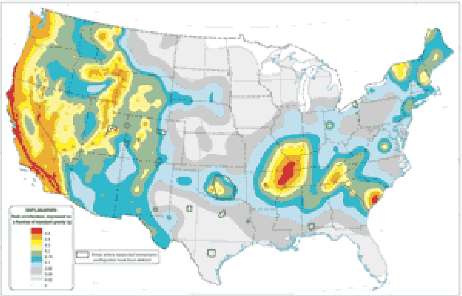
Perspectives on USGS Operational Earthquake Forecasting

Ned Field, USGS

(field@usgs.gov)

Seismic Hazard Analysis



e.g., Probability that shaking level will be exceeded

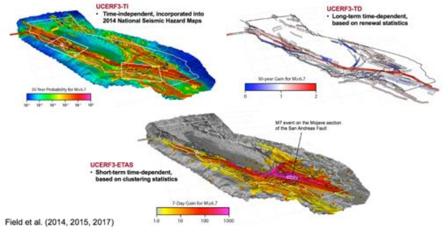
Two main model components:

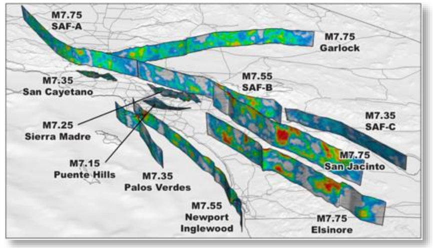
1) **Earthquake *Rupture* Forecast**

Gives the probability of all possible earthquake ruptures (or suite of stochastic event sets) for a region and over a specified timespan

Empirical
(e.g., UCERFs)

Physics Based
(e.g., RSQSim)

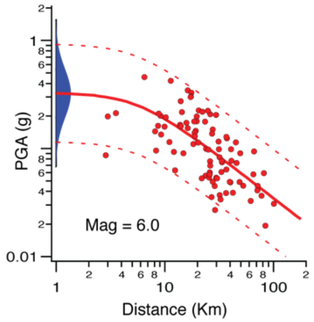




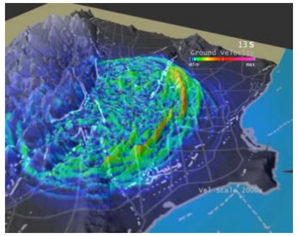
2) **Ground Motion Model**

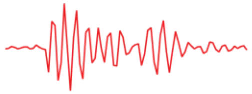
For a given earthquake rupture, this gives the probability that an intensity-measure type will exceed some level of concern (perhaps base on a set of synthetic seismograms)

Empirical
"Attenuation Relationships"



Physics-based
"Waveform Modeling"

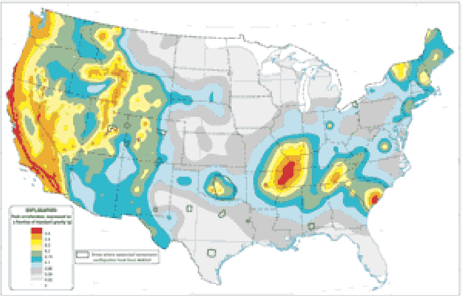




Seismic Hazard Analysis

Biggest future game changers

Two main model components:

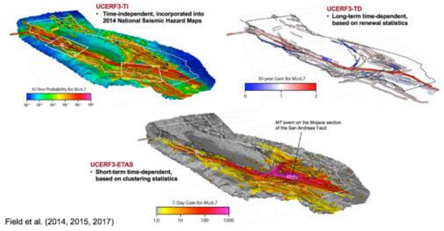


e.g., Probability that shaking level will be exceeded

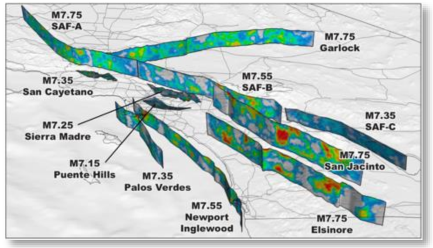
1) **Earthquake *Rupture* Forecast**

Full time dependence
(spatiotemporal clustering)

Empirical
(e.g., UCERFs)



Physics Based
(e.g., RSQSim)



2) **Ground Motion Model**

Non-ergodic models
(rupture-path-site specific)

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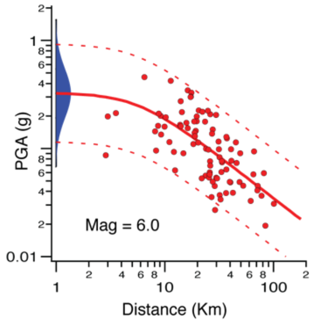

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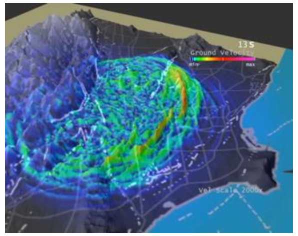
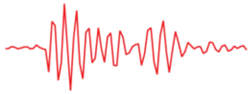
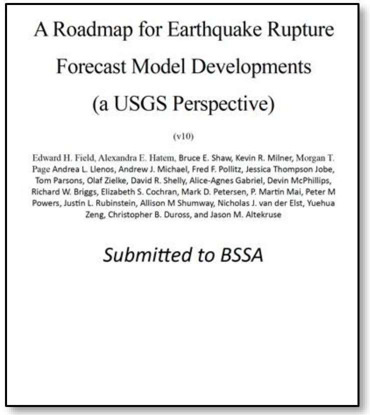




Biggest Issues and opportunities for future ERF models:



A Roadmap for Earthquake Rupture Forecast Model Developments (a USGS Perspective)

(v10)

Edward H. Field, Alexandra E. Hatem, Bruce E. Shaw, Kevin R. Milner, Morgan T. Page Andrea L. Llenos, Andrew J. Michael, Fred F. Pollitz, Jessica Thompson Jobe, Tom Parsons, Olaf Zielke, David R. Shelly, Alice-Agnes Gabriel, Devin McPhillips, Richard W. Briggs, Elizabeth S. Cochran, Mark D. Petersen, P. Martin Mai, Peter M Powers, Justin L. Rubinstein, Allison M Shumway, Nicholas J. van der Elst, Yuehua Zeng, Christopher B. Duross, and Jason M. Altekruse

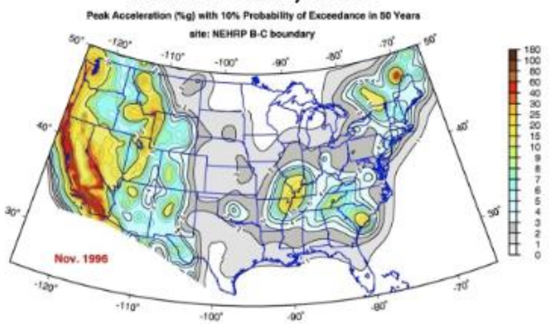
Submitted to BSSA

- **Full time-dependent earthquake rupture forecasts**
- Improved epistemic uncertainty representation
- Add “Valuation” to verification and validation protocols
- Improved Deformation Models (slip rates; off fault; reproducibility)
- Quantification of sampling errors for gridded seismicity
- More physics-based models (to make up for lack of large-event data)

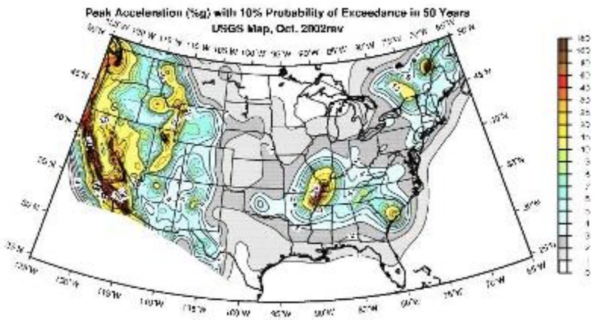
USGS National Seismic Hazard Model (NSHM)

Past & present models (e.g., 1996, 2002, 2008, 2014, 2018, 2023) provided **time-independent, individual-site hazard curves**, (and model ingredients)

Frankel et al., 1996



Frankel et al., 2002

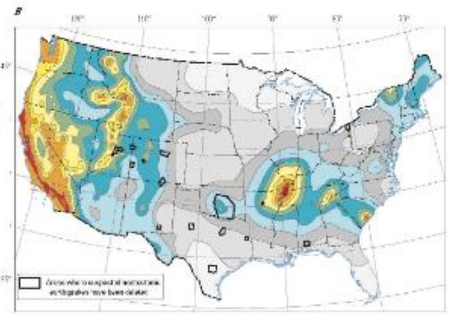


“defined for return periods greater than ~475 years…”

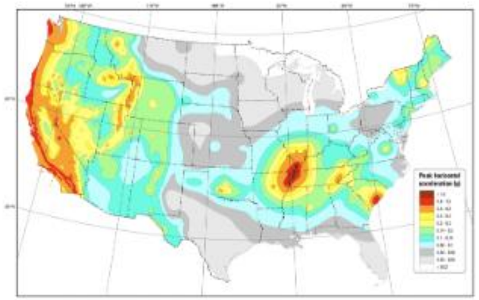
Petersen et al., 2023

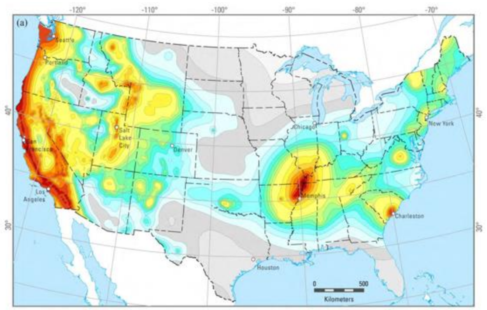
Petersen et al., 2008

Petersen et al., 2014



Petersen et al., 2020





USGS National Seismic Hazard Model (NSHM)

USGS science for a changing world

Past & present models (e.g., 1996, 2002, 2008, 2014, 2018, 2023) provided **time-independent, individual-site hazard curves**, (and model ingredients)

Tailored for building codes (buildings, highways, railways, pipelines, etc.), **but also used in insurance**, emergency management, and other risk mitigation efforts

Government

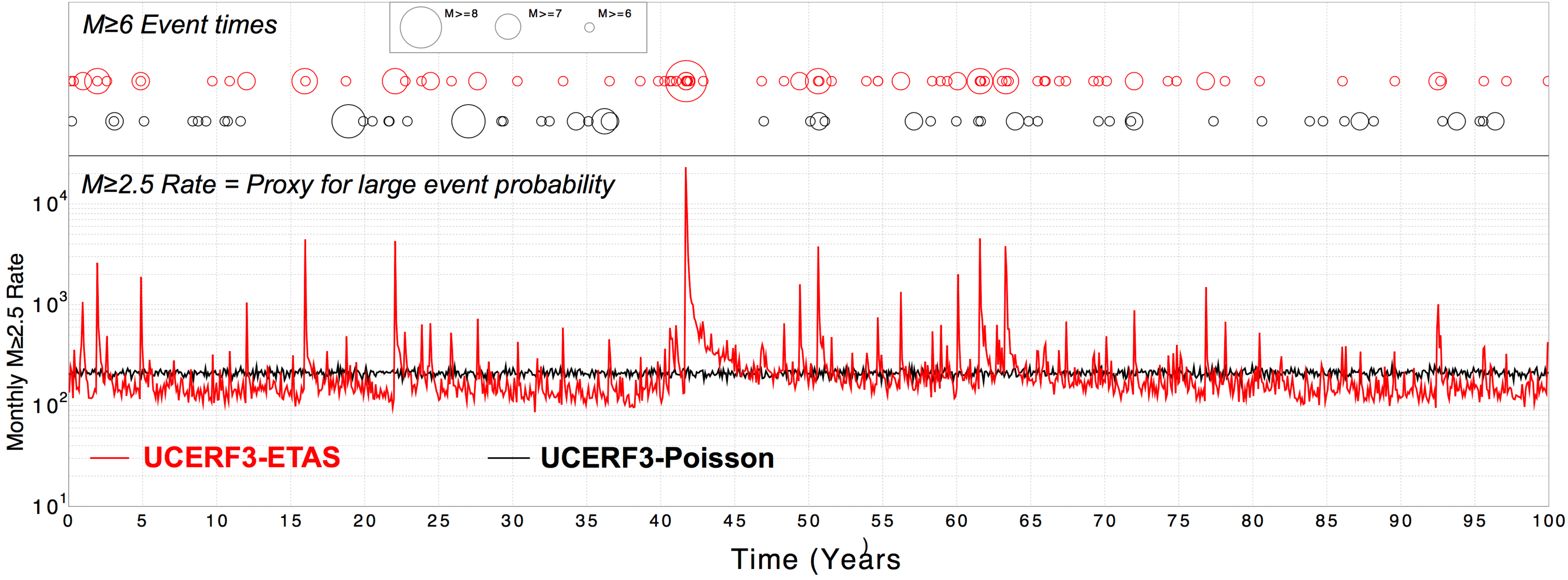
Building Codes

Building Seismic Safety Council

Insurance

Risk Modelers

International Organizations

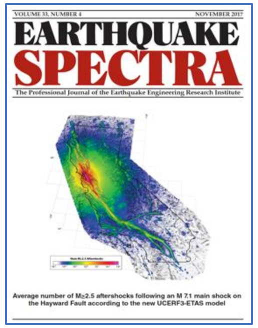


UCERF3-ETAS produces realistic earthquake catalogs (aftershocks/triggered events)

Black line represents Poisson process (NSHM23)
(same events with randomized event times)

This is what NSHMs have thus far assumed

e.g., Ave annual loss (AAL) used to set insurance rates in California; 10% differences/changes considered actionable

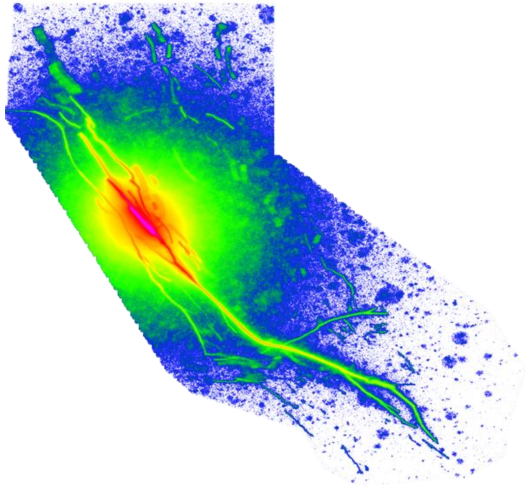


Field, Porter, and Milner (2017)

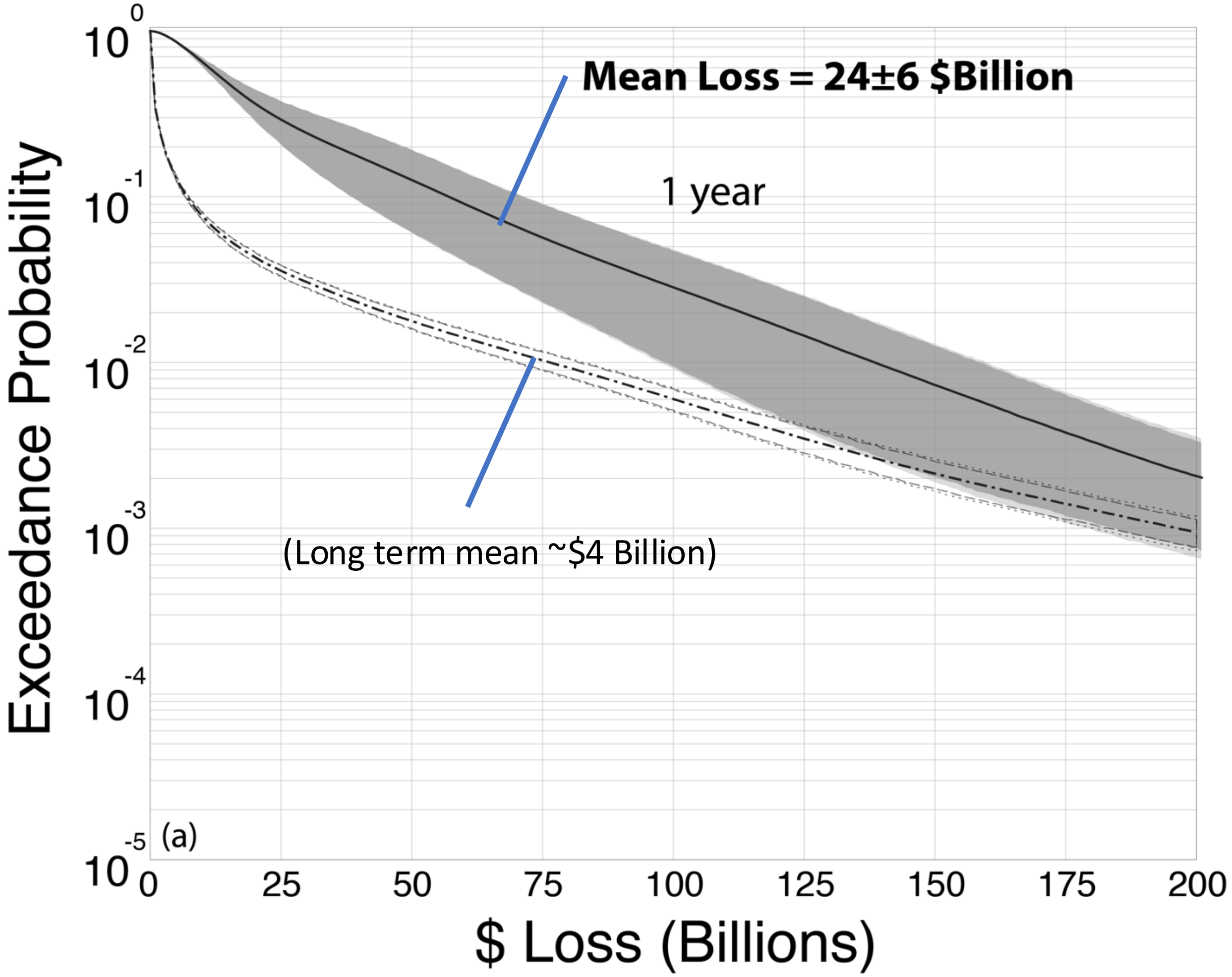
Expected AAL in CA increases by a factor of ~6 following an *M* 7.1 “Haywired” main shock,

Average rate of M≥2.5 events

Based on 200,000 catalogs



UCERF3-ETAS ***(2017)***



Biggest Issues and opportunities for future ERF models:

- **Full time-dependent earthquake rupture forecasts**
- Impro
- Add “V
- Impro
  reproc
- Quant
- More ... ent
  data)

Q: Why so little progress since 2017?

A: Building 2023 long-term model:

- Faults drive vast majority of hazard; challenges with:
  - fault slip rates (deformation models)
  - quantifying multi-fault ruptures
  - dealing with regional MDF bulges
  - dealing with a limited sample of historical seismicity
  - quantifying epistemic uncertainties

Biggest Issues and opportunities for future ERF models:

- **Full time-dependent earthquake rupture forecasts**
- Impr
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We now want to work toward a fully time-dependent nationwide model (something UCERF3-ETAS like)

Operationalizing such a model (continuous, real-time access) is a much greater challenge and will depend on demand/usefulness and resources

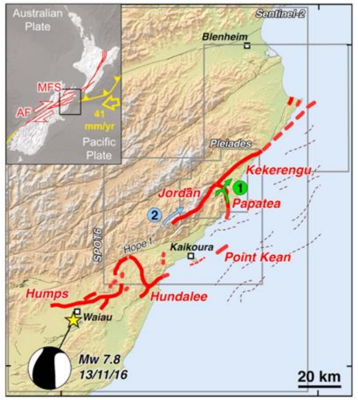
Uniform California Earthquake Rupture Forecast, version 3 (UCERF3)

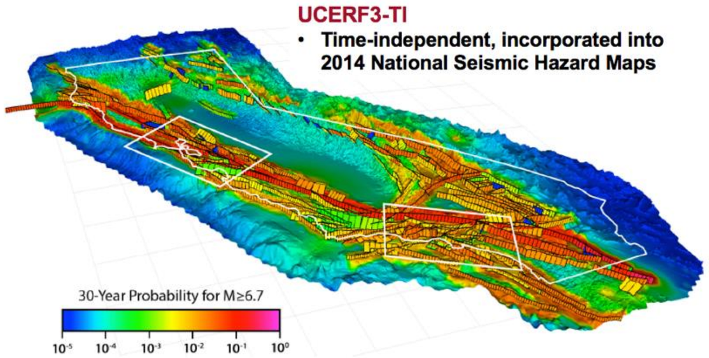
By the Working Group on California Earthquake Probabilities:

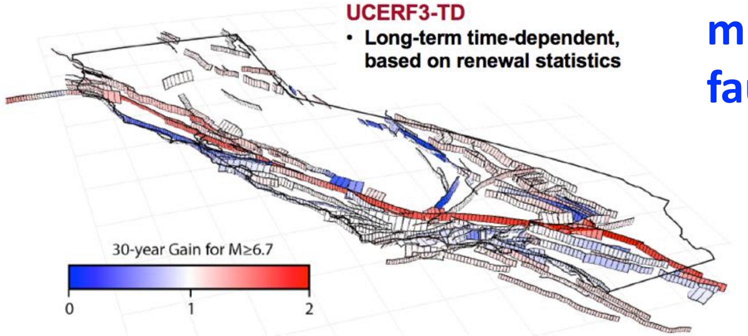
Edward H. Field, Thomas H. Jordan, Morgan T. Page, Kevin R. Milner, Bruce E. Shaw, Timothy E. Dawson, Glenn P. Biasi, Tom Parsons, Jeanne L. Hardebeck, Andrew J. Michael, Ray J. Weldon II, Peter M. Powers, Kaj M. Johnson, Yuehua Zeng, Karen R. Felzer, Nicholas van der Elst, Christopher Madden, Ramon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

- **Fault based**
- **Better geodetic constraints**
- **Relaxed segmentation**
- **Included multi-fault ruptures**

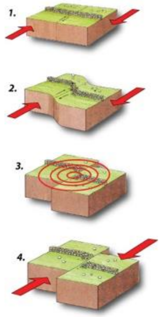
(e.g., Kaikoura)



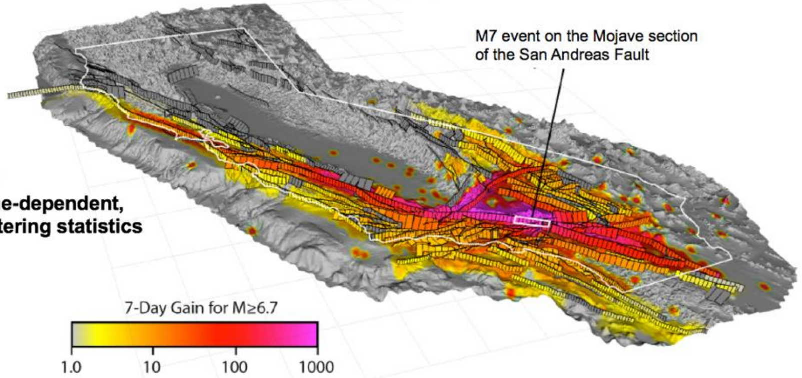




Improved elastic-rebound model (& on all faults)

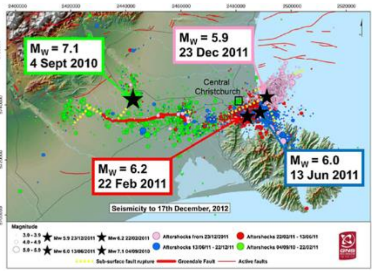


UCERF3-ETAS
• Short-term time-dependent, based on clustering statistics

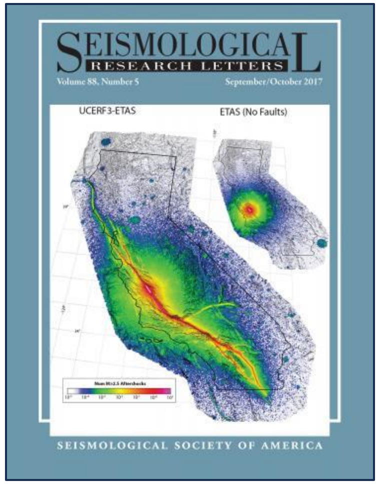


Field et al. (2014, 2015, 2017)

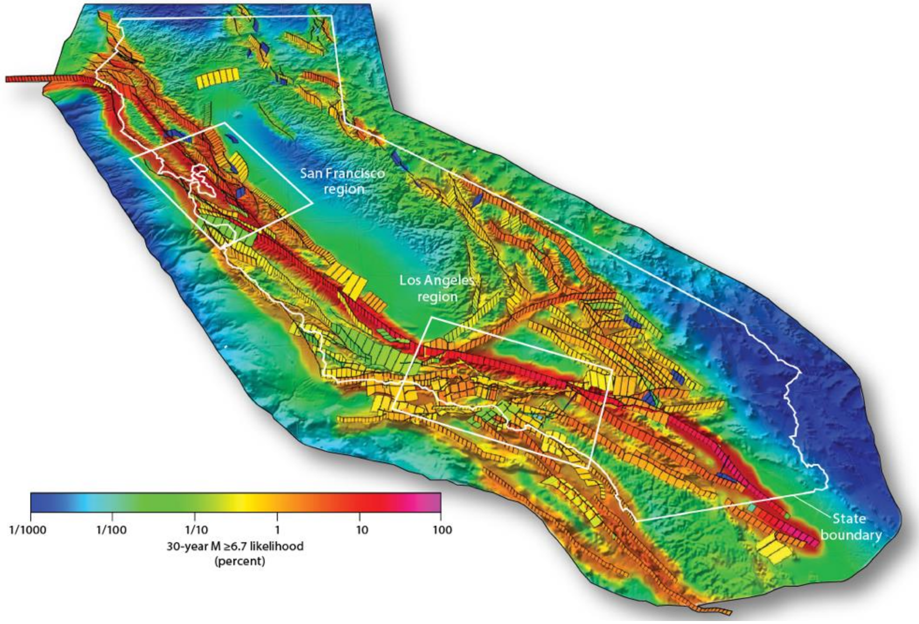
Included spatiotemporal clustering (e.g., aftershock sequences)



UCERF3-ETAS Model (2017) - fully time dependent prototype:



UCERF3-TD



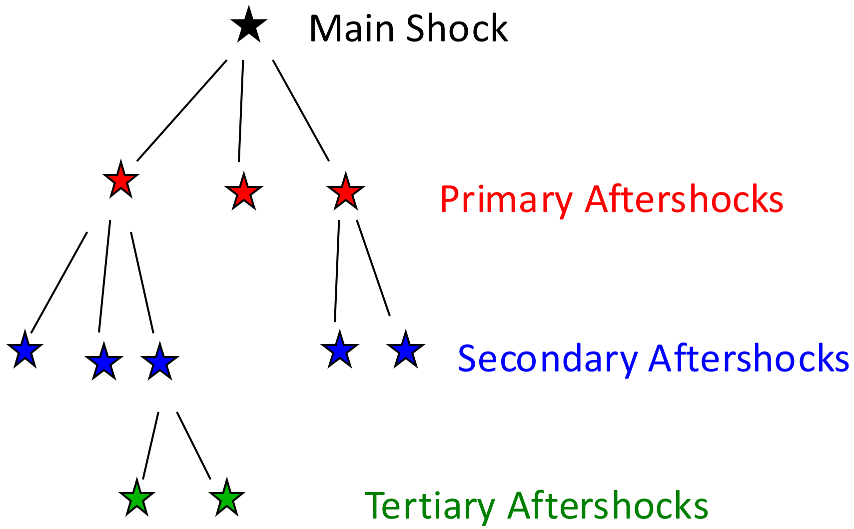
+

ETAS Model

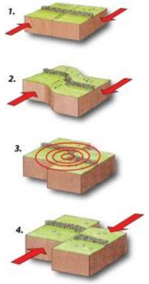
(Epidemic Type Aftershock Sequence)

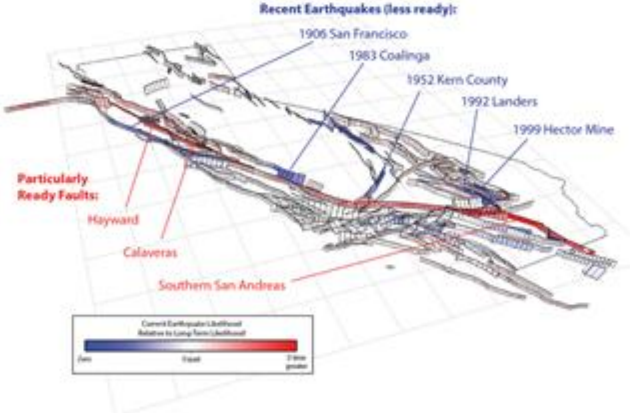
An empirically based description of triggering statistics (Ogata, 1998):

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



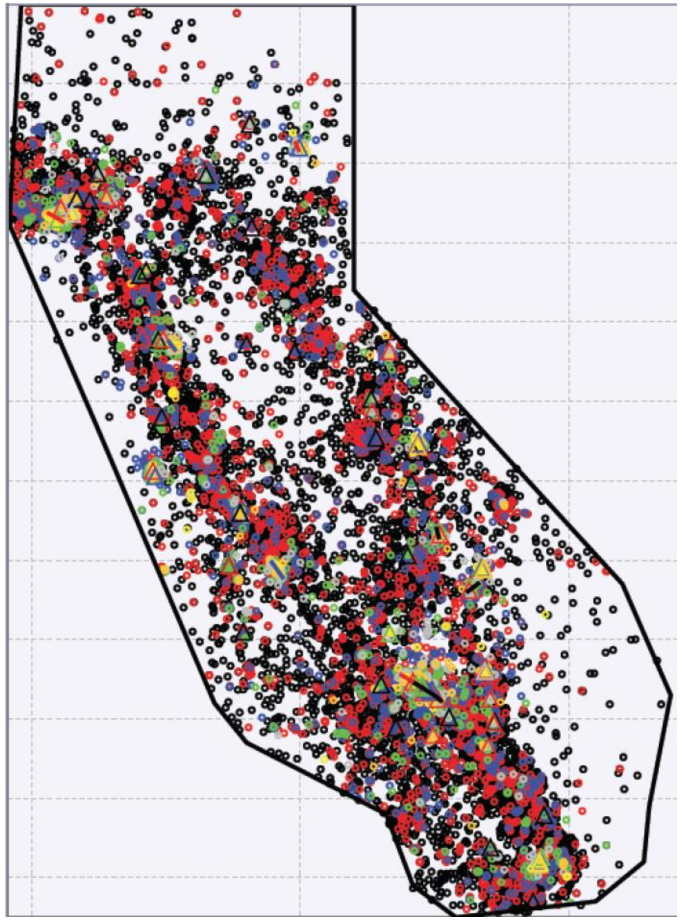
This includes longer-term elastic-rebound effects





UCERF3-ETAS Model (fully time dependent):

Product: synthetic catalog of events (stochastic event set)



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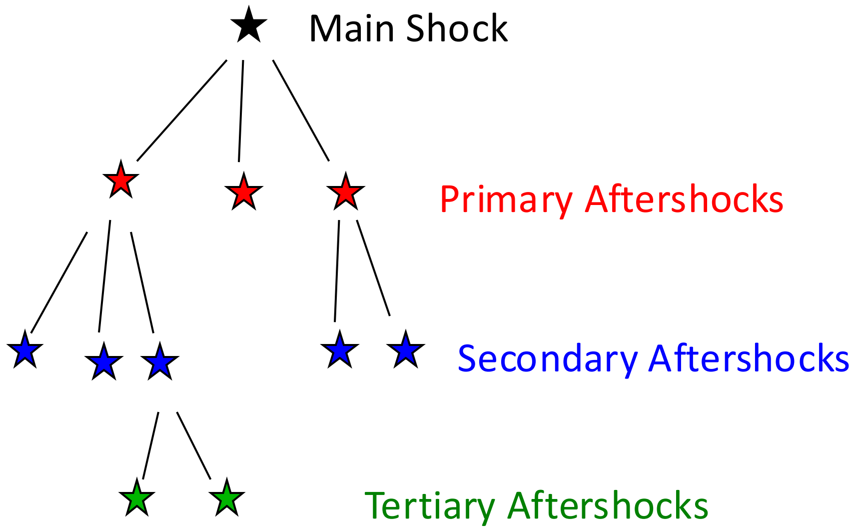


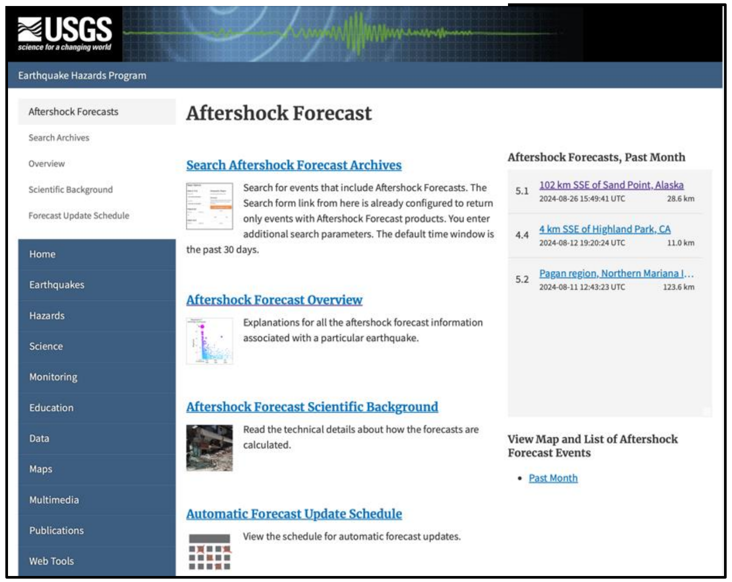
More specifically, we want:

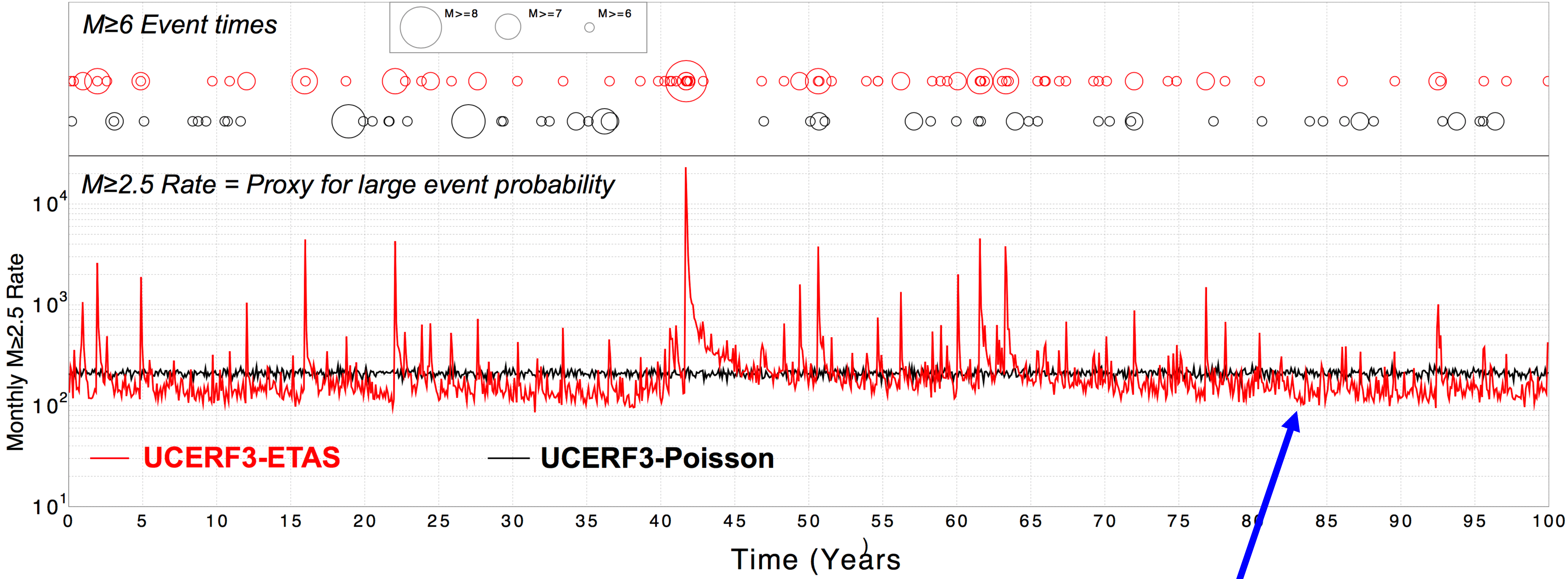
a) Full, fault-based ETAS model (3D)
b) No-faults ETAS model (3D)
c) Fast ETAS model (2D)

We also want to build on recent OAF developments:

- Sequence specific parameters
- Catalog completeness
- Pushing products to web pages

Andy Michael, Jeanne Hardebeck Nicholas van der Elst, Morgan Page, and others…





UCERF3-ETAS produces realistic earthquake catalogs (aftershocks/triggered events)

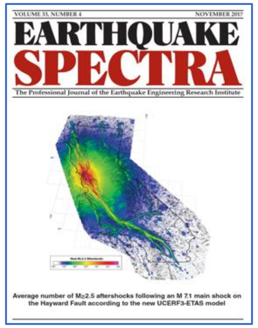
Quiet times - important information as well

Black line represents Poisson process (NSHM23)
(same events with randomized event times)

Some Scientific/Operational Challenges for Full Time Dependence:

1) Dealing with MFD characteristicness near faults (non-GR)
2) The need for elastic relaxation (to prevent re-rupture of the mainshock fault) & how this evolves with time
3) Can large triggered events nucleate from well within the main-shock rupture zone?
4) Long simulations require time dependent rates of spontaneous events; non-GR means space dependent too
5) Distance decay in 3D (with depth dependent probability of nucleation)
6) How do we deal with epistemic uncertainties (including from a testing perspective)?
7) Operationalizing CSEP and Turing tests
8) Add ***valuation*** to our verification & validation protocols (all modes wrong, are they useful?); must be done for specific hazard and risk metrics

e.g., Ave annual loss (AAL) used to set insurance rates in California; 10% differences/changes considered actionable



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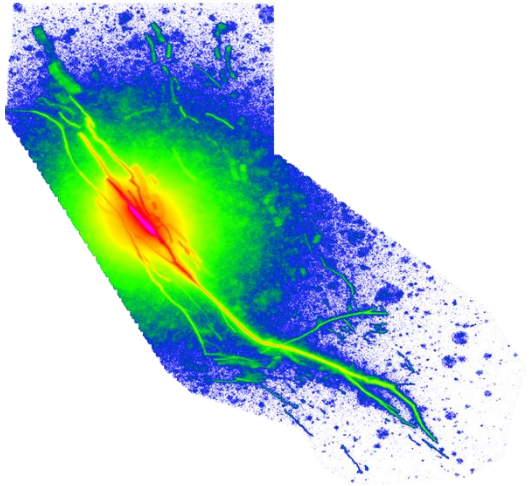
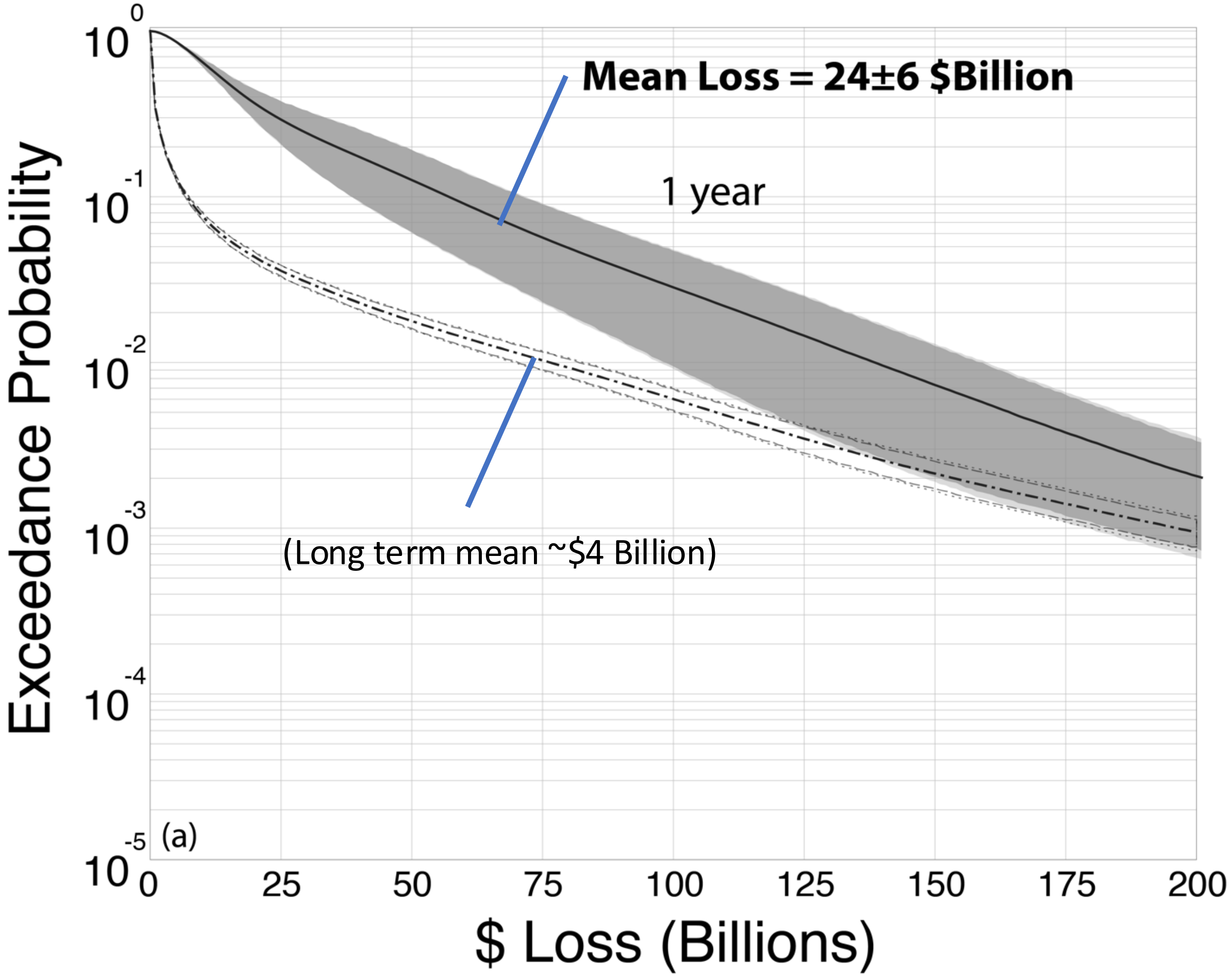




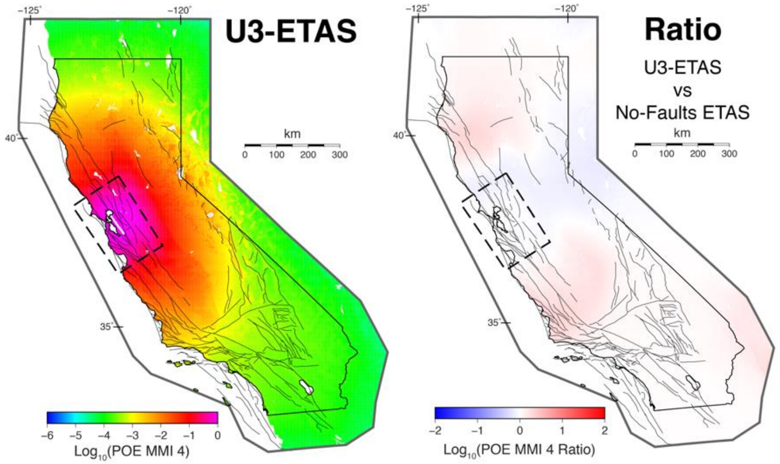
UCERF3-ETAS ***(2017)***

Are fault-based models always more useful (worth the effort)?

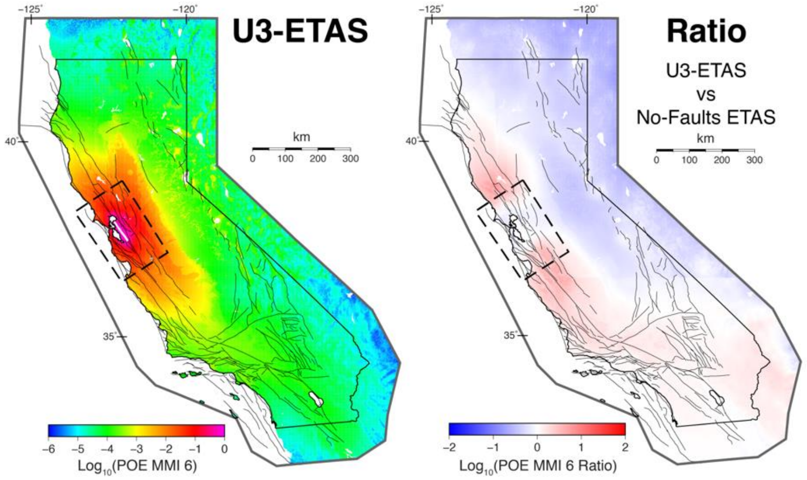
Not if the question is whether you will feel an aftershock

Yes, if you want to know the probability of big losses

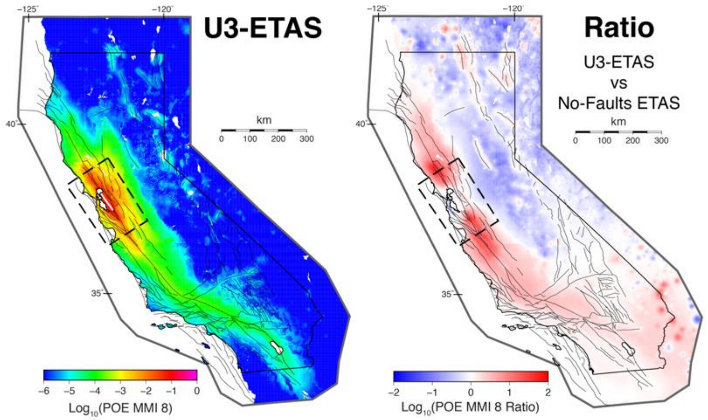
Exceed Prob for MMI 4 (light shaking)



Exceed Prob for MMI 6 (strong shaking)

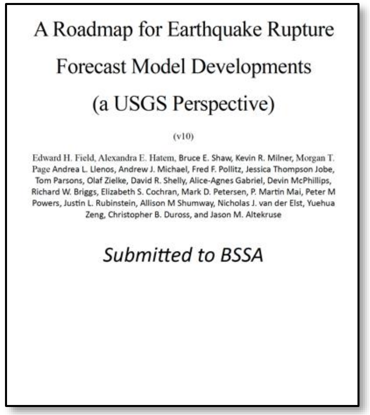


Exceed Prob for MMI 8 (severe shaking)



From: **Candidate Products for OEF Illustrated Using the HayWired Planning Scenario…** (Field and Milner,, 2018, *SRL*)

Biggest Issues and opportunities for future ERF models: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- Improved Deformation Models (slip rates; off fault; reproducibility)
- Quantification of sampling errors for gridded seismicity
- **More physics-based models (to make up for lack of large-event data) – Mendenhall postdoc opportunity!**

Some Scientific/Operational Challenges for Full Time Dependence:

1) Dealing with MFD characteristicness near faults (non-GR) (22-24, 29)
2) The need for elastic relaxation (to prevent re-rupture of the mainshock fault) & how this evolves with time (25-26)
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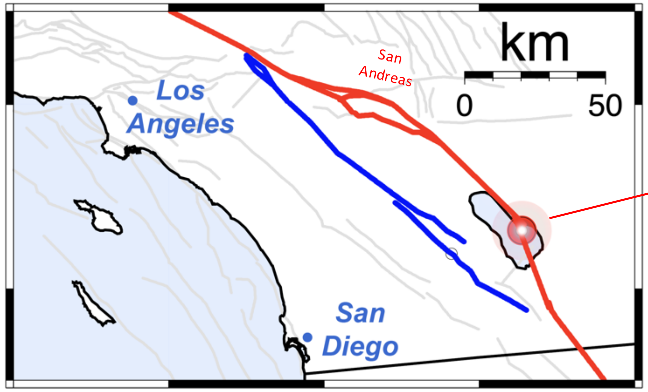
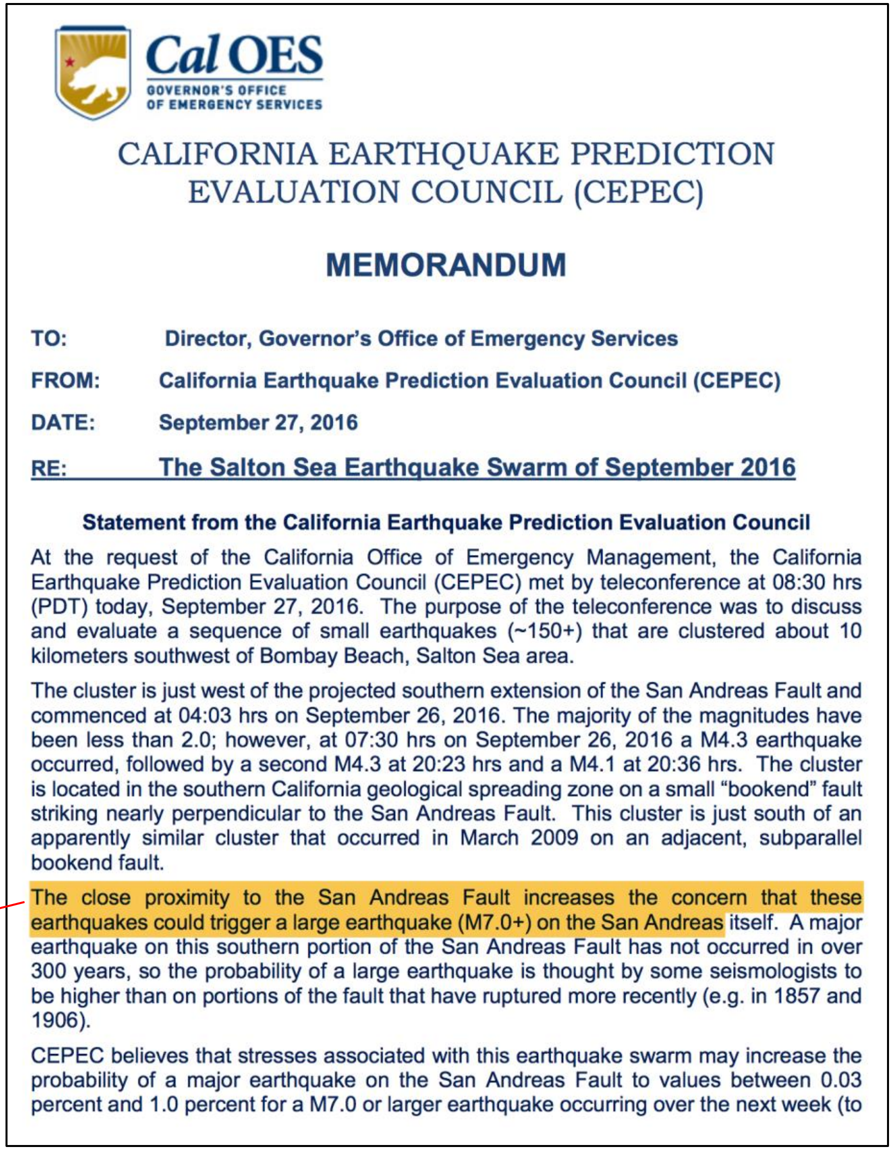
6) How do we deal with epistemic uncertainties (including from a testing perspective)?
7) Operationalizing CSEP and Turing tests
8) Add ***valuation*** to our verification & validation protocols (all modes wrong, are they useful?); must be done for specific hazard and risk metrics

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

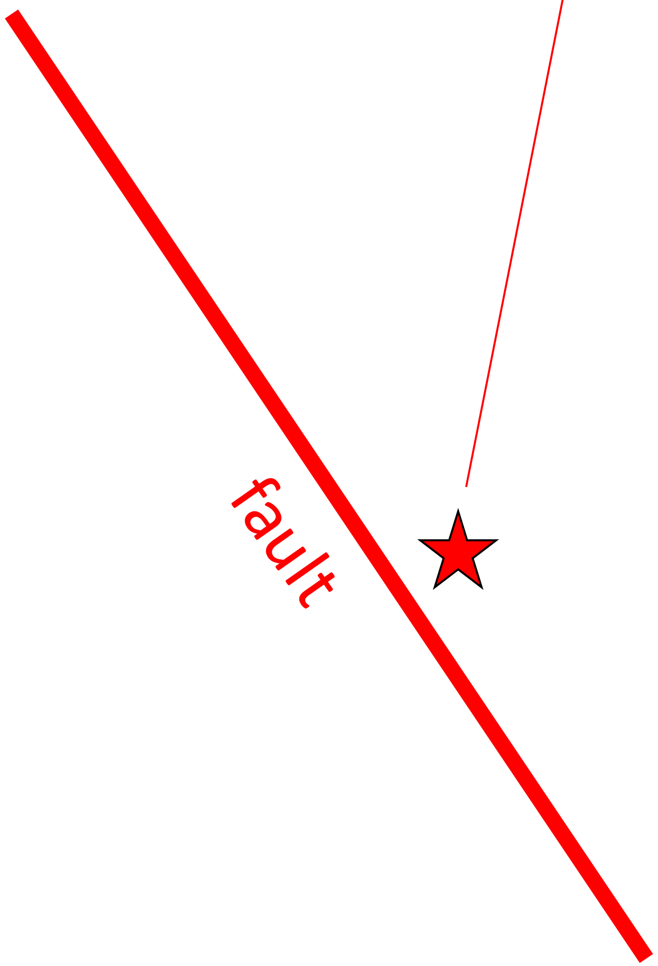
At the request of the California Office of Emergency Management, the California Earthquake Prediction Evaluation Council (CEPEC) met by teleconference at 08:30 hrs (PDT) today, September 27, 2016. The purpose of the teleconference was to discuss and evaluate a sequence of small earthquakes (~150+) that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

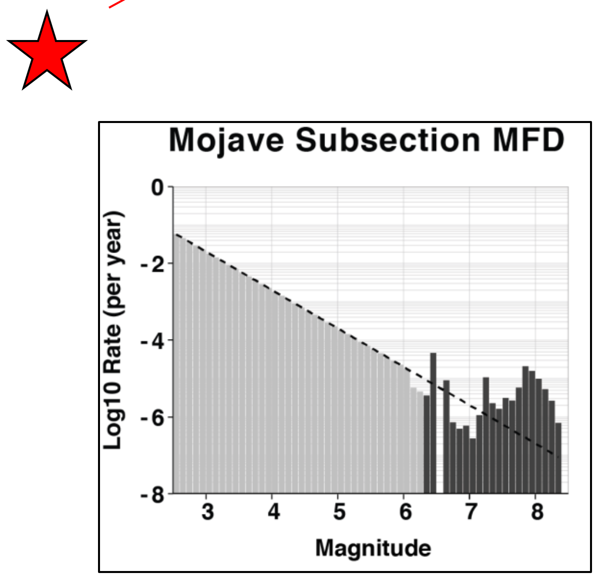
The cluster is just west of the projected southern extension of the San Andreas Fault and commenced at 04:03 hrs on September 26, 2016. The majority of the magnitudes have been less than 2.0; however, at 07:30 hrs on September 26, 2016 a M4.3 earthquake occurred, followed by a second M4.3 at 20:23 hrs 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).

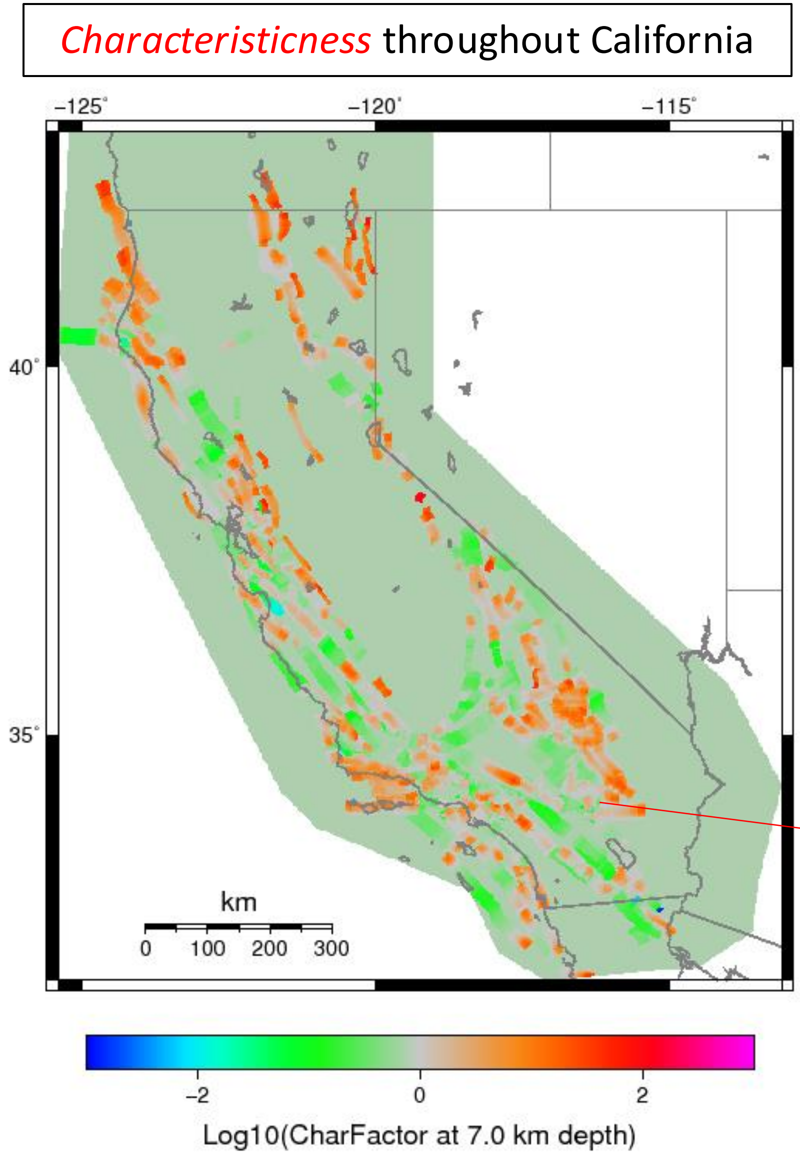
CEPEC believes that stresses associated with this earthquake swarm may increase the probability of a major earthquake on the San Andreas Fault to values between 0.03 percent and 1.0 percent for a M7.0 or larger earthquake occurring over the next week (to

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

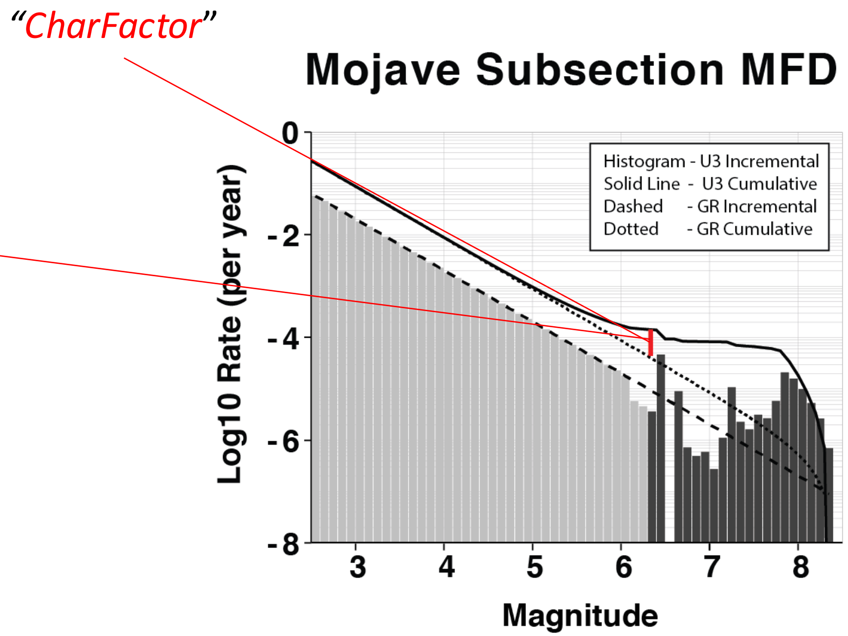




If you answered yes, then you also believe in characteristic MFDs on faults (Michael, 2012)



- *Most faults have positive characteristicness, but it's negative on some*
- *We must honor this characteristicness if long-term simulations are to reproduce long-term earthquake rates*
- ***Pure GR is not consistent with data, and would not provide higher conditional triggering probabilities near some faults***



Issues Encountered in Developing UCERF3-ETAS

1. **The most important influence on large-event triggering likelihood is the degree of characteristicness of the magnitude-frequency distribution (MFD) near faults, which varies widely throughout California.**
2. **Elastic rebound is required, and how it influences where large events can nucleate from is also important**

Excluding elastic rebound produces model instabilities (runaway sequences) in areas with high fault Characteristicness (i.e., branching ratios well above 1.0)

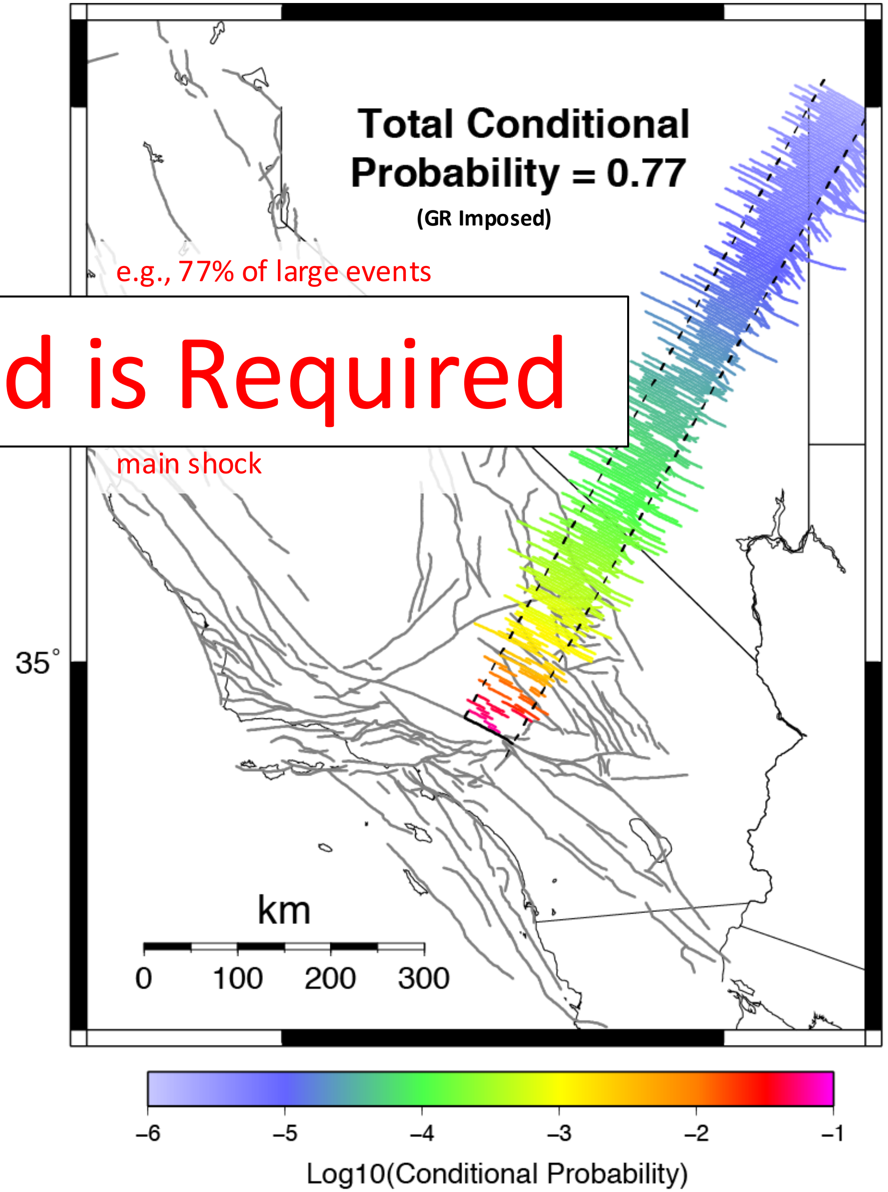
But what if faults really are GR (no

chara

elastic rebound still needed?

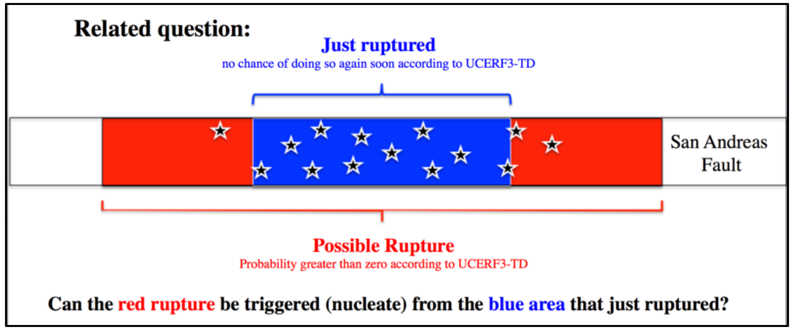
Elastic Rebound is Required

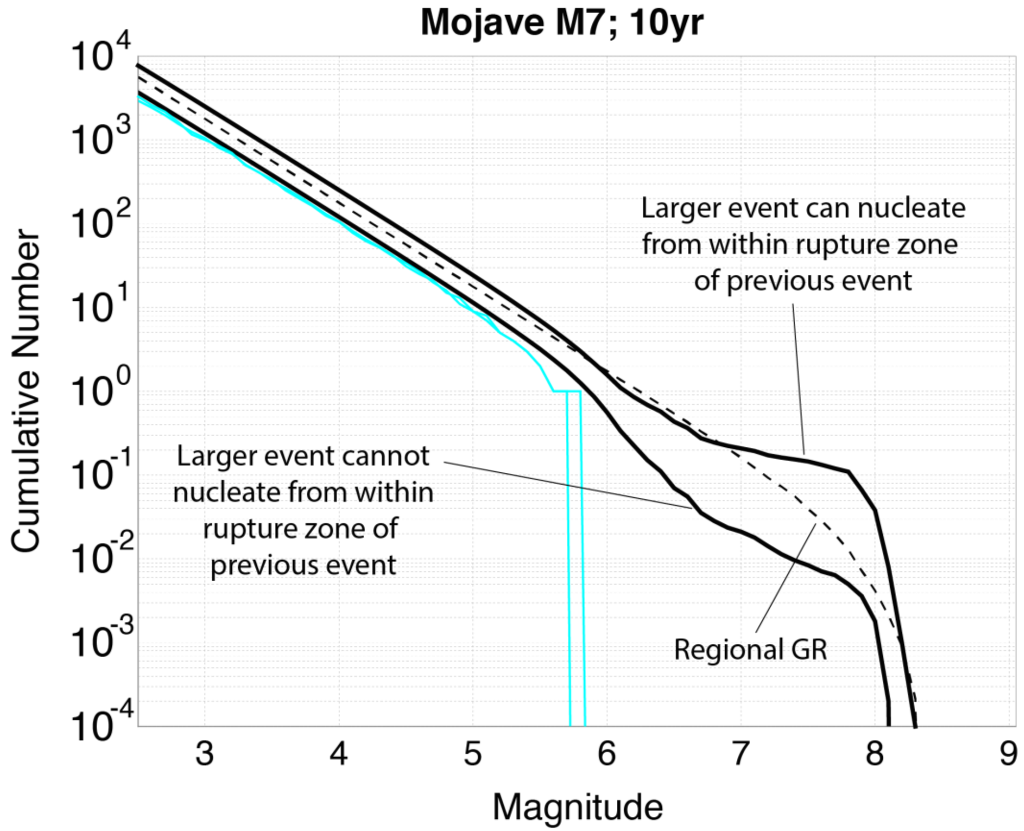
Yes – otherwise large triggered events simply re-rupture the main shock rupture surface way more than we see in nature.

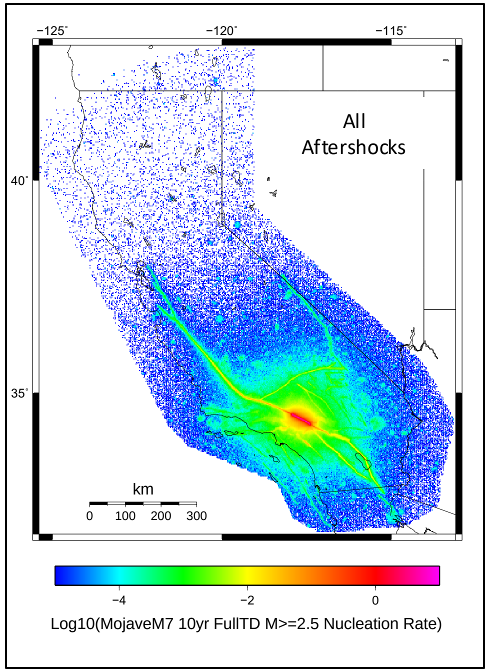


Example simulation for an M 7 event on the Mojave S.

(Ave of 10,000 realizations)







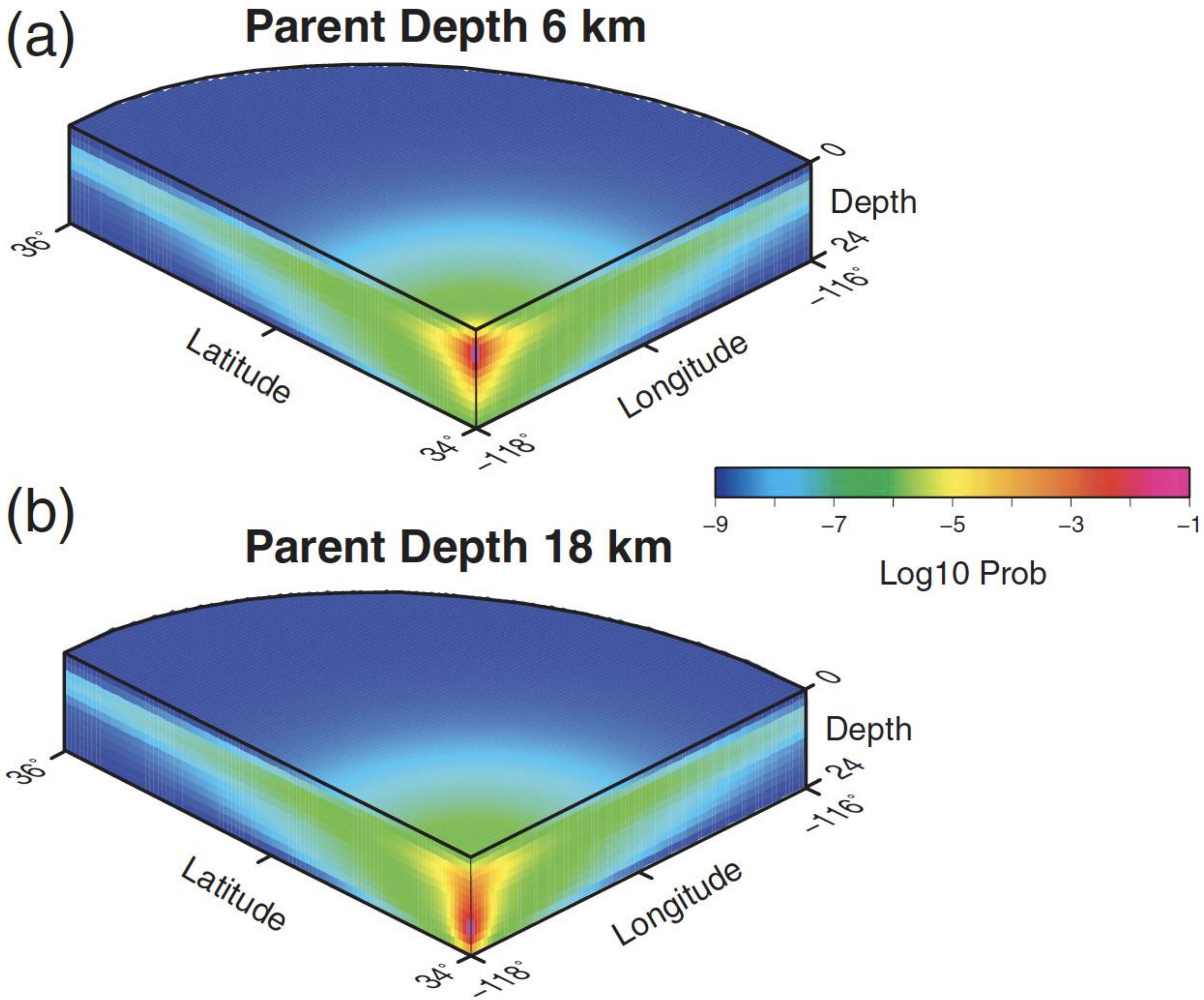
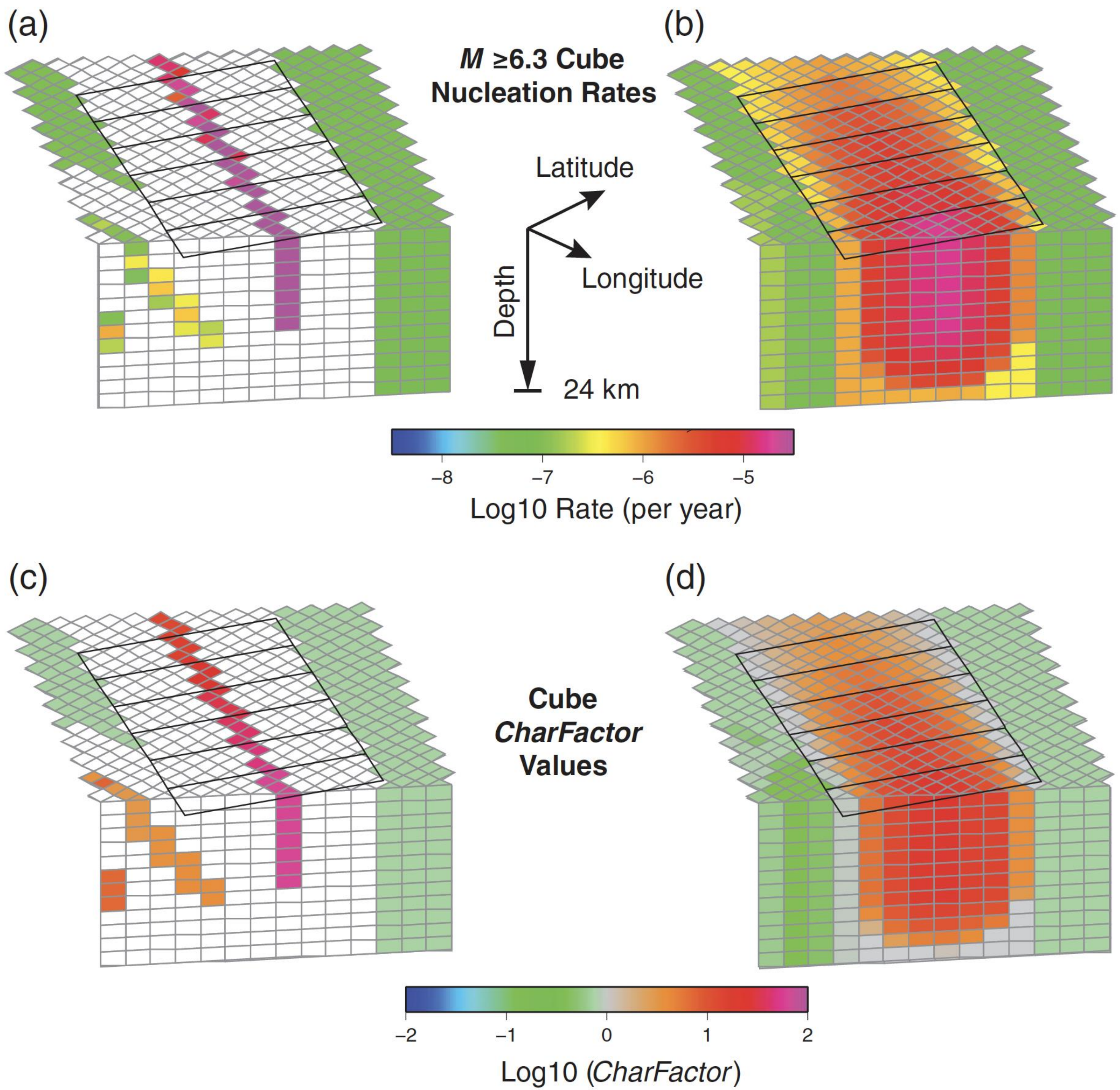


Figure 10. Illustration of the *DistanceDecayCubeSampler* described in the text, in which the relative likelihood of sampling an event in each location is shown by the color. (a) and (b) The cases in which the depth of the parent event is 6 and 18 km, respectively.

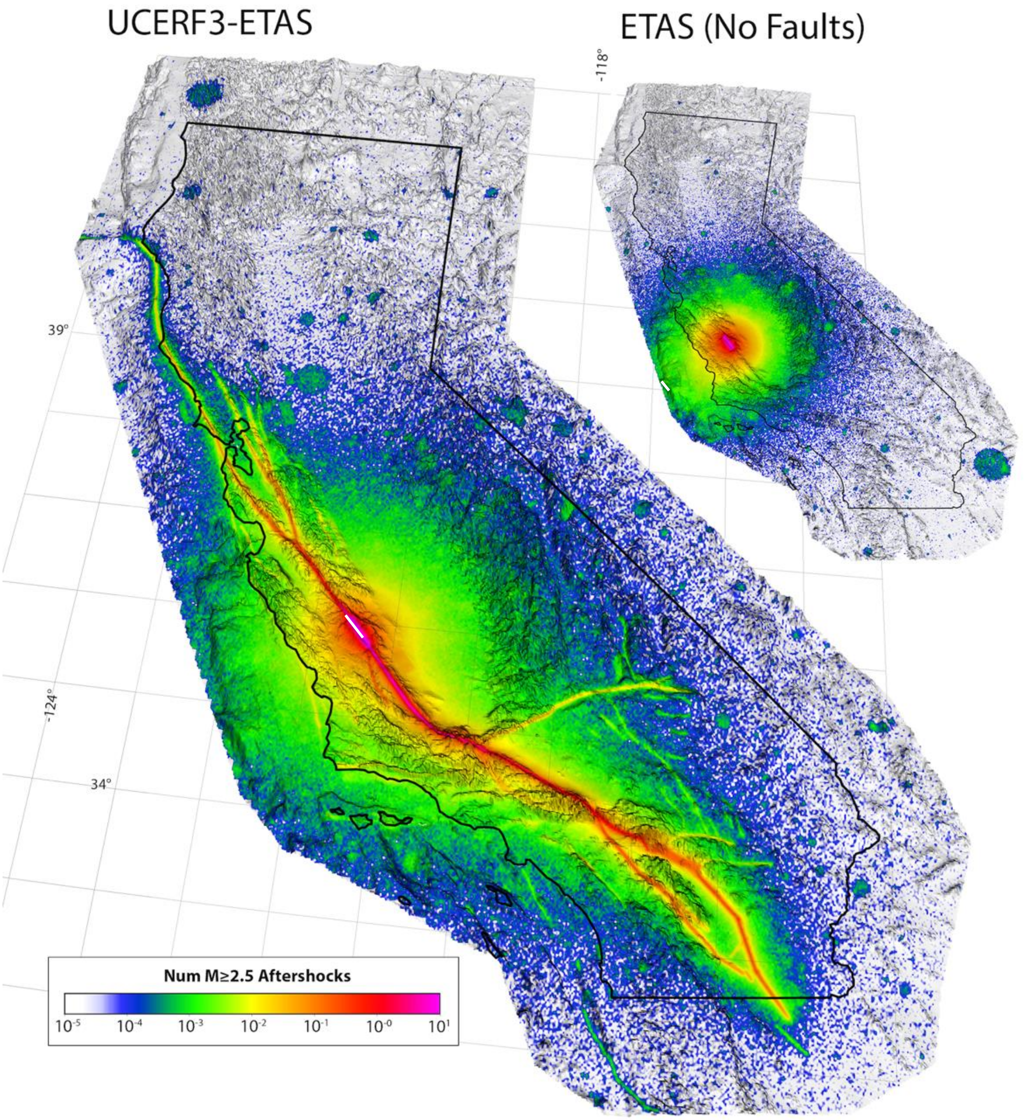


(a)
(b)
M ≥6.3 Cube
Nucleation Rates
Latitude
Longitude
Depth
24 km
−8
−7
−6
−5
Log10 Rate (per year)
(c)
(d)
Cube
CharFactor
Values
−2
−1
0
1
2
Log10 (CharFactor)

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 (Sieh, 1978; Meltzner and Wald, 1999).

UCERF3-ETAS gives a 6e-3 probability of this occurring.