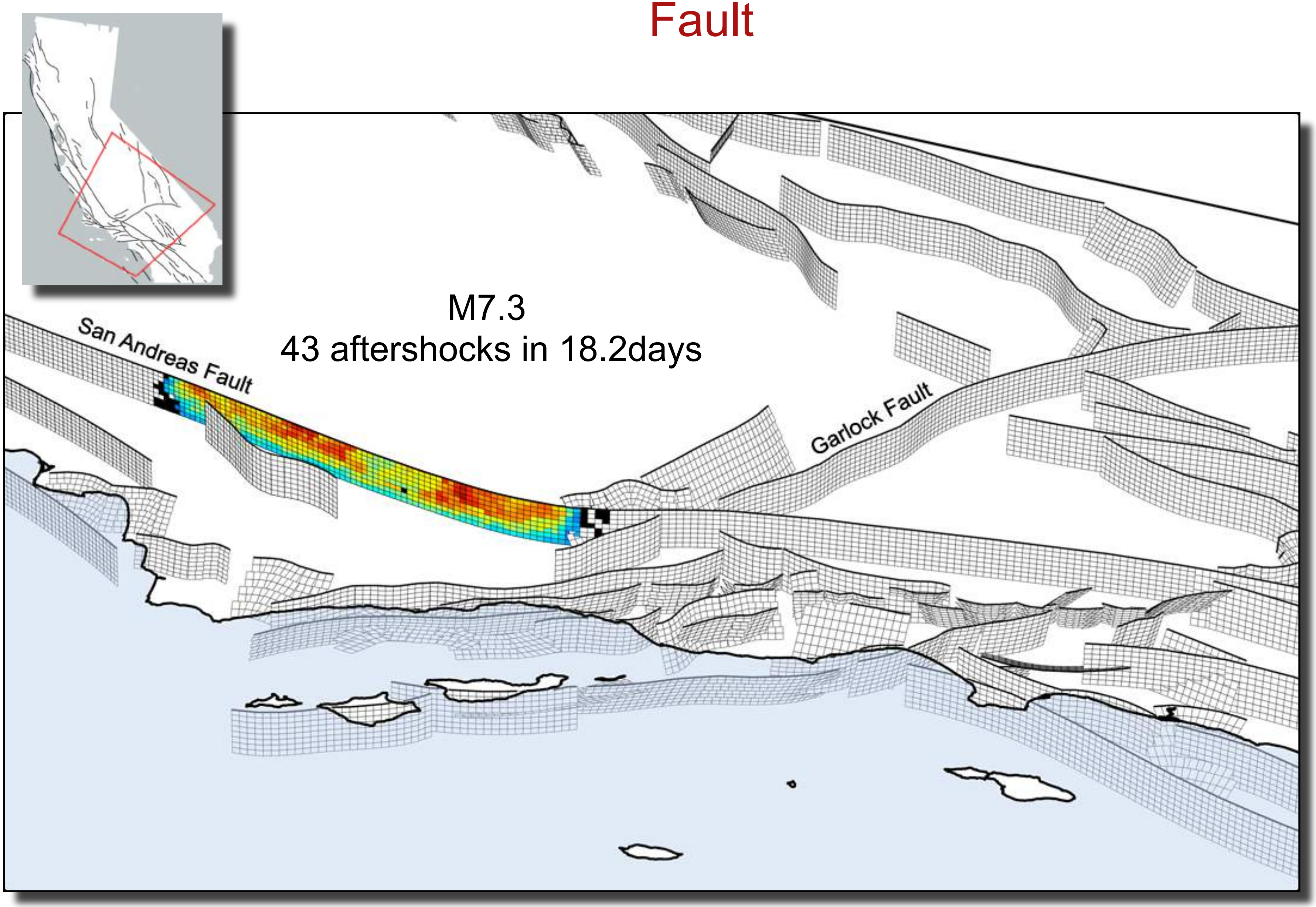
Simulation times
Total simulation time 4.1×10^{10} s (1300yr)
Total time in large SSEs 1.78×10^{8} s (~0.4% of sim time)
Total time all SSEs 2.01×10^{9} s (~5% of sim time)

Numbers of events
Large SSEs: 1766
Large EQS: 33
Large EQs with SSE before mainshock 14

42% of large EQs were preceded by SSEs
0.8% of large SSEs preceded large EQs



Large-earthquake cluster along southern San Andreas Fault



Jacqui Gilchrlst, PhD Thesis (2016)

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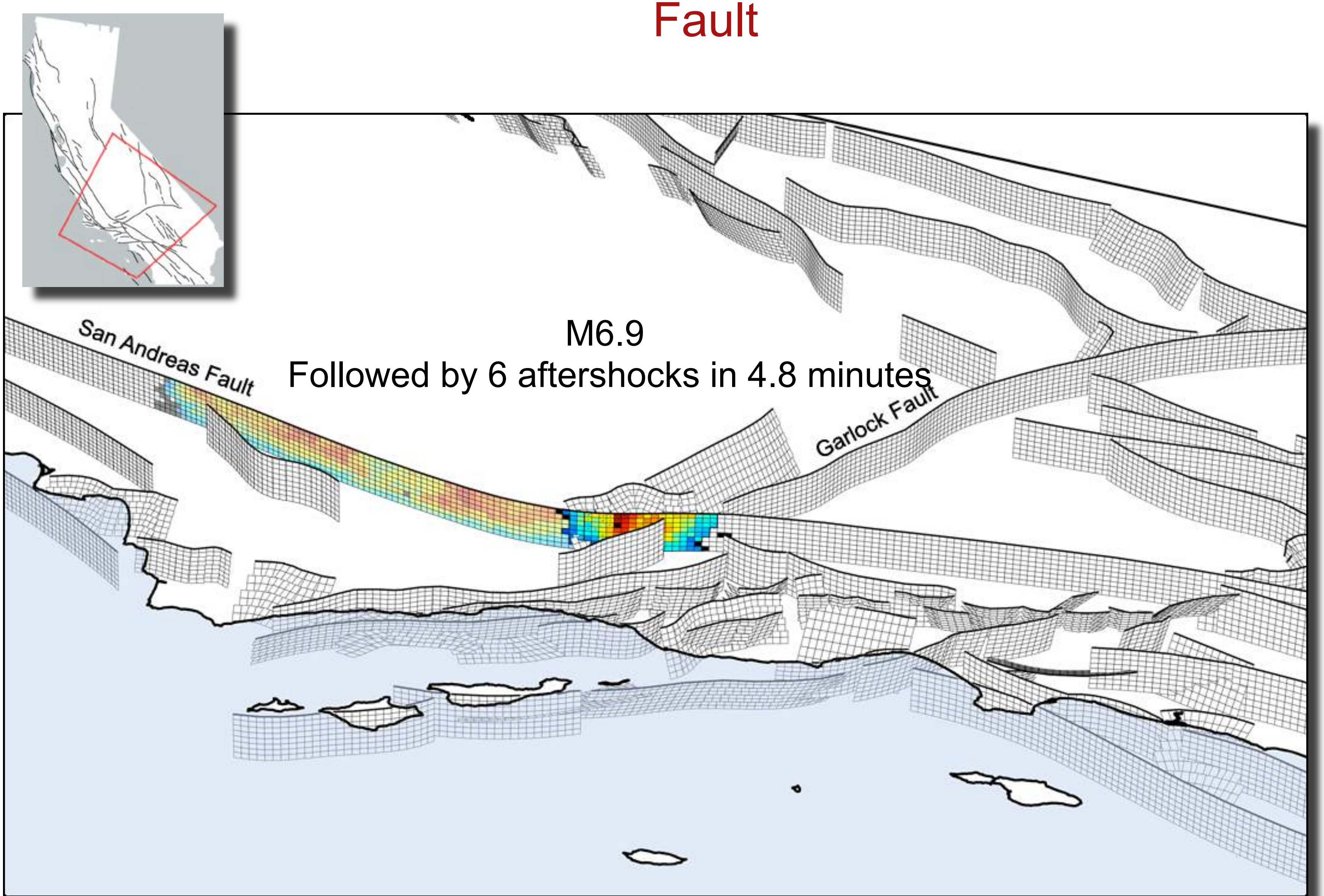

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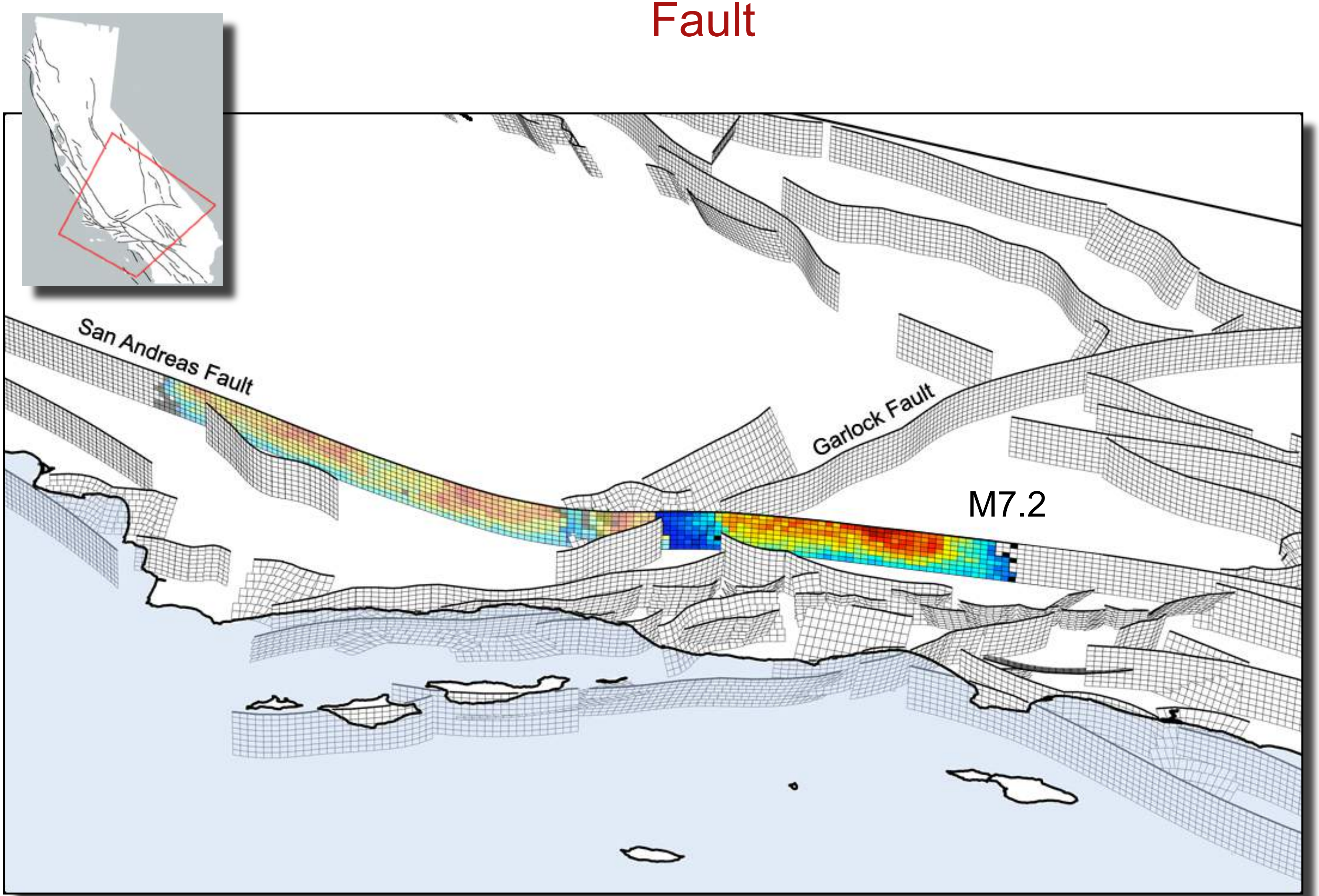


Jacqui Gilchrist, PhD Thesis (2016)

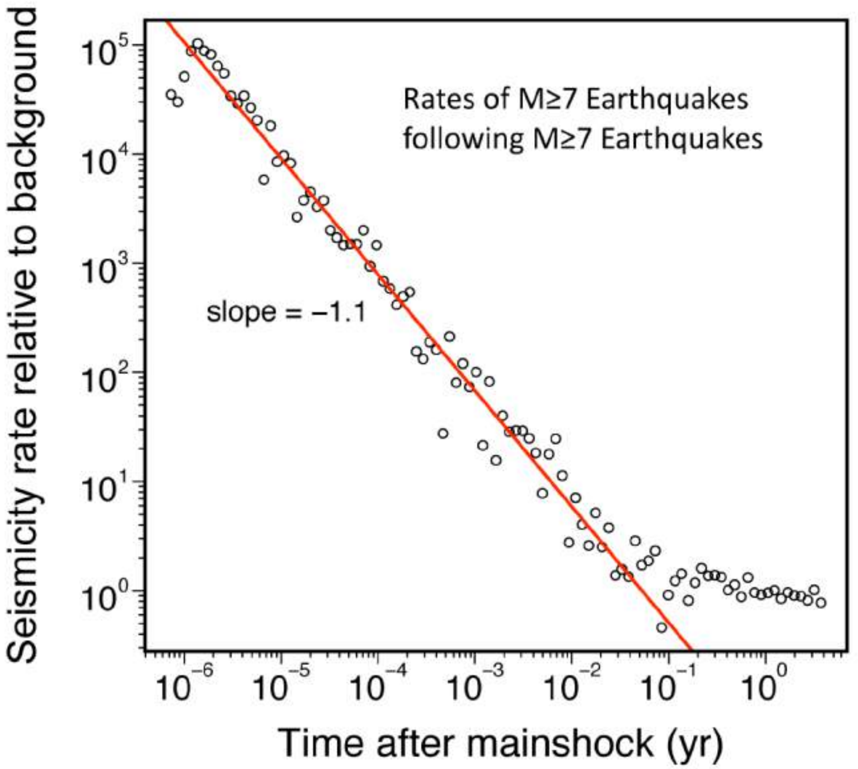
Clusters of Large Earthquakes

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

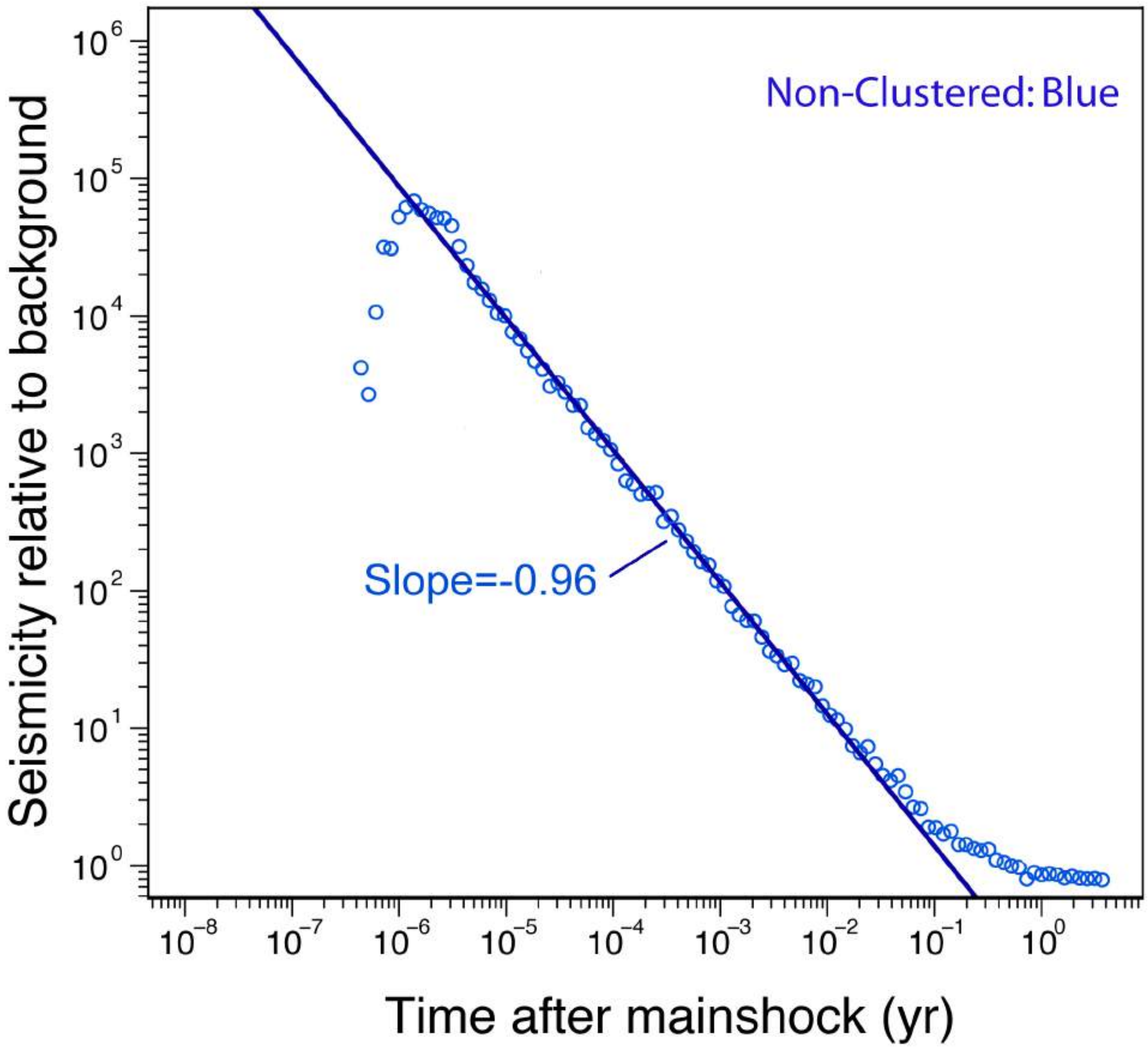
All Cal model – effect of *a*	$F_{cluster}$ M ≥ 7
All-Cal, *a* = 0.008	0.124
All-Cal, *a* = 0.009	0.117
All-Cal, *a* = 0.010	0.145
All-Cal, *a* = 0.012	0.171

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

All Cal Simulation



Aftershocks of Non-Clustered and Clustered M≥7 Events



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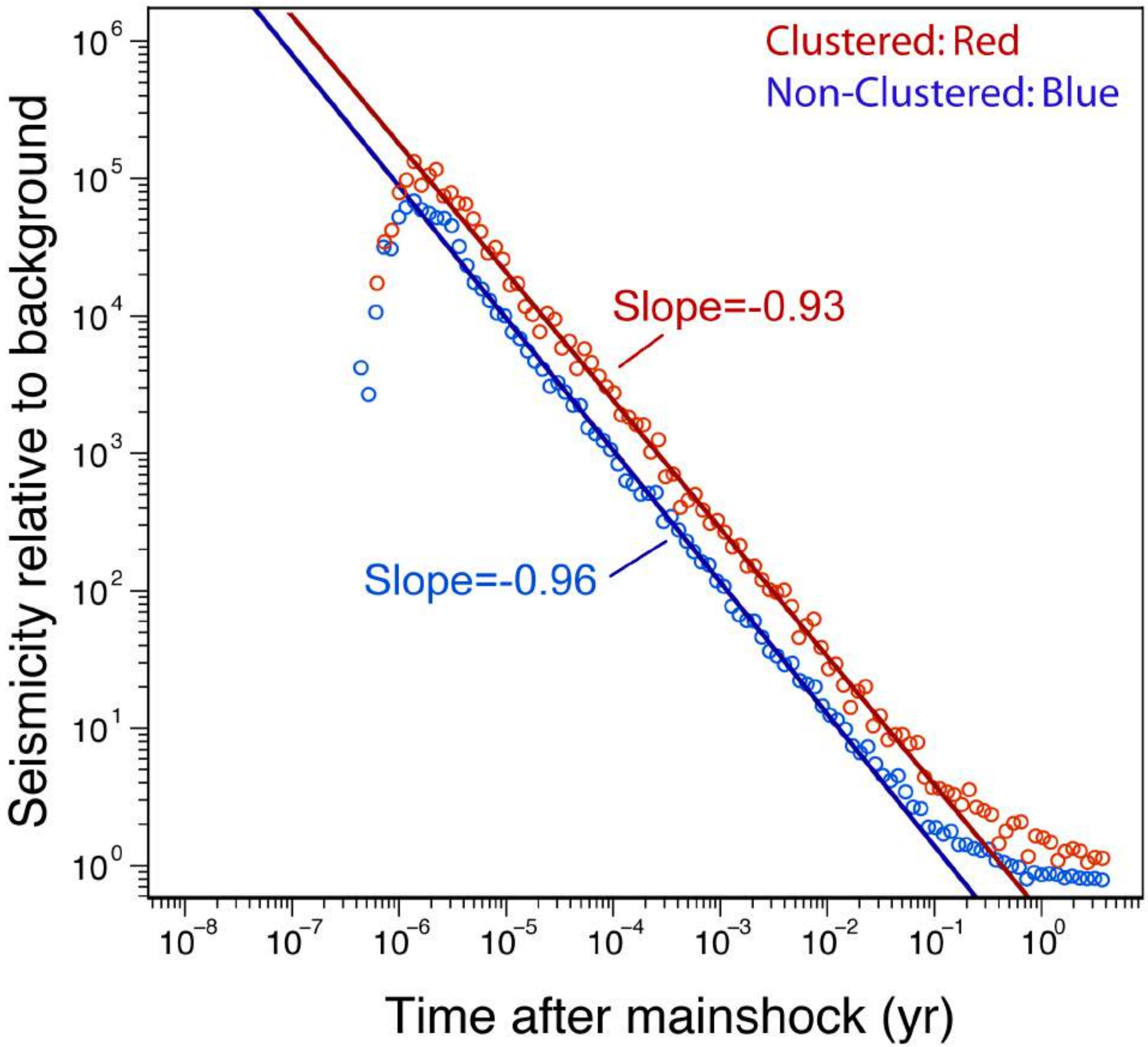

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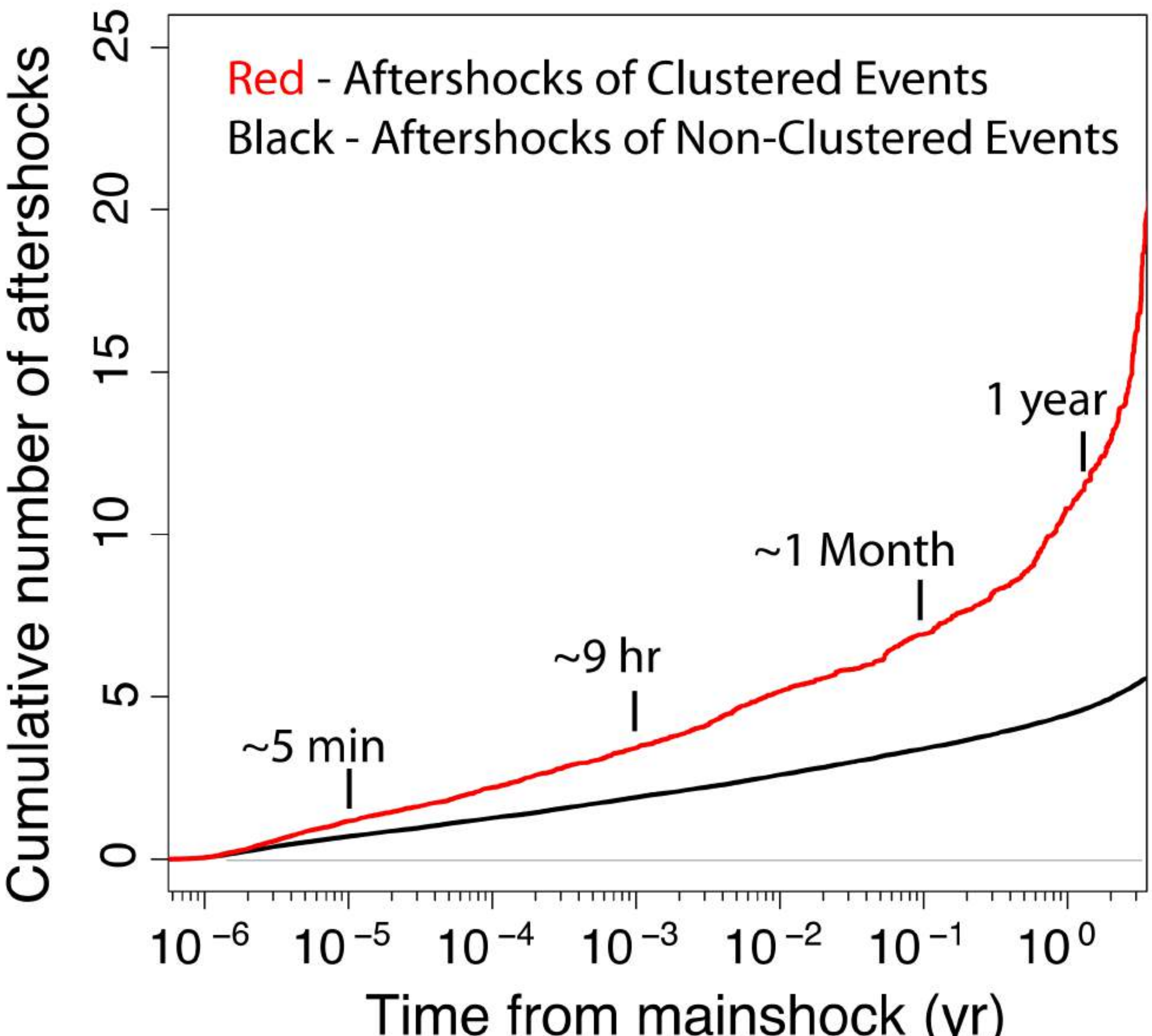
Aftershocks of Clustered and Non-Clustered M≥7 Events



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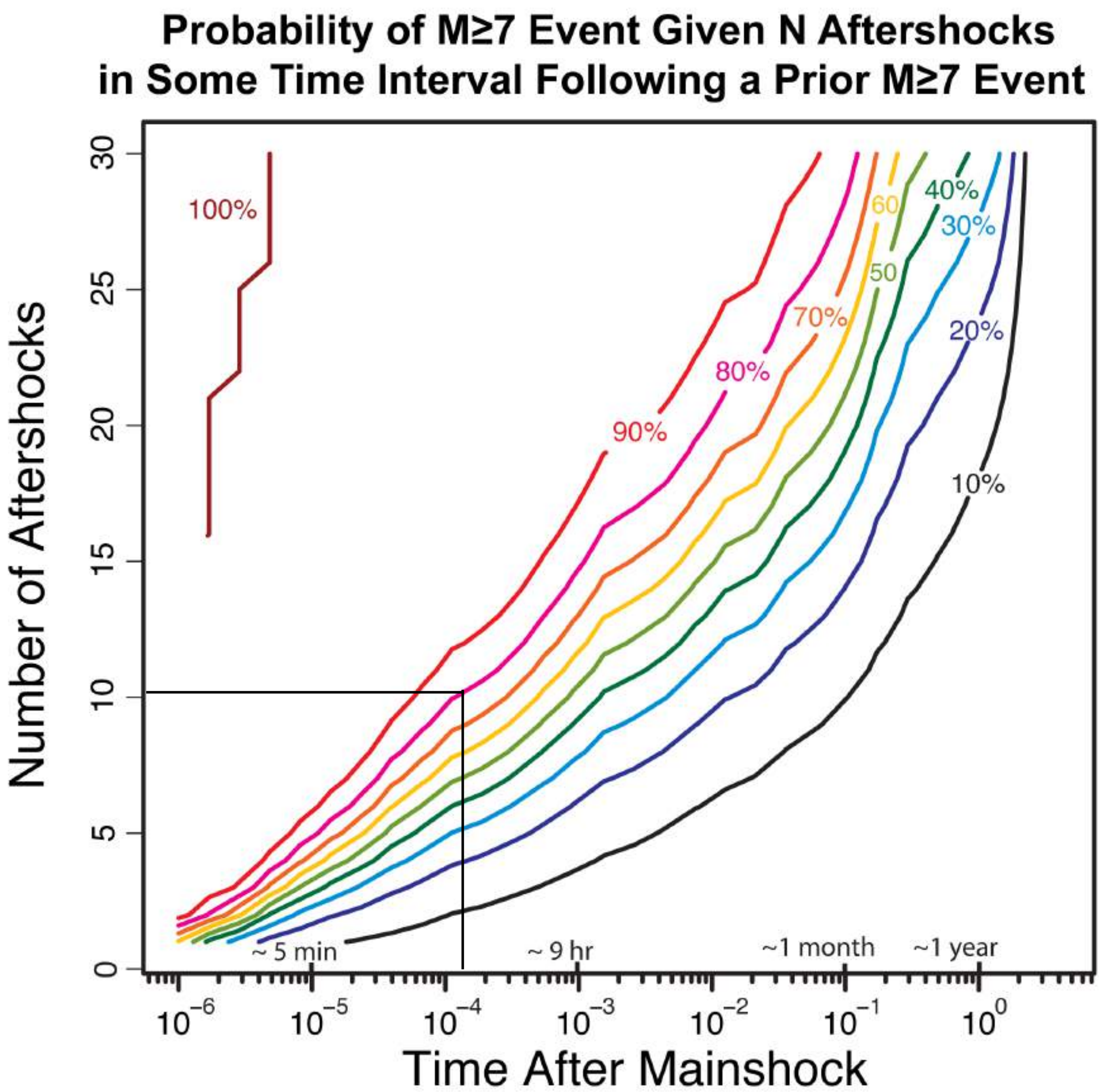
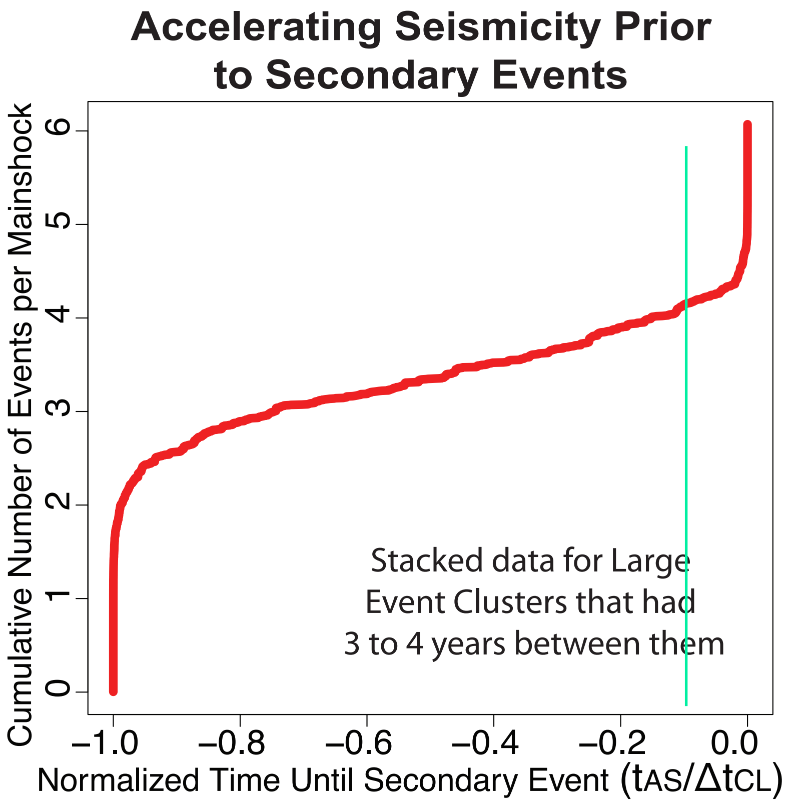
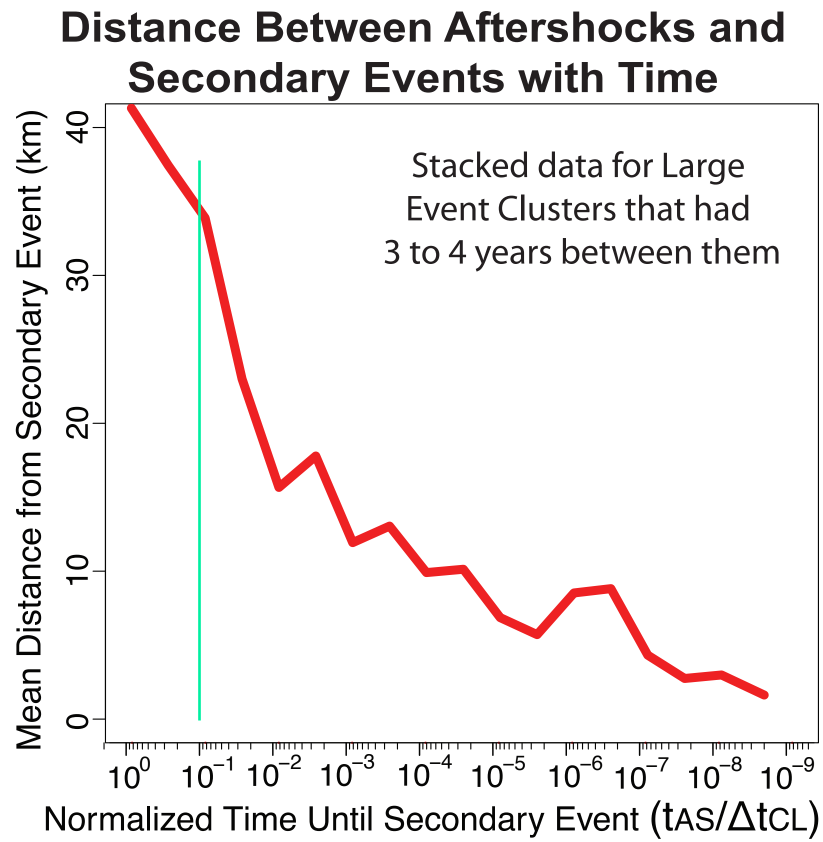
Probability Additional Earthquake M≥7 Within 50km of Earthquake M≥7



Jacqui Gilchrist, PhD Thesis (2016)

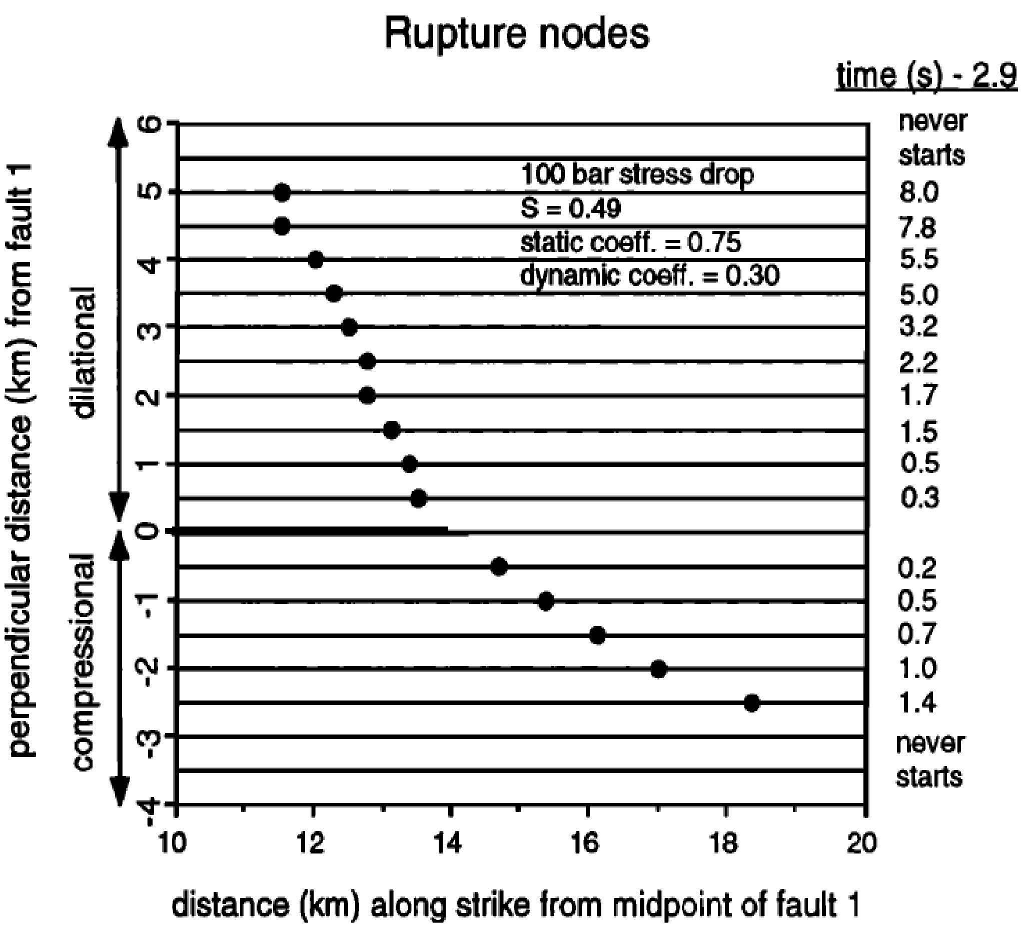
Transition from aftershocks of a prior M>7 event to foreshocks of an impending M>7 event

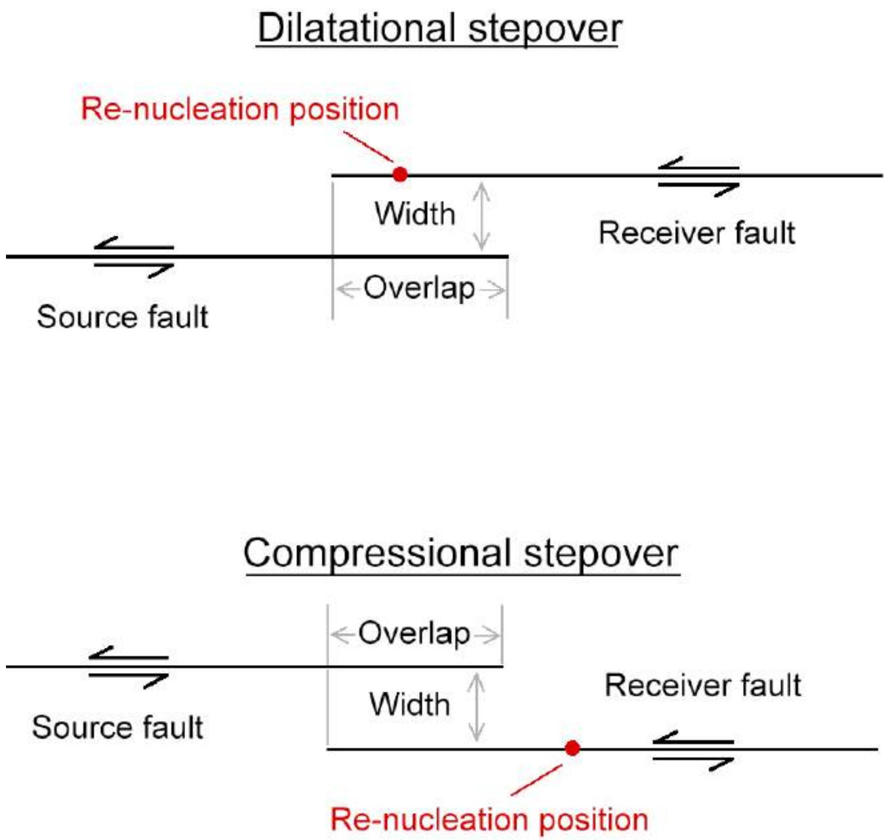




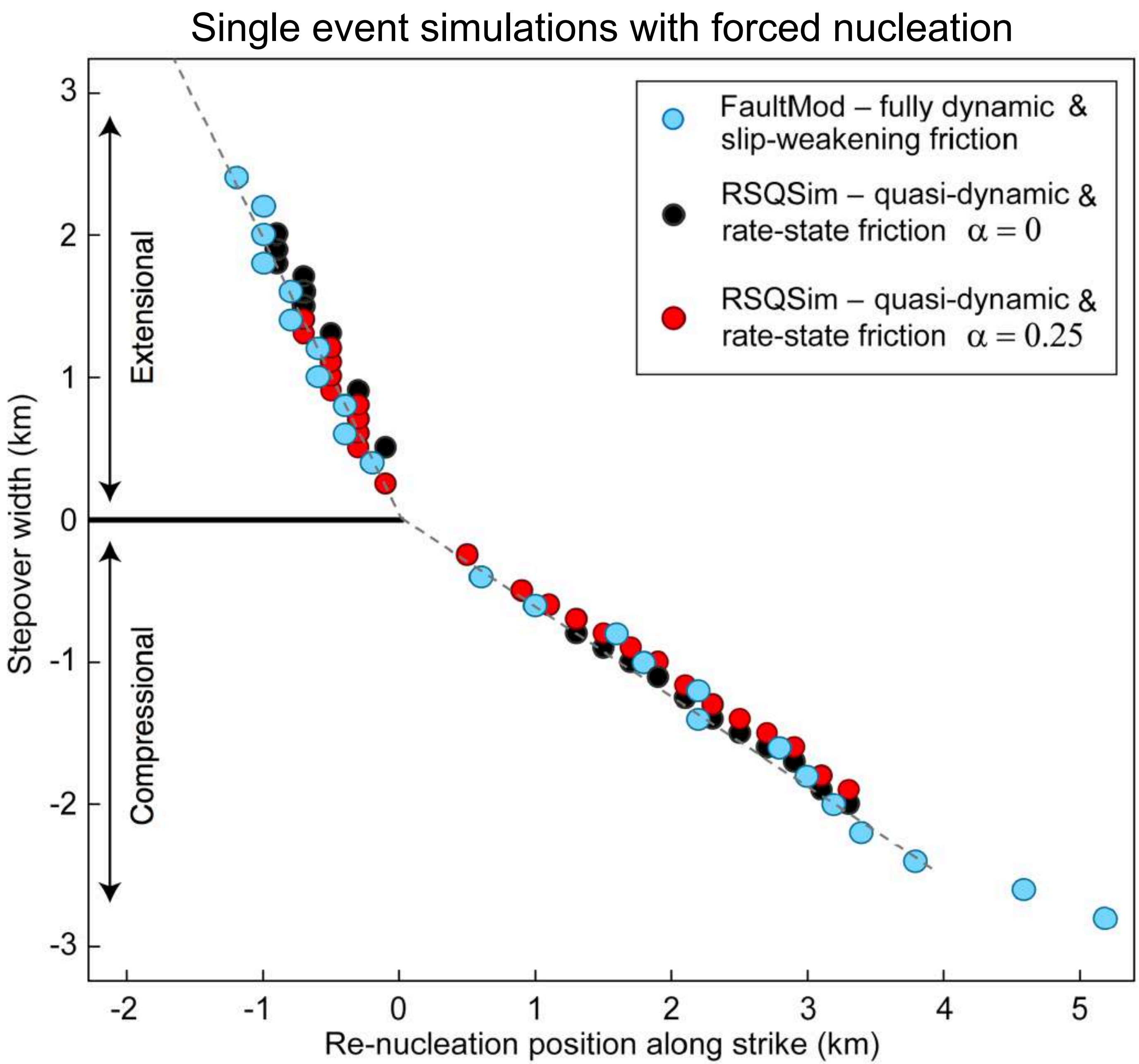
Jacqui Gilchrist, PhD Thesis (2016)

Simple geometric complexity – fault stepovers



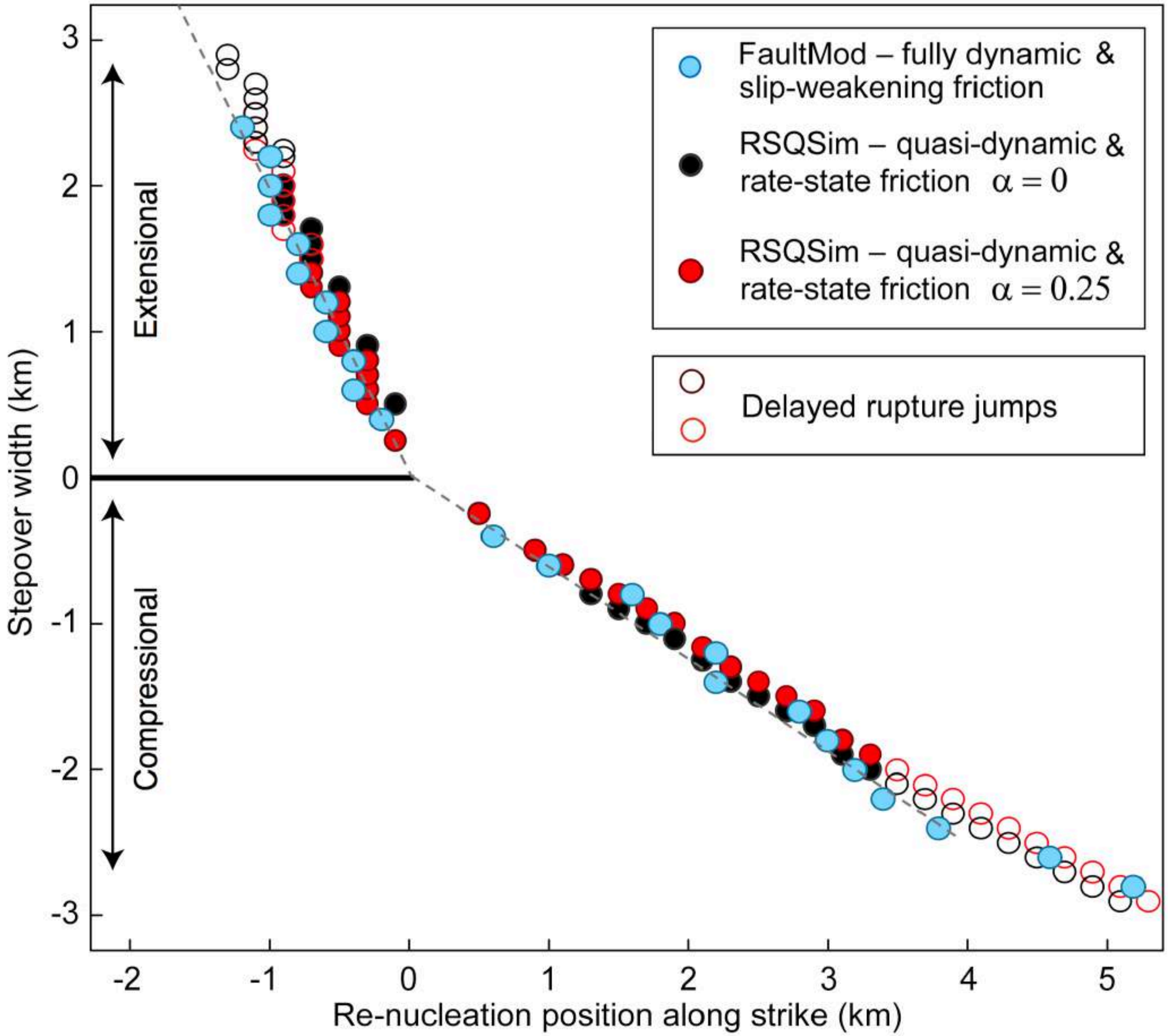


Harris and Day(1993)



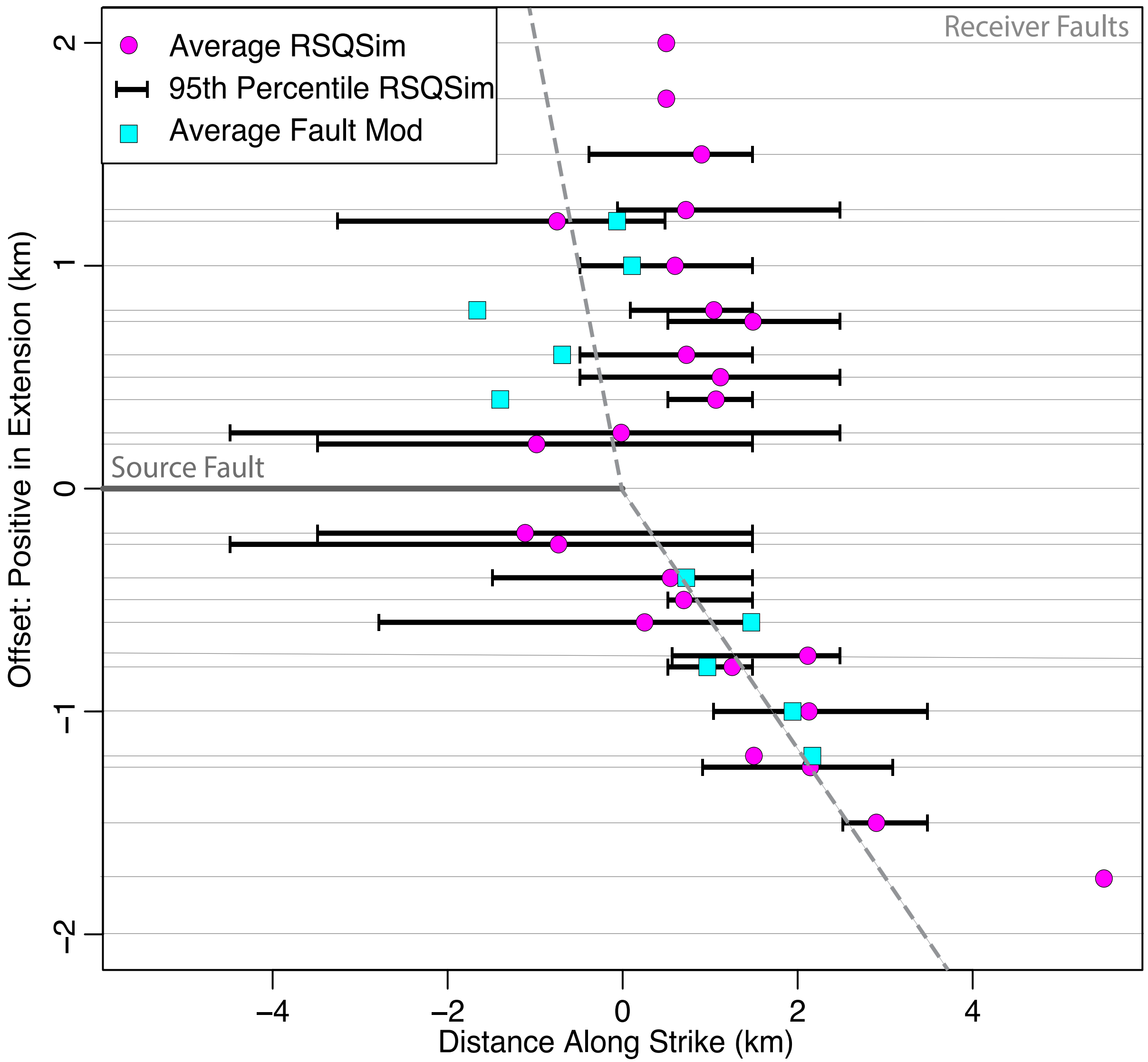
Kroll and others

Single event simulations with forced nucleation



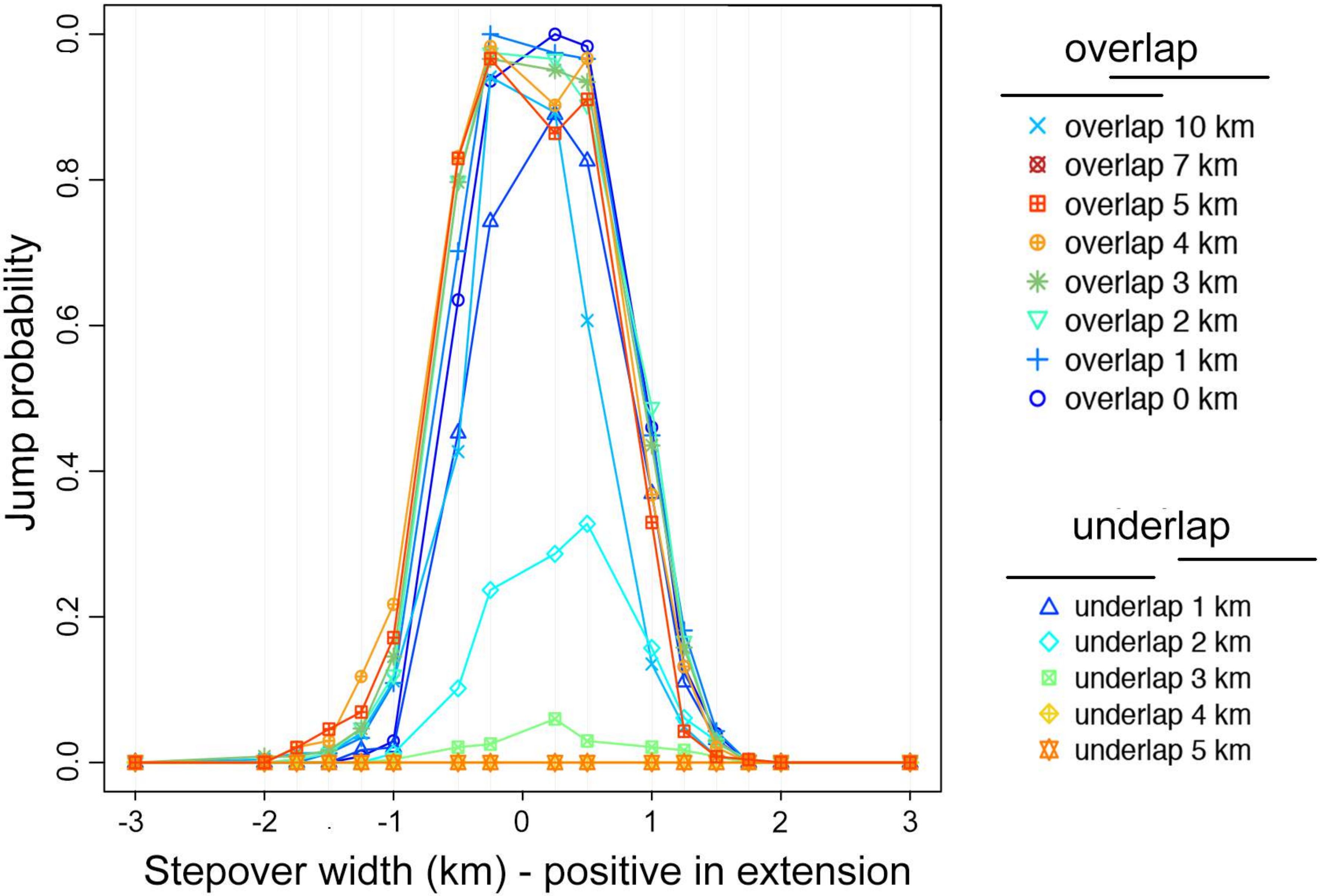
Kroll and others

Multi-cycle simulations with evolved stresses and spontaneous nucleation



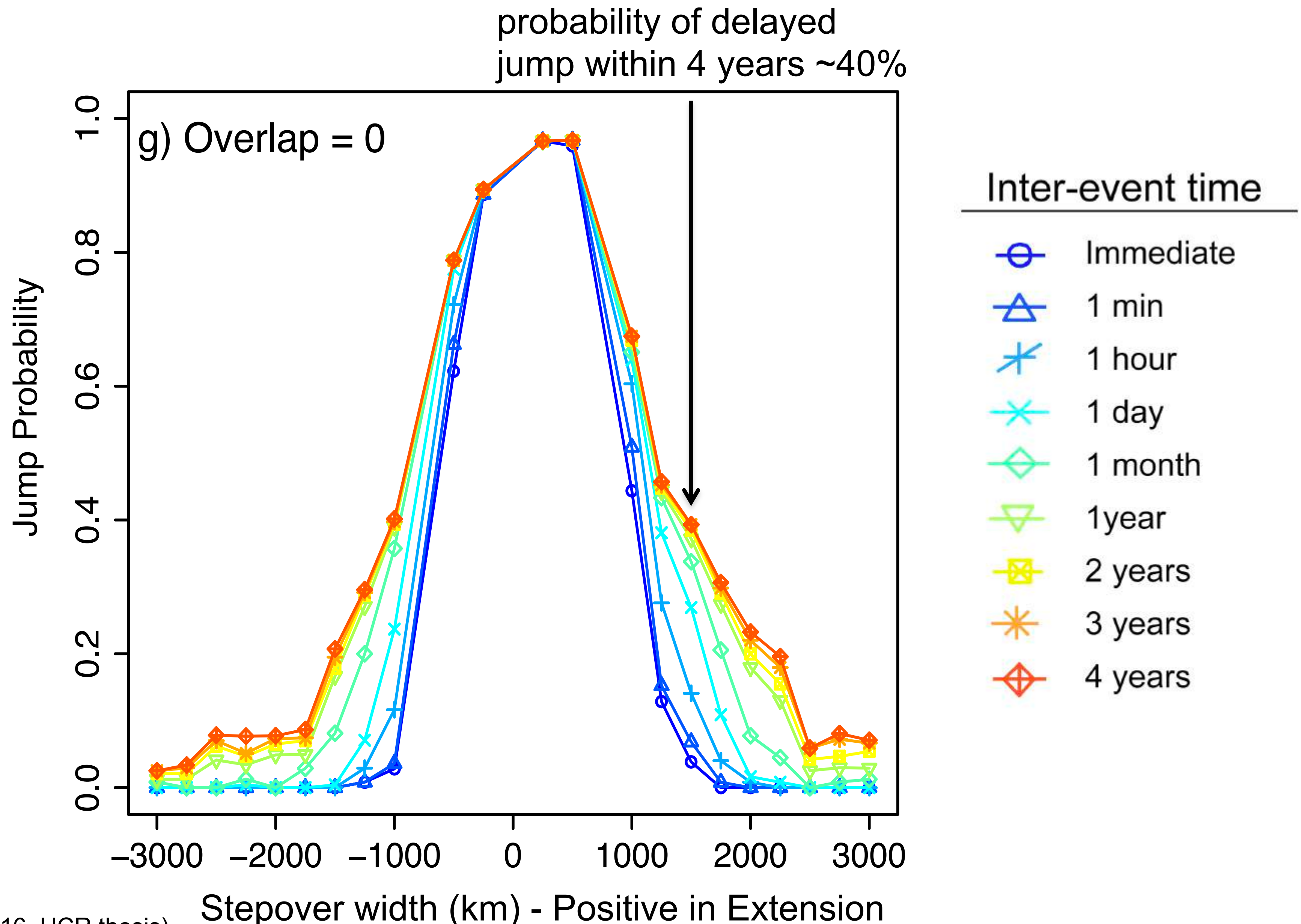
Kroll and others

Immediate rupture jump probabilities under evolved stress conditions



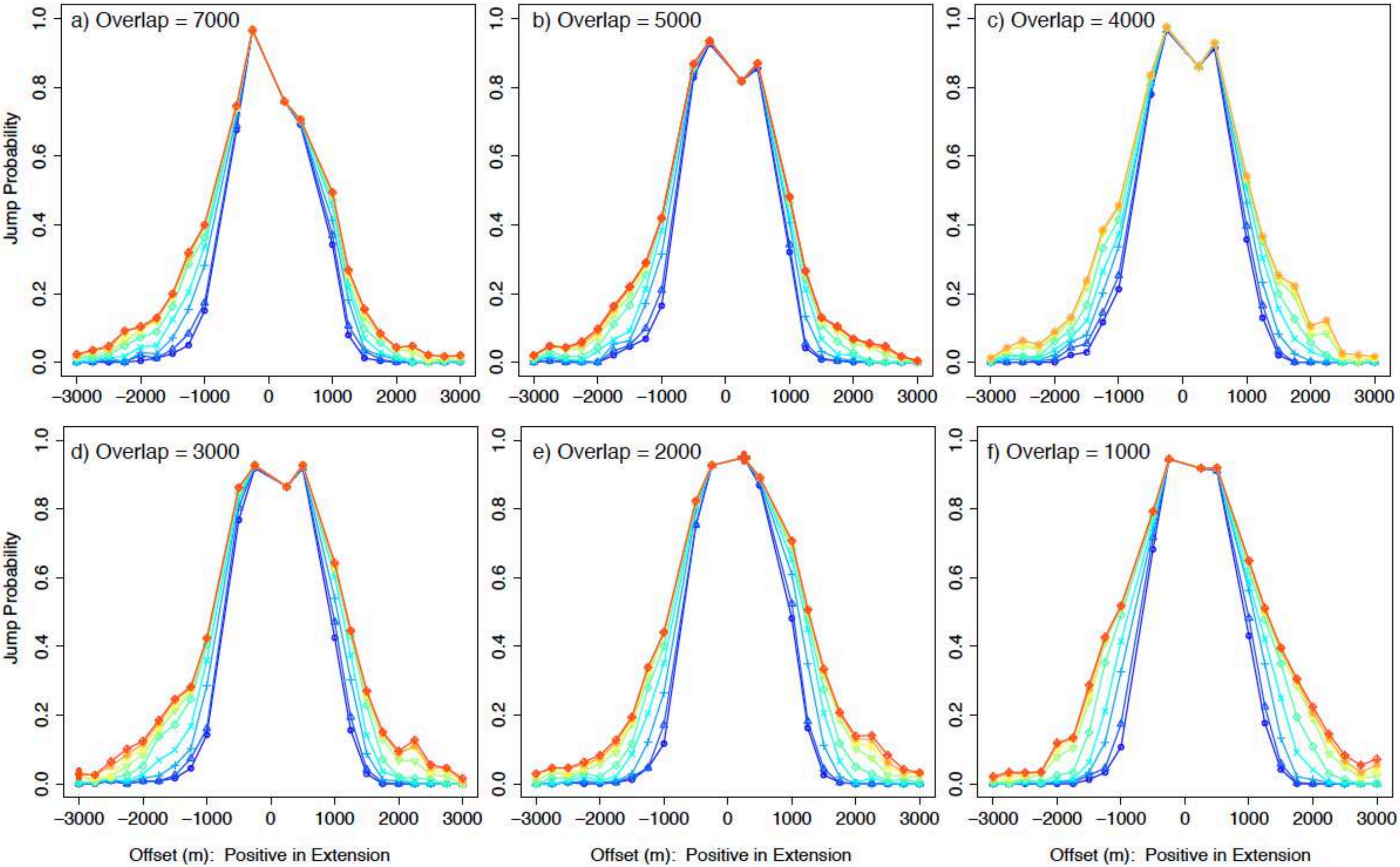
Kroll, (2016, UCR thesis)

Probability of immediate and delayed rupture jump



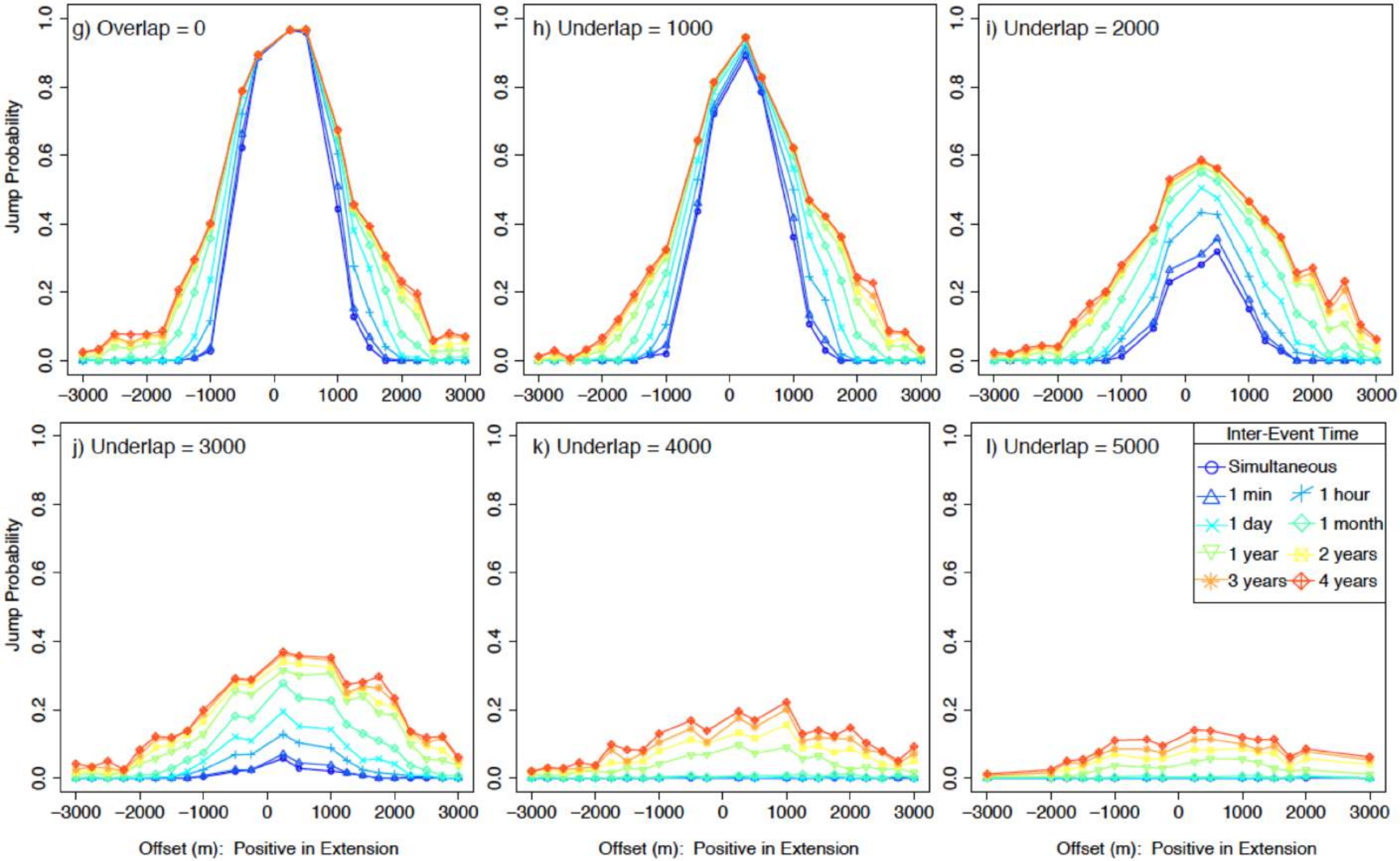
Kroll, (2016, UCR thesis)

Rupture jump probabilities (instantaneous and delayed)



Kroll, (2016, UCR thesis)

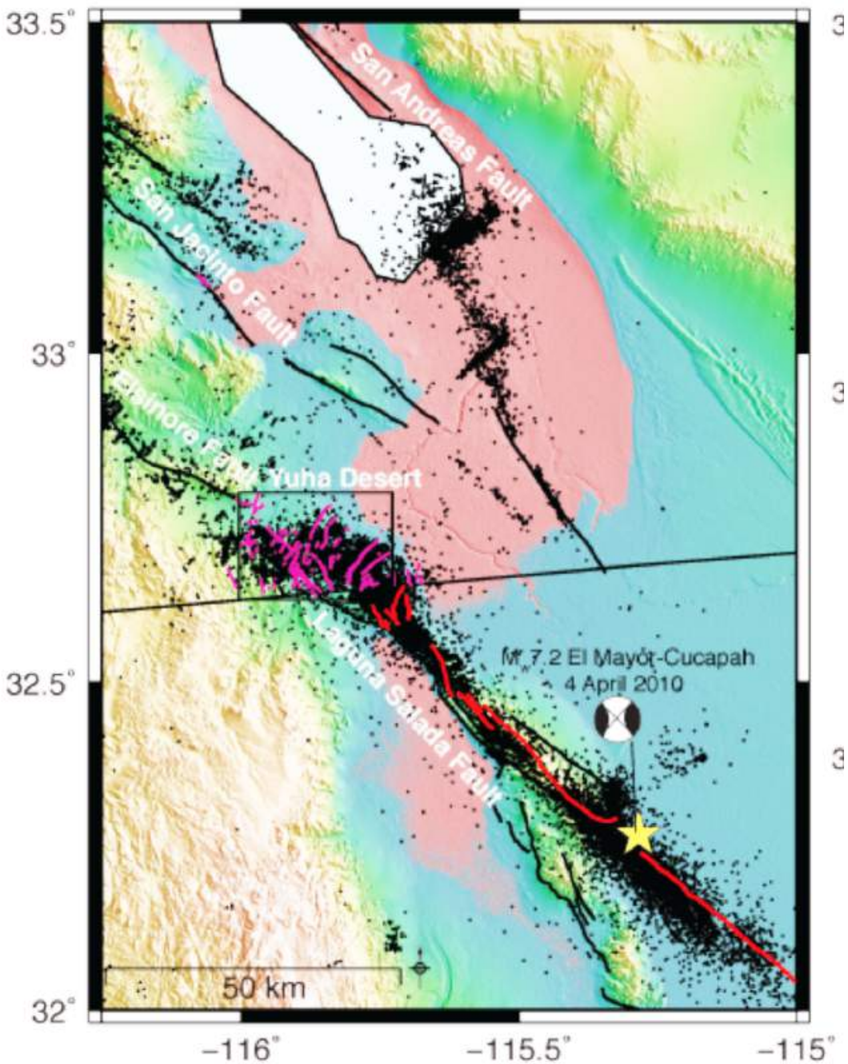
Rupture jump probabilities (instantaneous and delayed)



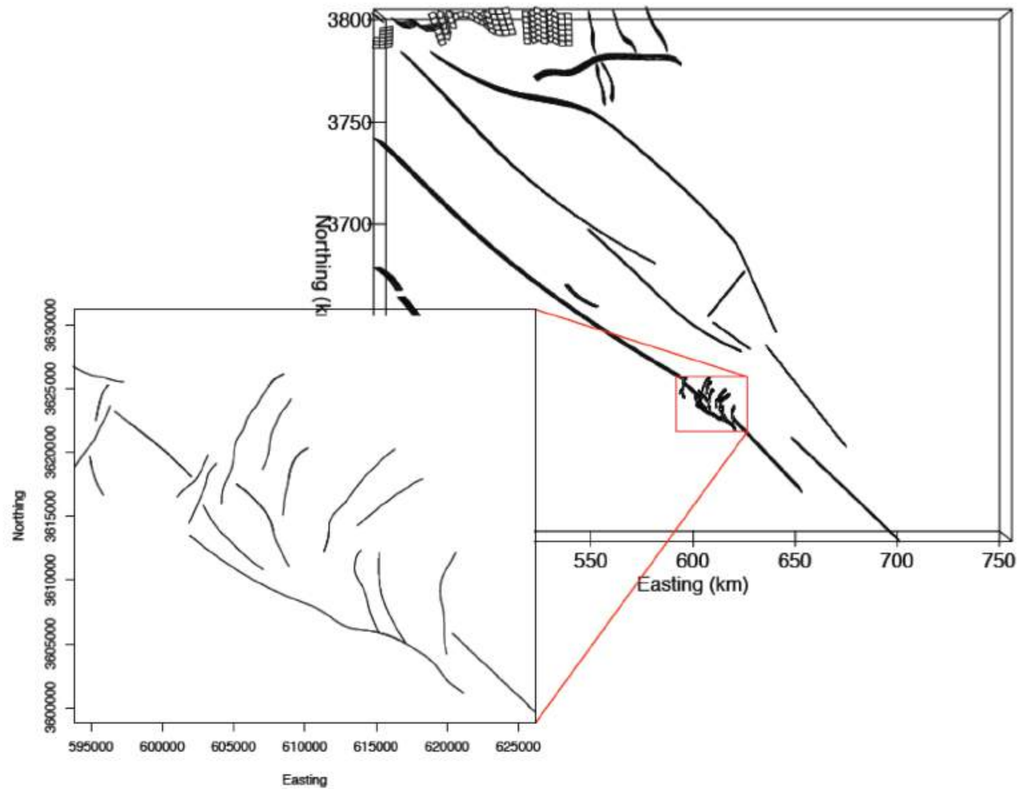
Kroll, (2016, UCR thesis)

Simulation of a complex fault system between the Elsinore and Laguna Salada faults

Aftershocks of 2010 M7.2 El Mayor Cucapah EQ

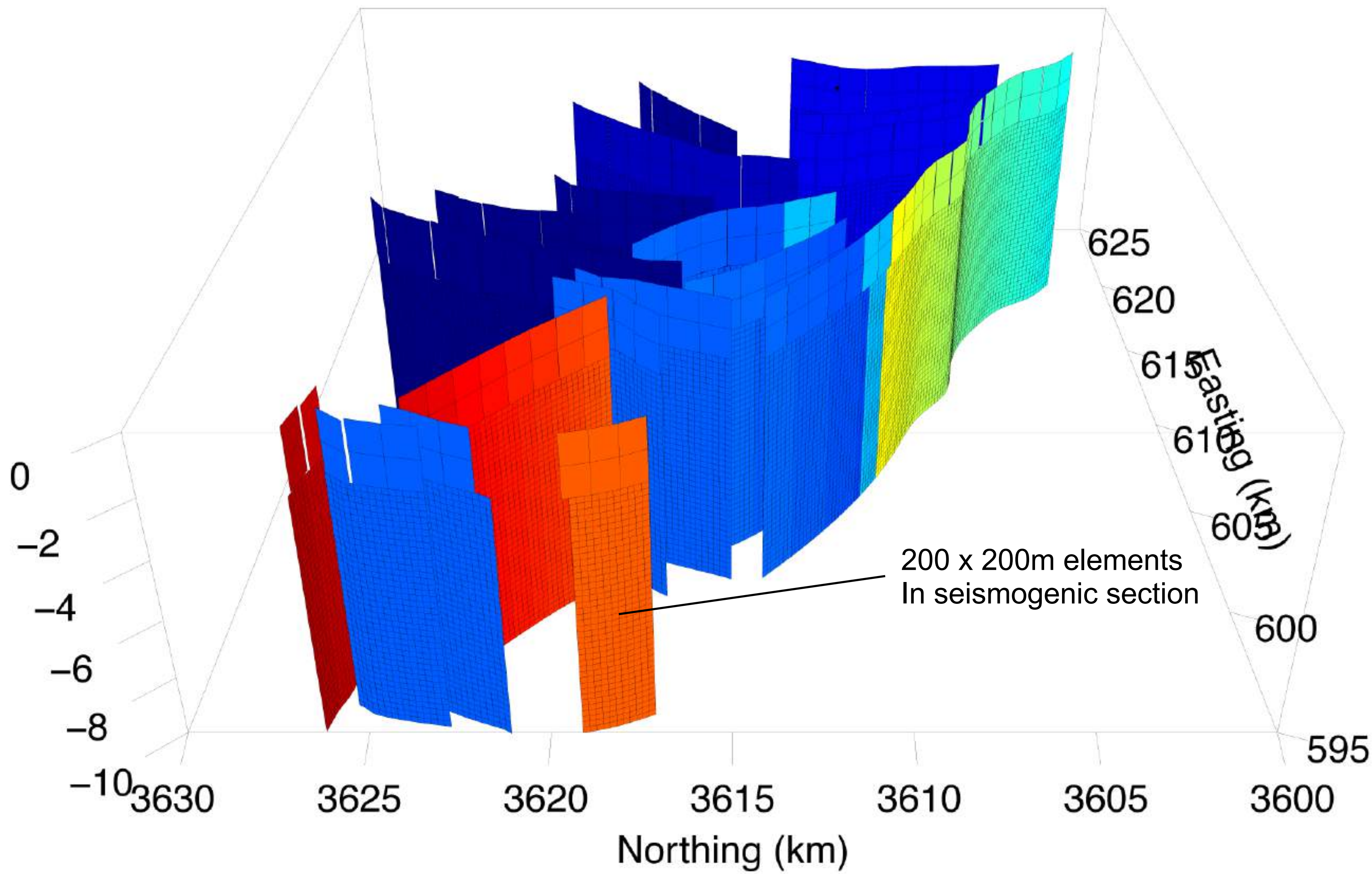


Faults from Fletcher et al., (2010) and triggered surface slip of Rymer et al. (2011)



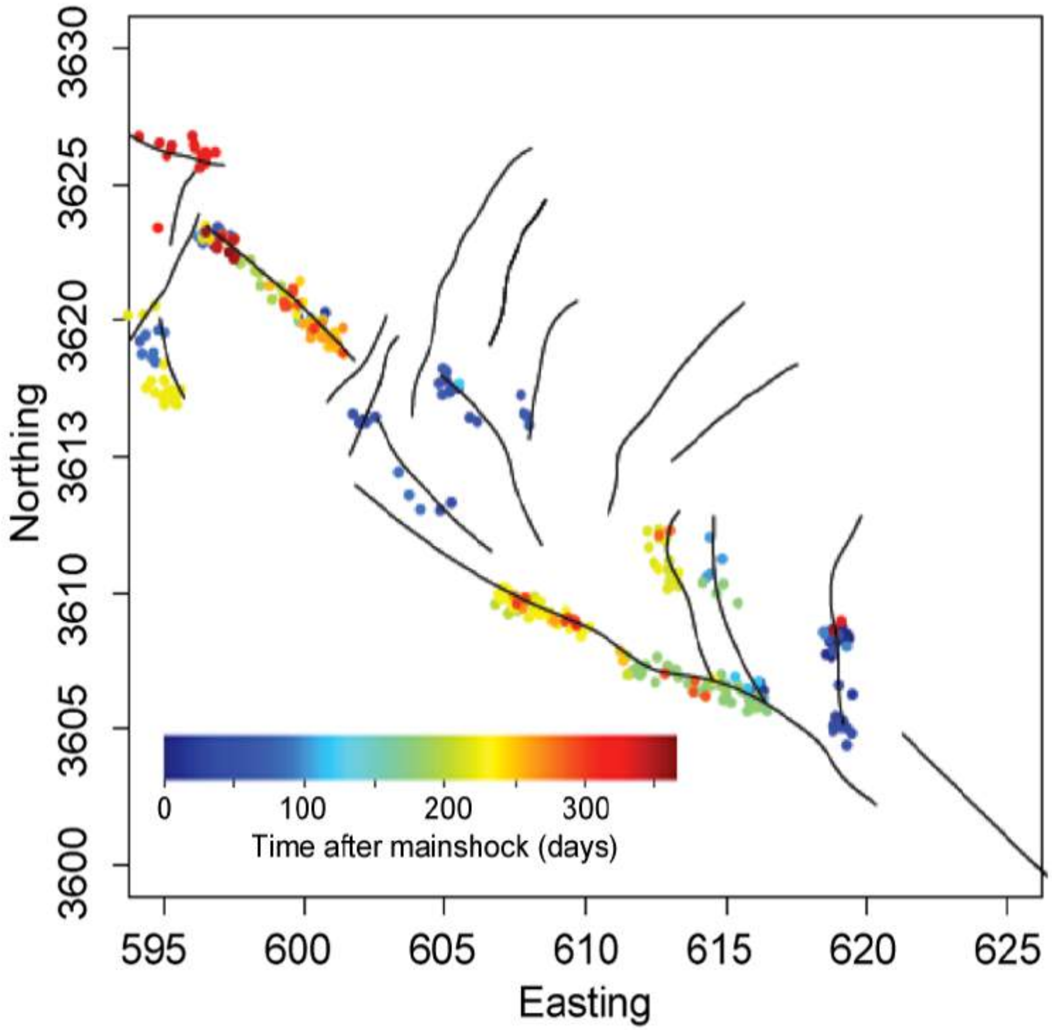
Kroll, (2016, UCR thesis)

Local fault model embedded in regional southern California UCERF3 model



Aftershocks to Laguna Salada mainshock similar to the M7.2 El Mayor-Cucapah earthquake

No through-going ruptures between Laguna-Salada and Elsinores faults



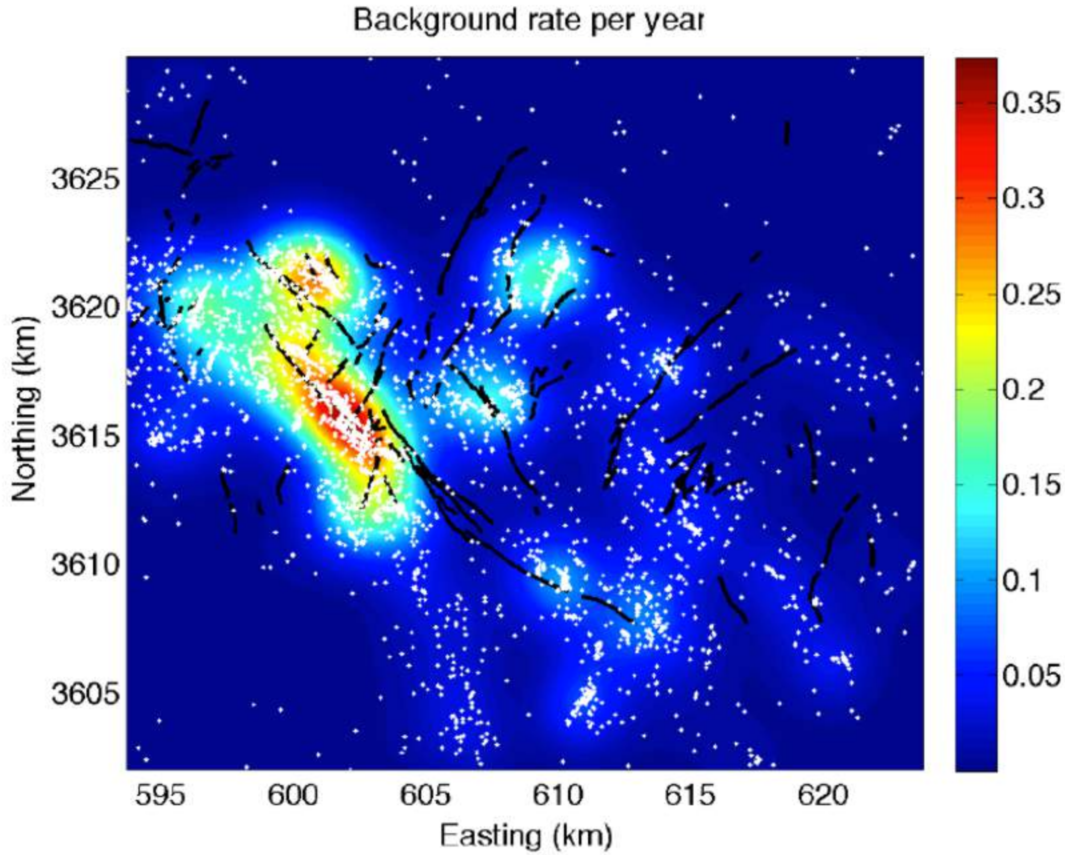
Kroll and others (unpublished)

Looking Ahead: Simulations that incorporate off-fault seismicity (as driven by tectonic stressing and on-fault slip history)

$$R = \frac{r}{\gamma \dot{S}_r}, \qquad d\gamma = \frac{1}{a\sigma}\left[dt - \gamma dS\right]$$

(Dieterich, 1994)

- Background rate r from recorded seismicity
- $S(t)$ from assumed tectonic stressing and RSQSim stress

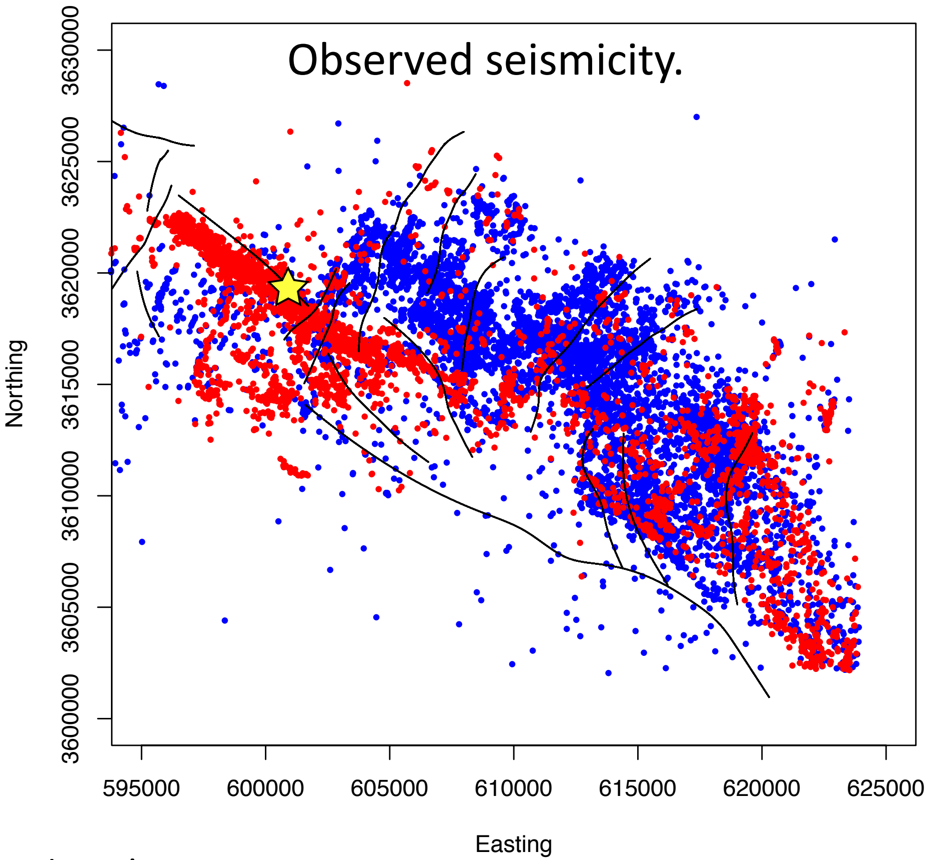


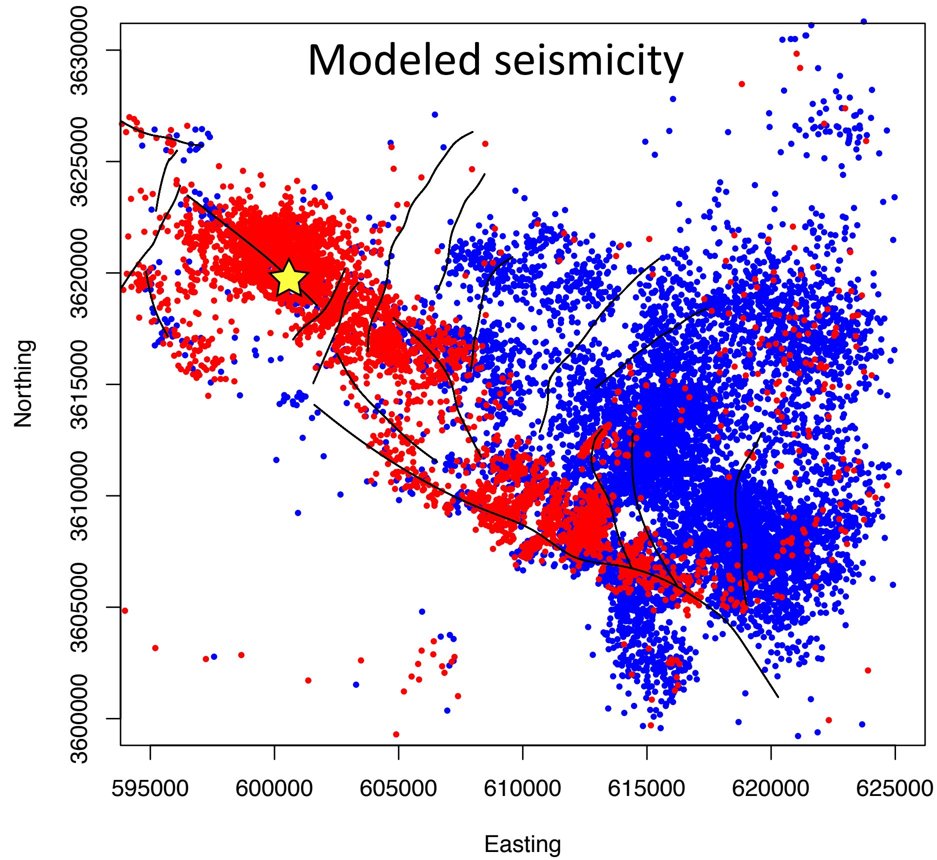
Kroll and others (unpublished)

Comparison of observed and modeled seismicity

- Seismicity between the M7.2 El Mayor-Cucapah earthquake and the M5.7 Ocotillo aftershock (Δt =71 days)
- Seismicity after Ocotillo (Δt=371days)

- Seismicity between a simulated Laguna Salada mainshock and a M5.9 aftershock (Δt= 400 days)
- Seismicity following aftershock (Δt=730 days)



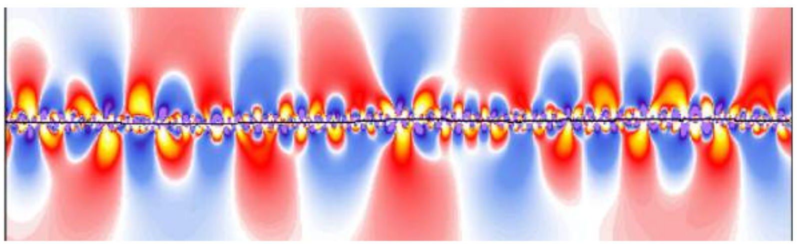


Locations:
Hauksson *et al.,* 2012; Kroll *et al.,* 2013

Incorporating stress relaxation into simulations

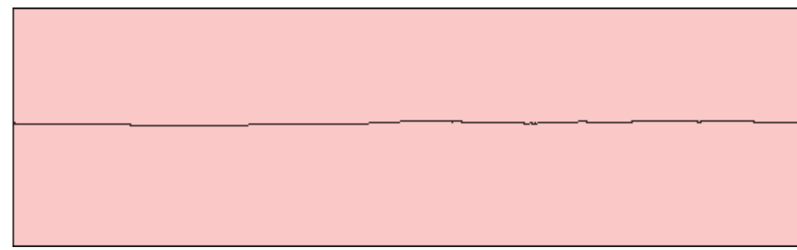
Concept for stress relaxation: Assume stresses fluctuate around a steady-state condition where the long-term growth of interaction stresses due to fault slip is balanced by off-fault yielding due to slip on minor fault.

Change of stress during earthquake

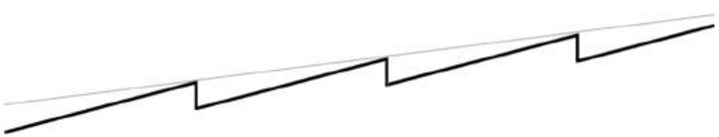


Δt

Relaxed state (+ tectonic stressing)



Elastic response



Elastic response
+
relaxation

Rate-State off-fault stress relaxation

Assume in the brittle crust that off-fault stress relaxation occurs through earthquakes. Bulk relaxation rate is proportional to earthquake rate, where

$$R = \frac{r}{\gamma \dot{S}_r}, \qquad d\gamma = \frac{1}{a\sigma}\left[dt - \gamma dS^E\right]$$

Relaxation rate of pressure and deviatoric components of the stress tensor

$$\dot{P}^R(t) = -\frac{c}{\gamma^P(t)}$$

$$d\gamma^P = \frac{1}{a\sigma}\left[dt - \gamma^P\left(\Lambda^E P^E\right)\right]$$

$$\text{where } \Lambda^E = sign\left(\dot{P}^{ss}\right)$$

$$\dot{\sigma}'^R_{ij}(t) = -\frac{C'_{ij}}{\gamma^D(t)}$$

$$d\gamma^D = \frac{1}{a\sigma}\left[dt - \gamma^D\left(\Lambda^E_{ij} : d\sigma'^E_{ij}\right)\right]$$

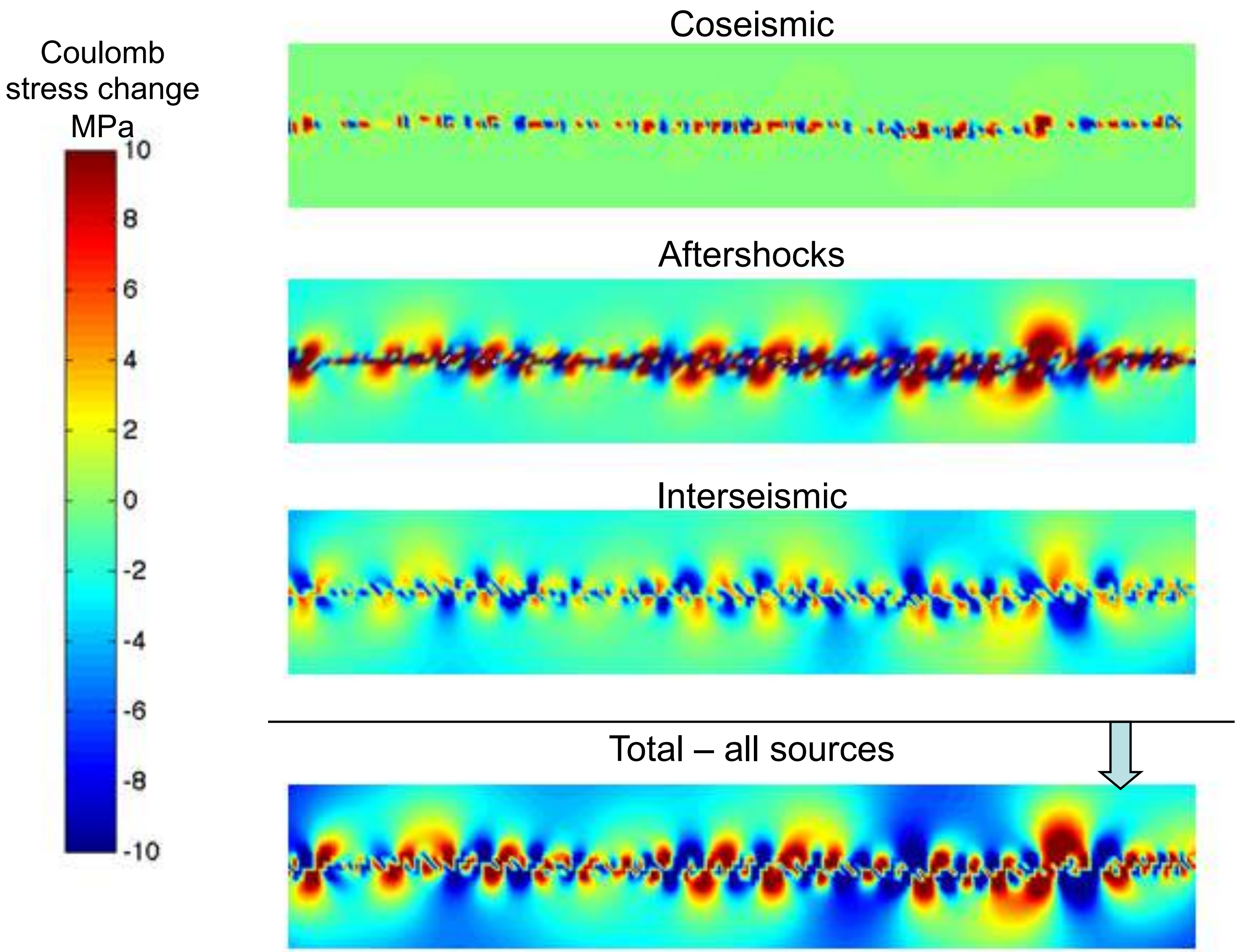
$$\text{where } \left\|\Lambda^E_{ij}\right\| = \sqrt{\Lambda^E_{ij} : \Lambda^E_{ij}} = 1.0$$

The functions Λ reflect the sign of the stress changes under steady-state slipping conditions, and act to pull the solutions toward an equilibrium stress state

Smith and Dieterich (in prep)

Off-fault stress relaxation for a full earthquake cycle

t_a=11 yr, T=150 yr



Smith and Dieterich (in prep)