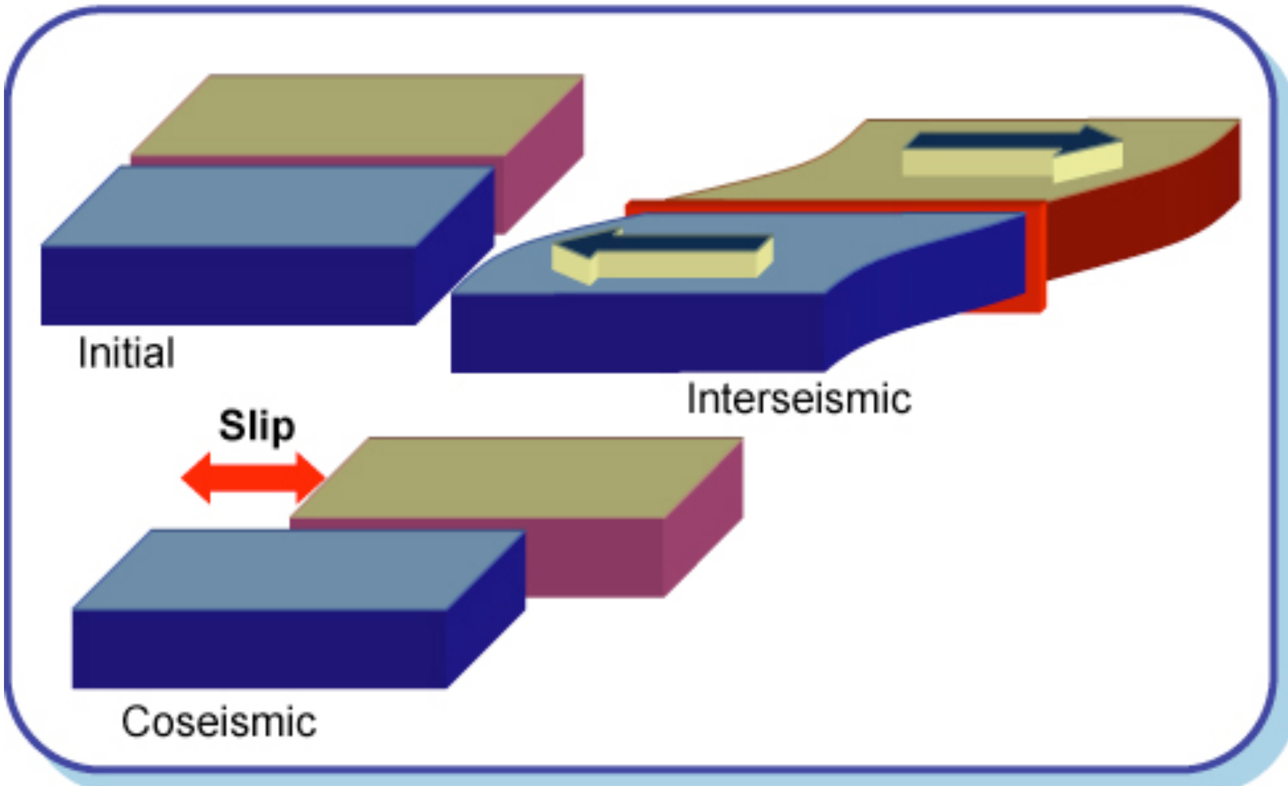
Probabilistic seismic hazard in the San Francisco Bay area based on physical models

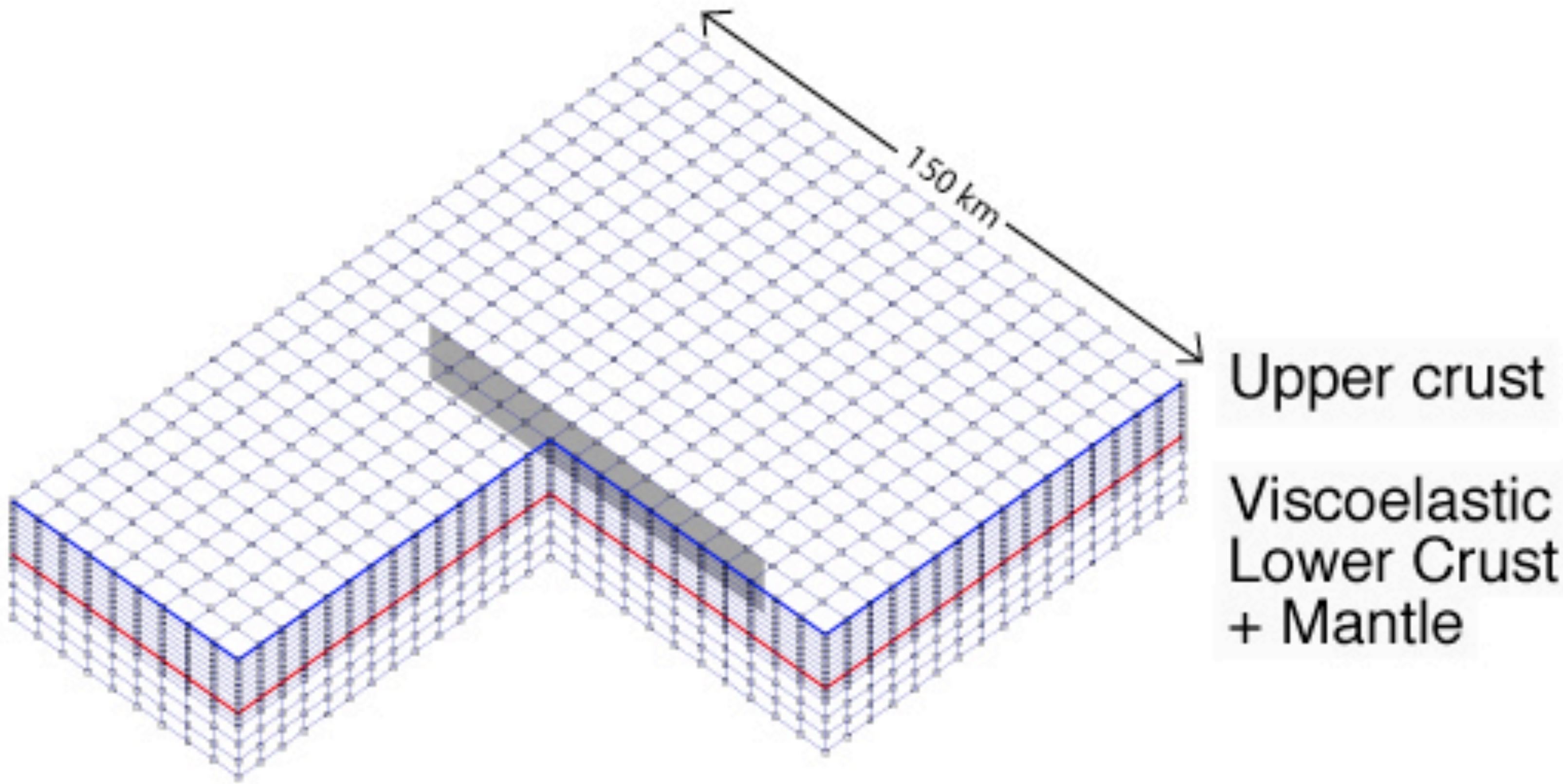
Fred Pollitz and David Schwartz, *USGS Menlo Park*

- SFBR stress evolution with prescribed earthquake history in an interacting 10-fault system
- Future rupture probabilities using the time-predictable model
- SFBR stress evolution with simulated seismicity
- Fault system behavior using 30000-yr simulated seismicity

Stress evolution using prescribed earthquake history

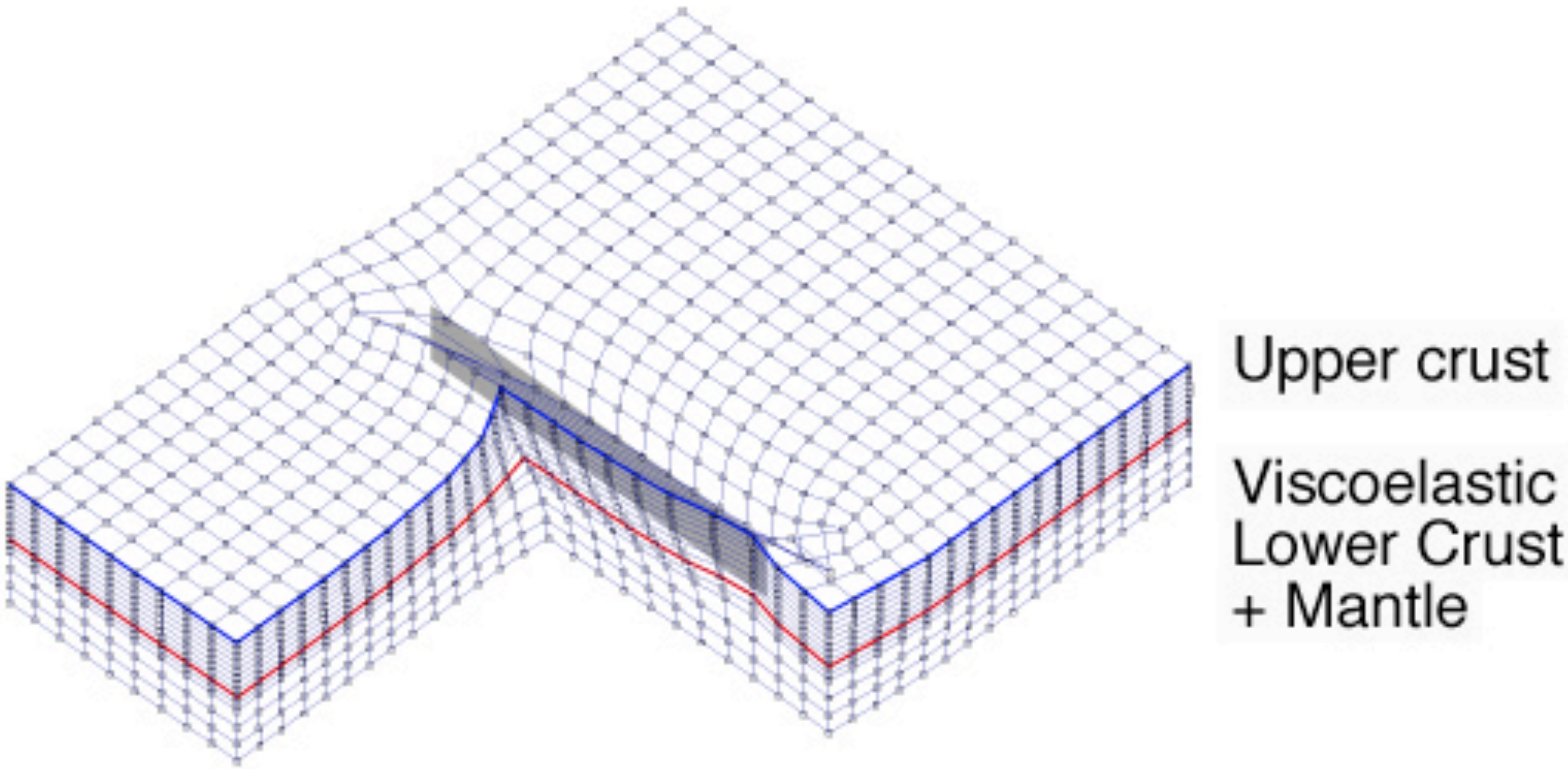


Initial

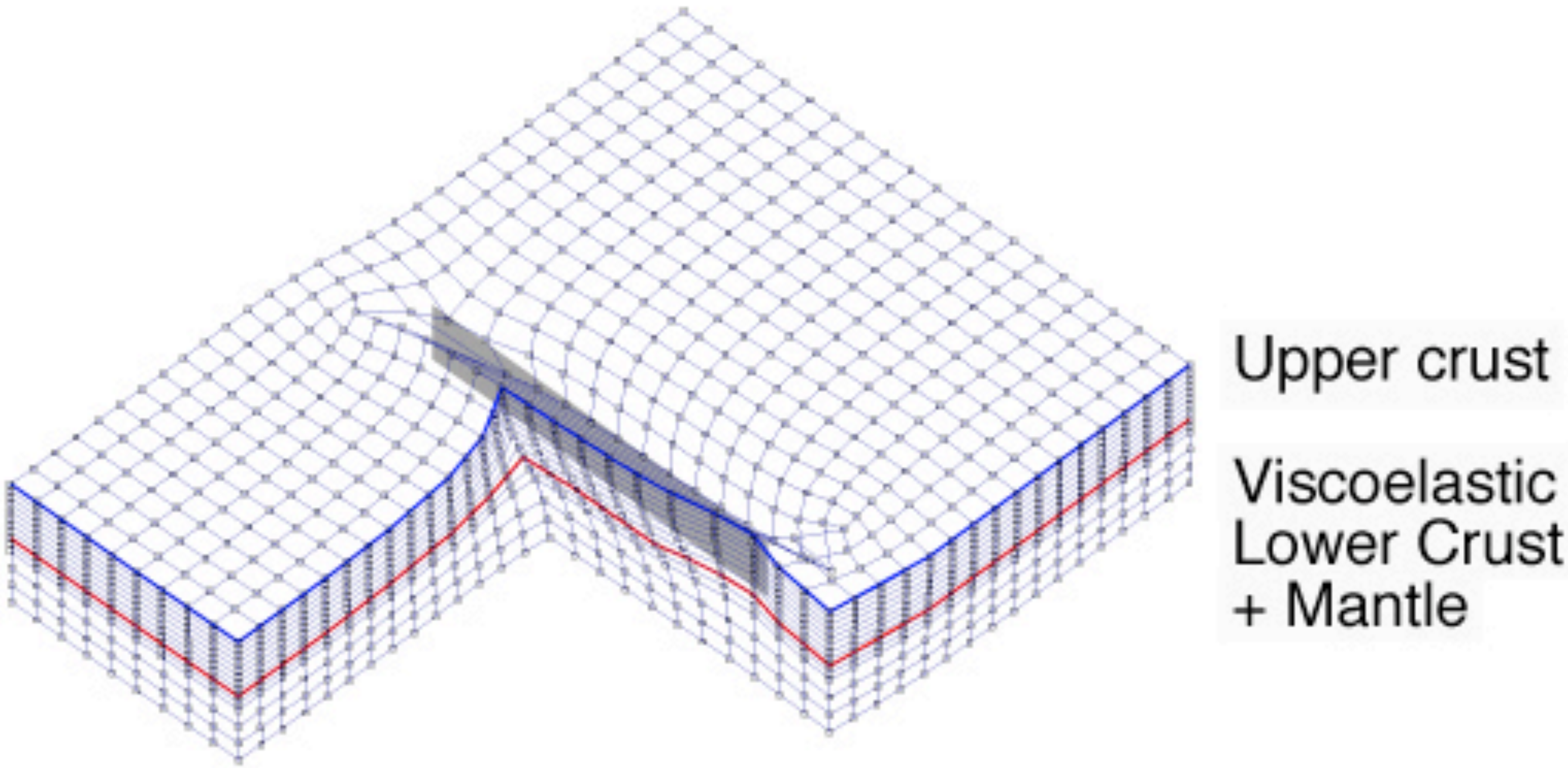


Coseismic

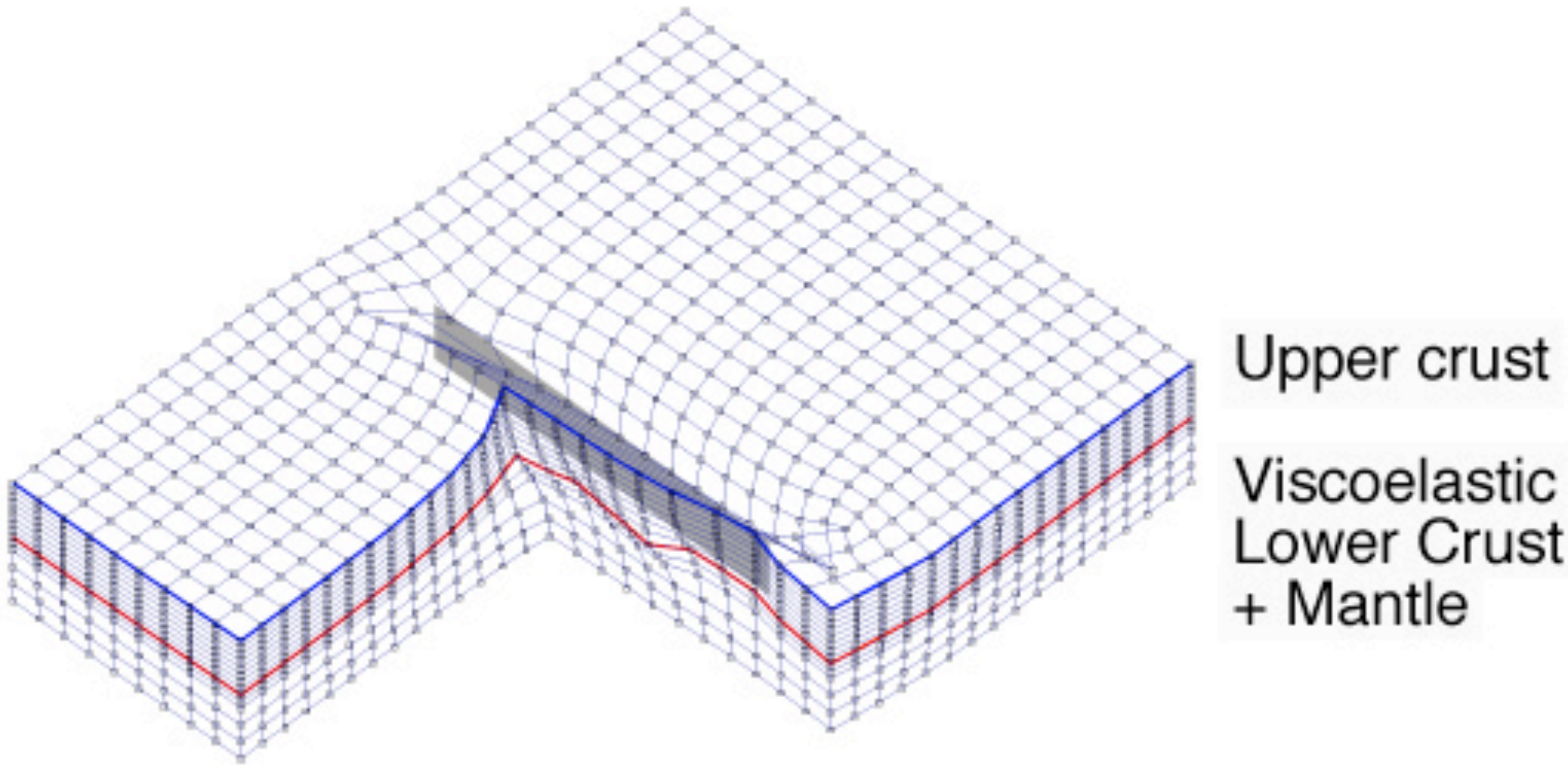
Slip = 1 meter
Deformation x 40000



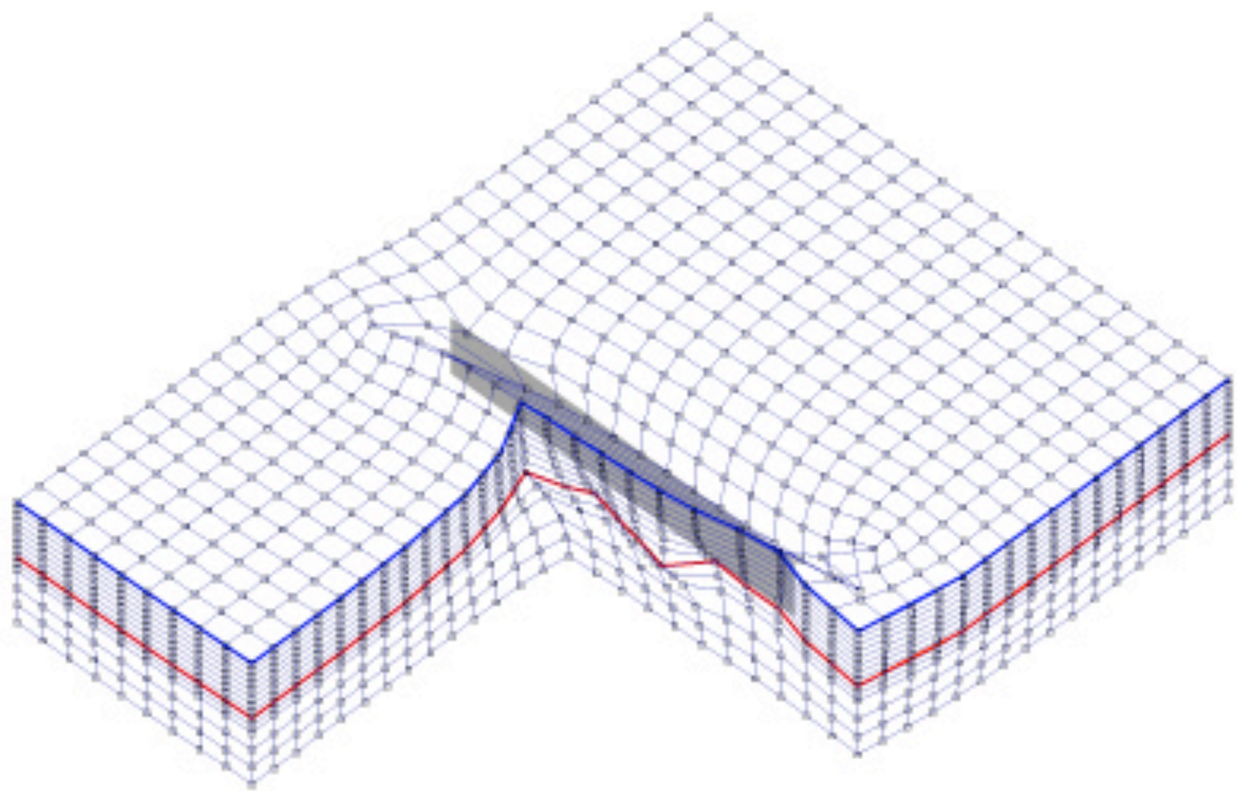
1 year



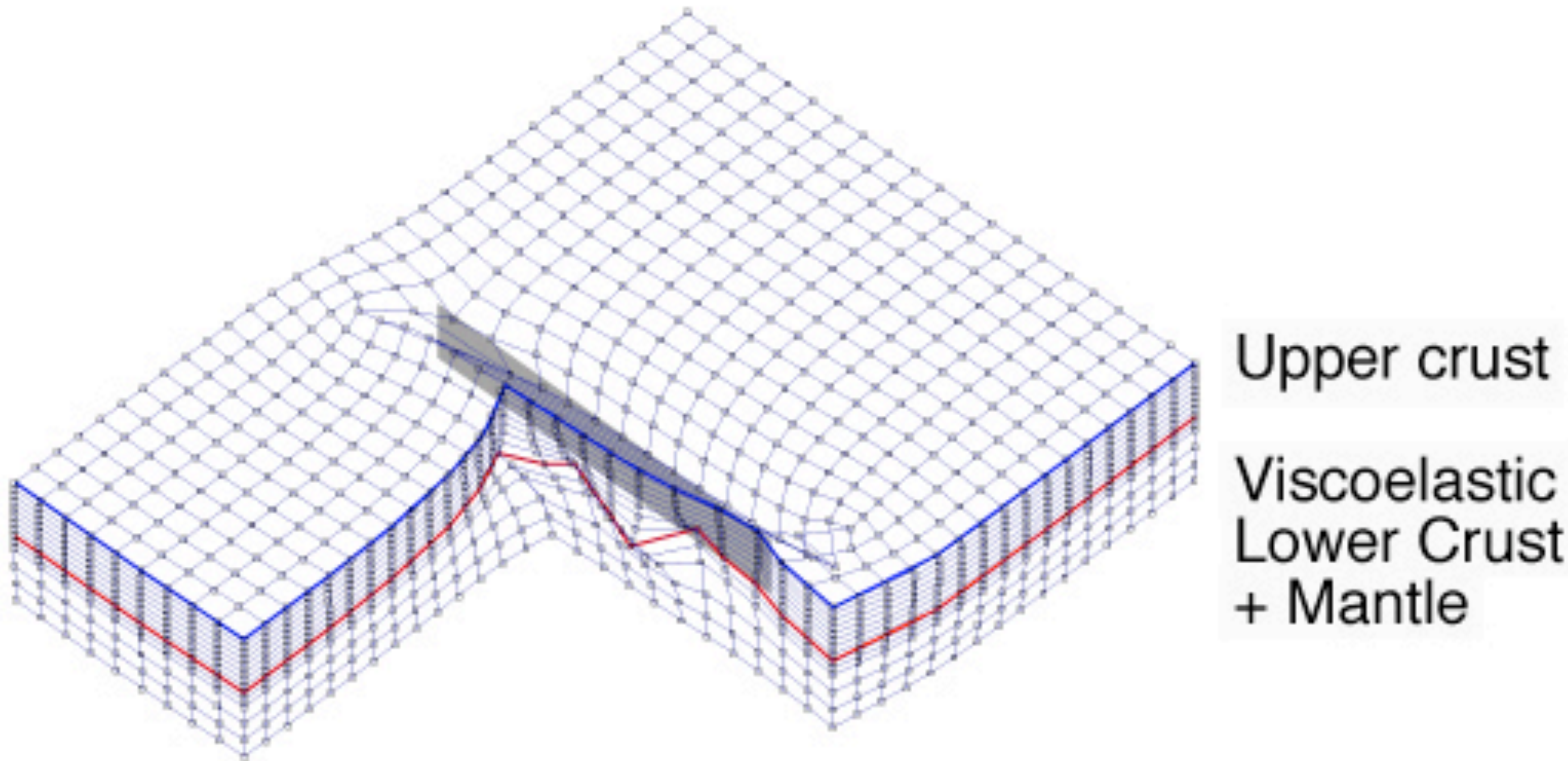
5 years



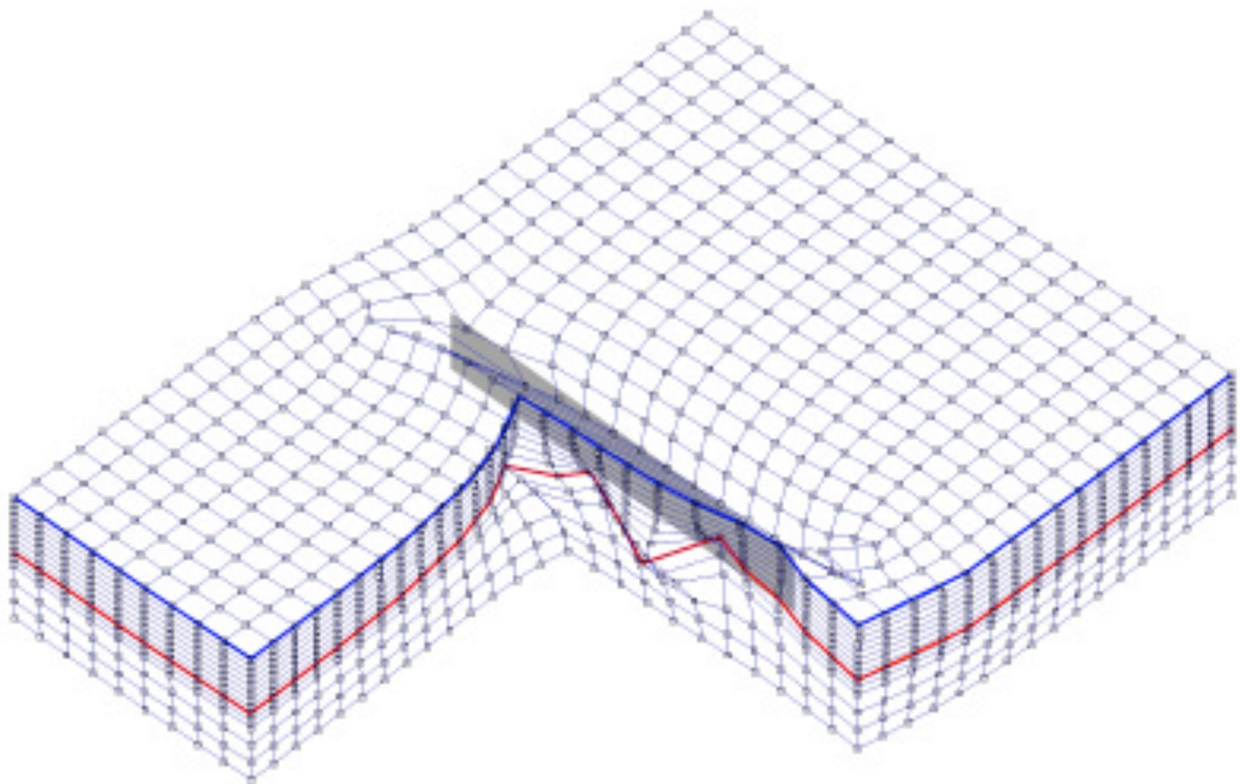
10 years



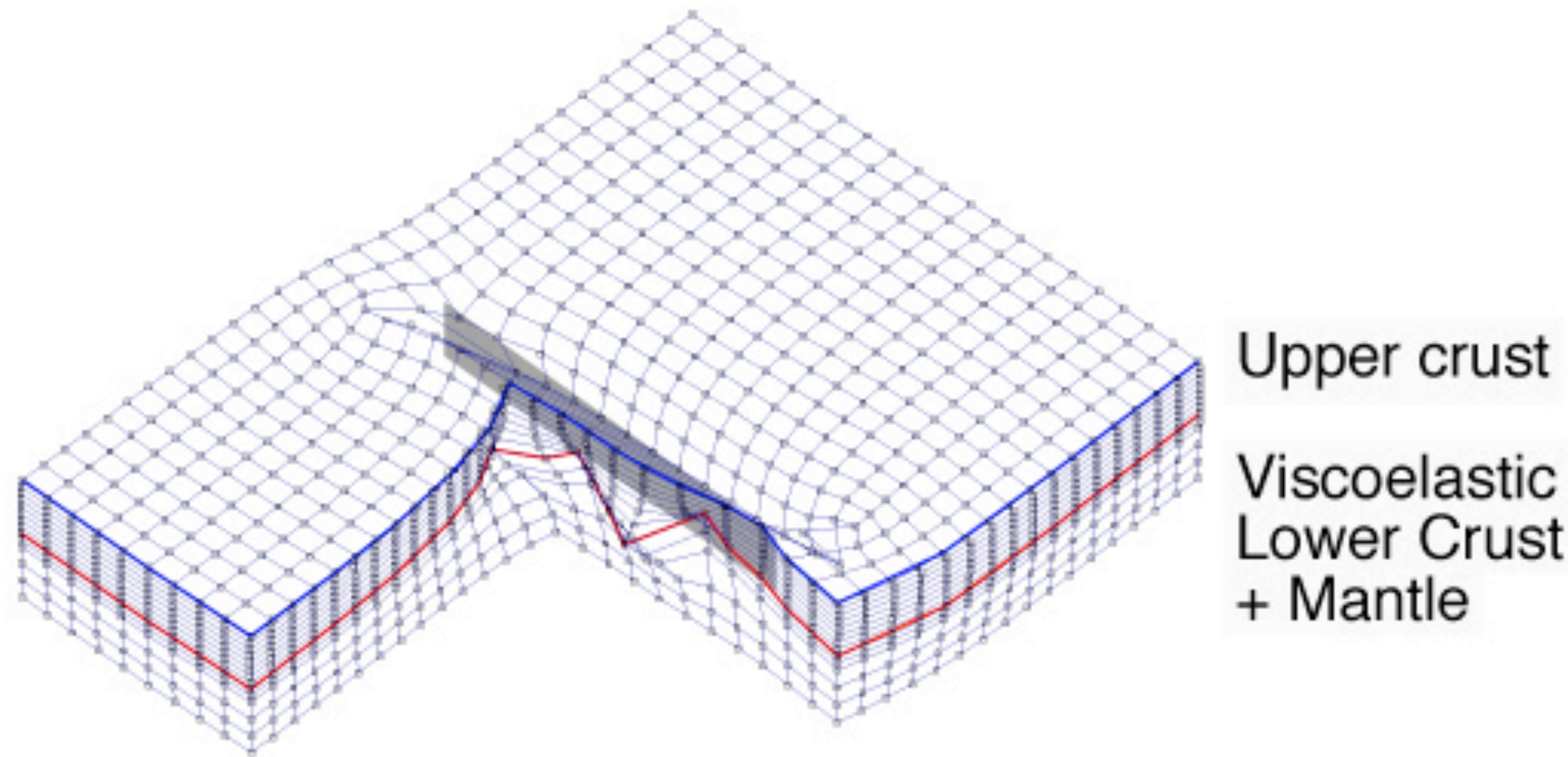
20 years



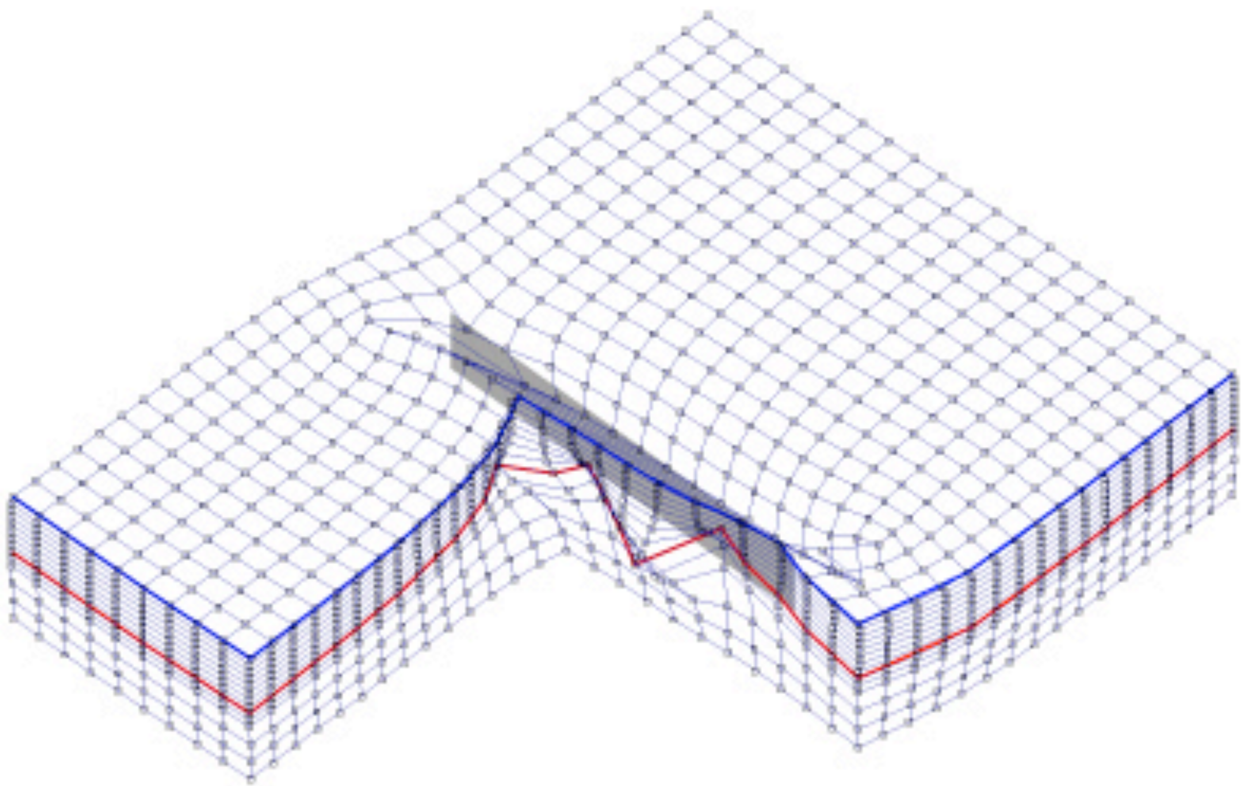
30 years



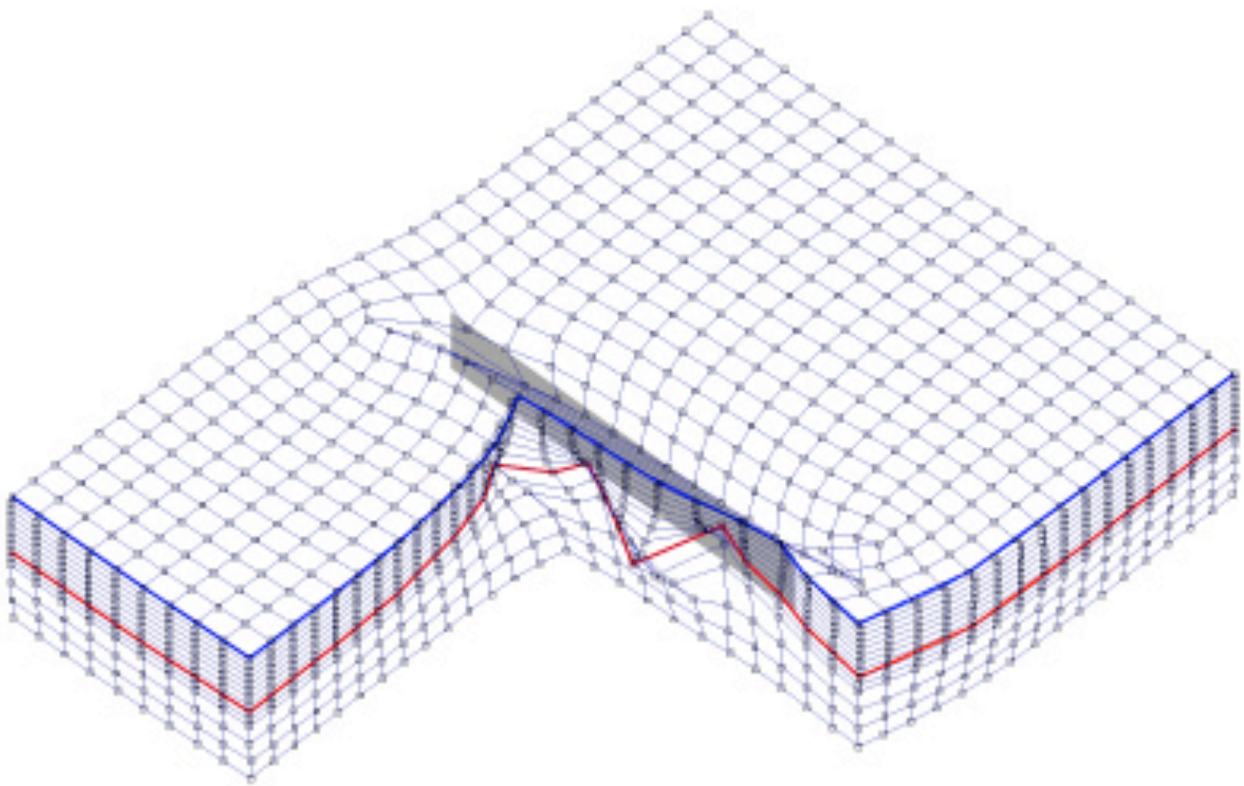
40 years

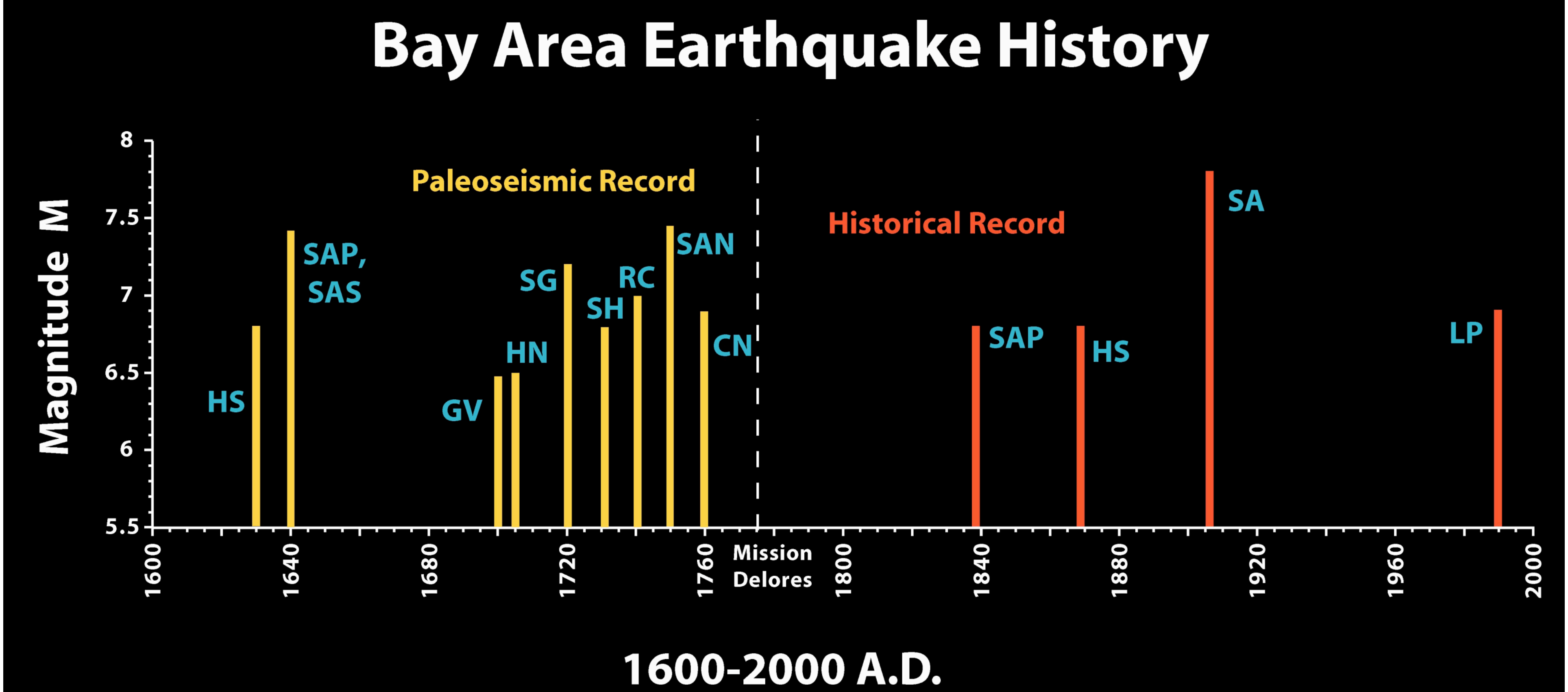


50 years

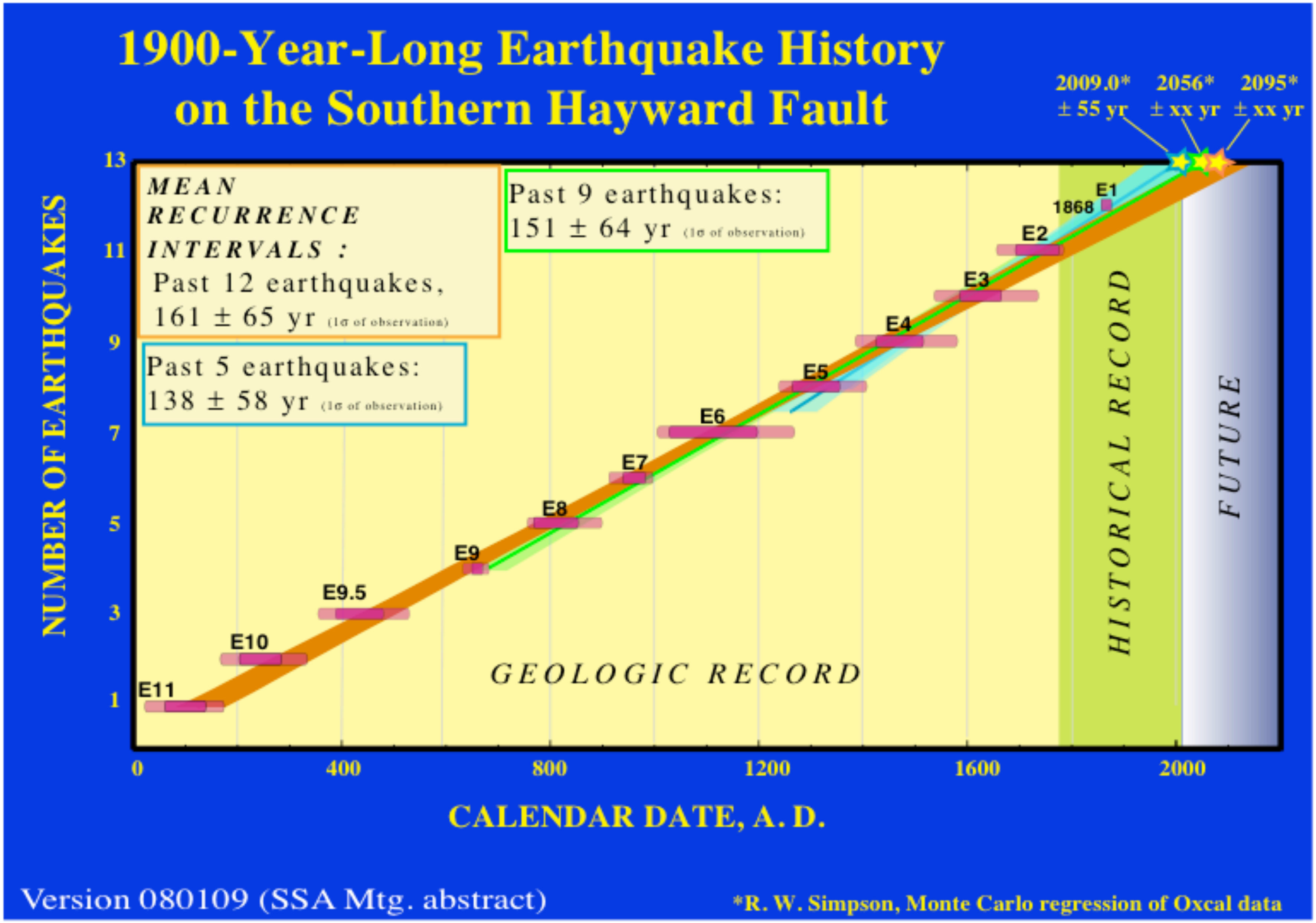


60 years

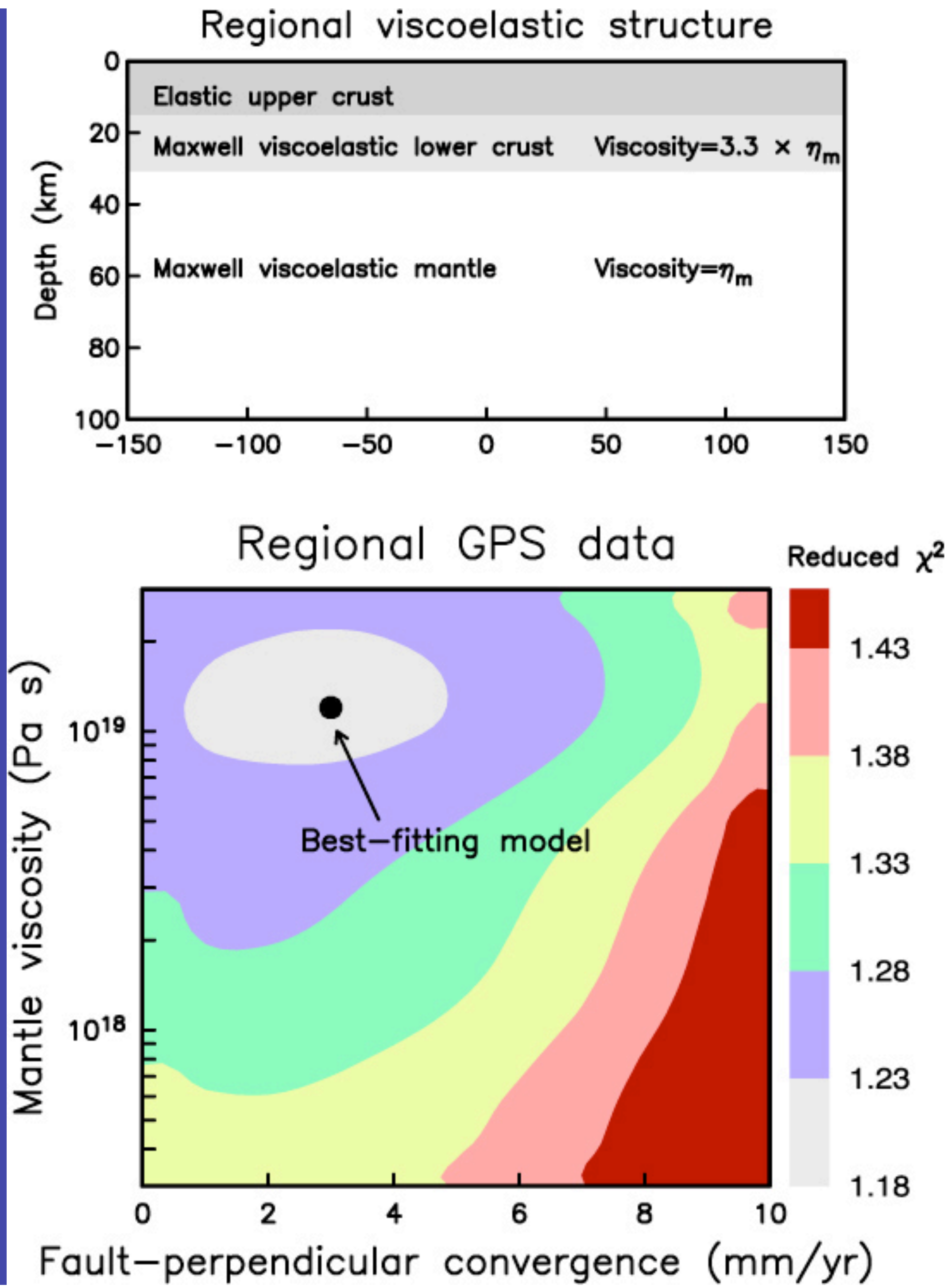




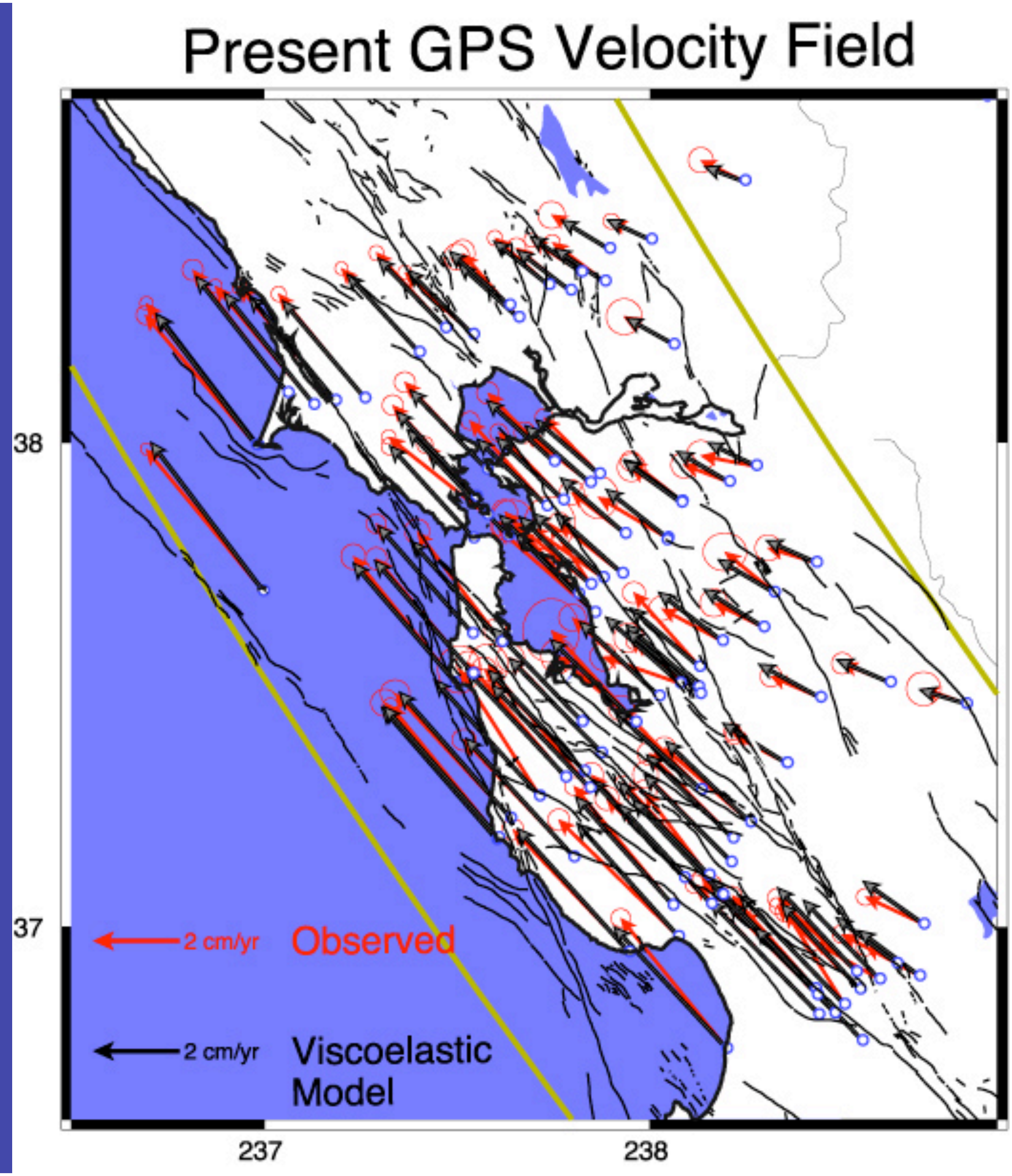
(figure courtesy of David Schwartz)


1900-Year-Long Earthquake History
on the Southern Hayward Fault
2009.0*
± 55 yr
2056*
± xx yr
2095*
± xx yr
MEAN RECURRENCE INTERVALS :
Past 12 earthquakes,
161 ± 65 yr (1σ of observation)
Past 9 earthquakes:
151 ± 64 yr (1σ of observation)
Past 5 earthquakes:
138 ± 58 yr (1σ of observation)
E1
1868
E2
E3
E4
E5
E6
E7
E8
E9
E9.5
E10
E11
GEOLOGIC RECORD
HISTORICAL RECORD
FUTURE
NUMBER OF EARTHQUAKES
13
11
9
7
5
3
1
0
400
800
1200
1600
2000
CALENDAR DATE, A. D.
Version 080109 (SSA Mtg. abstract)
*R. W. Simpson, Monte Carlo regression of Oxcal data

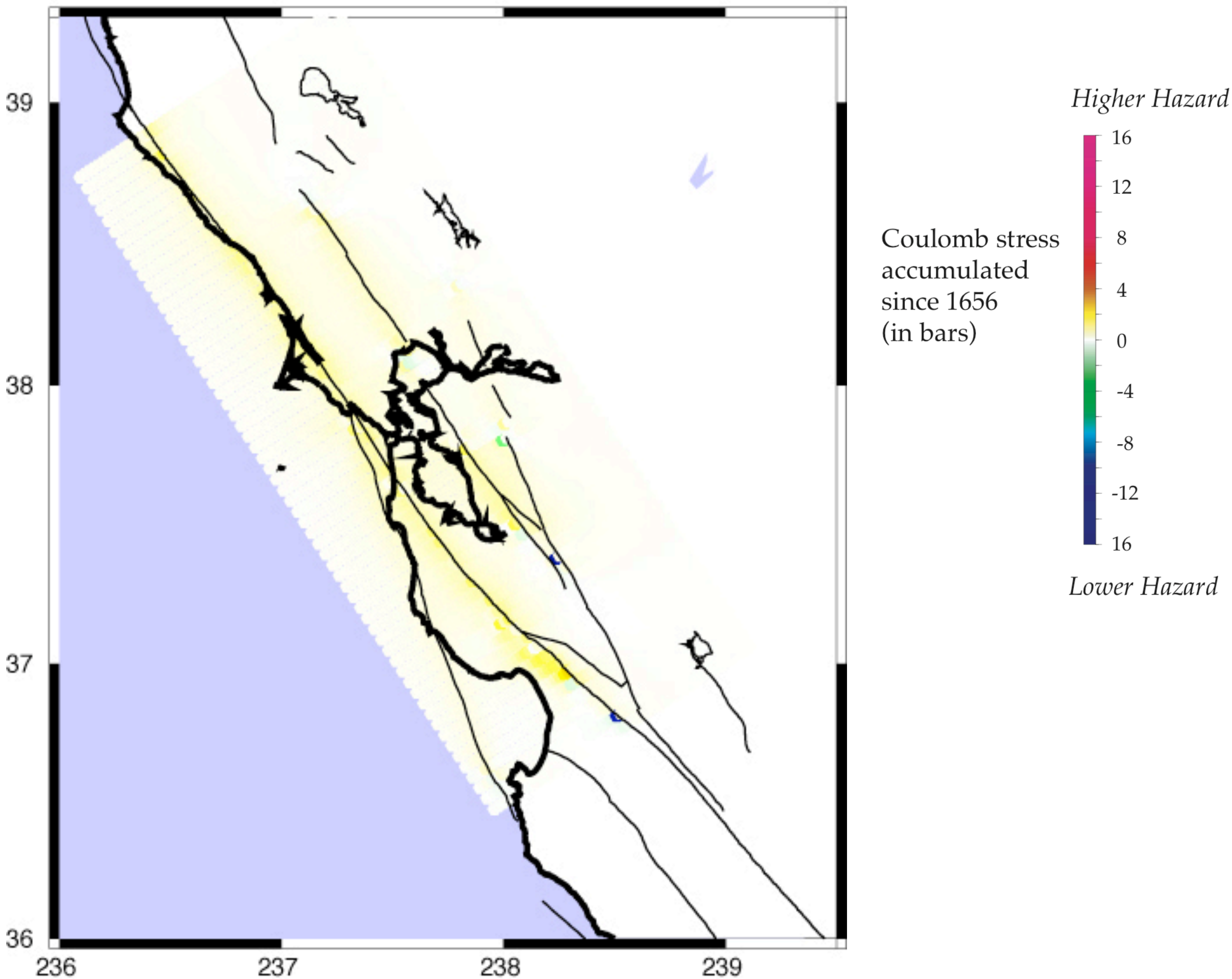
Regional viscoelastic structure is well constrained by the GPS velocity field (Pollitz and Nyst, 2004)



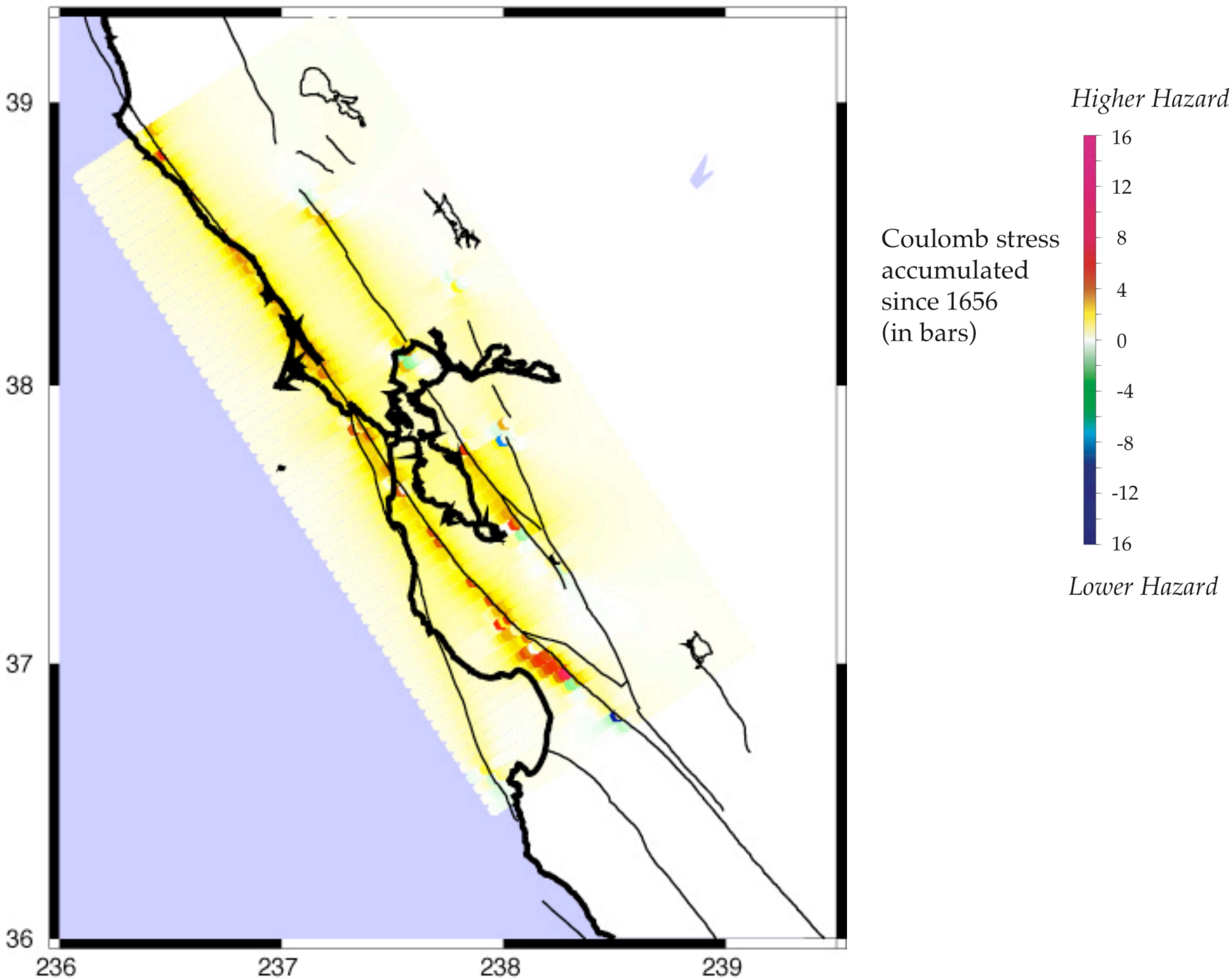
Visccoelastic model yields good fit to regional GPS velocity field

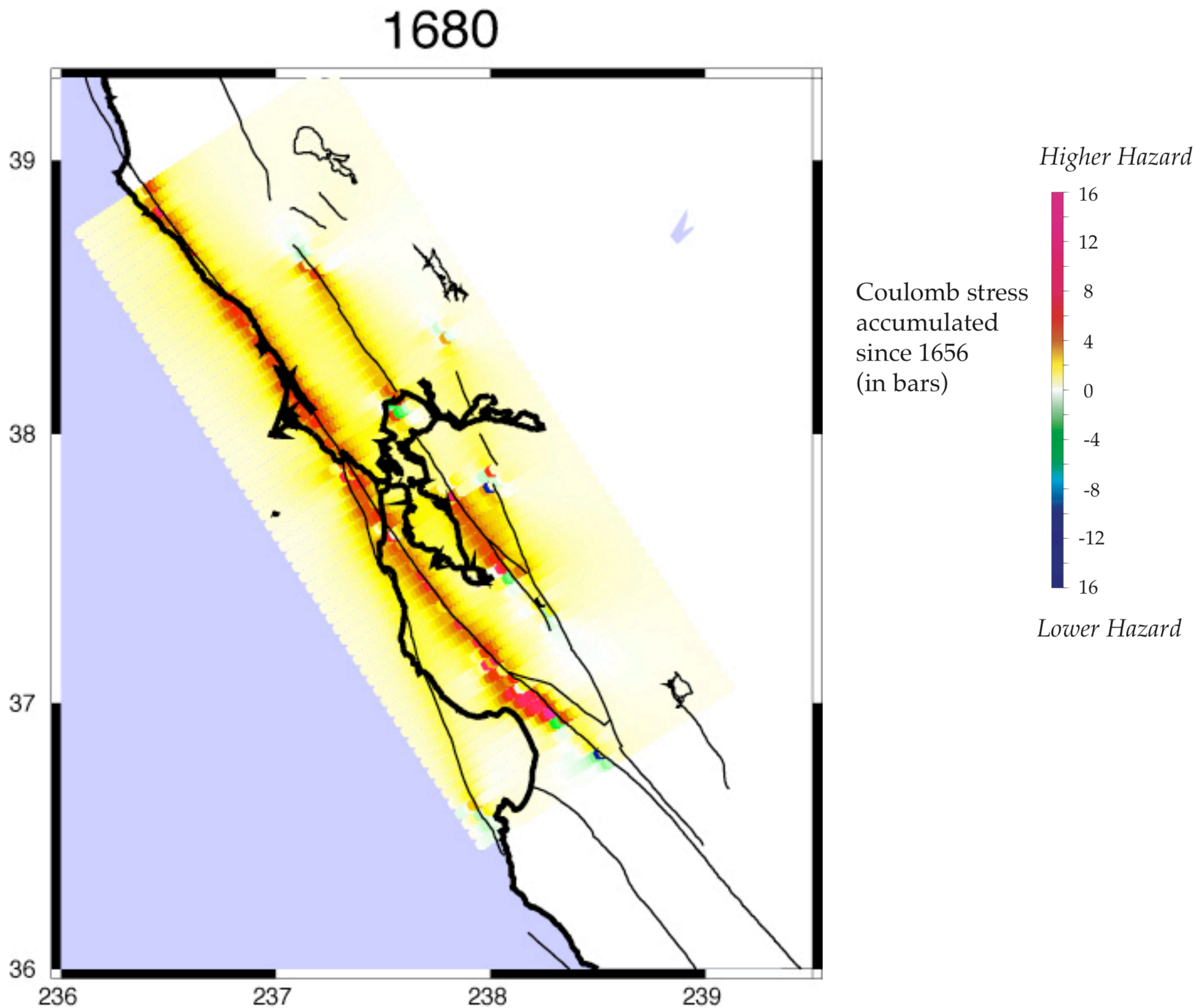


1660

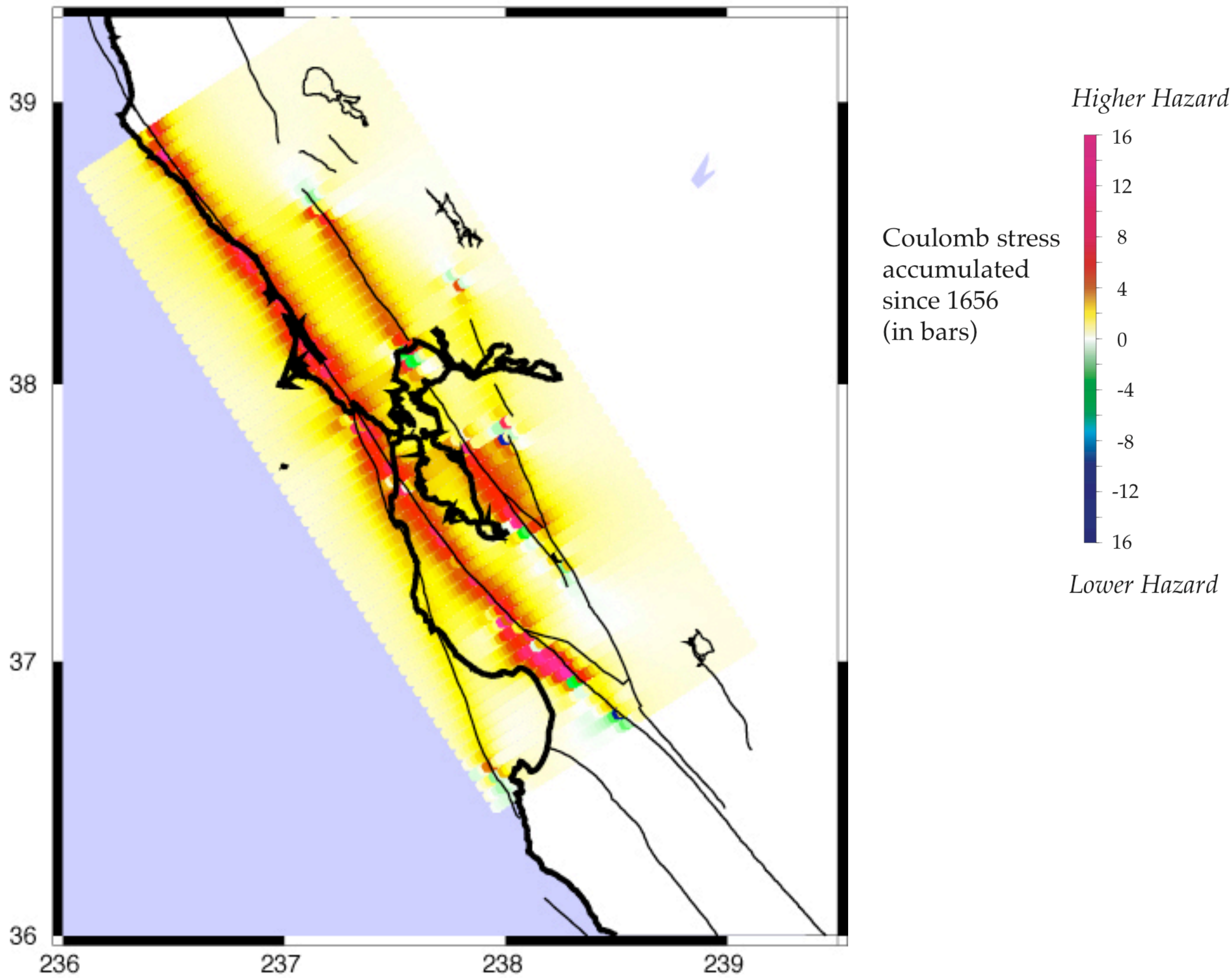

39
38
37
36
236
237
238
239
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard
Coulomb stress accumulated since 1656 (in bars)

1670

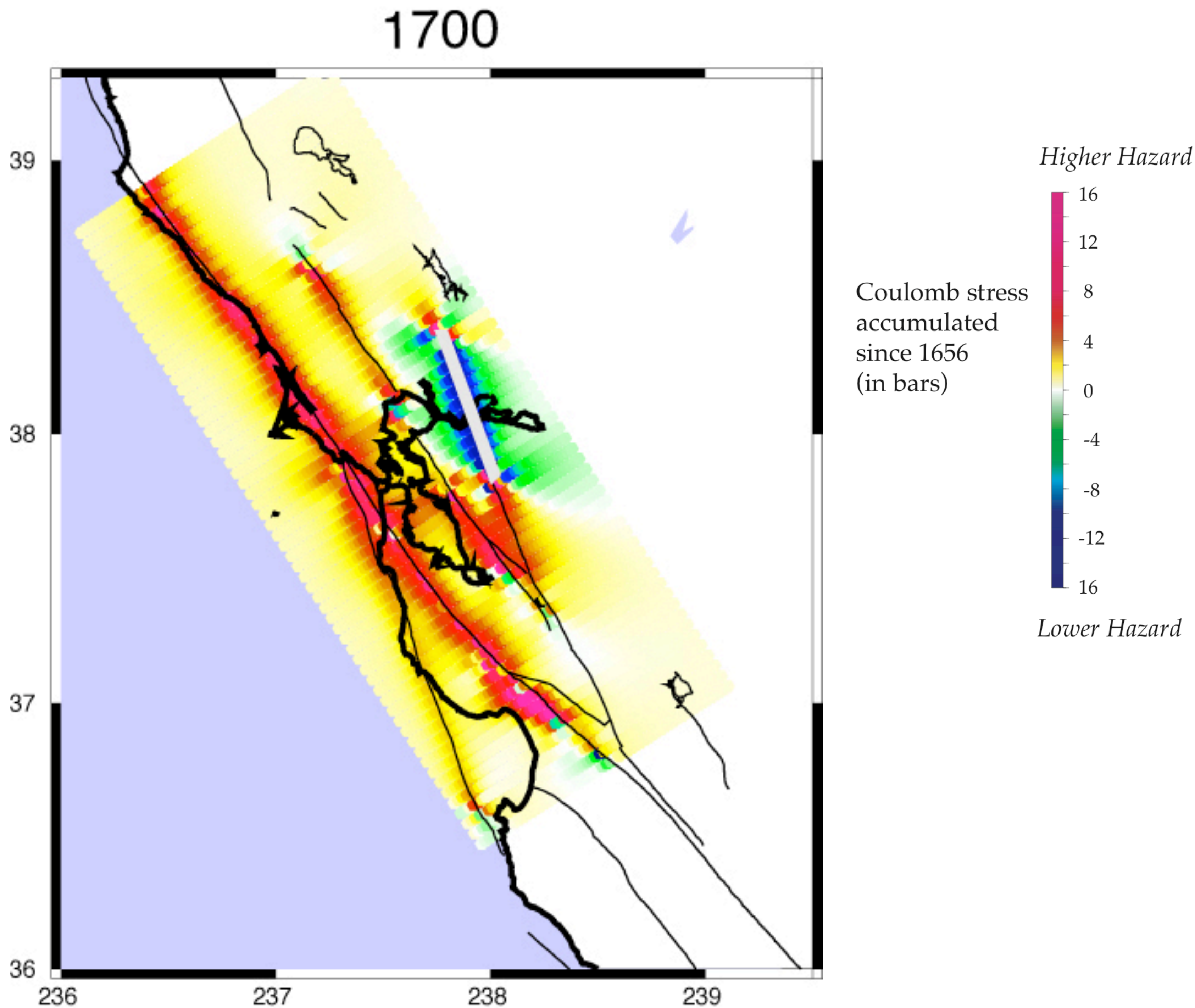

39
38
37
36
236
237
238
239
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard
Coulomb stress
accumulated
since 1656
(in bars)

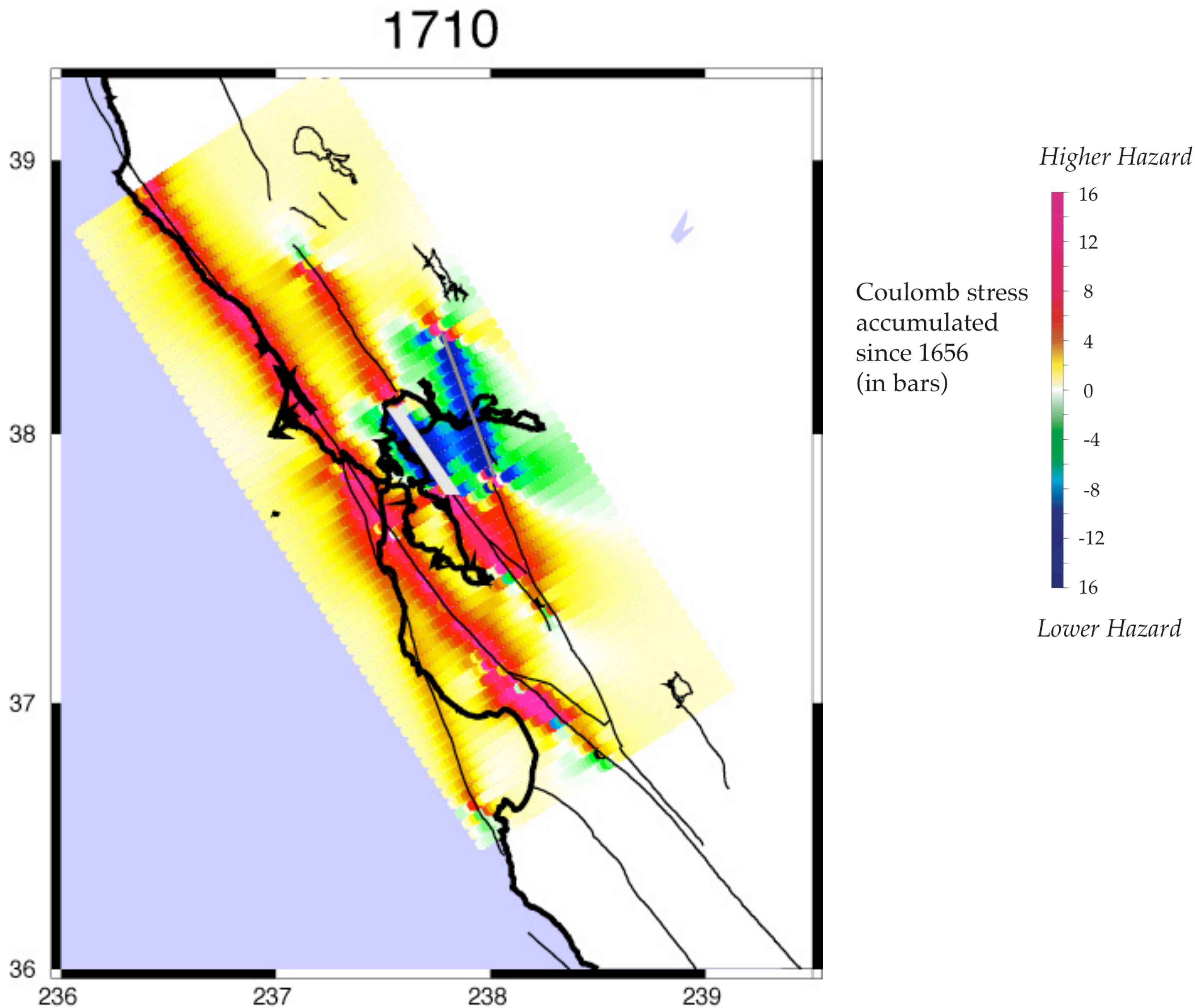

1680
39
38
37
36
236
237
238
239
Coulomb stress accumulated since 1656 (in bars)
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard

1690



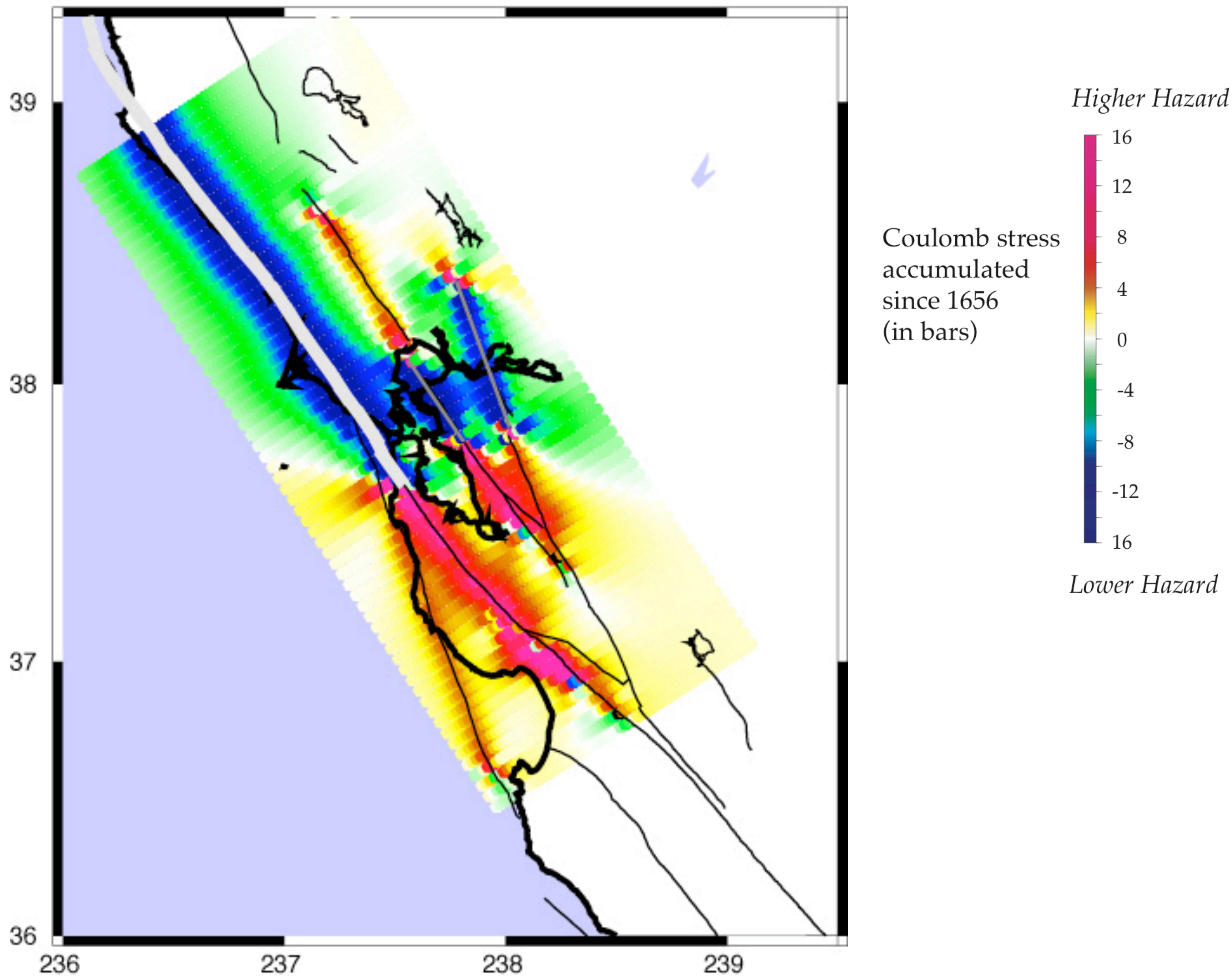
39
38
37
36
236
237
238
239
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard
Coulomb stress
accumulated
since 1656
(in bars)


1700
39
38
37
36
236
237
238
239
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard
Coulomb stress accumulated since 1656 (in bars)

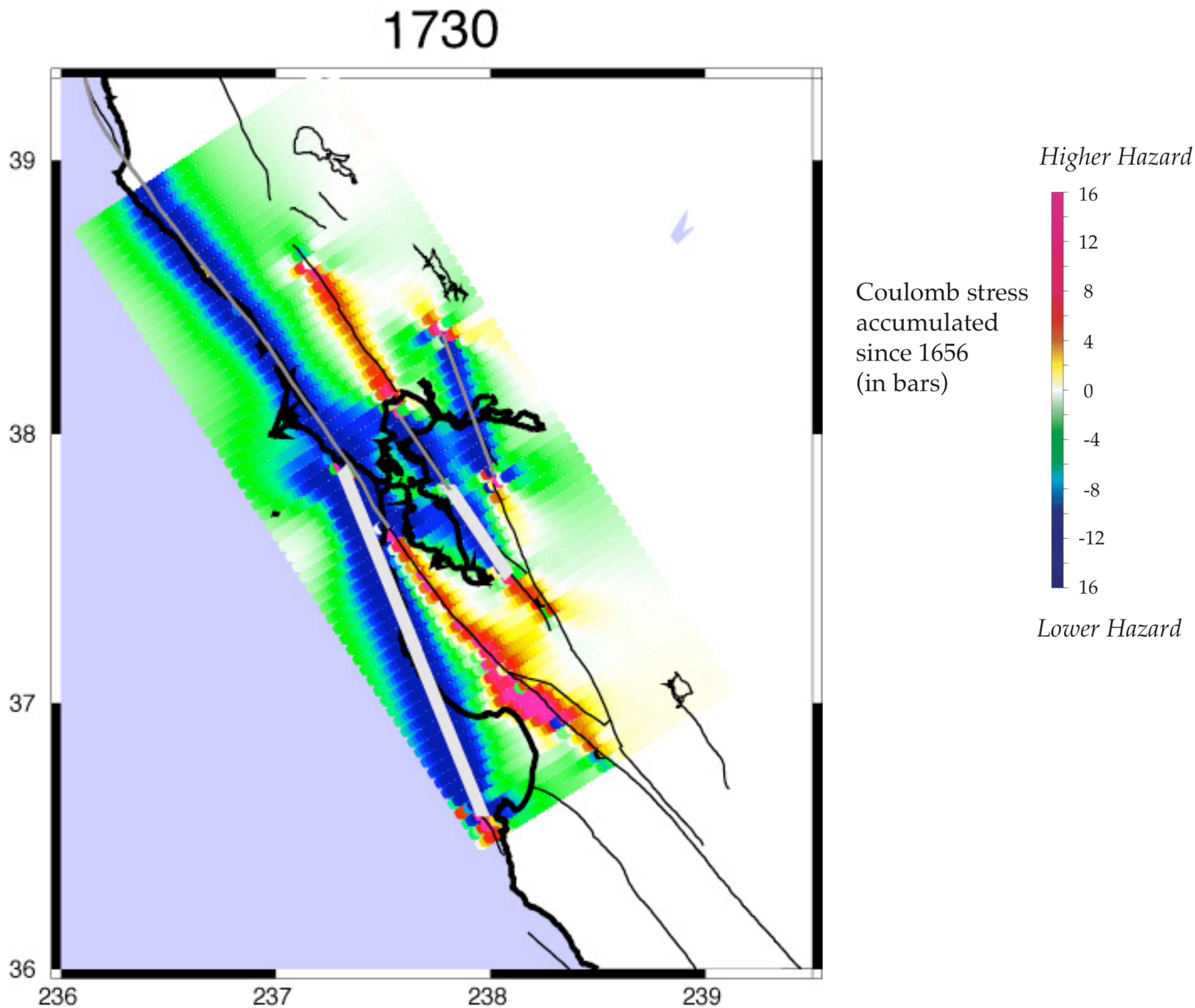


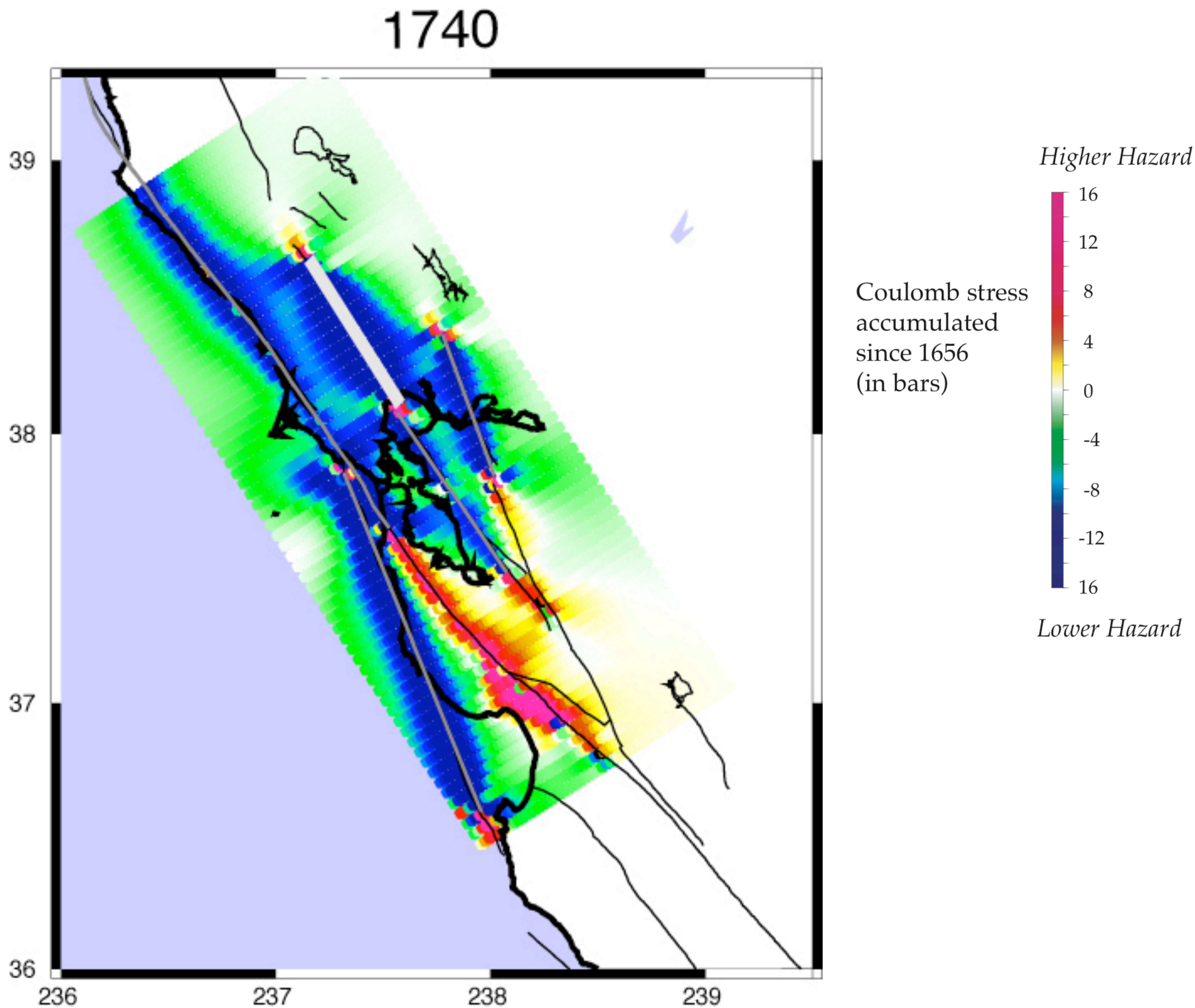
1710
39
38
37
36
236
237
238
239
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard
Coulomb stress
accumulated
since 1656
(in bars)

1720

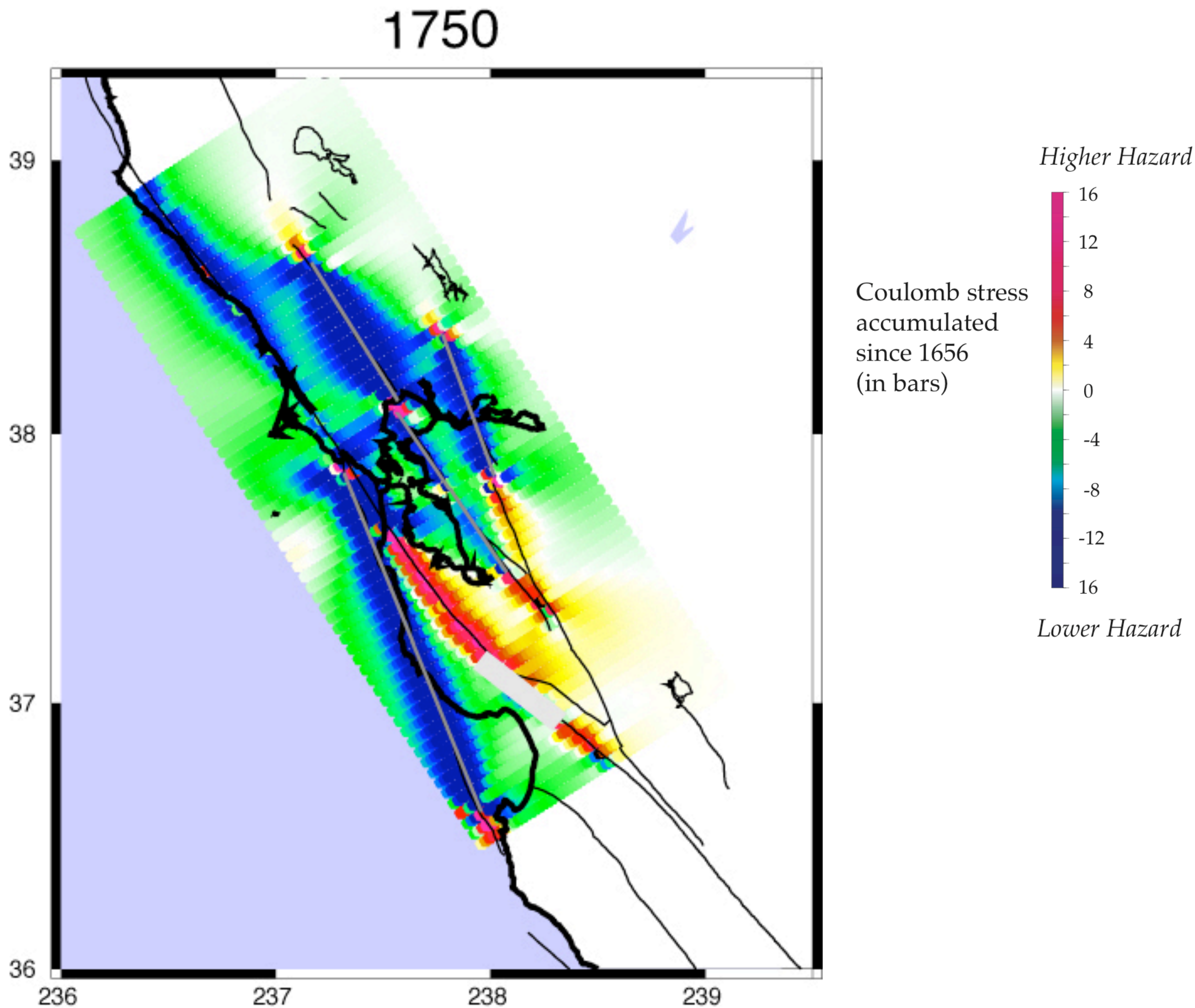


Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard
Coulomb stress accumulated since 1656 (in bars)
39
38
37
36
236
237
238
239

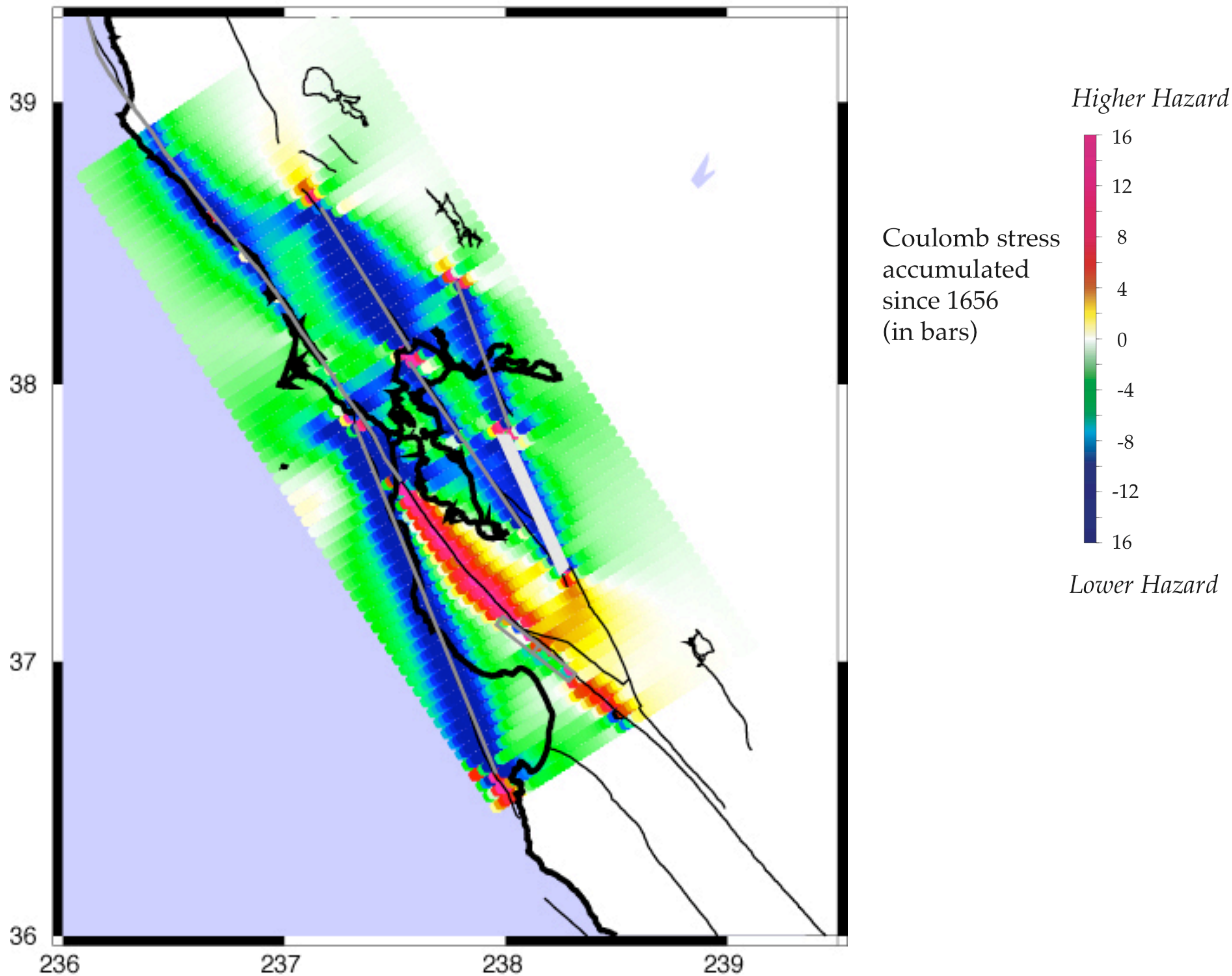

1730
39
38
37
36
236
237
238
239
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard
Coulomb stress accumulated since 1656 (in bars)



1740
39
38
37
36
236
237
238
239
Coulomb stress accumulated since 1656 (in bars)
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard

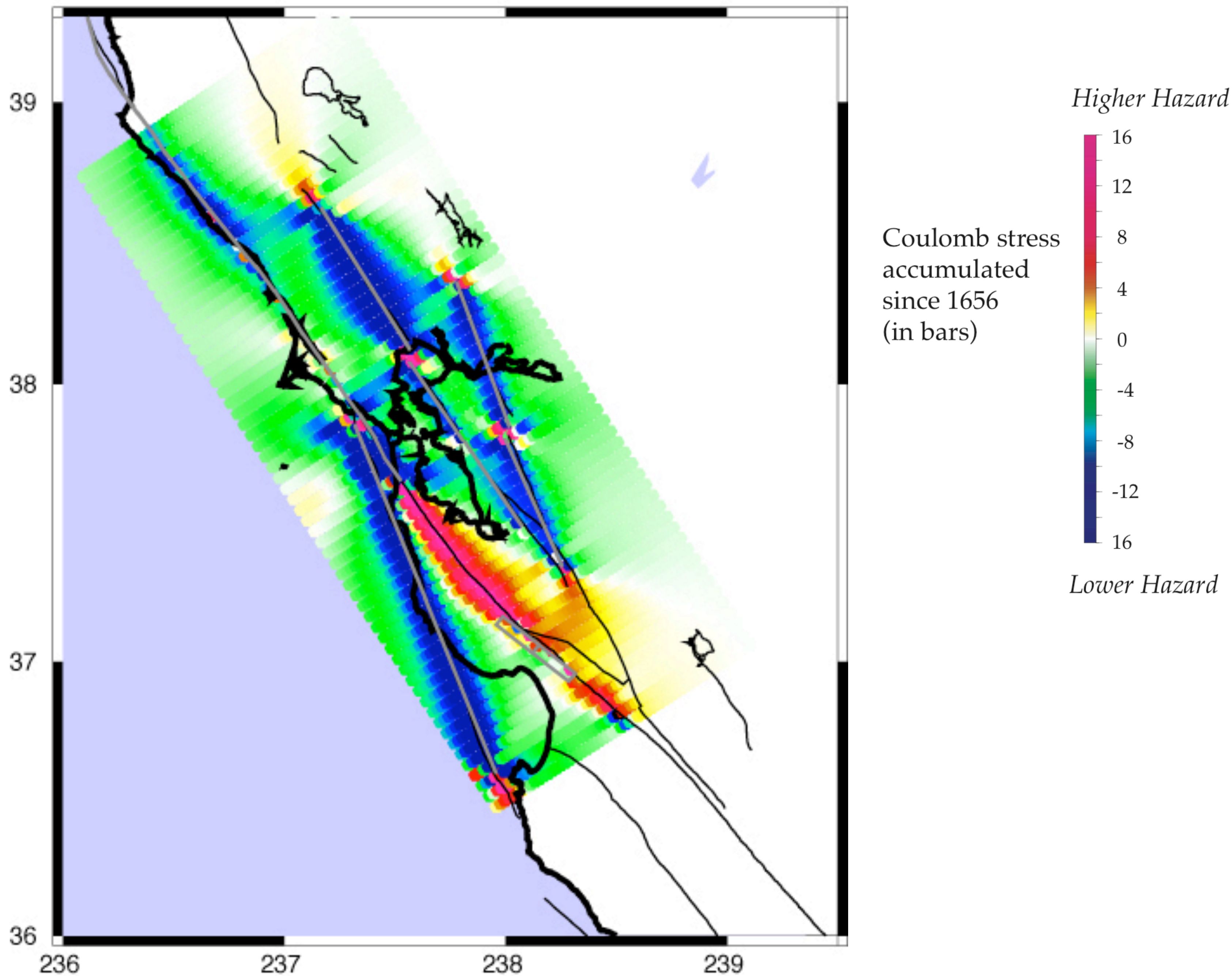

1750
39
38
37
36
236
237
238
239
Coulomb stress accumulated since 1656 (in bars)
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard

1760



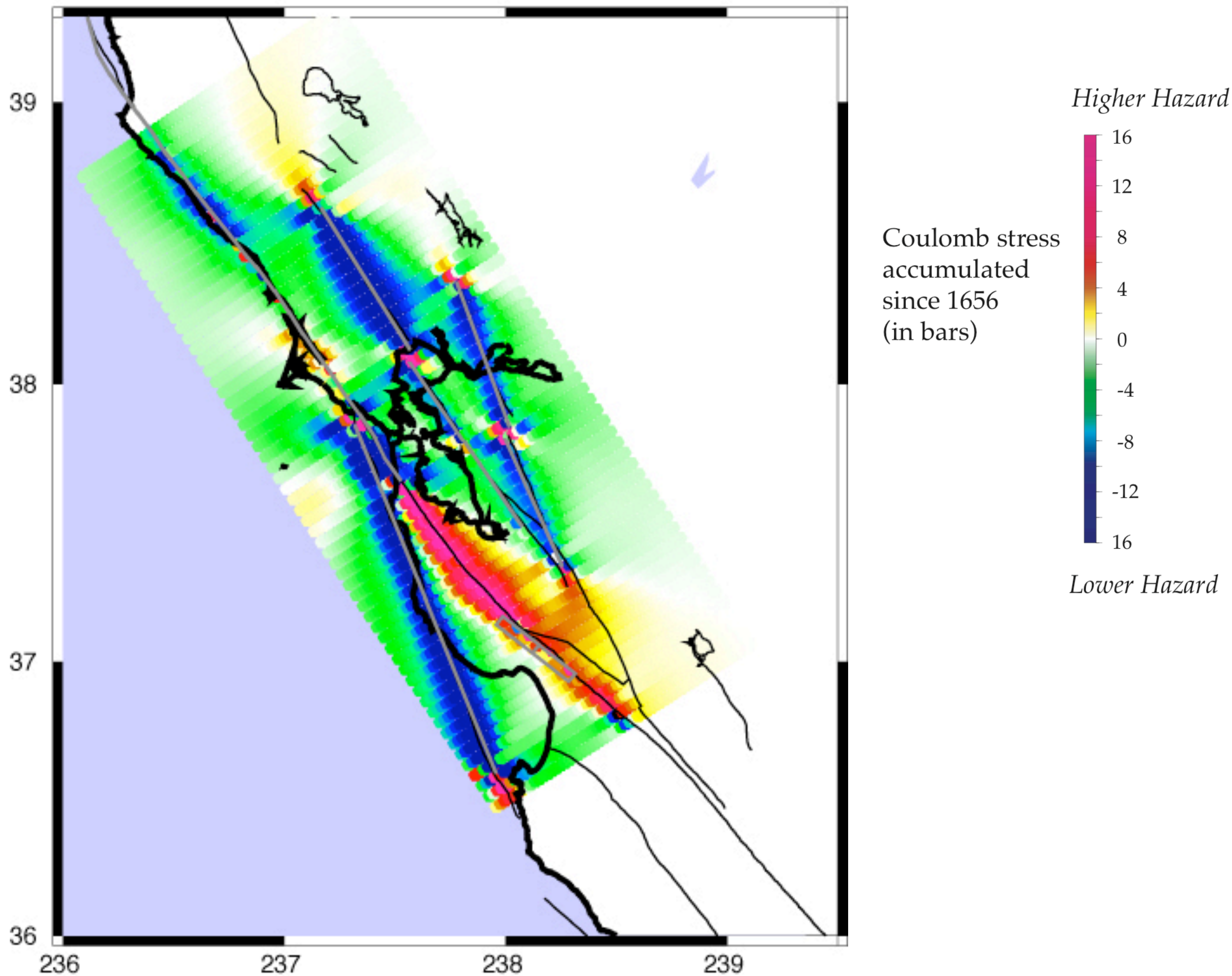
39
38
37
36
236
237
238
239
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard
Coulomb stress
accumulated
since 1656
(in bars)

1770

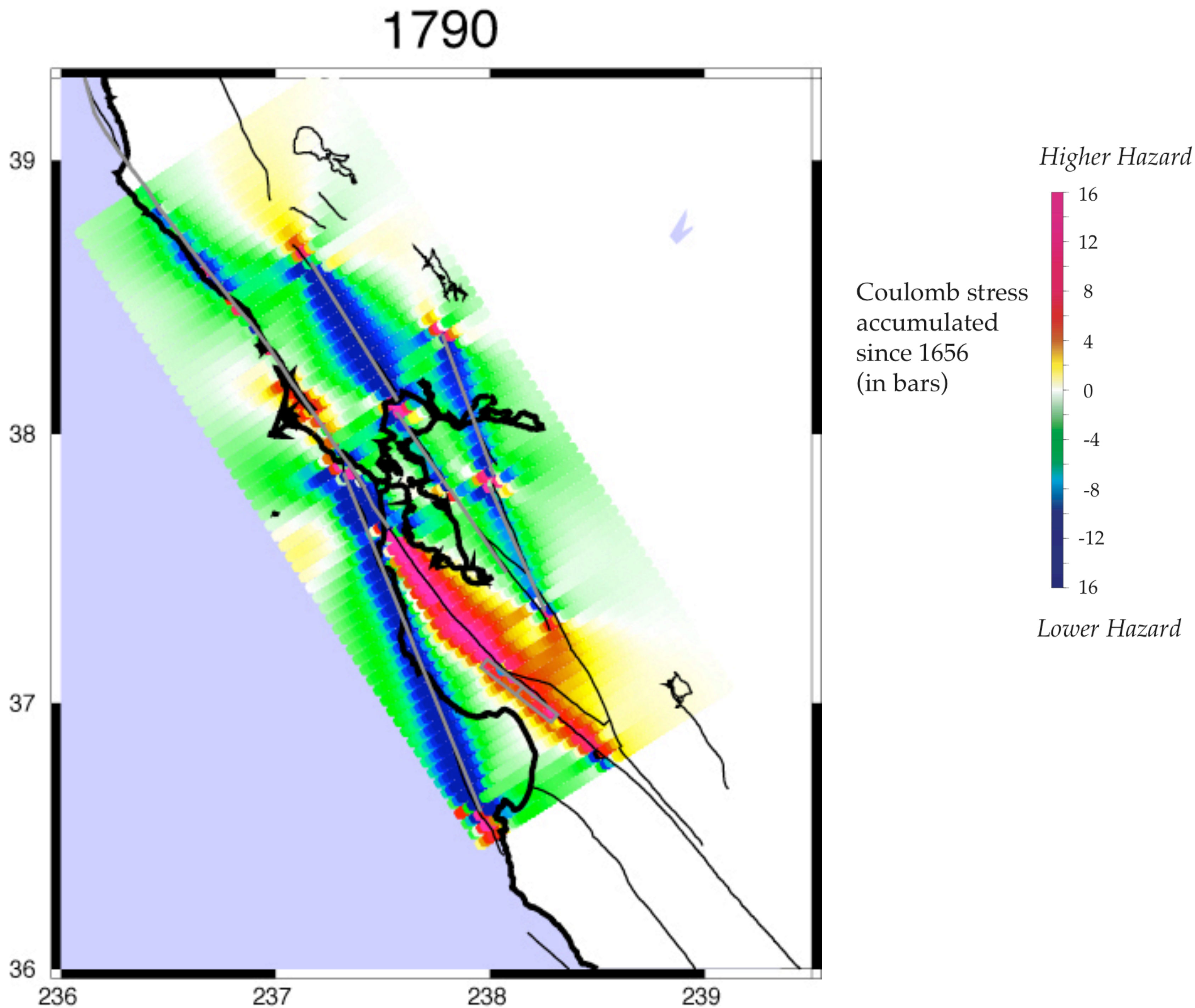


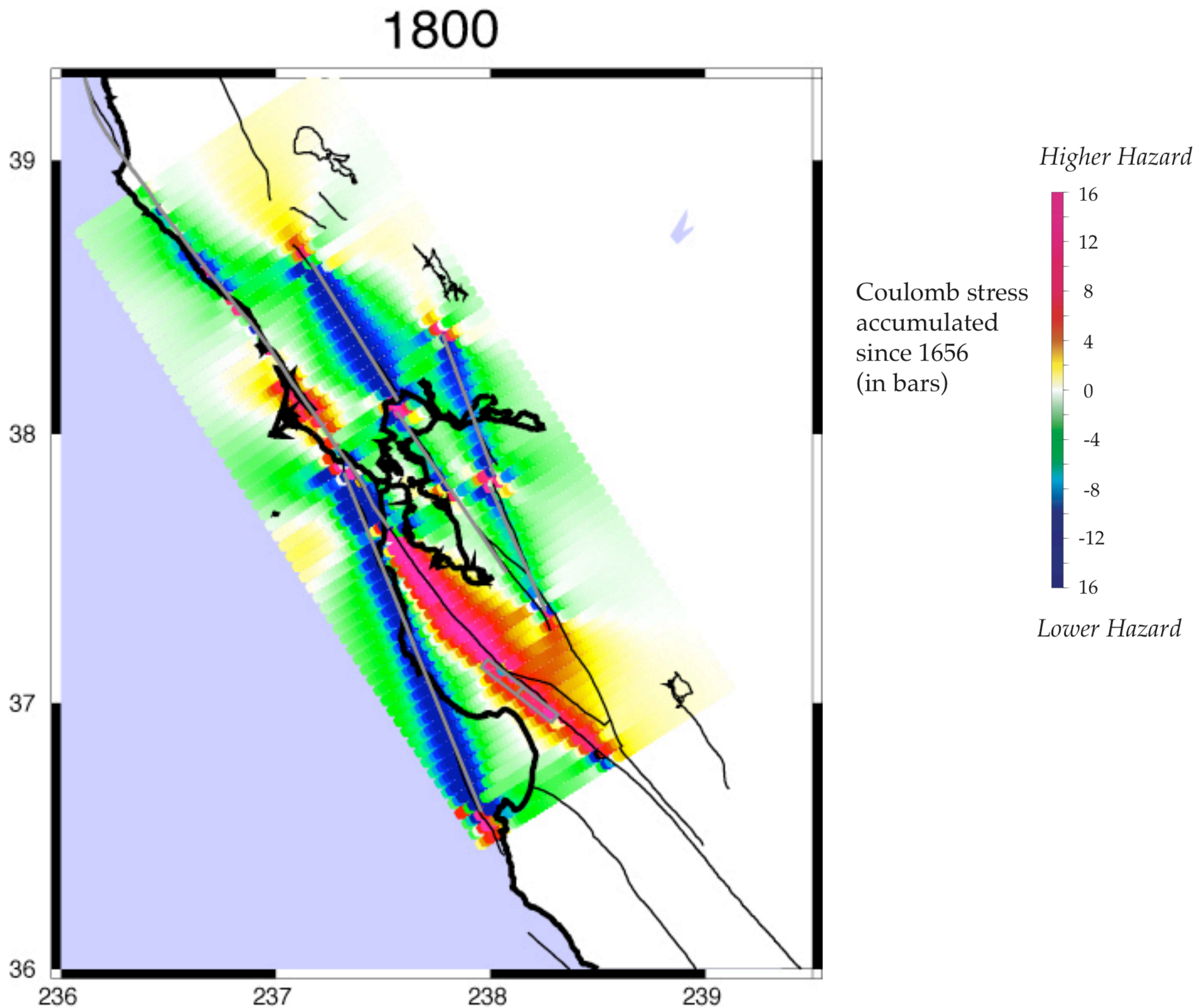
39
38
37
36
236
237
238
239
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard
Coulomb stress
accumulated
since 1656
(in bars)

1780

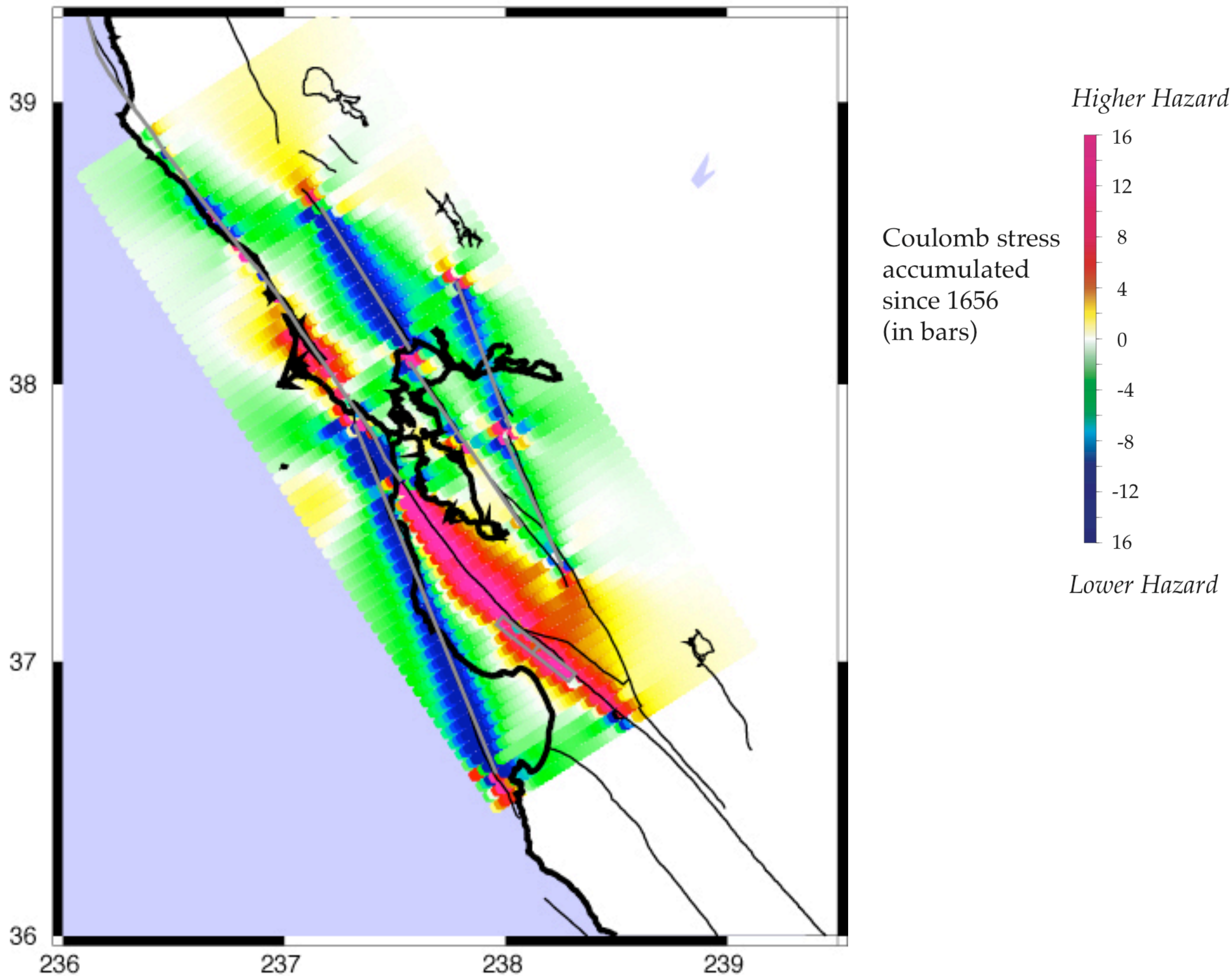


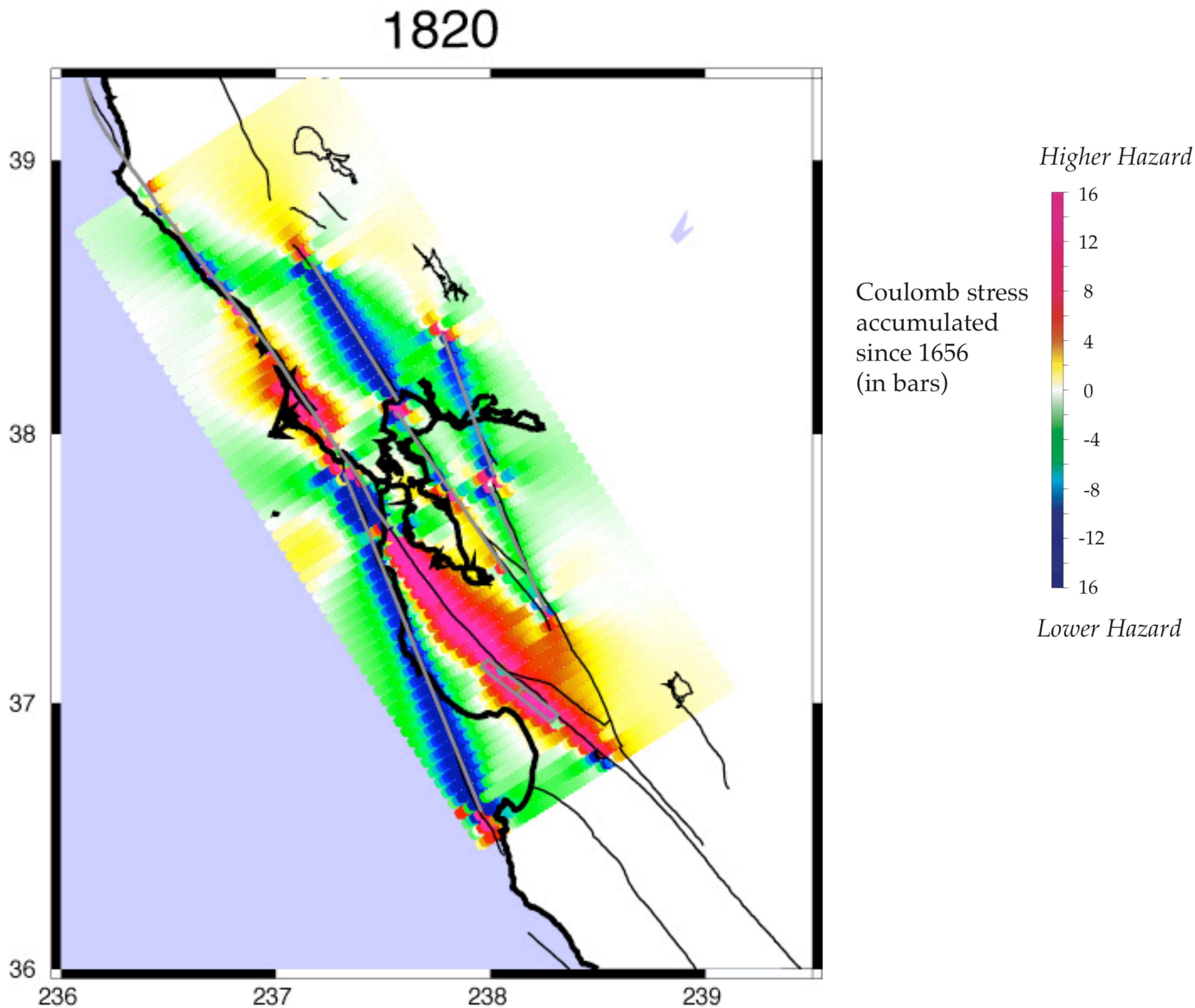
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard
Coulomb stress
accumulated
since 1656
(in bars)
39
38
37
36
236
237
238
239


1790
39
38
37
36
236
237
238
239
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard
Coulomb stress
accumulated
since 1656
(in bars)

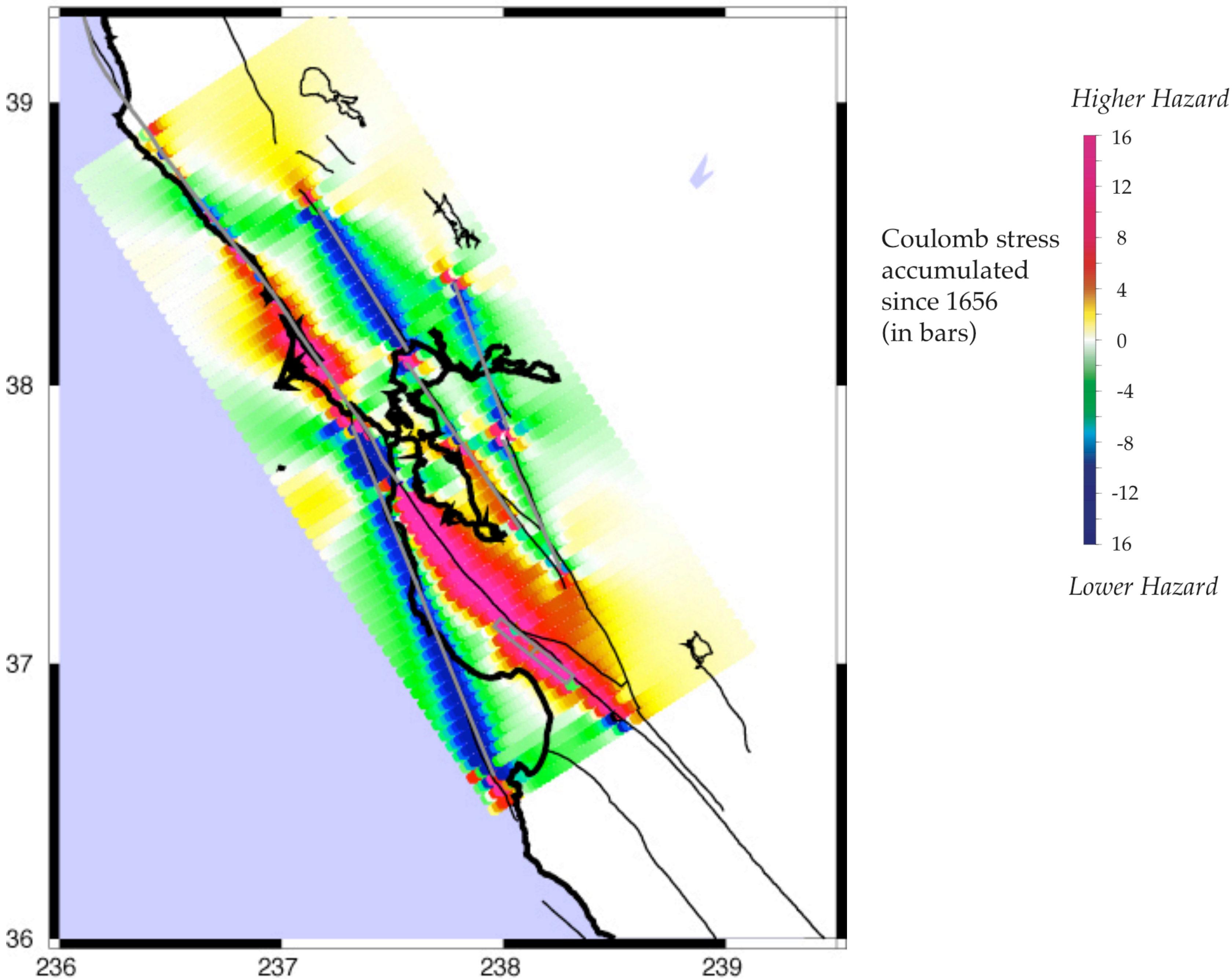

1800
39
38
37
36
236
237
238
239
Coulomb stress
accumulated
since 1656
(in bars)
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard

1810


39
38
37
36
236
237
238
239
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard
Coulomb stress
accumulated
since 1656
(in bars)

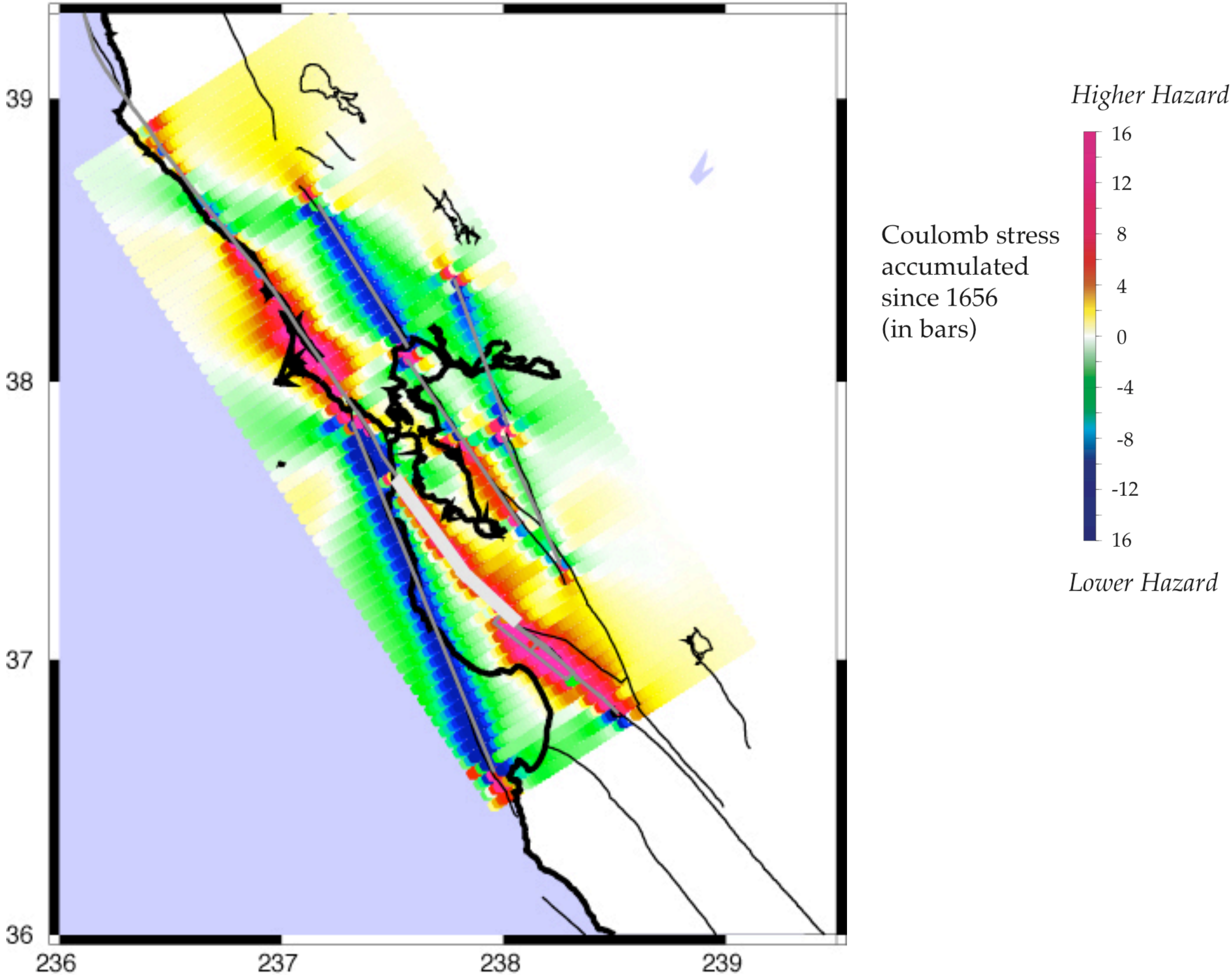

1820
39
38
37
36
236
237
238
239
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard
Coulomb stress accumulated since 1656 (in bars)

1830

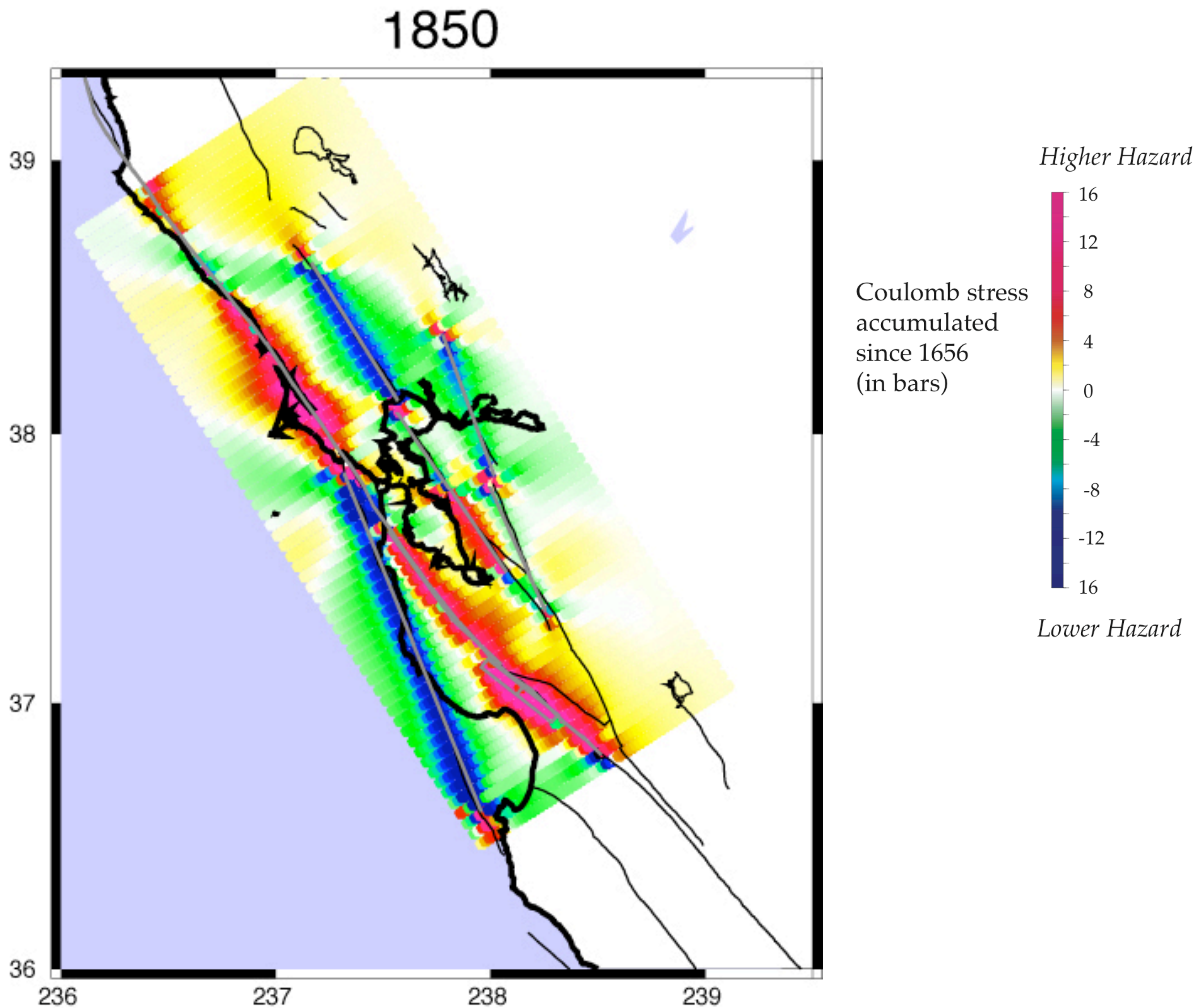


Coulomb stress accumulated since 1656 (in bars)

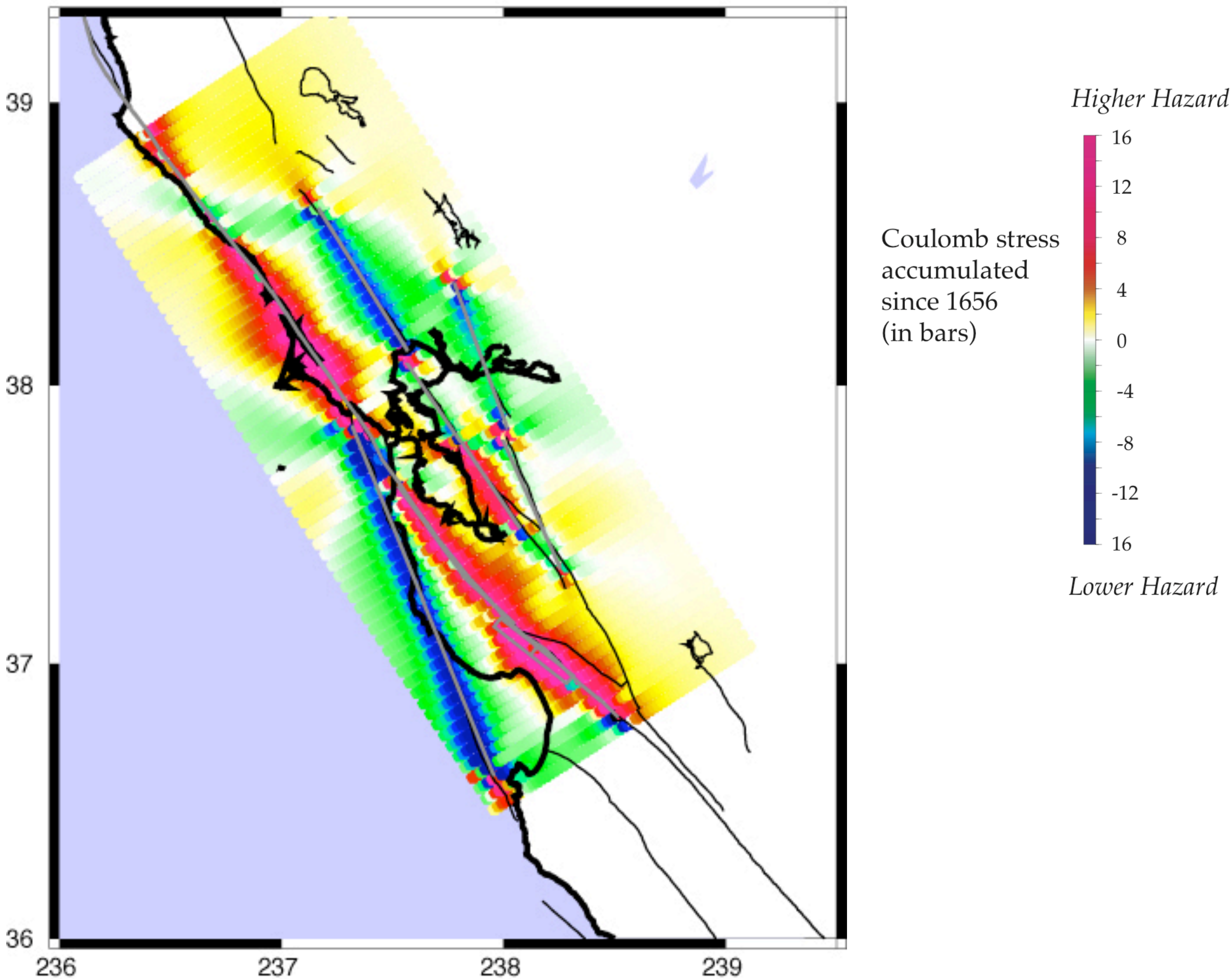
1840



39
38
37
36
236
237
238
239
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard
Coulomb stress
accumulated
since 1656
(in bars)

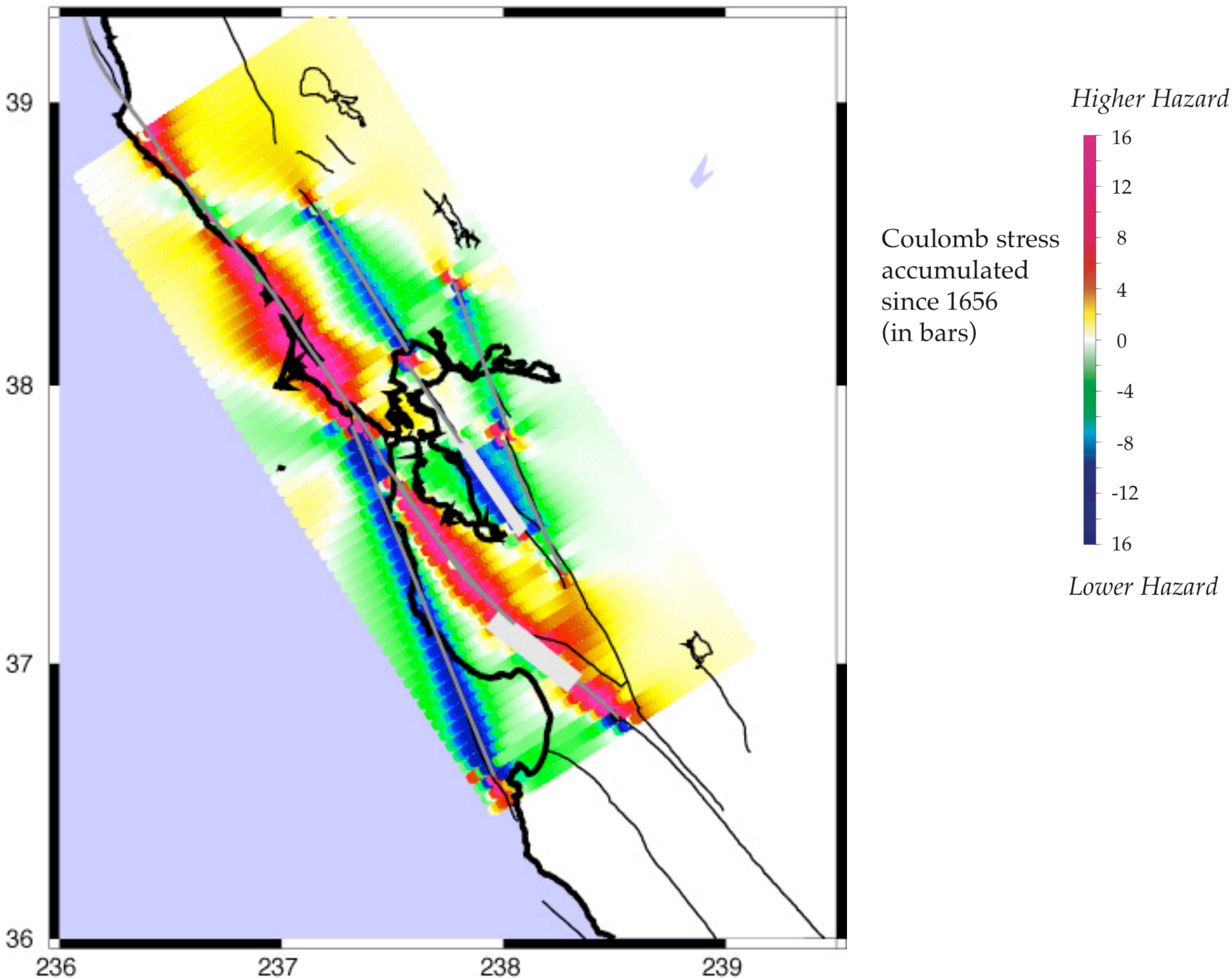

1850
39
38
37
36
236
237
238
239
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard
Coulomb stress
accumulated
since 1656
(in bars)

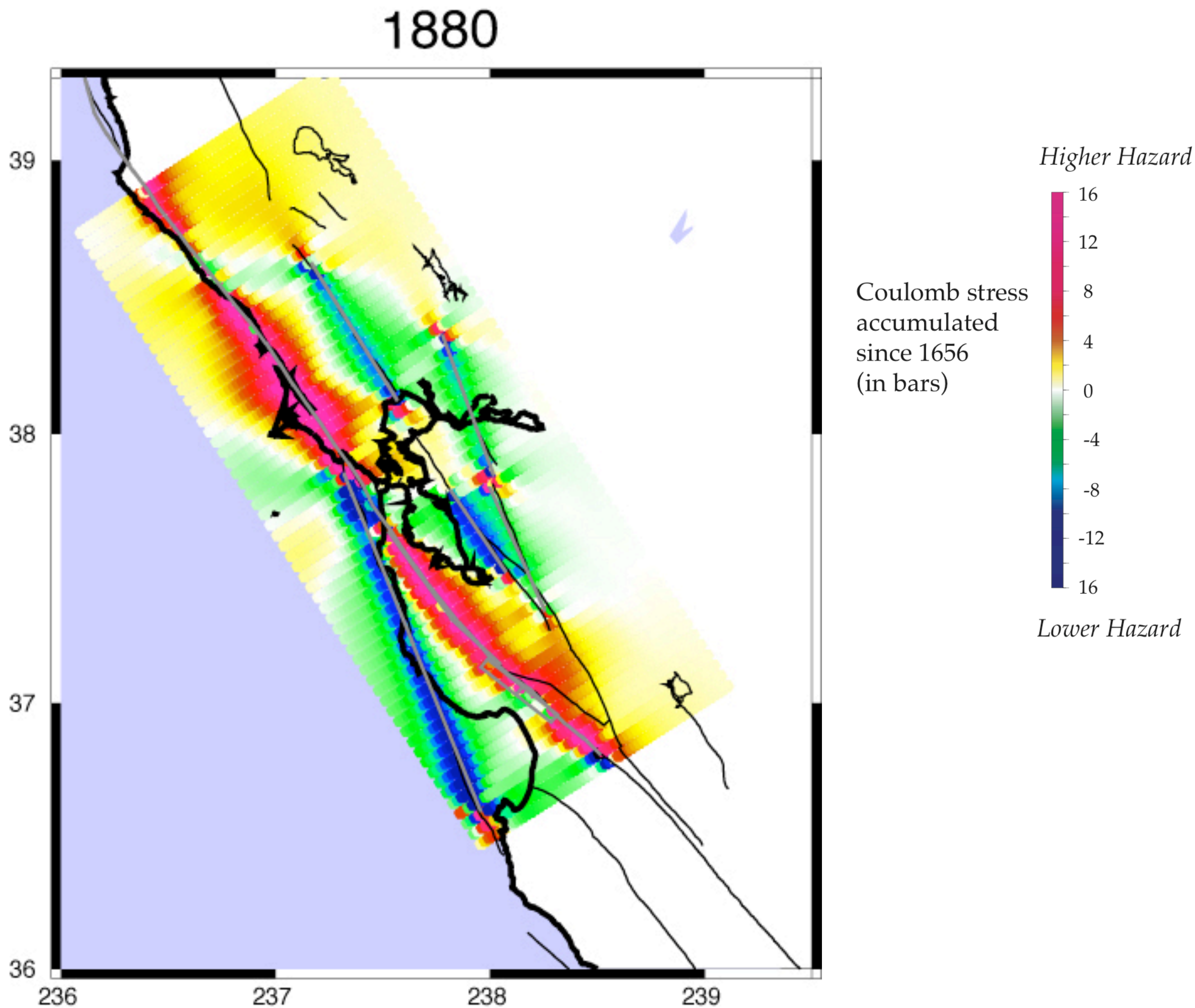
1860

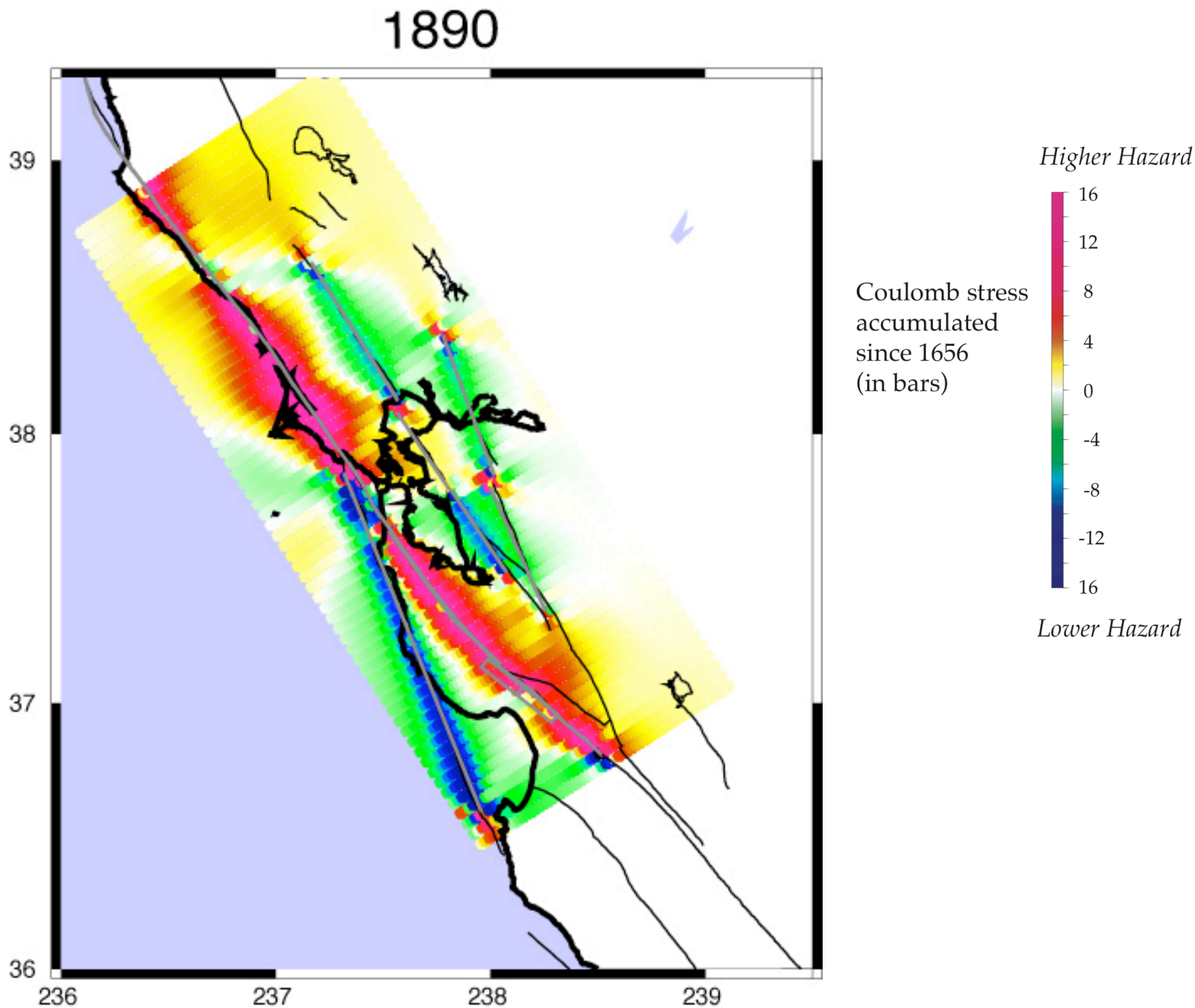


39
38
37
36
236
237
238
239
Coulomb stress
accumulated
since 1656
(in bars)
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard

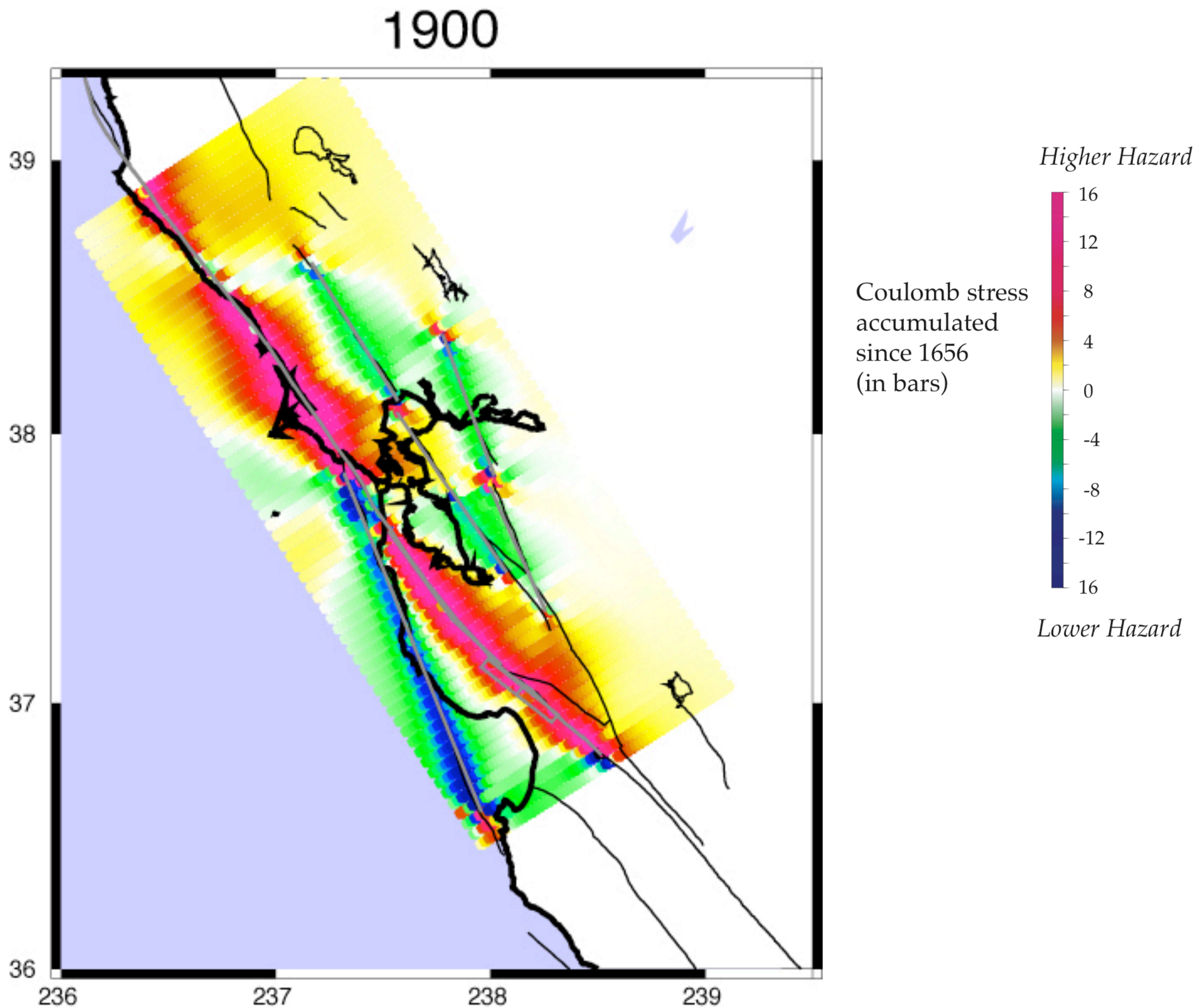
1870

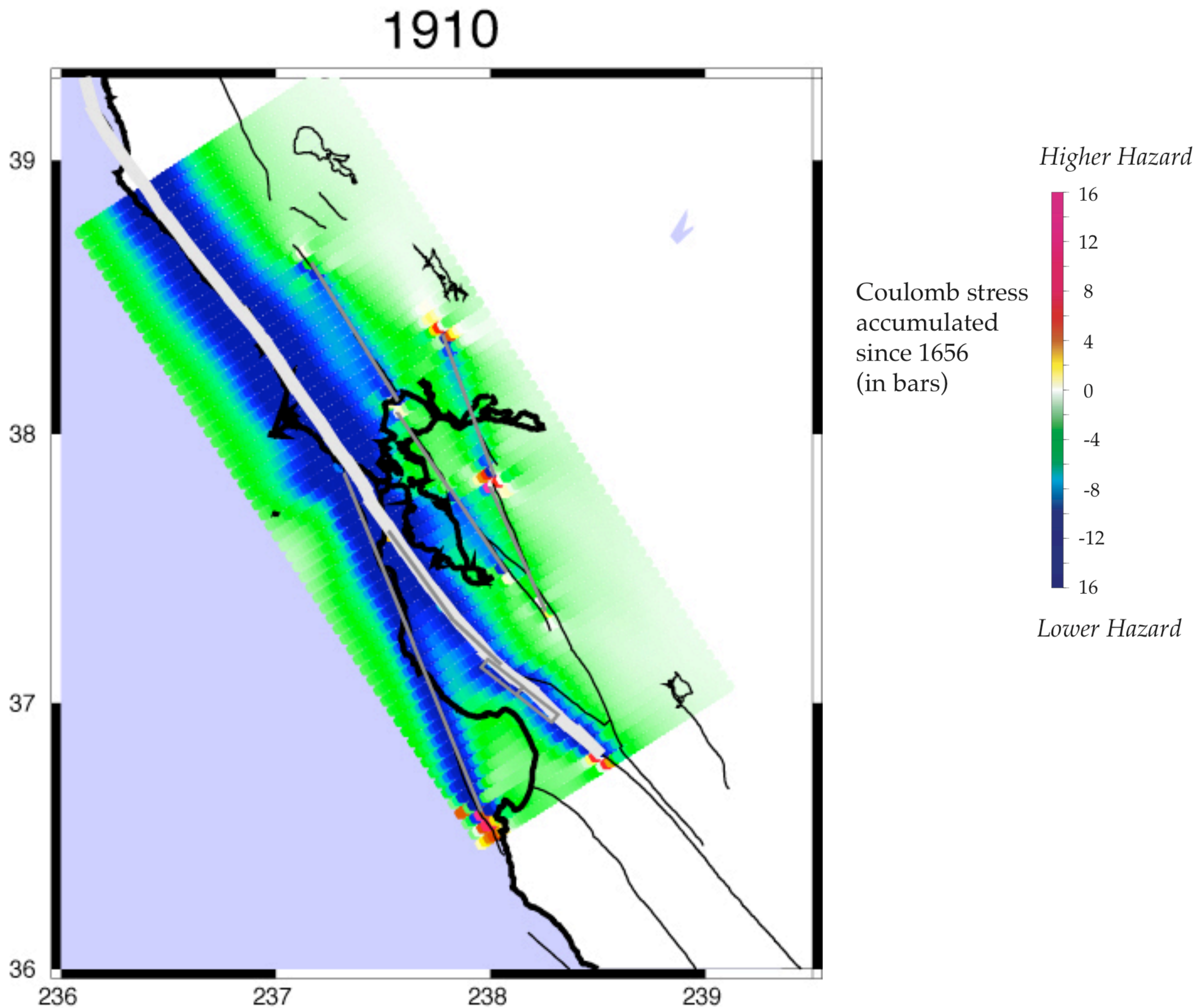

39
38
37
36
236
237
238
239
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard
Coulomb stress
accumulated
since 1656
(in bars)

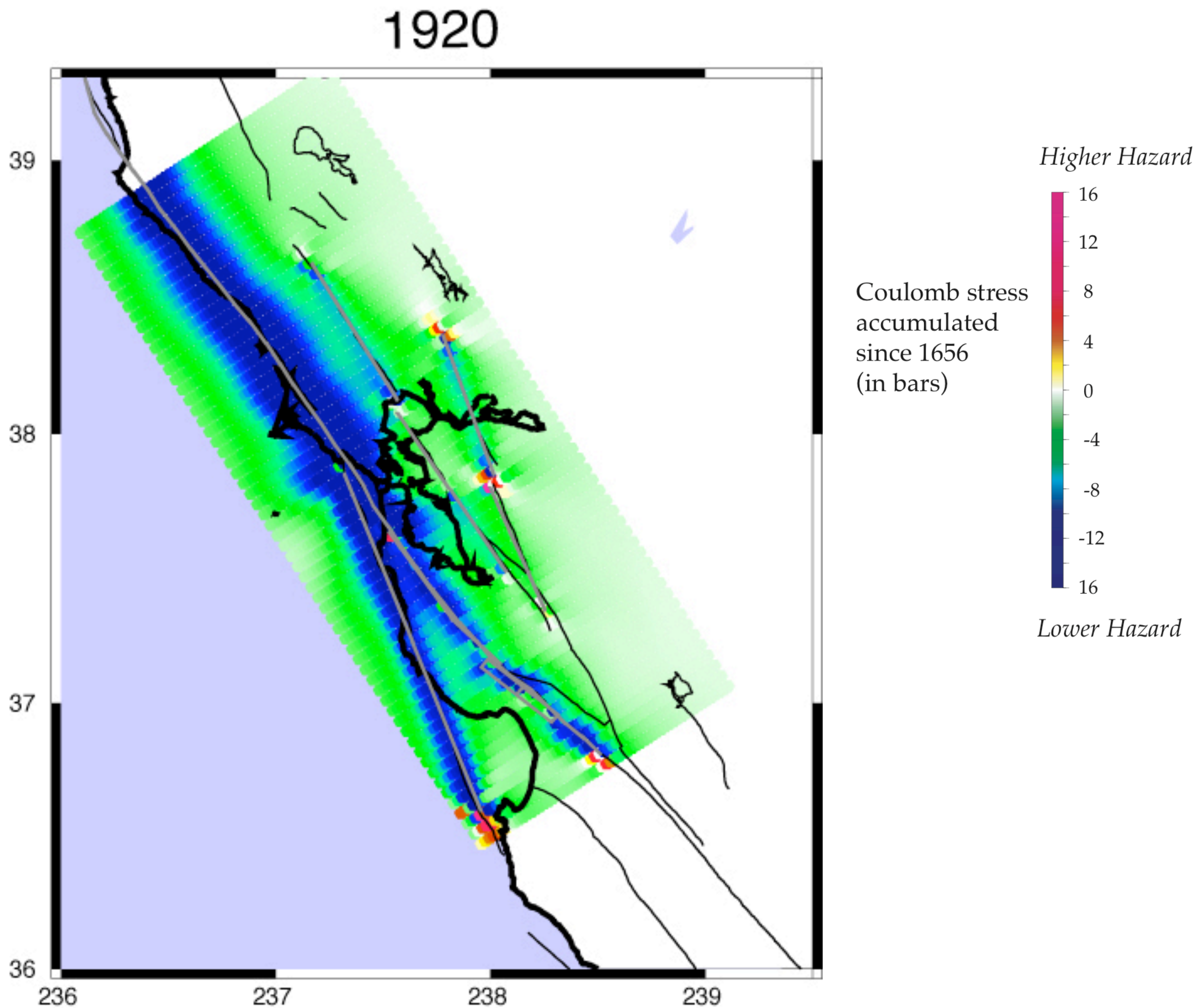

1880
39
38
37
36
236
237
238
239
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard
Coulomb stress
accumulated
since 1656
(in bars)

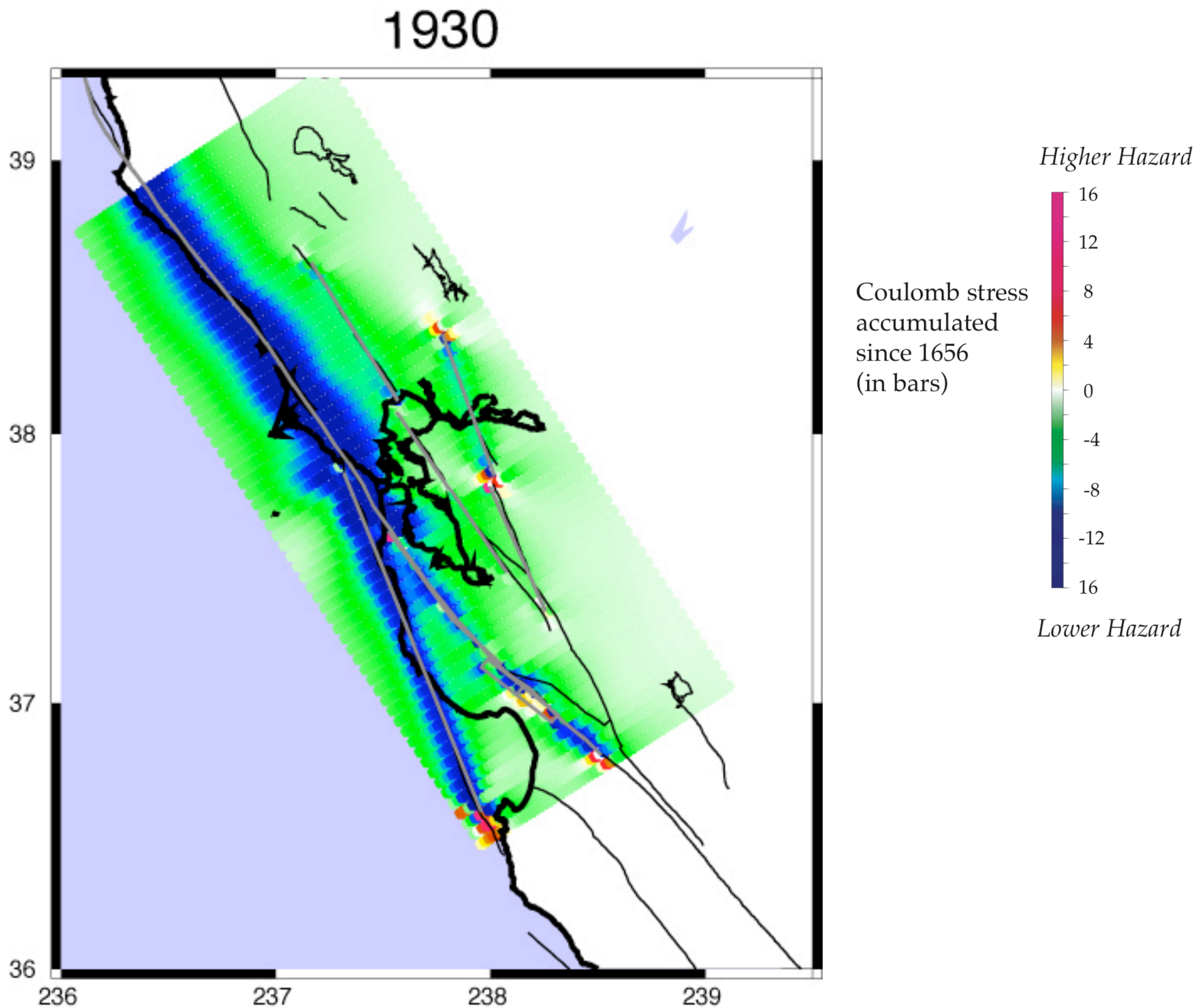


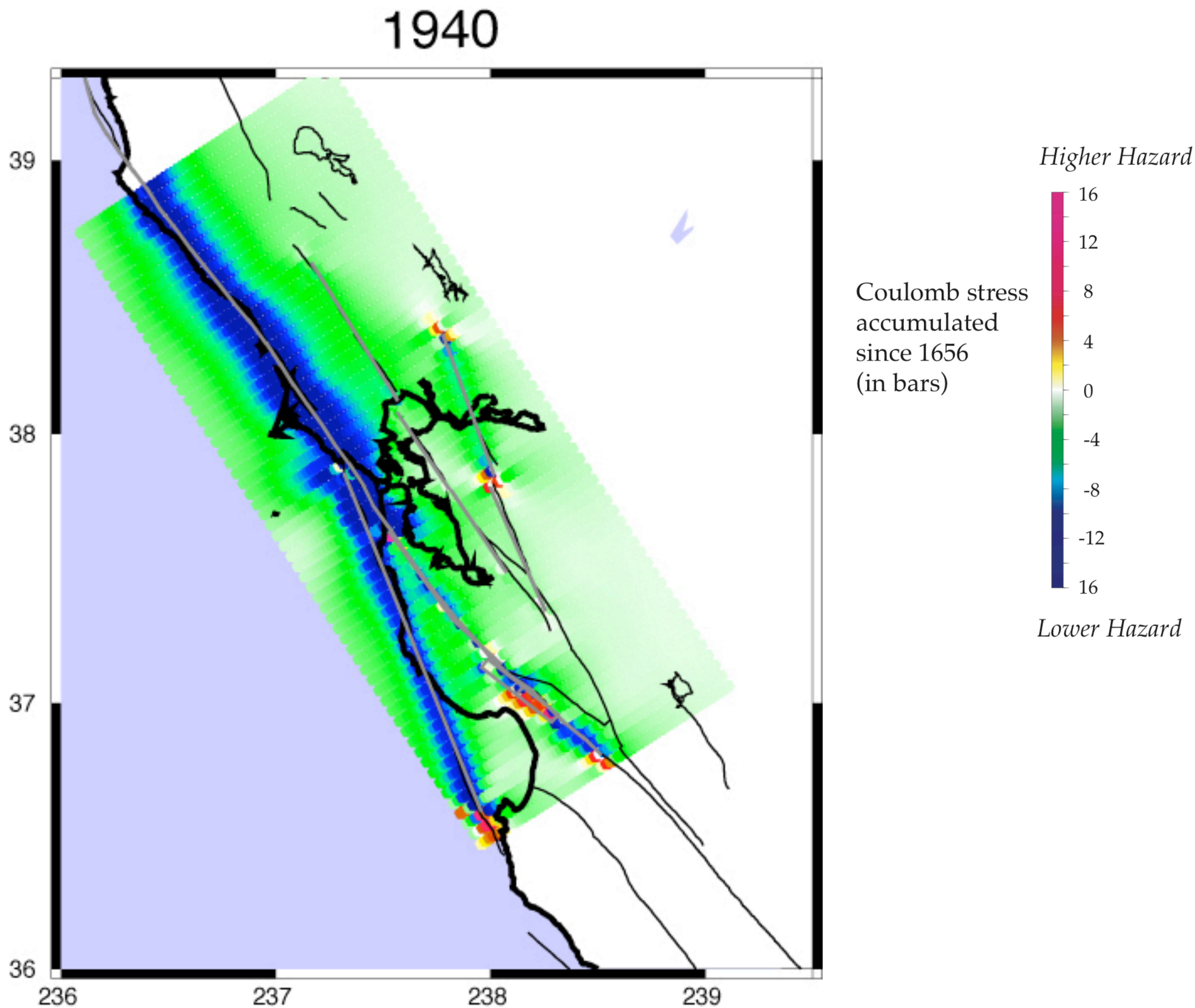
1890
39
38
37
36
236
237
238
239
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard
Coulomb stress accumulated since 1656 (in bars)

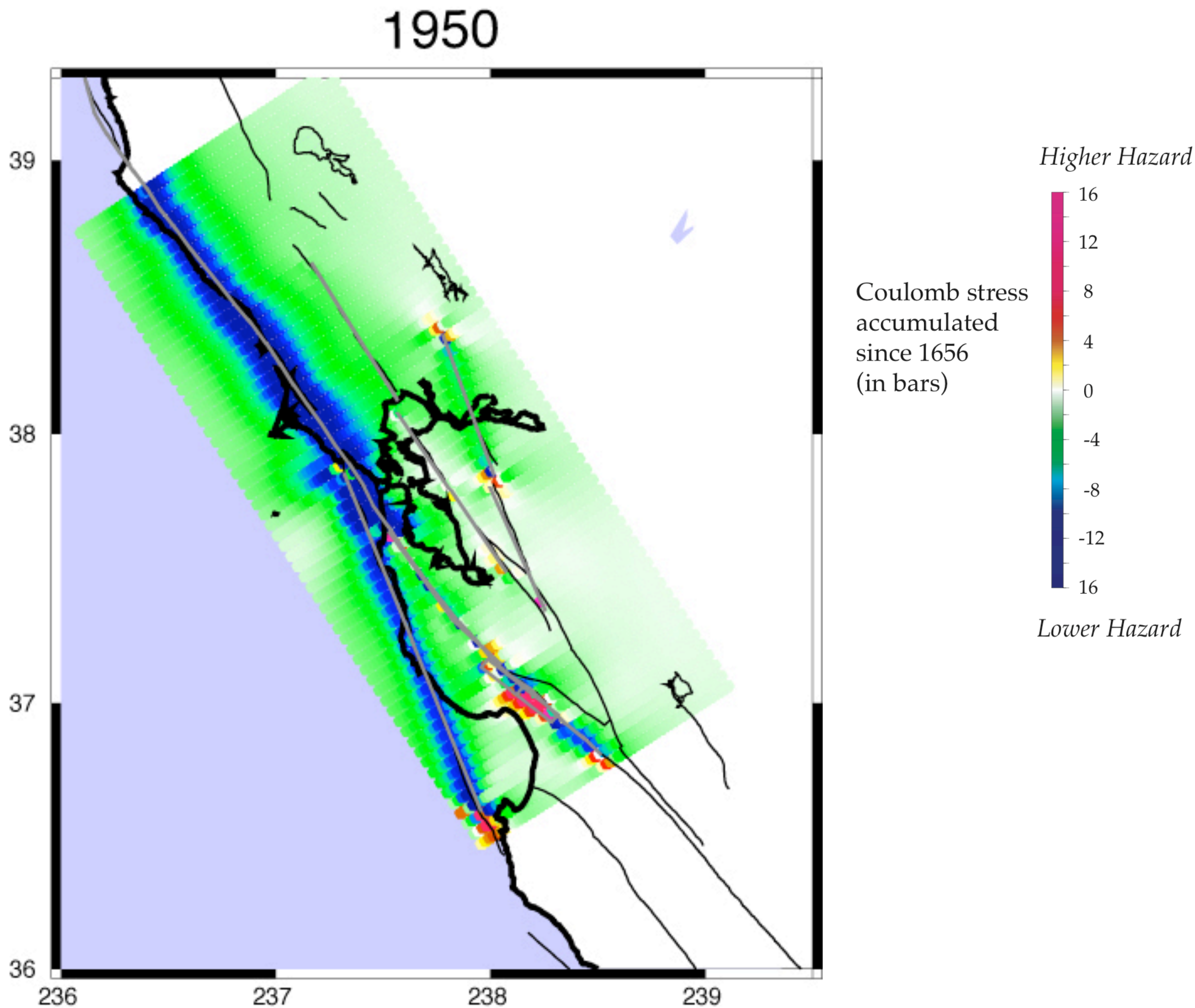

1900
39
38
37
36
236
237
238
239
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard
Coulomb stress
accumulated
since 1656
(in bars)


1910
39
38
37
36
236
237
238
239
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard
Coulomb stress accumulated since 1656 (in bars)

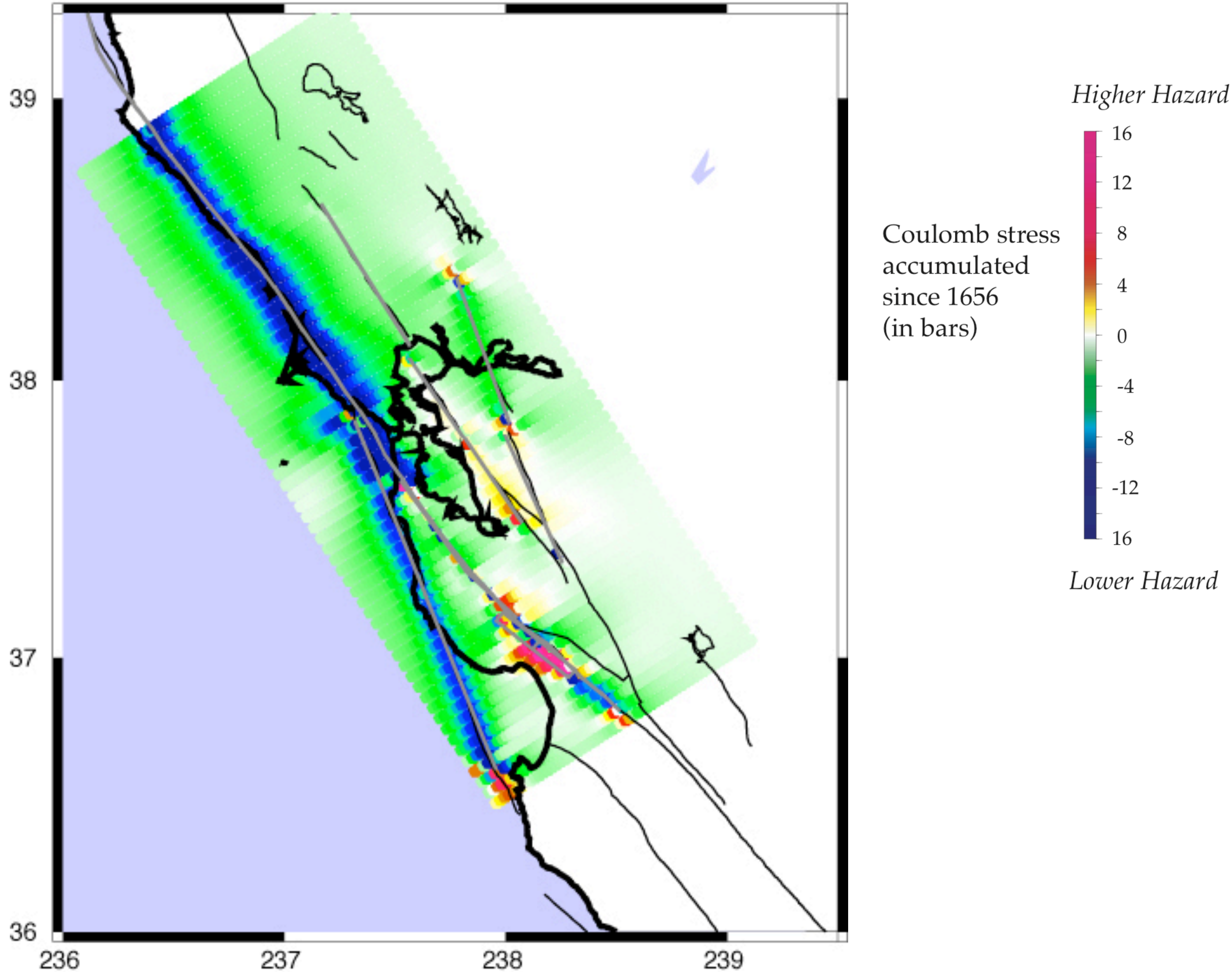

1920
39
38
37
36
236
237
238
239
Coulomb stress accumulated since 1656 (in bars)
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard


1930
39
38
37
36
236
237
238
239
Coulomb stress
accumulated
since 1656
(in bars)
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard

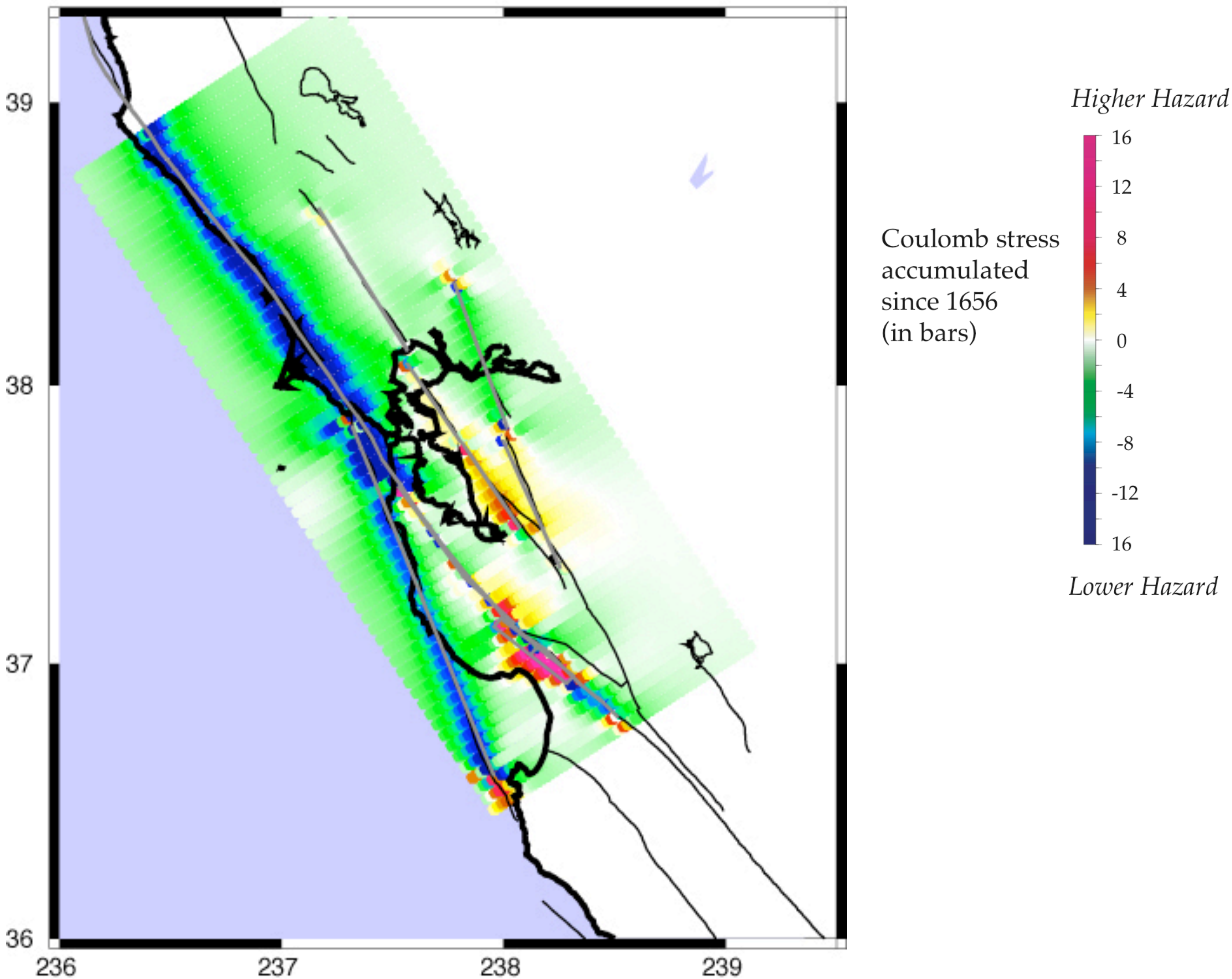

1940
39
38
37
36
236
237
238
239
Coulomb stress
accumulated
since 1656
(in bars)
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard


1950
39
38
37
36
236
237
238
239
Coulomb stress accumulated since 1656 (in bars)
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard

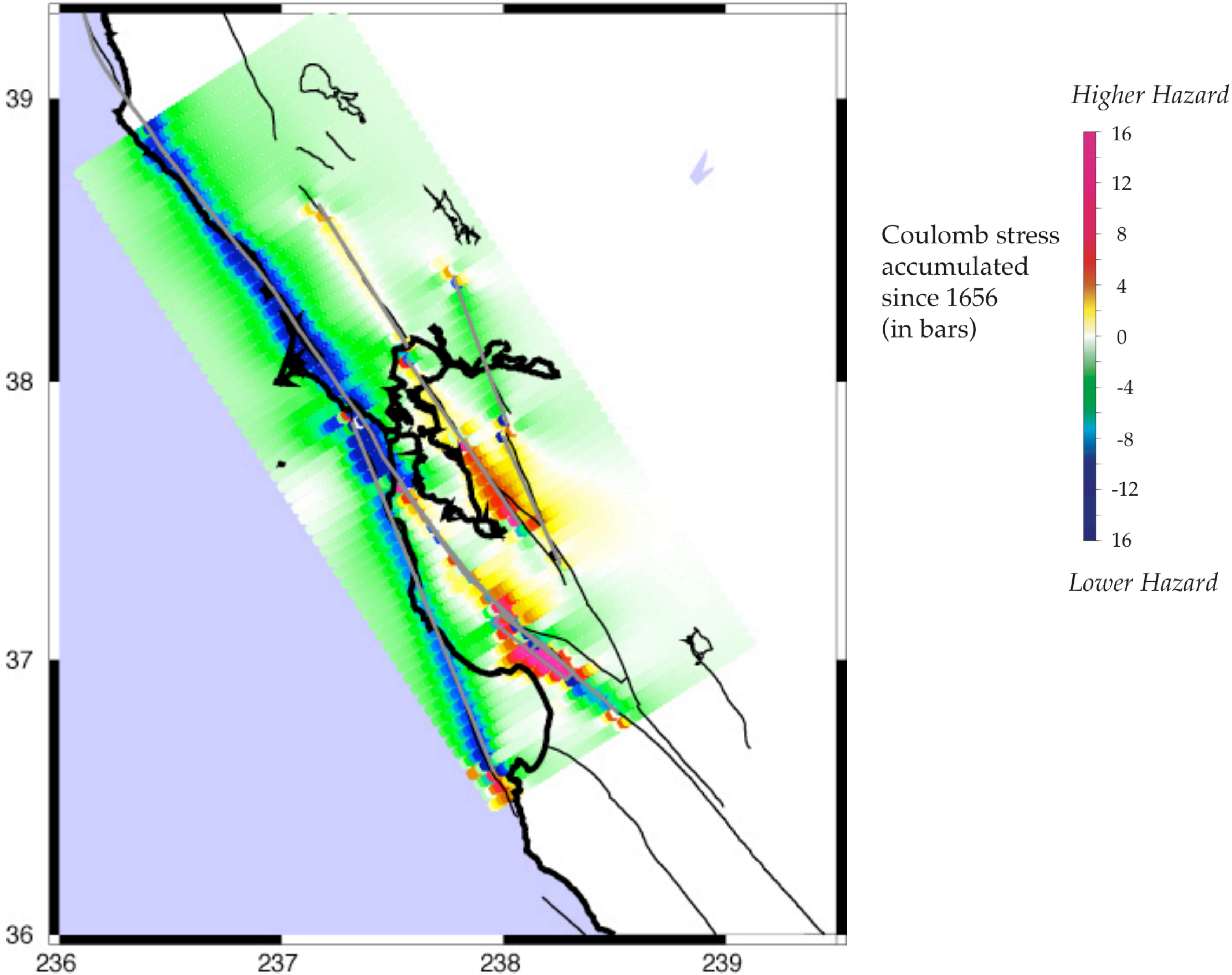
1960


39
38
37
36
236
237
238
239
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard
Coulomb stress
accumulated
since 1656
(in bars)

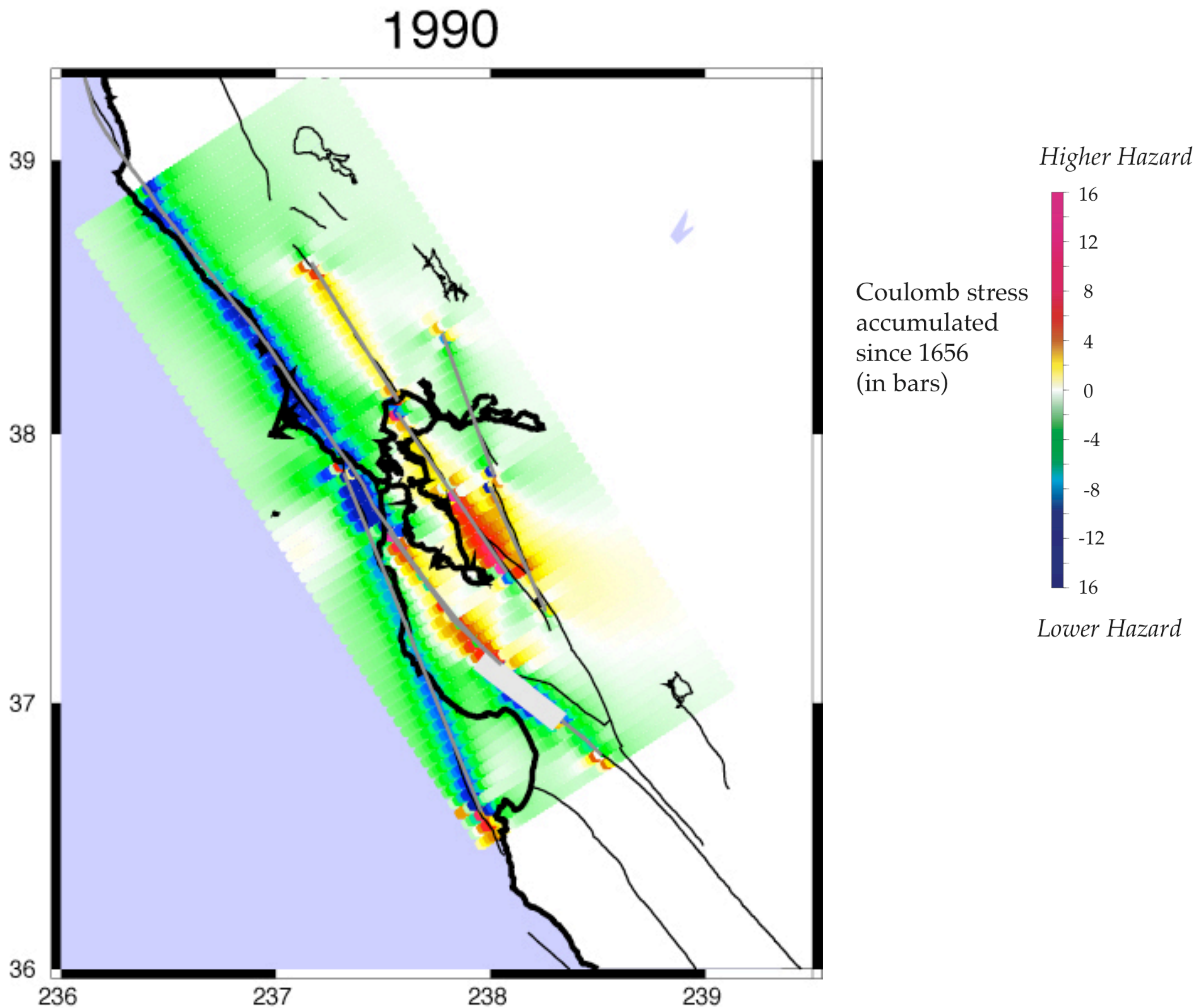
1970

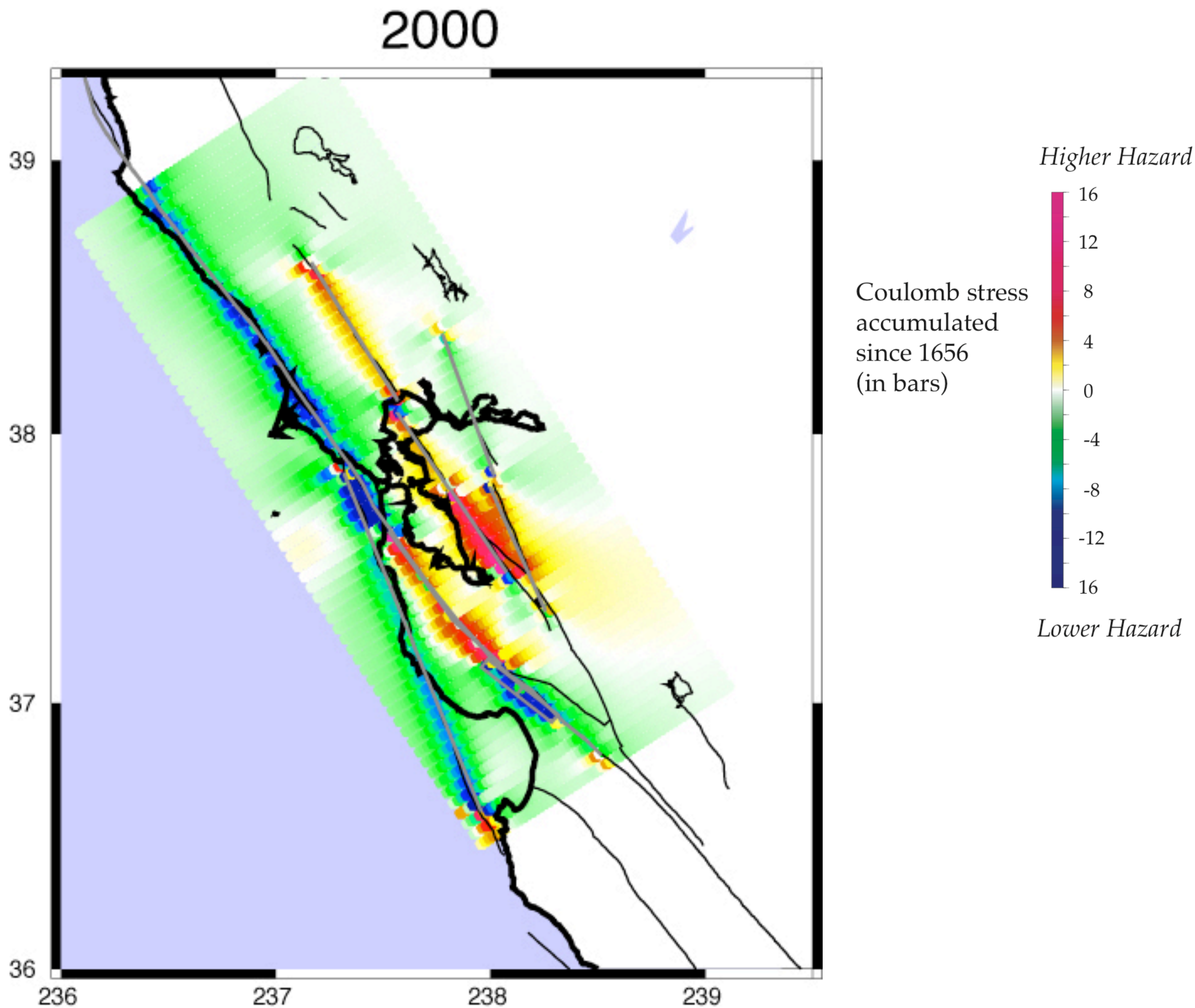

39
38
37
36
236
237
238
239
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard
Coulomb stress accumulated since 1656 (in bars)

1980

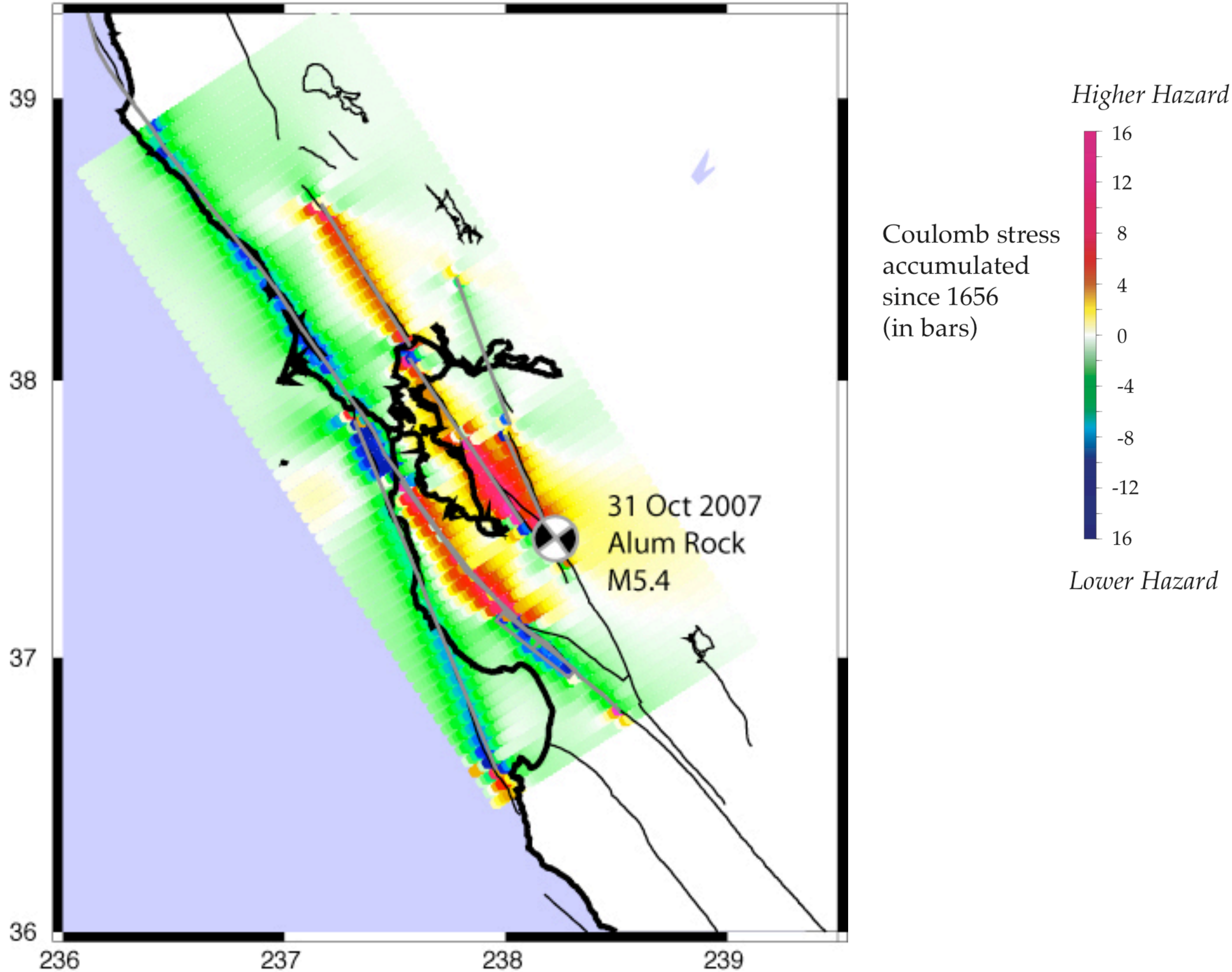


39
38
37
36
236
237
238
239
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard
Coulomb stress
accumulated
since 1656
(in bars)


1990
39
38
37
36
236
237
238
239
Coulomb stress accumulated since 1656 (in bars)
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard


2000
39
38
37
36
236
237
238
239
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard
Coulomb stress accumulated since 1656 (in bars)

2010



31 Oct 2007
Alum Rock
M5.4
Coulomb stress
accumulated
since 1656
(in bars)
Higher Hazard
16
12
8
4
0
-4
-8
-12
16
Lower Hazard
39
38
37
36
236
237
238
239

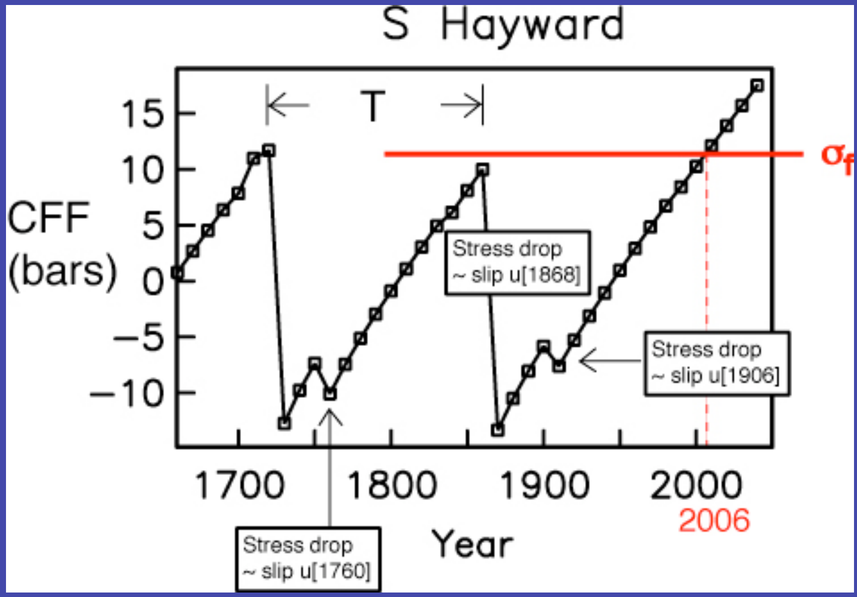
Perturbations

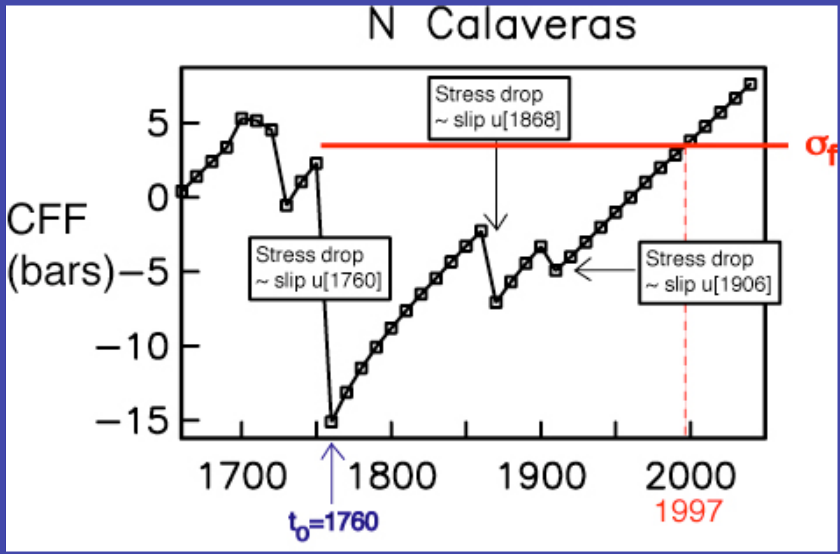
Viscoelastic cycle parameters

- Recurrence interval T
- Slip {u} of past repeating earthquakes
- Date t_0 of last earthquake (prehistoric ruptures)

Failure stress

- Stress threshold σ_f applicable to future event





Future rupture probabilities based on:

- Perturbation of controlling parameters of a deterministic viscoelastic-cycle model

- Time-predictable model: Entire fault will fail when a representative fault patch returns to same state of stress (+perturbation) that it had just before the previous event

- Monte Carlo simulation

Monte Carlo simulation

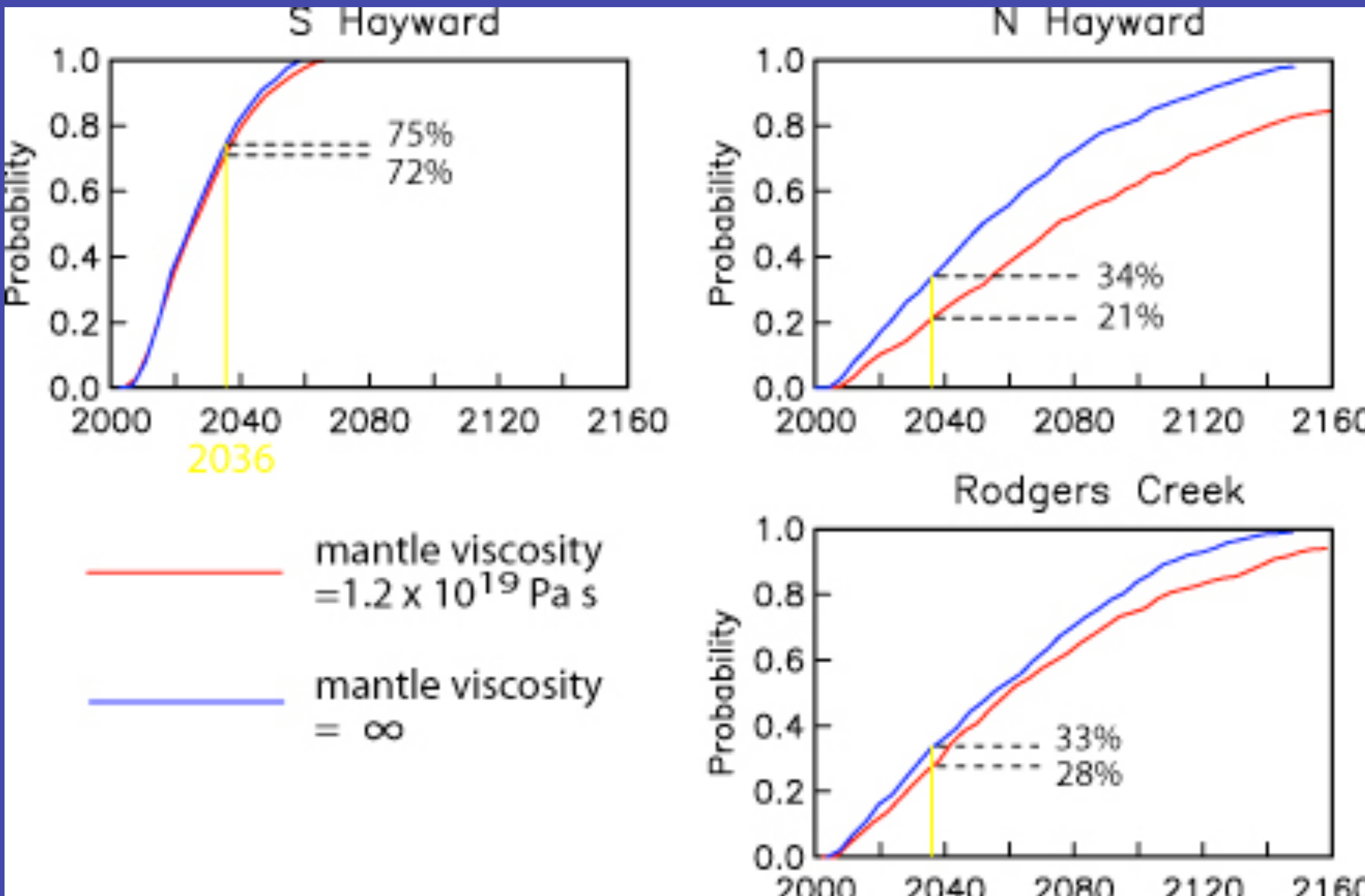
- On given fault patch, estimate distribution of future rupture times t, subject to 1000 realizations of perturbations of T, {u}, t_0 (for every event) and σ_f (for failure stress on the patch)

- Enforce net slip rate condition

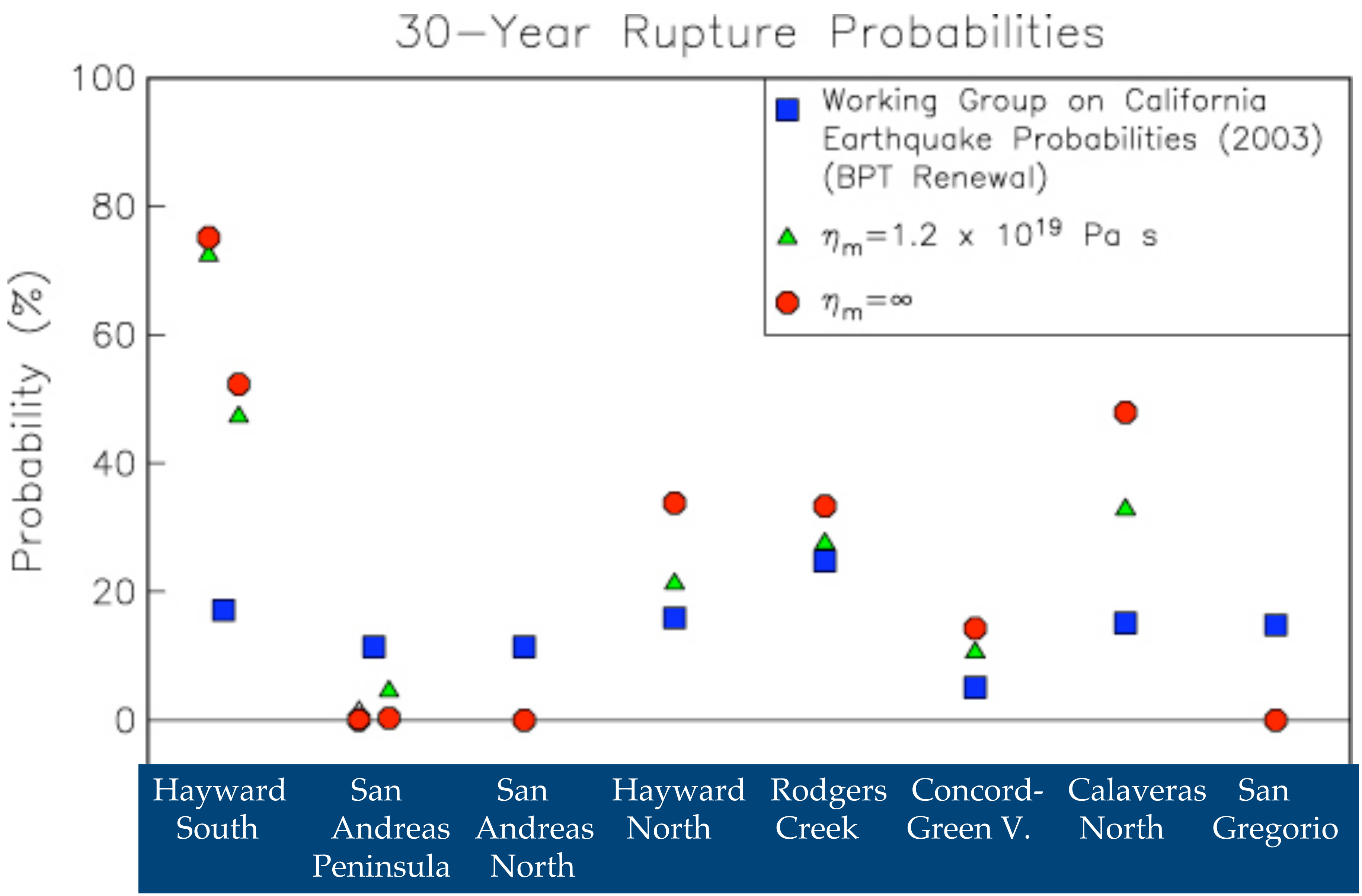
$$\sum_{\text{profile}} \frac{\text{perturbed } u}{\text{perturbed } T} = 36 \text{ to } 41 \text{ mm/yr}$$

- t > 2006 to derive conditional probability curves

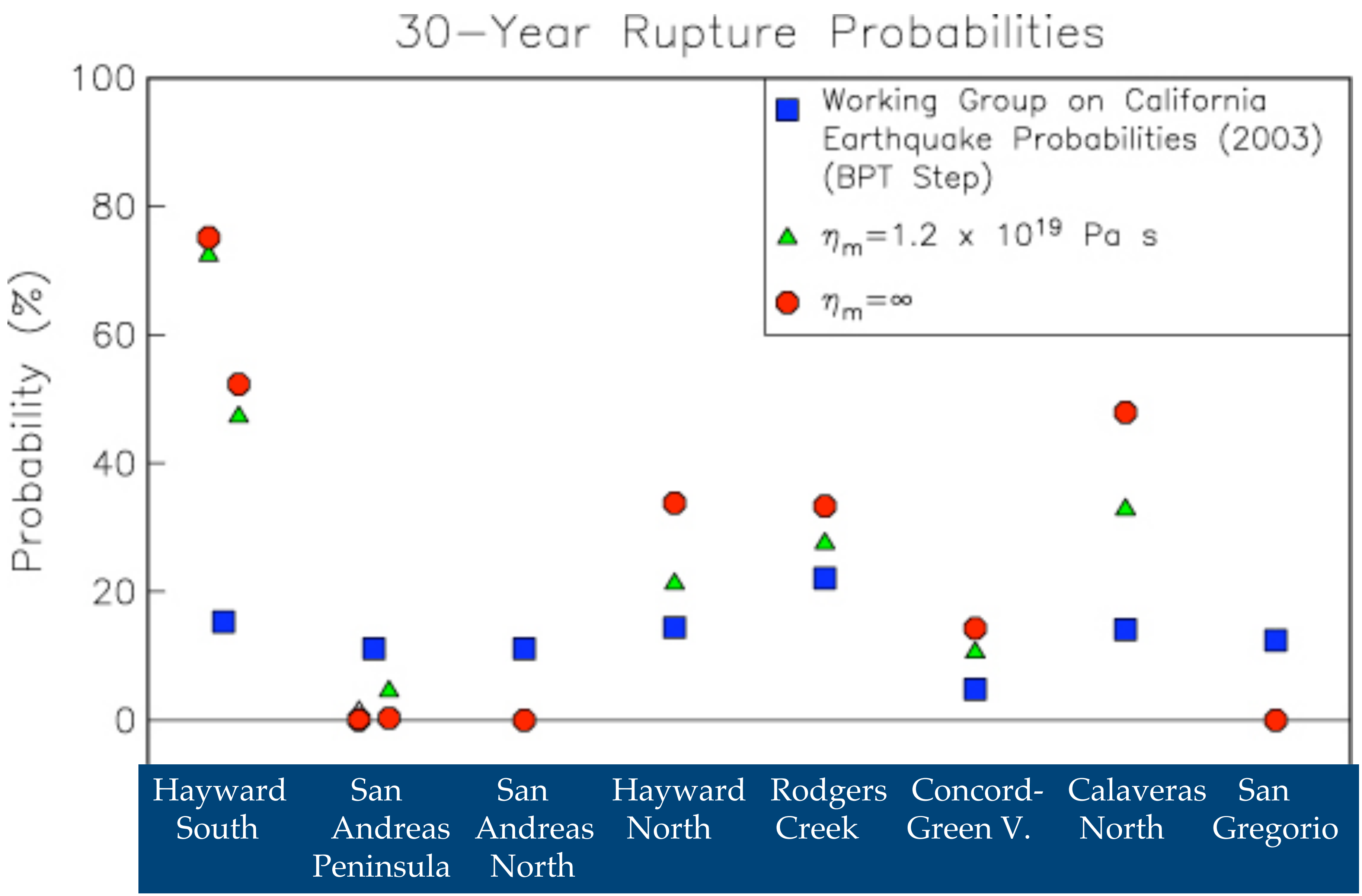
- No interaction of future ruptures with one another

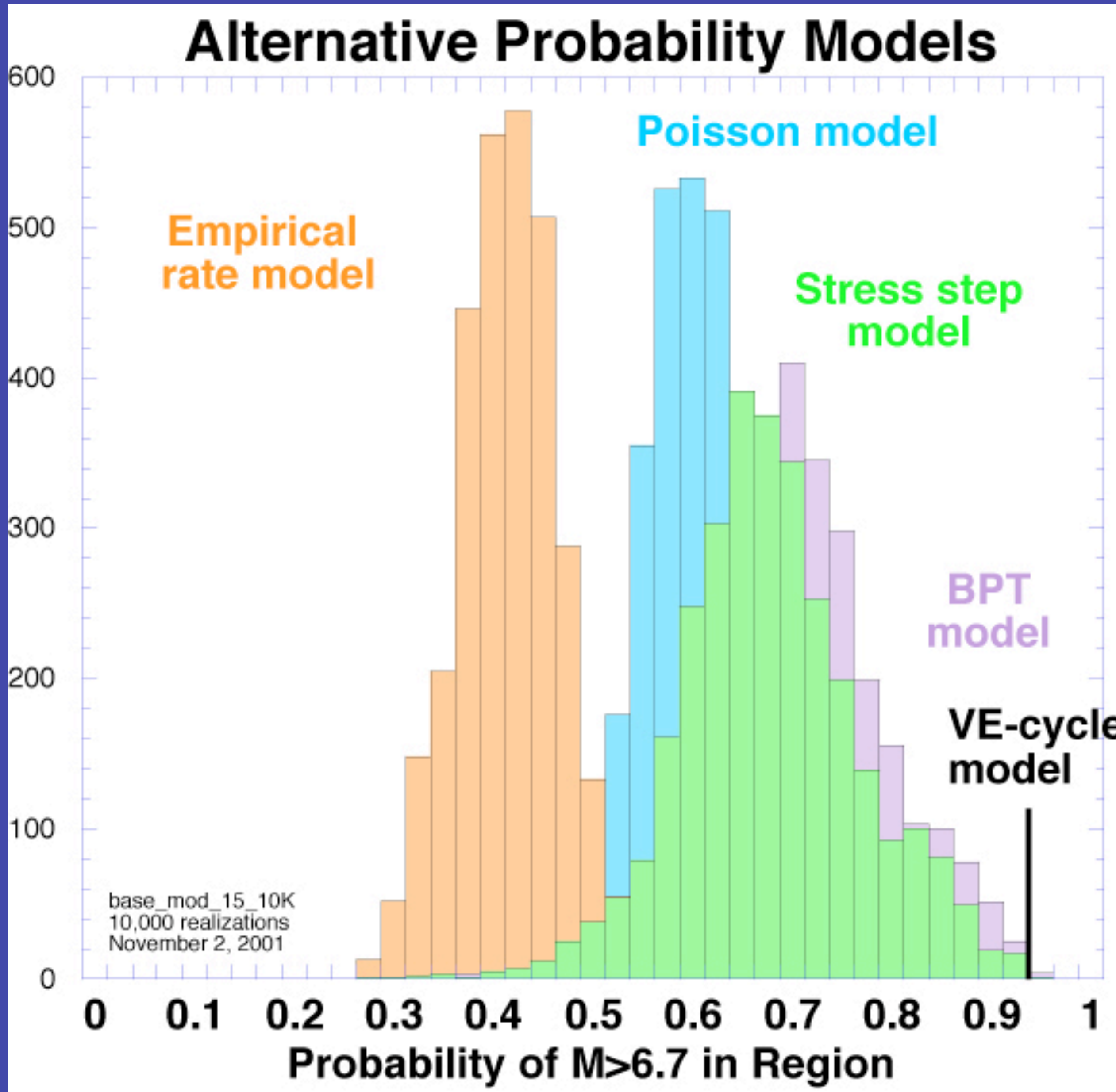


S Hayward
N Hayward
Rodgers Creek
Probability
1.0
0.8
0.6
0.4
0.2
0.0
2000
2040
2080
2120
2160
2036
75%
72%
34%
21%
33%
28%
mantle viscosity
=1.2 x 10^19 Pa s
mantle viscosity
= ∞



30–Year Rupture Probabilities
Probability (%)
100
80
60
40
20
0
Working Group on California Earthquake Probabilities (2003) (BPT Renewal)
η_m=1.2 x 10^{19} Pa s
η_m=∞
Hayward South
San Andreas Peninsula
San Andreas North
Hayward North
Rodgers Creek
Concord-Green V.
Calaveras North
San Gregorio


30-Year Rupture Probabilities
Probability (%)
100
80
60
40
20
0
Working Group on California Earthquake Probabilities (2003) (BPT Step)
η_m=1.2 x 10^{19} Pa s
$\eta_m=\infty$
Hayward South
San Andreas Peninsula
San Andreas North
Hayward North
Rodgers Creek
Concord-Green V.
Calaveras North
San Gregorio



Alternative Probability Models
600
500
400
300
200
100
0
Empirical rate model
Poisson model
Stress step model
BPT model
VE-cycle model
base_mod_15_10K
10,000 realizations
November 2, 2001
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
Probability of M>6.7 in Region

Conclusions

- Probability density functions depend on rheology

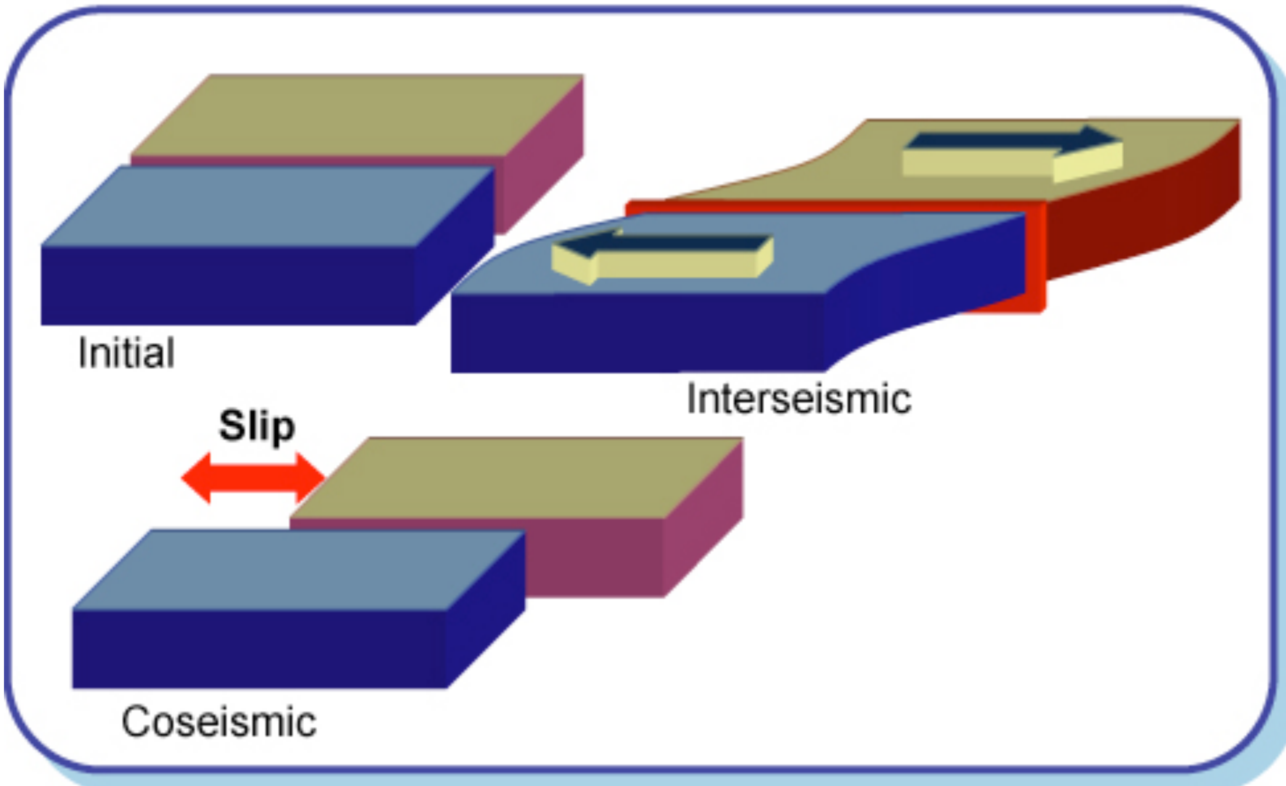
- 30-year rupture probabilities are:

45-75%	Southern Hayward Fault
30-35%	Rodgers Creek Fault
30-50%	Northern Calaveras Fault

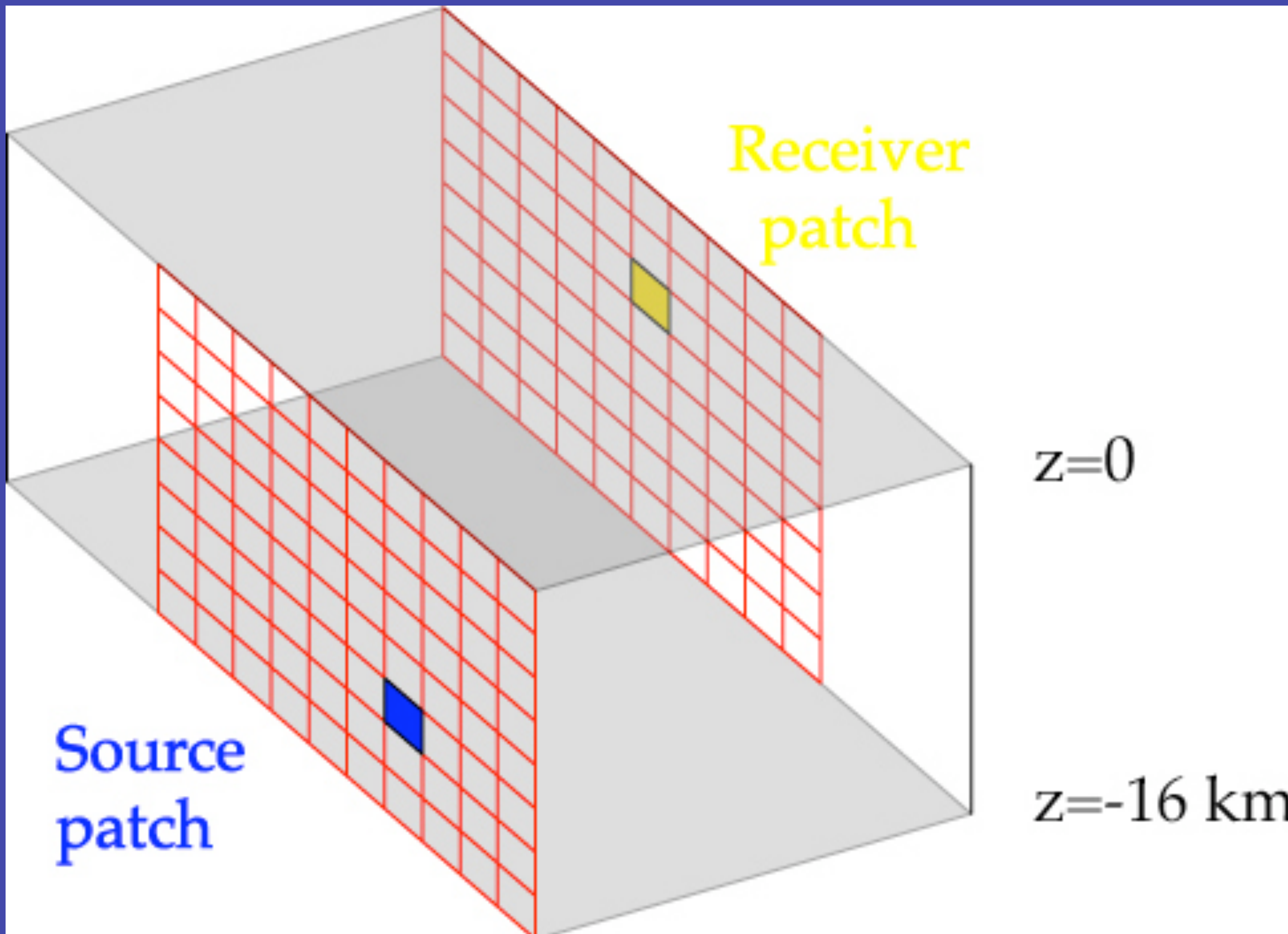
- Future single-segment rupture probabilities are generally greater than estimated by WGCEP02

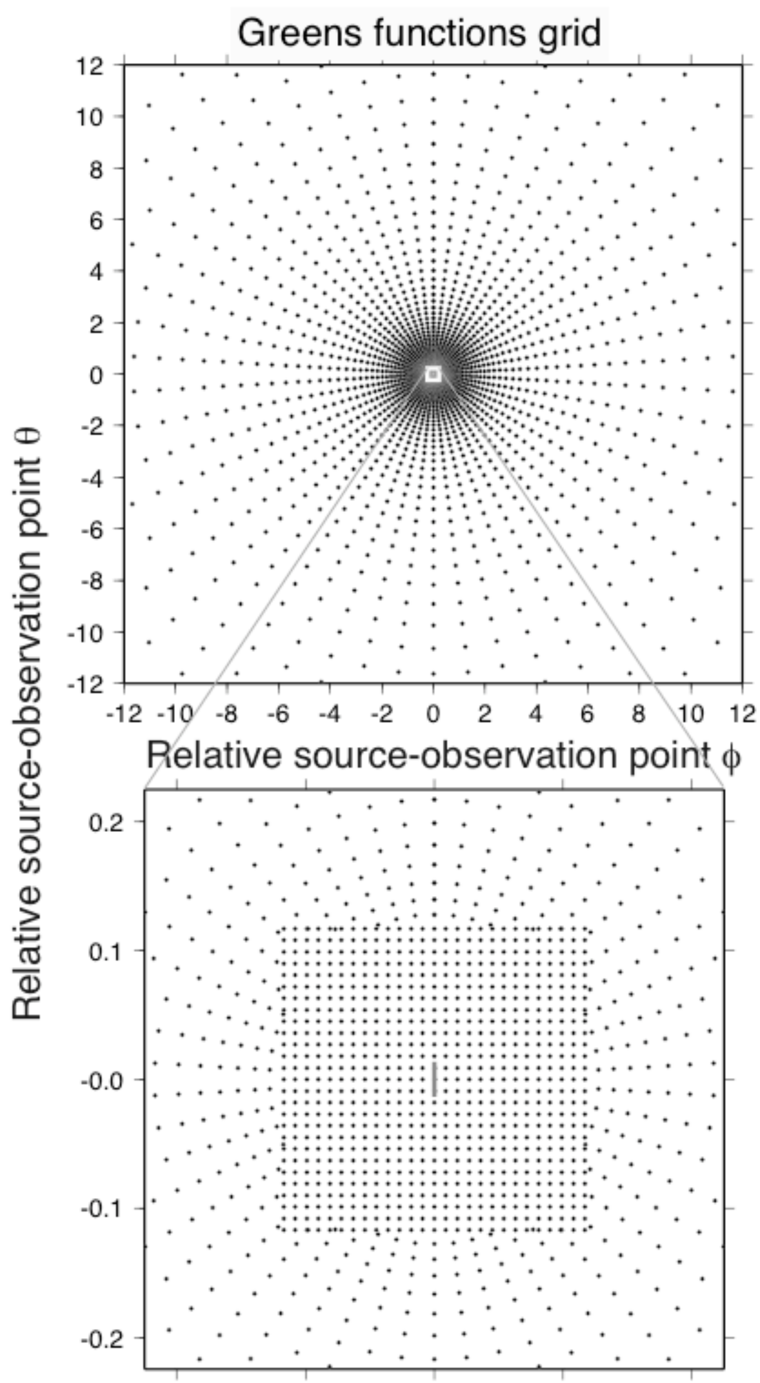
- No single model should be used to assess to time-dependent rupture probabilities. We suggest that several models, including the present one, be used in a comprehensive PSHA methodology, as was done bv WGCEP02

SFBR stress evolution using simulated seismicity: Viscoelastic Earthquake Simulator



Fault interaction





Viscoelastic Greens functions =

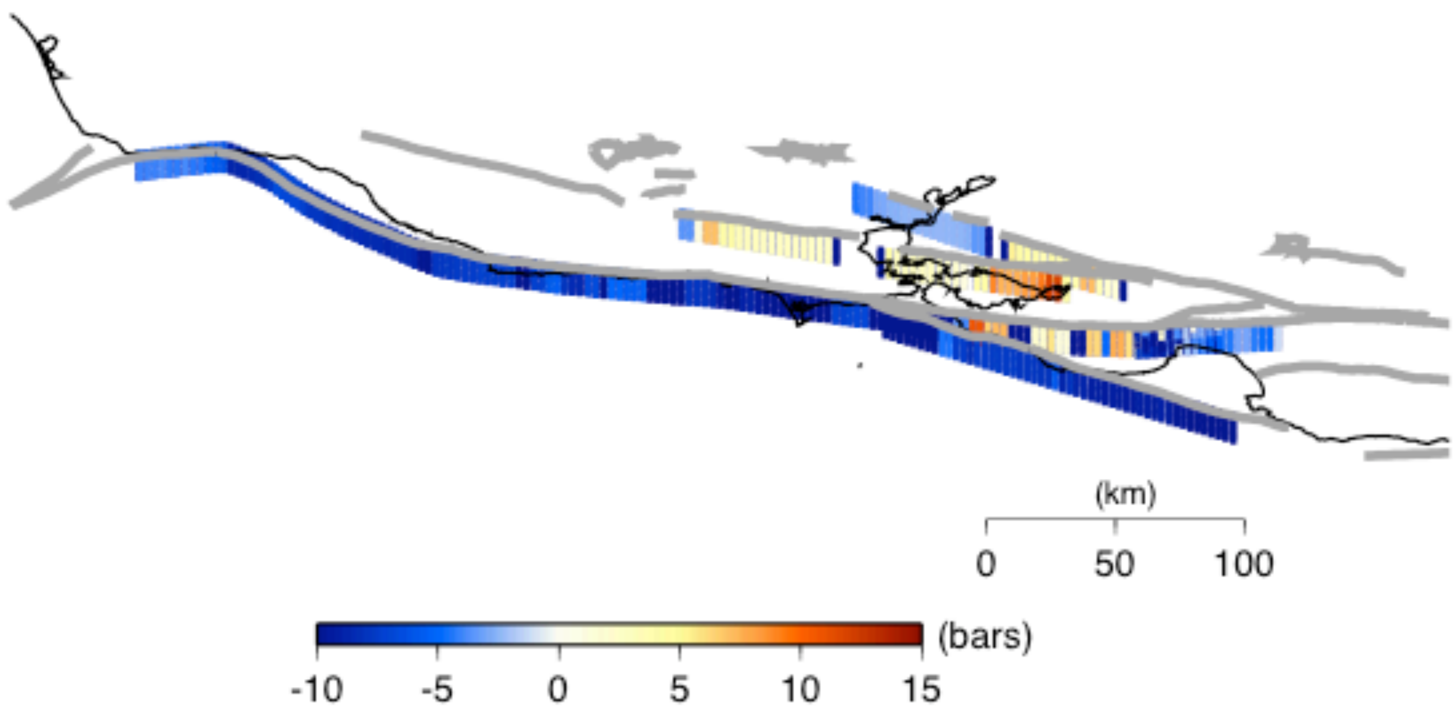
x 3721 [map points]
x 8 [source depths]
x 8 [obs. depths]
x 11 [sample times]
x 6 [stress tensor components]

= 1.5×10^7

Survey of Seismicity Simulators

	Dieterich &Richards-Dinger	Rundle et al. (2006)	Ward (2000)	Lapusta &Rice (2002)	Duan &Oglesby (2005)	Pollitz
static stress transfer	✓	✓	✓	✓	✓	✓
viscoelastic stress transfer	X	X	X	X	X	✓
3D faults	✓	X	X	X	✓	✓
layered elasticity	X	X	X	X	X	✓
dynamic rupture physics	X	X	X	✓	✓	X
rate/state friction	✓	✓	X	✓	✓	X
dipping faults	X	X	X	X	✓	✓
multiple faults	✓	✓	✓	X	X	✓

Initial stress



Coulomb stress

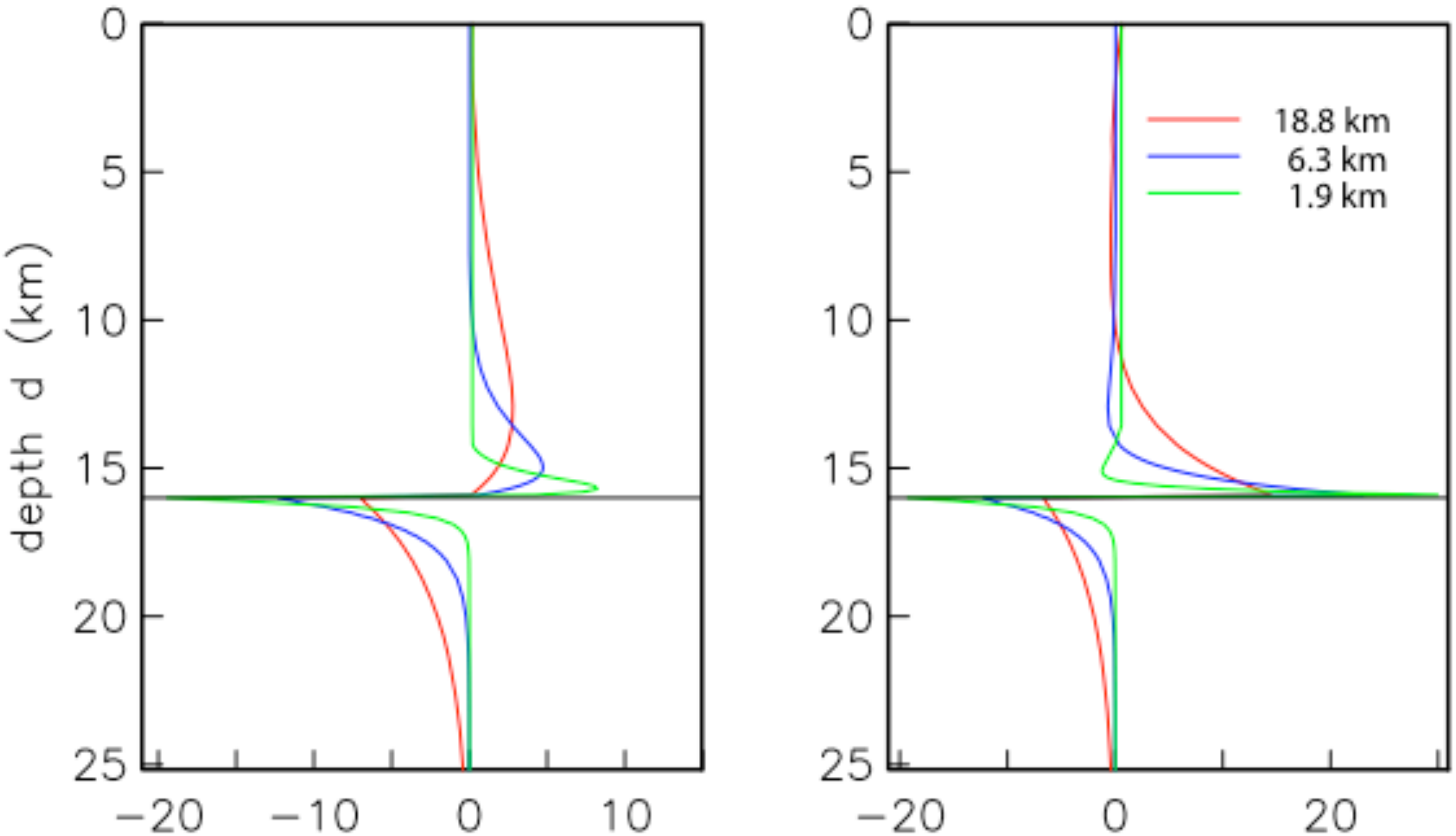
Tectonic Loading

System is loaded by backslip imposed on a thin elastic plate.
This is a consequence of:

- Zero long-term strength below the base of the elastic plate

- Summation of viscoelastic relaxation from an infinite series of past events (on a given fault) assumed to have occurred with a definite mean recurrence interval

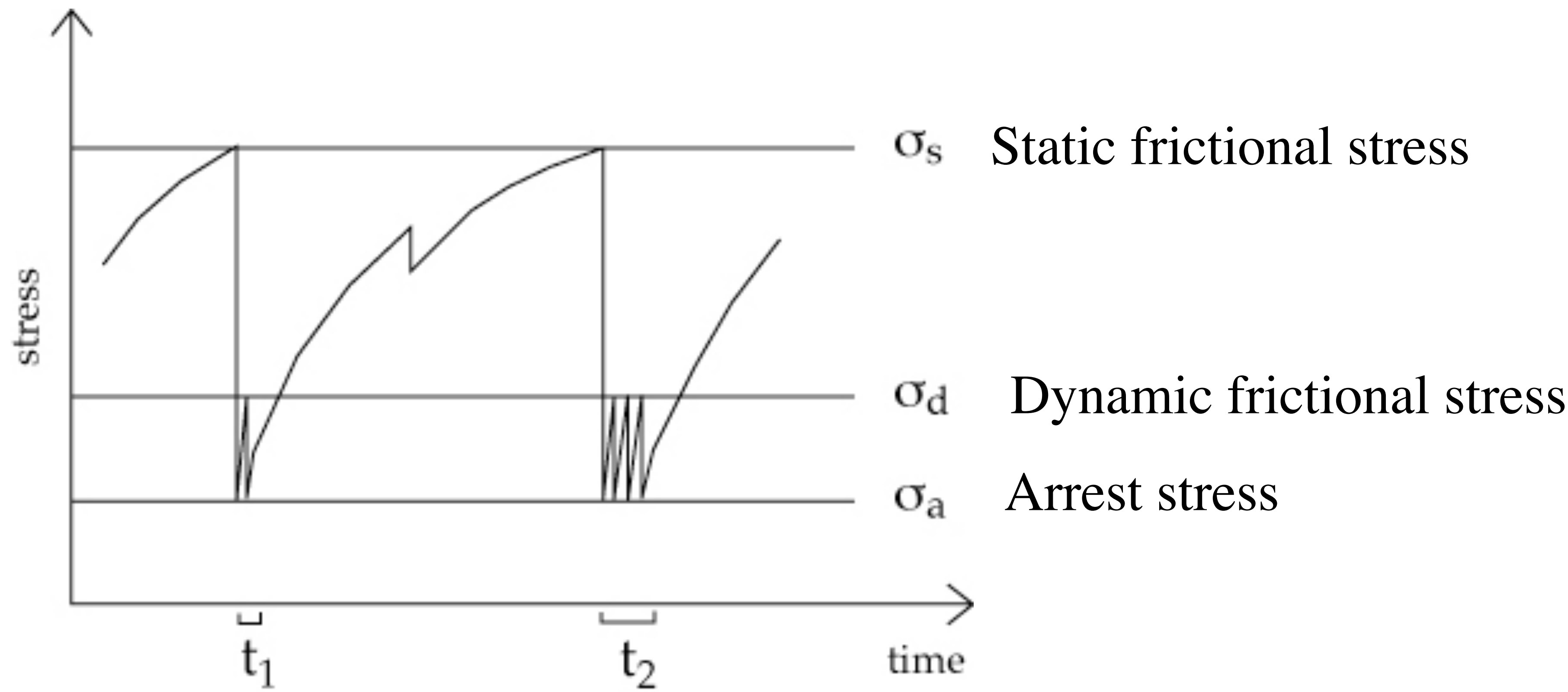
Viscoelastic mode response functions



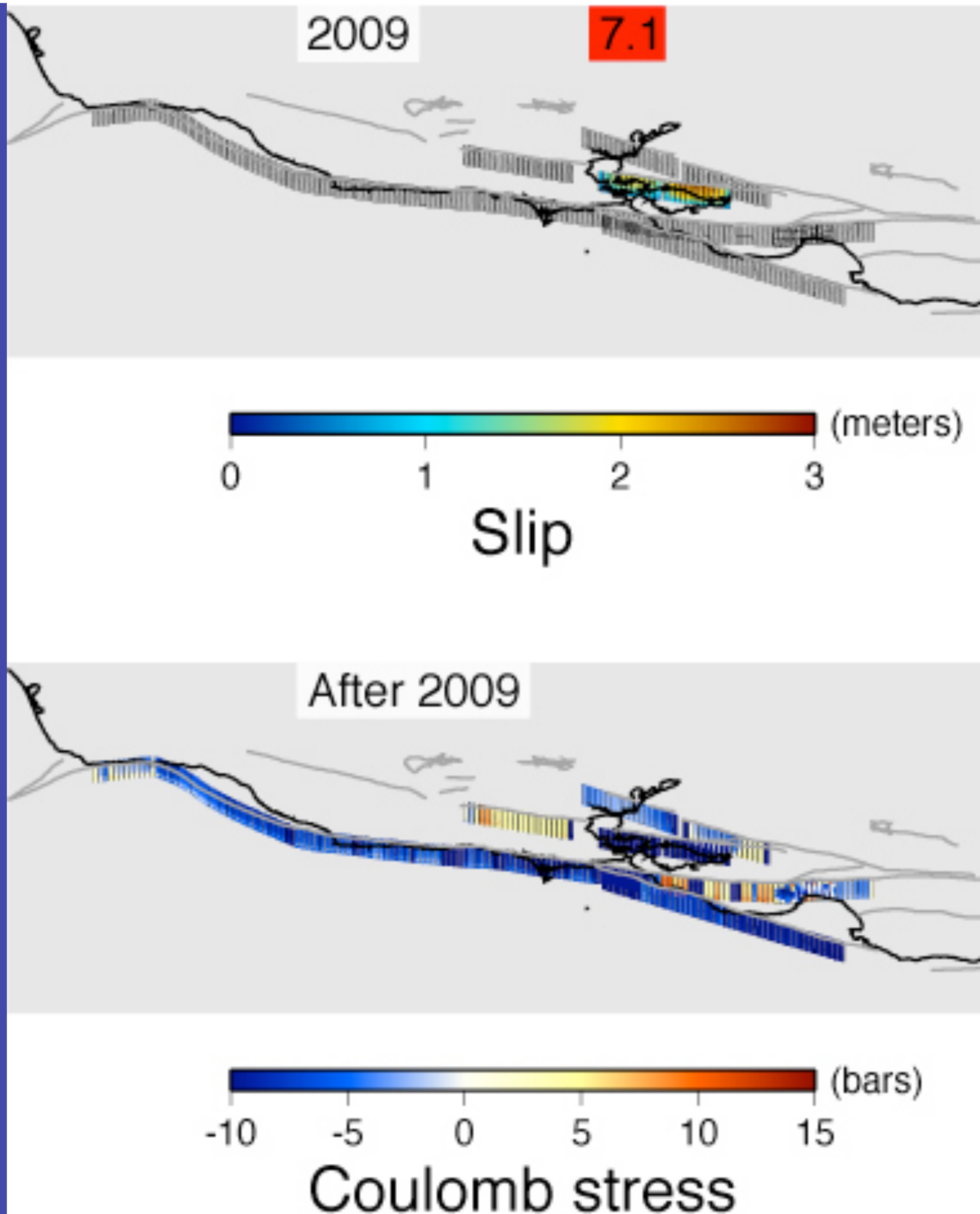
Vertical displacement

Horizontal displacement

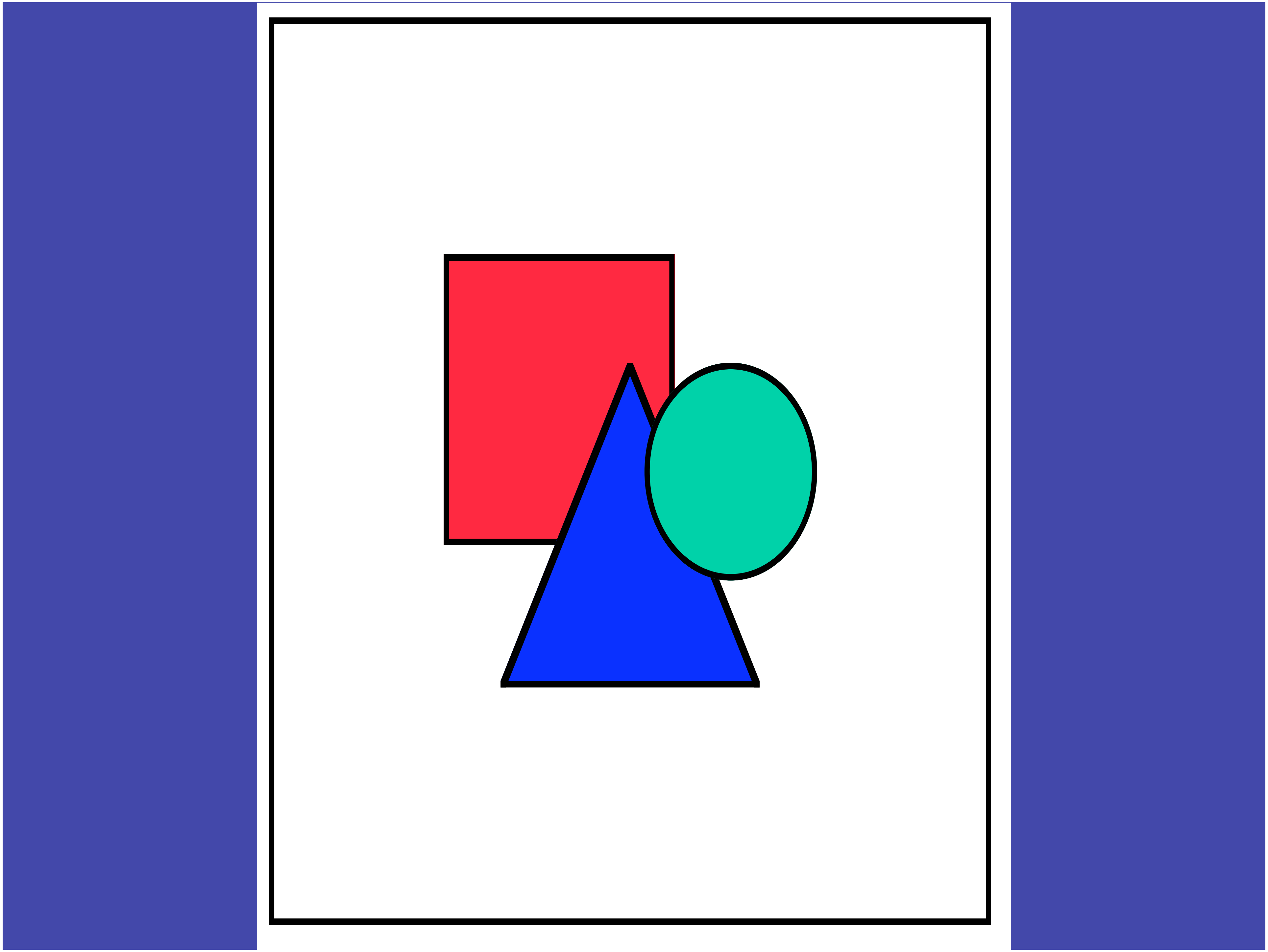
Stress history on a single fault patch

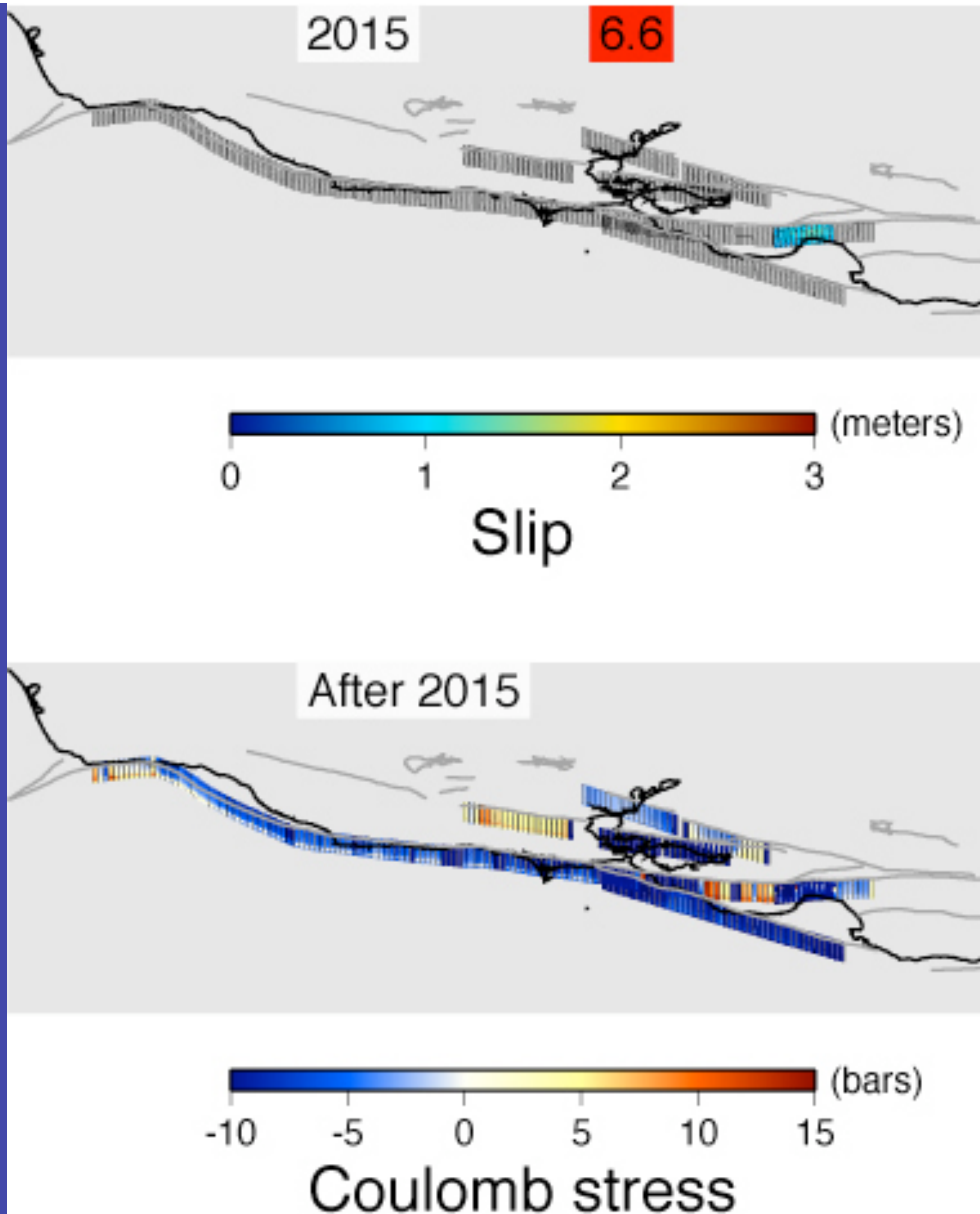


Dynamic overshoot parameter: $D = (\sigma_\mathrm{s} - \sigma_\mathrm{a})/(\sigma_\mathrm{s} - \sigma_\mathrm{d})$

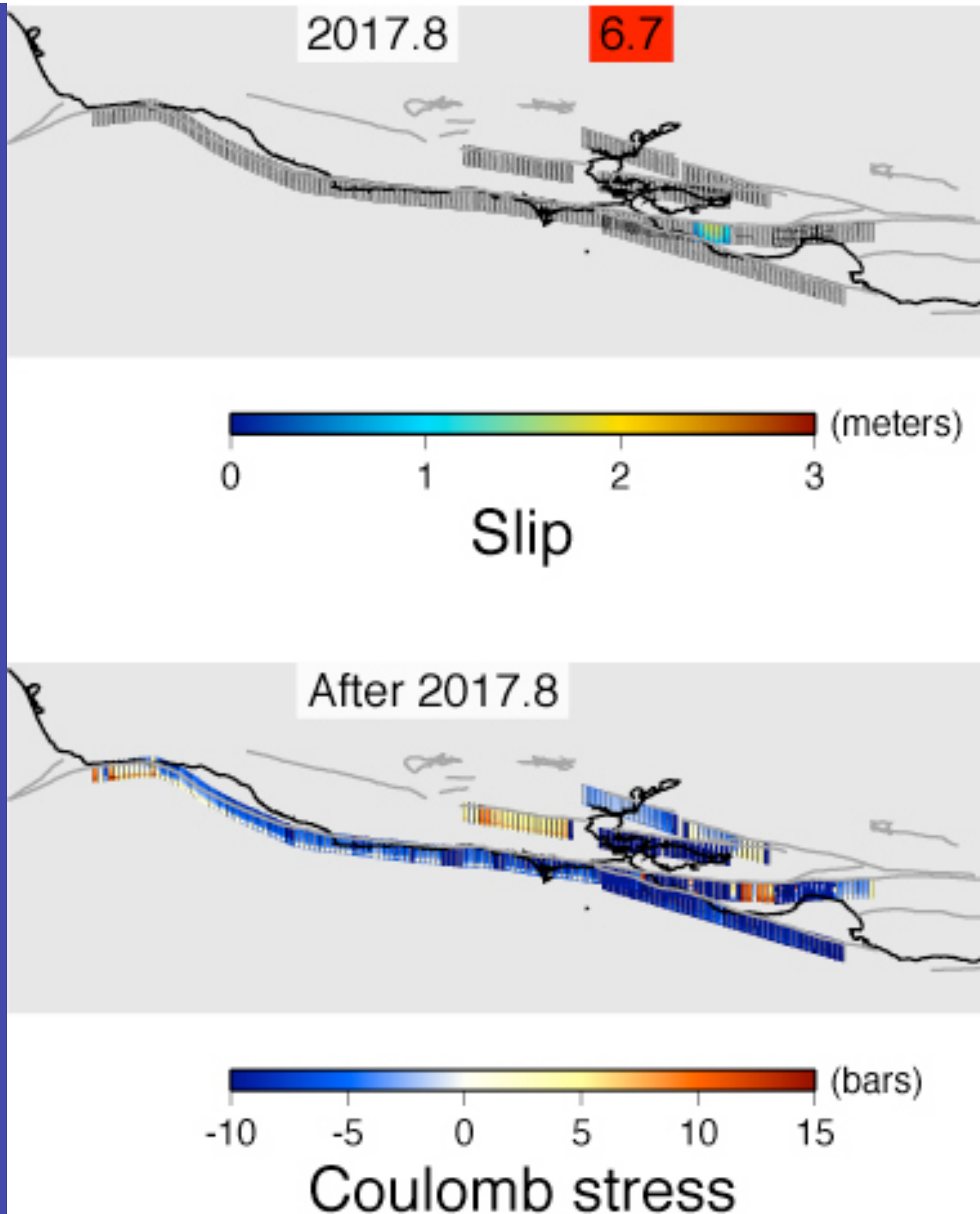


2009
7.1
(meters)
0
1
2
3
Slip
After 2009
(bars)
-10
-5
0
5
10
15
Coulomb stress

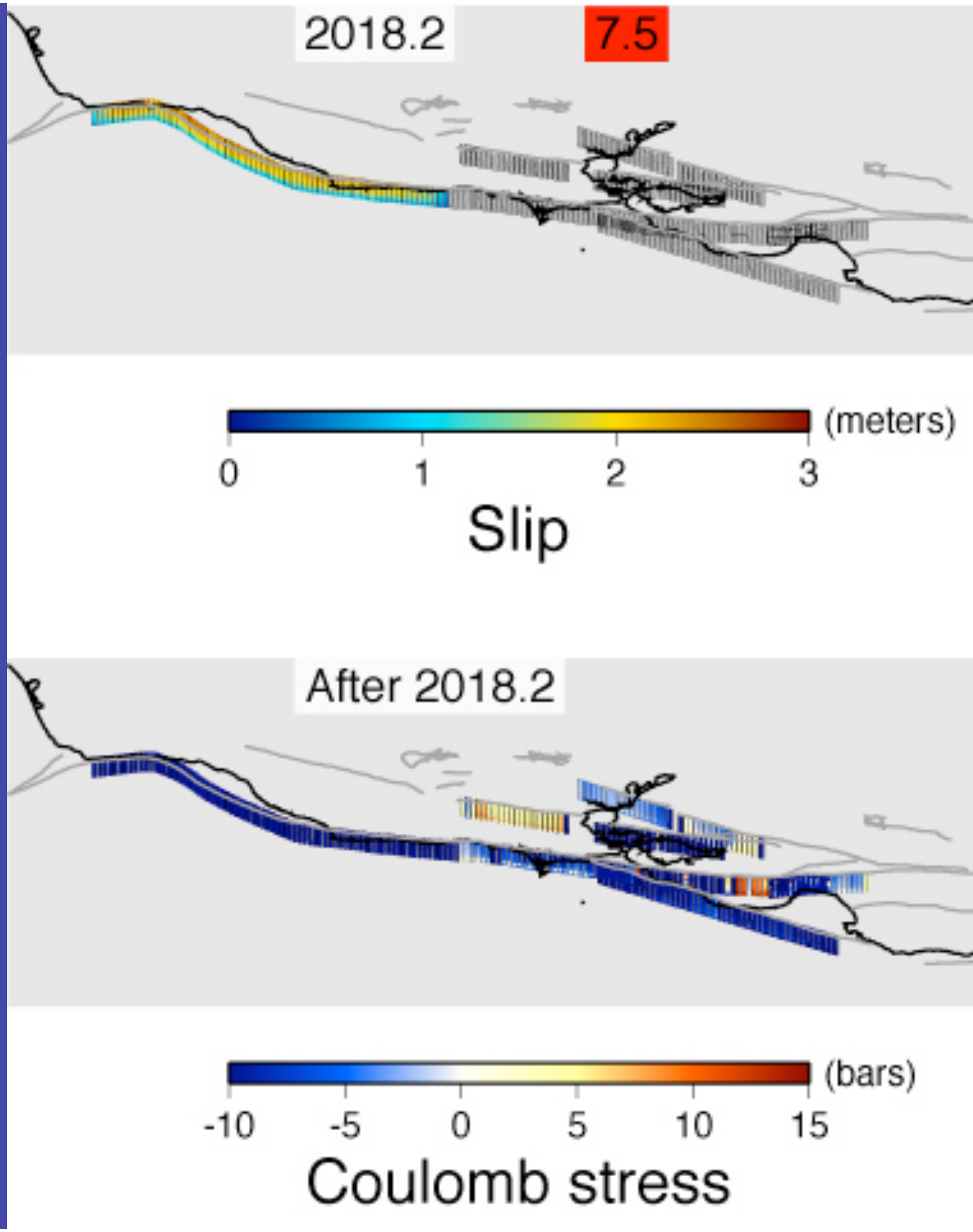


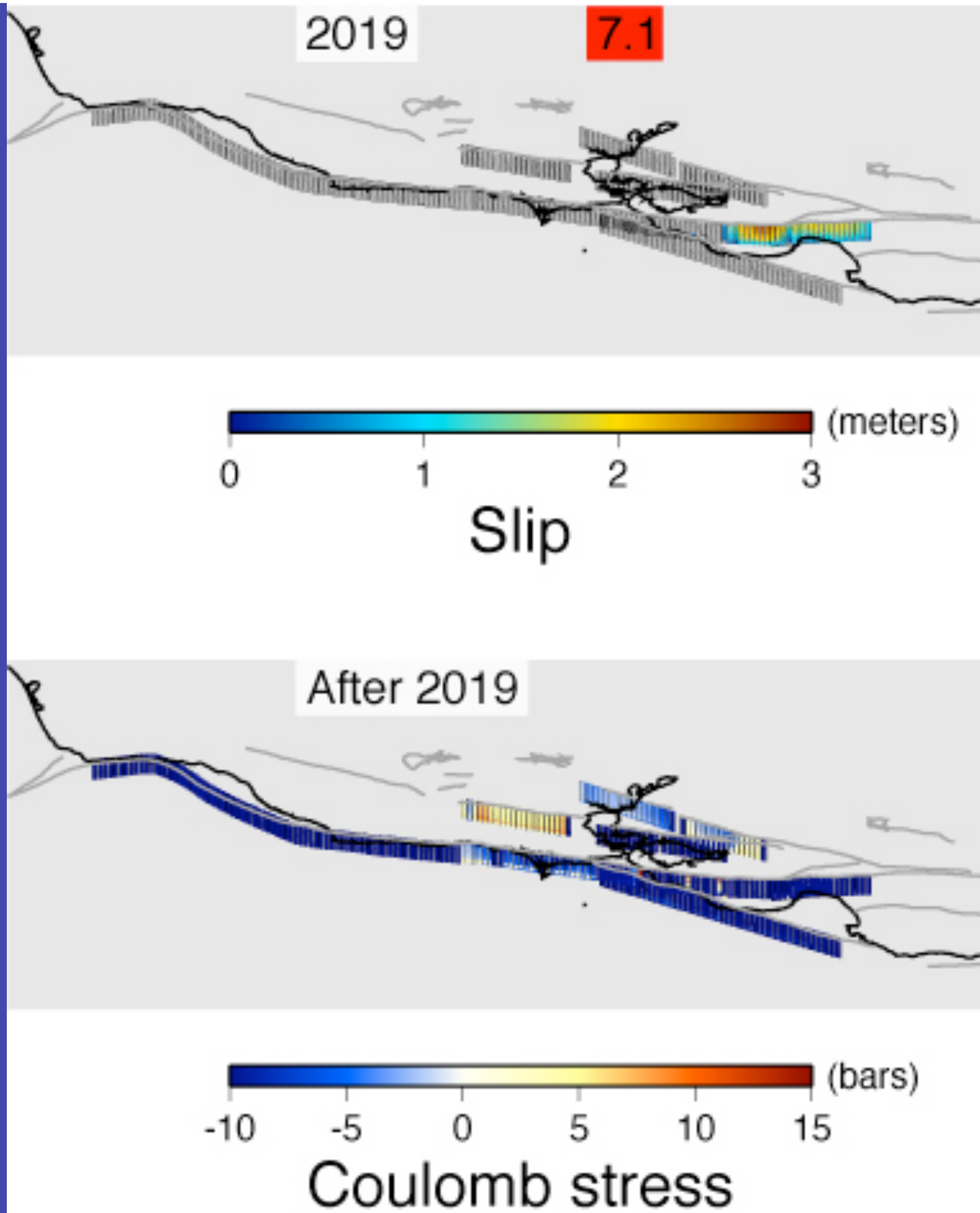


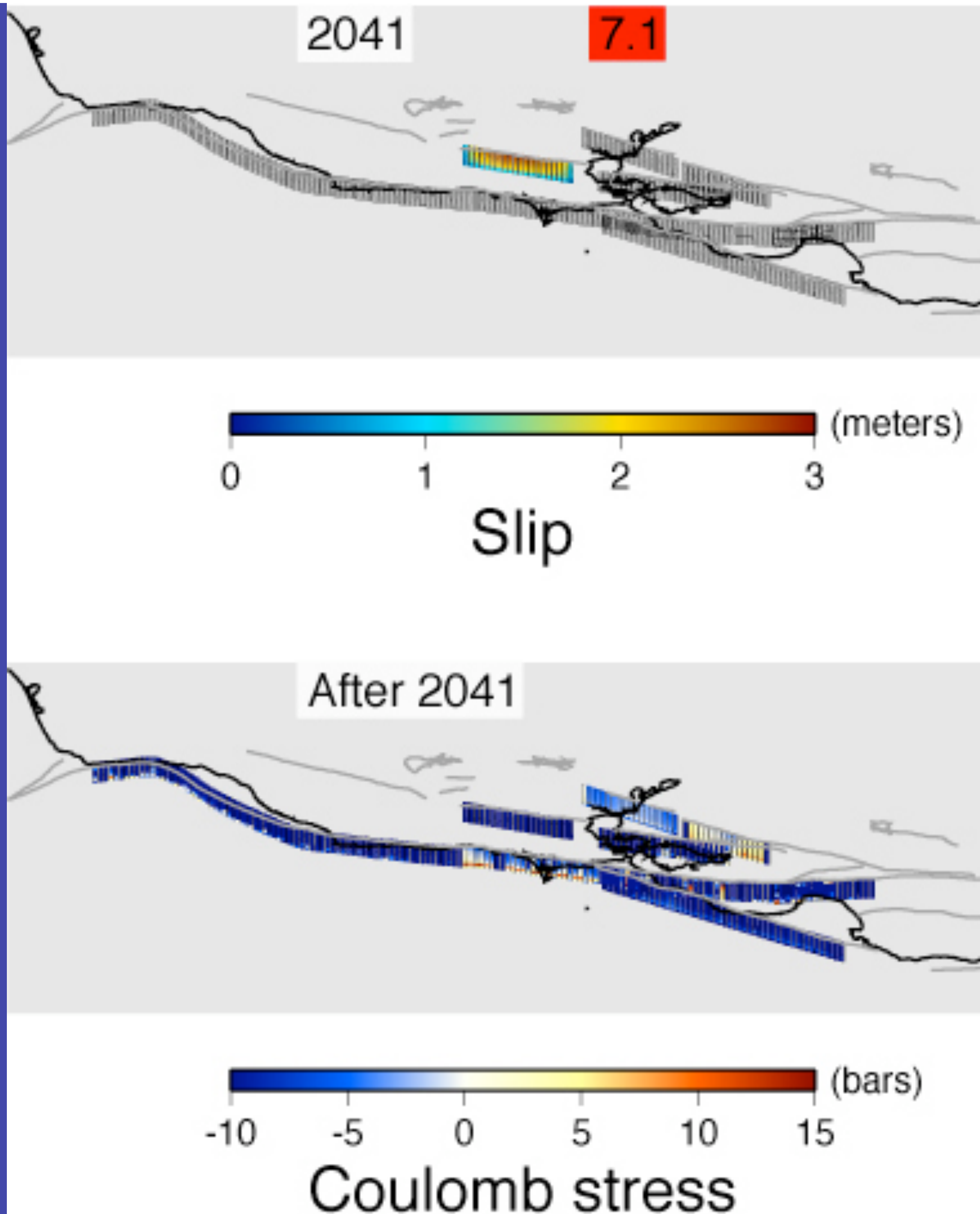
2015
6.6
(meters)
0
1
2
3
Slip
After 2015
(bars)
-10
-5
0
5
10
15
Coulomb stress

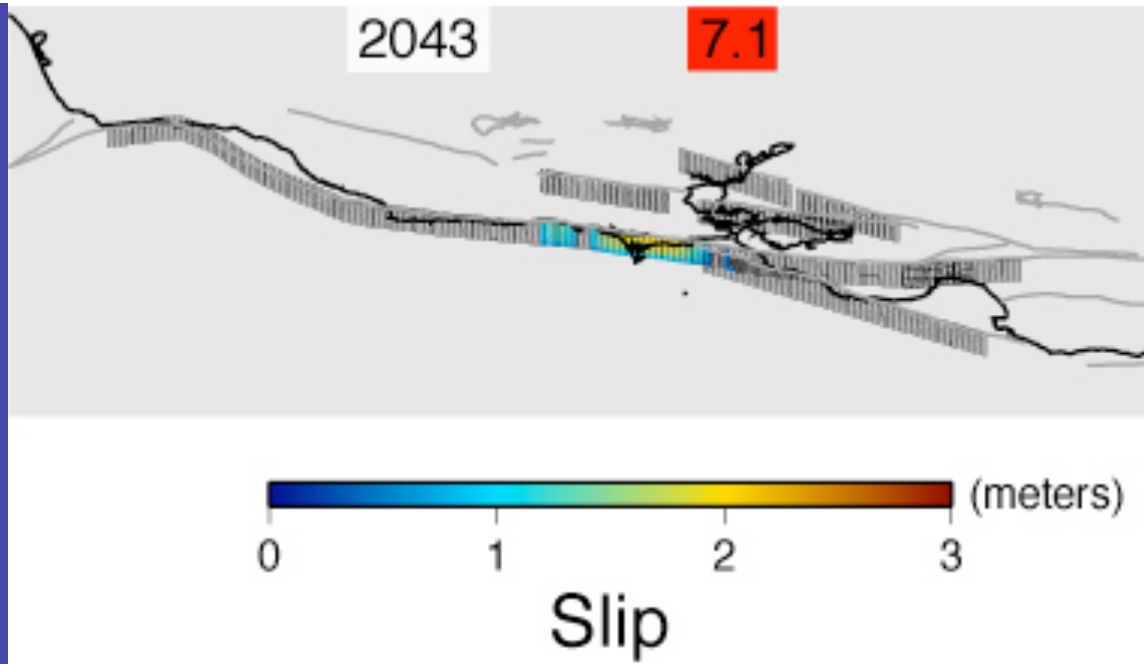


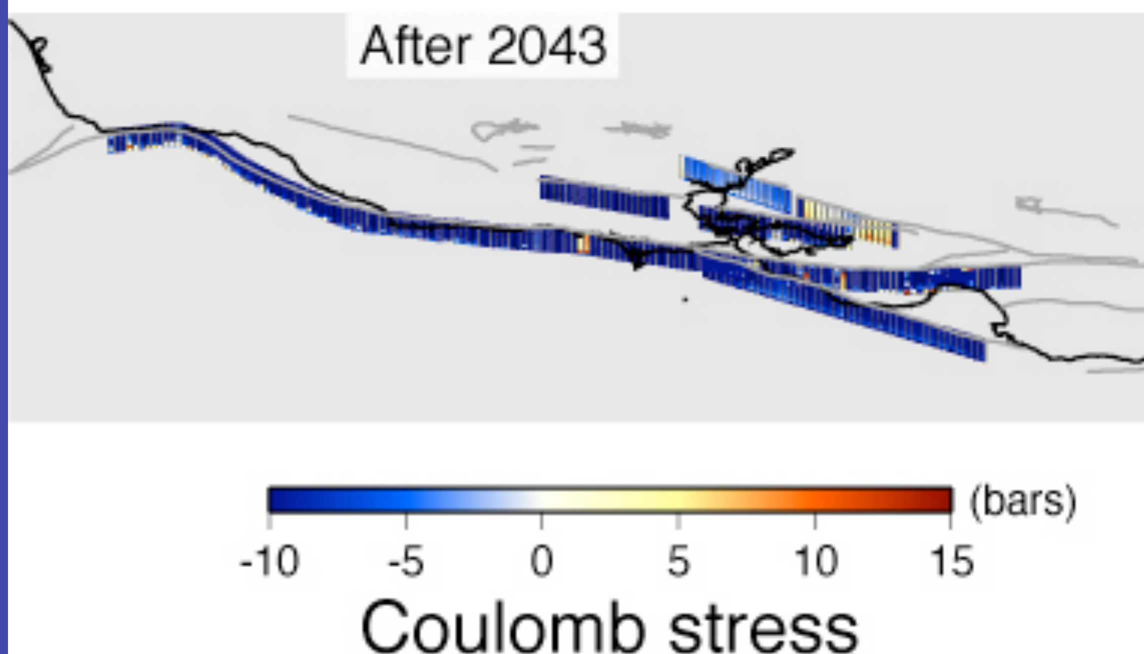
2017.8
6.7
(meters)
0
1
2
3
Slip
After 2017.8
(bars)
-10
-5
0
5
10
15
Coulomb stress

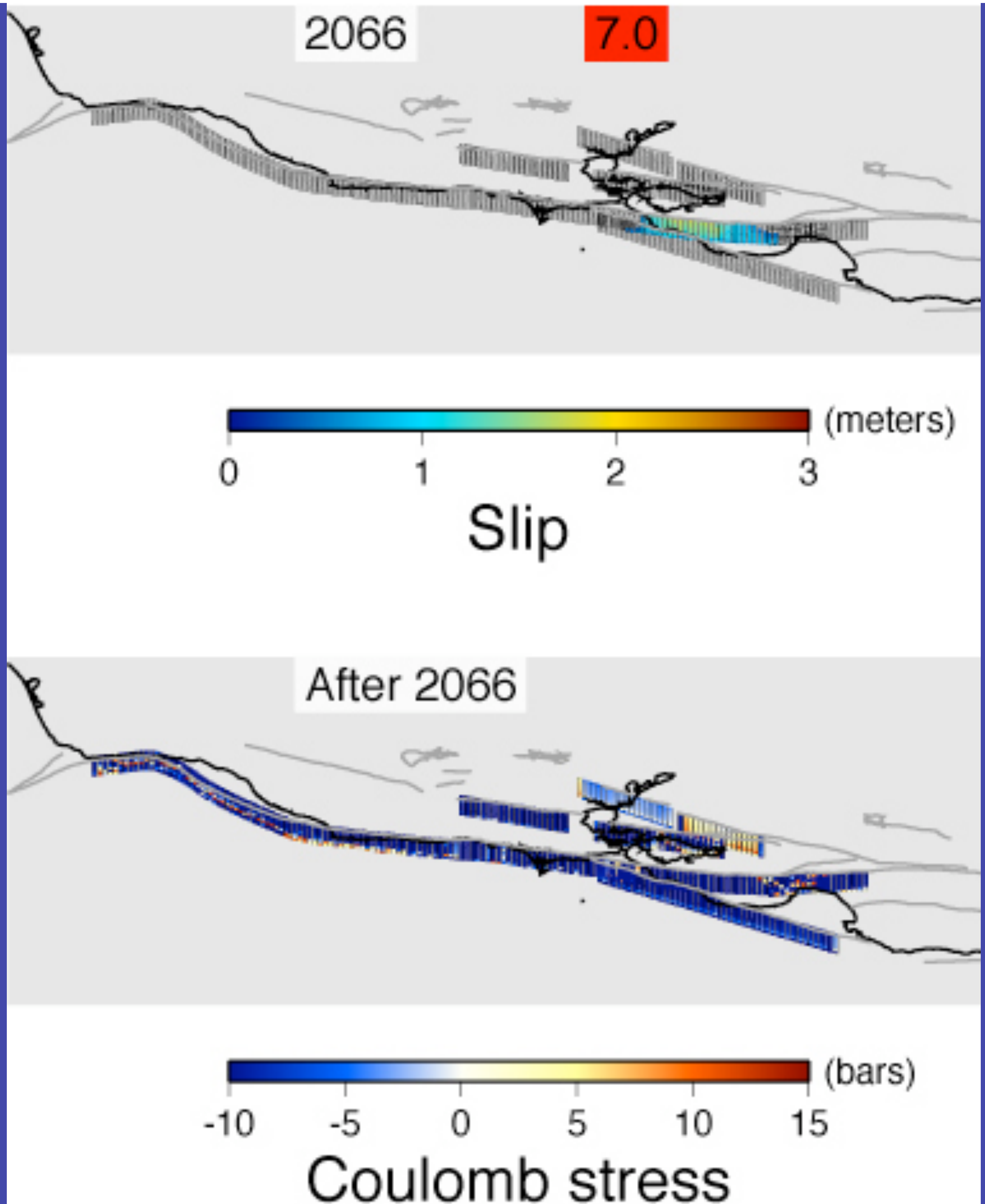

2018.2
7.5
(meters)
0
1
2
3
Slip
After 2018.2
(bars)
-10
-5
0
5
10
15
Coulomb stress


2019
7.1
(meters)
0
1
2
3
Slip
After 2019
(bars)
-10
-5
0
5
10
15
Coulomb stress

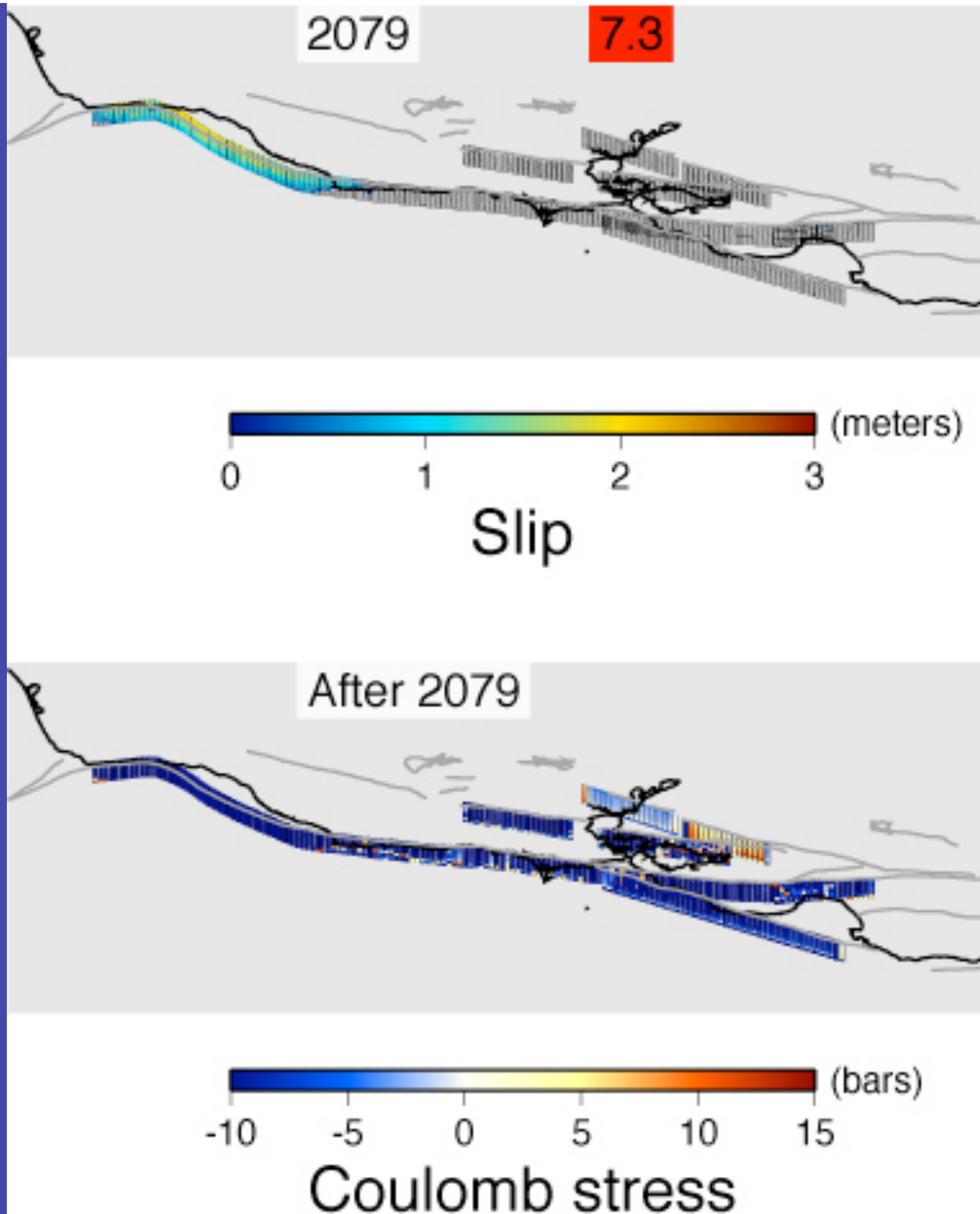

2041
7.1
(meters)
0
1
2
3
Slip
After 2041
(bars)
-10
-5
0
5
10
15
Coulomb stress

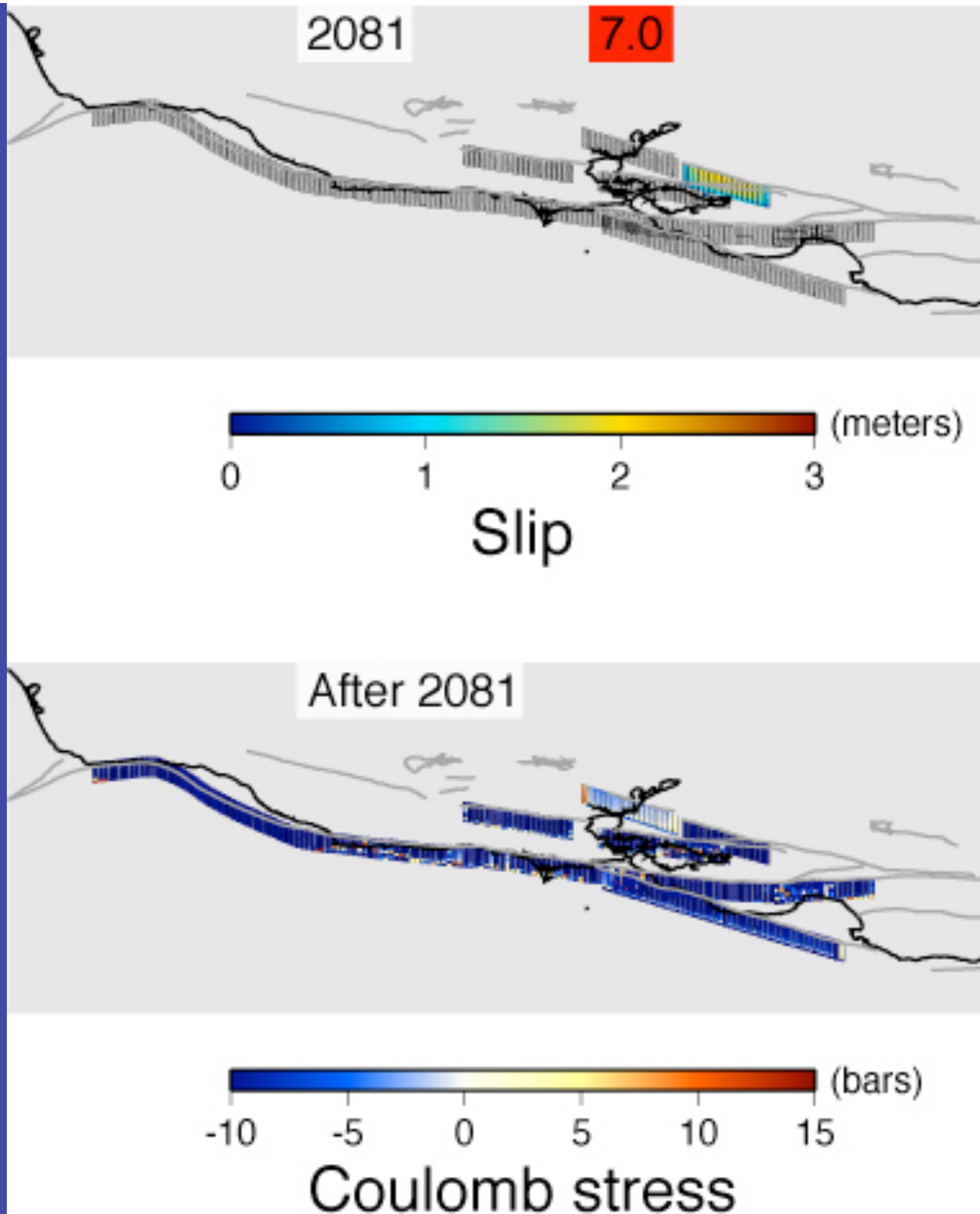

2043
7.1
(meters)
0
1
2
3
Slip


After 2043
(bars)
-10
-5
0
5
10
15
Coulomb stress

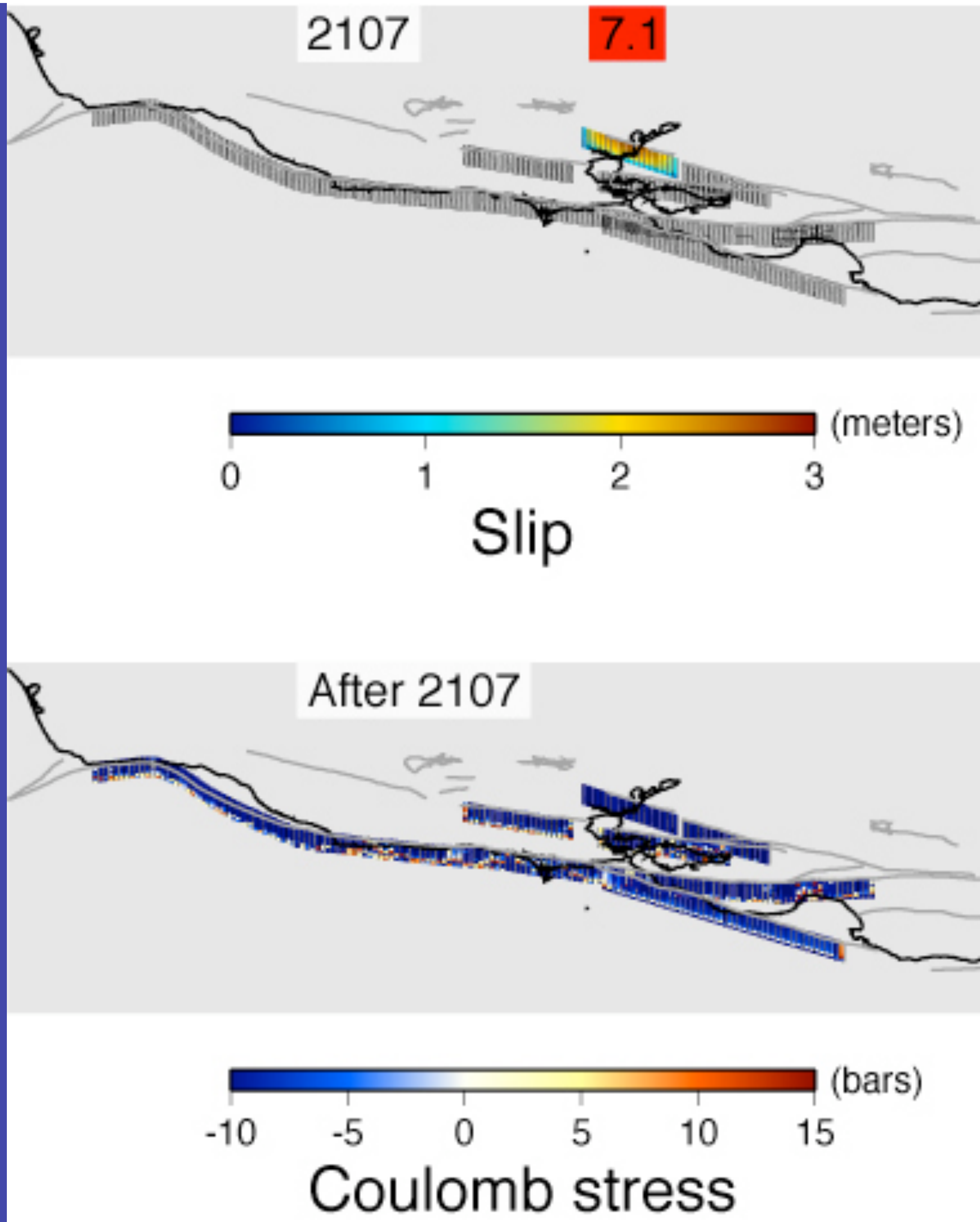


2066
7.0
(meters)
0
1
2
3
Slip
After 2066
(bars)
-10
-5
0
5
10
15
Coulomb stress


2079
7.3
(meters)
0
1
2
3
Slip
After 2079
(bars)
-10
-5
0
5
10
15
Coulomb stress



2081
7.0
(meters)
0
1
2
3
Slip
After 2081
(bars)
-10
-5
0
5
10
15
Coulomb stress



2107
7.1
(meters)
0
1
2
3
Slip
After 2107
(bars)
-10
-5
0
5
10
15
Coulomb stress

Stress functions

- Average stress
- Standard deviation of stress
- Configurational entropy

$$\mathrm{AS(t)} = \frac{1}{\mathrm{N}} \sum_{\mathrm{i=1}}^{\mathrm{N}} \tau_{\mathrm{i}}(\mathrm{t})$$

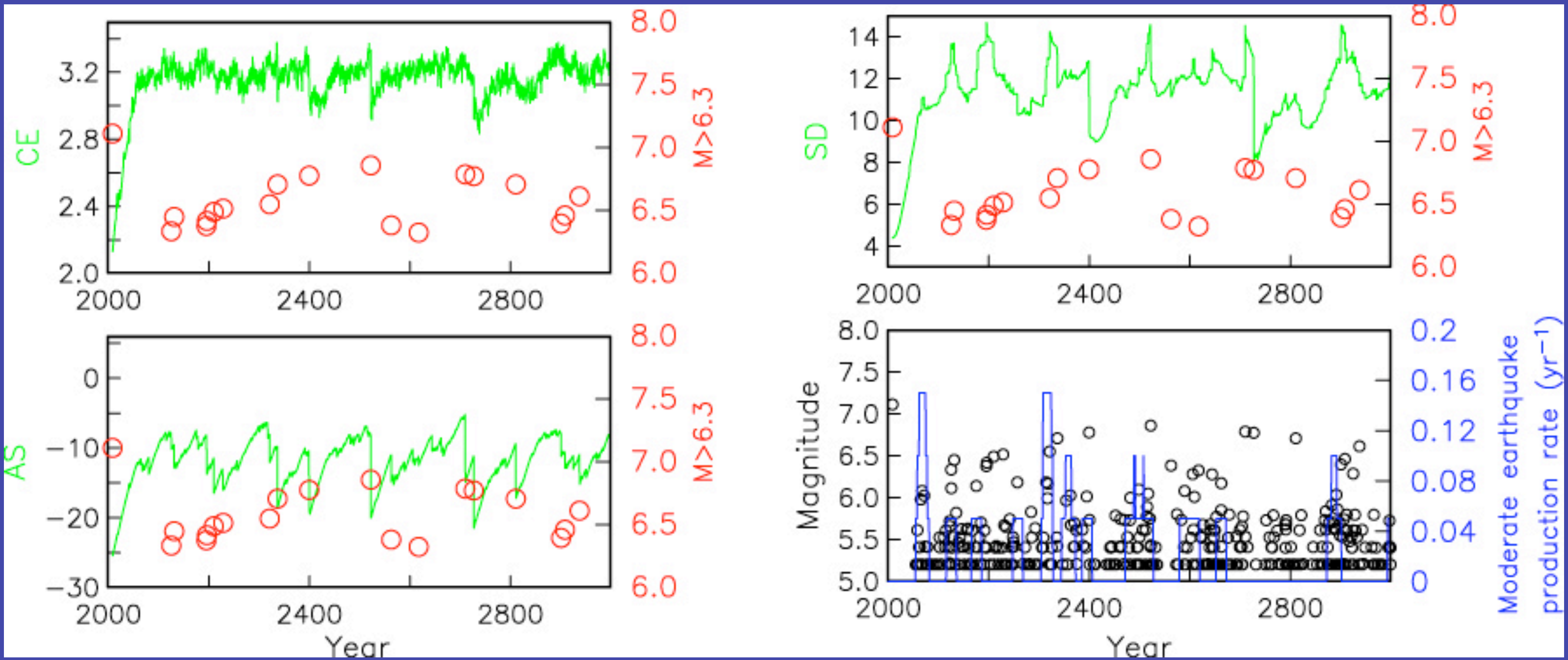
$$\mathrm{SD(t)} = \sqrt{\frac{1}{\mathrm{N}} \sum_{\mathrm{i=1}}^{\mathrm{N}} [\tau_{\mathrm{i}}(\mathrm{t}) - \mathrm{AS(t)}]^2}$$

$$\mathrm{CE(t)} = - \int \mathrm{p[s(t)]} \ln\{\mathrm{p[s(t)]}\} \, \mathrm{ds}$$

Seismicity functions

- Interevent-time histograms
- Magnitude-frequency statistics
- Foreshock-mainshock statistics
- Conditional rupture probability

N+S Hayward Fault: Stress history from 30000-year seismicity simulations



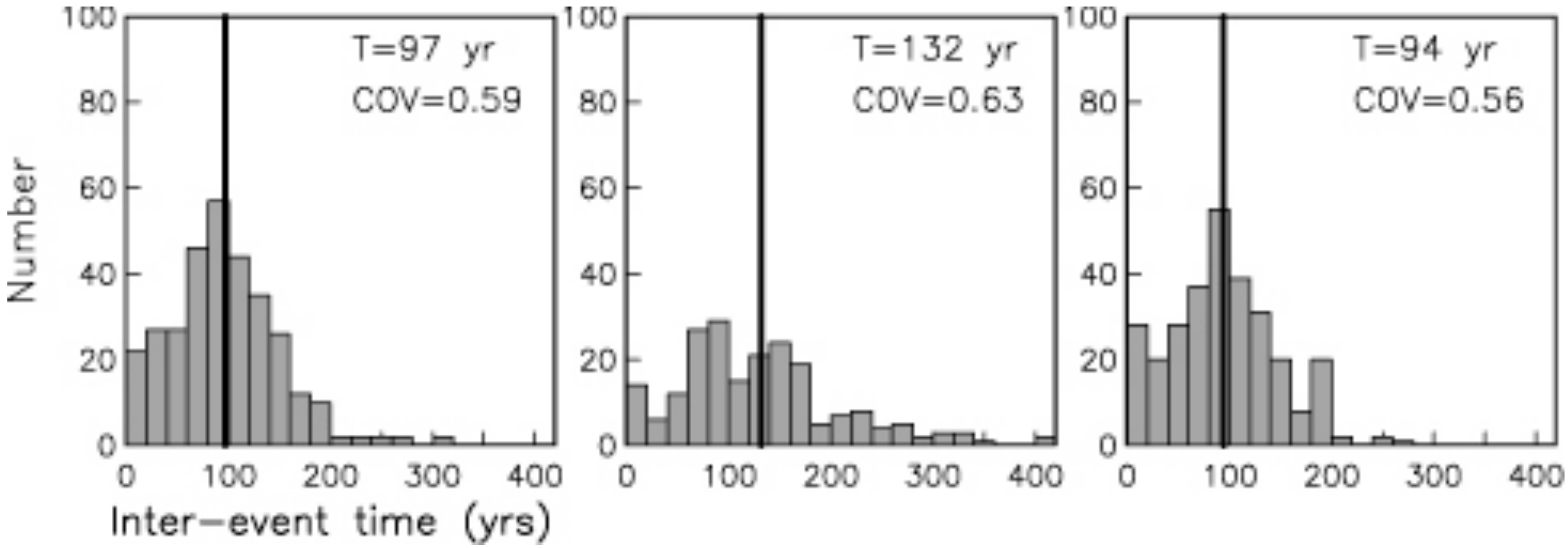
N+S Hayward Fault

M>6.5

D=1.5
$\eta=1.2\times10^{19}$ Pa s

D=2.0
$\eta=1.2\times10^{19}$ Pa s

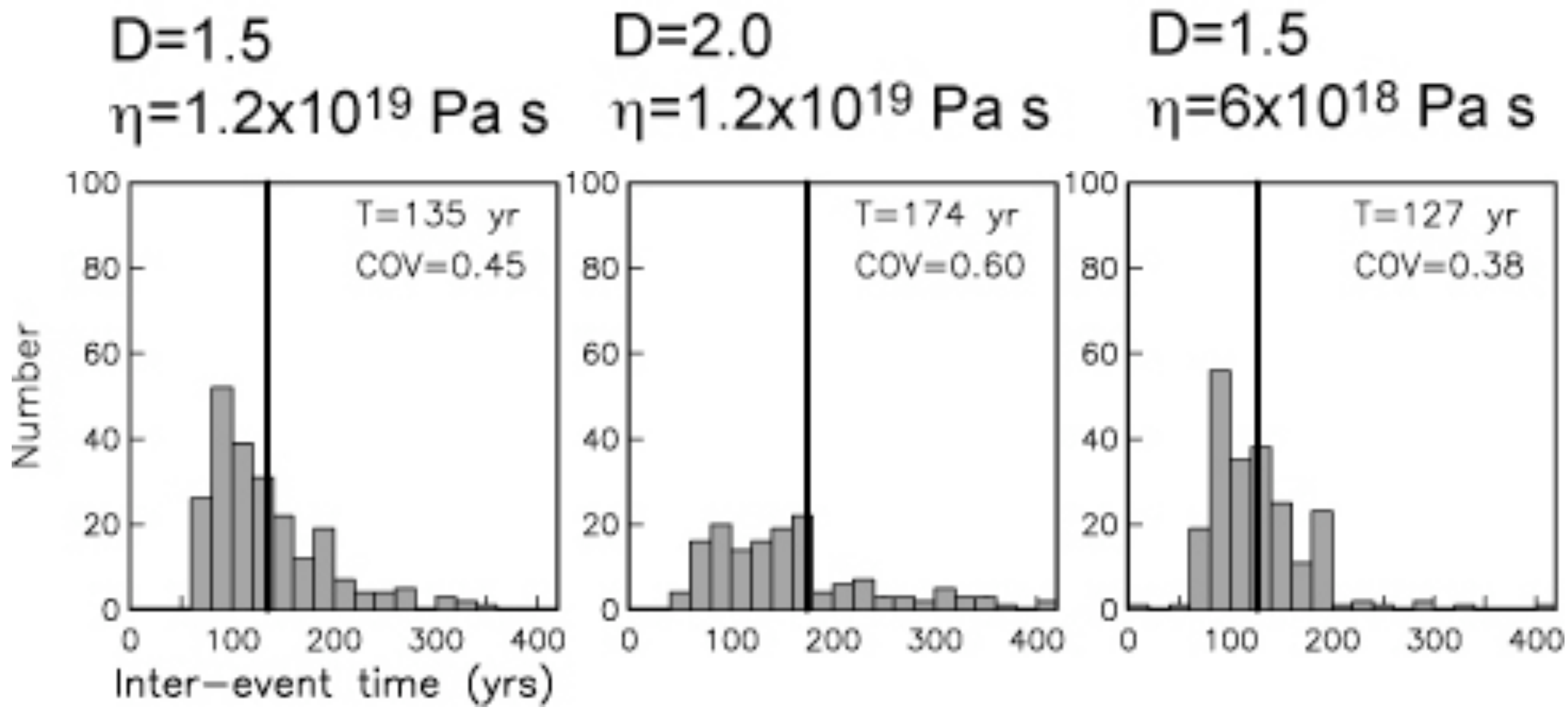
D=1.5
$\eta=6\times10^{18}$ Pa s



D=dynamic overshoot parameter
η=mantle viscosity

S Hayward Fault

M>6.5



D=dynamic overshoot parameter
η=mantle viscosity

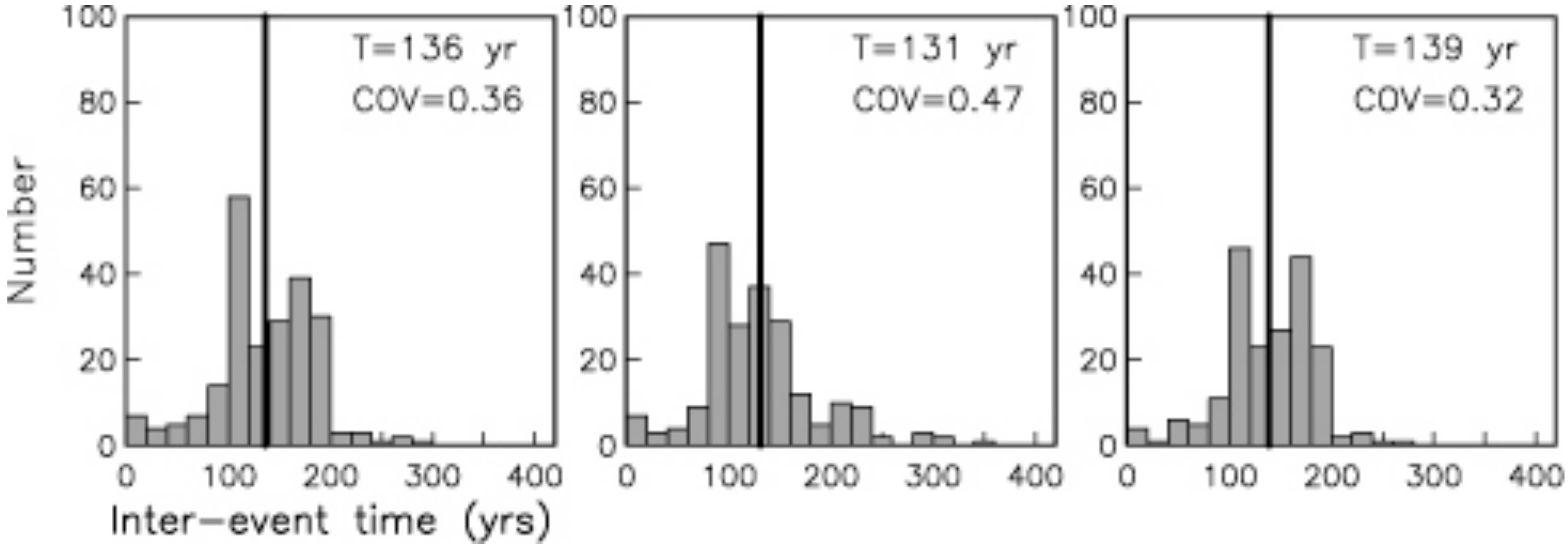
Rodgers Creek Fault

M>6.5

D=1.5
$\eta=1.2\times10^{19}$ Pa s

D=2.0
$\eta=1.2\times10^{19}$ Pa s

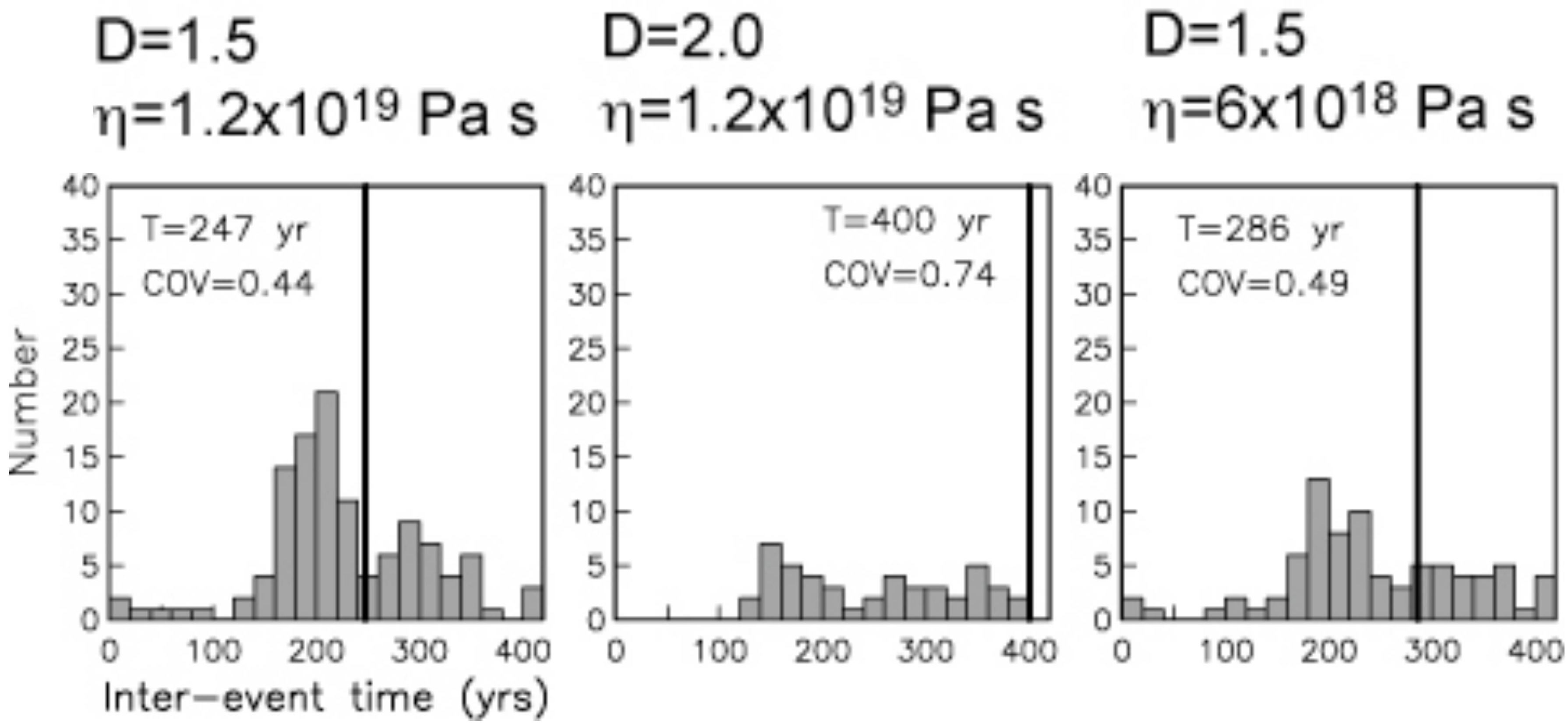
D=1.5
$\eta=6\times10^{18}$ Pa s



D=dynamic overshoot parameter
η=mantle viscosity

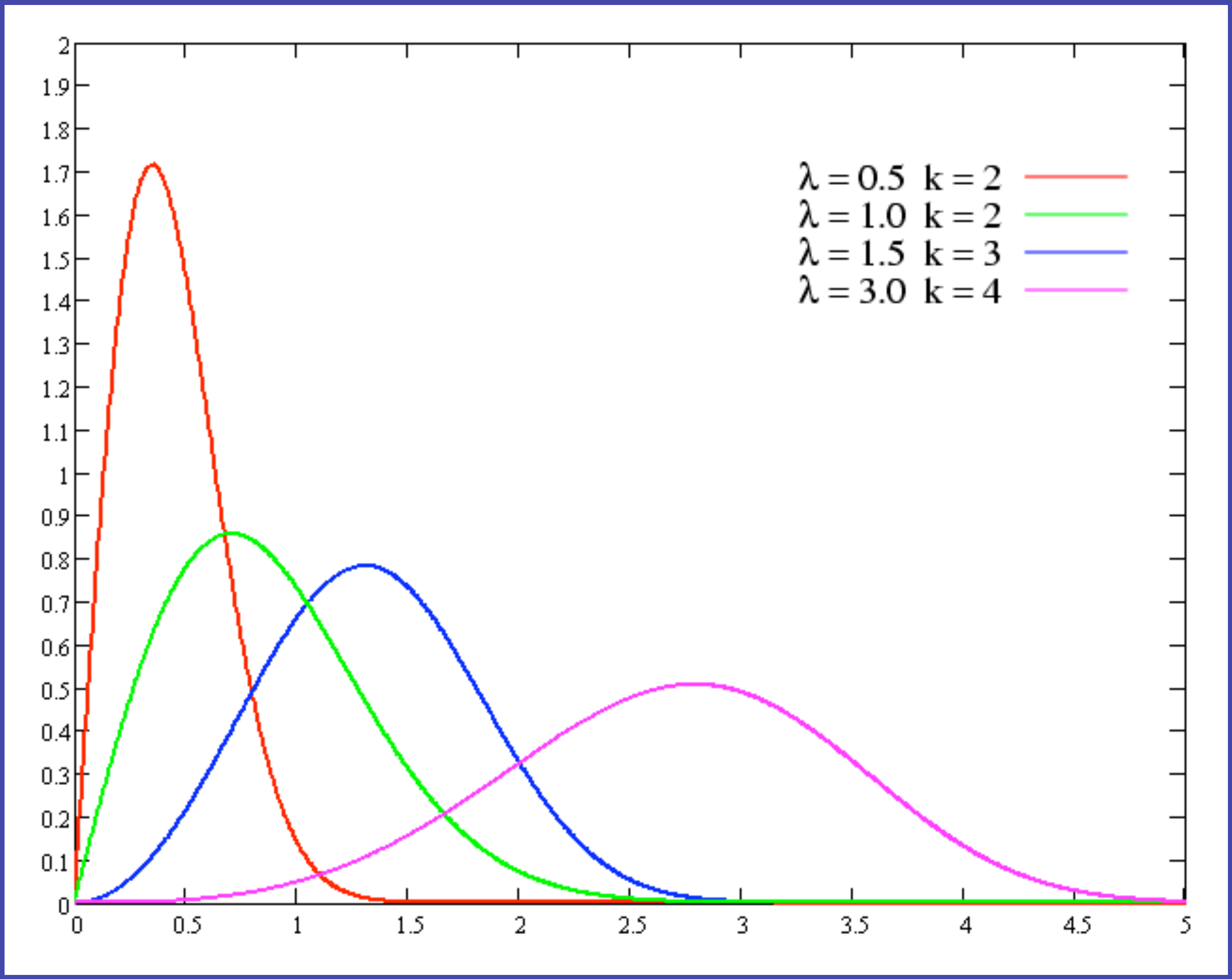
N Calaveras Fault

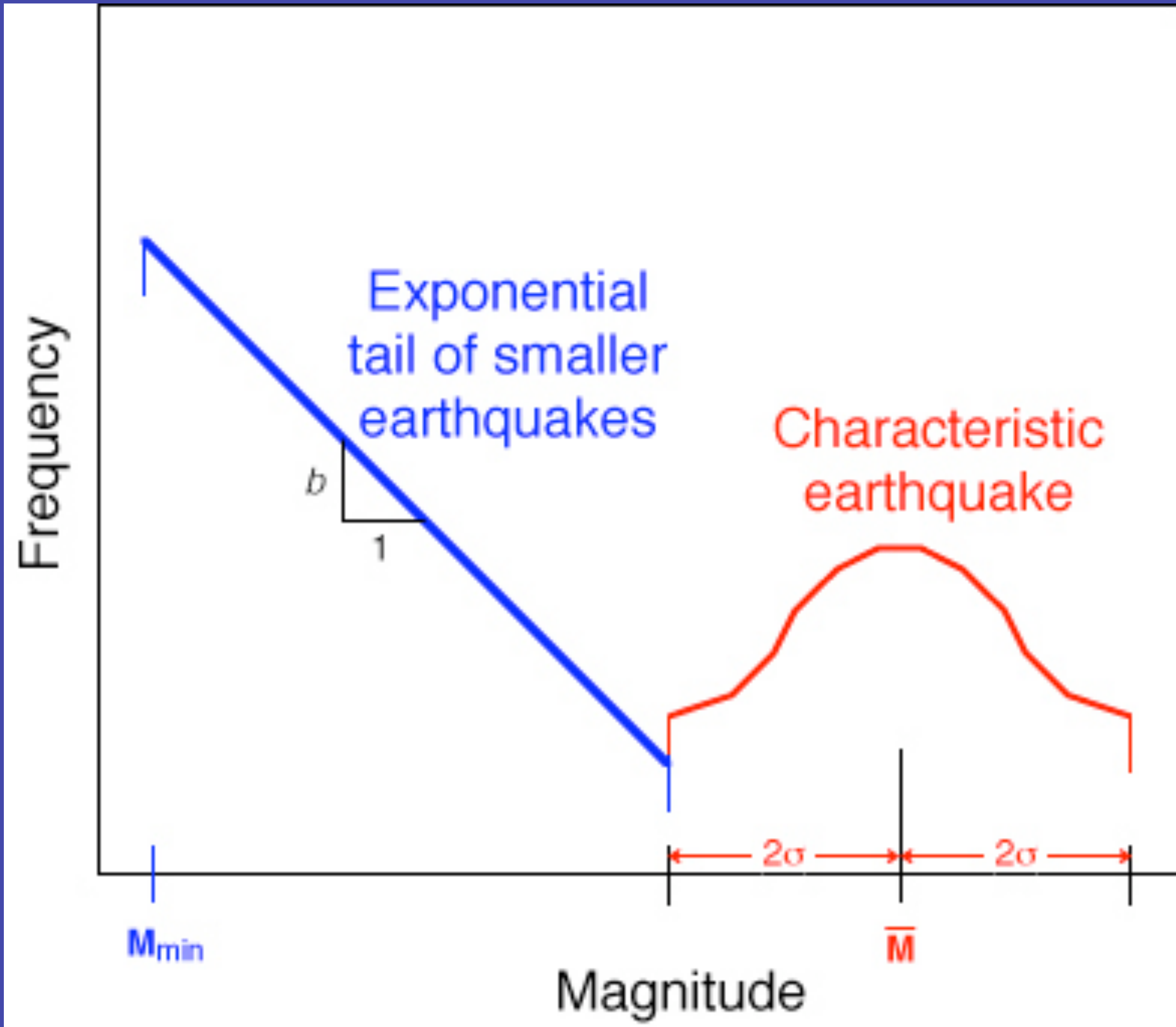
M>6.5



D=dynamic overshoot parameter
η=mantle viscosity

Weibull distribution

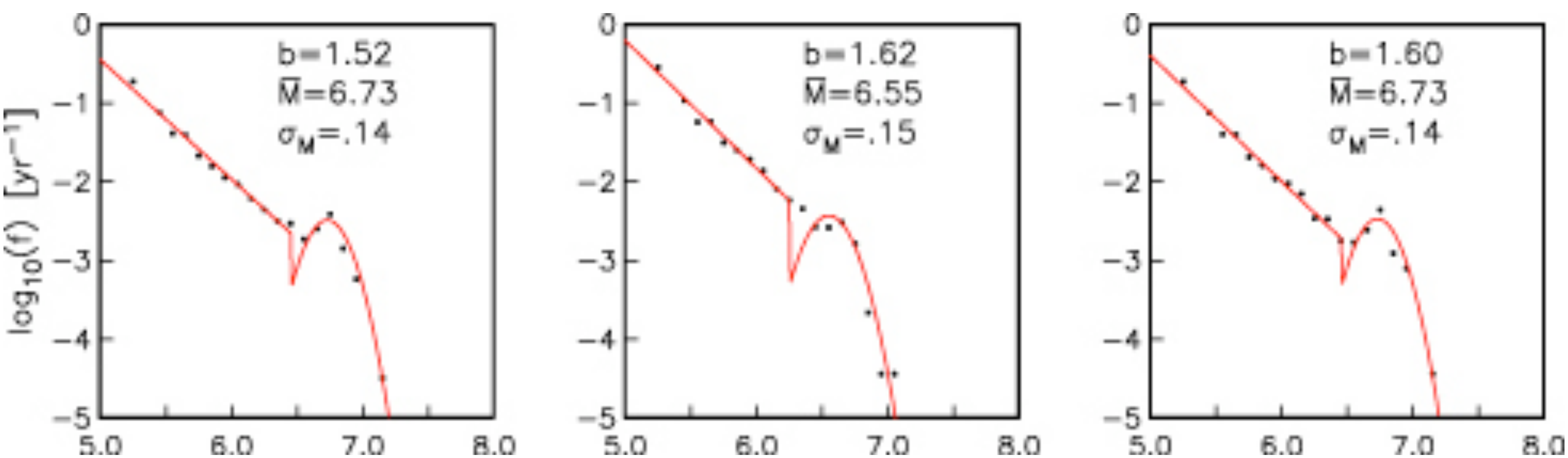




Frequency
Exponential
tail of smaller
earthquakes
b
1
Characteristic
earthquake
2σ
2σ
Mmin
M̄
Magnitude

N+S Hayward Fault

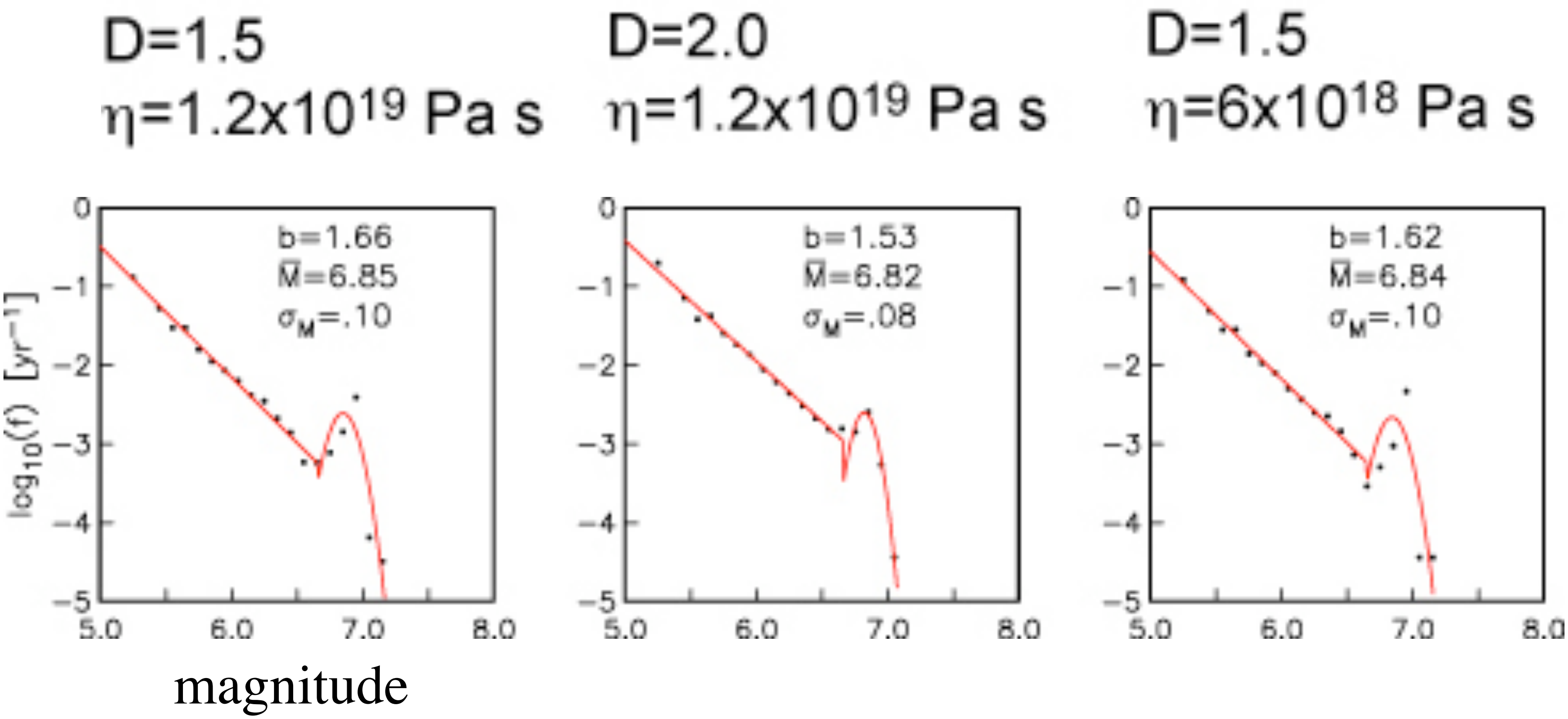
D=1.5 | D=2.0 | D=1.5
η=1.2x10^19 Pa s | η=1.2x10^19 Pa s | η=6x10^18 Pa s



magnitude

D=dynamic overshoot parameter
η=mantle viscosity

Rodgers Creek Fault

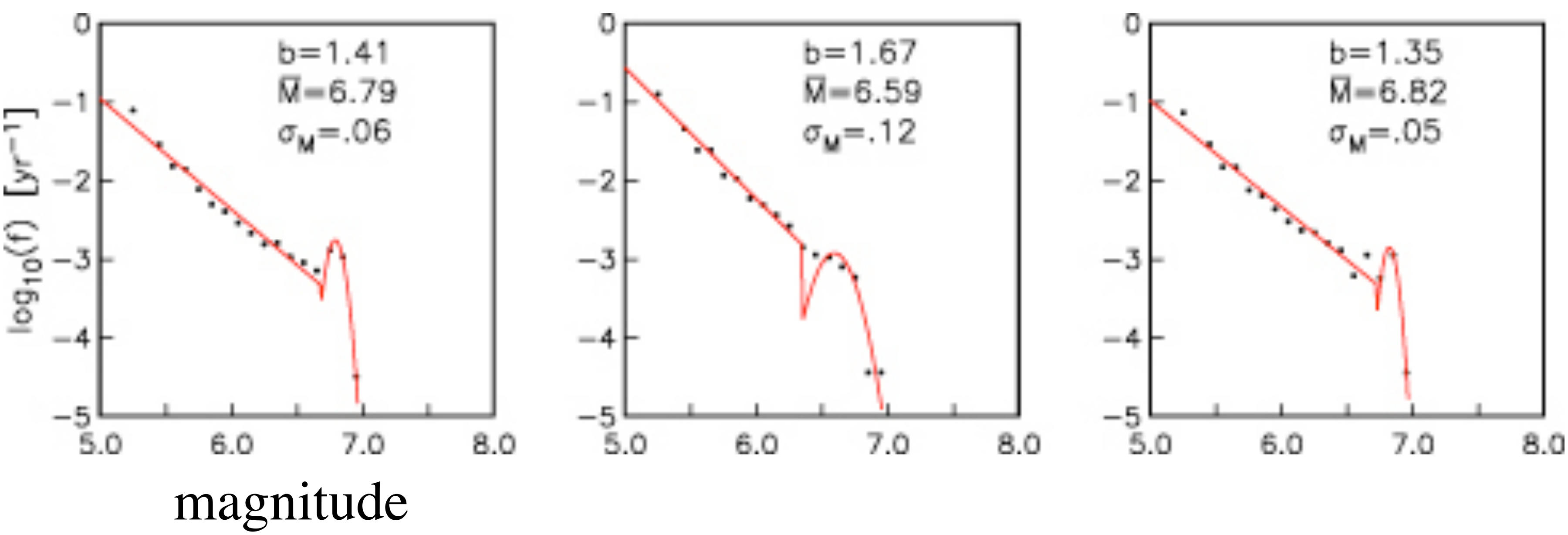


D=dynamic overshoot parameter

η=mantle viscosity

N Calaveras Fault

D=1.5 $\eta=1.2\text{x}10^{19}$ Pa s	D=2.0 $\eta=1.2\text{x}10^{19}$ Pa s	D=1.5 $\eta=6\text{x}10^{18}$ Pa s



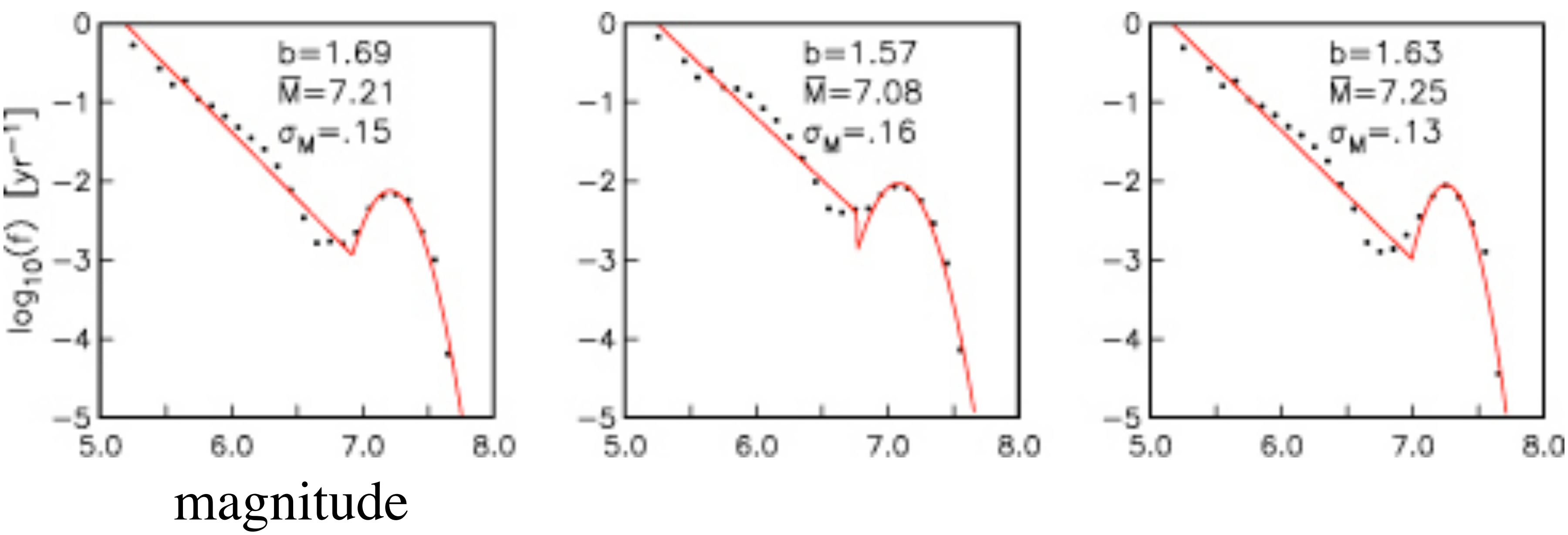
D=dynamic overshoot parameter
η=mantle viscosity

San Andreas Fault

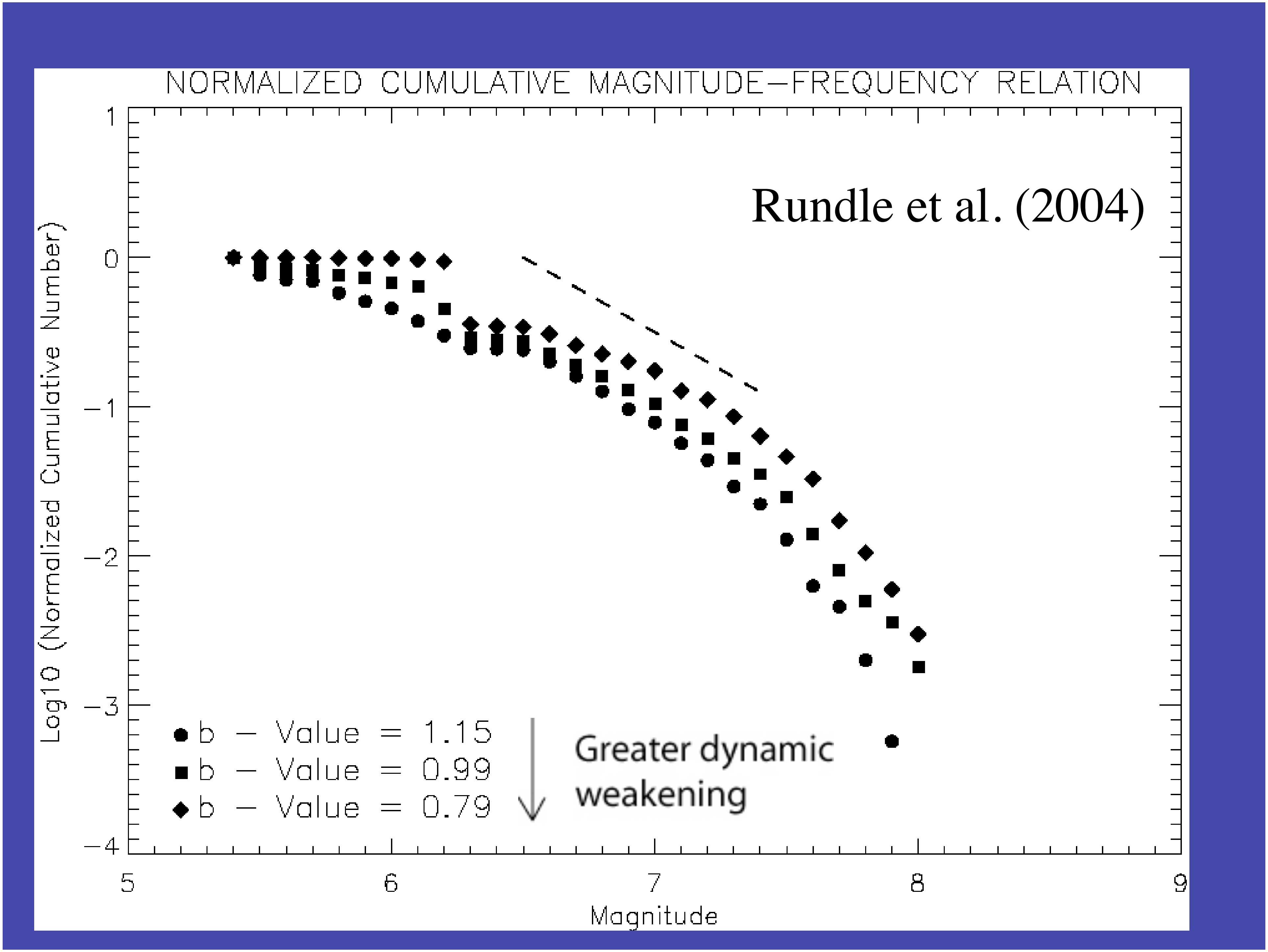
D=1.5
η=1.2x10^{19} Pa s

D=2.0
η=1.2x10^{19} Pa s

D=1.5
η=6x10^{18} Pa s

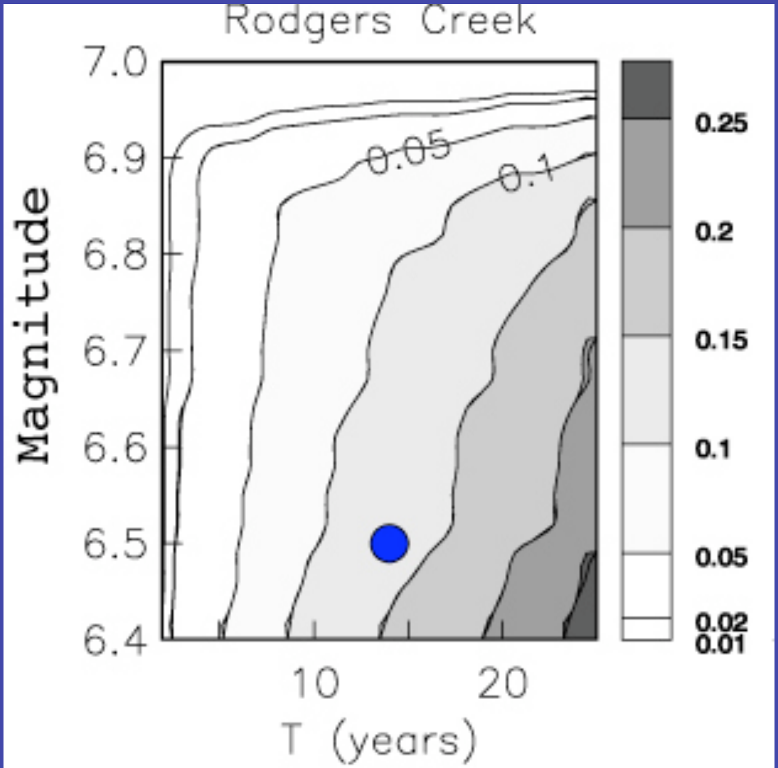


D=dynamic overshoot parameter
η=mantle viscosity

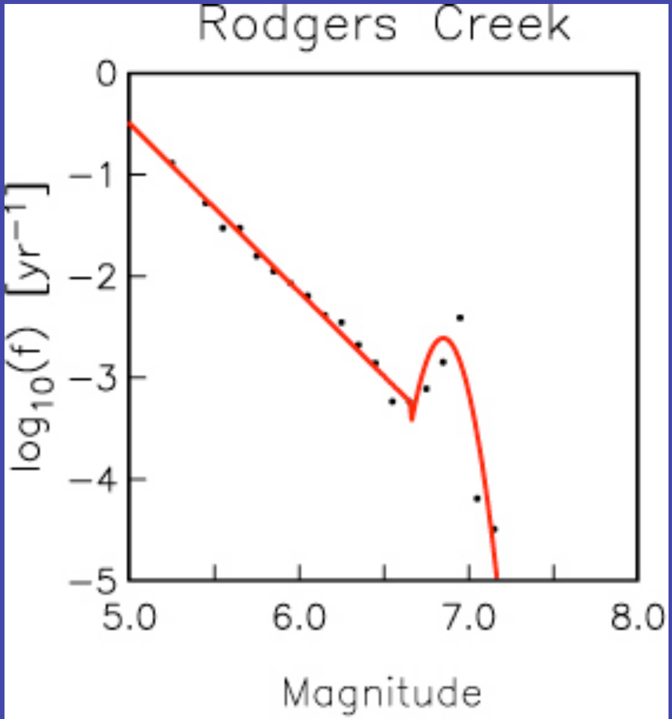


NORMALIZED CUMULATIVE MAGNITUDE–FREQUENCY RELATION
Rundle et al. (2004)
Log10 (Normalized Cumulative Number)
1
0
−1
−2
−3
−4
5
6
7
8
9
Magnitude
b − Value = 1.15
b − Value = 0.99
b − Value = 0.79
Greater dynamic weakening

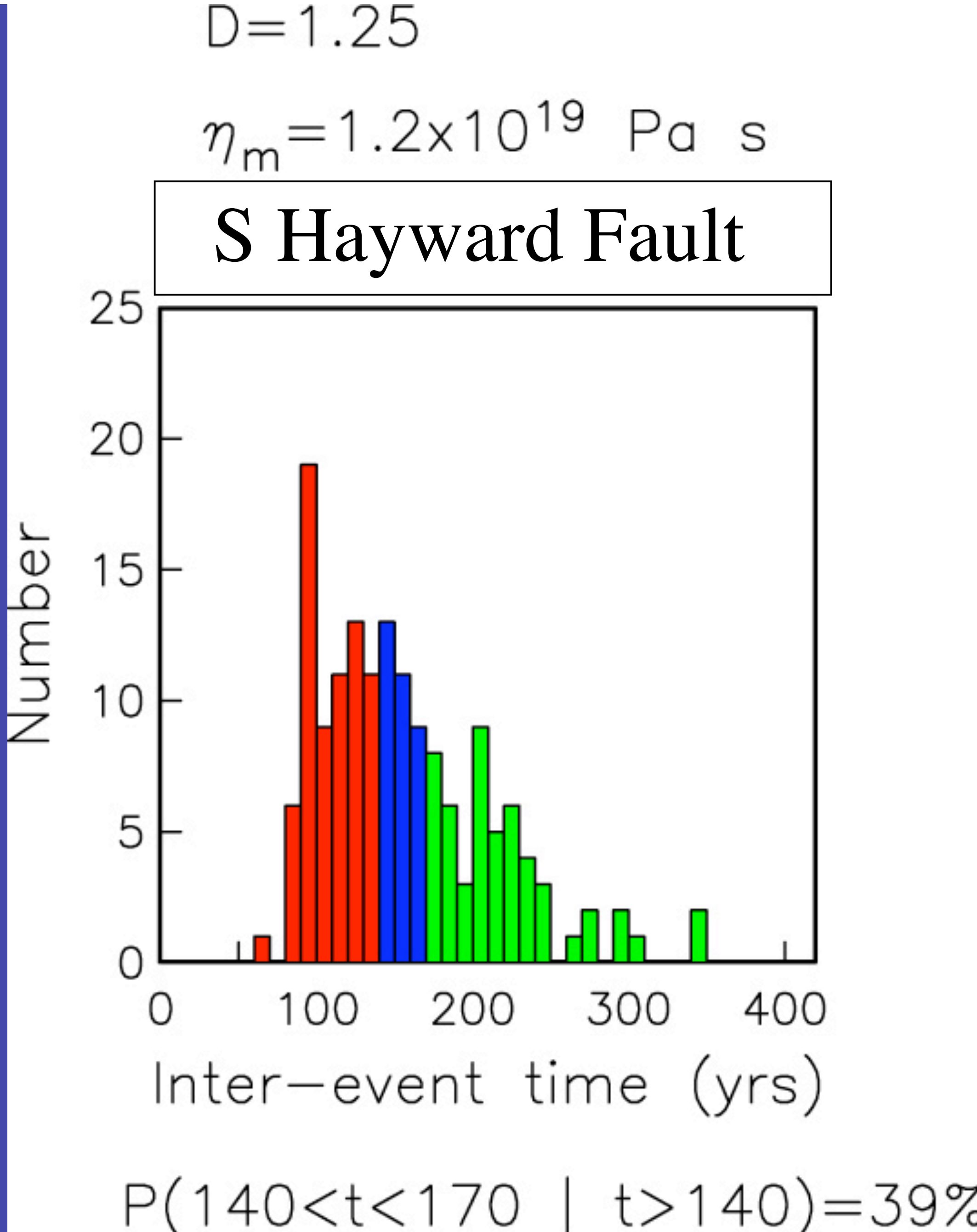
Foreshock-mainshock statistics



13% probability of M>6.5 mainshock following a moderate event within 14 years

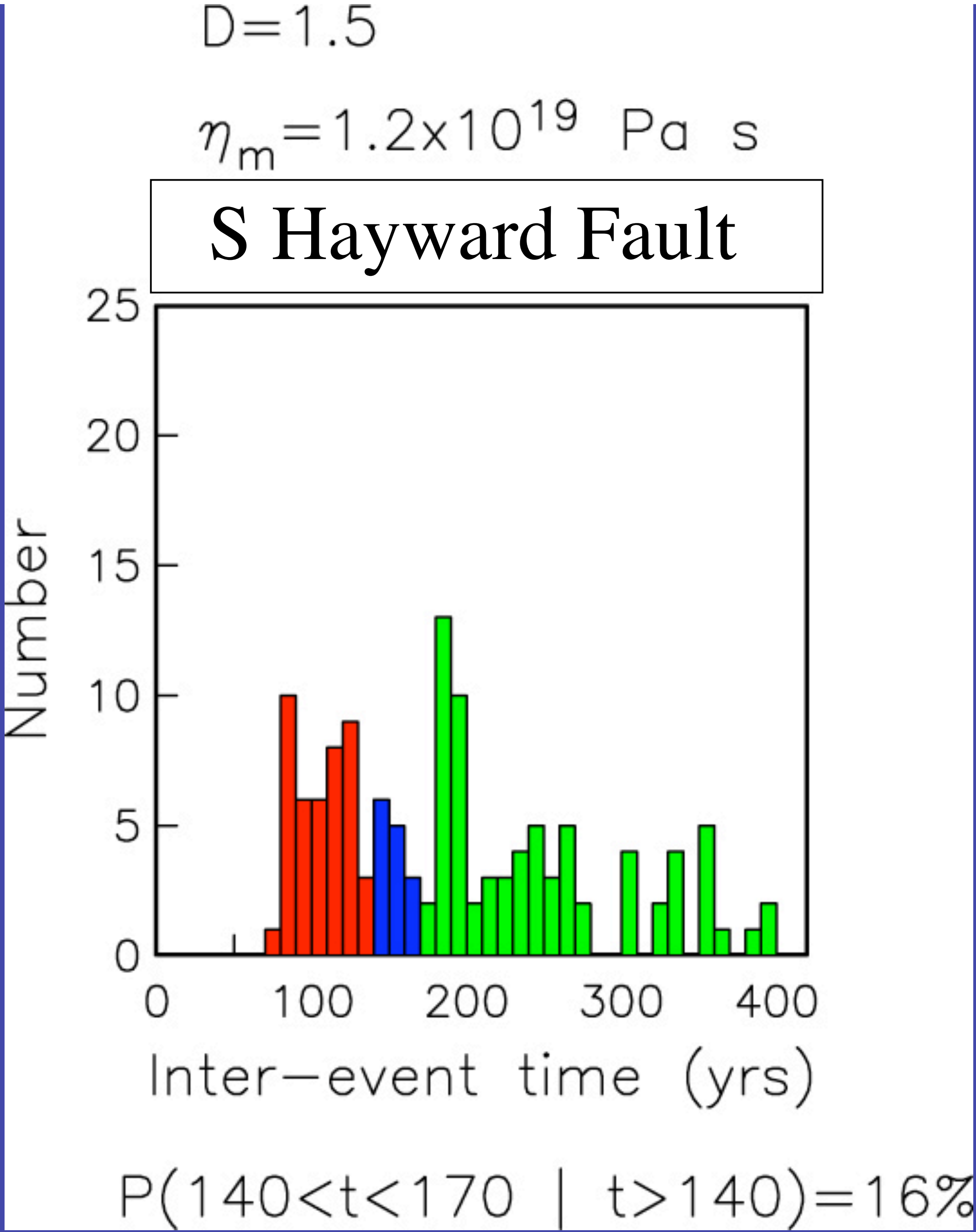


10% chance of M>6.5 quake occurring during a random 14-year long time interval



M>6.7

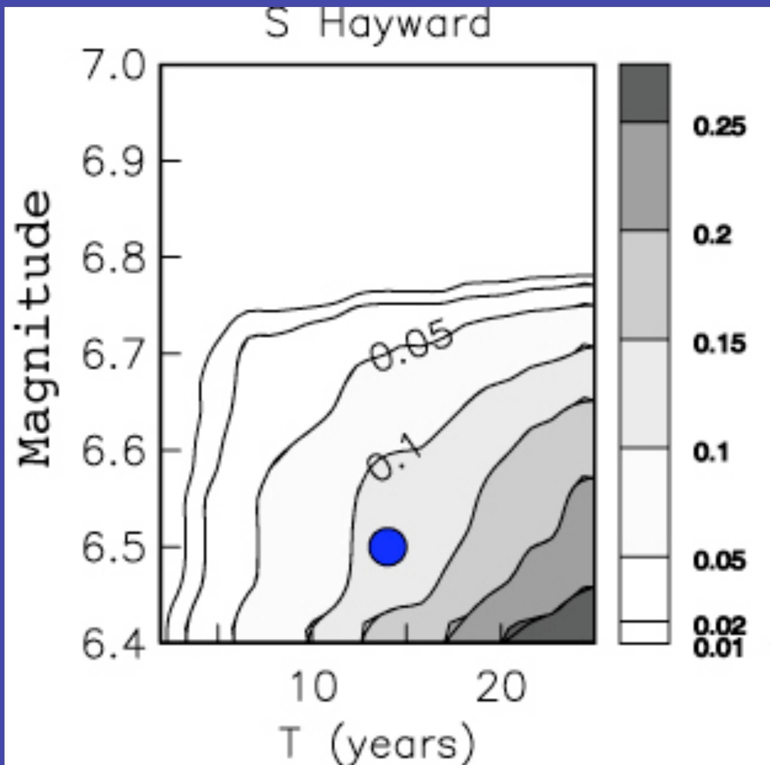
Conditional rupture probability



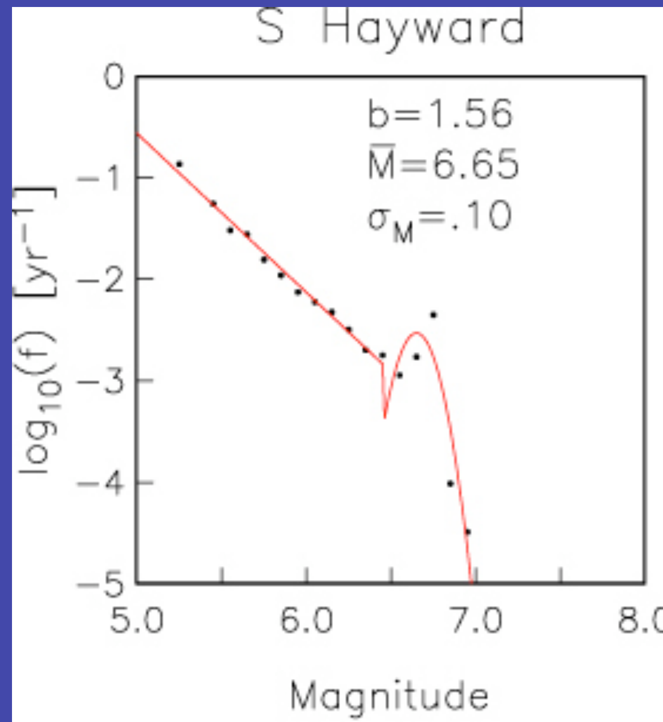
M>6.7

Conditional rupture probability

Foreshock-mainshock statistics

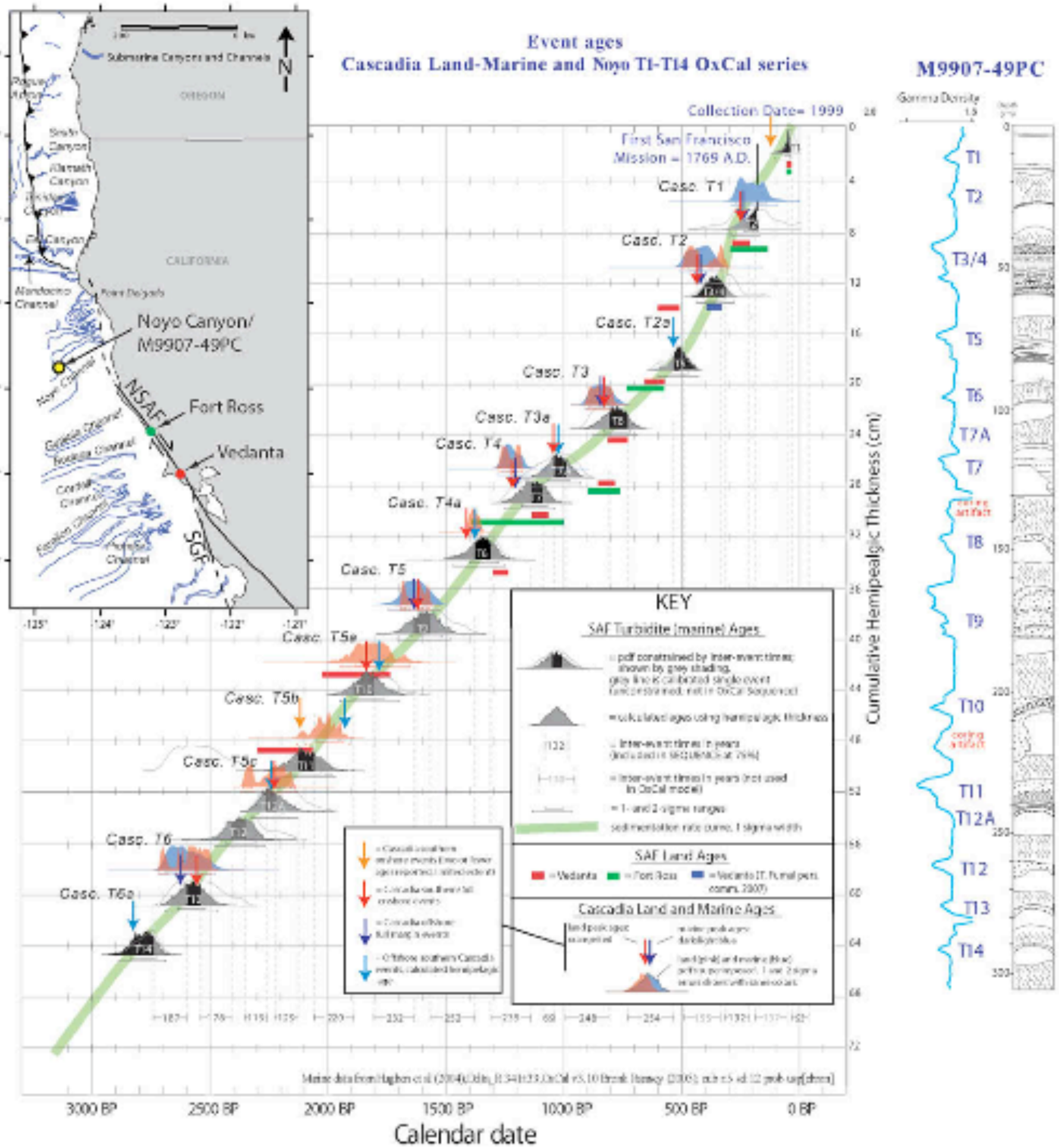


12% probability of M>6.5 mainshock following a moderate event within 14 years

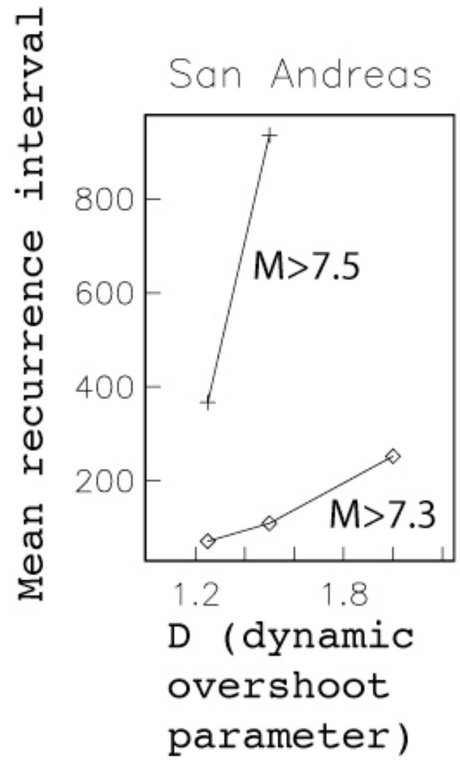


10% chance of M>6.5 quake occurring during a random 14-year long time interval

Goldfinger et al. (2008)

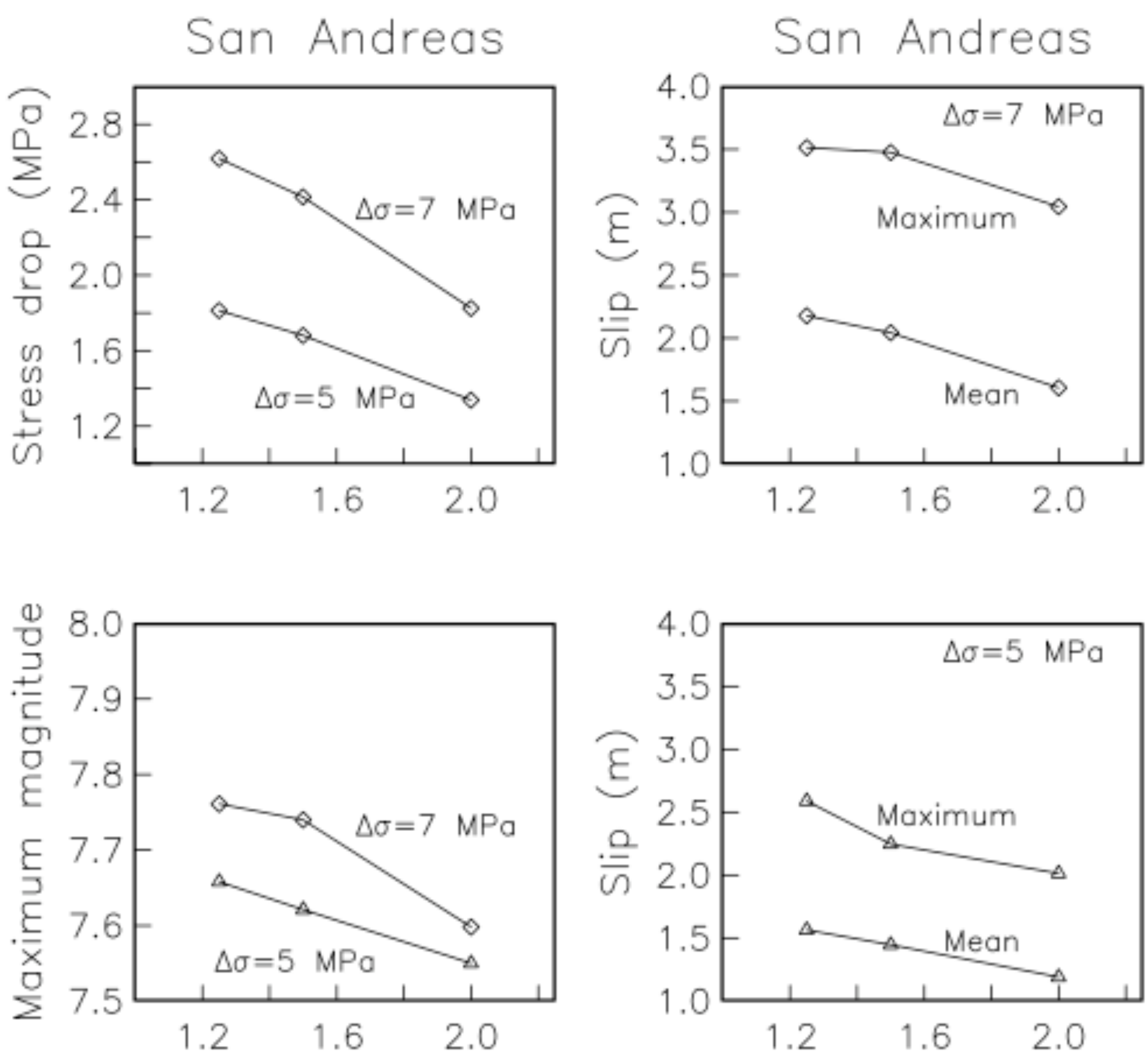


Simulator



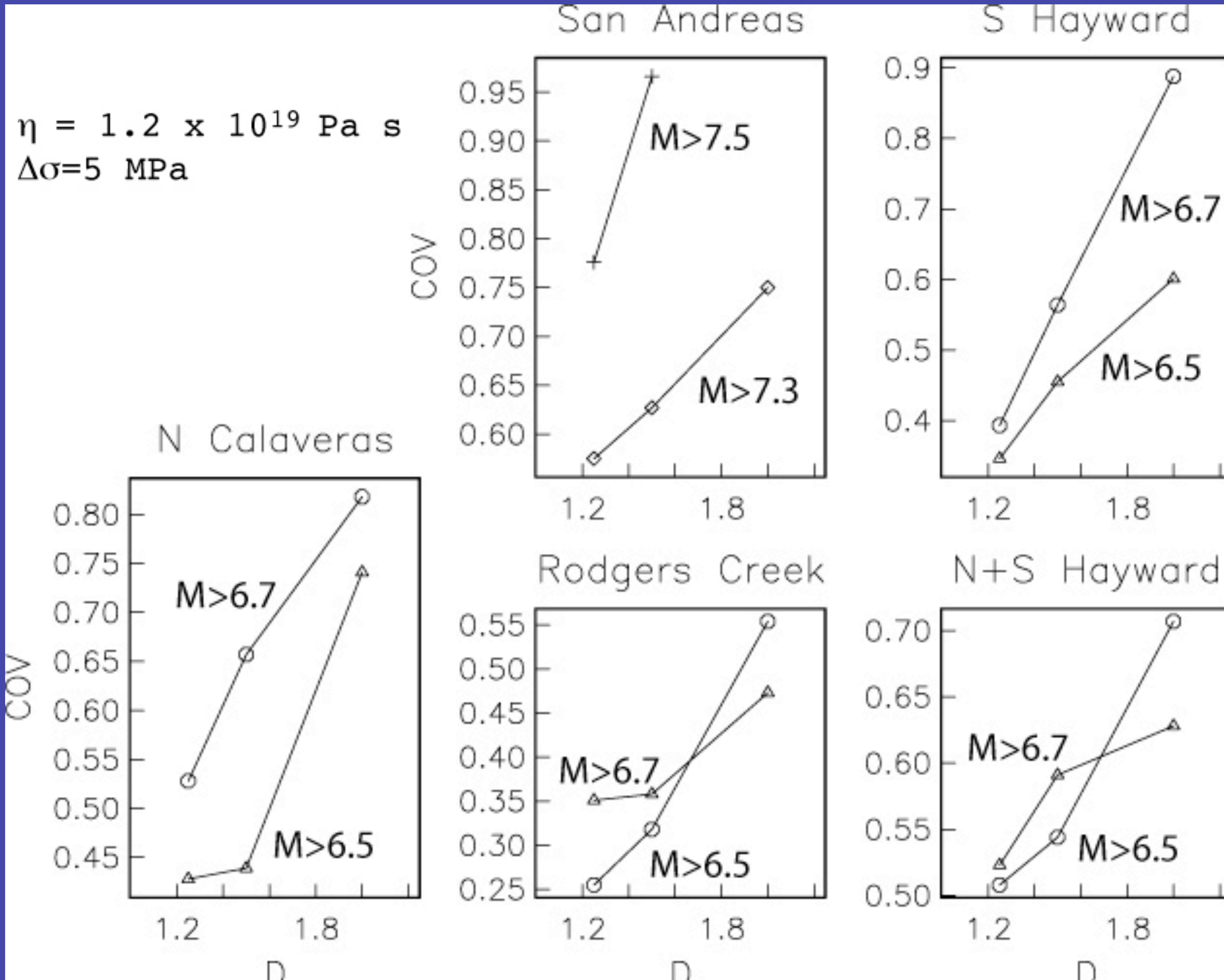
η=1.2 x 10^{19} Pa s

$\Delta\sigma$=5 MPa

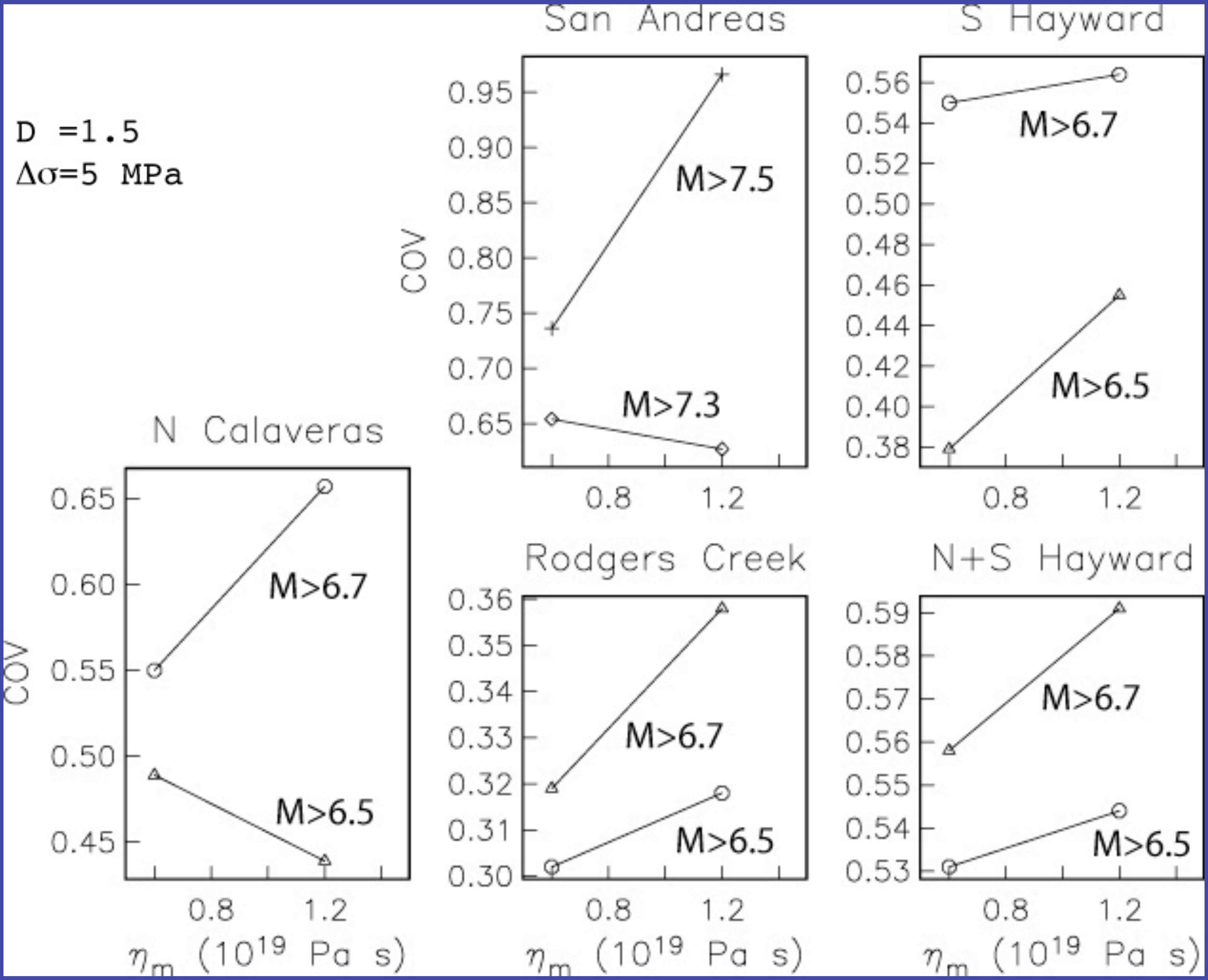


D (dynamic overshoot parameter)

$\eta = 1.2 \times 10^{19}$ Pa s



η = 1.2 x 10^19 Pa s
Δσ=5 MPa
San Andreas
S Hayward
N Calaveras
Rodgers Creek
N+S Hayward
COV
D
M>7.5
M>7.3
M>6.7
M>6.5



D =1.5
Δσ=5 MPa
San Andreas
M>7.5
M>7.3
COV
S Hayward
M>6.7
M>6.5
N Calaveras
M>6.7
M>6.5
COV
Rodgers Creek
M>6.7
M>6.5
N+S Hayward
M>6.7
M>6.5
η_m (10^19 Pa s)

Conclusions

- Viscoelastic earthquake simulator is feasible
- Fault system behavior is sensitive to
  simple parameters
- Fault interaction and viscoelasticity
  --> One-fault models or purely elastic models
  will not capture likely range of complexity