What triggers most earthquakes?
The answer lies in the shadows

A presentation of Sevilgen, Stein, and Pollitz (Proc Natl Acad Sci USA, 2012)
1992 M=7.3 Landers shock promotes the M=6.5 Big Bear shock 3 hr later

First 3 hr of Landers aftershocks plotted

from Stein (2003)
...and promotes the M=7.1 Hector Mine shock 7 yr later

from Stein (2003)
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)

Arguments for dynamic stress triggering

❖ 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)
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❖ **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)

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

\[ \tau_s + \mu \sigma_n = \Delta \sigma_{CFF} \]

 specified receiver faults: 0/90/0  Depth: 10 km

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

\[ \text{Shear stress change, } \tau_s = \text{friction coeff, } \mu \times \text{normal stress change, } \sigma_n \]
Here’s how we calculate the static Coulomb stress change imparted by a strike-slip source.

Shear stress change, \( \tau_s \) + friction coeff, \( \mu \times \) normal stress change, \( \sigma_n \) = Coulomb stress change, \( \sigma_C (\Delta CFF) \)
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
- Long pre- and post-mainshock record of seismicity
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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)
Ruptures
26 Dec 2004 M=9.1
28 Mar 2005 M=8.6

Oblique subduction along the Sunda trench

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Oblique subduction along the Sunda trench produces the Andaman backarc system.
Transform sections
Pre-mainshock seismicity illuminates the megathrust and backarc system.
Ruptures
26 Dec 2004 M=9.1
28 Mar 2005 M=8.6

Backarc seismicity changes after the 2004 mainshock

Seismicity (Pesicek et al., 2010)
- Before 2004 rupture (30 Years)
- After 2004 rupture (5 years)
Ruptures
26 Dec 2004 M=9.1
28 Mar 2005 M=8.6

After 2004 rupture (5 years)
Andaman backarc system

Seismicity changes after the 2004 mainshock

Seismicity (Pesicek et al., 2010)
- Before 2004 rupture (30 Years)
- After 2004 rupture (5 years)
Northern backarc shuts down after 2004

Before 2004 rupture (30 Years)

After 2004 rupture (5 Years)
Earthquakes masked

After M=9.2

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After $M=9.2$ Earthquakes masked

Before $M=9.2$

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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

Log earthquake frequency (interevent time, days)\(^{-1}\)

Aftershocks

Log time (day)

Omori \(p=1\)

3 hr 5 yr
‘Triggered’ seismicity along the backarc behaves like aftershocks

Aftershocks

Background

Log earthquake frequency

(interevent time, days)$^{-1}$

Log time (day)

Linear time (year)

Omoti

$p=1$

3 hr

5 yr

1980

1990

2000
Strike-slip focal mechanisms all but cease after mainshock.
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Before 2004 mainshock (26 yr)
- Focal mechanism
  - strike-slip %
  - normal %
- Earthquakes masked
- 28 earthquakes

After 2004 mainshock (5 yr)
- Focal mechanism
  - strike-slip %
  - normal %
- Myanmar
- Andaman Sea
- 21 earthquakes
Strike-slip focal mechanisms all but cease after mainshock

Rate of strike-slip mechanisms drops by 2/3, rift mechanisms increase 8-fold
Observed quakes: right-lateral events halted, rifts activated

Andaman

basin

Right-lat. transform-rift system

promoted
inhibited
Static stress consistent with observations for fault friction <0.5
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The 53% gain in promoted mechanisms has a significance level of 0.03%.
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**Dynamic Coulomb stress modeling strategy**

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

Coulomb stress change (bar)
at 10 km depth with friction = 0.2

on rift normal faults
on rift normal faults

Coulomb stress change (bar)

at 10 km depth with friction= 0.2

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on rift normal faults

Coulomb stress change (bar)

at 10 km depth with friction = 0.2

Sunda

Andaman backarc system

Sunda

92° 94° 96° 98°

200 km

Time (sec): 0

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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

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If anything, dynamic stress should have favored transform earthquakes.
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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
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

![Map showing locations of magnitude ≥ 5 earthquakes before mainshock.](image)

Worldwide earthquakes *after* mainshock

![Map showing transient stress distribution after mainshock.](image)