Limitations of Earthquake Triggering Models*

Peter Shearer
IGPP/SIO/U.C. San Diego

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Earthquake Research Institute

* in Southern California
Why do earthquakes cluster in time and space?

- Earthquake triggering. Event A increases probability of future nearby events. Very clear in aftershock sequences, although mechanism (static vs. dynamic triggering) is debated.

- Underlying physical changes, such as slow creep, pore fluid pressure variations, etc. Often invoked to explain earthquake swarms.
Southern California Seismicity
1994 Northridge Earthquake (M 6.7)
Omori’s Law (Omori, 1894)

\[ n(t) = K(t + c)^{-1} \]

![Graph showing event rate over days from mainshock for Northridge aftershocks](image-url)
Secondary aftershocks
Epidemic Type Aftershock Sequences (ETAS) modeling

\[
\lambda(x, t) = \lambda_0 + \sum_i \kappa 10^{\alpha (m_i - m_0)} (t_i + c)^{-p} r_i^{-q}
\]

where:
- \(\lambda(x, t)\) = predicted event density
- \(\lambda_0\) = background rate (untriggered)
- \(\kappa\) = triggering productivity parameter
- \(m_i\) = magnitude of each earthquake
- \(m_0\) = minimum magnitude of the counted events
- \(\alpha \approx 1\) (larger earthquakes trigger more events)
- \(t_i\) = time from the \(i\)th event to \(t\)
- \(c\) and \(p\) (\(\approx 1\)) are the Omori decay constants
- \(r_i\) = distance from the \(i\)th event to \(x\)
- \(q\) defines the decay with distance
Aftershock distance dependence (Felzer & Brodsky, 2006)

- Used relocated southern California catalog
- Stacked “mainshocks” to get average aftershock densities
- Results suggest $q \sim 3.3$ in $r^{-q}$ dependence of aftershocks on distance

5 minutes after 7,396 M 2–3 and 2,355 M 3–4 mainshocks

2 days after 9 M 5–6 mainshocks

30 minutes after 2,355 M 3–4 mainshocks
Gutenberg-Richter relation

\[ \log_{10} N = a - bM \]

\( b \) value, generally observed to be 0.8 to 1.2

productivity parameter (for aftershock sequences, \( a \) can be estimated from:

Bath’s Law: the largest aftershock is about one magnitude smaller than the mainshock)

Northridge data

\[ b = 0.83 \]

\[ N \ (> M) \]

\[ M \]

\[ 5.9 \]

\[ 6.7 \]
Simulated catalog

$$\lambda(x, t) = \lambda_0 + \sum_i \kappa_i 10^{(m_i - m_0)} (t_i + c)^{-p} r_i^{-q}$$

Example run of *Aftsimulator.m* program (Karen Felzer)
Uses $\alpha = 1$, $p = 1.34$, $q = 3.37$, G-R relation with $b = 1$
$\lambda_0(x) =$ background rate for S. Calif. (Andy Michael)
What features of real catalogs do ETAS-type models miss?

- Swarms and swarm-like behavior
- Differences in precursory activity between target events of different sizes
- Time-symmetric time/space clustering of small earthquakes
Swarms near Northridge
Southern California earthquake “bursts”

Selection criteria:

• 40 events within 2 km radius in 28 days

• fewer than 4 events in prior 28 days

• no more than 20% additional events between 2 and 4 km radius

14 start with largest event (mainshock-like)

57 start with smaller event (swarm-like)
Southern California bursts

X first event

largest event

swarm-like

mainshock-like

swarm-like
Swarm-like behavior: Evidence against simple triggering cascade

- Interval of steady seismicity rate
- Tendency for largest event to strike later in sequence
- Large spatial extent of swarms compared to their cumulative moment
- Often involve spatial migration of seismicity
- Weak correlation between number of events and magnitude of largest events
- Suggested underlying physical cause, such as pore fluid pressure changes and/or aseismic slip
- Swarms are distributed across region, not restricted to volcanic or geothermal areas
ETAS-like models predict triggered earthquakes have random sizes

- Triggering model provides probability of earthquake in this space/time box, given the past history of seismicity

- But if an earthquake occurs, its size is randomly drawn from the G-R relation

- Thus, the average precursory seismicity behavior should be **identical** before earthquakes of any given size
Test using LSH catalog (Lin et al., 2007)

- 1981–2005, relocated using waveform cross-correlation to precision of tens of meters
- Windowed to inside network only, $M \geq 1.5$, 173,058 quakes
- Target events excluded for several months following $M \geq 6$ mainshocks, and for 3 days following $M \geq 4$ quakes

Guoqing Lin
Space/time behavior of precursory seismicity

\[ n = \frac{\sum D}{dt} \]

\[ D = \frac{n}{N(t_2 - t_1)(4/3)\pi(r_2^3 - r_1^3)} \]

- Precursory event rate
- Total number of precursory events
- Number of target events
- Volume of shell
Magnitude dependence of precursory seismicity rate

target event size

\[
\begin{array}{ccc}
M 3-4 & \div & M 2-3 \\
\end{array}
\]

\[
\begin{array}{ccc}
M 4-5 & \div & M 2-3 \\
\end{array}
\]
Linear event density in day before target quakes

\[ D_{\text{lin}} = \frac{n}{N(r_2 - r_1)} \]
“Extra” precursory events at larger magnitudes

Extra events in each distance bin per target event (compared to M 2-3 results)

\[ E = \frac{n}{N} - \frac{n(M_{2-3})}{N(M_{2-3})} \]
How robust is this result?

- M $\geq$ 1 catalog
- M $\geq$ 2 catalog
- Halved aftershock exclusion period
- Doubled aftershock exclusion period
- Catalog with less accurate locations but more uniformly processed
Precursory Seismicity in Southern California

• Enhanced activity in 1-day period preceding M 3-5 quakes compared to M 2-3 quakes at distances of 0.5 to 2 km.

• Anomaly onset roughly agrees with expected source radius of target quakes.

• Reduced activity at shorter distances.

• Not useful for prediction of individual quakes.

• These anomalies are NOT predicted by standard earthquake triggering models.
Aftershock study of Rubin & Gillard (2000)

- High-precision relocations of 4300 quakes on central San Andreas Fault
- Plot shows first event following M 1–3.5 mainshocks, scaled by expected source radius of mainshock, assuming 10 MPa stress drop
- “Hole” indicates likely slip plane
- A really nice study!
Mogi doughnuts (*Mogi*, 1969)

Kanamori (1981)

idealized version
Felzer & Brodsky (2006), revisited

- Picked target events with no larger earthquake within 3 days before and 0.5 day afterward
- Plotted events within 30 minutes after M 3–4 targets

their plot (SHLK catalog)  
my plot (LSH catalog)
But similar behavior seen *before* target earthquakes

30 minutes **before**

243 “foreshocks”

30 minutes **after**

605 “aftershocks”
Behavior for M 2-3 targets is nearly time-symmetric

30 minutes before

322 “foreshocks”

30 minutes after

396 “aftershocks”
Felzer & Brodsky (2006), revisited

- Picked target events with no larger earthquake within 3 days before and 0.5 day afterward
- Plotted events within 5 minutes after M 2–3 and M 3–4 targets

Felzer & Brodksy (2006)
M 2–4 triggering only resolvable to distances of 1 to 3 km

- F&B exclusion criteria
- $M \geq 1.5$
- $\pm 1$ hour from target event times
What causes precursory clustering?

Simple AB/BA symmetry argument?

No! Plots are only of events *smaller* than targets.
What causes precursory clustering?

Expected behavior from foreshock triggering?
(sometimes mainshocks are really big aftershocks)

To test this, I performed 100 simulations of S. Calif. seismicity using *Aftsimulator.m* program (Karen Felzer) with $\alpha = 1$, $p = 1.34$, $q = 3.37$, G-R relation with $b = 1$

$\lambda_0(x) =$ background rate for S. Calif. (Andy Michael)

\[
\lambda(x, t) = \lambda_0 + \sum_i \kappa 10^{\alpha(m_i-m_0)}(t_i + c)^{-p r_i^{-q}}
\]
Data vs ETAS synthetics (M ≥ 1.5)
What causes precursory clustering?

- Simulations suggest that the bulk of time-symmetric clustering for M 1.5–4 earthquakes in southern California is *not* caused by ETAS-like triggering, but by some other process.

- More simulations are needed to test this conclusion, but it’s hard to see how runs that satisfy Bath’s Law will produce time-symmetric behavior.

- Swarms provide additional evidence for an underlying physical driving mechanism for clustering.

- Important issue for earthquake prediction (ETAS models are totally random and limit how good predictions can be).
Circles show $M \geq 4$