

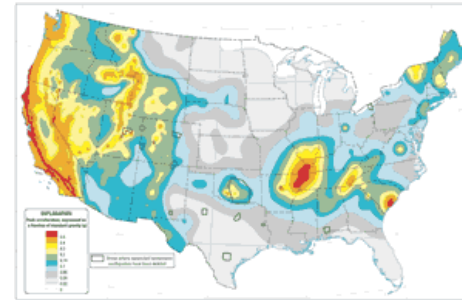
Earthquake Rupture Forecasts - Opportunities & Challenges

Edward (Ned) Field, USGS Golden

Nov. 14, 2018 NAS-COSG fall meeting

Probabilistic Seismic Hazard Analysis

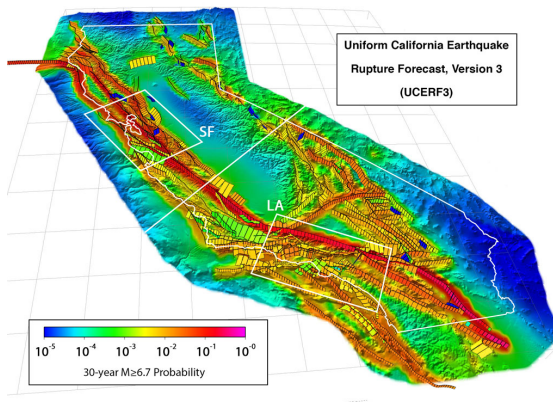
Two main model components:



*Probability
that shaking
level will be
exceeded*

1) Earthquake *Rupture* Forecast

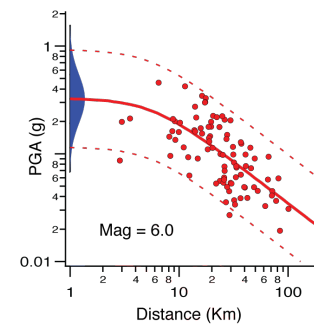
Gives the probability of all possible earthquake ruptures (fault offsets) throughout the region and over a specified time span



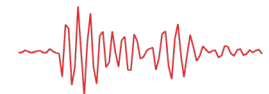
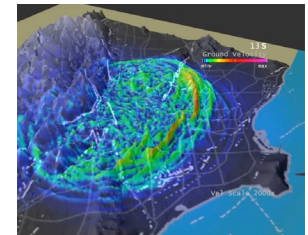
2) Earthquake *Shaking* model

For a given earthquake rupture, this gives the probability that an intensity-measure type will exceed some level of concern

Empirical “Attenuation Relationships”



Physics-based “Waveform Modeling”



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Talk Outline

- 1) The Anatomy of an Earthquake Rupture Forecast
- 2) Representation of Epistemic Uncertainties
- 3) Operational Earthquake Forecasting (real-time info)
- 4) The Need for More Physics-Based Approaches
- 5) The Importance of Model “Valuation” (in addition to Verification and Validation)

Earthquake Rupture Forecasts - Opportunities & Challenges

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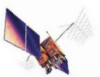
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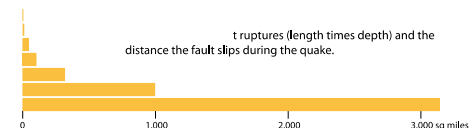
1) The Anatomy of an Earthquake Rupture Forecast

System-Level Science: *the integration of diverse sources of knowledge about a complex system with the goal of obtaining predictive understanding*

Earthquake Forecast Ingredients:



Physics – scaling laws

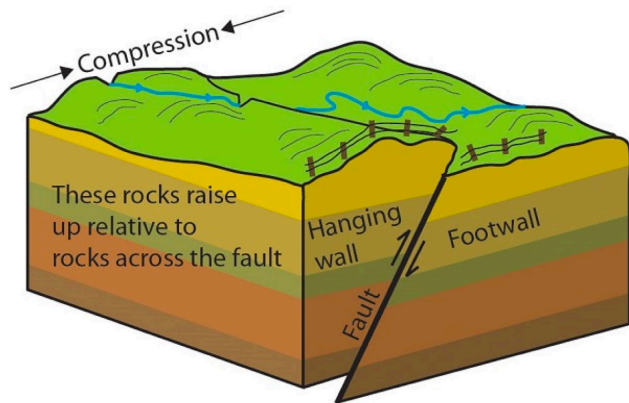


1) The Anatomy of an Earthquake Rupture Forecast

Fault Information:

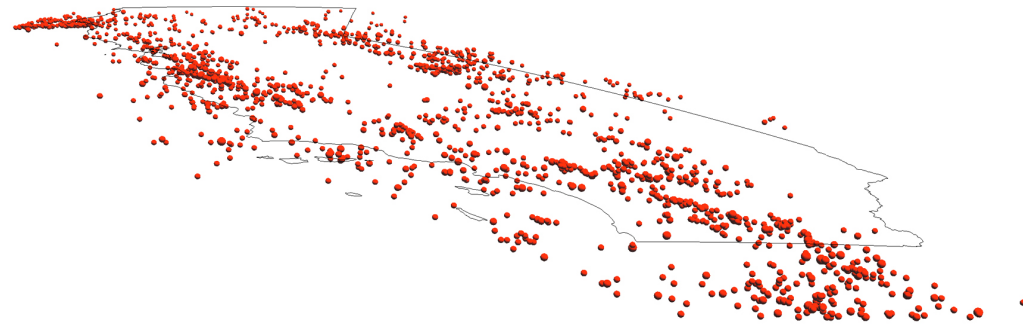
&/Or

Seismicity Information:



<https://www.nps.gov/articles/faults-and-fractures.htm>

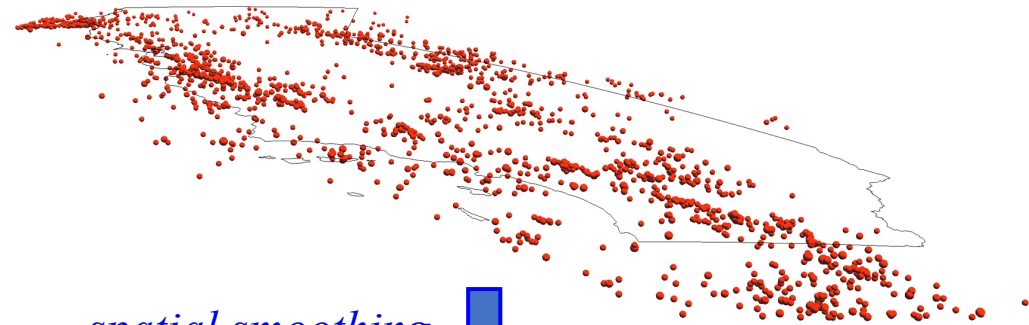
Observed $M \geq 4$ earthquakes in California



1) The Anatomy of an Earthquake Rupture Forecast

Seismicity Information:

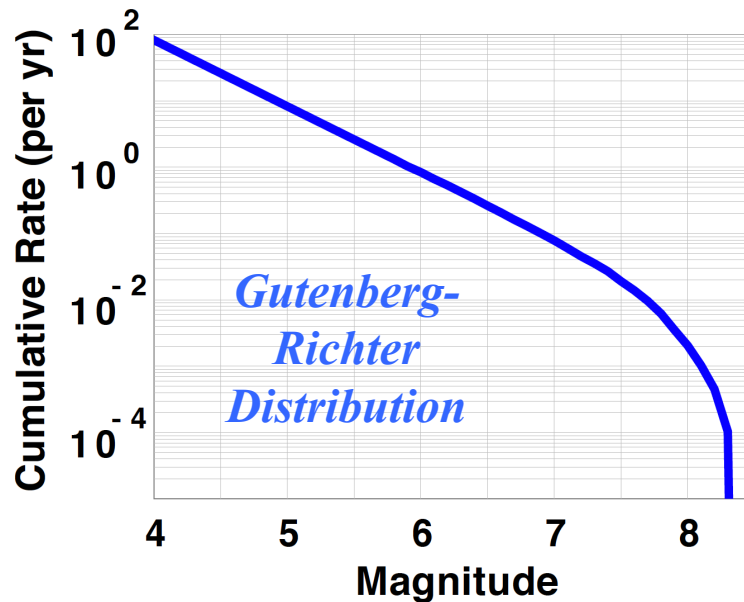
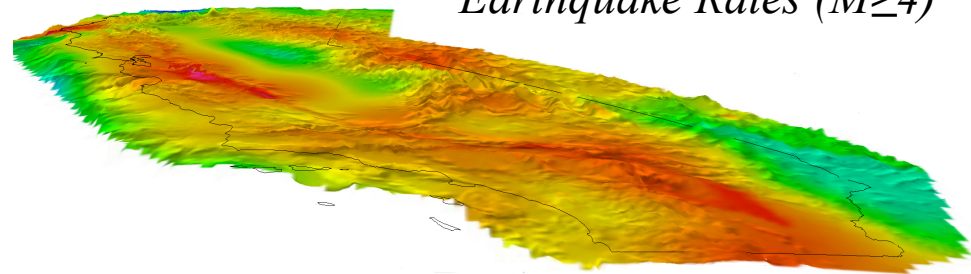
Observed $M \geq 4$ earthquakes in California



spatial smoothing

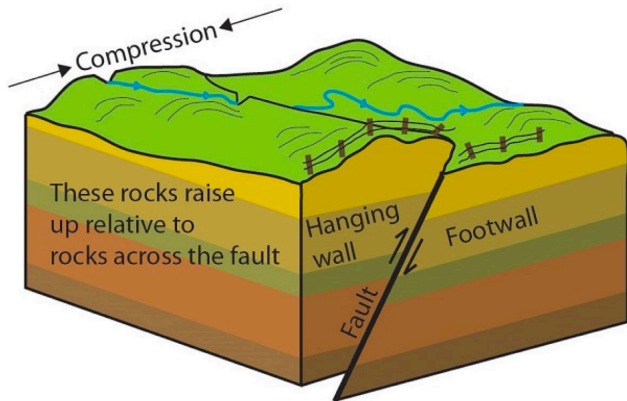


Earthquake Rates ($M \geq 4$)



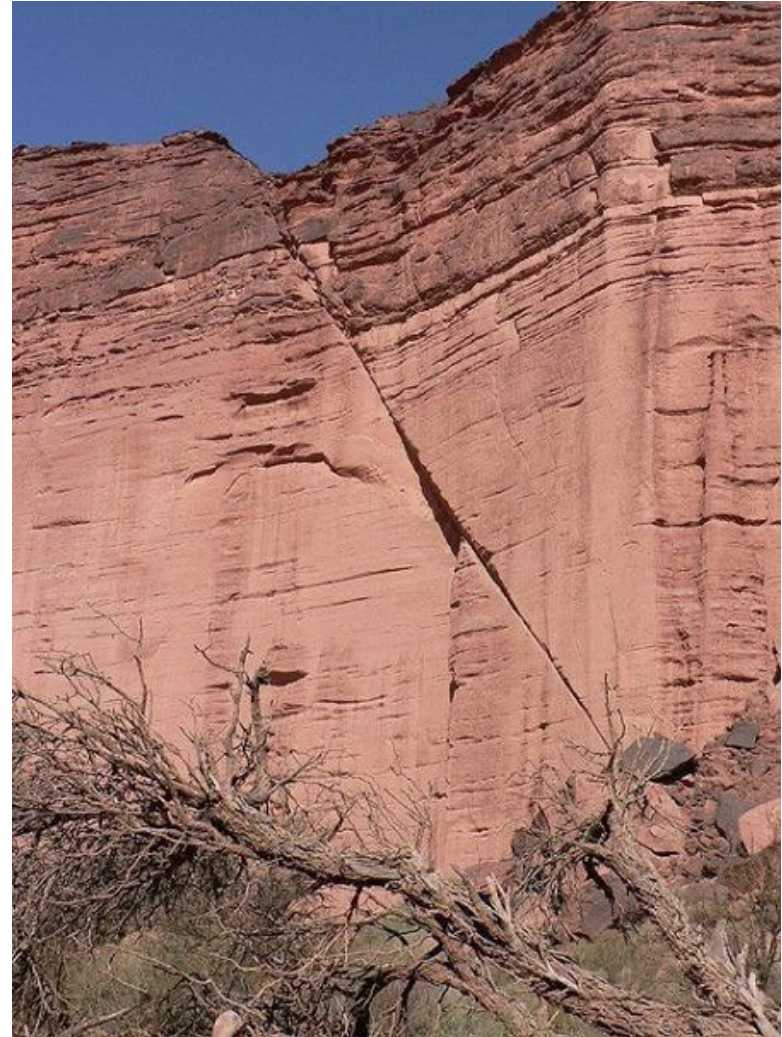
1) The Anatomy of an Earthquake Rupture Forecast

Fault Information:



<https://www.nps.gov/articles/faults-and-fractures.htm>

Magnitude
&
Rate/Probability?

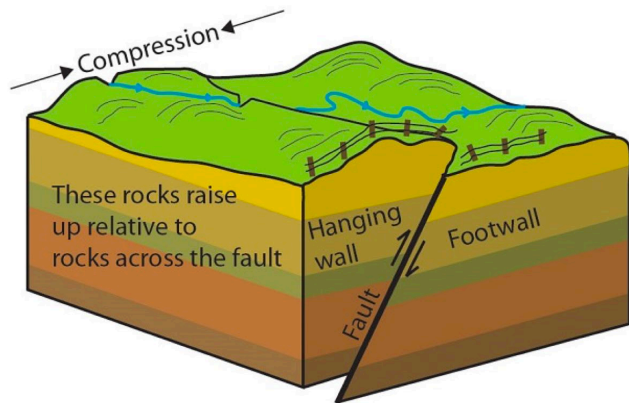


<https://www.pinterest.com/pin/157485318200616906/>

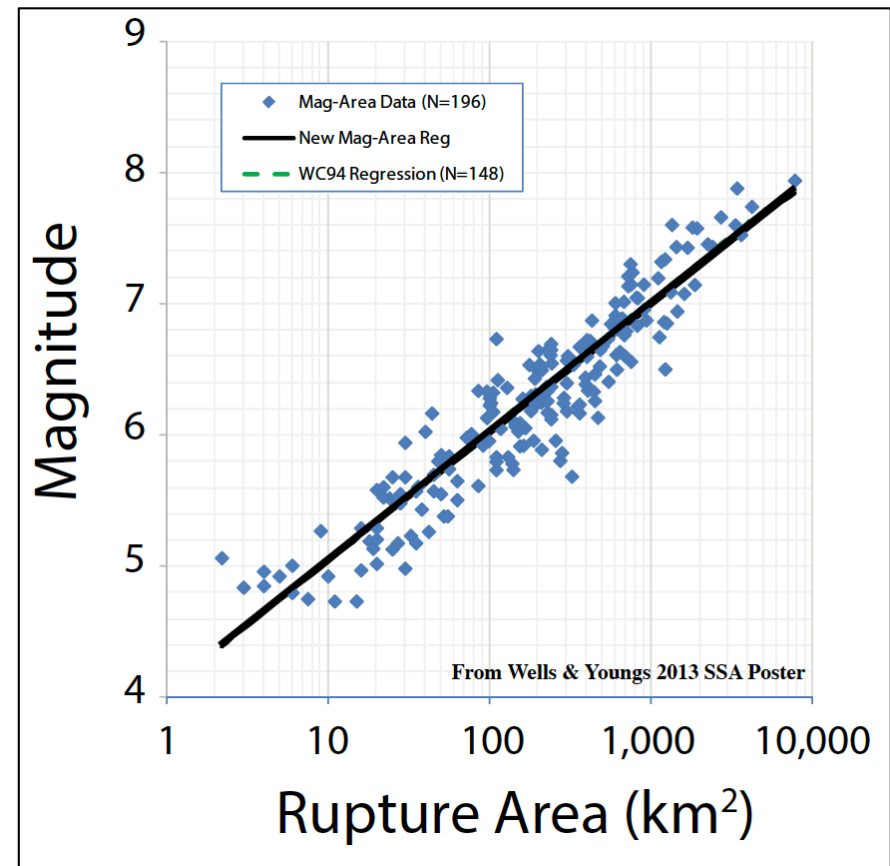
1) The Anatomy of an Earthquake Rupture Forecast

$$Magnitude = \log(\text{SurfaceArea}) + 4$$

Fault Information:



<https://www.nps.gov/articles/faults-and-fractures.htm>

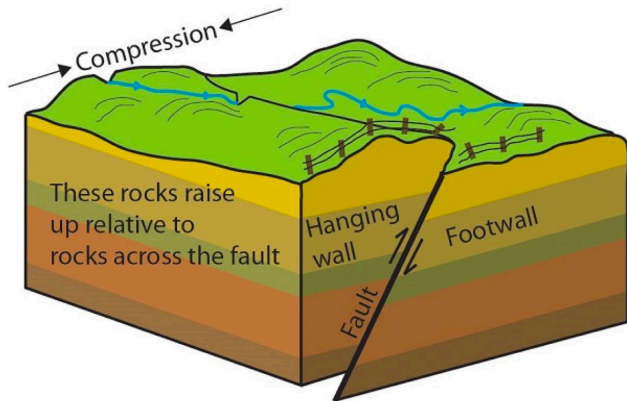


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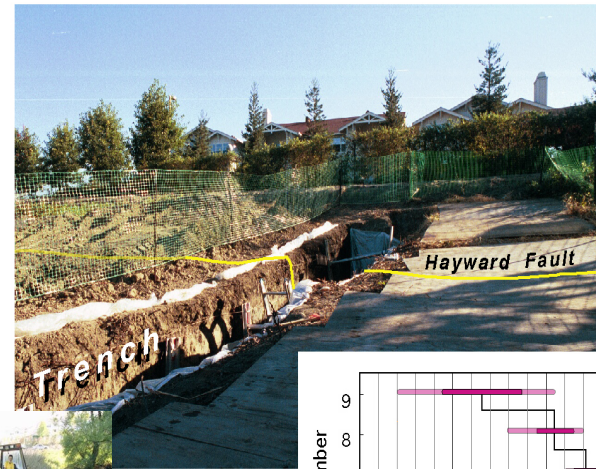
$$\text{Magnitude} = \log(\text{SurfaceArea}) + 4$$

$$\text{Long-Term Rate} = 1/\text{ObsRecurrenceInterval}$$

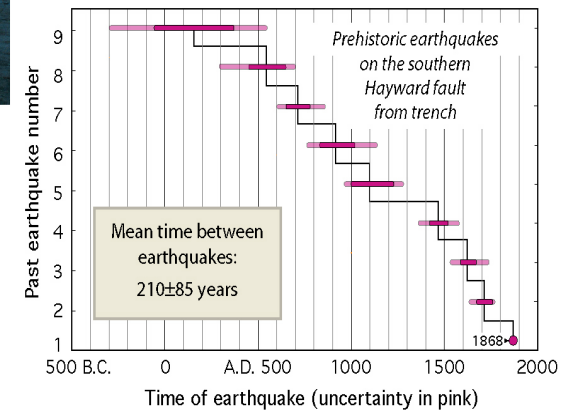


<https://www.nps.gov/articles/faults-and-fractures.htm>

Paleoseismic Study

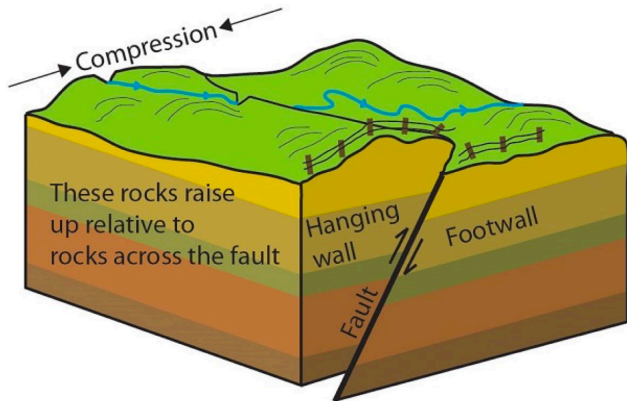


Fault trenching by Jim Lienkaemper and colleagues revealed 9 shocks in the past 2000 years.



1) The Anatomy of an Earthquake Rupture Forecast

Fault Information:



<https://www.nps.gov/articles/faults-and-fractures.htm>

$$Magnitude = \log(SurfaceArea) + 4$$

$$Long-Term\ Rate = 1/ObsRecurrenceInterval$$

or

$$Long-Term\ Rate = \frac{[SlipRate \times SurfaceArea \times \mu]}{10^{(1.5 \times Magnitude + 9.05)}}$$

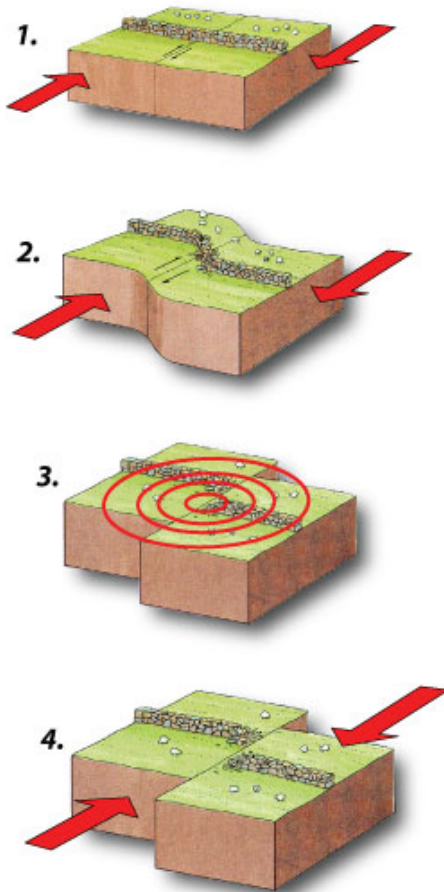


e.g., *SlipRate* on the San Andreas Fault is about 3 cm/yr

1) The Anatomy of an Earthquake Rupture Forecast

Fault Information:

Reid's
(1906)
elastic-
rebound
theory



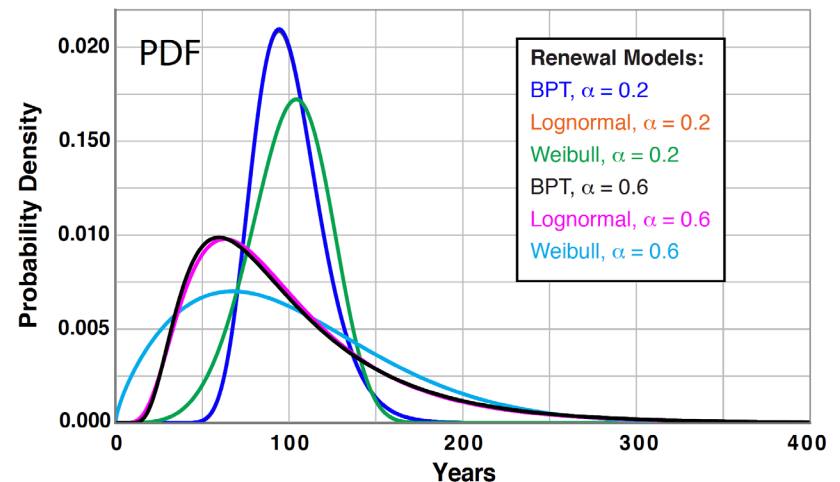
$$Magnitude = \log(SurfaceArea) + 4$$

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or

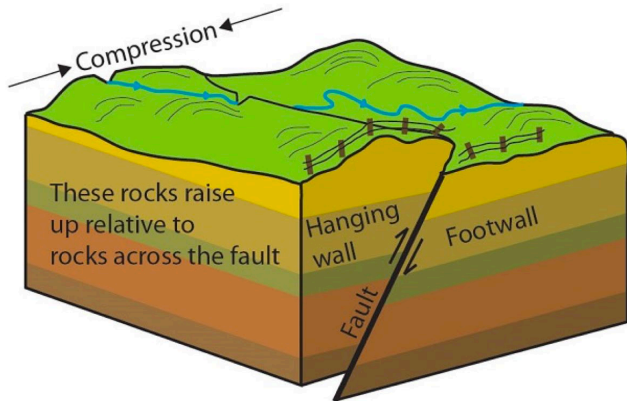
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Conditional Probability (Given Date of Last Rupture):



1) The Anatomy of an Earthquake Rupture Forecast

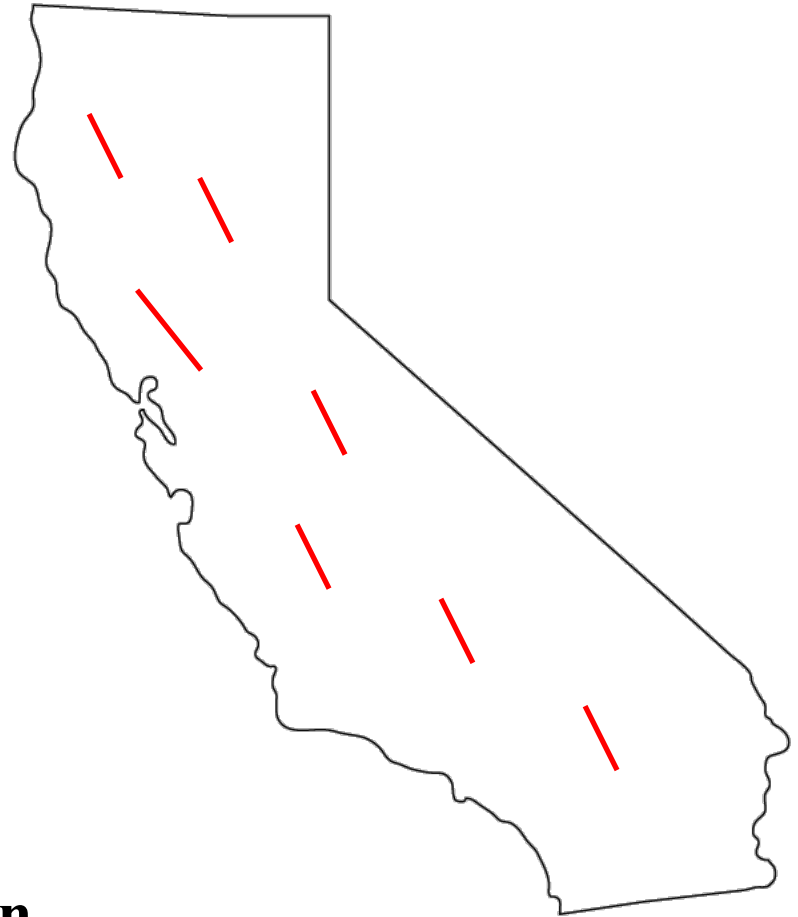
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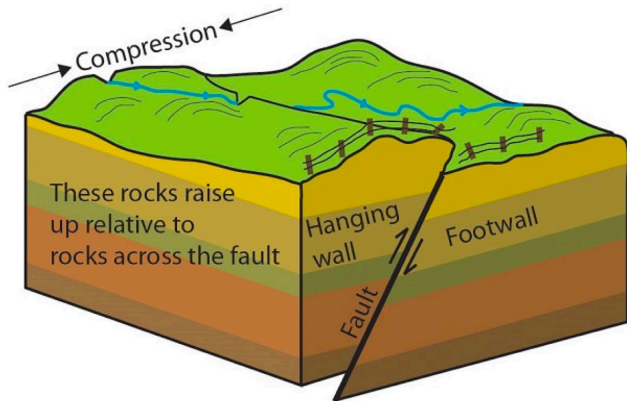
*Magnitude,
Long-Term Rate, &
Conditional Probability*

Repeat for each fault in the region



1) The Anatomy of an Earthquake Rupture Forecast

Fault Information:



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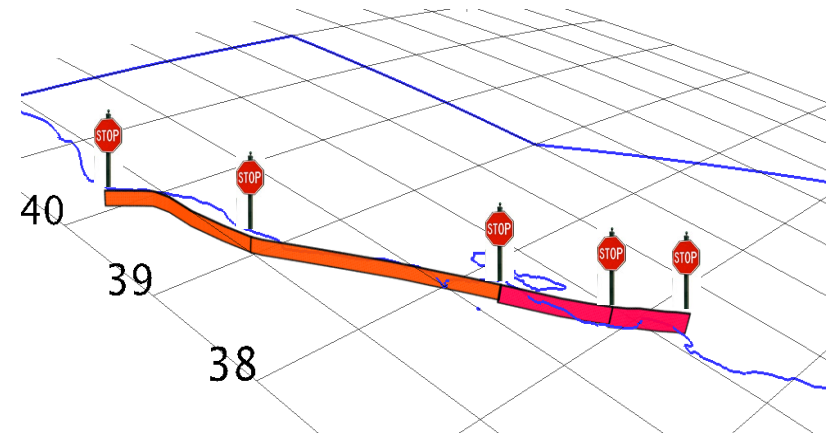
*Magnitude,
Long-Term Rate, &
Conditional Probability*

For each fault in the region

Complication:

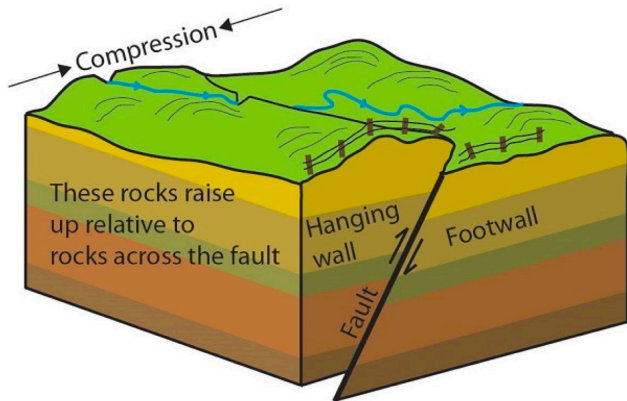
Some faults are quite long, so they certainly have more than one sized earthquake

Option 1: Assume “Segementation”



1) The Anatomy of an Earthquake Rupture Forecast

Fault Information:



<https://www.nps.gov/articles/faults-and-fractures.htm>

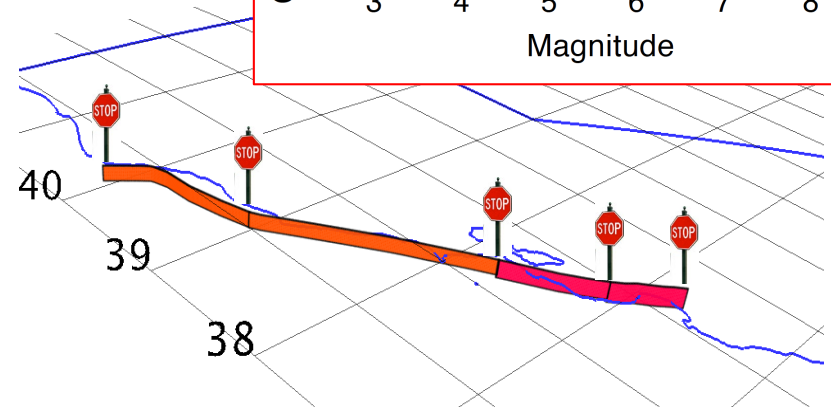
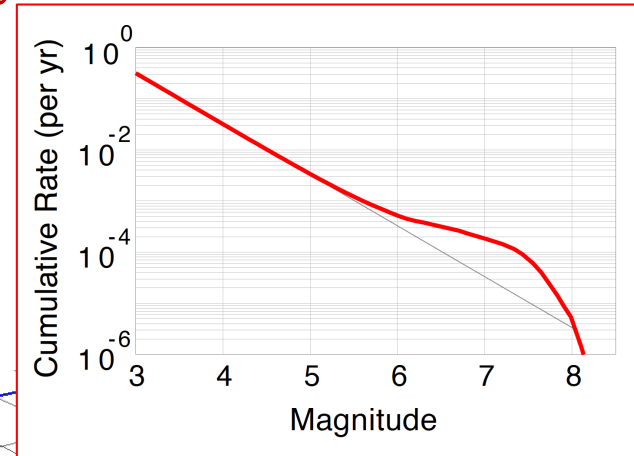
*Magnitude,
Long-Term Rate, &
Conditional Probability*

For each fault in the region

Complication:

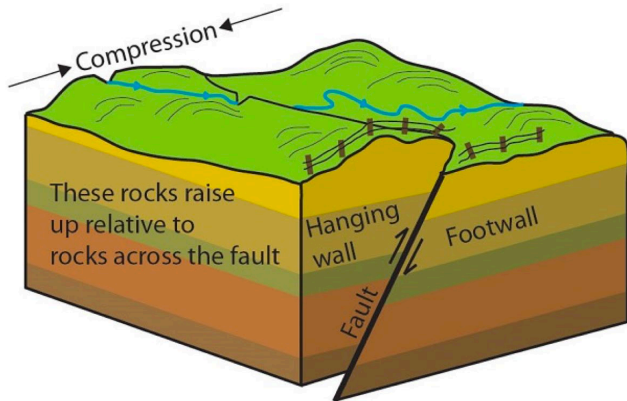
Some faults are quite long, so they certainly have more than one sized earthquake

*Option 2:
Assume a range
of magnitudes &
their relative
frequency*



1) The Anatomy of an Earthquake Rupture Forecast

Fault Information:

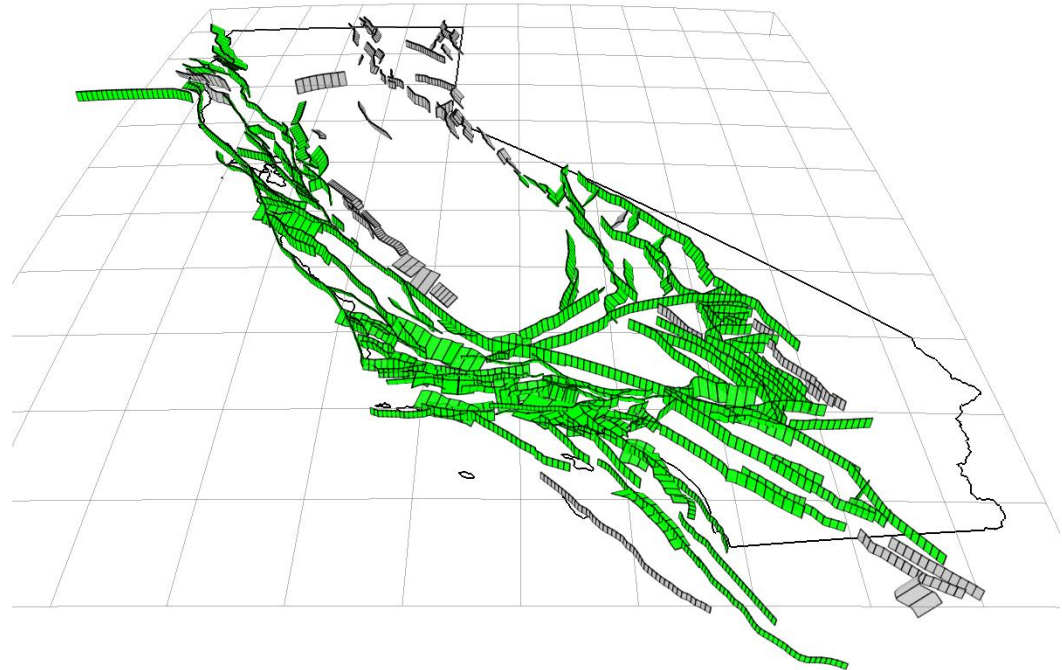


<https://www.nps.gov/articles/faults-and-fractures.htm>

*Magnitude,
Long-Term Rate, &
Conditional Probability*

Further Complication:

Areas like California actually represent and inter-connected fault system (not a set of isolated faults)



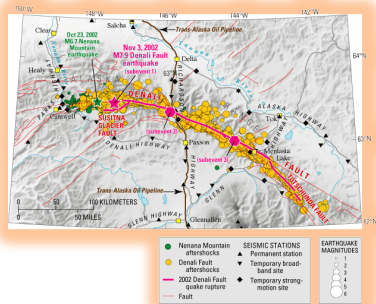
1) The Anatomy of an Earthquake Rupture Forecast

Fault Information:

Plus, theory and observations imply ruptures can bust “segment” boundaries and jump faults ($\leq \sim 5\text{km}$)

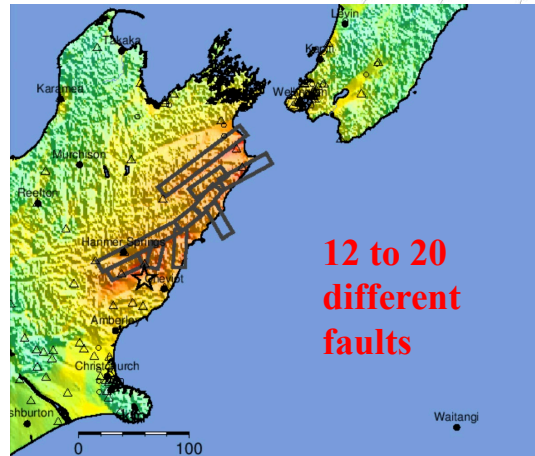
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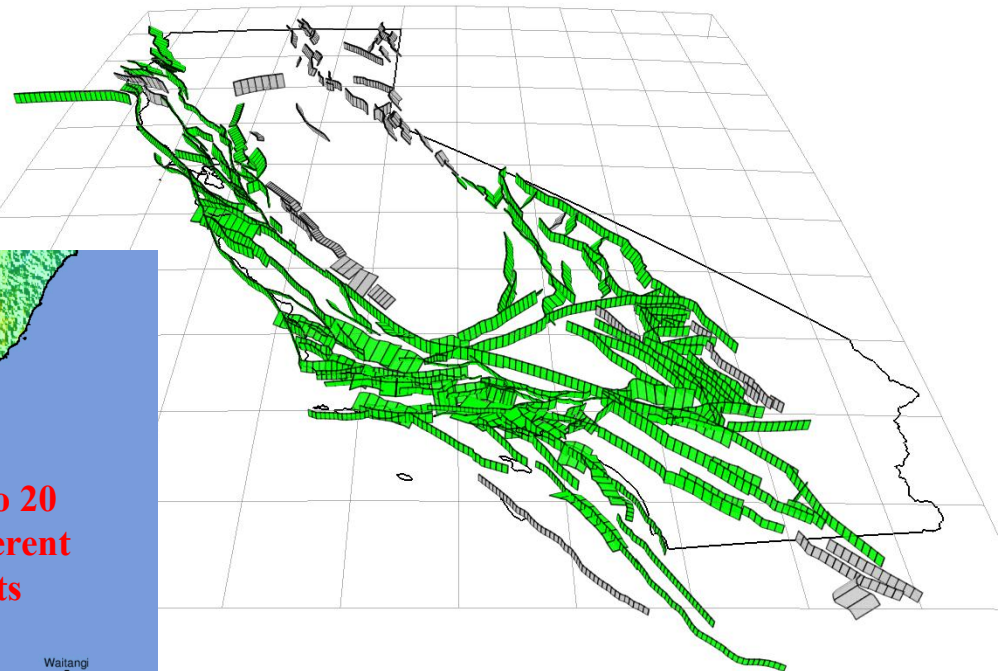


**2002 M 7.9
Denali Quake**

**2016 M 7.8
NZ Kaikoura
Earthquake**

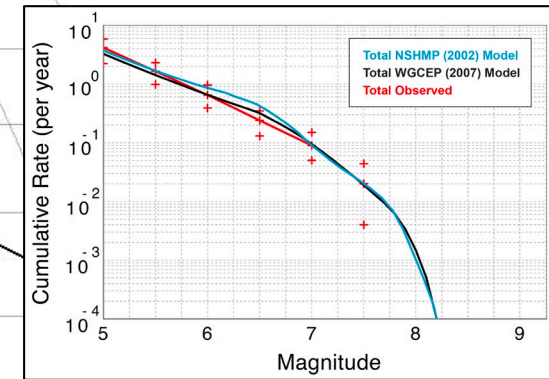
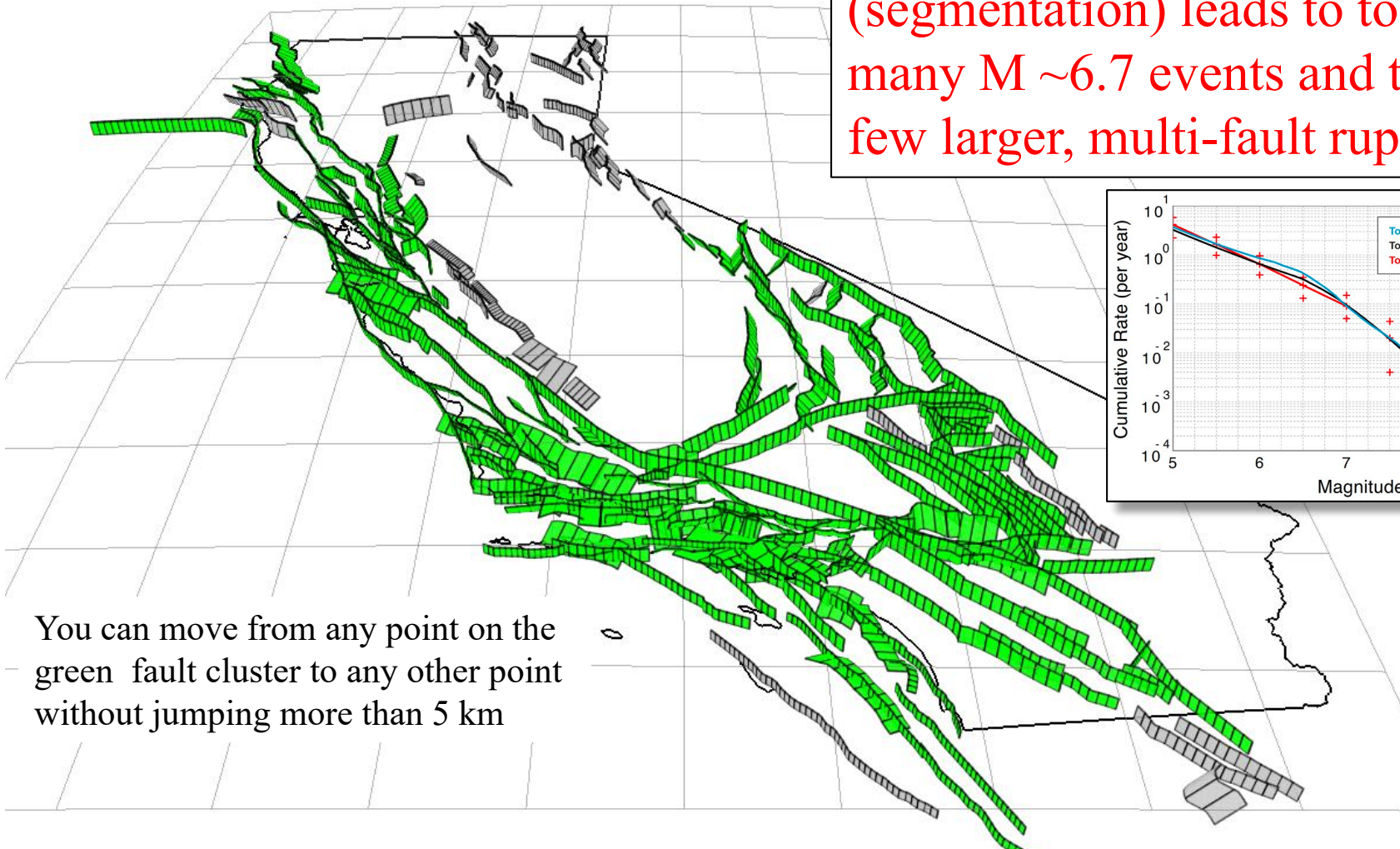


**12 to 20
different
faults**



1) The Anatomy of an Earthquake Rupture Forecast

Limiting the size of ruptures (segmentation) leads to too many $M \sim 6.7$ events and too few larger, multi-fault ruptures



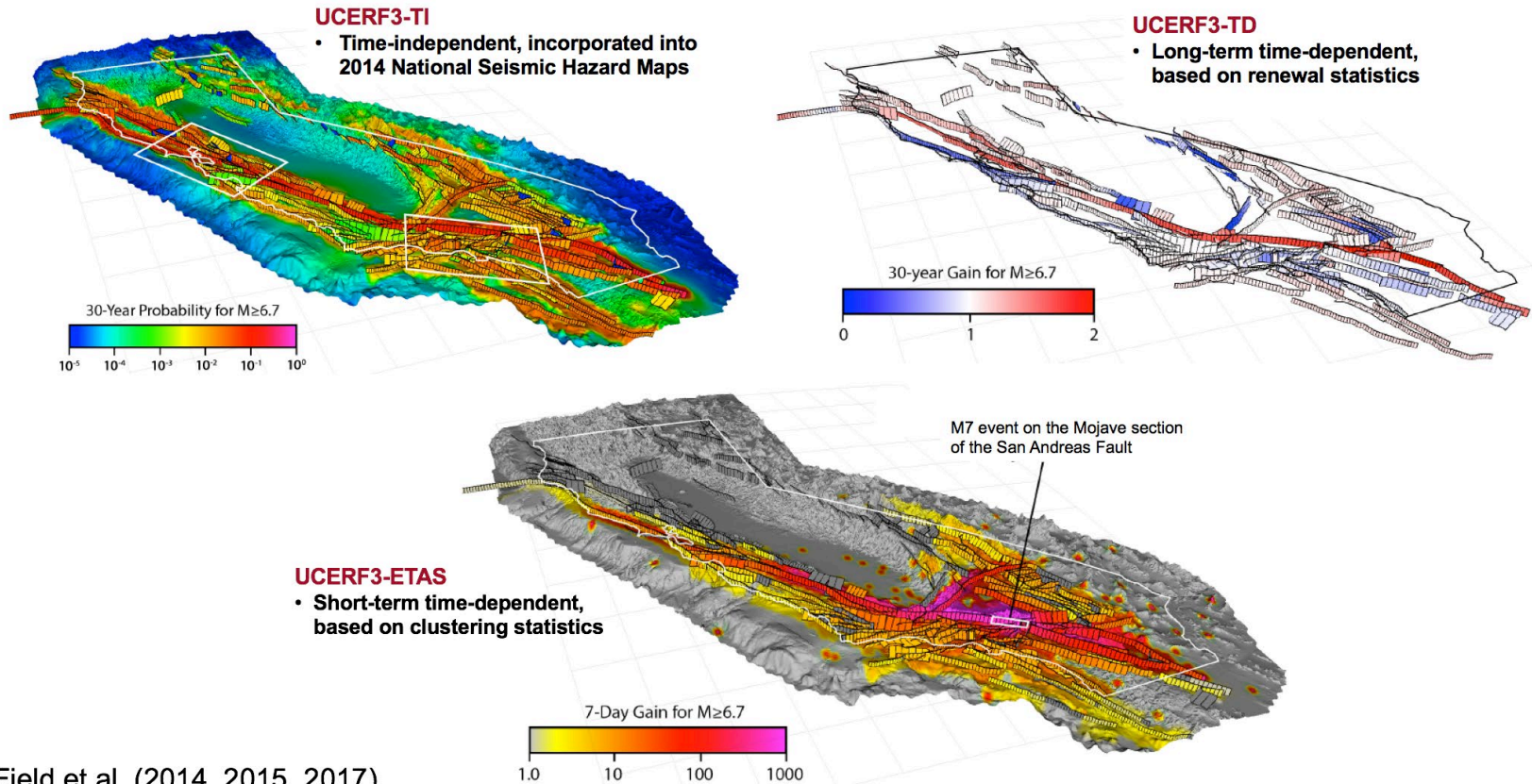
You can move from any point on the green fault cluster to any other point without jumping more than 5 km

1) The Anatomy of an Earthquake Rupture Forecast

3rd Uniform California Earthquake Rupture Forecast (UCERF3)

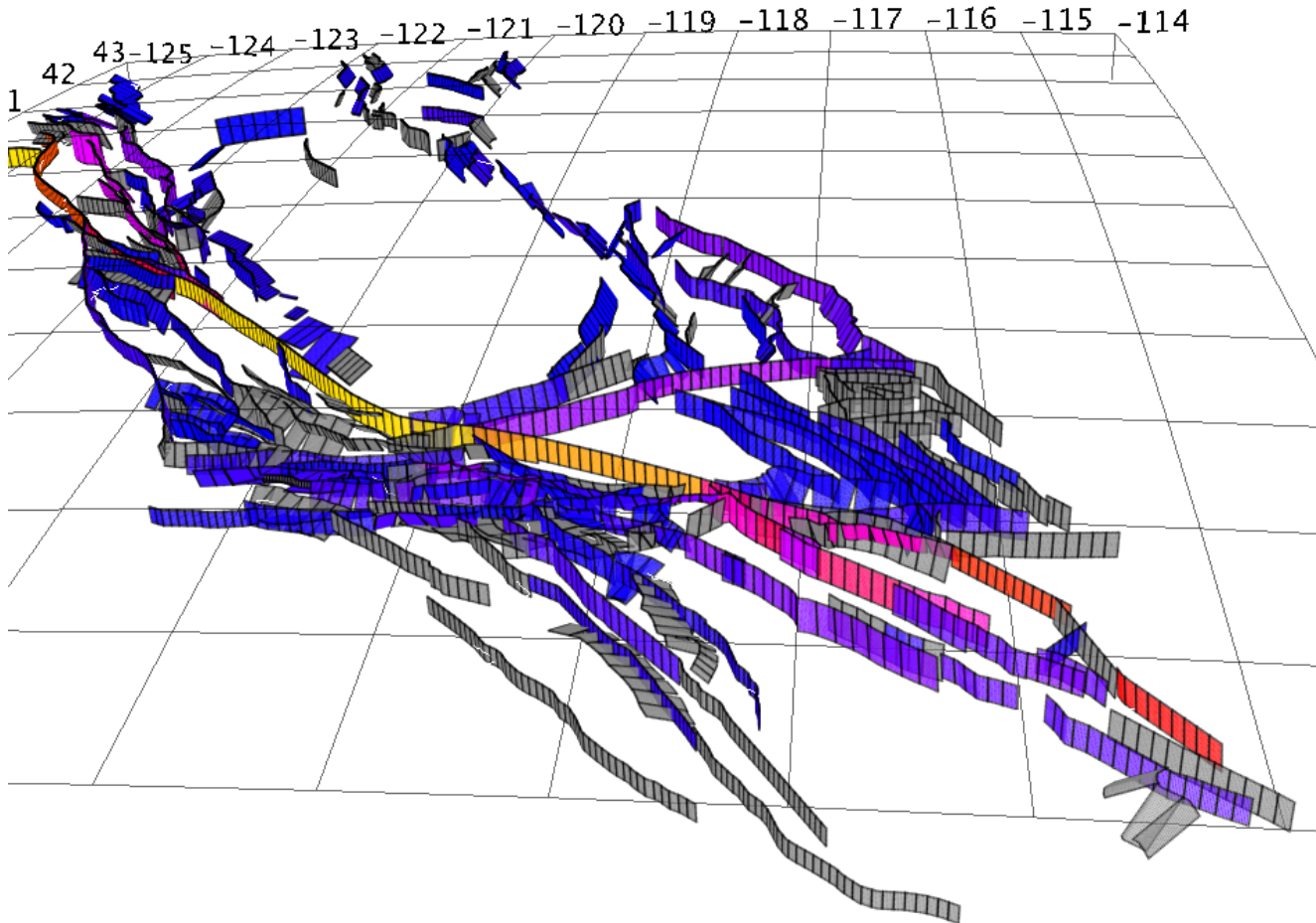
by the Working Group on California Earthquake Probabilities

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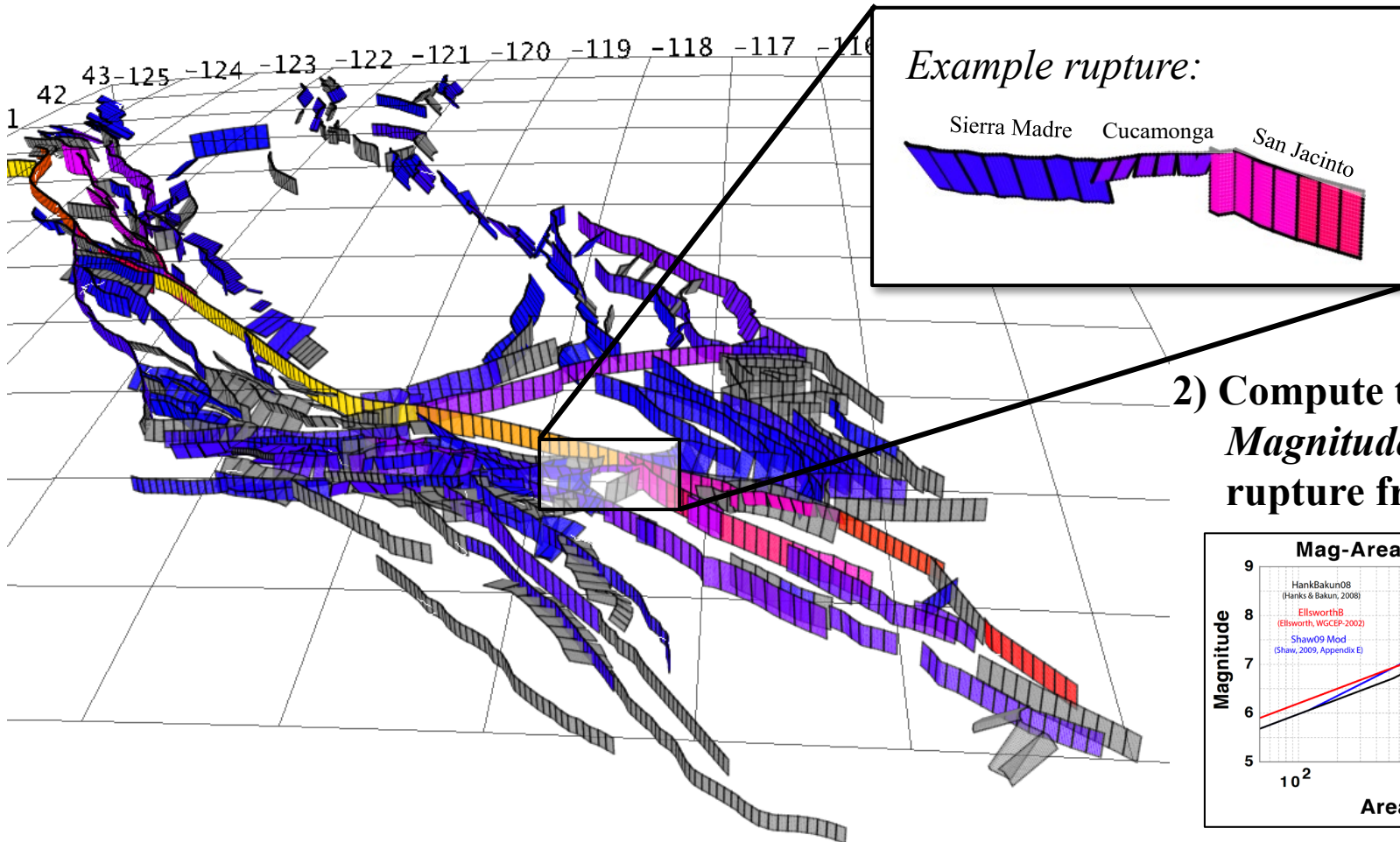
The UCERF3 “Grand” Inversion

- 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 $\leq 5\text{km}$); $\sim 250,000$ ruptures compared to $\sim 8,000$ in UCERF2)

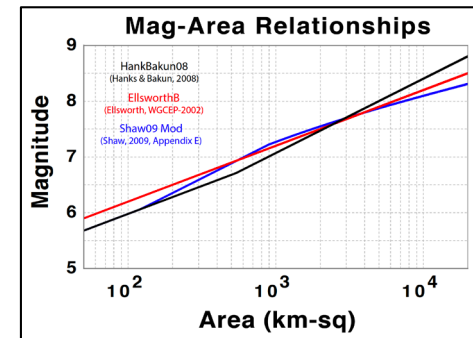


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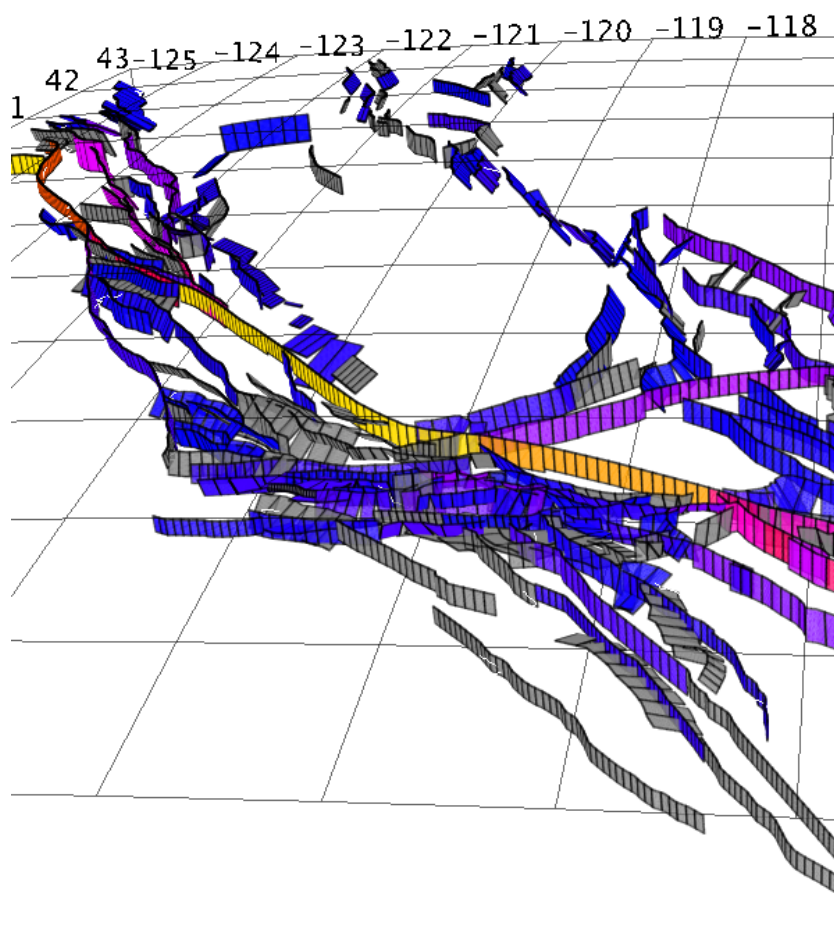


- 2) Compute the *Magnitude* of each rupture from its area



The UCERF3 “Grand” Inversion

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



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)*

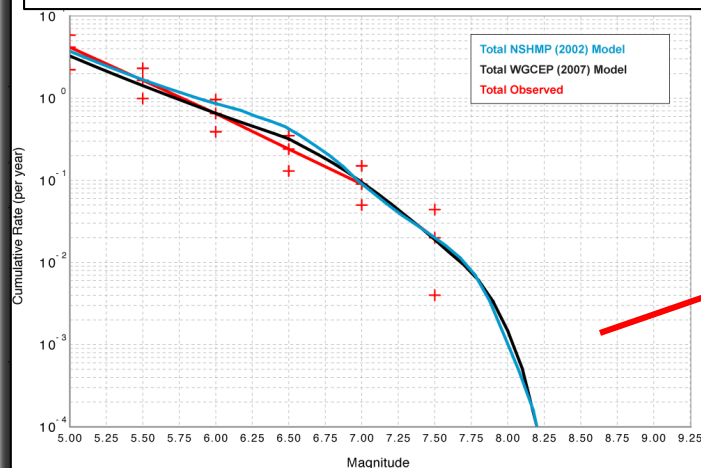
Other Equations

⋮

The UCERF3 “Grand” Inversion

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

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

$$\sum_{r=1}^R D_{sr} f_r = v_s$$

(1) *Fault Slip Rates*

$$\sum_{r=1}^R G_{sr} P_r^{paleo} f_r = f_s^{paleo}$$

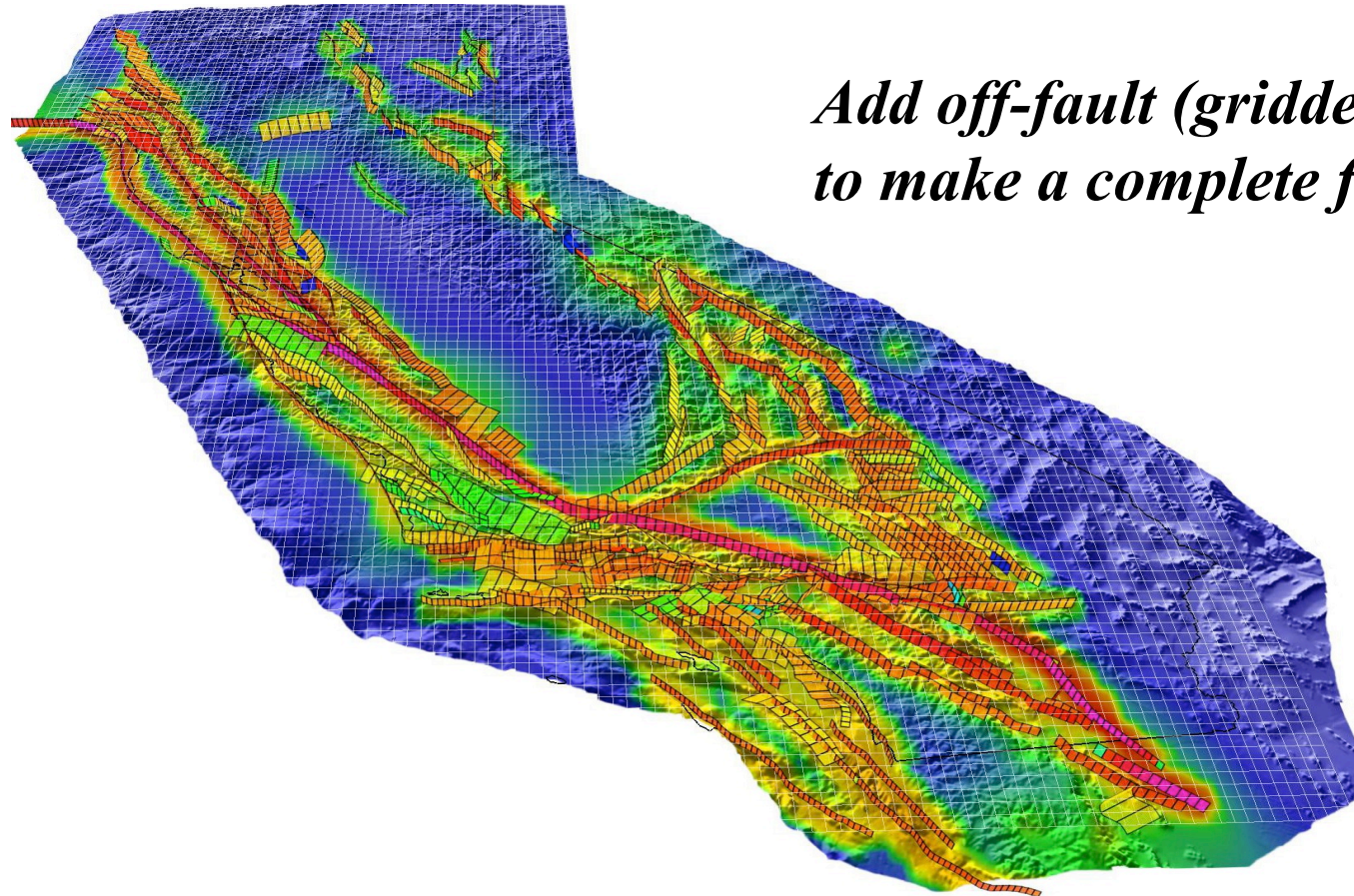
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Other Equations

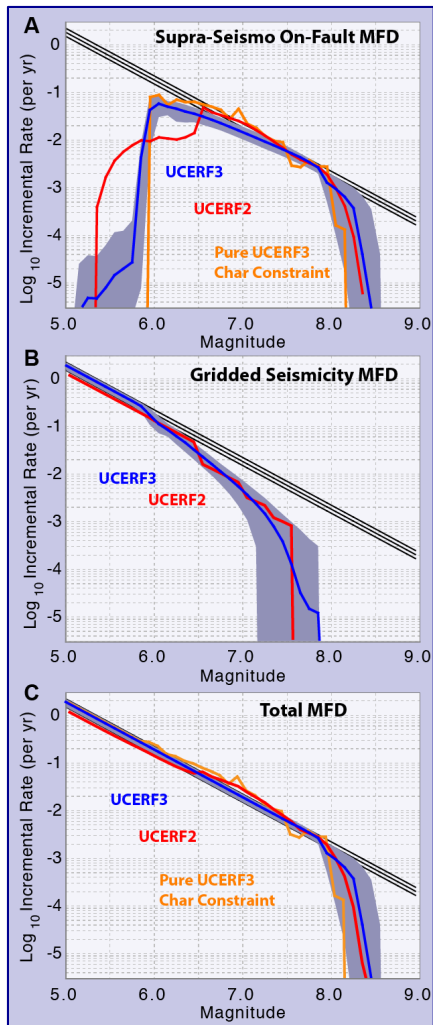
⋮



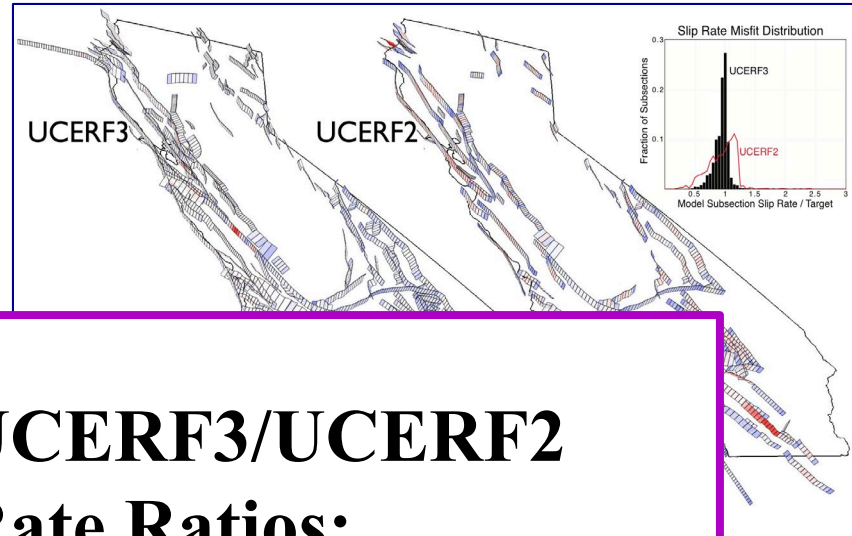
*Add off-fault (gridded) seismicity
to make a complete forecast*

UCERF3 Data Fits (better than UCERF2):

Region MFDs



Slip Rates:

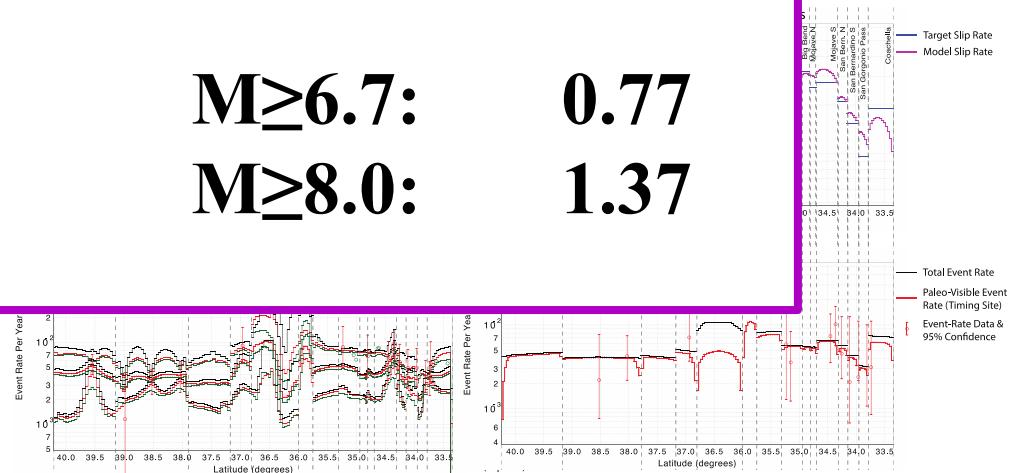


UCERF3/UCERF2 Rate Ratios:

$$M \geq 6.7: \quad 0.77$$

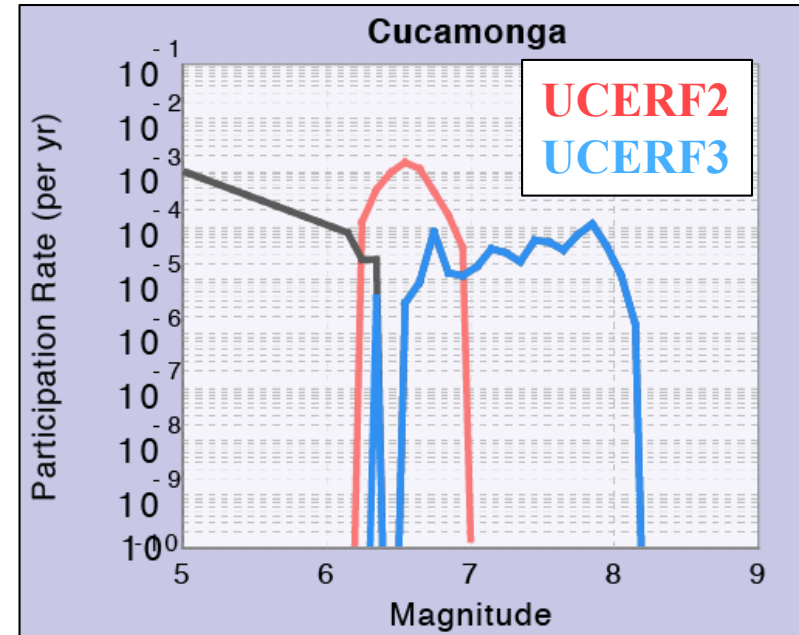
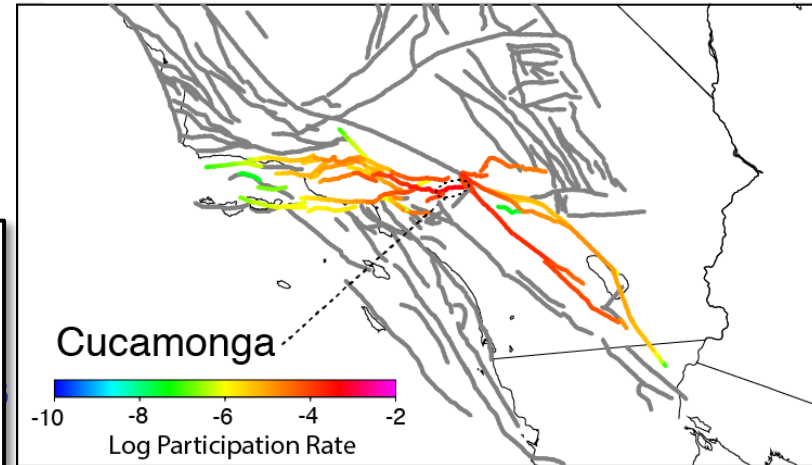
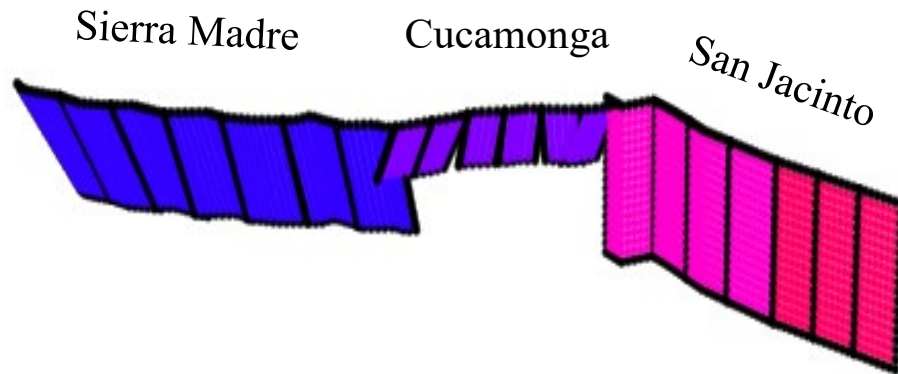
$$M \geq 8.0: \quad 1.37$$

Paleo
Event
Rate



The most dramatic change:

Example rupture:

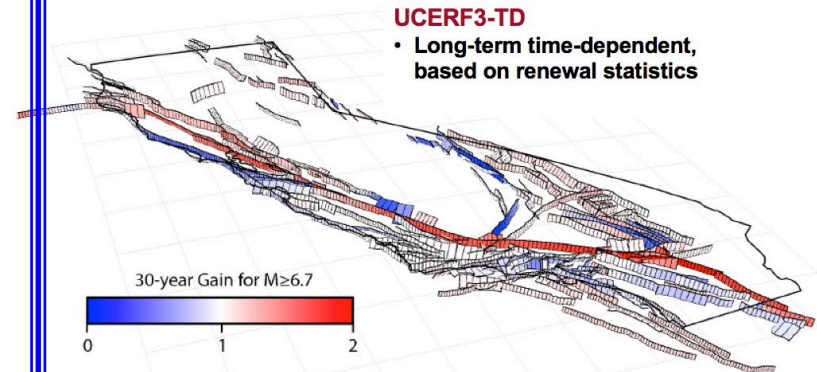
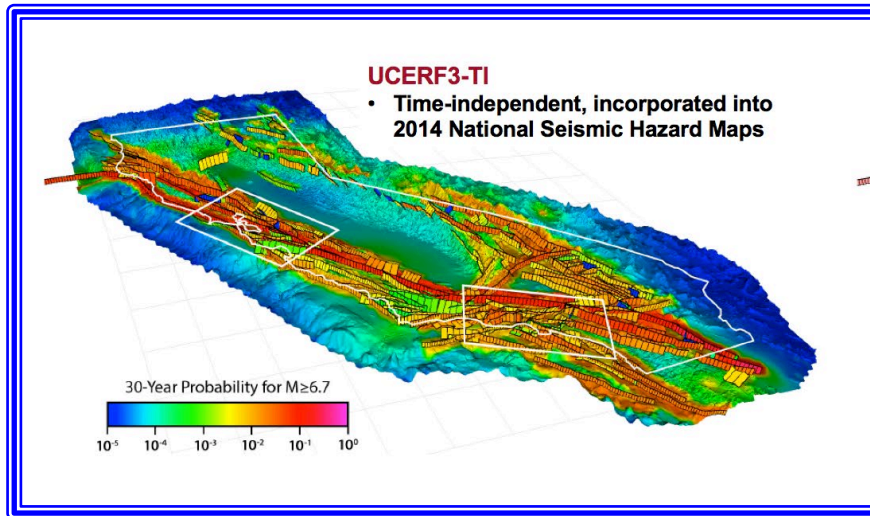


1) The Anatomy of an Earthquake Rupture Forecast

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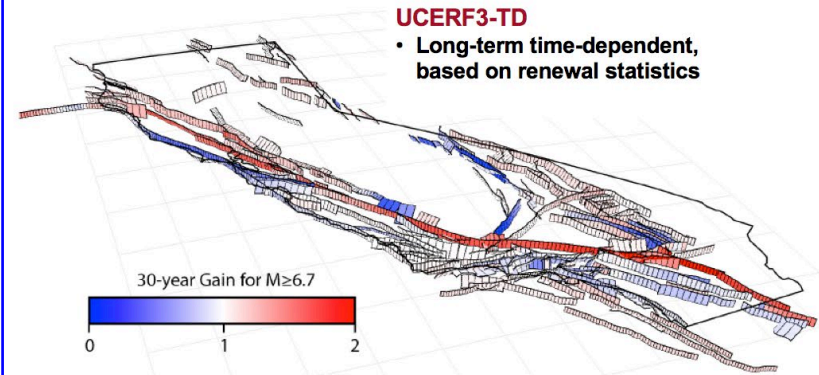
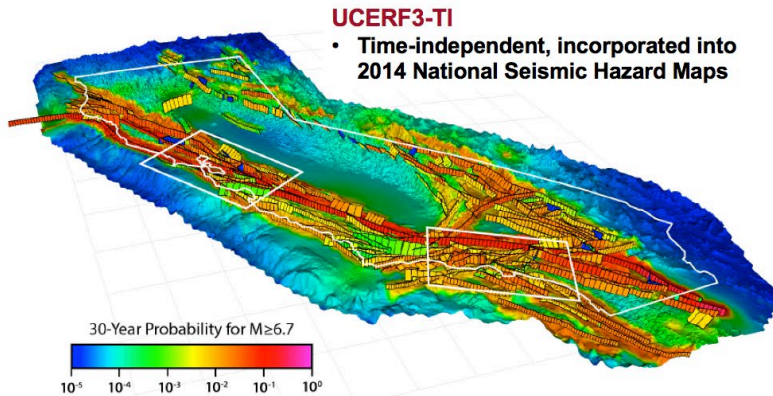


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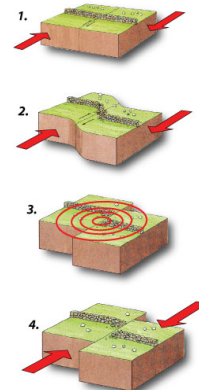
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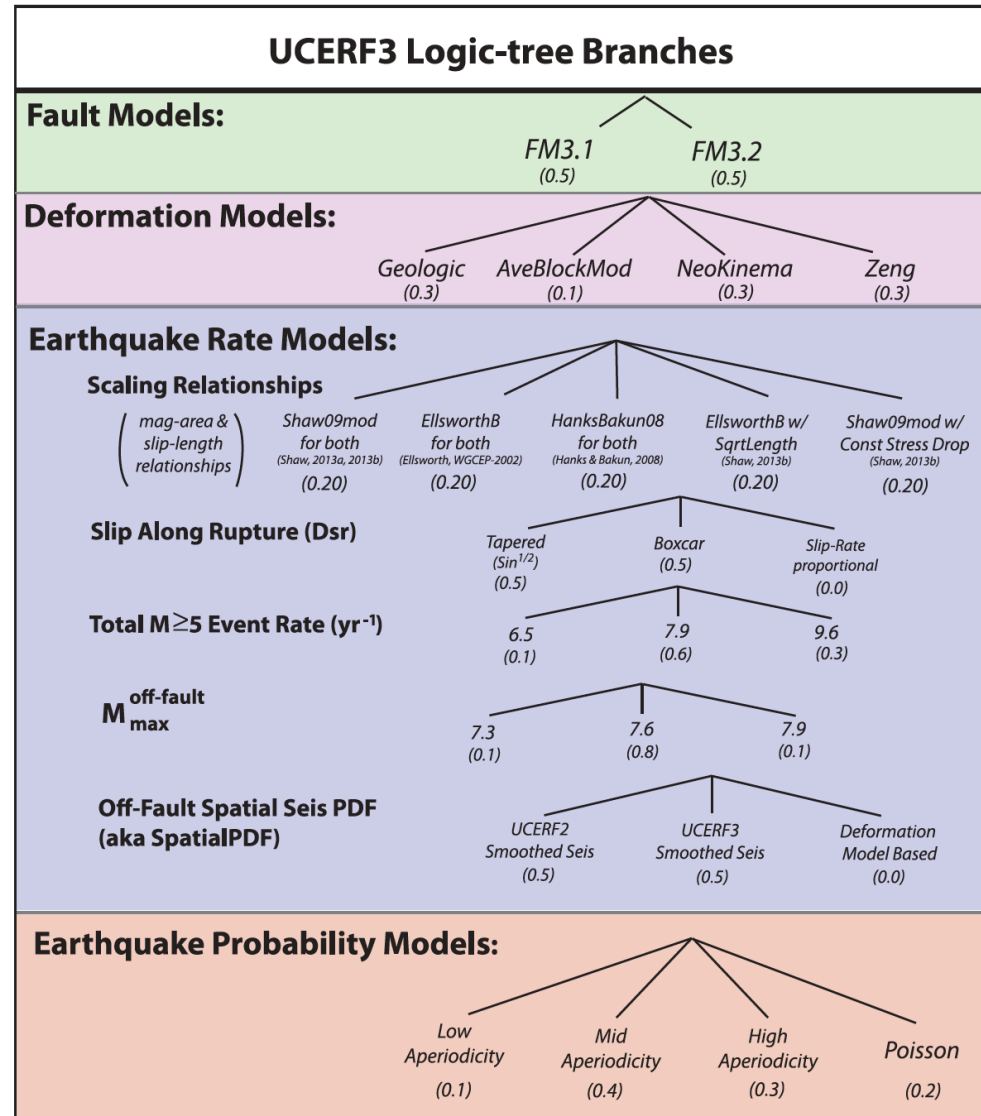
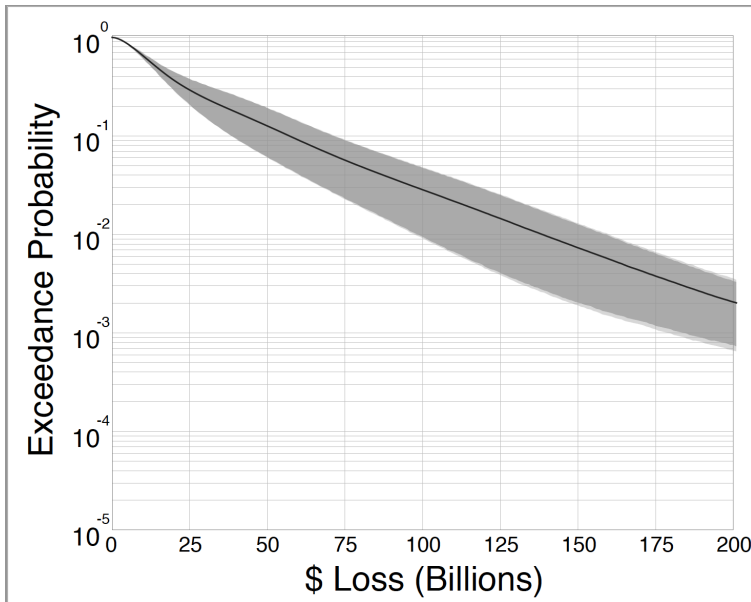
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- 3) Operational Earthquake Forecasting
- 4) The Need for More Physics-Based Approaches
- 5) The Importance of Model “Valuation” (in addition to Verification and Validation)

2) Representation of Epistemic Uncertainties

There are lots of epistemic uncertainties (usually represented with logic trees)

These imply uncertainty in our hazard and risk estimates



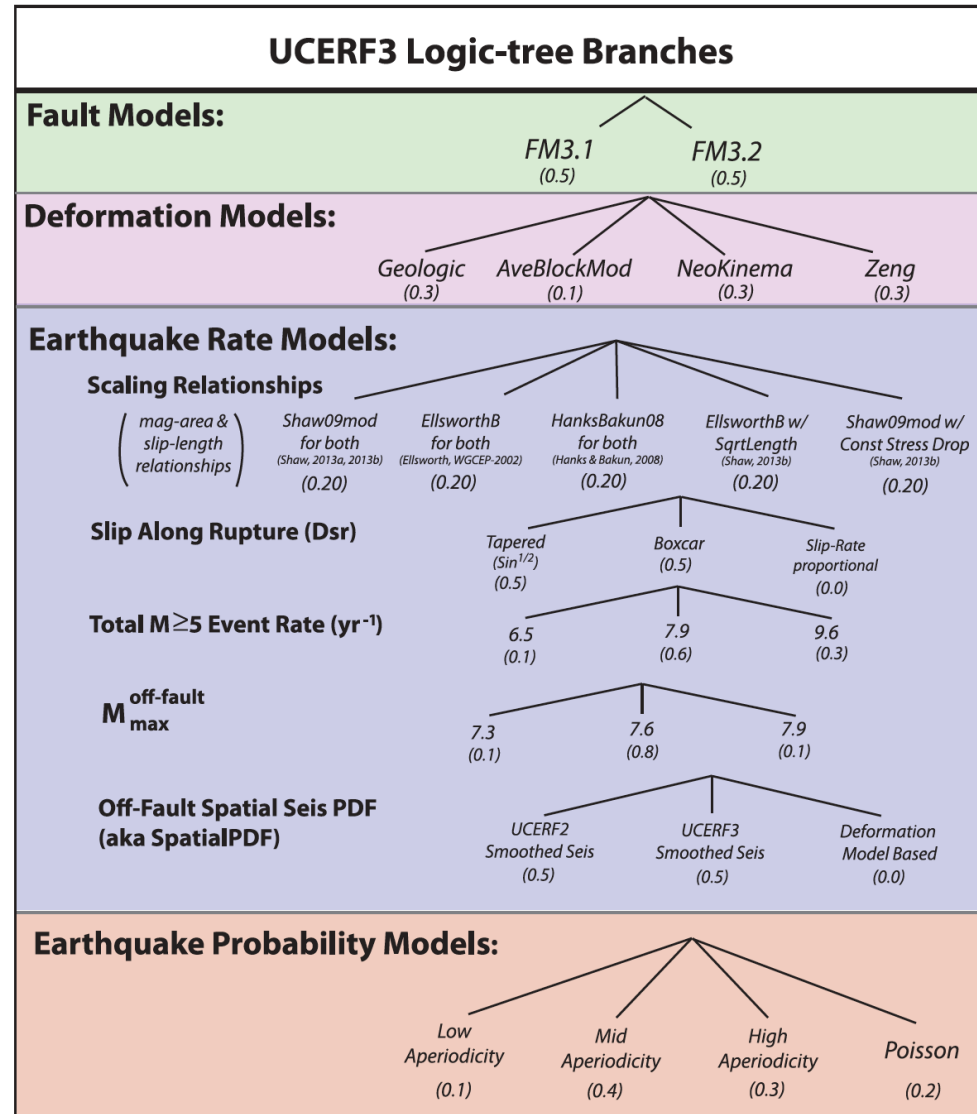
2) Representation of Epistemic Uncertainties

There are lots of epistemic uncertainties (usually represented with logic trees)

These imply uncertainty in our hazard and risk estimates

So far, each new model has increased these uncertainties, meaning we have not yet turned the corner in terms of new science reducing uncertainties (we have yet to define the full uncertainties).

We need to do better, (but it's hard)



Talk Outline

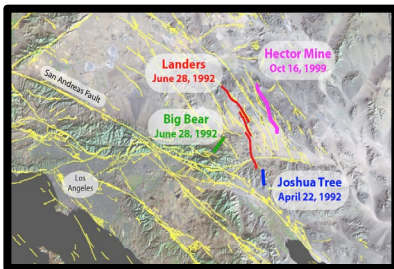
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3) Operational Earthquake Forecasting (OEF)

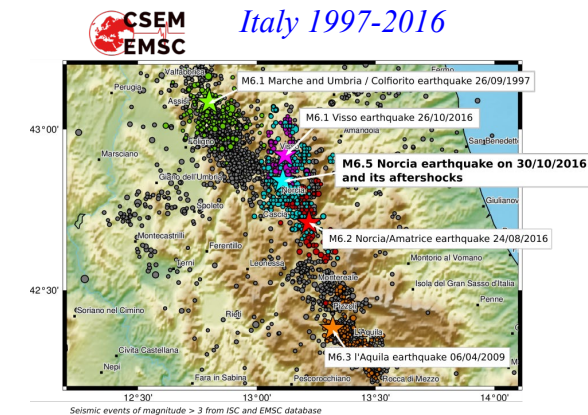
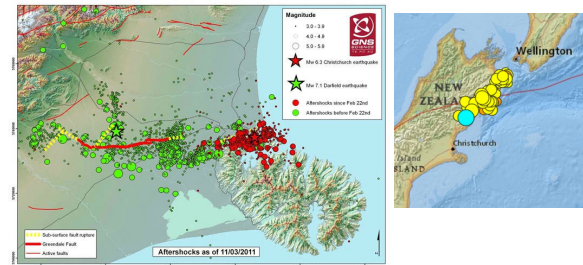
The timely dissemination of authoritative information about potentially damaging earthquakes, including triggered events

Aftershocks (triggered events) can be large and damaging...

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



Darfield → Christchurch → M7.8 Kaikoura



Falls under the USGS statutory responsibility (Disaster Relief Act of 1974, appendix E)

There is ongoing debate about whether OEF is useful enough to be worth deploying

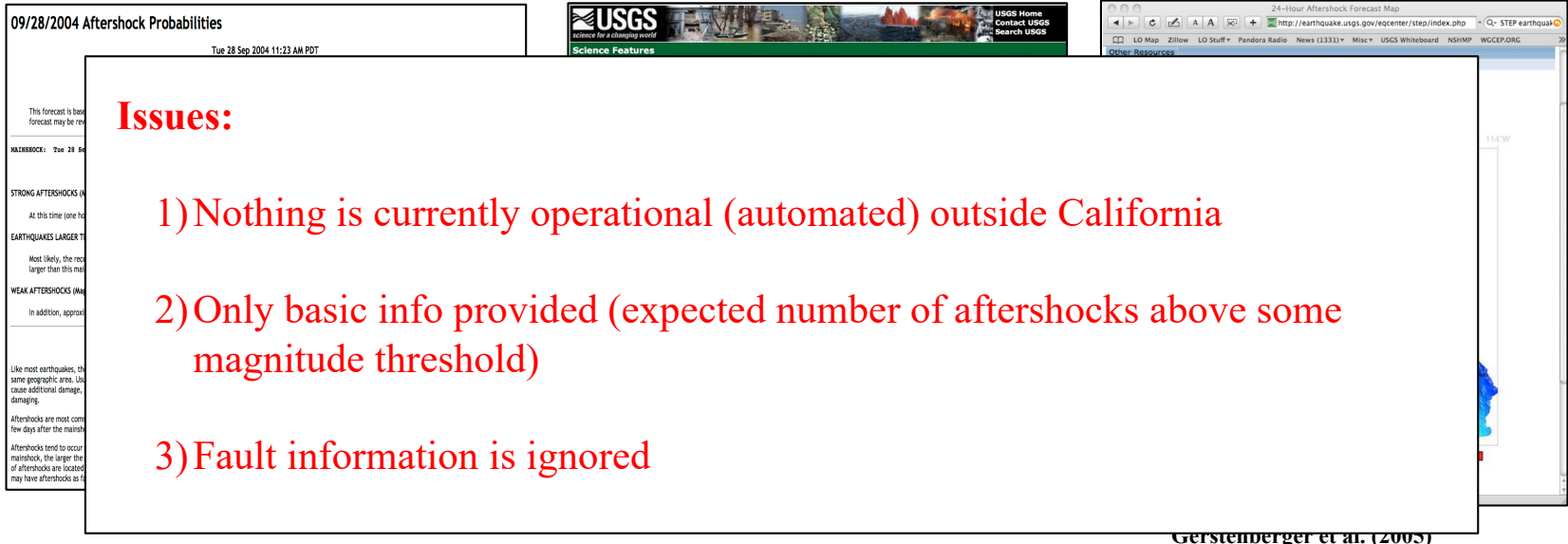
3) Operational Earthquake Forecasting (OEF)

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

Auto notifications for $M \geq 5$ events in California

Occasional ad hoc notifications elsewhere (hand built; slow)

STEP aftershock hazard (2005-2010)



The screenshot shows a USGS webpage titled "09/28/2004 Aftershock Probabilities" dated "Tue 28 Sep 2004 11:23 AM PDT". It includes a "USGS Home" link and a "Science Features" banner. A sidebar on the left lists "STRONG AFTERSHOCKS" and "WEAK AFTERSHOCKS". The main content area displays "Issues:" followed by three red bullet points. To the right, a "24-Hour Aftershock Forecast Map" is visible, showing a map of California with a red dot indicating the mainshock location. The map is titled "http://earthquake.usgs.gov/eqcenter/step/index.php" and includes a "USGS Whiteboard" and "NSHMP" link.

Issues:

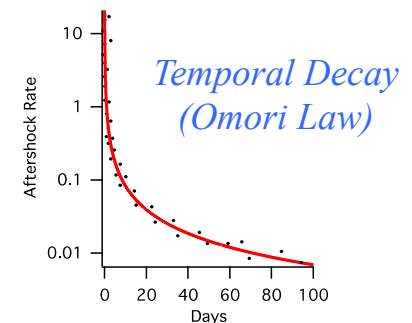
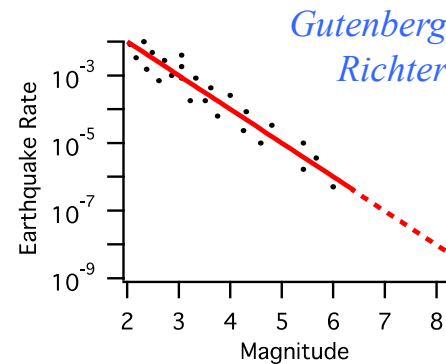
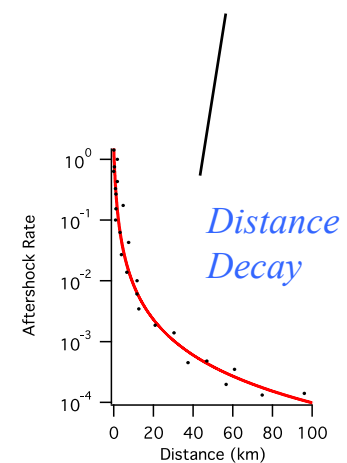
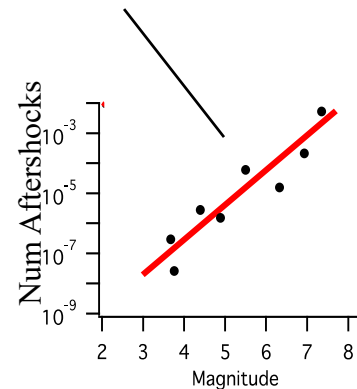
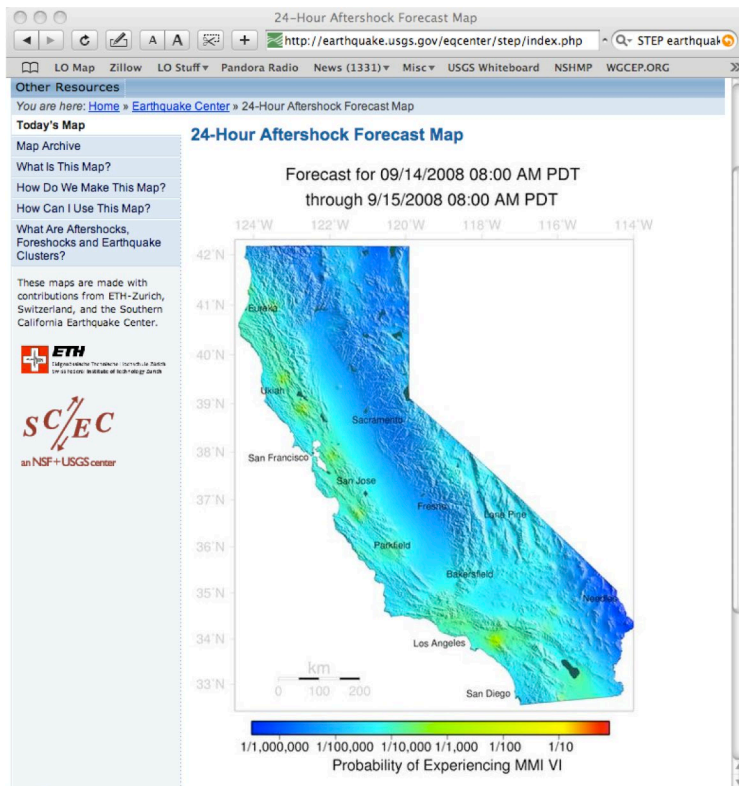
- 1) Nothing is currently operational (automated) outside California
- 2) Only basic info provided (expected number of aftershocks above some magnitude threshold)
- 3) Fault information is ignored

Gerstenberger et al. (2005)

3) Operational Earthquake Forecasting (OEF)

e.g., the “STEP” model (Gerstenberger et al., 2005)

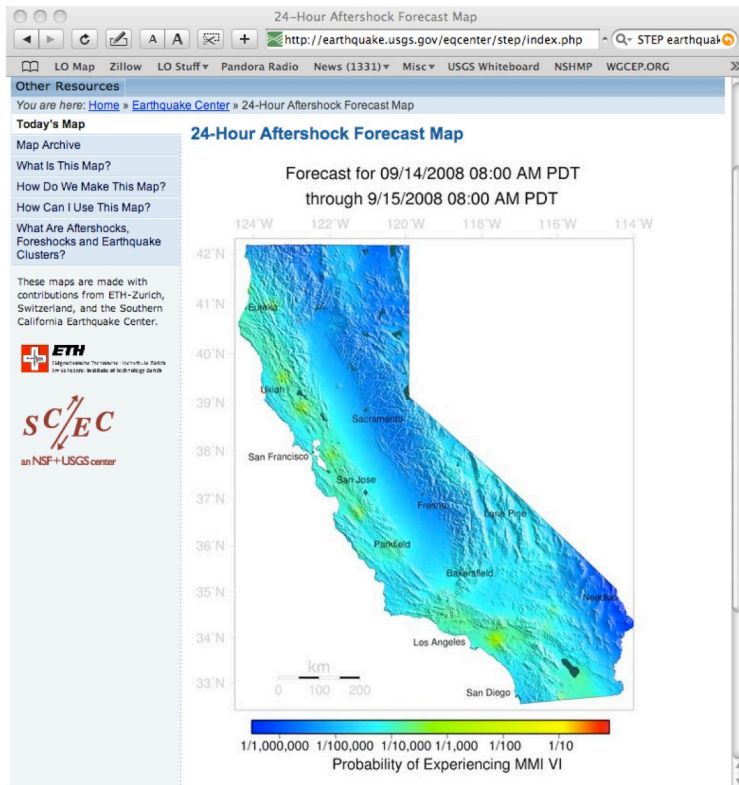
$$\text{Rate of aftershocks} \propto 10^{(aM_{\text{mainshock}})} \times 10^{-bM} \times (t + c)^{-p} \times (r + d)^{-q}$$



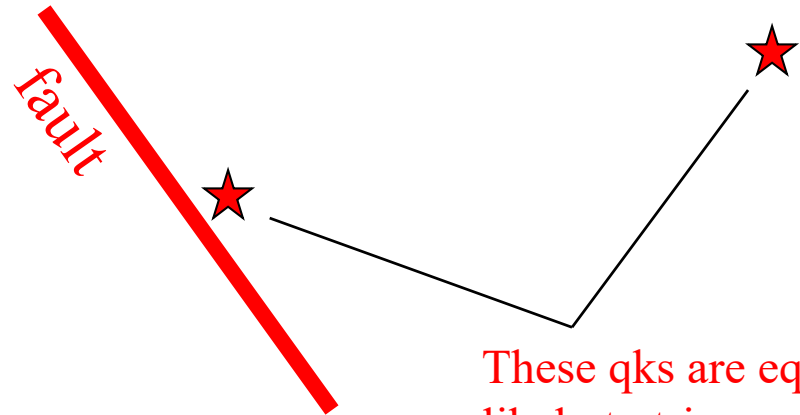
3) Operational Earthquake Forecasting (OEF)

e.g., the “STEP” model (Gerstenberger et al., 2005)

$$\text{Rate of aftershocks} \propto 10^{(aM_{\text{mainshock}})} \times 10^{-bM} \times (t + c)^{-p} \times (r + d)^{-q}$$



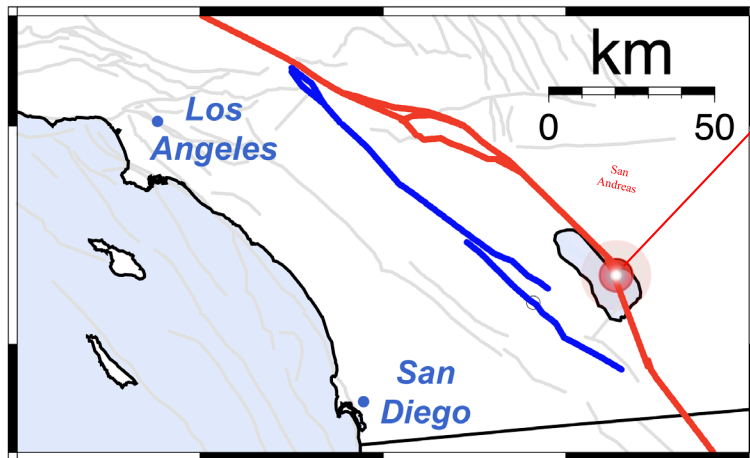
But again, there is no information about faults



These qks are equally likely to trigger something big

3) Operational Earthquake Forecasting (OEF)

e.g., the California Earthquake Prediction Evaluation Council issues warnings when small earthquakes are occurring near the San Andreas Fault.



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

3) Operational Earthquake Forecasting (OEF)

e.g., the *California Earthquake Prediction Evaluation Council* warnings when small earthquakes are occurring near the San Andreas



Cal OES
GOVERNOR'S OFFICE
OF EMERGENCY SERVICES

CALIFORNIA EARTHQUAKE PREDICTION
EVALUATION COUNCIL (CEPEC)

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. (Jen Khan/Los Angeles Times)

By **Brittney 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
Auto Insurance As Low As \$19.32 US
Auto Insurance - Don't Overpay On Insurance
www.insurance.com

Franchises under \$10,000
Franchises for less than \$10K, 100's of low cost franchises.
www.franchisegator.com

Try Mac Cleaner
Your Mac will always be as clean as new!
Download
www.maccleaner.com

Reverse Phone Lookup
Enter Any Number & Search Free, Get Name & Address Instantly!
phonecheckpeople.com

In Case You Missed It

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

RANDOM

of Emergency Services
Prediction Evaluation Council (CEPEC)

Earthquake Swarm of September 2016

Earthquake Prediction Evaluation Council

of Emergency Management, the California (CEPEC) met by teleconference at 08:30 hrs for the purpose of the teleconference was to discuss earthquakes (~150+) that are clustered about 10 miles from the Salton Sea area.

southern extension of the San Andreas Fault and on September 26, 2016 a M4.3 earthquake at 0:23 hrs and a M4.1 at 20:36 hrs. The cluster is thought by some seismologists to be on the San Andreas Fault. This cluster is just south of an area that ruptured in March 2009 on an adjacent, subparallel

as Fault increases the concern that these earthquakes (M7.0+) on the San Andreas itself. A major earthquake has not occurred in over 100 years.

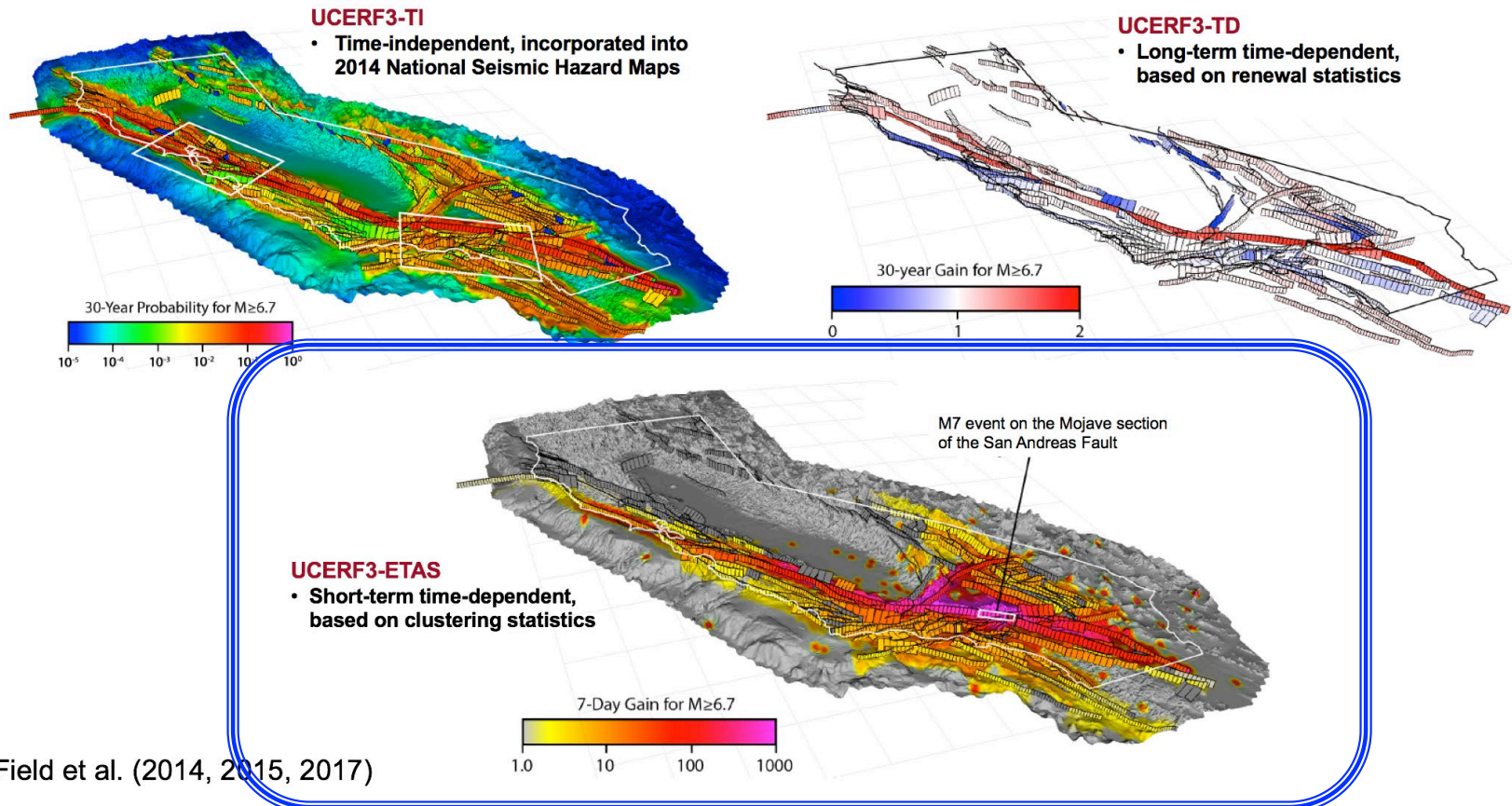
earthquake is thought by some seismologists to be higher than on portions of the fault that have ruptured more recently (e.g. in 1857 and 1906).

3) Operational Earthquake Forecasting (OEF)

3rd Uniform California Earthquake Rupture Forecast (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



3) Operational Earthquake Forecasting (OEF)

UCERF3-ETAS in a Nutshell

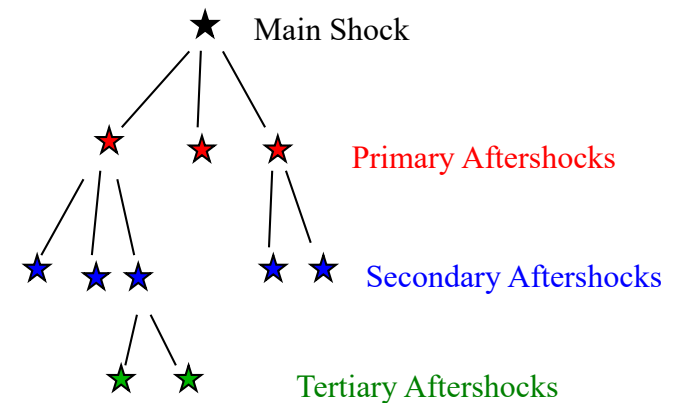
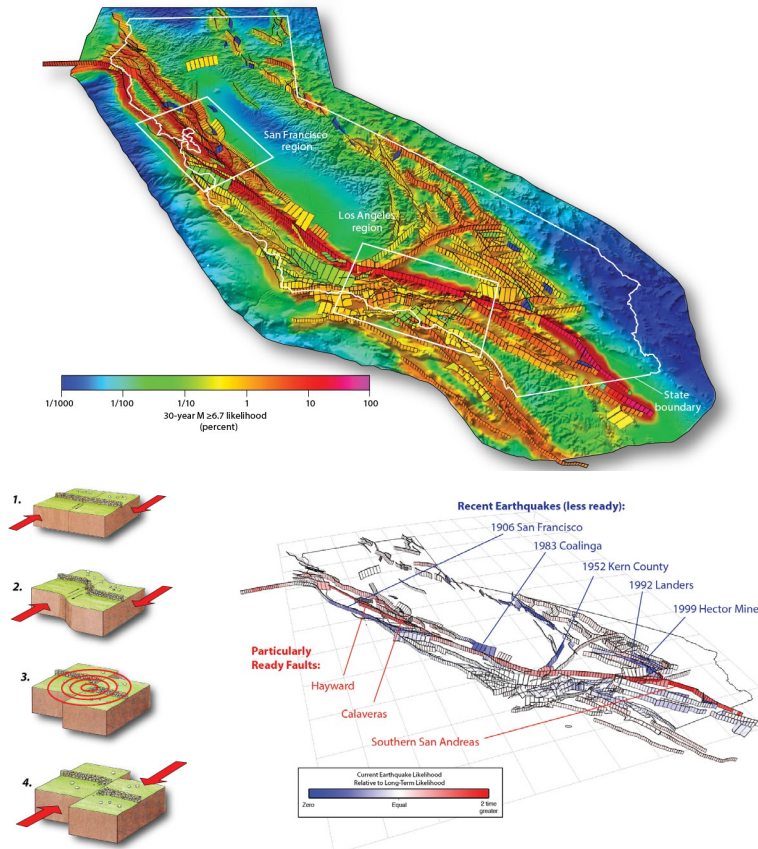
UCERF3-TD



ETAS Model
(Epidemic Type Aftershock Sequence)

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

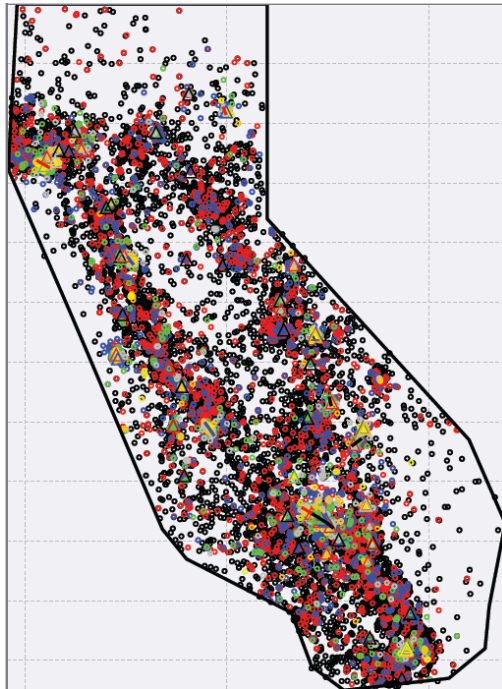
$$\lambda(t, \mathbf{x}) = \lambda_0(\mathbf{x}) + \sum_{\{i: t_i < t\}} k 10^{a(M_i - M_0)} (t - t_i + c)^{-p} c_s (r + d)^{-q}$$



3) Operational Earthquake Forecasting (OEF)

UCERF3-ETAS in a Nutshell

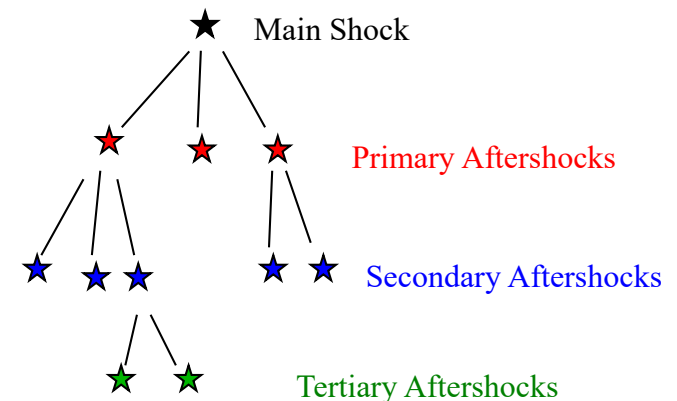
Product: synthetic catalog of events (stochastic event set)



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

$$\lambda(t, \mathbf{x}) = \lambda_0(\mathbf{x}) + \sum_{\{i: t_i < t\}} k 10^{a(M_i - M_0)} (t - t_i + c)^{-p} c_s (r + d)^{-q}$$



3) Operational Earthquake Forecasting (OEF)

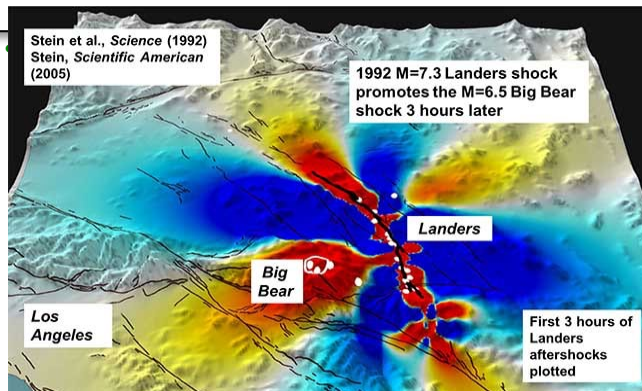
UCERF3-ETAS in a Nutshell

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

Bookkeeping is somewhat complicated due to need for elastic-rebound updating and numerical efficiency

ETAS is only a statistical proxy for whatever physics is involved..

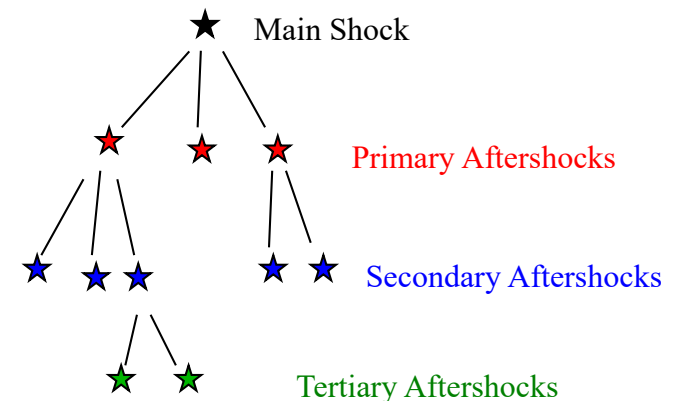
Updating with ongoing seismicity will capture, at least partially, any static or dynamic stress triggering effects



ETAS Model
(Epidemic Type Aftershock Sequence)

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

$$\lambda(t, \mathbf{x}) = \lambda_0 \mu(\mathbf{x}) + \sum_{\{i: t_i < t\}} k 10^{a(M_i - M_0)} (t - t_i + c)^{-p} c_s (r + d)^{-q}$$

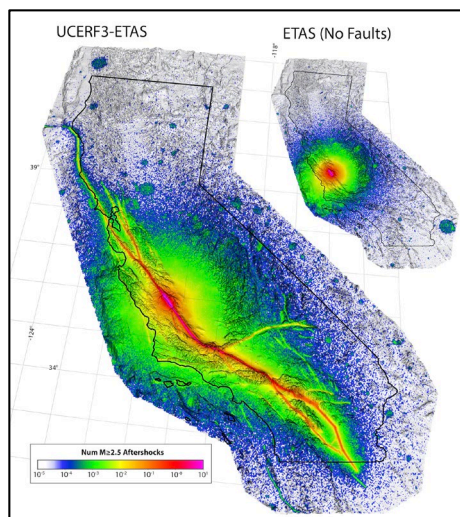


3) Operational Earthquake Forecasting (OEF)

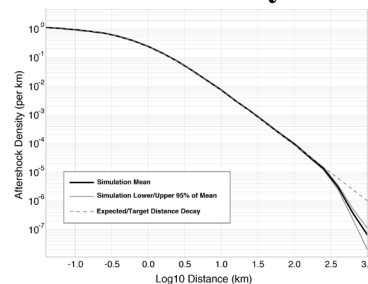
UCERF3-ETAS in a Nutshell

The most realistic model we have...

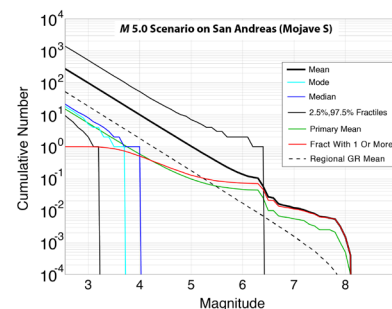
Nucleation Rates



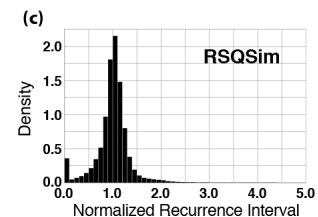
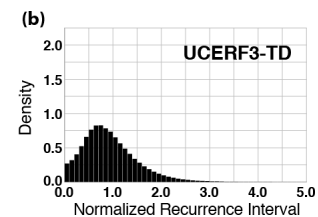
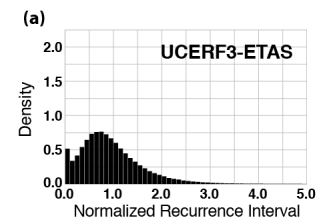
Distance Decay



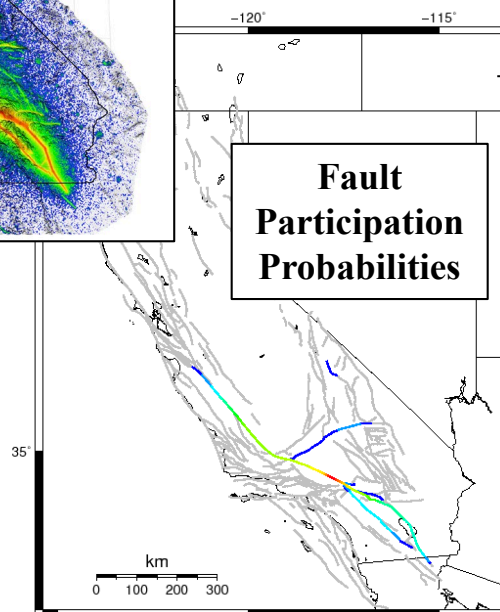
Mag-Frequency Dist.



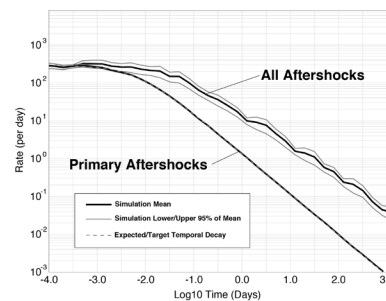
Elastic Rebound



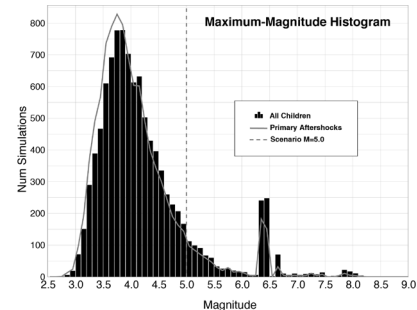
Fault Participation Probabilities



Temporal Decay

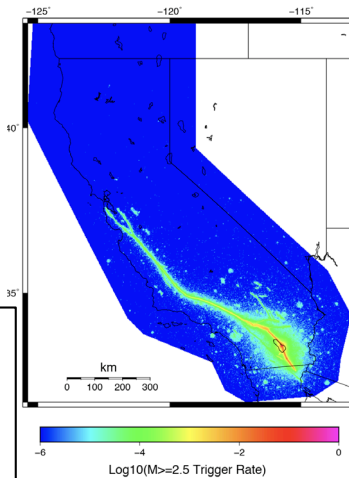
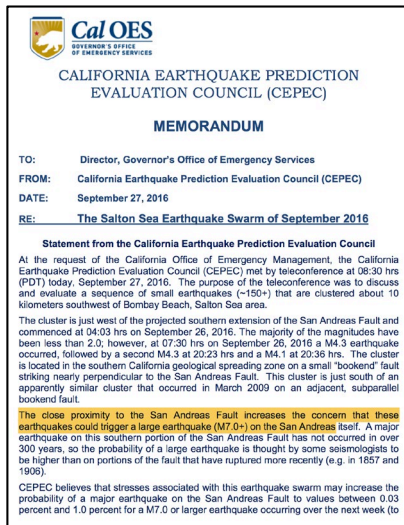


Max Triggered Magnitude

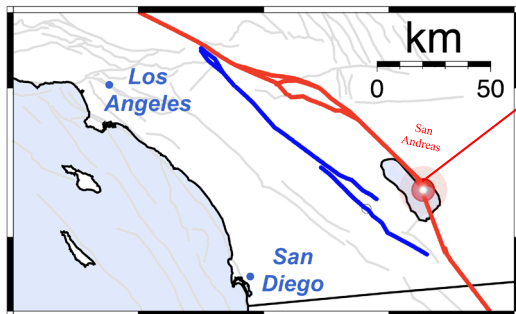


3) Operational Earthquake Forecasting (OEF)

Swarms near Bombay Beach

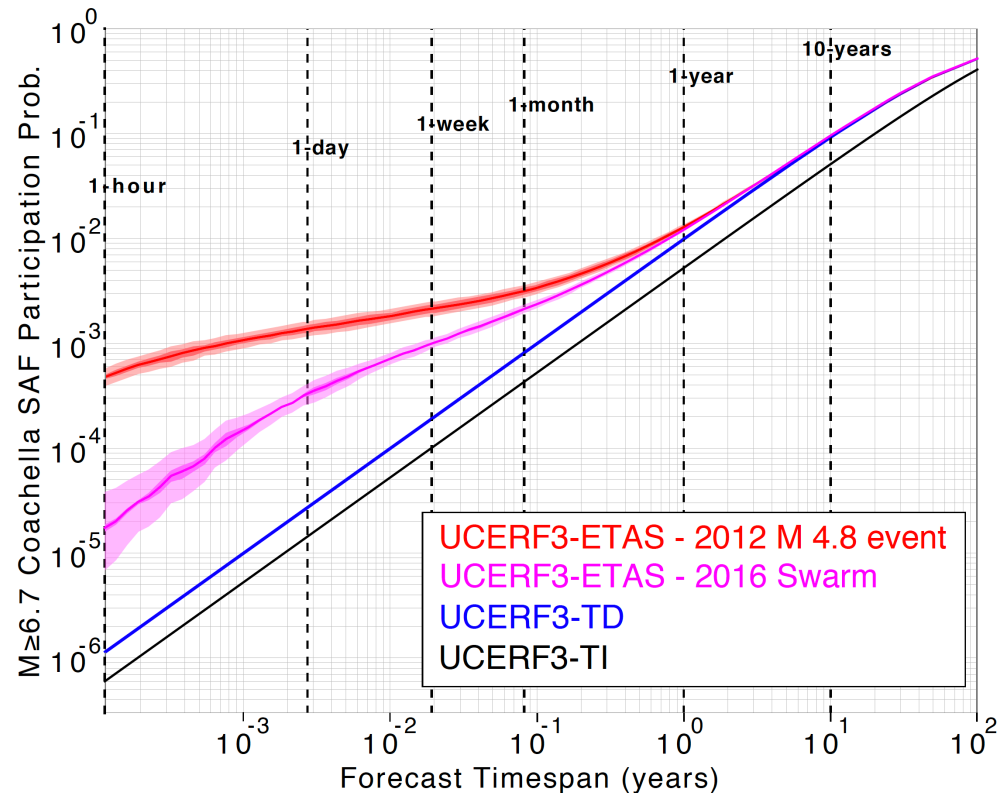


**For
improved
NEPEC
notifications**



200,000 UCERF3-ETAS Simulations

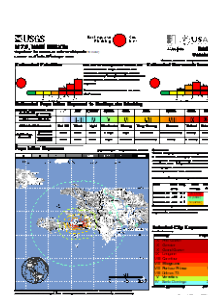
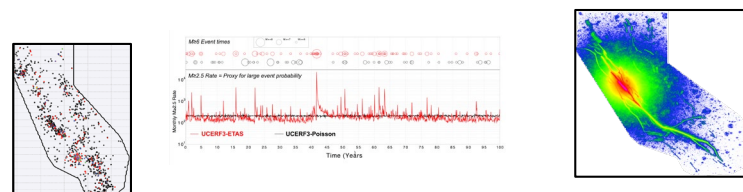
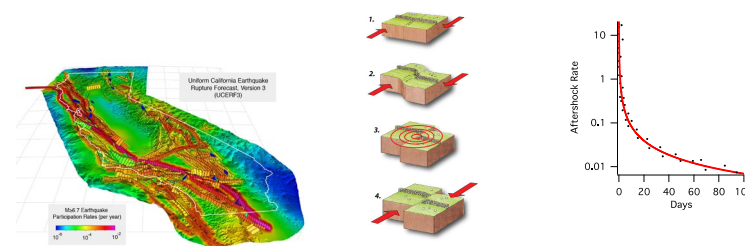
Likelihood of something big on nearby SAF



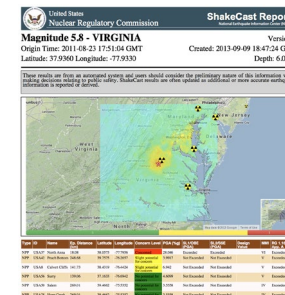
3) Operational Earthquake Forecasting (OEF)

UCERF3-ETAS: 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)
- Published in *BSSA* and *SRL*, and “Turing tests” in *BSSA* (Page & van der Elst, 2018)
- **Within reach: USGS PAGER- and ShakeCast-type products, but giving risk from *triggered* events**



PAGER



ShakeCast

3) Operational Earthquake Forecasting (OEF)

UCERF3-ETAS: a scientifically plausible, operationalizable, end-to-end forecast for California that:

Scientific Implications:

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

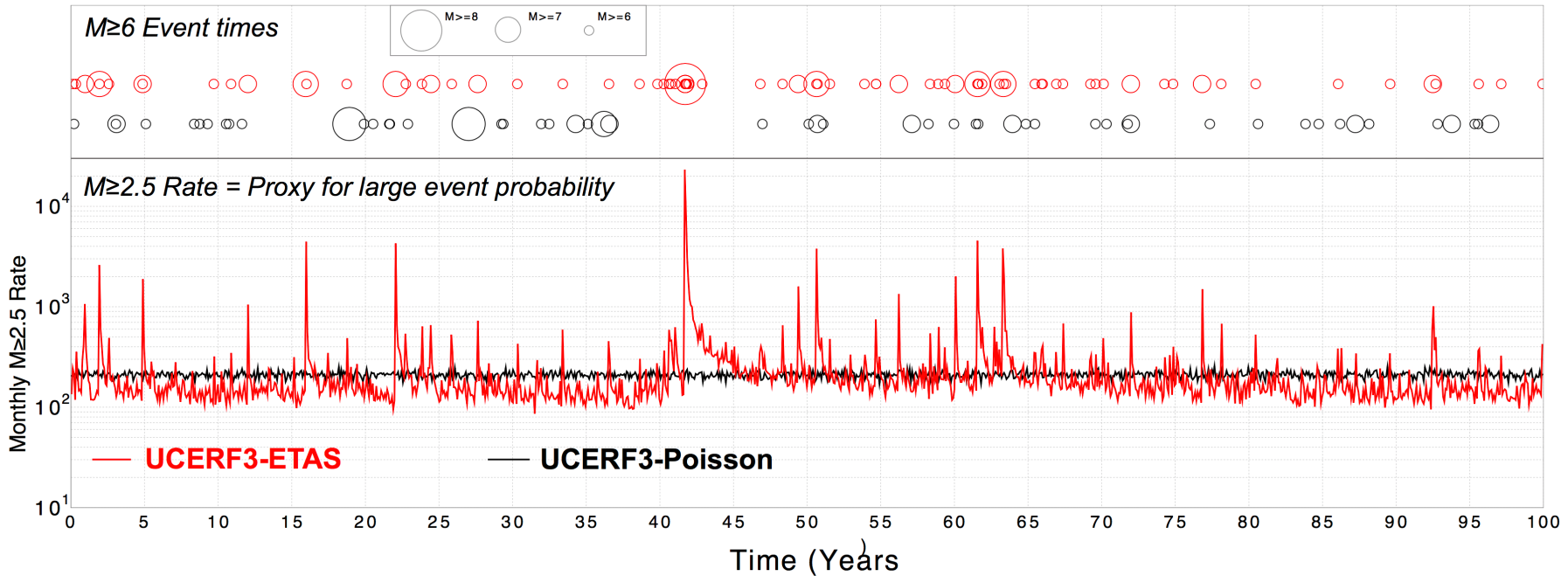
Practical Issues:

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

Is it, or any such model for that matter, useful enough to be worth operationalizing?

3) Operational Earthquake Forecasting (OEF)

Statewide Rate vs Time



All OEF models essentially assume that large-event likelihood, and therefore risk, correlates with small-event rates (big events start out small)

3) Operational Earthquake Forecasting (OEF)

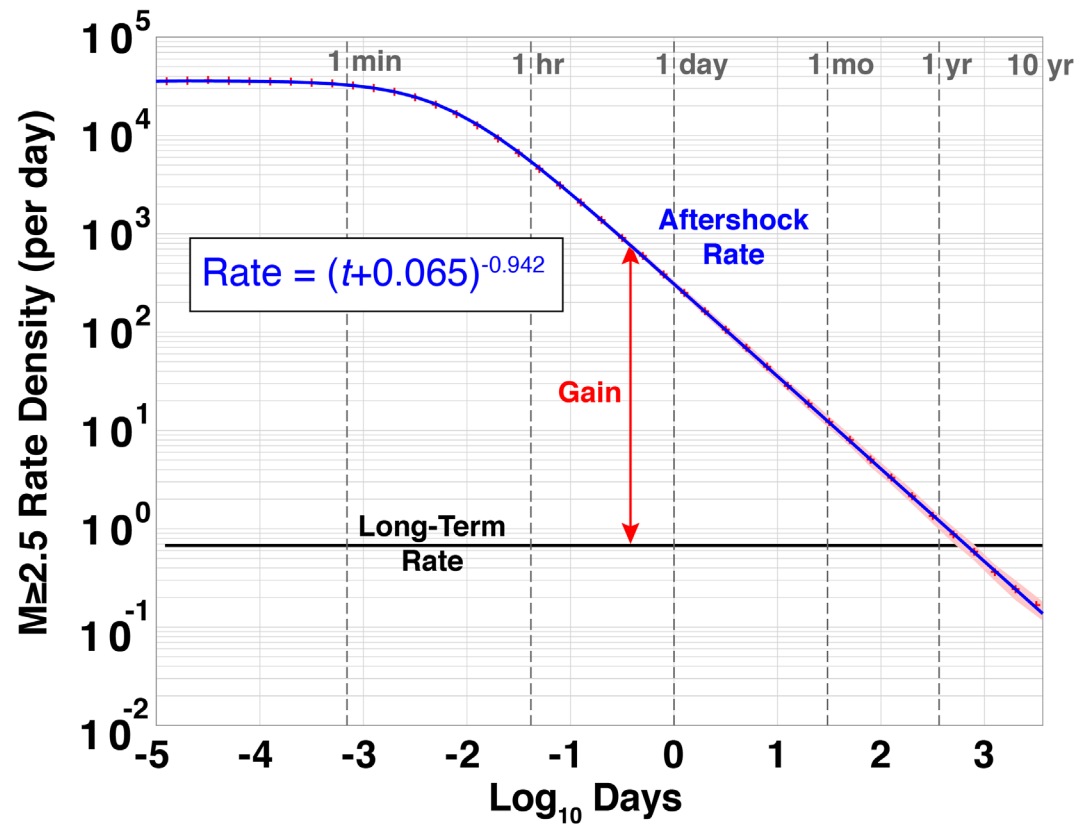
“Gain”

current rate/risk
versus long-term
average rate/risk

Some contend
that this rapid
decay aftershock
probabilities
renders these
models useless

e.g., “it’s all over in a day”

M 7.1 “HayWired” Scenario Aftershocks near SF



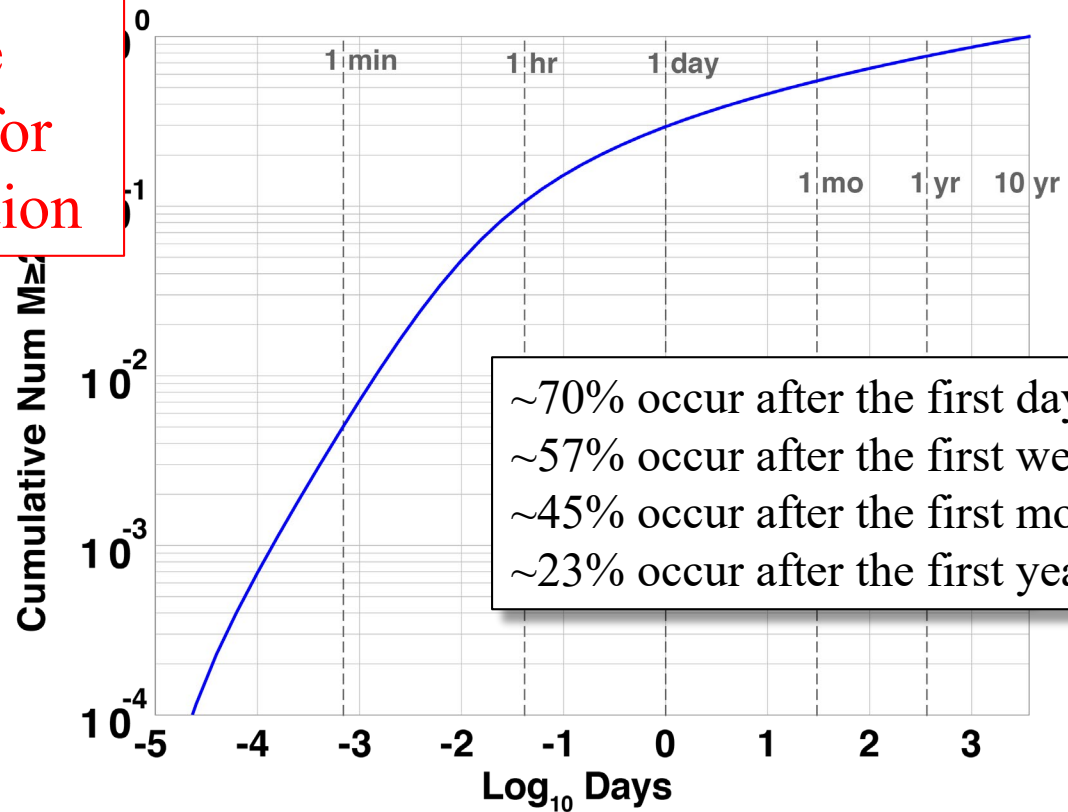
3) Operational Earthquake Forecasting (OEF)

Not true, and many potential users have expressed a desire for more OEF information

~~Some contend that this rapid decay aftershock probabilities renders these models useless~~

~~e.g., “it’s all over in a day”~~

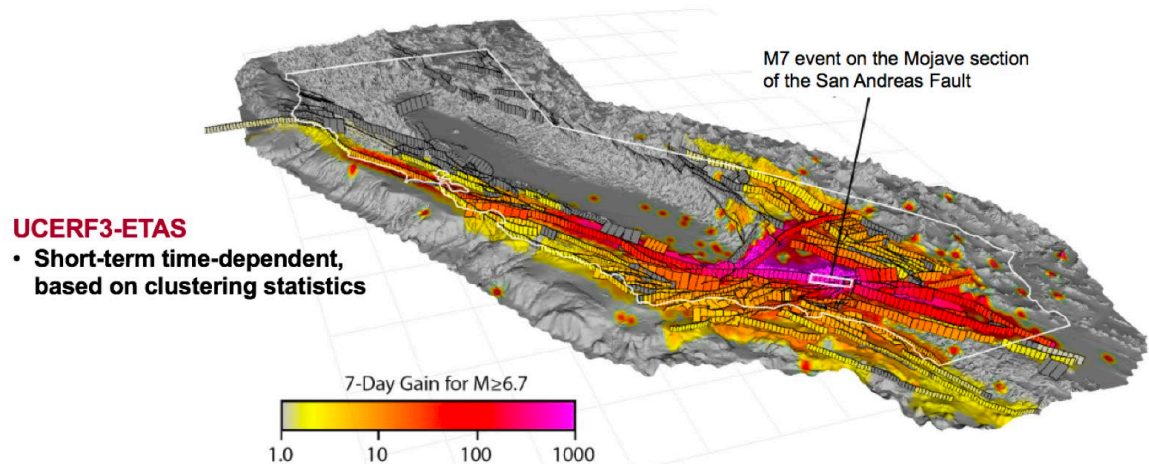
M 7.1 “HayWired” Scenario Aftershocks near SF



3) Operational Earthquake Forecasting (OEF)

UCERF3-ETAS: a scientifically plausible, operationalizable, end-to-end forecast for California that:

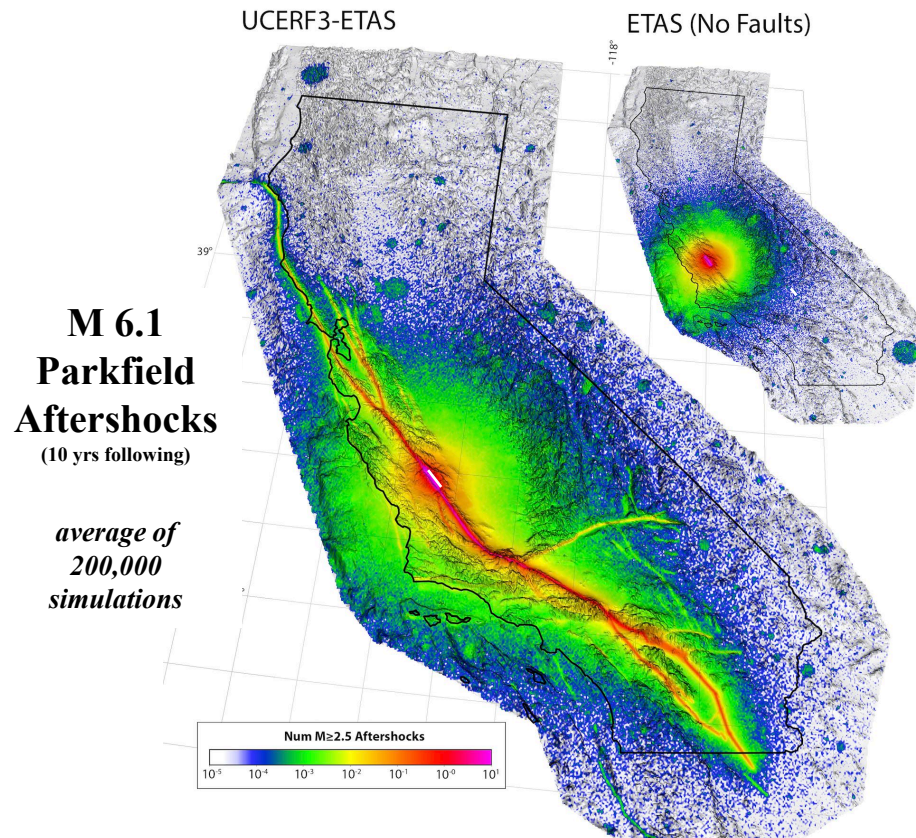
OK, but
UCERF3-ETAS is
complicated and
computationally
expensive; is it
really more
valuable than the
simpler
alternatives?



3) Operational Earthquake Forecasting (OEF)

UCERF3-ETAS: a scientifically plausible, operationalizable, end-to-end forecast for California

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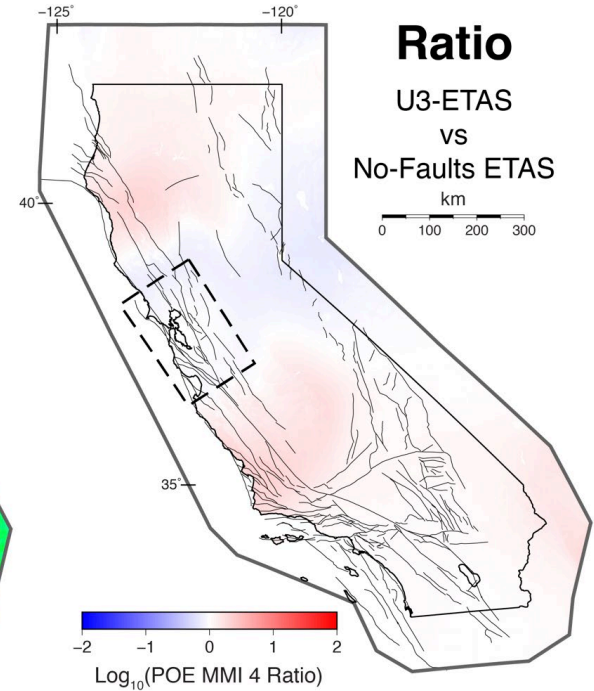
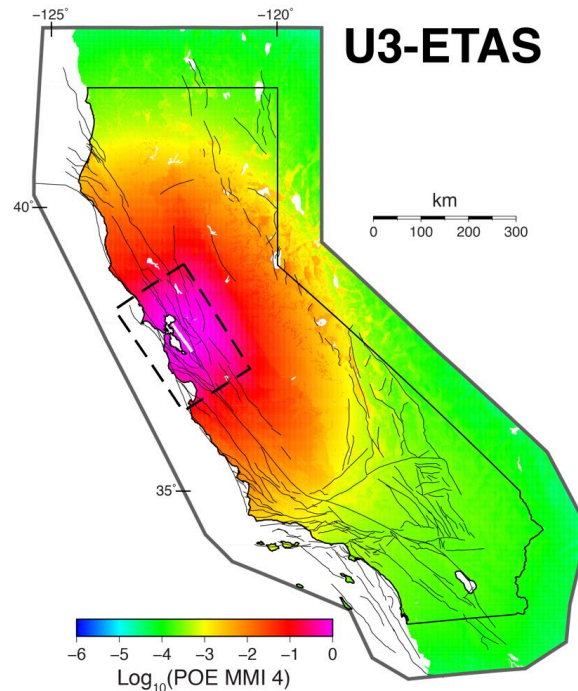
Note that the M7.8 1857 Fort Tejon earthquake is believed to have been preceded by an M6.1 Parkfield foreshock (Sieh, 1978; Meltzner and Wald, 1999).

3) Operational Earthquake Forecasting (OEF)

UCERF3-ETAS: a scientifically plausible, operationalizable, end-to-end forecast for California

M 7.1 “HayWired” Scenario Aftershocks near SF

Exceed Prob for MMI 4 (light shaking)



OK, but
UCERF3-ETAS is
complicated and
computationally
expensive; is it
really more
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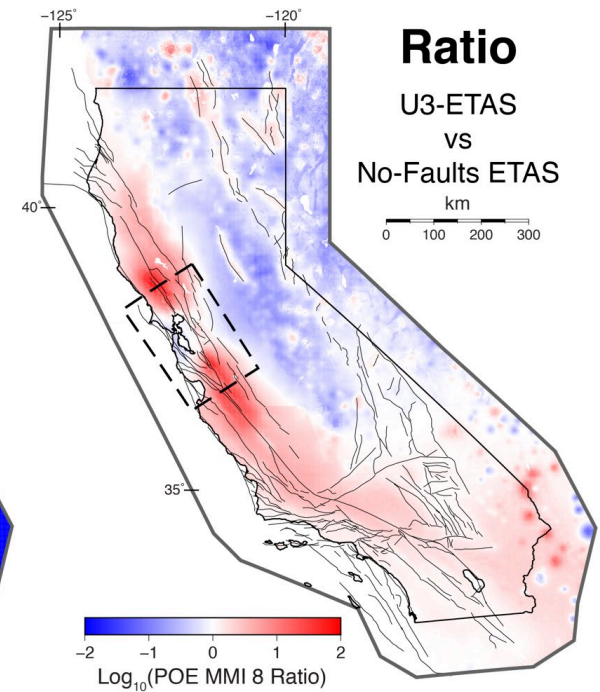
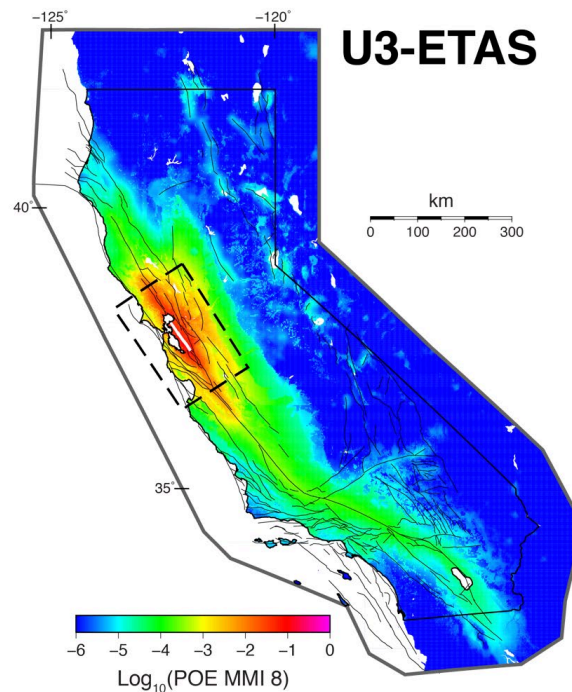
3) Operational Earthquake Forecasting (OEF)

UCERF3-ETAS: a scientifically plausible, operationalizable, end-to-end forecast for California

M 7.1 “HayWired” Scenario Aftershocks near SF

Exceed Prob for MMI 8 (severe shaking)

OK, but
UCERF3-ETAS is
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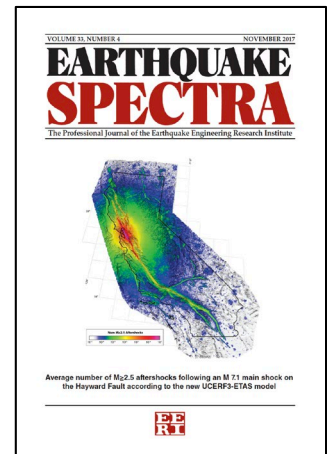
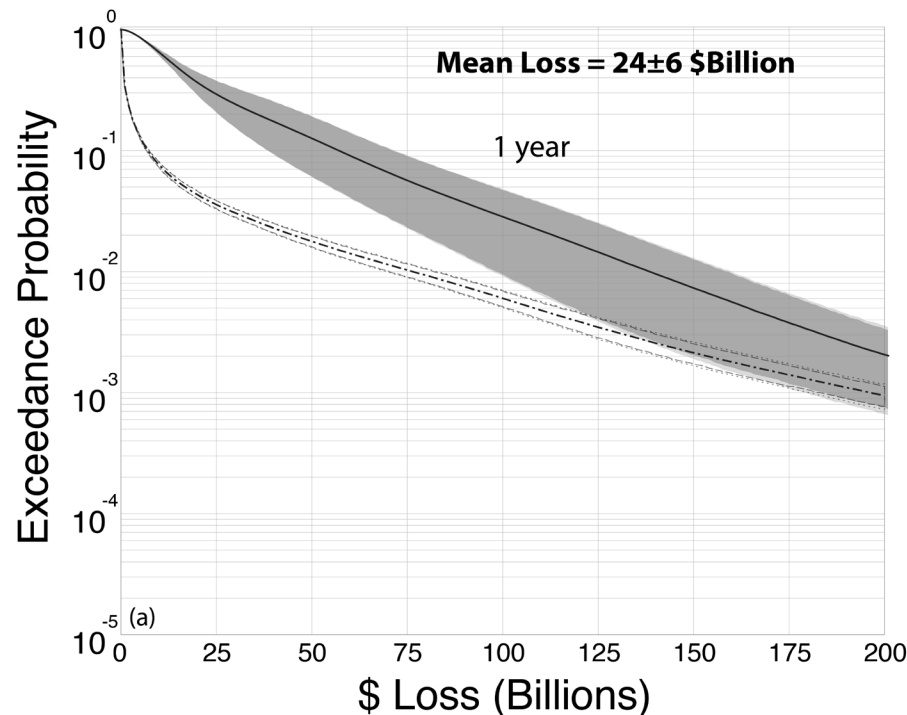


3) Operational Earthquake Forecasting (OEF)

UCERF3-ETAS: a scientifically plausible, operationalizable, end-to-end forecast for California

M 7.1 “HayWired” Scenario Aftershocks near SF

OK, but
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3) Operational Earthquake Forecasting (OEF)

UCERF3-ETAS: a scientifically plausible, operationalizable, end-to-end forecast for California

OK, but
UCERF3-ETAS is
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valuable than the
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alternatives?

**So the answer is yes and no;
for some uses UCERF3-
ETAS will be more valuable.**

**But valuable enough to
justify the cost of
operationalization?**

3) Operational Earthquake Forecasting (OEF)

Lots of Different Uses



Candidate OEF Models:

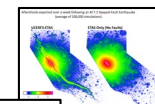
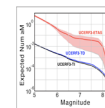
- 1) Reasenberg & Jones (1989)
- 2) STEP (Gerstenberger et al., 2005)
- 3) ETAS (Ogata, 1988)
- 4) UCERF3-ETAS (Field et al., 2017)



Lots of Different Products

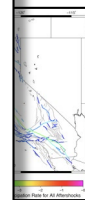
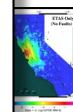
Potential OEF Products

- 1) Magnitude Probability Distribution
- 2) Magnitude Probability Map



We need to be able to quantify the value of alternative models with respect to the various uses, especially since “all models are wrong”.

This is a grand challenge.



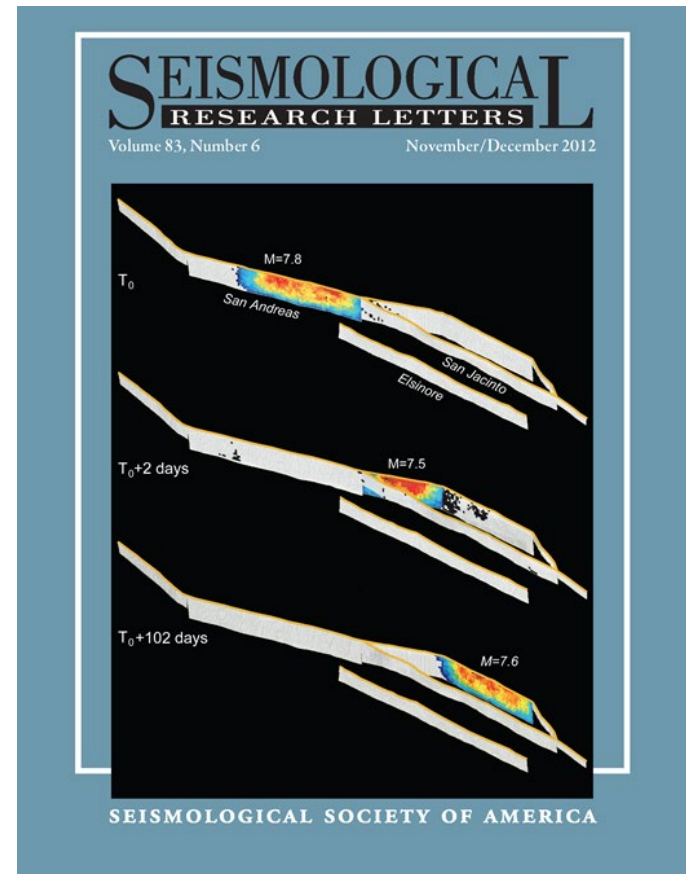
Talk Outline

- 1) The Anatomy of an Earthquake Rupture Forecast
- 2) Representation of Epistemic Uncertainties
- 3) Operational Earthquake Forecasting
- 4) The Need for More Physics-Based Approaches
- 5) The Importance of Model “Valuation” (in addition to Verification and Validation)

4) The Need for More Physics-Based Approaches

Our traditional statistical approach is limited by lack of data where we need it most (at large magnitudes).

Physics-based earthquake simulators apply tectonic loading to a fault system and utilize frictional properties on those faults to determine when and where earthquakes occur, with each earthquake transferring stress and thereby influencing future earthquake occurrences.

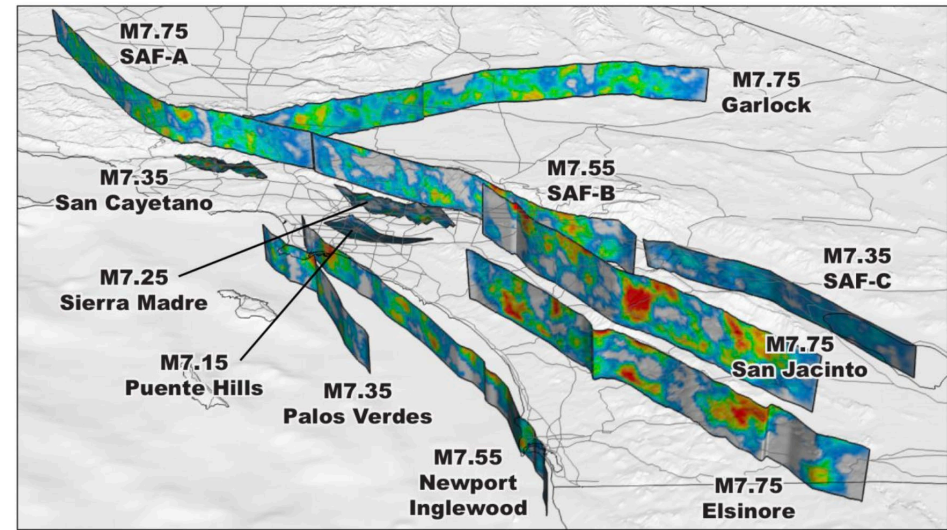


e.g., Rundle (1988), Ward (2000), Sachs et al. (2012), Ward (2012), Richards-Dinger and Dieterich (2012), Pollitz (2012), Shaw (2017), Schultz et al. (2017), Tullis et al. (2012), and Shaw et al. (2018)

4) The Need for More Physics-Based Approaches

e.g., **Rate State Earthquake Simulator** (**RSQSim**; Dieterich & Richards-Dinger, 2012)

- Physics-based multi-cycle simulator
 - Tectonic loading of faults by backslip approximation
 - Rupture nucleation by rate and state-dependent friction
 - Radiation damping and dynamic overshoot
 - Slip-mediated stress transfer in homogeneous elastic halfspace
- No prescribed ruptures
- Synthetic catalogs of thousands to millions of years of earthquake sequences



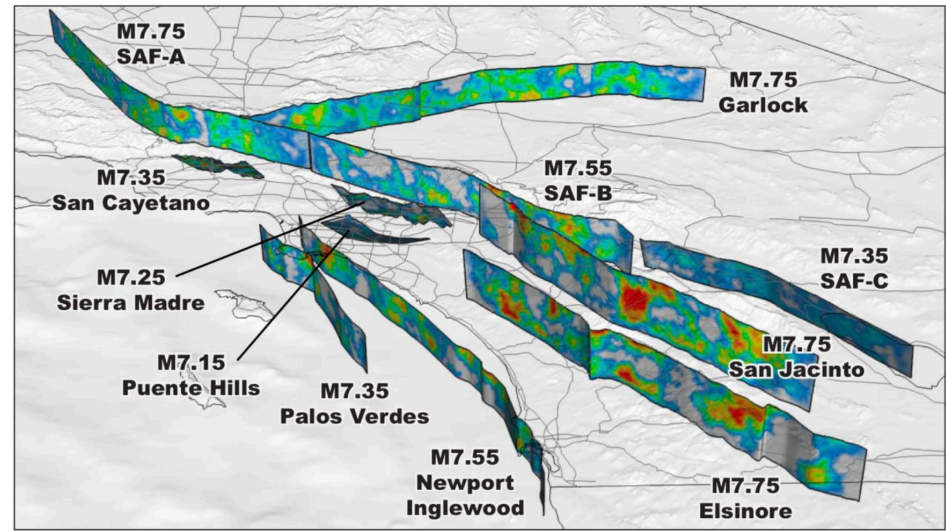
4) The Need for More Physics-Based Approaches

e.g., **Rate State Earthquake Simulator**
(RSQSim; Dieterich & Richards-Dinger, 2012)

Critics say that physics-based simulators need even more physics (e.g., dynamic waves)

But all models are wrong;
don't let perfection be the
enemy of an adequate or
more useful approximation

The question is what robust inferences can be made from current models



4) The Need for More Physics-Based Approaches

UCERF3 Questions/Issues/Uncertainties (to fix in UCERF4?):

- 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 $M \geq 5.0$ events (cat. completeness, temporal changes)
- 6) Paleoseismic RI i
for the prob of mi
- 7) Defining date-of-
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**

odels

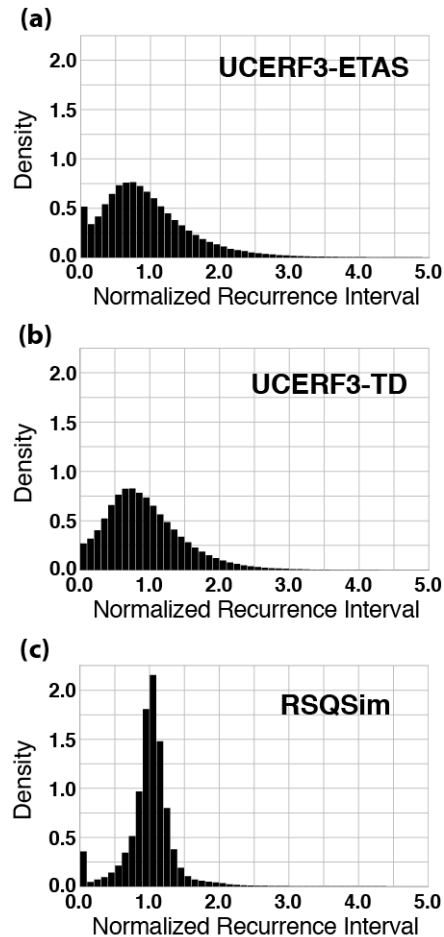
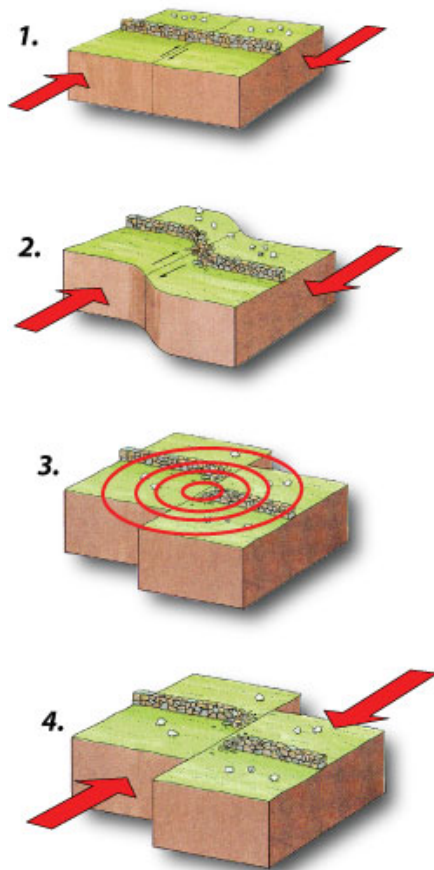
on all

vs

- 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?)

4) The Need for More Physics-Based Approaches

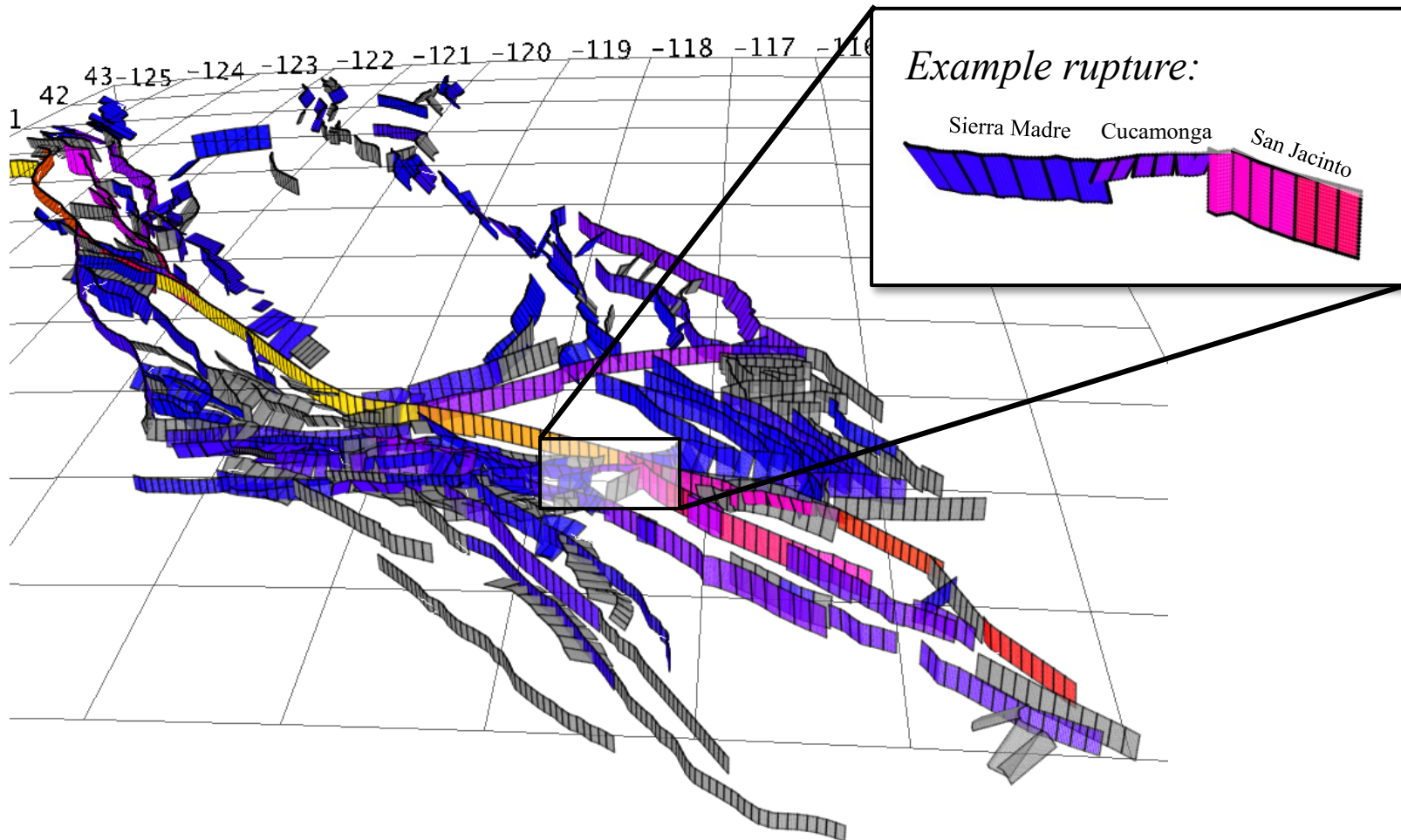
Elastic Rebound



Can we get beyond assuming a statistical distribution of recurrence intervals?

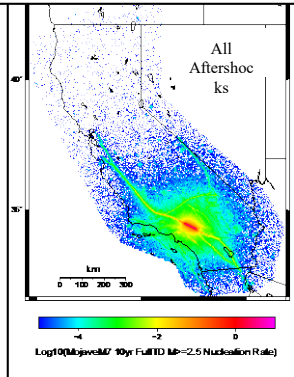
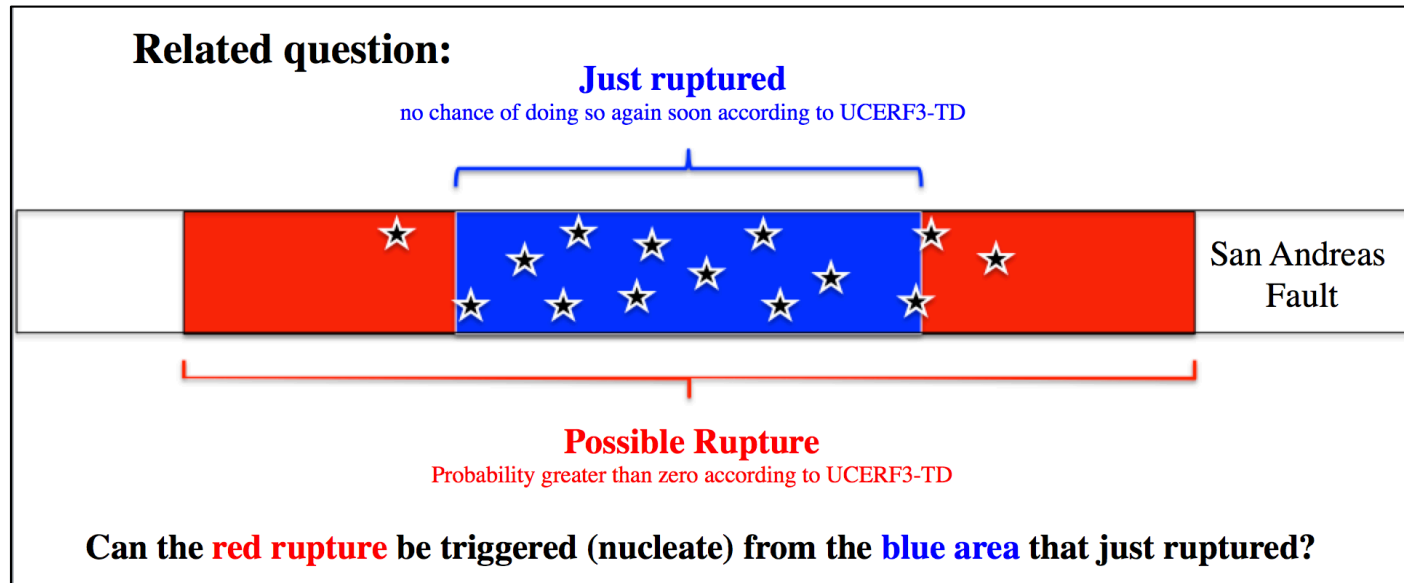
4) The Need for More Physics-Based Approaches

The likelihood of various multi-fault ruptures?

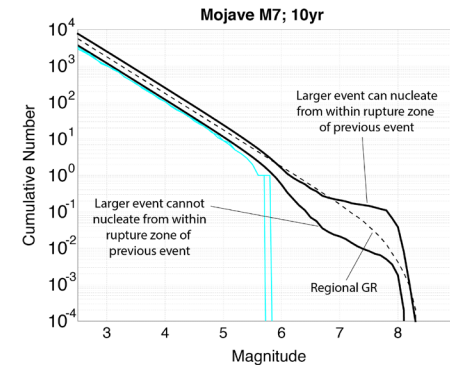


4) The Need for More Physics-Based Approaches

Earthquake triggering details?



UCERF3-ETAS



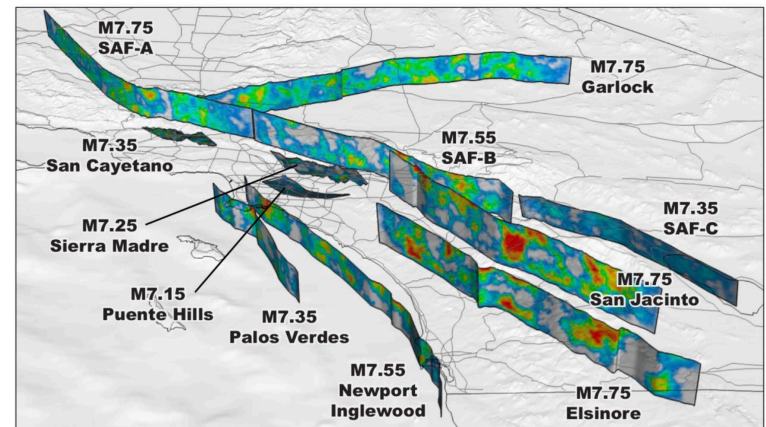
4) The Need for More Physics-Based Approaches

Rate State earthQuake Simulator (RSQSim; Dieterich & Richards-Dinger, 2012)

What robust inferences can be made with current models?

What developments are needed to make these models even more useful?

These models are expensive to develop and maintain, so what's their net value?



Earthquake Rupture Forecasts - Opportunities & Challenges

Edward (Ned) Field, USGS Golden

Nov. 14, 2018 NAS-COSG fall meeting

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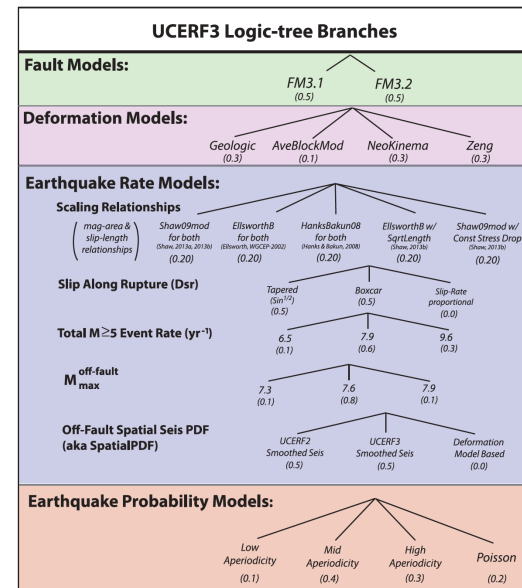
5) The Importance of Model “Valuation” (in addition to Verification and Validation)

Any new model is still going to be wrong (embodying assumptions, approximations, and uncertainties).

Scientists always want to make model improvements.

But does an “improvement” really represent added value (is it worth the effort)?

Which model uncertainties should we try to reduce?



5) The Importance of Model “Valuation” (in addition to Verification and Validation)

Any new model is still going to be wrong (embodying assumptions, approximations, and uncertainties).

Scientists always want to make model improvements.

But does an “improvement” really represent added value (is it worth the effort)?

We’ve only scratched the surface in terms of addressing this model valuation question.

It’s difficult to answer (a grand challenge) because of the many potential uses...

5) The Importance of Model “Valuation” (in addition to Verification and Validation)

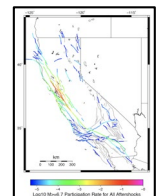
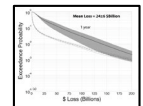
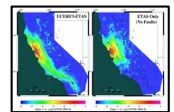
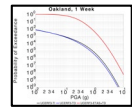
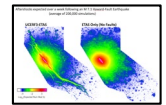
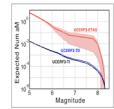
Lots of Different Uses



Lots of Different Products

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



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