Large Earthquake Temporal Clustering and Seismic Hazard Assessment

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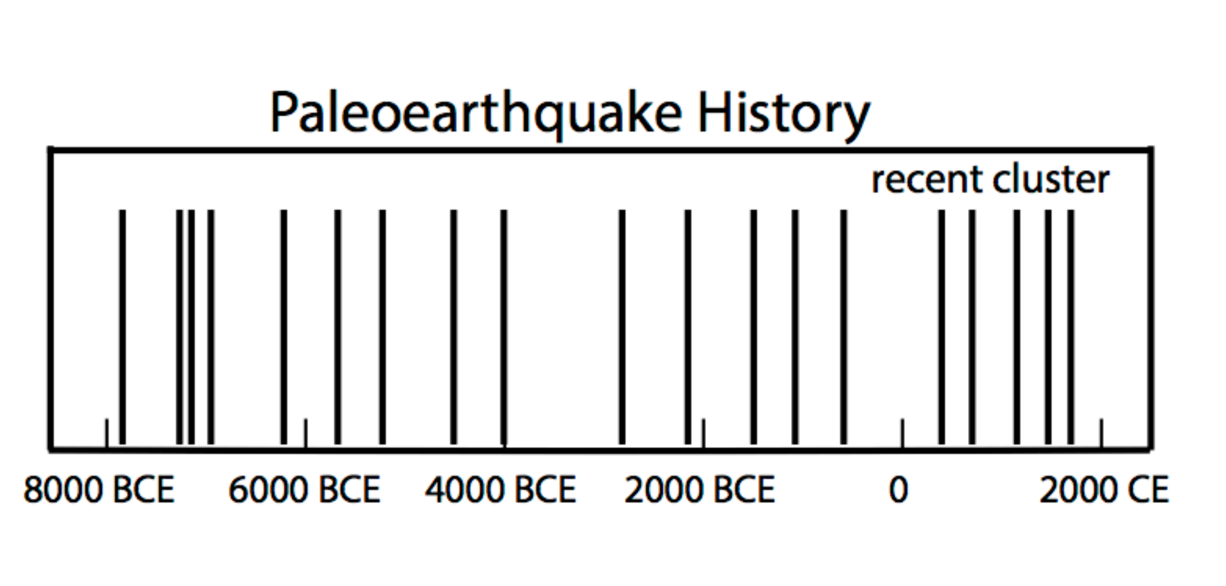
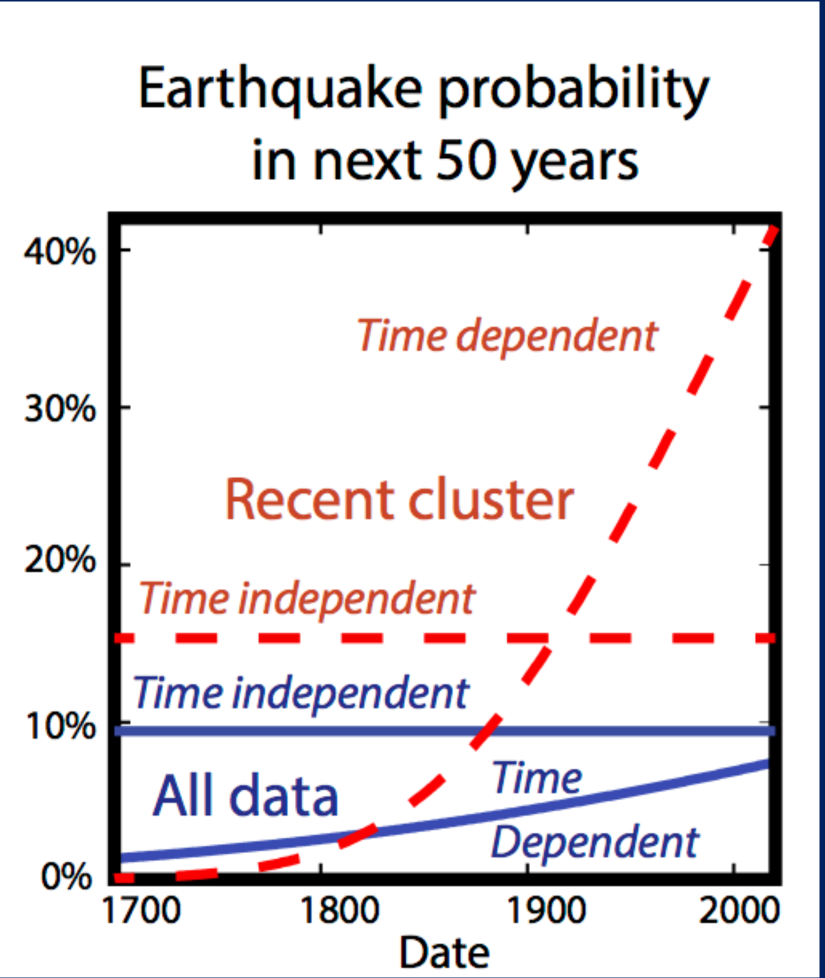
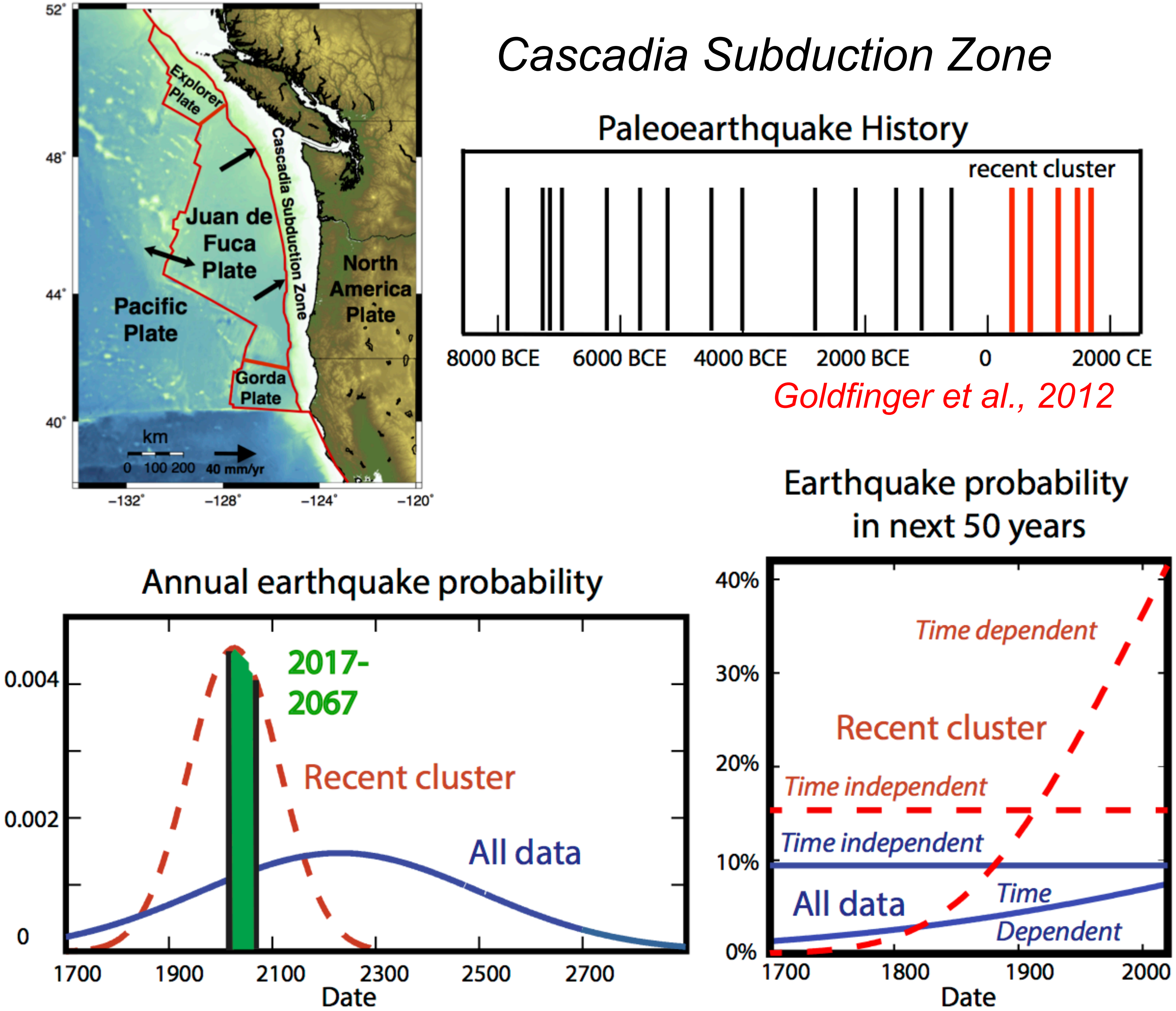




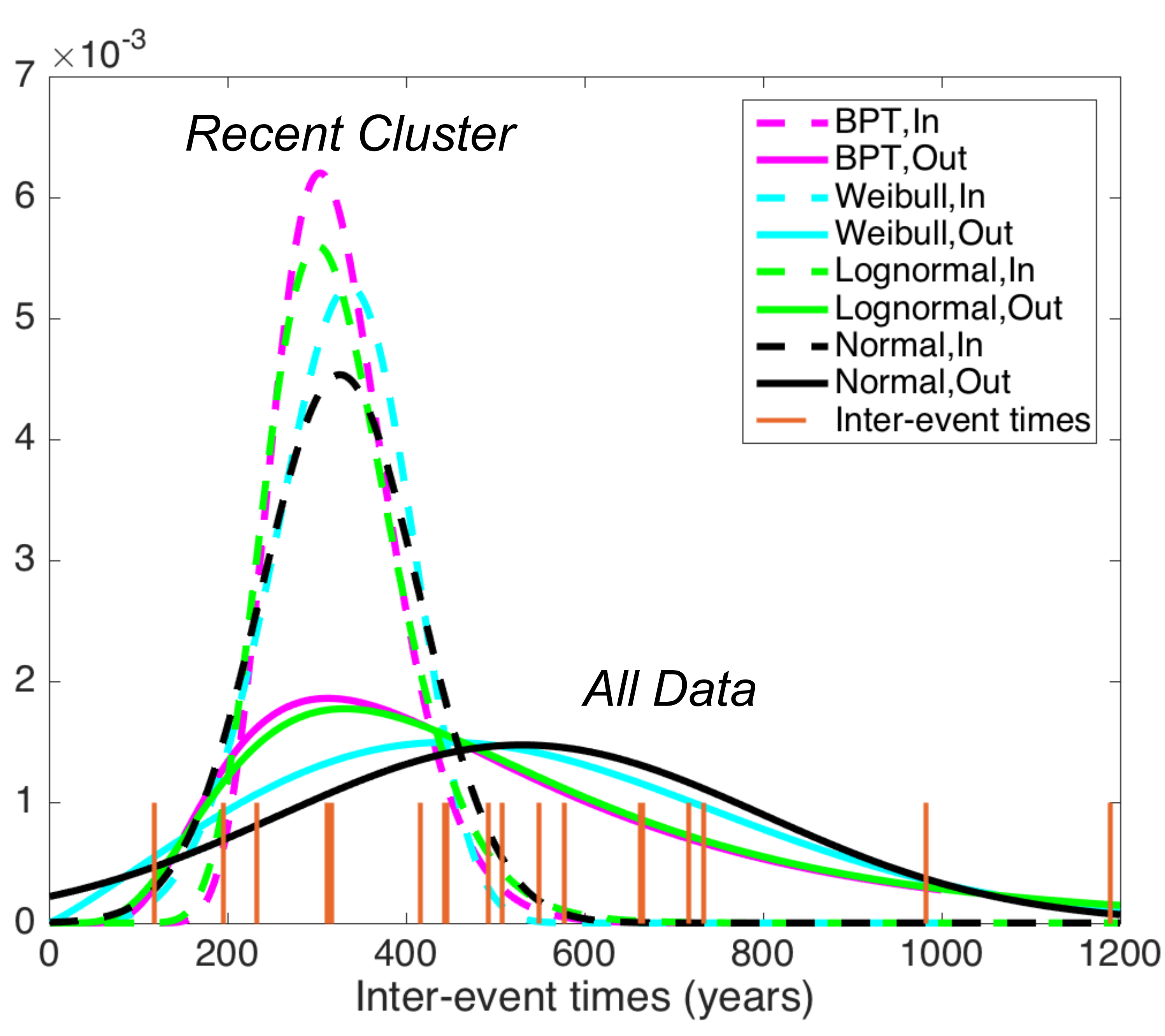
Temporal clusters have major effect on assumed earthquake probabilities

- Are we still in the most recent cluster?
  - The chosen answer changes inferred probabilities dramatically
  - Assuming we are still in the recent cluster makes the next earthquake much (~6x) more likely sooner



Cascadia inter-event time distribution

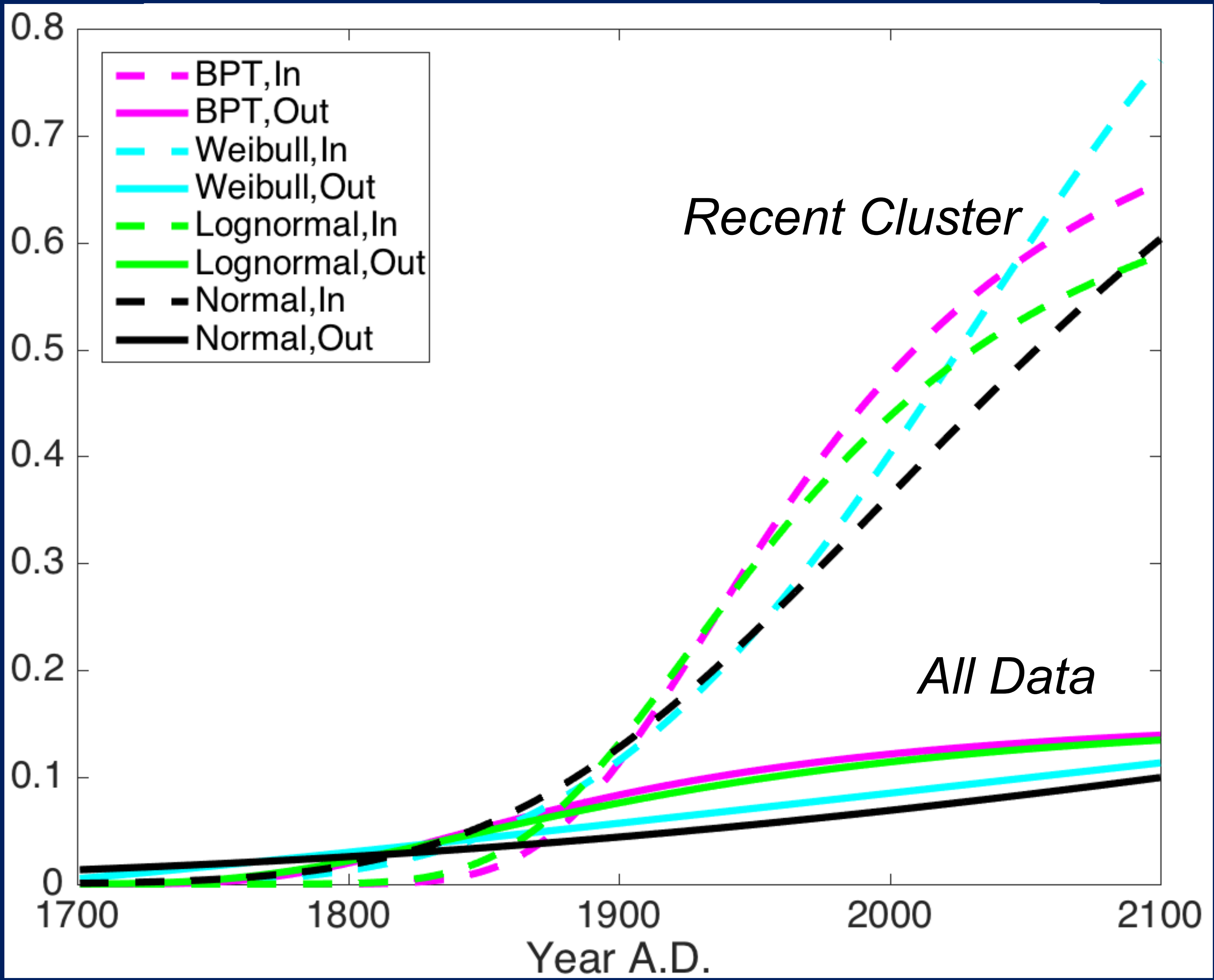
- Whether we are in the most recent cluster matters much more than the PDF assumed
- Within cluster, inter-event times have smaller mean and standard deviation, making the next earthquake more likely sooner
- Chi-square goodness-of-fit test fails to reject any of the commonly used PDFs at 10% level
    - Even 10,000 year record with 19 events is insufficient to confidently distinguish among PDFs
    - For practical purposes, it is debatable which PDF is best



Cascadia conditional probabilities for earthquake in next 50 years, given that last one happened in 1700

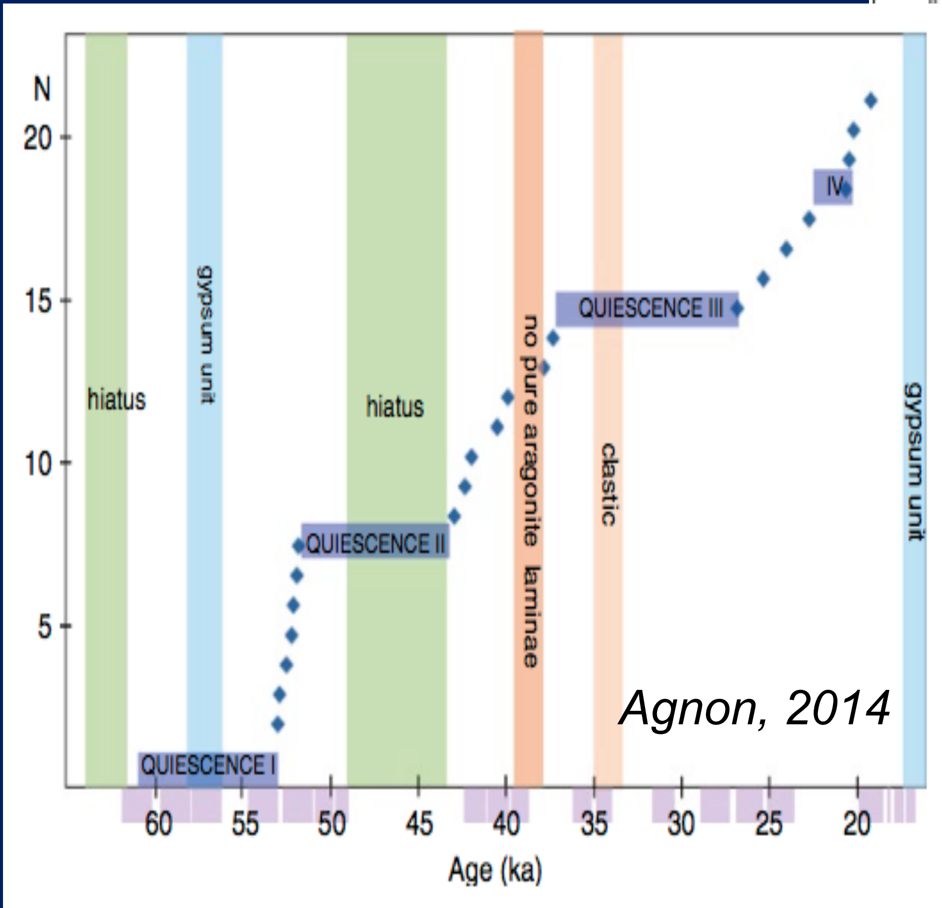
- Whether we are in the most recent cluster matters much more than the PDF assumed

- Within cluster, inter-event times have smaller mean and standard deviation, making the next earthquake appear more likely sooner

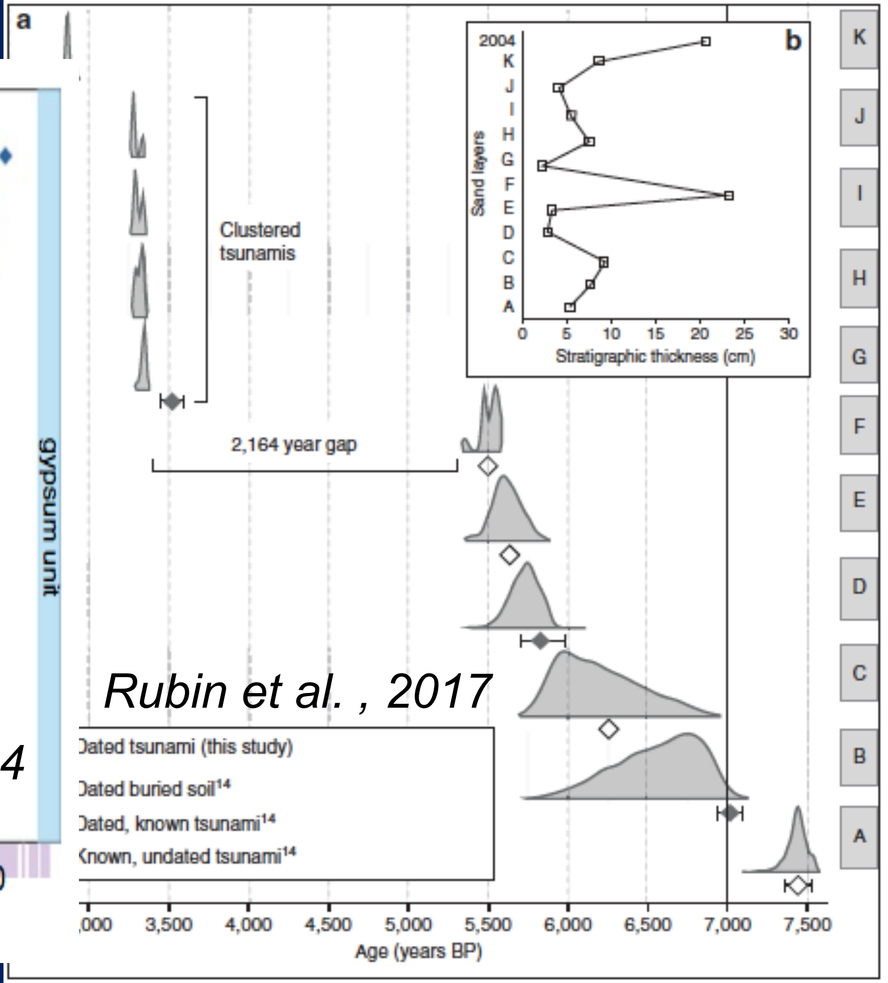


Clusters/supercycles often appear in paleoseismic records, but are not included in hazard assessment because the underlying processes are not yet understood

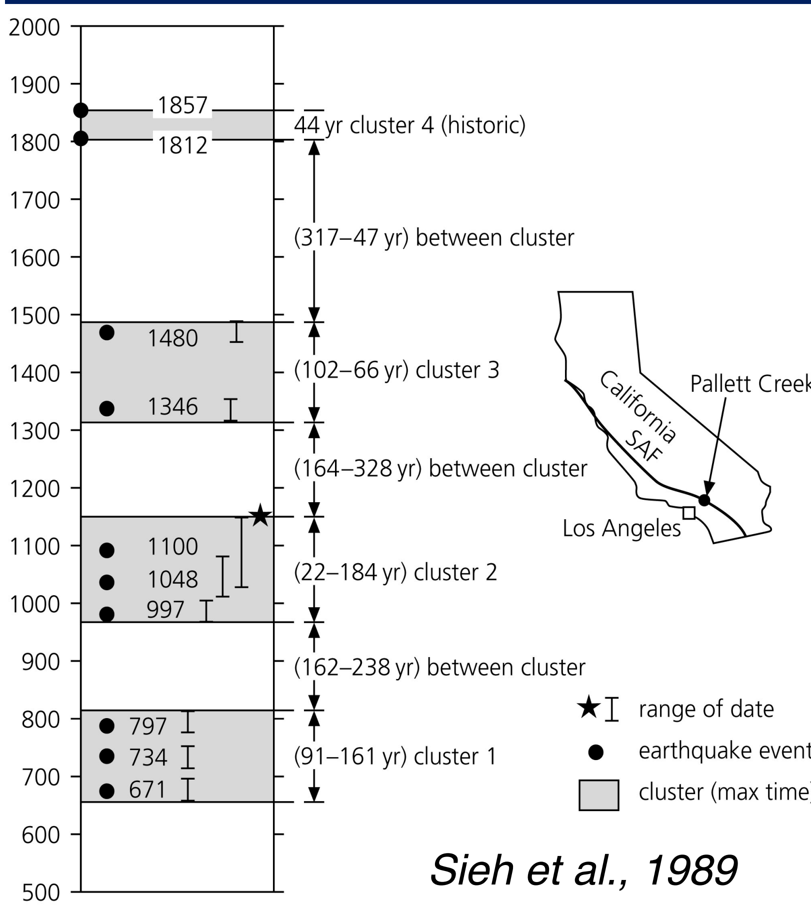
Dead Sea Transform, Israel



Paleo-Tsunami Record, Sumatra



Pallett Creek, San Andreas

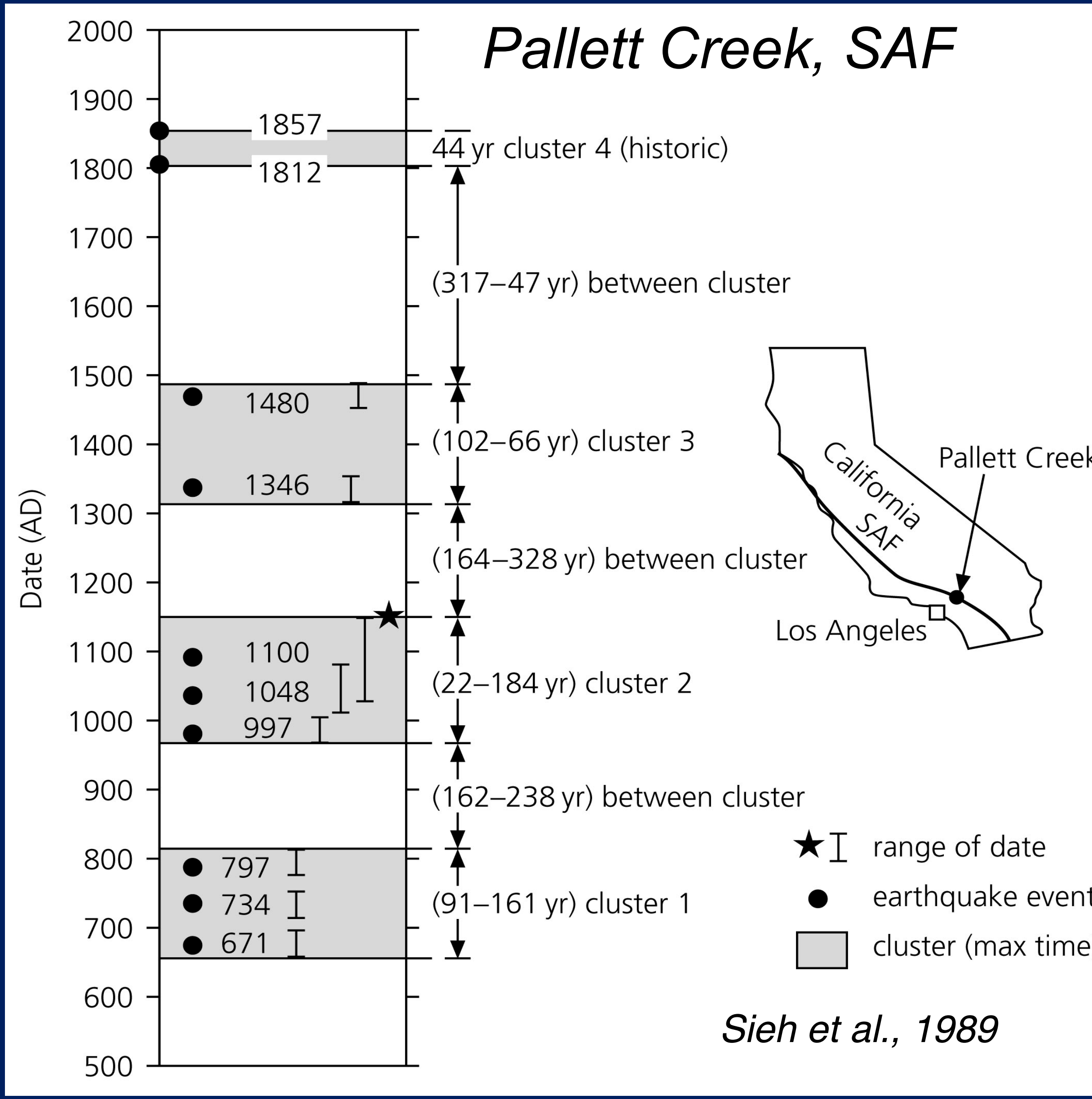


How could steady plate motion give earthquake clusters?

Long earthquake records at plate boundaries often show large earthquakes in temporal clusters (supercycles) separated by less active intervals (temporal gaps).

These are intriguing because the boundary is presumably being loaded by steady plate motion.

μ = 131 yr ; σ =104 yr



Possibilities

1) Apparent clusters are *artifacts* of the limits of the paleoseismic record (missing events, dating…)

2) Clusters result by *chance* from faulting process

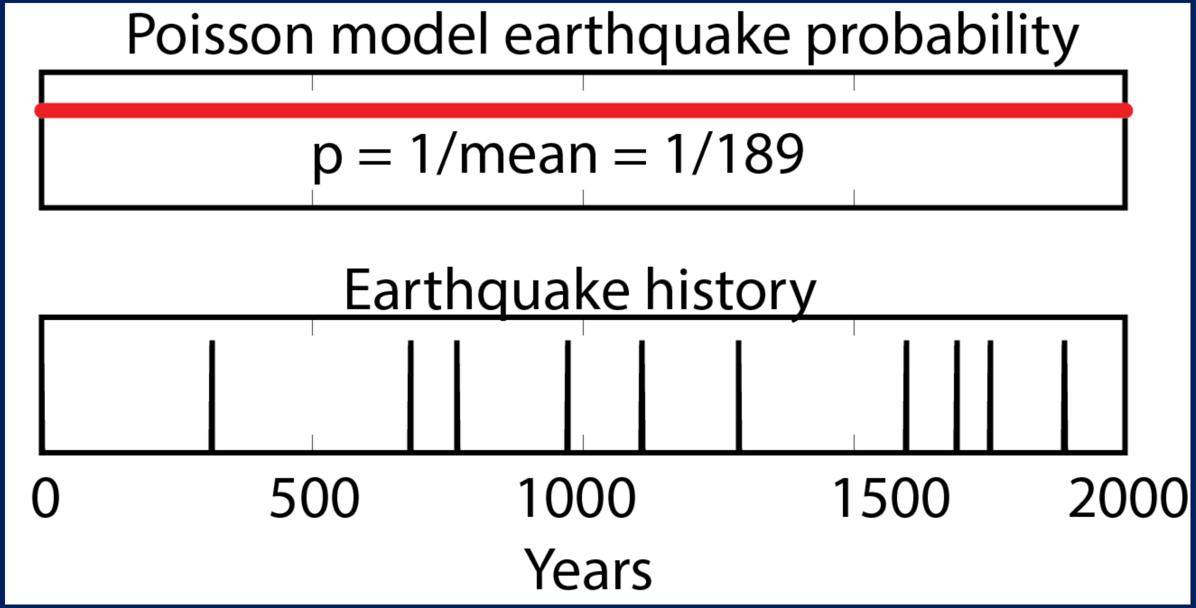
3) Clusters result from *interactions* between nearby fault segments

4) Clusters result from *intrinsic properties* of the faulting process, notably long-term fault memory

Fault with no memory
Earthquake probability constant (Poisson process): clusters result by *chance*

Fault has no "memory" so earthquakes are equally likely at any time (no elastic rebound / earthquake cycle)

Short intervals –clusters - and long intervals – gaps – result



μ = 189 yr ; σ =107 yr

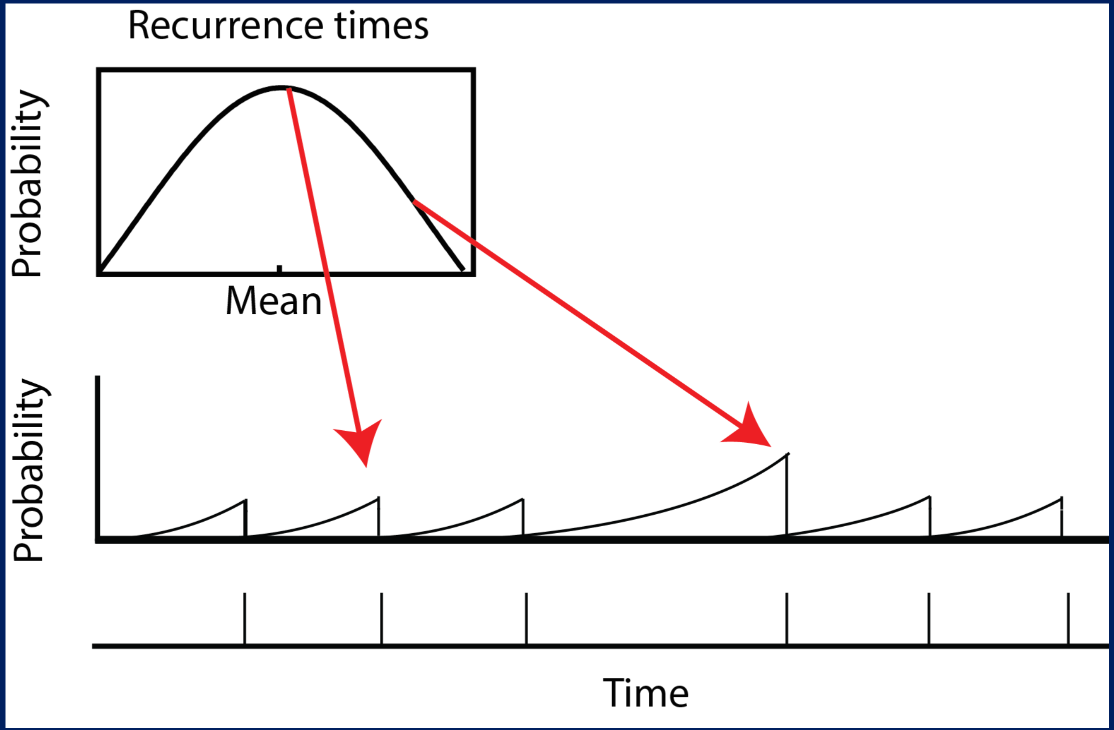
As record length increases, standard deviation σ of recurrence intervals approaches mean μ

Model often used in hazard analysis

Fault with short-term memory: Seismic cycle

In standard cycle model, probability increases with time. Fault “remembers” only last event. Cycle restarts after each event, with length described by an assumed probability distribution of recurrence times

Recurrence is quasi-periodic about mean, but short intervals – clusters - and long intervals – gaps – can result

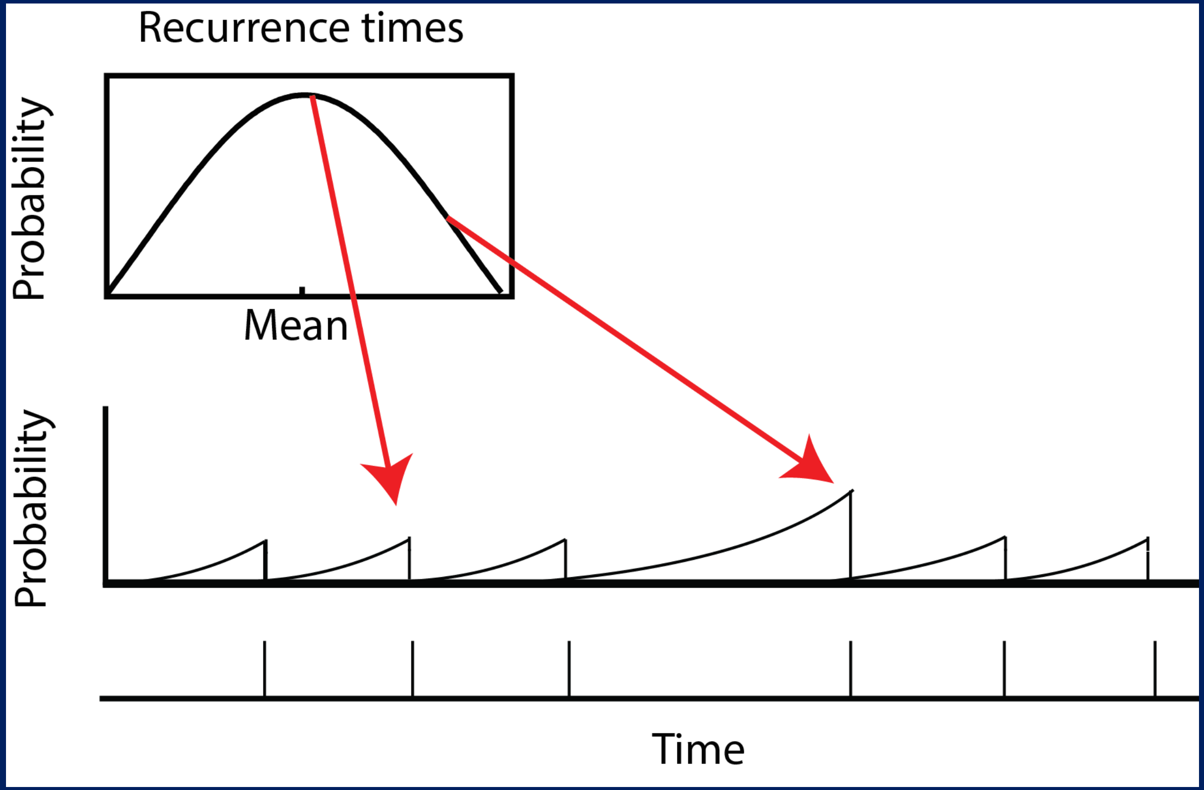


As record length increases, standard deviation of recurrence intervals σ small relative to mean μ

Model increasingly used in hazard analysis

Standard seismic cycle model resets probability to zero after each large earthquake

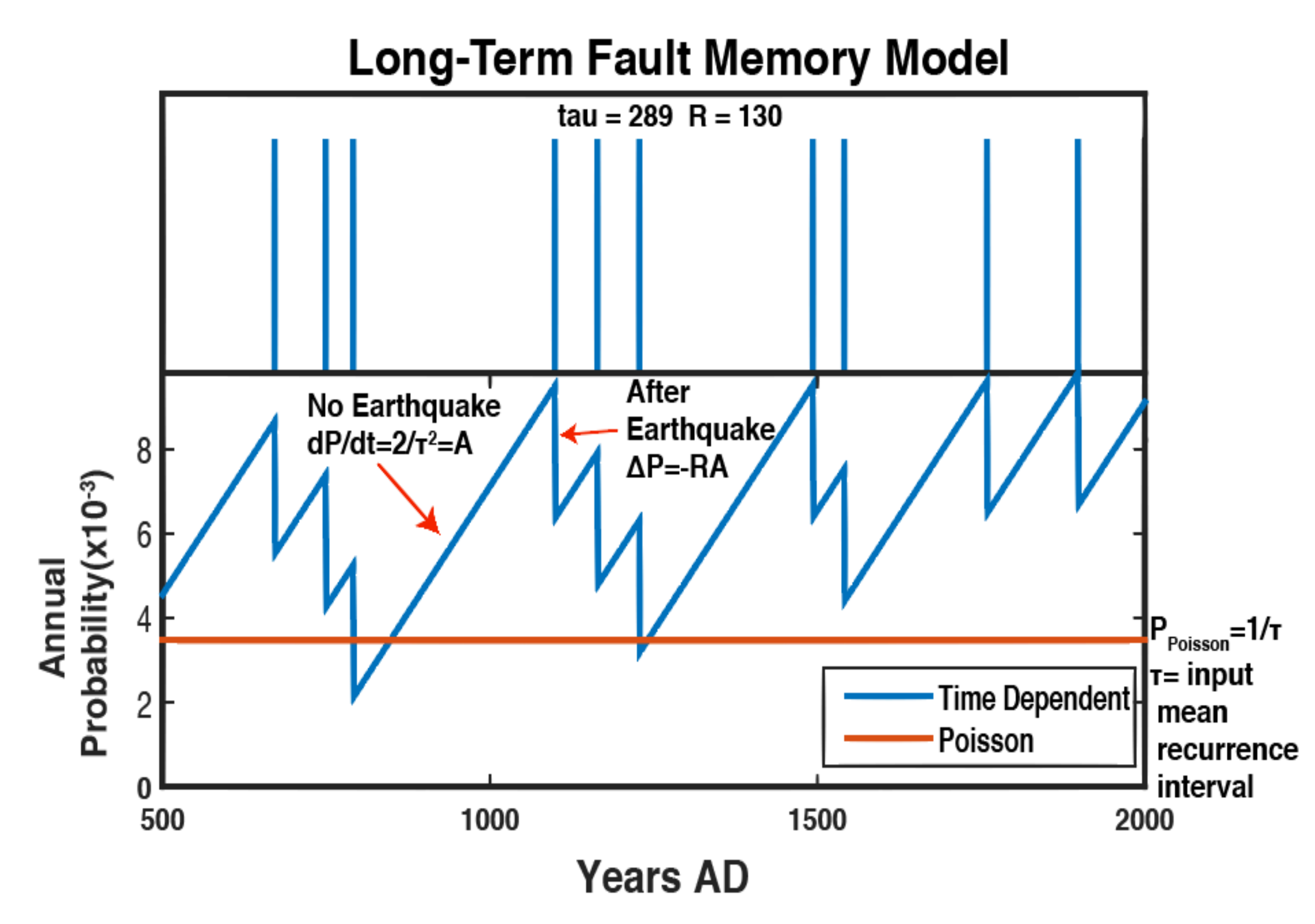
"Resetting of the clock during each earthquake not only is conceptually important but also forms the practical basis for all earthquake forecasting because earthquake recurrence is statistically modeled as a renewal process...In a renewal process, intervals between earthquakes must be unrelated so their variability can be expressed by (and conditional probabilities calculated from) independent random variables. Thus, if the next earthquake depends upon the strain history prior to that earthquake cycle, both our understanding of Earth and our forecasts of earthquake hazard must be modified."



– Weldon et al., 2004

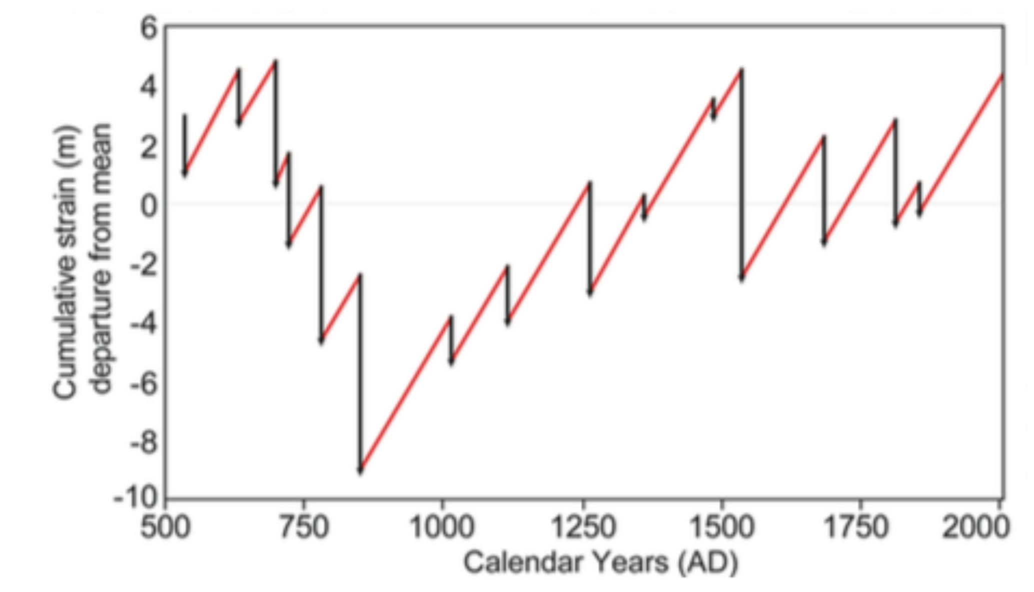
Alternative: Fault With Long-Term Memory

Modified earthquake cycle model: probability of an event increases with time until one happens, after which it decreases, but not necessarily to zero. Probability of the next earthquake depends on prior history over multiple cycles.



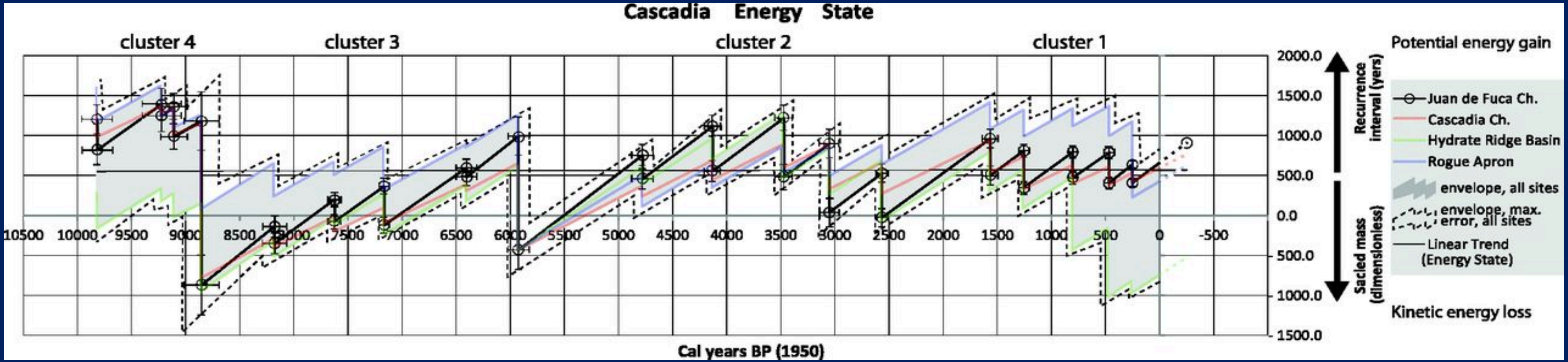
Clusters happen because after a period of quiescence, the probability can remain higher than the long-term average for several cycles.

Probability model simulates proposed long-term variations in stored elastic strain or strain energy



San Andreas

Weldon et al., 2004



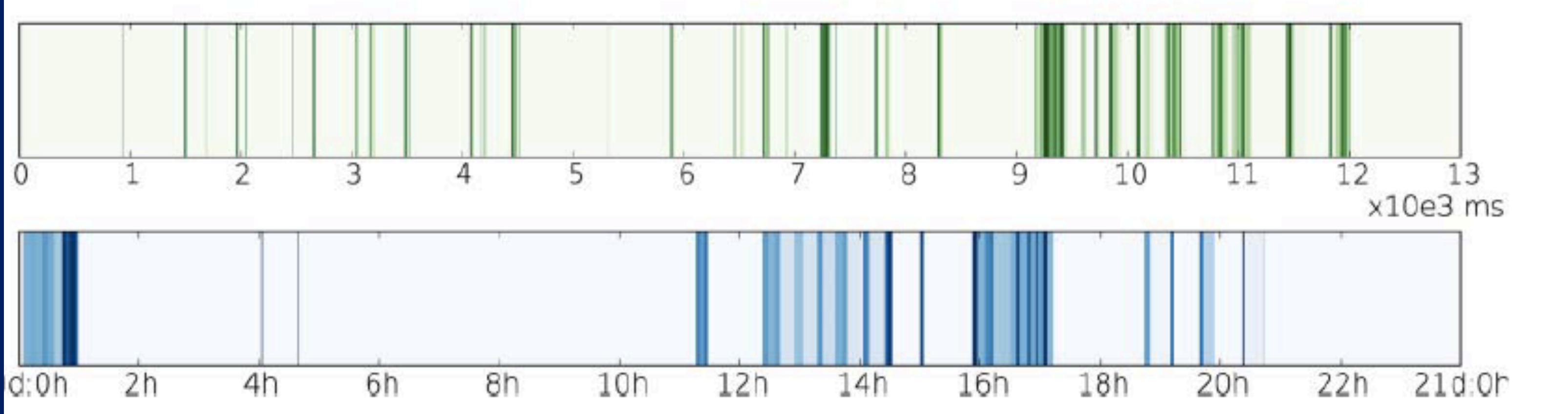
Cascadia *Goldfinger et al., 2012*

Clusters, termed "burstiness" in complex dynamic systems literature, attributed to long-term memory

Karsai et al, 2015

Firing sequence of a single neuron

Outgoing mobile phone sequence of an individual



Many systems display *"a bursty, intermittent nature, characterized by short timeframes of intense activity followed by long times of no or reduced activity," (Goh and Barabasi, 2008).*

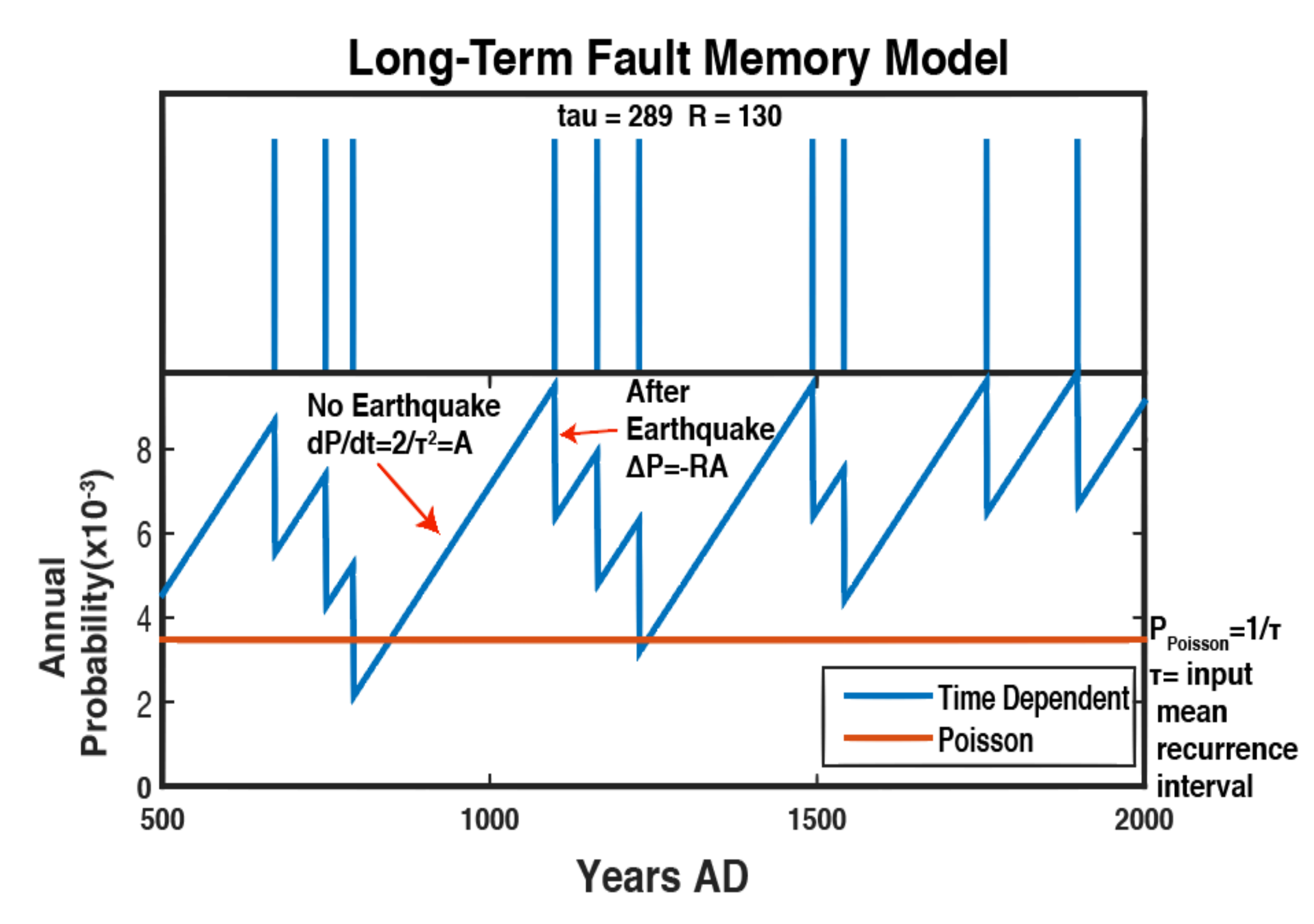
We model large earthquake recurrence history using concepts in dynamic systems allowing transitions between states so a system's state depends on its history (path dependence) and so has long-term memory *(Beran et al., 2013).*

Long-Term Fault Memory (LTFM) Model

Simple model has two parameters:

Probability grows with time at rate dP/dT = A (strain accumulation)

Drops after earthquake by –RA (partial strain release)



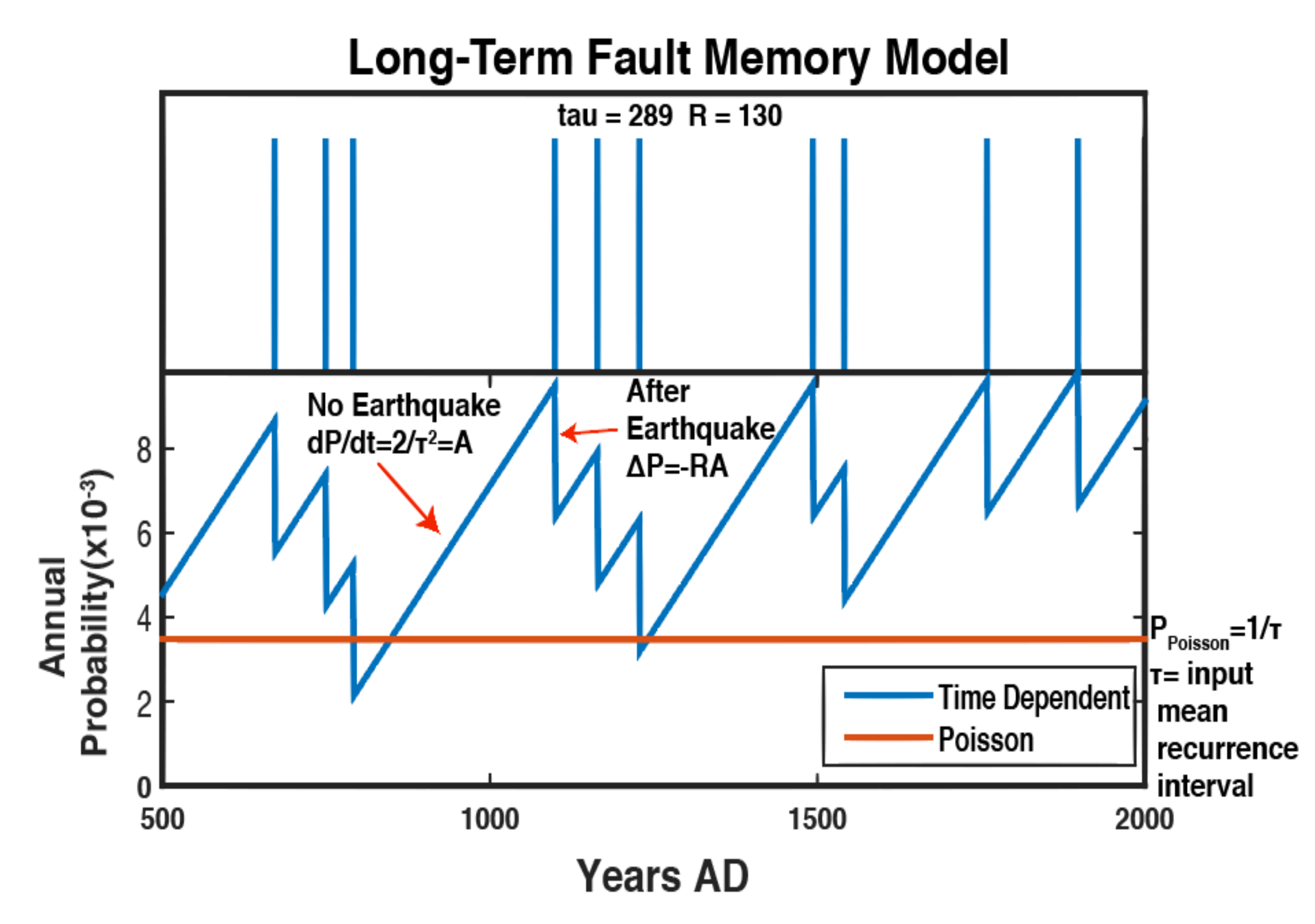
A controls long-term seismicity rate

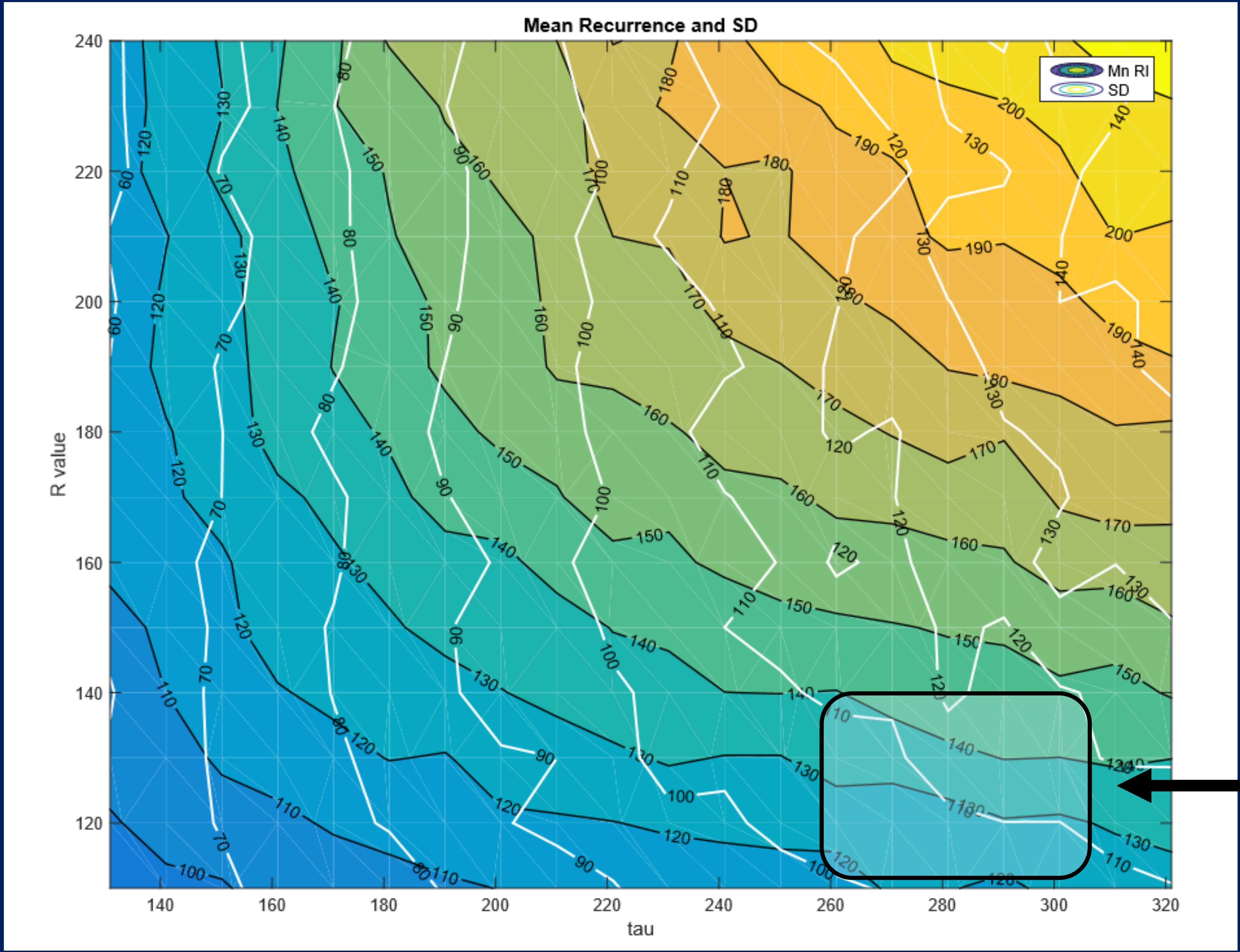
R controls cluster length – small R yields long-term memory & more clusters

Large R gives usual cycle model with only short-term memory

Use simple model to

- Simulate clustering behavior in paleoseismic records
- Explore much longer-term variability
- Gain insight into earthquake probability for hazard estimation

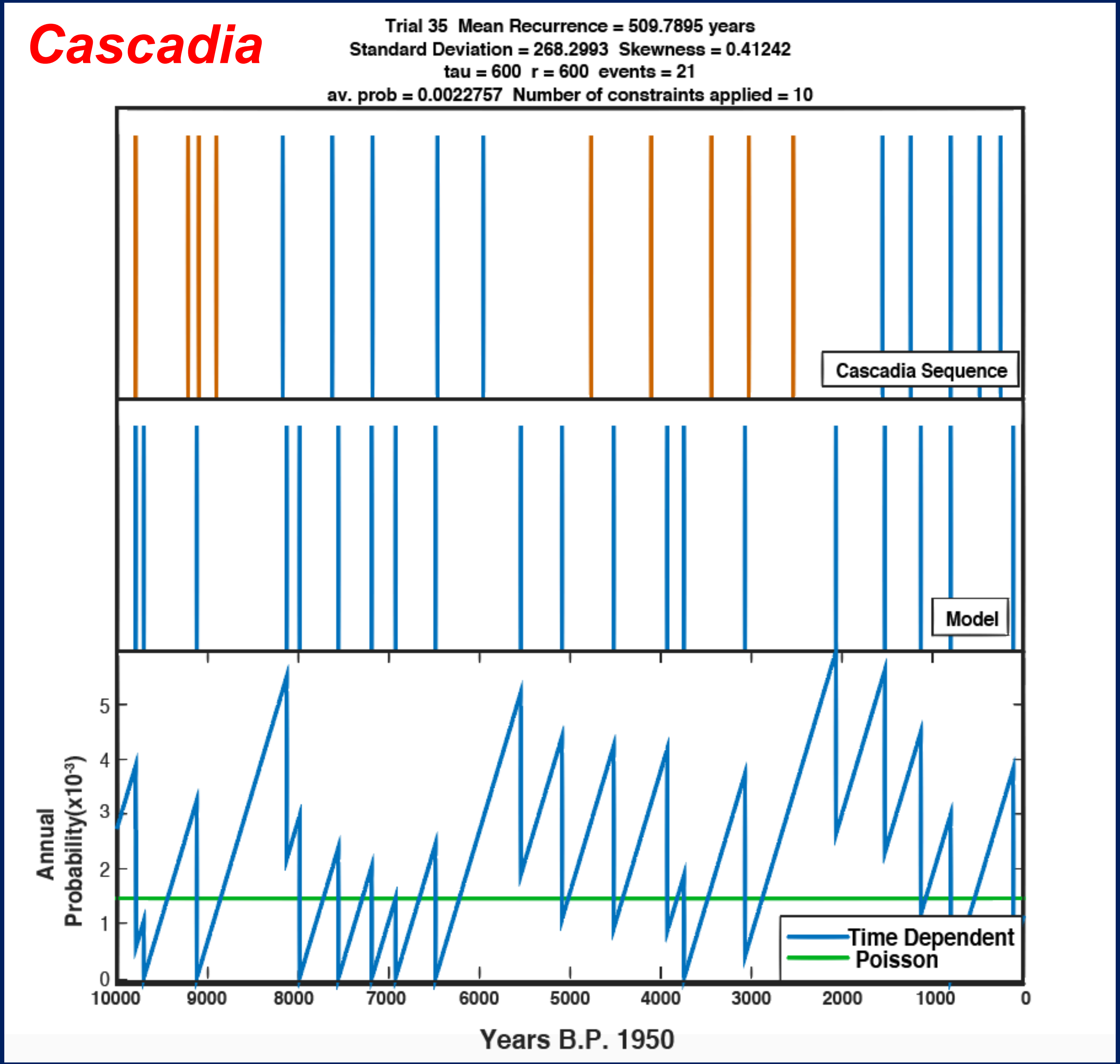




Explore model space and contour mean recurrence and standard deviation for average of 100 runs at each (tau,R) point

$tau=(2/A)^{1/2}$

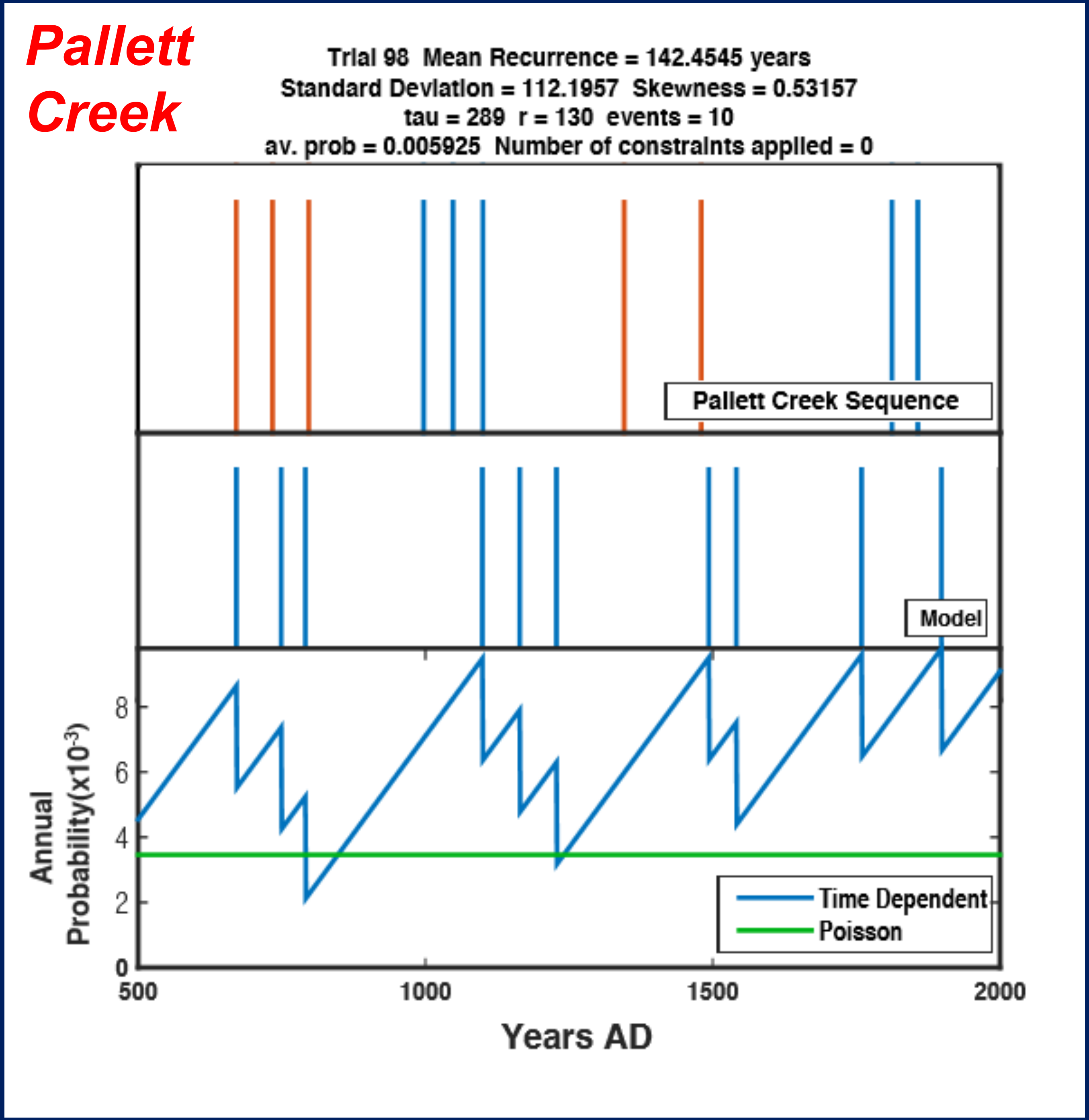
Region of model space with similar properties to those observed



Model parameters that give clustering behavior similar to that observed

Event timing differs due to model's stochastic nature

Clusters as defined by Goldfinger, 2012

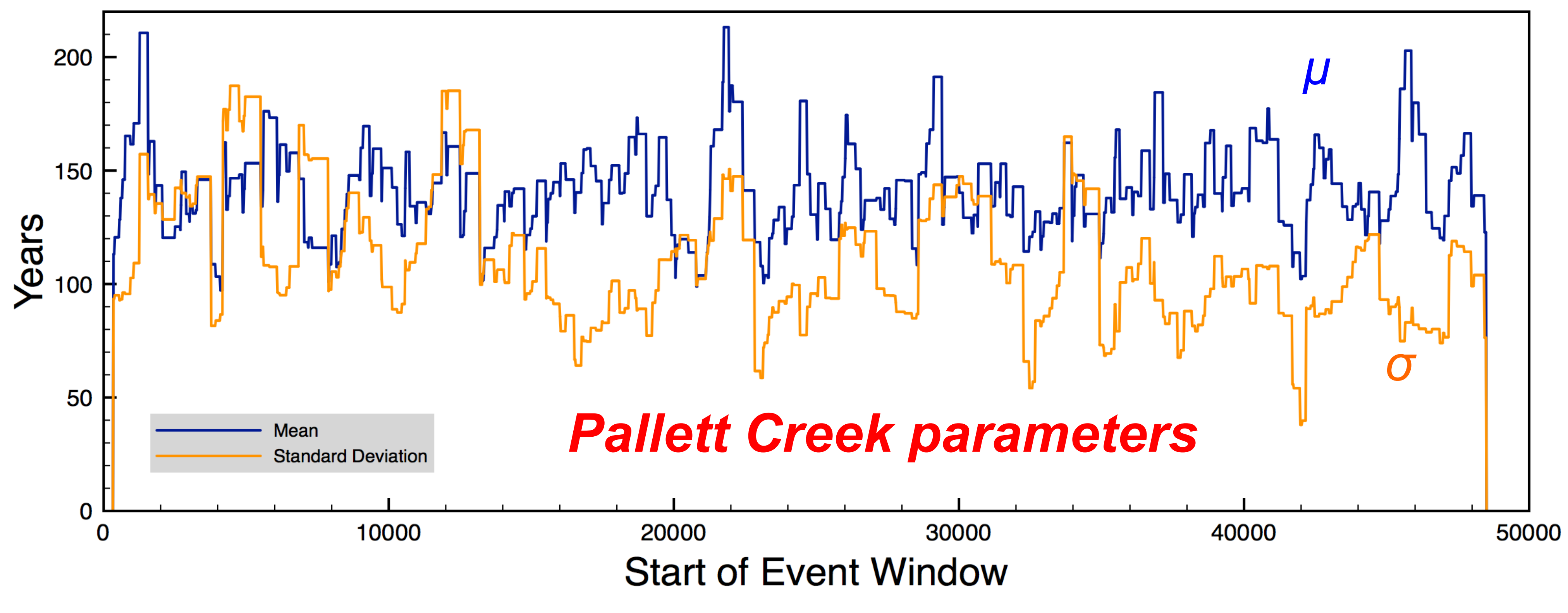


Model parameters that give clustering behavior similar to that observed

Event timing differs due to model's stochastic nature

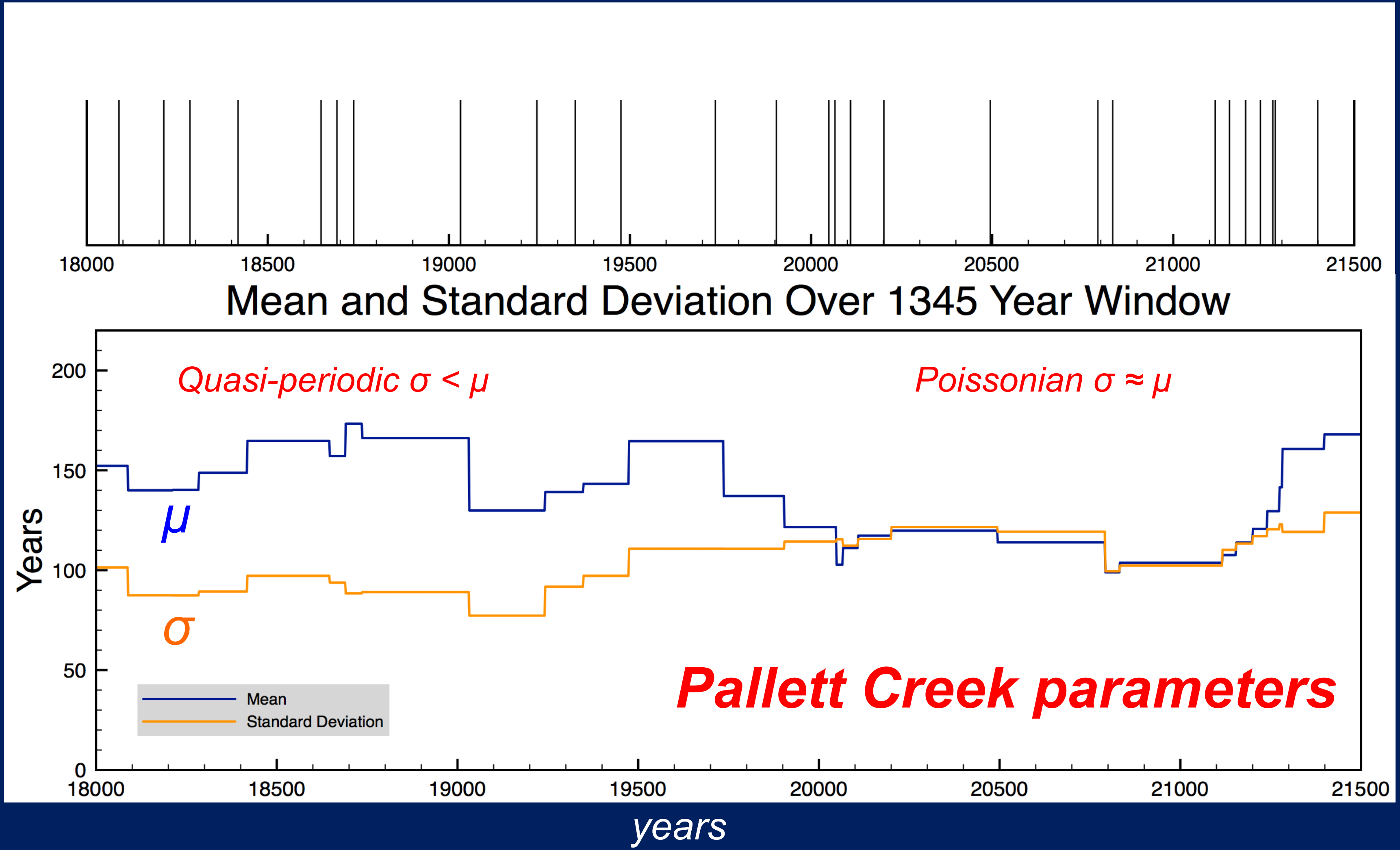
- Simulation is stable over long time periods, consistent with steady plate motion
- Recurrence similar for typical paleoseismic record lengths, but with interesting variability

Mean and standard deviation of recurrence interval for 1345 year window



Implication for hazard estimation

σ and μ vary for paleoseismic records of a given length: some records would look quasi-periodic (seismic cycle), whereas others would look more Poissonian (clustered)



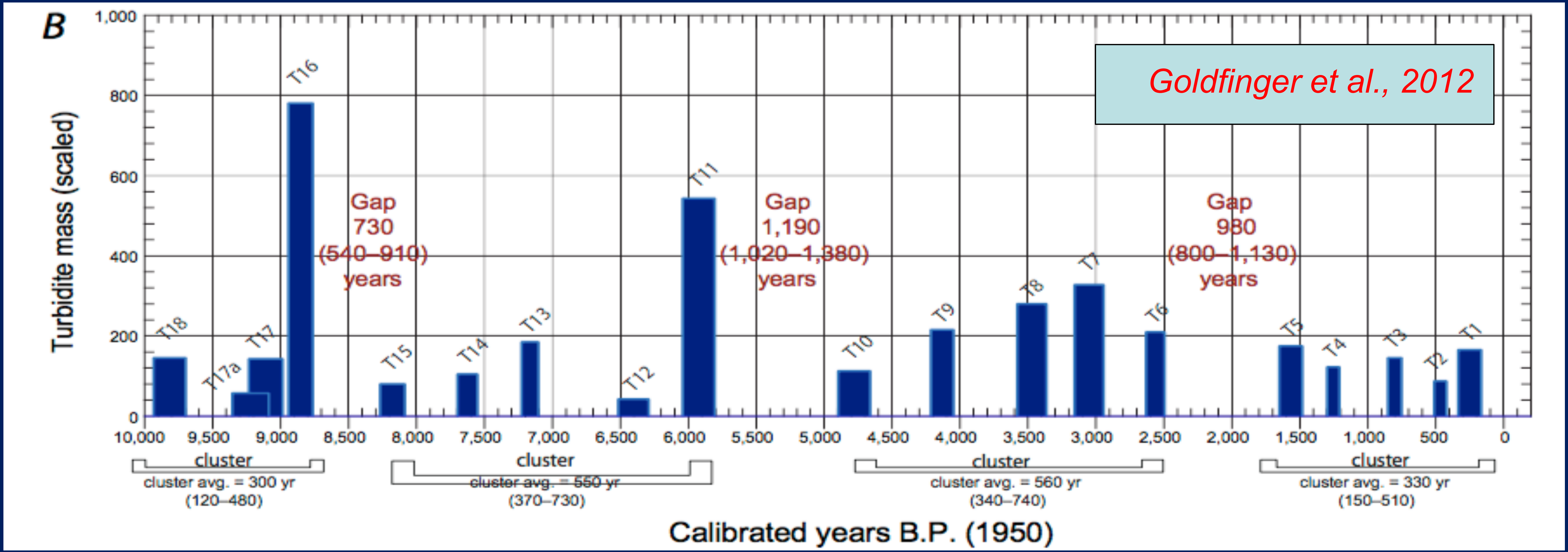
Summary

- Where temporal clusters occur, whether cluster is assumed ongoing can dramatically affect inferred earthquake probabilities
  - Clustering effect can be significantly larger than that of the assumed PDF for recurrence times

- Simple model for earthquake probability incorporating long-term fault memory (LTFM) into seismic cycle simulates observed clustering behavior:
  - For a given fault, some paleoseismic records of same length would look quasi-periodic (seismic cycle), others would look more Poissonian (clustered), σ and μ vary
  - If system has long-term memory, inter-event times are not independent and cannot be used to infer PDF
  - Could include variable magnitude (strain release) & fault interactions

- Clustering significant for hazard estimation, justifying further study

Cascadia Turbidite record



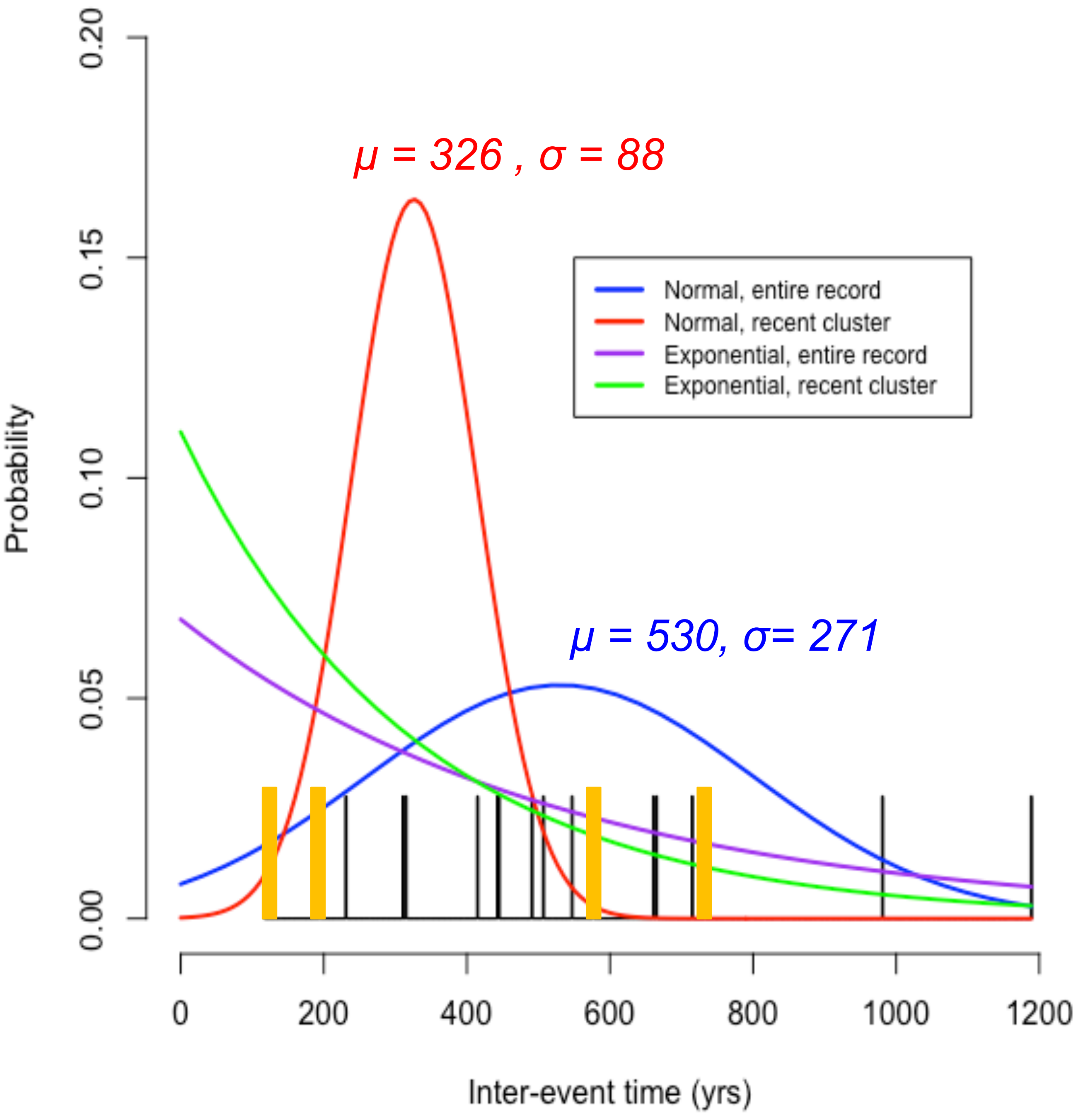
Past 10,000 yrs gives mean recurrence μ = 530 yr and σ = 271 yr.

Recent cluster (1500 yr) gives smaller μ = 326 yr and lower σ = 88 yr.

Recent cluster yields 6x higher probability of earthquake in next 20 years

Cascadia inter-event time distribution suggests Long-Term Fault Memory

- Cascadia inter-event times are not well fit either assuming:
    - Exponential (Poisson) distribution (implies more short intervals)
    - Chi-square test fails to reject any of these and other standard statistical models
- Such models assume inter-event times are independent, i.e. probability of large earthquake resets to zero after each event.
- If system has long-term memory, inter-event times are not independent



Earthquake probability estimates depend on:

- Assumed probability density function (Poisson, Gaussian, lognormal, Weibull, Browning passage, etc.).
- Parameters (mean, σ, etc.) assumed for the chosen pdf.

Both are chosen based on the short available record, which may not reflect long-term behavior