Why we need Multicycle Physics-Based Earthquake Simulators

Edward (Ned) Field
(with help from many others)

SCEC 2026 Annual Meeting

Main messages here:

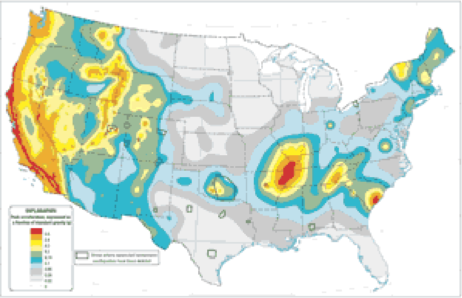
- **Multicycle Physics-Based Earthquake Simulators are critical to improving seismic hazard and risk estimates**

- **We must not let perfection be the enemy of more useful model (e.g., accusations of "not enough physics in your physics-based model" have plagued previous developments)**

- **A more wrong model can actually be more useful**

- **Ask not whether a model is right, but whether some useful inferences can be made from it**

Seismic Hazard & Risk Analysis (e.g., NSHM)



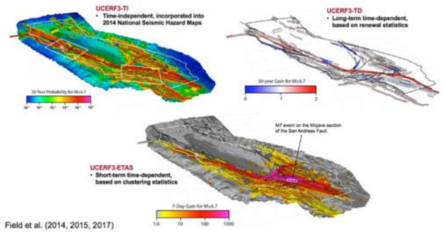
e.g., Probability that shaking level will be exceeded

Two main model components:

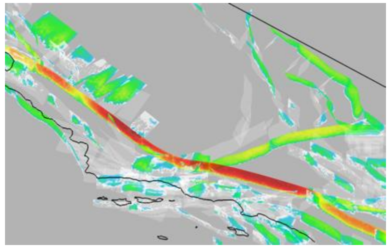
1) **Earthquake *Rupture* Forecast**

Gives the probability of all possible earthquake ruptures (or suite of synthetic catalogs) for a region and over a specified timespan

Empirical (e.g., UCERFs)



Physics Based (e.g., MCQSim)



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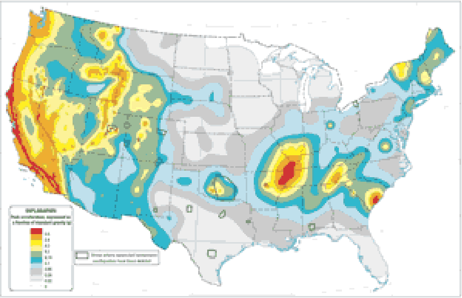

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Biggest game changers?

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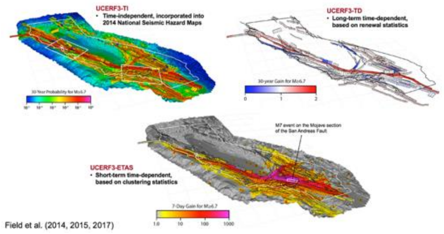
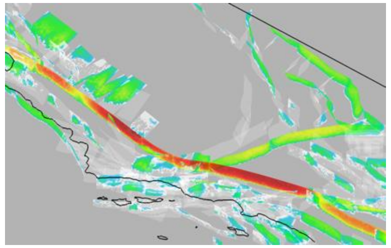
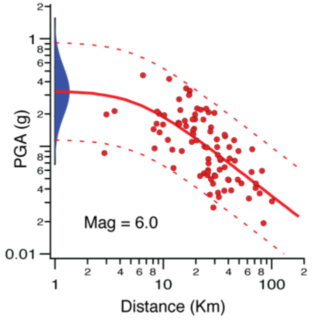




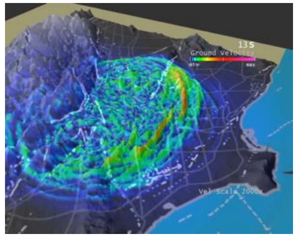
2) **Ground Motion Model**

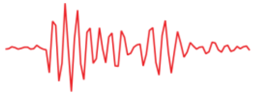
Non-ergodic models
(source-path-site specific)

Empirical "Attenuation Relationships"



Physics-based "Waveform Modeling"





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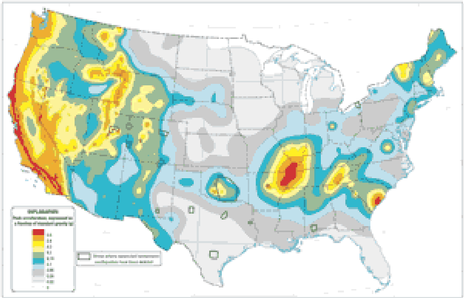

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Full time dependence
(spatiotemporal clustering)

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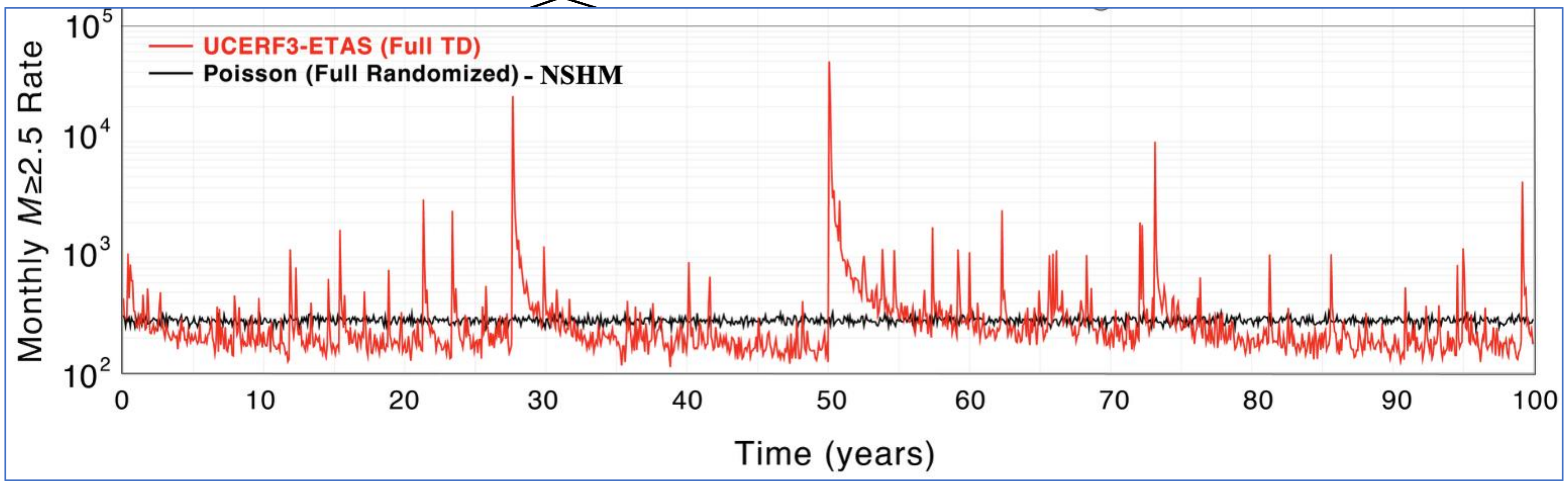
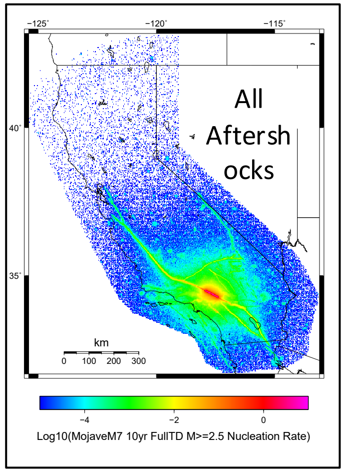
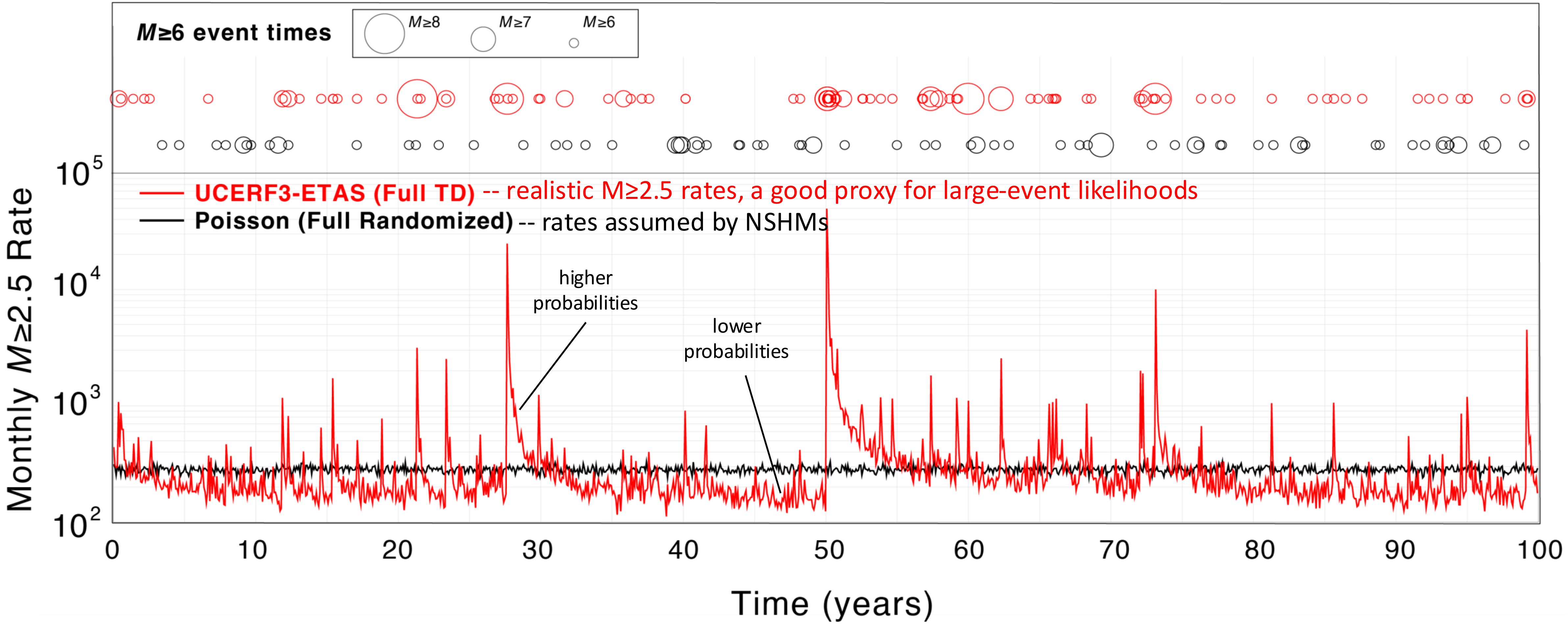




USGS National Seismic Hazard Model (NSHM)

Past & present USGS NSHMs (e.g., 1996, 2002, 2008, 2014, 2018, 2023) provided **time-independent, individual-site hazard curves, meaning they are tailored for building codes**



USGS National Seismic Hazard Model (NSHM)

USGS
science for a changing world

Building Codes

ICC INTERNATIONAL CODE COUNCIL

ASCE AMERICAN SOCIETY OF CIVIL ENGINEERS

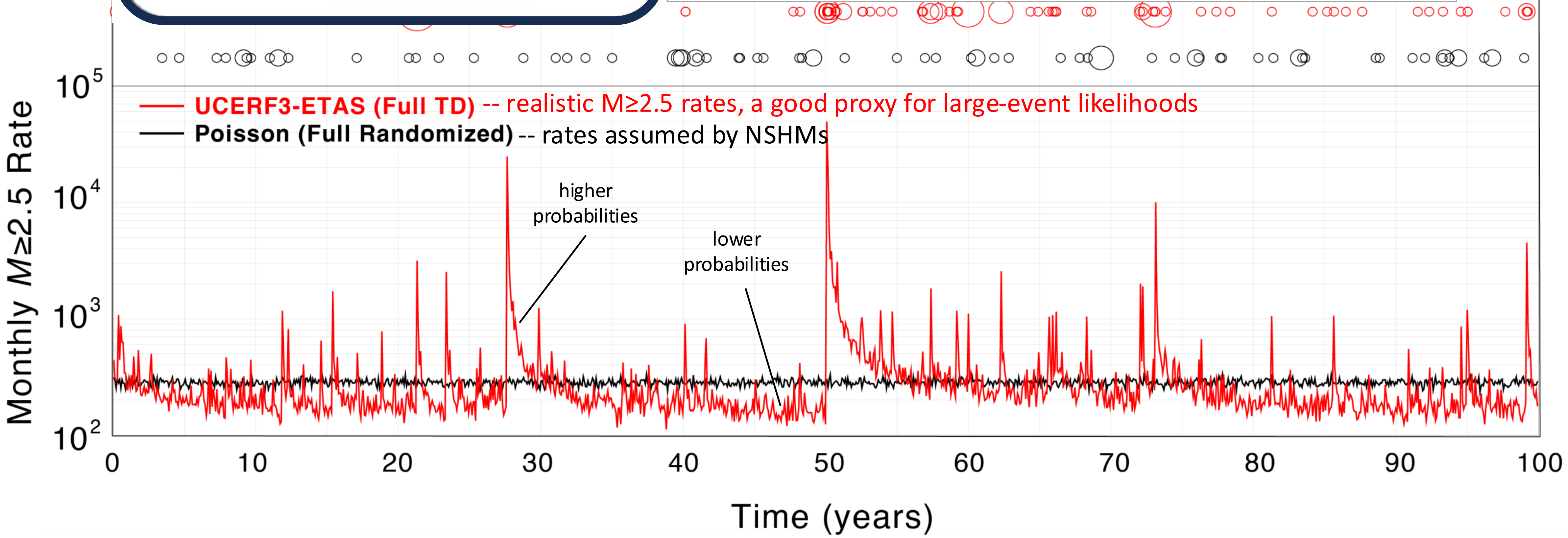
AREMA American Railway Engineering and Maintenance-of-Way Association

AASHTO American Association of State Highway and Transportation Officials 1914

Building Seismic Safety Council
a council of the National Institute of Building Sciences

Poisson is good enough for long-term building codes

(the less "right" model is more useful here)



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Building Codes

INTERNATIONAL CODE COUNCIL · ASCE American Society of Civil Engineers · AREMA American Railway Engineering and Maintenance-of-Way Association · AASHTO

Building Seismic Safety Council

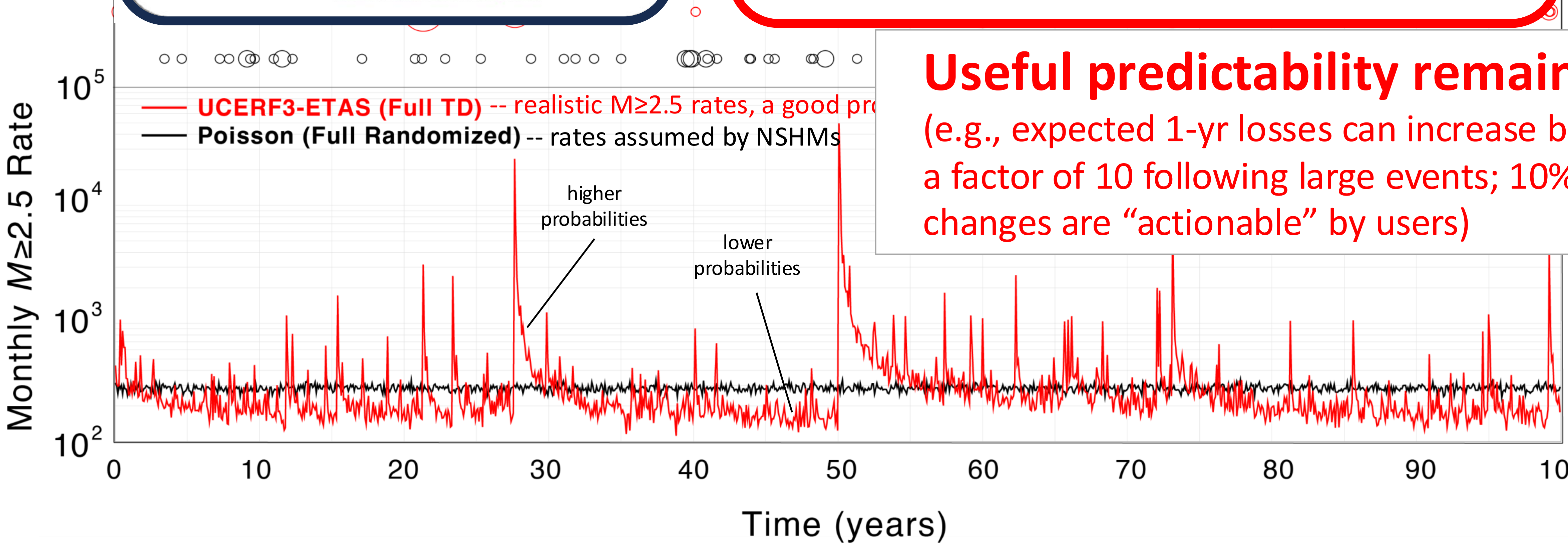
a council of the National Institute of Building Sciences

Insurance

CEA California Earthquake Authority · AIG

Risk Modelers

CoreLogic · Verisk · Moody's RMS · GEM Global Earthquake Model working together to assess risk



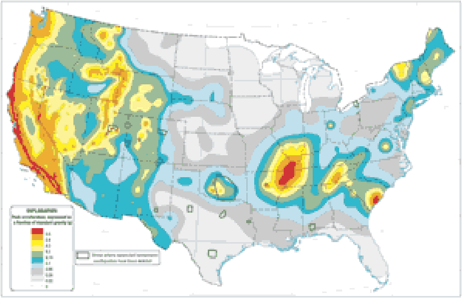
Useful predictability remains

(e.g., expected 1-yr losses can increase by a factor of 10 following large events; 10% changes are “actionable” by users)

Seismic Hazard & Risk Analysis (e.g., NSHM)

Biggest game changers?

Two main model components:



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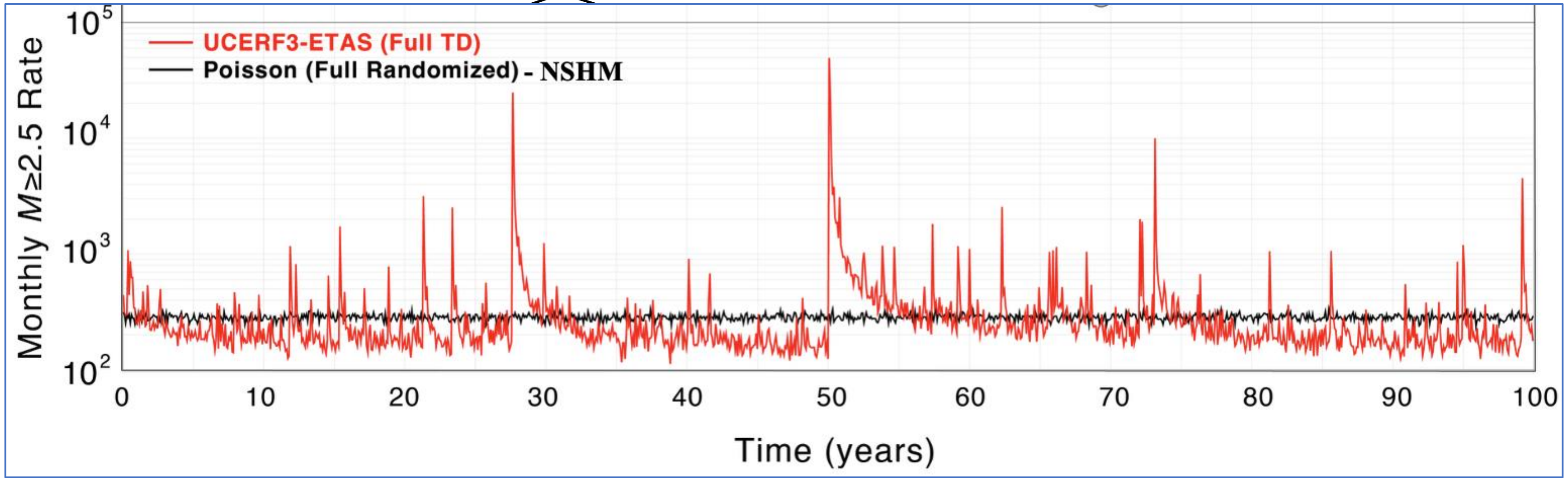
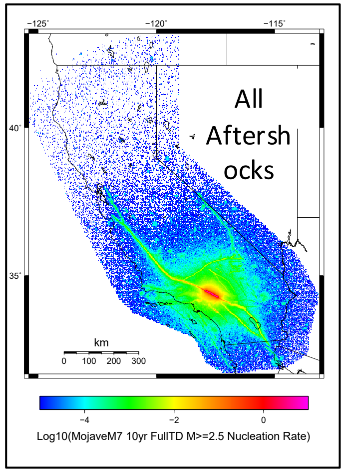


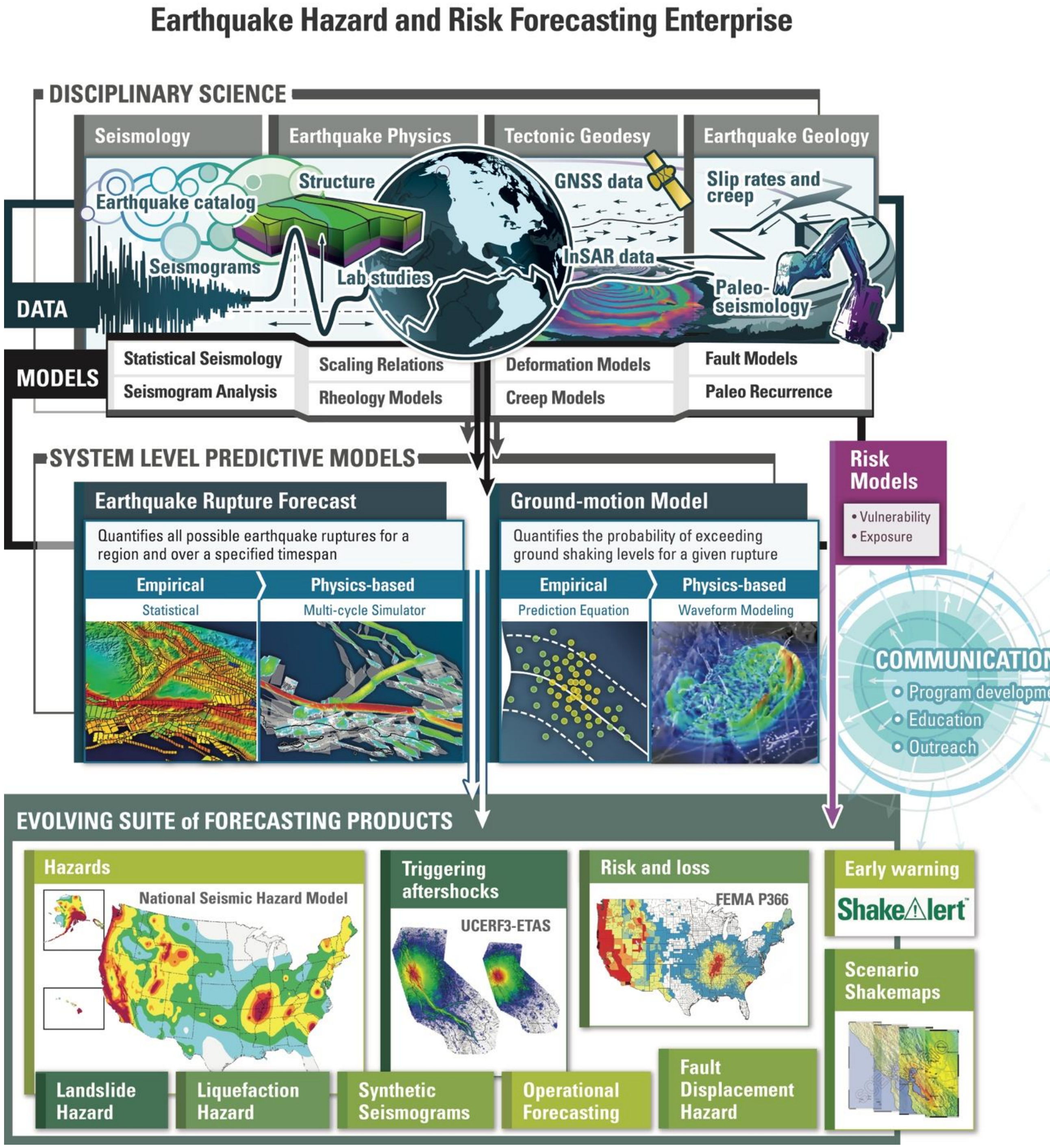


A Scientific Vision and Roadmap for Earthquake Rupture Forecast Developments, A USGS Perspective

Edward H. Field; Alexandra E. Hatem; Bruce E. Shaw; Morgan T. Page; P. Martin Mai; Kevin R. Milner; Andrea L. Llenos; A hompson Jobe; Tom Parsons; Olaf Zielke; David R. Shelly ichard W. Briggs; Elizabeth S. Cochran; Nicolas Luco; Ma Rubinstein; Allison M. Shumway; Nicholas J. van der Elst; Yuehua Zeng; Christopher B. Duross; Jason M. Altekruse

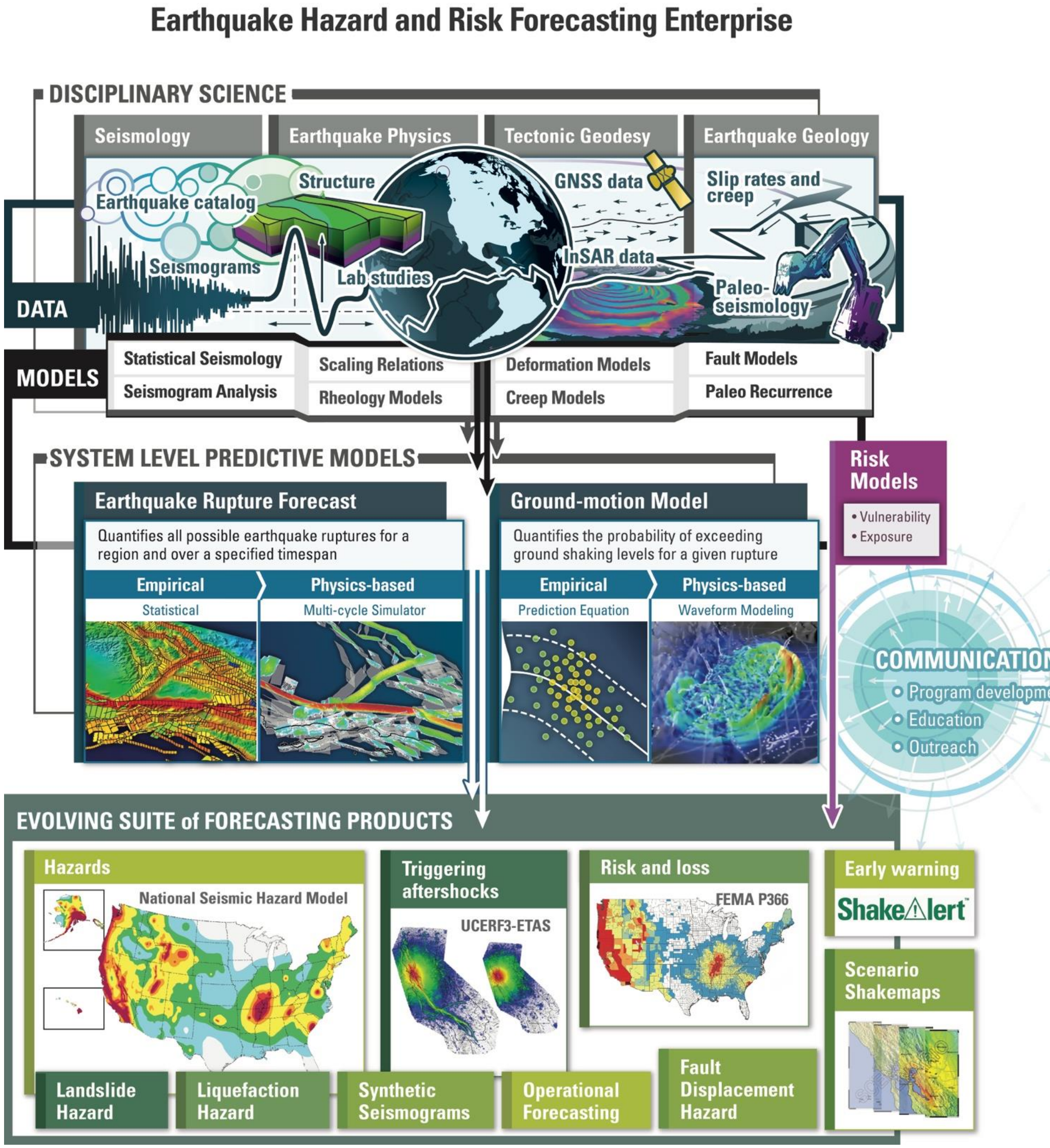
(26 co-authors)

BSSA, Dec. 2025



A Scientific Vision and Roadmap for Earthquake Rupture Forecast Developments, A USGS Perspective

- **System level problem**
- **Modularity is key, as is the ability to plug state-of-art components together (the computational infrastructure is everything)**
- **Assumptions, approximations, and uncertainties everywhere**
- **Epistemic uncertainties must be quantified & propagated**
- ***We're in constant triage mode***



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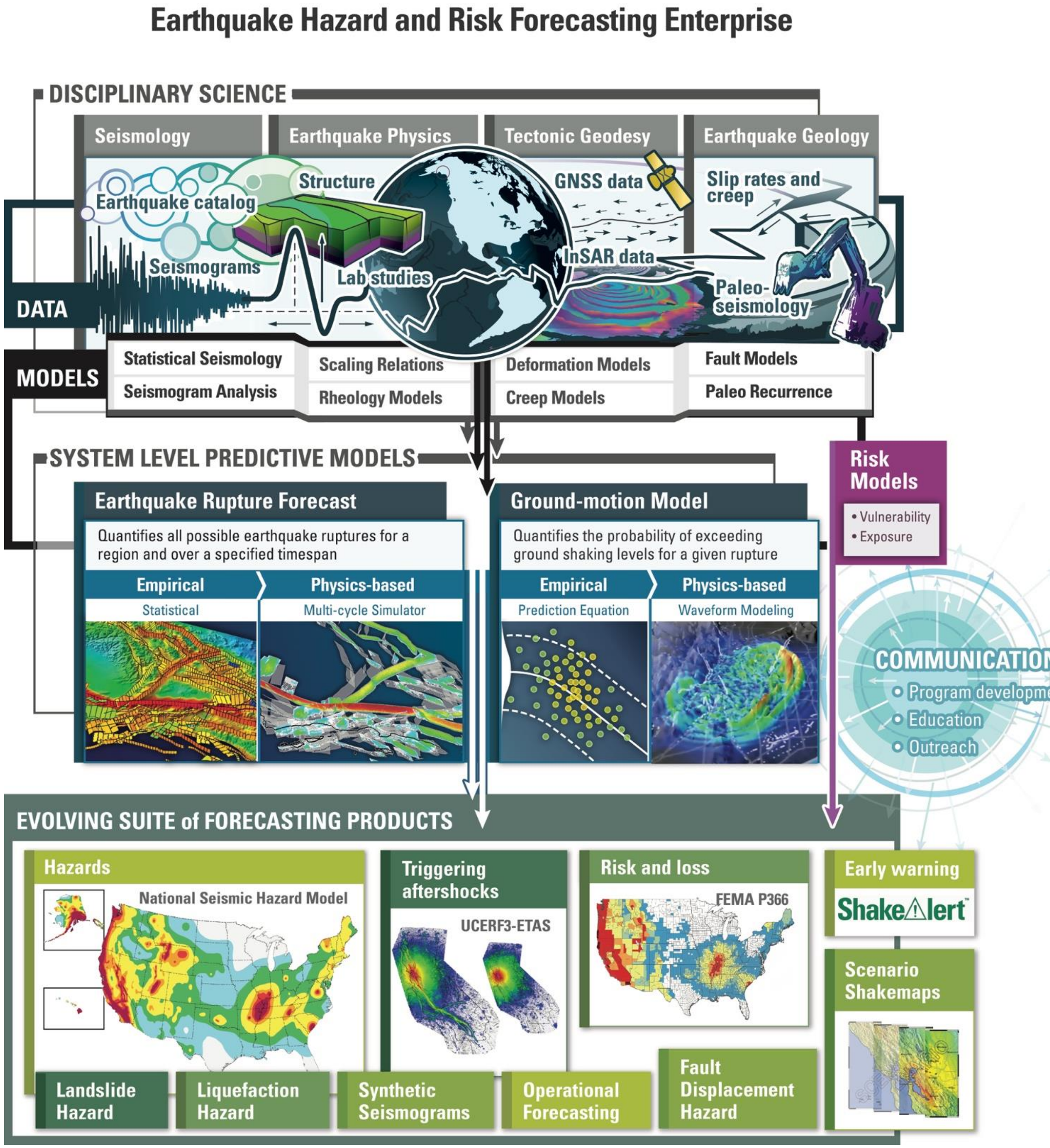
Broader ERF Development Goals

1) **Develop fully time-dependent models** (with spatiotemporal clustering)

2) Integrate risk related valuation metrics

3) Improved epistemic uncertainty representation

4) **Multi-cycle physics-based simulators** (to address several first-order questions)



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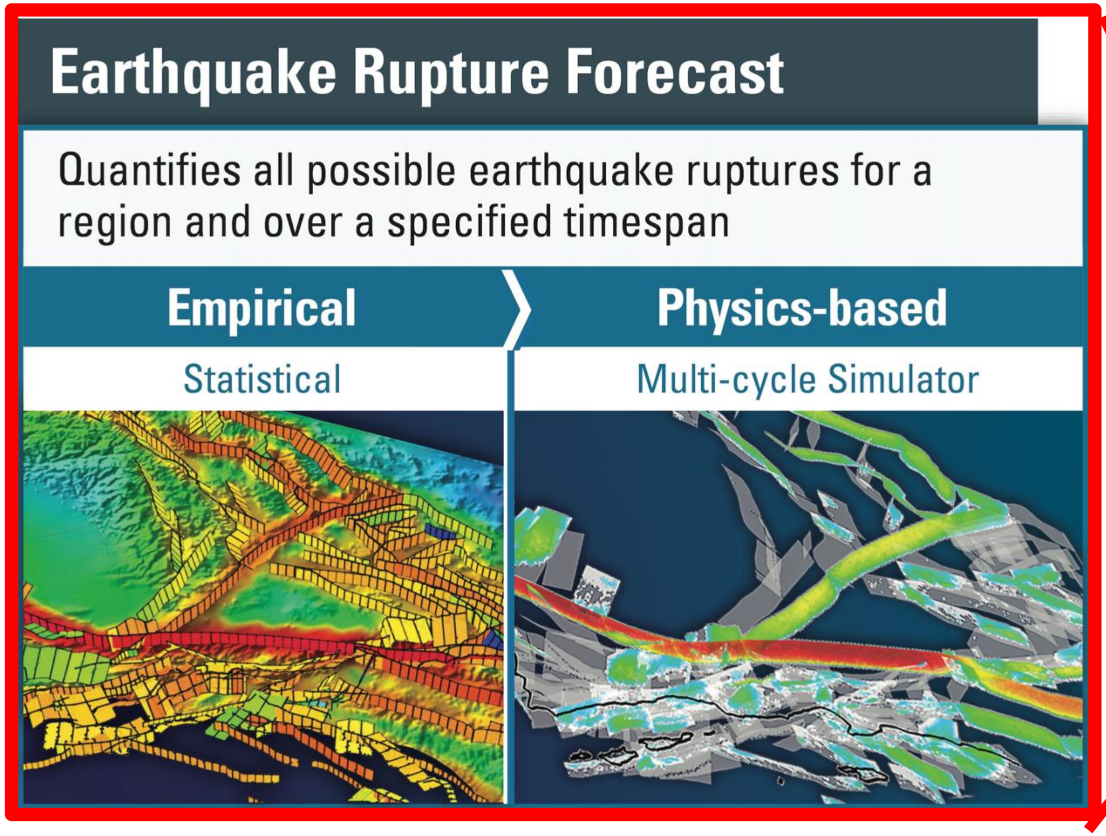

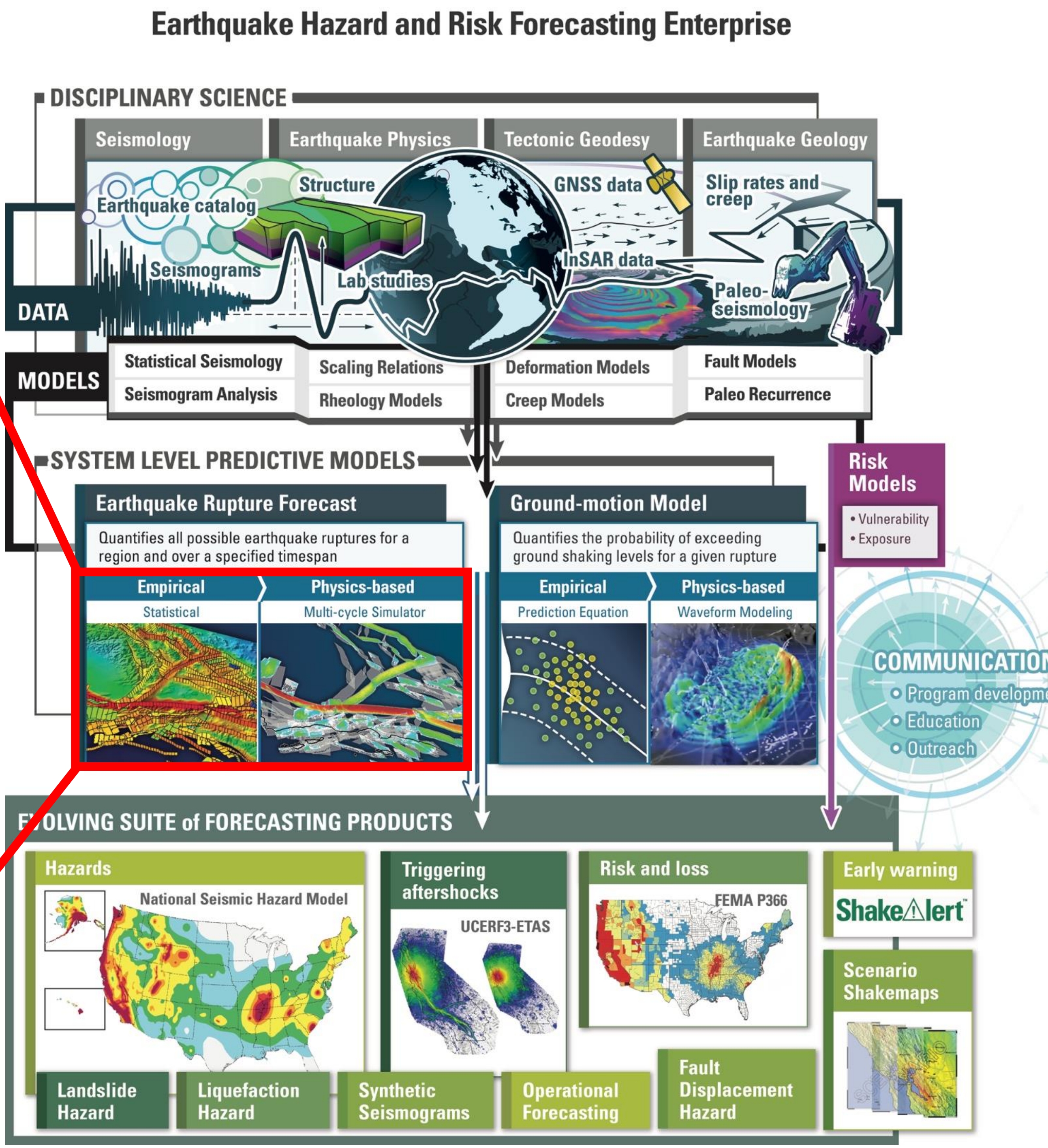

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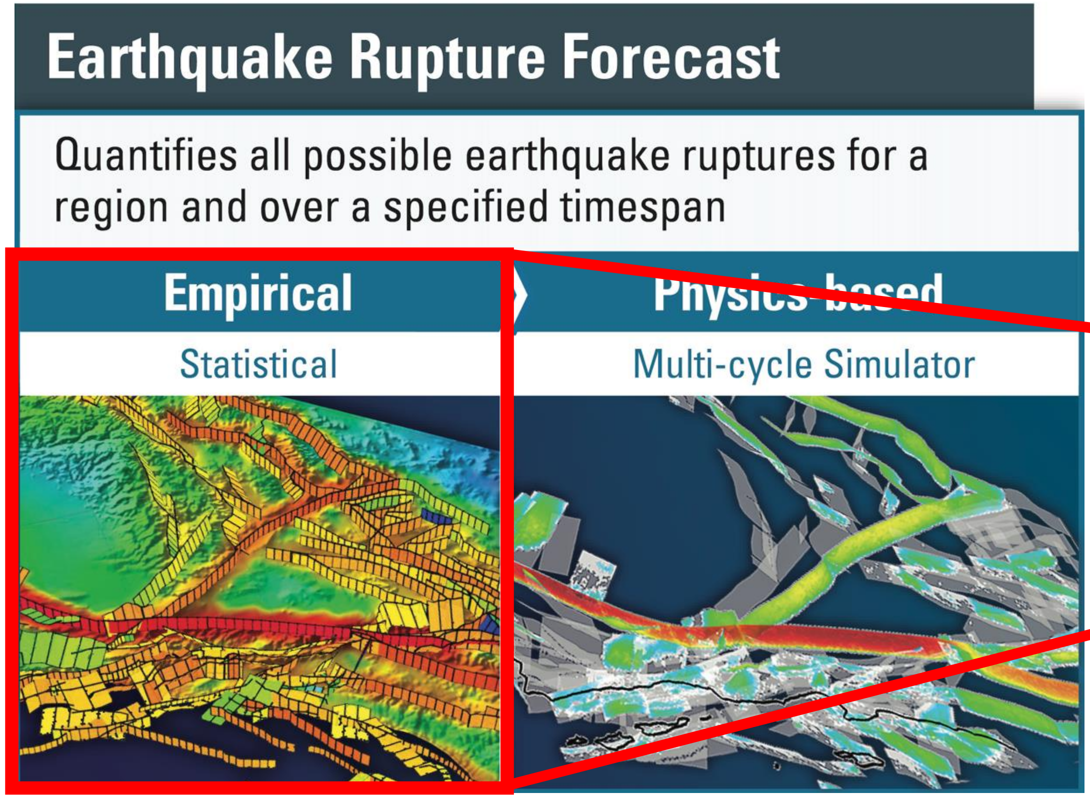
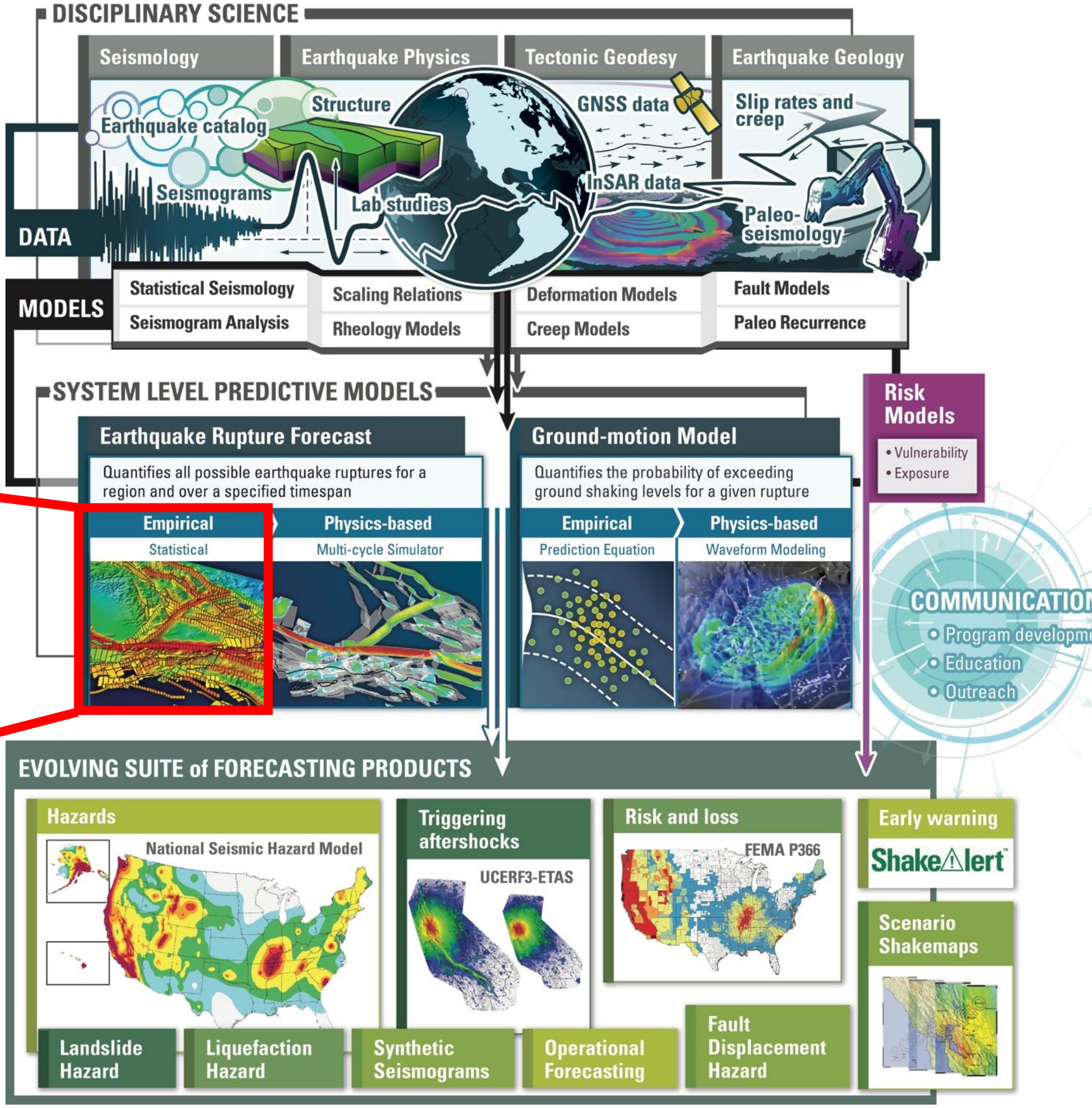


Earthquake Hazard and Risk Forecasting Enterprise



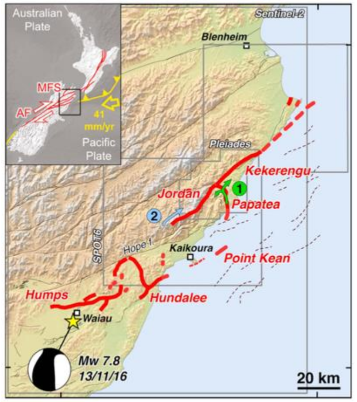
Uniform California Earthquake Rupture Forecast, version 3 (UCERF3)

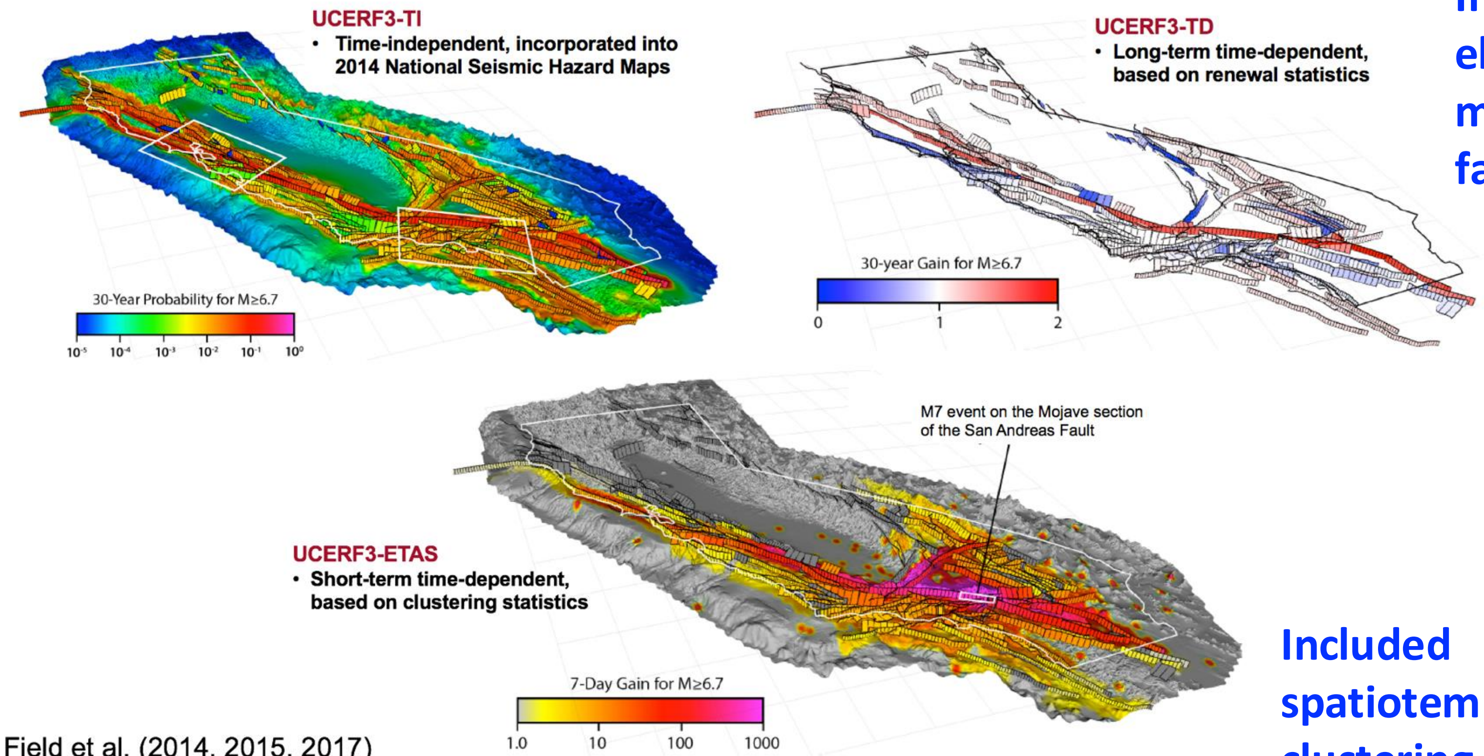
By the Working Group on California Earthquake Probabilities:

We're now in the process of doing this nationwide

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

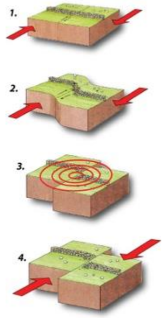
(e.g., Kaikoura)



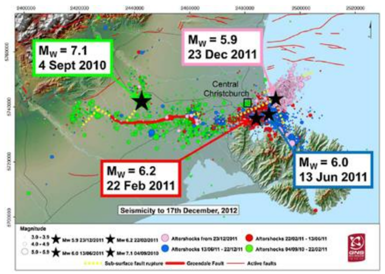


Field et al. (2014, 2015, 2017)

Improved elastic-rebound model (& on all faults)



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



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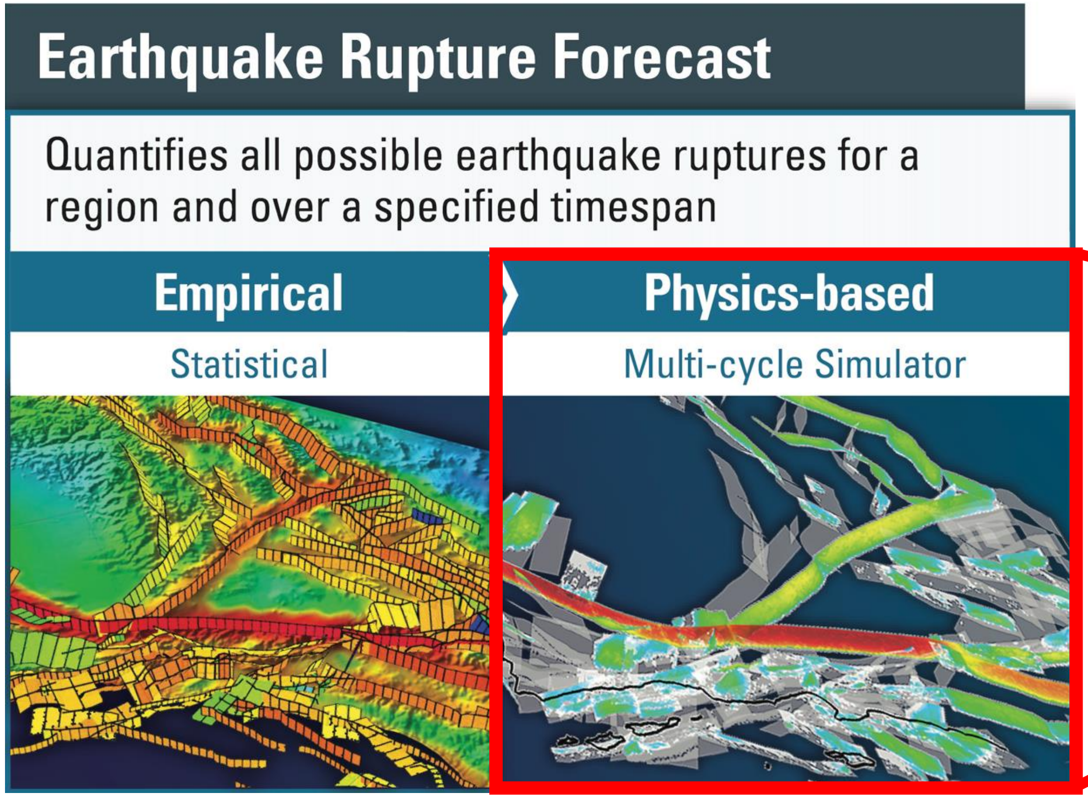
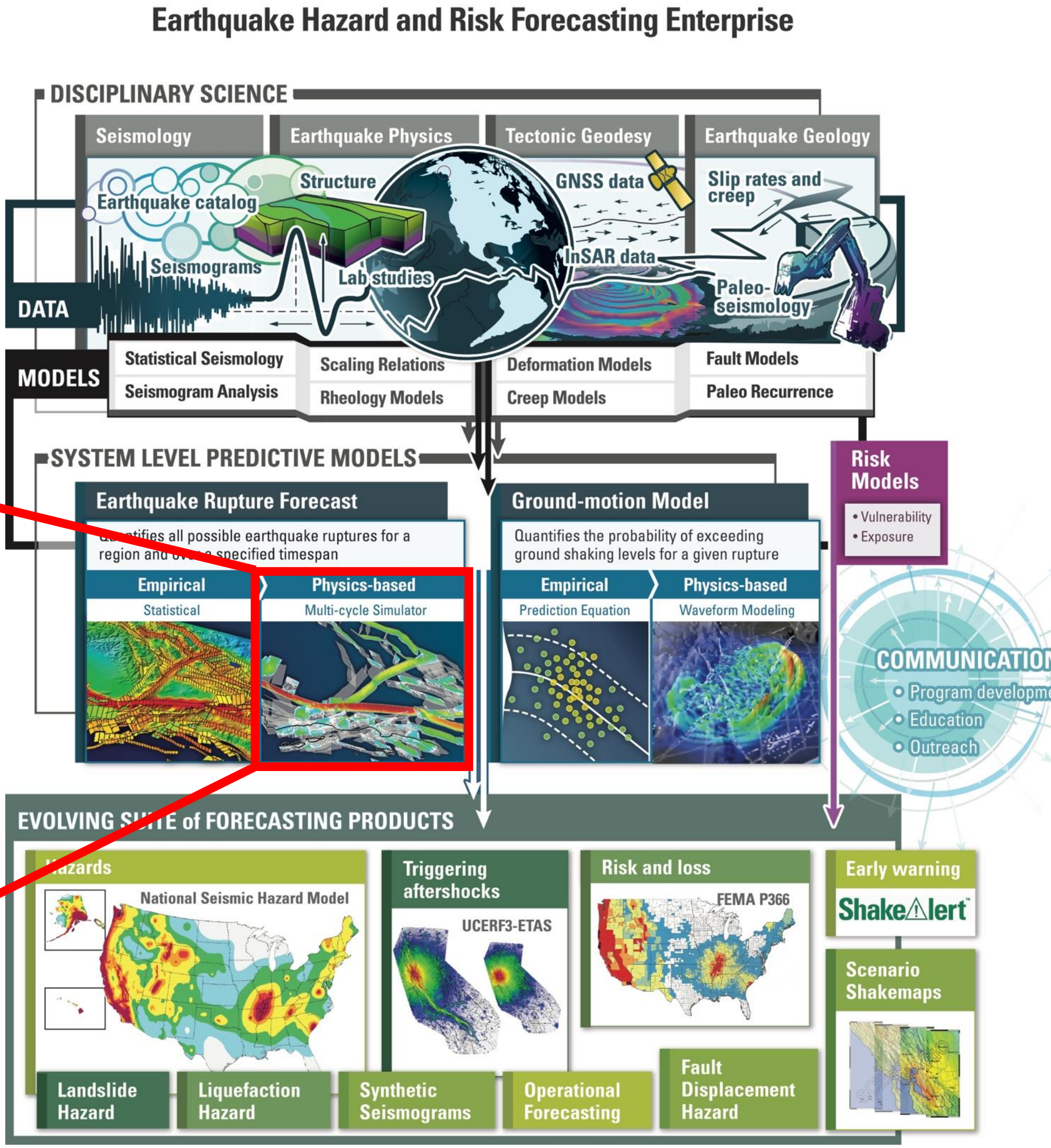
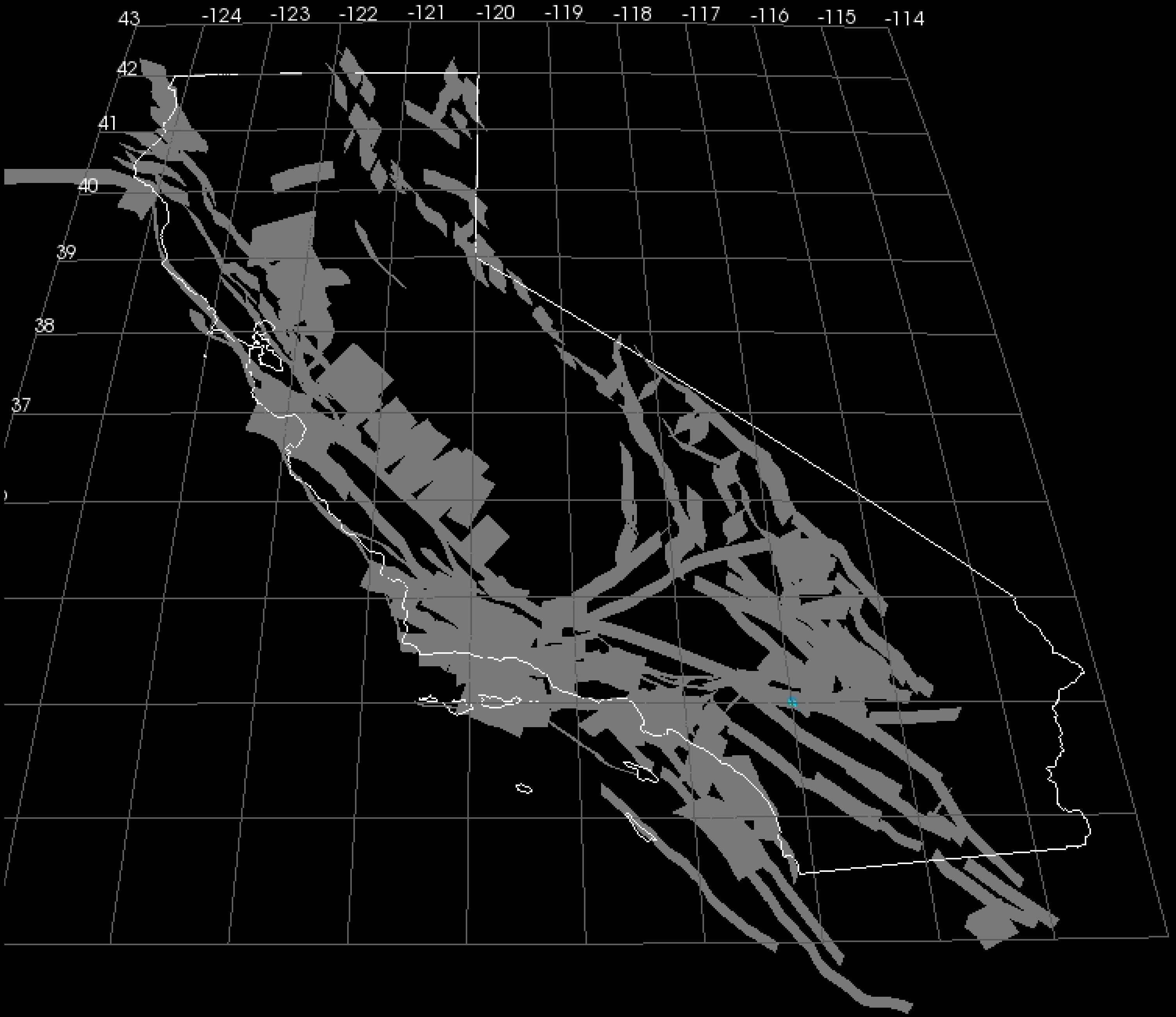




Multicycle, Physics-Based Earthquake Simulators:

generate synthetic rupture catalogs for large fault systems over thousands of earthquake cycles by modeling stress accumulation, rupture nucleation, friction evolution, and multi-fault interactions (and generally approximating dynamic effects).



RSQSim results from Bruce Shaw and animation from Kevin Milner (100 yrs/sec)

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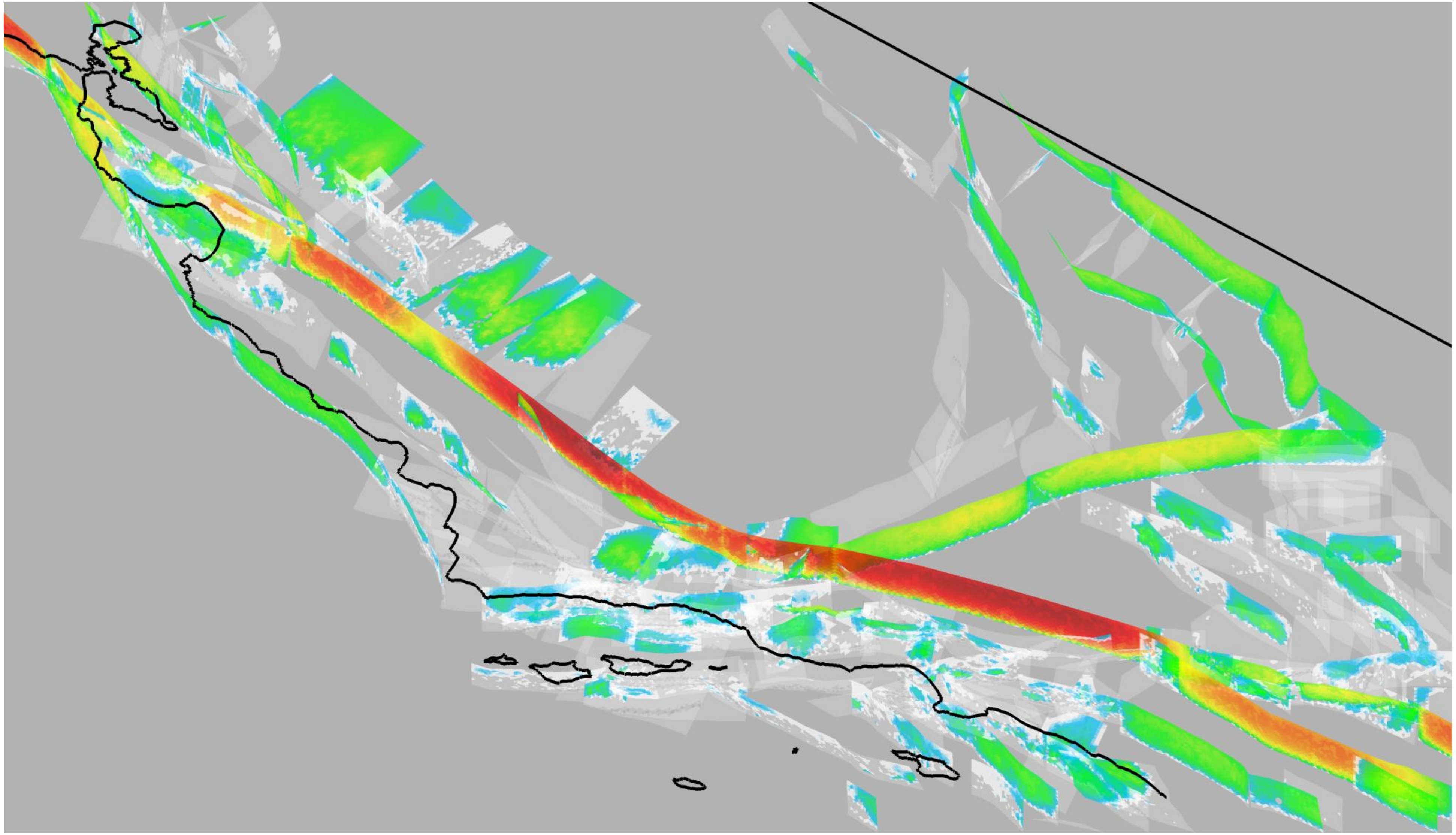
2000 yrs of accumulated slip from MCQsim (Zielke and Mai, 2023)



Multicycle, Physics-Based Earthquake Simulators:

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Full ERF replacement? giving the probability of every possible rupture conditioned on what we know about past events?

Not Yet, because we cannot simply start these models at present conditions and get multiple realizations of what comes next ; this is due the "spin up" time needed before realistic, stable behavior emerges, leaving one to search for periods in a simulation that match as close as possible to the historical record (e.g., Aalsburg et al., 2010).

In other words, even if these models were a perfect representation of nature, there would still be work in terms of figuring out how to use them to infer time-dependent earthquake probabilities.

Multicycle, Physics-Based Earthquake Simulators:

generate synthetic rupture catalogs for large fault systems over thousands of earthquake cycles by modeling stress accumulation, rupture nucleation, friction evolution, and multi-fault interactions (and generally approximating dynamic effects).

Alternatively, we can use them to test assumptions made, or implications of, our more empirical models:

- Average rupture rates
- Multifault rupture plausibility (Milner et al., 2022)
- Scaling relationships
- Average slip along rupture, especially for multifault events
- MFDs near faults (non-Gutenberg–Richter?)
- Influence of creep (area versus slip-rate reduction) and seismogenic depths
- **Elastic rebound predictability** (e.g., Field et al., 2015)
- **Spatiotemporal clustering (e.g., is ETAS adequate at large magnitudes?)**
- Other time dependencies (mode switching, super cycles, and paleo hiatus)

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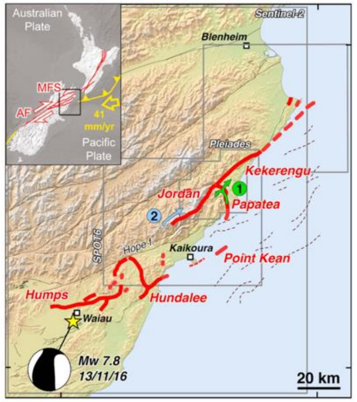
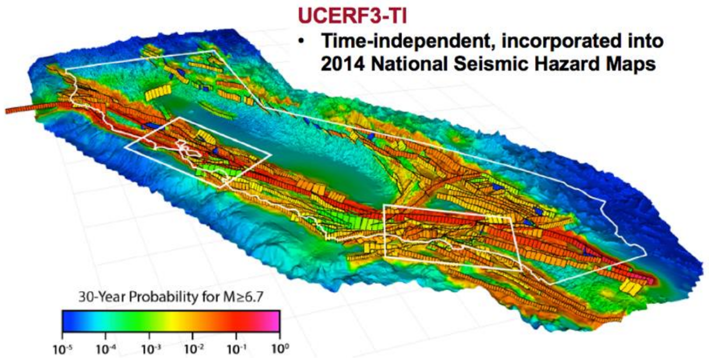
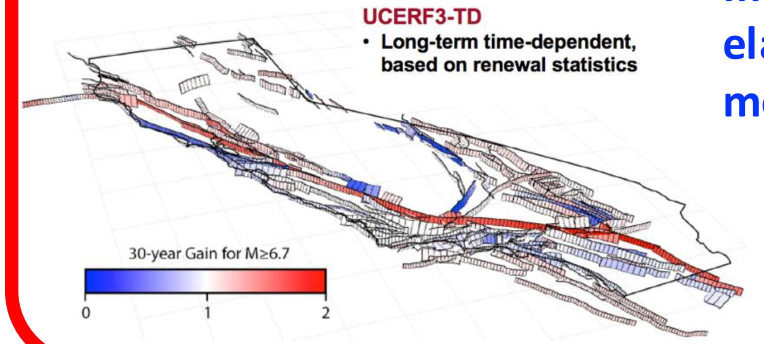
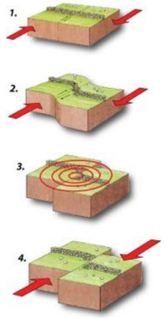
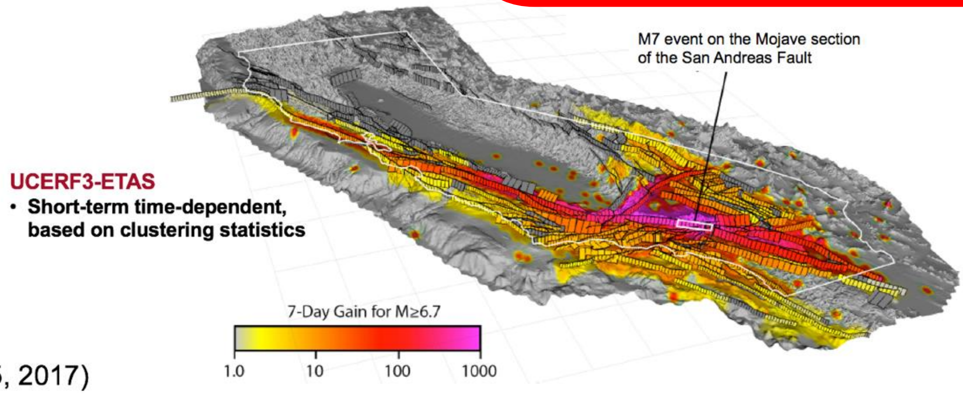






Improved elastic-rebound model





Field et al. (2014, 2015, 2017)

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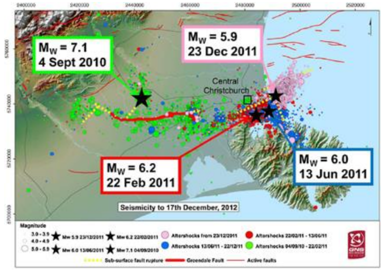
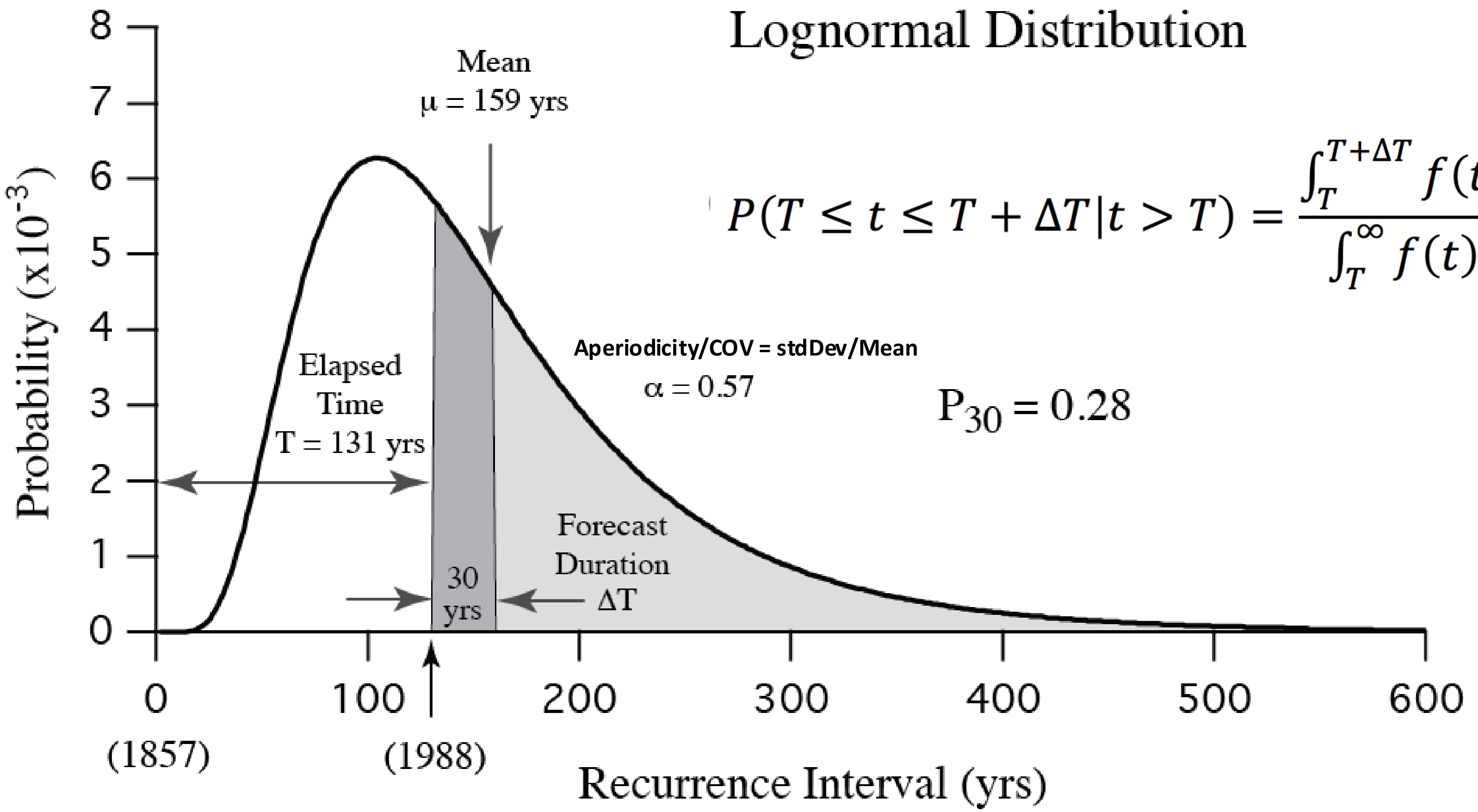


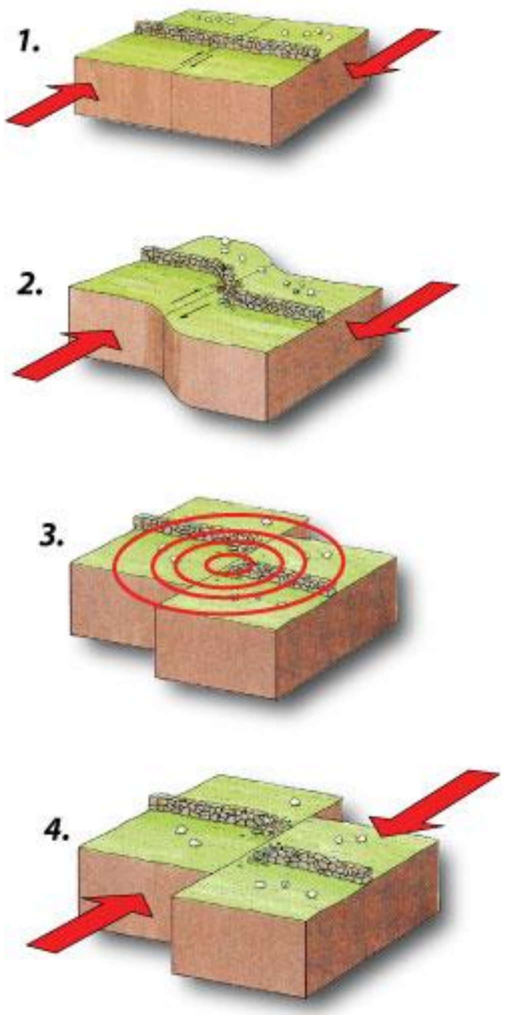
Reid's (1911) Elastic-Rebound Theory:

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

Modeled with a point-process renewal model:



$$P(T \le t \le T + \Delta T | t > T) = \frac{\int_T^{T+\Delta T} f(t)dt}{\int_T^{\infty} f(t)dt}$$



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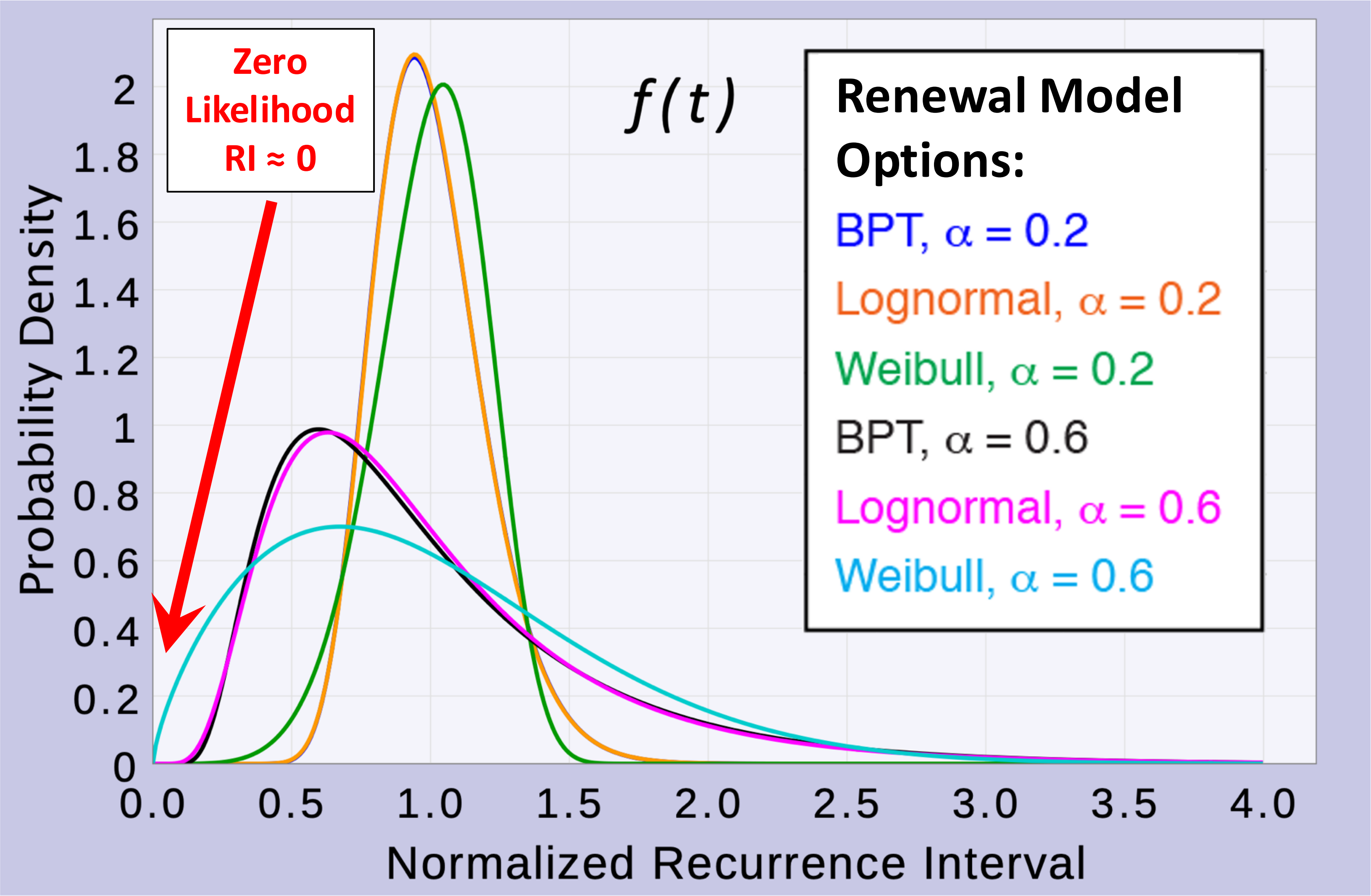

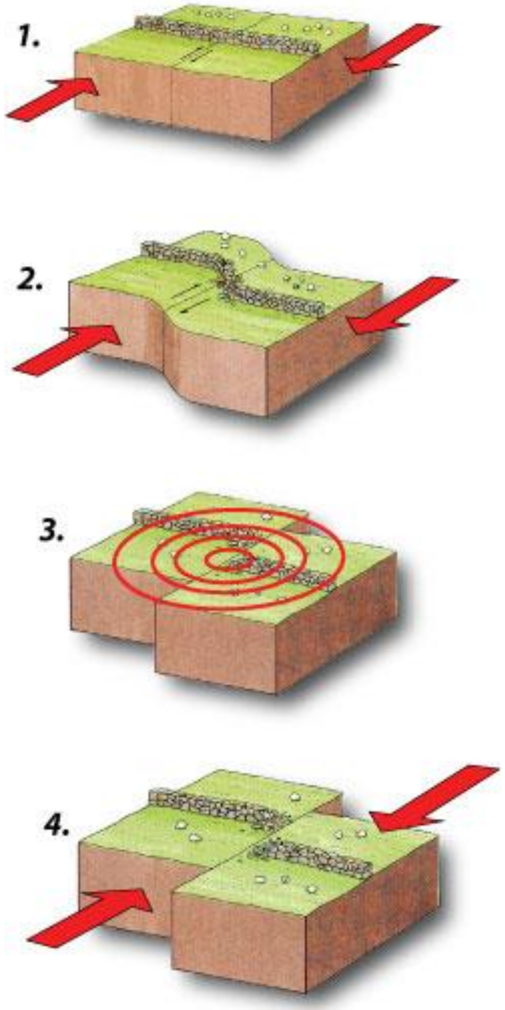

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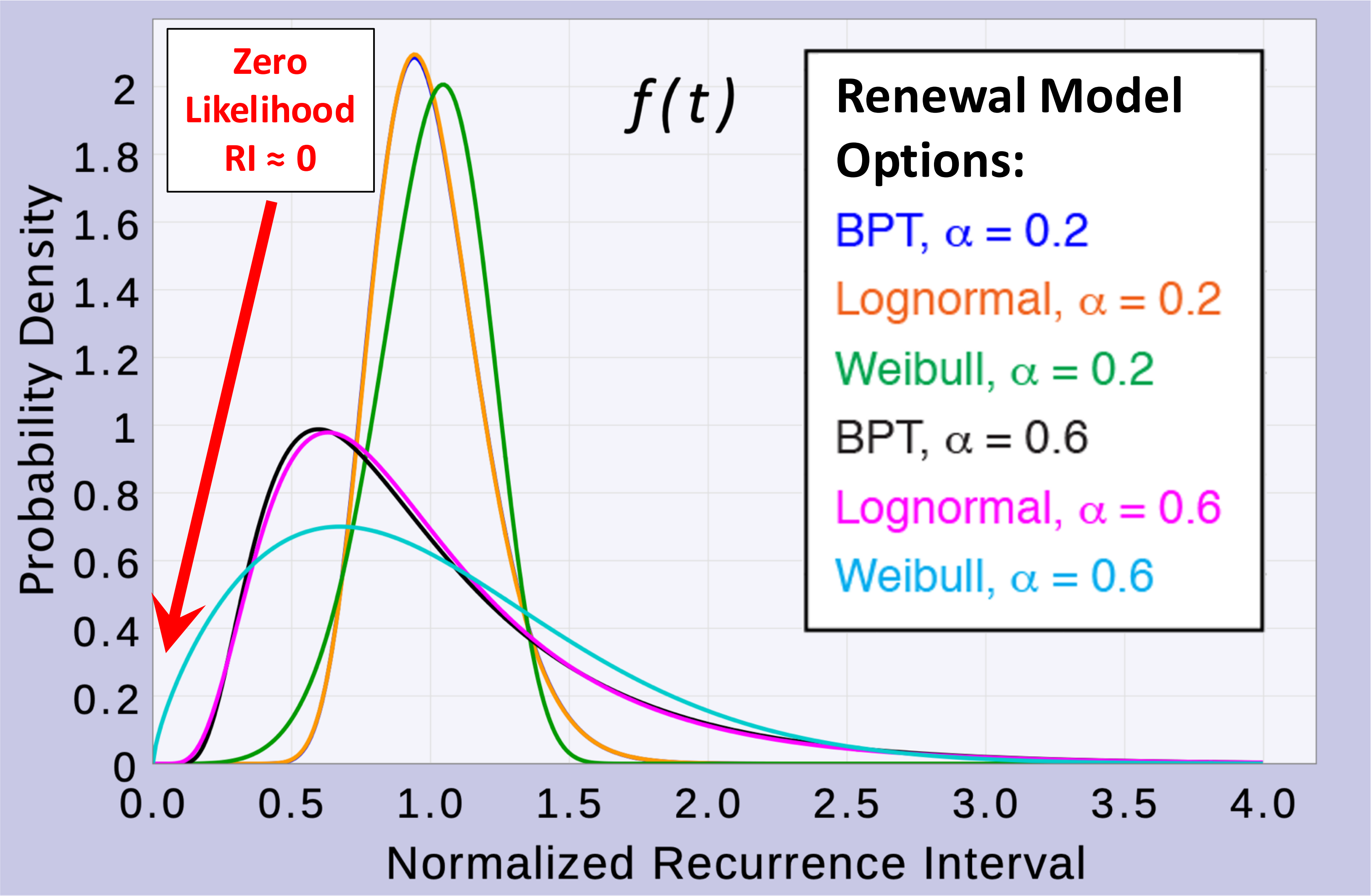
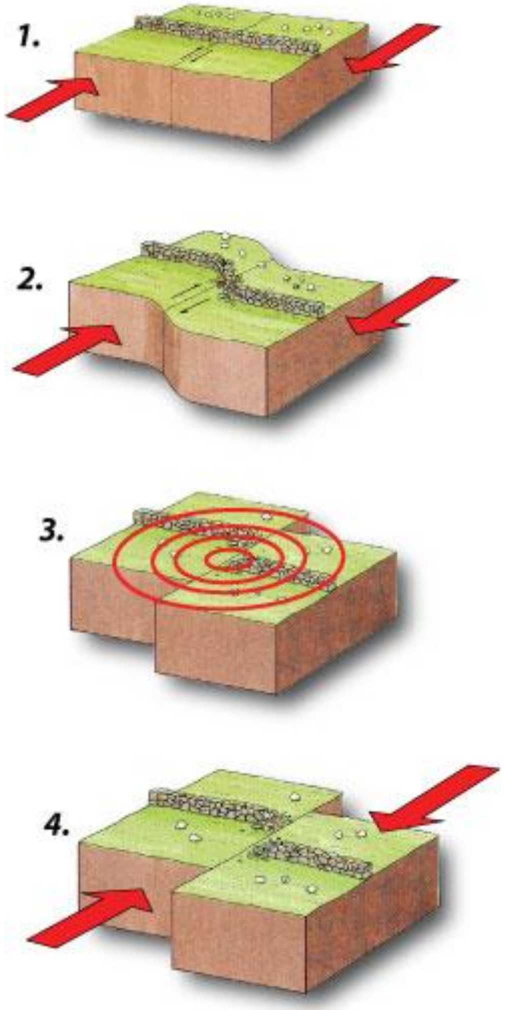
UCERF2 and predecessor California models assumed that every point on every fault exhibits one of these renewal models (i.e., what you'd see in a paleoseismic trench)





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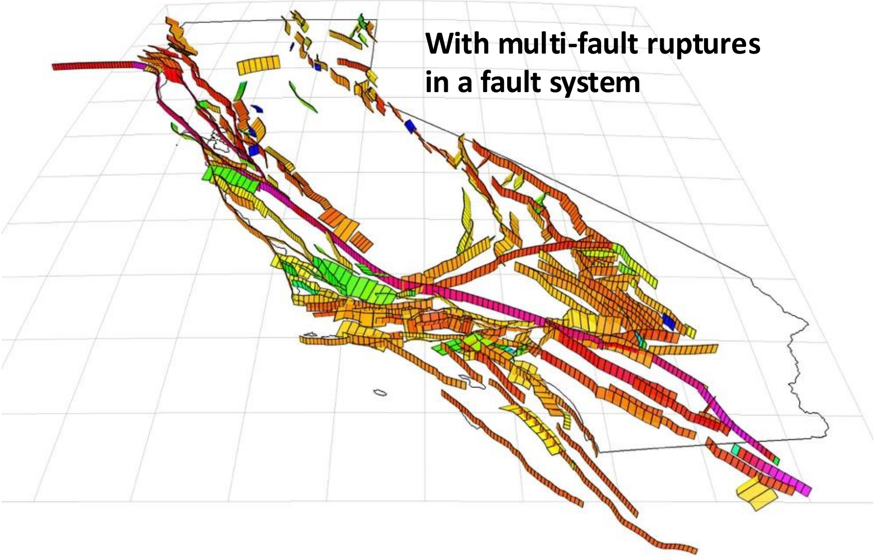
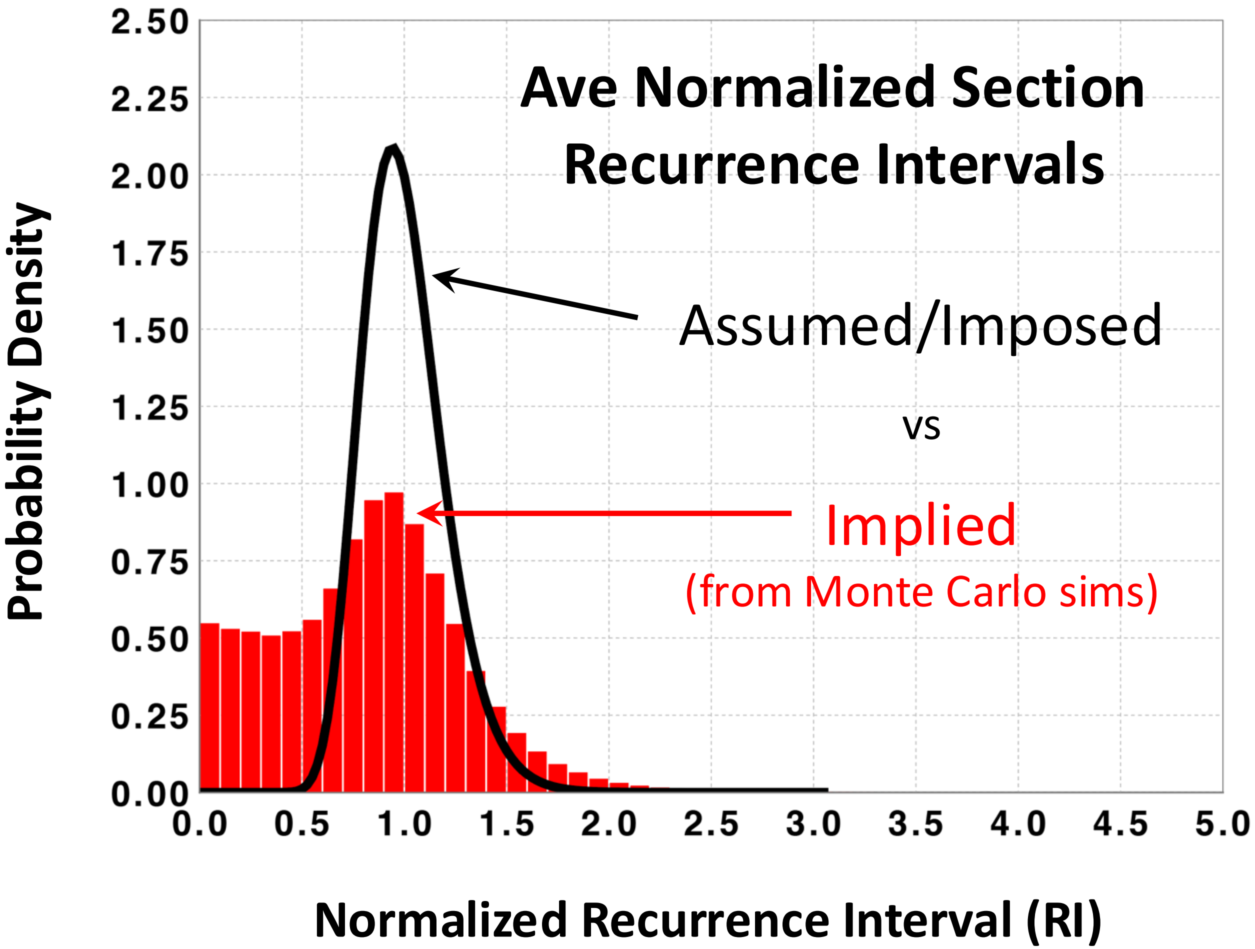




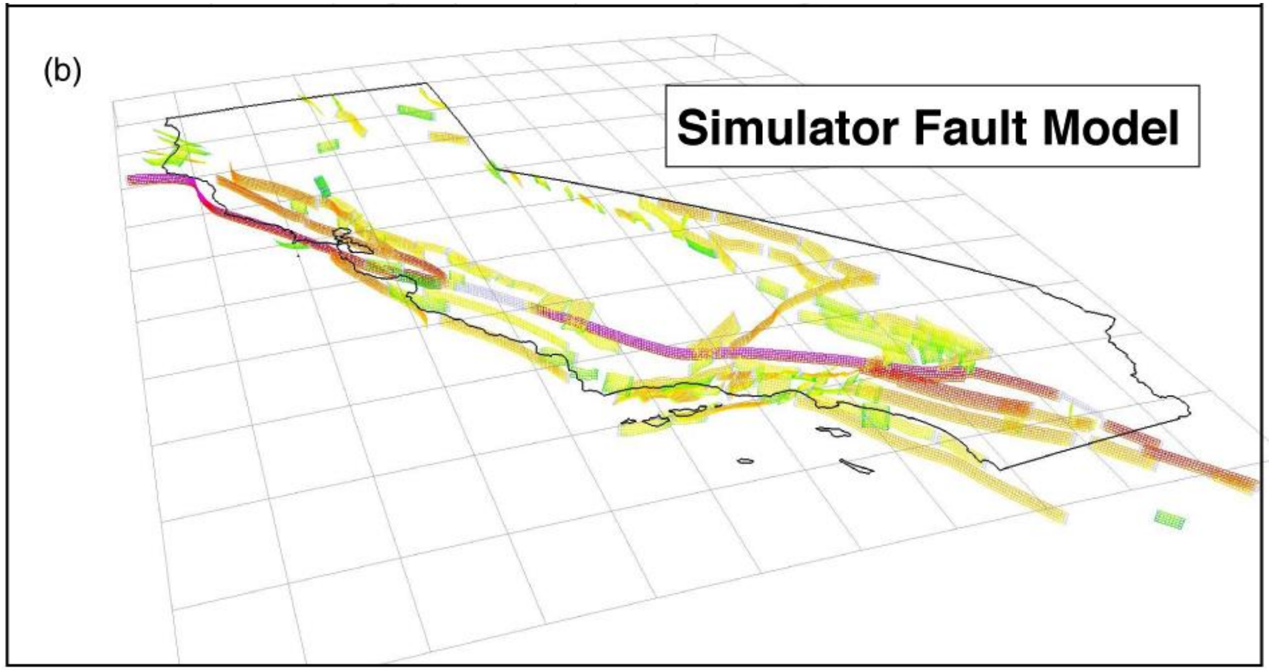
This model is not self consistent

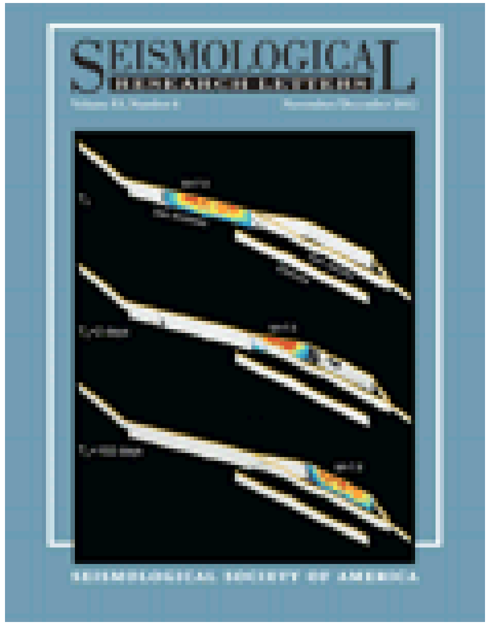
What's going on?

Multicycle Physics-based earthquake simulators

Produce ruptures throughout fault system over thousands of years (unsegmented)

Let's look at the behavior for large (supra-seismogenic) events



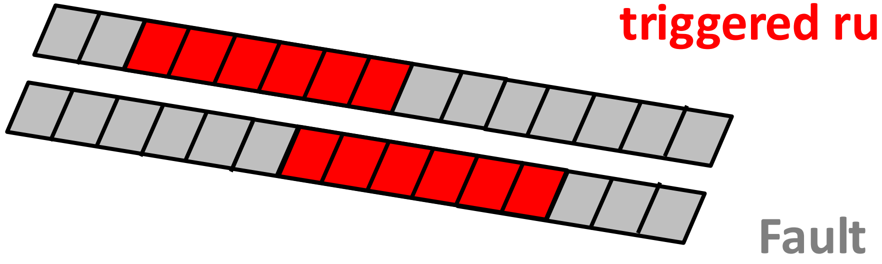


SRL "focused issue"
(2012, v. 83, #6)

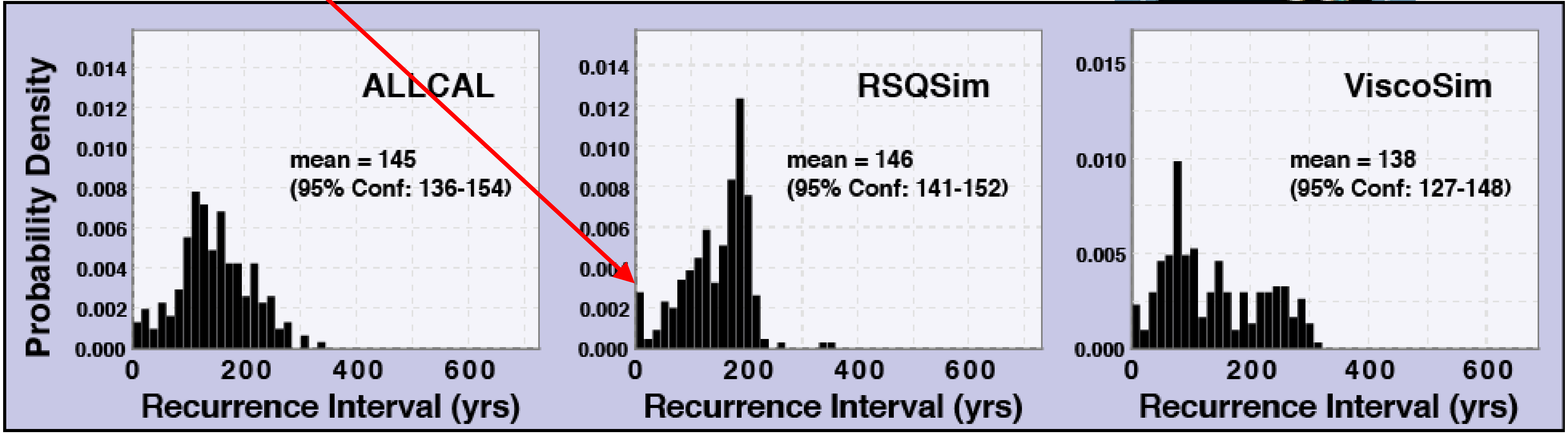
- ALLCAL (Ward)
- ~~Virtual Ca (Sachs et al.)~~
- RSQSim (Richards-Dinger & Dieterich)
- ViscoSim (Pollitz)

Multicycle Physics-based earthquake simulators

Height of first bin is not zero!



Recurrence Intervals at **Pitman Canyon site**

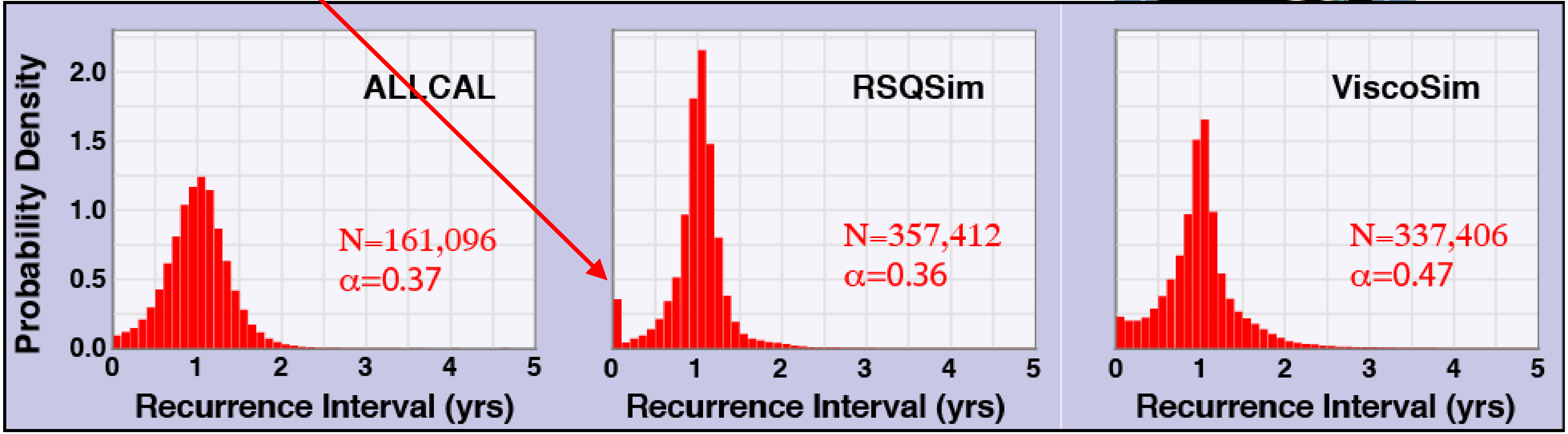


Multicycle Physics-based earthquake simulators

Height of first bin is not zero!

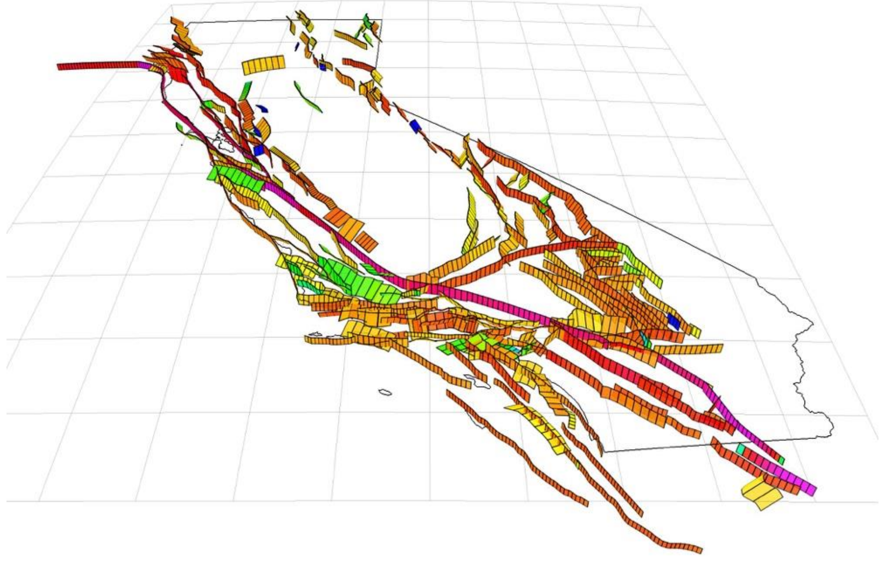
There is no good reason to presume that recurrence intervals at a point on a fault conform to any classic renewal models…

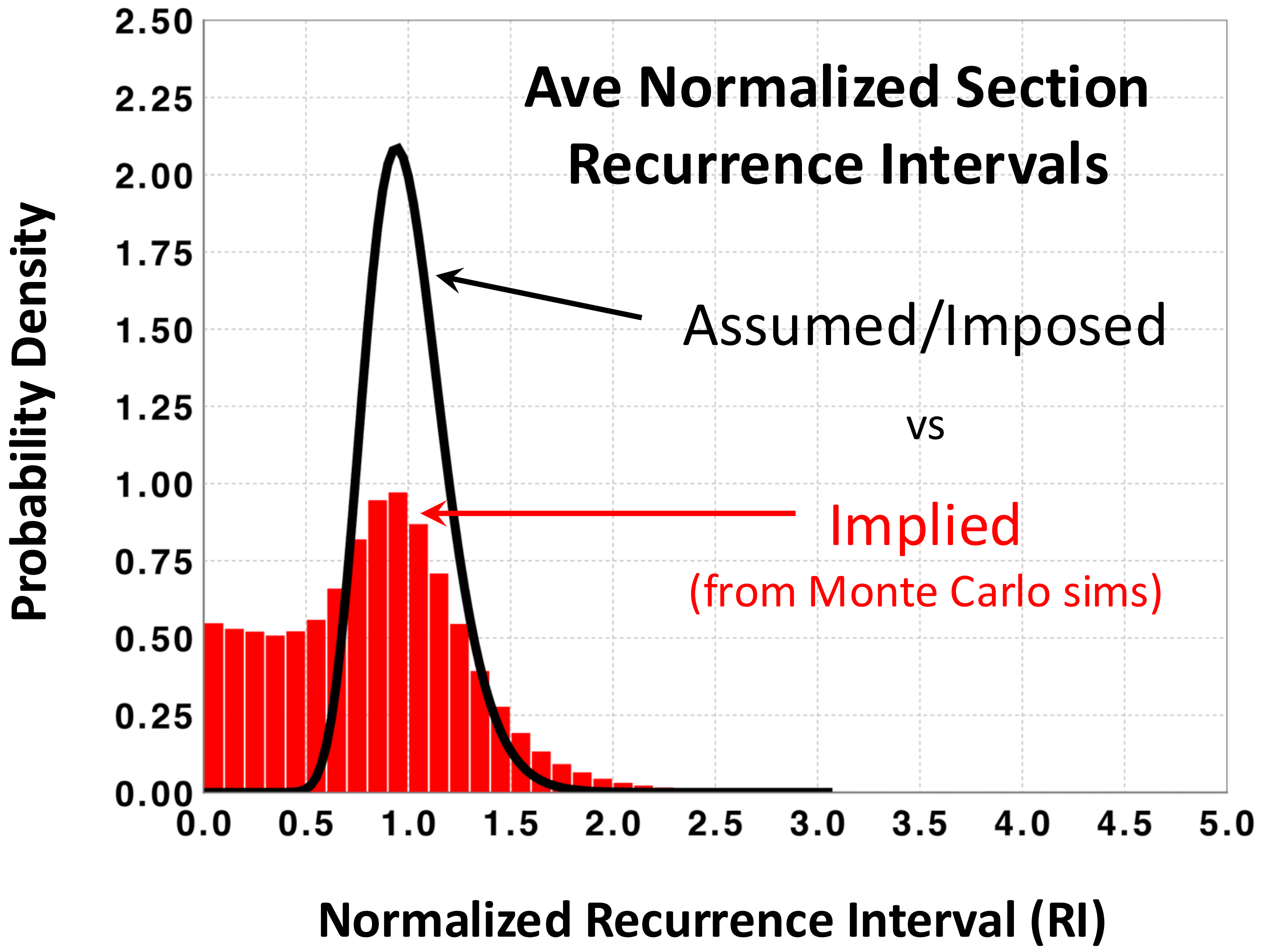
Recurrence Intervals **averaged over all sites**



Reid's (1911) Elastic-Rebound Theory:

UCERF2 and predecessor California models assumed that every point on every fault exhibits one of these renewal models (i.e., what you'd see in a paleoseismic trench)

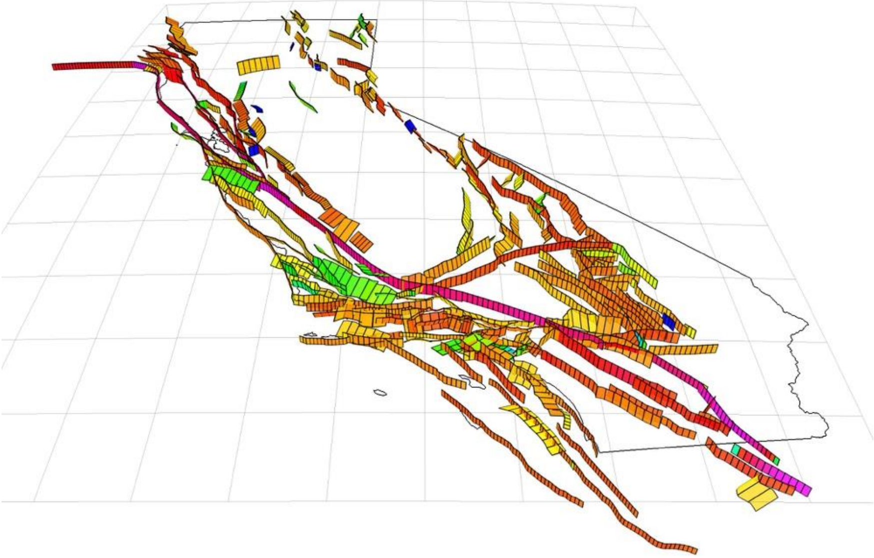


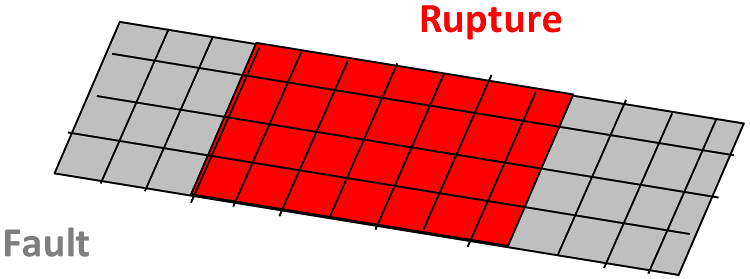


How do we fix this?

Reid’s (1911) Elastic-Rebound Theory:

We changed the recurrence of what question in UCERF3:





Rather than assuming points on faults follow a renewal model...

We hypothesized that the average normalized time since previous event for every large rupture follows a renewal model

$$\eta_r = \frac{1}{N} \sum \frac{T_{er}}{\mu_e}$$

Time Since Last Event for Element

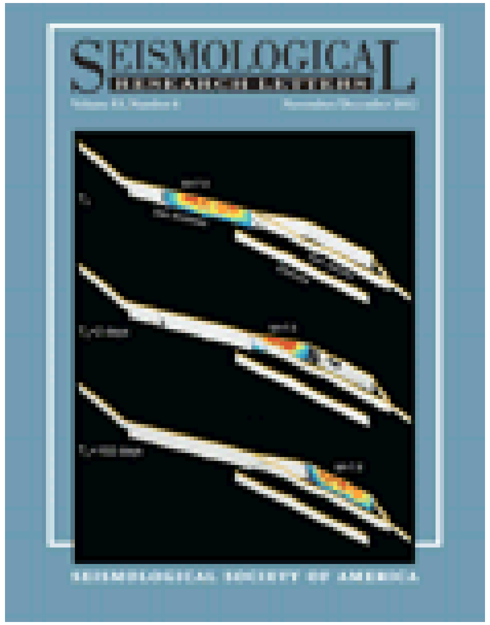
Ave RI for element

A PDF/histogram of these should look like a renewal model

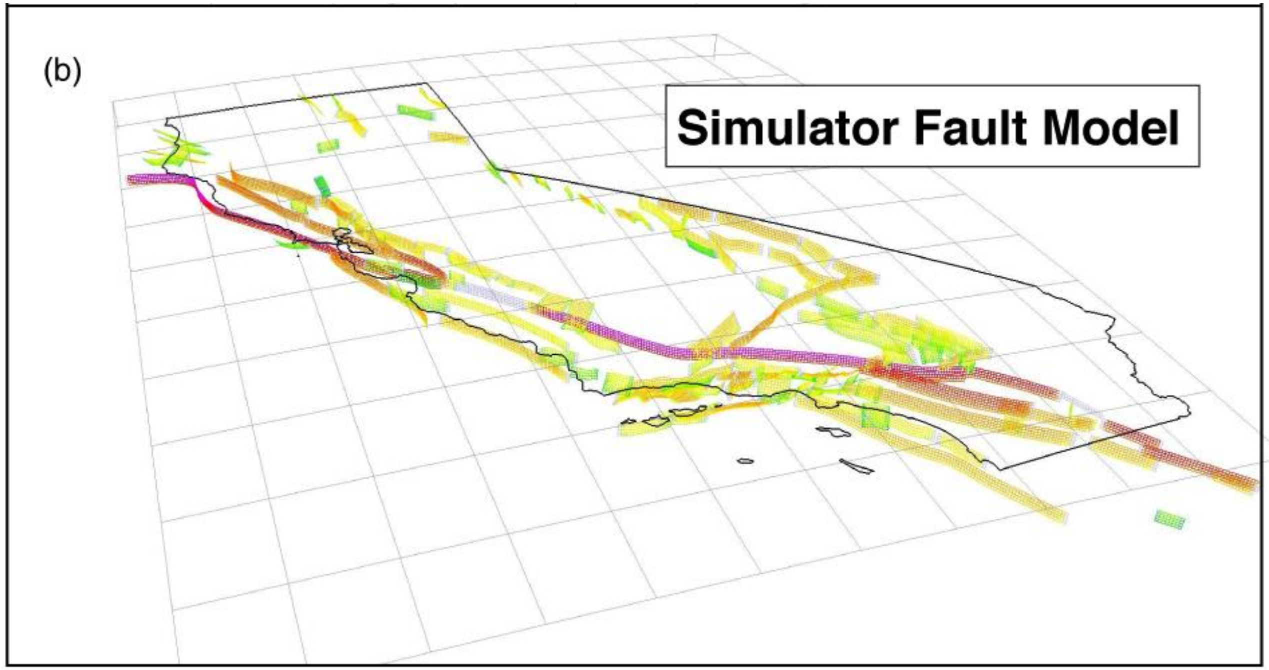
How can we test this?

Multicycle Physics-based earthquake simulators!

Let’s look at the behavior for large (supra-seismogenic) events

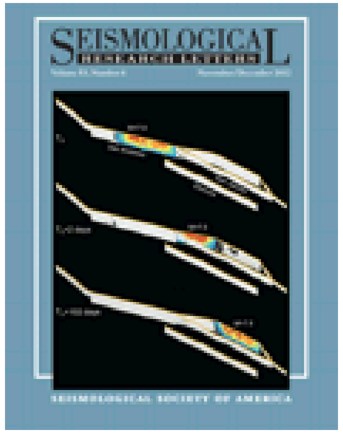


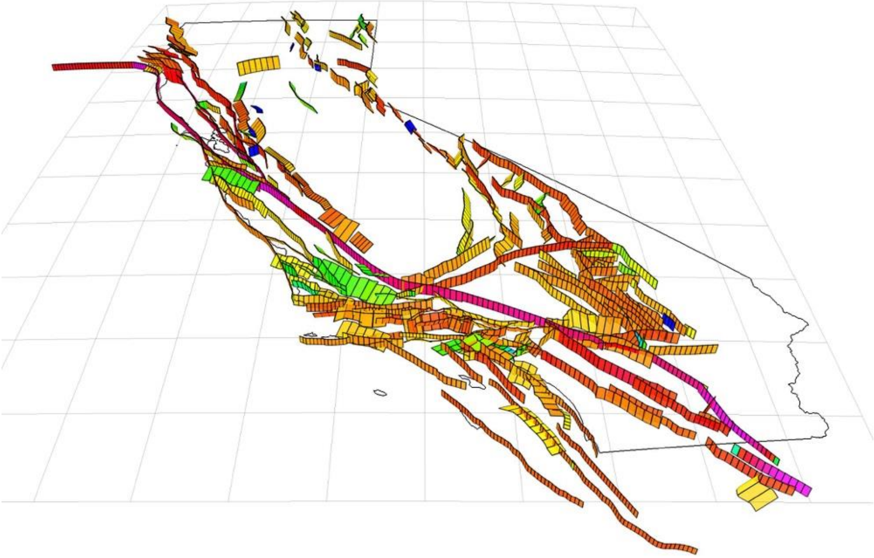
SRL “focused issue”
(2012, v. 83, #6)



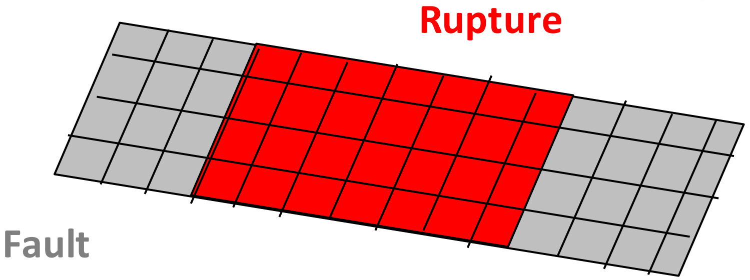
- ALLCAL (Ward)
- ~~Virtual Ca (Sachs et al.)~~
- RSQSim (Richards-Dinger & Dieterich)
- ViscoSim (Pollitz)

Multicycle Physics-based earthquake simulators





To test the UCERF3 hypothesis that average normalized time since previous event for every large rupture follows a renewal model



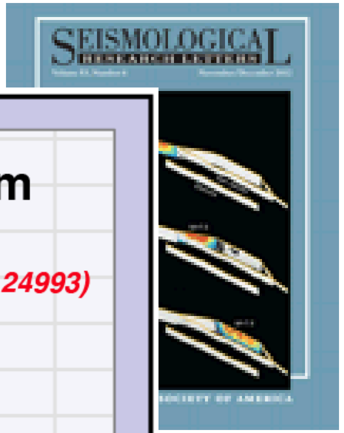
$$\eta_r = \frac{1}{N}\sum \frac{T_{er}}{\mu_e}$$

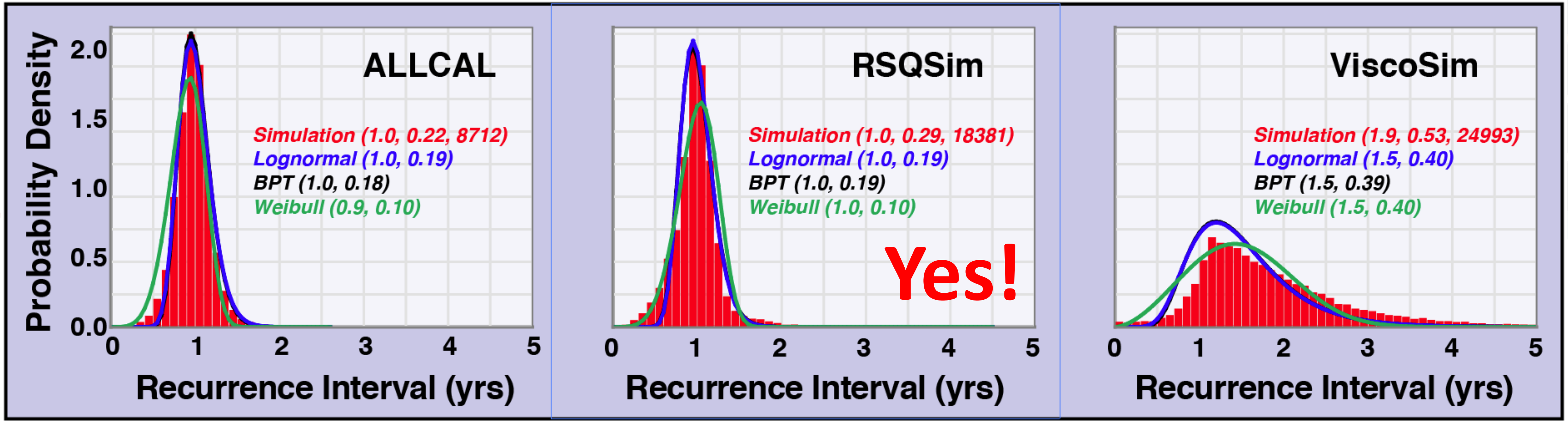
Time Since Last Event for Element

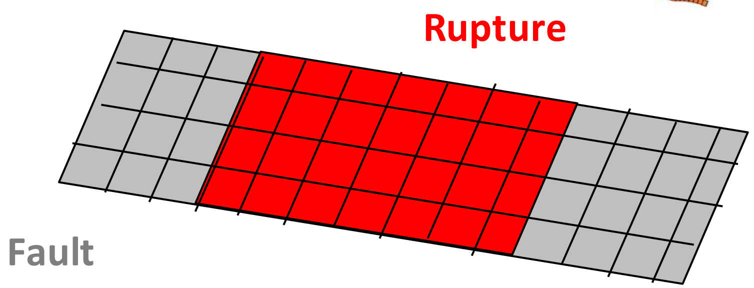
Ave RI for element

A PDF/histogram of these should look like a renewal model

Multicycle Physics-based earthquake simulators







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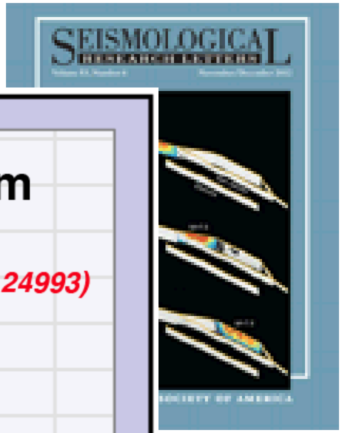
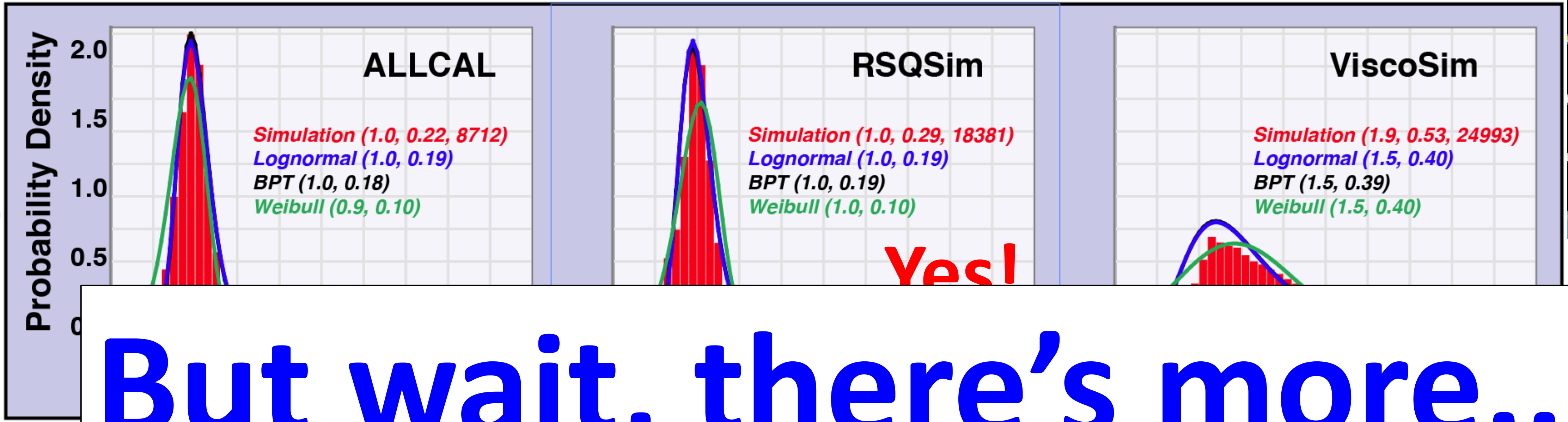
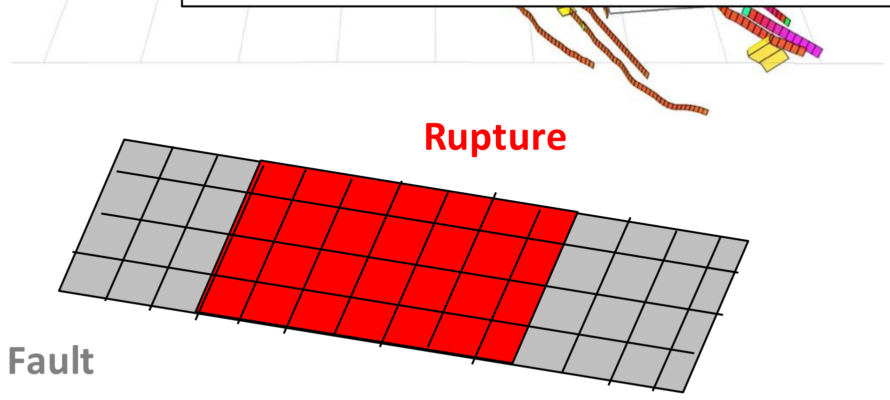




But wait, there's more…



$$\eta_r = \frac{1}{N}\sum \frac{T_{er}}{\mu_e}$$

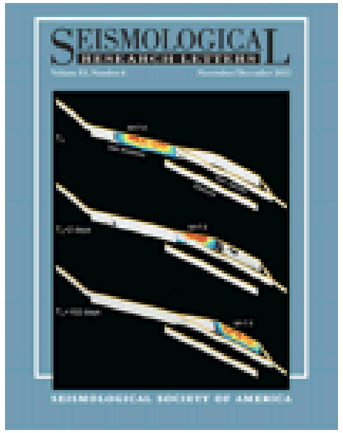
Time Since Last Event for Element

Ave RI for element

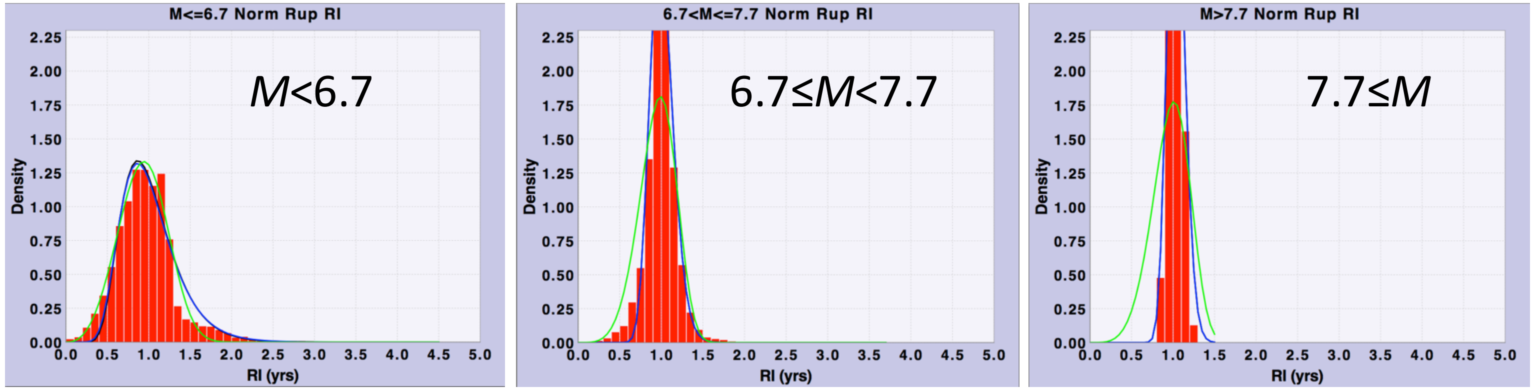
A PDF/histogram of these should look like a renewal model

Multicycle Physics-based earthquake simulators

also evidence of mag-dependent aperiodicity



RSQSim:



Aperiodicity/COV:

	M≤6.7	6.7<M≤7.7	M>7.7	Element Ave
ALLCAL	0.29	0.20	0.12	0.37
RSQSim	0.42	0.21	0.09	0.36
ViscoSim	0.51	0.49	0.09	0.47

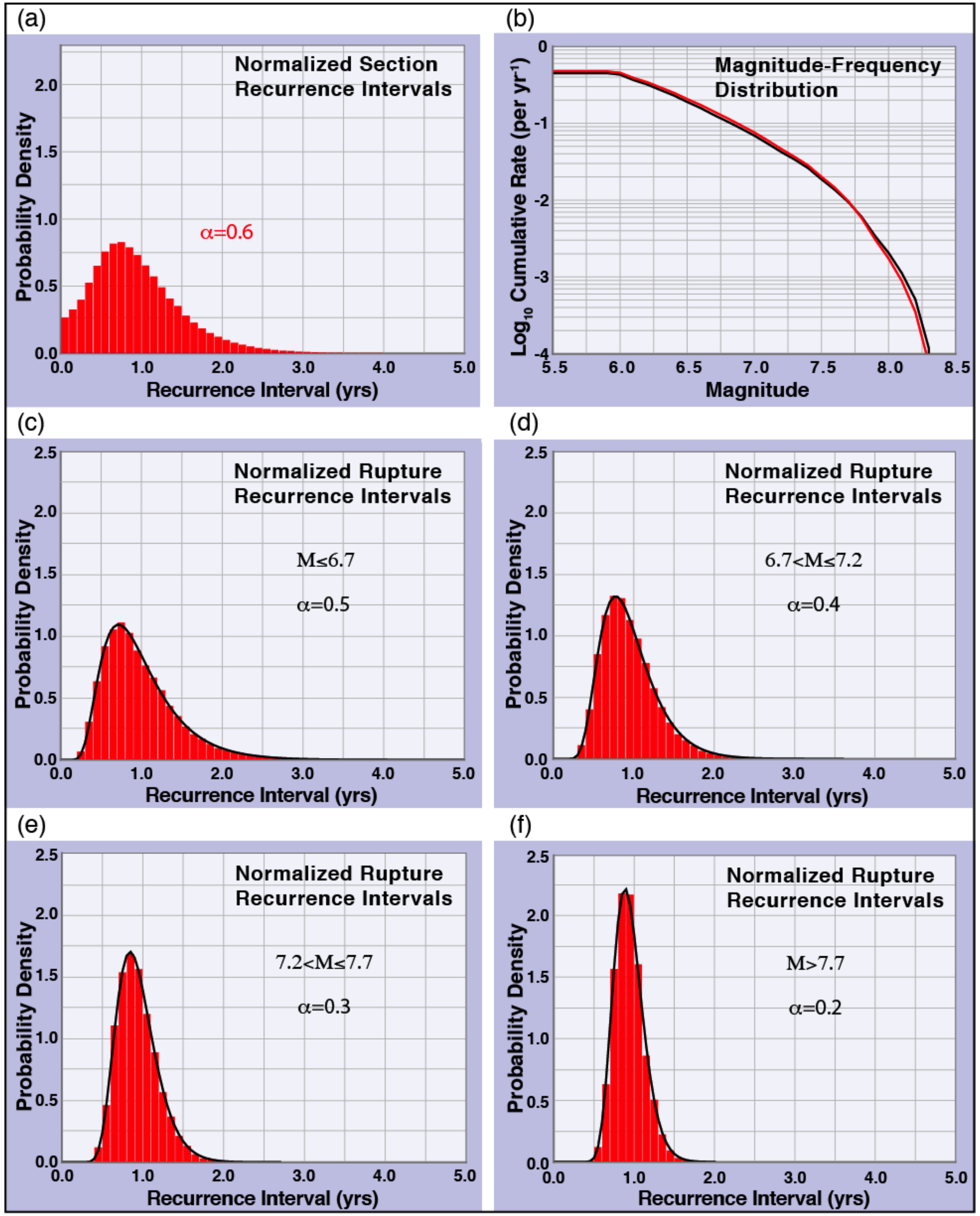
This inference influenced the final UCERF3-TD Model:

Mag-Dependent Aperiodicity M≤6.7, 6.7<M≤7.2, 7.2<M≤7.7, M>7.7
LOW RANGE: 0.4, 0.3, 0.2, 0.1
MID RANGE: 0.5, 0.4, 0.3, 0.2
HIGH RANGE: 0.6, 0.5, 0.4, 0.3

A more self consistent model

Don't expect paleo trenches to look like a renewal model

200,000 year Monte Carlo Simulation



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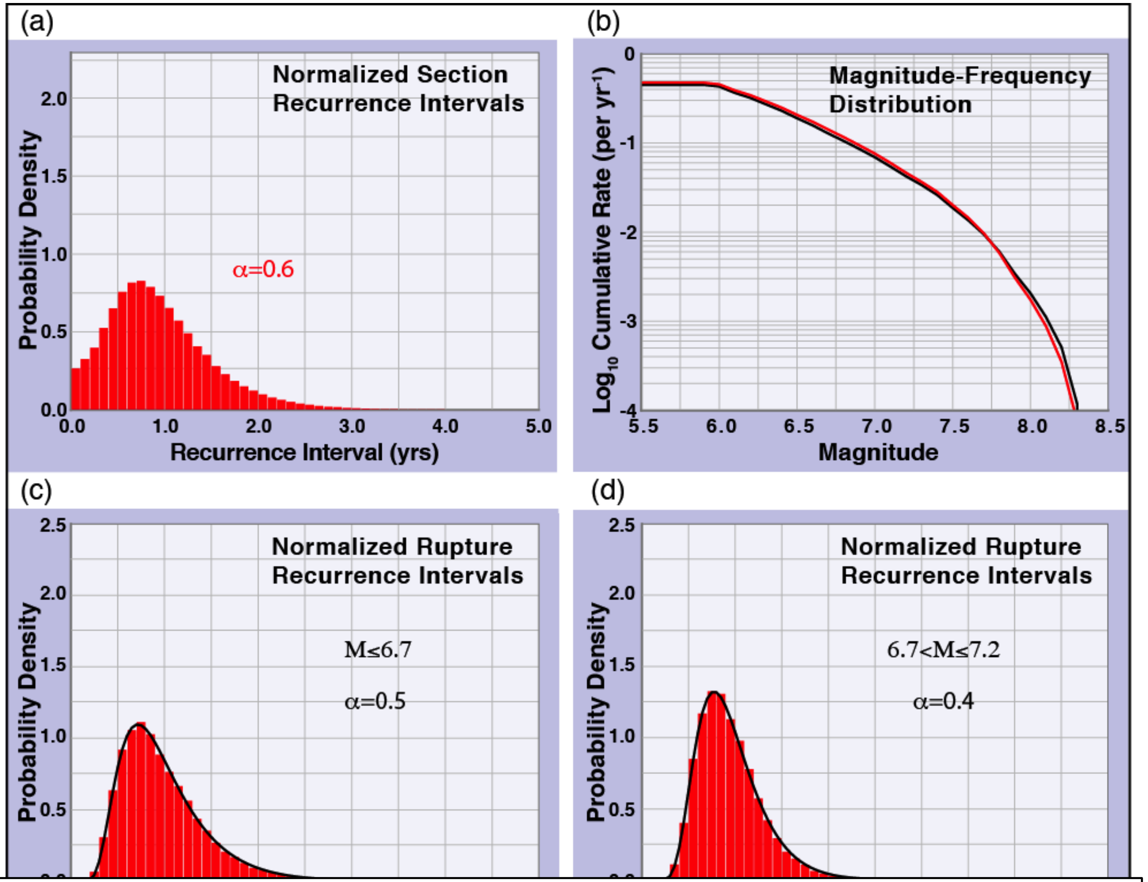

But wait, couldn't all these simulators be wrong with respect to this inference?

Simulation

Recurrence Interval (yrs) Recurrence Interval (yrs)

This inference influenced the final UCERF3-TD Model:

Mag-Dependent Aperiodicity M≤6.7, 6.7<M≤7.2, 7.2<M≤7.7, M>7.7
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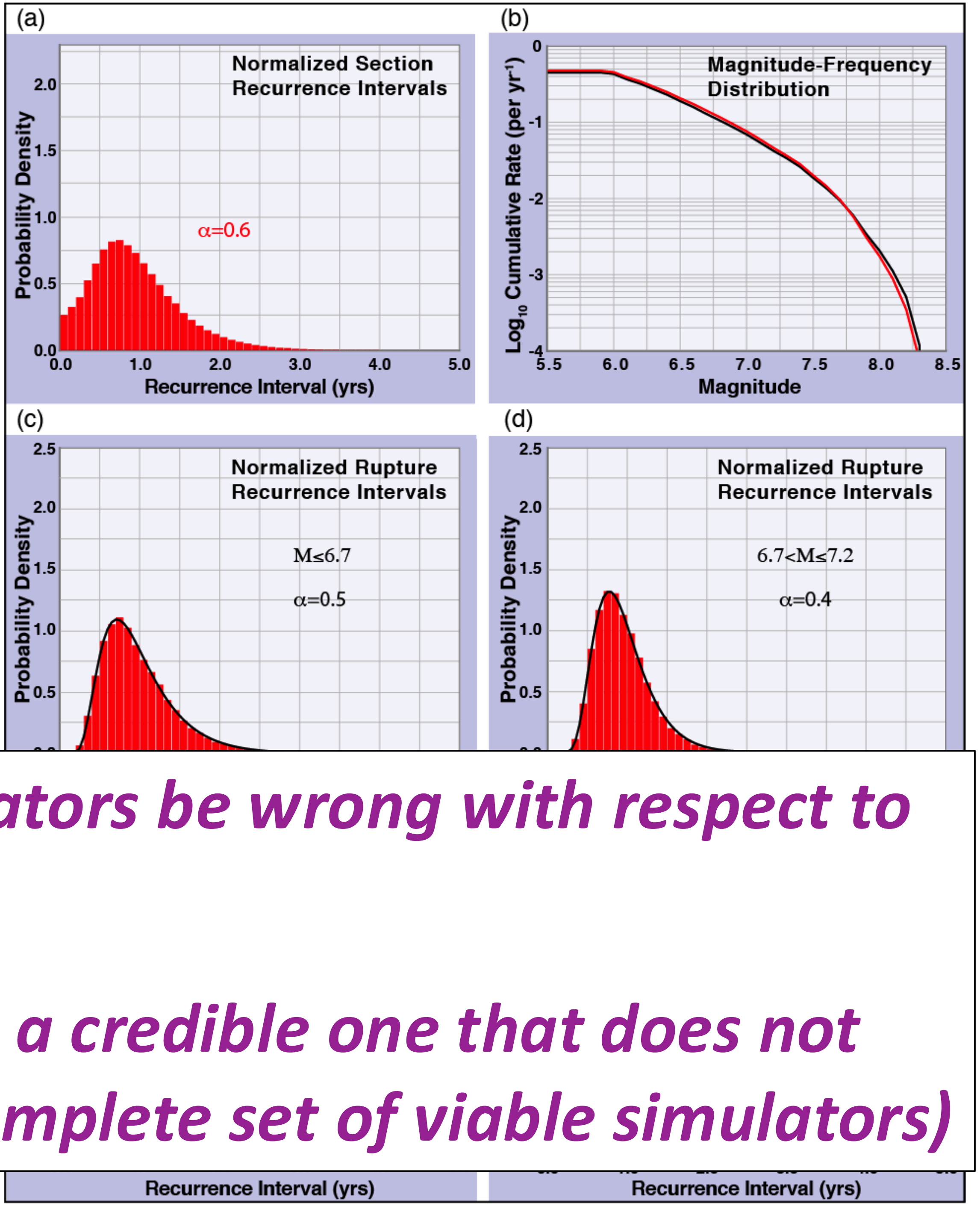
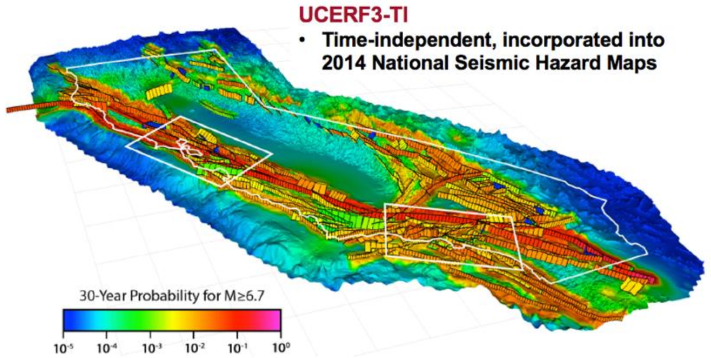


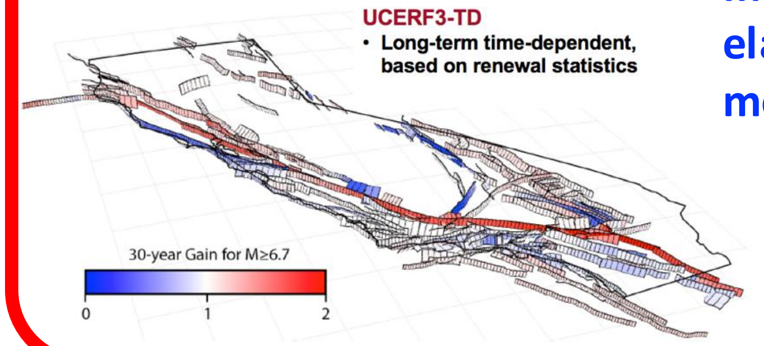
Simulation

But wait, couldn't all these simulators be wrong with respect to this inference?

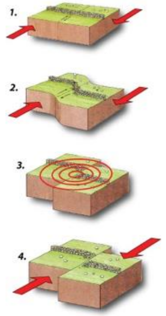
Of course, so your job is to create a credible one that does not show this behavior (we need a complete set of viable simulators)

We're now in the process of doing this nationwide



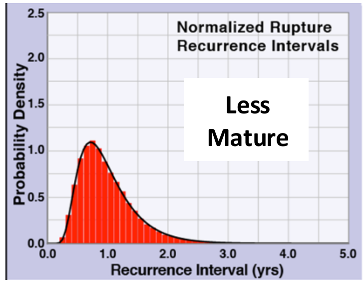


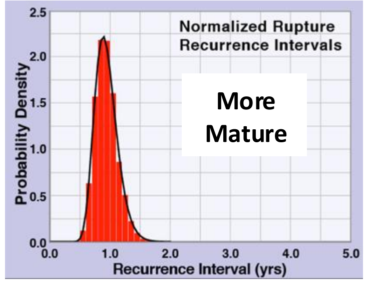
Improved elastic-rebound model



Ongoing implementation has led to a new hypothesis:

- Should aperiodicity/COV depend on fault maturity?
- We wish we had a suite of simulators to test this idea
- Until that time, we are using expert judgement





Multicycle, Physics-Based Earthquake Simulators:

generate synthetic rupture catalogs for large fault systems over thousands of earthquake cycles by modeling stress accumulation, rupture nucleation, friction evolution, and multi-fault interactions (and generally approximating dynamic effects).

Use them to test assumptions made, or implications of, our more empirical models:

- Average rupture rates
- Multifault rupture plausibility (Milner et al., 2022)
- Scaling relationships
- Average slip along rupture, especially for multifault events
- MFDs near faults (non-Gutenberg–Richter?)
- Influence of creep (area versus slip-rate reduction) and seismogenic depths
- Elastic rebound predictability (e.g., Field et al., 2015)
- **Spatiotemporal clustering (e.g., is ETAS adequate at large magnitudes?)**
- Other time dependencies (mode switching, super cycles, and paleo hiatus)

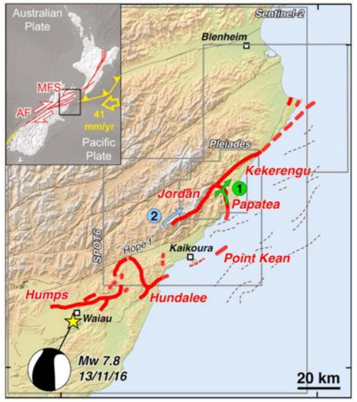
Uniform California Earthquake Rupture Forecast, version 3 (UCERF3)

By the Working Group on California Earthquake Probabilities:

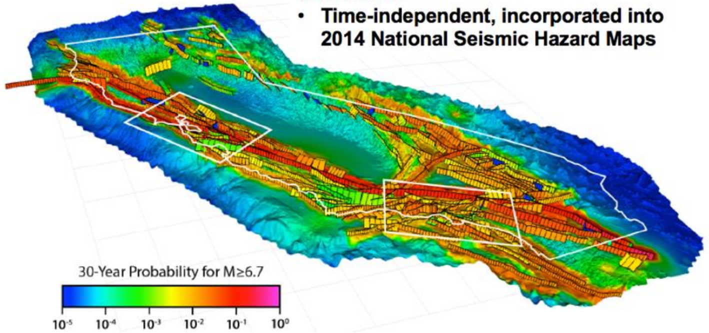
We're now in the process of doing this nationwide

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

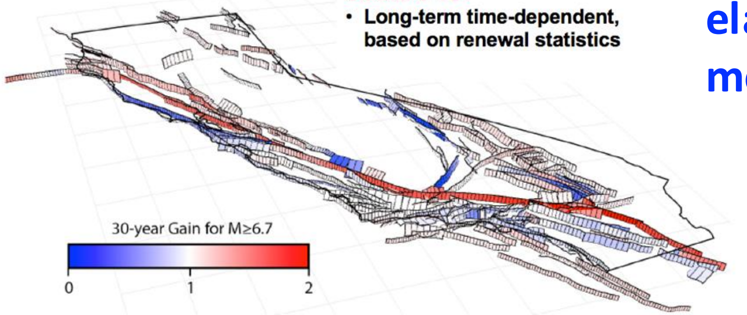
(e.g., Kaikoura)



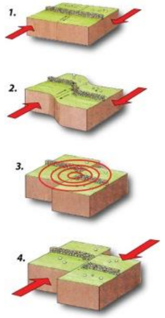
UCERF3-TI
- Time-independent, incorporated into 2014 National Seismic Hazard Maps



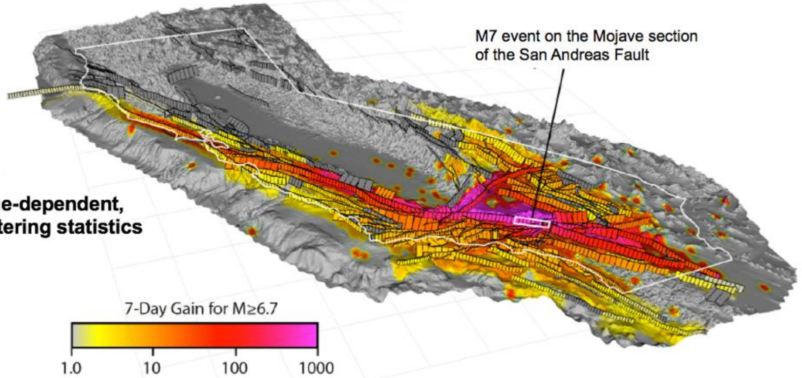
UCERF3-TD
- Long-term time-dependent, based on renewal statistics



Improved elastic-rebound model

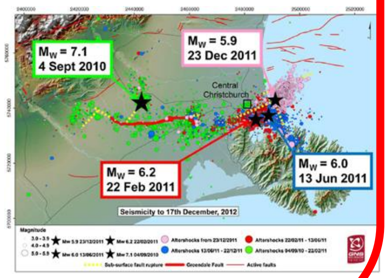


UCERF3-ETAS
- Short-term time-dependent, based on clustering statistics

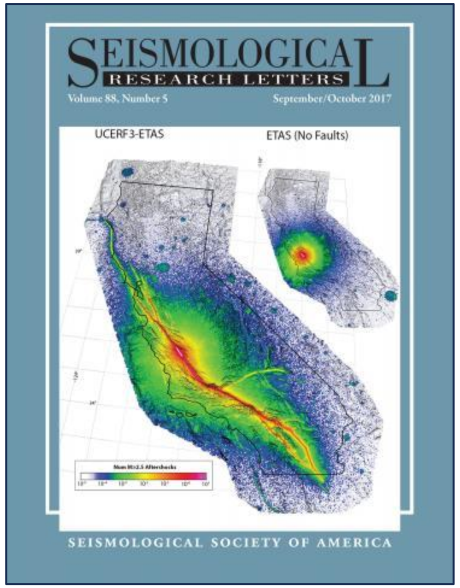


Field et al. (2014, 2015, 2017)

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



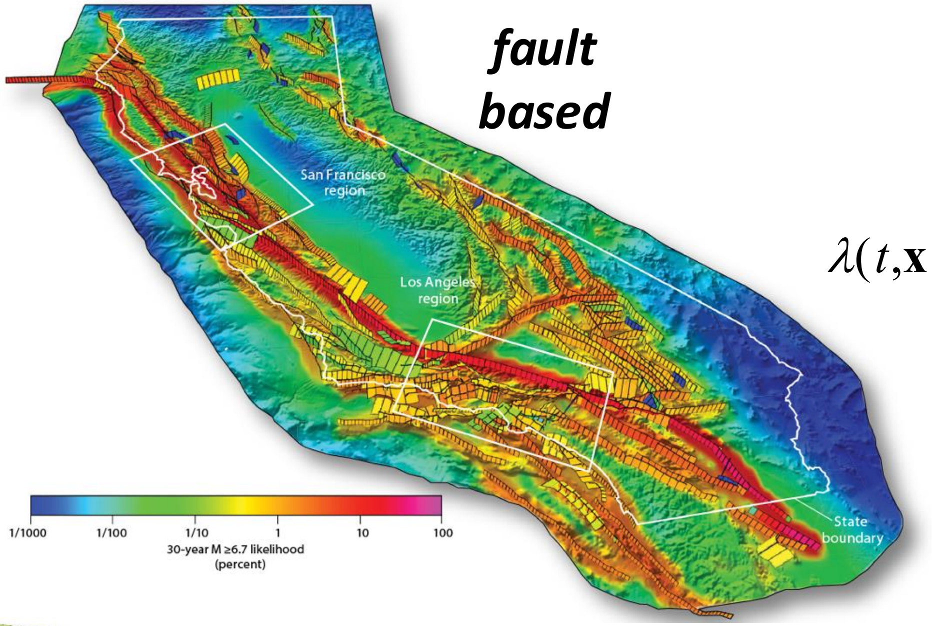
UCERF3-ETAS Model (2017, 2021) - fully time dependent prototype:



UCERF3-TD

+

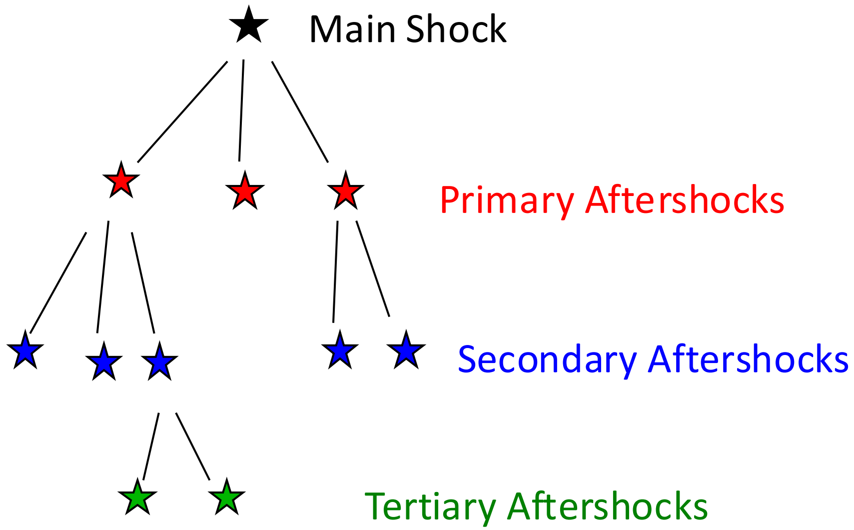
ETAS Model
(Epidemic Type Aftershock Sequence)



fault based

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

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

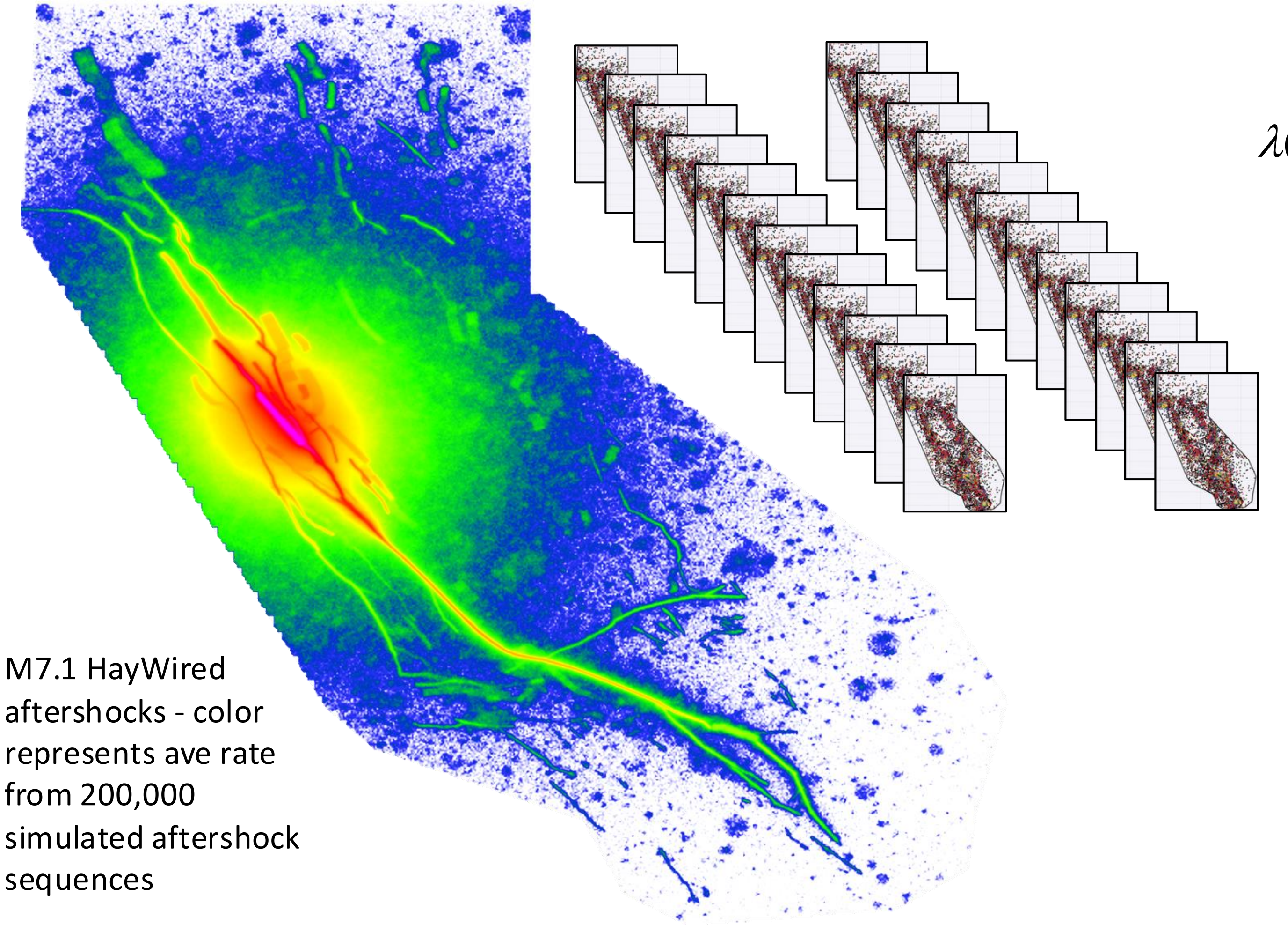


including longer-term elastic-rebound effects

ETAS captures the notion that every earthquake, large and small, has a ~10% chance of triggering something bigger in the year that follows

UCERF3-ETAS Model (2017, 2021) - fully time dependent prototype:

Product: synthetic catalogs of events (stochastic event sets; as many as needed) for any specified timespan and condition on all past events

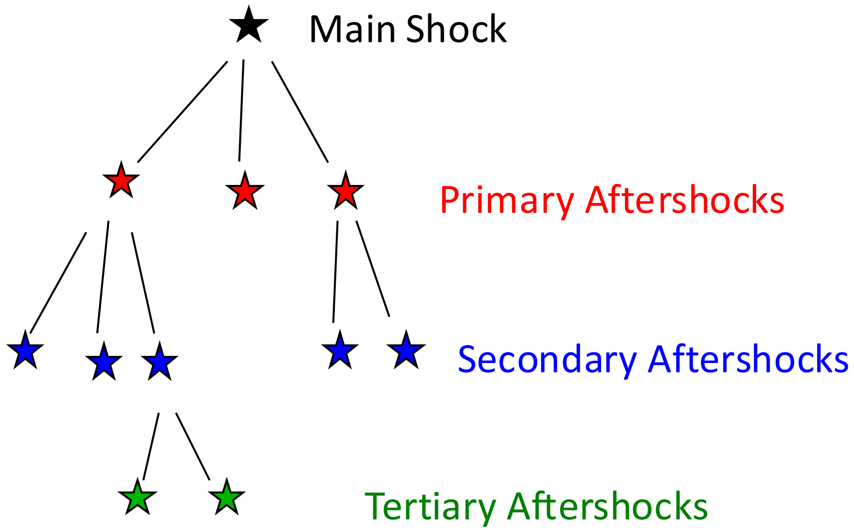


M7.1 HayWired aftershocks - color represents ave rate from 200,000 simulated aftershock sequences

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 Model (2017, 2021) - fully time dependent prototype:

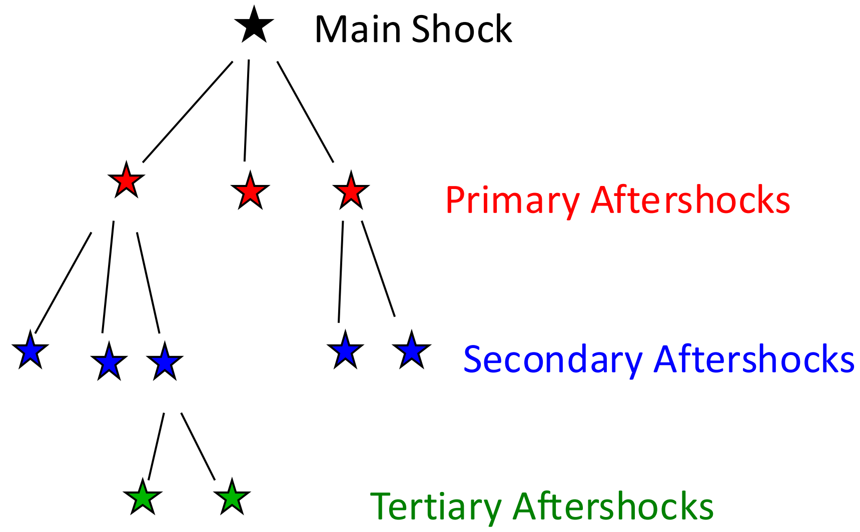
Spatiotemporal Clustering Challenges:

1) The need for elastic relaxation (to prevent mainshock re-rupture)
2) **Can large, triggered events nucleate from well within the main-shock rupture zone; how does this evolve with time?**
3) Dealing with MFD characteristicness (non-GR) near faults
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) Dealing with epistemic uncertainties

ETAS Model
(Epidemic Type Aftershock Sequence)

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

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

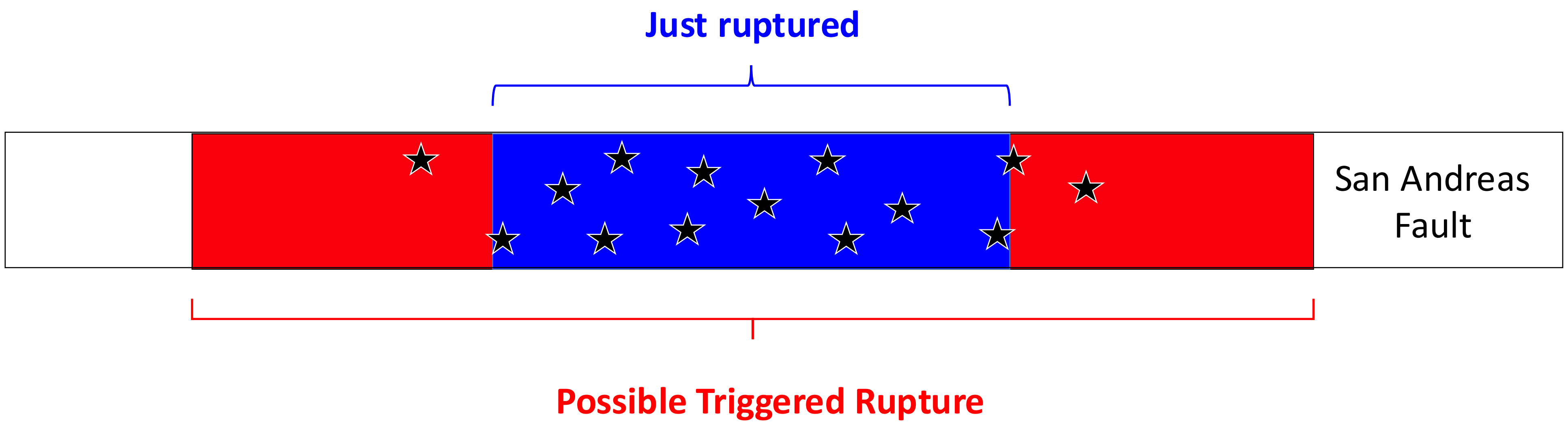


UCERF3-ETAS Model (2017, 2021) - fully time dependent prototype:

Spatiotemporal Clustering Challenges:

1) The need for elastic relaxation (to prevent mainshock re-rupture)
2) **Can large, triggered events nucleate from well within the main-shock rupture zone; how does this evolve with time?**

Can the **red rupture** be triggered (nucleate) from well withing the just-ruptured **blue area**?



UCERF3-ETAS Model (2017, 2021) - fully time dependent prototype:

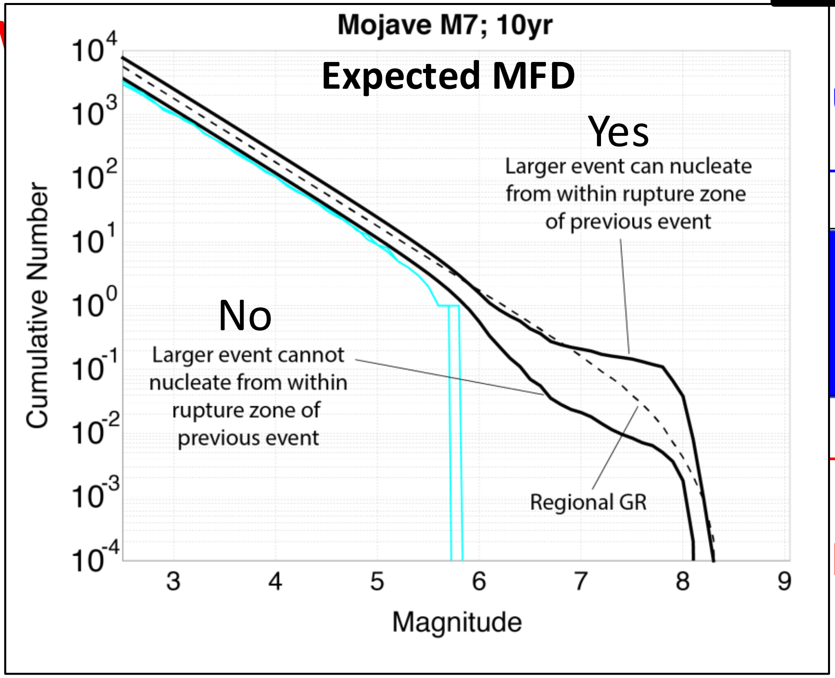
Spatiotemporal Clustering Chall

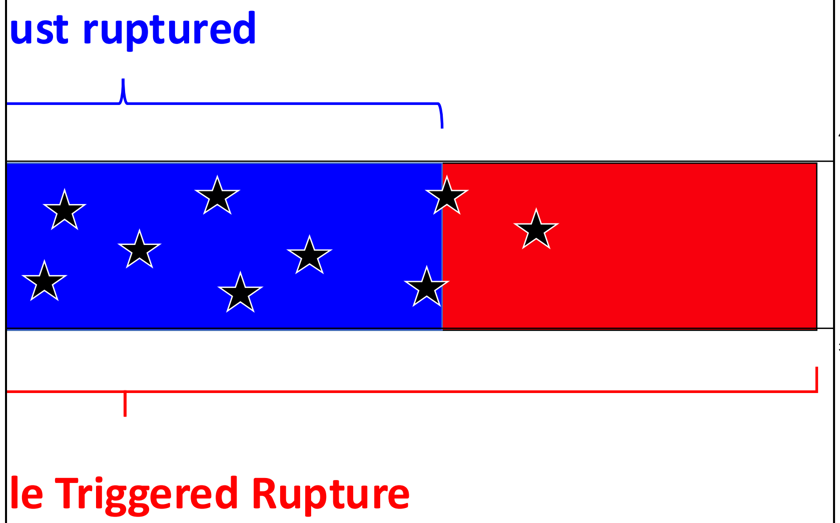
1) The need for elastic relaxation (to
prevent mainshock re-rupture)

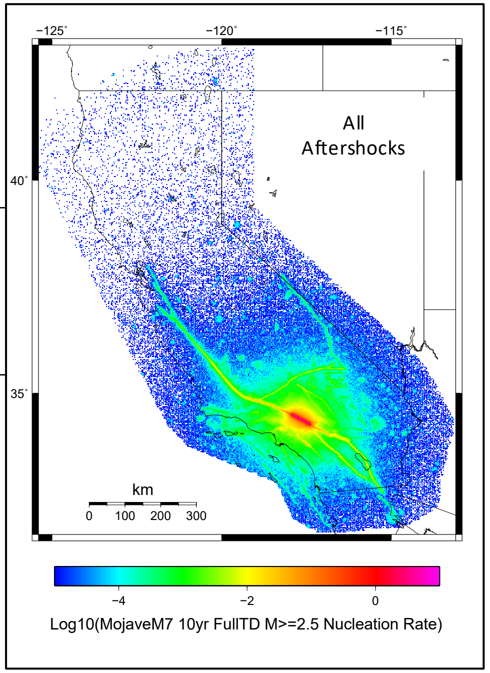
2) **Can large, triggered events nu
from well within the main-sho
rupture zone; how does this e
w**

Again, we wish we has a suite of simulators to test this question

For now, we use expert opinion to include the range of viable options







Multicycle, Physics-Based Earthquake Simulators:

generate synthetic rupture catalogs for large fault systems and over thousands of earthquake cycles by modeling stress accumulation, rupture nucleation, friction evolution, and multi-fault interactions (and generally approximating dynamic effects)

Alternatively, we can use them to **test assumptions** made, or implications of, our more empirical models:

- Average rupture rates

"Indispensable", "Our best hope"

But not a panacea; these & more fully dynamic models will be wrong too, especially given perpetual uncertainties in structural details at depth

The question is what inferences are useful and robust given the assumptions, approximations, and uncertainties

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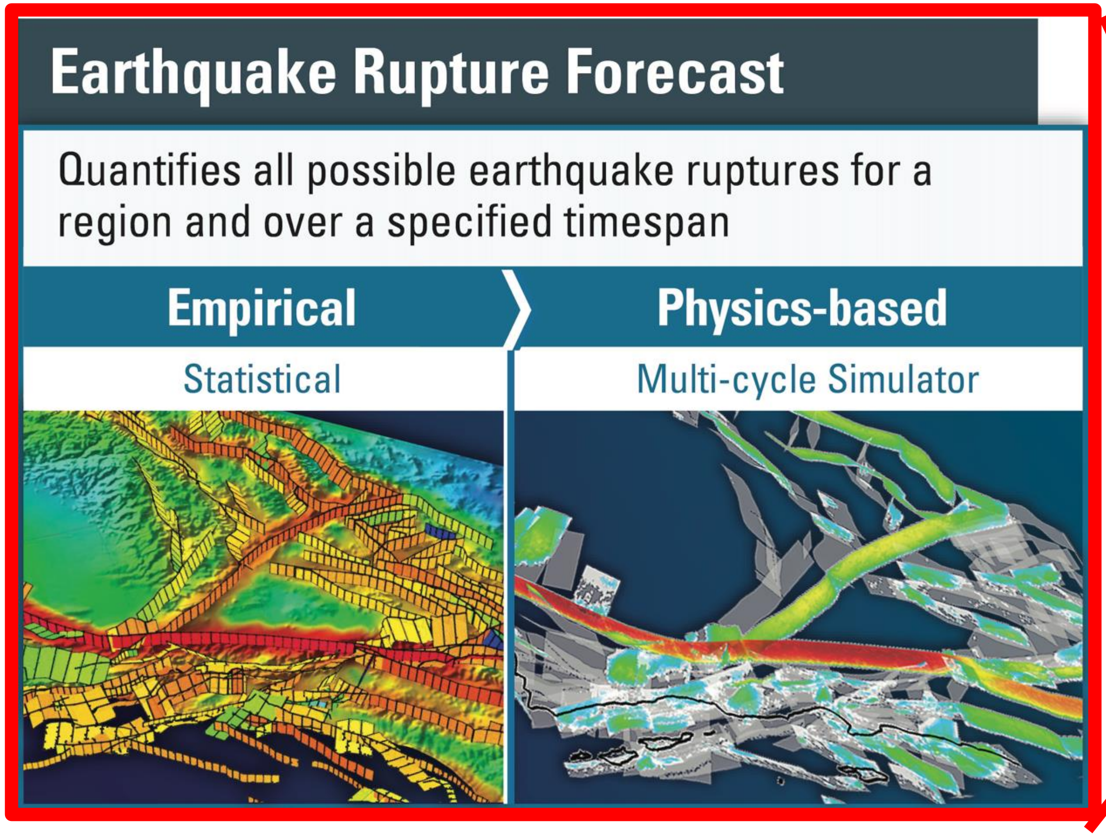
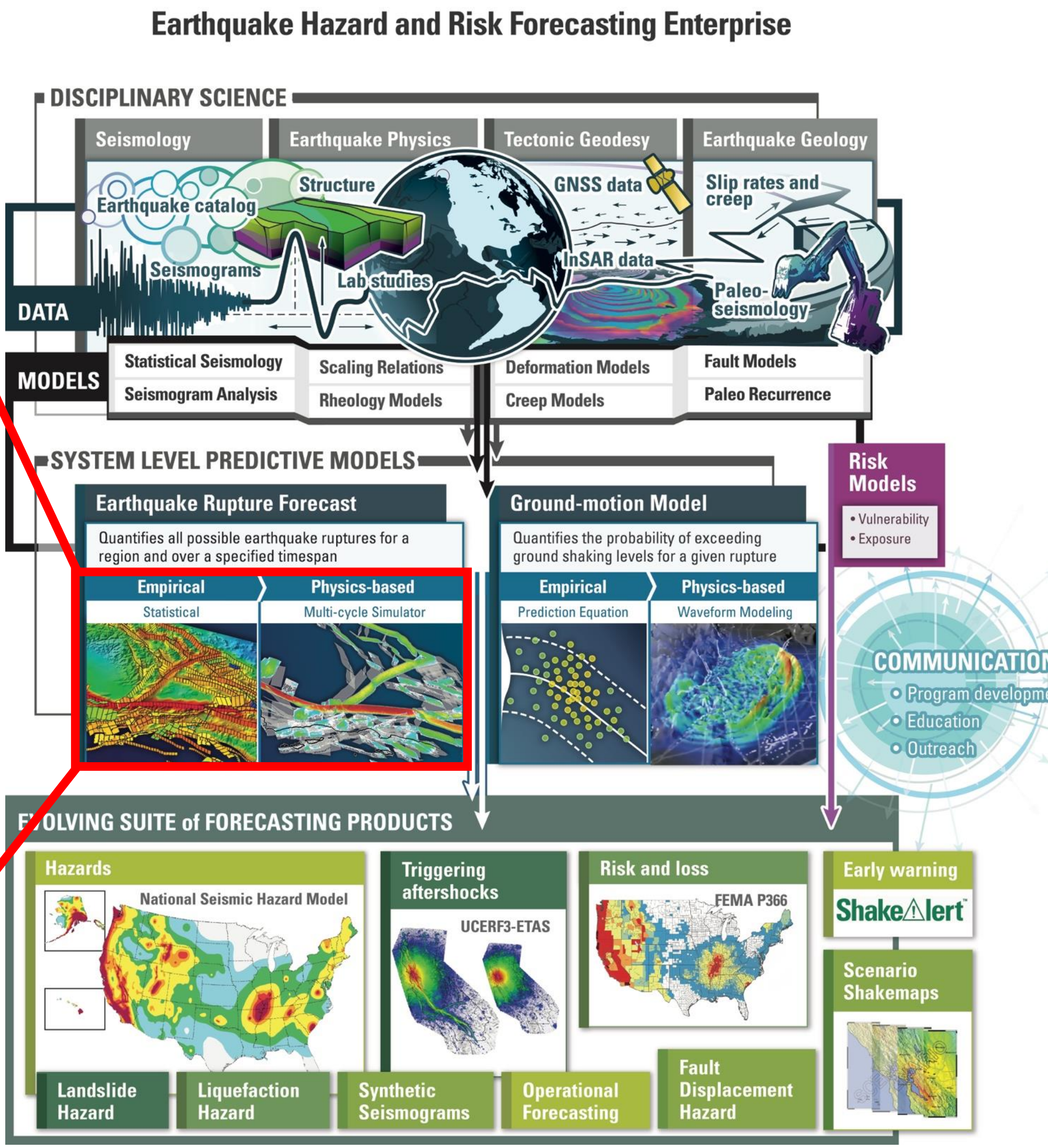
arge magnitudes?)

- Other time dependencies (mode switching, super cycles, and paleo hiatus)

A Scientific Vision and Roadmap for Earthquake Rupture Forecast Developments, A USGS Perspective

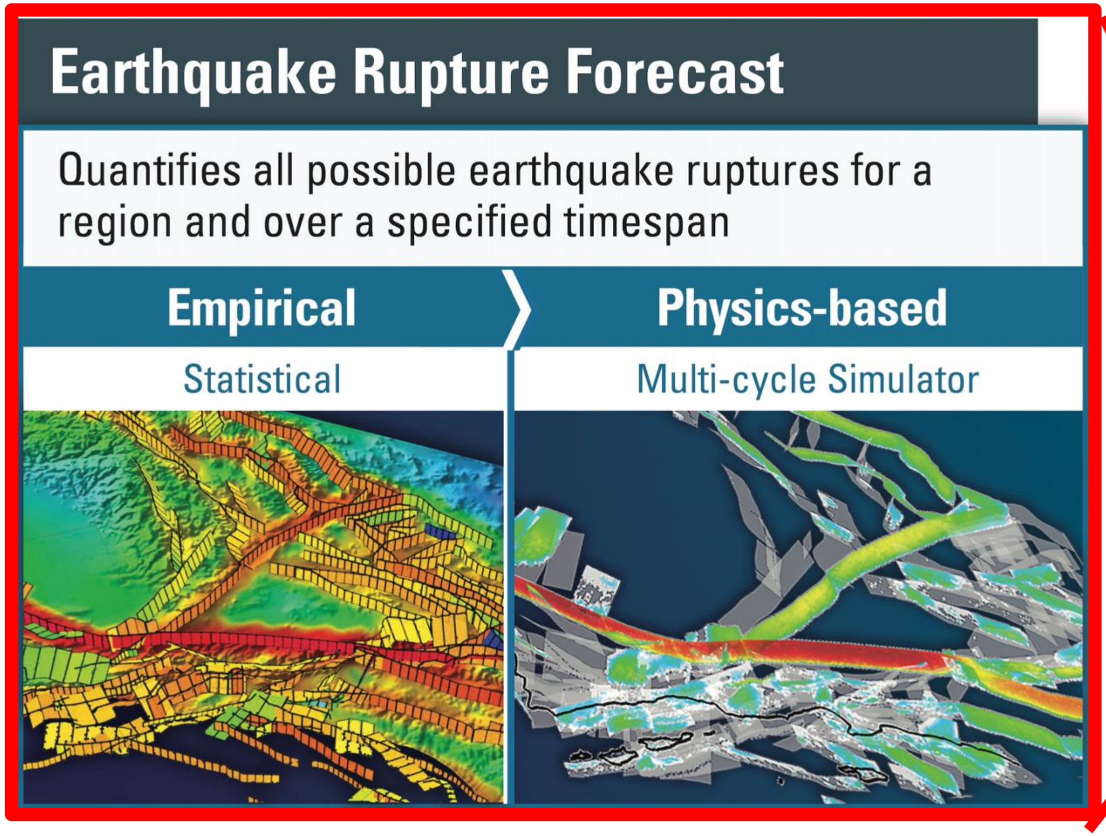




The USGS can handle this one

But not this one (IMO) We need SCEC!

A Scientific Vision and Roadmap for Earthquake Rupture Forecast Developments, A USGS Perspective

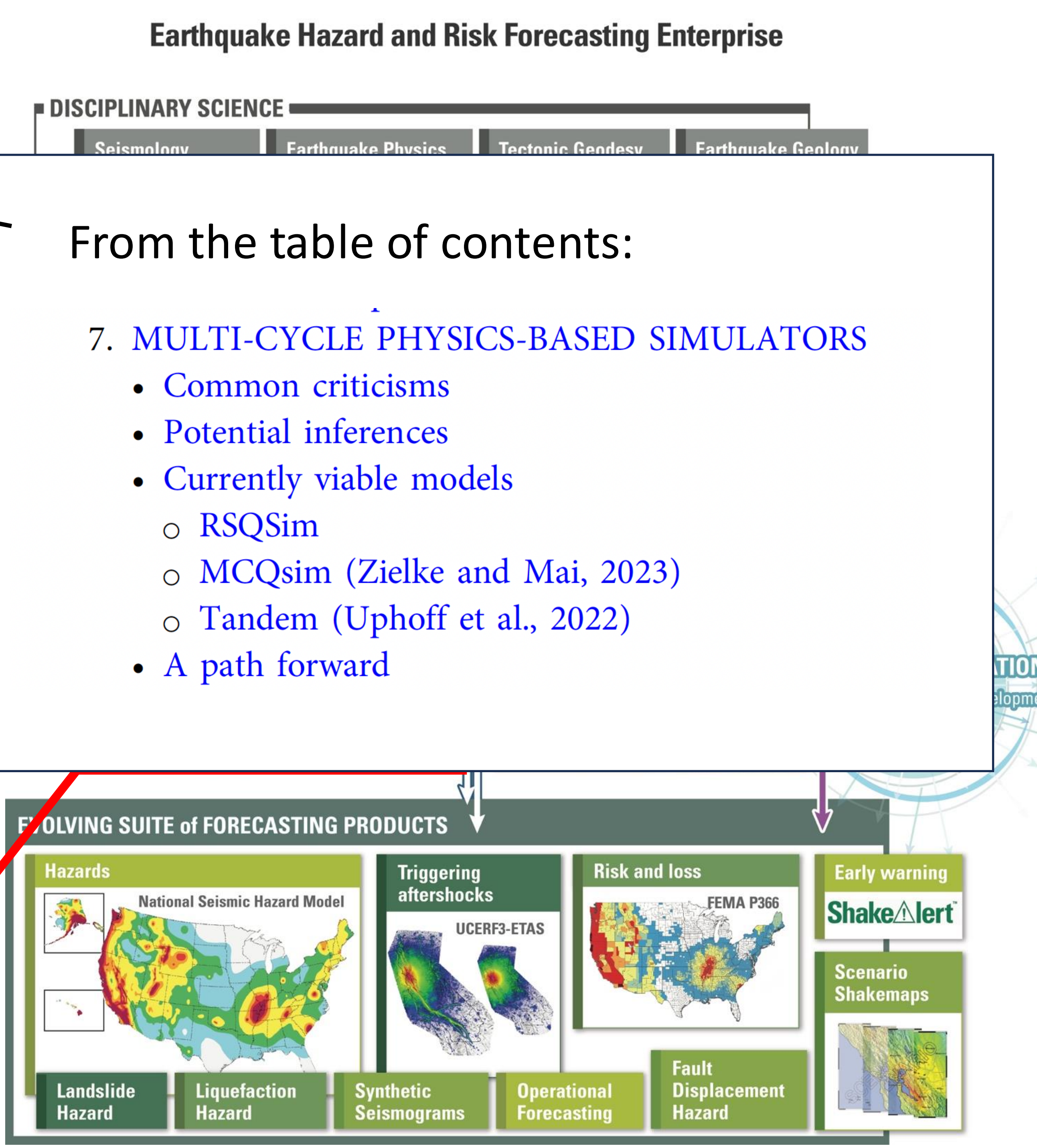


The USGS can handle this one

But not this one (IMO)

From the table of contents:

7. MULTI-CYCLE PHYSICS-BASED SIMULATORS
   - Common criticisms
   - Potential inferences
   - Currently viable models
     - RSQSim
     - MCQsim (Zielke and Mai, 2023)
     - Tandem (Uphoff et al., 2022)
   - A path forward



Multicycle, Physics-Based Earthquake Simulators:

generate synthetic rupture catalogs for large fault systems and over thousands of earthquake cycles by modeling stress accumulation, rupture nucleation, friction evolution, and multi-fault interactions (and generally approximating dynamic effects)

Core Activities:

- **Develop** multiple MP-BES models (RSQSim, Tandem, MCQSim, and hopefully others)
- **Standardize** model inputs (fault geometry, slip rates, constitutive laws, paleoseismic constraints)
- **Sustain** HPC resources (e.g., Quakeworx)
- **Unify** output formats for interoperability
- **Define** standard *Verification*, *Validation*, and *Valuation* metrics (*VVV*s), including geologic constraints, CSEP and "Turing tests", and usefulness-oriented inference metrics (page 18 here)
- **Automate** *VVV* generation via post-processing pipelines
- **Specify** test calculations and compare model results statistically, including full dynamic models
- **Leverage** machine learning to detect robust, emergent predictability patterns
- **Quantify** epistemic uncertainties, including limited knowledge of subsurface structure
- **Explore** usage assuming a given model is correct (not straightforward given spin-up requirement)
- **Ensure** documentation, accessibility, and reproducibility standards (i.e., FAIR principles)

Main messages here:

- **Multicycle Physics-Based Earthquake Simulators are critical to improving seismic hazard and risk estimates**
- **We must not let perfection be the enemy of more useful model (e.g., accusations of "not enough physics in your physics-based model" have plagued previous developments)**
- **A more wrong model can actually be more useful**
- **Ask not whether a model is right, but whether useful inferences can be made from it**

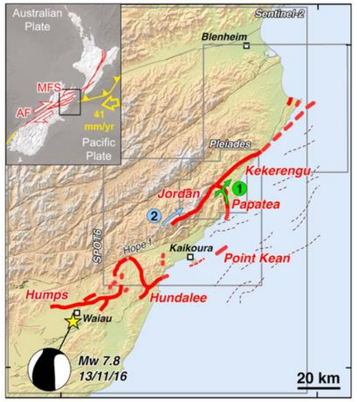
Uniform California Earthquake Rupture Forecast, version 3 (UCERF3)

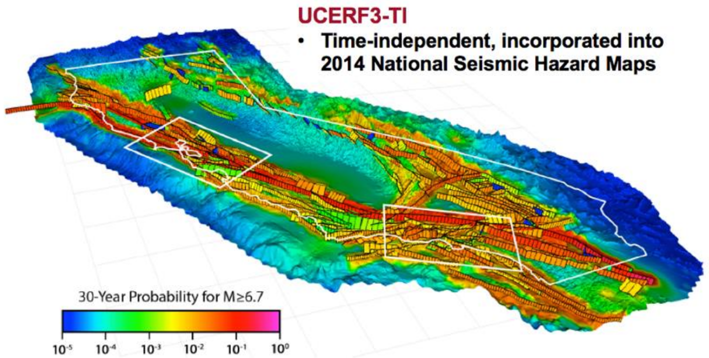
By the Working Group on California Earthquake Probabilities:

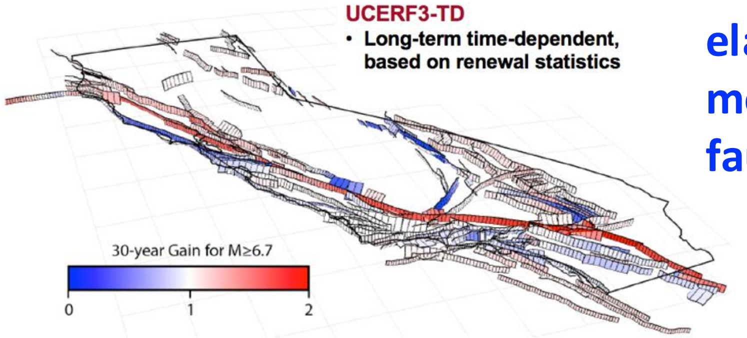
We're now in the process of doing this nationwide

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

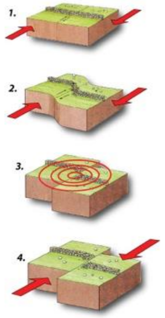
(e.g., Kaikoura)

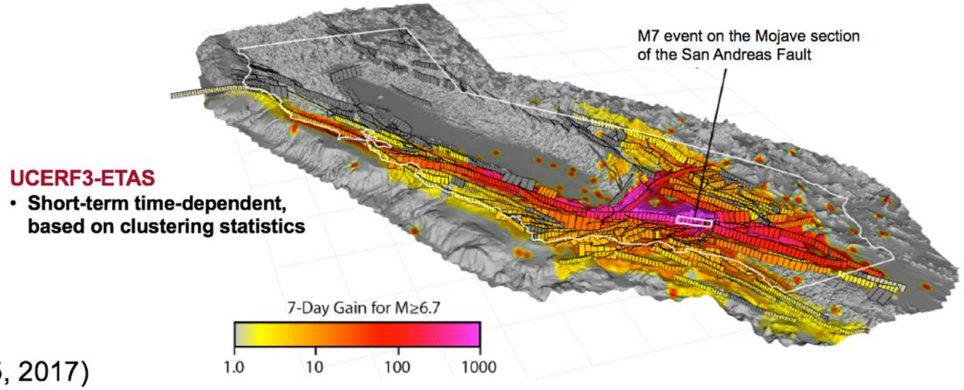






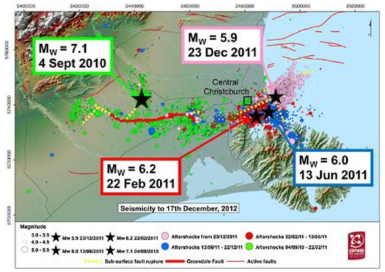
Improved elastic-rebound model (& on all faults)





Field et al. (2014, 2015, 2017)

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



To ChatGPT:

“Please make an image reflecting how the UCERF3-ETAS development represents is a house of cards, a sausage making process (ingredients we are not proud of), and ultimately a fool’s errand”

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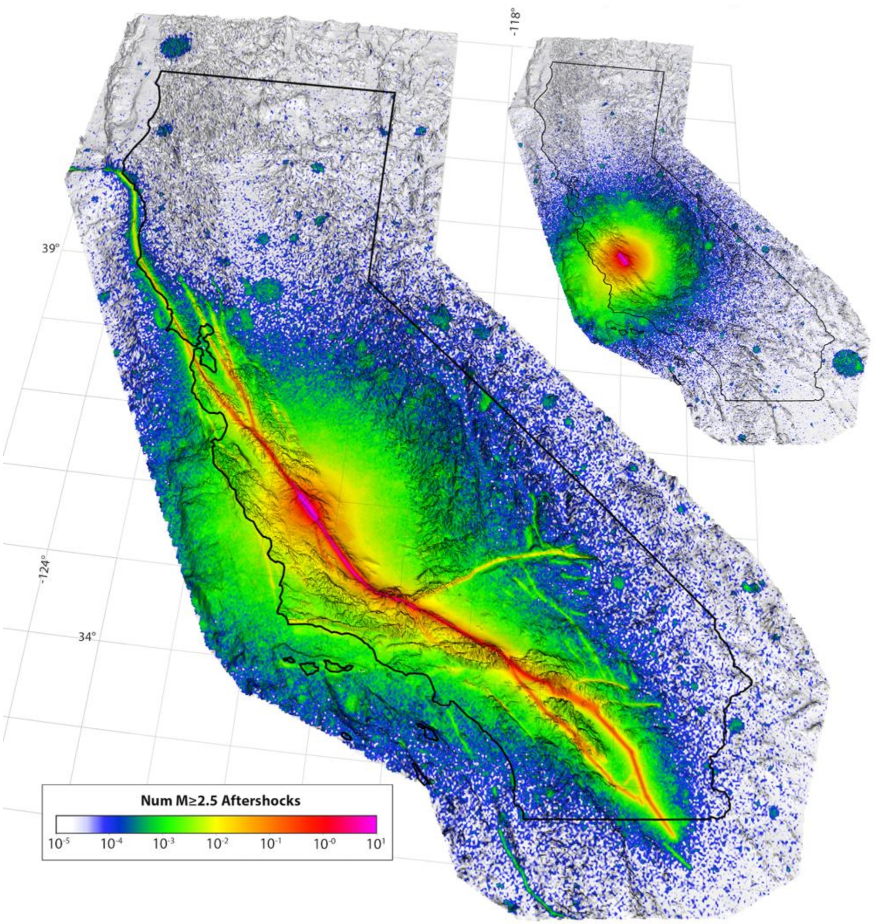
UCERF3-ETAS vs No-faults ETAS (3D)



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