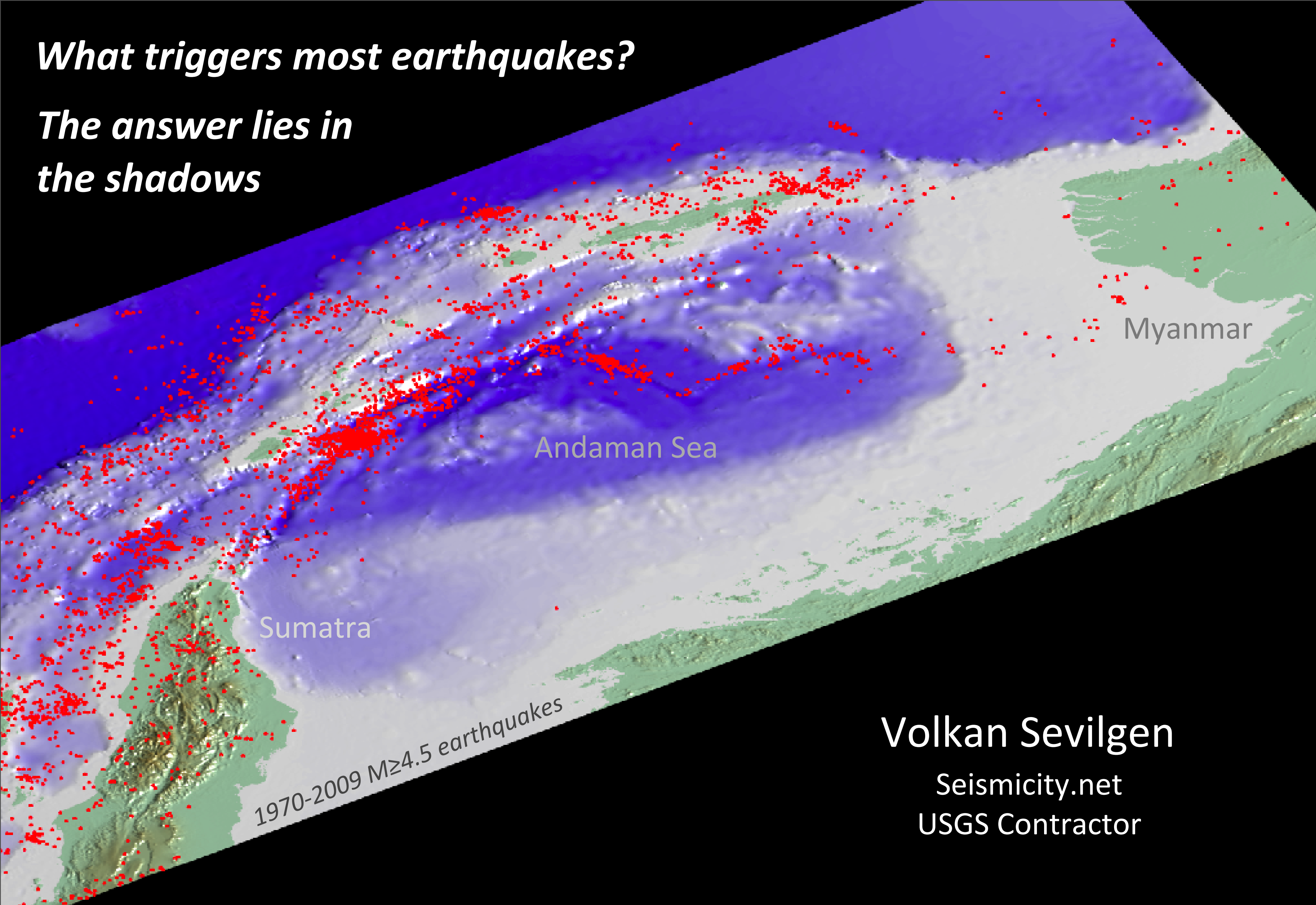
What triggers most earthquakes?

The answer lies in the shadows

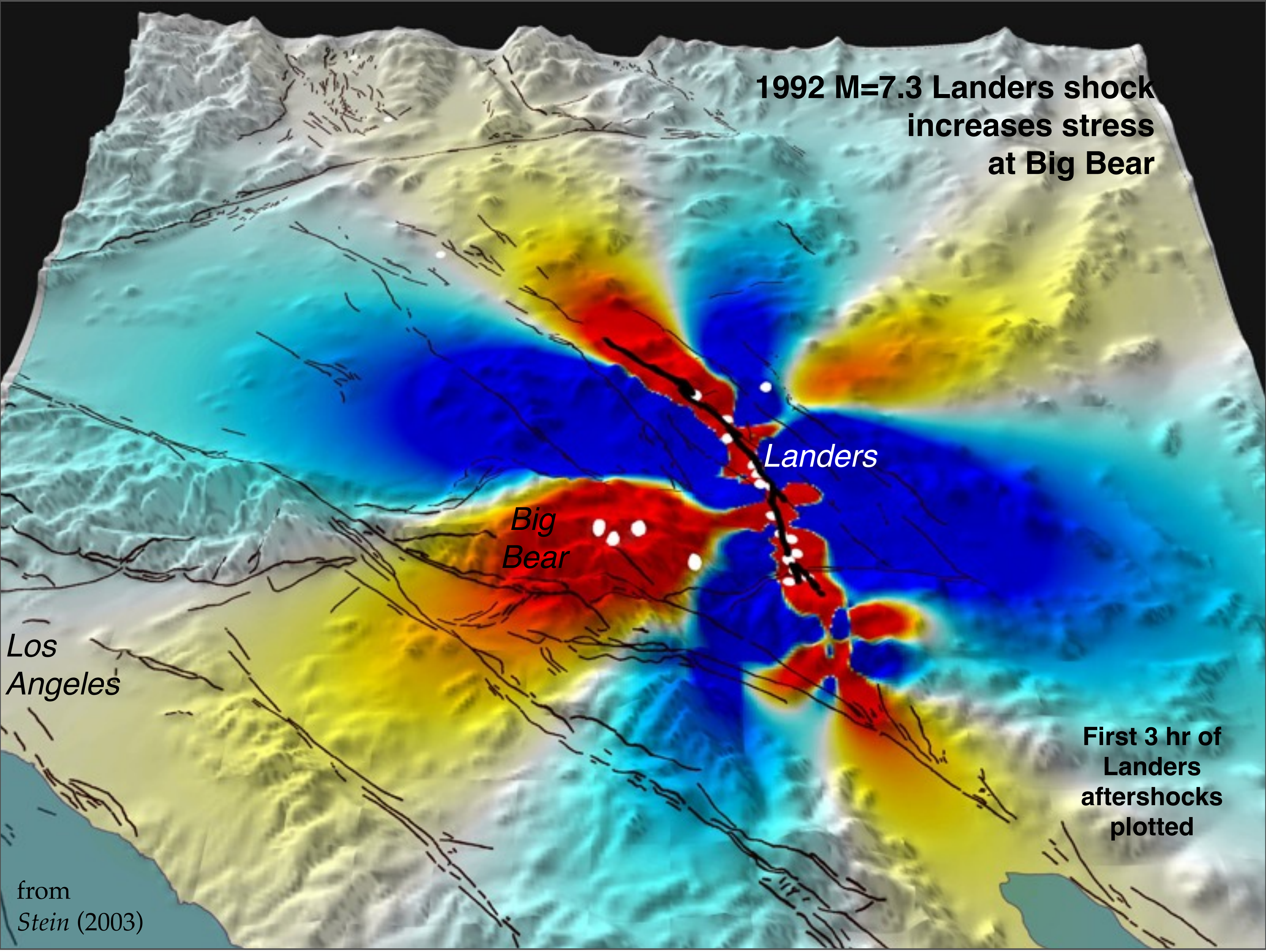


Volkan Sevilgen

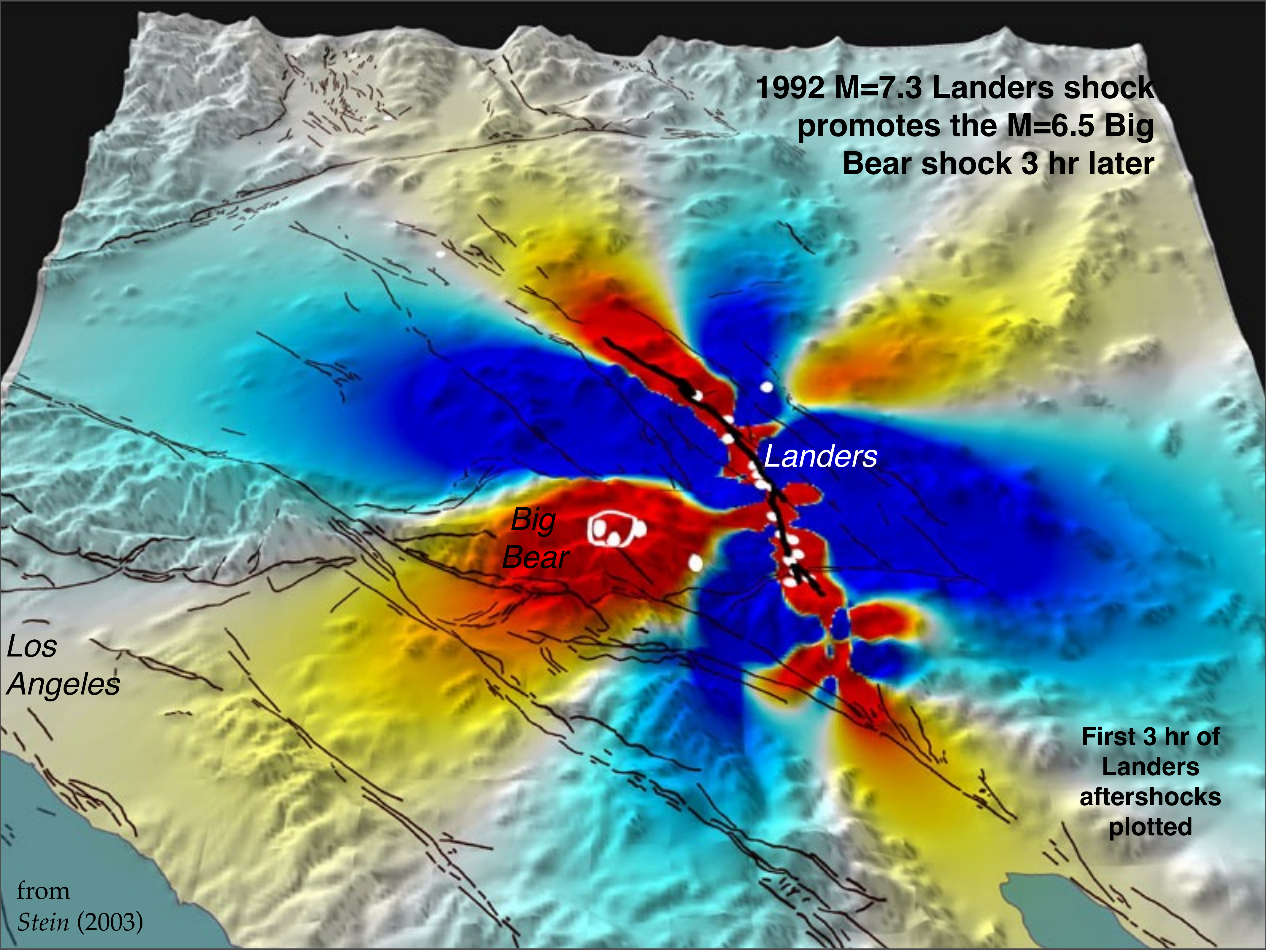
Seismicity.net

USGS Contractor

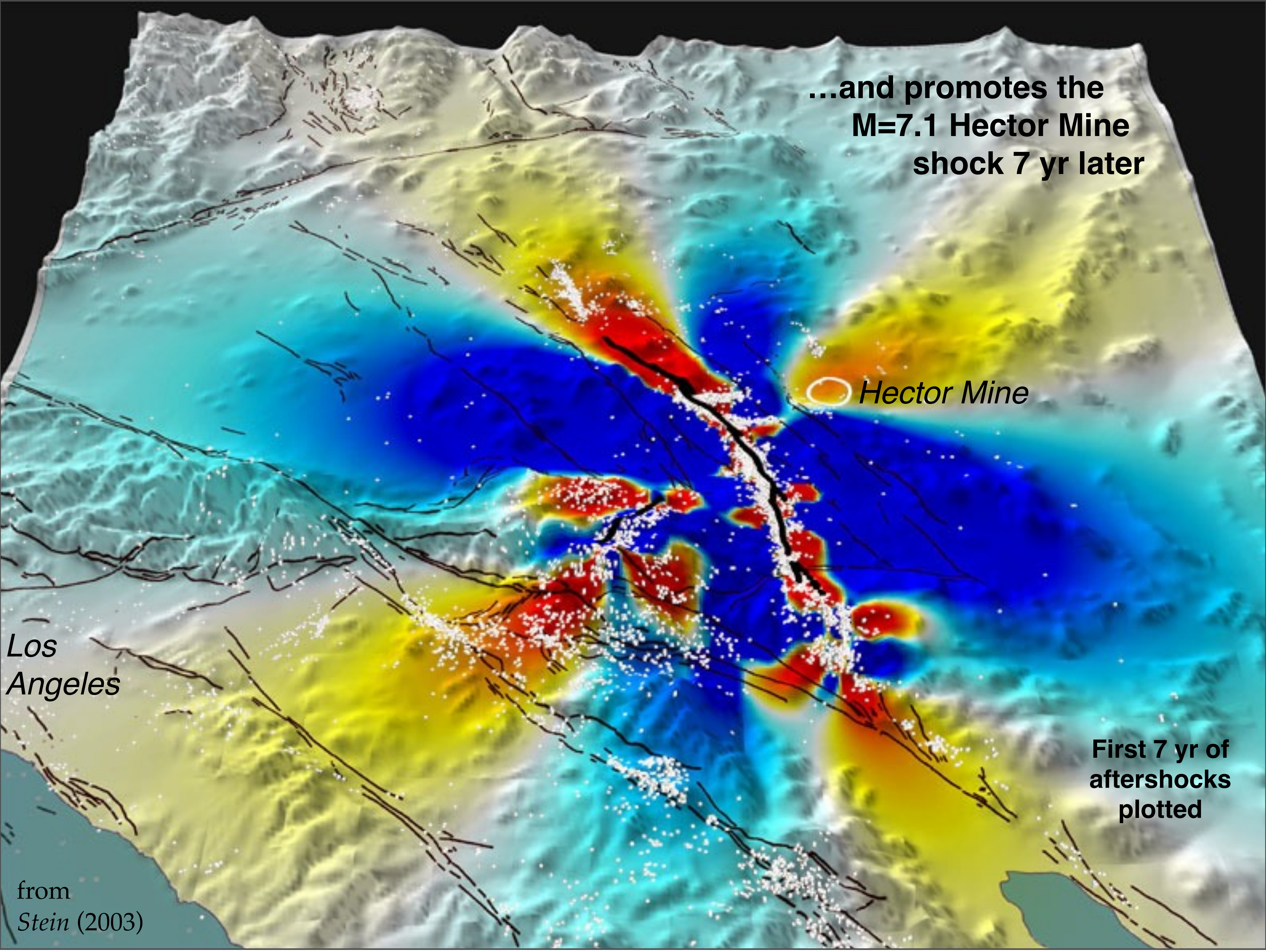
A presentation of Sevilgen, Stein, and Pollitz (*Proc Natl Acad Sci USA*, 2012)



1992 M=7.3 Landers shock
increases stress
at Big Bear
Landers
Big
Bear
Los
Angeles
First 3 hr of
Landers
aftershocks
plotted
from
Stein (2003)



1992 M=7.3 Landers shock promotes the M=6.5 Big Bear shock 3 hr later
Landers
Big Bear
Los Angeles
First 3 hr of Landers aftershocks plotted
from *Stein* (2003)


…and promotes the
M=7.1 Hector Mine
shock 7 yr later
Hector Mine
Los
Angeles
First 7 yr of
aftershocks
plotted
from
Stein (2003)

Arguments for dynamic stress triggering

- Remote triggering by Love waves (*Hill et al*, 1993; *Brodsky et al*, 2000; *Brodsky & Prejean*, 2005; *Gomberg & Johnson*, 2005; *Velasco et al*, 2008; *Pollitz et al*, 2012)
- Tremor is triggered by large distant quakes (*Peng et al*, 2008; *Peng & Chao*, 2008)
- Directivity distorts aftershock zones (*Kilb et al*, 2000 & 2002; *Doser et al*, 2009)
- No seismicity rate drop in stress shadows (*Marsan*, 2003; *Felzer & Brodsky*, 2004)

Arguments for static stress triggering

- Correlation of stress change & seismicity rate change (*Stein*, 1999; *Parsons*, 2002)
- Tidal triggering of quakes & tremor (*Cochran et al*, 2004; *Tanaka et al*, 2004)
- Swarms triggered by creep (*Vidale & Shearer*, 2006; *Lohman & McGuire, 2007*)
- Seismicity rate drop in stress shadows (*Harris & Simpson*, 1998; *Toda & Stein*, 2004; *Ma et al*, 2005; *Marsan & Nalbant, 2005: Toda et al*, 2005; *Mallman & Parsons*, 2008; *Chan & Stein*, 2009)

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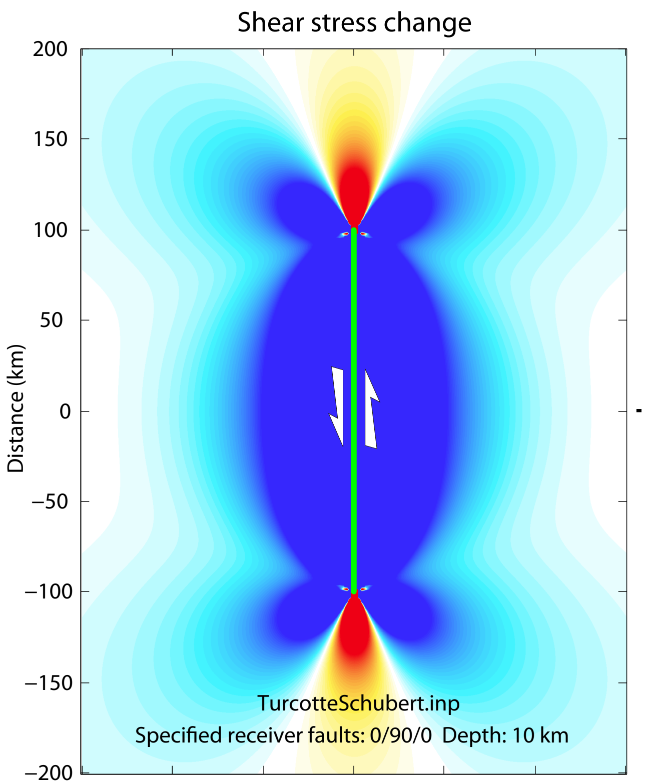
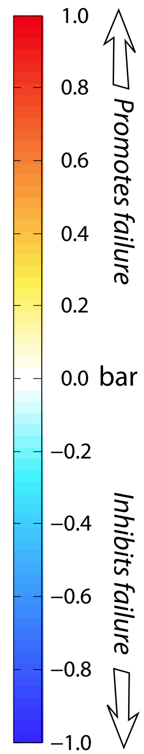
The term '*stress shadow*' is first coined by Ruth Harris and Bob Simpson in their 1998 paper.

Here's how we calculate the static Coulomb stress change imparted by a strike-slip source



Shear stress change, τ_S



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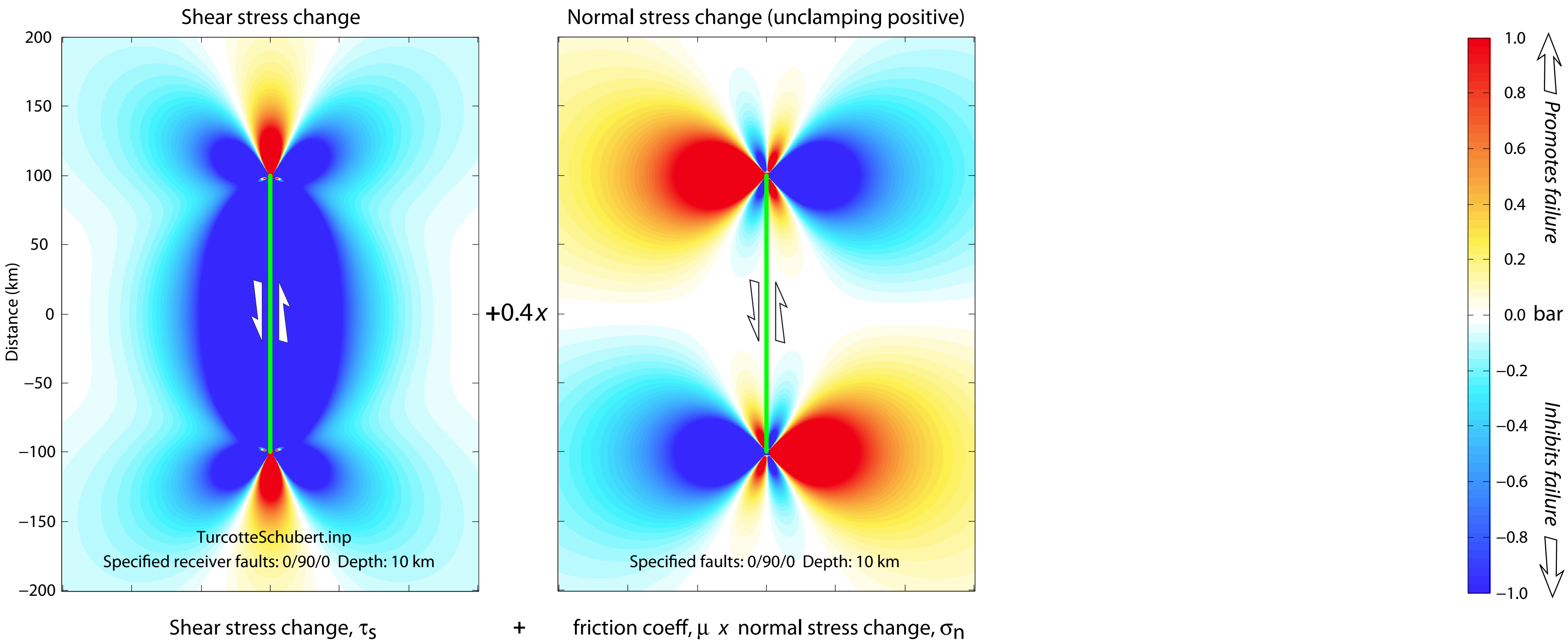

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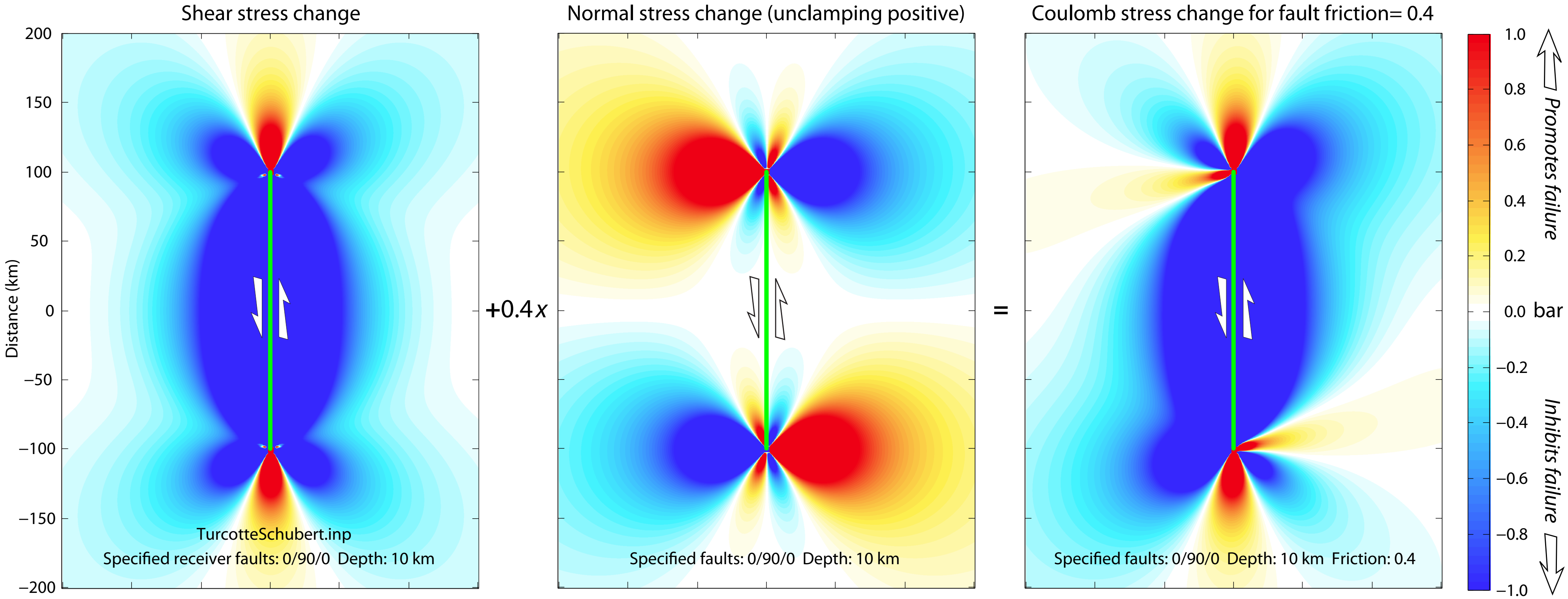
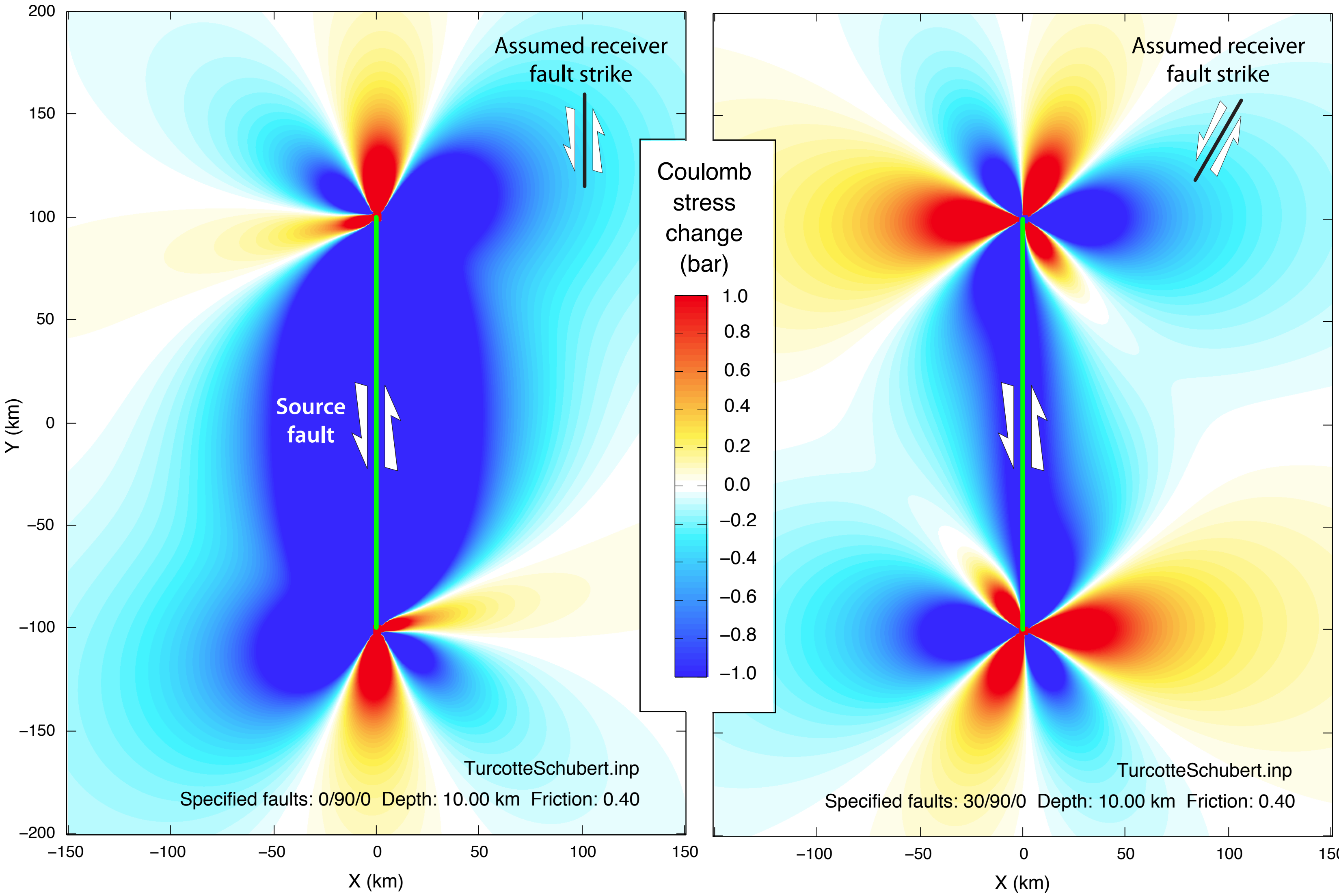


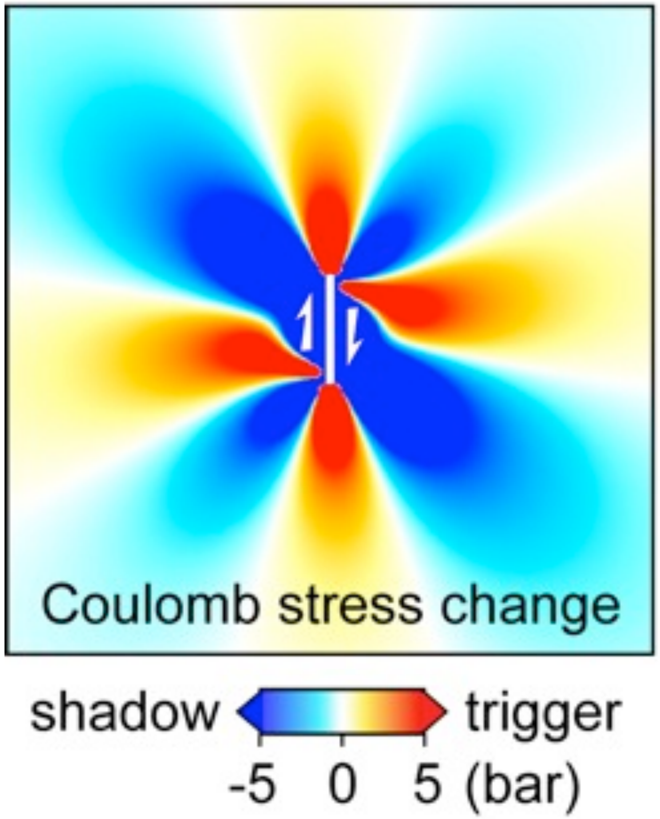
Shear stress change, τ_s + friction coeff, μ x normal stress change, σ_n = Coulomb stress change, σ_c (ΔCFF)

The Coulomb Stress change depends on the receiver fault strike dip, and rake

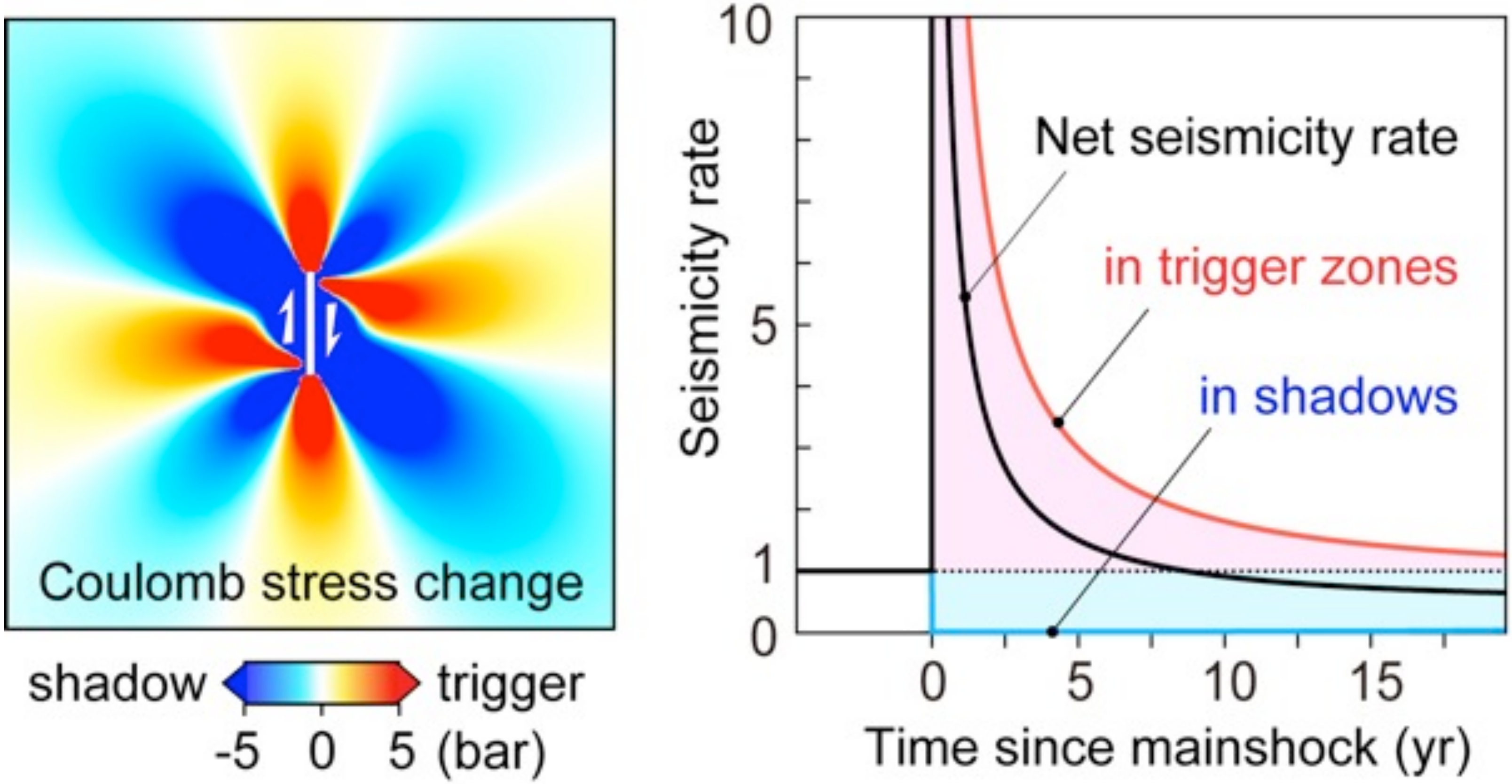


A stress shadow for one receiver fault orientation can be a stress trigger zone for another

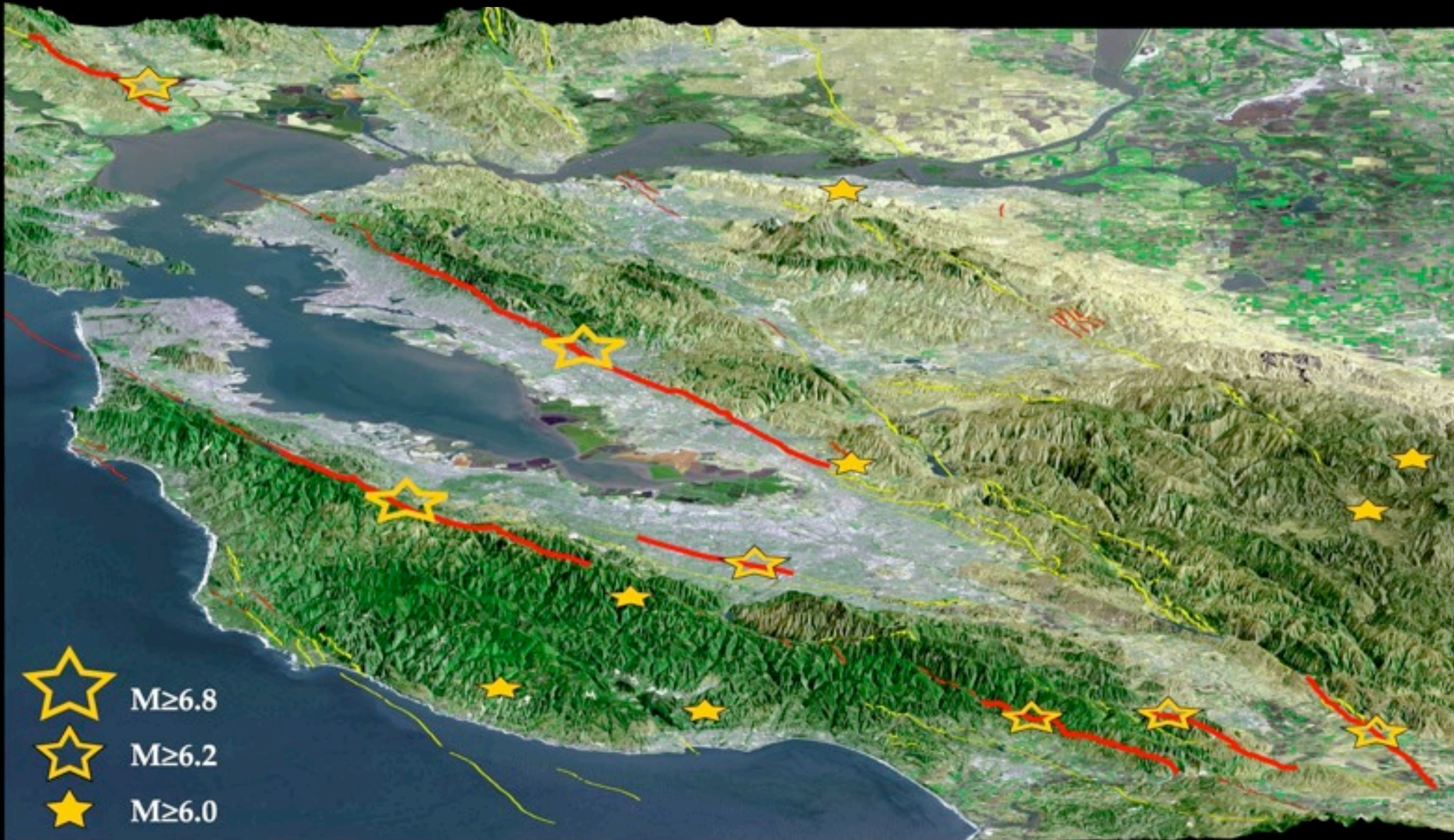
Overcoming the stress shadow/seismicity rate drop imbalance



Overcoming the stress shadow/seismicity rate drop imbalance



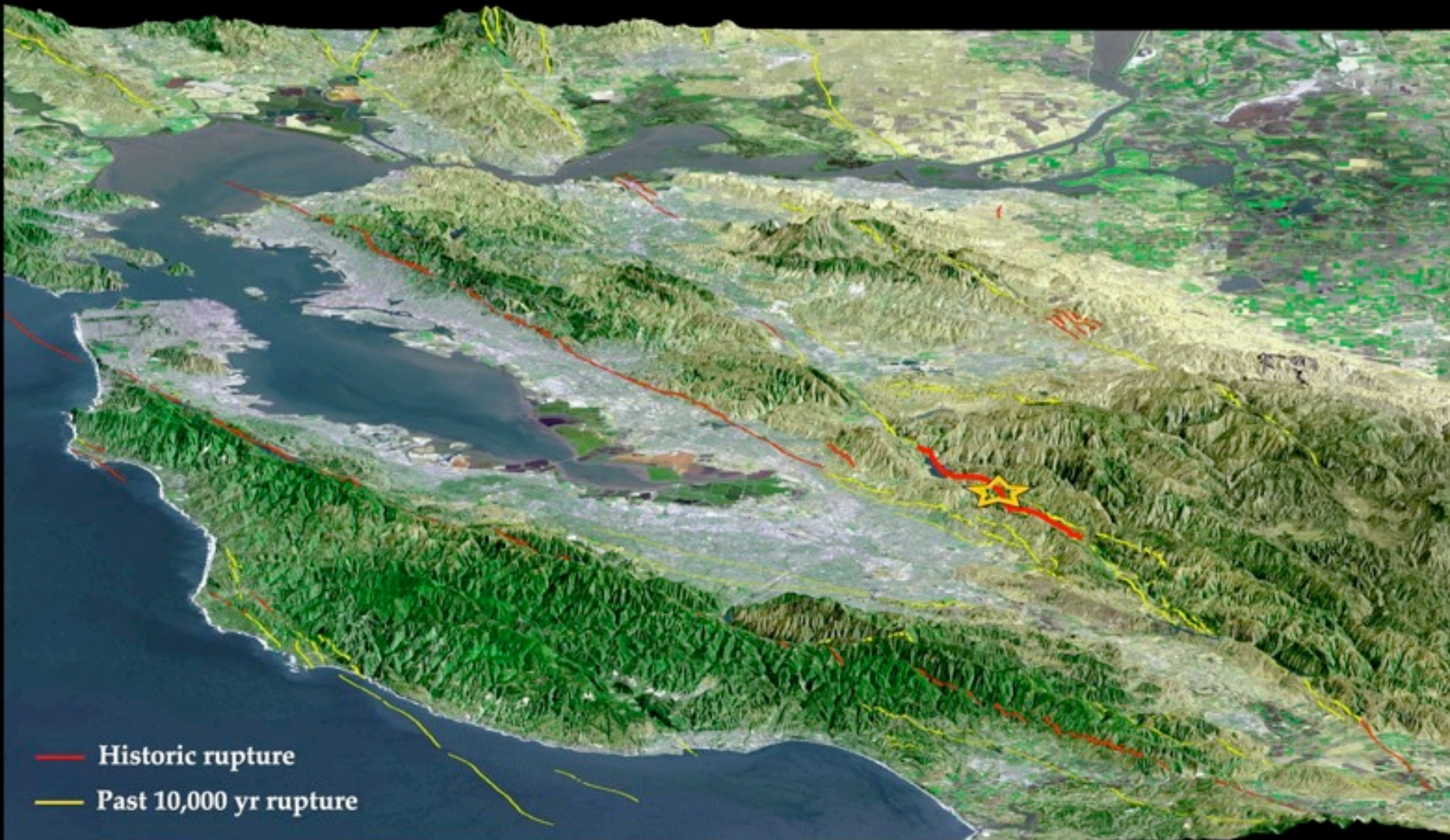
Bay area shocks during the 75 years *before* 1906



from *Stein* (Nature, 2003)

Earthquakes from *Bakun* [1999] and *Ellsworth* [1990]

Bay area shocks during the 75 years *after* 1906



from *Stein* (Nature, 2003)

1911 M=6.2 shock from *Bakun* [BSSA, 1999]

Needed for the ideal test case

- Large mainshock transmits stress over great distance
- Simple rupture propagation for dynamic calculations
- Receiver faults physically separated from source fault
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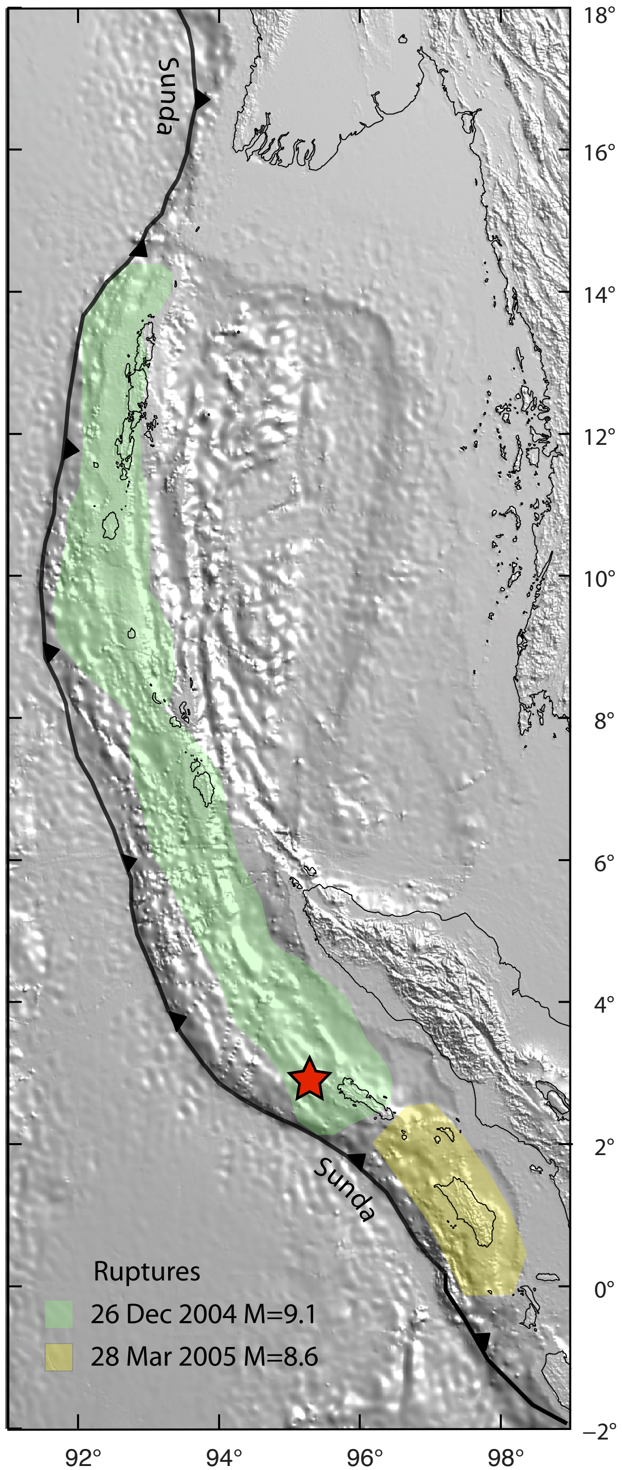
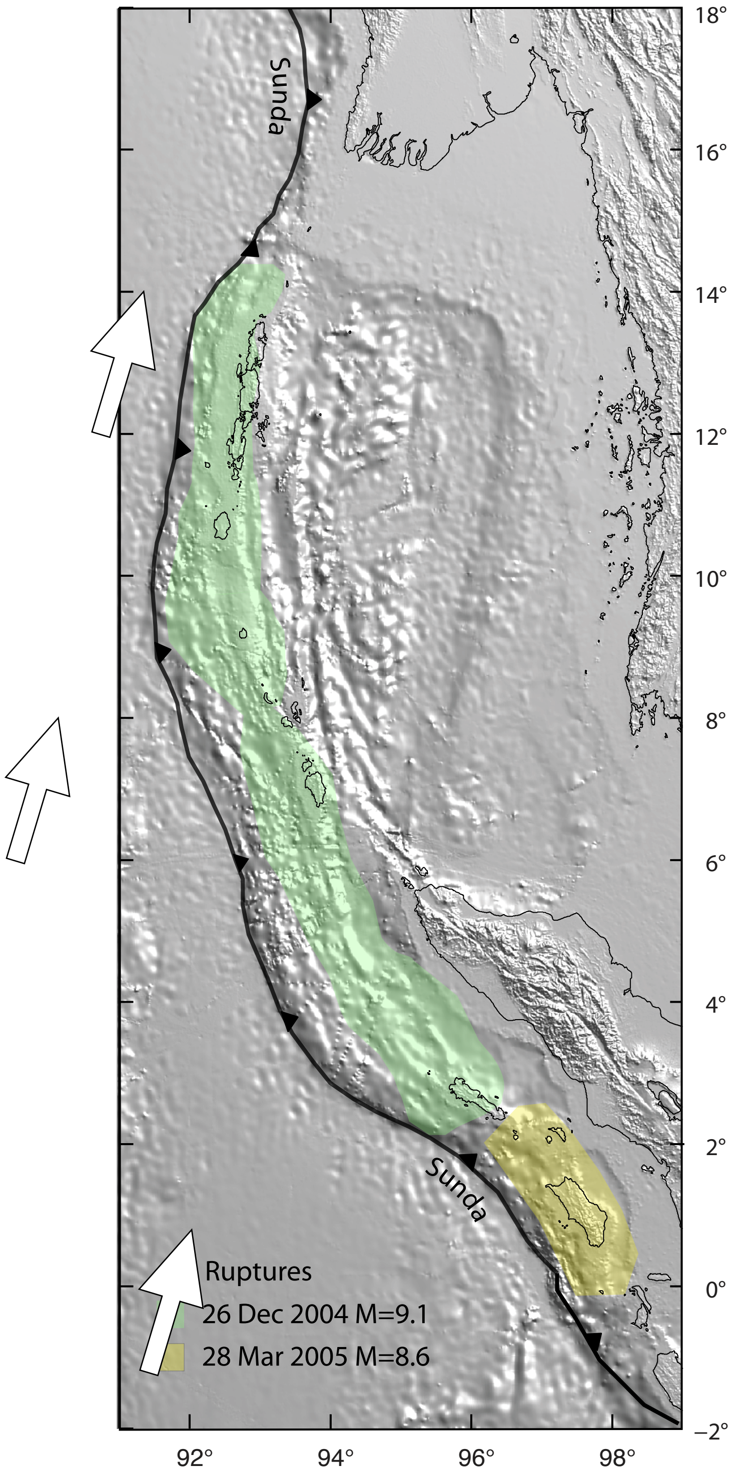
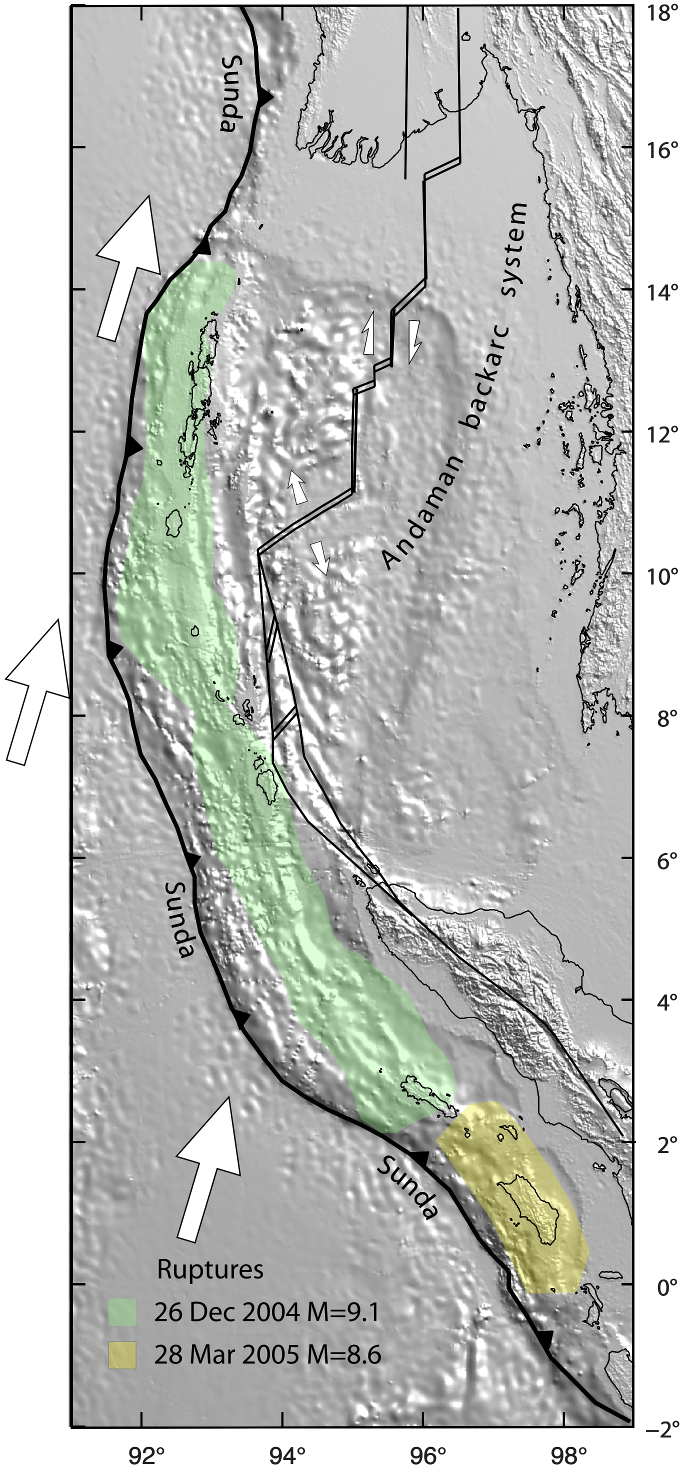
Stress transfer from 2004 M=9.2 Sumatra mainshock to Andaman backarc rift-transform system fulfills these



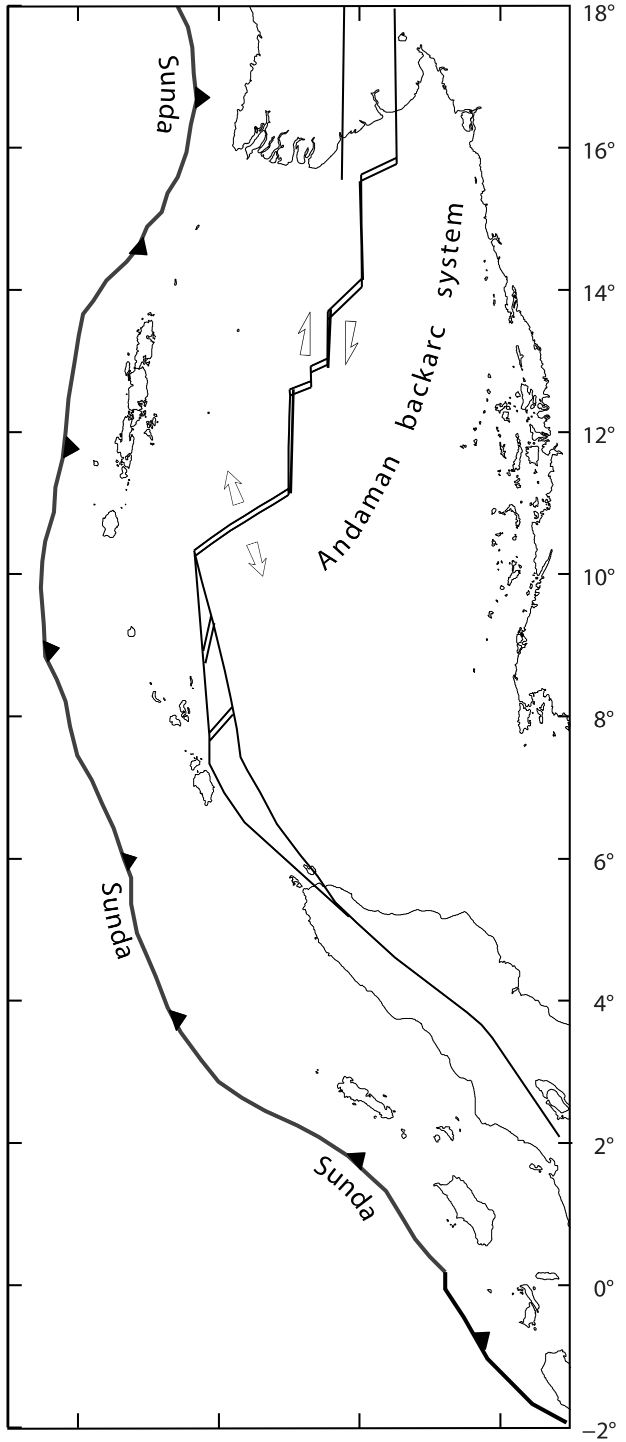
2004 rupture area
Northward rupture at
2.8 km/sec (Ishii et al, 2005)

Oblique subduction along the Sunda trench

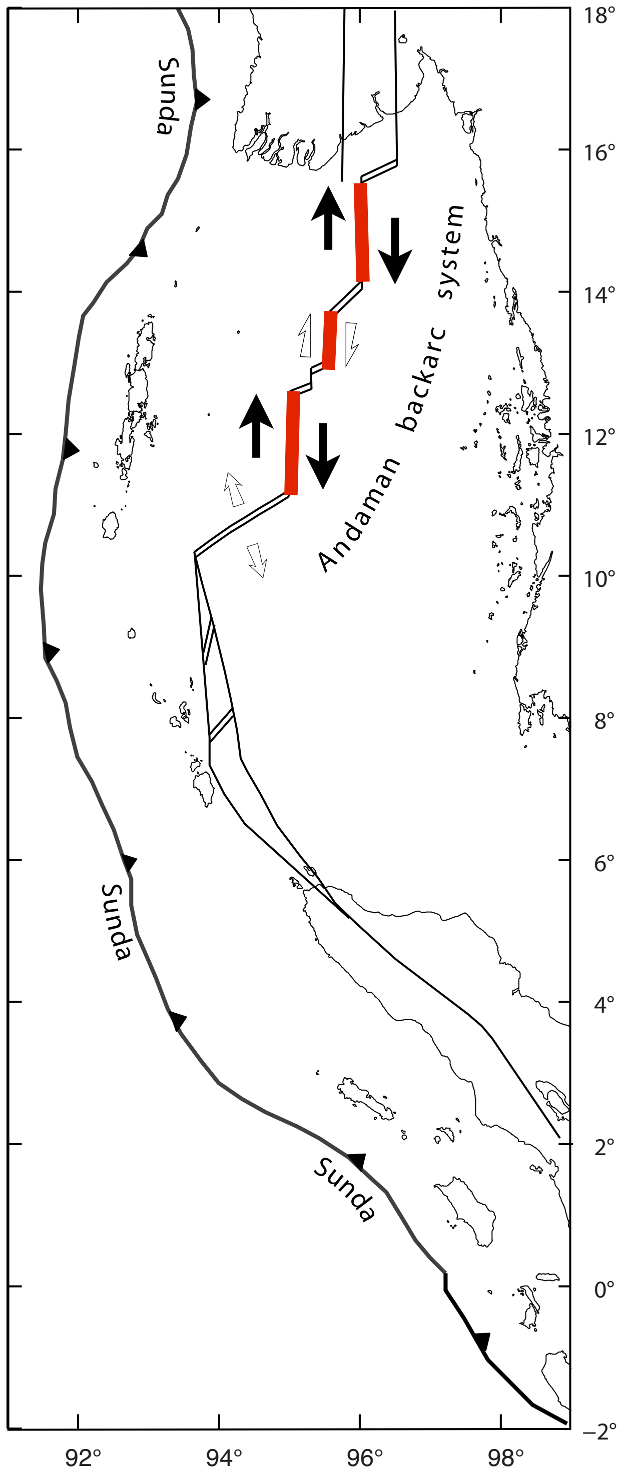




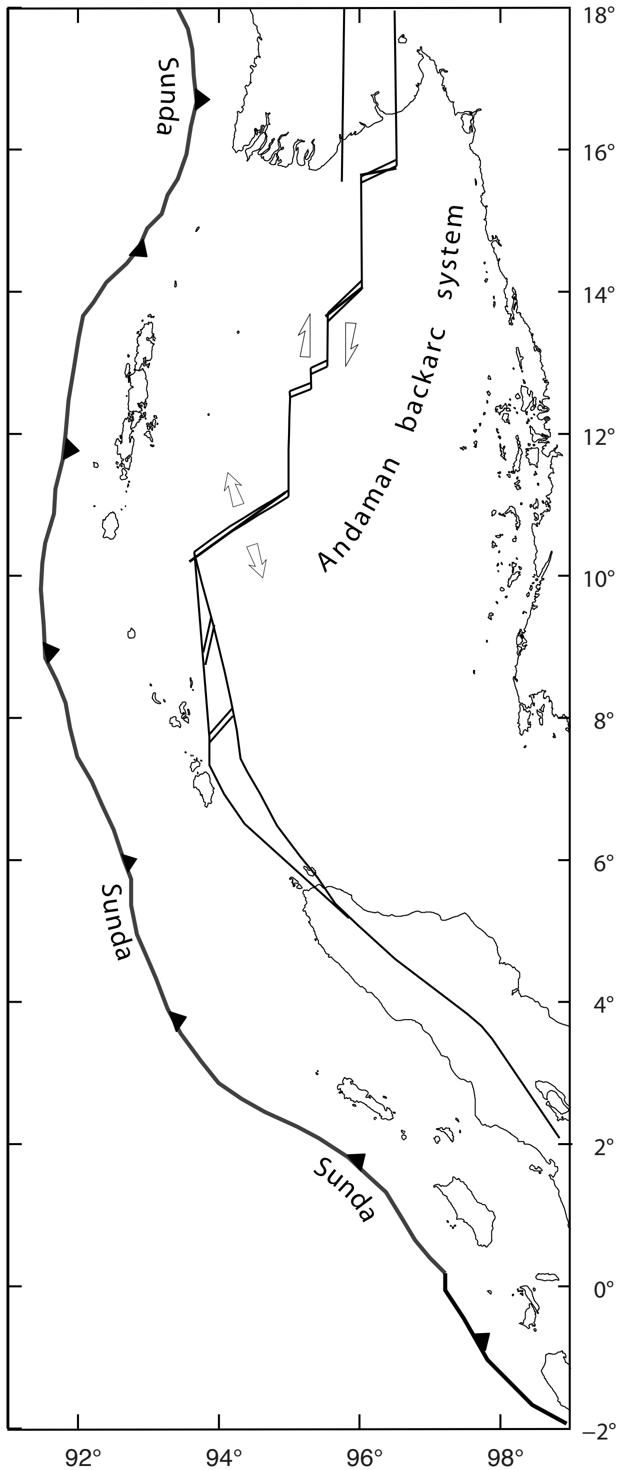
Oblique subduction along the Sunda trench produces the Andaman backarc system



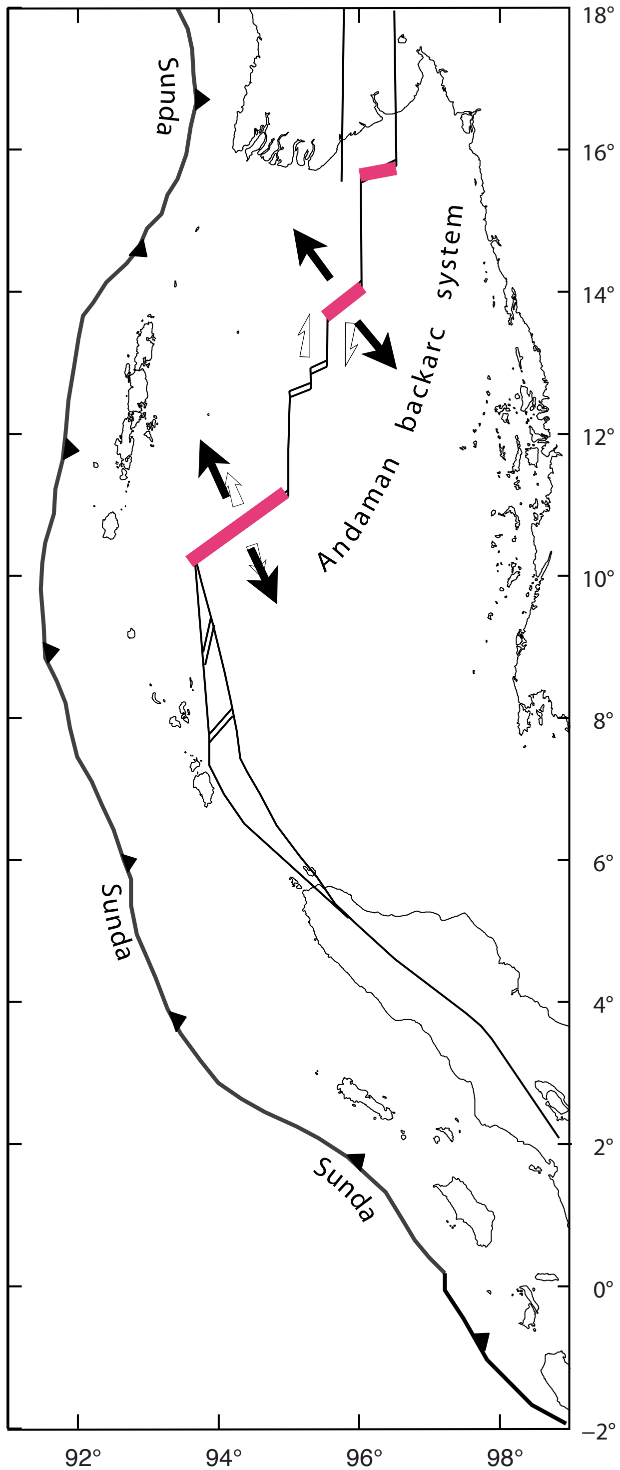
Sunda
Andaman backarc system
Sunda
Sunda
18°
16°
14°
12°
10°
8°
6°
4°
2°
0°
−2°
92°
94°
96°
98°



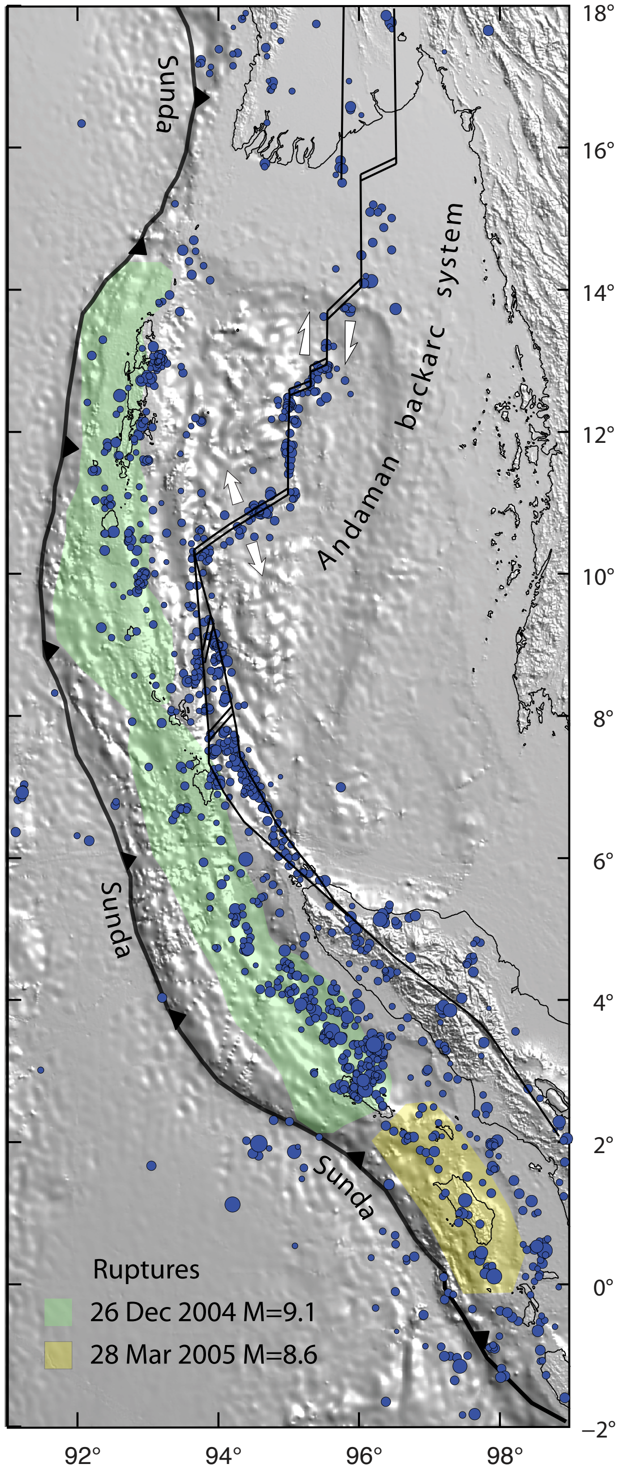
Transform sections



Transform sections



Rift sections



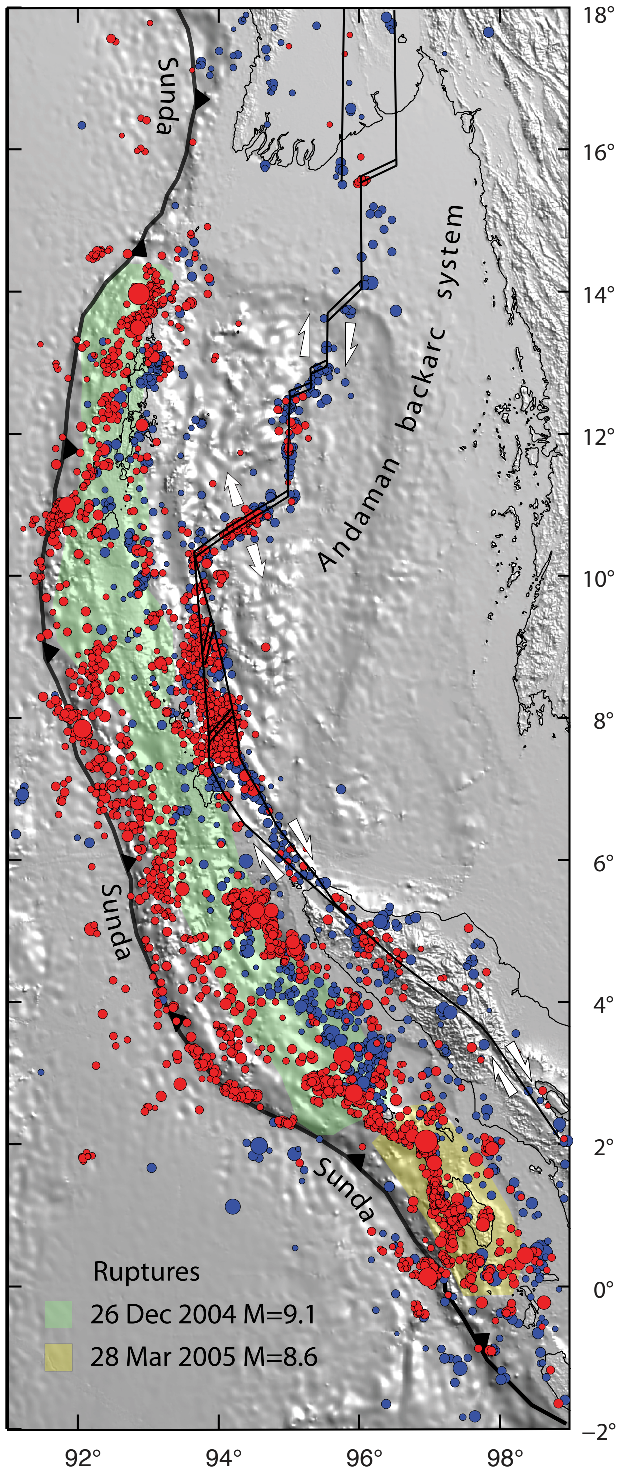
Pre-mainshock seismicity illuminates the megathrust and backarc system

Seismicity (Pesicek etal, 2010)

● Before 2004 rupture (30 Years)

M 8 7 6 5 4

Backarc seismicity changes after the 2004 mainshock



Seismicity (Pesicek etal, 2010)

- Before 2004 rupture (30 Years)
- After 2004 rupture (5 years)

M 8 7 6 5 4

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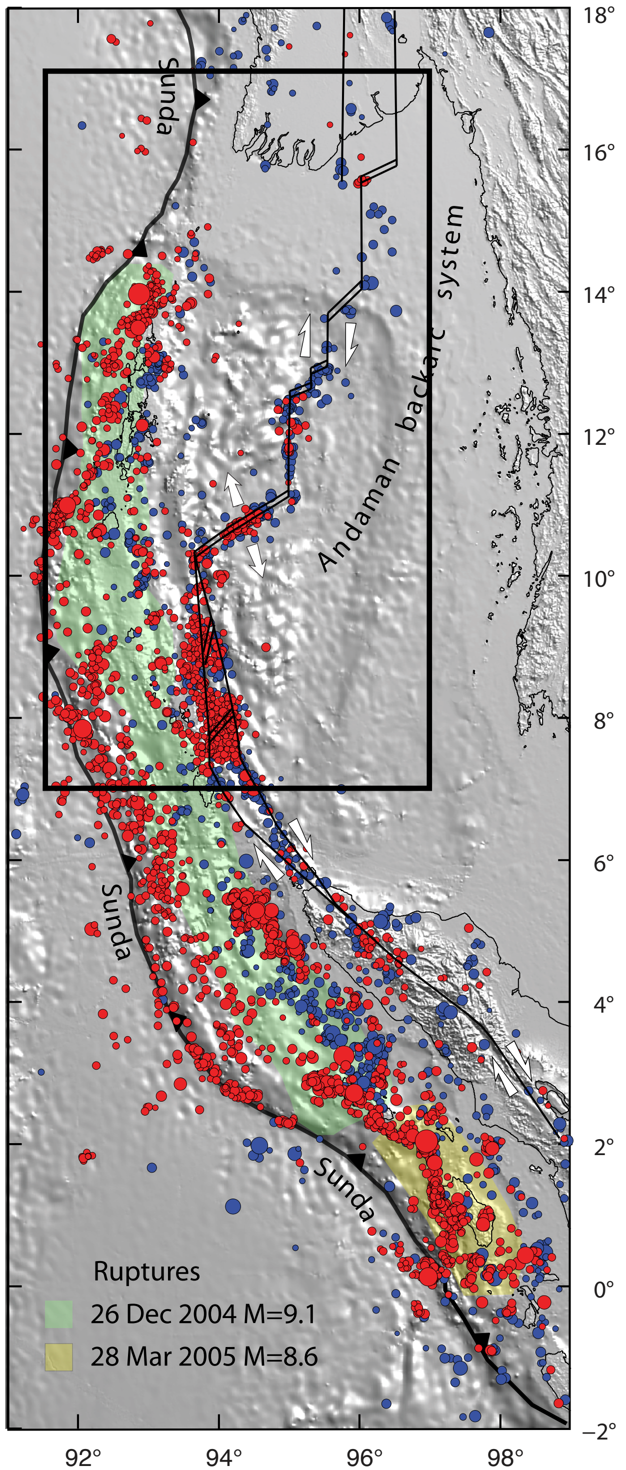

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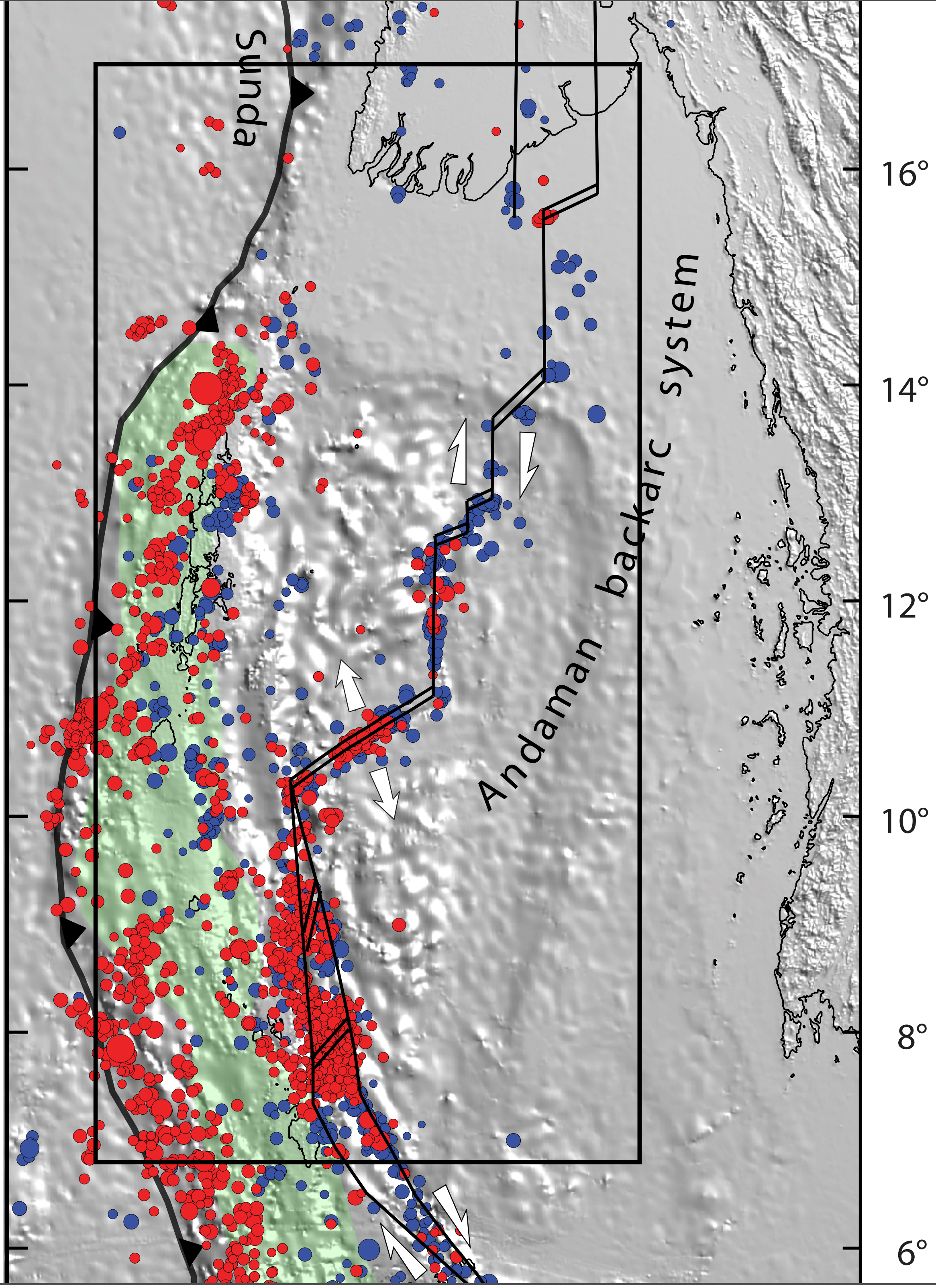
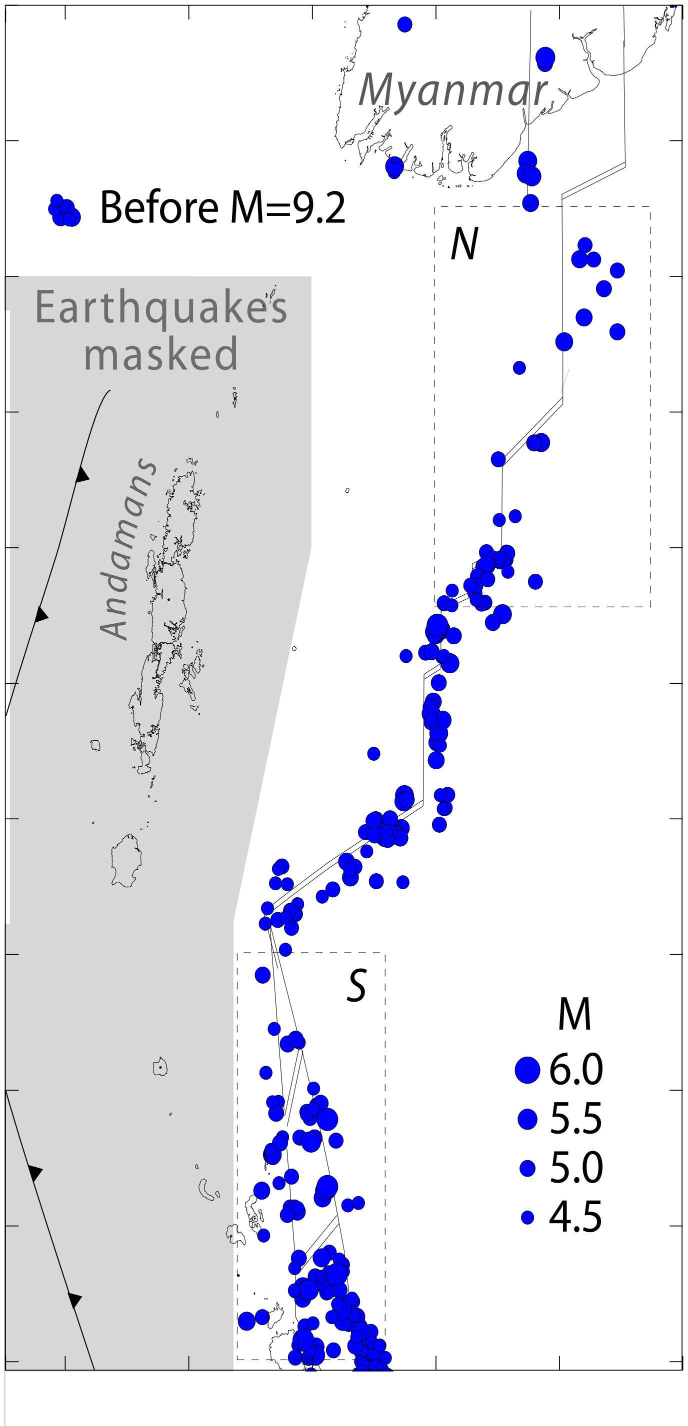
M 8 7 6 5 4

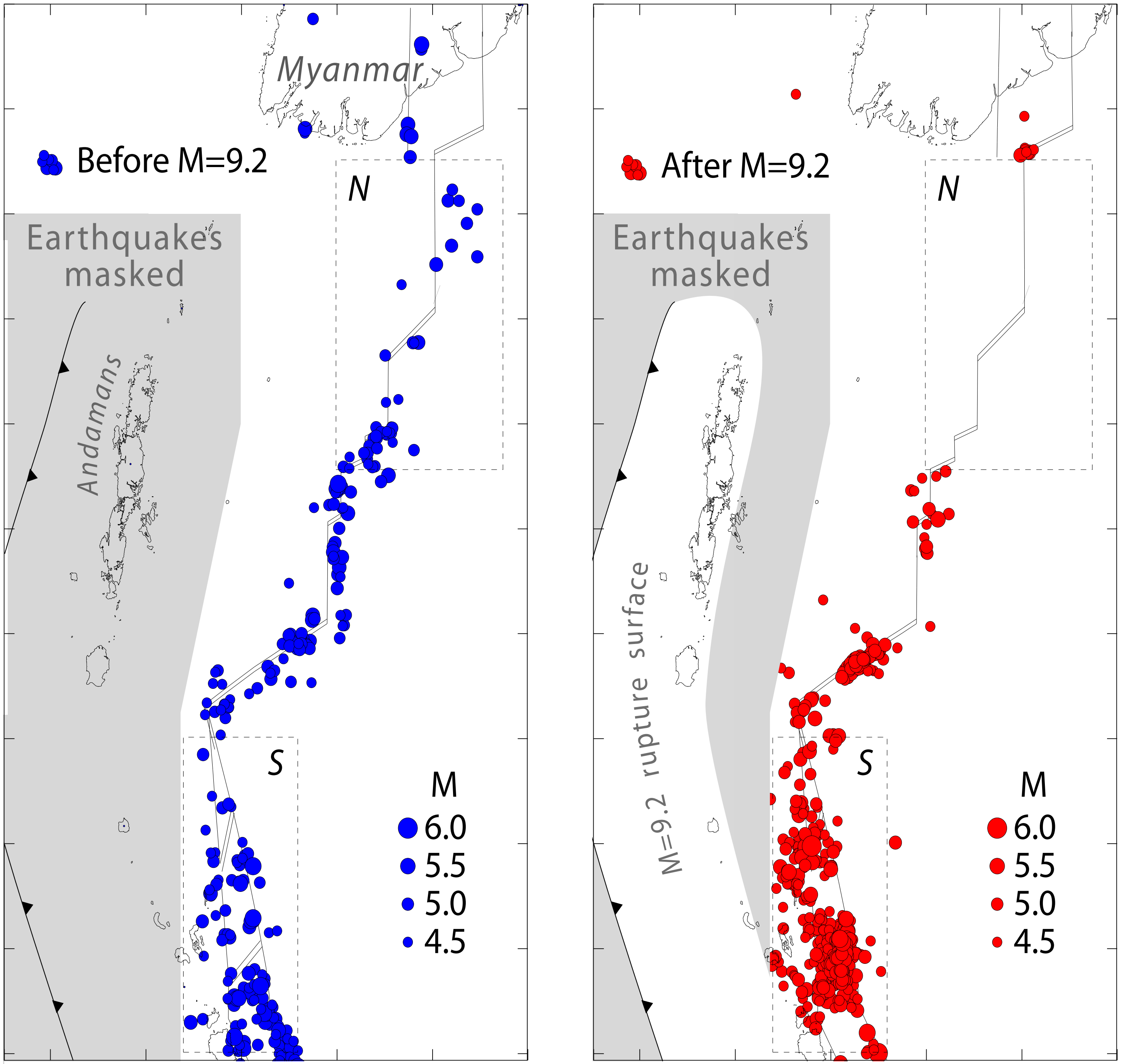


Northern backarc shuts down after 2004

Before 2004 rupture (30 Years)

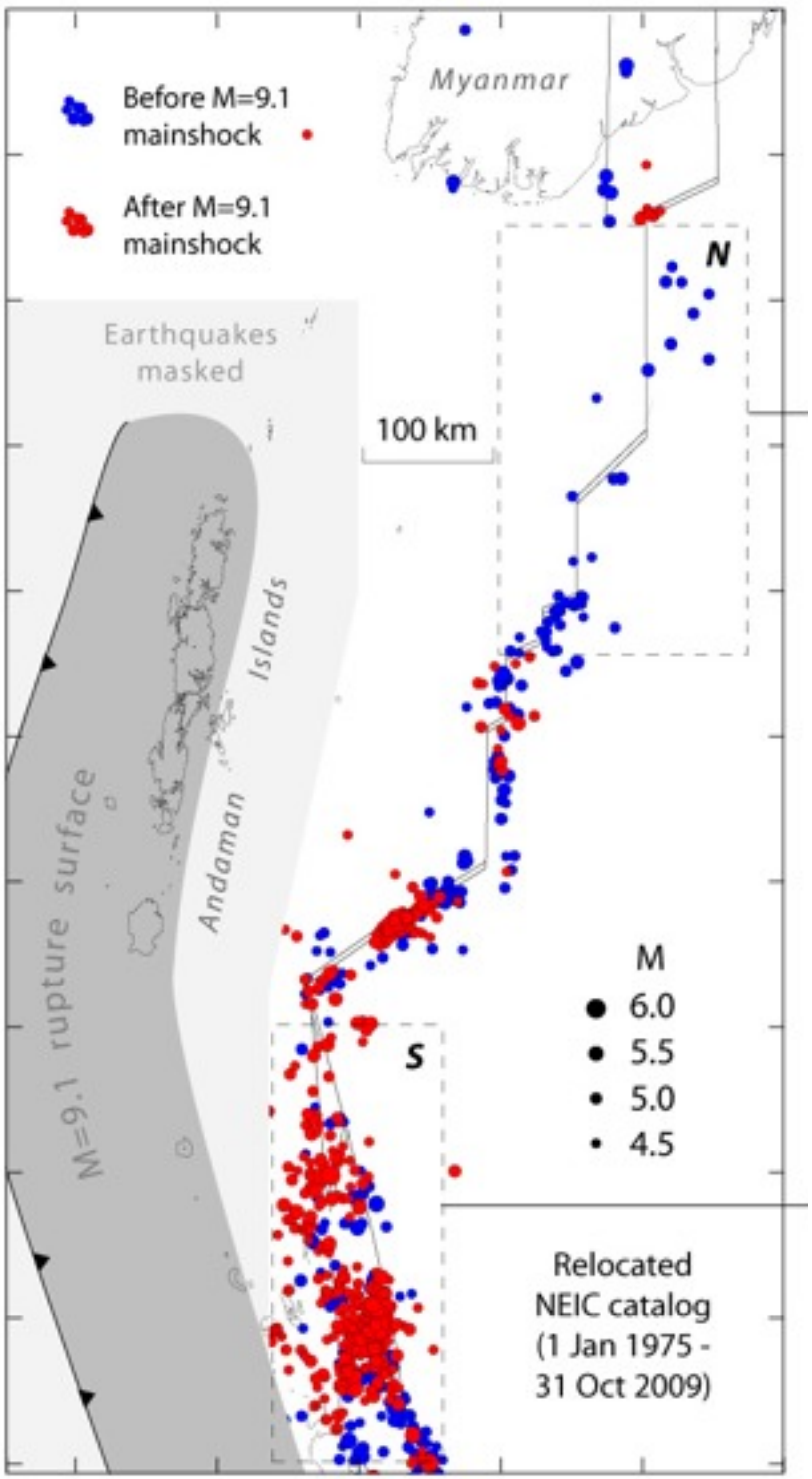
After 2004 rupture (5 Years)


Myanmar
Before M=9.2
Earthquakes masked
Andamans
N
S
M
6.0
5.5
5.0
4.5



Myanmar
Before M=9.2
N
Earthquakes masked
Andamans
S
M
6.0
5.5
5.0
4.5
After M=9.2
N
Earthquakes masked
M=9.2 rupture surface
S
M
6.0
5.5
5.0
4.5

After M=9.2 quake, Box *N* shuts down and Box *S* turns on—both for 5 years



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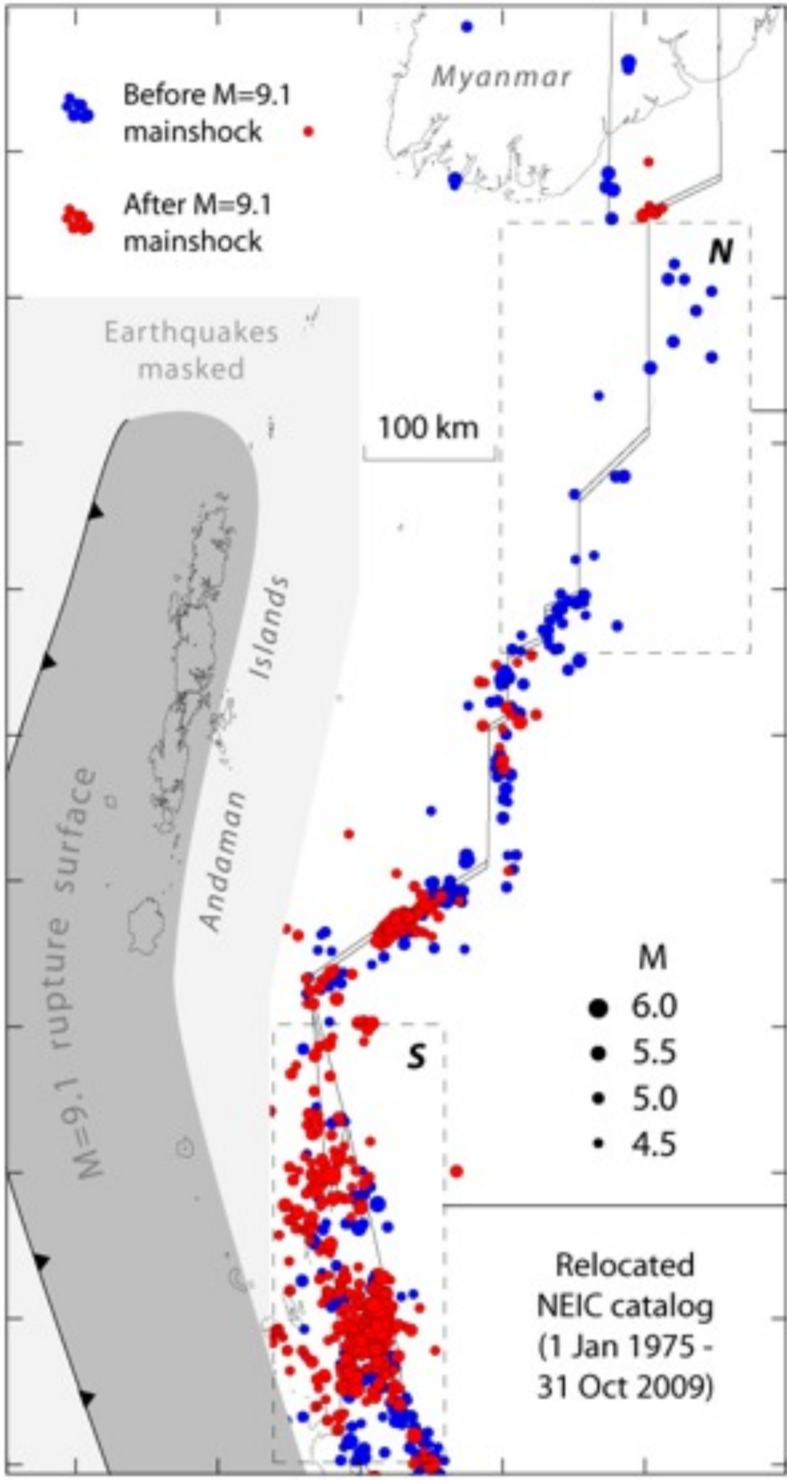
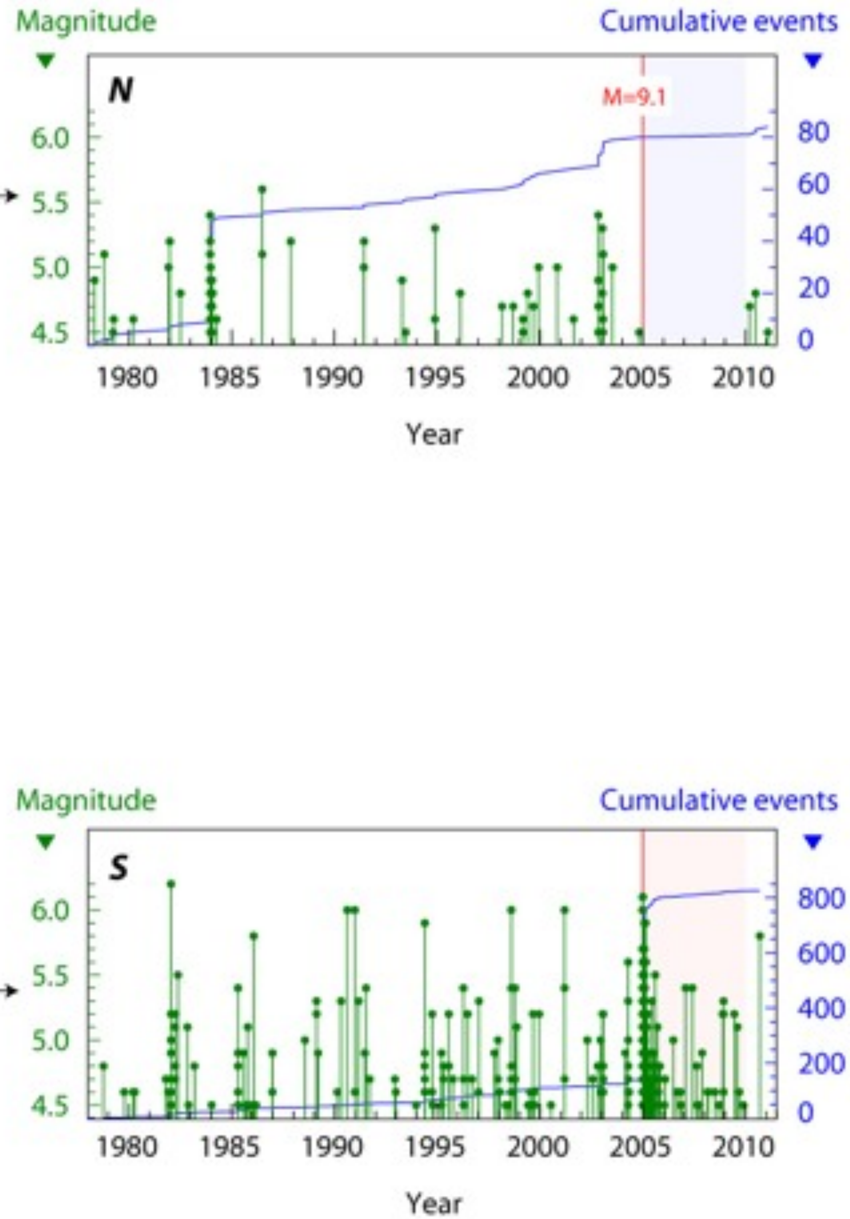
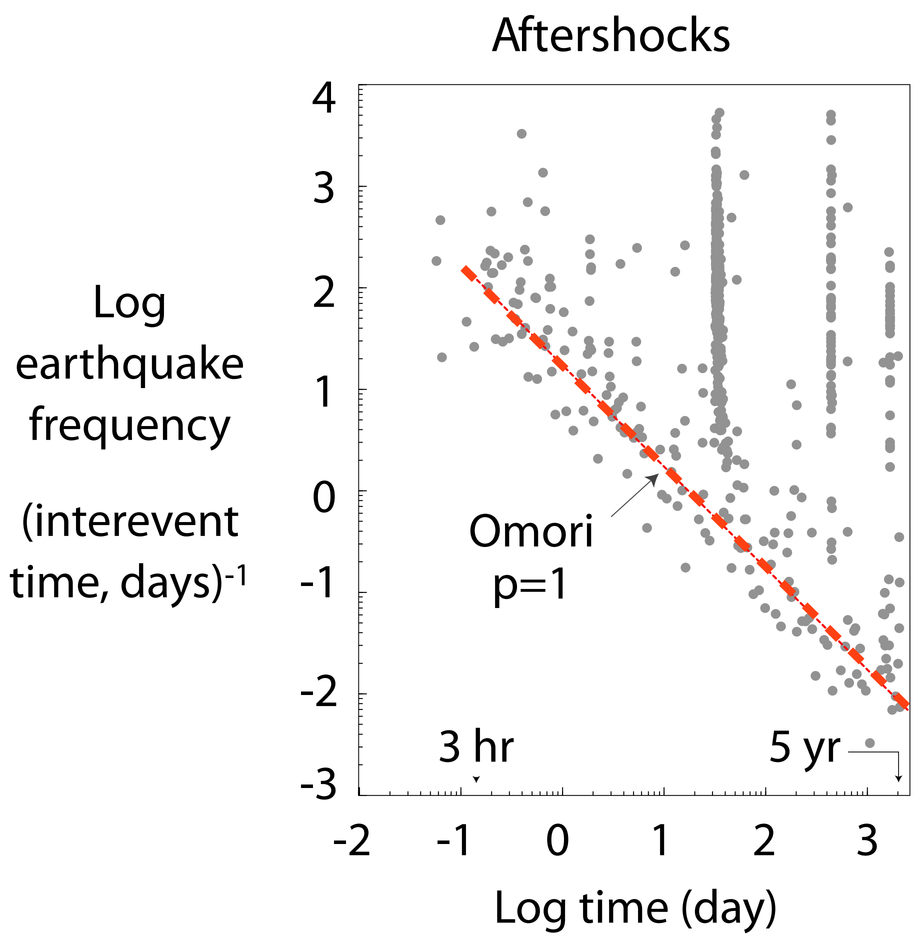




‘Triggered’ seismicity along the backarc behaves like aftershocks



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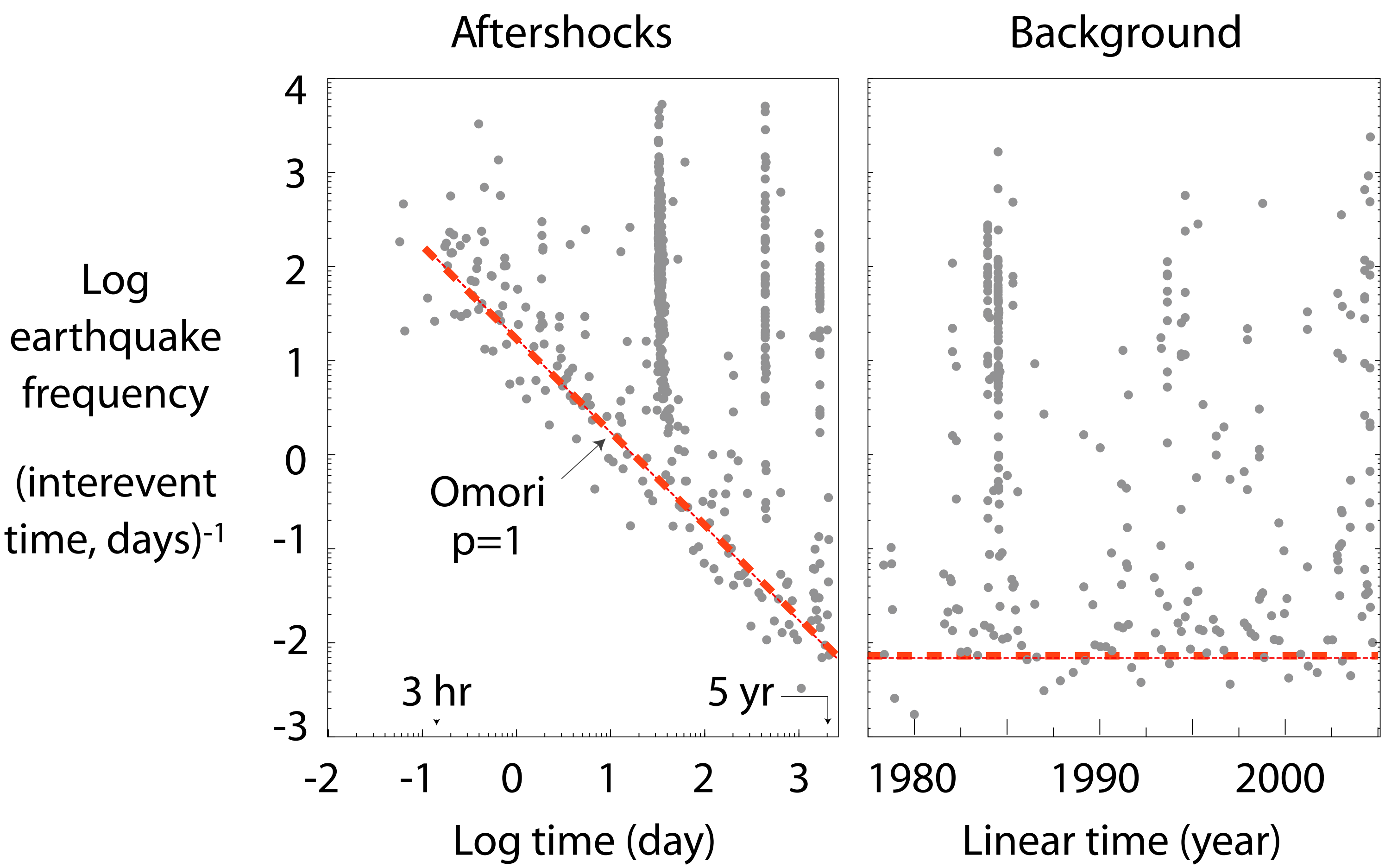
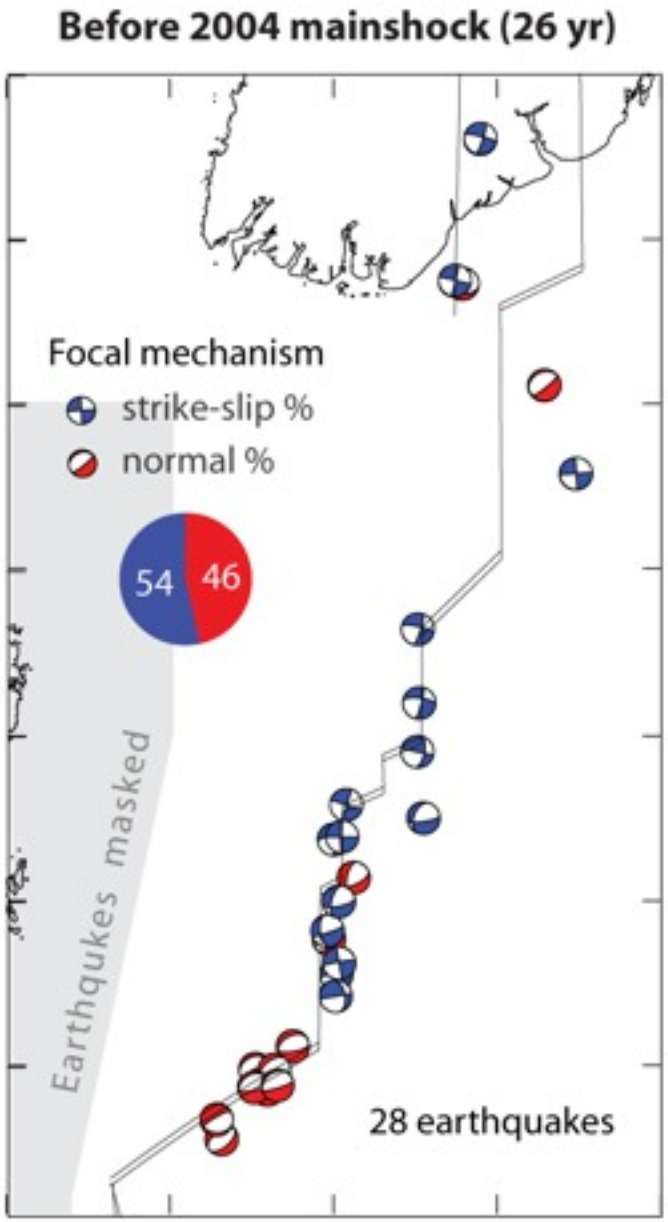


Strike-slip focal mechanisms all but cease after mainshock



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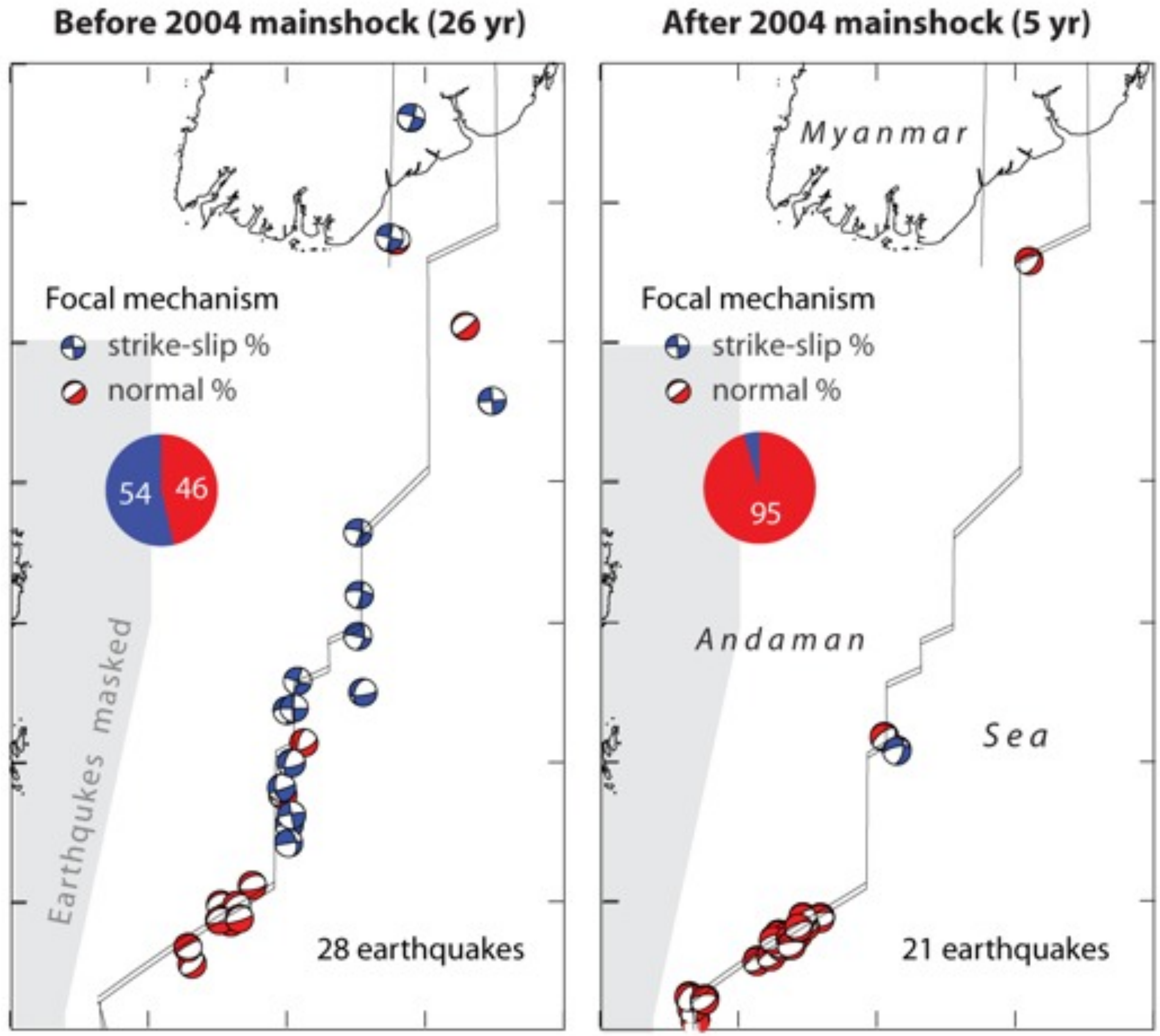

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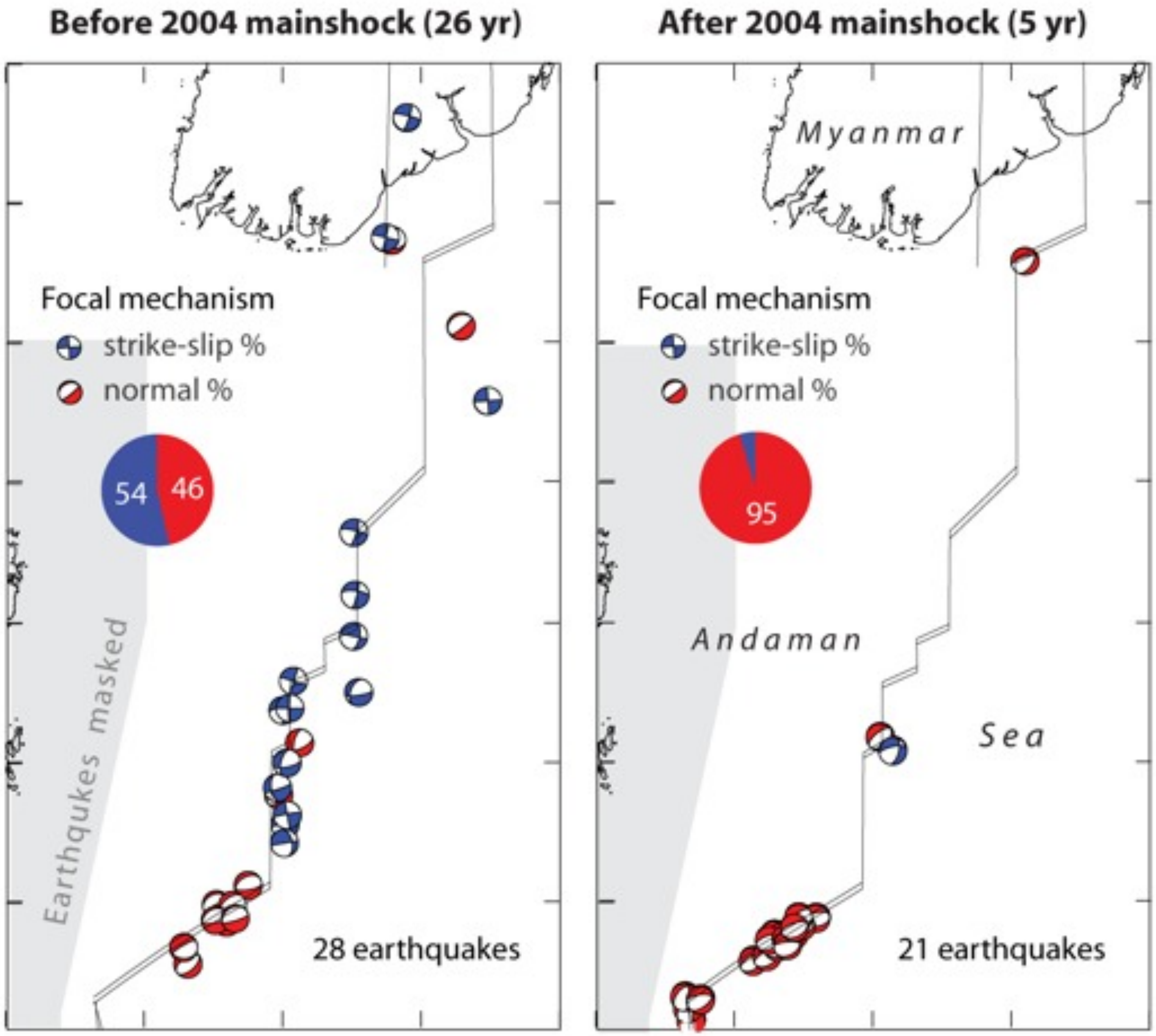
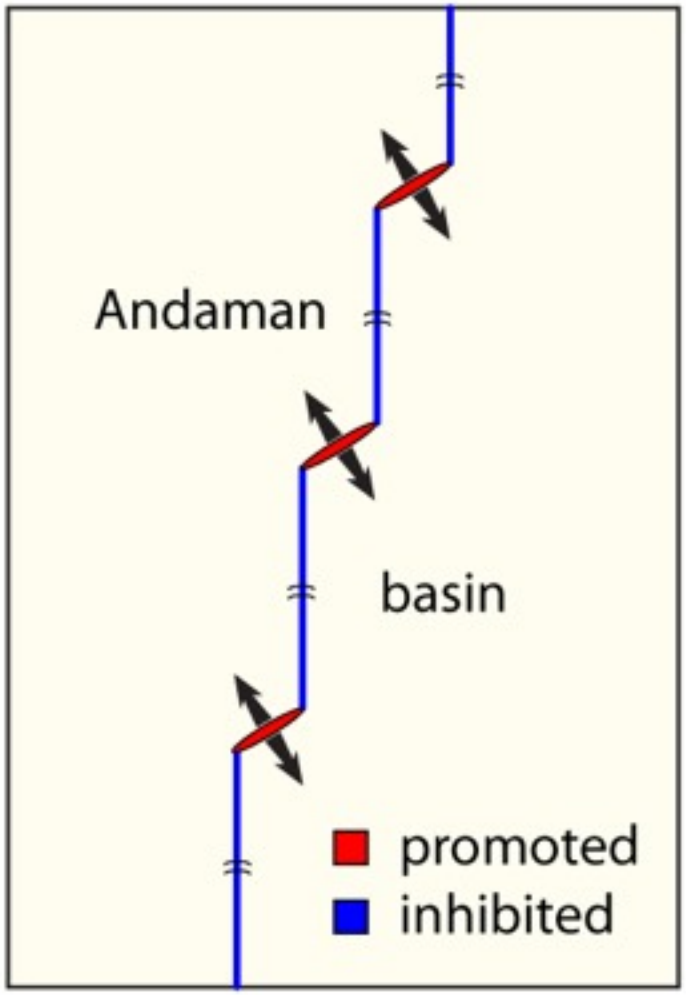


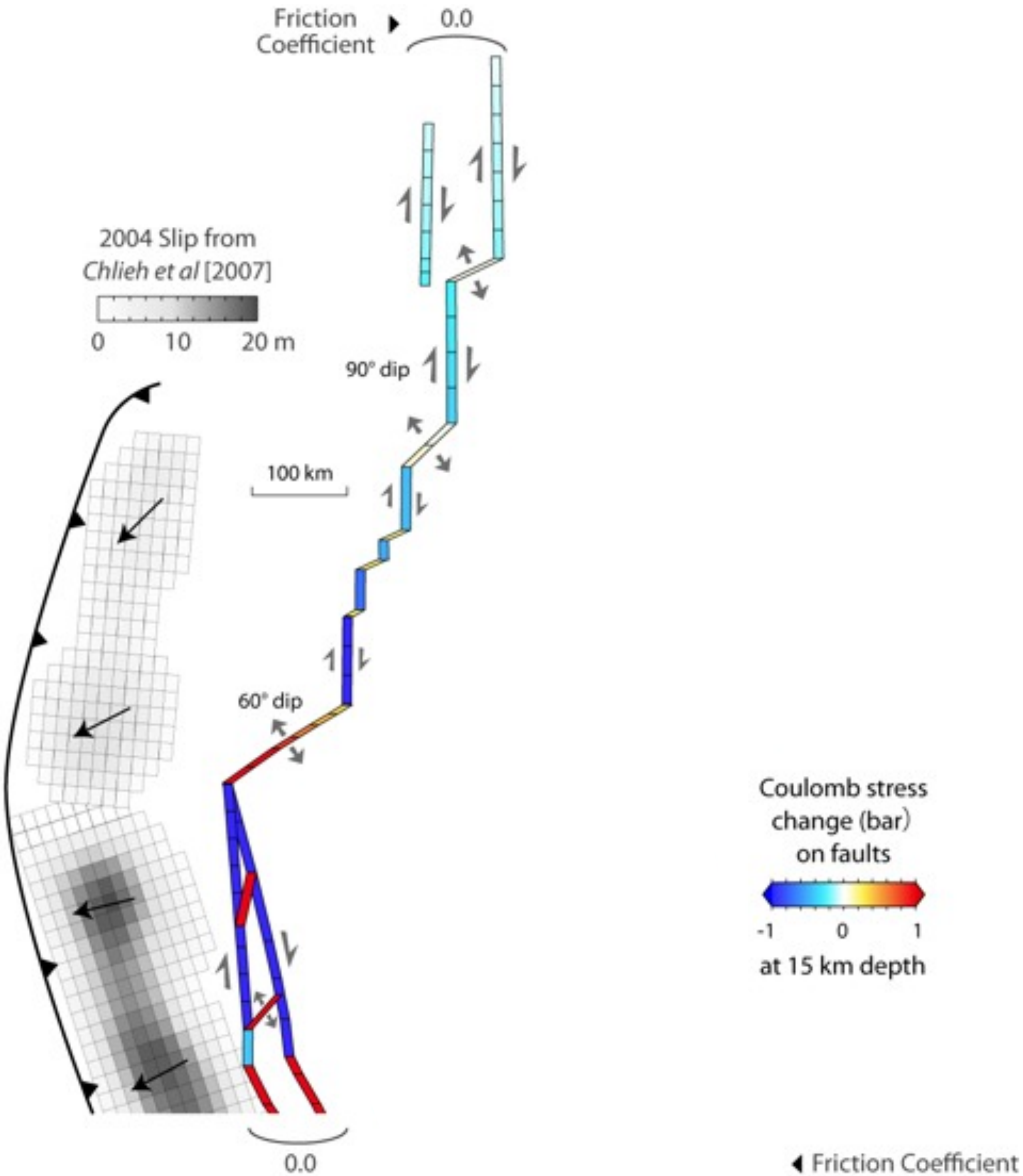
Rate of strike-slip mechanisms drops by 2/3, rift mechanisms increase 8-fold

Observed quakes: right-lateral events halted, rifts activated



Right-lat. transform-rift system

Static stress consistent with observations for fault friction <0.5



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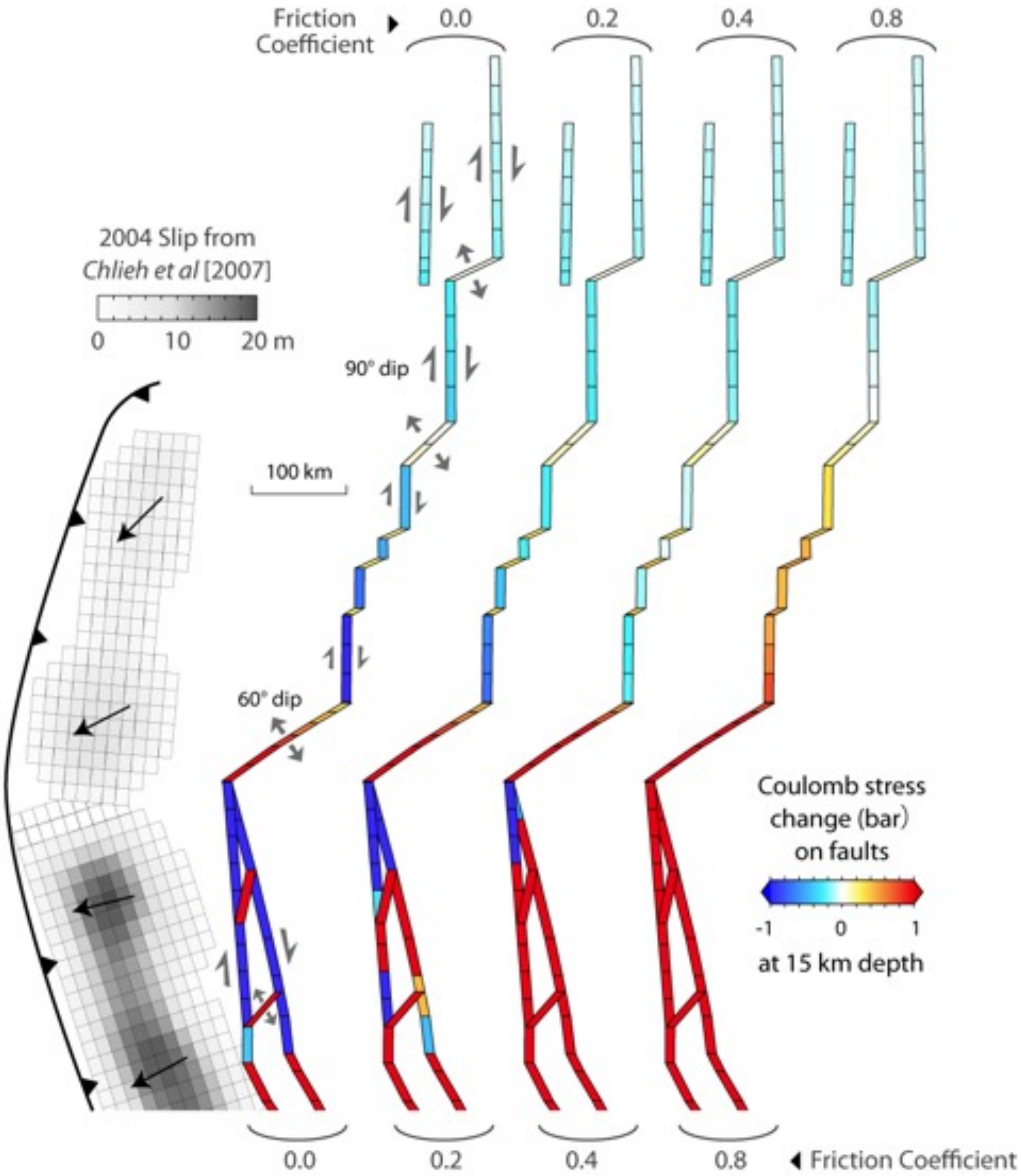
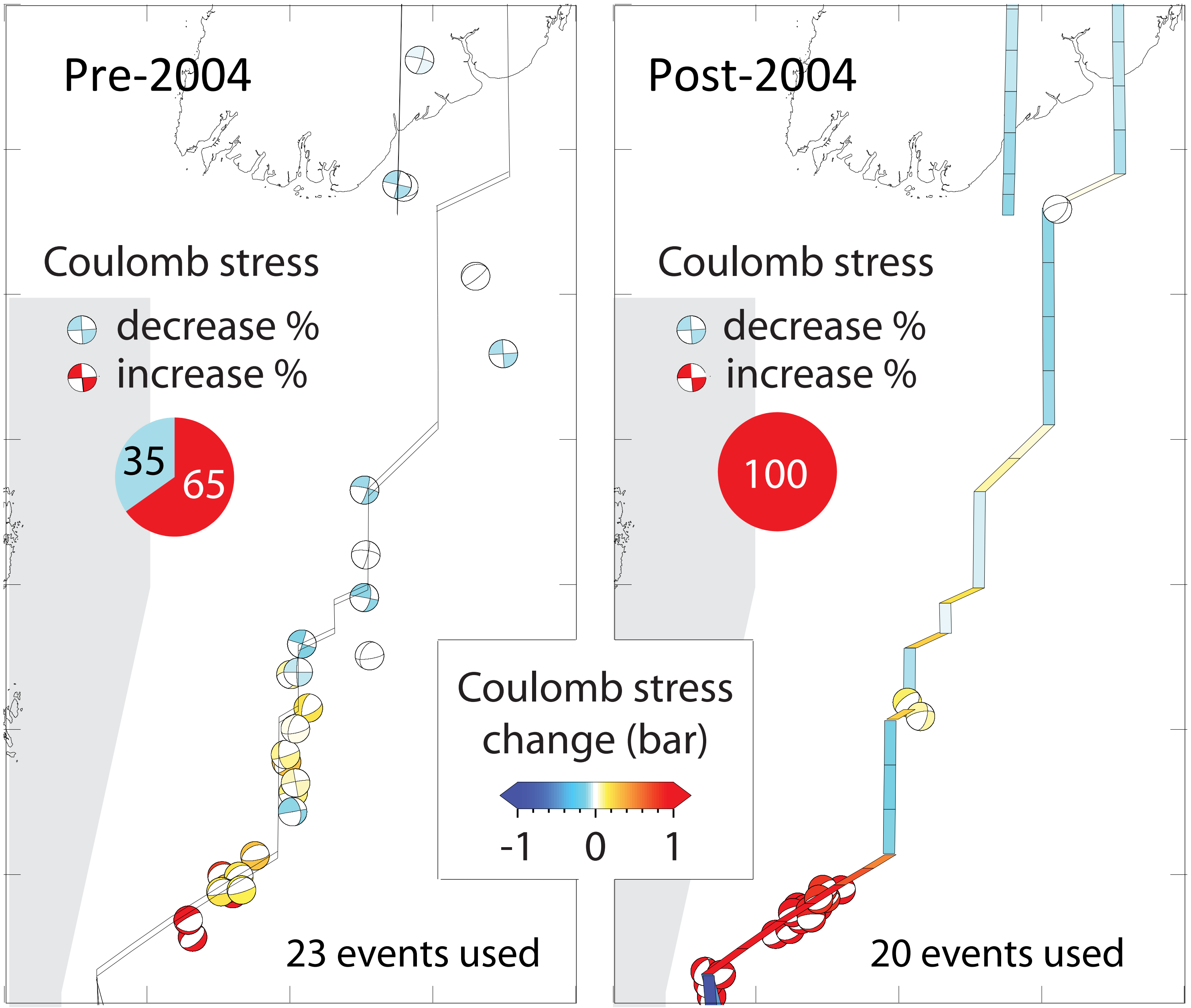


Focal mechanism change explained by static stress



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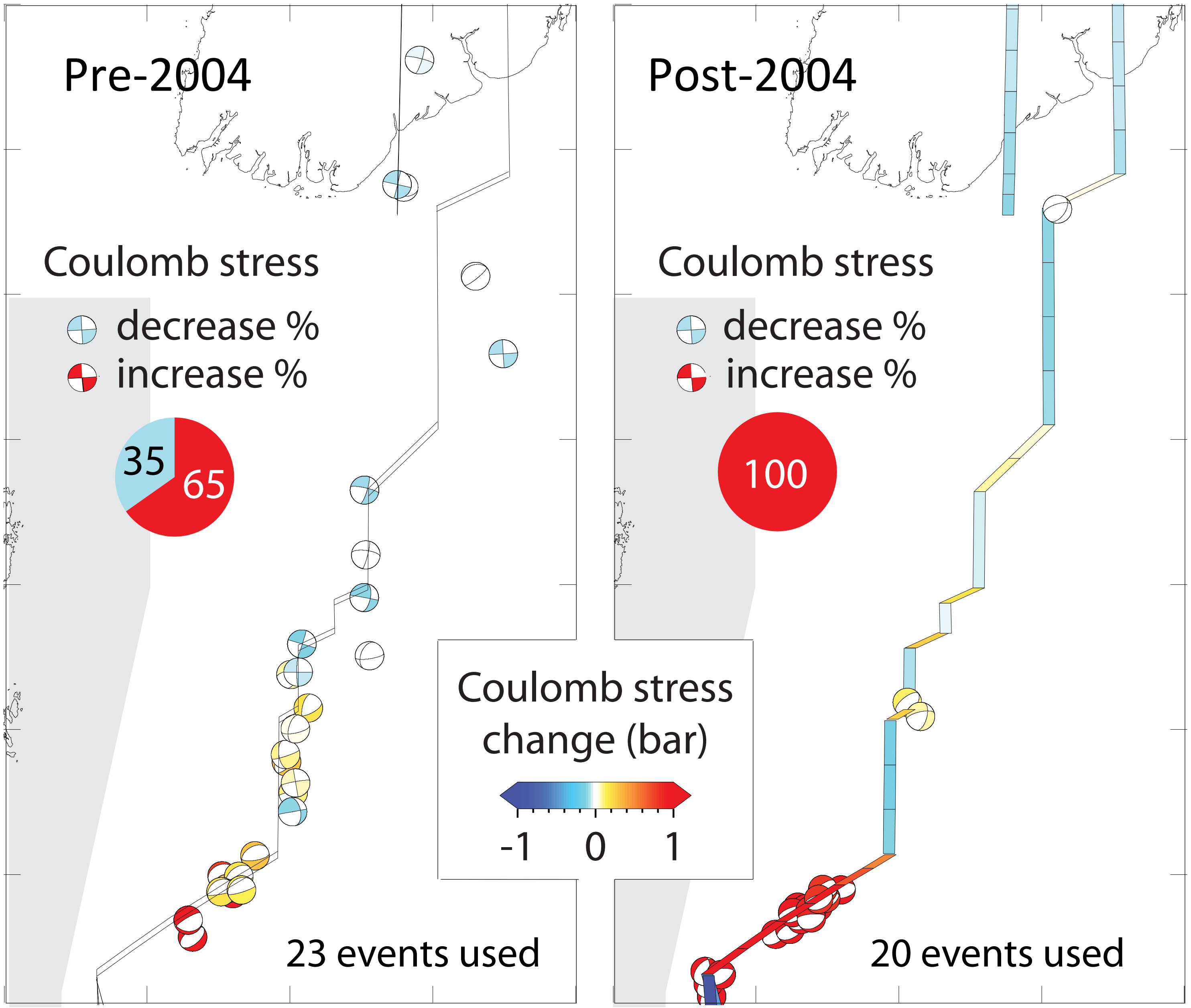
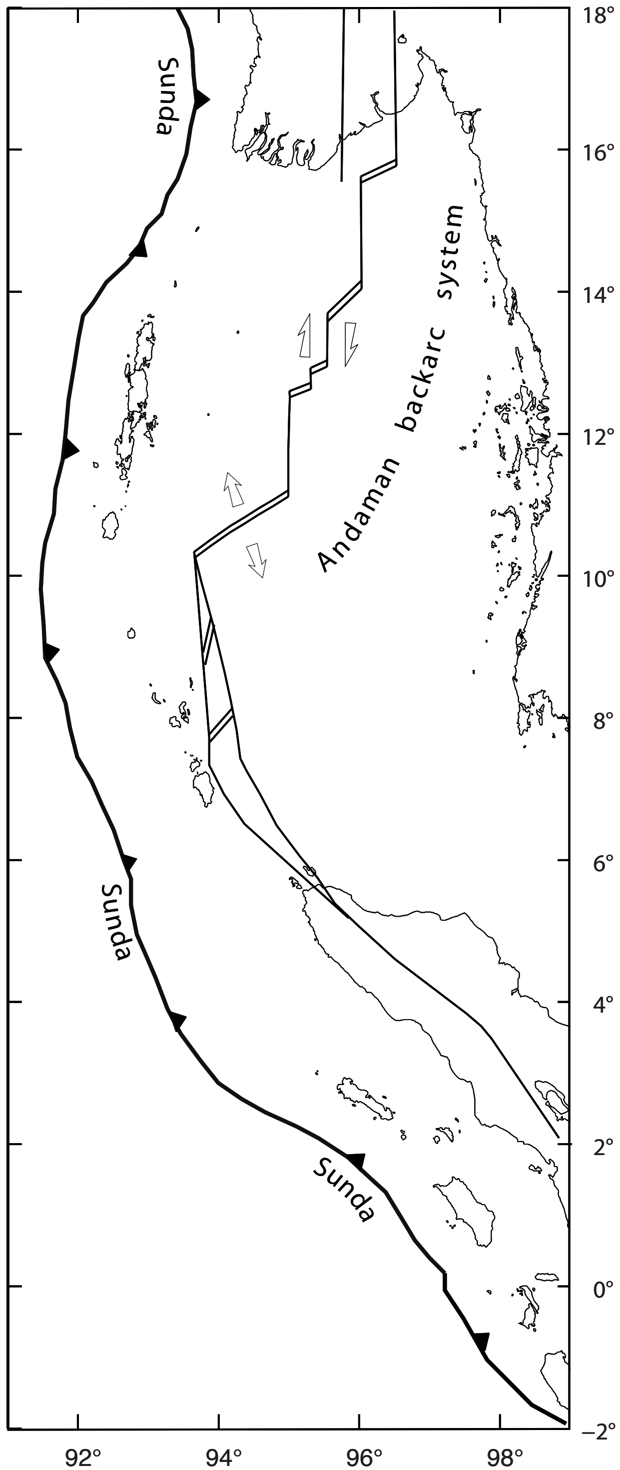


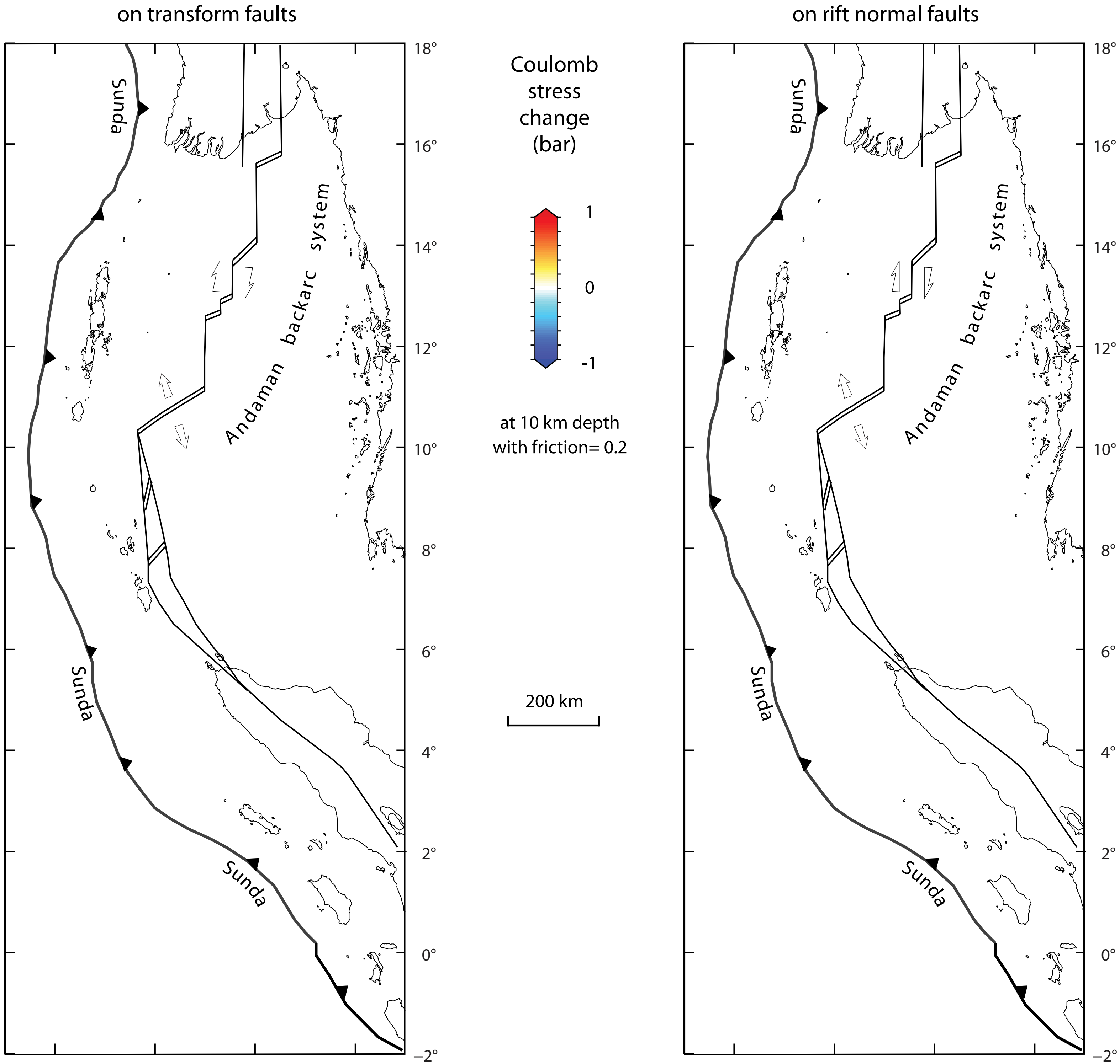
The 53% gain in promoted mechanisms has a significance level of 0.03%

Dynamic Coulomb stress modeling strategy

- Direct Green's function method (*Freiderich & Dalkolmo* 1995, *Pollitz et al* 2012)
- Isotropic PREM earth model, with all spherical harmonic degrees from 0 to 3000
- Low-pass filtered with 10-s corner period (higher frequencies lost)
- 6 x 6 km cells, calculated at 10 km depth, for friction of 0.2
- Banerjee et al (2007) source with 2.8 km/s rupture propagation over 6000 patches
- Method validated against *Aki* (1980), *Bouchon* (1981), *Nissen-Meyer et al* (2007)

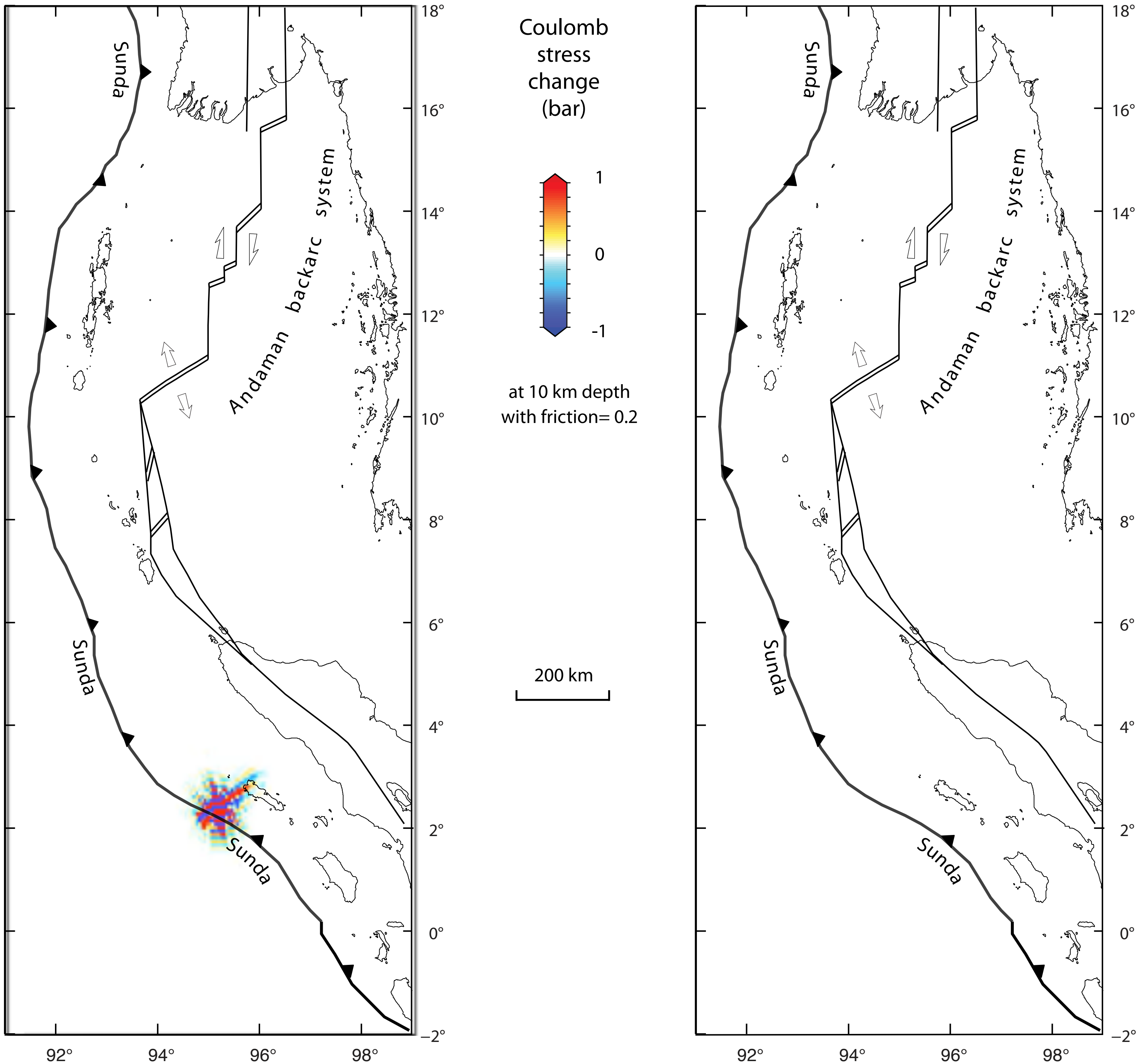


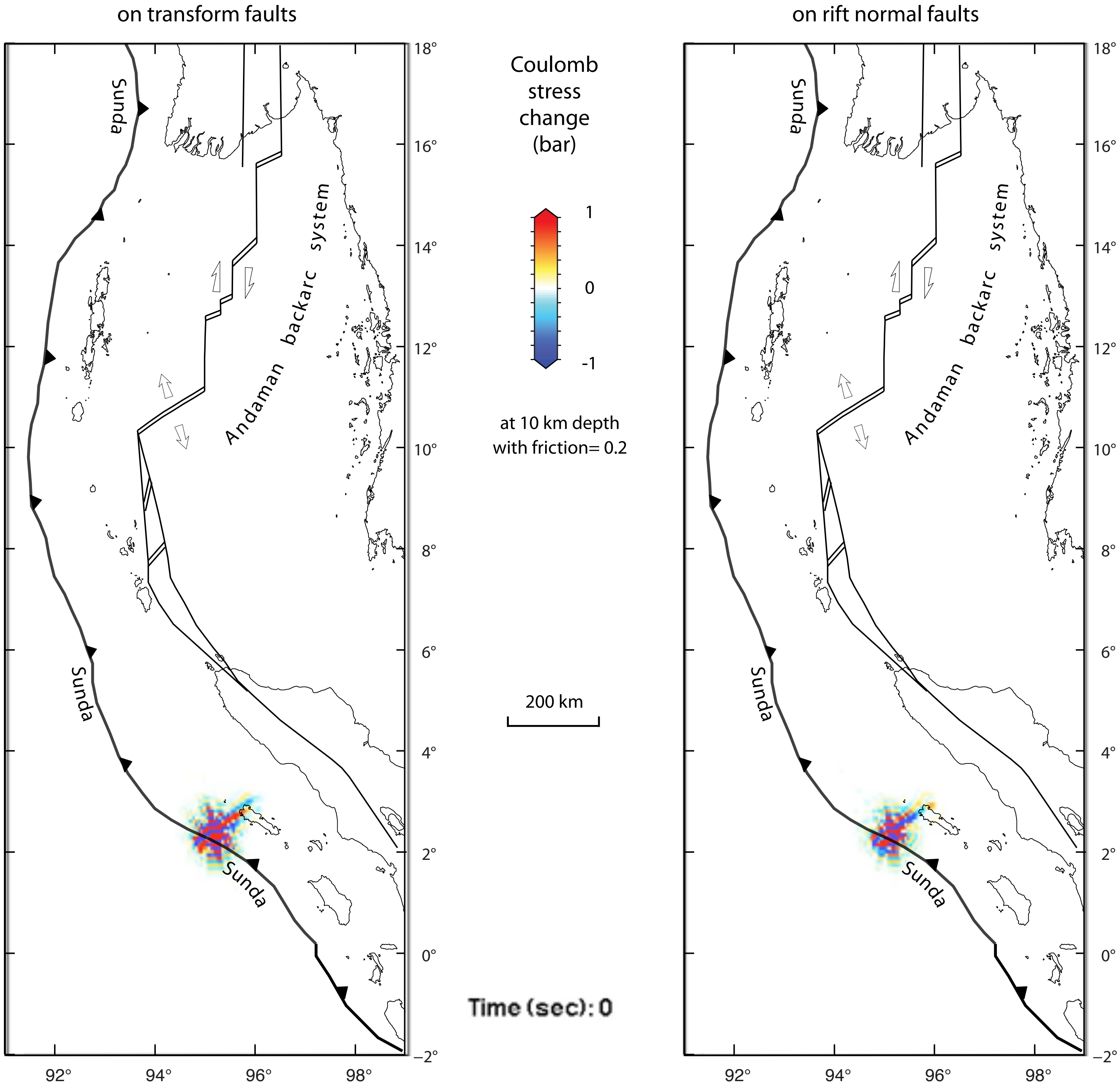
Two side-by-side animations with stress resolved on transforms and rifts


on transform faults
on rift normal faults
Coulomb stress change (bar)
1
0
-1
at 10 km depth
with friction= 0.2
200 km
Sunda
Sunda
Sunda
Andaman backarc system
18°
16°
14°
12°
10°
8°
6°
4°
2°
0°
−2°
92°
94°
96°
98°

on transform faults

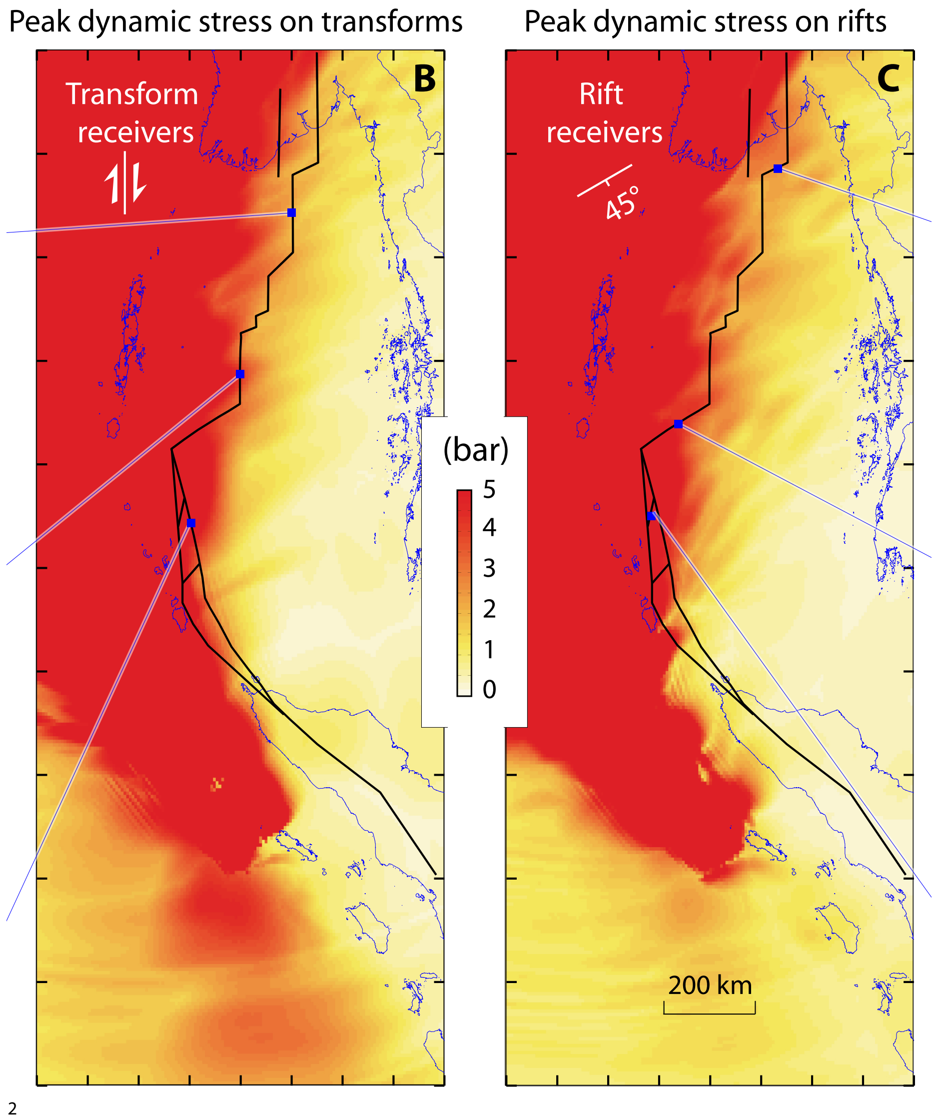
on rift normal faults





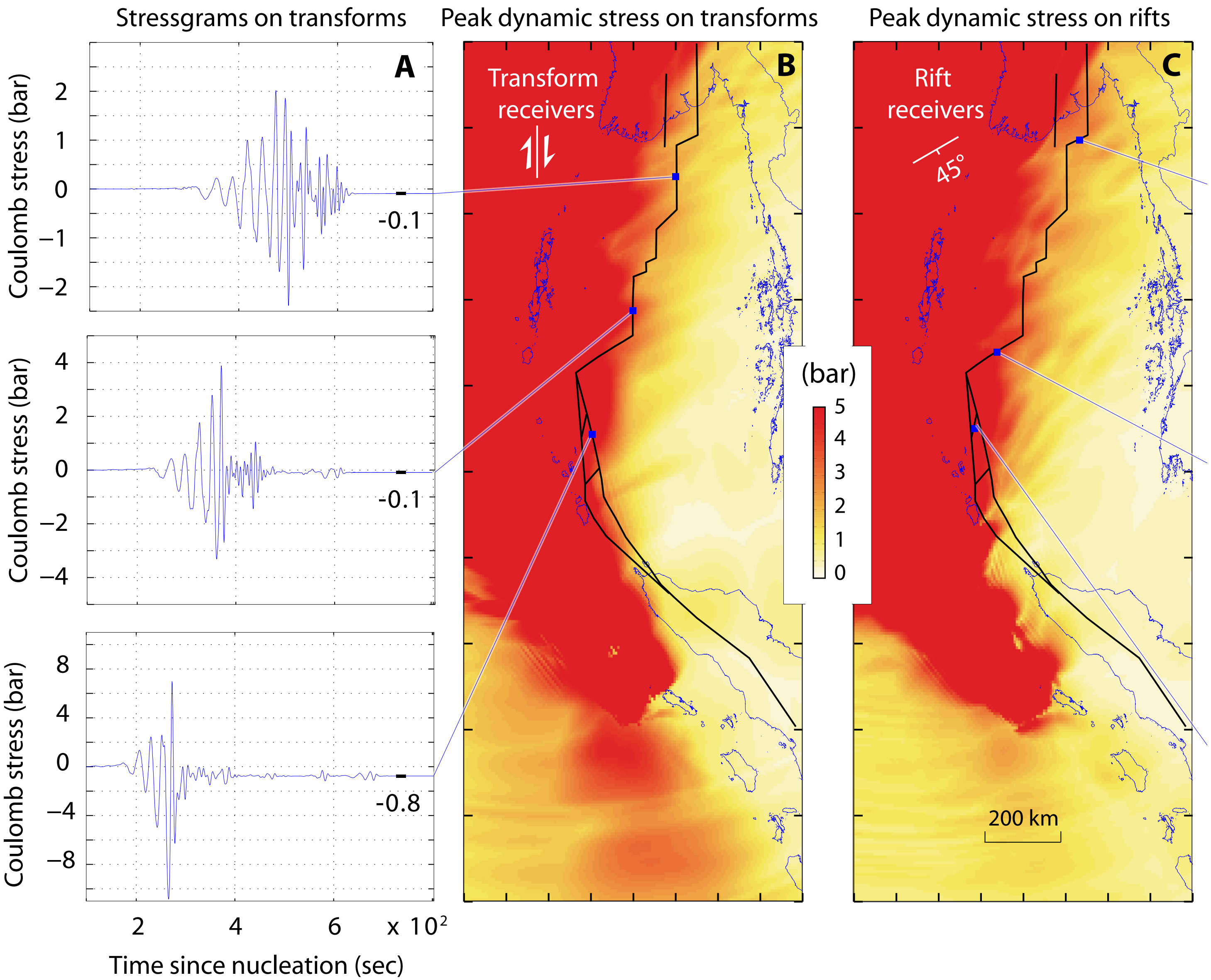
on transform faults
on rift normal faults
Coulomb
stress
change
(bar)
1
0
-1
at 10 km depth
with friction= 0.2
200 km
Time (sec): 0
Sunda
Sunda
Sunda
Andaman backarc system
18°
16°
14°
12°
10°
8°
6°
4°
2°
0°
−2°
92°
94°
96°
98°

No clear difference between peak dynamic stress on rifts and transforms



Peak dynamic stress is highest stress ever attained over 1000 s minus static stress

No clear difference between peak dynamic stress on rifts and transforms



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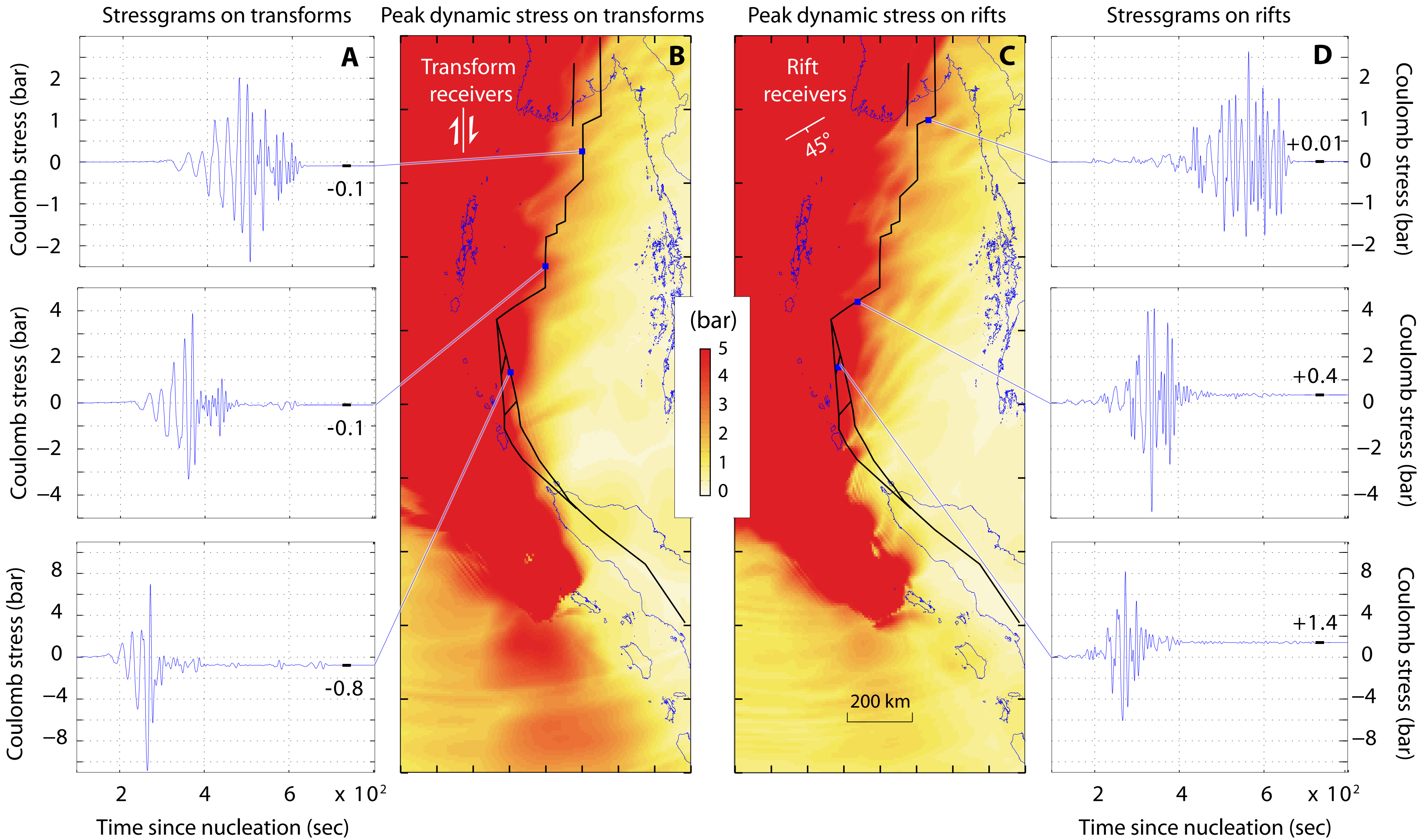
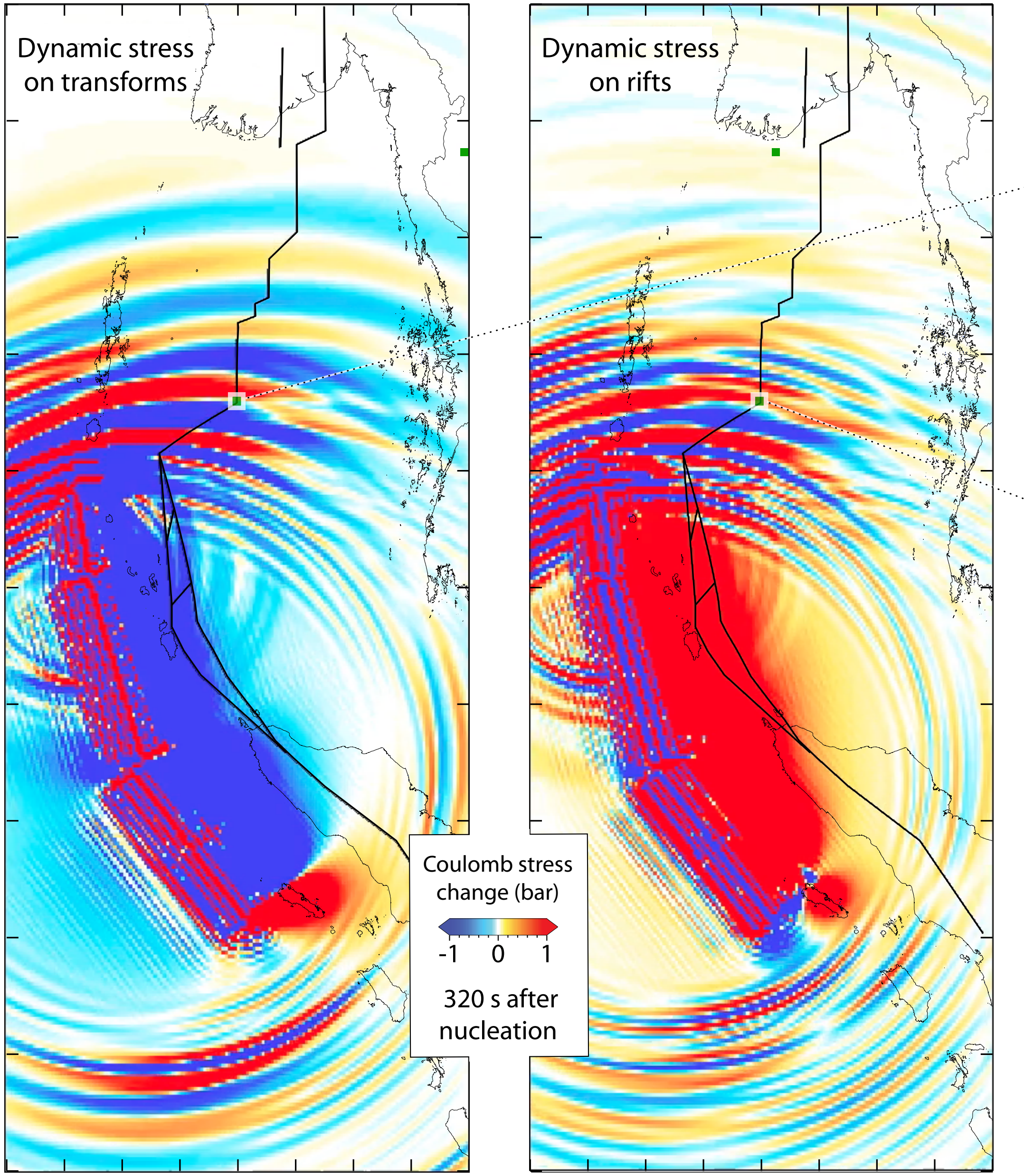


Peak dynamic stress is highest stress ever attained over 1000 s minus static stress

If anything, dynamic stress should have favored transform earthquakes



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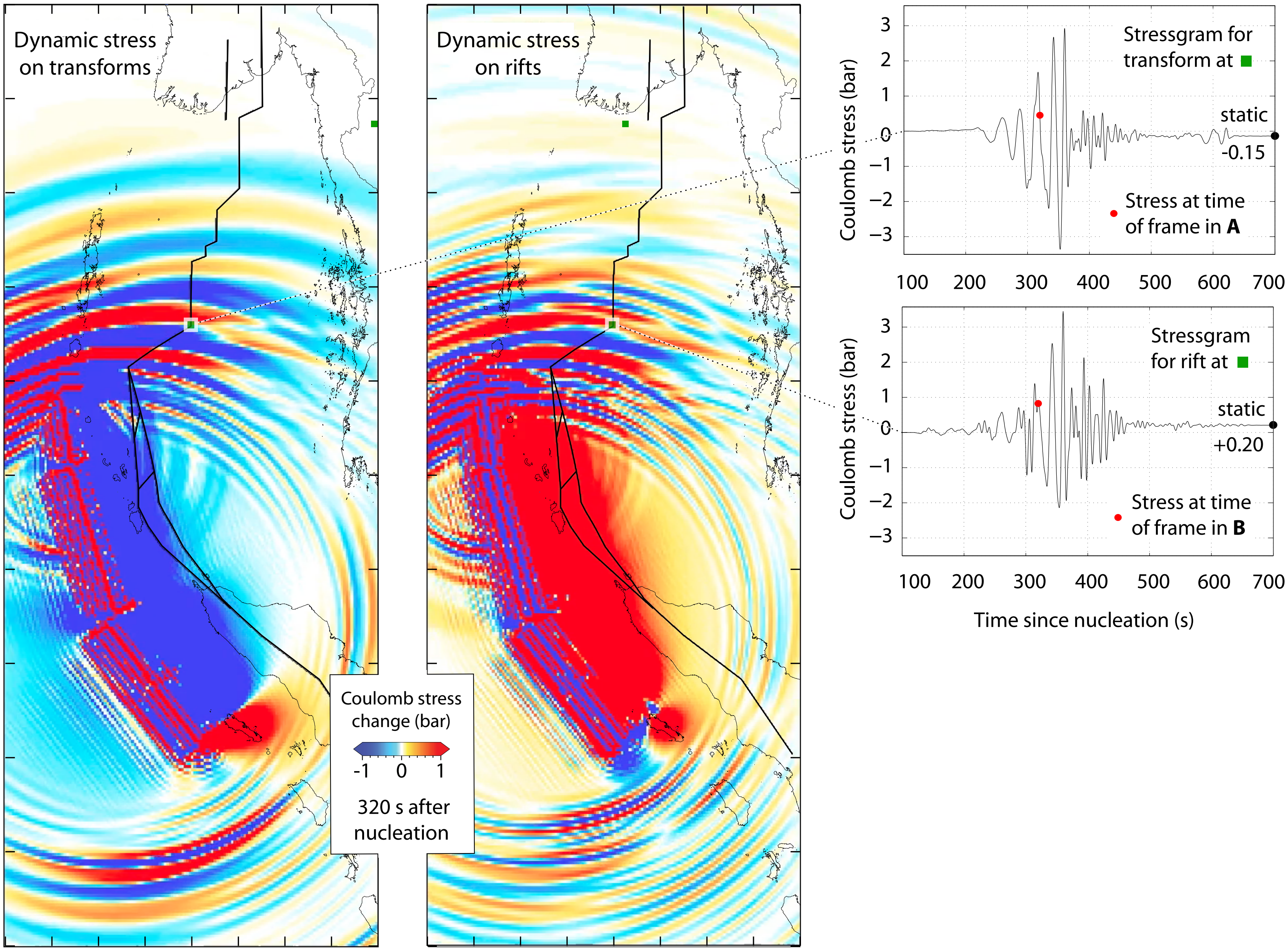

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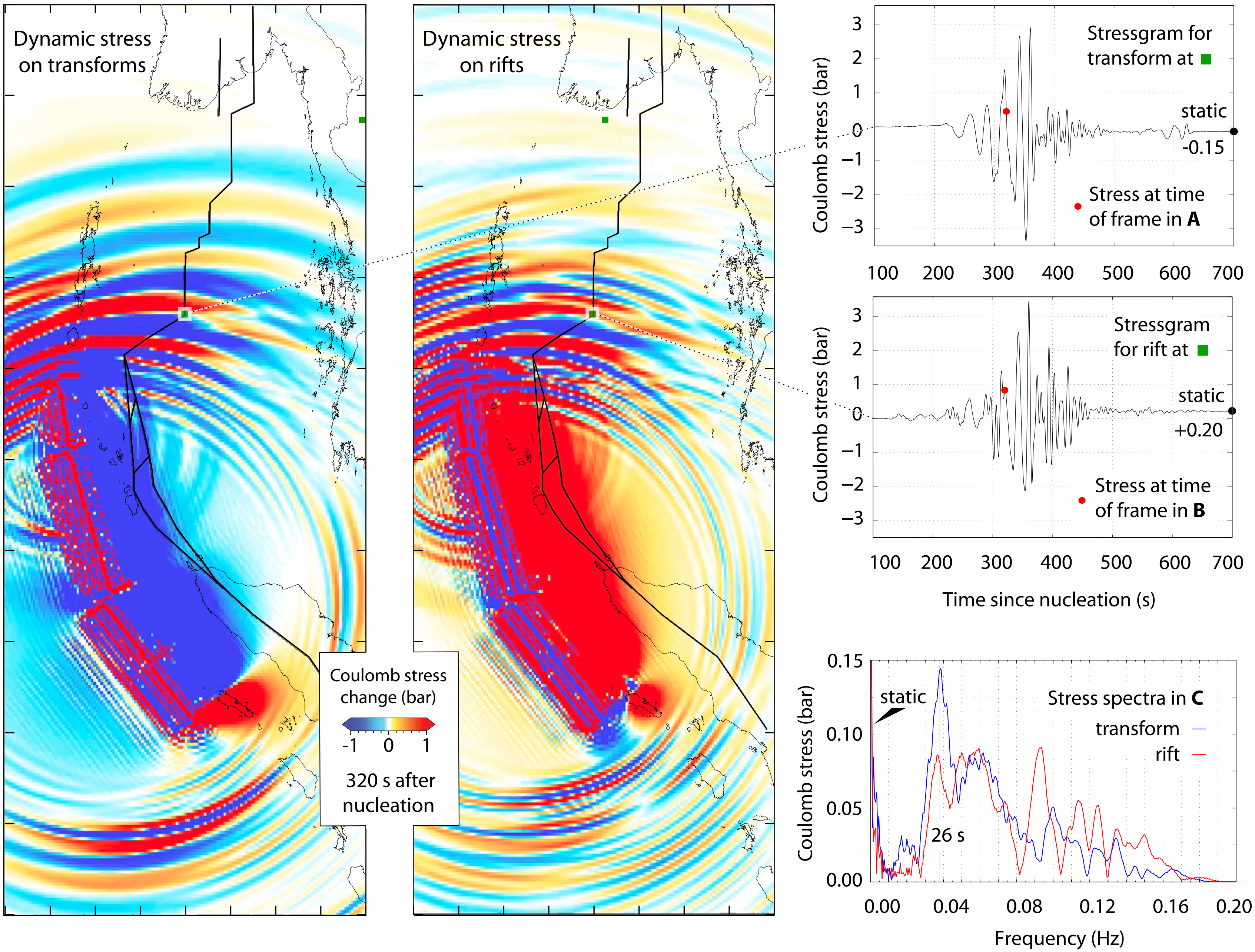
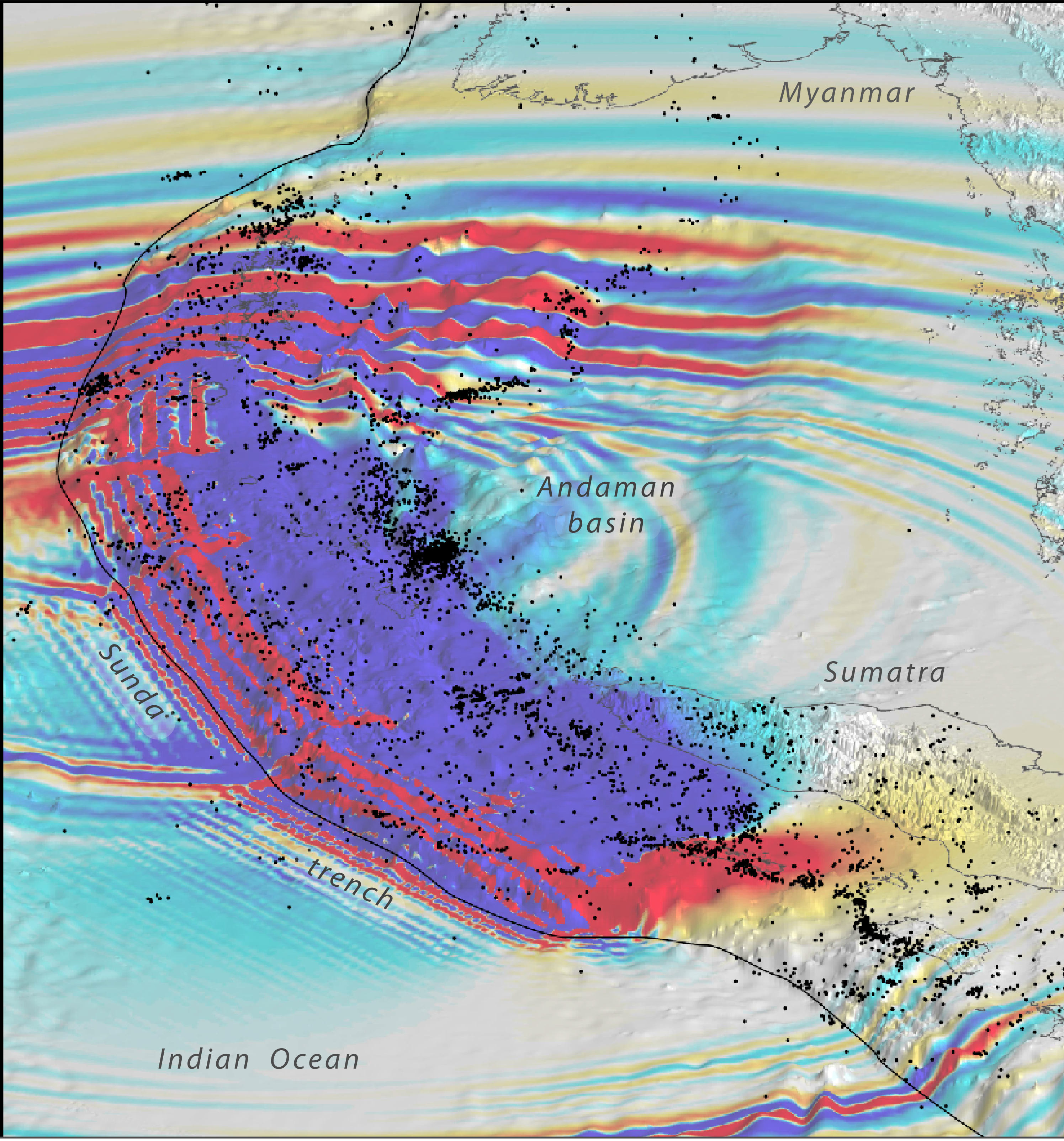
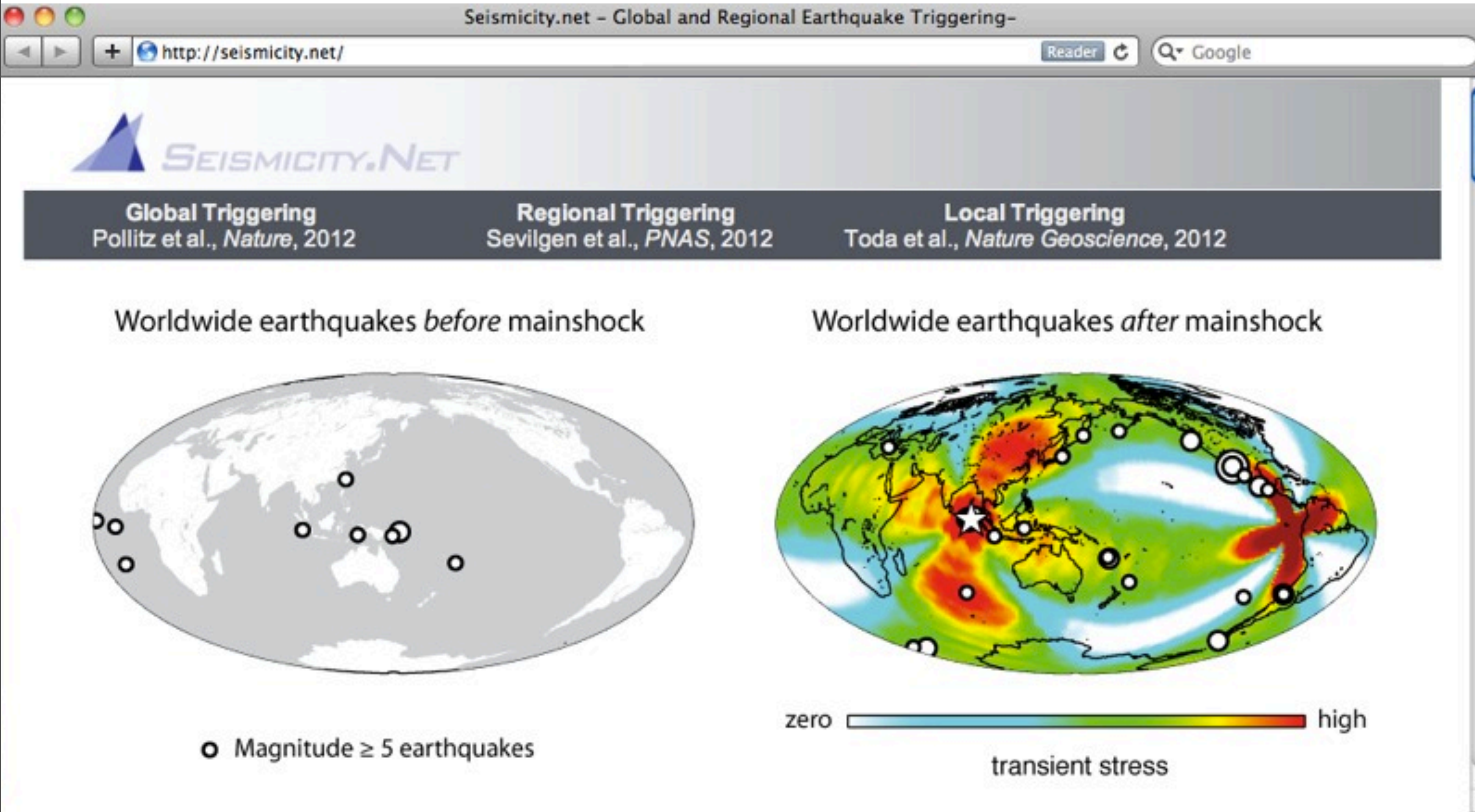




At least for 3 hr to 5 yr after the 2004 mainshock, quakes as far as 400 km away respond to the static stress changes

Sevilgen, Stein & Pollitz
Proc Natl Acad Sci USA, 2012


Seismicity.net - Global and Regional Earthquake Triggering-
http://seismicity.net/
Reader
Google
SEISMICITY.NET
Global Triggering
Pollitz et al., Nature, 2012
Regional Triggering
Sevilgen et al., PNAS, 2012
Local Triggering
Toda et al., Nature Geoscience, 2012
Worldwide earthquakes before mainshock
Worldwide earthquakes after mainshock
Magnitude ≥ 5 earthquakes
zero
high
transient stress