# Rapid Regional-Scale Earthquake Simulators

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# Objective

Generate long, regional synthetic catalogs to address questions relating to seismic hazard, predictability, and interaction in models with physically realistic constitutive properties

- Catalog length: 10,000s of years, 100,000s of events
- Earthquake size: M4 - M8+
- Fault system: faults of all orientations and slip modes, 10,000 - 100,000 $km^2$ (SCEC-CFM)
- Number of elements: 10,000s, each of area ~$km^2$
- Fast enough to run in ~days of CPU time on a standard workstation

# Applications and approach

Applications

- Better understand physics of system-level processes that control earthquake occurrence
- Platform for integrating of geologic, geodetic, seismological observations
- Possible use in probabilistic evaluation of earthquake occurrence

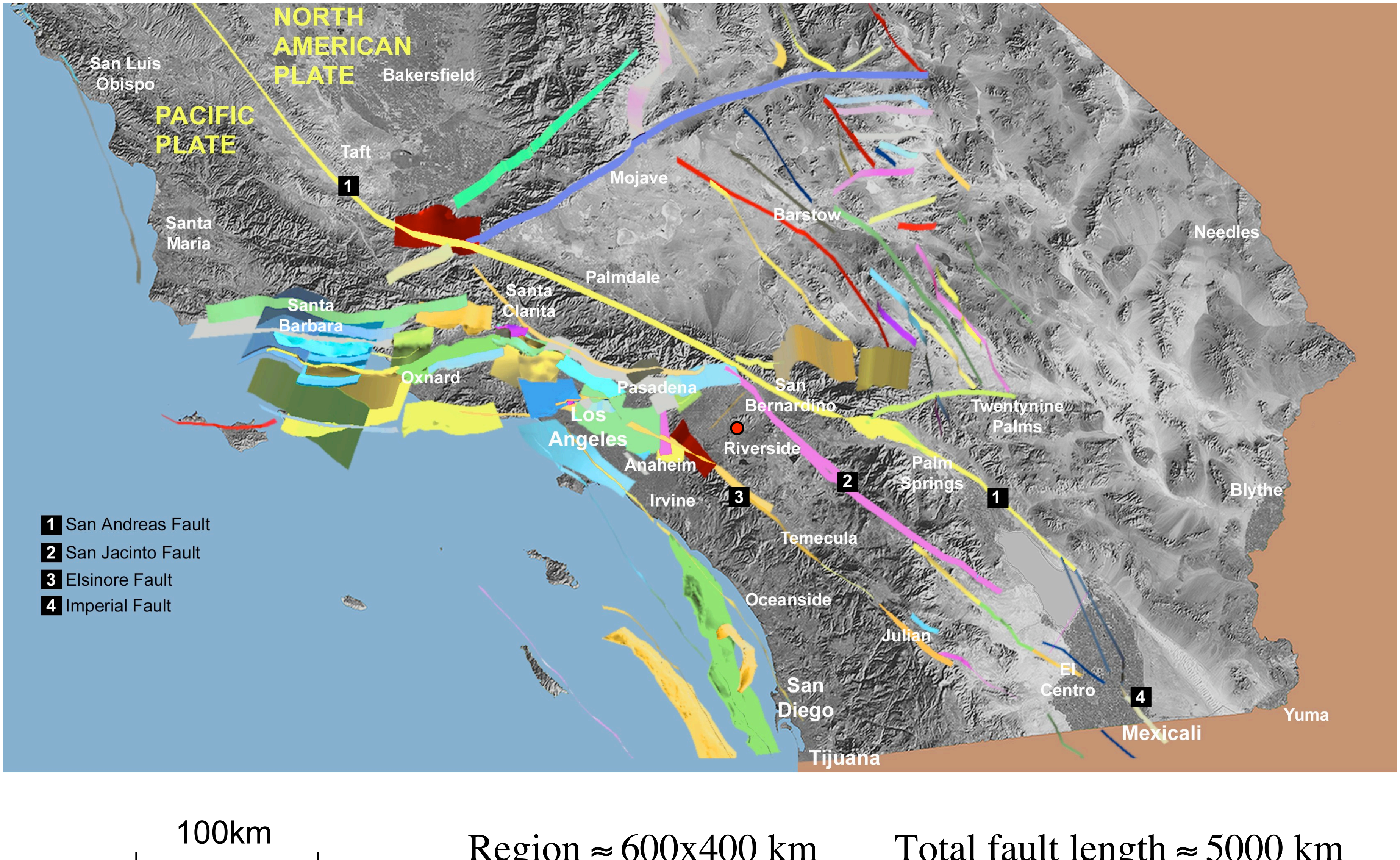
Approach

- Develop appropriate simplifications and approximations to permit accurate and rapid physics-based simulations of large numbers of earthquakes ($10^5$-$10^6$).
- Complex system - wide range of length scales
  - Fault system geometry
  - M3.5 - M8 (Catalog comparisons)
- Off-fault deformation, stress relaxation and seismicity
- Validate and refine simulators based on comparisons with fully dynamic rupture simulations. *From some initial stress state, how well do simulators predict the extent of rupture and spatial variation of earthquake fault slip* (*stress state after the event*)*?*

# Overview

- Boundary elements – 30,000 fault elements
  - Detailed representation of fault network geometry
  - Simulations M3.5-8 for southern California
- 3D stress interactions
- Strike-slip, dip-slip, and mixed mode fault slip
- Basic elements of rate-state friction (healing, nucleation)
  - Time-dependent nucleation
  - Full representation of normal stress history effects
- Inputs
  - Fault slip rate (currently loading by back-slip)
  - Rate-state friction parameters: $\mu_0$, *A, B, D$_c$*
  - Elastic modulii
  - EQ slip speed (shear wave speed $\beta$), factor for reduction of *A* during rupture, dynamic overshoot factor
  - Initial stress conditions on each element

# Southern California Earthquake Center (SCEC) Community Fault Model




Region ≈ 600x400 km    Total fault length ≈ 5000 km

# Some details

- Computations are based on changes of fault sliding state with full representation of normal stress interactions
  - 0 – Locked fault: aging by log time of stationary contact
  - 1 – Nucleating slip: analytic solutions with rate-state friction
  - 2 – Earthquake slip: quasi-dynamic use shear impedance to set slip speed
- Very fast computation
  - Event driven steps. Between steps, stressing rates are constant
  - Employ analytic solutions for nucleation
  - During earthquake slip, the initiation or termination of slip at an element requires one multiply and one divide operation to update stressing rate conditions at every element. Computation time for an event of fixed size embedded in a fault system with N elements scales as $\sim N^{1.1}$
  - Model with 30,000 fault elements, 100,000 earthquakes requires less than 24 hours on single 2.5 GHz, G5 processor

## Governing equations:

- Constitutive relation: $\tau_i = \sigma_i \left( \mu_0' + A \ln \dot{\delta}_i + B \ln \theta_i \right)$

- State evolution: $\dot{\theta}_i = 1 - \frac{\dot{\delta}_i \theta_i}{D_c} - \frac{\alpha \theta_i}{B \sigma_i} \dot{\sigma}_i$

- Stress evolution: $\dot{\tau}_i = \dot{\tau}_i^{\text{tect}} + K_{ij}^{\tau} \dot{\delta}_j \quad \dot{\sigma}_i = \dot{\sigma}_i^{\text{tect}} + K_{ij}^{\sigma} \dot{\delta}_j$

- Terms in red are additional ones due to normal stress variations (Linker and Dieterich, 1992)
- Interaction coefficients, *K*, calculated from the dislocation solutions of Okada, 1992
- Tectonic stressing rates derived from backslipping the model
- Numerical integration too slow for the scale of problems we would like to address

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- State evolution: $\dot{\theta}_i = 1 - \dfrac{\dot{\delta}_i \theta_i}{D_c} - \dfrac{\alpha \theta_i}{B \sigma_i} \dot{\sigma}_i$
- Stress evolution: $\dot{\tau}_i = \dot{\tau}_i^{\text{tect}} + K_{ij}^{\tau} \dot{\delta}_j \quad \dot{\sigma}_i = \dot{\sigma}_i^{\text{tect}} + K_{ij}^{\sigma} \dot{\delta}_j$

State 0: locked fault

$$\dot{\theta} \approx 1 - \frac{\alpha \theta}{B \sigma} \dot{\sigma}$$

$$\dot{\delta} = \frac{D_c}{\theta}$$

State 1: nucleation

$$\dot{\theta} \approx -\frac{\dot{\delta} \theta}{D_c} - \frac{\alpha \theta}{B \sigma} \dot{\sigma}$$

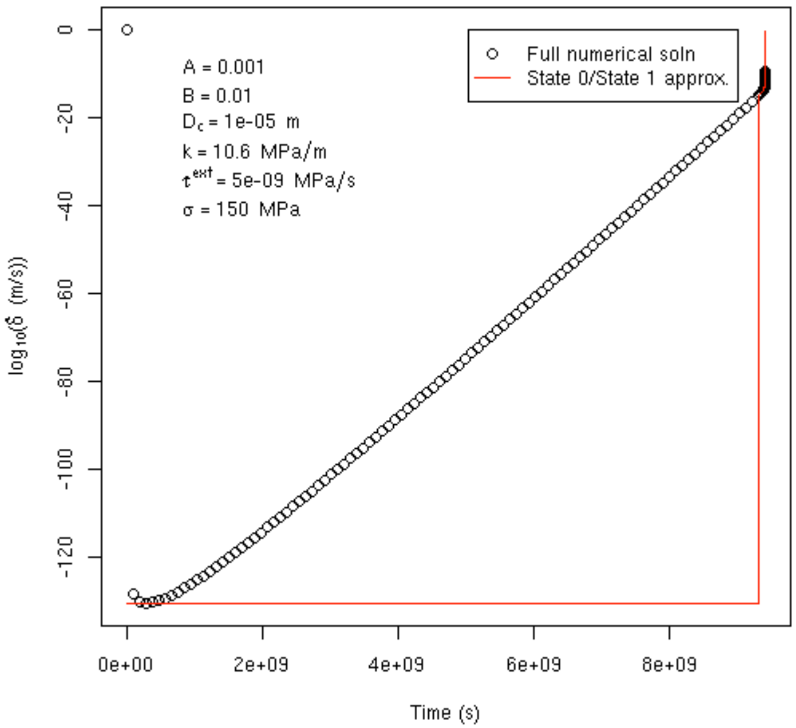
$$\dot{\delta} = \dot{\delta}^{\text{EQ}} = \frac{2 \beta \Delta \tau}{G}$$

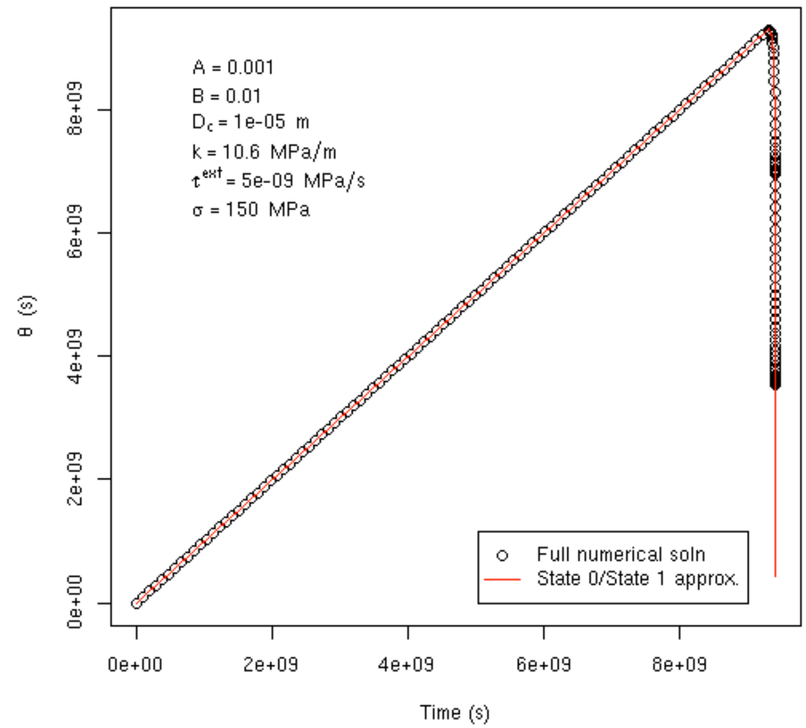
State 2: seismic slip

$$\dot{\delta} = \dot{\delta}^{\text{EQ}}$$

$$\tau = \tau^{\text{SS}}(\dot{\delta}^{\text{EQ}})$$

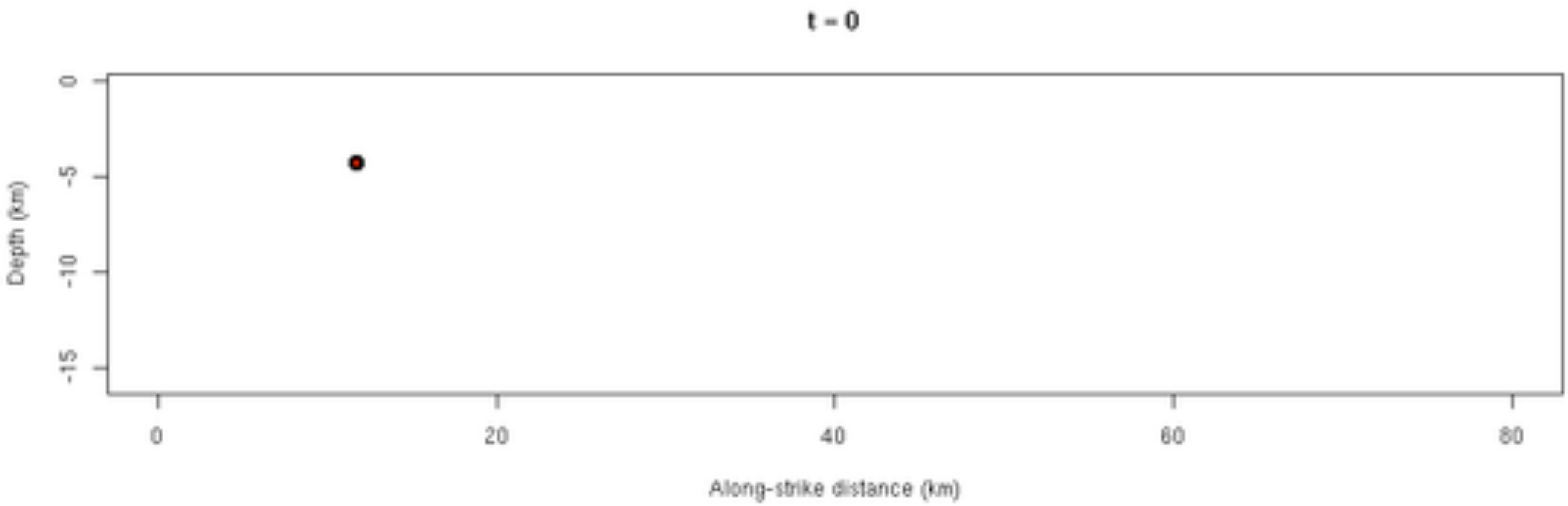
*State 0/State 1 approximations compared to full numerical integration for a single patch*



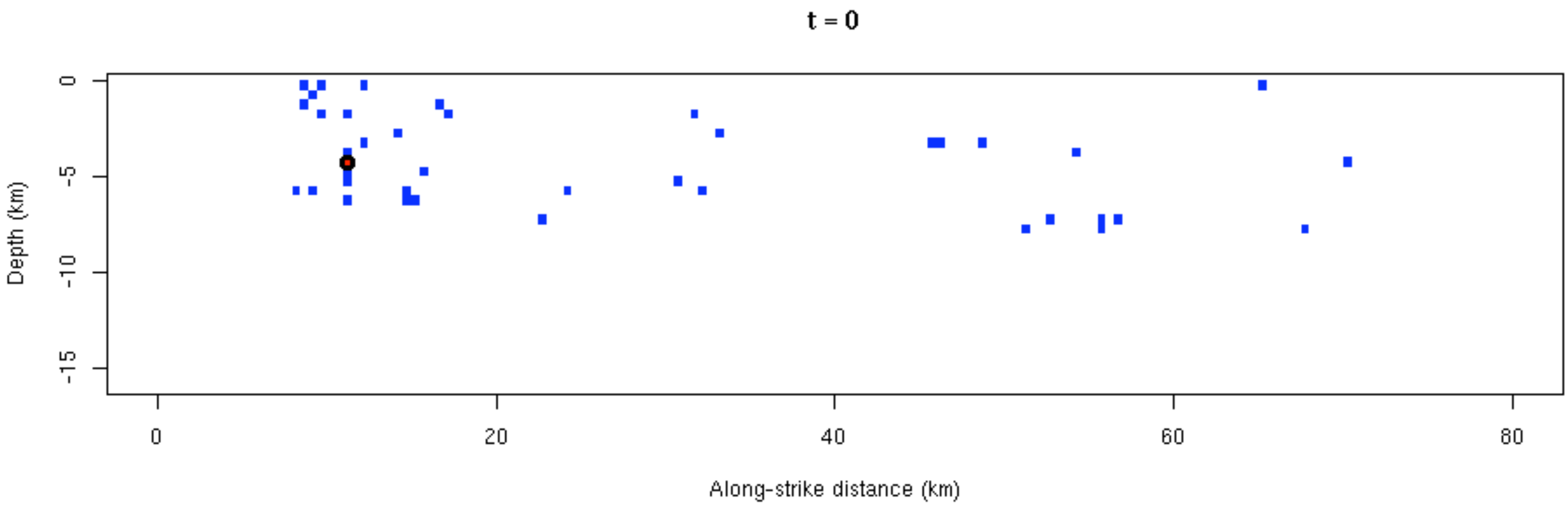



# Example Ruptures

Smooth Initial Stress (w/ block of higher normal stress)



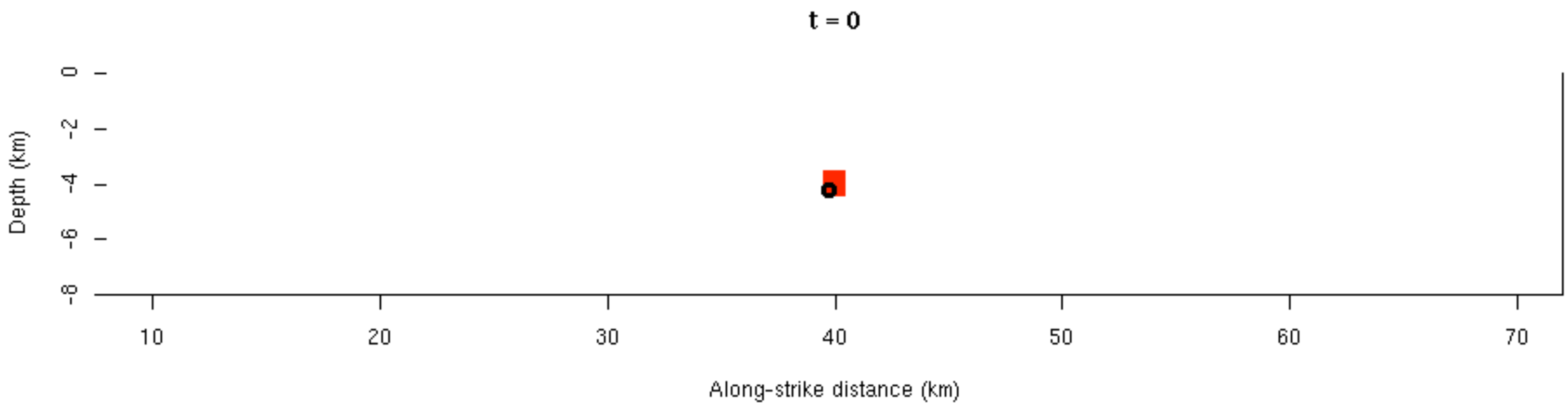
Inherited rough initial stress
(w/ block of higher normal stress)



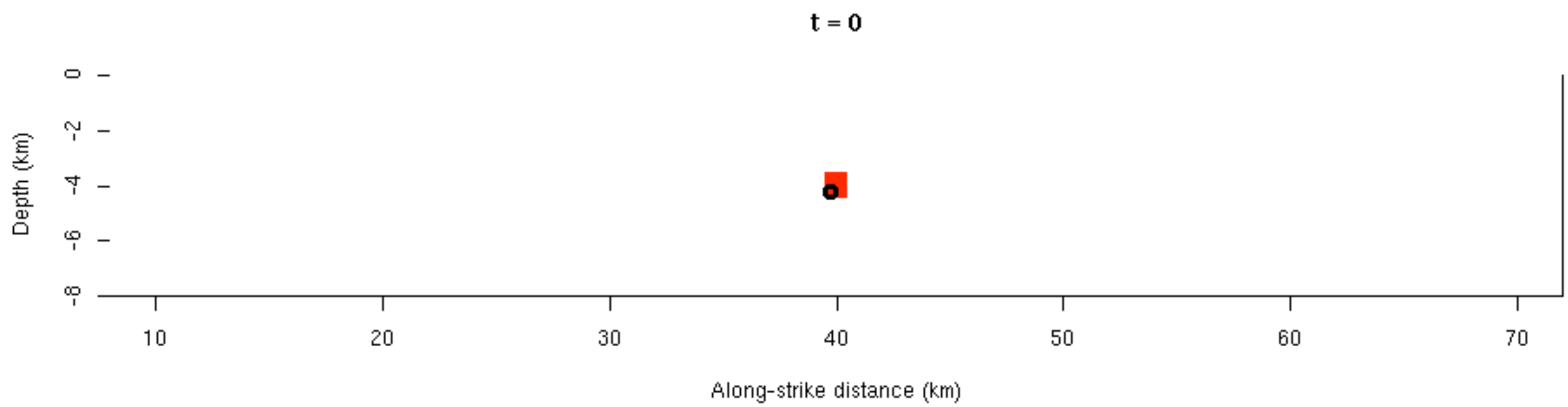
# Effect of Overshoot on Rupture Characteristics

## Bilateral Rupture

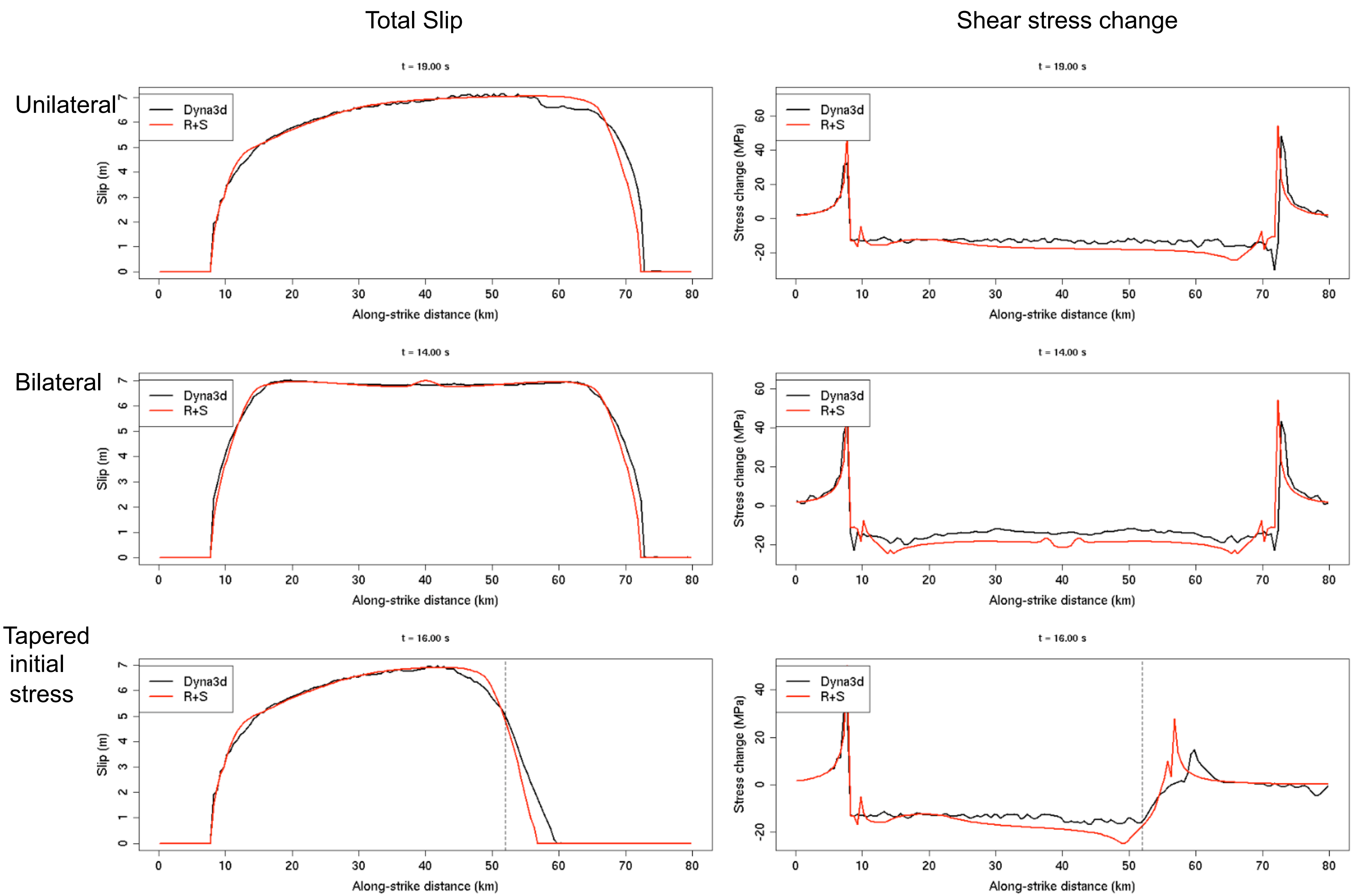
Large overshoot (13%)



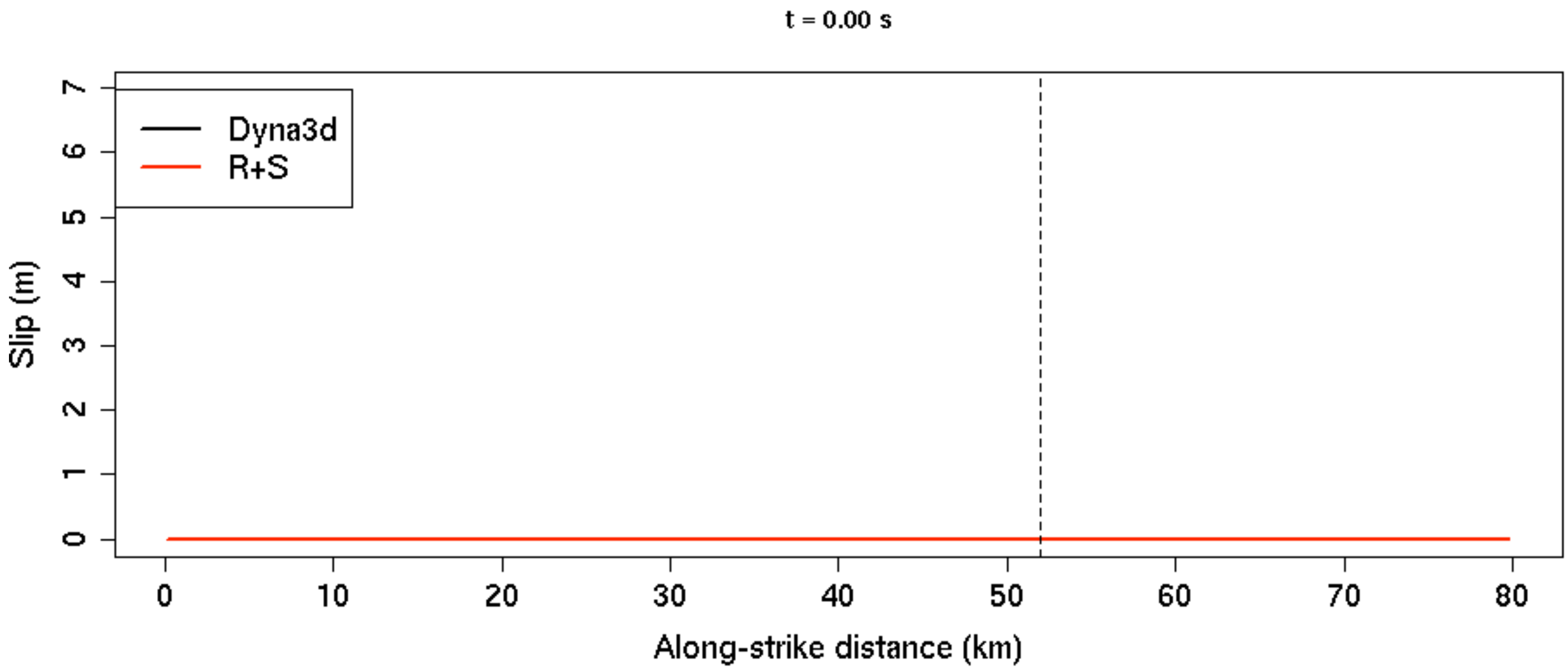

Small overshoot (1%)



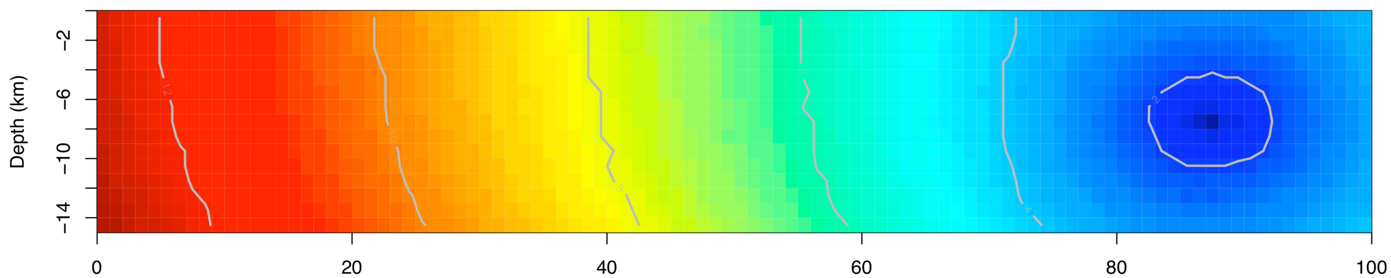
# Comparison with Fully Dynamic Rupture
# Slip-Weakening Friction



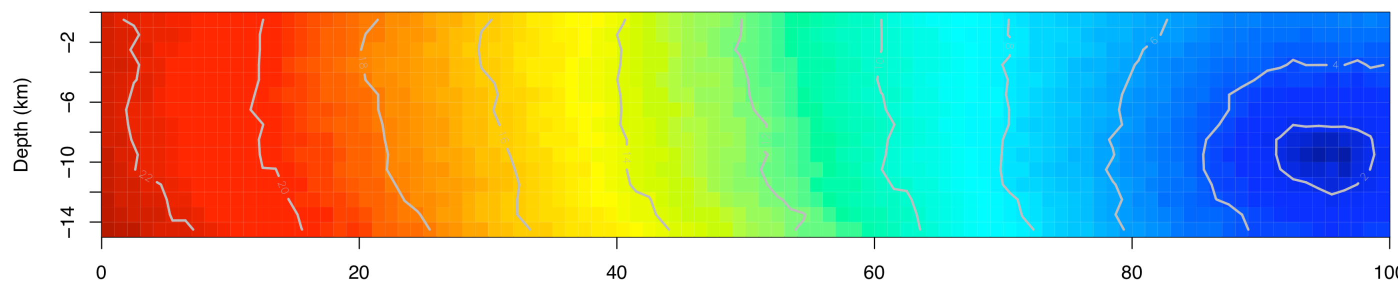
# Slip (tapered initial stress)



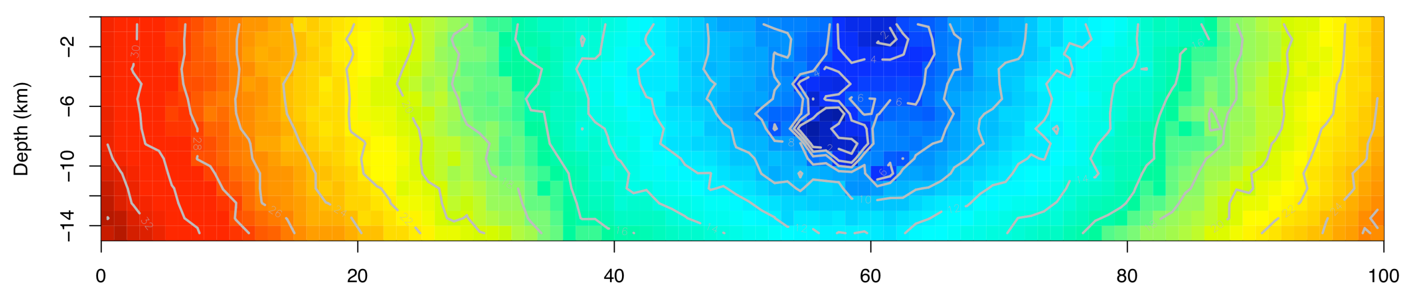
# Effect of heterogeneous stress and geometrical complexity on rupture speed




Planar fault – smooth initial stress



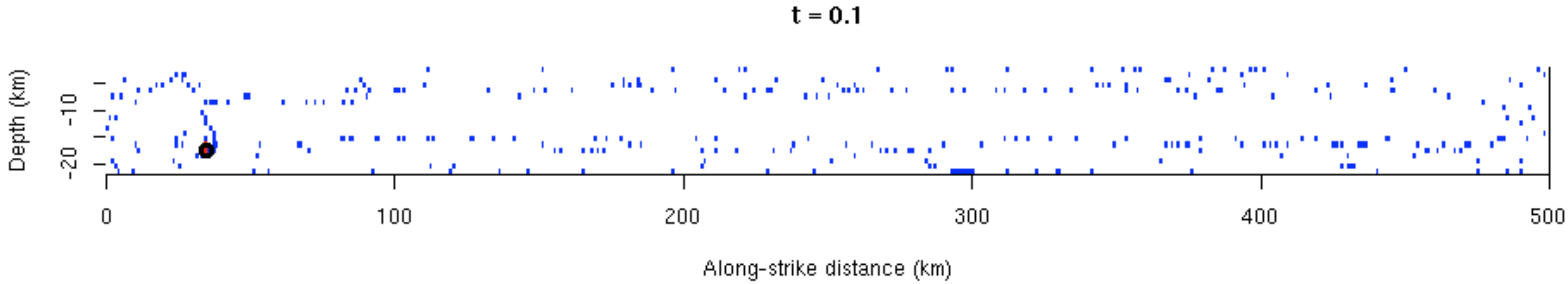

Planar fault – rough initial stress




Fractally rough fault

# M8 events on fault with 10,000 fault elements

2x vertical exaggeration




Simulation:

- 50,000 events
- M4.0-8.0
- Computation time ~ 60 minutes on Mac G5 using a single 2.2 GHz CPU

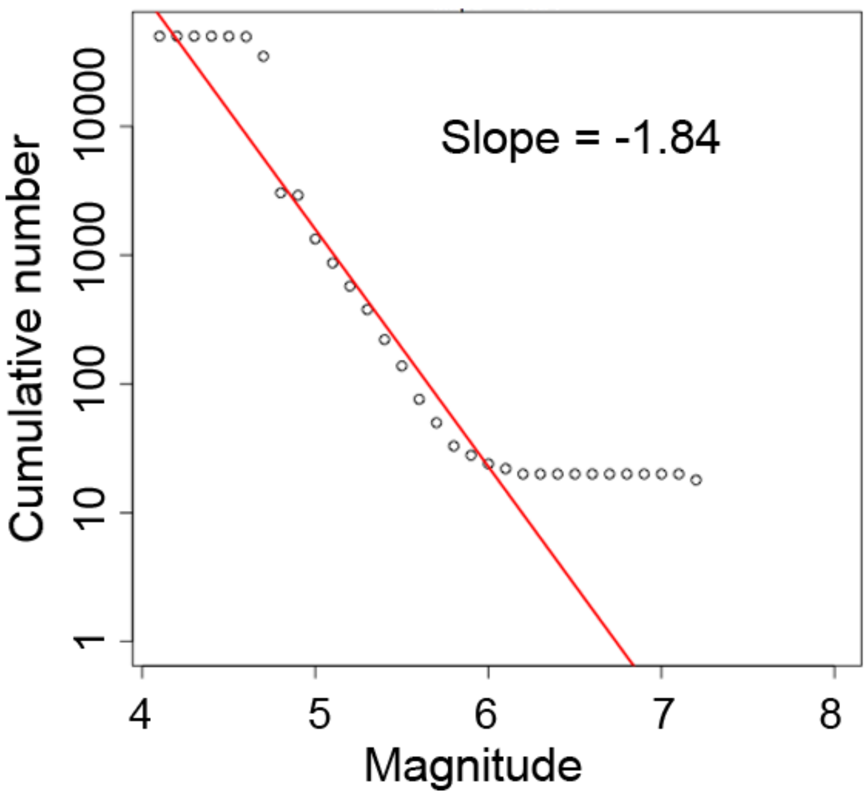
M8 events:

- Duration 215s, 204s
- Rupture speed 2.2–2.4 km/s

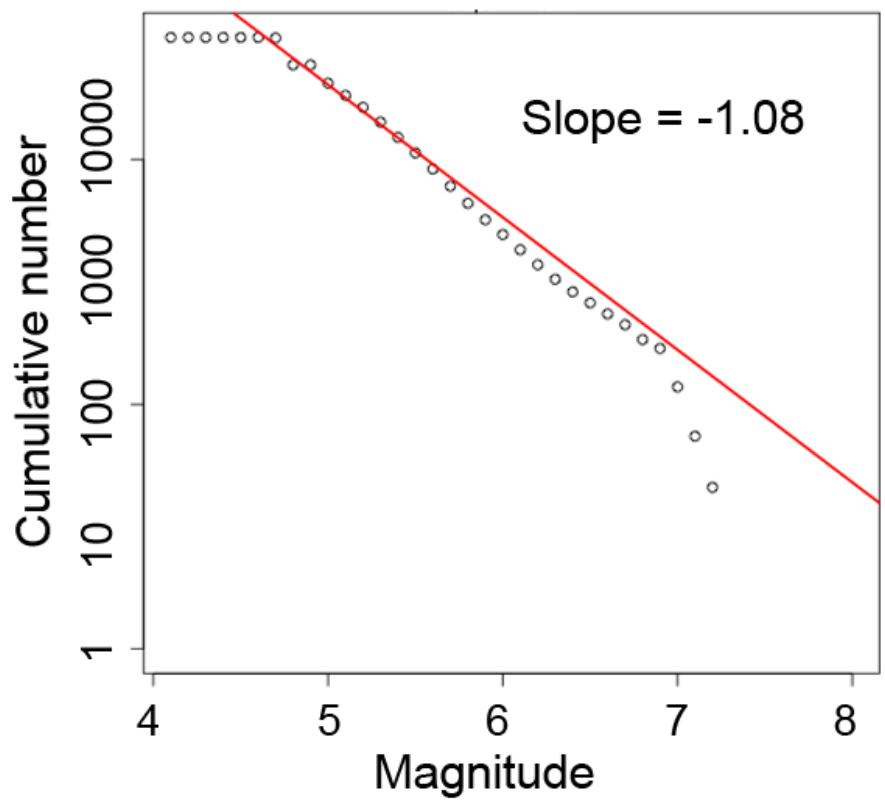
# Magnitude - Frequency

We reduce the constitutive factor *A* during rupture propagation by a multiplying factor *C*. At short rupture lengths *A* strongly inhibits rupture propagation. At long rupture lengths, the value of *A* has little effect.

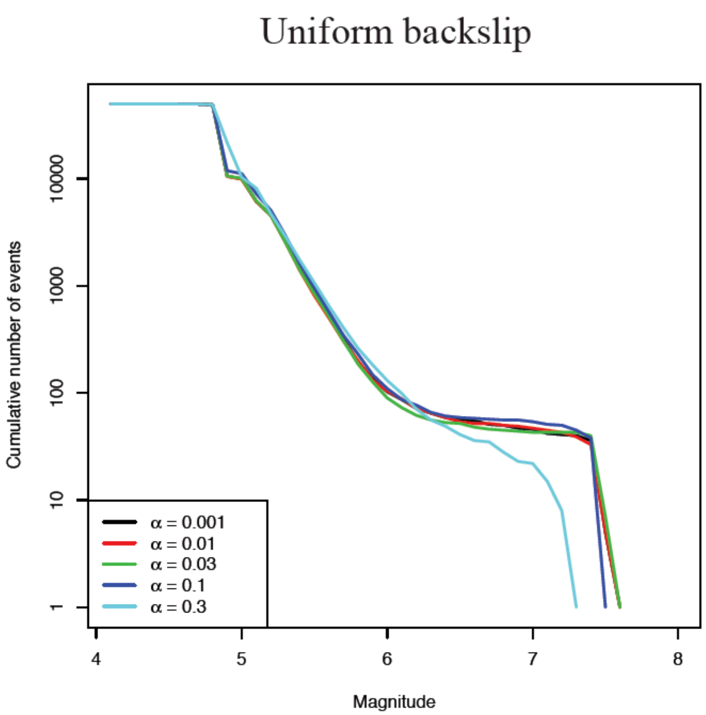
*C* = 0.1

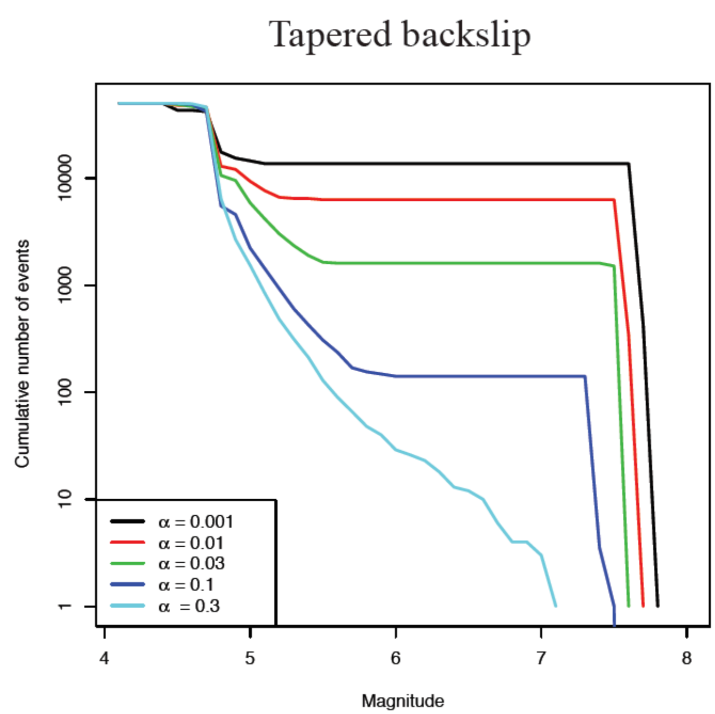


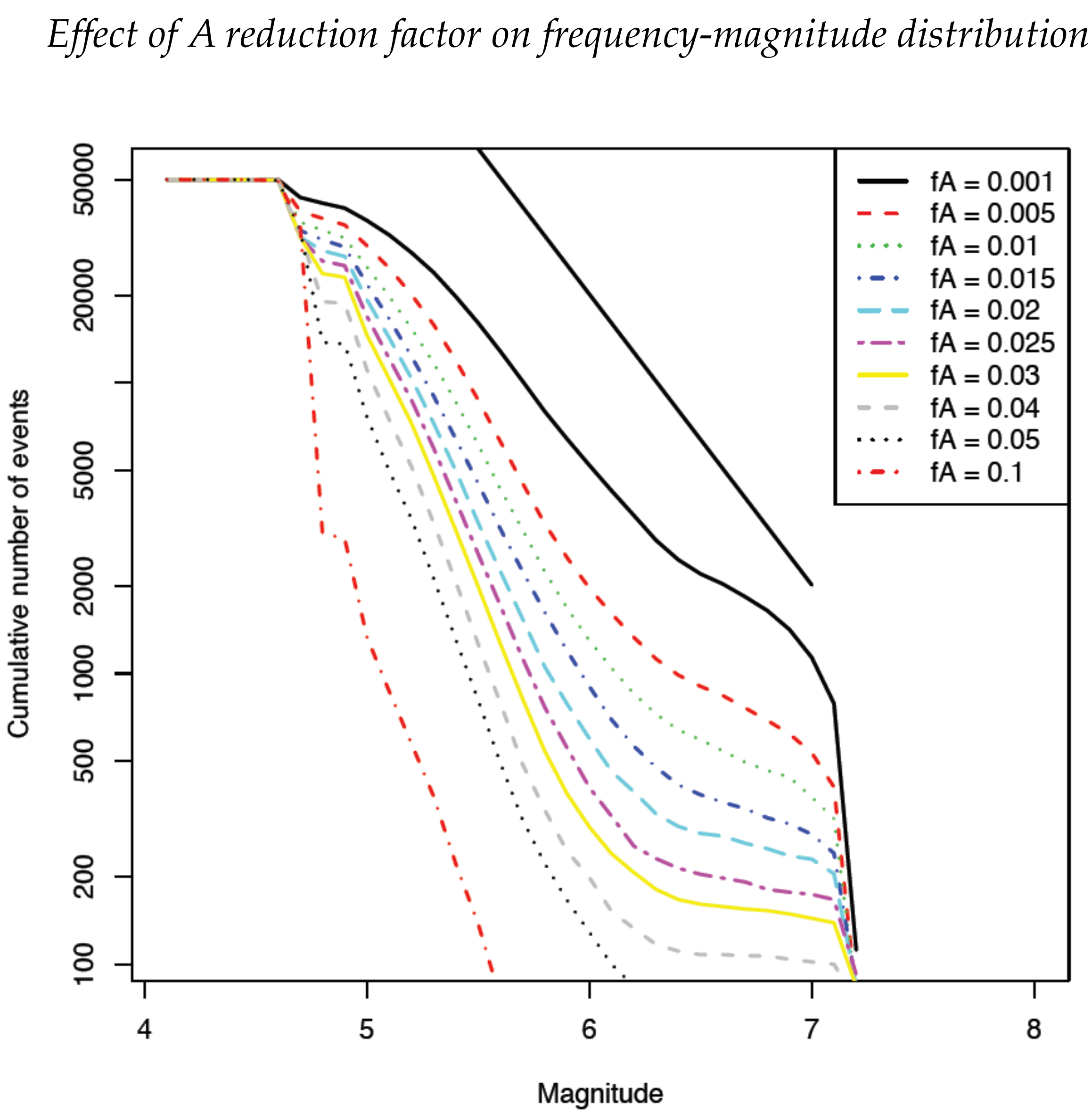

*C* = 0.005



# Effects of stressing rate and fractal roughness on frequency-magnitude distribution

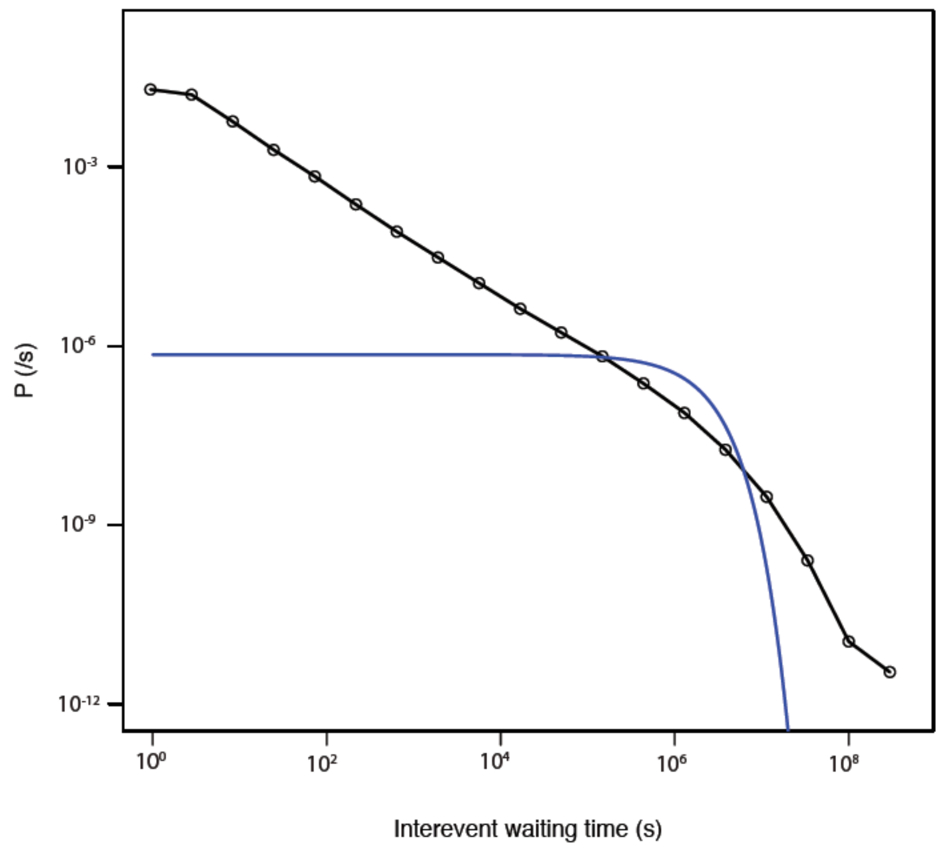




Effect of A reduction factor on frequency-magnitude distribution
Cumulative number of events
50000
20000
5000
2000
1000
500
200
100
4
5
6
7
8
Magnitude
fA = 0.001
fA = 0.005
fA = 0.01
fA = 0.015
fA = 0.02
fA = 0.025
fA = 0.03
fA = 0.04
fA = 0.05
fA = 0.1

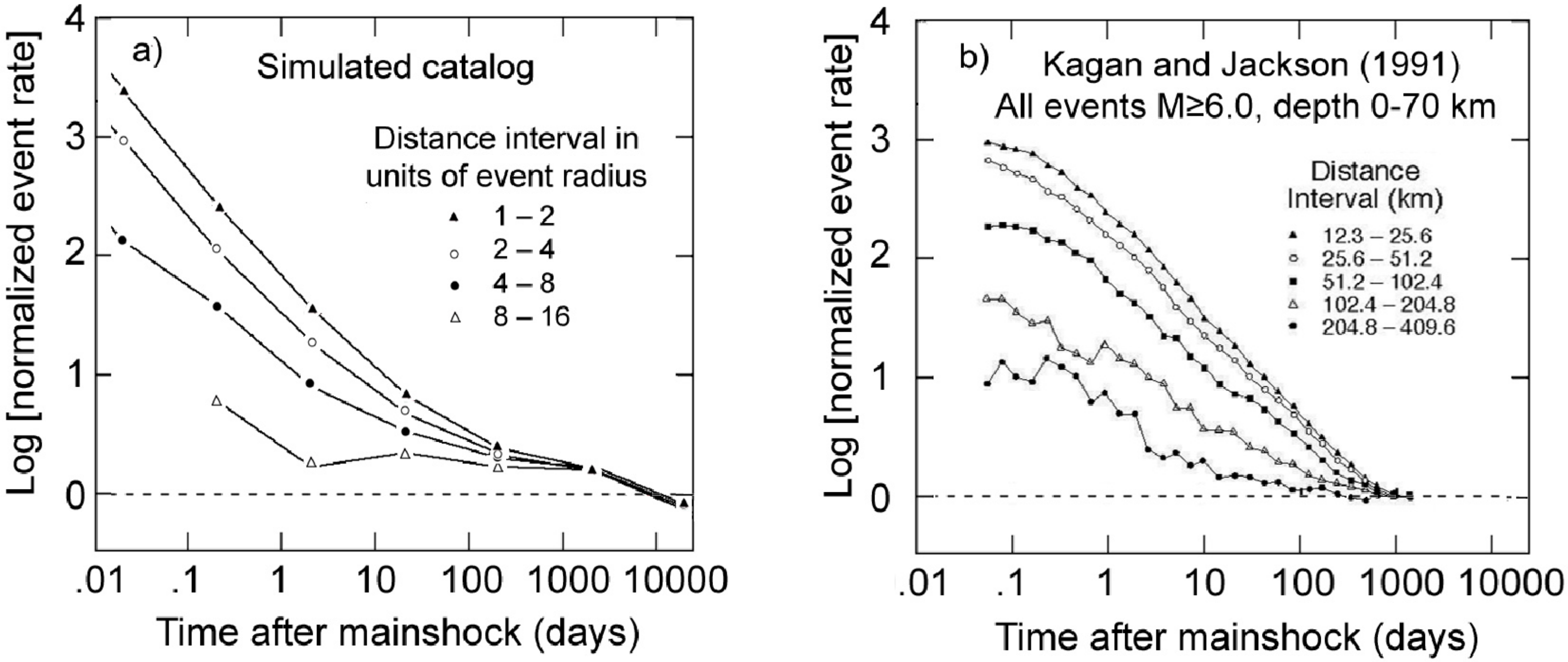
# Temporal clustering/Waiting time distribution



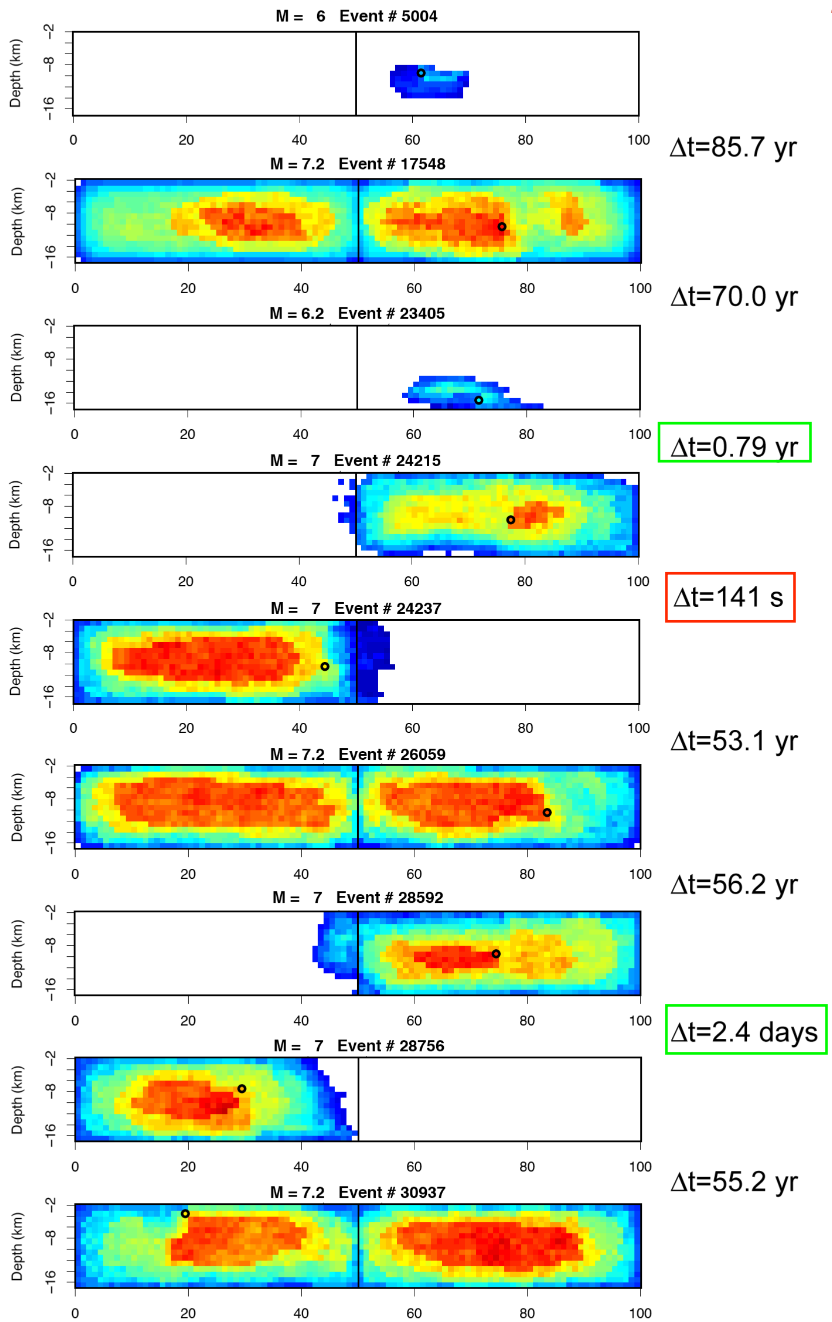

Blue line is the interevent time pdf for a Poisson process.

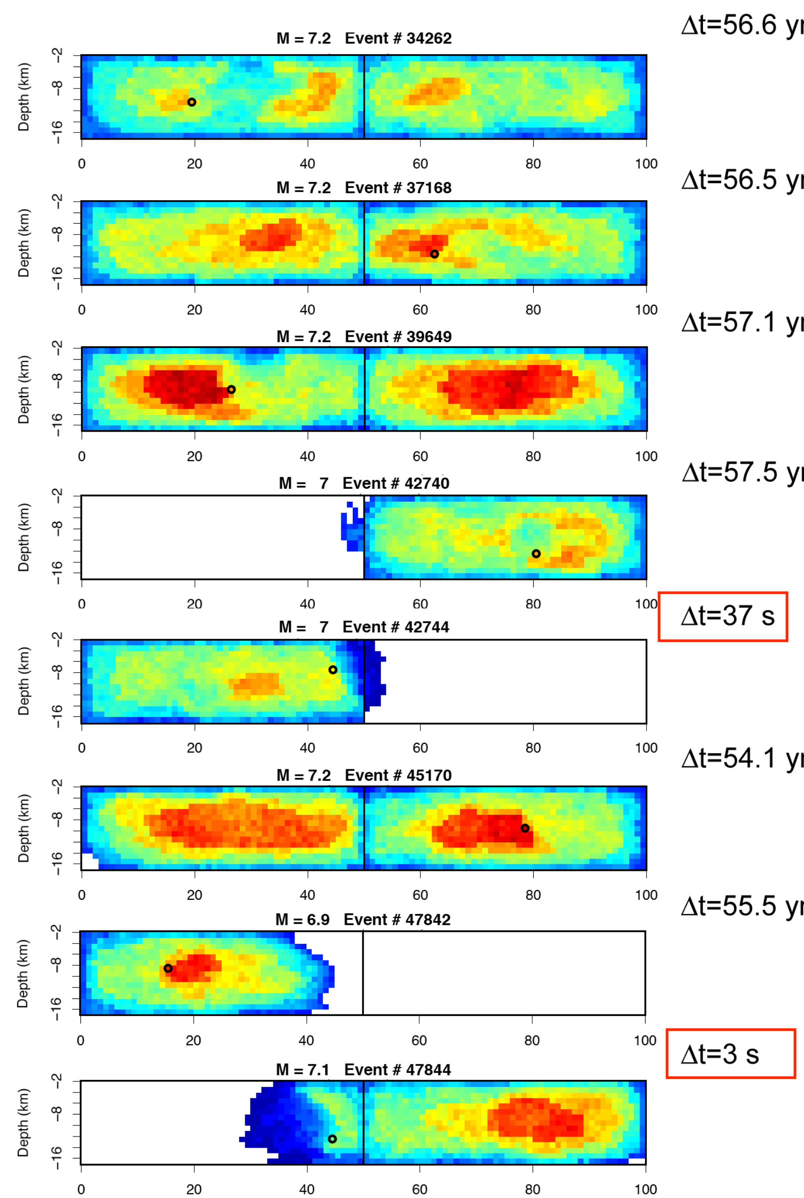
Observed power-law distribution with an exponent of -0.92 matches the interevent time distribution for real southern California seismicity (Davidsen and Goltz, 2004)

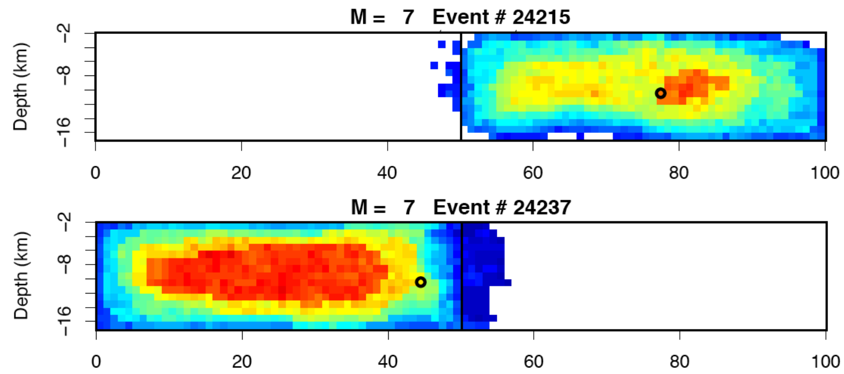
# Clustering – Earthquake Pairs by Distance and Time



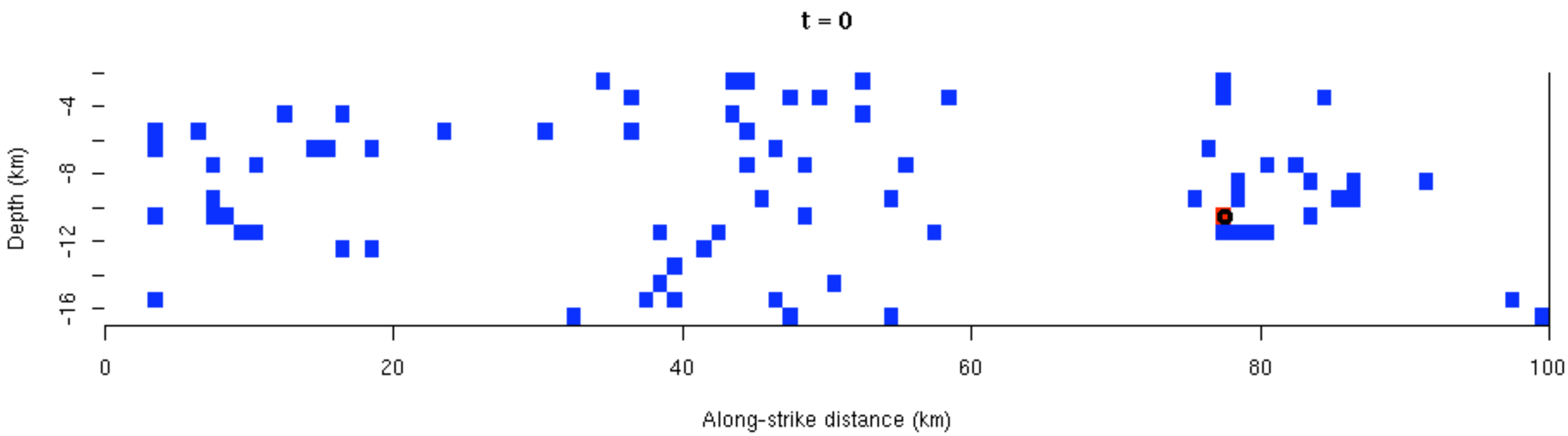
# 200 m Compressive Stepover
# All events M≥6.0



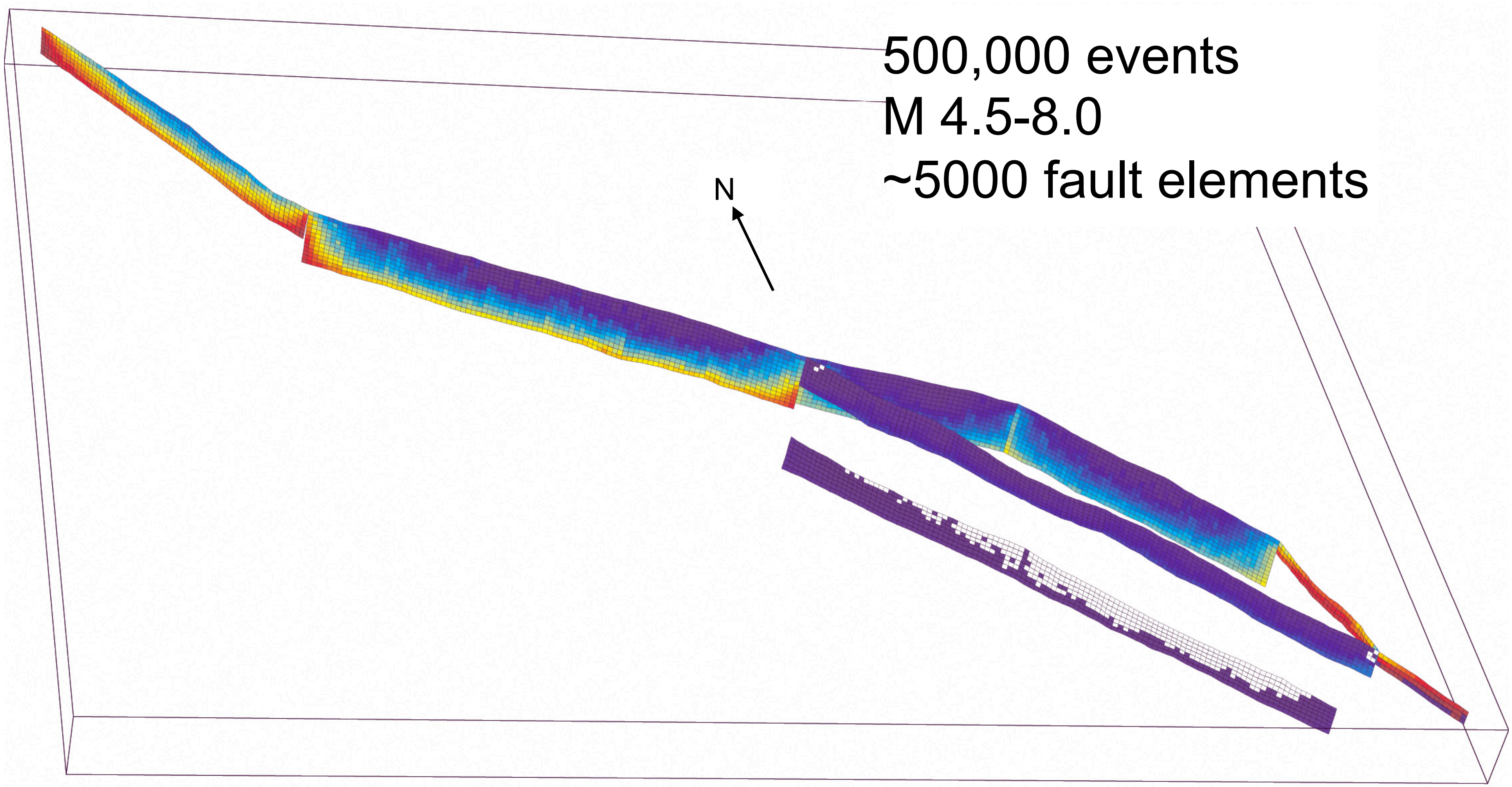






- End of first M7 event – 27.9 s
- 21 aftershocks in interval between first and second M7 events
- Start of second M7 event – 169 s



# Simplified southern San Andreas simulation




Nucleation density

# Southern San Andreas Simulation

*220 events > M 7* *137 were isolated by at least 4 years*
*34 pairs*
*5 triples*

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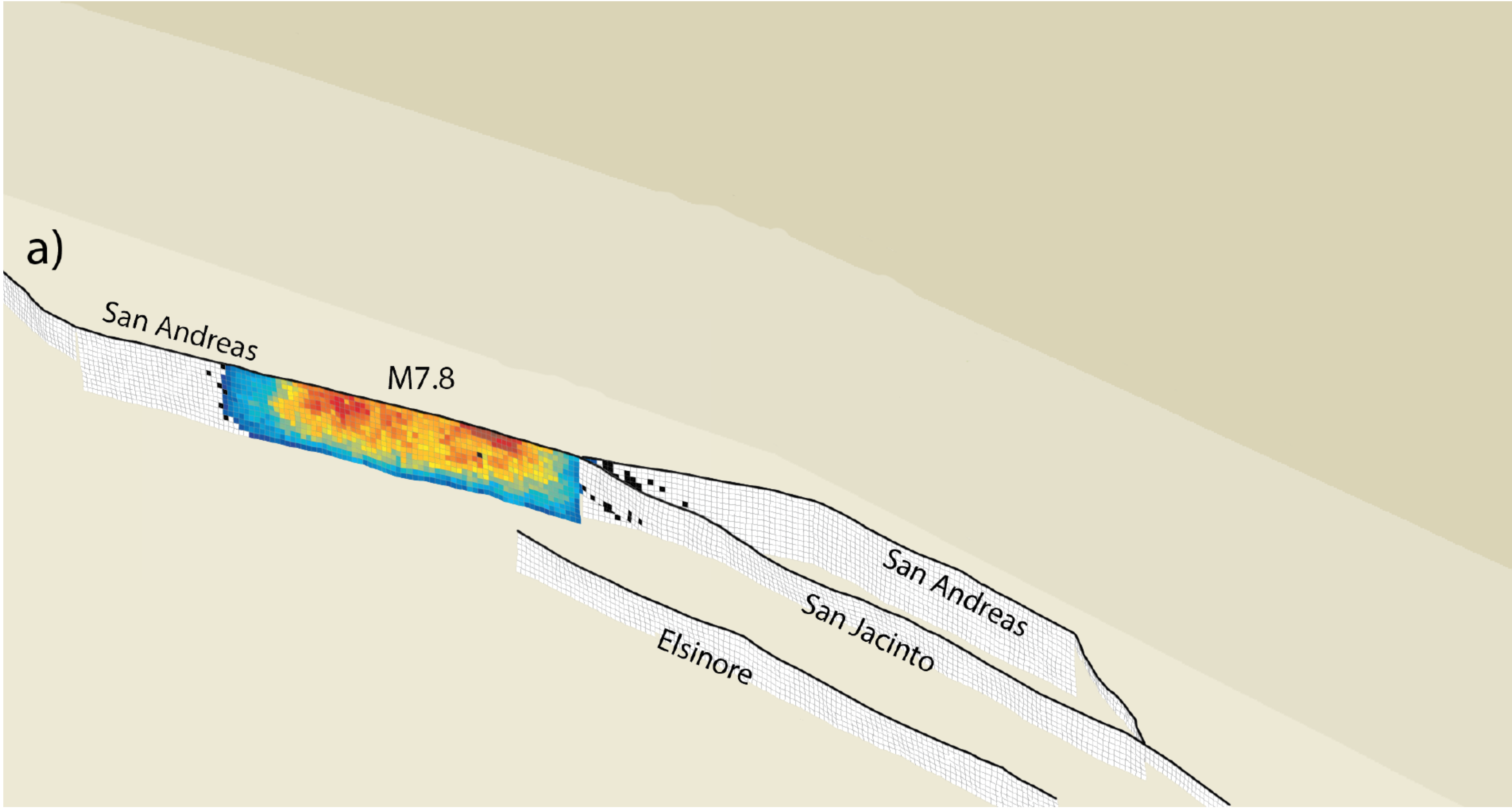


*There were 72 aftershocks in the 2-day interval between the M7.8 and M7.5 events*

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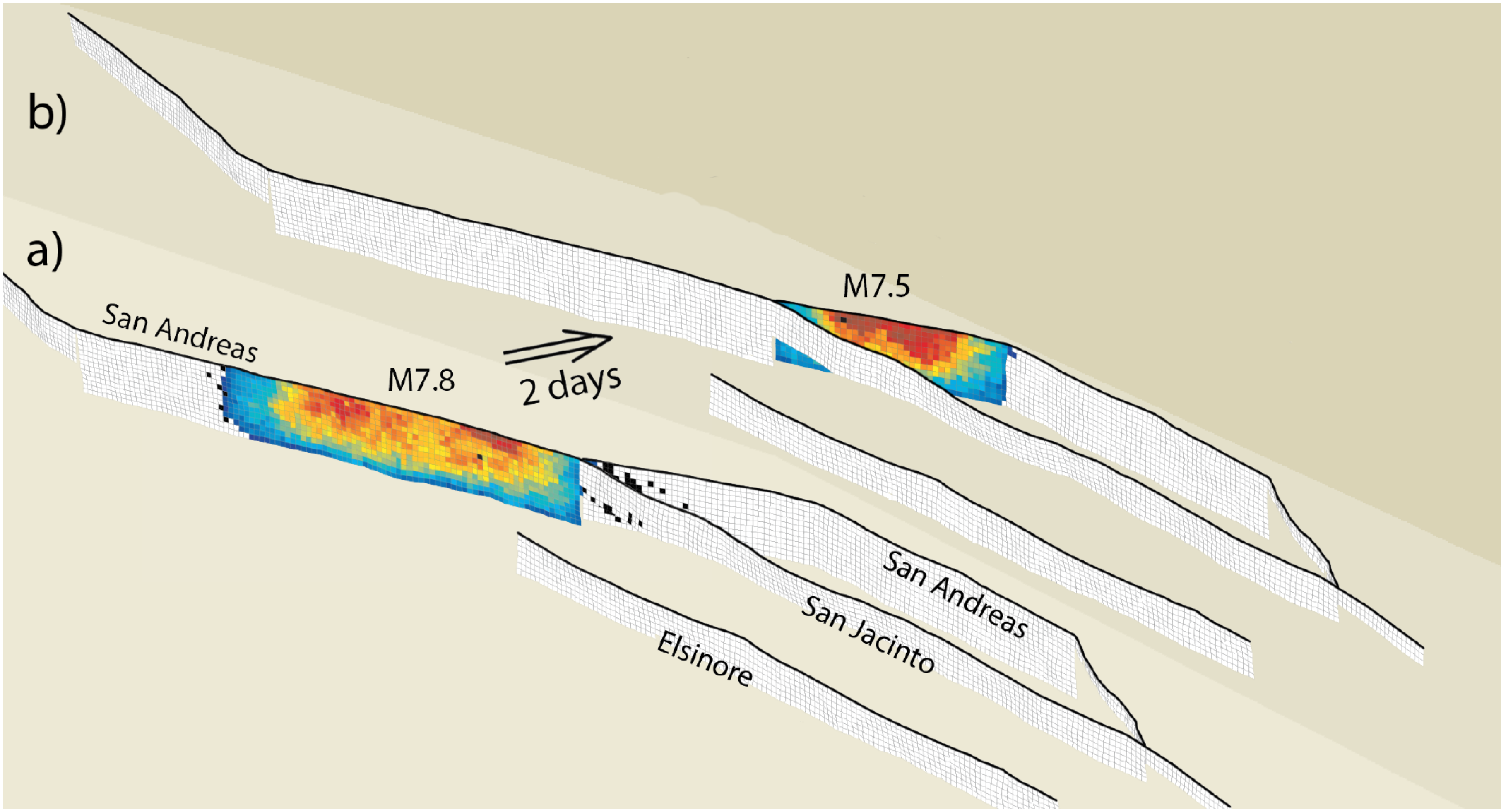


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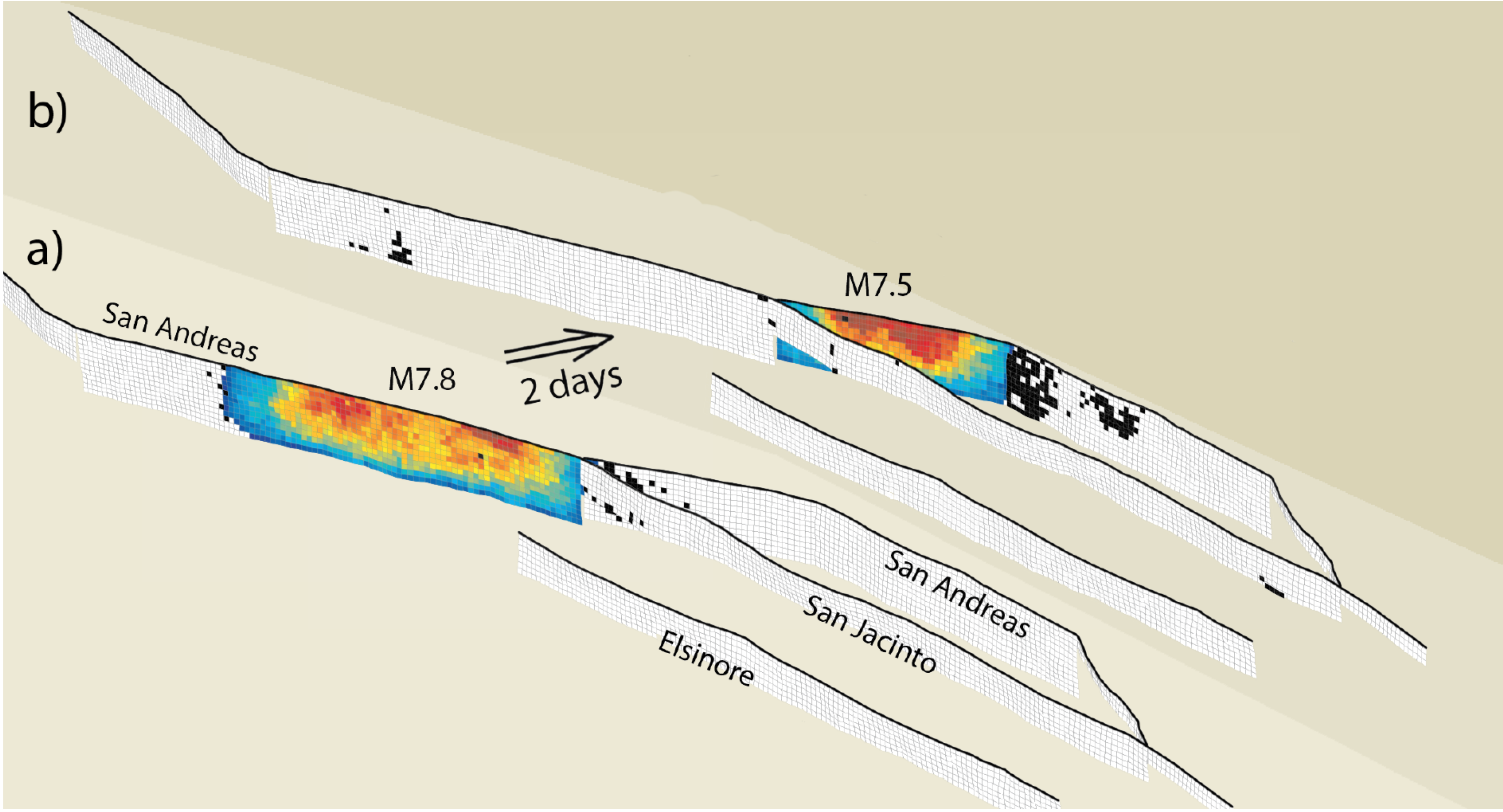


*There were 72 aftershocks in the 2-day interval between the M7.8 and M7.5 events and 183 aftershocks in the 100-day interval between the M7.5 and M7.6 events.*

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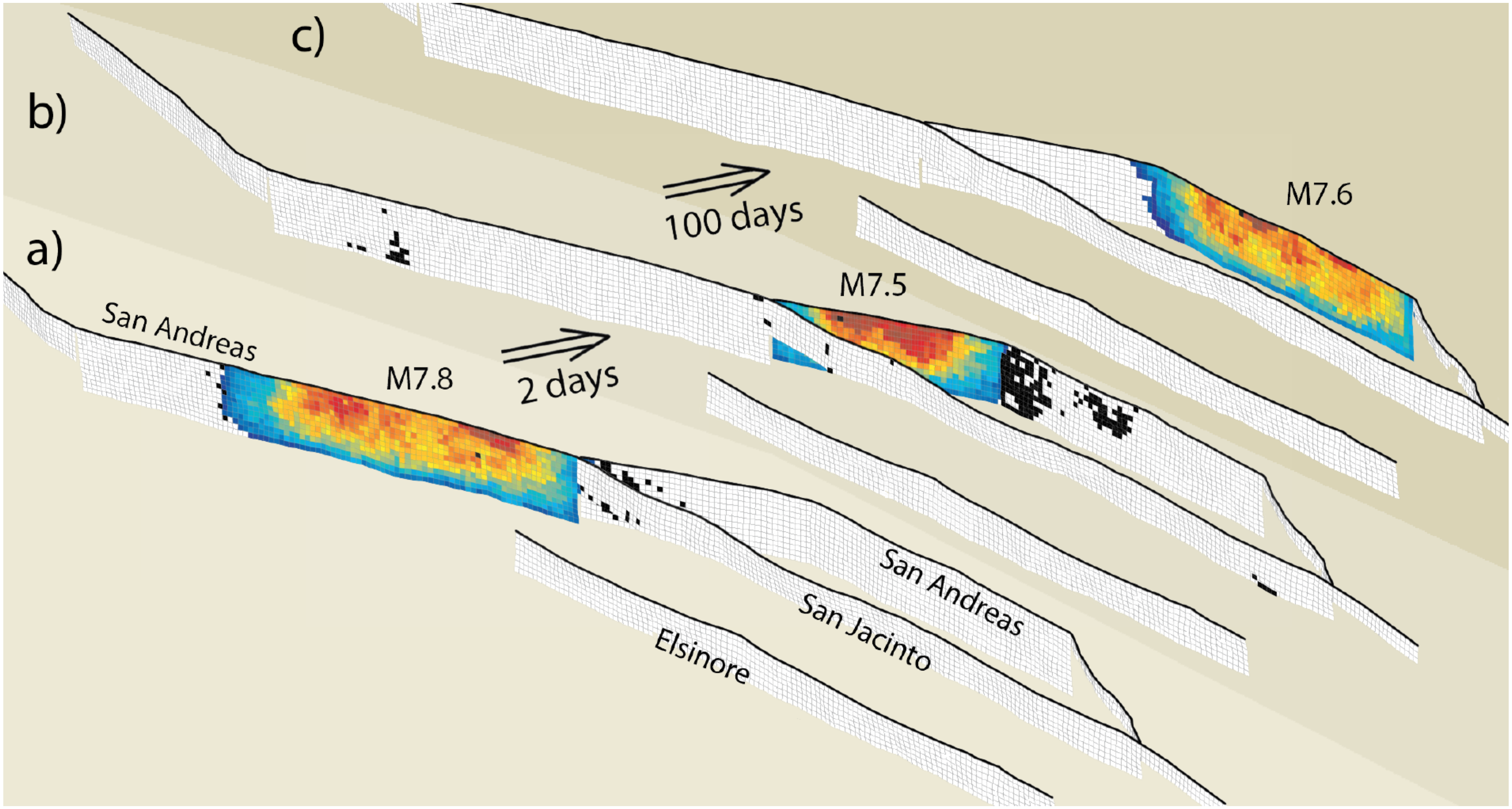


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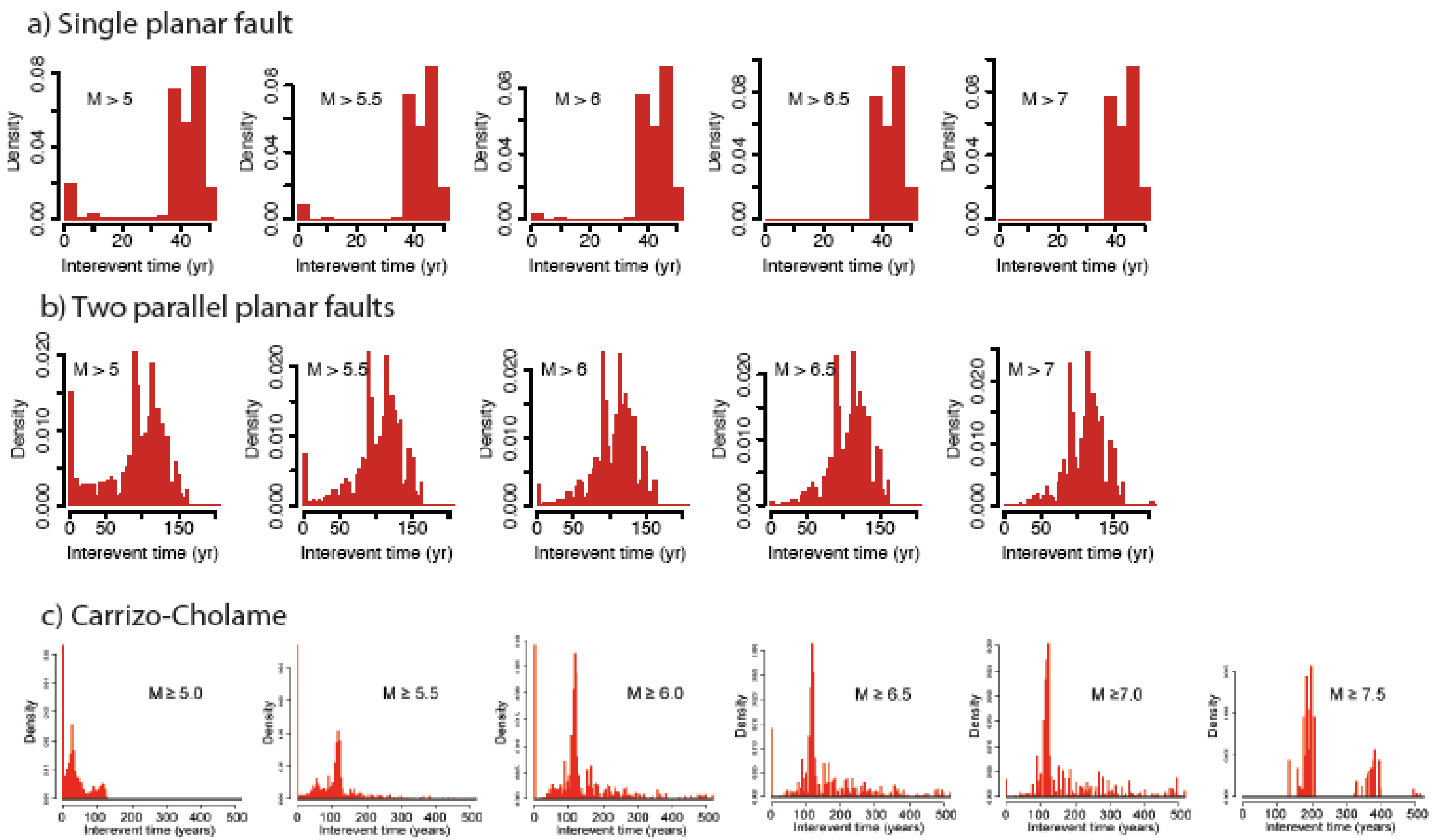
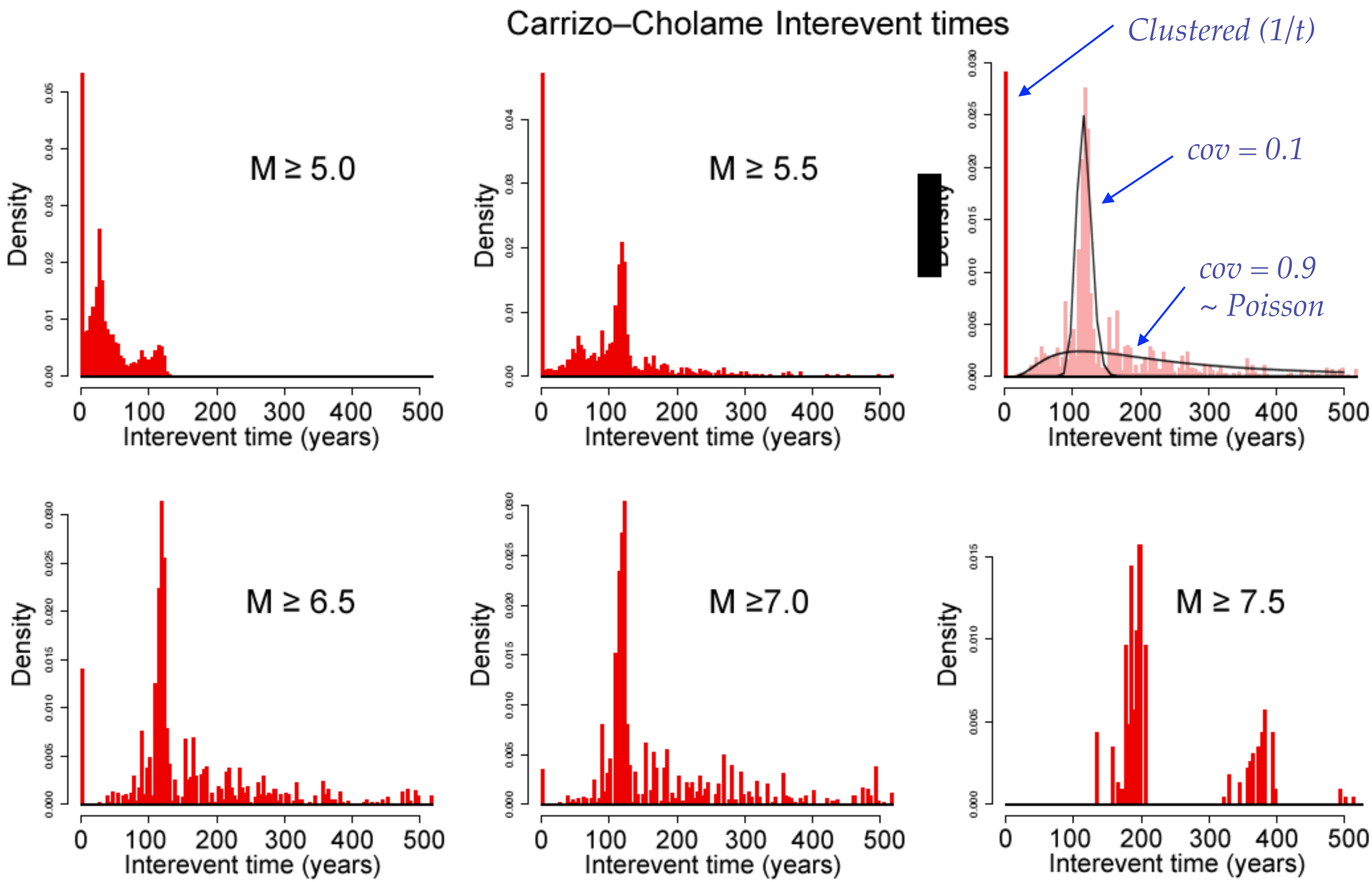
# Effect of interactions on recurrence



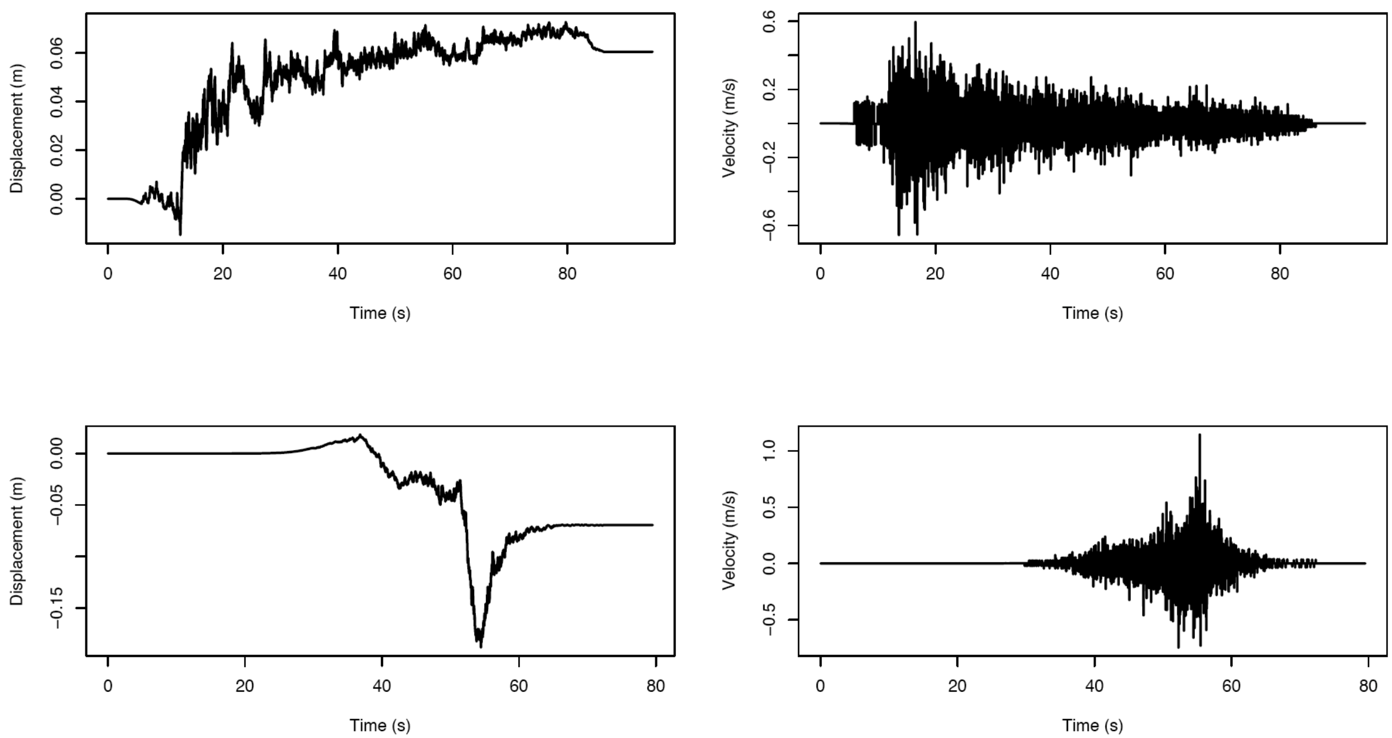
# Statistics for recurrence of earthquake slip at a specific point

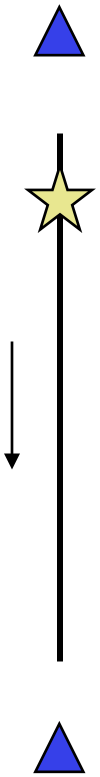


# Inclusion of dynamic stresses

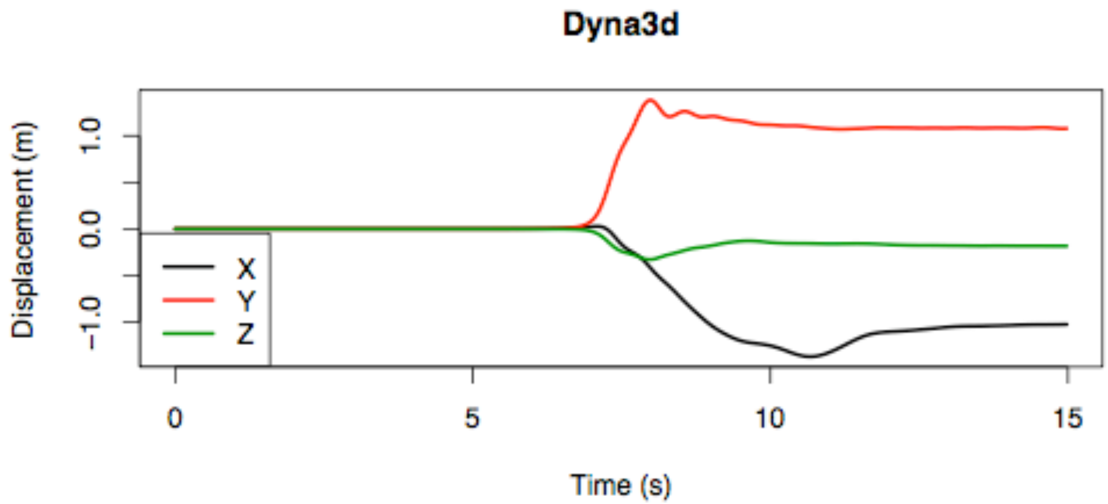
*M7.3 with heterogeneous initial stress (from long simulation)*

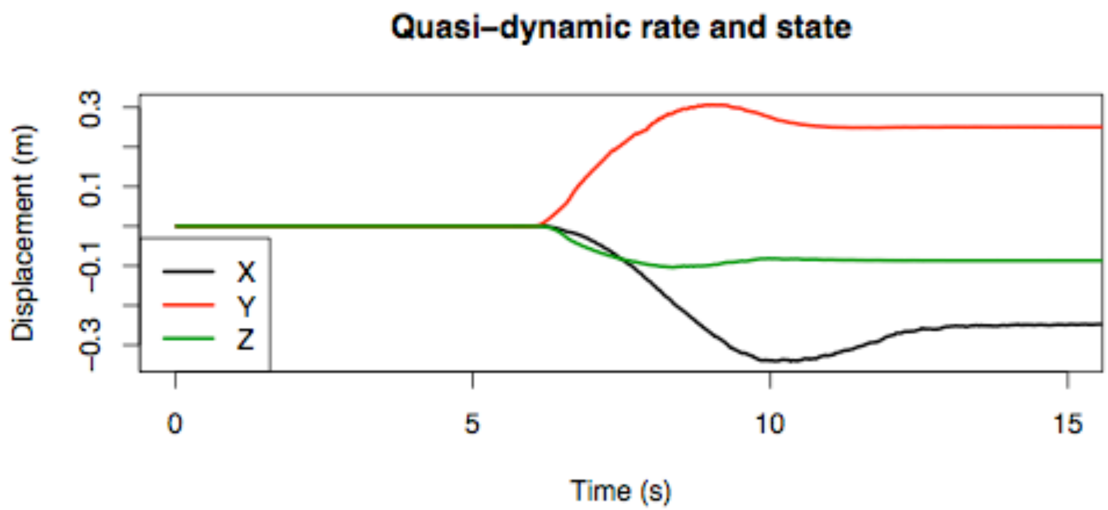
*Displacement* | *Velocity*

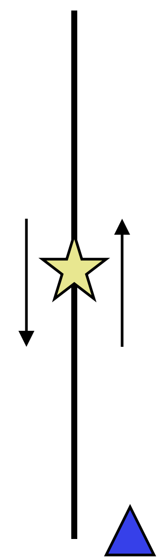


*M7.0 with homogeneous initial stress*



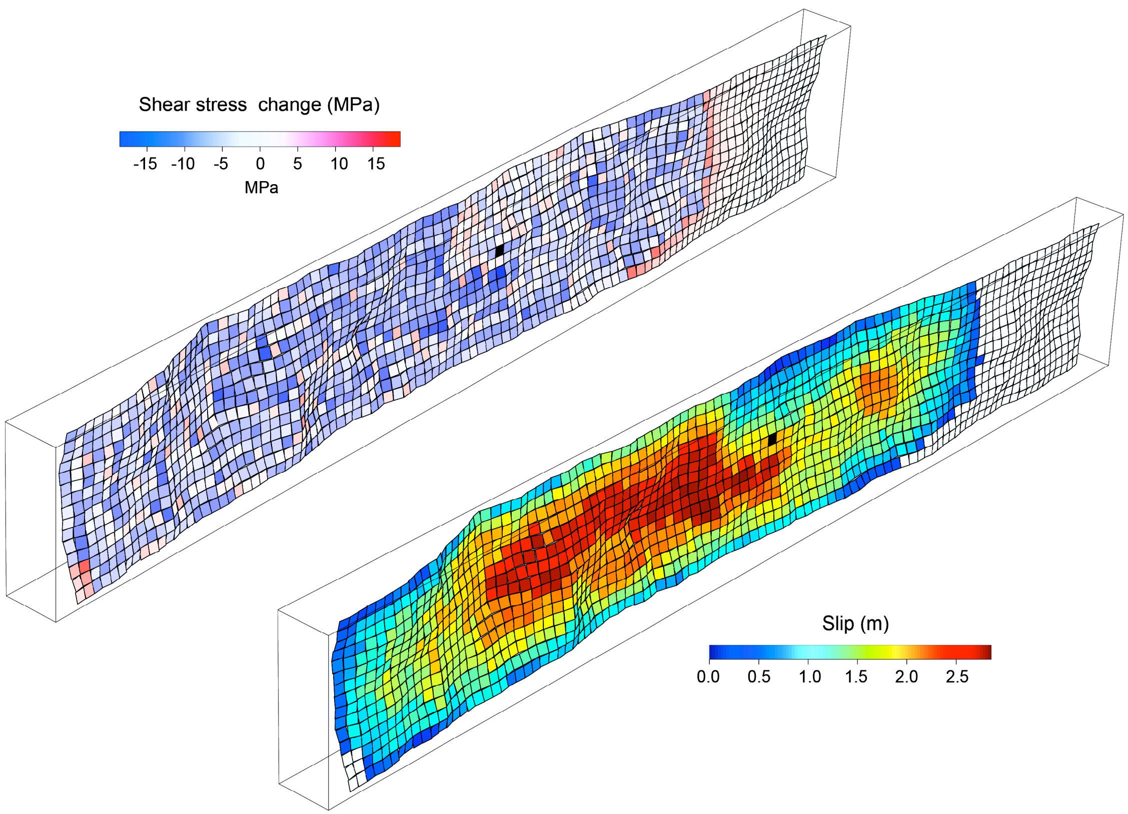
# Further improvements

- More elaborate slip velocity functions
- Delay static stresses and add dynamic stresses
- Further comparisons:
  - Heterogeneous initial stresses
  - Fault bends
  - Fault stepovers
- Add off-fault stress relaxation and distributed seismicity
- Aseismic slip, viscoelasticity, and/or poroelasticity?
- Barnes-Hut or Fast Multipole schemes?

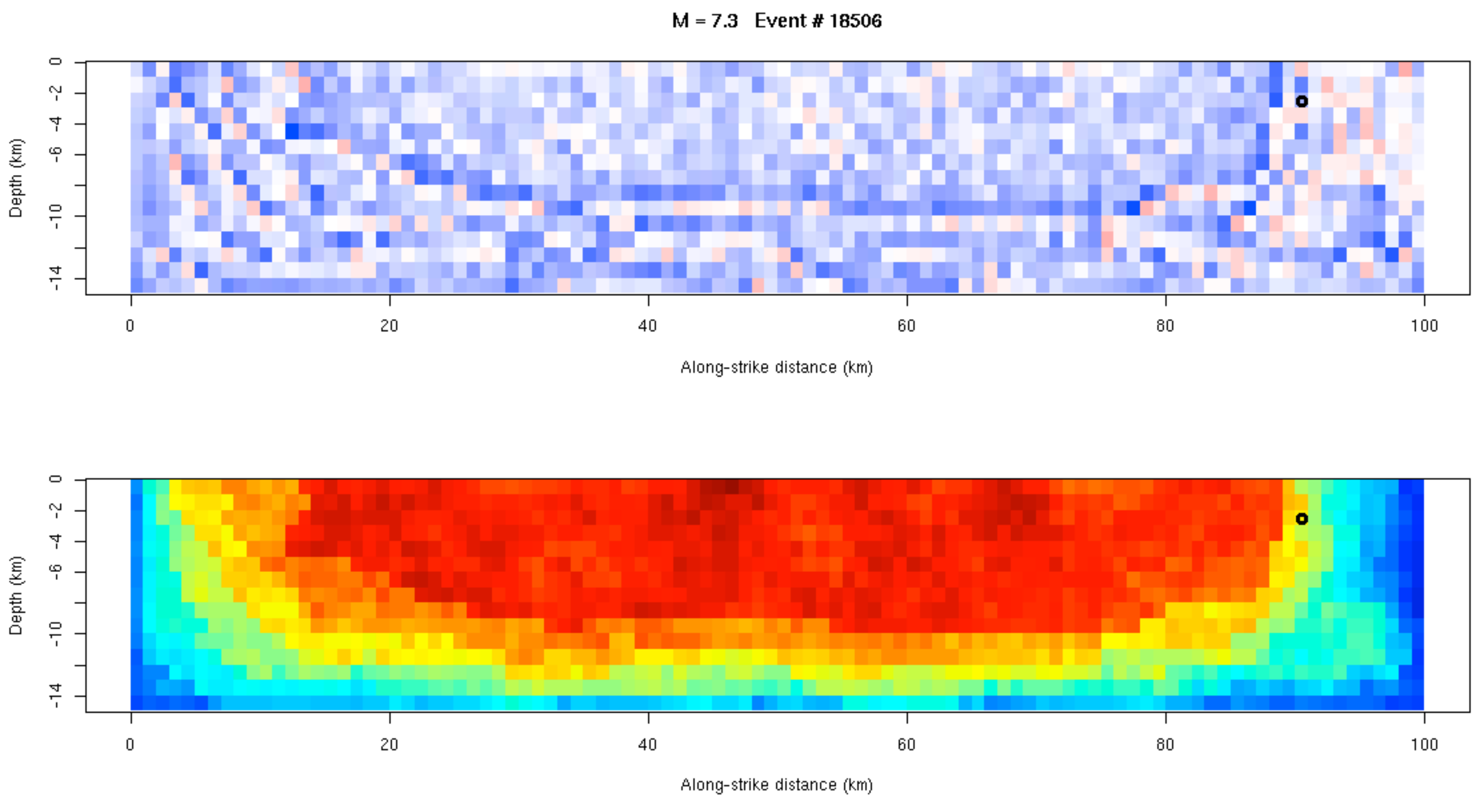
# Summary

- Simulations are quite accurate (extent of rupture and slip distribution)
- Model is expandable
  - Dynamic effects - triggering
  - Off-fault seismicity and rate-state relaxation
- Fundamental characteristics of catalogs are generated and can be studied
  - Magnitude-frequency statistics
  - Foreshocks
  - Aftershocks
  - Occasional large event clusters
- Earthquake Recurrence
  - Appears to reflect mixture of processes recognized in catalogs (Poisson, clustered, quasi-periodic)
  - Step-overs and sharp bends appear to produce (weak?) segmentation

# *Event on fault with fractal topography*

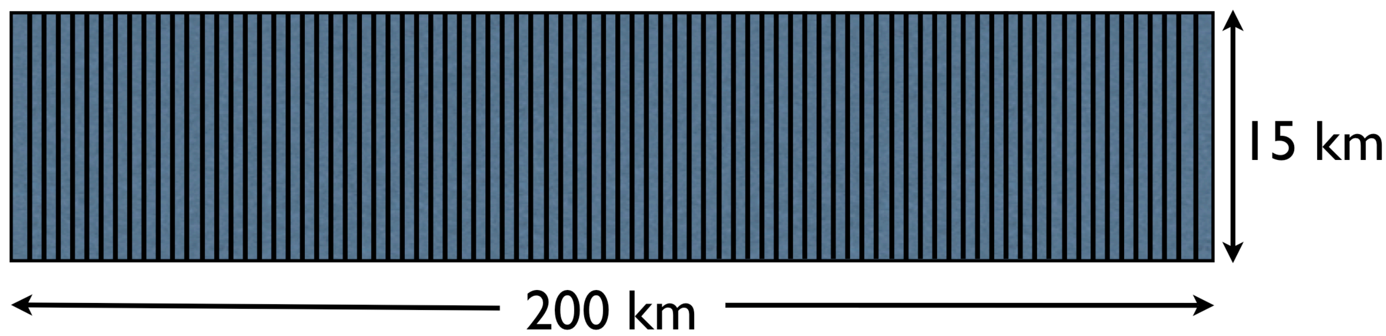


*Stress change and slip distributions for a large event*

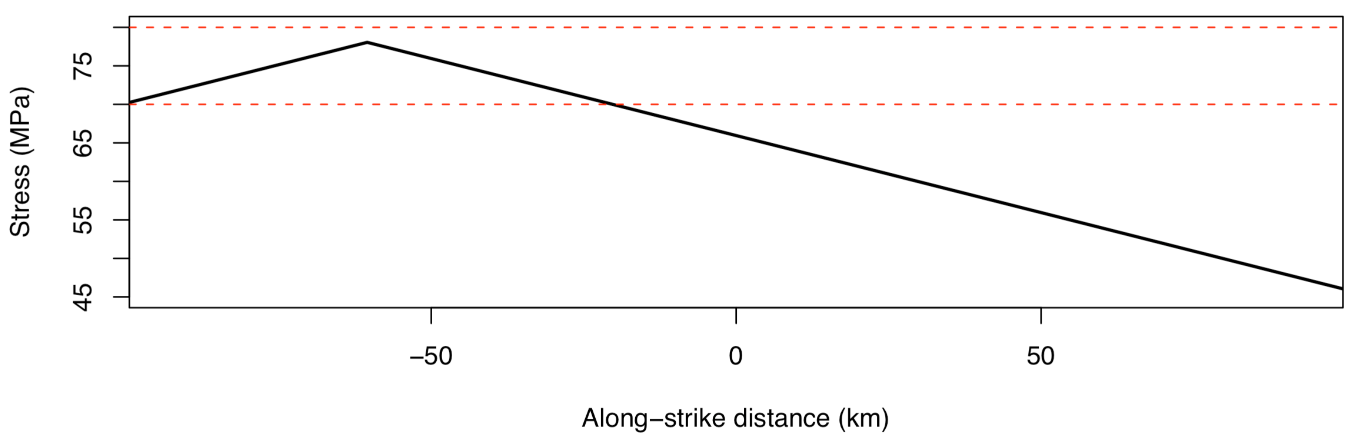


# SCEC sponsored earthquake simulator comparisons

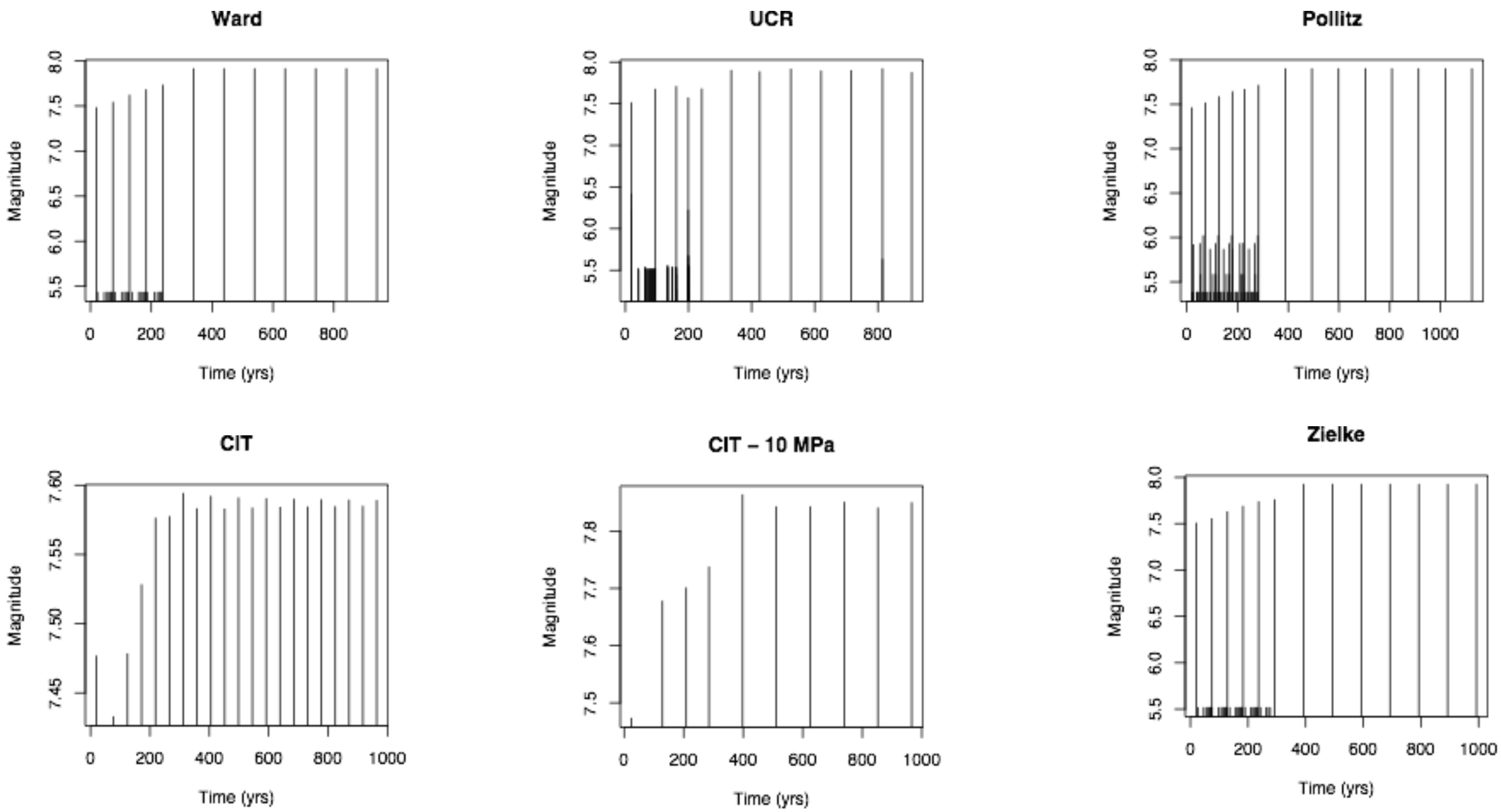
2nd EQ simulator test problem

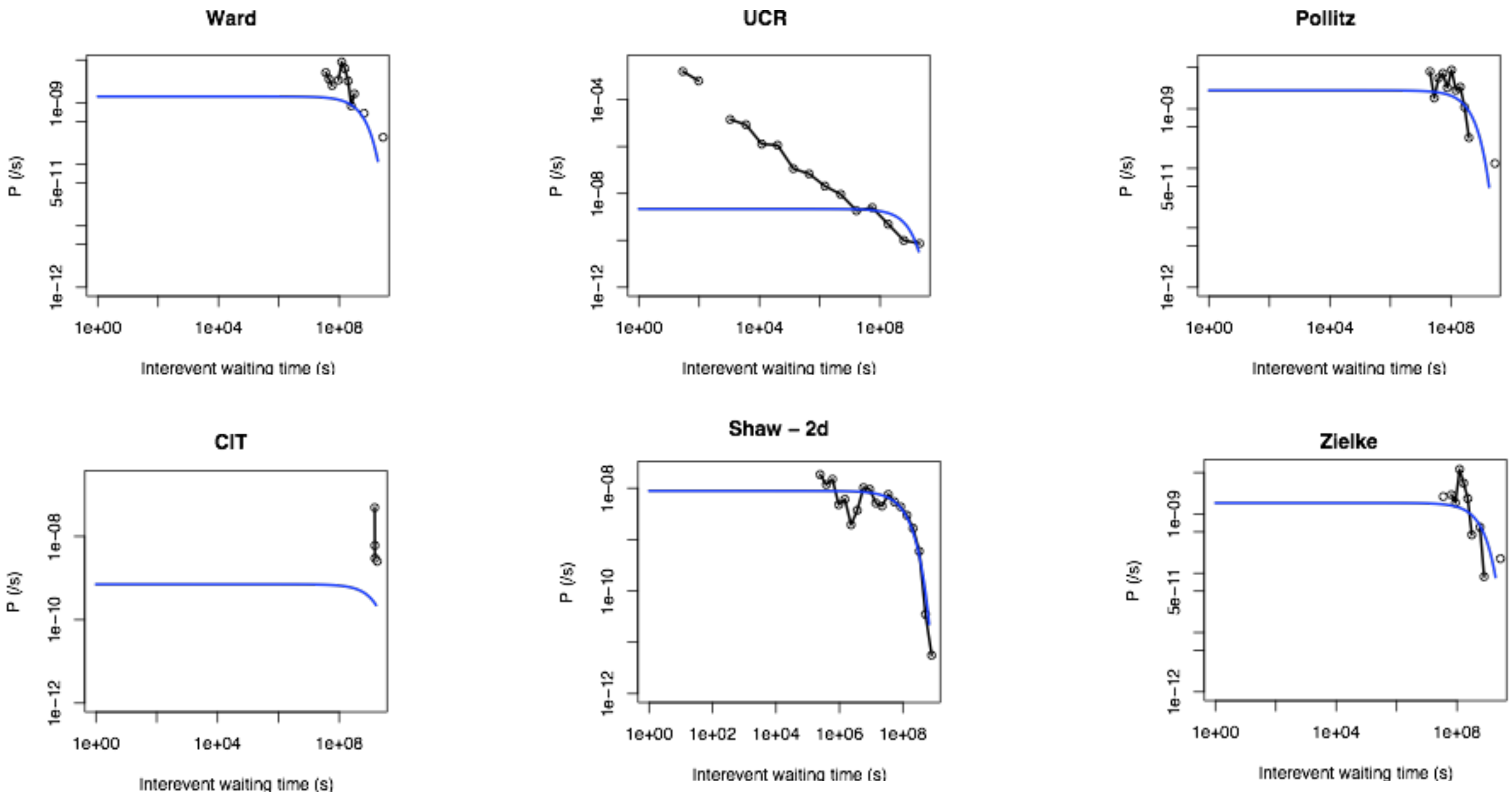


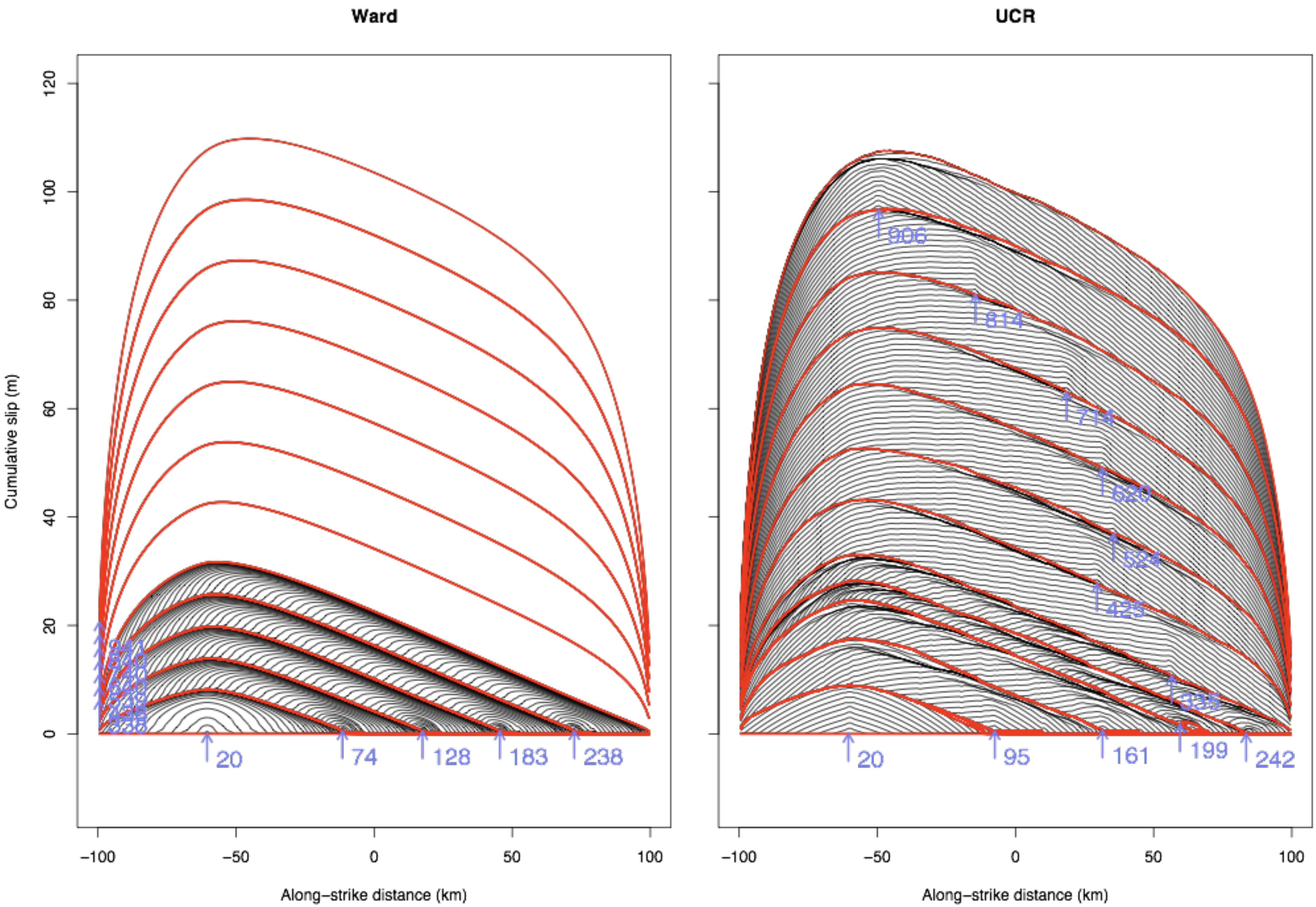

Initial stress



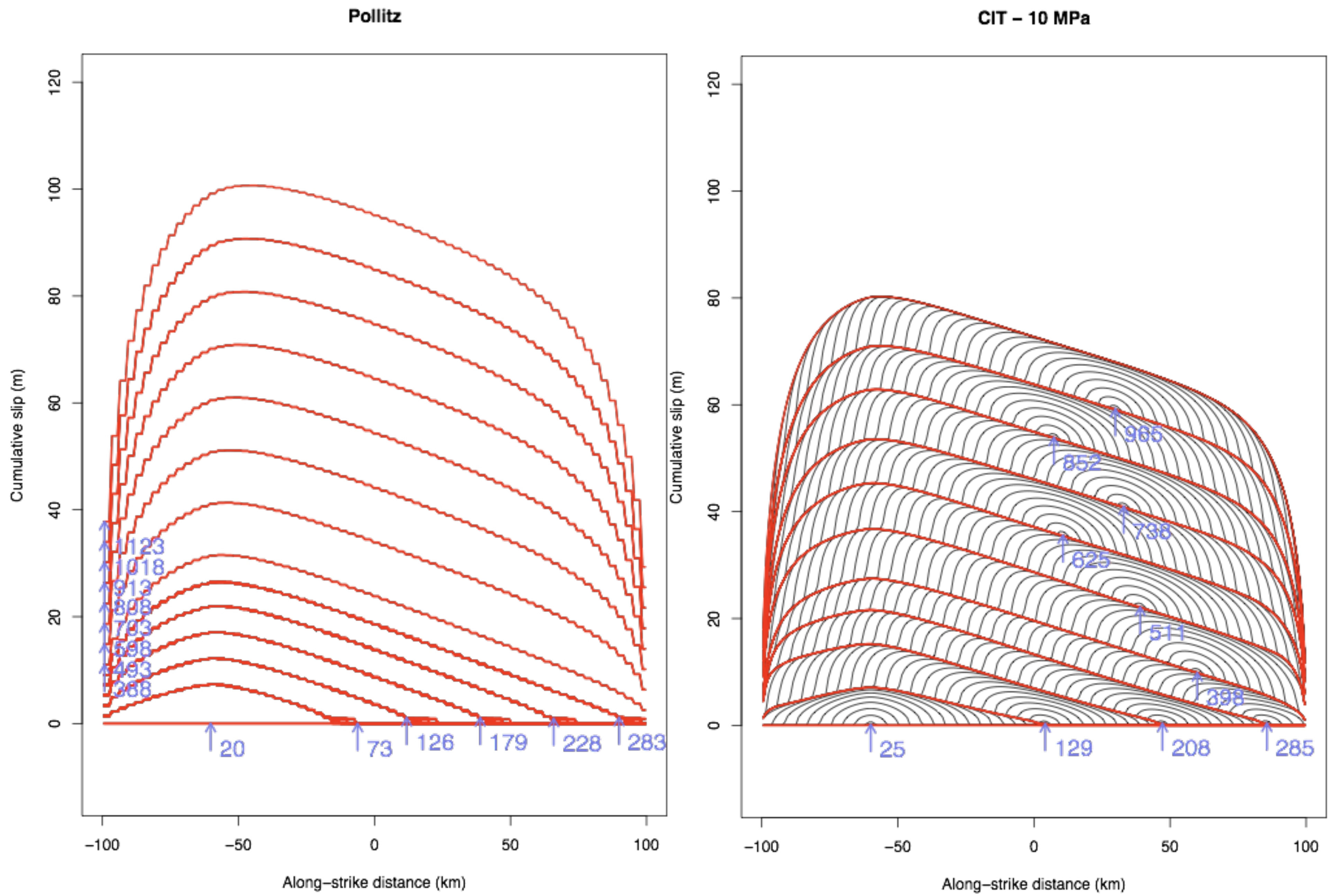

Uniform stress loading (0.1 MPa/yr) => non-uniform long-term slip


Ward
UCR
Pollitz
CIT
CIT – 10 MPa
Zielke
Magnitude
Time (yrs)


Ward
UCR
Pollitz
CIT
Shaw – 2d
Zielke
P (/s)
Interevent waiting time (s)
1e+00
1e+02
1e+04
1e+06
1e+08
1e−04
1e−08
1e−09
5e−11
1e−10
1e−12

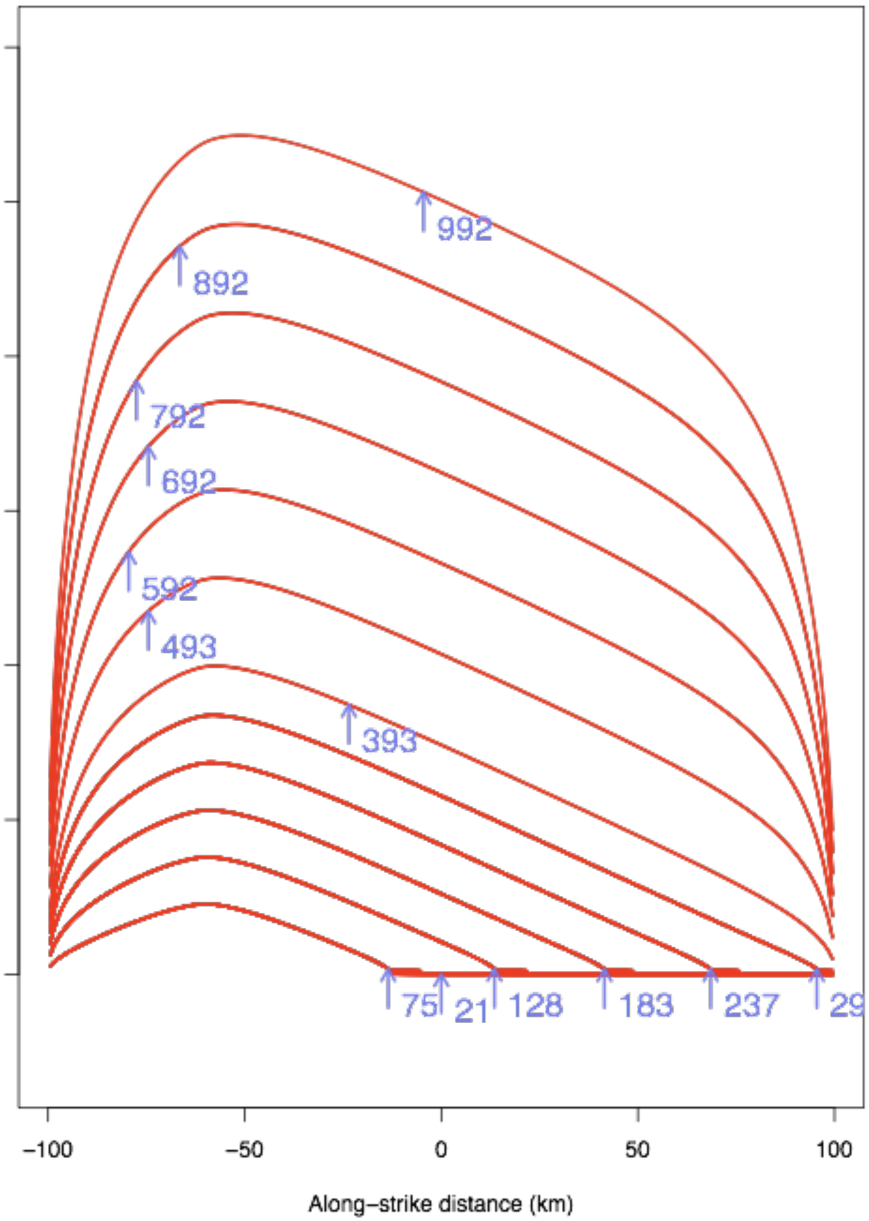


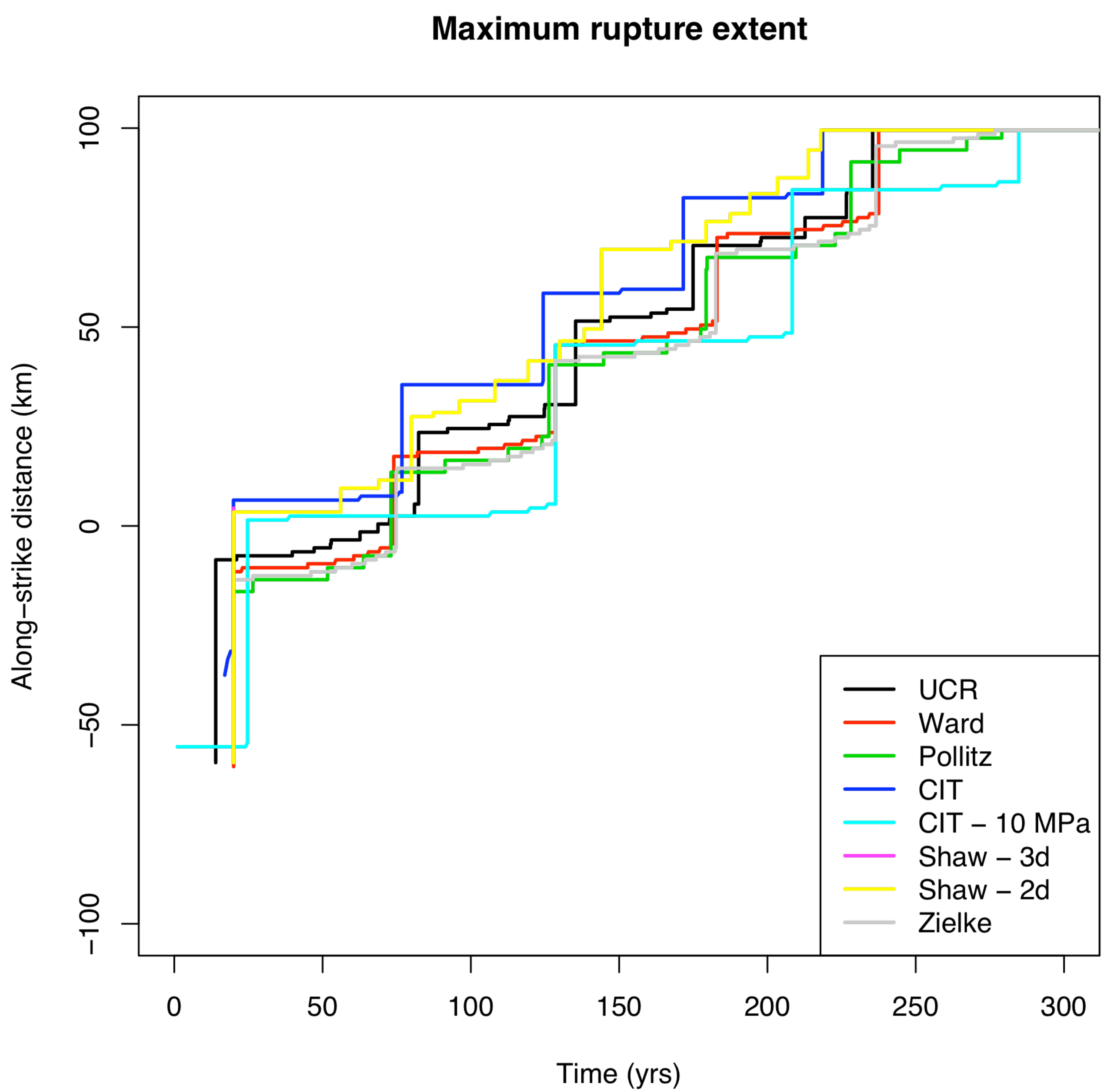
Ward
UCR
Cumulative slip (m)
Along−strike distance (km)
Along−strike distance (km)
0
20
40
60
80
100
120
−100
−50
0
50
100
20
74
128
183
238
20
95
161
199
242
335
425
524
620
714
814
906

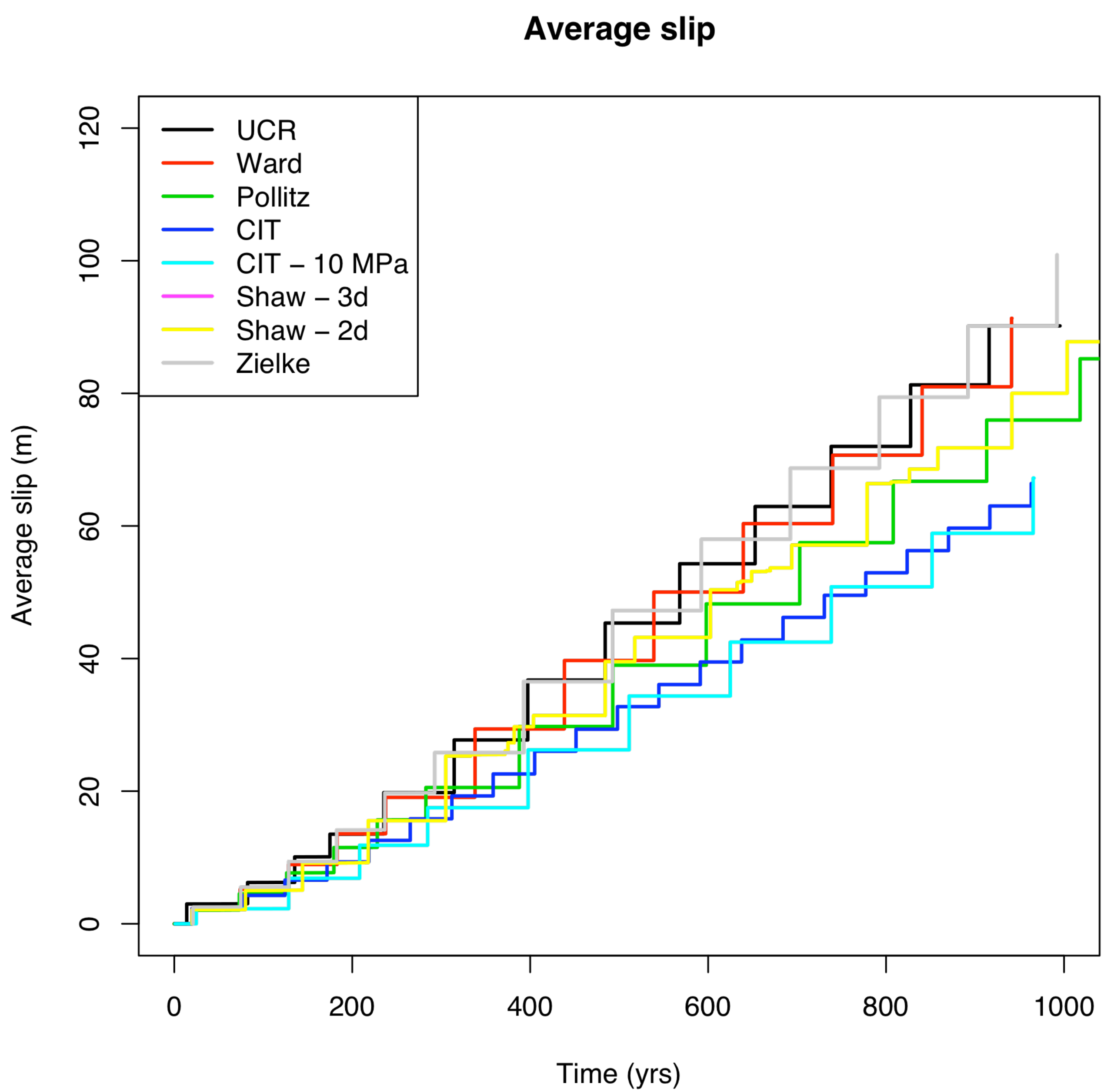


Pollitz
CIT – 10 MPa
Cumulative slip (m)
Along–strike distance (km)
0
20
40
60
80
100
120
−100
−50
0
50
100
1123
1018
913
808
703
598
493
388
20
73
126
179
228
283
965
852
738
625
511
398
25
129
208
285

# Zielke


992
892
792
692
592
493
393
75
21
128
183
237
29
−100
−50
0
50
100
Along−strike distance (km)


Maximum rupture extent
Along−strike distance (km)
−100
−50
0
50
100
Time (yrs)
0
50
100
150
200
250
300
UCR
Ward
Pollitz
CIT
CIT − 10 MPa
Shaw − 3d
Shaw − 2d
Zielke



Average slip
UCR
Ward
Pollitz
CIT
CIT – 10 MPa
Shaw – 3d
Shaw – 2d
Zielke
Average slip (m)
0
20
40
60
80
100
120
0
200
400
600
800
1000
Time (yrs)