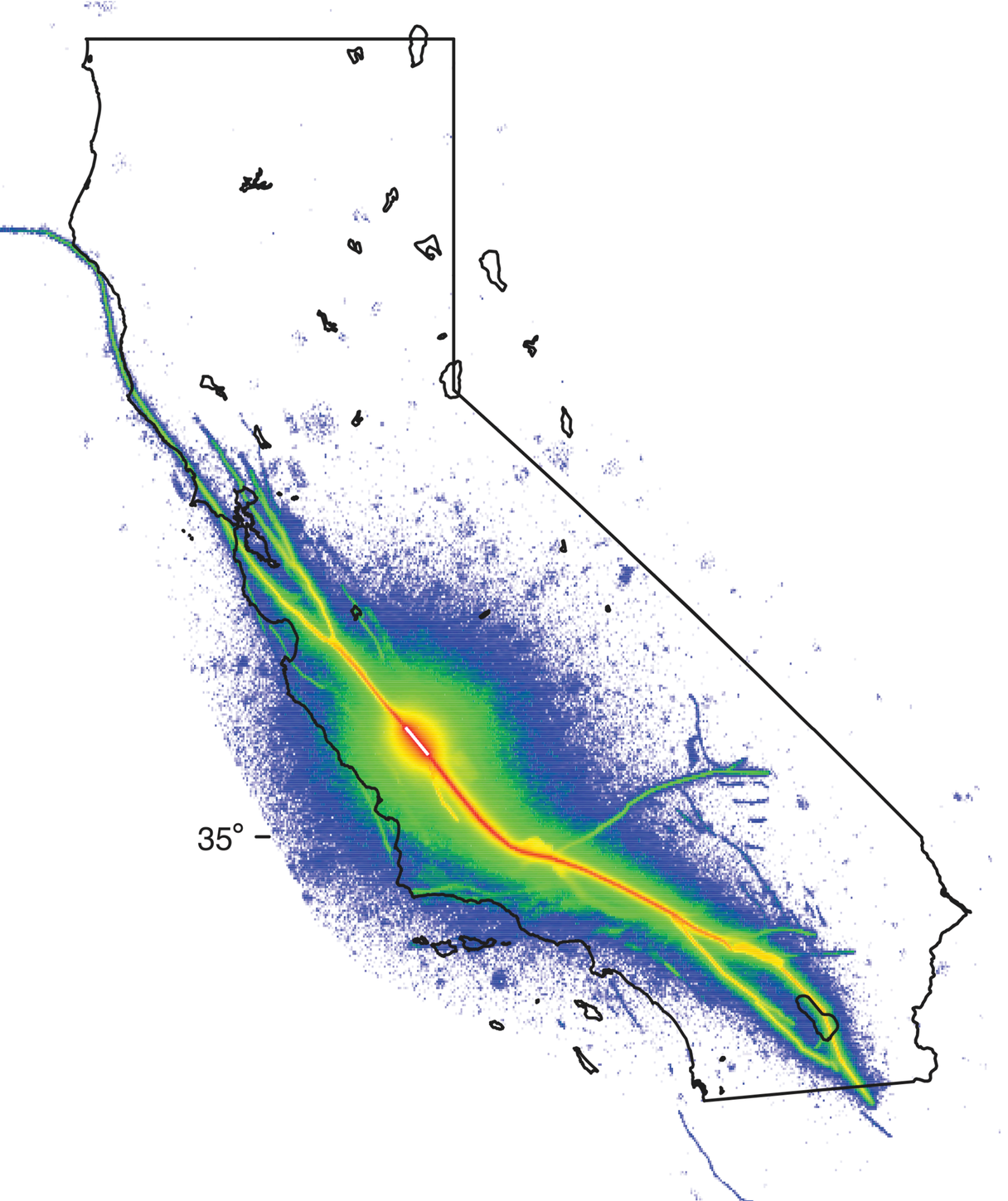
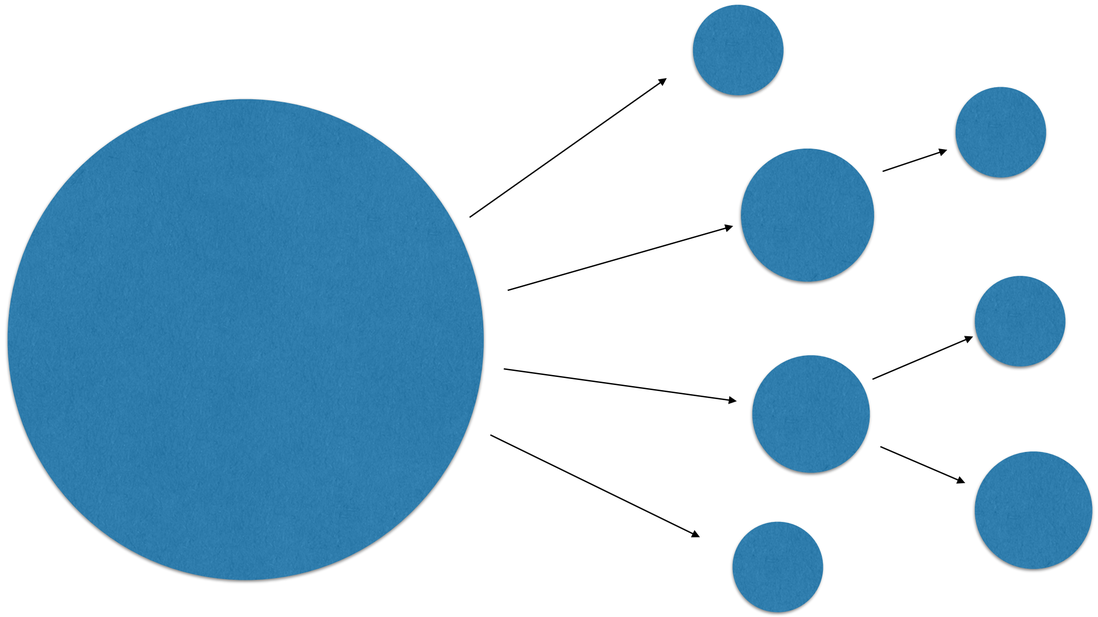


Aftershock and Foreshock Probabilities in California

Morgan Page, USGS

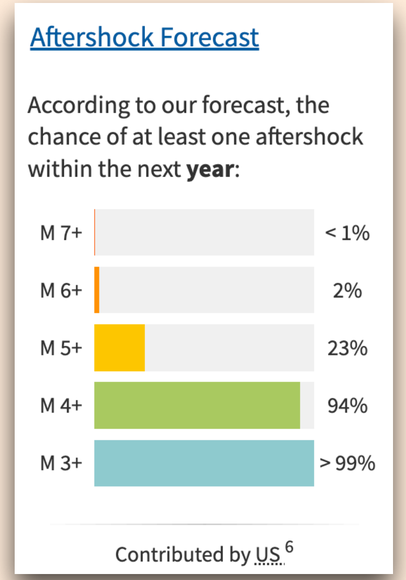


USGS Domestic Aftershock Forecasts

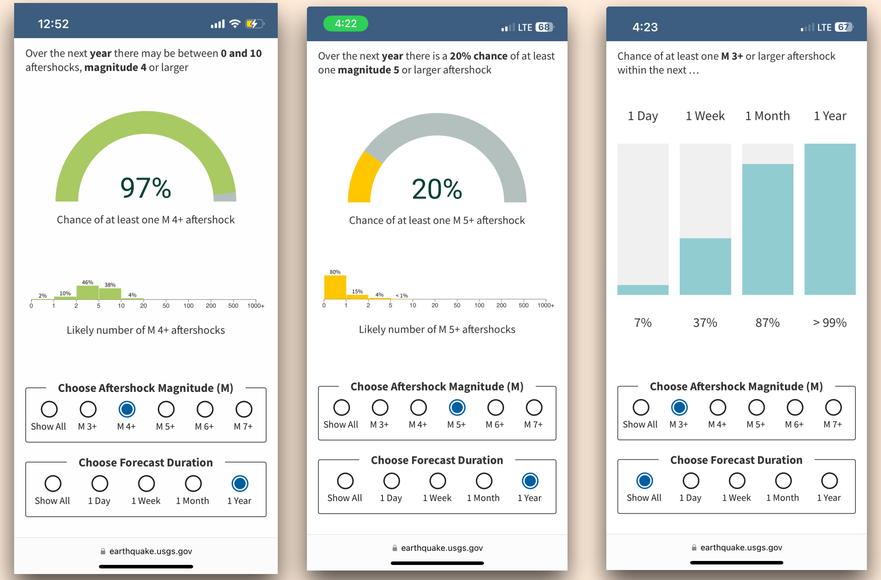
Temporal forecasts produced automatically for M4+ mainshocks in the Continental US

Initial forecast ~20 min after mainshock, then regularly updated

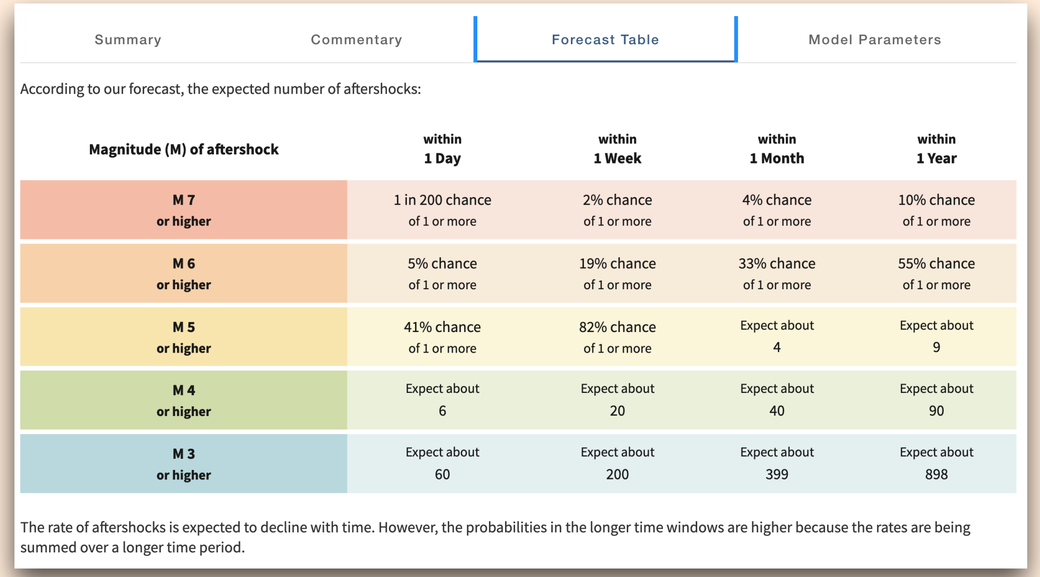
Forecast "pin" on USGS event page



Interactive graphics showing aftershock probabilities and number uncertainty



Forecast table



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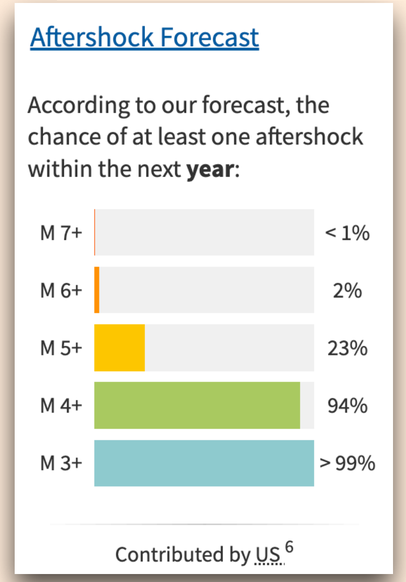

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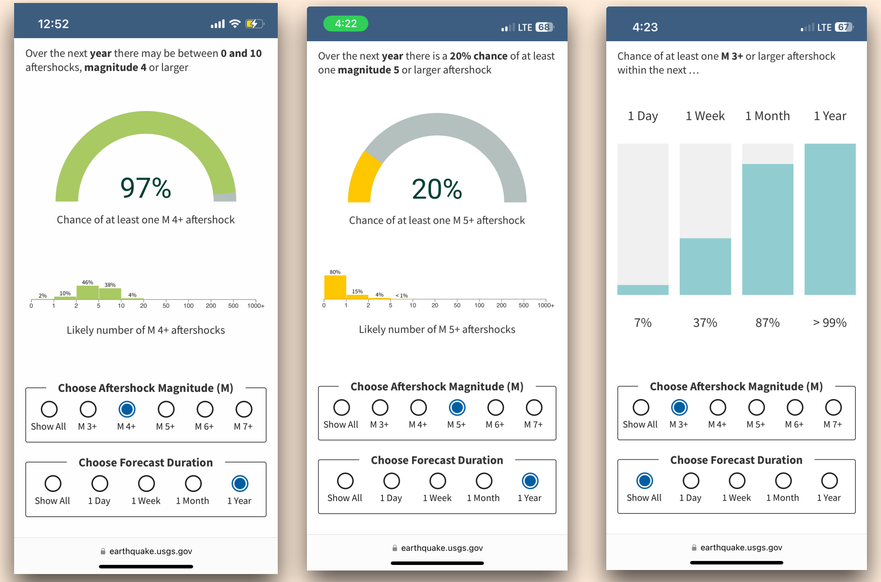
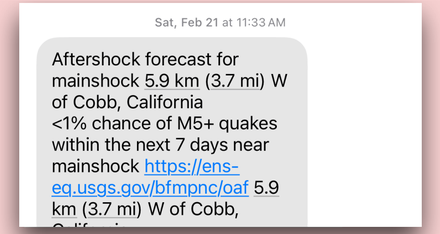
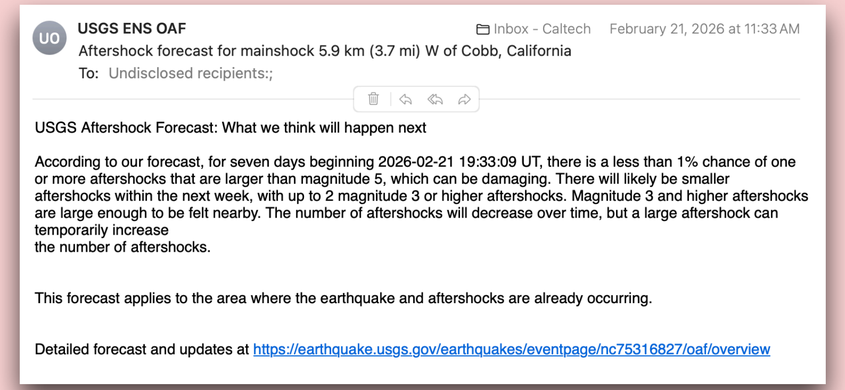


Earthquake Notification Service (ENS) now supports aftershock forecast messages

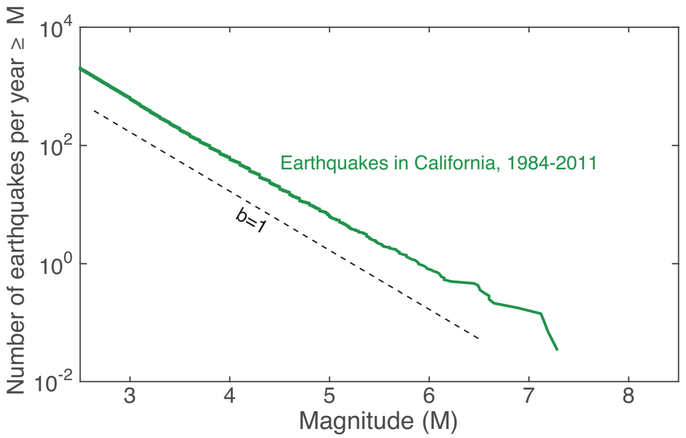


Sign up for texts or emails here:
https://earthquake.usgs.gov/ens/



The Basics of Earthquake Forecasting

The Statistical Seismologist's Approach

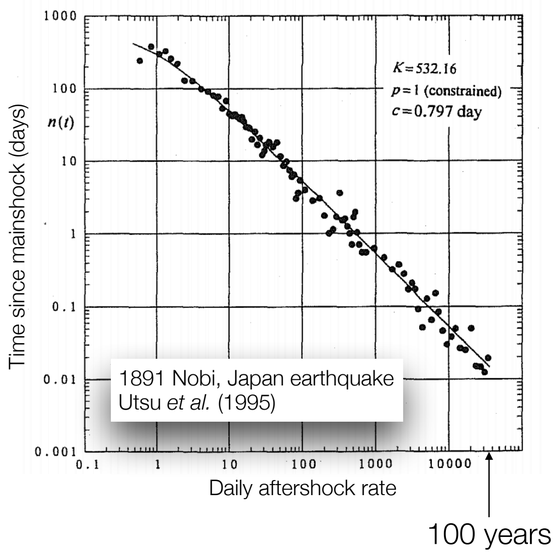


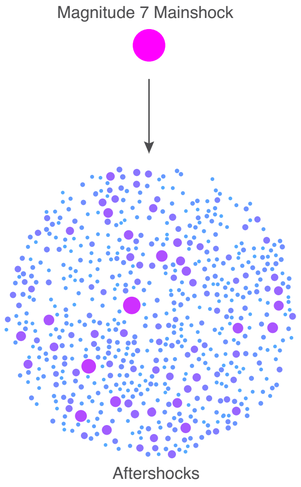
Gutenberg-Richter Magnitude Scaling

$$N(M) \propto 10^{(a-bM)}$$

Omori Decay of Aftershock Rate

$$\lambda(t) = (t+c)^{-p}$$



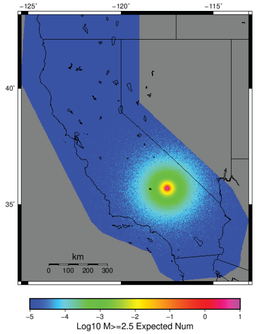


Big earthquakes trigger more aftershocks

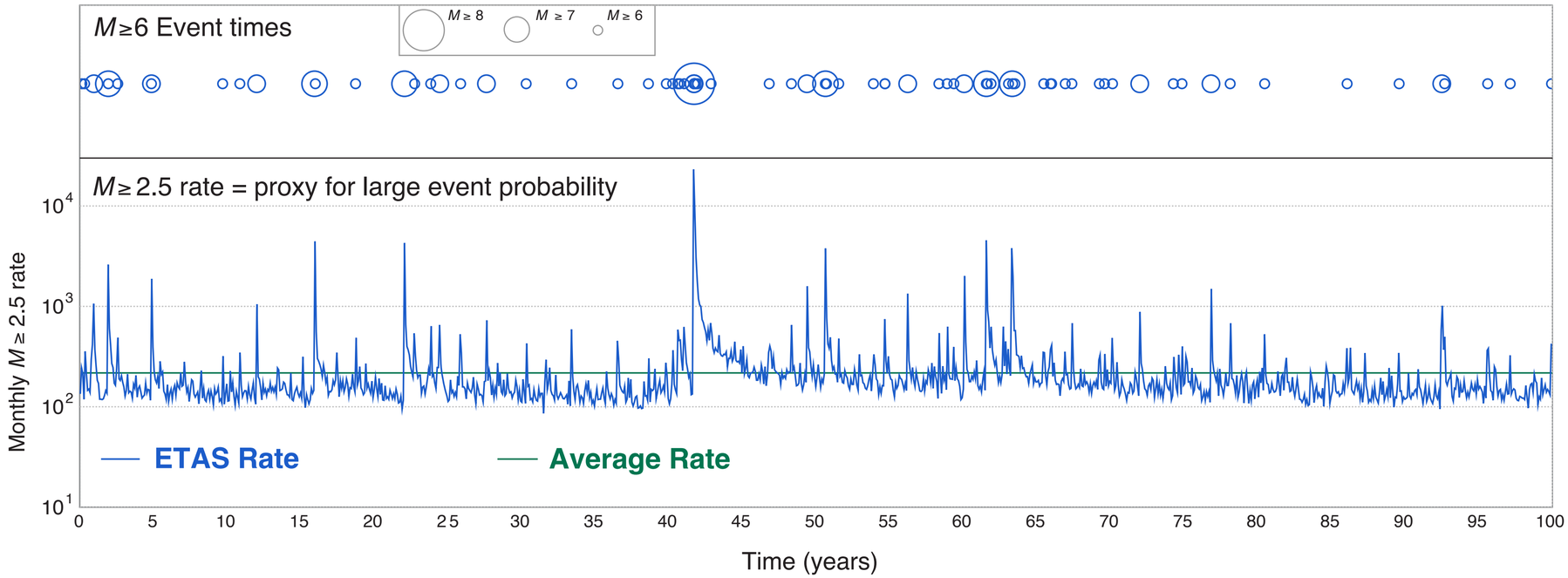
$$\lambda \propto 10^{b(M)}$$

Aftershock rates decay with distance from the mainshock

$$p(r) \propto N(r)\left(r^2 + d^2\right)^{-\gamma/2}$$



What do changing earthquake probabilities look like in time?

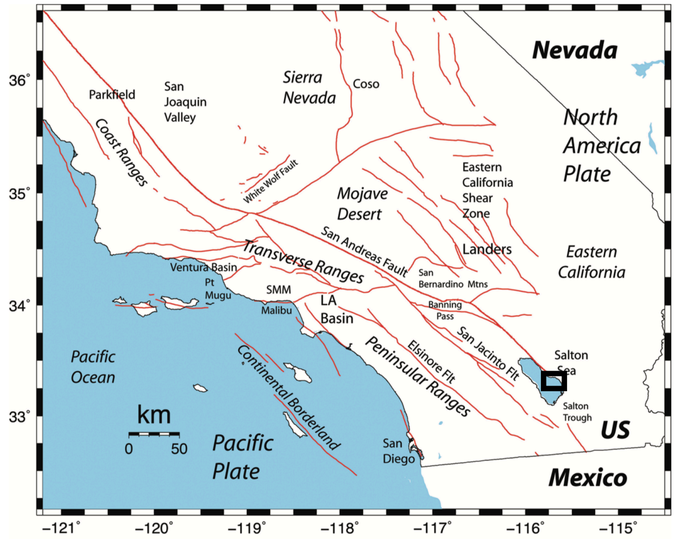


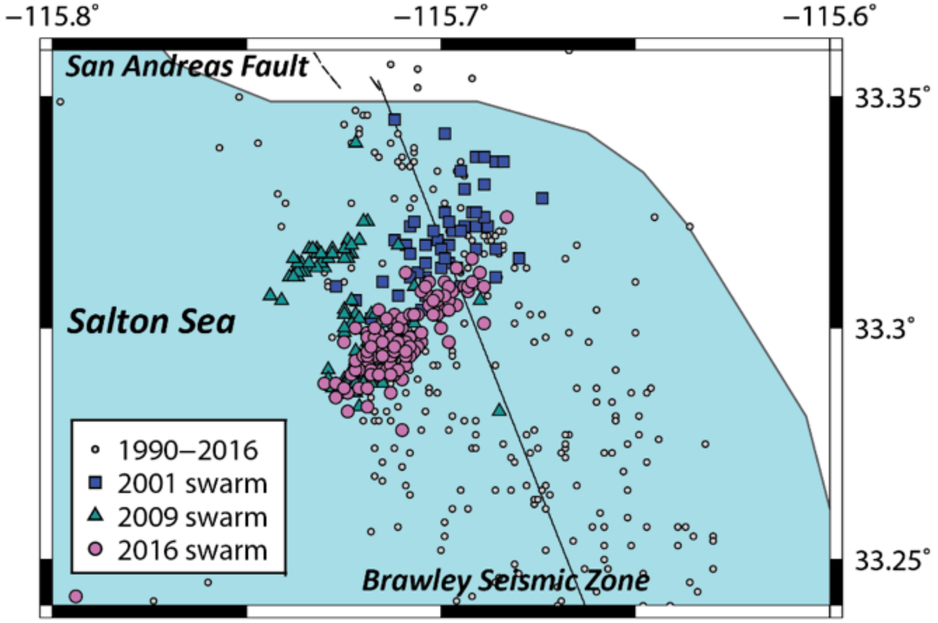
Field and Milner (2018)

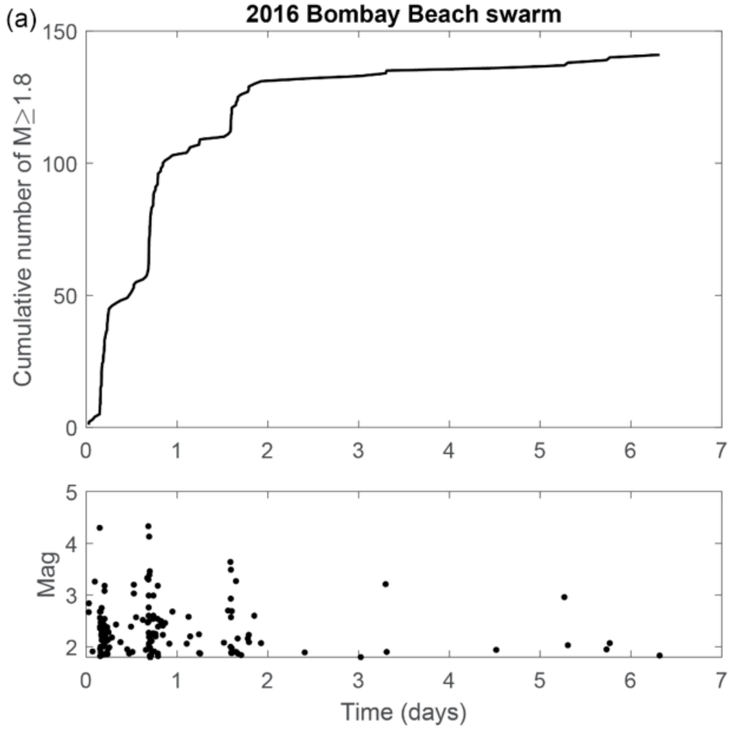
Foreshocks do not appear to be (strongly) predictive of future earthquake size, but foreshock/aftershock statistics predict orders of magnitude changes in the earthquake rate.

Case Study #1: 2016 Bombay Beach Swarm

The 2016 Bombay Beach Swarm

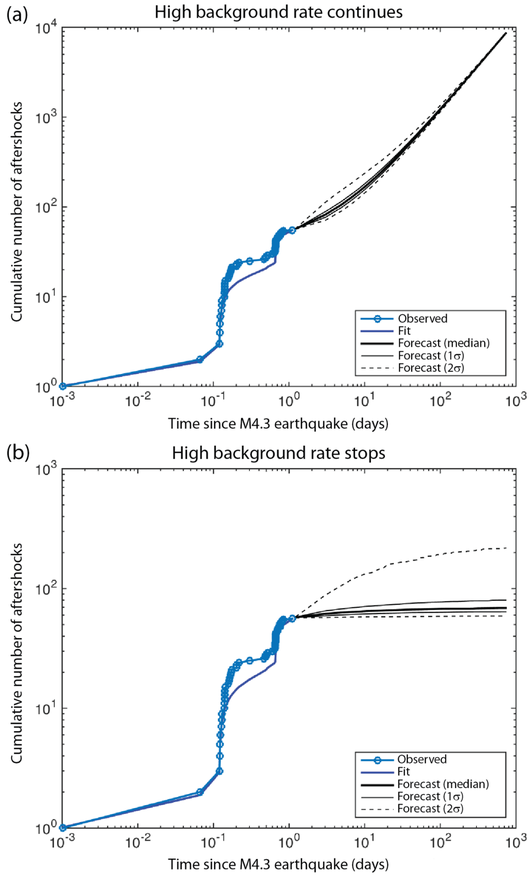






McBride *et al.* (2019)

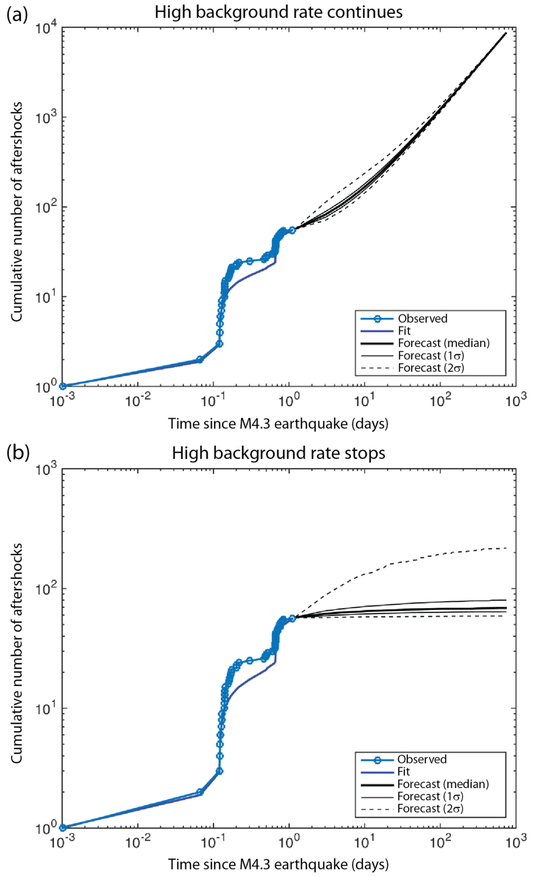
Major forecast uncertainties



How long will increased rate of earthquakes last?

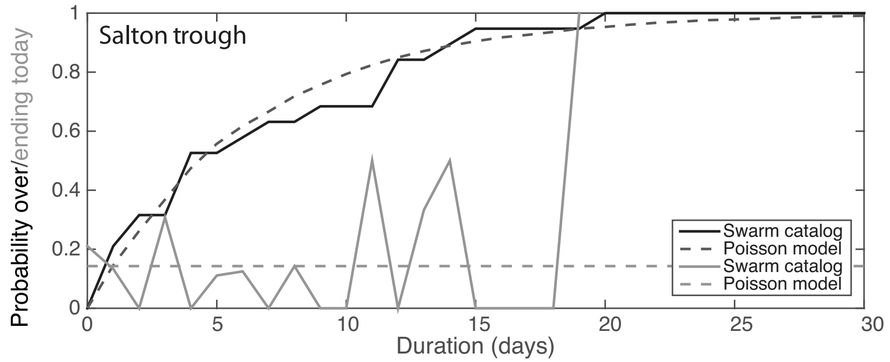
Llenos and van der Elst, 2019

Major forecast uncertainties



How long will increased rate of earthquakes last?

Swarm duration in Salton trough are well-fit by a Poisson model

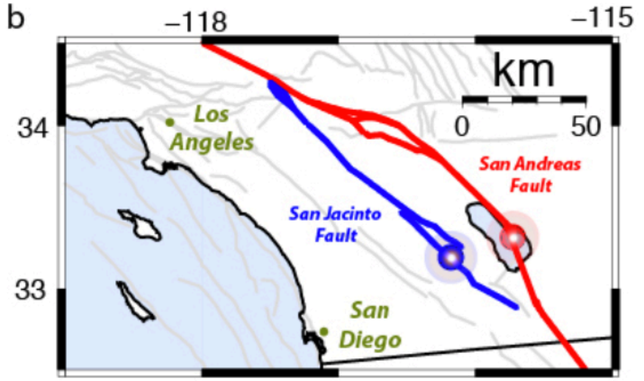


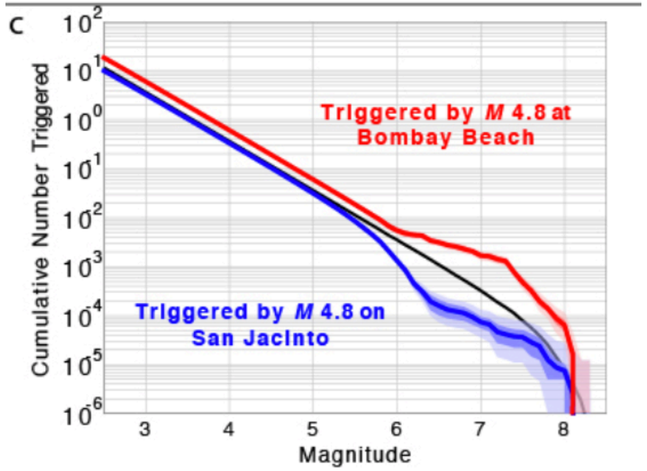
15% chance of terminating each day

Average length of 7 days

Llenos and van der Elst, 2019

Major forecast uncertainties

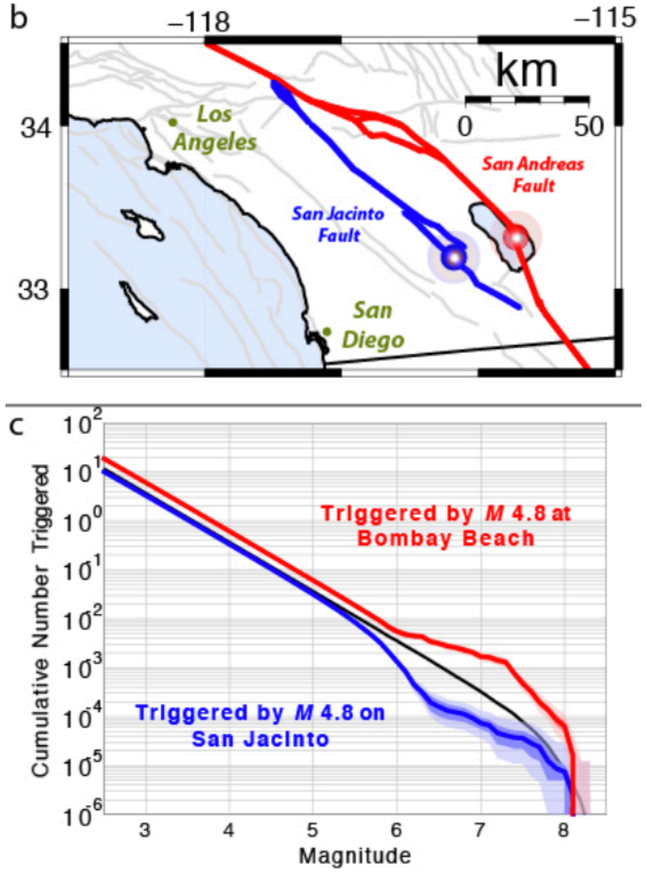




Field *et al.*, 2017

What is the appropriate magnitude distribution for the Southern San Andreas?

Major forecast uncertainties



Field *et al.*, 2017

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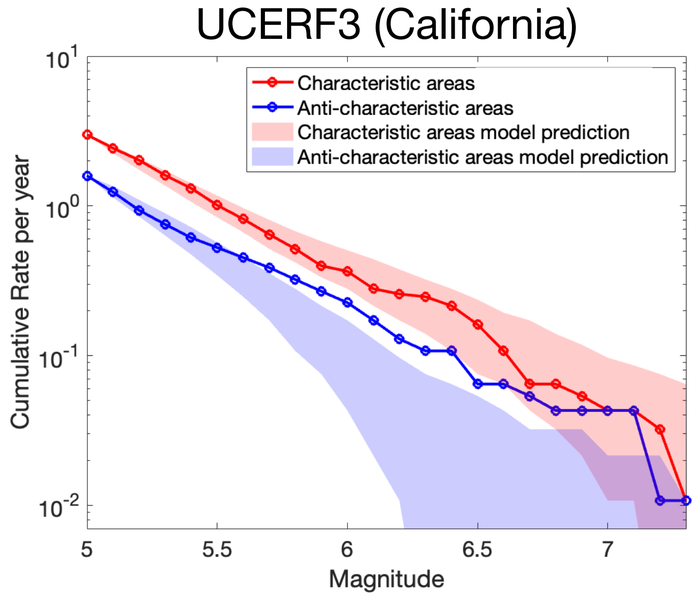
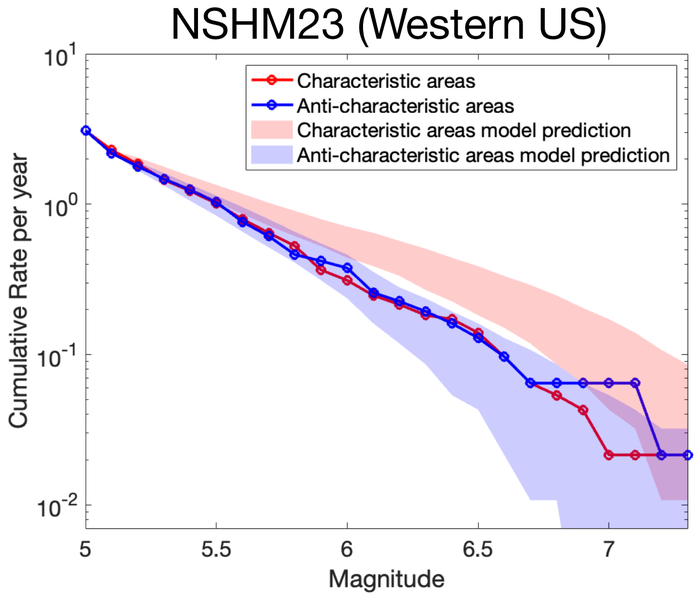
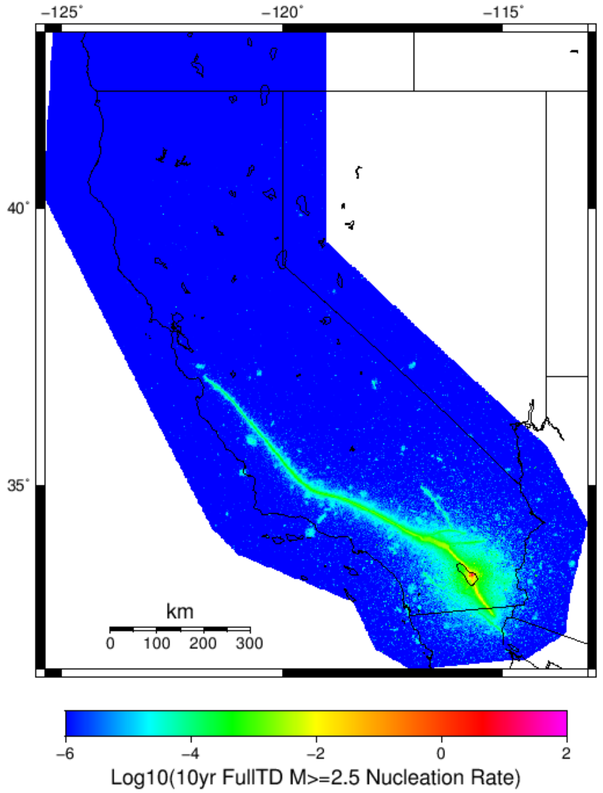


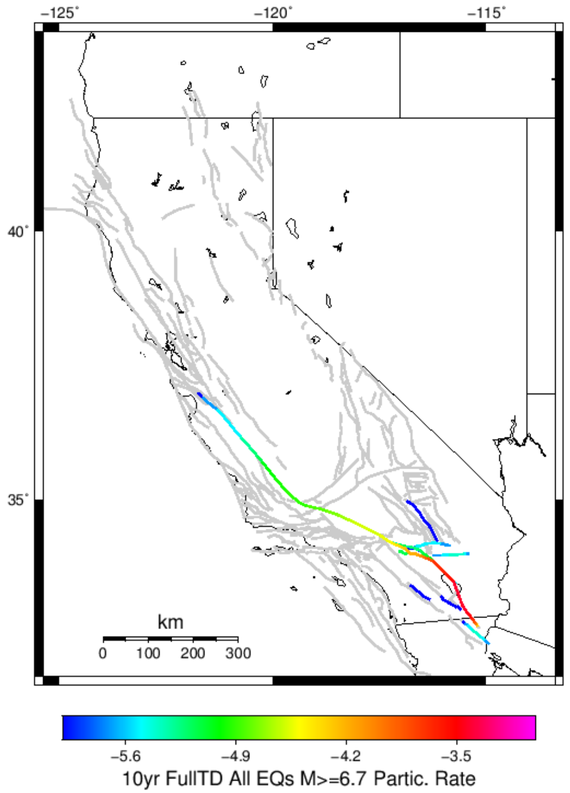


Recent USGS hazard models have different magnitude distributions on faults vs. “background” areas, but there are discrepancies between these models and observations

UCERF3 Forecast following Bombay Swarm

What faults are likely to be triggered?



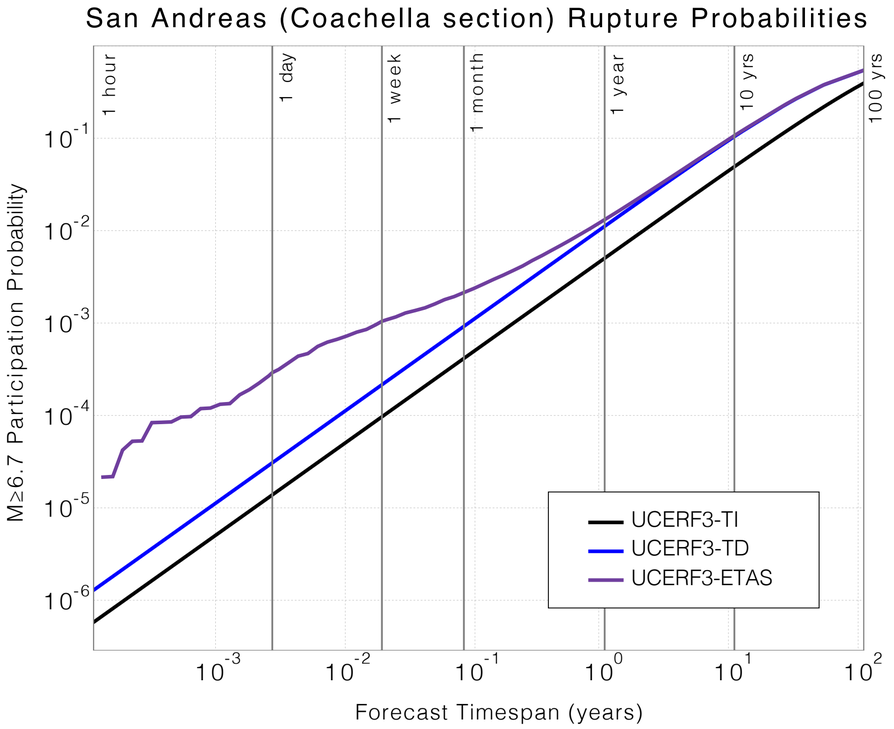


Aftershock forecast following Bombay Beach swarm

Average of 100,000 simulations

UCERF3 Forecast following Bombay Swarm

How are probabilities elevated compared to long-term rate?



During seismic swarms, the chance of a large earthquake can change by orders of magnitude

These elevated probabilities decay quickly

Proximity to major faults is a concern
(but it is not proven that proximity to major faults elevates foreshock probability)

Major forecast uncertainties

lead to factor of 30 difference in hazard estimate

U.S. Geological Survey (USGS)
September 27, 2016 ·

Earthquake Swarm Activity Near Bombay Beach

An earthquake swarm near Bombay Beach, California, started on 2016 Sept. 26 at 4:03 am (PDT) in the Brawley Seismic Zone, which lies near the southern terminus of the San Andreas Fault.

The swarm includes 142 events so far (as of 26 Sep 2016, 11:31PM PDT) in the magnitude range M1.4 to M4.3. Relocations of these events show that they are occurring in the depth range 4 to 9 km.

The earthquakes are occurring near a set of north-northeast trending cross-faults in the Salton Sea. The cross-faults are part of a fault network that connect the southernmost end of the San Andreas fault with the Imperial fault. Some of the cross-faults are oriented such that they add stress to the San Andreas fault and the San Jacinto fault system when they rupture in small earthquakes like those in the ongoing swarm.

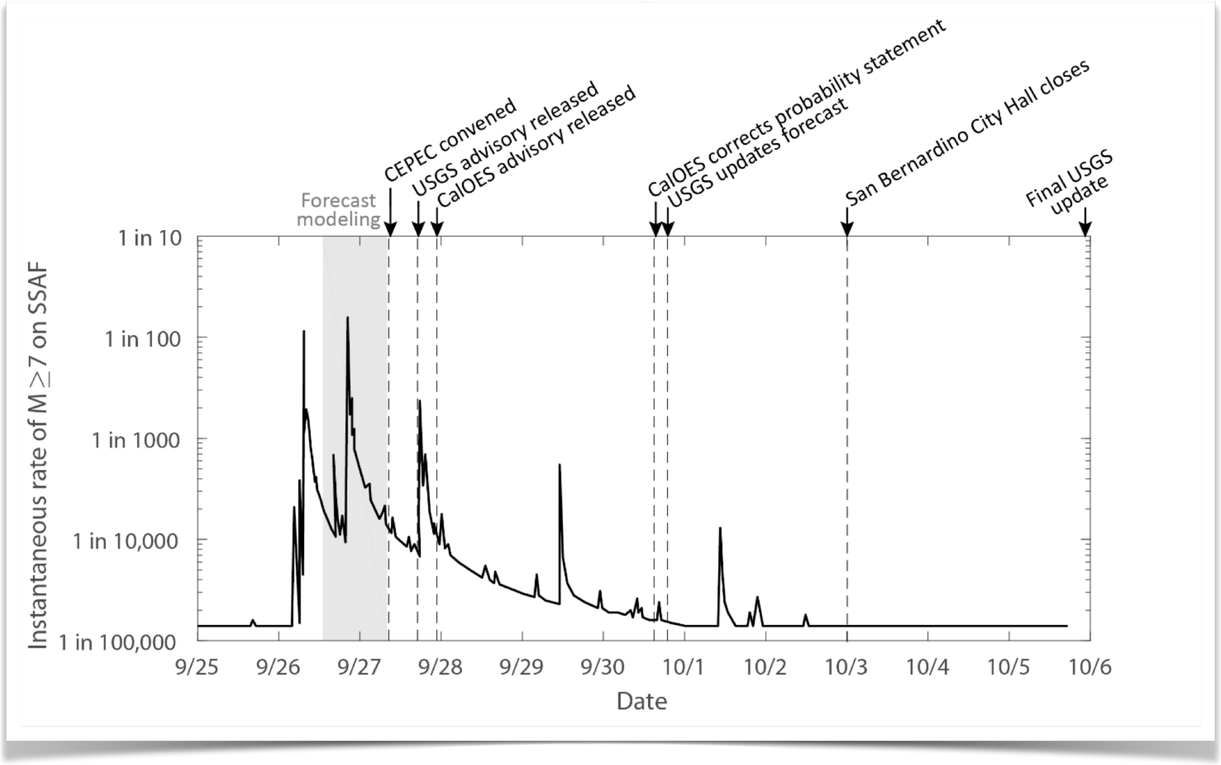
Earthquake Swarms & Probabilities

Swarm-like activity in this region has occurred in the past, so this week's activity, in and of itself, is not necessarily cause for alarm.

Preliminary calculations indicate that, as of 10:00 am (PDT) Sept. 27, 2016, there is a 0.03%-1% chance (1 in 3000 to 1 in 100) of a magnitude 7 or greater earthquake being triggered on the Southern San Andreas fault within the next next seven days through October 4, with the likelihood decreasing over time. This probability range is estimated using several models developed in California to assess foreshock/aftershock probabilities.

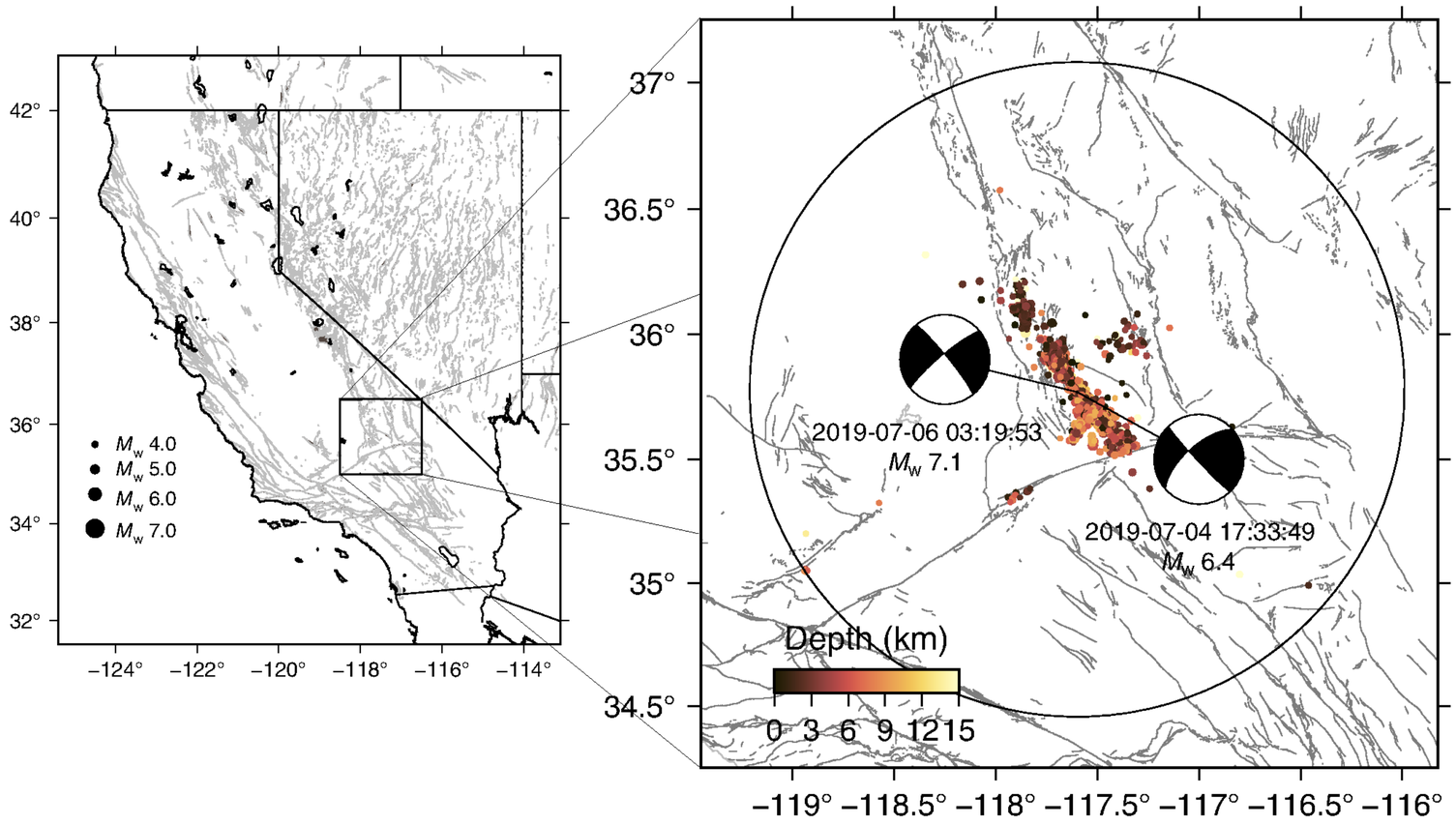
Learn more at: http://earthquake.usgs.gov/

0.03% to 1% chance of M≥7 earthquake next 7 days



McBride *et al.* (2019)

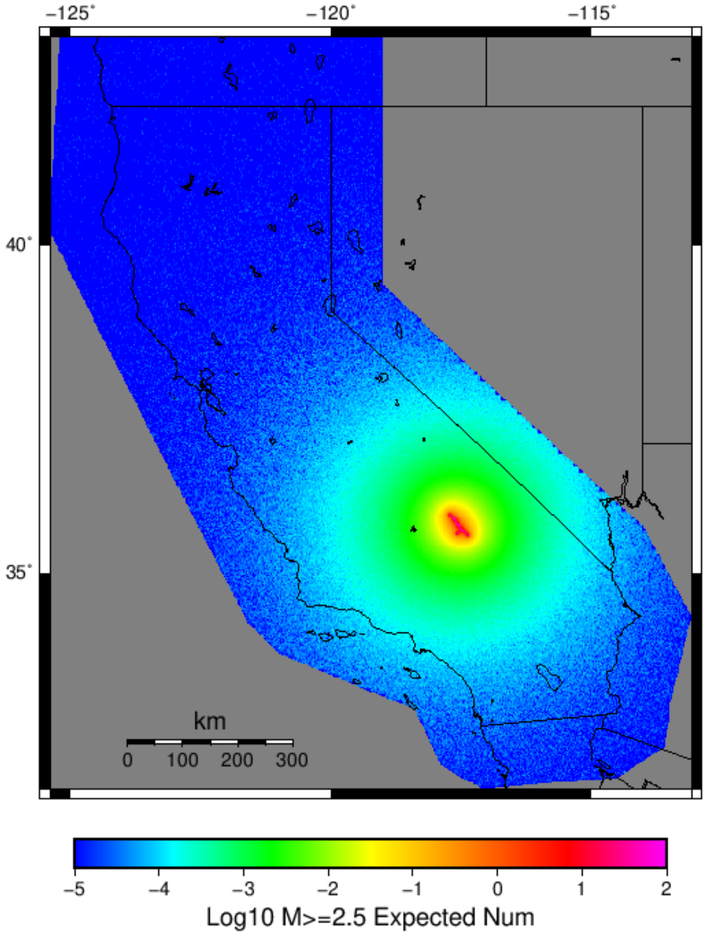
Case Study #2: Ridgecrest



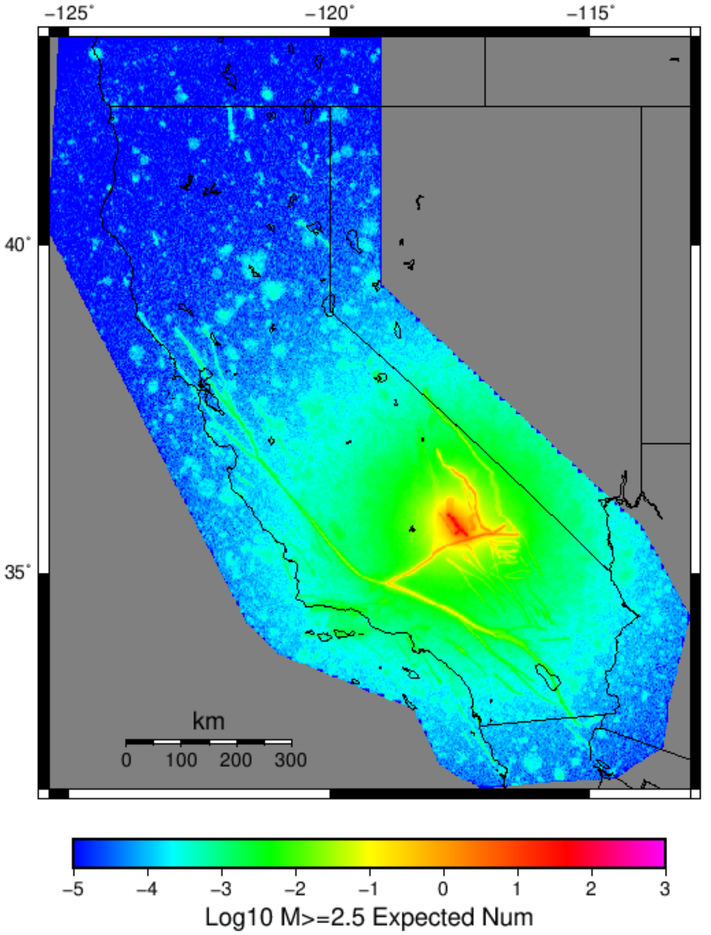
Savran *et al.*, 2020

UCERF3-ETAS Results

100,000 10-year simulations starting immediately after M7.1



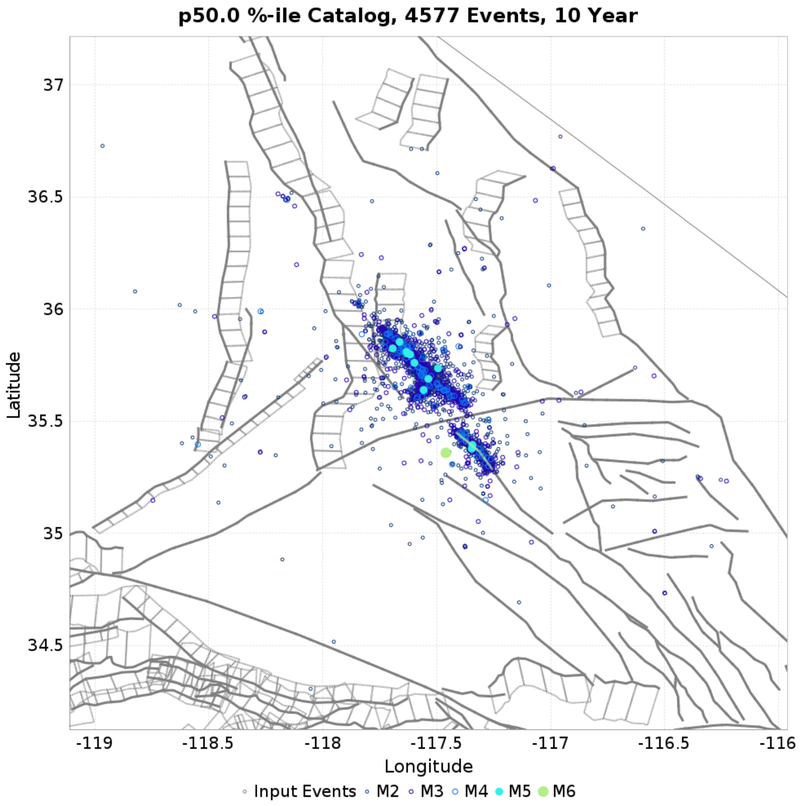
Primary Aftershock Epicenters (M≥2.5)



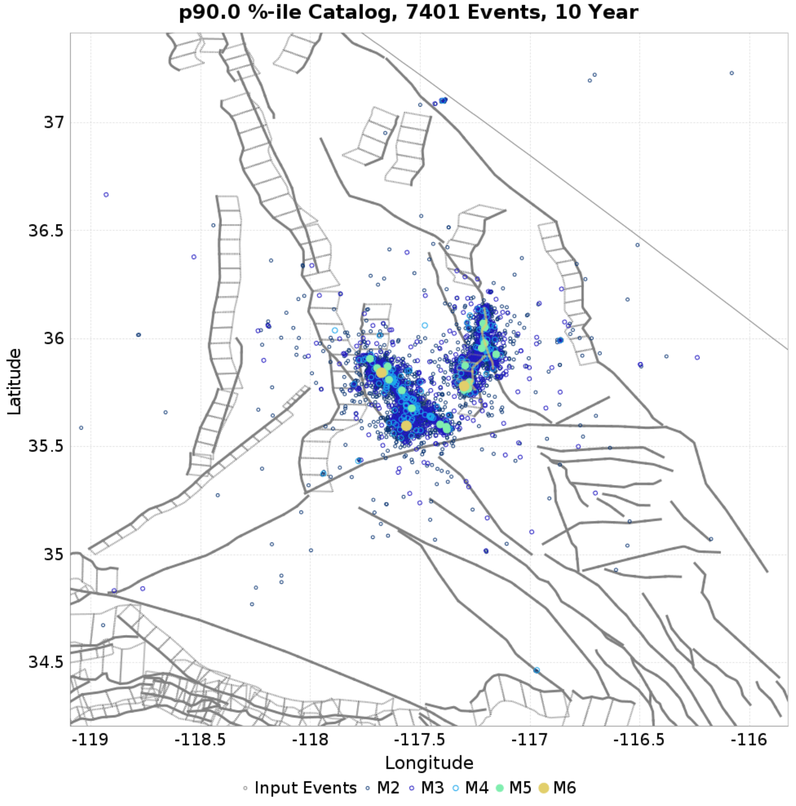
All Aftershock Epicenters (M≥2.5)

UCERF3-ETAS Scenarios

at different percentiles



50% percentile

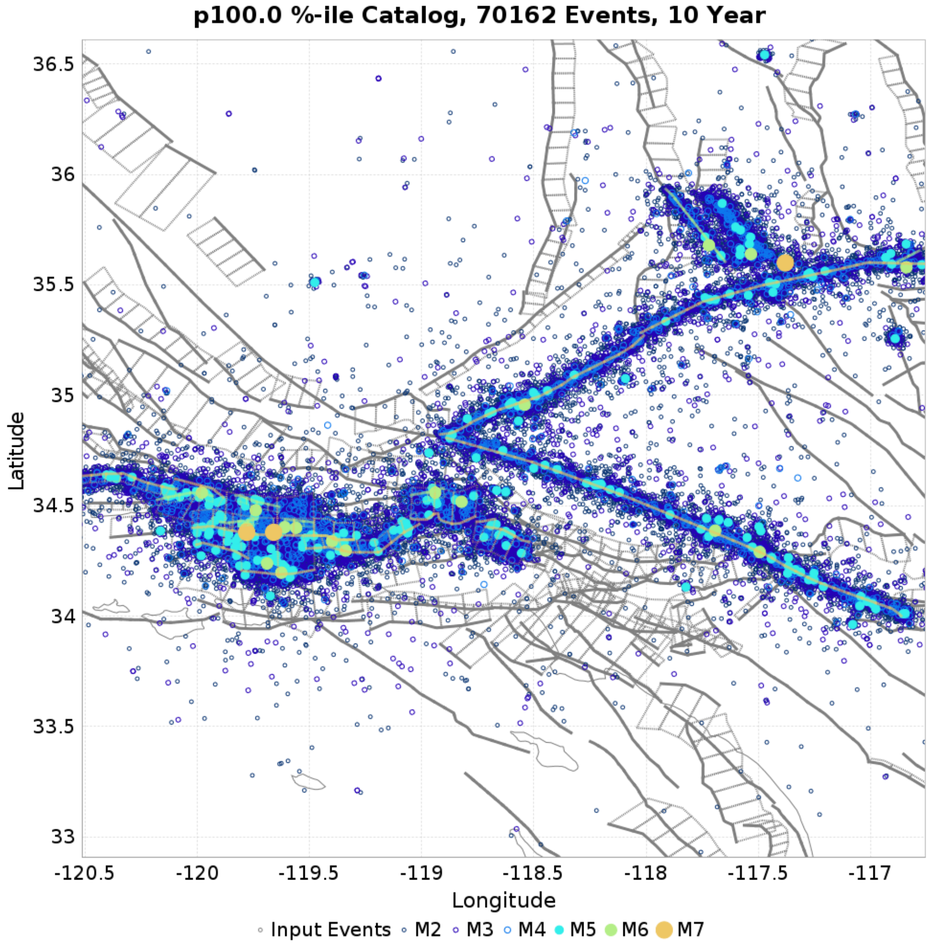


90% percentile

Milner *et al.*, 2020

UCERF3-ETAS Scenarios

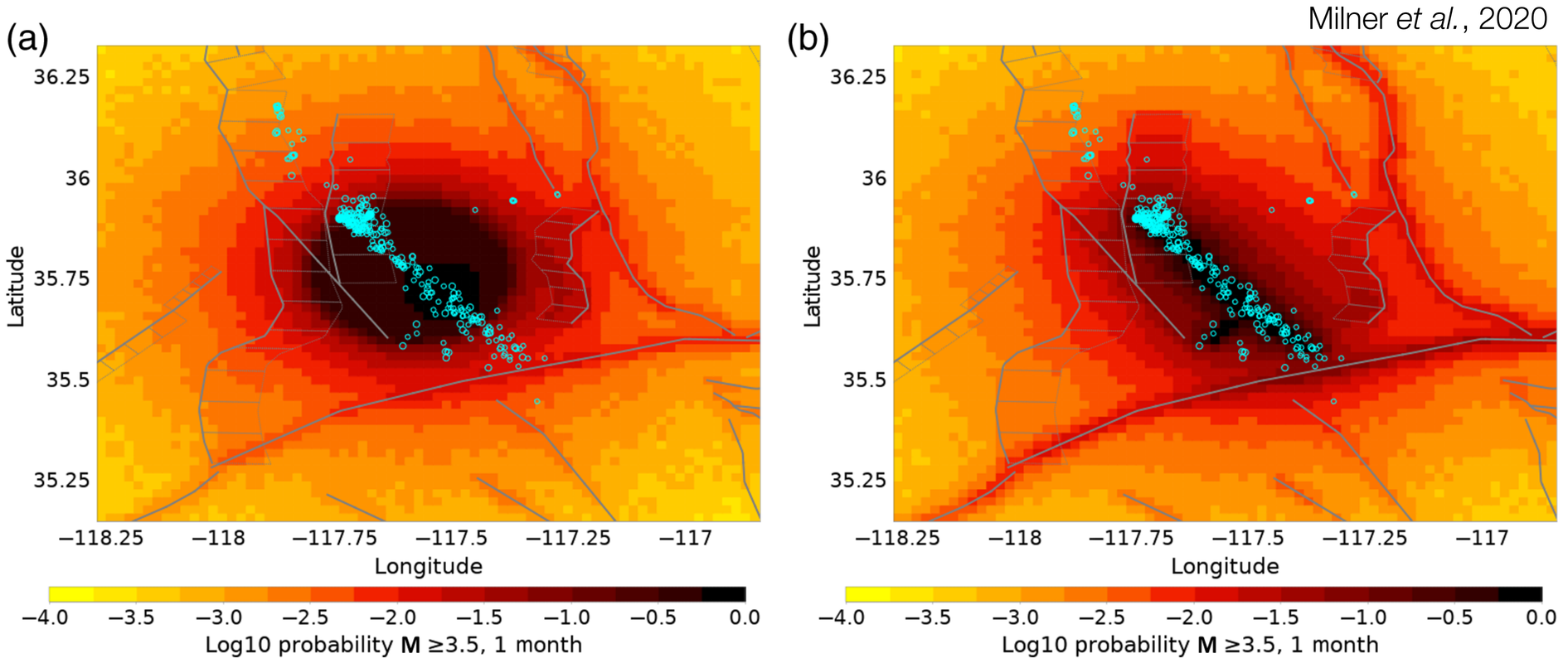
…and the worst of 100,000 simulations



Milner *et al.*, 2020

Aftershock forecasting results are very sensitive to how mainshock fault is modeled

Milner *et al.*, 2020



Original aftershock forecast based on point source

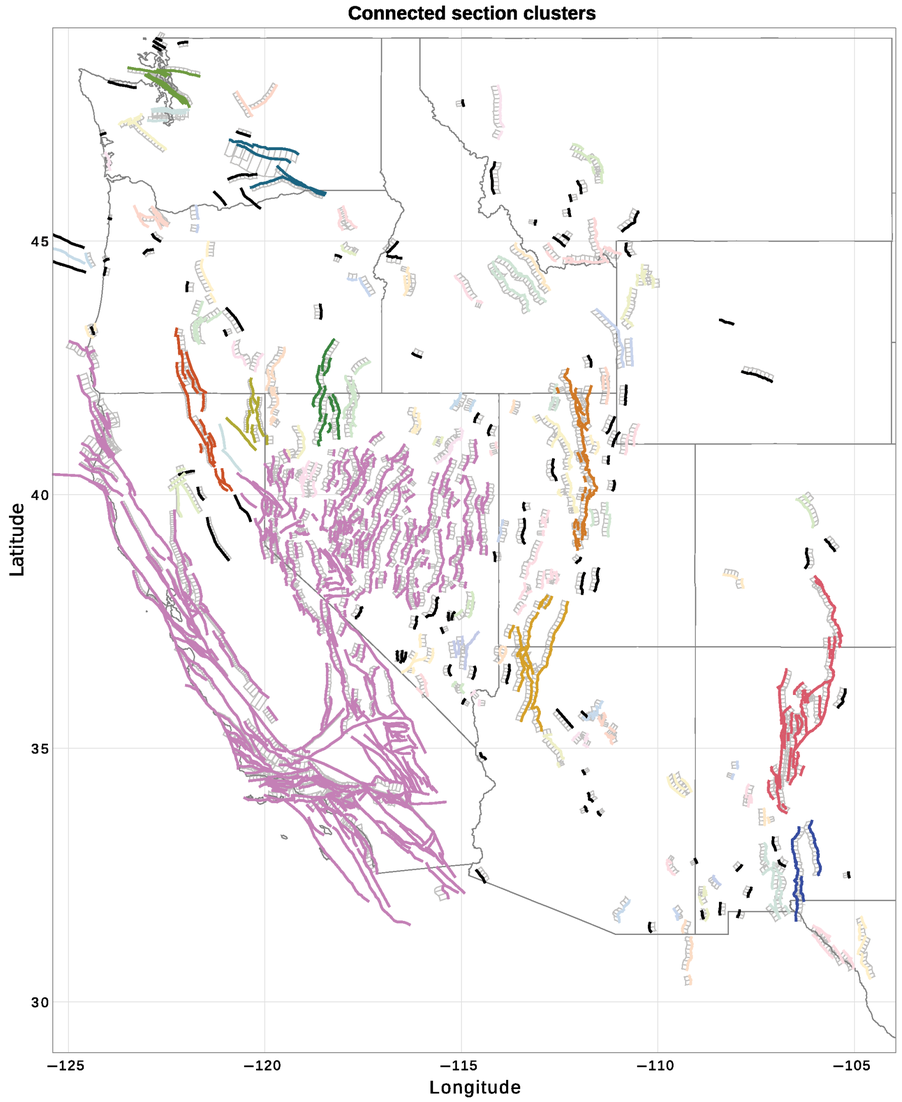
↓

0.65% chance of triggering Garlock fault

Revised aftershock forecast with extended mainshock source

↓

1.7-5.1% chance of triggering Garlock fault (depending on how far south rupture extends)



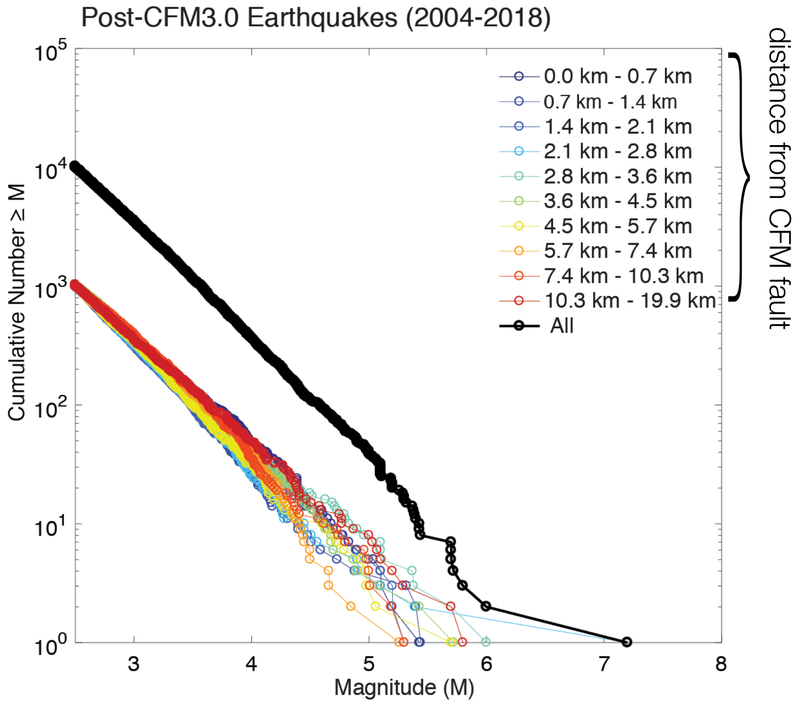
Field *et al.* (2024)

The fault system forms a complex, connected network

Are earthquakes near major faults more dangerous? Are they larger or more likely to trigger a large earthquake?

Are earthquakes near major faults more dangerous?

In the instrumental catalog, we do **not** see that earthquakes near major faults are larger.



Page and van der Elst, 2018

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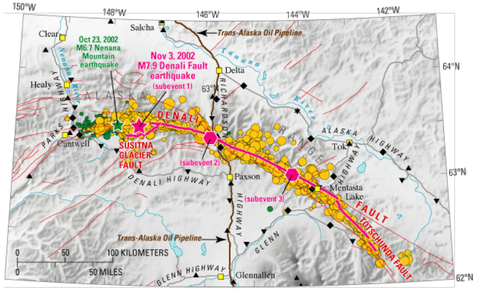
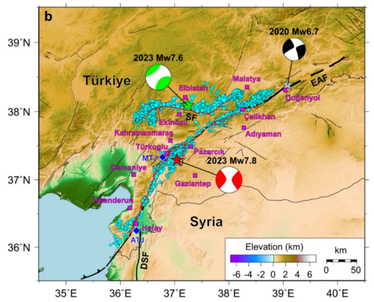
2002 M7.9 Denali, Alaska earthquake



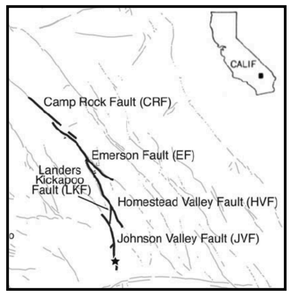
USGS Fact Sheet 014-03

2023 Turkiye / Syria earthquakes



Liu *et al.*, 2023

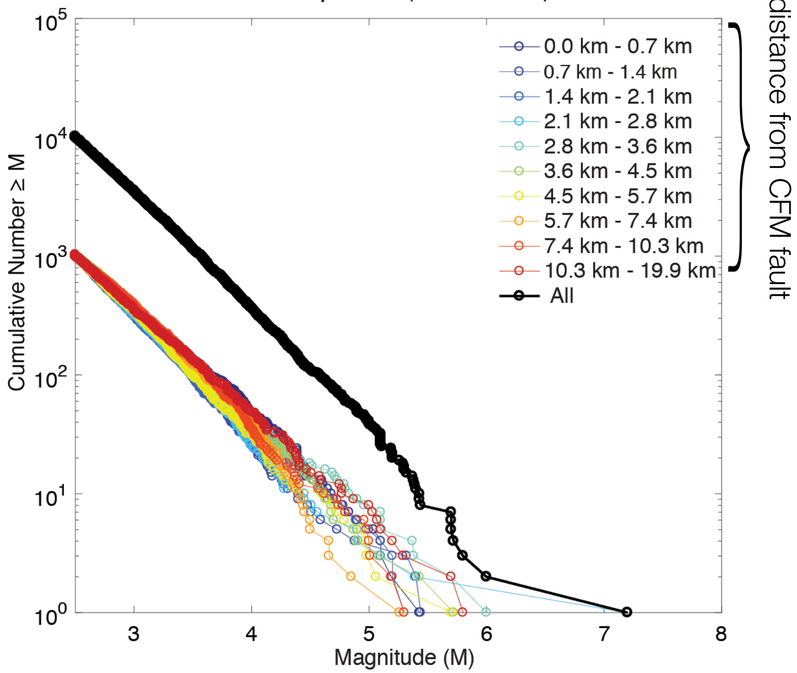
1992 M7.3 Landers, California earthquake



Langenheim and Jachens, 2002

Large earthquakes often begin on secondary faults and/or link up multiple faults

Post-CFM3.0 Earthquakes (2004-2018)



Page and van der Elst, 2018

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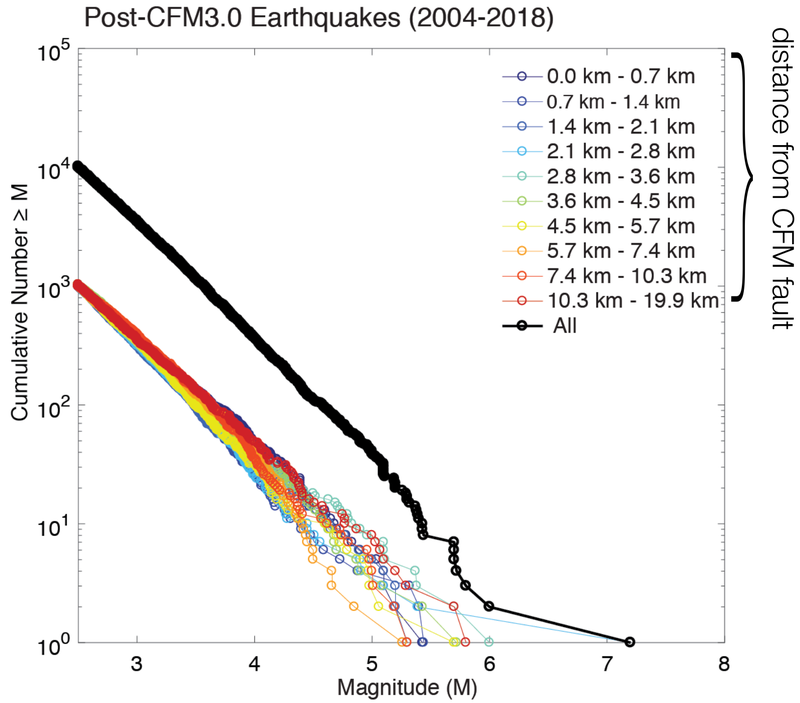
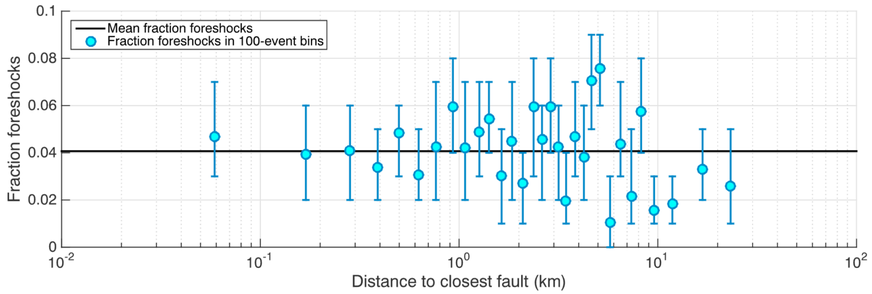
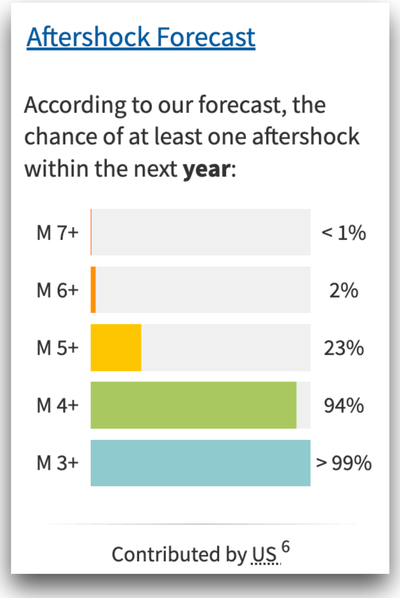


We also do **not** see that earthquakes near major faults produce more aftershocks or are more likely to be a foreshock to a larger event.



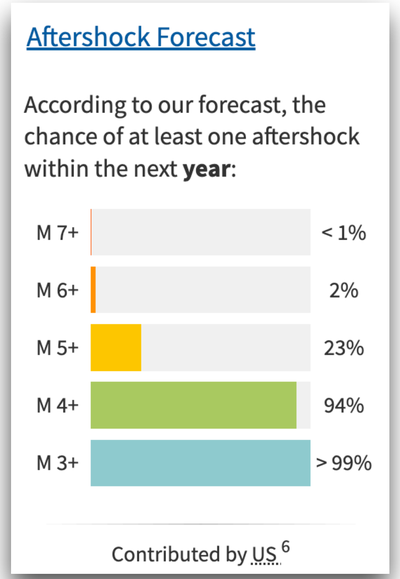
Page and van der Elst, 2018

Conclusions



The USGS rapidly produces public aftershock forecasts following M4+ earthquakes in the continental US.

Conclusions



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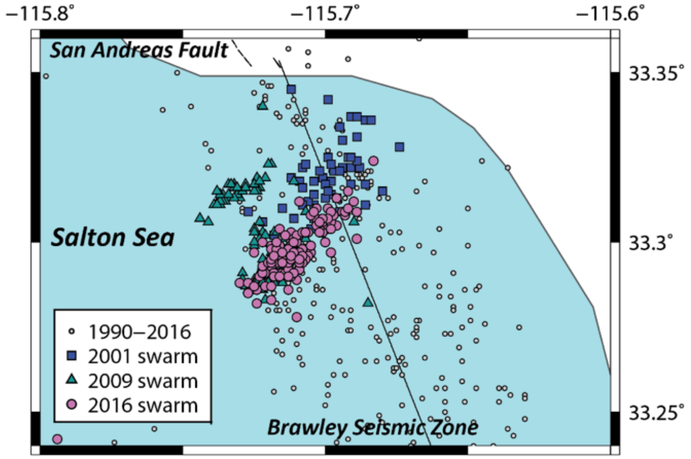
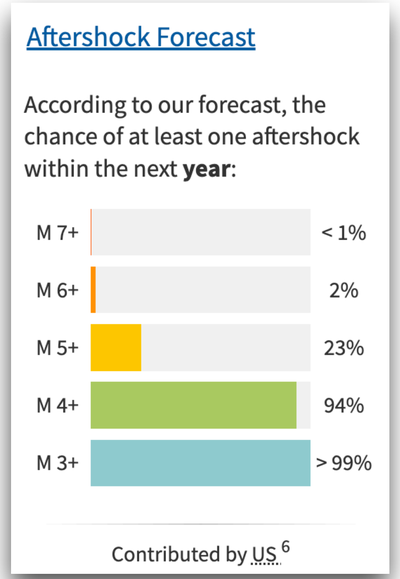


In a swarm situation, ad-hoc forecasts can be produced, but there remains large uncertainty regarding the swarm duration.

Conclusions



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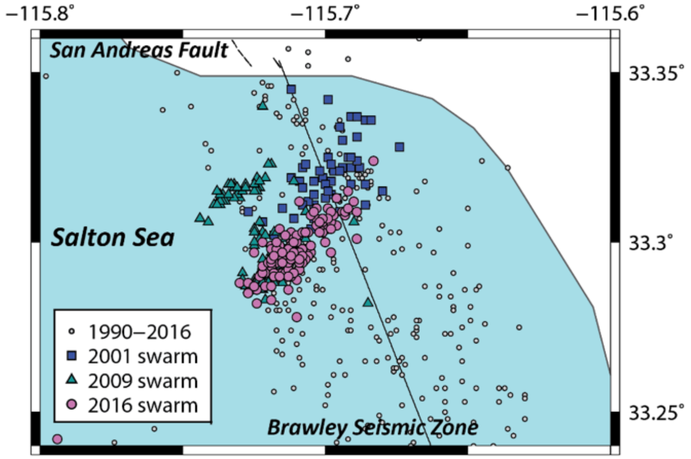
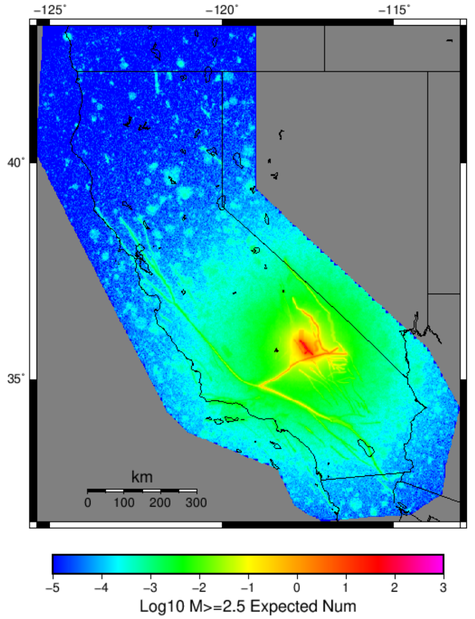


In a swarm situation, ad-hoc forecasts can be produced, but there remains large uncertainty regarding the swarm duration.



Fault-based models like UCERF3 can produce forecasts that take into account hazardous faults nearby.

These models assume non-Gutenberg-Richter behavior on faults & are very sensitive to uncertainties in fault proximity.