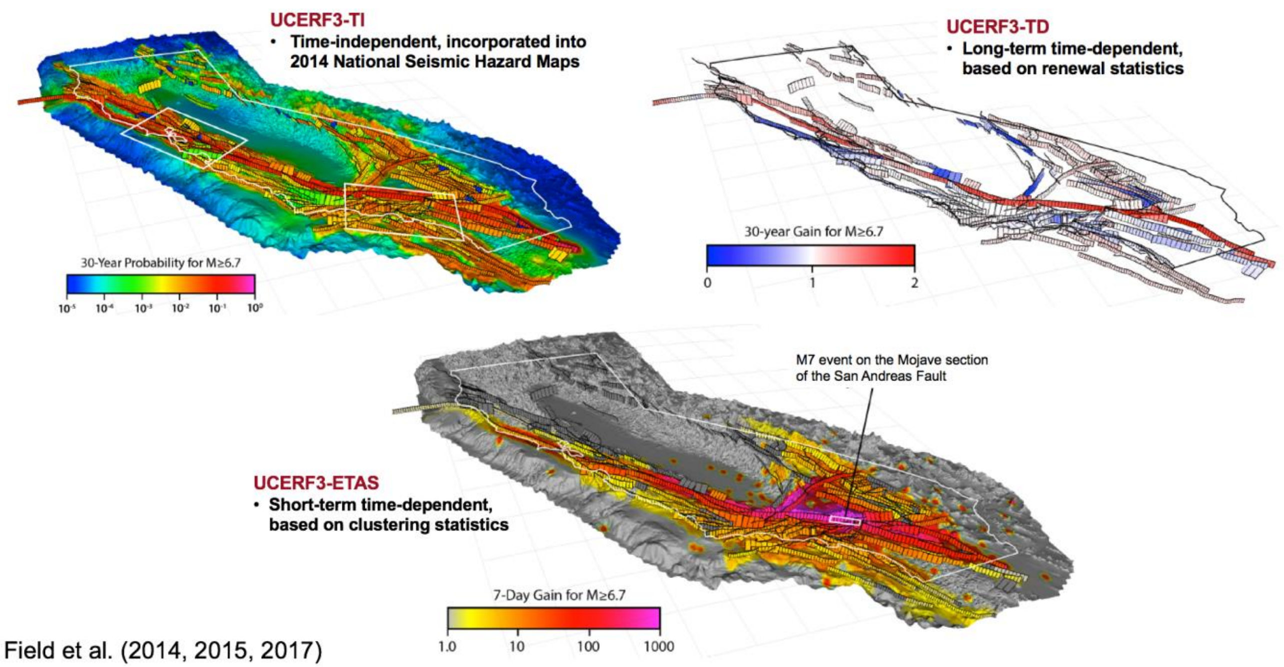
Overview of the

3rd Uniform California Earthquake Rupture Forecast (UCERF3)

Edward (Ned) Field & other WGCEP participants:

Thomas H. Jordan, Morgan T. Page, Kevin R. Milner, Bruce E. Shaw, Timothy E. Dawson, Glenn P. Biasi, Tom Parsons, Jeanne L. Hardebeck, Andrew J. Michael, Ray J. Weldon II, Peter M. Powers, Kaj M. Johnson, Yuehua Zeng, Karen R. Felzer, Nicholas van der Elst, Christopher Madden, Ramon Arrowsmith, Maximilian J. Werner, Wayne R. Thatcher



Field et al. (2014, 2015, 2017)

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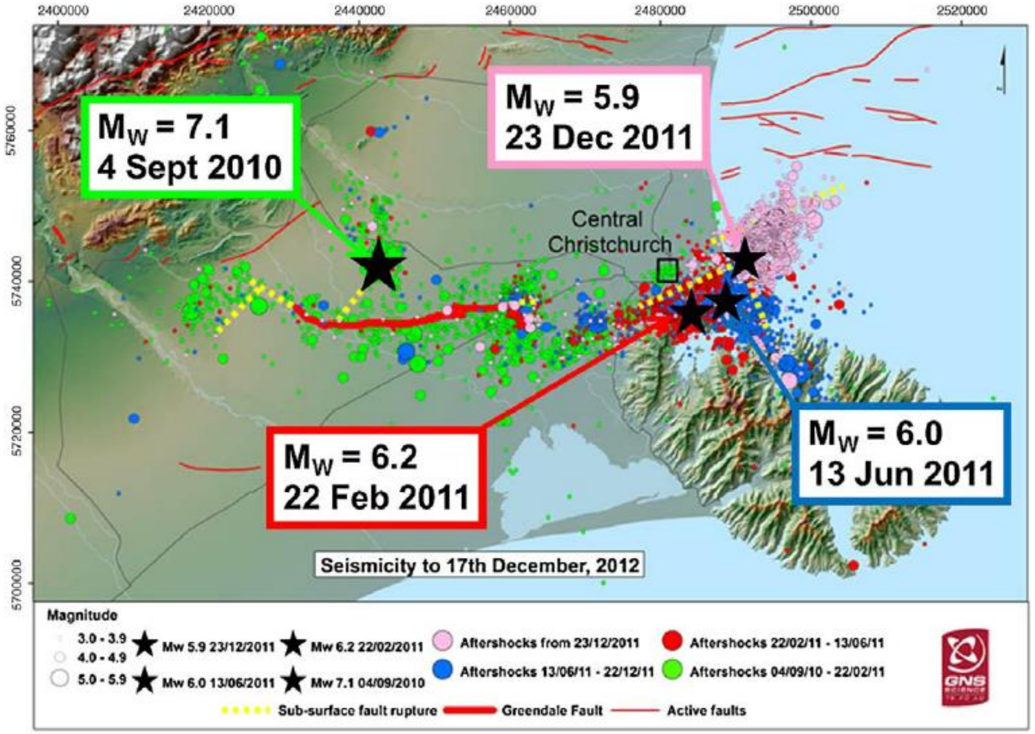
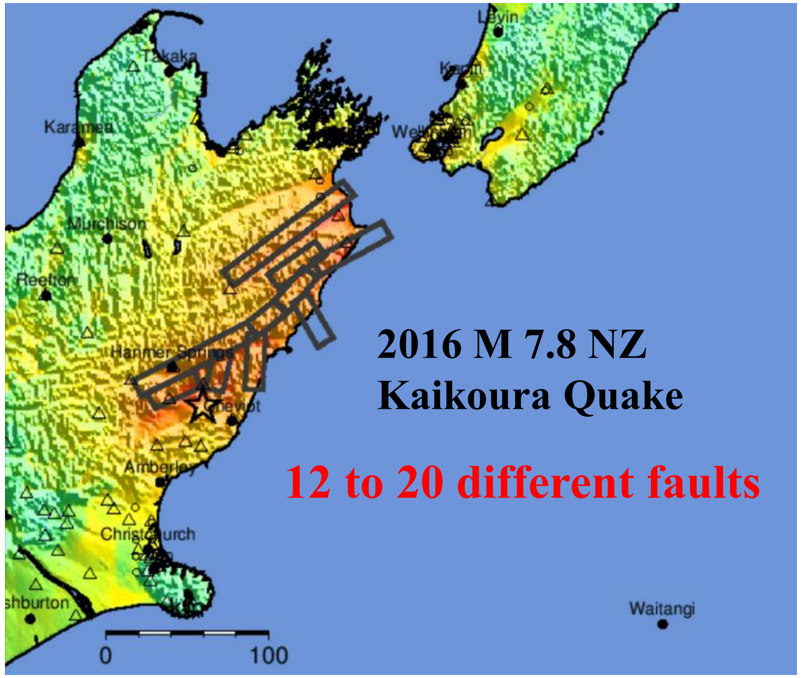
Biggest Issues: previous models lacked multi-fault ruptures and spatiotemporal clustering (potentially damaging aftershocks)

NZ Canterbury earthquake sequence



O'Rourke et al. (2014)



UCERF3 Implications

Practical:

- ***Both multi-fault ruptures and spatiotemporal clustering are included (e.g., as basis for OEF)***
- Question: ***is UCERF3 useful enough to be worth operationalizing?*** (model value depends on hazard or risk metric, and will therefore vary between applications)

Scientific:

- UCERF3 implies ***Gutenberg Richter is not applicable to all faults***
- Combining finite faults with spatiotemporal clustering implies a need for ***elastic rebound/relaxation*** (otherwise large triggered events would simply re-rupture the main-shock rupture surface much more than we see in nature)

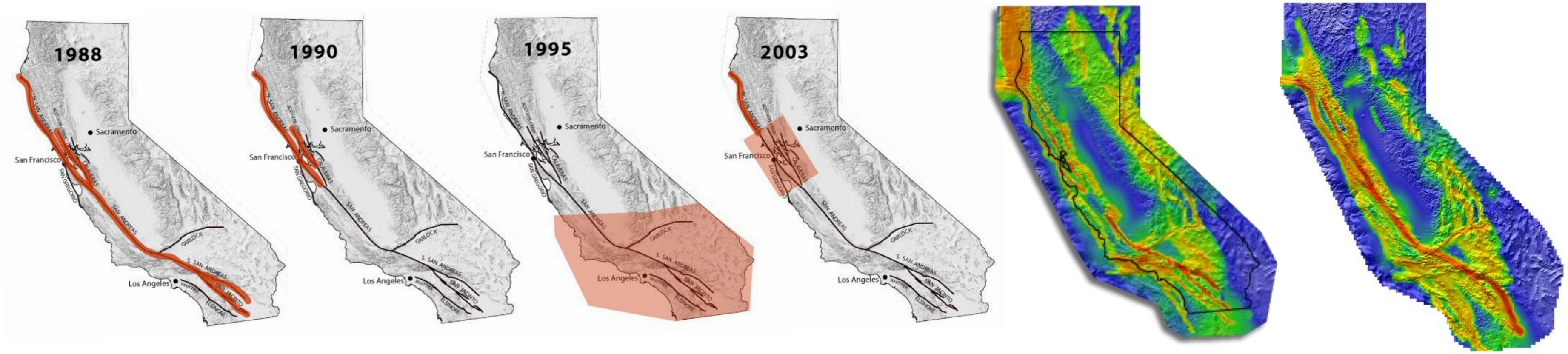
Working Groups on California Earthquake Probabilities (WGCEPs)

(the most official time-dependent earthquake forecasts for California)

A better and more useful approximation

UCERF2
2007

UCERF3
2014, 2016, 2017



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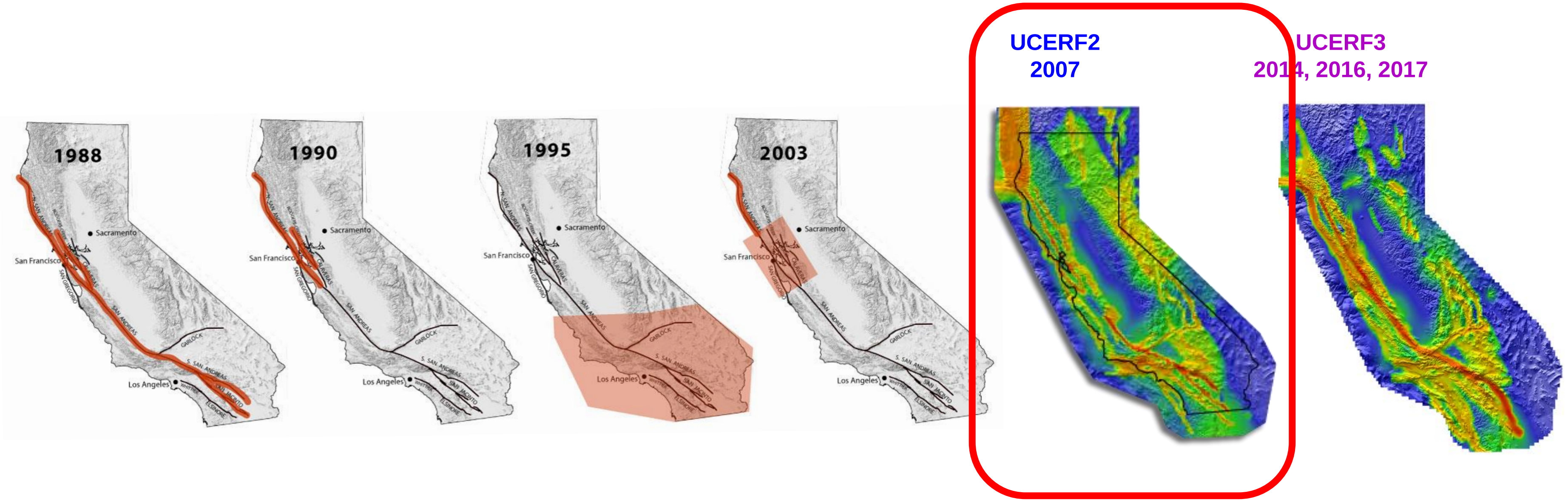


What's wrong here?

UCERF2 Problems:

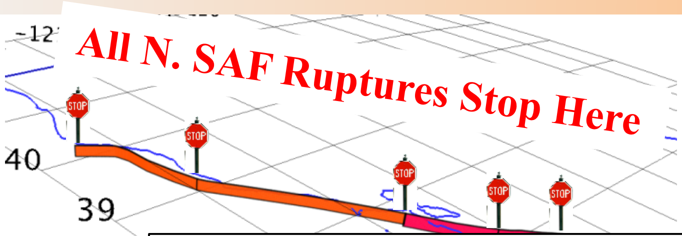
1) Assumes segmentation

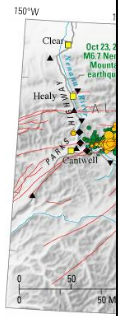
2) Excludes multi-fault ruptures

3) Over-predicts M ~6.7 events

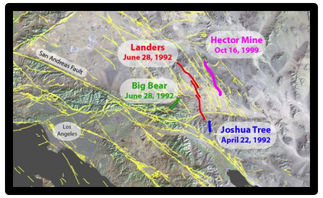
4) Elastic rebound not self-consistent

5) Lacks spatiotemporal clustering

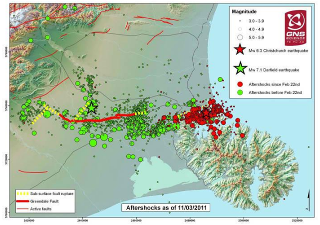




These inadequacies were recognized in the UCERF2 report (2007), and since exemplified by several earthquakes.



Christchurch NZ



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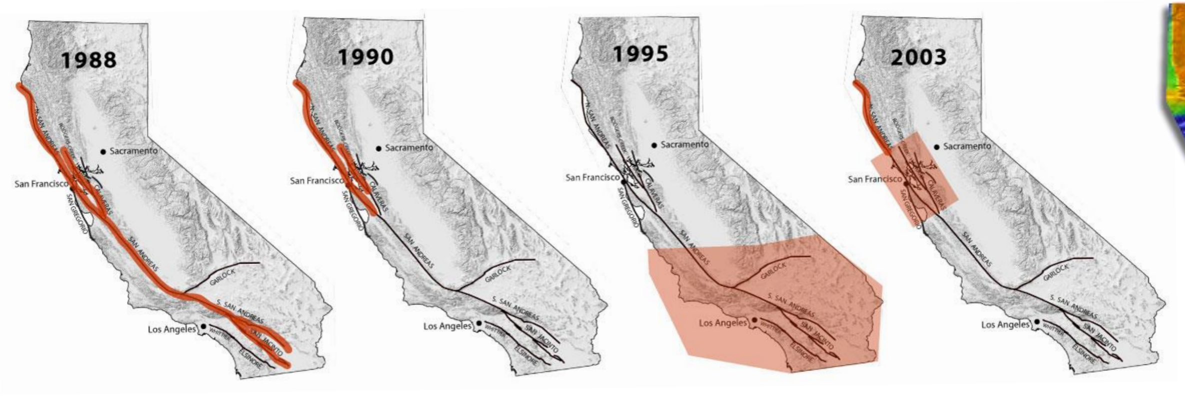
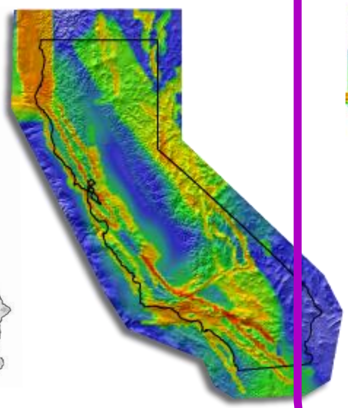
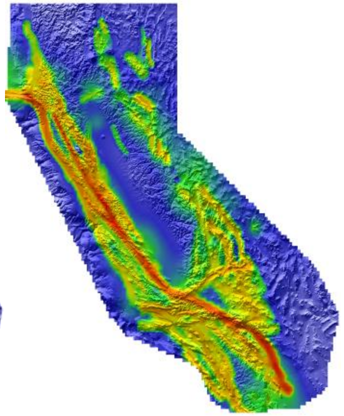


UCERF2
2007



UCERF3
2014, 2016, 2017



What's the solution?

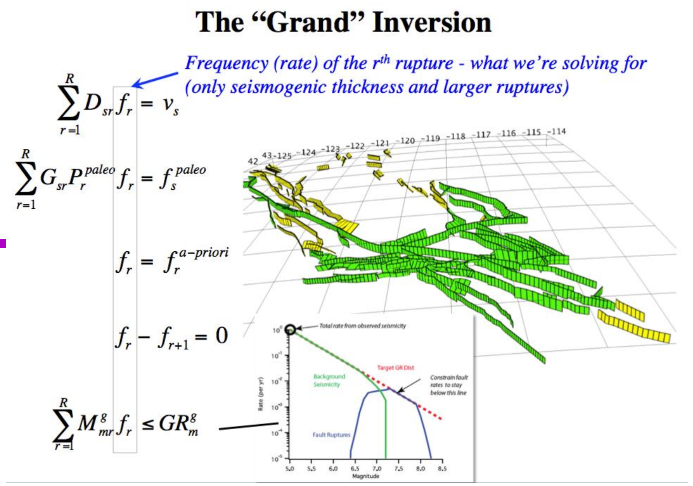
UCERF2 Issues:

UCERF3 Solutions:

1) Assumes segmentation

2) Excludes multi-fault ruptures

3) Over-predicts M ~6.7 events



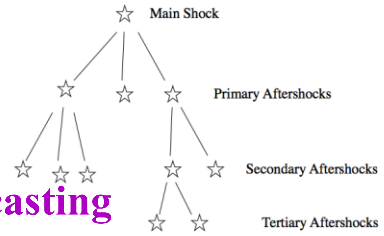
4) Elastic rebound not self-consistent

New method supported by physics-based simulators

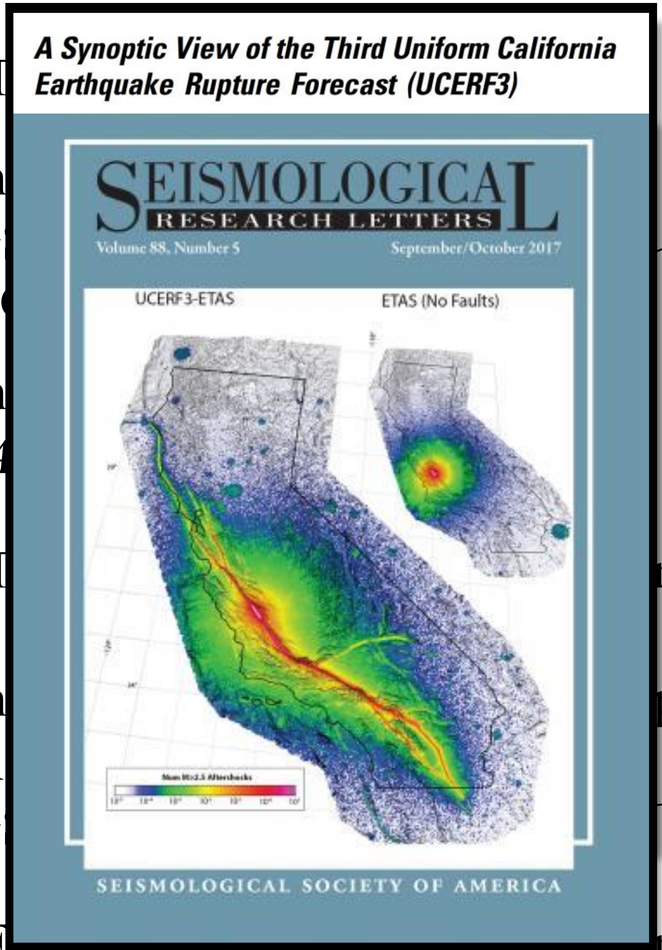
5) Lacks spatiotemporal clustering

ETAS

Operational Eqk Forecasting



UCERF3 Publications



UCERF3-T

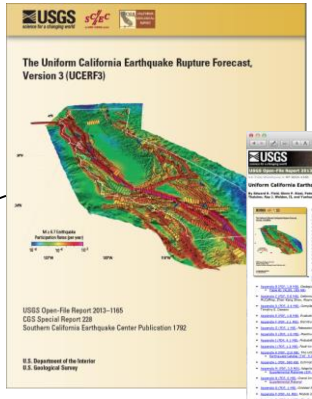
- Main USG (also
- Main *BSSA*

UCERF3-T nt Model)

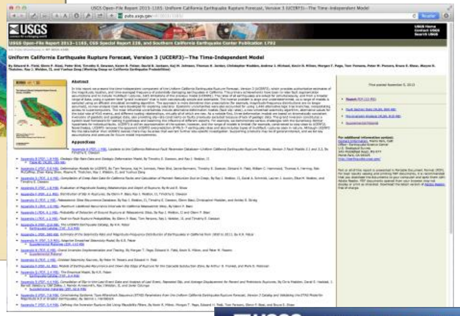
- Main publi pers
- USG

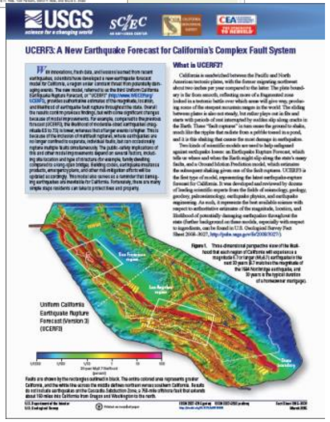
UCERF3-E ng Model for OEF)

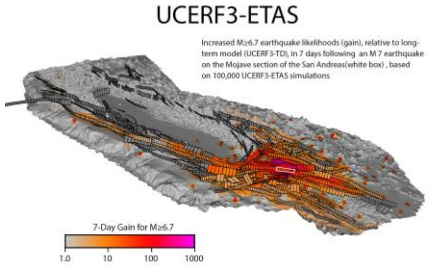
- BSSA (*June, 2017*)



http://pubs.usgs.gov/of/2013/1165







UCERF3 Publications

UCERF3-TI (Time-Independent Model):

- Main report and 20 Appendices in USGS OFR 2013-1165
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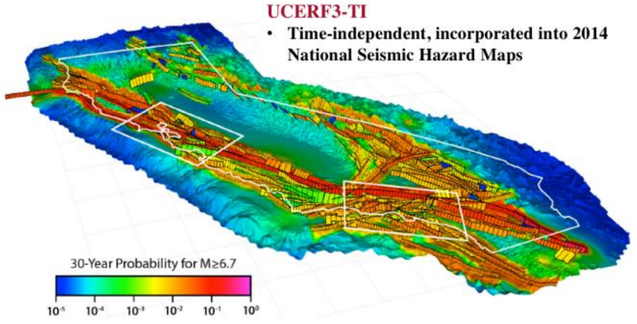
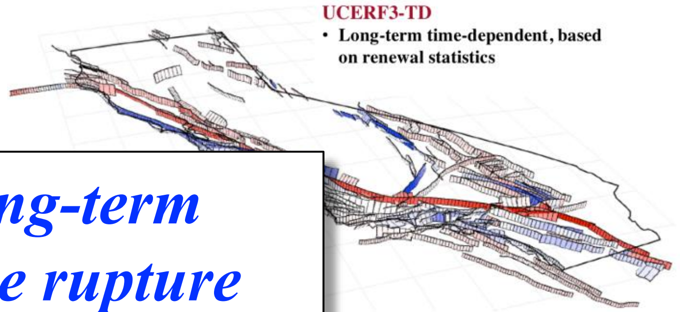


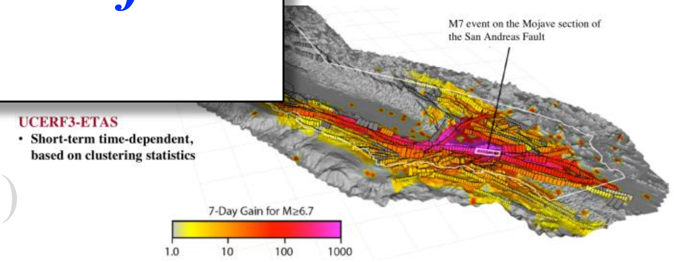
UCERF3-TD (Long-Term Time Dependent Model)



- Main r
  publis
- USGS

The goal here is to define the long-term rate of every possible earthquake rupture throughout the region (at some level of discretization)

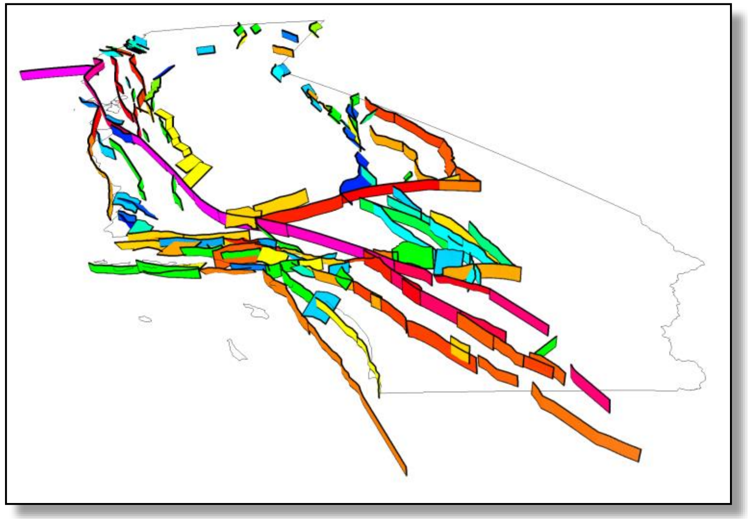
UCERF3-ET



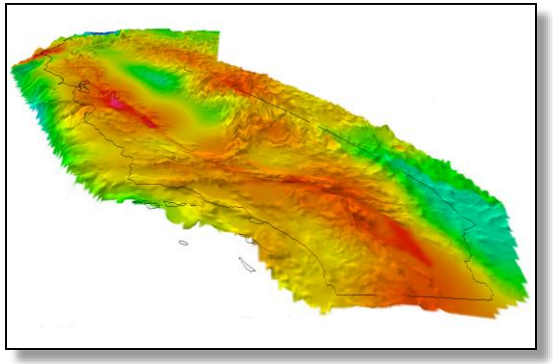
- Published in *BSSA* (June, 2017; available on line)

Old approach to defining long-term earthquake rates:

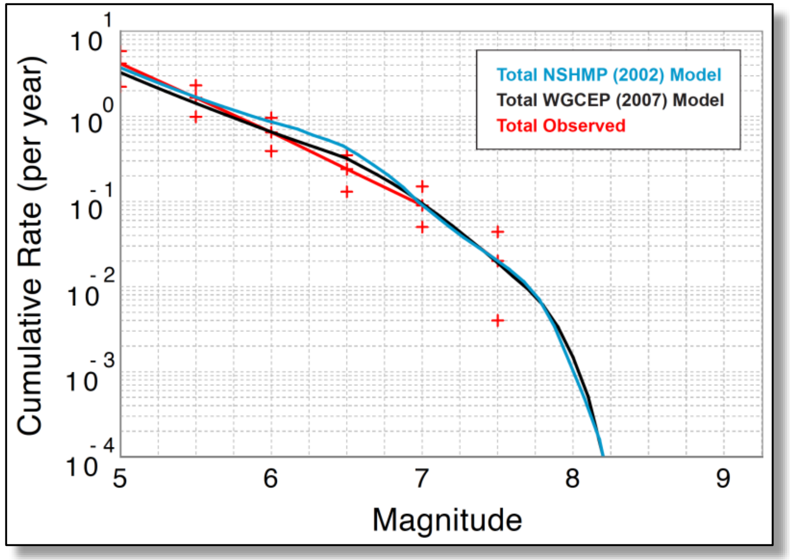
Assume faults are separate and cannot rupture together



Add in off-fault seismicity

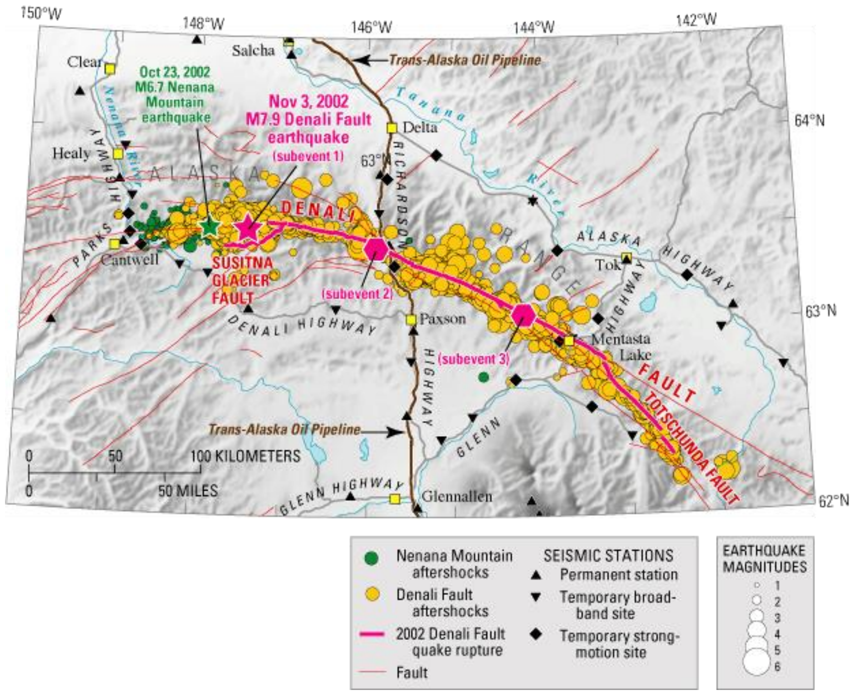


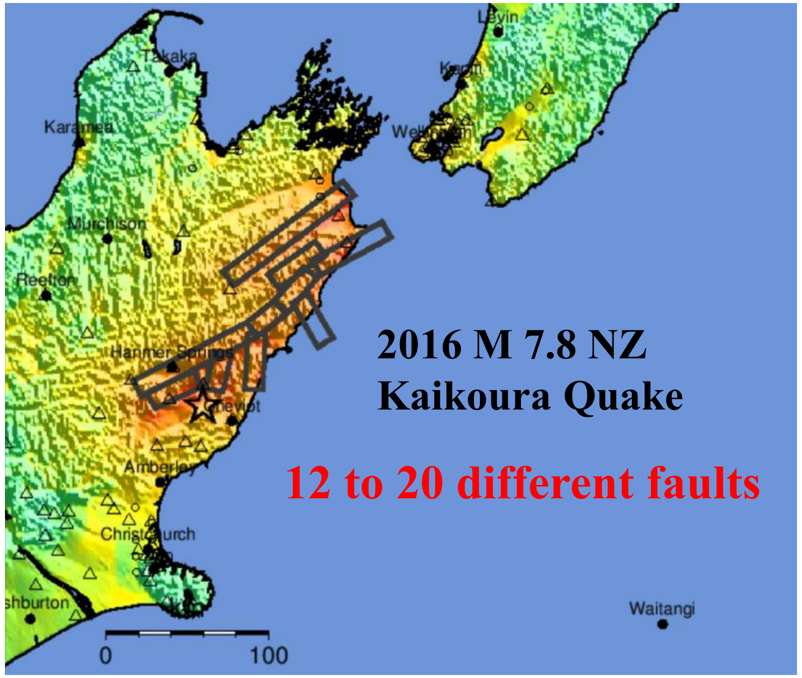
Adding it all up … over prediction



We’ve now seen several multi-fault ruptures; e.g.,

2002 M 7.9 Denali Quake

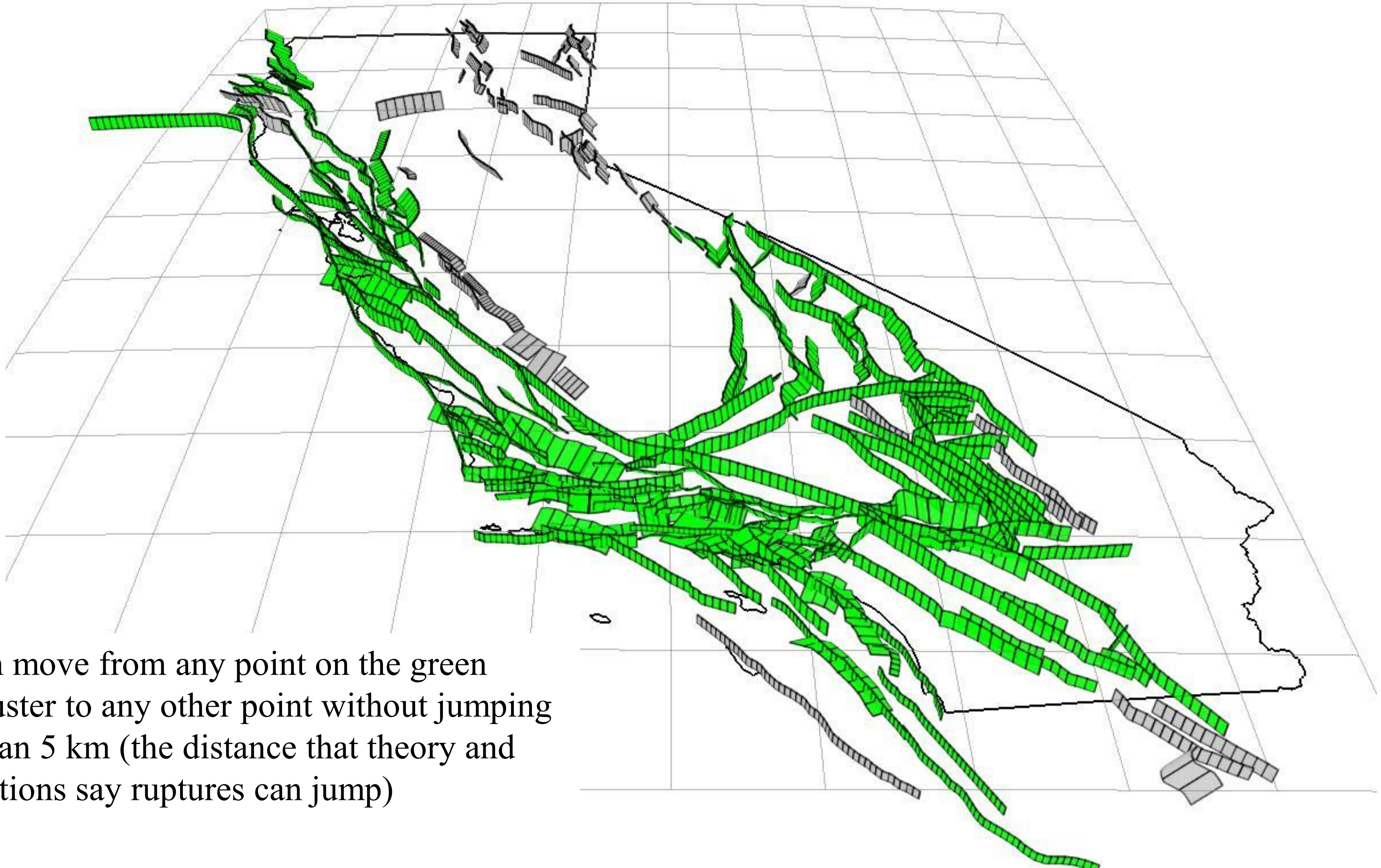




2016 M 7.8 NZ Kaikoura Quake

12 to 20 different faults

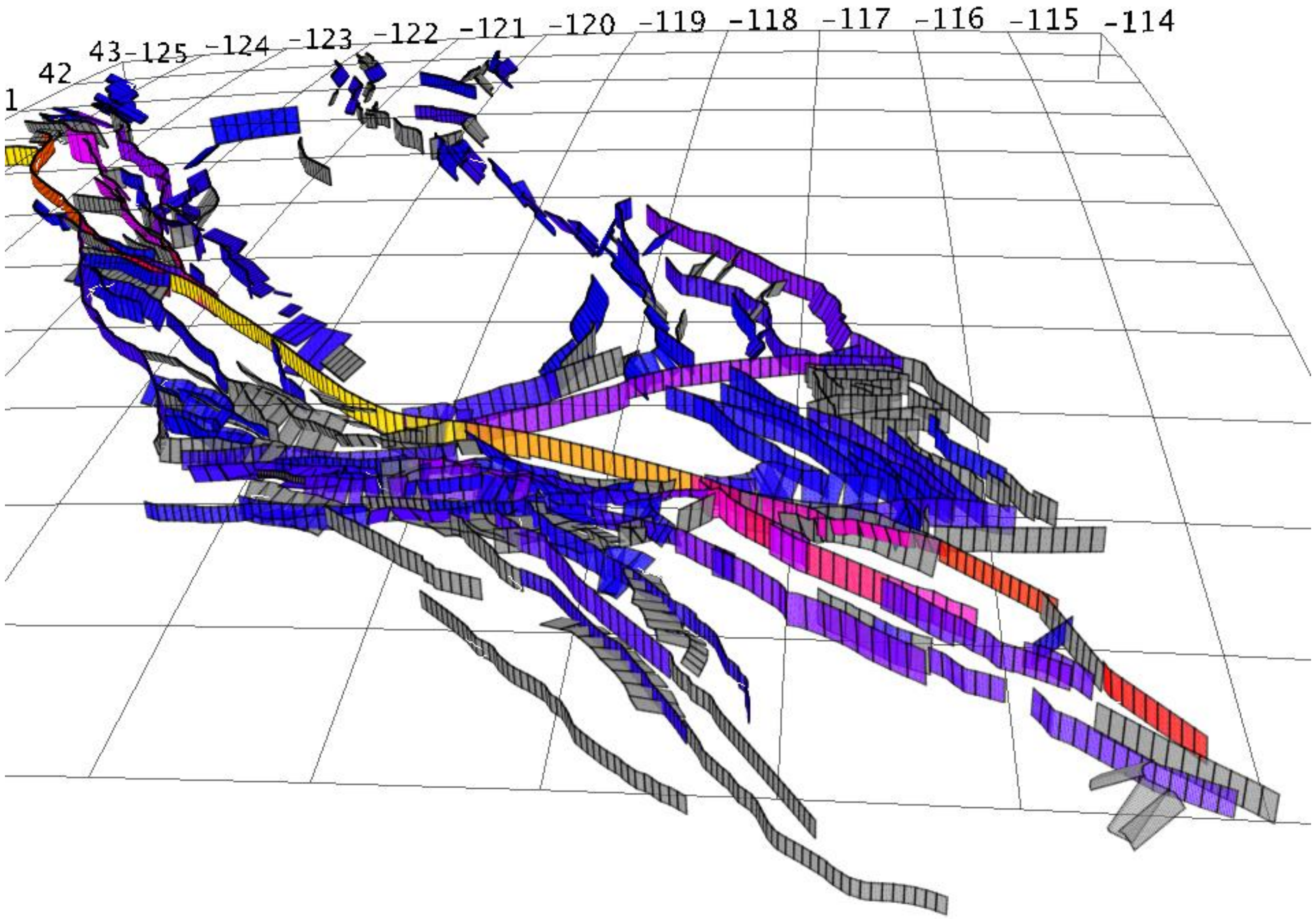
And filling out the fault inventory has revealed an interconnected fault system



You can move from any point on the green fault cluster to any other point without jumping more than 5 km (the distance that theory and observations say ruptures can jump)

The UCERF3 "Grand" Inversion

1) **Divide faults into subsections and define all ruptures as the set of 2 or more contiguous subsections that pass a plausibility test (e.g., fault gap ≤5km);** ~250,000 ruptures compared to ~8,000 in UCERF2)



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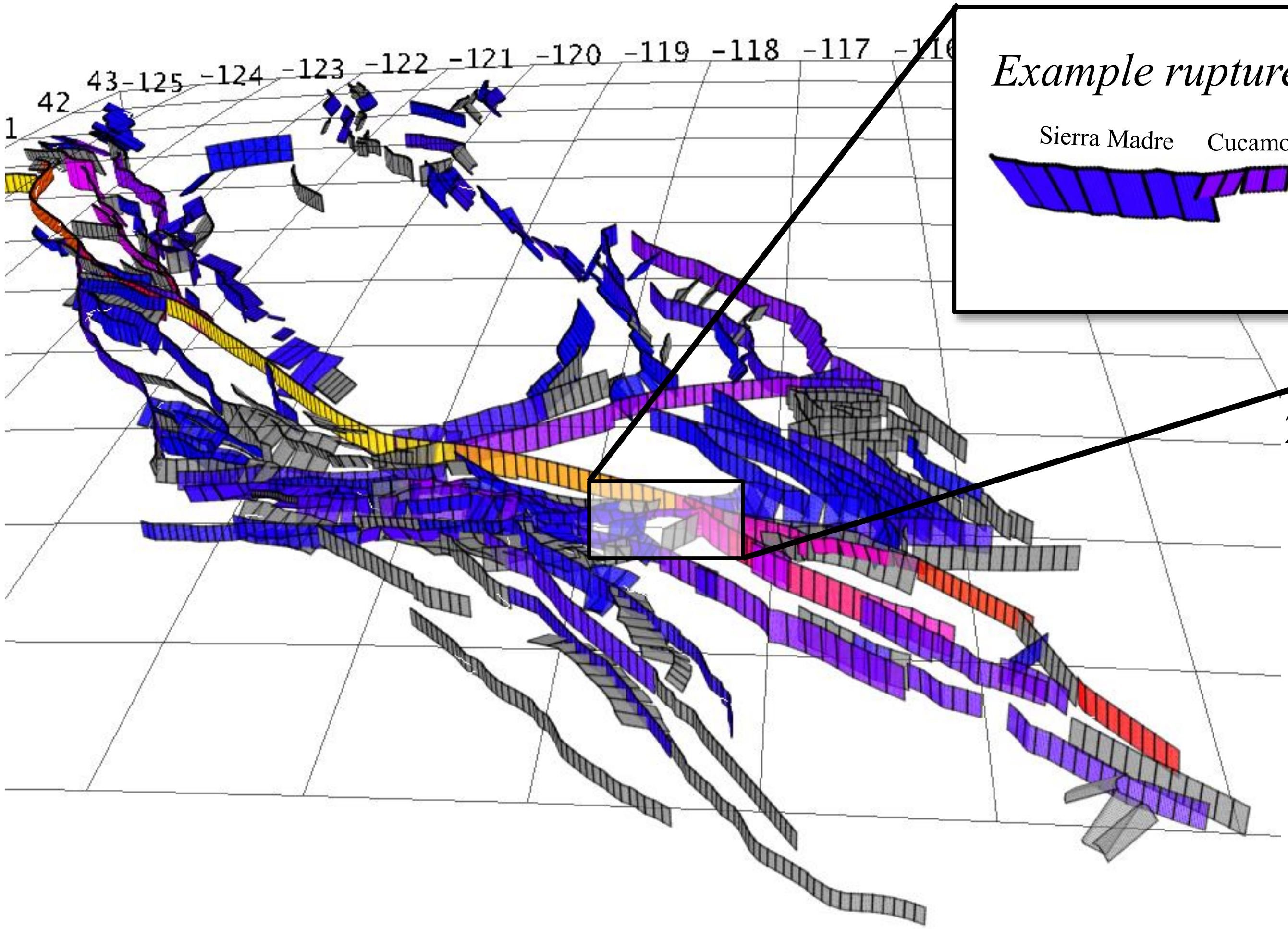
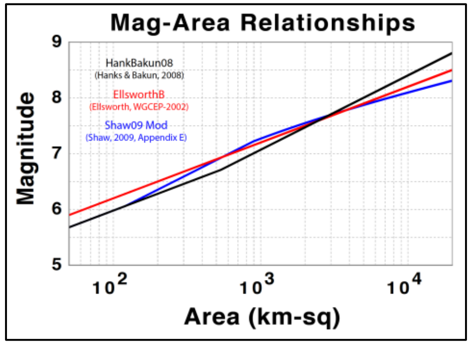
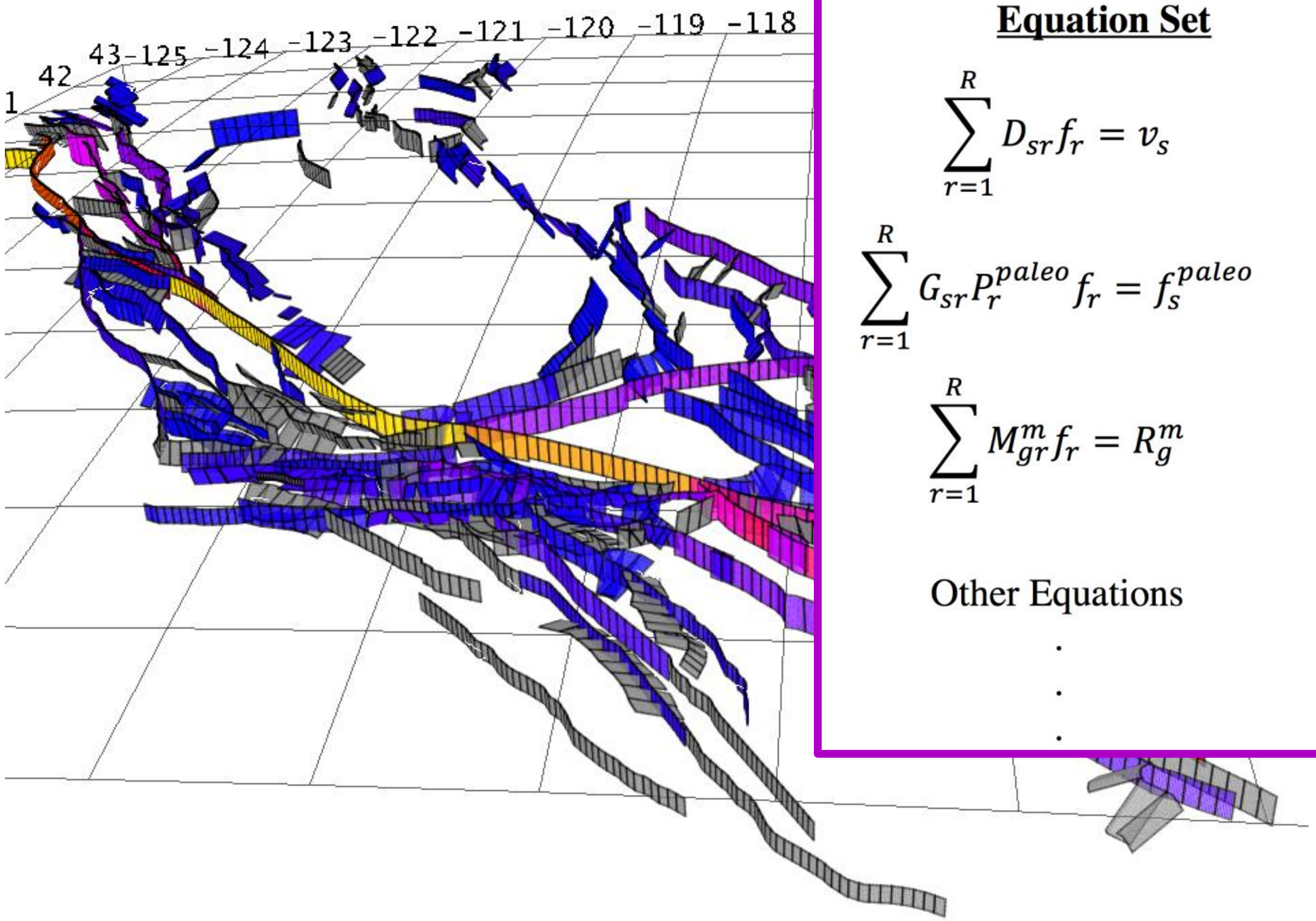


2) Compute the *Magnitude* of each rupture from its area



The UCERF3 “Grand” Inversion

3) Solve for the rate of each rupture (f_r) from a system of equations/constrains



Equation Set		Description
$\sum_{r=1}^{R} D_{sr} f_r = v_s$	(1)	***Fault Slip Rates***
$\sum_{r=1}^{R} G_{sr} P_r^{paleo} f_r = f_s^{paleo}$	(2)	***Paleoseismic Event Rate*** *(32 sites in CA)*
$\sum_{r=1}^{R} M_{gr}^{m} f_r = R_g^{m}$	(3)	***Regional MFD Constraint*** *(GR)*

Other Equations

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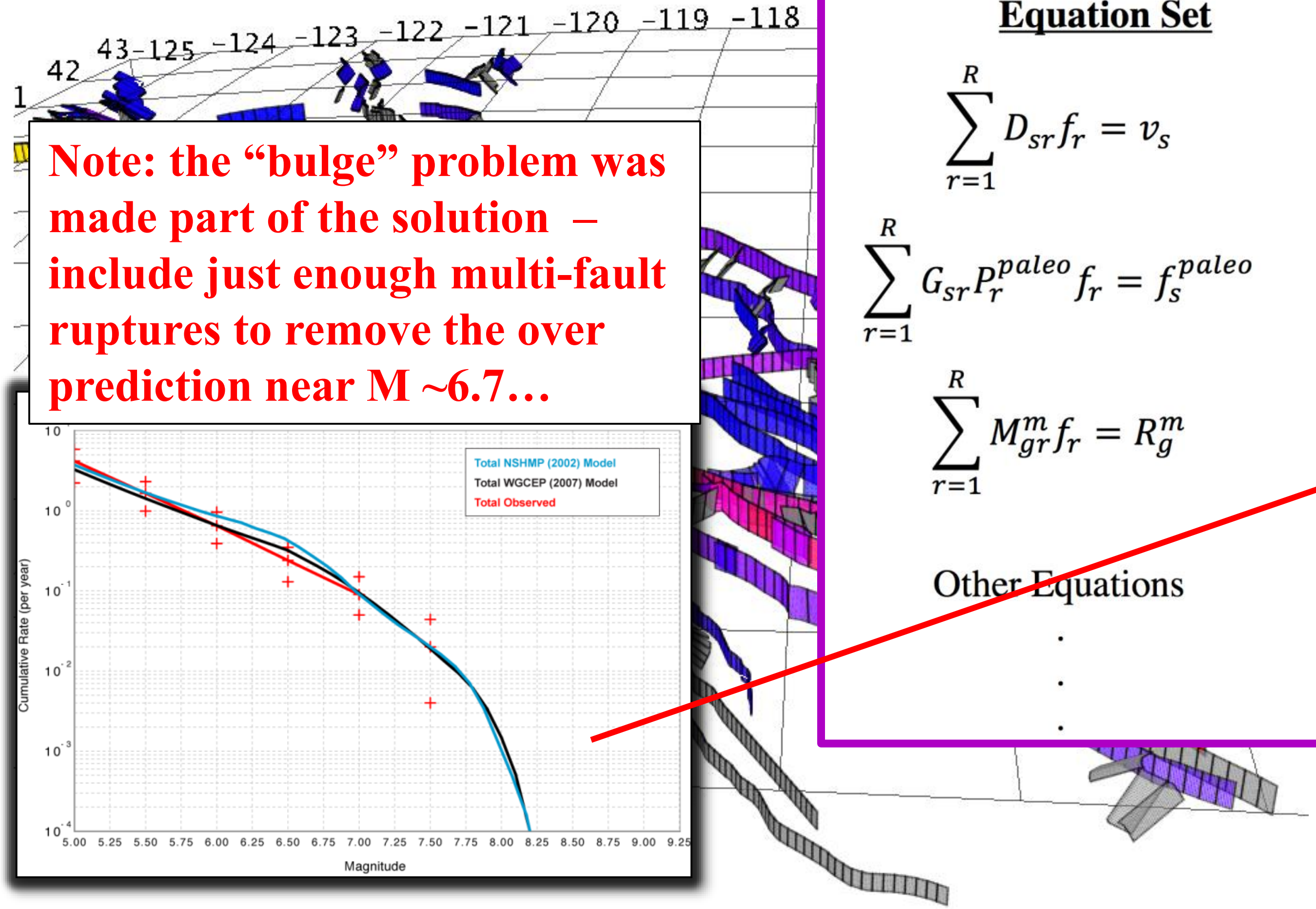
The UCERF3 "Grand" Inversion

3) Solve for the rate of each rupture (f_r) from a system of equations/constrains



Note: the "bulge" problem was made part of the solution – include just enough multi-fault ruptures to remove the over prediction near M ~6.7…

Equation Set		**Description**
$\sum_{r=1}^{R} D_{sr} f_r = v_s$	(1)	***Fault Slip Rates***
$\sum_{r=1}^{R} G_{sr} P_r^{paleo} f_r = f_s^{paleo}$	(2)	***Paleoseismic Event Rate*** *(32 sites in CA)*
$\sum_{r=1}^{R} M_{gr}^{m} f_r = R_g^{m}$	(3)	***Regional MFD Constraint*** *(GR)*

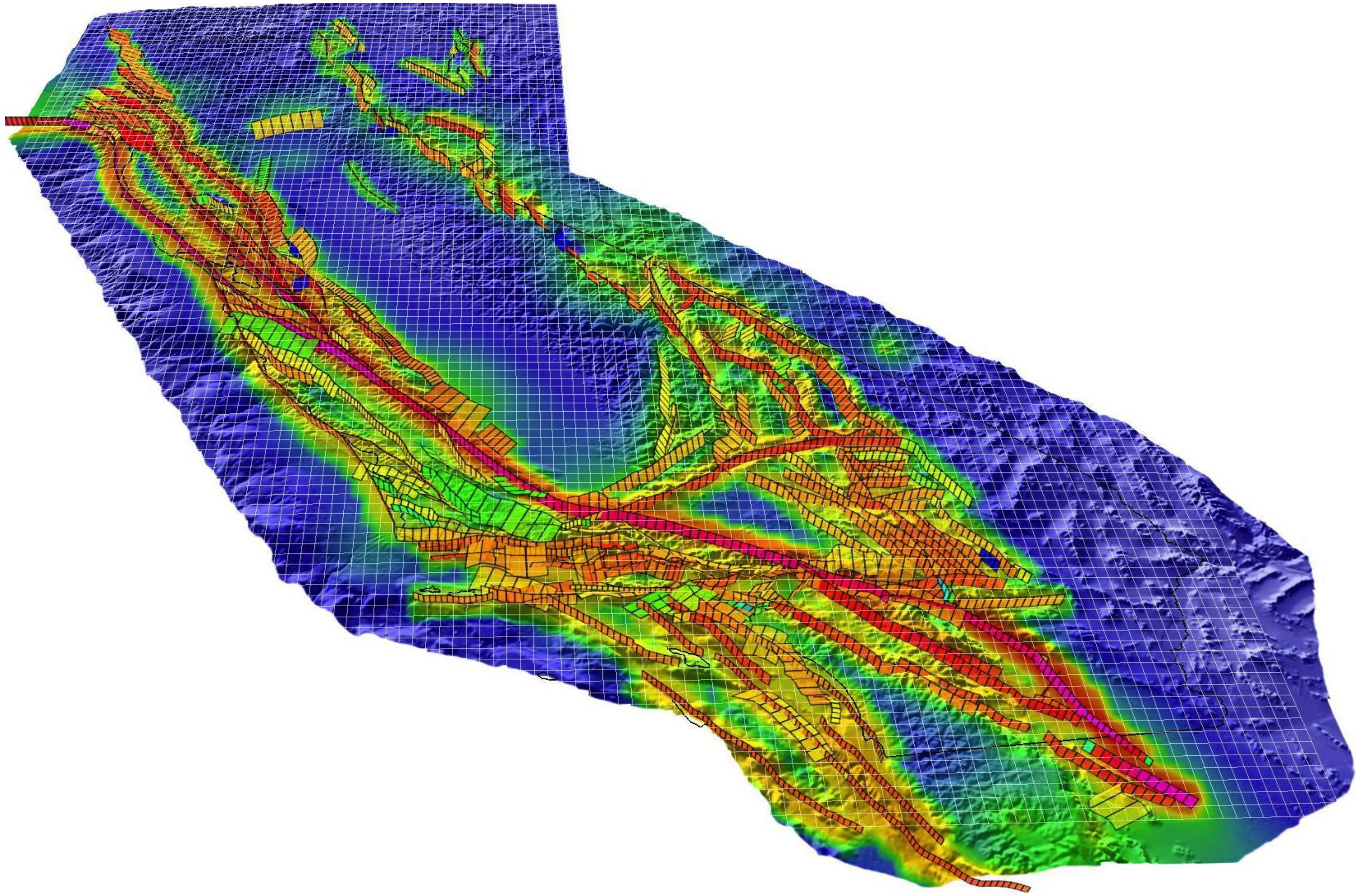
Other Equations

.

.

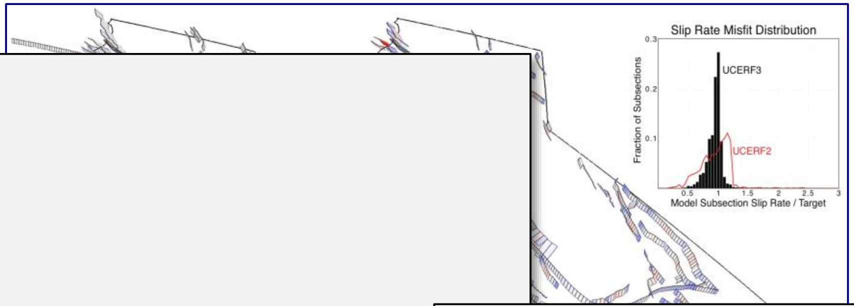
.

Add off-fault (gridded) seismicity to make a complete forecast



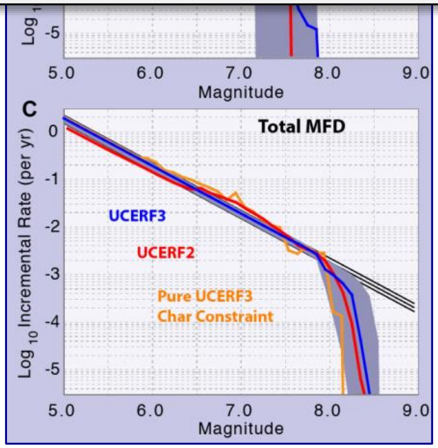
Data Fits (better than UCERF2):

Region MFDs

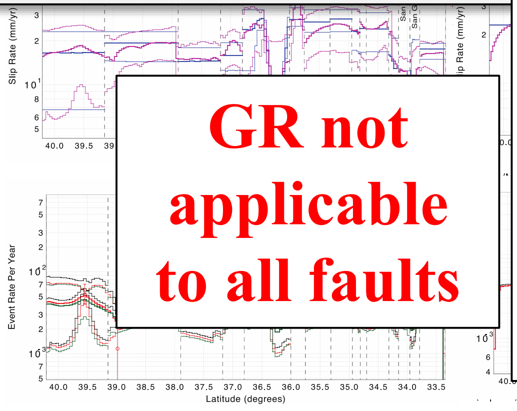


UCERF3-TI:

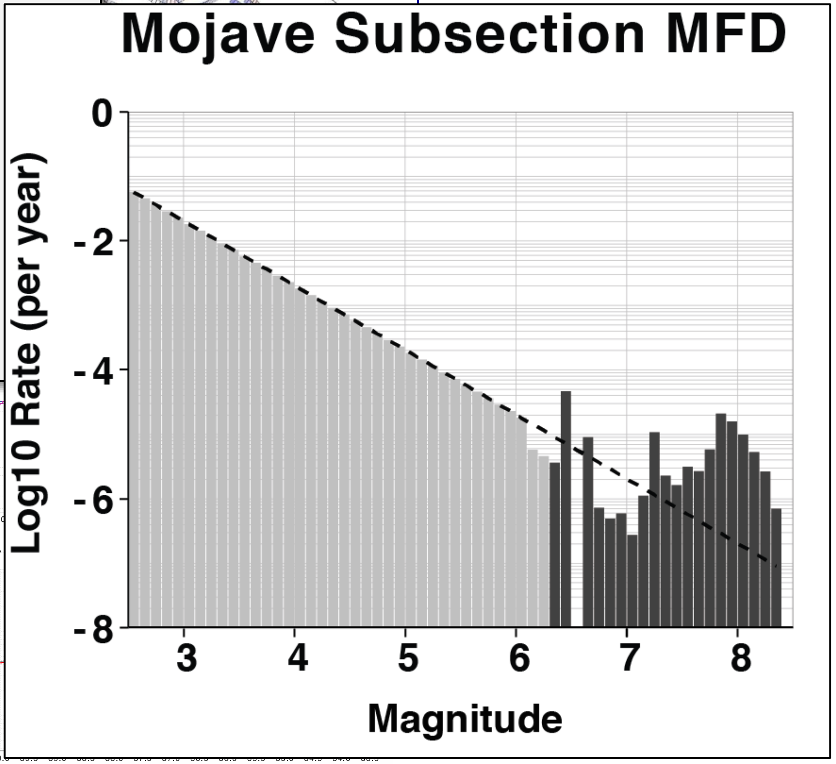
- ✓ Fits a broader range of data better
- ✓ Relaxes segmentation assumptions
- ✓ Incorporates multi-fault ruptures
- ✓ Samples a wider range of epistemic uncertainties
- ✓ Is relatively simple, reproducible, and extensible
- ✓ **Enables hypothesis testing (e.g., GR on all faults?)**



Paleo Event Rates:



GR not applicable to all faults



UCERF3 Publications

UCERF3-TI (Time-Independent Model):

- Main report and 20 Appendices in USGS OFR 2013-1165
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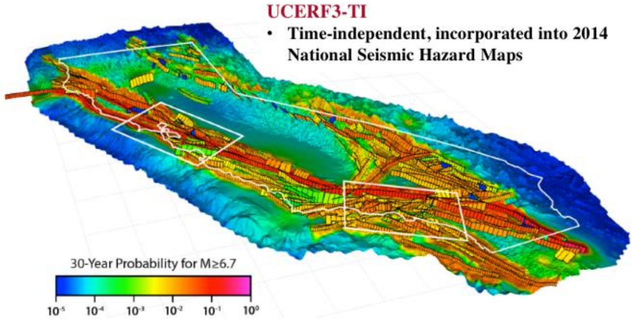


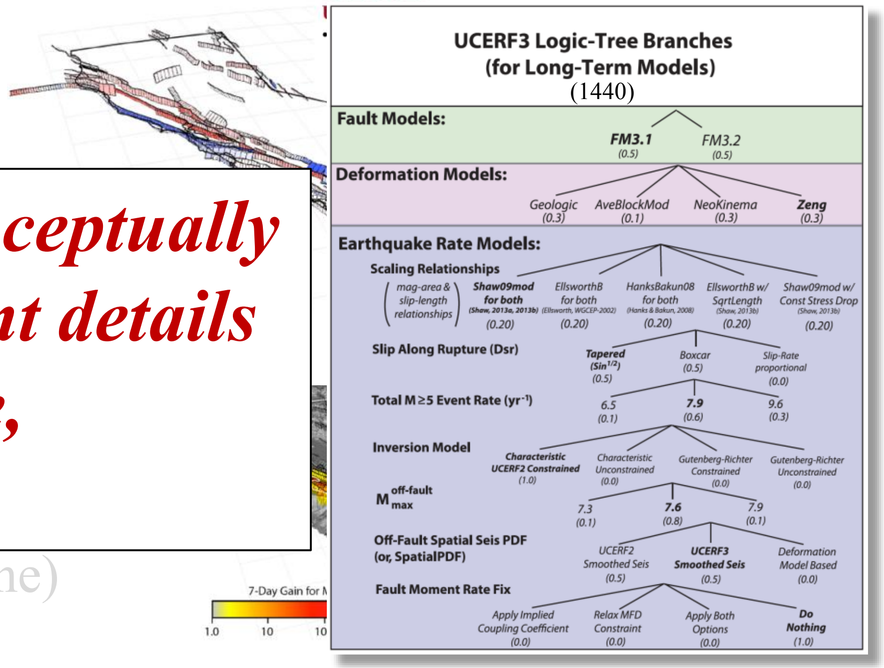
UCERF3-TD (Long-Term Time Dependent Model)

- Main publis
- USGS

UCERF3-E

- Published in *BSSA* (June, 2017; available on line)

The grand inversions is conceptually simple, but a lot of important details have been glossed over here, including uncertainties.



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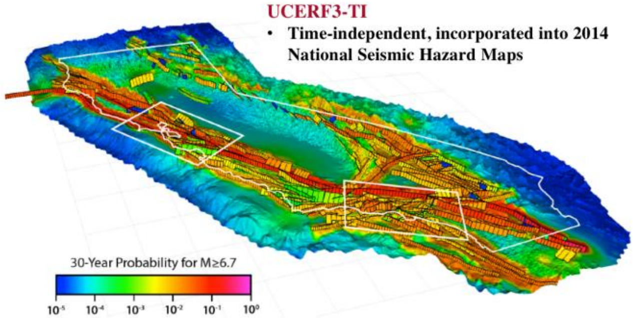
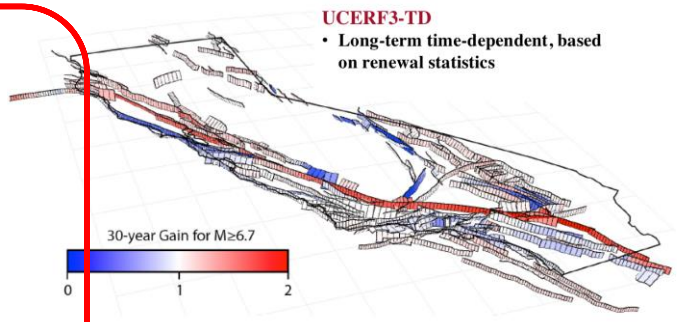


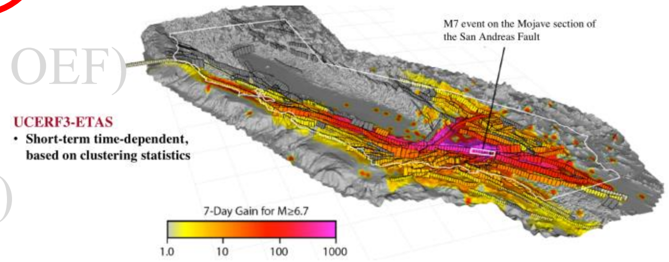
UCERF3-TD (Long-Term Time Dependent Model)

- Main report & two methodology papers published in *BSSA (*April, 2015*)*
- USGS Fact sheet too

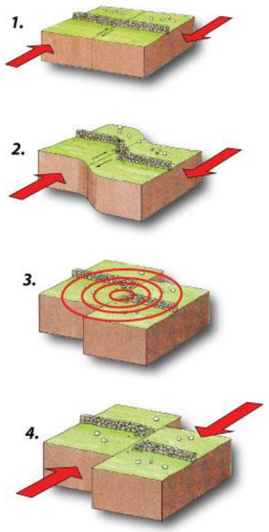


UCERF3-ETAS (Spatiotemporal Clustering Model for OEF)

- Published in *BSSA* (June, 2017; available on line)

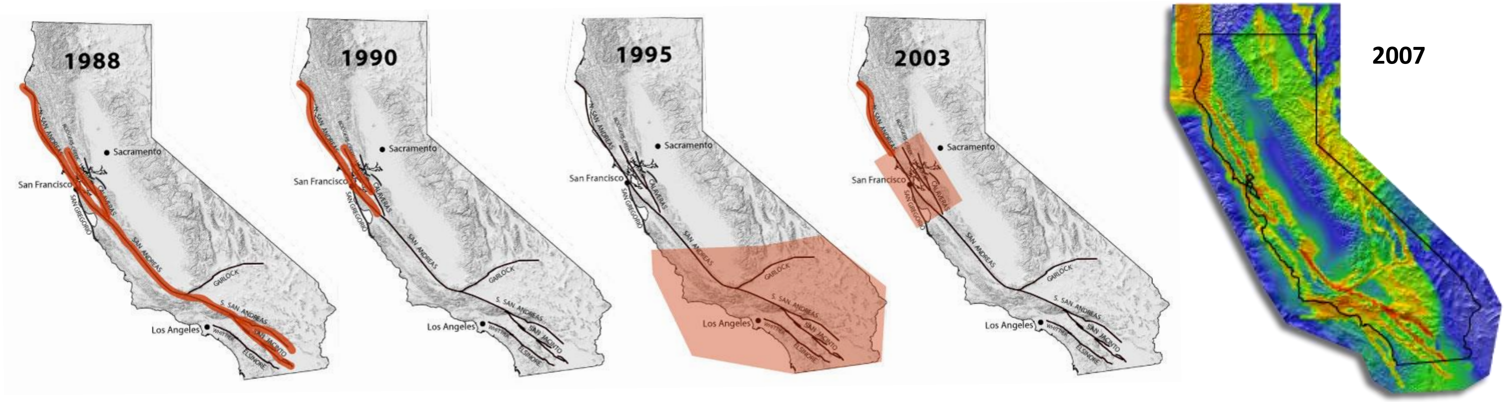


Reid's (1911) Elastic-Rebound Theory:



Rupture probabilities drop on a fault after experiencing a large rupture and build back up with time as tectonic stresses re-accumulate

The basis of all previous WGCEP models:



Problem – WGCEP 2003/2007 algorithm is biased and not self-consistent for un-segmented models

UCERF2 Methodology (from WGCEP 03):

Based on a weight-average of section probability gains

$$P_r^{U2} = f_r \frac{\sum \left(P_s^{BPT} \dot{M}o_s / f_s \right)}{\sum \dot{M}o_s} \approx P_r^{Pois} \frac{\sum \dot{M}o_s \left(P_s^{BPT} / P_s^{Pois} \right)}{\sum \dot{M}o_s}$$

UCERF3 Methodology:

Based on a weight-average of section recurrence intervals and time-since-last-event

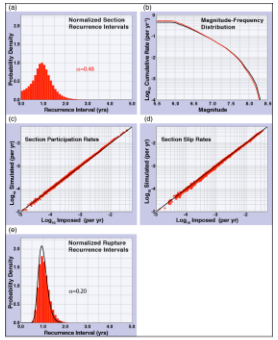
$$\mu_r^{cond} = \frac{\sum \mu_s A_s}{\sum A_s}$$

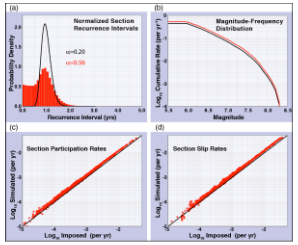
$$\eta_r = \frac{\sum (T_s/\mu_s) A_s}{\sum A_s}$$

$$P_r^{BPT} = P_r^{BPT}\left(\eta_r, \frac{\Delta T}{\mu_r^{cond}}, \alpha\right)$$

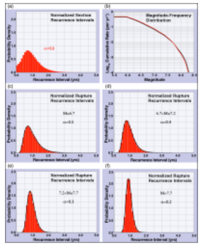
$$P_r^{U3} = P_r^{BPT} \left[\frac{\mu_r^{cond}}{\mu_r} \right]$$

UCERF3-TD Elastic-Rebound Model:





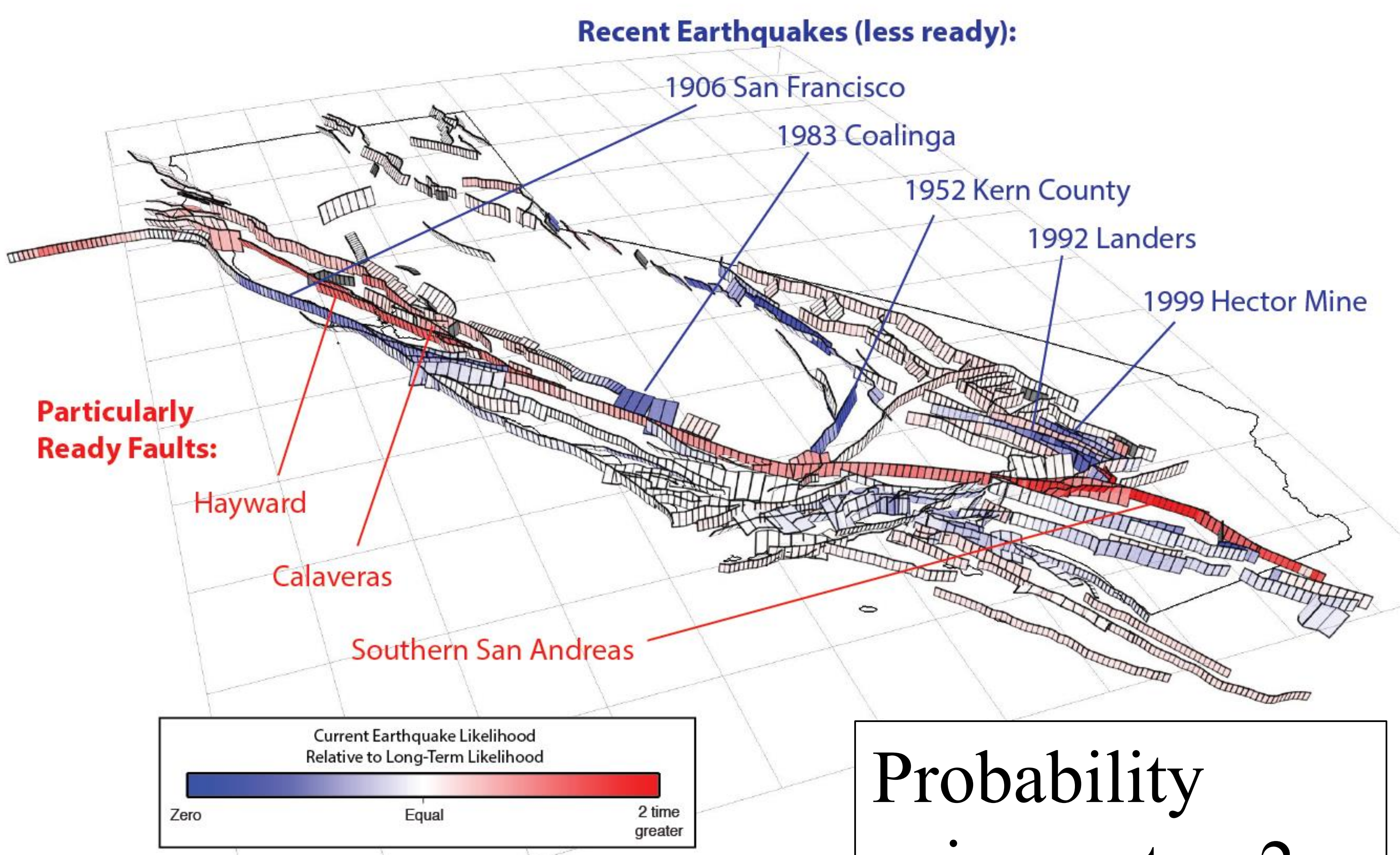
- ✓ **Much more self consistent & less biased**, as shown by Monte Carlos simulations



- ✓ Supports magnitude-dependent aperiodicity
- ✓ Accounts for historic open interval (e.g., *last event was sometime before ~1875*), so time-dependent model **now applied to all faults** (which is influential)
- ✓ Consistent with physics-base simulators (a WGCEP first)

- ✓ Model is more testable

UCERF3-TD



Probability gains up to ~2

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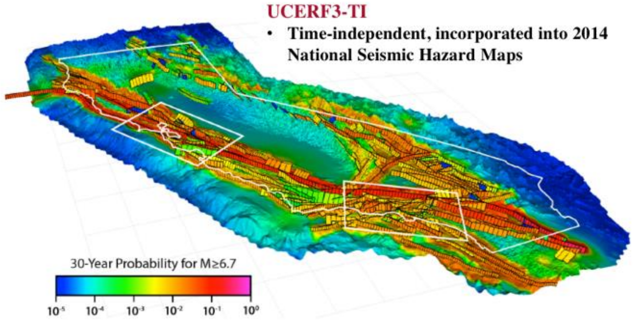

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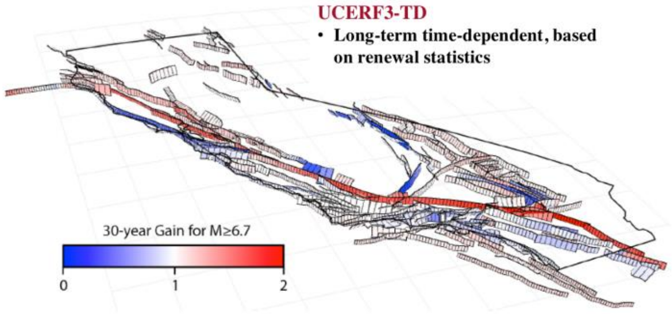
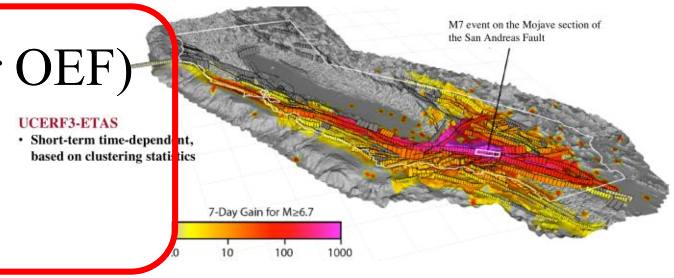
- Main report & two methodology papers published in *BSSA (*April, 2015*)*
- USGS Fact sheet too



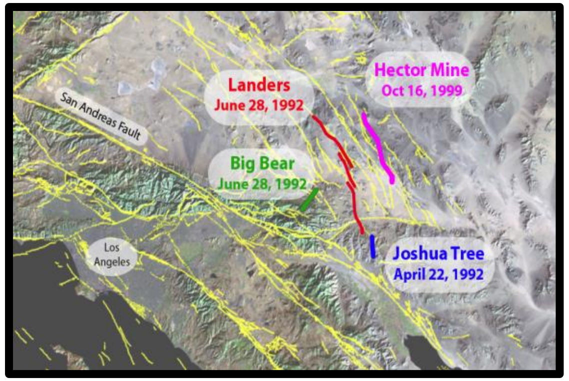
UCERF3-ETAS (Spatiotemporal Clustering Model for OEF)

- *BSSA* (June, 2017)



Why? Because aftershocks (triggered events) can be large and damaging…

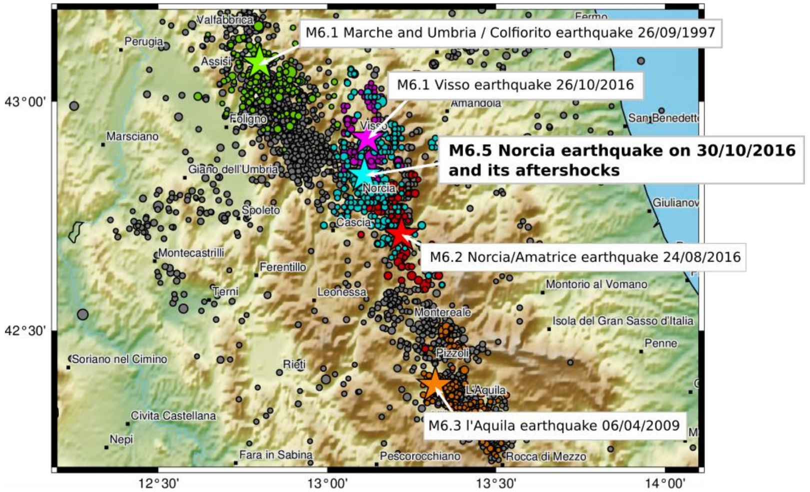
J-tree → Landers → Big Bear → Hector Mine in 1990s



Italy 1997-2016

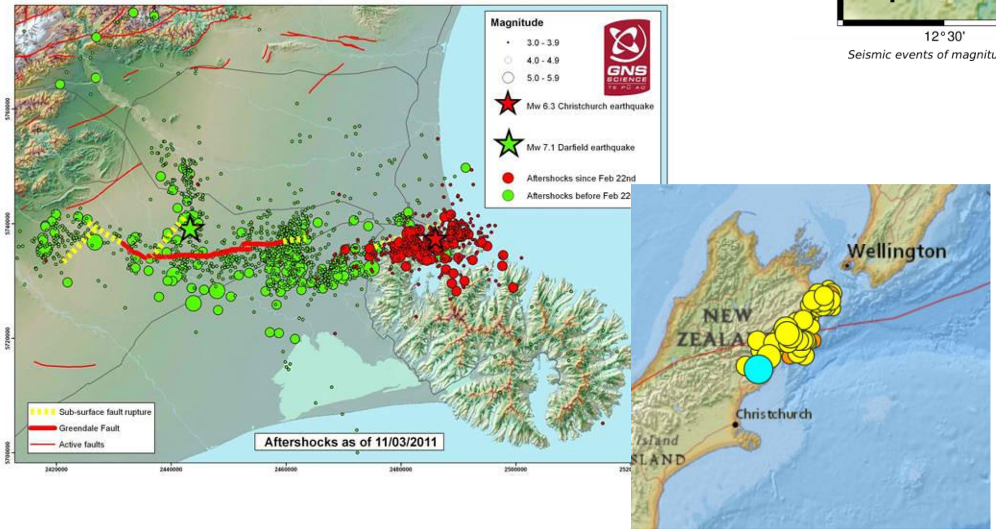
CSEM EMSC

Distribution of main seismic sequences in Italy from 1997 to 02/11/2016



Seismic events of magnitude > 3 from ISC and EMSC database

Darfield → Christchurch → M7.8 Kaikoura

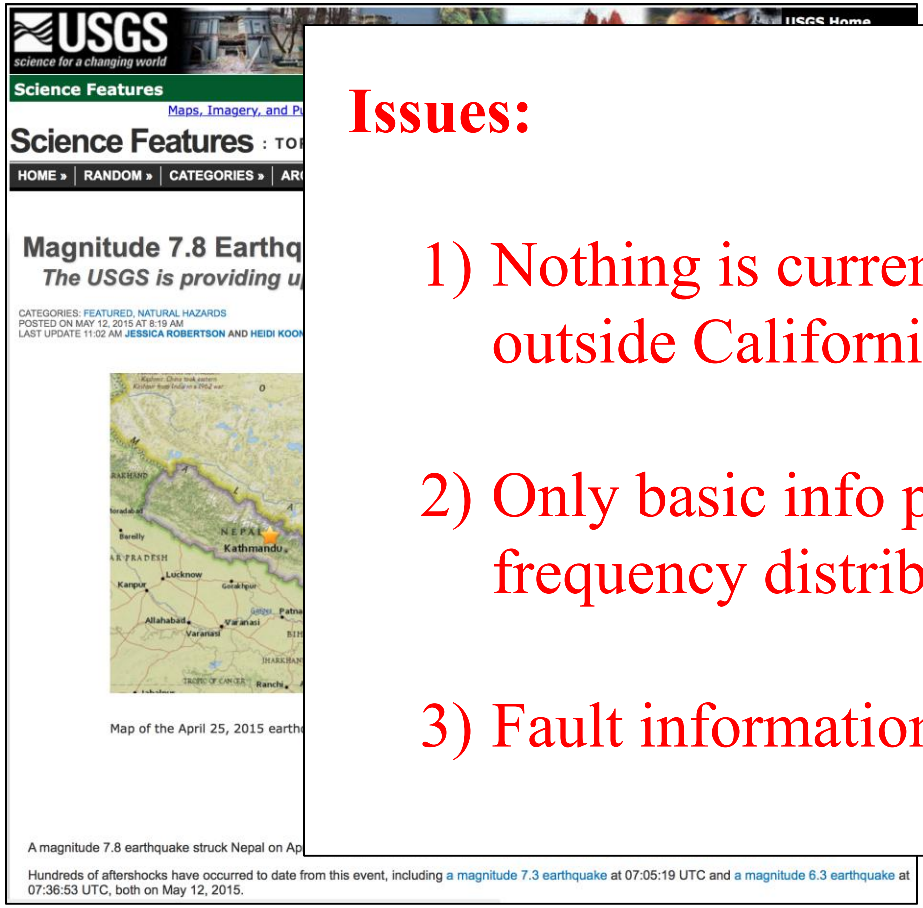


Goal: Operational Earthquake Forecasting (OEF)

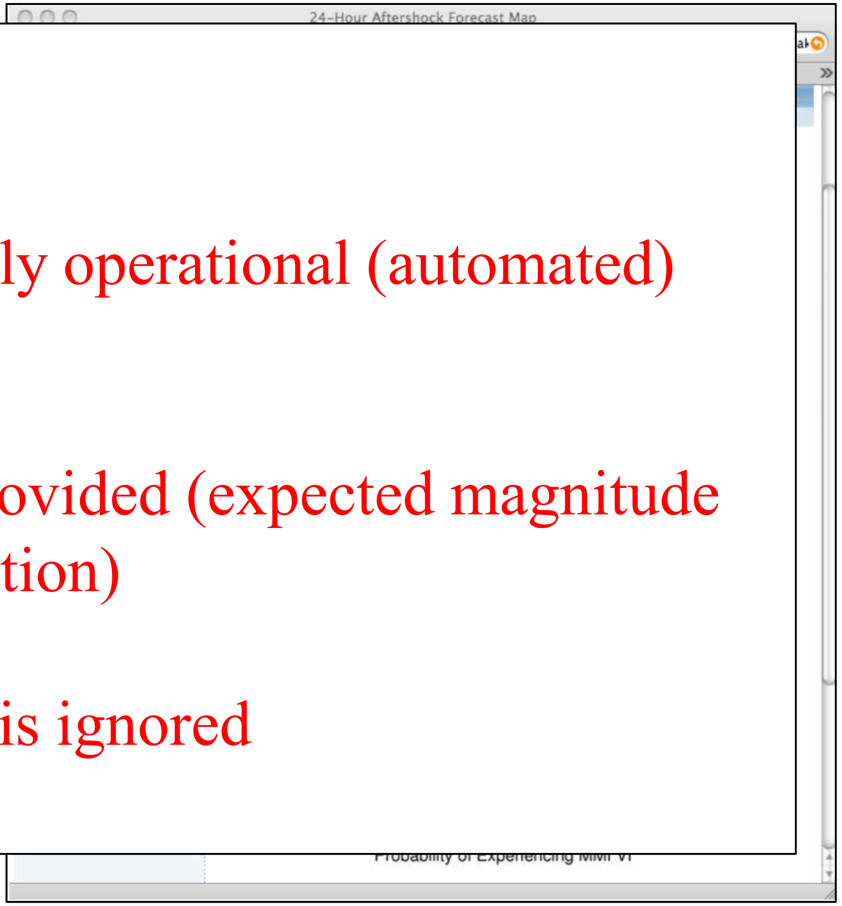
Real-time, authoritative information on earthquake likelihoods (including aftershocks) to inform seismic risk mitigation efforts (Jordan and Jones, 2010; Jordan et al., 2011).

The USGS has been releasing aftershock information since the 1980s…

Ad hoc notifications (hand built; slow)



STEP aftershock hazard (2005-2010)



Issues:

1) Nothing is currently operational (automated) outside California

2) Only basic info provided (expected magnitude frequency distribution)

3) Fault information is ignored

Currently Viable OEF Models

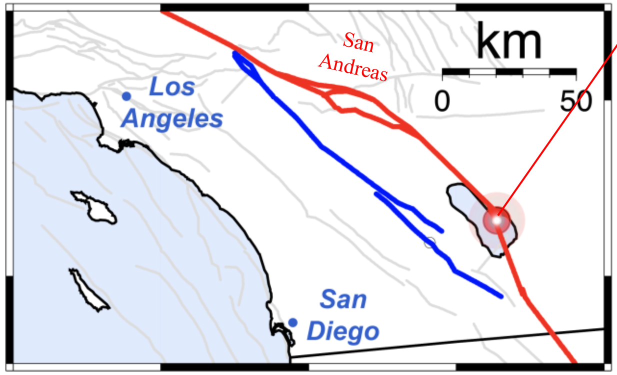
1) Reasenberg & Jones (1989)
2) STEP (Gerstenberger et al., 2005)
3) ETAS (Ogata, 1988)

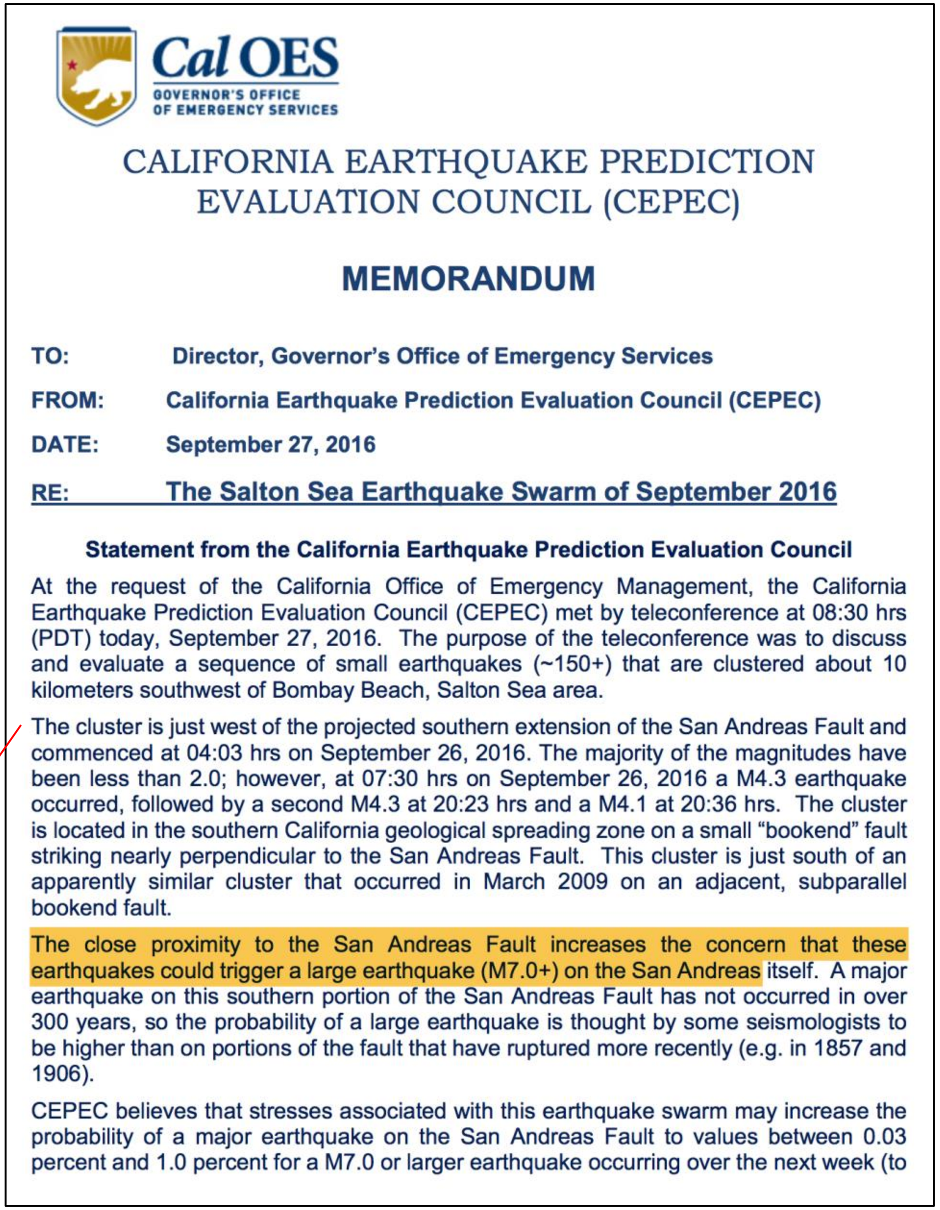
All these ignore faults

- All imply that he most likely place for next event is the location of the most recent one (opposite of Reid's elastic rebound)
- Experts think that fault proximity is important when it comes to triggering large earthquakes

Faults are important…

*i.e., **CEPEC** - the California Earthquake Prediction Evaluation Council (which advised the governor/CalOES) gets on the phone when small earthquakes are occurring near the San Andreas Fault.*





Cal OES
GOVERNOR'S OFFICE OF EMERGENCY SERVICES

CALIFORNIA EARTHQUAKE PREDICTION EVALUATION COUNCIL (CEPEC)

MEMORANDUM

TO: Director, Governor's Office of Emergency Services

FROM: California Earthquake Prediction Evaluation Council (CEPEC)

DATE: September 27, 2016

RE: **The Salton Sea Earthquake Swarm of September 2016**

Statement from the California Earthquake Prediction Evaluation Council

At the request of the California Office of Emergency Management, the California Earthquake Prediction Evaluation Council (CEPEC) met by teleconference at 08:30 hrs (PDT) today, September 27, 2016. The purpose of the teleconference was to discuss and evaluate a sequence of small earthquakes (~150+) that are clustered about 10 kilometers southwest of Bombay Beach, Salton Sea area.

The cluster is just west of the projected southern extension of the San Andreas Fault and commenced at 04:03 hrs on September 26, 2016. The majority of the magnitudes have been less than 2.0; however, at 07:30 hrs on September 26, 2016 a M4.3 earthquake occurred, followed by a second M4.3 at 20:23 hrs and a M4.1 at 20:36 hrs. The cluster is located in the southern California geological spreading zone on a small "bookend" fault striking nearly perpendicular to the San Andreas Fault. This cluster is just south of an apparently similar cluster that occurred in March 2009 on an adjacent, subparallel bookend fault.

The close proximity to the San Andreas Fault increases the concern that these earthquakes could trigger a large earthquake (M7.0+) on the San Andreas itself. A major earthquake on this southern portion of the San Andreas Fault has not occurred in over 300 years, so the probability of a large earthquake is thought by some seismologists to be higher than on portions of the fault that have ruptured more recently (e.g. in 1857 and 1906).

CEPEC believes that stresses associated with this earthquake swarm may increase the probability of a major earthquake on the San Andreas Fault to values between 0.03 percent and 1.0 percent for a M7.0 or larger earthquake occurring over the next week (to

Faults are important…

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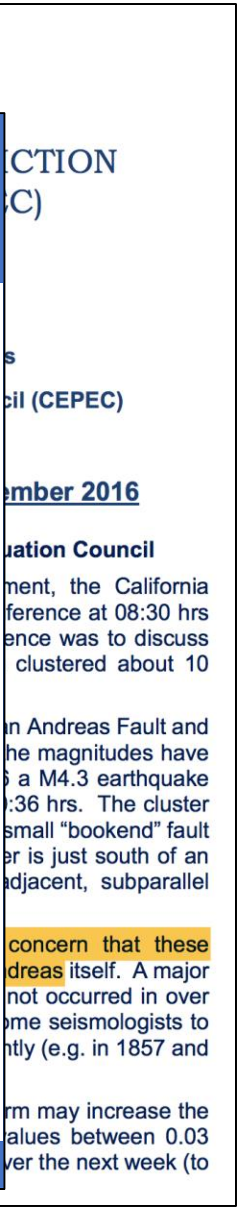
Cal OES
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Los Angeles Times

In a first for San Bernardino, heightened earthquake risk temporarily closes City Hall

San Bernardino City Hall will be closed Monday and Tuesday, in response to a heightened earthquake risk in Southern California. (Irfan Khan/Los Angeles Times)

By Brittny Mejia

OCTOBER 3, 2016, 2:15 PM

The seismically vulnerable San Bernardino City Hall will be closed through Tuesday in response to a heightened earthquake risk in Southern California, city officials said.

The decision to close City Hall on Monday and Tuesday comes in response to a swarm of earthquakes in the Salton Sea area last week, which temporarily increased the likelihood of a major earthquake in Southern California.

US Residents Born Before 1966 Are In For a Surprise
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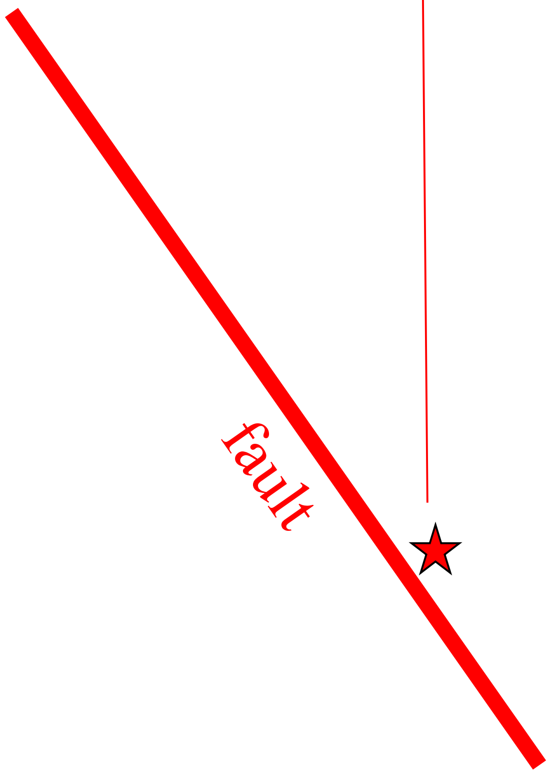
In Case You Missed It

The question: is this M 5 earthquake more likely to trigger something big (e.g., M≥6.7) than this one?



If you answered yes, then you also believe in characteristic MFDs on faults

Currently Viable OEF Models

1) Reasenberg & Jones (1989)
2) STEP (Gerstenberger et al., 2005)
3) ETAS (Ogata, 1988)

All these ignore faults

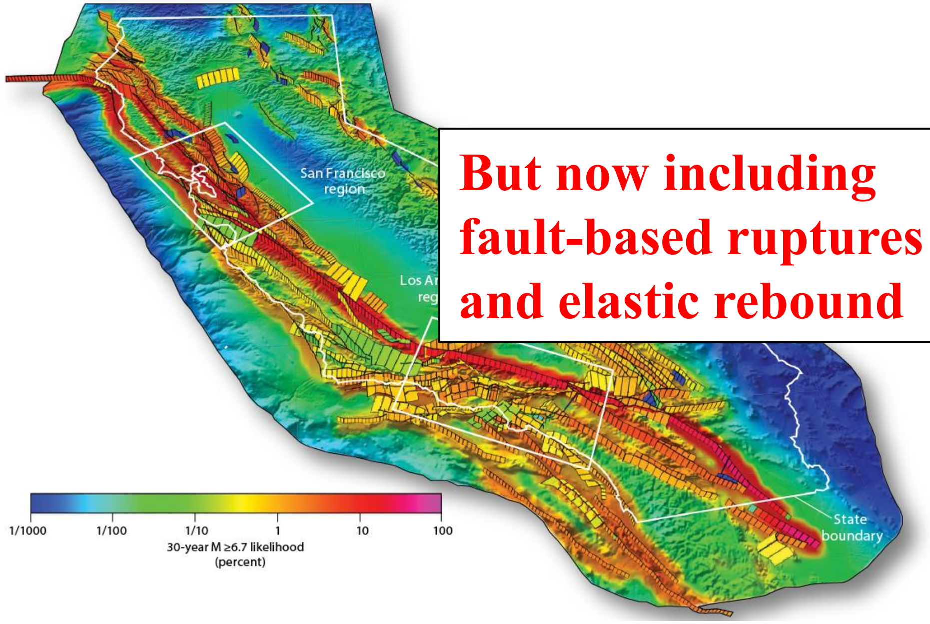
4) **UCERF3-ETAS (Field et al., 2017)**

- Includes faults (considers proximity, long-term event rate, and elastic-rebound readiness)

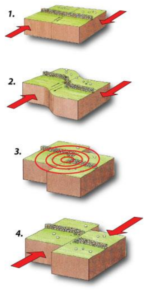
UCERF3-ETAS in a Nutshell

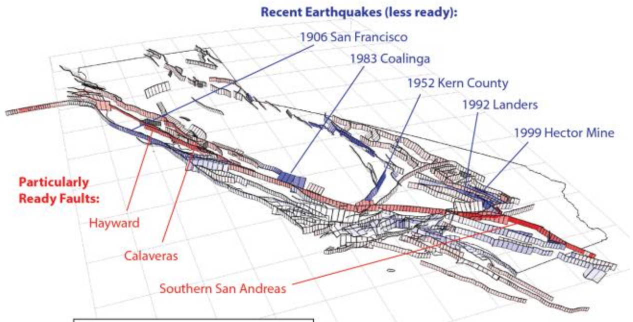
UCERF3-TD

+



But now including fault-based ruptures and elastic rebound



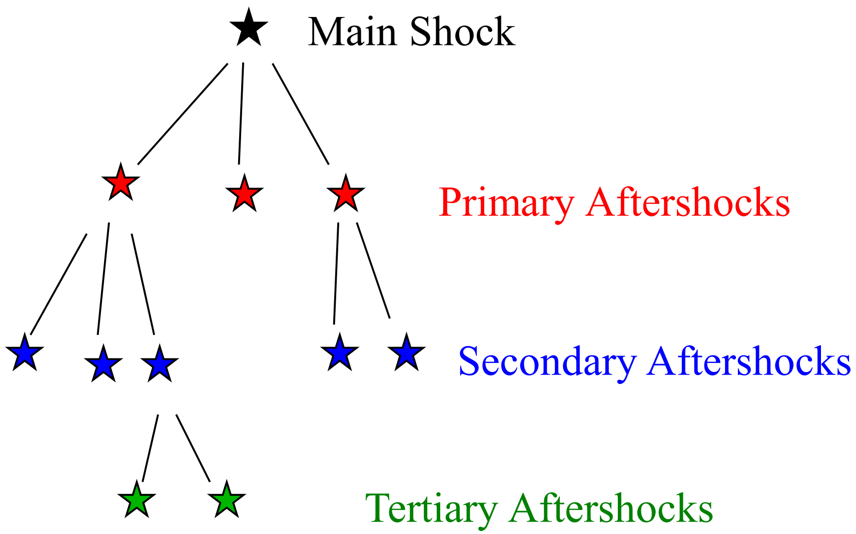


ETAS Model

(Epidemic Type Aftershock Sequence)

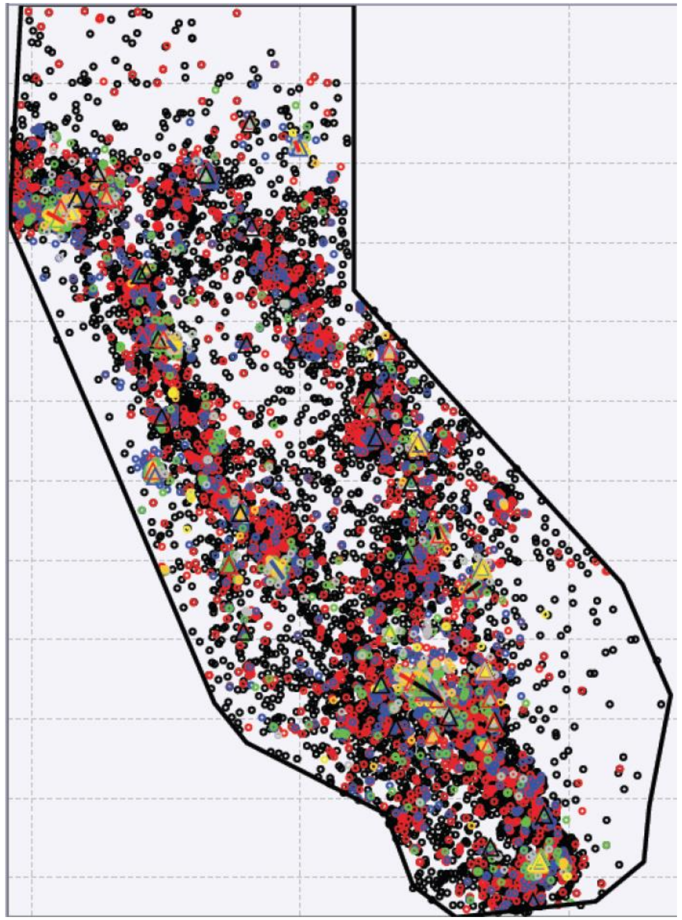
An empirically based description of triggering statistics (Ogata, 1998):

$$\lambda(t,\mathbf{x}) = \lambda_o \mu(\mathbf{x}) + \sum_{\{i:\, t_i < t\}} k 10^{a(M_i - M_{\min})} (t - t_i + c)^{-p} c_S (r + d)^{-q}$$



UCERF3-ETAS in a Nutshell

Product: synthetic catalog of events (stochastic event set)



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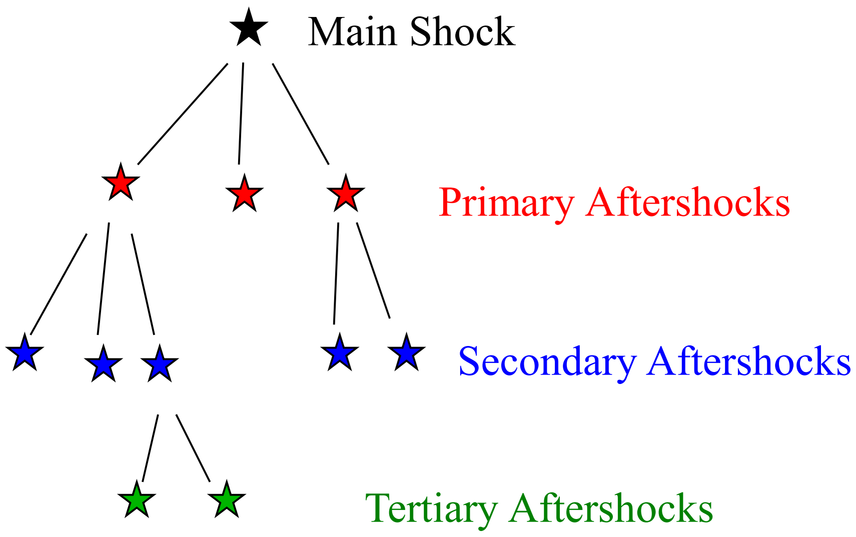


UCERF3-ETAS in a Nutshell

Product: synthetic catalog of events (stochastic event set) obtained by doing the following:

- Discretize UCERF3 region into 2
- For every observed and simulated randomly sample a number of tri their origin times (using ETAS pa
- For each event, we randomly sam according to the distance decay f
- We then chose a rupture based on probability that each can nucleate cube, and considering elastic rebo
- We also allow spontaneous events to occur, which can also produce aftershocks

ETAS Model

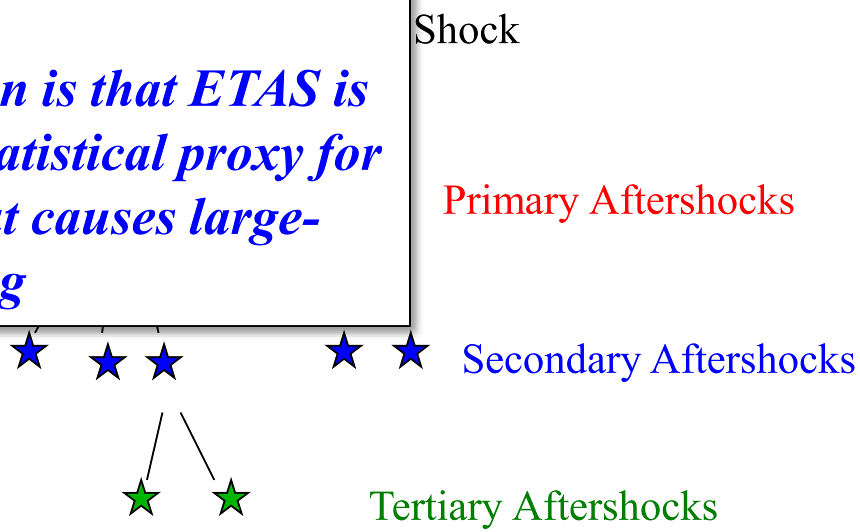
(Epidemic Type Aftershock Sequence)

ased description of ics (Ogata, 1998):

$$\ldots^{a(M_i - M_{\min})}(t - t_i + c)^{-p} c_S (r + d)^{-q}$$

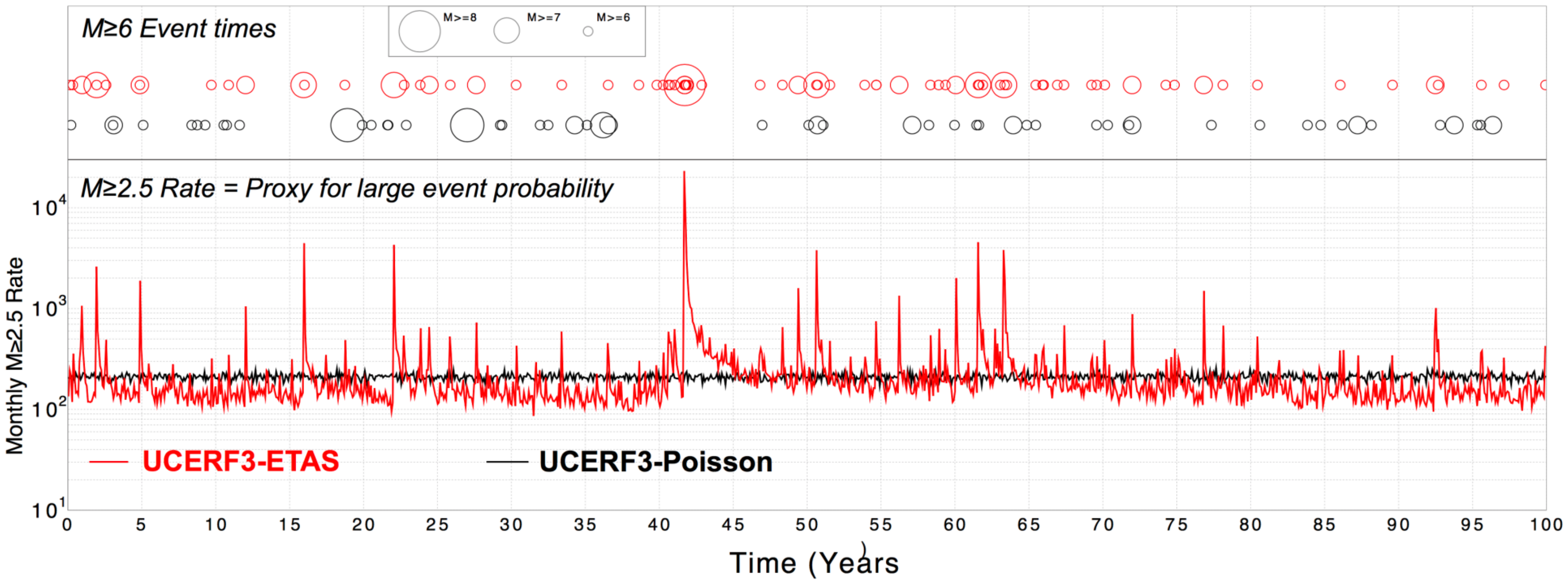
See BSSA paper for details (bookkeeping is somewhat complicated due to need for elastic-rebound updating and numerical efficiency)

The assumption is that ETAS is an adequate statistical proxy for the physics that causes large-event triggering



Results…

Like all candidate OEF models, we essentially correlate changes in the rate of little earthquakes with the likelihood of having big ones

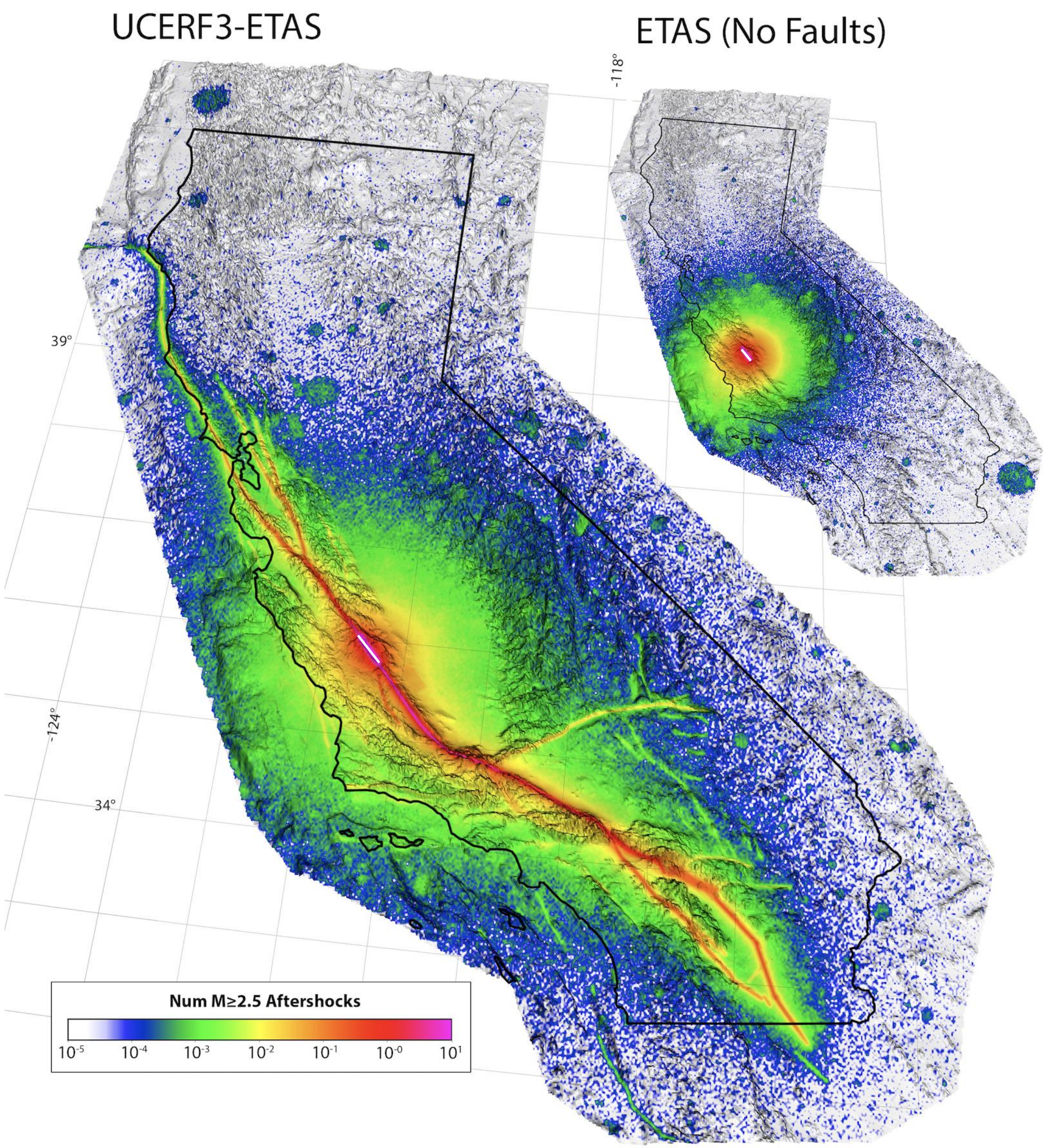


SCEC USGS CGS California Geological Survey

M 6.1 Parkfield Aftershocks

(10 yrs following)

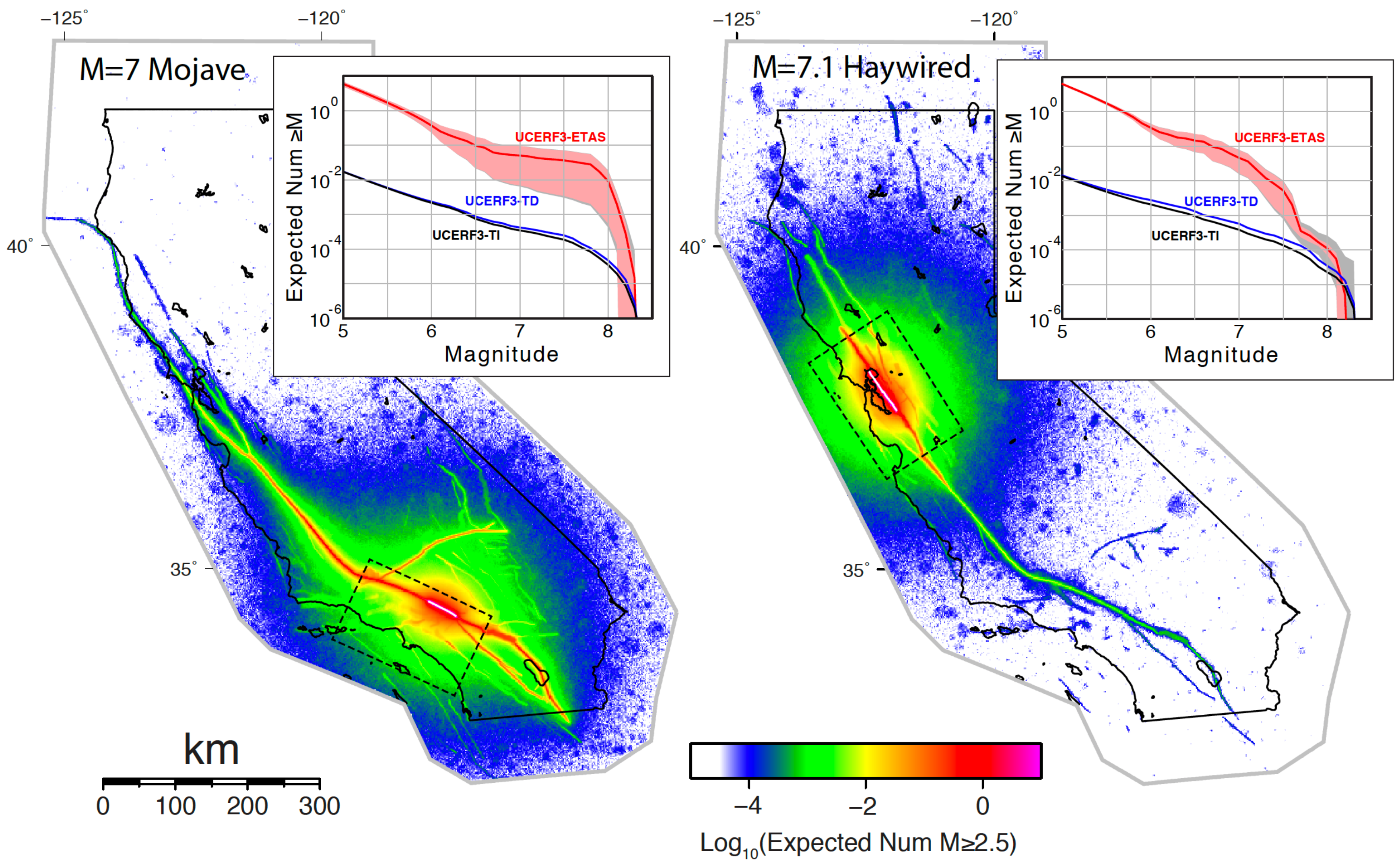
average of 200,000 simulations



Note that the M7.8 1857 Fort Tejon earthquake is believed to have been preceded by an M6.1 Parkfield foreshock (UCERF3-ETAS gives a 6e-3 probability of this occurring)

Aftershocks expected over a week following two main shock scenarios

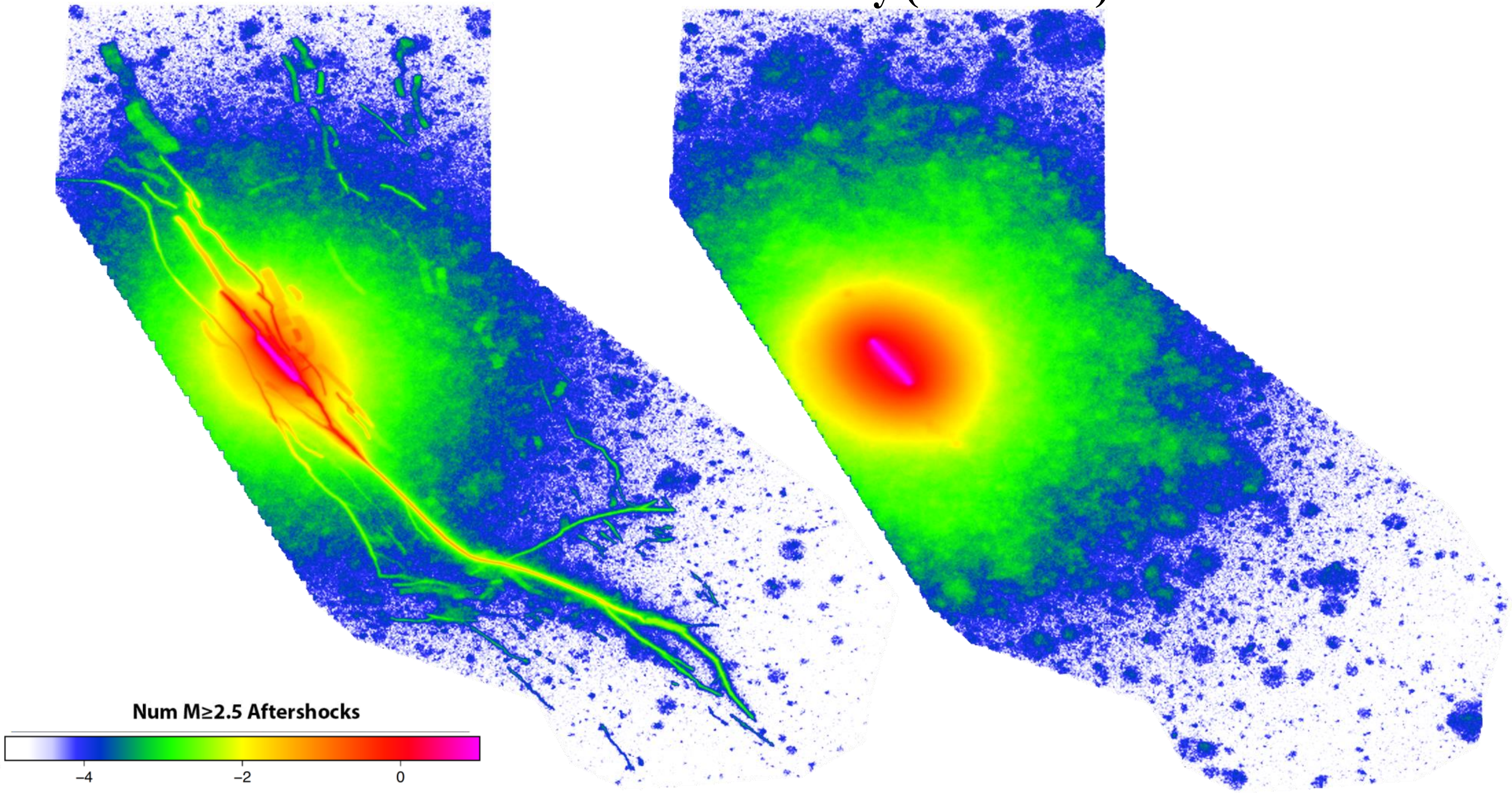
The average of 200,000 UCERF3-ETAS simulations



M 7.1 "HayWired" Scenario Aftershocks

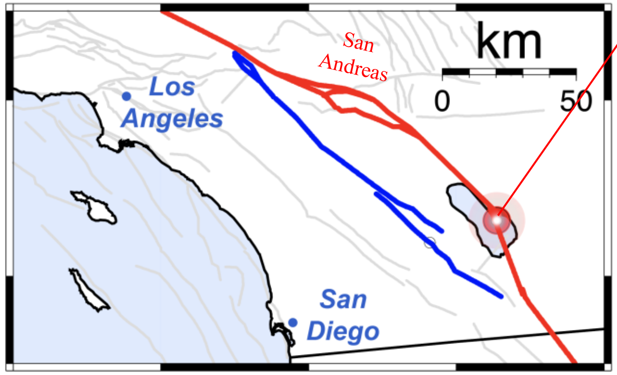
The average of 200,000 UCERF3-ETAS simulations

UCERF3-ETAS | **ETAS Only (No Faults)**



Swarm near Bombay Beach

CEPEC Notification



Cal OES
GOVERNOR'S OFFICE OF EMERGENCY SERVICES

CALIFORNIA EARTHQUAKE PREDICTION
EVALUATION COUNCIL (CEPEC)

MEMORANDUM

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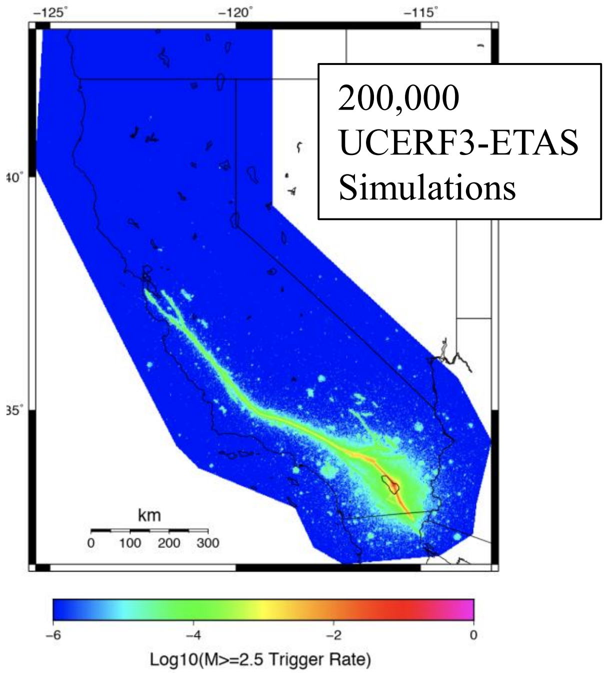
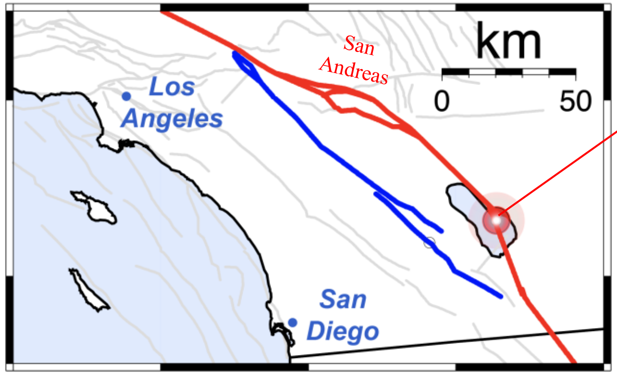
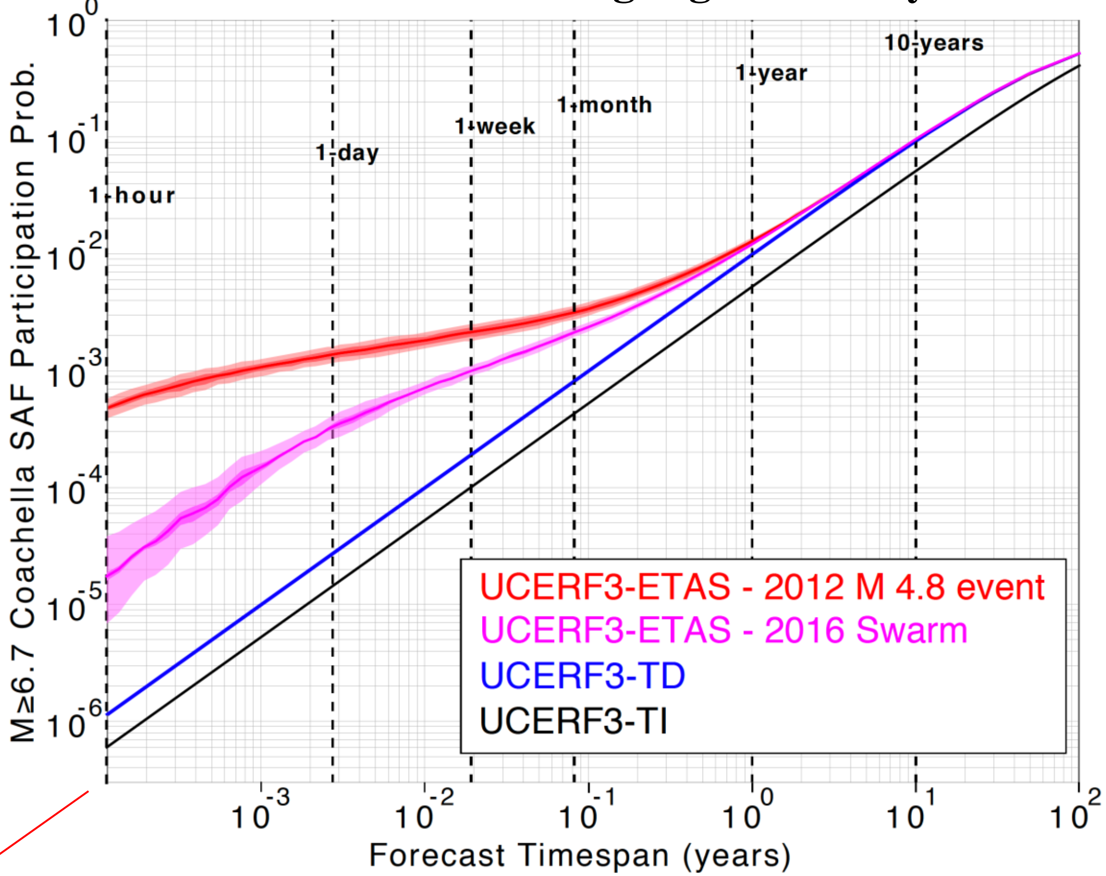
Swarm near Bombay Beach



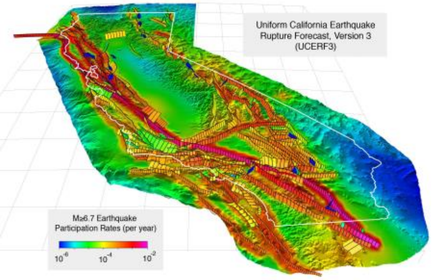


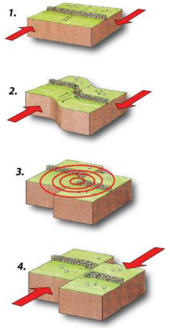
Likelihood of something big on nearby SAF

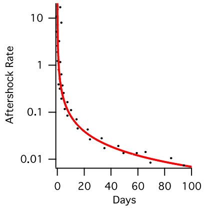


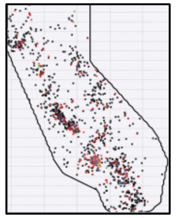
UCERF3 Summary: we now have a scientifically plausible, operationalizable, end-to-end forecast for California that:

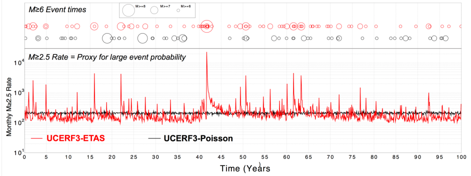
- Relaxes segmentation and includes multi-fault ruptures
- Includes elastic rebound and spatiotemporal clustering
- Generates synthetic catalogs (stochastic event sets)
- Within reach: USGS PAGER- and ShakeCast-type products, but giving risk from triggered events

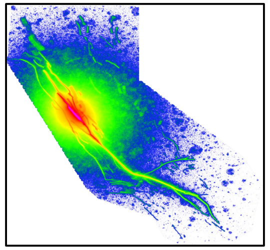


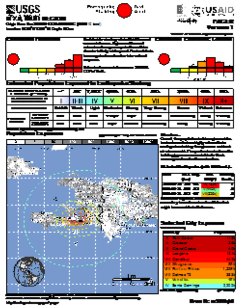




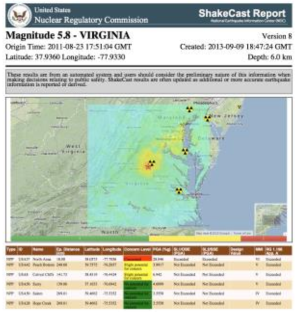








PAGER



ShakeCast

UCERF3 Summary: we now have a scientifically plausible, operationalizable, end-to-end forecast for California.

***Scientific Implications*:**

Combing spatiotemporal clustering with faults implies a need for both characteristic magnitude-frequency distributions and elastic rebound (longstanding debate settled?)

***Practical Implications*:**

Deploying UCERF3-ETAS as an Operational Earthquake Forecasting (OEF) system will take considerable time, effort, and resources

All models embody assumptions, approximations, and uncertainties, so the question is whether UCERF3-ETAS is right enough to be useful, and useful enough to be worth operationalizing; thus, we need to add ***valuation*** to our verification and validation protocol

Does UCERF3-ETAS/OEF have potential value?

Currently Viable OEF Models

1) Reasenberg & Jones (1989)
2) STEP (Gerstenberger et al., 2005)
3) ETAS (Ogata, 1988)

All these ignore faults

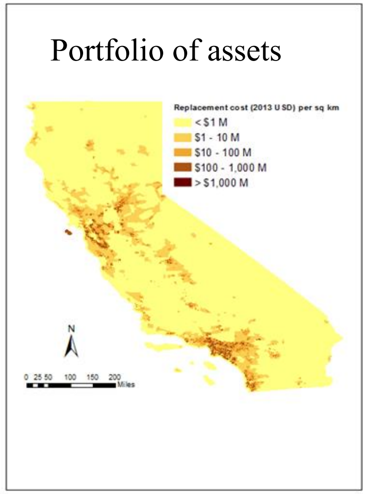
4) **UCERF3-ETAS (Field et al., 2017)**

Is this really more valuable than the other models, especially given it is more computationally expensive?

Does UCERF3-ETAS/OEF have potential value?

Answer depends on:

1) What one is concerned about



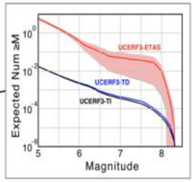
Does UCERF3-ETAS/OEF have potential value?

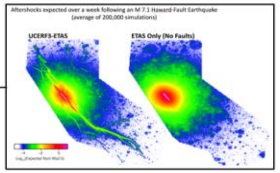
Answer depends on:

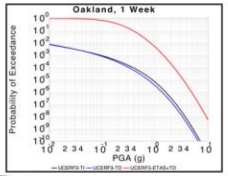
1) What one is concerned about

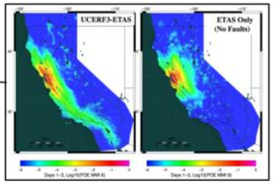
2) The product of interest
(the hazard or risk metric)

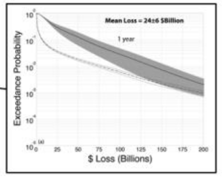
Potential OEF Products	
1)	Magnitude Probability Distribution
2)	Magnitude Probability Map
3)	Hazard Curve
4)	Hazard Map
5)	Loss Exceedance Curve
6)	Loss Exceedance Map
7)	Fault participation probability
8)	Gains for 1-7 above
9)	Stochastic event sets
10)	Example aftershock scenario events

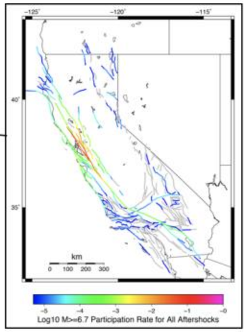


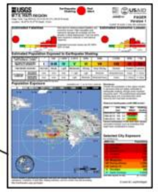












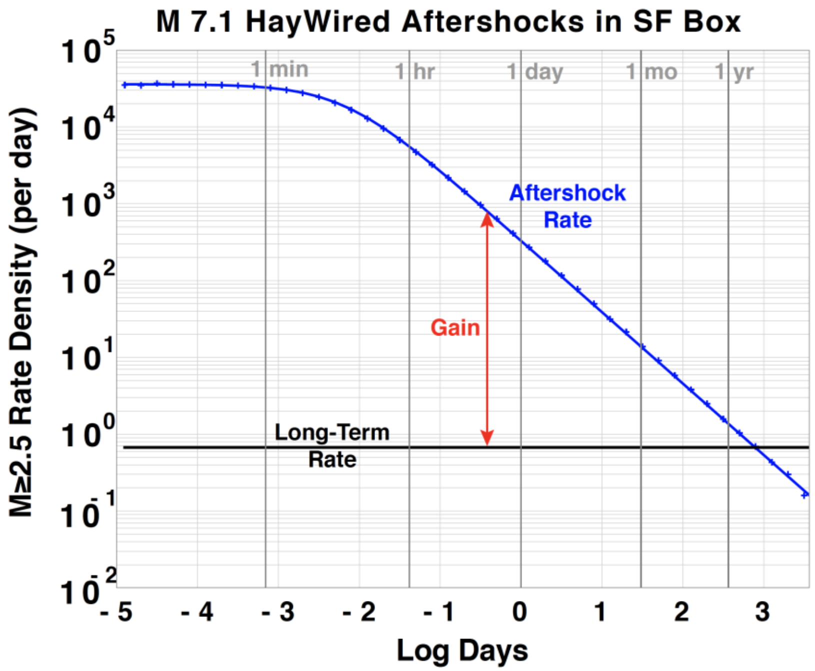
Does UCERF3-ETAS/OEF have potential value?

Answer depends on:

1) What one is concerned about

2) The product of interest (the hazard or risk metric)

3) What gains would be actionable (compared to long-term averages)



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Answer depends on:

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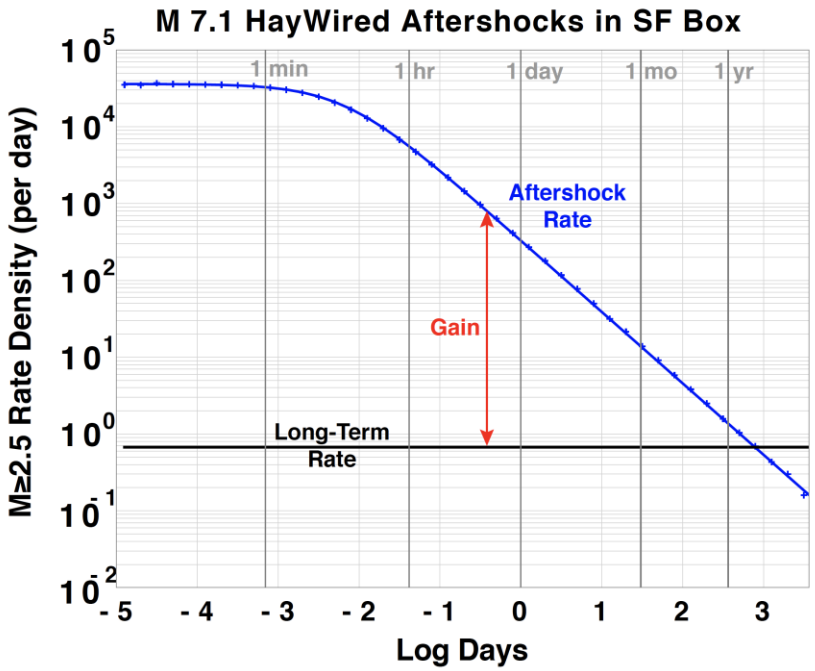
2) The product of interest (the hazard or risk metric)

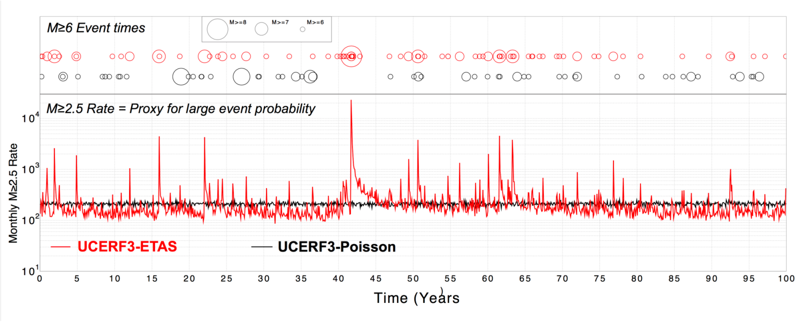
3) What gains would be actionable (compared to long-term averages)

4) The decision making timeframe (because gains decay rapidly)



Does UCERF3-ETAS/OEF have potential value?

Example with respect to statewide losses:



How do expected, statewide losses change with time, or after large main shocks?

A Prototype Operational Earthquake Loss Model for California Based on UCERF3-ETAS – A First Look at Valuation

Edward Field,[a)] M.EERI, Keith Porter,[b)] M.EERI, and Kevin Milner[c)] M.EERI

We present a prototype operational loss model based on UCERF3-ETAS, which is the third Uniform California Earthquake Rupture Forecast with an Epidemic Type Aftershock Sequence (ETAS) component. As such, UCERF3-ETAS represents the first earthquake forecast to relax fault segmentation assumptions and to include multi-fault ruptures, elastic-rebound, and spatiotemporal clustering, all of which seem important for generating realistic and useful aftershock statistics. UCERF3-ETAS is nevertheless an approximation of the system, however, so usefulness will vary and potential value needs to be ascertained in the context of each application. We examine this question with respect to statewid

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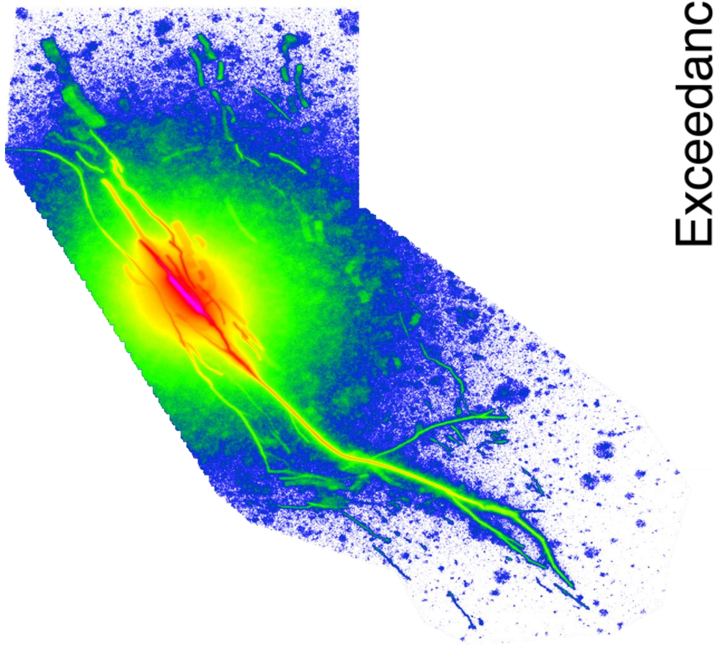
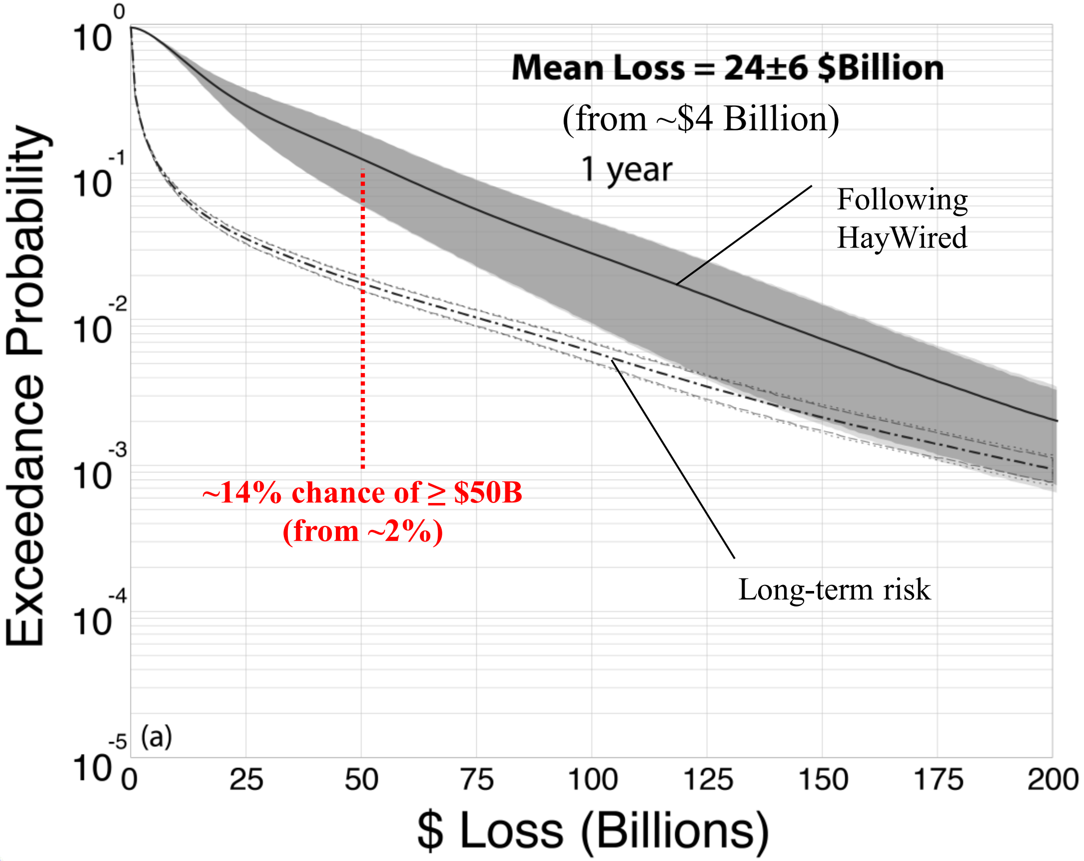
Does UCERF3-ETAS/OEF have potential value?

1-year, statewide losses following *M* 7.1 Hayward main shock

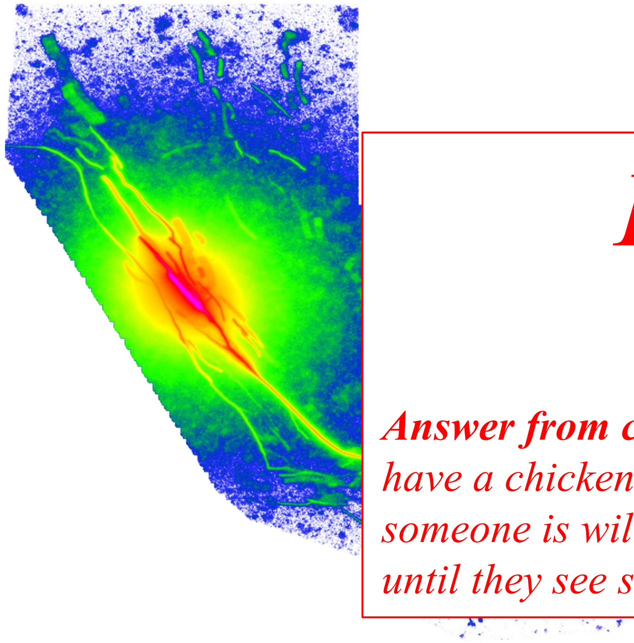




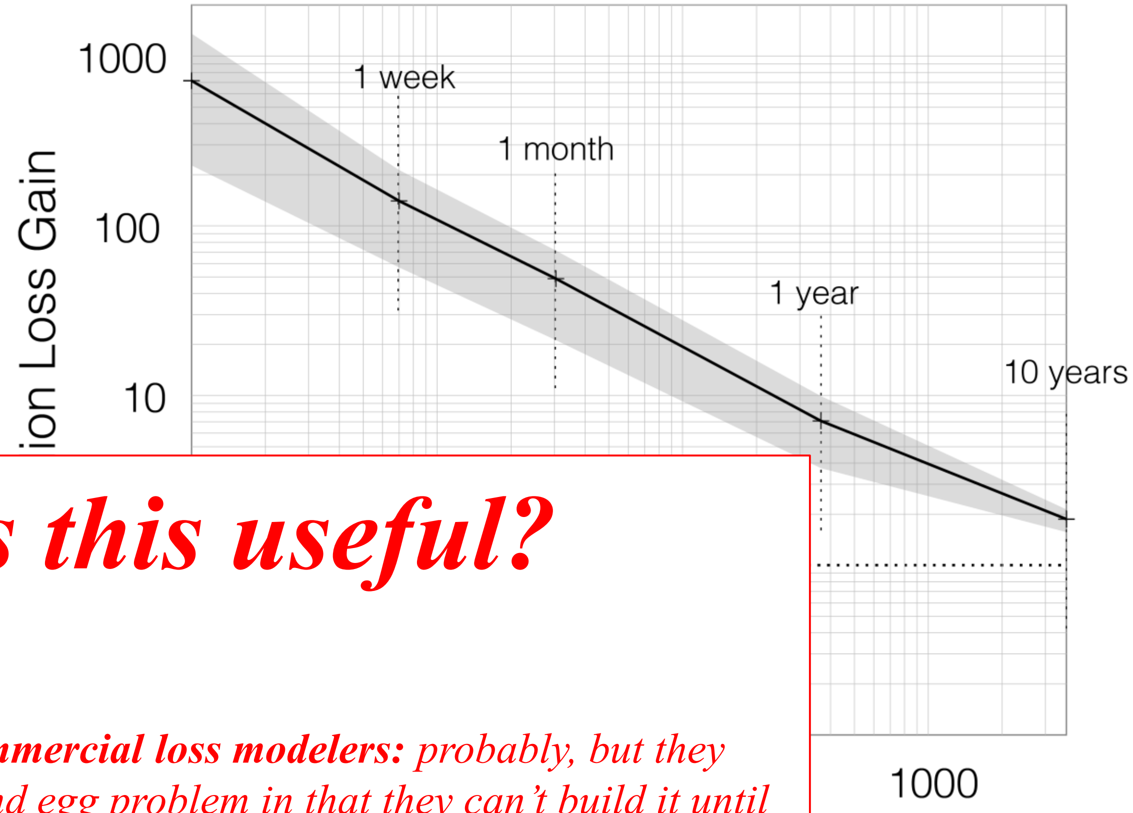
1yr Probability Gain = ~7

Does UCERF3-ETAS/OEF have potential value?

1-year, statewide losses following *M* 7.1 Hayward main shock



Gain decay with time



Is this useful?

Answer from commercial loss modelers: *probably, but they have a chicken and egg problem in that they can't build it until someone is willing to pay for it, and clients don't want to pay until they see some results*

Does Some form of OEF have potential value?

Answer depends on:

1) What one is concerned about

2) What product they want (the hazard of risk metric)

3) What gains would be actionable (compared to long-term averages)

4) The decision making timeframe (because gains decay rapidly)

- *So we are still in the process of getting answers to these questions (and this may take some time)*

- *Given budgetary constraints, the USGS will need to partner with stakeholders to go beyond traditional capabilities*

What about UCERF4?

- Need time for the community to figure out what we would want to “fix”
- Host workshops in about six months to discuss?

SCEC USGS CGS CALIFORNIA GEOLOGICAL SURVEY

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UCERF3 Questions/Issues/Uncertainties:

1) Artificial distinction between on- and off-fault qks
2) What do modeled faults actually represent (braided?)
3) What is the actual fault interconnectivity?
4) Slip rates (GPS vs geology, backslip, block models)
5) Total regional rate of M≥5.0 events (cat. completeness, temporal changes)
6) Paleoseismic RI i… models for the pr…
7) Defining date-of-… all faults
8) Mmax off model…
9) Likelihood of mu… physics)
10) 70% aseismicity off faults?
11) Smoothed-seismicity model applicability (deformation model alternatives?)
12) Spatial resolution of Gutenberg Richter assumption
13) Better sampling of viable models (U3 held close to U2; physics narrows solution space?)

We need physics-based simulators to help solve these

14) Manifestation of creep (e.g., area vs slip-rate reduction?)
15) Magnitude-area and slip-length scaling (surface slip obs, depth of rupture)
16) Average slip along rupture (boxcar? multi-rainbow for multi-fault ruptures?)
17) Finite faults + clustering stats requires Elastic Rebound
18) Elastic-rebound predictability (spatial overlap of large aftershocks; COV variations)
19) To what extent can large triggered events nucleate from within rupture area of main shock?
20) Are triggering stats really applicable to larger events, especially sequence-specific ones?
21) Time evolution of MFDs at both low and high magnitudes?
22) Difference between multi-fault rupture and quickly triggered separate event
23) In addition to verification and validation, we also need ***valuation*** of our models (all are wrong; is a new one more useful?)

Overview of the

3rd Uniform California Earthquake Rupture Forecast (UCERF3)

Edward (Ned) Field & other WGCEP participants:

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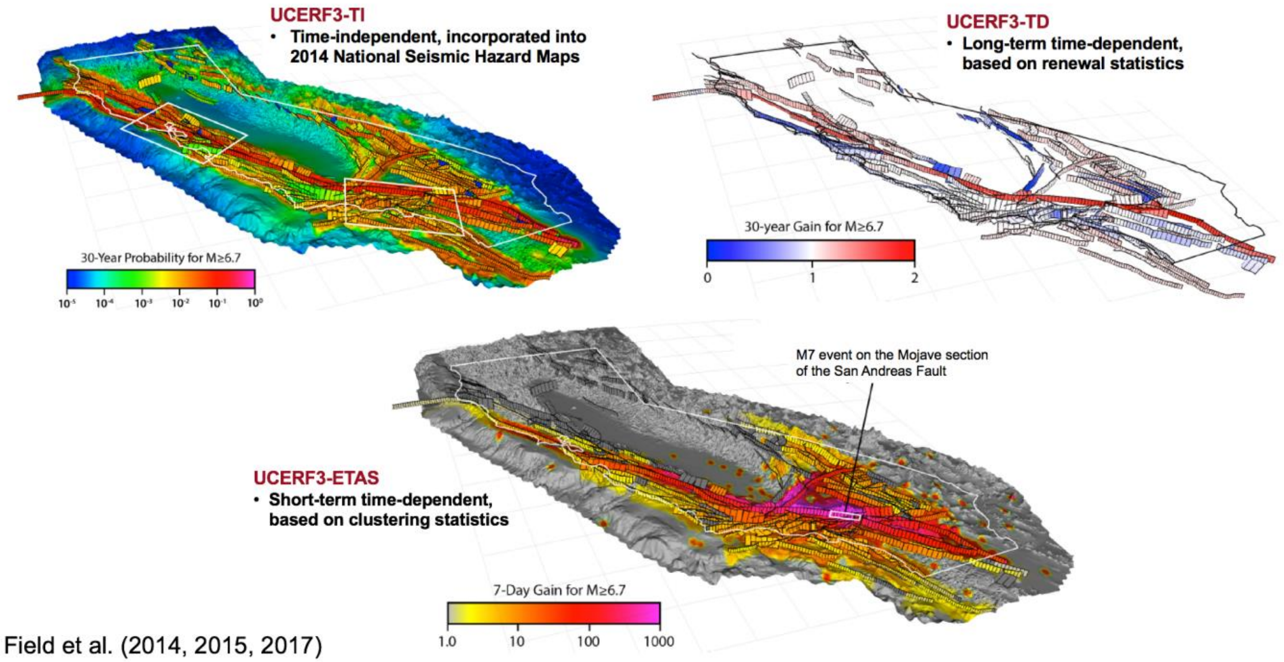

Field et al. (2014, 2015, 2017)