TIME-DEPENDENT SEISMIC HAZARD

INTRODUCTION AND GLOBAL PERSPECTIVES

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working together
to assess risk

GEM
GLOBAL EARTHQUAKE MODEL

OQ
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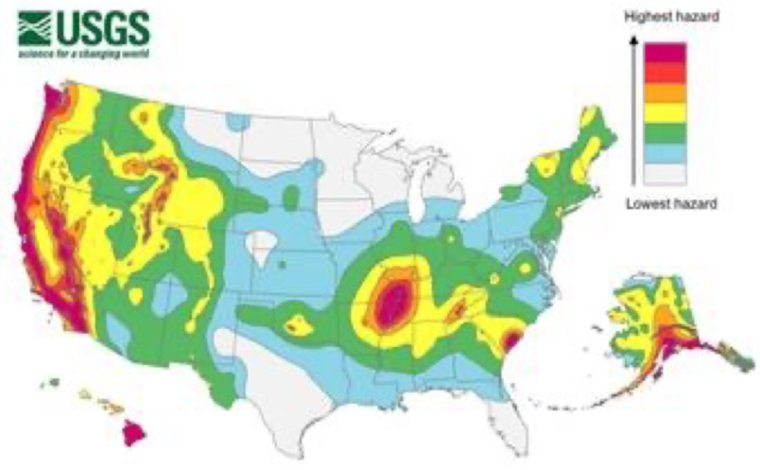
Seismic Hazard Analysis: Goals

Seismic Hazard Analysis (SHA):

Computes the values of ground-shaking expected at a site during a given time interval.

Probabilistic Seismic Hazard Analysis (PSHA):

- Calculates probability of exceeding some intensity of ground shaking
- Integrates over all potential sources
- Incorporates parameter uncertainties, randomness



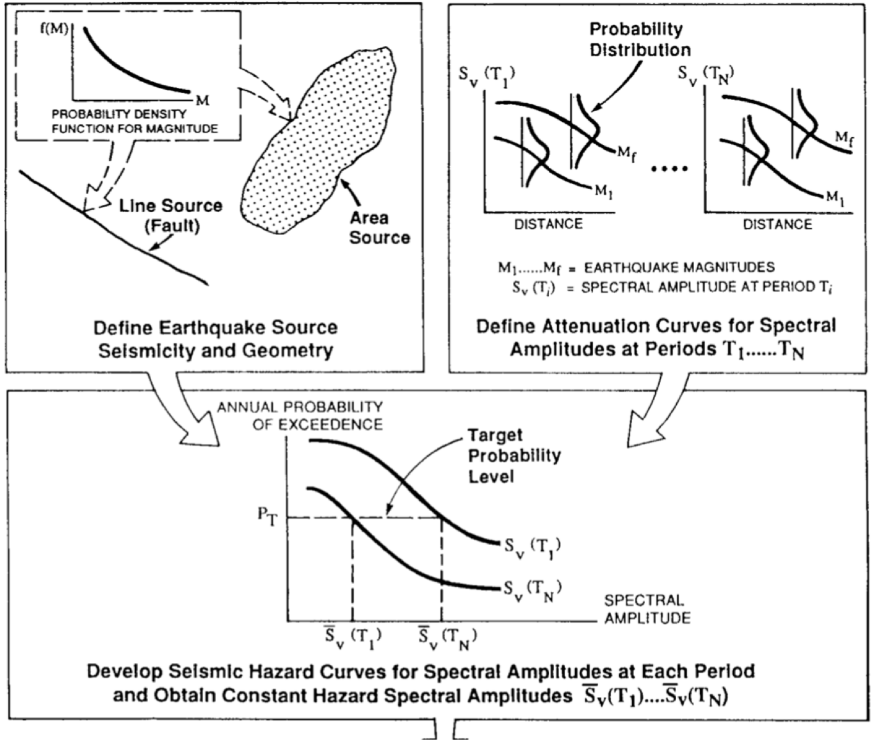
From https://www.usgs.gov/programs/earthquake-hazards

PSHA: Model components

Components of a PSHA model:

1. Seismic Source Characterization
   Defines position of sources and their earthquake occurrence characteristics

2. Ground Motion Characterization
   Defines the models used to compute the expected ground-motion at the sites of interest – given an earthquake (rupture)



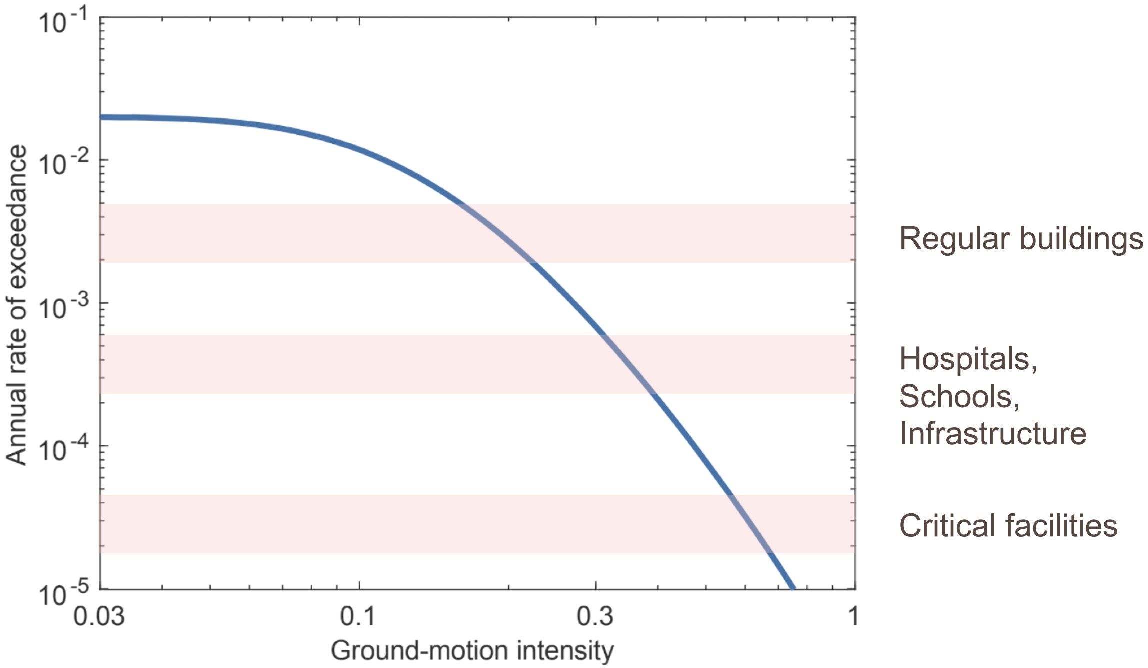
McGuire (2004)

PSHA results: the hazard curve

Rate (probability) of exceeding specified ground motion intensity level

Stronger shaking (larger M, closer) less frequent

Different users interested in different rates/ return periods



Time dependence in earthquake occurrence

Three classes of phenomena:

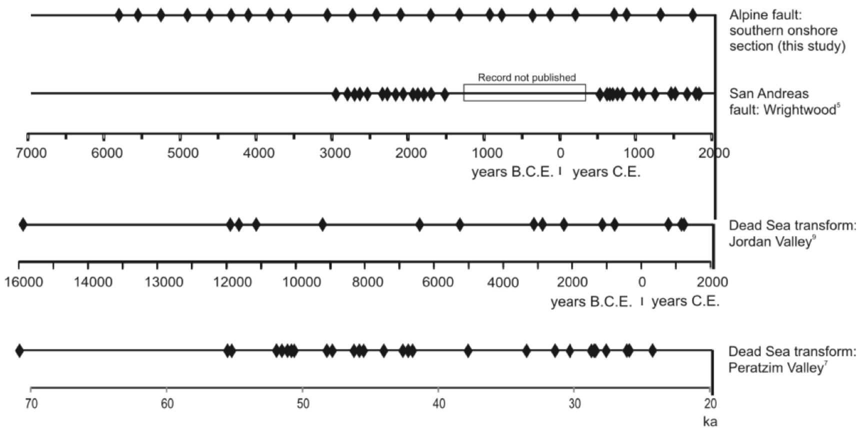
1. Quasi-periodic recurrence of large earthquakes on single source

2. Aftershocks and foreshocks

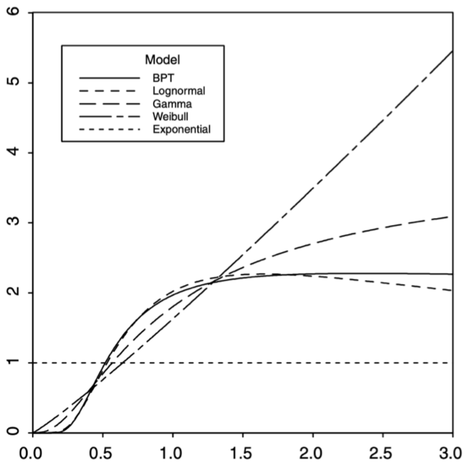
3. Clustered/triggered mainshocks on nearby sources

Quasi-periodic earthquakes and characteristic faults

- Major earthquakes on some faults are somewhat regularly spaced in time
- Probability of next earthquake drops following last earthquake, increases with time (variable after mean)
- Tied to ‘characteristic’ earthquake, where all of fault (or fault segment) ruptures in large event, releasing accumulated stress/strain
- Faults must have persistent segmentation



Berryman et al. (2012)



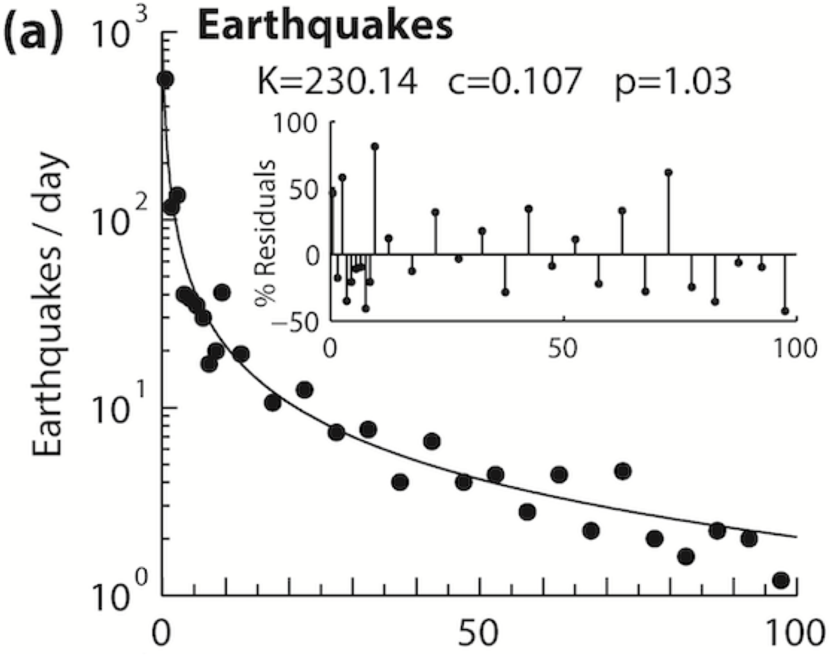
Matthews et al. (2002)

Aftershocks

Most well-observed time-dependent behavior

Aftershock rates decrease in minutes to decades following mainshock (Omori's law)

Aftershocks tend to be smaller than mainshocks (Bath's law)



Quigley and Forte (2017)

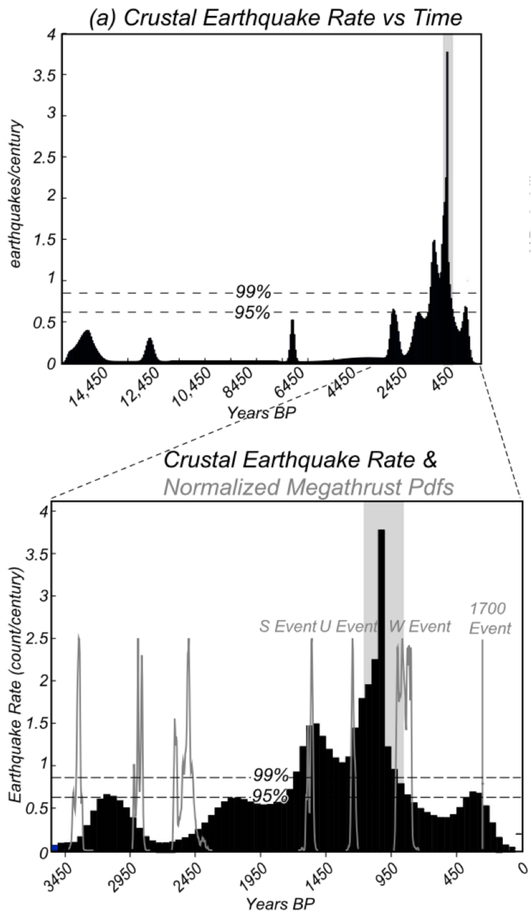
Clustered mainshocks

Nearby faults rupture relatively closely in time

- Separated by seconds to centuries (but less than mean interevent times)
- Well described in instrumental and paleoseismic catalogs

Statistically unlikely to be random; probably evidence of earthquake triggering, stress interaction

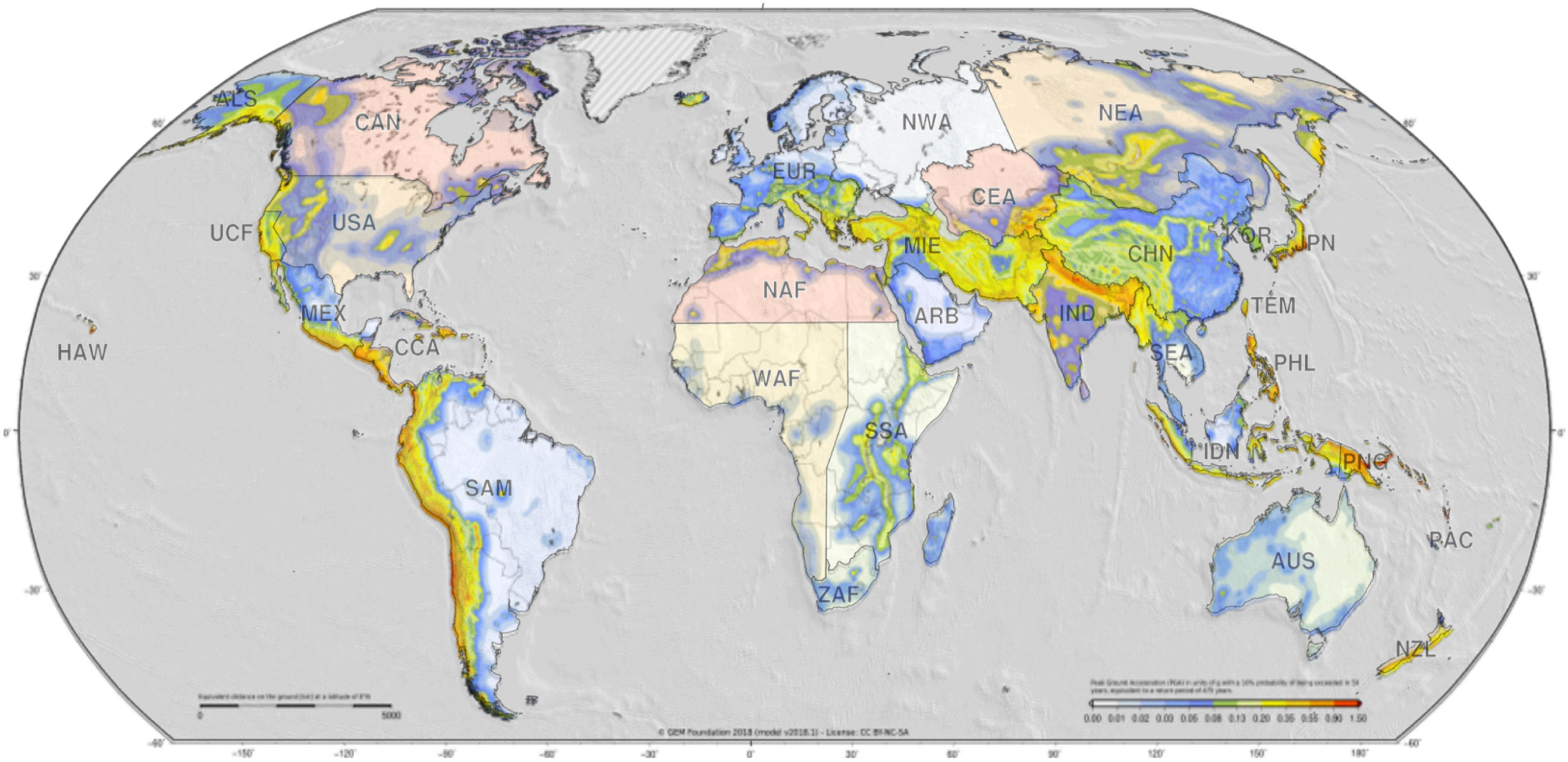
Multiple non-exclusive physical mechanisms suspected



Sherrod and Gomberg (2014)

GEM Hazard Mosaic

Out of 31 models only 2 are time-dependent models (JPN + Cluster model in USGS Conterminous US model) + UCERF3 (in the mosaic we included the time-independent version)



From Pagani et al. (2020)

Types of time-dependent PSHA

Multiple modeling strategies for different phenomena

1. Aftershock PSHA

2. Clustered mainshocks

3. Periodic, characteristic sources

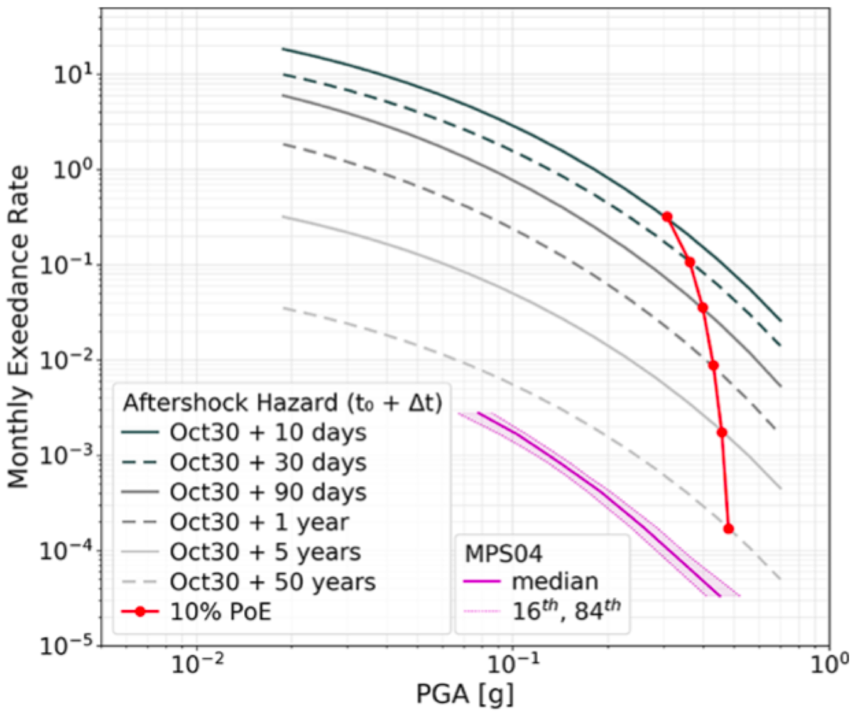
4. Evolutionary/ interactive models

Aftershock PSHA

PSHA including aftershocks (conditional on mainshock occurrence) can be calculated following major events

Elevated hazard levels for days to decades after event; eventually will decay to mean rate

Some statistical methods to incorporate into national-scale PSHA (e.g. Epidemic Type Aftershock Sequences)



Gee et al. (2021)

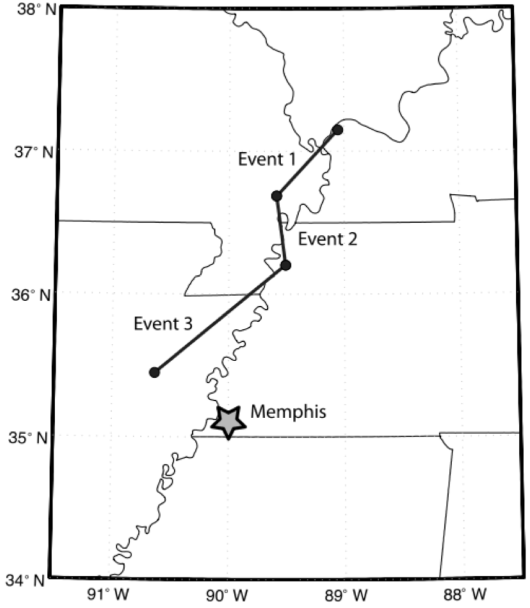
Cluster models

Seismic cluster

- Group of several ruptures
- Cluster floats in time (time-independent rate), ruptures occur at same time

Can allow for complex behavior

- Mutually exclusive rupture combinations (e.g., single M 9 or multiple M 8 subduction zone events)



From Boyd (2012)

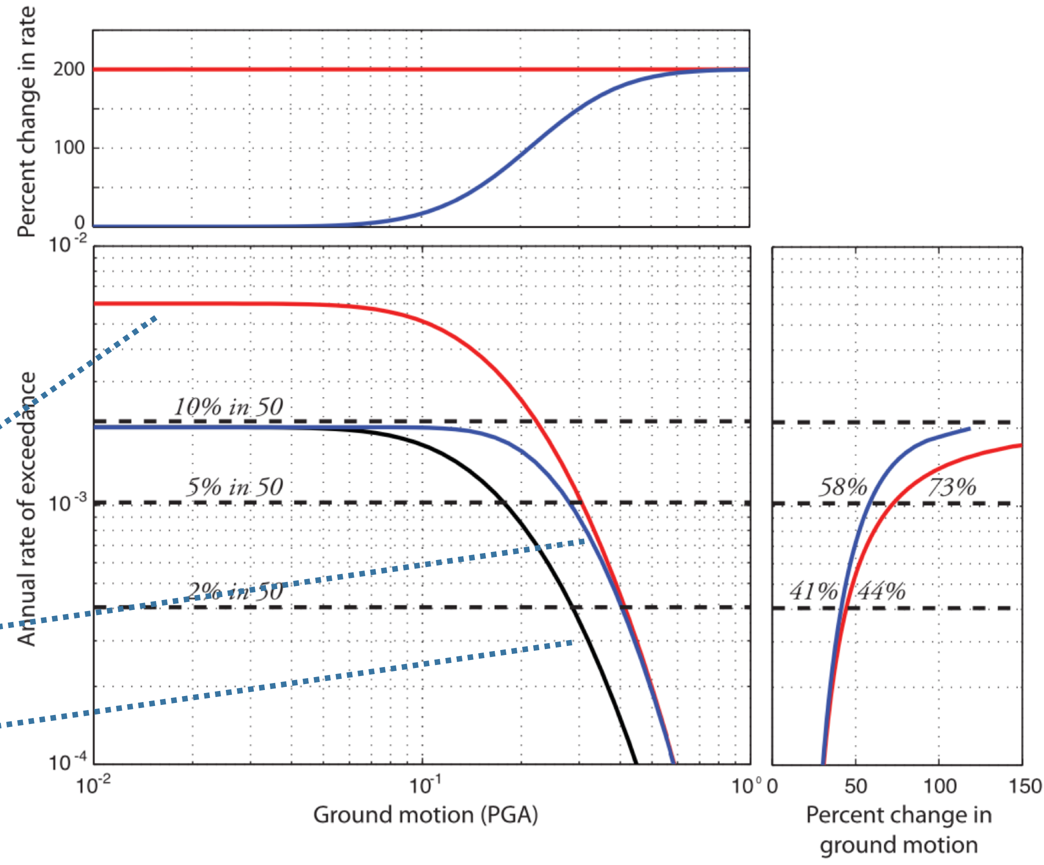
Cluster models

Ground motions vary between single-mainshock rate at short return periods and independent source rates at long return periods

Three independent events

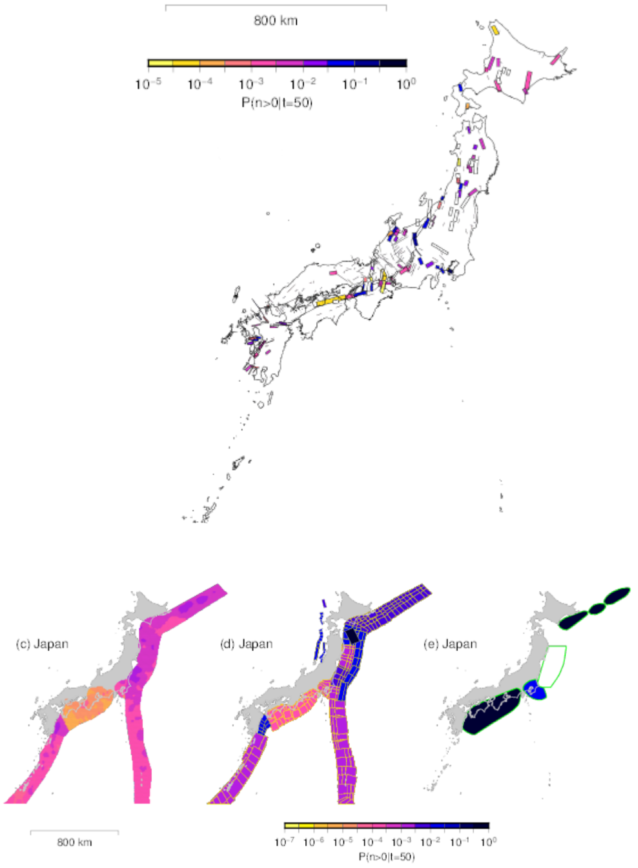
Cluster

Single event



Boyd (2012)

Time-dependent characteristic ruptures in Japan



Modified from Pagani et al. (2016)

Characteristic earthquakes for shallow crust faults. The JPN14 model contains 233 shallow faults with a time-independent model and 123 faults with a time-dependent behavior (see Fujiwara et al., 2009).

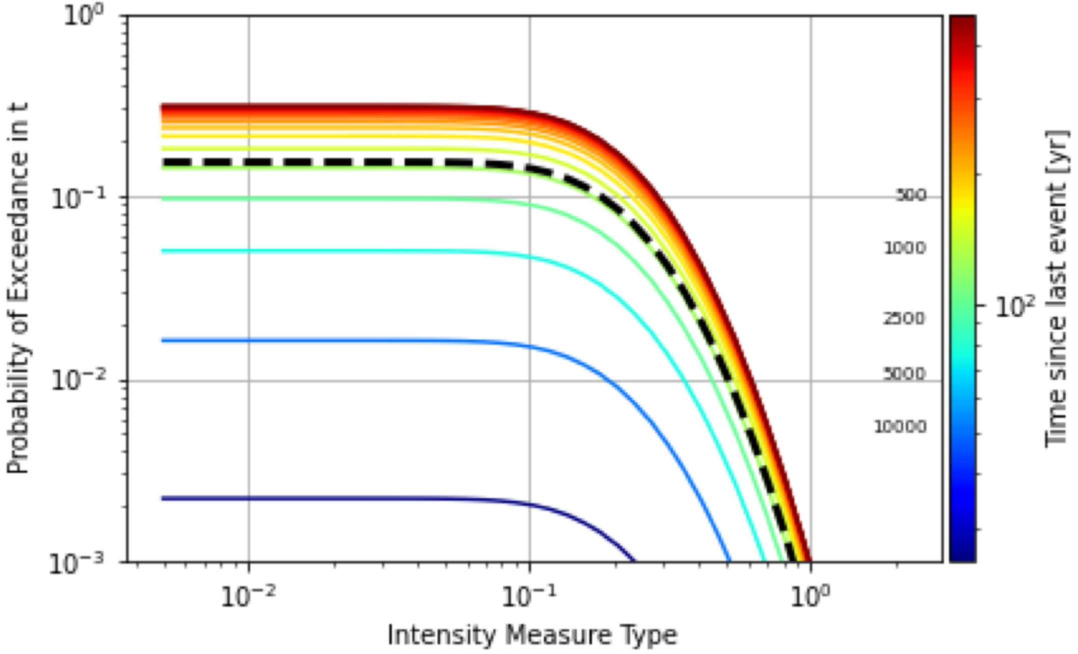
Segmented subduction zone some (e.g., Nankai) with time-dependent mutually exclusive ruptures (only for the largest events)

Hazard curve for quasi-periodic source (BPT)

Poisson (time independent)
   overestimates hazard soon after earthquake occurs

Poisson underestimates the
   hazard for some time after the mean recurrence

At lower exceedance
   probabilities (stronger shaking), time dependence vs. independence less impactful



Problems with characteristic ruptures

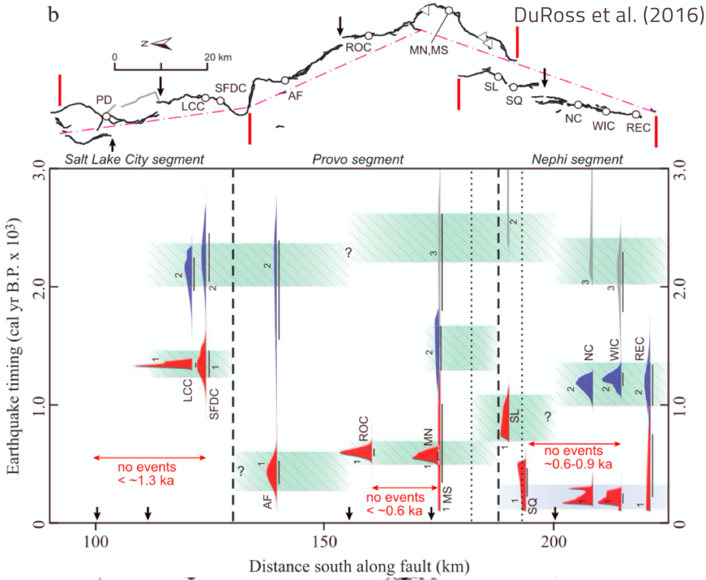
Modern and paleoseismic observations support varying segment behavior

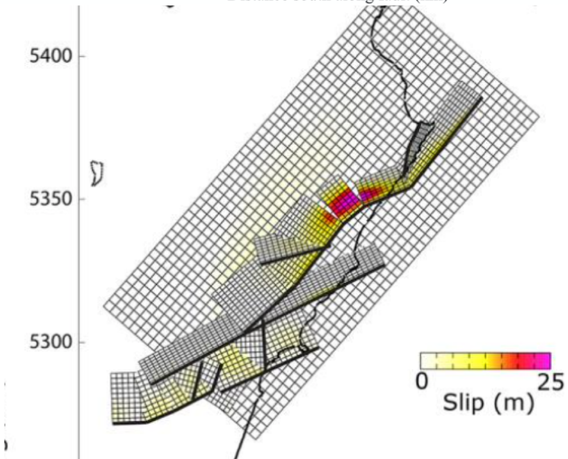
- sub-segment ruptures
- multi-segment ruptures
- multi-fault ruptures

Does a small or moderate earthquake 'reset the clock'?

Should we use a different variable than *time*? Shear stress? Elastic strain/ potential slip?

DuRoss et al. (2016)





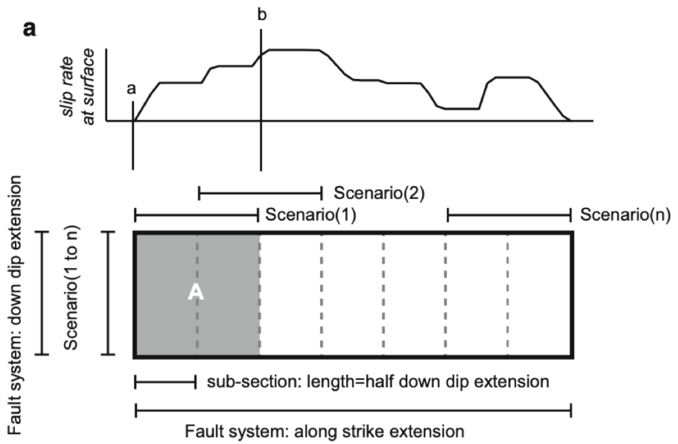
Hamling et al. (2017)

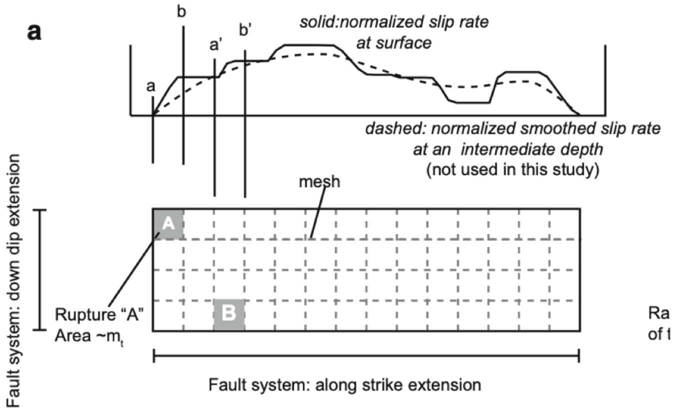
Sub-segment and floating ruptures

Moderate (4 < M <6.5) magnitude earthquakes may not rupture entire fault segment

Need smaller discretization of fault surface.

Need to track more variables (*time* or something else?)





Visini et al. (2020)

Rupture interaction

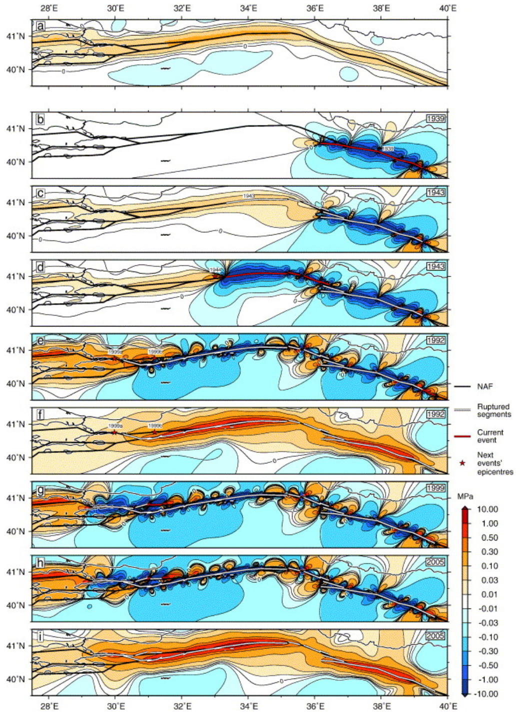
Rupture interaction means rupture dependence

Model complexity increases dramatically (approx N -> N²) to account for interaction

Physics, statistics still unknown

Difficult (or impossible) to integrate over all sources, states

Requires simulation



Lorenzo-Martin et al. 2006

$$
\begin{array}{cccccccc}
p(A_1) & & p(A_1|A_1) & p(A_1|A_2) & p(A_1|A_3) & p(A_1|B_1) & p(A_1|B_2) \\
p(A_2) & & p(A_2|A_1) & p(A_2|A_2) & p(A_2|A_3) & p(A_2|B_1) & p(A_2|B_2) \\
p(A_3) & \Rightarrow & p(A_3|A_1) & p(A_3|A_2) & p(A_3|A_3) & p(A_3|B_1) & p(A_3|B_2) \\
p(B_1) & & p(B_1|A_1) & p(B_1|A_2) & p(B_1|A_3) & p(B_1|B_1) & p(B_1|B_2) \\
p(B_2) & & p(B_2|A_1) & p(B_2|A_2) & p(B_2|A_3) & p(B_2|B_1) & p(B_2|B_2)
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Simulations and model evolution

Simulations are only (known) tractable way of accounting for rupture interaction, model evolution through time

Epidemic-Type Aftershock Sequence (ETAS) most commonly used

- Recursive: Each quake produces aftershocks -> aftershocks produce their own aftershocks
- Rupture interaction/triggering defined statistically, not physically
- UCERF3-ETAS coupled ETAS with elastic rebound model

Physics-based models are 'research topic', not widely used in PSHA

- May use rate-state friction, elastic (+viscoelastic) stress evolution, etc.
- Computationally demanding (especially viscoelasticity, afterslip)

Lots of room for different combinations of physics and statistics

Summary

Broad range of time-dependent earthquake behaviors

Multiple modeling strategies to deal with different phenomena

Physics not well incorporated (also not fully understood)

Until time-dependent PSHA is widely implemented and vetted, we may not understand its impact.