USGS

science for a changing world

Earthquakes ❖ Volcanoes ❖ Landslides ❖ Floods ❖ Space Weather ❖ Wildfires ❖ Coastal Erosion

Using Earthquake Clustering for Short-Term Forecasting

Dr. Lucile Jones

Standing in for Andy Michael, USGS Seismologist

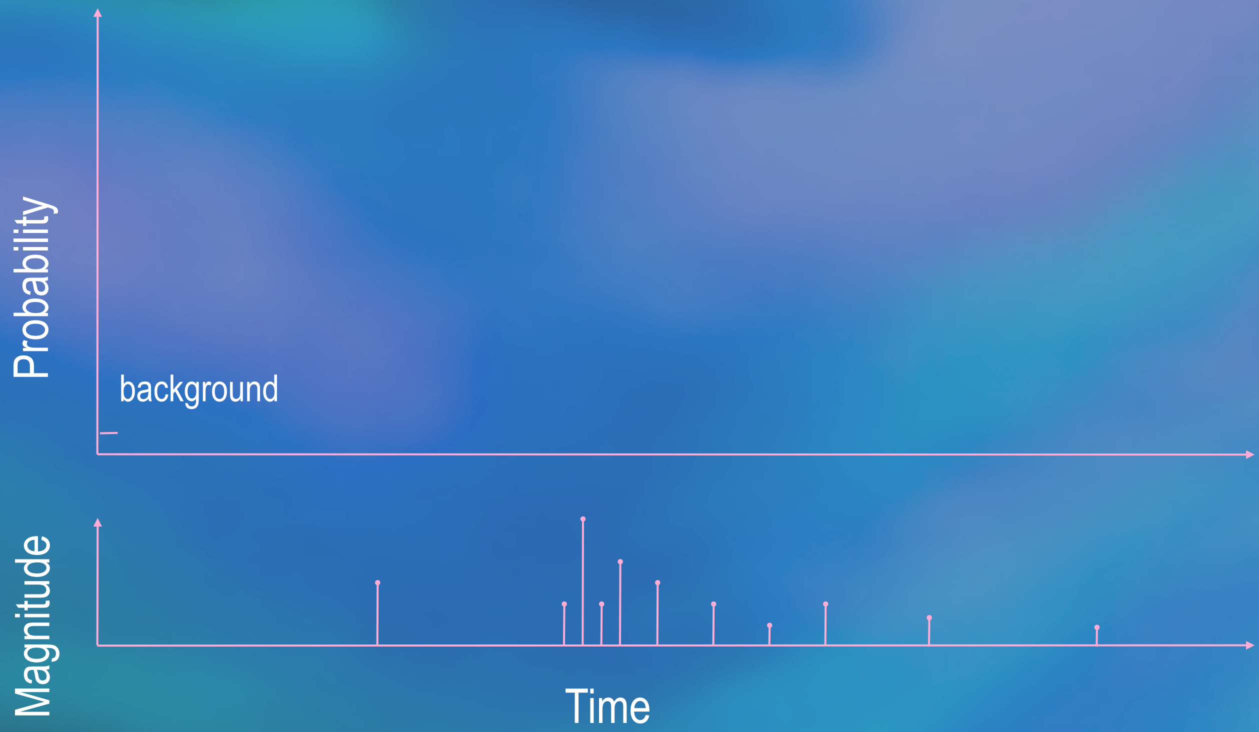
Chief Scientist, Multi Hazards Demonstration Project

U. S. Geological Survey

What is Operational in California?

- Aftershock statistics based on Reasenberg & Jones (1989)
- Automatic updates of STEP aftershock model – probability of earthquake shaking
- Foreshock model (based on Agnew and Jones, 1992) used with discussion after possible foreshocks
- STEP is being tested in CSEP

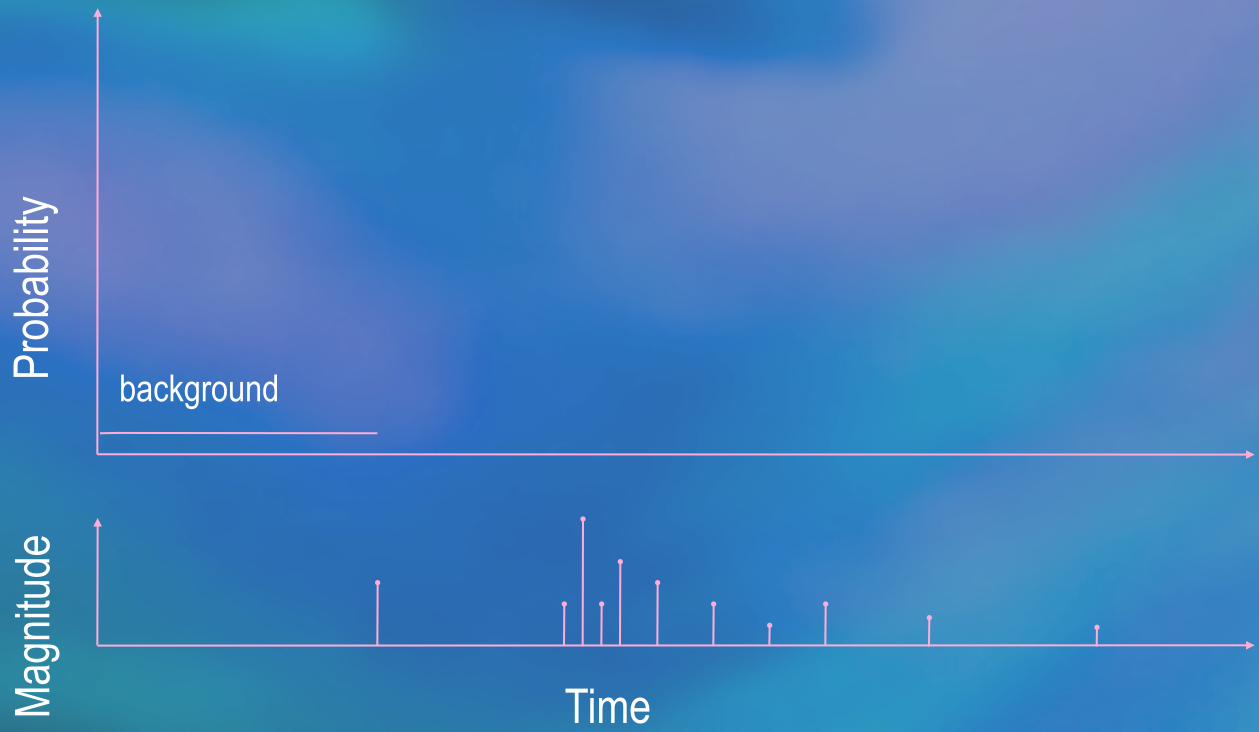
Earthquake Clustering



Aftershocks/Foreshocks > 50% of all events in California

USGS

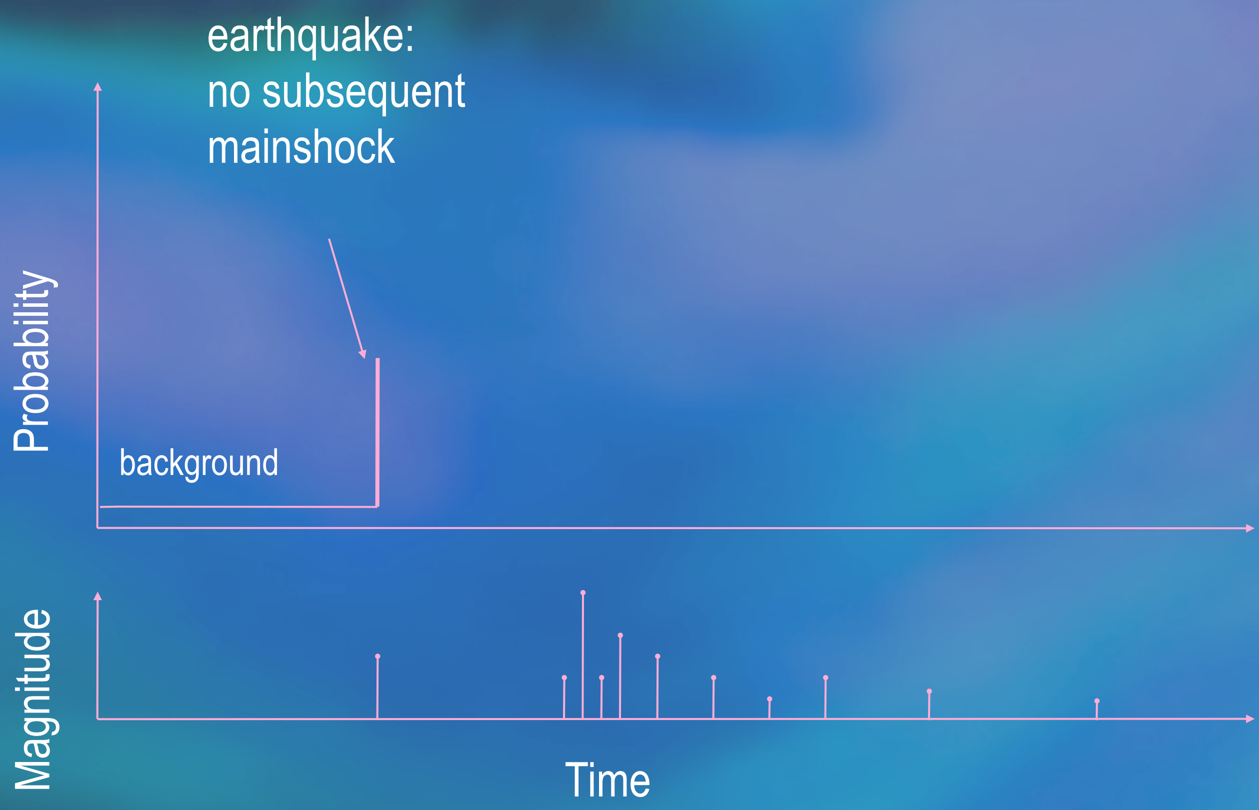
Earthquake Clustering



Aftershocks/Foreshocks > 50% of all events in California

USGS

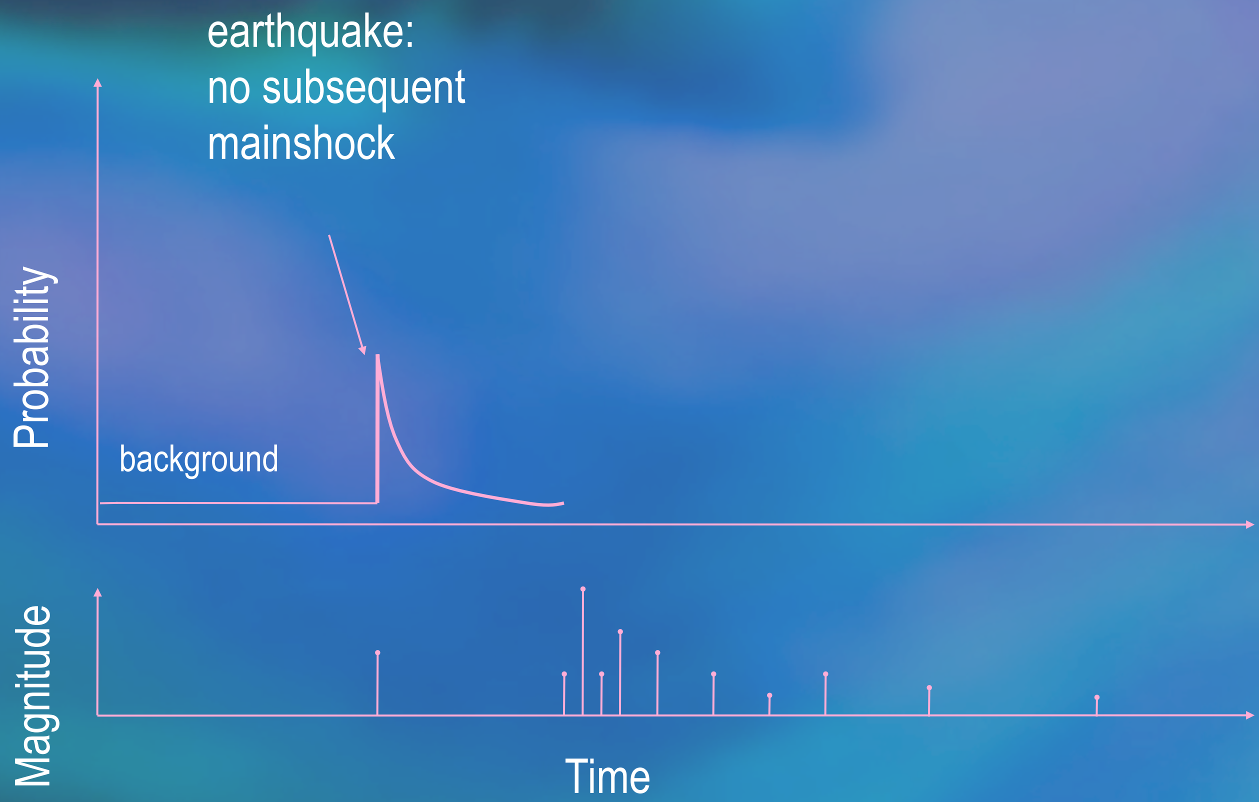
Earthquake Clustering



Aftershocks/Foreshocks > 50% of all events in California

USGS

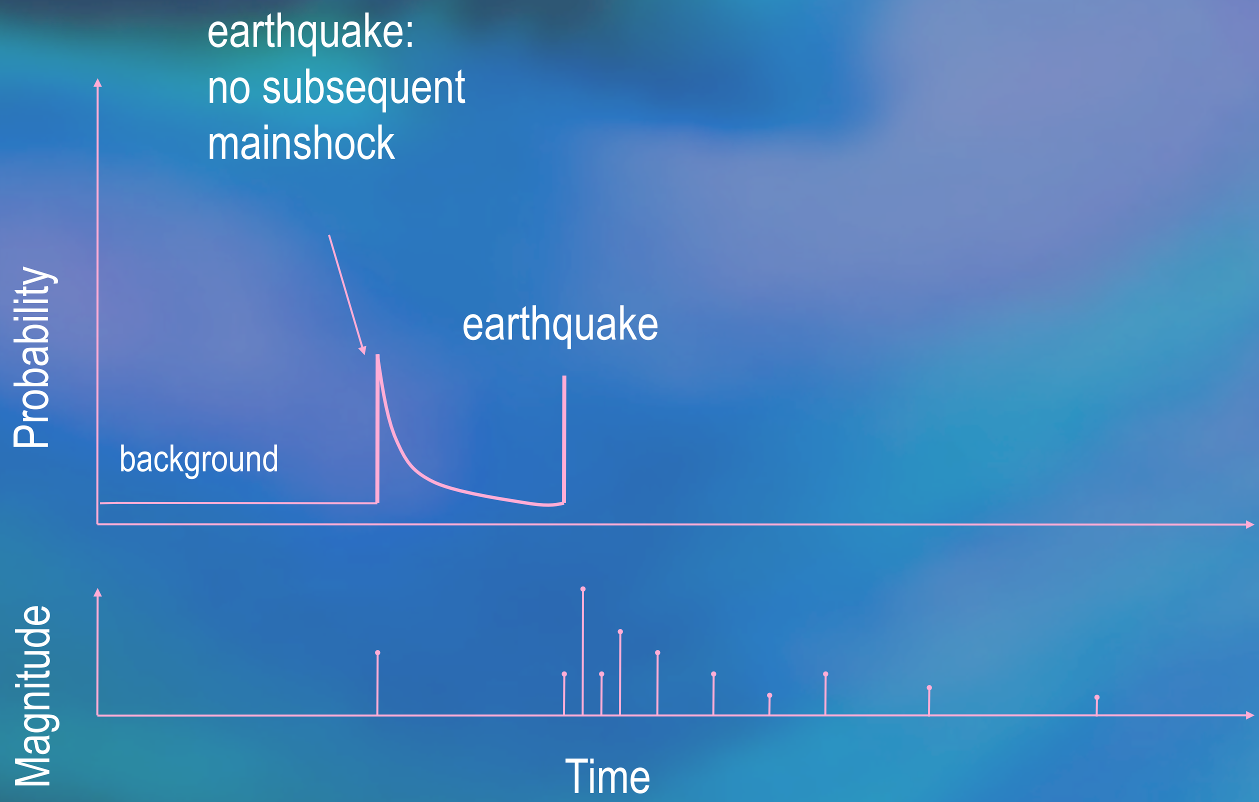
Earthquake Clustering



Aftershocks/Foreshocks > 50% of all events in California

USGS

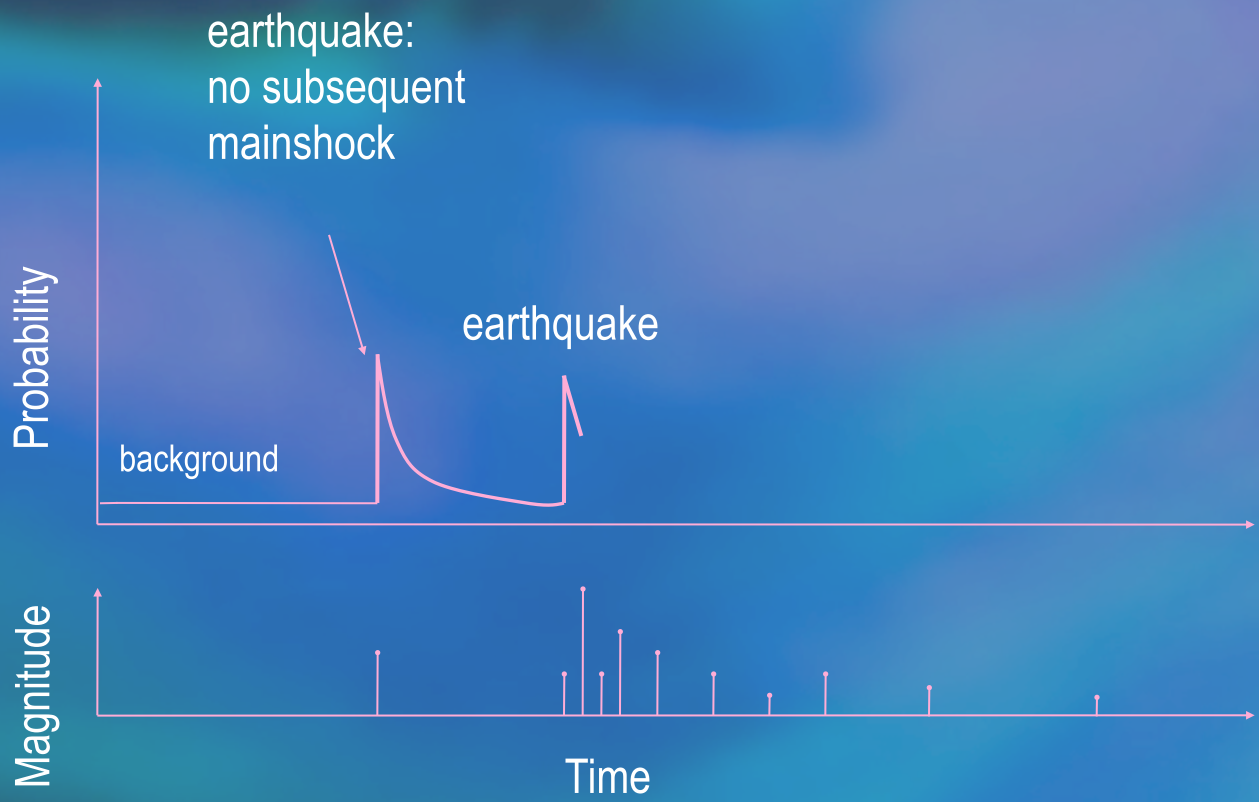
Earthquake Clustering



Aftershocks/Foreshocks > 50% of all events in California

USGS

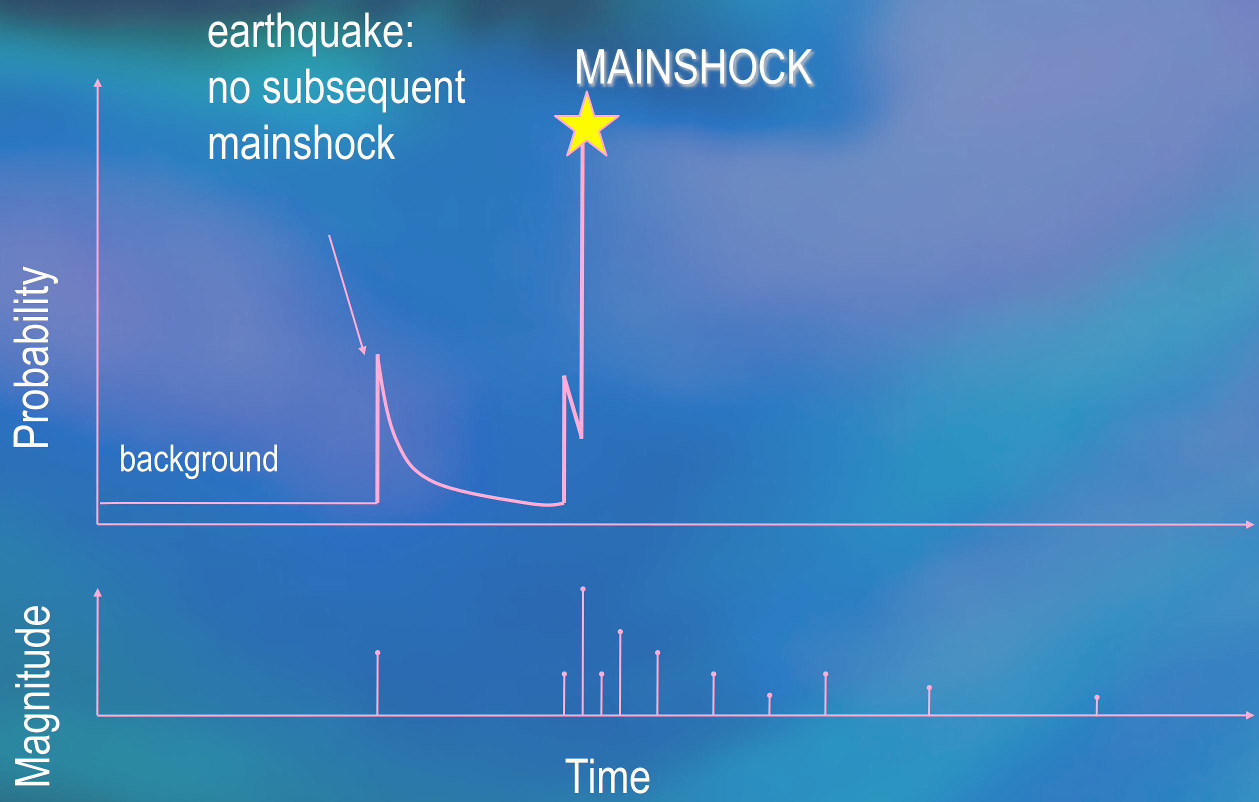
Earthquake Clustering



Aftershocks/Foreshocks > 50% of all events in California

USGS

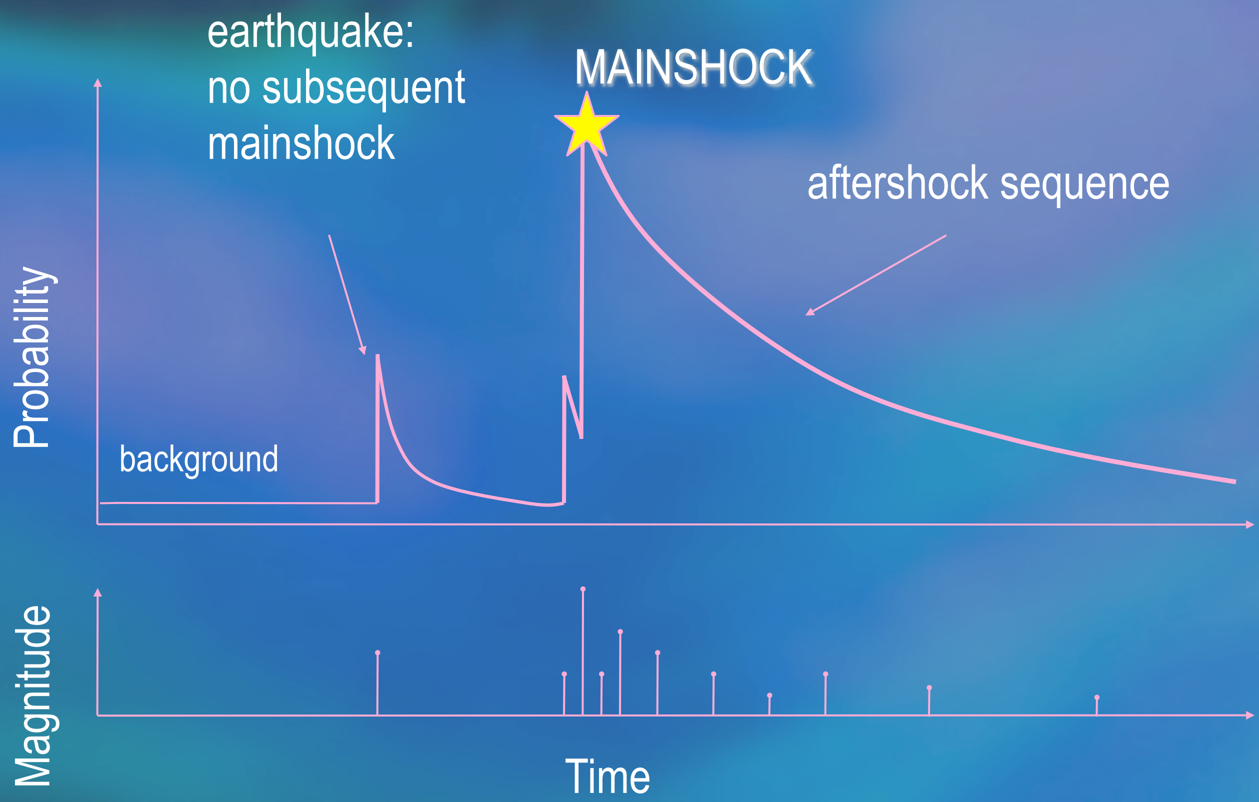
Earthquake Clustering



Aftershocks/Foreshocks > 50% of all events in California

USGS

Earthquake Clustering



Aftershocks/Foreshocks > 50% of all events in California

USGS

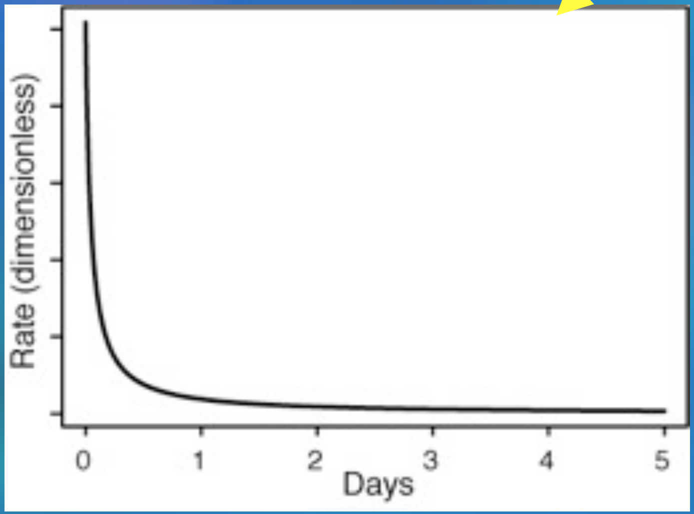
Aftershock probabilities

- Probability determined from Omori's Law and Gutenberg-Richter relation
  - Reasenberg and Jones, 1989
- Rupture forecast, not shaking
- First issued as public statements in 1989

Aftershock probabilities

- Probability determined from Omori's Law and Gutenberg-Richter relation
  - Reasenberg and Jones, 1989
- Rupture forecast, not shaking
- First issued as public statements in 1989

N =f(1/t)

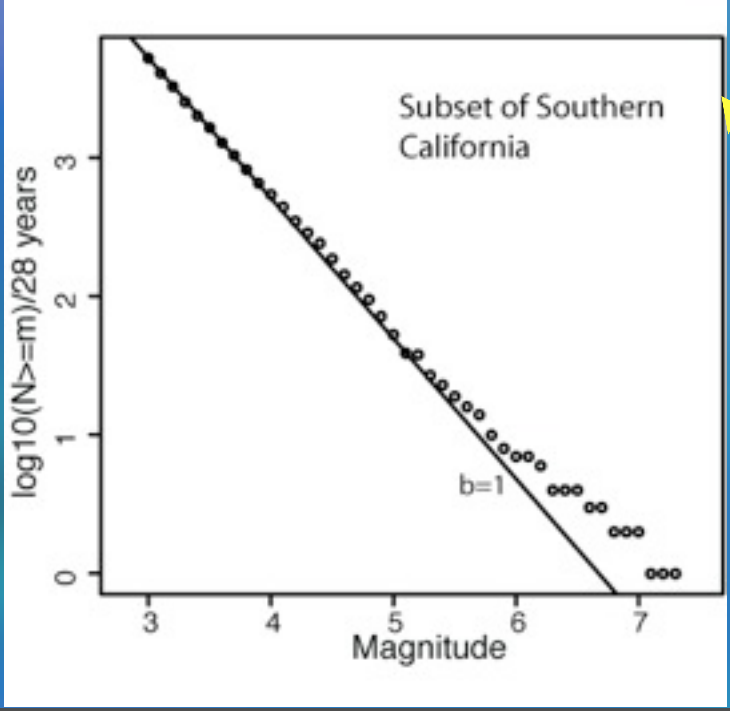


USGS

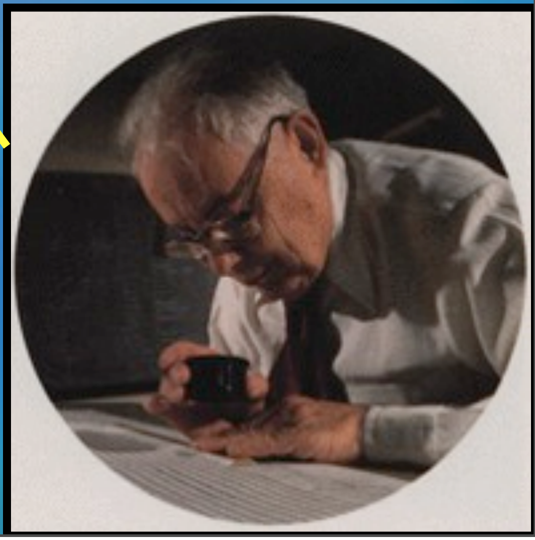
Aftershock probabilities

- Probability determined from Omori's Law and Gutenberg-Richter relation
  - Reasenberg and Jones, 1989
- Rupture forecast, not shaking
- First issued as public statements in 1989

N =f(1/t)



N = f(10^{-bM})



USGS

Reasenberg and Jones (1989)

$$\lambda(t,M) = 10^{a'+b(M_i - M)}(t+c)^{-p}$$

$$\lambda(t,M) = k10^{bM_i}10^{-bM}(t+c)^{-p}$$

Rate

Overall Productivity

Productivity vs. Initiating Event Magnitude

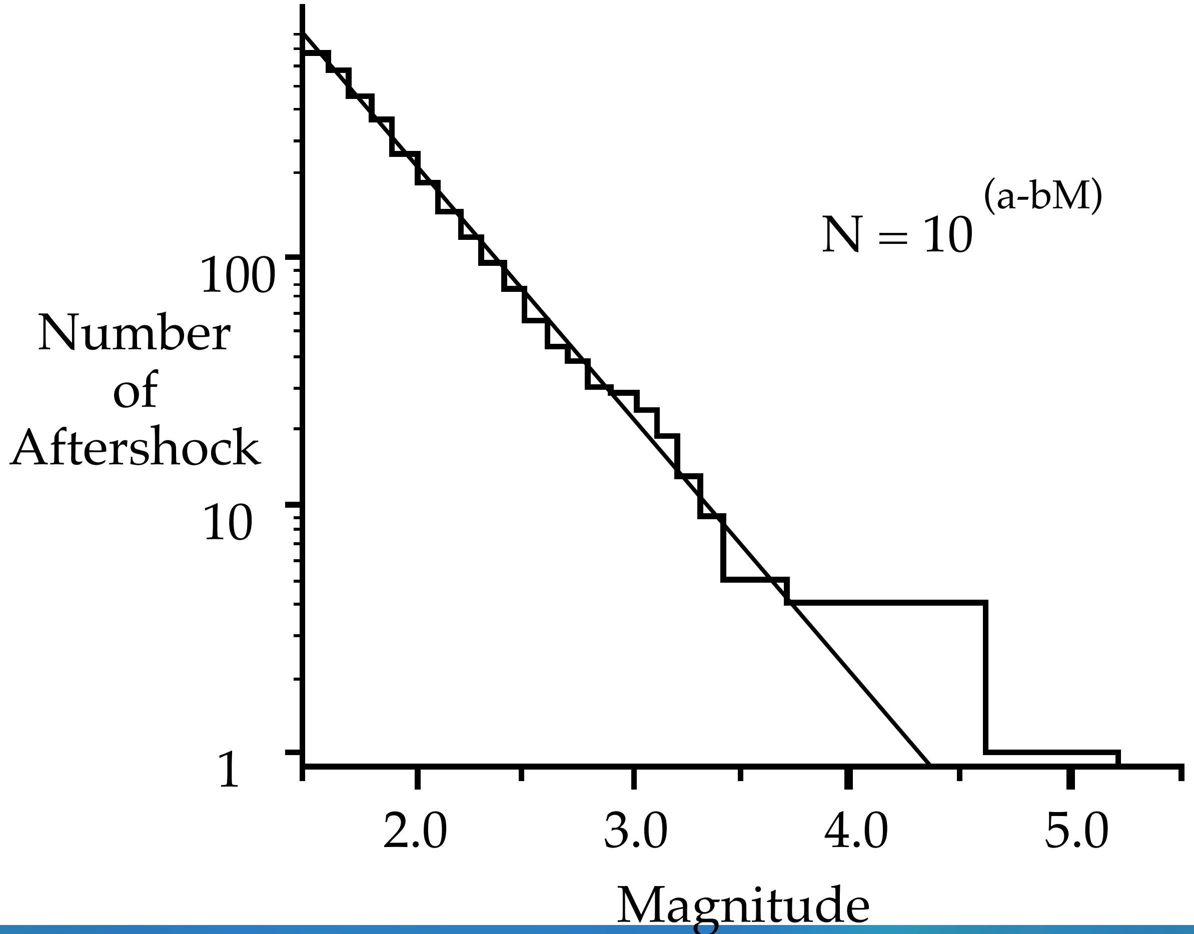
Probability of m≥M given an Earthquake P(m≥M|E) (Mmin=0)

modified-Omori Decay

USGS

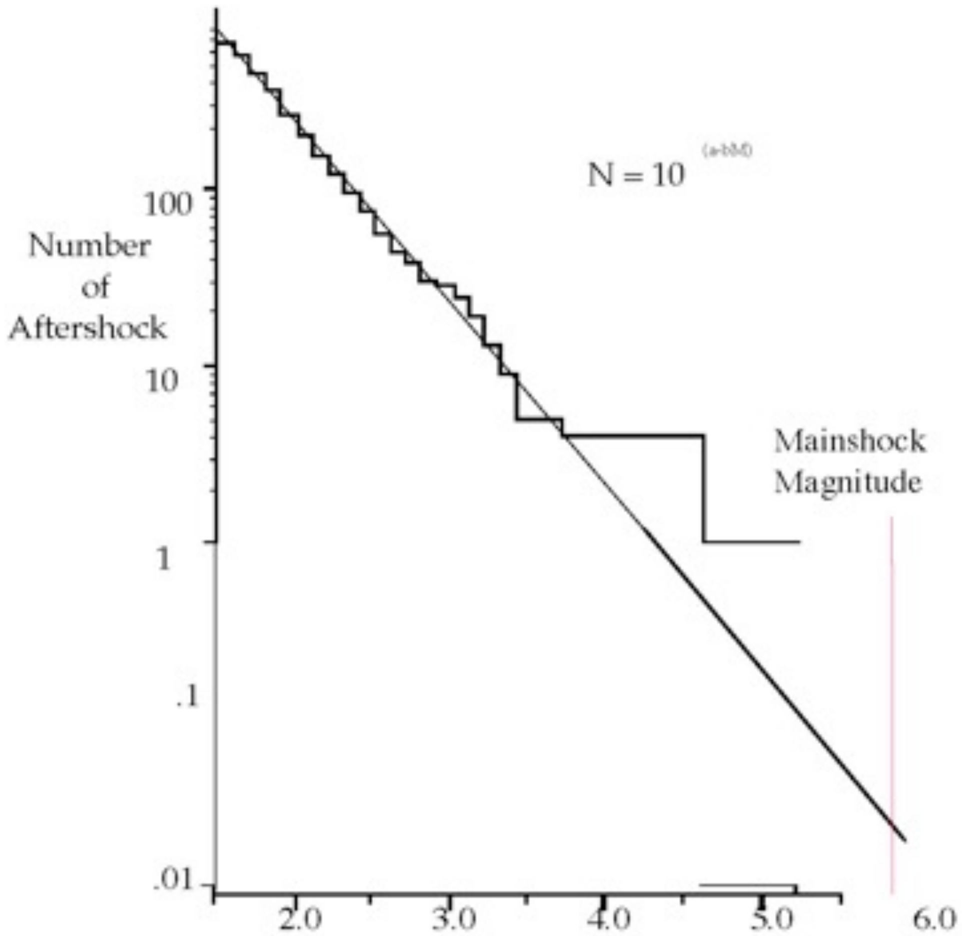
Small earthquakes are more common

Each unit smaller has 10 times more earthquakes



USGS

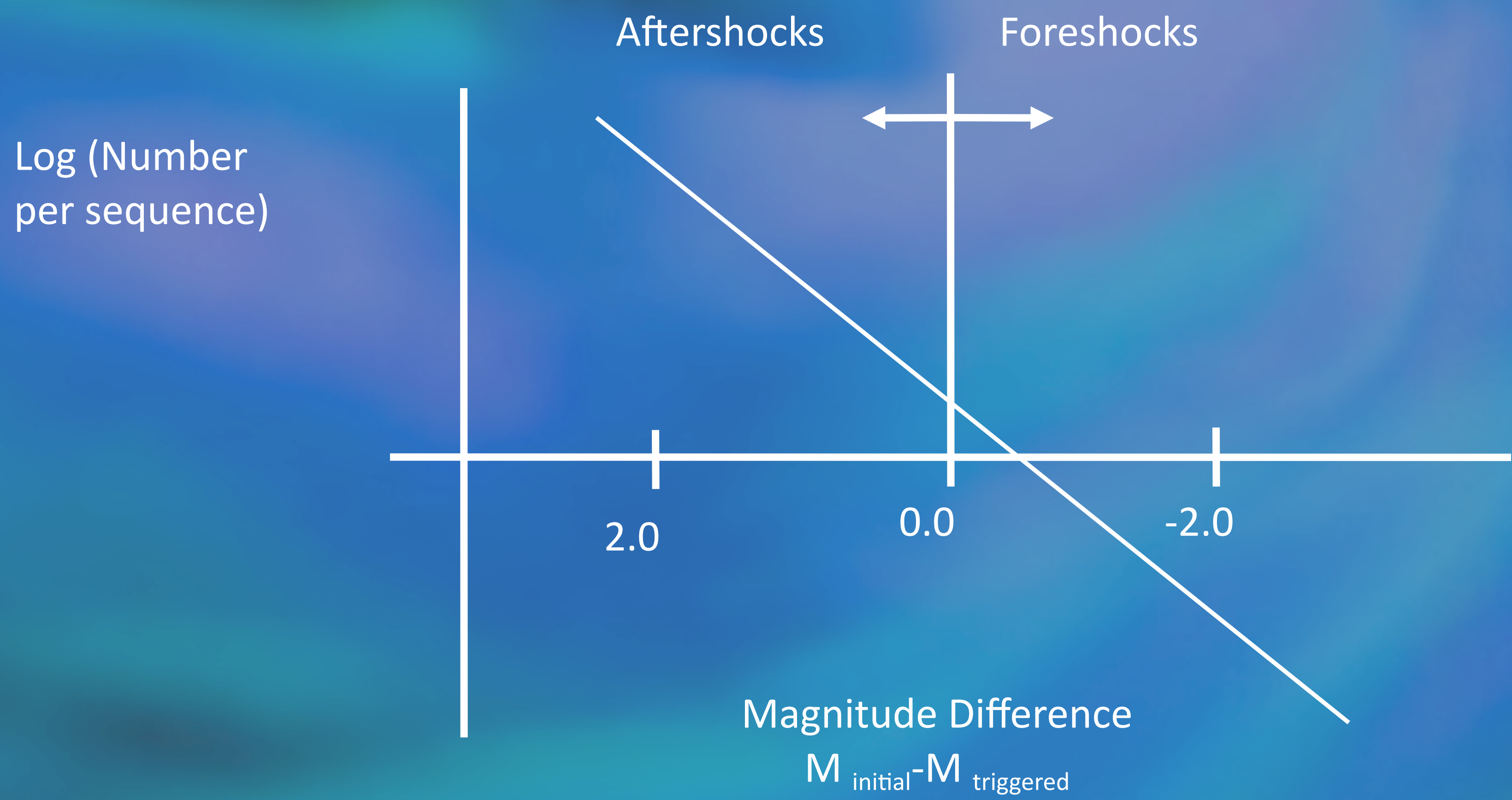
But what if we look below N=1?



USGS

Self-similar Model

Foreshocks as mainshocks with large aftershocks



USGS

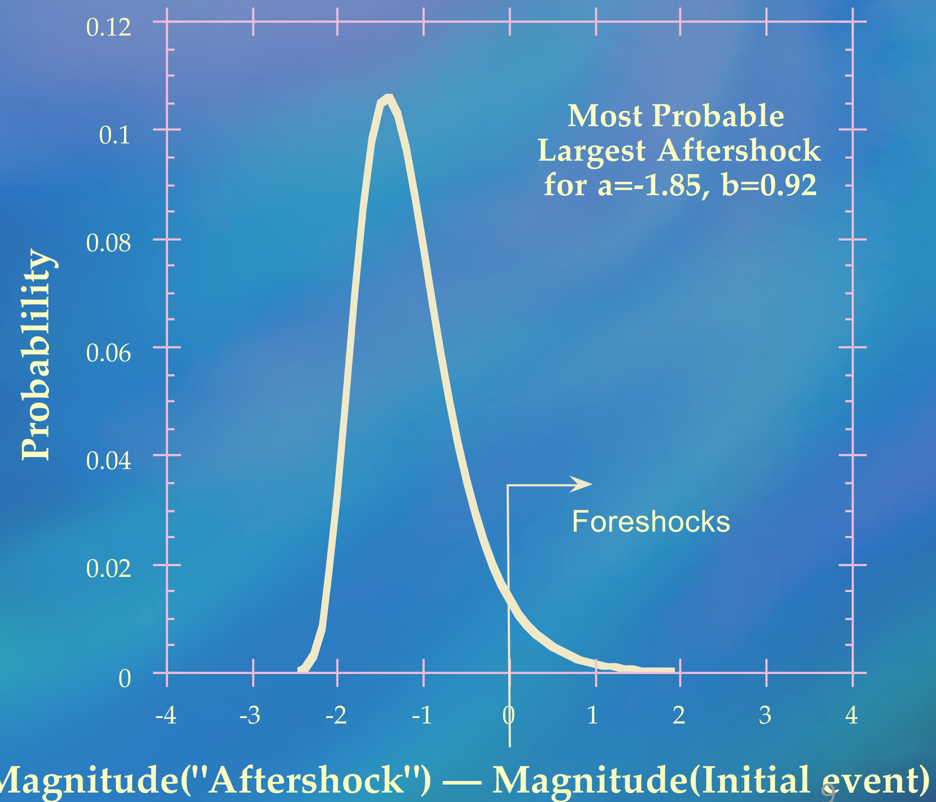
Evidence for Self-similar Model

- Decay of foreshocks
- Magnitude distribution

USGS

Evidence for Self-similar Model

- Decay of foreshocks
- Magnitude distribution



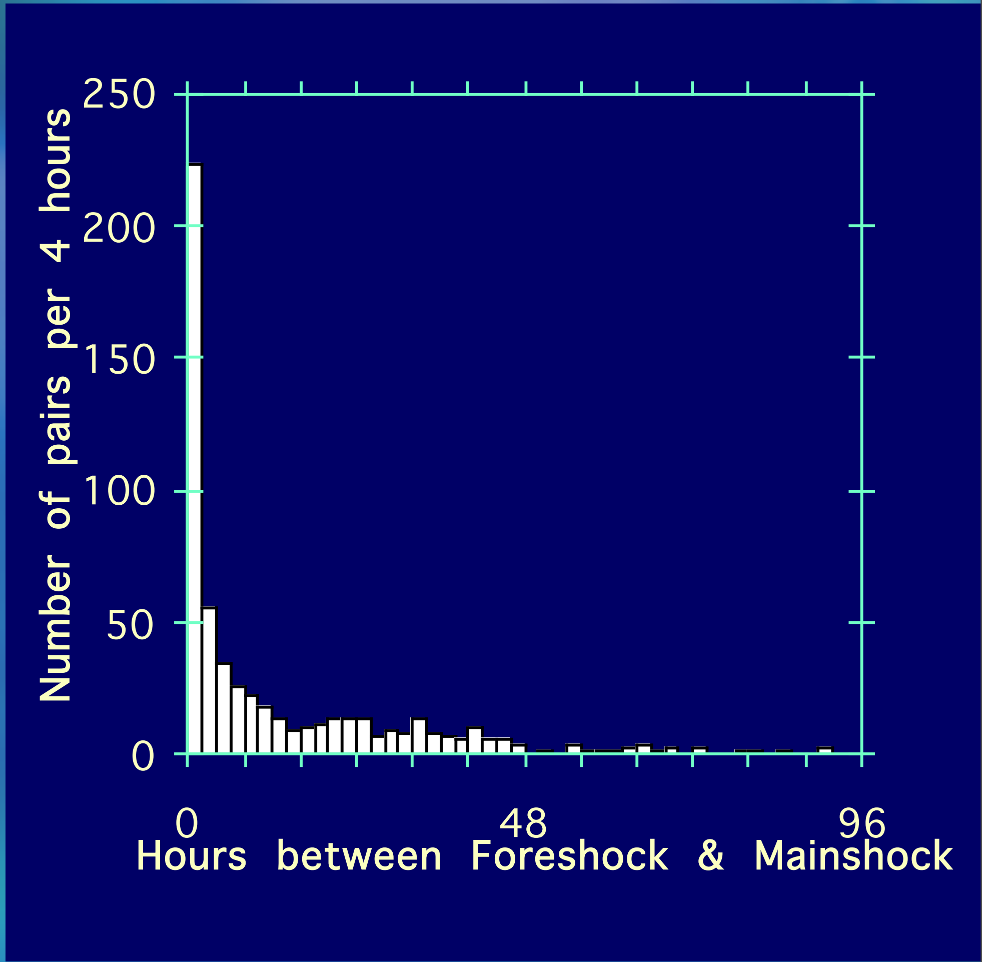
USGS

This is exactly what happens

- Rate of mainshocks after foreshocks

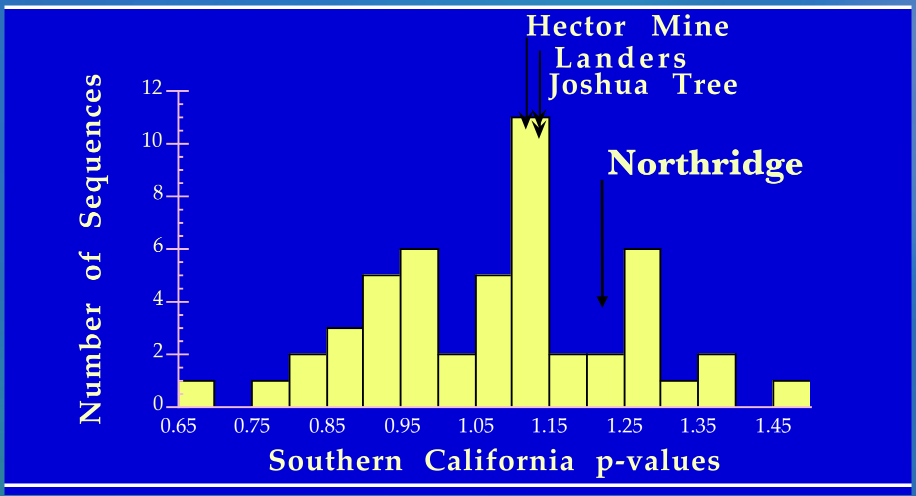
=

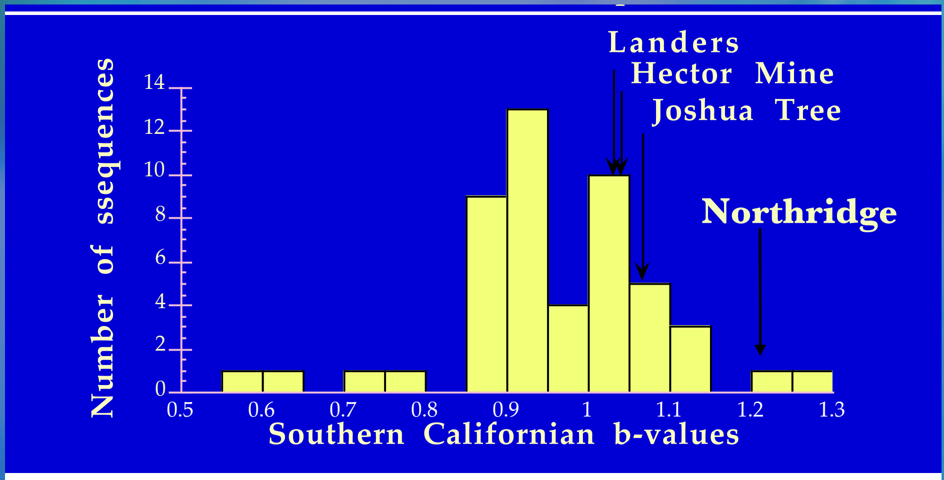
- Rate of aftershocks after mainshocks

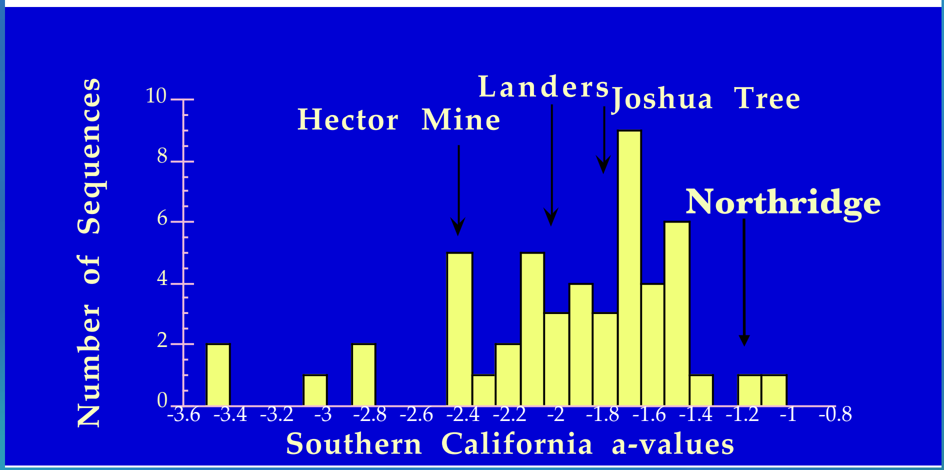


USGS

The parameters vary





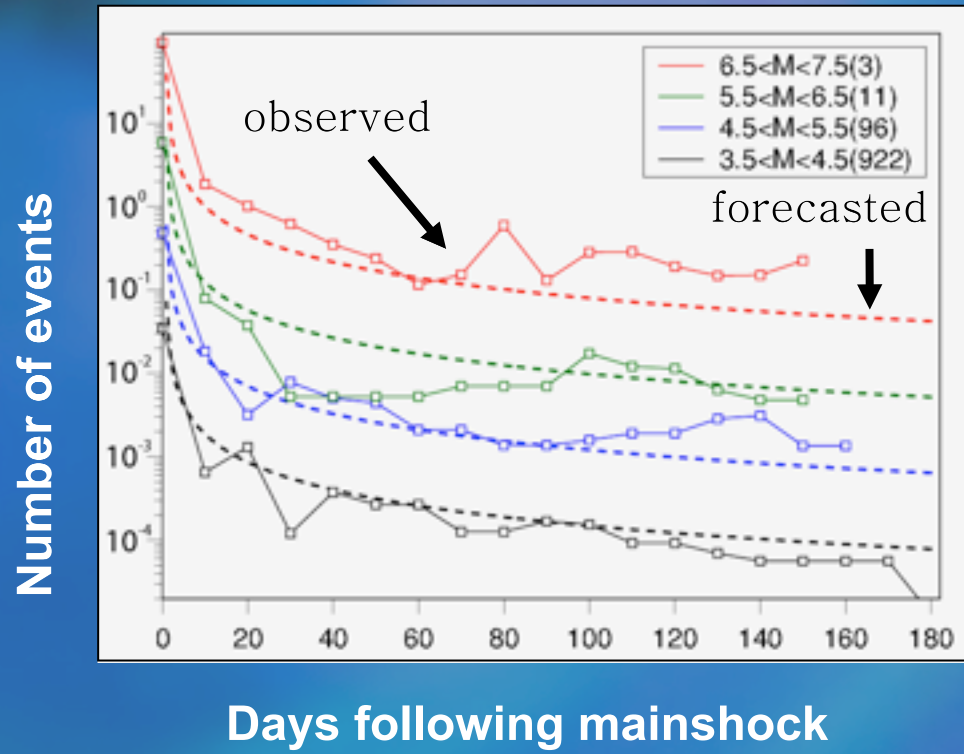


USGS

Generic Aftershock Model

Generic parameters calculated using California aftershock sequences (1932-1987)

Only requires mainshock magnitude as input

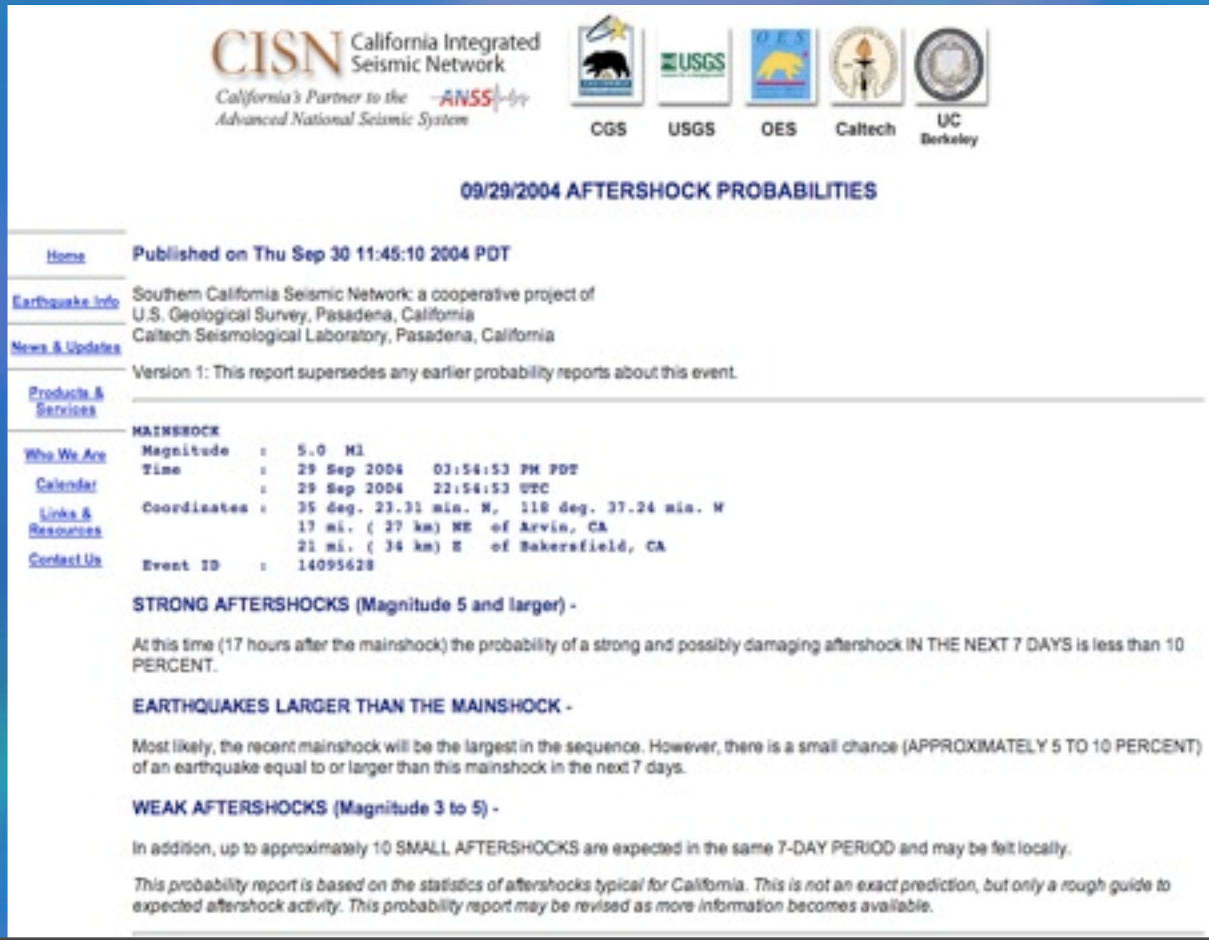


California aftershock rates (1988-2003) vs. Generic model

USGS

Issued as probability statement

- Predicting events without spatial information
- Time decay not communicated
  - Message on Internet can be days out of date


CISN California Integrated Seismic Network
California's Partner in the ANSS Advanced National Seismic System

CGS USGS OES Caltech UC Berkeley

09/29/2004 AFTERSHOCK PROBABILITIES

Home
Earthquake Info
News & Updates
Products & Services
Who We Are
Calendar
Links & Resources
Contact Us

Published on Thu Sep 30 11:45:10 2004 PDT

Southern California Seismic Network: a cooperative project of
U.S. Geological Survey, Pasadena, California
Caltech Seismological Laboratory, Pasadena, California

Version 1: This report supersedes any earlier probability reports about this event.

```
MAINSHOCK
 Magnitude    :    5.0  Ml
 Time         :    29 Sep 2004    03:54:53 PM PDT
              :    29 Sep 2004    22:54:53 UTC
 Coordinates  :    35 deg. 23.31 min. N,   118 deg. 37.24 min. W
                   17 mi. ( 27 km) NE  of Arvin, CA
                   21 mi. ( 34 km) E   of Bakersfield, CA
 Event ID     :    14095628
```

STRONG AFTERSHOCKS (Magnitude 5 and larger) -

At this time (17 hours after the mainshock) the probability of a strong and possibly damaging aftershock IN THE NEXT 7 DAYS is less than 10 PERCENT.

EARTHQUAKES LARGER THAN THE MAINSHOCK -

Most likely, the recent mainshock will be the largest in the sequence. However, there is a small chance (APPROXIMATELY 5 TO 10 PERCENT) of an earthquake equal to or larger than this mainshock in the next 7 days.

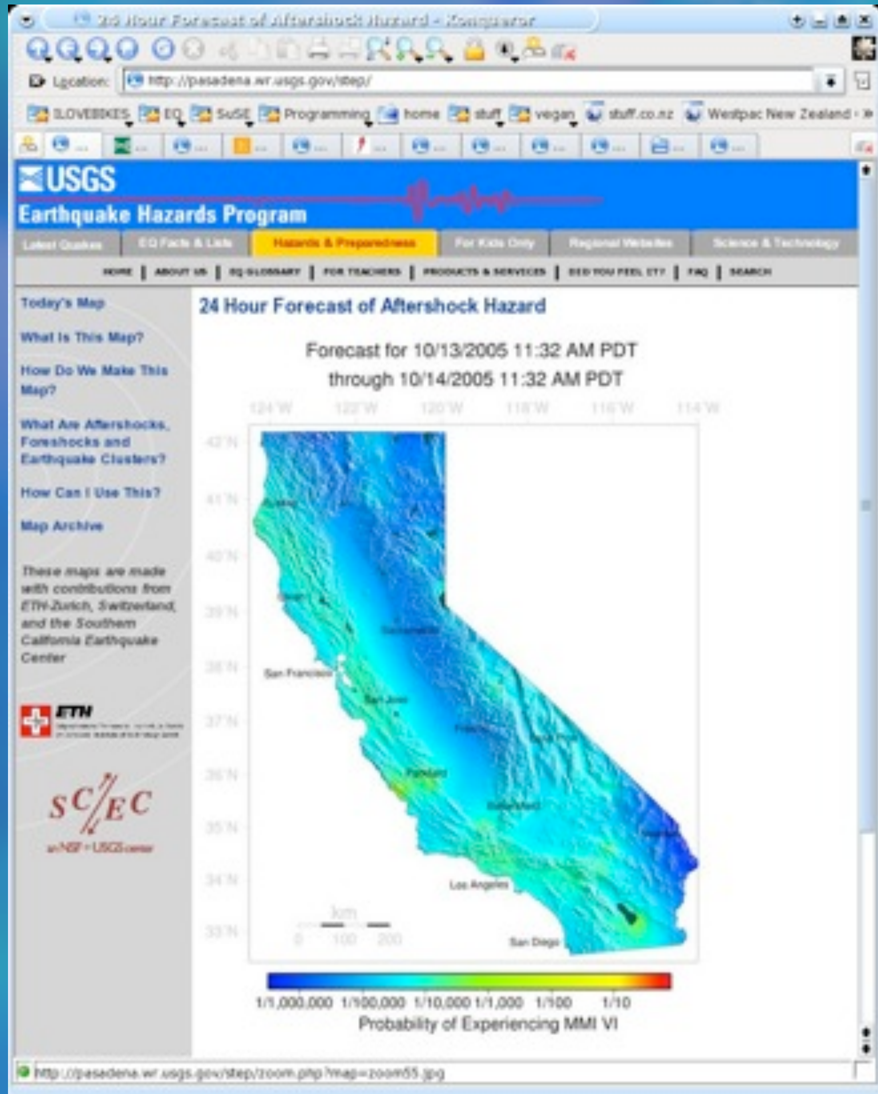
WEAK AFTERSHOCKS (Magnitude 3 to 5) -

In addition, up to approximately 10 SMALL AFTERSHOCKS are expected in the same 7-DAY PERIOD and may be felt locally.

This probability report is based on the statistics of aftershocks typical for California. This is not an exact prediction, but only a rough guide to expected aftershock activity. This probability report may be revised as more information becomes available.

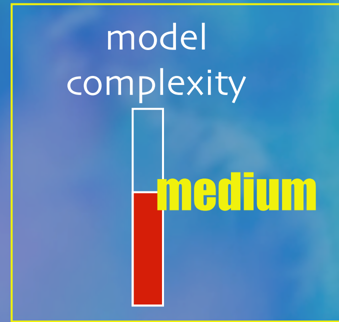
Short Term Earthquake Probabilities (STEP)

- 24 hour forecast
- probability of exceeding MMI VI
- automatic calculations
- online
- real-time
- updated every half-hour



USGS

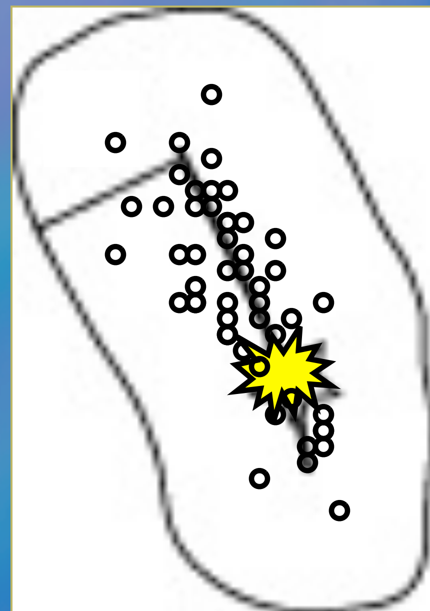
The Aftershock Models



Sequence Specific Model

needs minimum of 100 aftershocks before estimating parameters

One set of model parameters (Gutenberg-Richter and modified Omori laws) calculated for the entire aftershock sequence



The aftershock zone

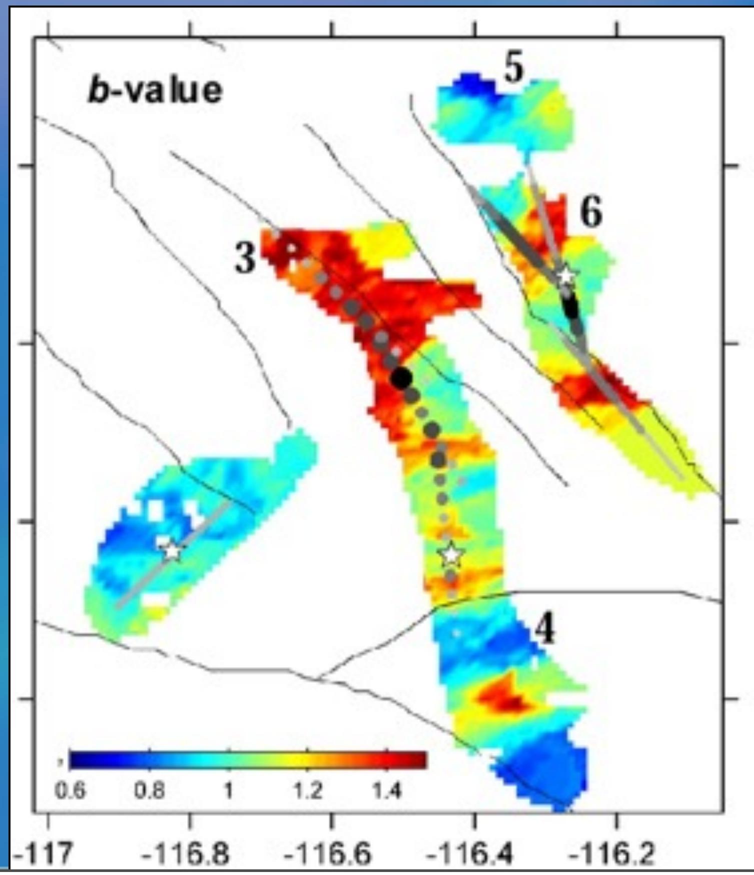
USGS

The Aftershock Models

Spatially Varying Model

model complexity
highest

Gutenberg-Richter and modified Omori law parameters are mapped at 5km spacing



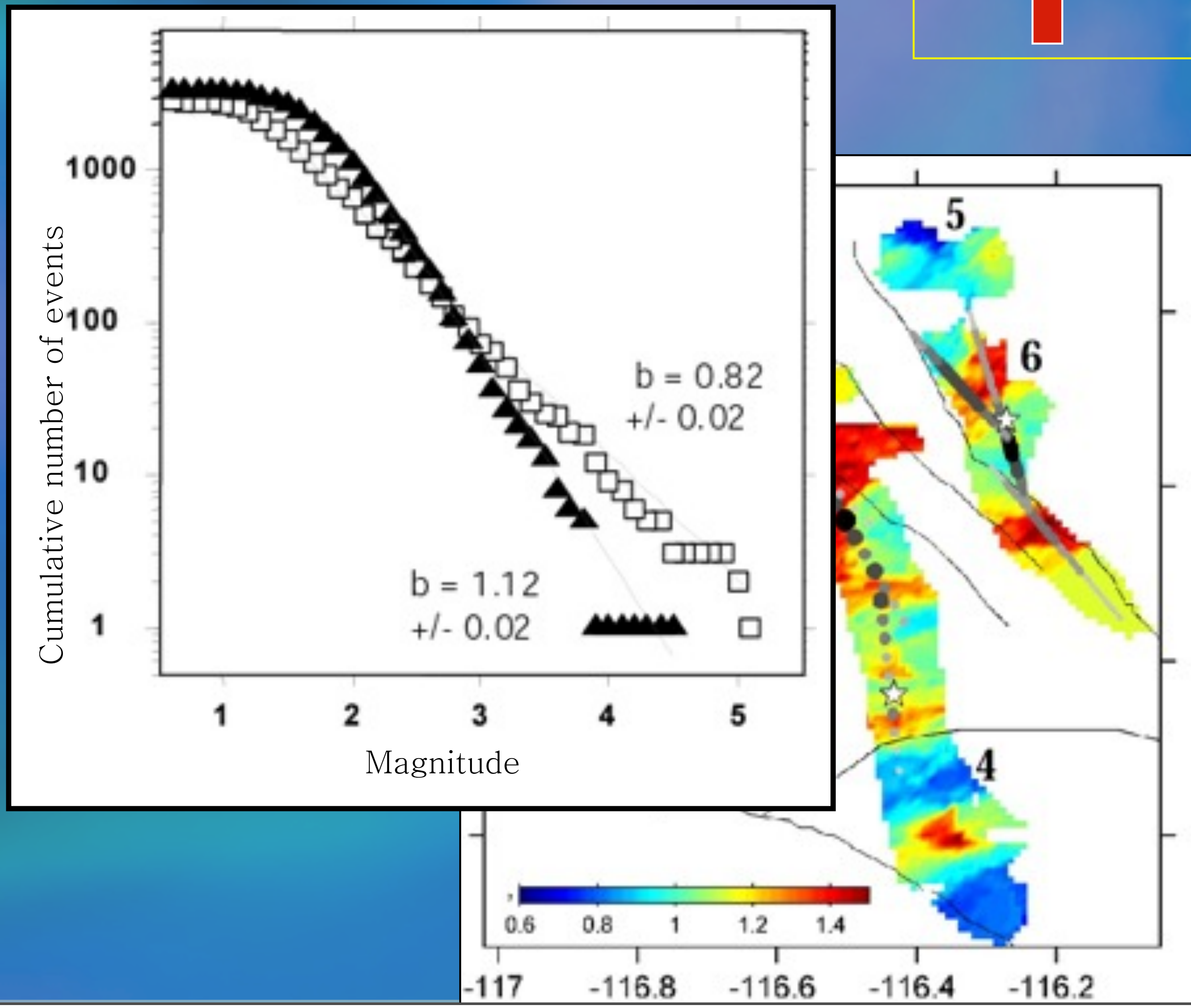
USGS

The Aftershock Models

model complexity
highest

Spatially Varying Model

Gutenberg-Richter and modified Omori law parameters are mapped at 5km spacing



USGS

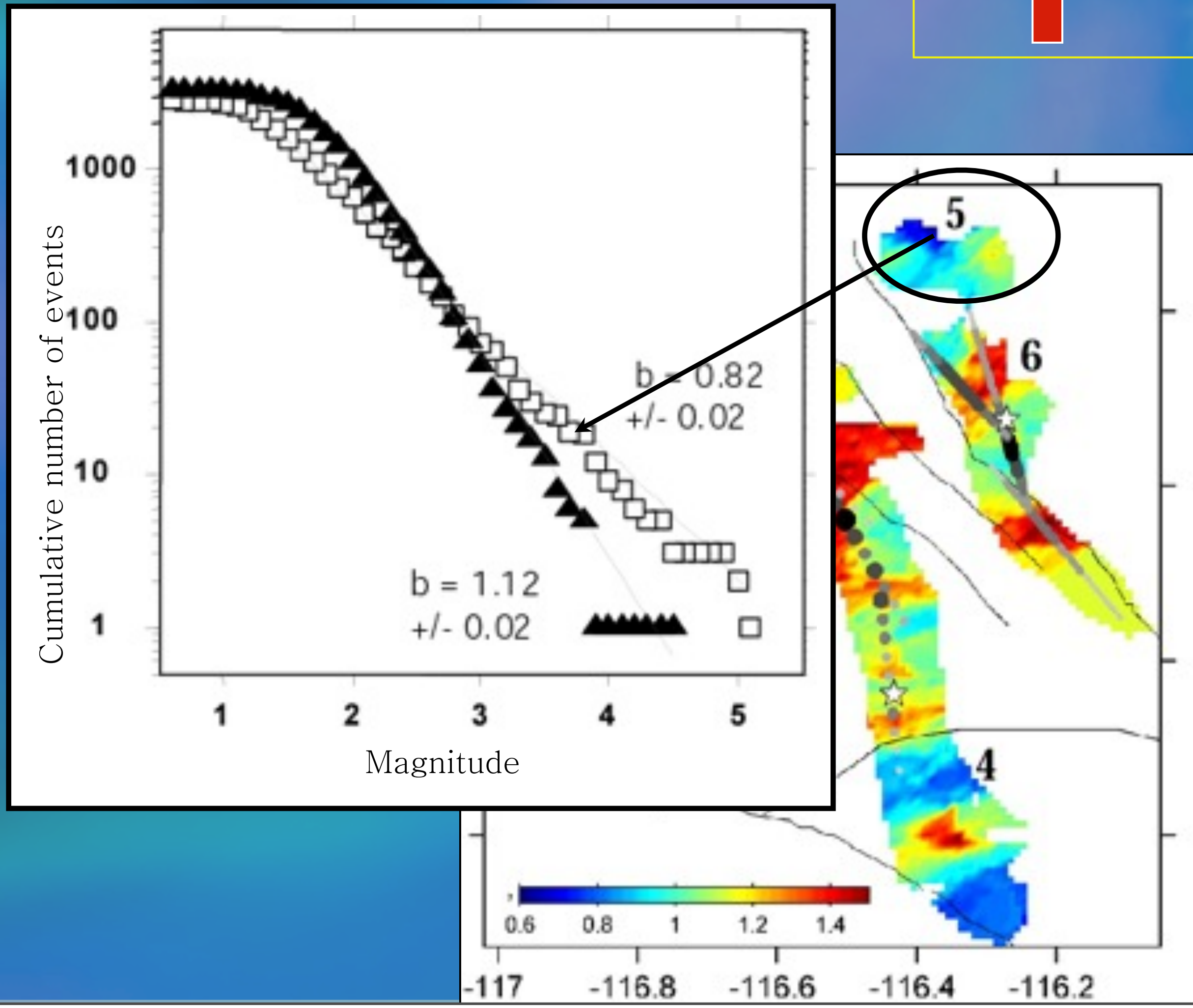
The Aftershock Models

model complexity

highest

Spatially Varying Model

Gutenberg-Richter and modified Omori law parameters are mapped at 5km spacing



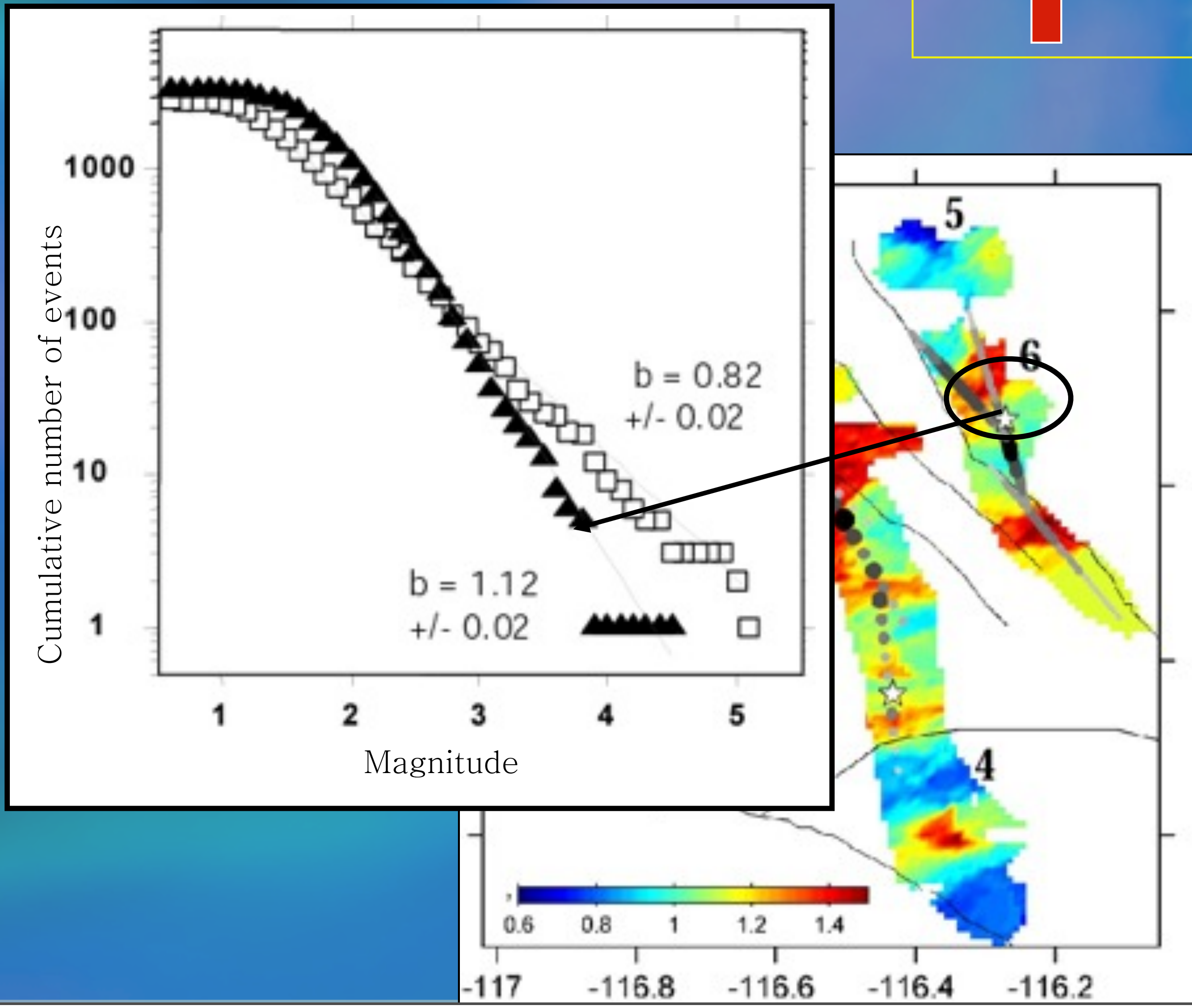
USGS

The Aftershock Models

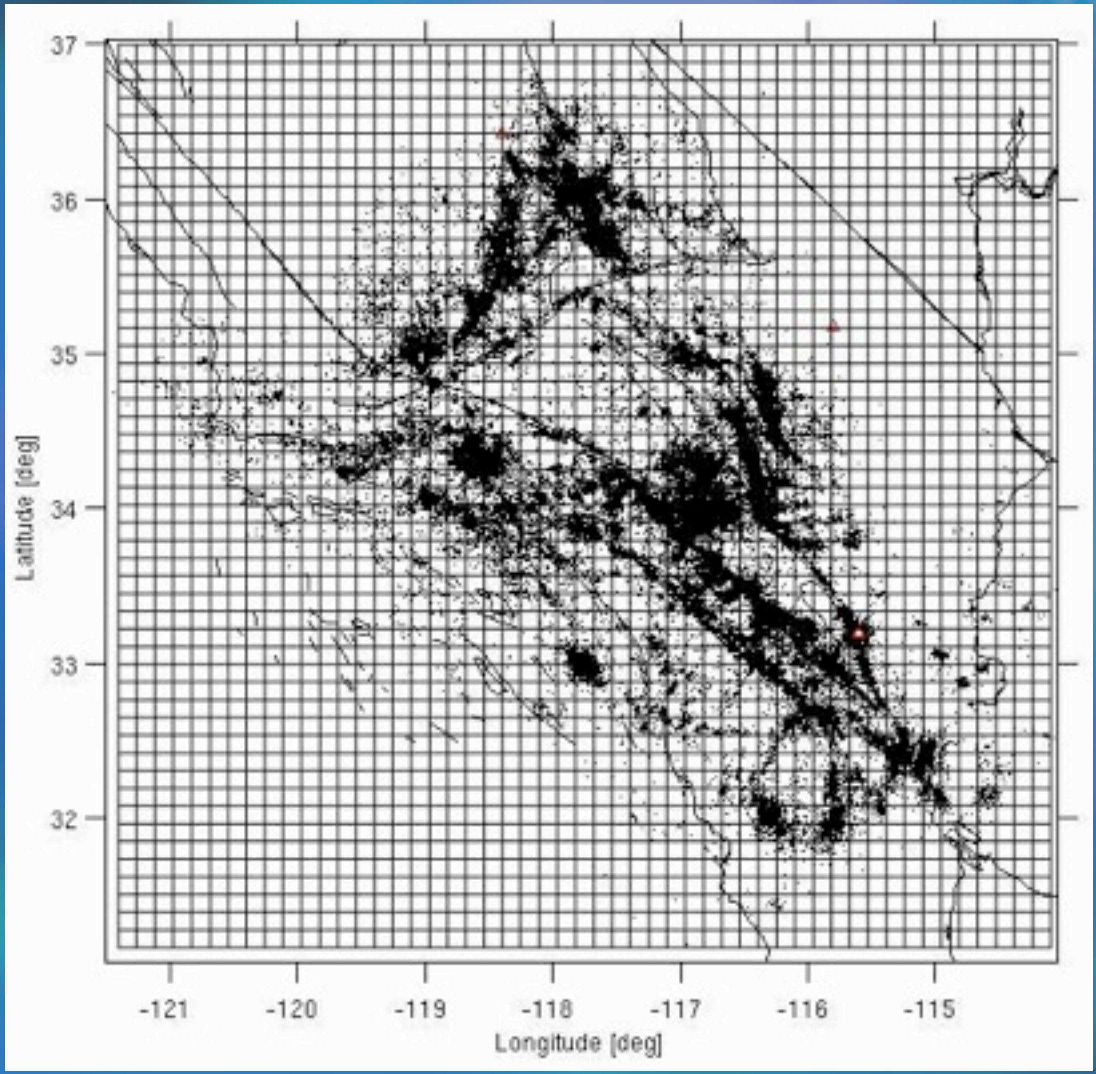
model complexity
highest

Spatially Varying Model

Gutenberg-Richter and modified Omori law parameters are mapped at 5km spacing



Our forecasts are consistent with actual earthquakes



USGS

Should we say the same thing after every event?

Agnew and Jones, JGR, 1991:

“But it ought to be possible to do better:

Should we say the same thing after every event?

Agnew and Jones, JGR, 1991:

“But it ought to be possible to do better:

the probability of a very large earthquake should be higher if the candidate foreshock were to occur near a fault capable of producing that mainshock than if it were located in an area where we believe such a mainshock to be unlikely.

Should we say the same thing after every event?

Agnew and Jones, JGR, 1991:

“But it ought to be possible to do better:

the probability of a very large earthquake should be higher if the candidate foreshock were to occur near a fault capable of producing that mainshock than if it were located in an area where we believe such a mainshock to be unlikely.

Moreover, the chance of a candidate earthquake actually being a foreshock should be higher if the rate of background (nonforeshock) activity were low.”

USGS

After discarding aftershocks,
earthquakes are divided into three categories for statistical purposes:

Mainshocks: which we want to forecast
Foreshocks: which are always followed by mainshocks
Background Events: which are never followed by mainshocks

USGS

After discarding aftershocks,
earthquakes are divided into three categories for statistical purposes:

Mainshocks: which we want to forecast
Foreshocks: which are always followed by mainshocks
Background Events: which are never followed by mainshocks

When a moderate event occurs we can't tell if it is
a **foreshock** or a **background** event.

USGS

After discarding aftershocks,
earthquakes are divided into three categories for statistical purposes:

Mainshocks: which we want to forecast
Foreshocks: which are always followed by mainshocks
Background Events: which are never followed by mainshocks

When a moderate event occurs we can't tell if it is a **foreshock** or a **background** event.

We calculate the probability that it is a **foreshock** by

$$PF = \frac{\text{Rate of }\textbf{Foreshocks}}{\text{Rate of }\textbf{Foreshocks} + \text{Rate of }\textbf{Background Events}}$$

USGS

After discarding aftershocks,
earthquakes are divided into three categories for statistical purposes:

Mainshocks: which we want to forecast
Foreshocks: which are always followed by mainshocks
Background Events: which are never followed by mainshocks

When a moderate event occurs we can't tell if it is
a **foreshock** or a **background** event.

We calculate the probability that it is a **foreshock** by

$$PF = \frac{\text{Rate of } \textbf{Foreshocks}}{\text{Rate of } \textbf{Foreshocks} + \text{Rate of } \textbf{Background Events}}$$

Rate of **Foreshocks** =
Rate of **Mainshocks** * Probability of **Foreshocks** Before **Mainshocks**

USGS

Seemingly good behavior

$$PF = \frac{\text{Rate of Mainshocks * Prob of Foreshocks | Mainshock}}{\text{(Rate of Mainshocks * Prob of Foreshocks | Mainshock + Rate of Background Events)}}$$

The resulting probability goes

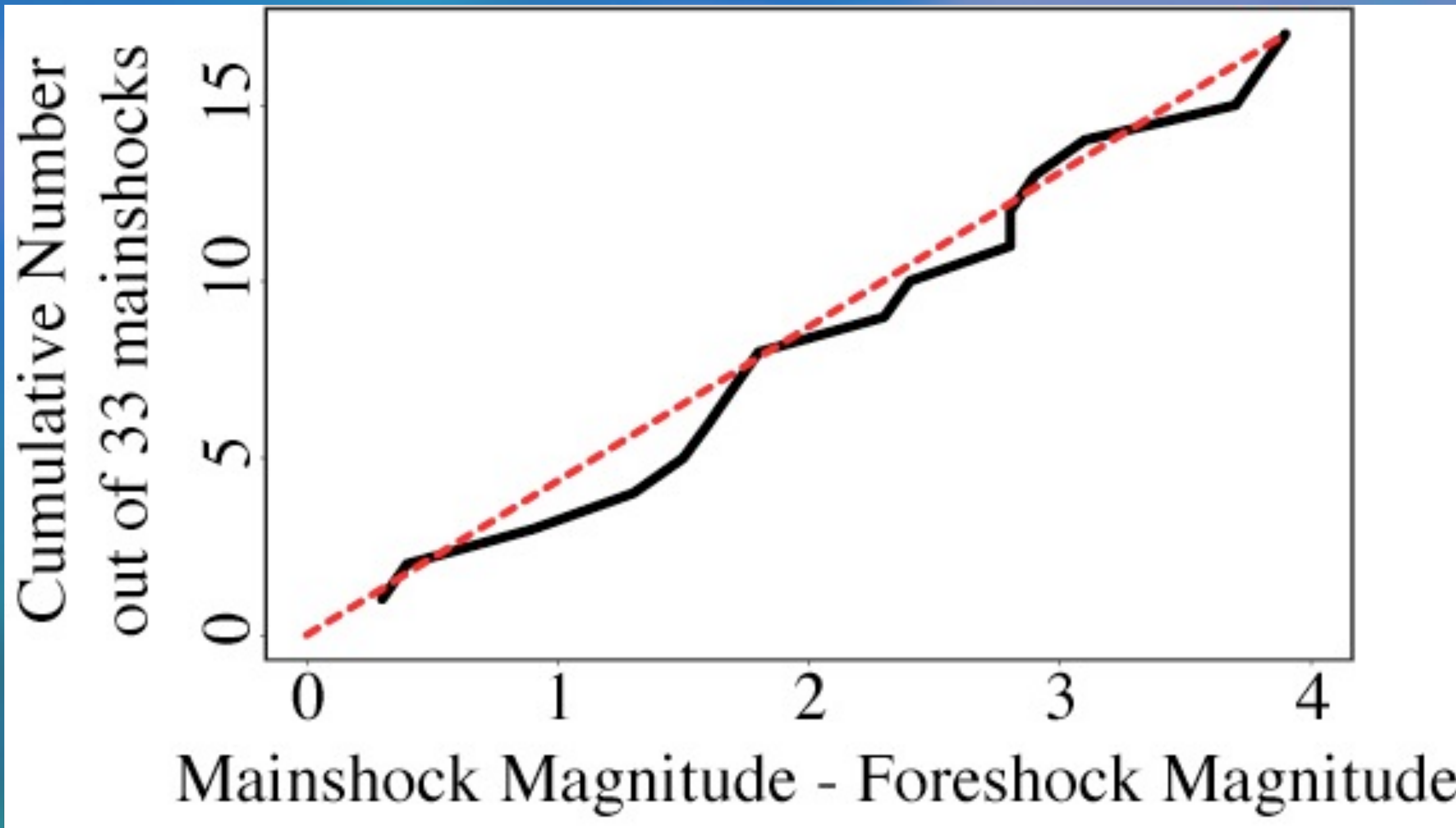
- up with higher mainshock rate and
- down with higher background rate.

USGS

The rate at which mainshocks are preceded by foreshocks:

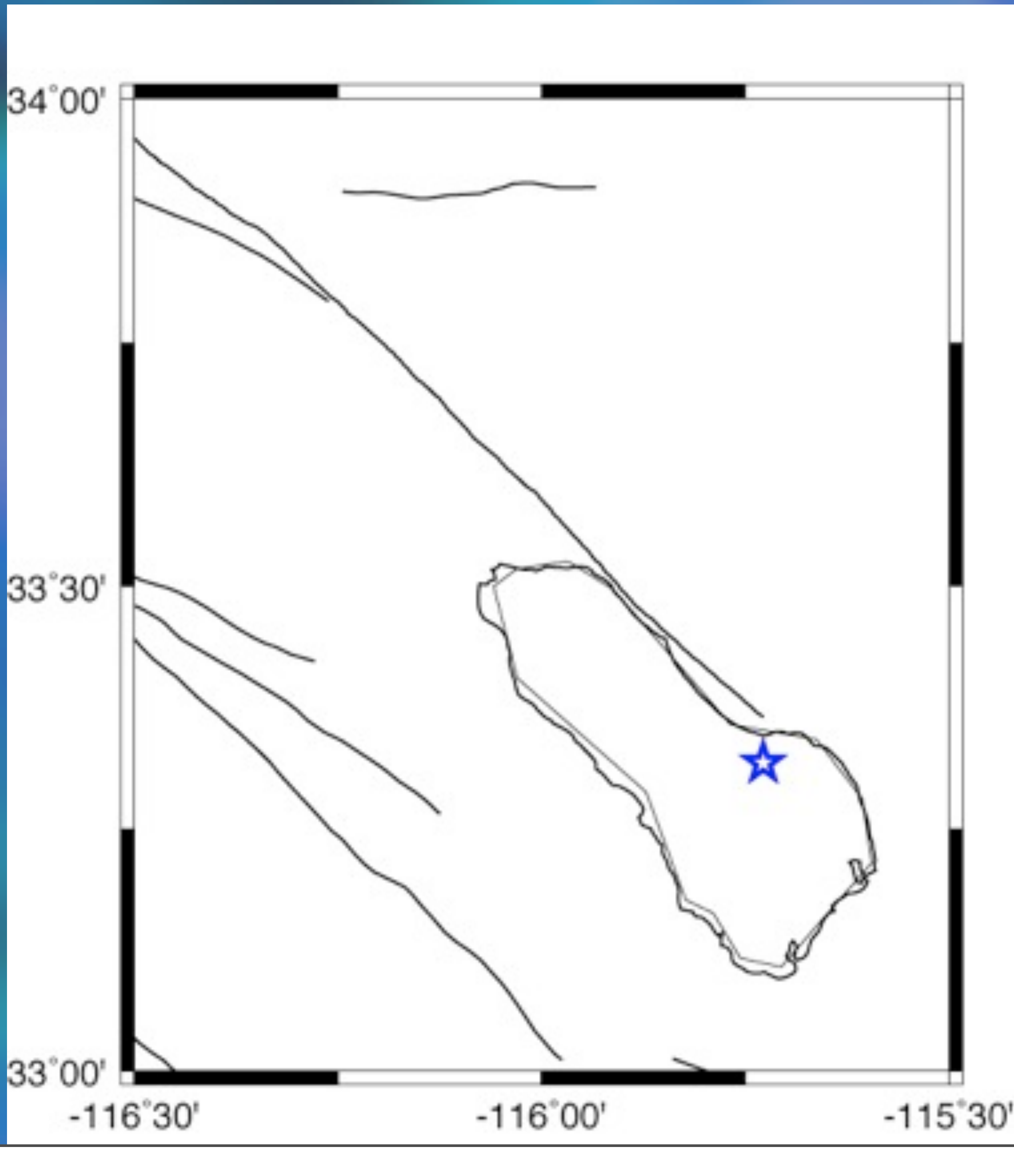
50% of San Andreas stress province M≥5 mainshocks have an M≥2 foreshock within 3 days, and 10 km.

(Jones, 1984; Michael & Jones, 1998).



M4.8 Event At Bombay Beach On March 24, 2009

Could It Be A Foreshock To A Larger Earthquake In The Next 3 Days?

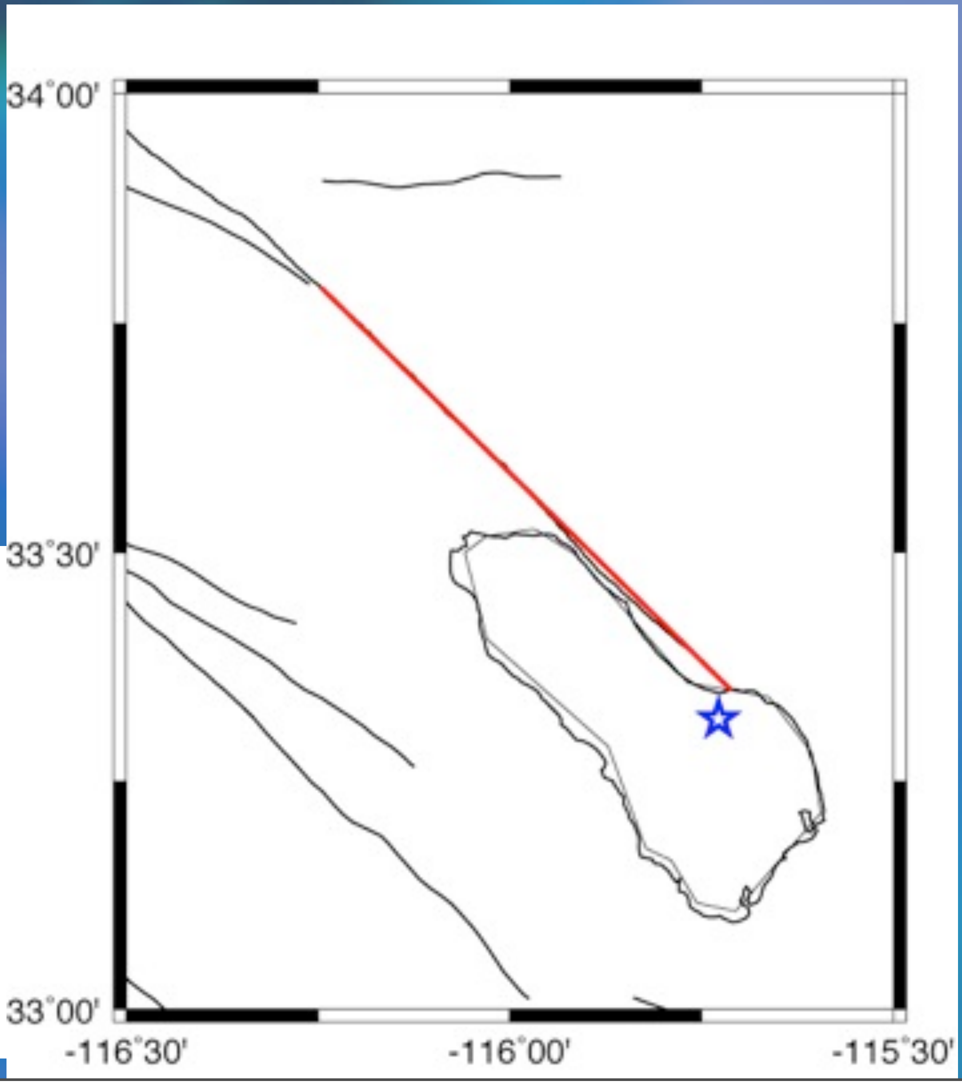


USGS

M4.8 Event At Bombay Beach On March 24, 2009

Could It Be A Foreshock To A Larger Earthquake In The Next 3 Days?

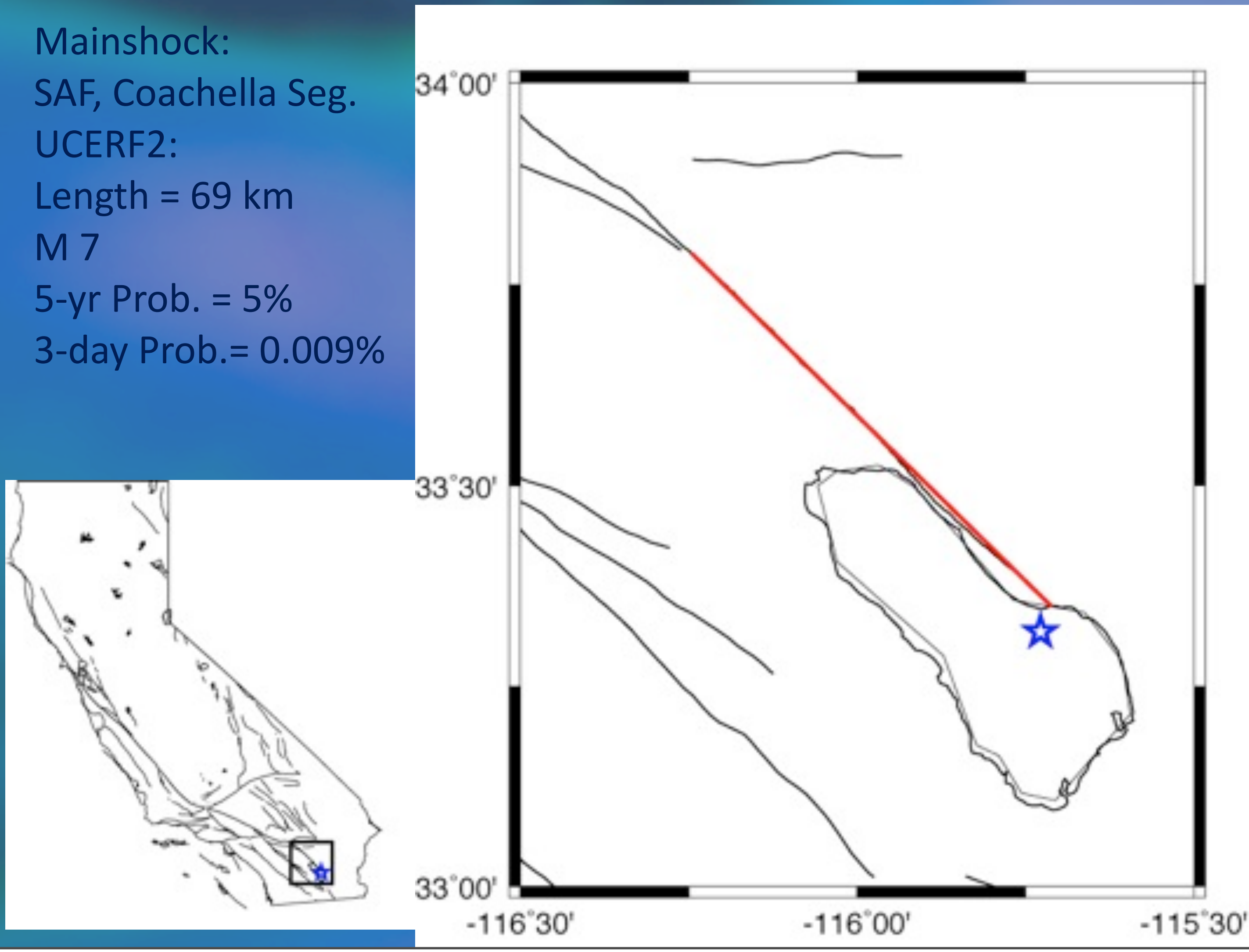
Mainshock:
SAF, Coachella Seg.
UCERF2:
Length = 69 km
M 7
5-yr Prob. = 5%
3-day Prob.= 0.009%



M4.8 Event At Bombay Beach On March 24, 2009

Could It Be A Foreshock To A Larger Earthquake In The Next 3 Days?

Mainshock:
SAF, Coachella Seg.
UCERF2:
Length = 69 km
M 7
5-yr Prob. = 5%
3-day Prob.= 0.009%

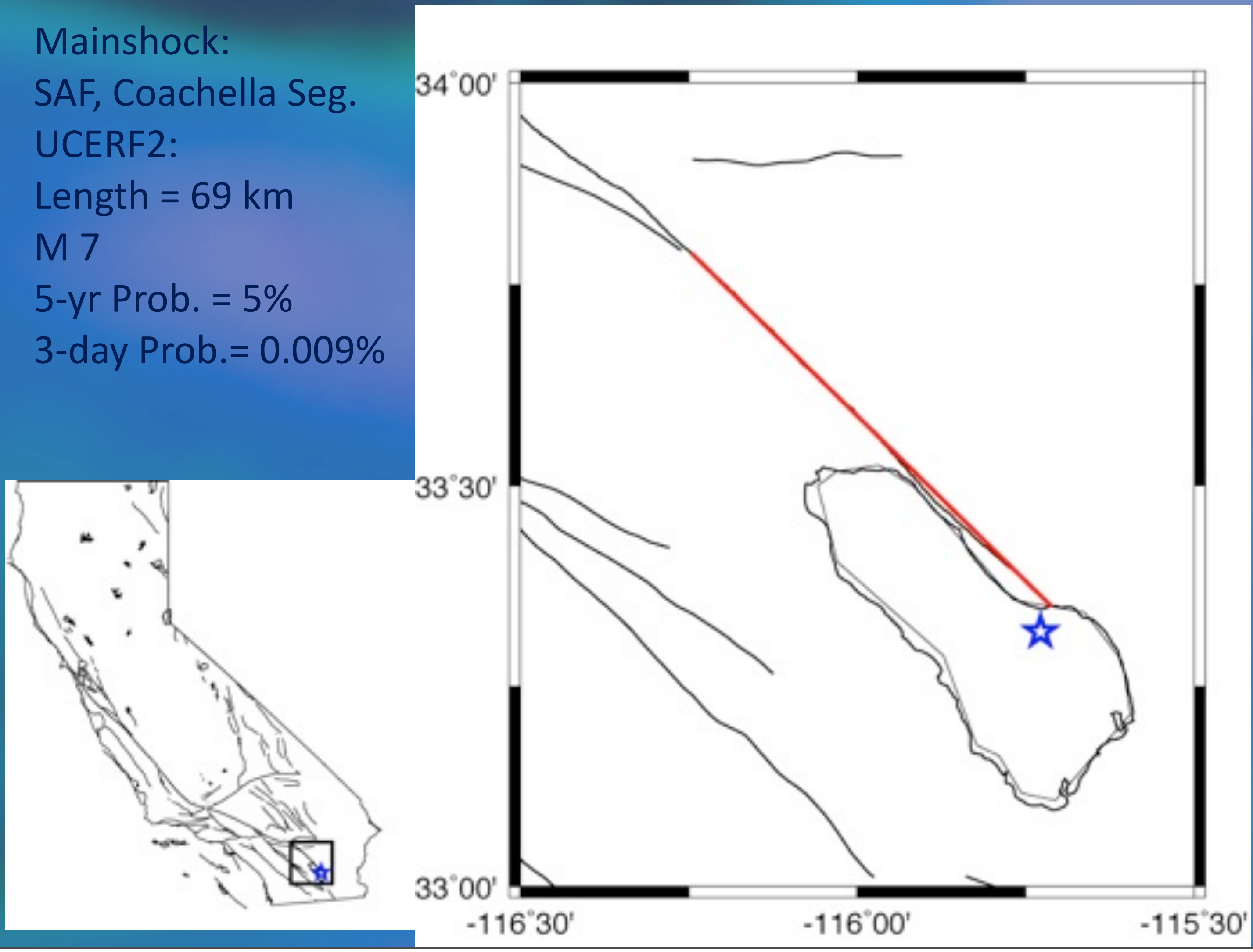


Reasenberg & Jones, 1989:
Probability of M4.8 being followed by an M≥7 event
PF = 0.05%

M4.8 Event At Bombay Beach On March 24, 2009

Could It Be A Foreshock To A Larger Earthquake In The Next 3 Days?

Mainshock:
SAF, Coachella Seg.
UCERF2:
Length = 69 km
M 7
5-yr Prob. = 5%
3-day Prob.= 0.009%

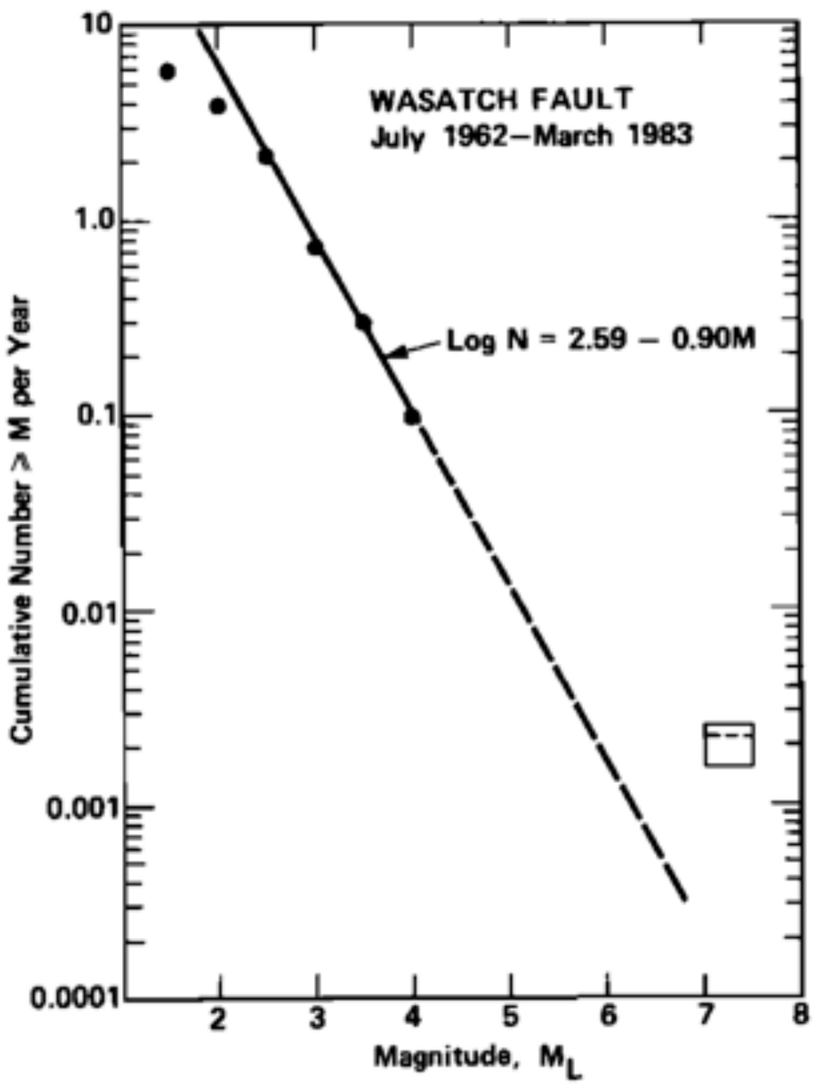


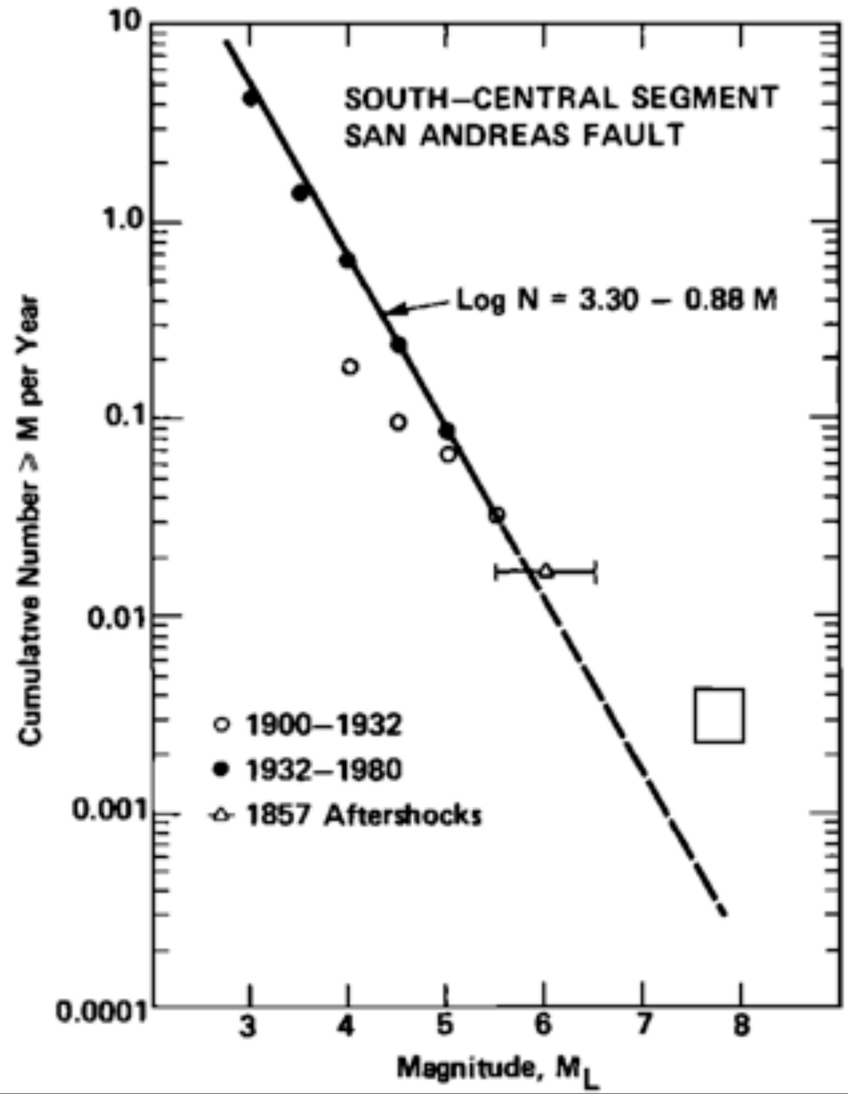
Reasenberg & Jones, 1989:
Probability of M4.8 being followed by an M≥7 event
PF = 0.05%

Agnew and Jones, 1991:
PF = 4%

Fault Behavior and Characteristic Earthquakes: Examples From the Wasatch and San Andreas Fault Zones

David P. Schwartz and Kevin J. Coppersmith





Gutenberg-Richter + Characteristic Earthquake Relationships – Michael 2010

$$N(m \geq M) = 10^{a-bM} + DH(M_c - M)$$

- D: Rate of Characteristic Earthquake
- H: Heaviside Function
- M_c: Magnitude of Characteristic Earthquake

Gutenberg-Richter + Characteristic Earthquake Relationships – Michael 2010

$$N(m \geq M) = 10^{a-bM} + DH(M_c - M)$$

- D: Rate of Characteristic Earthquake
- H: Heaviside Function
- M_c: Magnitude of Characteristic Earthquake

$$P(m \geq M \mid E) = \frac{10^{a-bM} + DH(M_c - M)}{10^{a-bM_{\min}} + D}$$

USGS

Approximate the Probability of an $M \geq M_c$ event following an $M=M_i$ event

assuming:

- rate of $M=0$ events 10^a >> D the rate of M_c events
- rate of M_i events 10^{a-bMi} >> D the rate of M_c events
- D >> 10^{a-bMc} the Gutenberg-Richter rate of $M \geq M_c$
- small probabilities so $P \approx \lambda$

USGS

Characteristic Reasenberg & Jones Approximate Model

$$P(M \geq M_c) \approx kI_t \frac{D}{10^{a-bM_i}}$$

Agnew & Jones Approximate Model

$$P(C \mid F \cup B) \approx \frac{2N_m}{(10^{b\mu} - 10^{-b\mu})} \frac{D}{10^{a-bM_i}}$$

Both models are

- proportional to the rate of characteristic events
- inversely proportional to the rate of initiating events

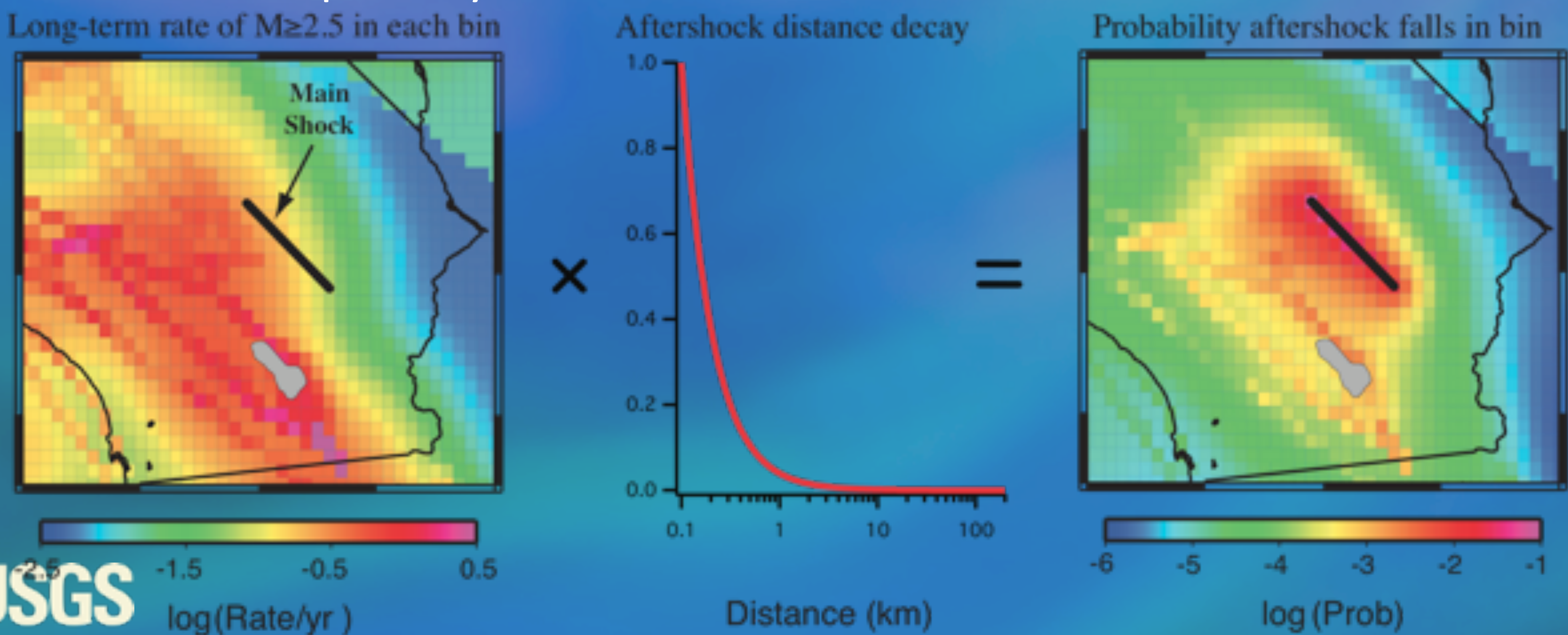
USGS

ETAS-based simulations for UCERF3?

a) For given start time and forecast duration, collect all observed M≥2.5 events, plus randomly sample spontaneous (non-triggered) events from the model.

b) For each main shock in (a), randomly sample times of occurrence of ***Primary*** aftershocks from modified Omori law.

c) Use the long-term nucleation rate of M>2.5 events throughout the region, plus a spatial decay of R^{-n} from the main shock surface, to sample a grid-cell location for each primary aftershock.

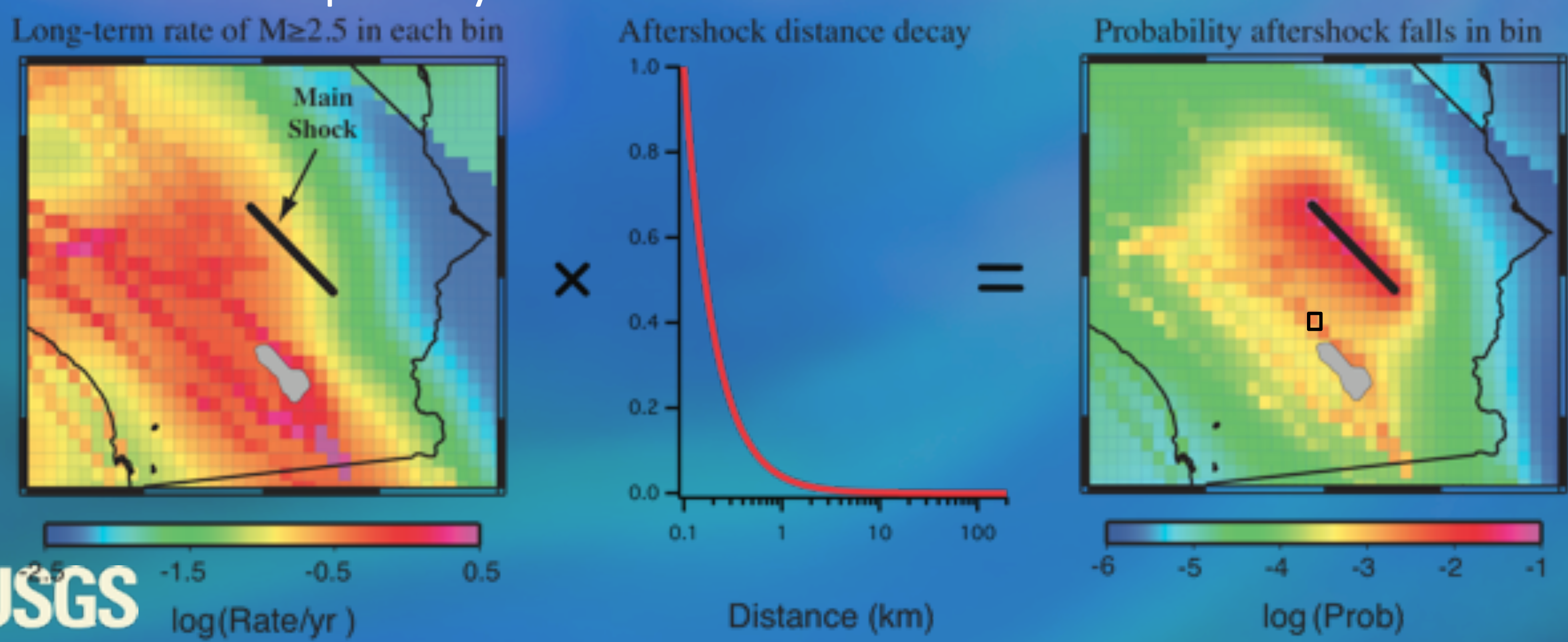


ETAS-based simulations for UCERF3?

a) For given start time and forecast duration, collect all observed M≥2.5 events, plus randomly sample spontaneous (non-triggered) events from the model.

b) For each main shock in (a), randomly sample times of occurrence of ***Primary*** aftershocks from modified Omori law.

c) Use the long-term nucleation rate of M>2.5 events throughout the region, plus a spatial decay of R^{-n} from the main shock surface, to sample a grid-cell location for each primary aftershock.



USGS