Rashomon at the Sound

Reconstructing all possible paleoearthquake histories in the Puget Lowland through topological search

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CASCADIA REGION EARTHQUAKE SCIENCE CENTER

NSF

Rashomon (1950)

A violent crime committed in the woods in medieval Japan

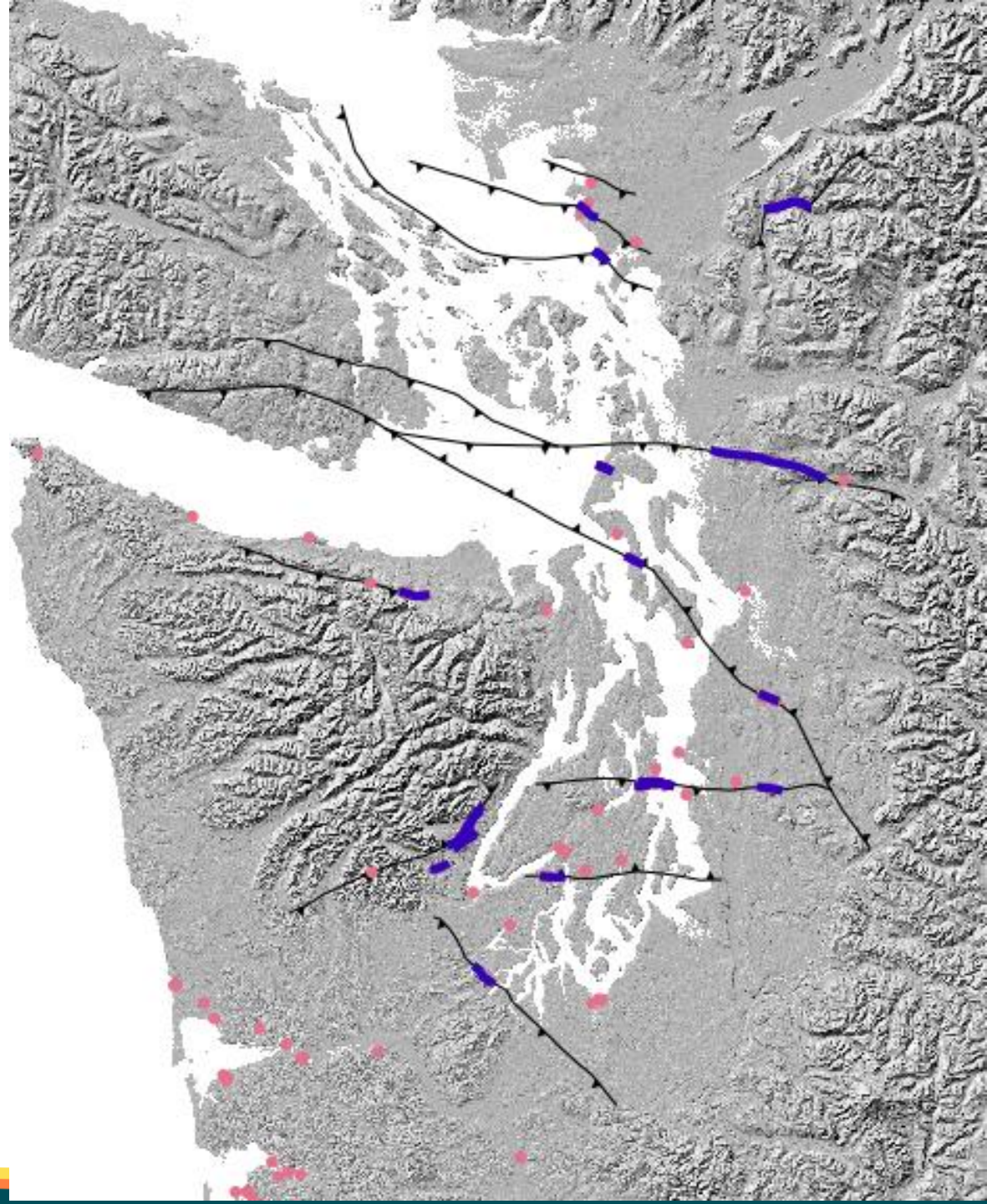
Four witnesses provide four **different**, **mutually exclusive** testimonies that involve **same key observations**

Paleoseismic Data

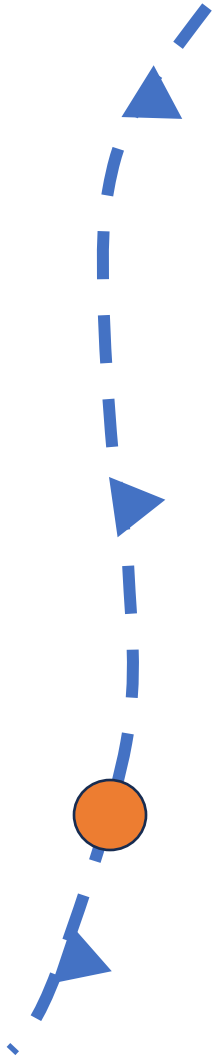
Decades of research yields **~30** paleoseismic events observed in trenches (+shorelines, etc.) since deglaciation

Comprehensive but not complete catalog of dated surface-breaking earthquakes

Data modified from Styron and Sherrod (2001)



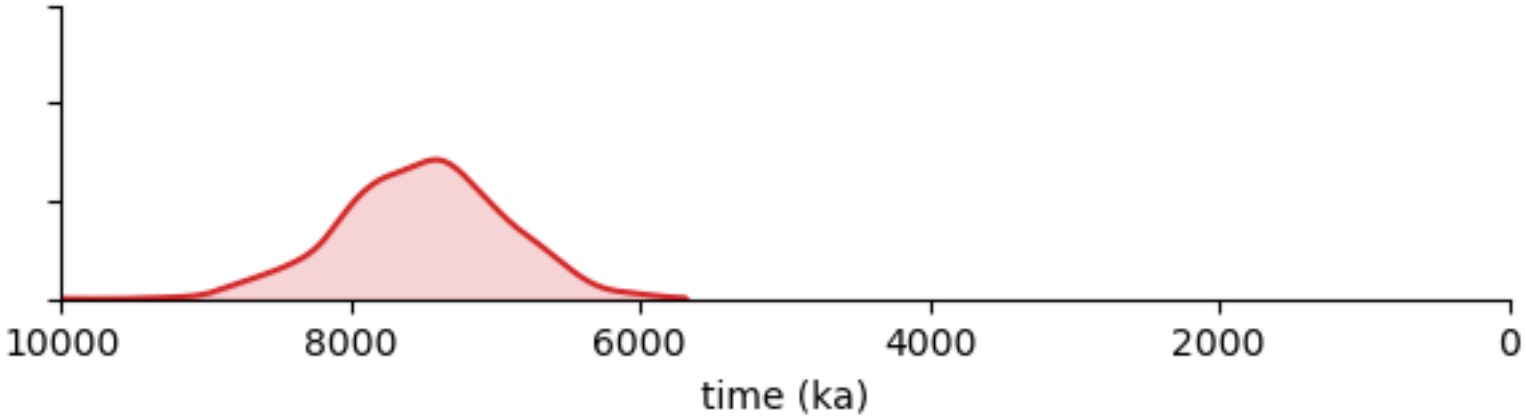
Data Limitations



Paleoseismic observations are:

Date ranges of (seismic) ground deformation

at **points** or **short rupture traces**.



Desire for Complete Knowledge

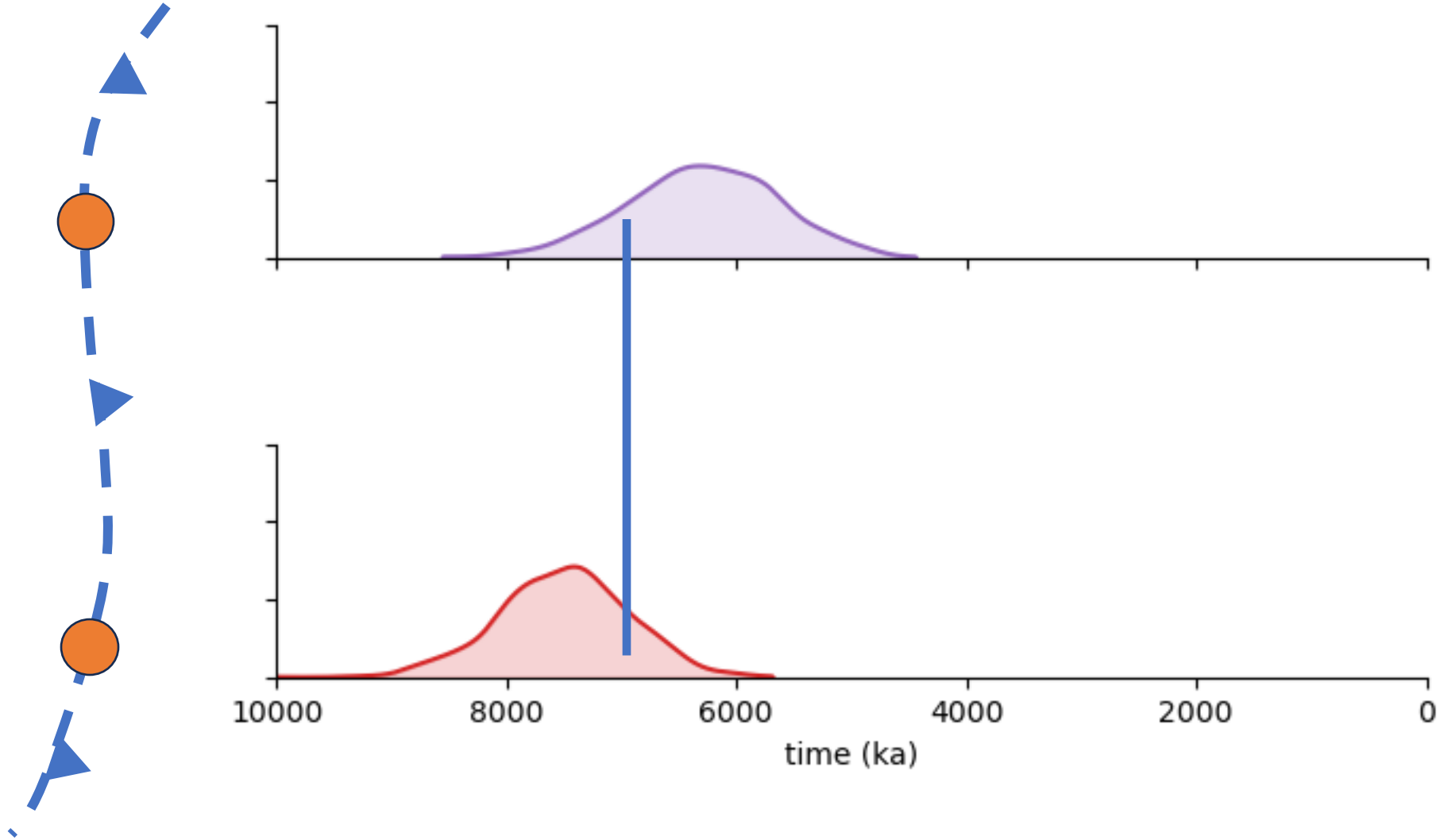
Perfect Paleoseismology would tell us the **times**, **magnitudes**, and **rupture extents** of past earthquakes.

This would inform us about **recurrence intervals**, **magnitude-frequency distributions** and other hazard-relevant quantities

More broadly, we could use this to understand **earthquake triggering** and **clustering**, and other phenomena scientifically

But the dots don't tell us this.

Connecting the Dots



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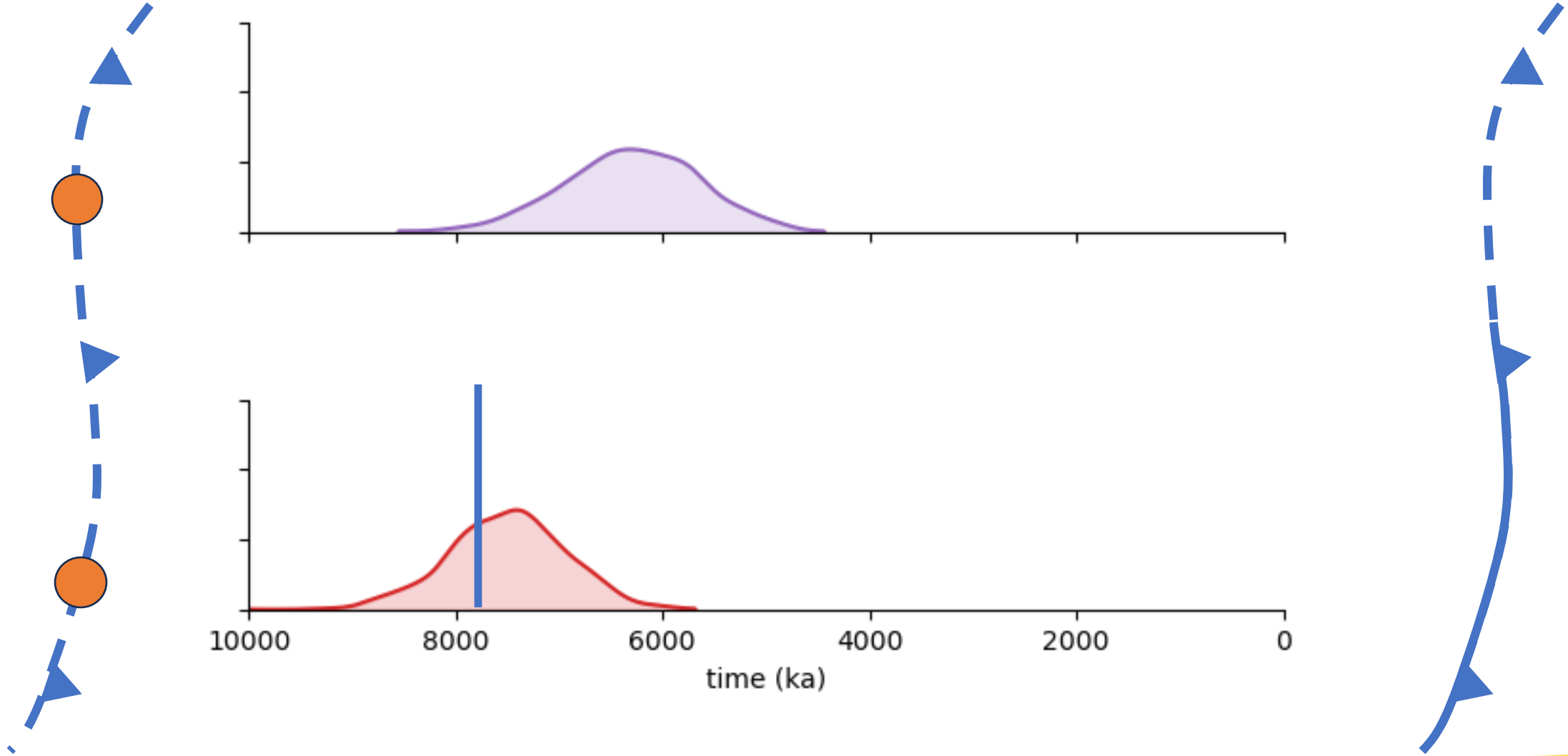

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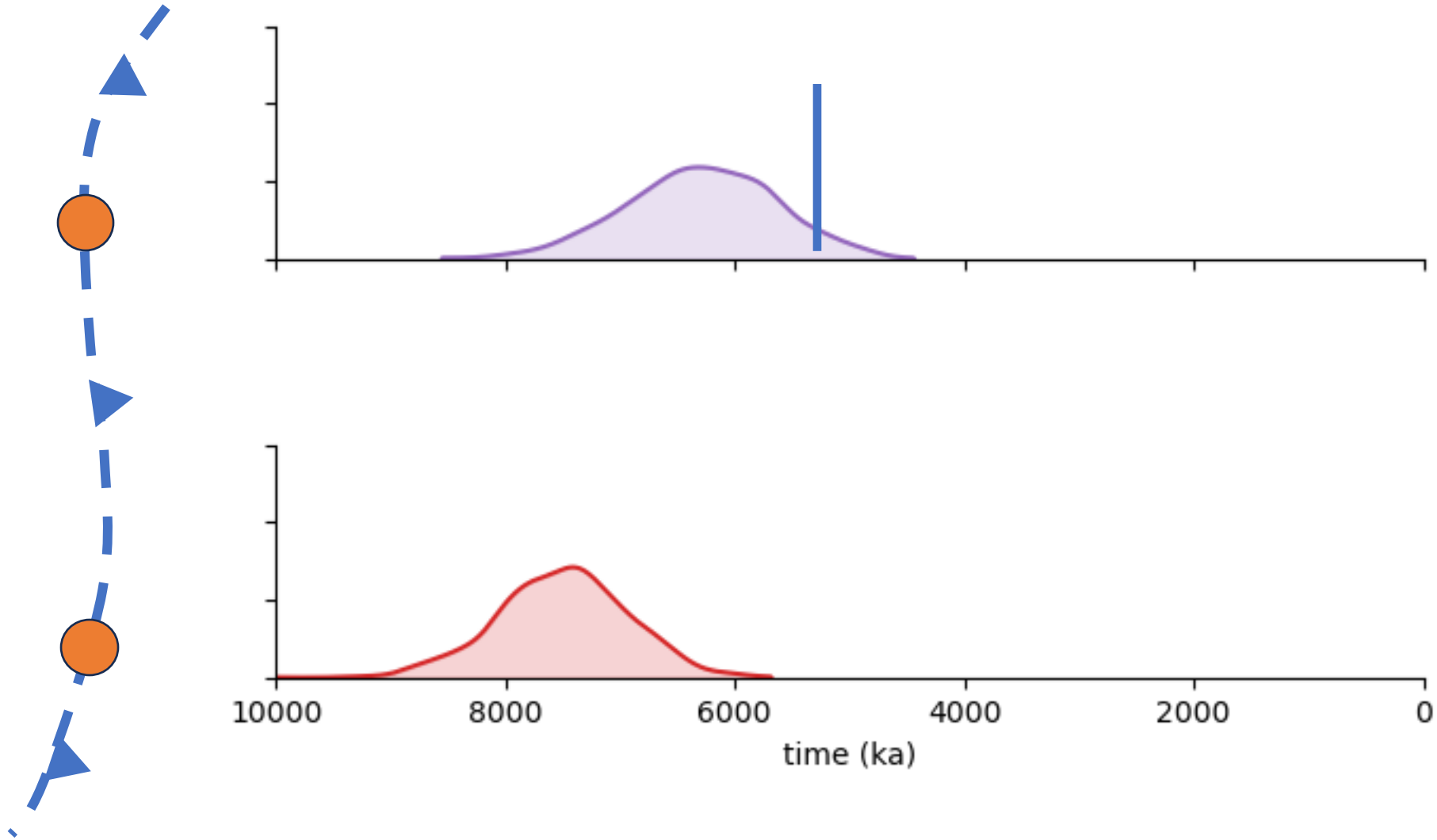
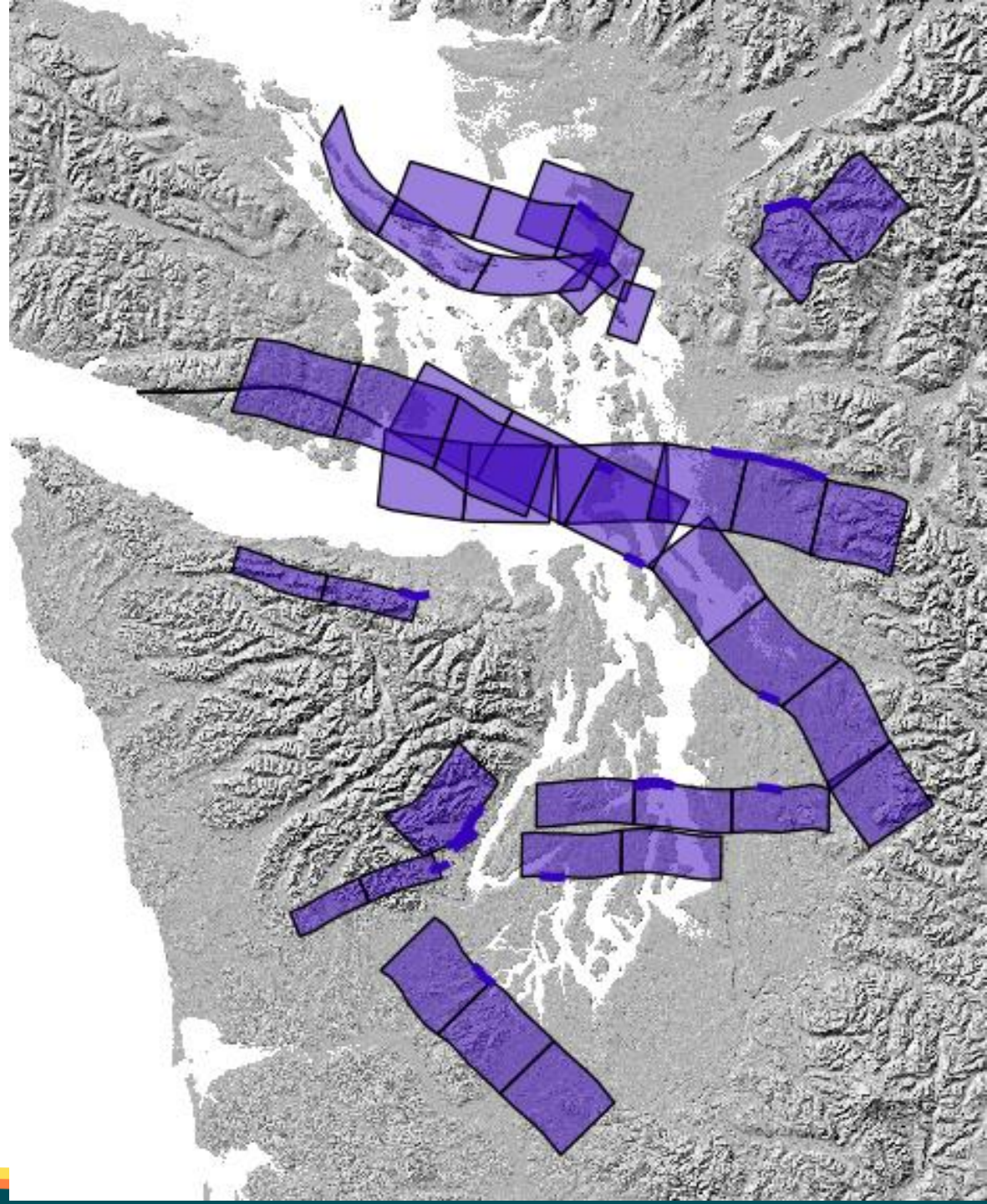


Defining ruptures

Discretize faults into ~20 km square subfaults

All contiguous sets of subfaults on same fault form all single-fault ruptures

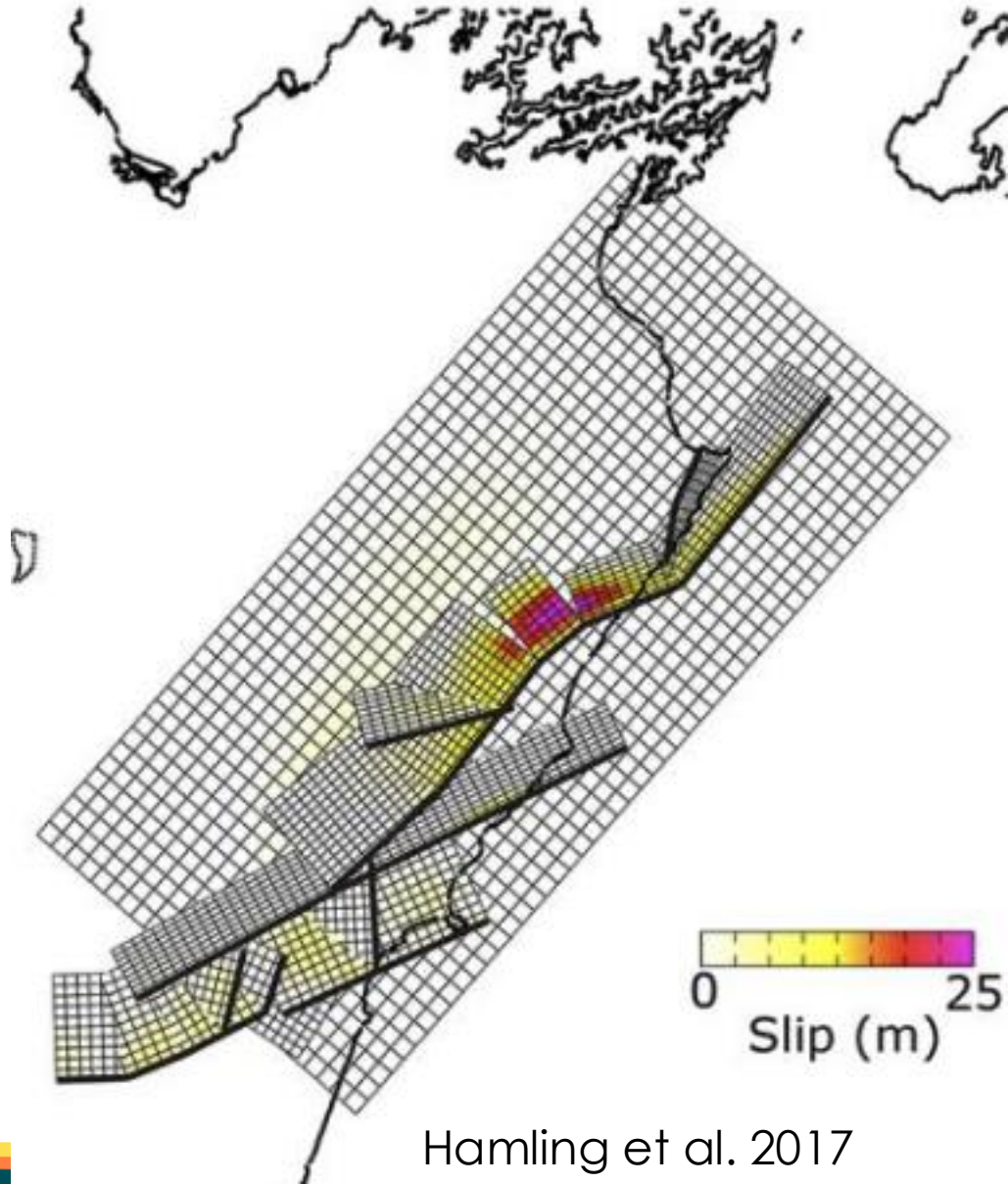


Multifault ruptures

Abundant observations of earthquakes rupturing multiple distinct (intersecting or nearby) faults

Cannot ignore in PSHA

Definition more complicated than single-fault ruptures



Hamling et al. 2017

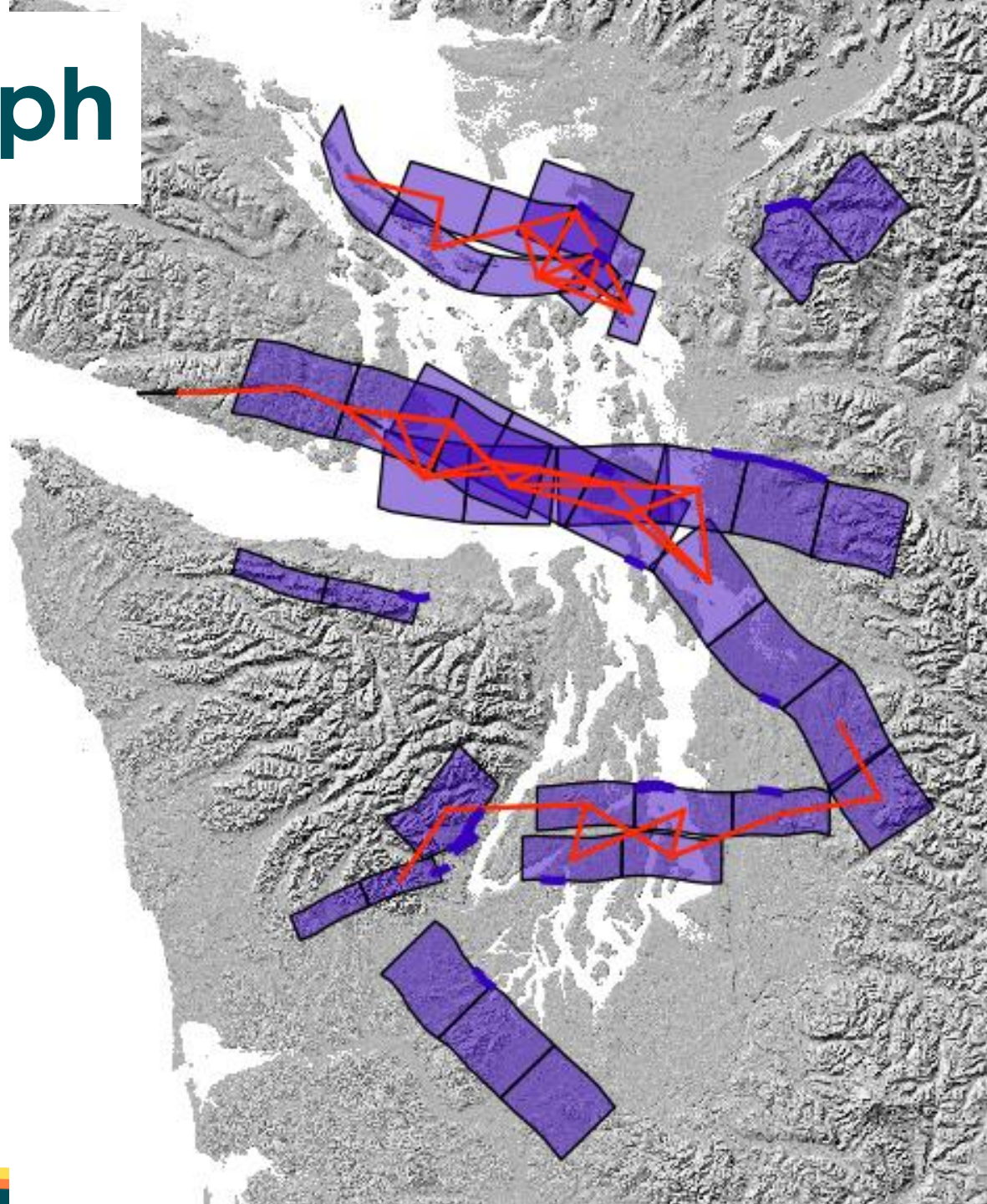
Rupture adjacency graph

Multifault ruptures depend **adjacent** faults with compatible geometries

Subfault adjacence (based on parameters, e.g. jump distance, strike angle, overlap) graph created

Every graph is a matrix:

Graph operations through lin alg



All Possible (Past) Earthquakes

Depth-first search over adjacence matrix yields all unique sets of subfaults, i.e. all possible ruptures:

- **75 single-fault ruptures** and **36,702 multifault ruptures**

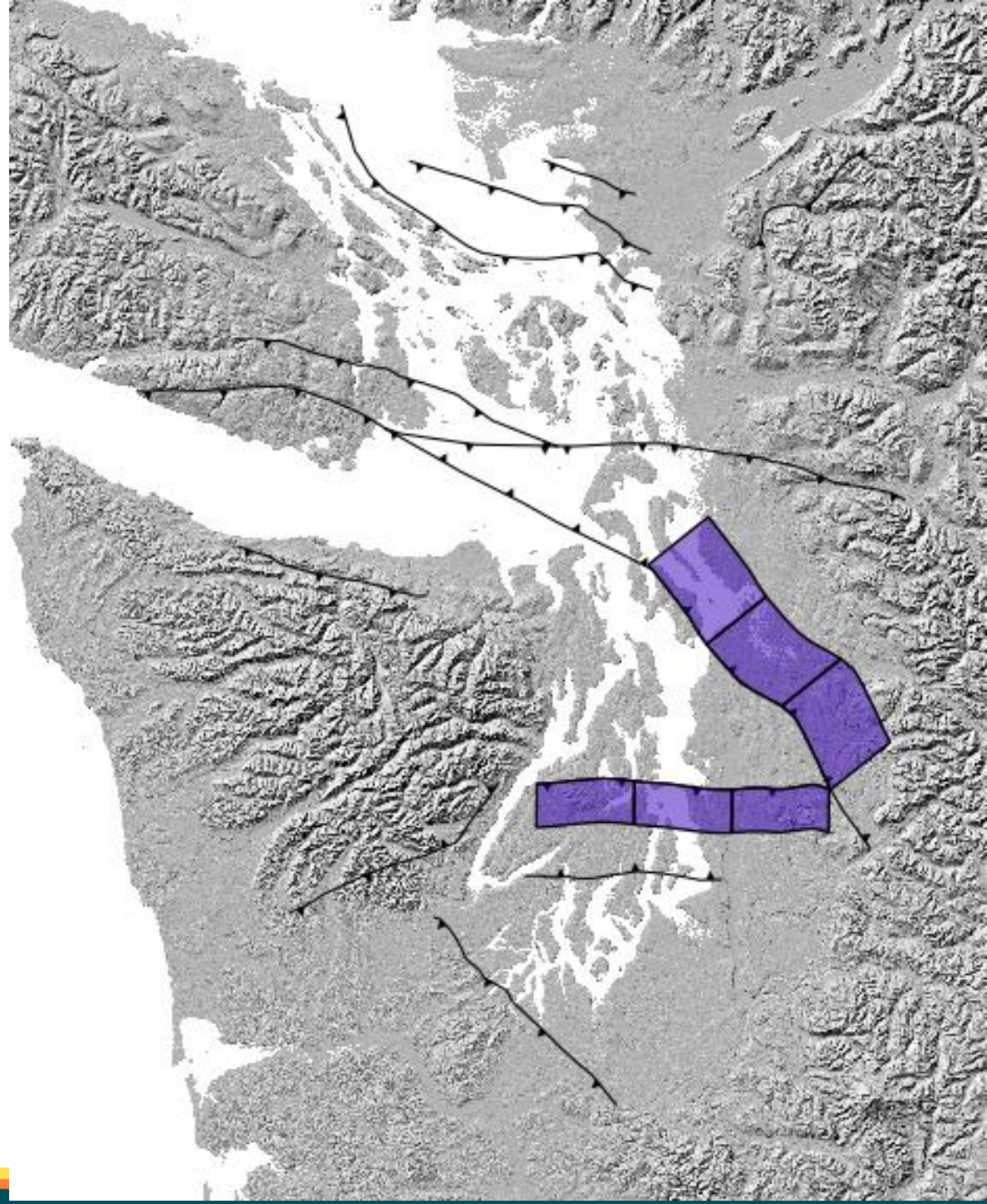
Stochastically filtered by plausibility constraints:

- Jump distance, kinematic compatibility to **1,864** ruptures

Filtered by paleoseismic data:

- All ruptures must hit a trench+ site

Example multifault rupture



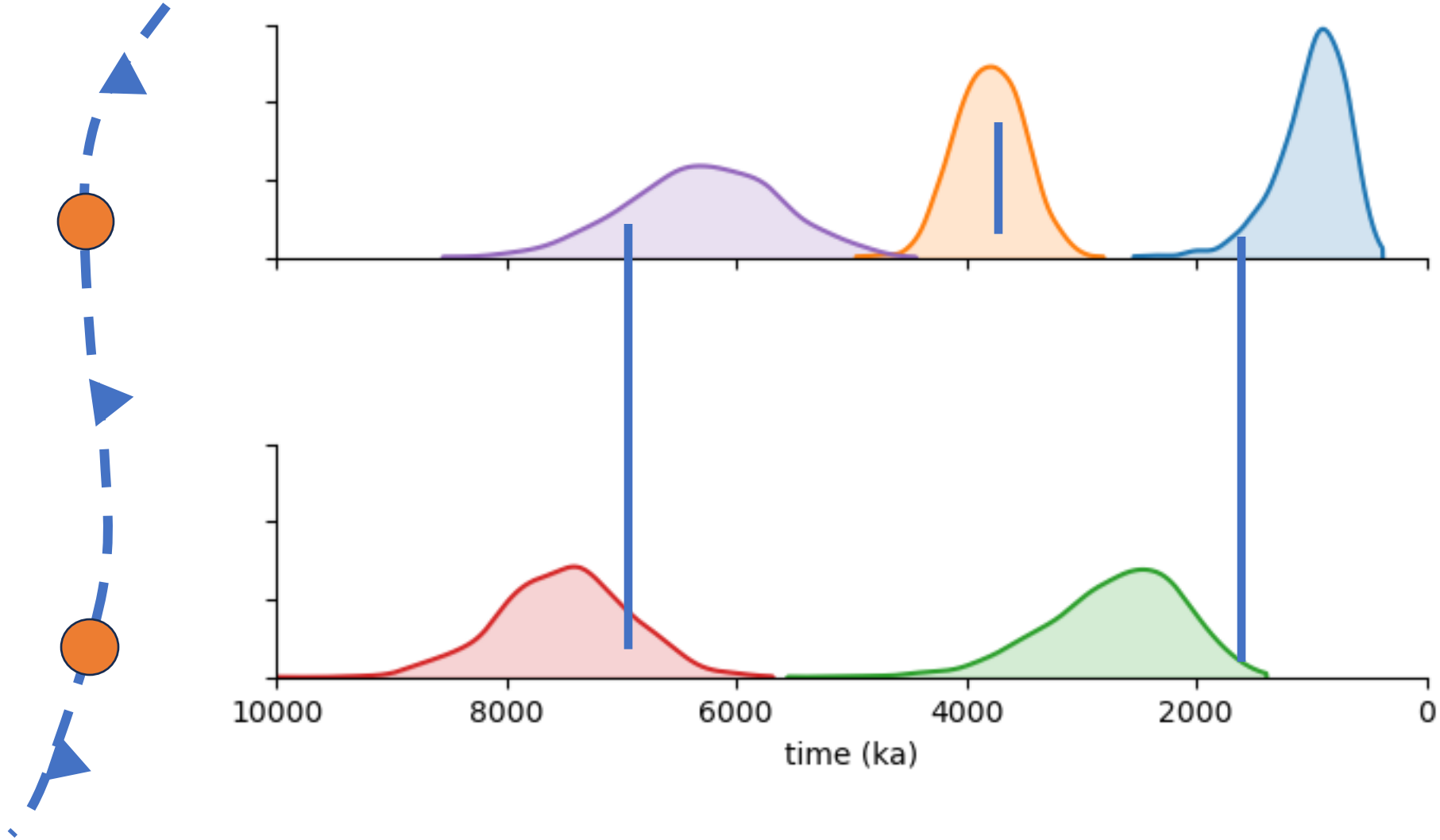
So what?

Far more potential ruptures than observations

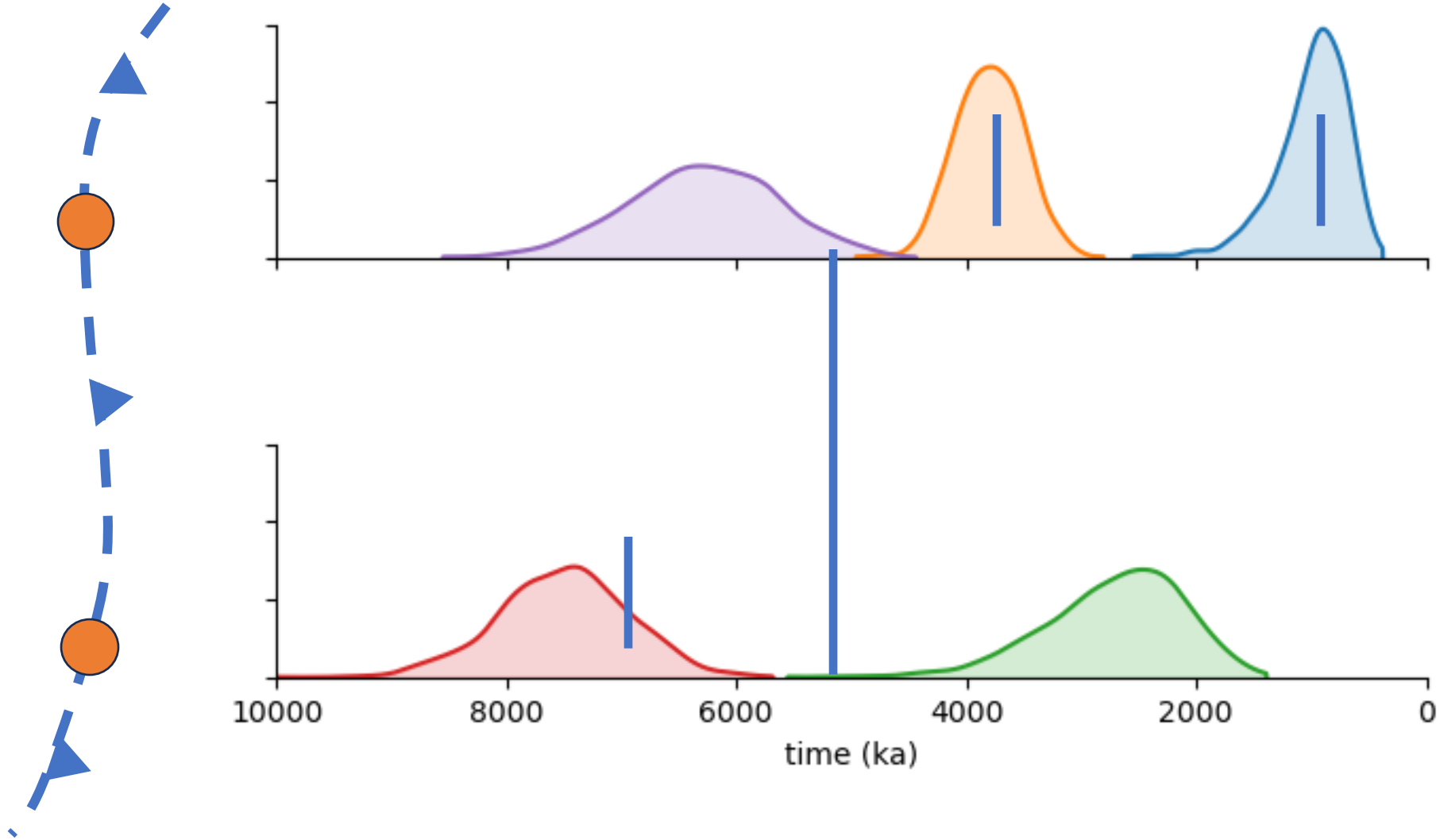
Potential ruptures based on **same sparse data** but are **mutually exclusive** in a historical context

Possibility of one rupture hitting observed events in one or more trenches contingent on other ruptures hitting same events in same trenches (each event occurred only once)

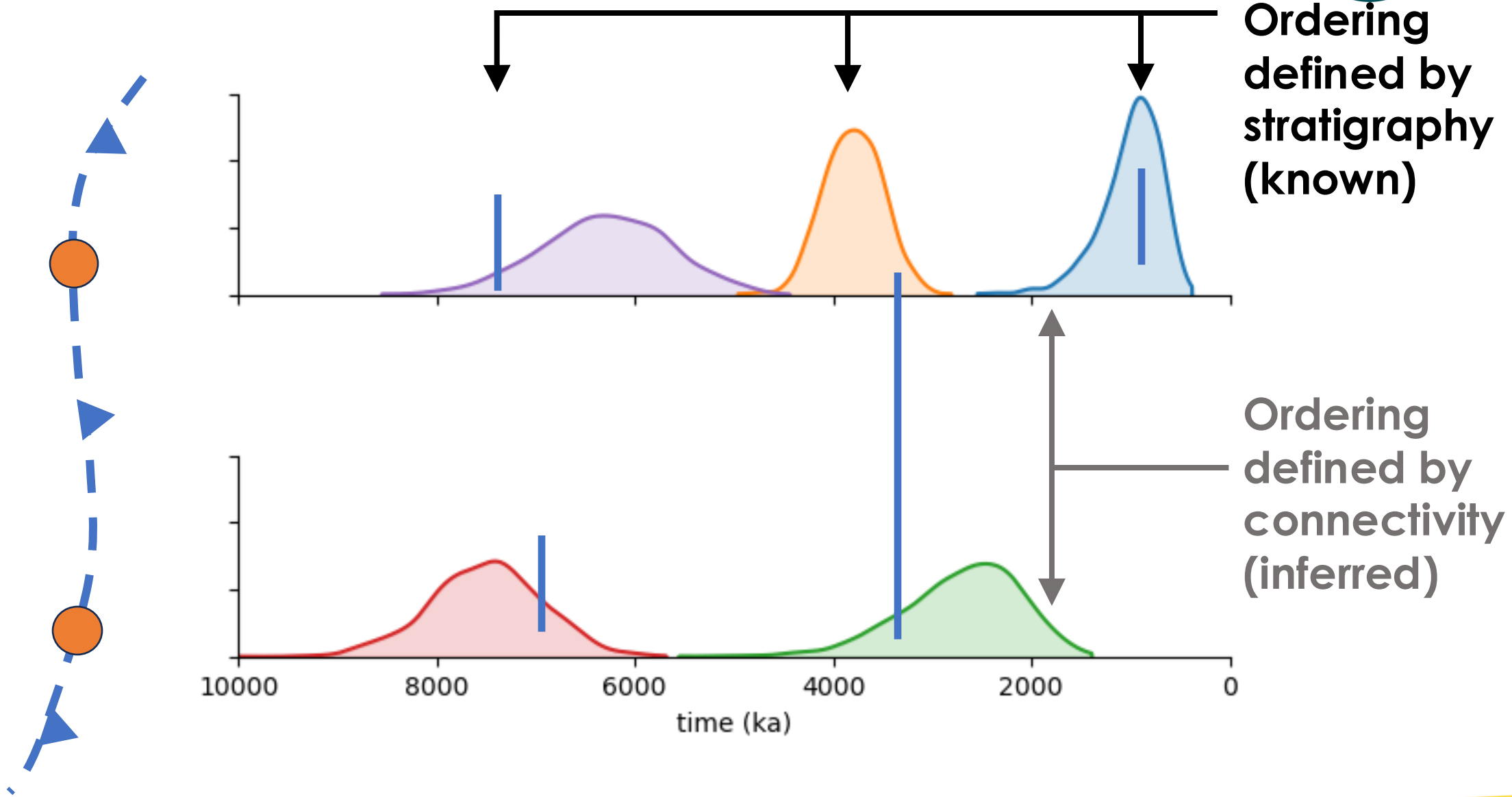
Mutual Contingency



Mutual Contingency



Partially-ordered sets



Event-Time connectivity

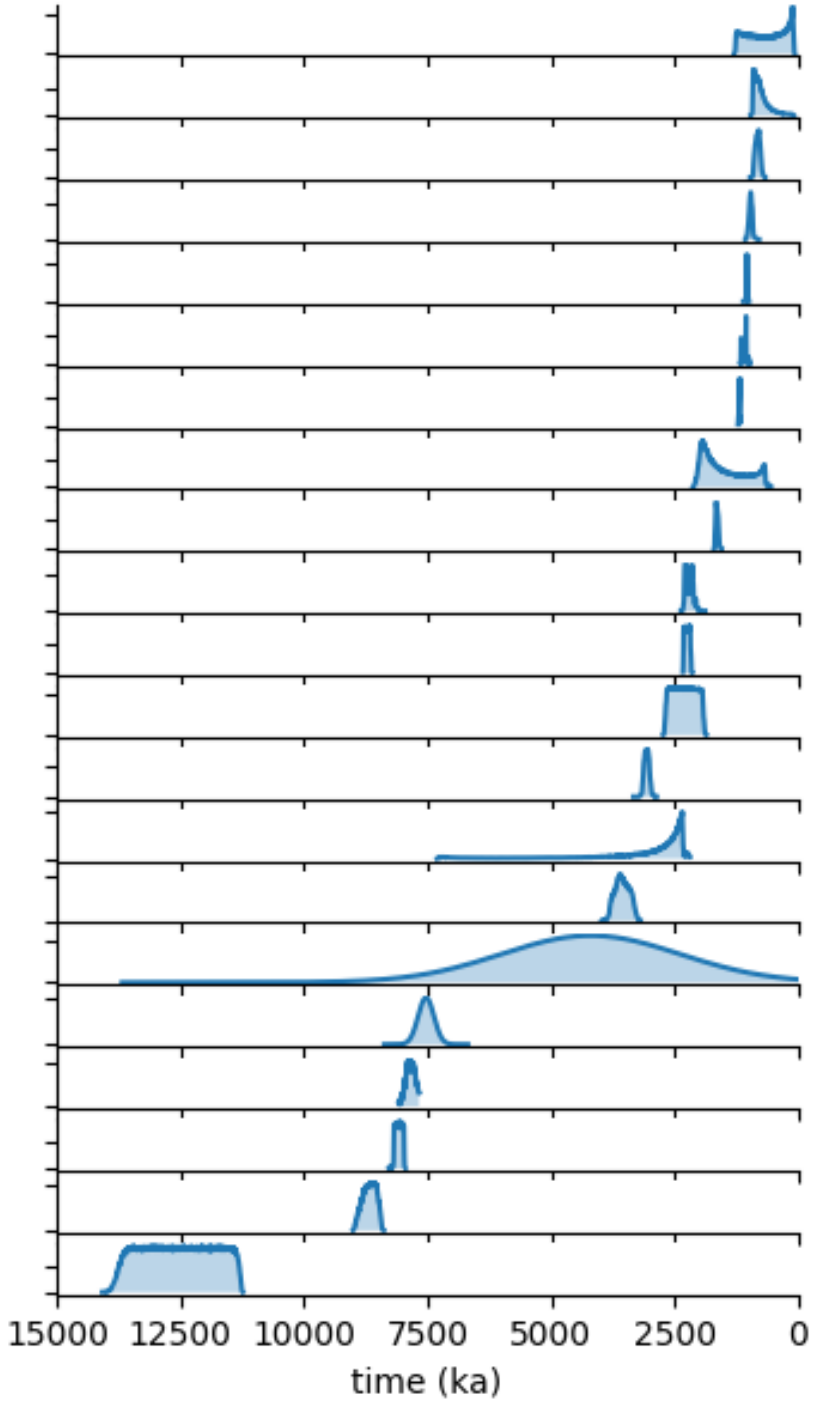
A graph is made of all paleoseismic events (spatial points, time pdfs) that are spatially connected (via possible ruptures) and also have time overlap.

A feasible event sequence is a partially-ordered set of single or linked trench events, where each trench event is present once.

Each single or linked event is not uniquely tied to a given rupture--for some, many possible ruptures hit the right trench(es).

Example event sequence

[('SFZ_EQ_C', 'TFZ_EQ', 'smf_E3'),
('SFZ_EQ_A', 'VasaParkEQ', 'smf_E1'),
('DDMFZ_EQ1', 'EL', 'Leech_E2'),
('DDMFZ_EQ2', 'SWIF_EQ1'),
('Birch_Bay_Uplift', 'Sandy_Point_EQ_C'),
('SFZ_EQE',),
('kendall_EQC',),
('SFZ_EQ_D',),
('SFZ_EQ_B', 'smf_E2'),
('West_Point_Sewer_Log_Death',),
('RSC5_Death',),
('LCBC_EQ3',),
('Leech_E1',),
('sandypt_eqB',),
('kendall_EQB',),
('LCBC_EQ2',),
('SWIF_EQ2',),
('sandypt_eqA',),
('kendall_eqA',),
('Leech_E3',),
('SFZ_EQ_V',)]



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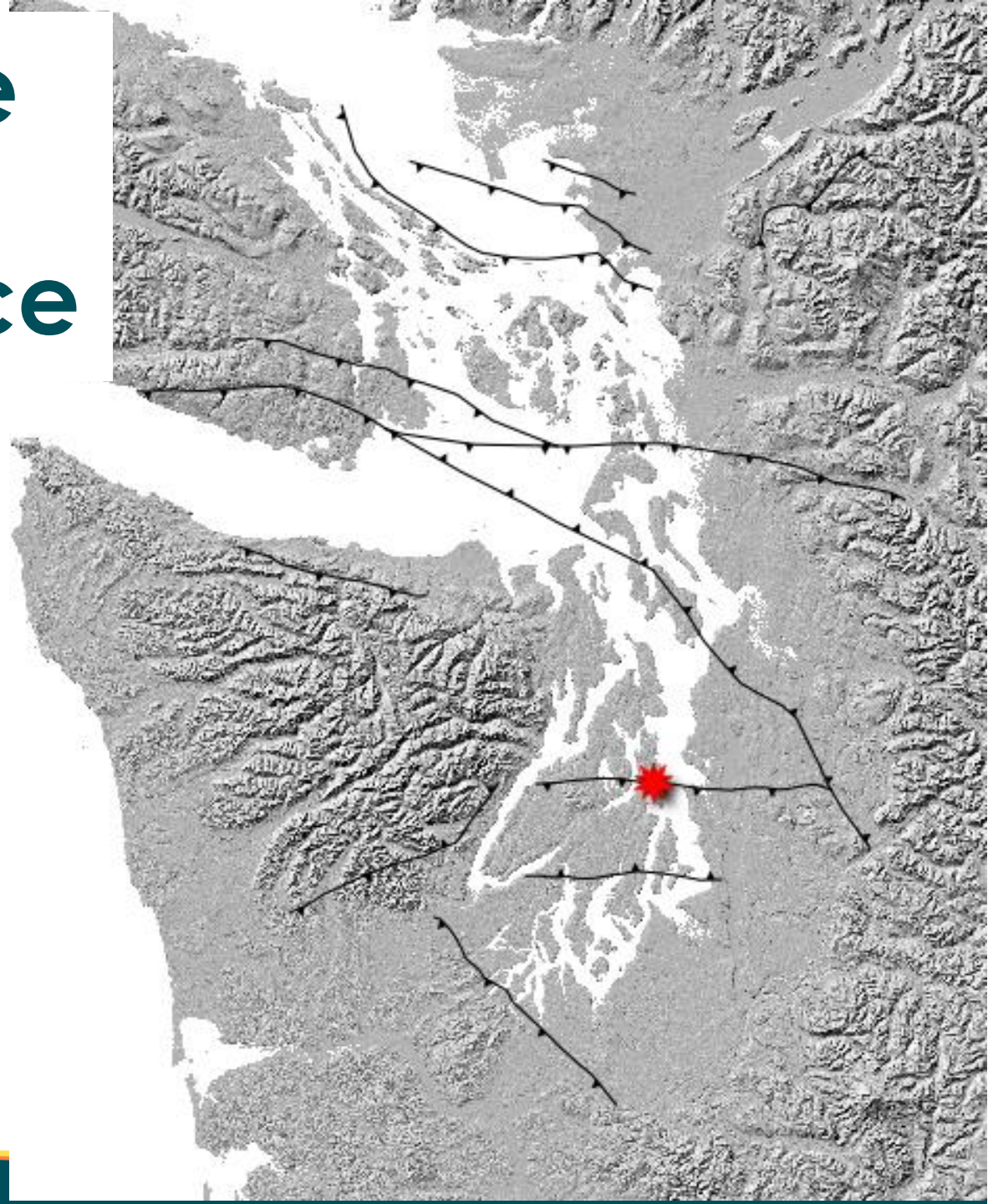

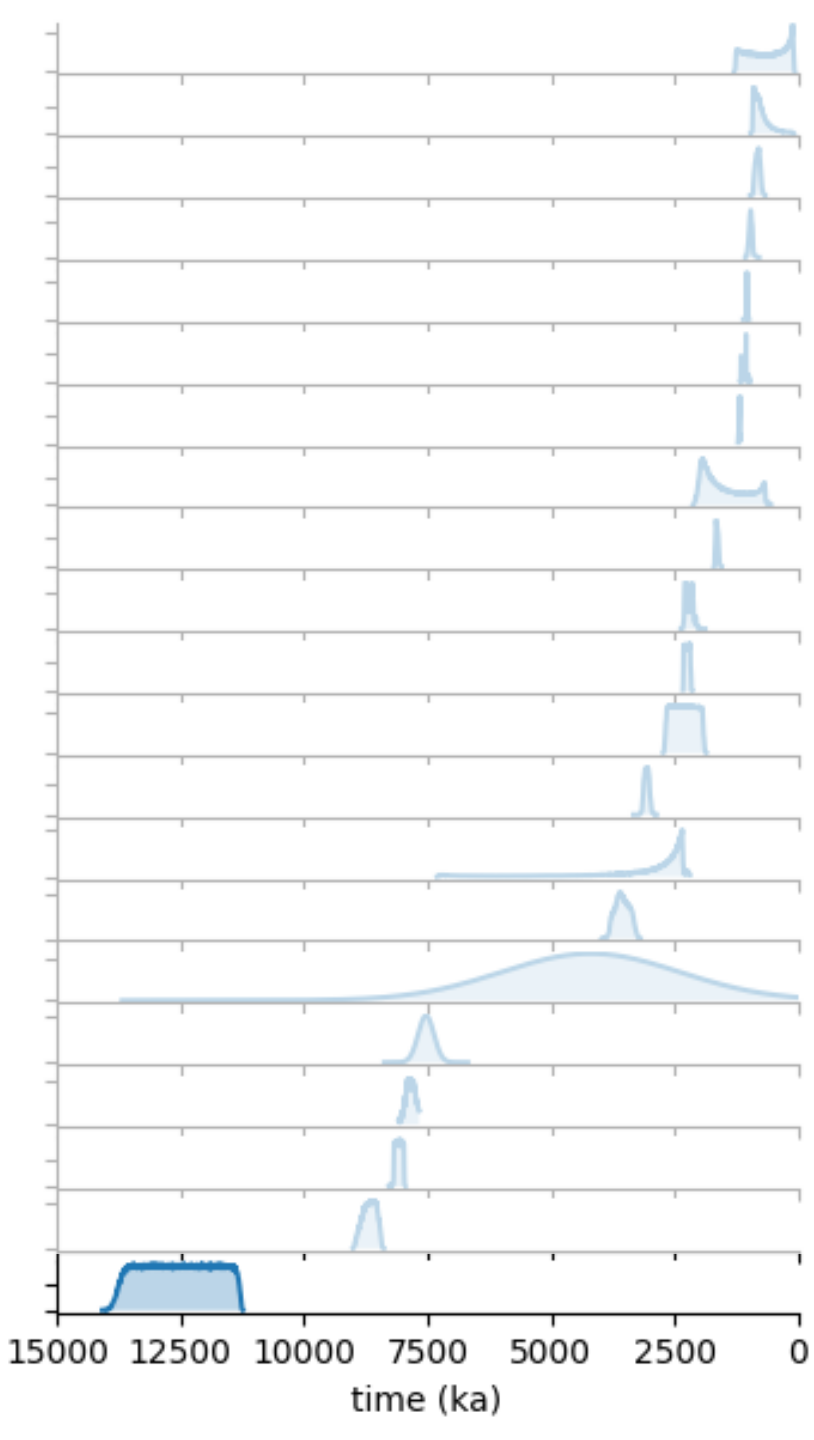

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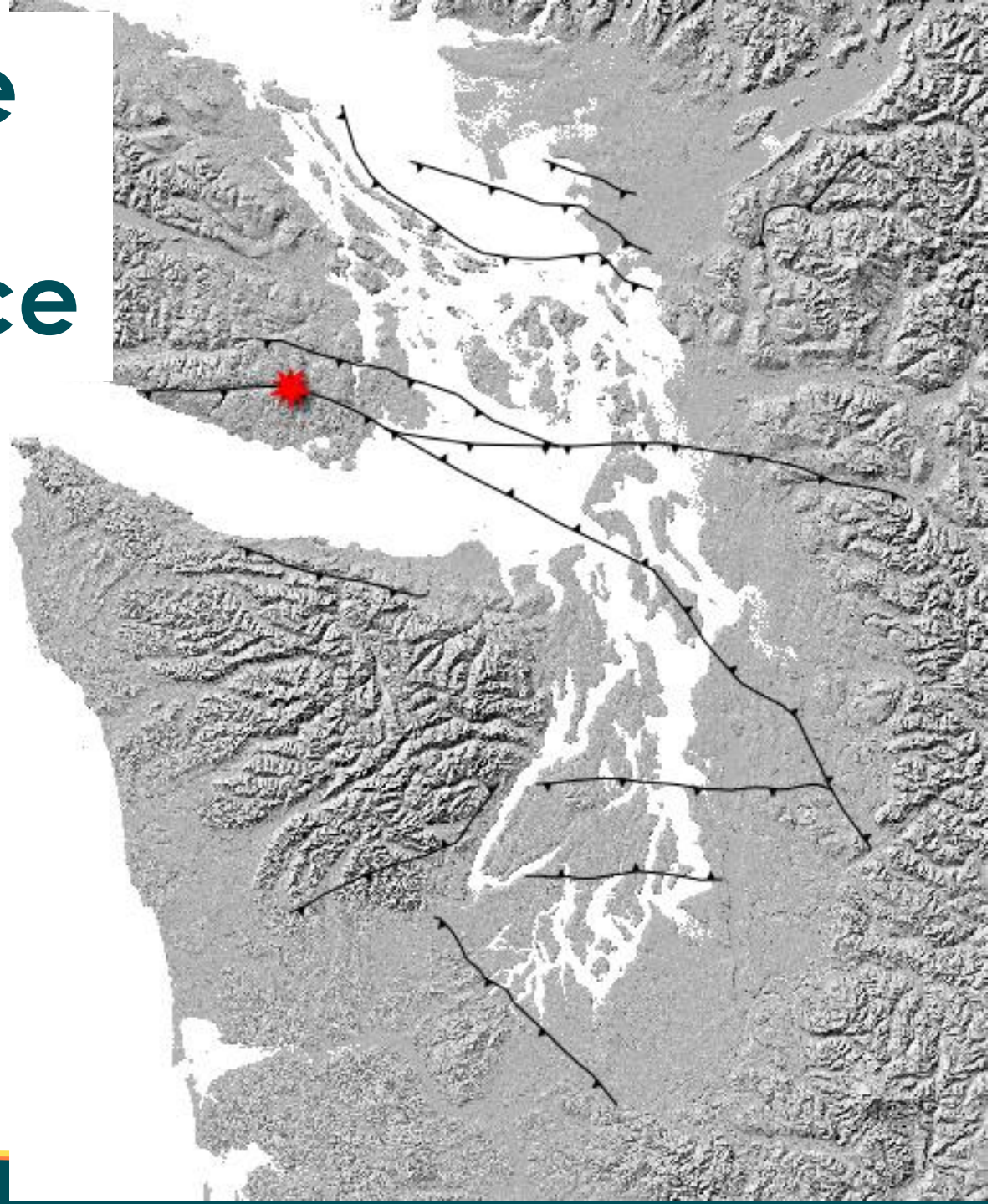

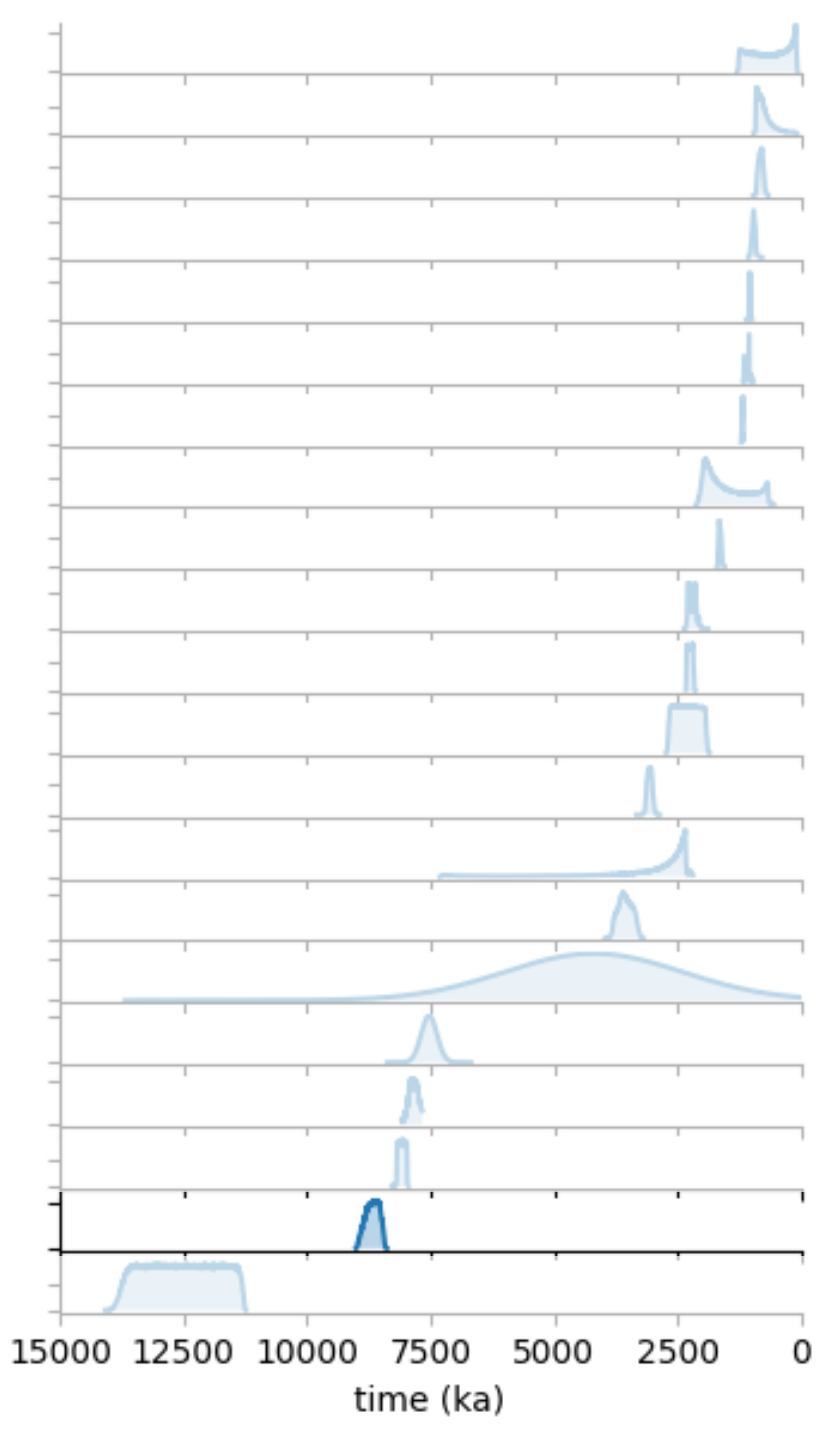

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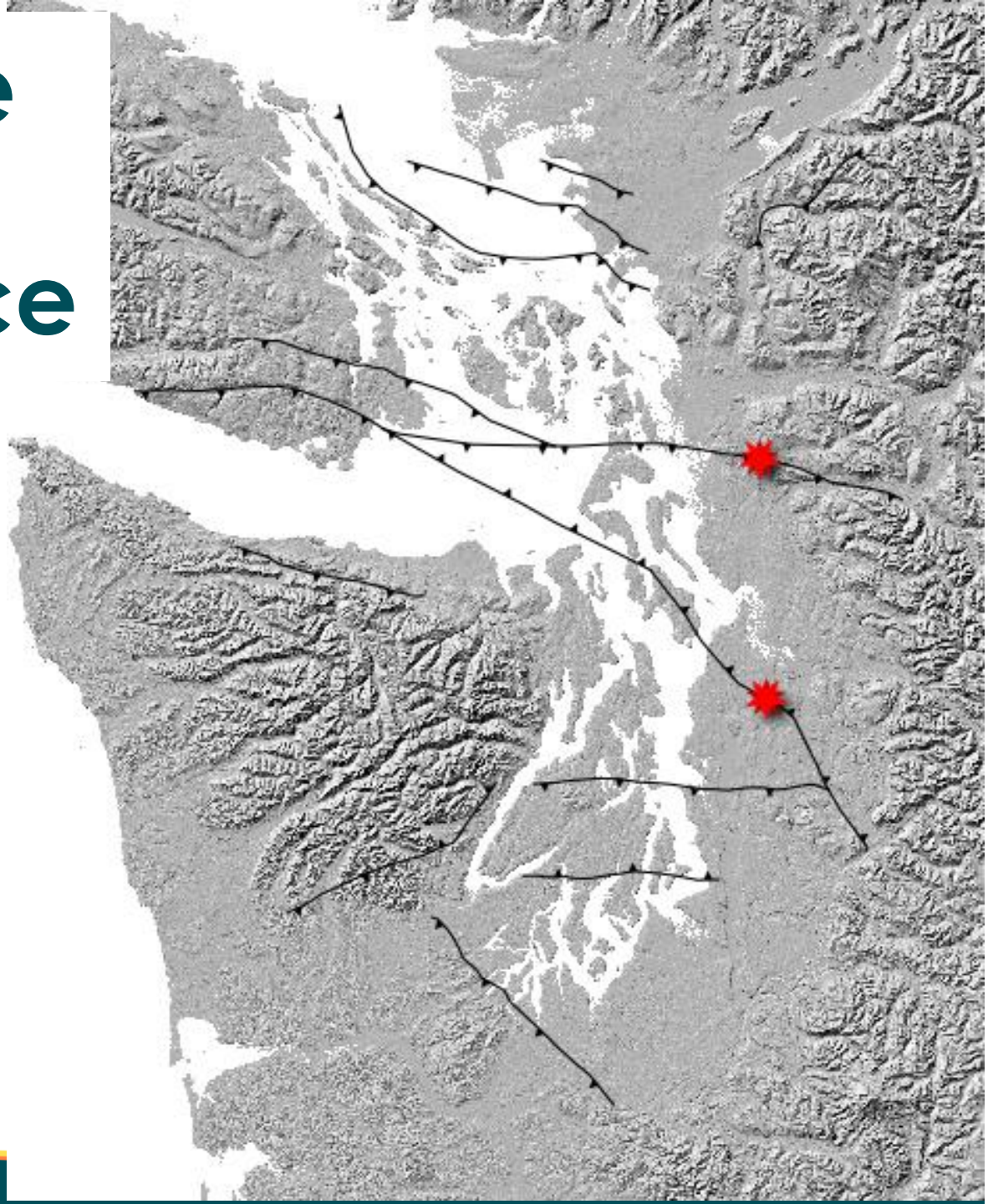

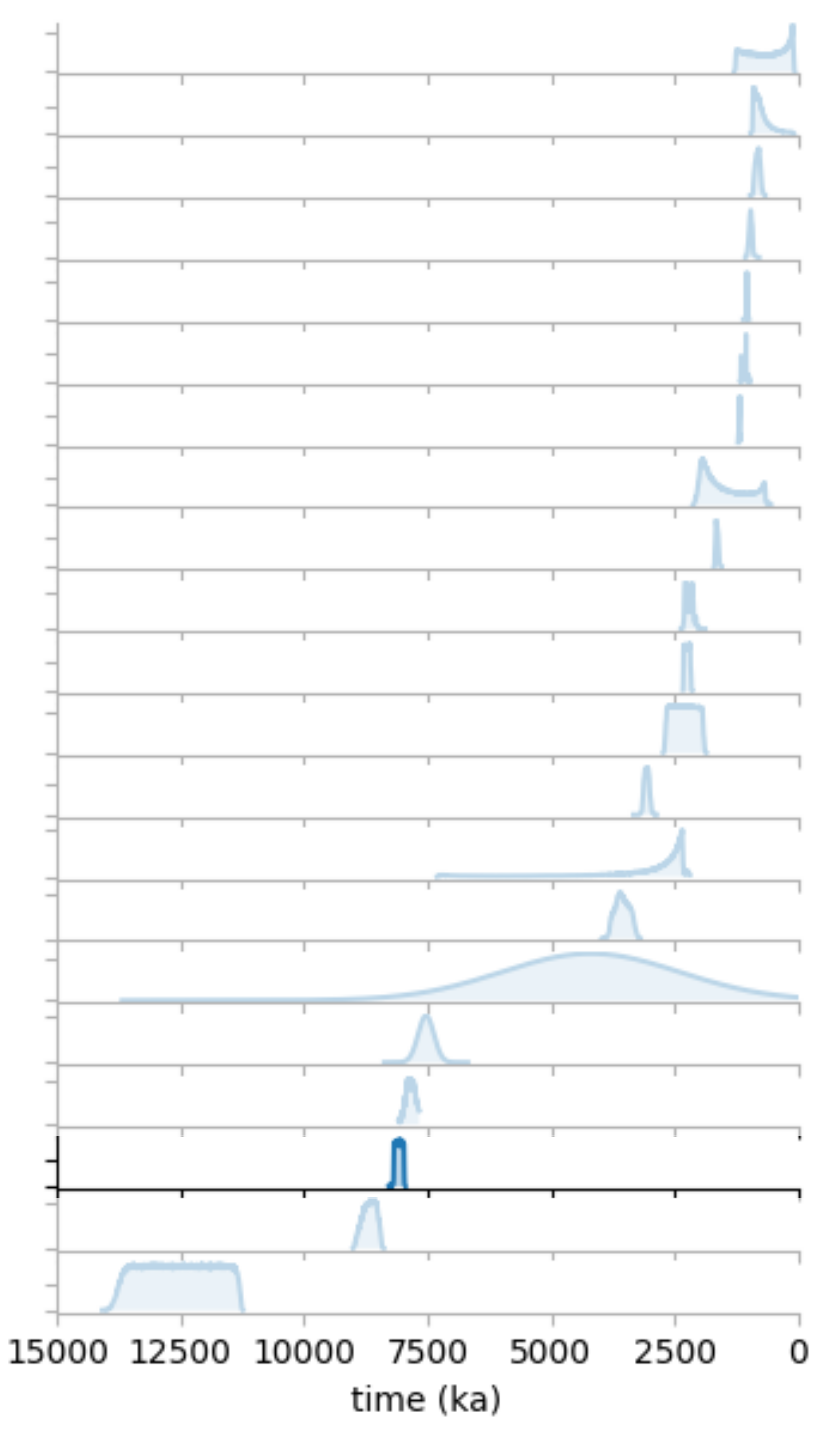

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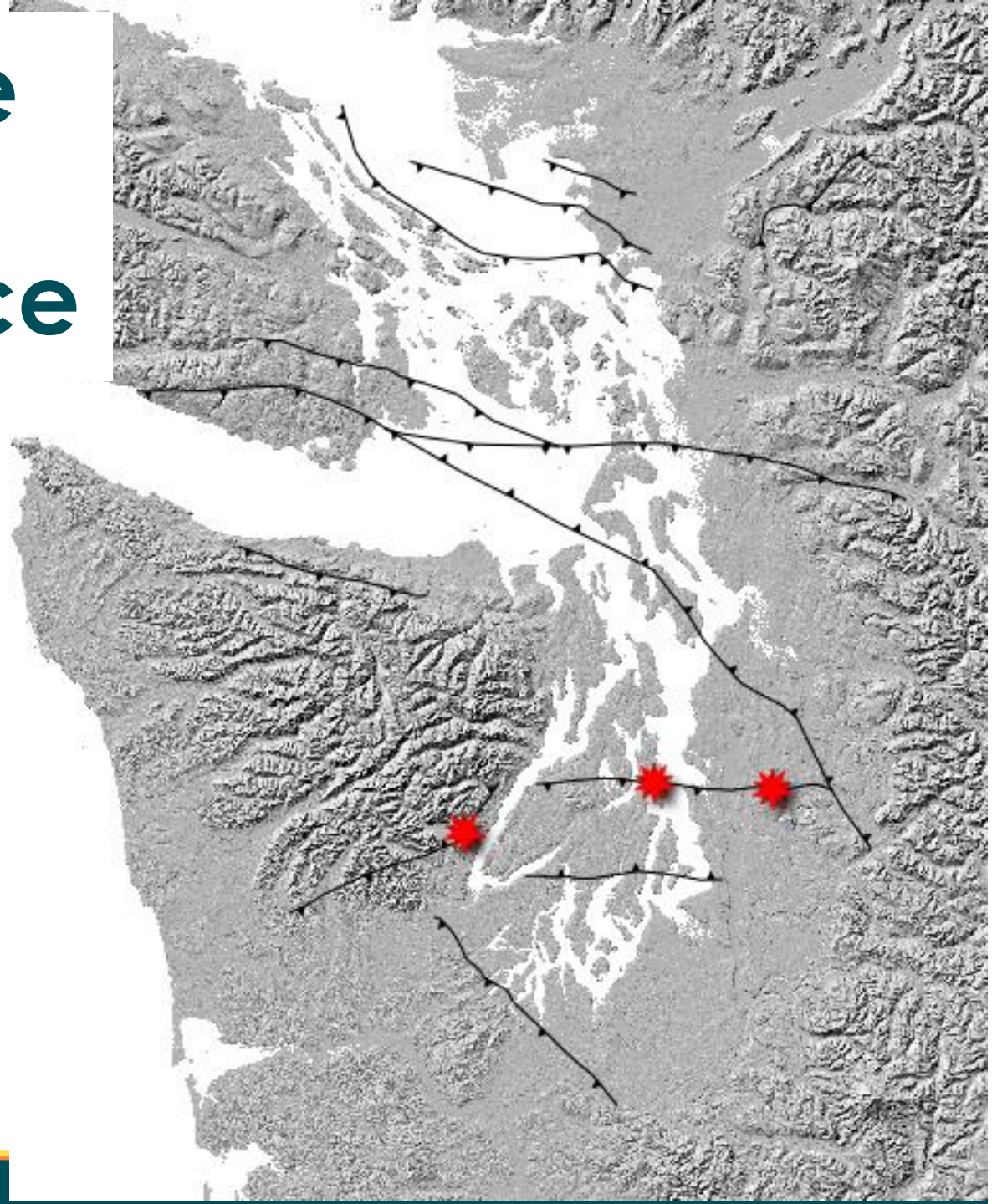

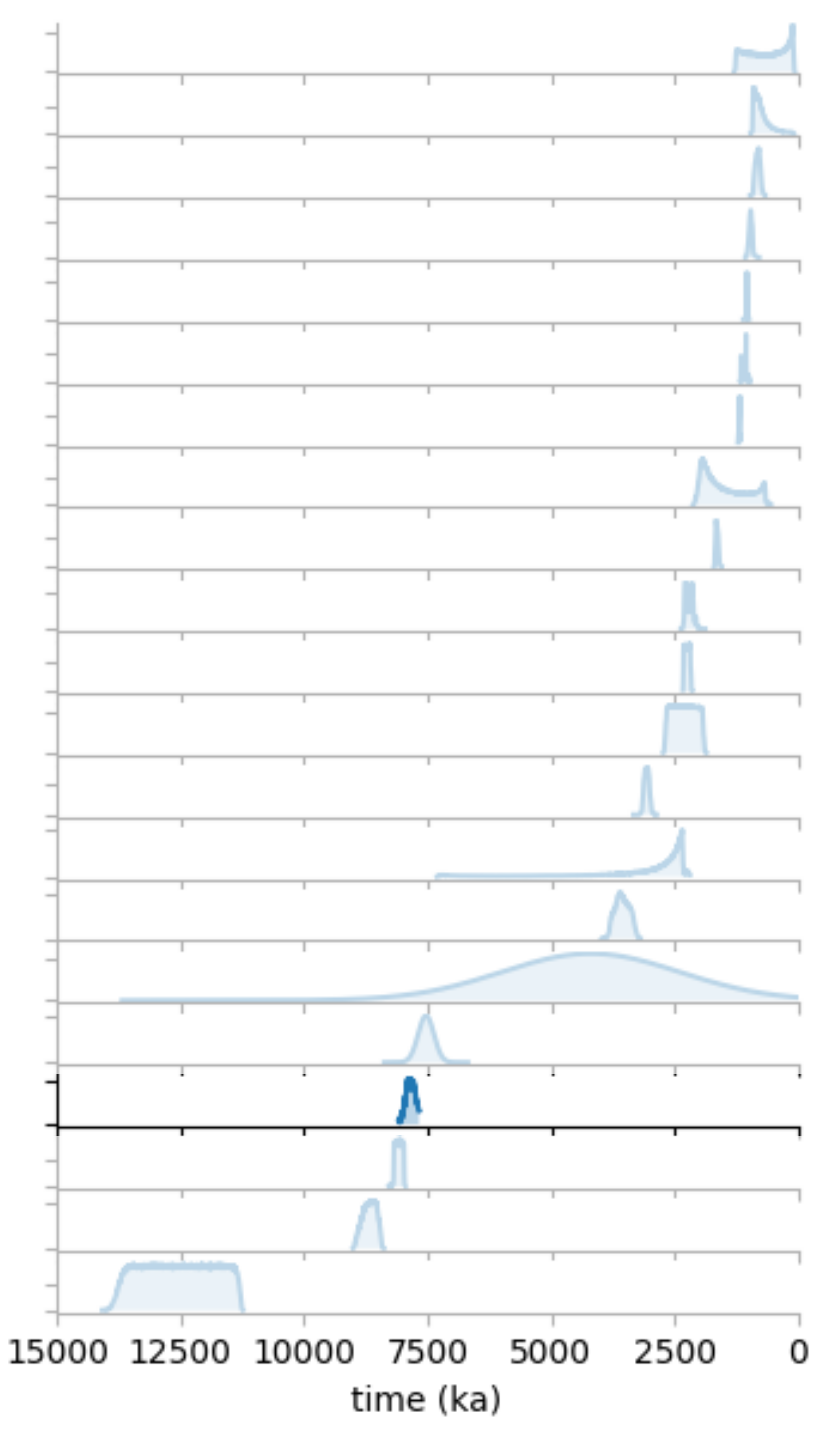

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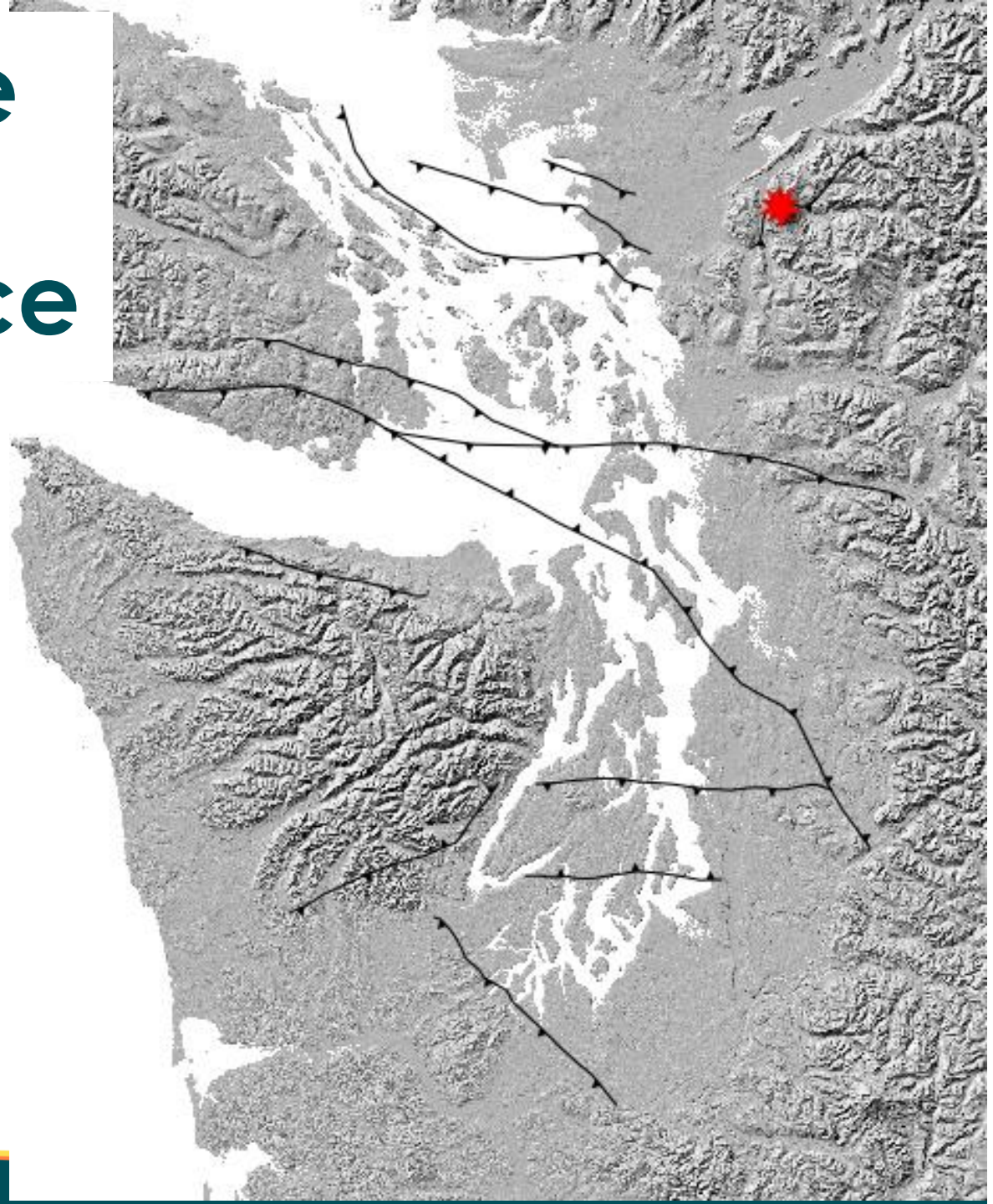

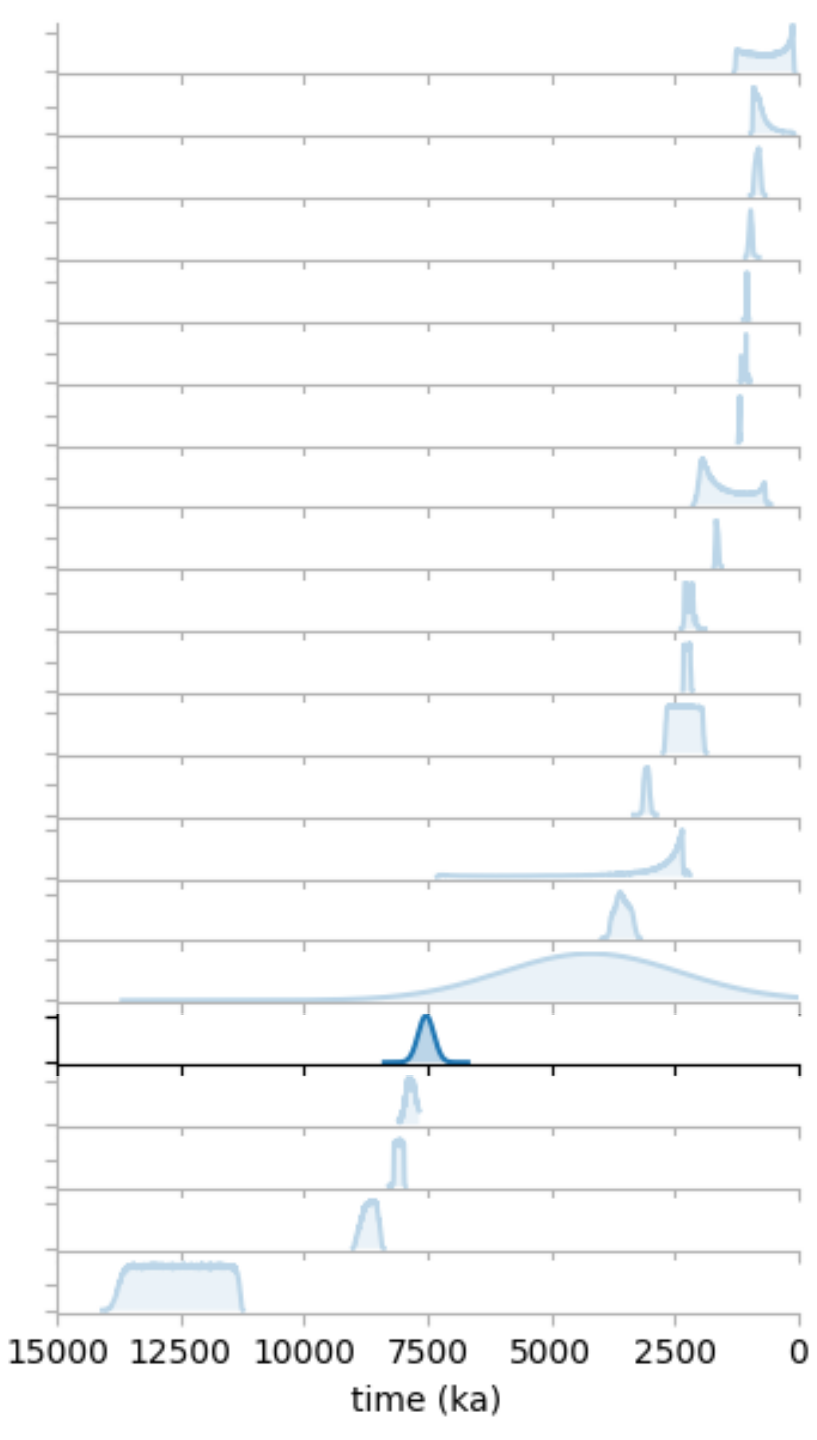

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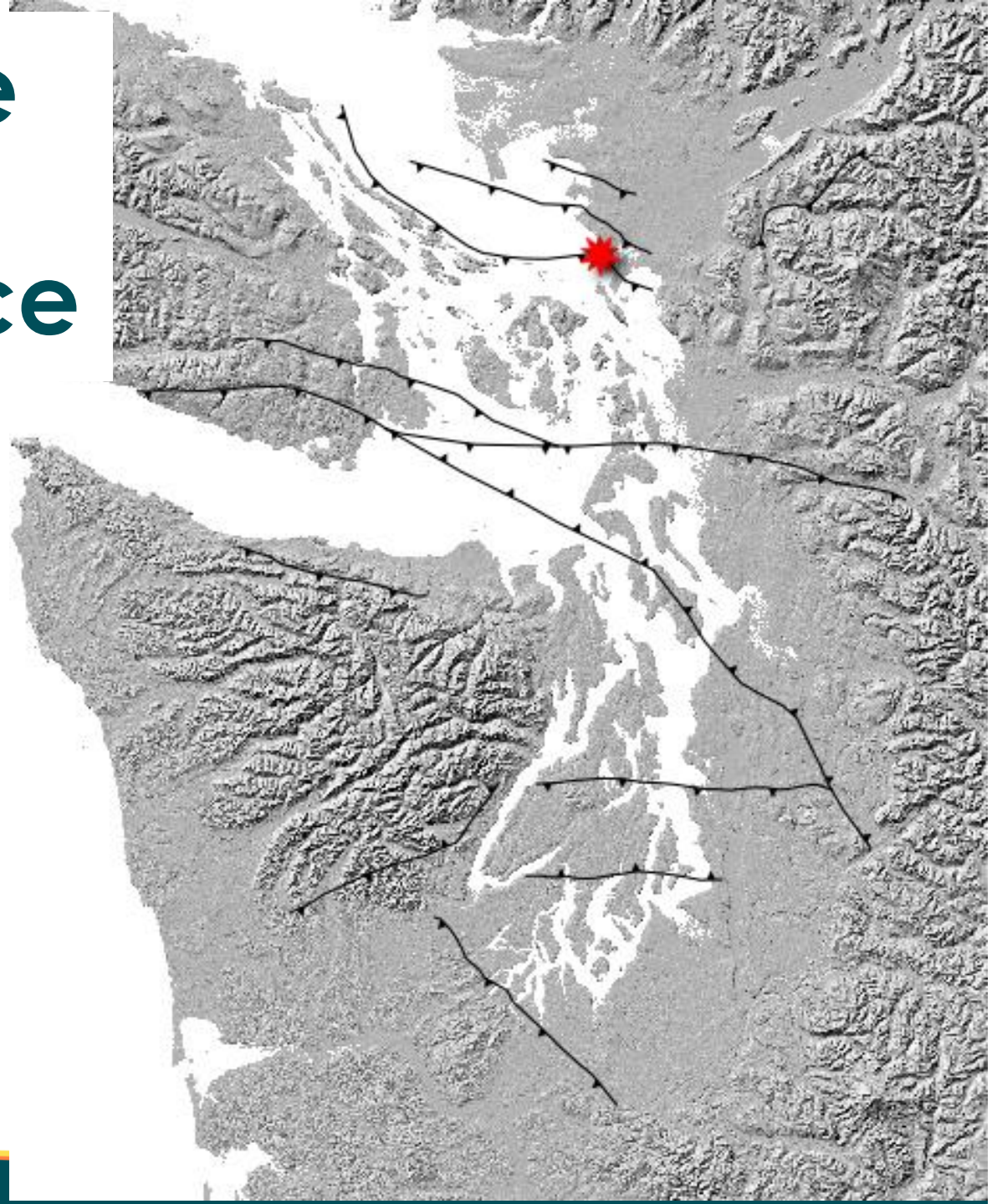

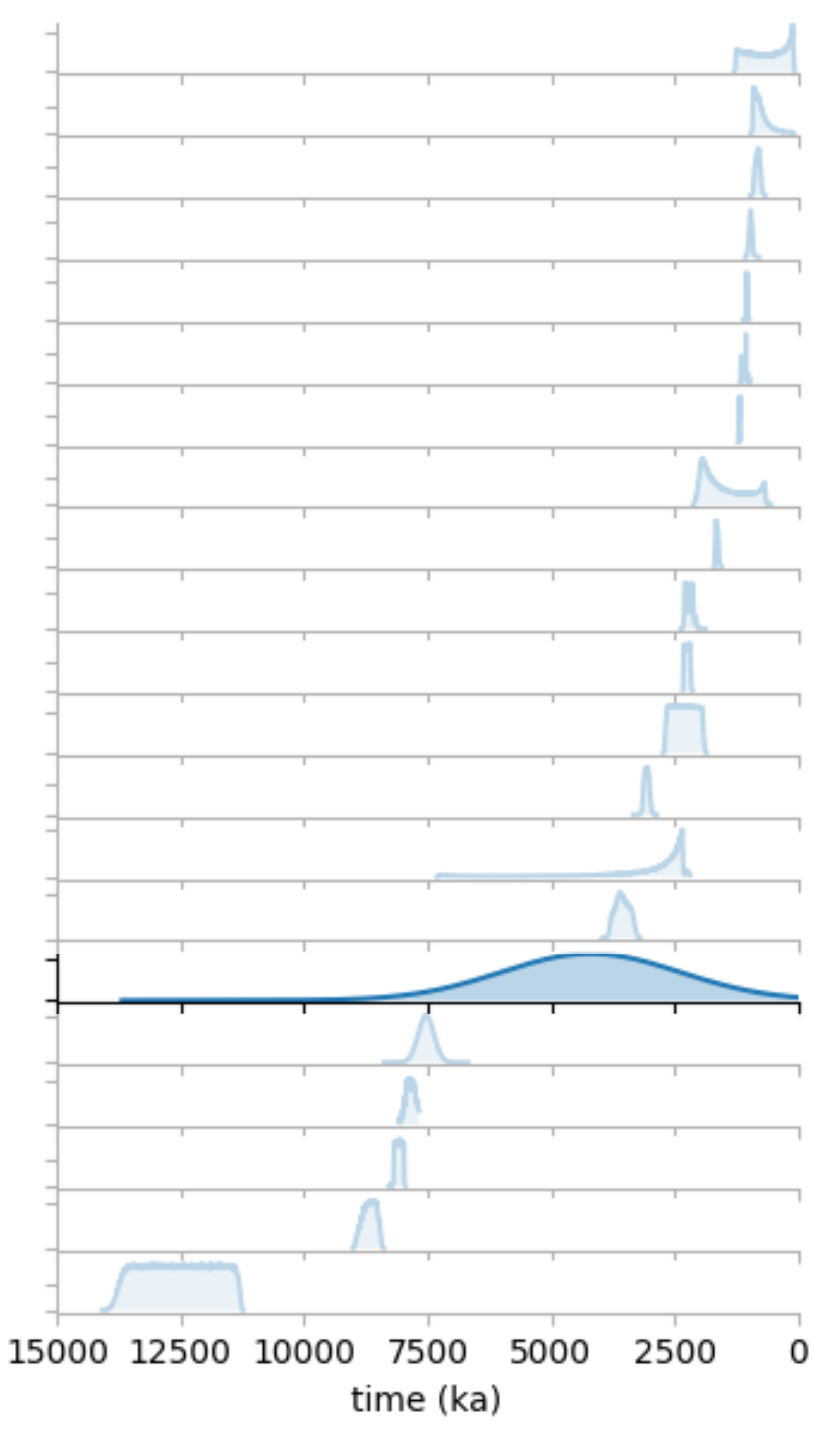

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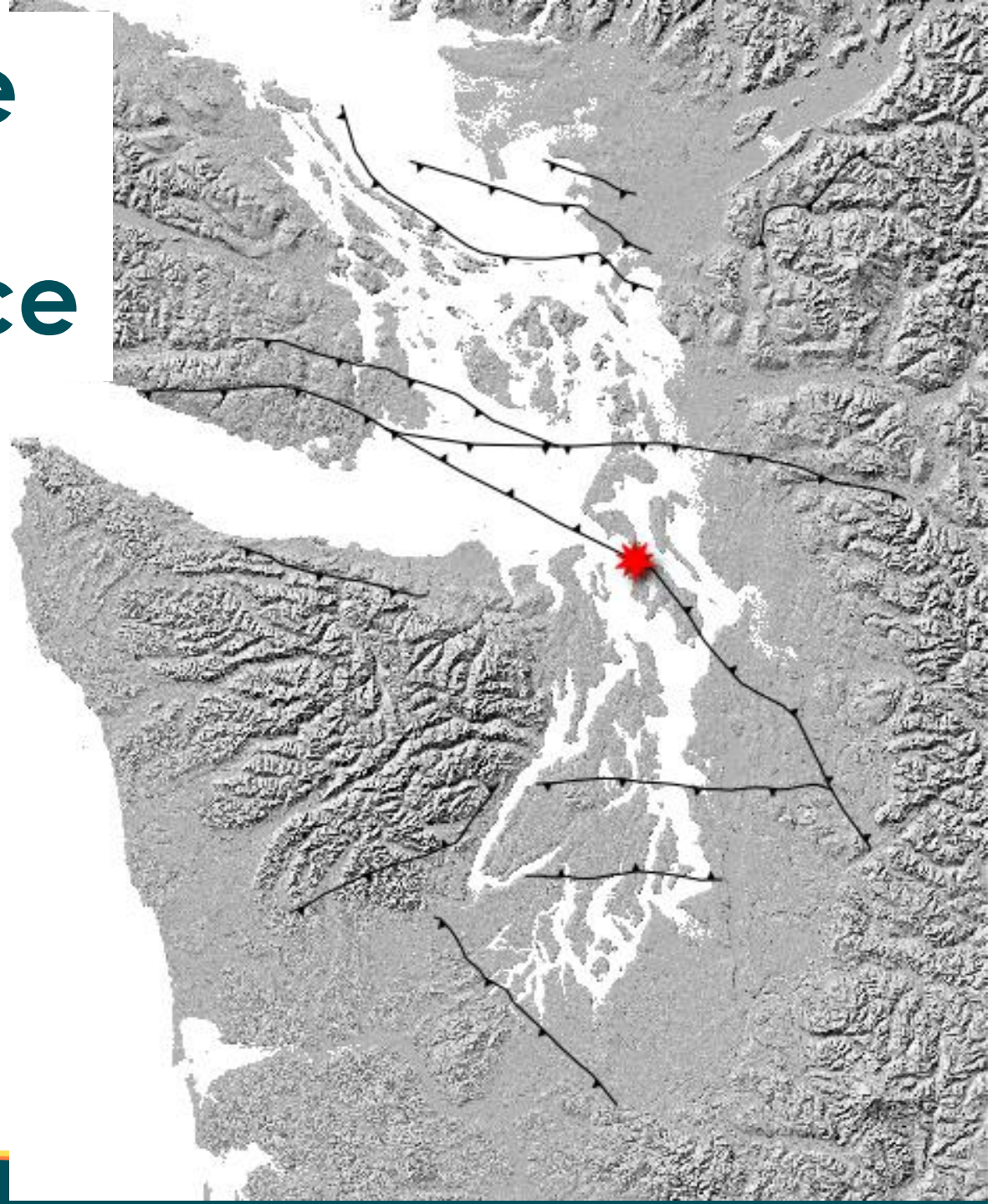

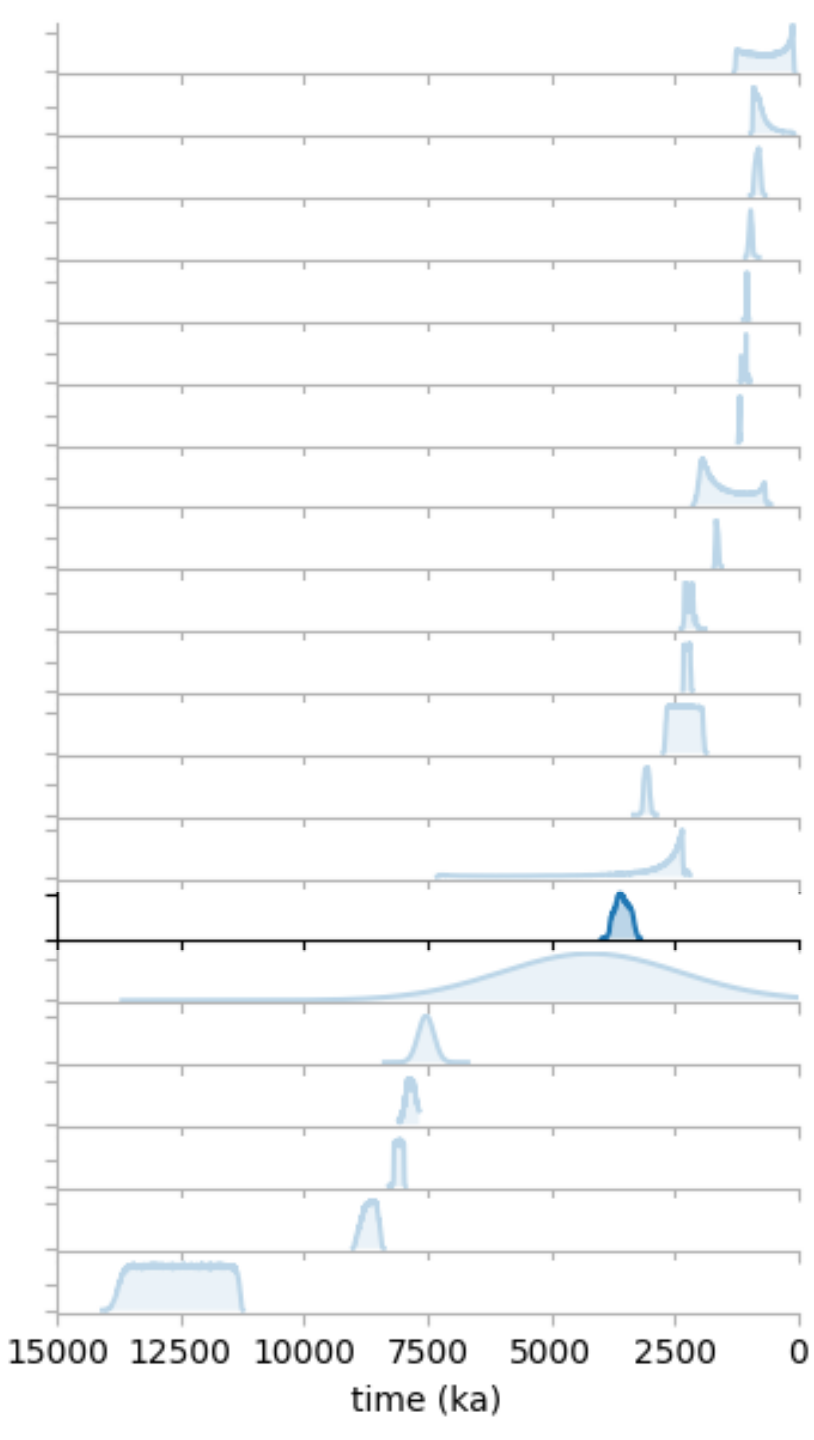

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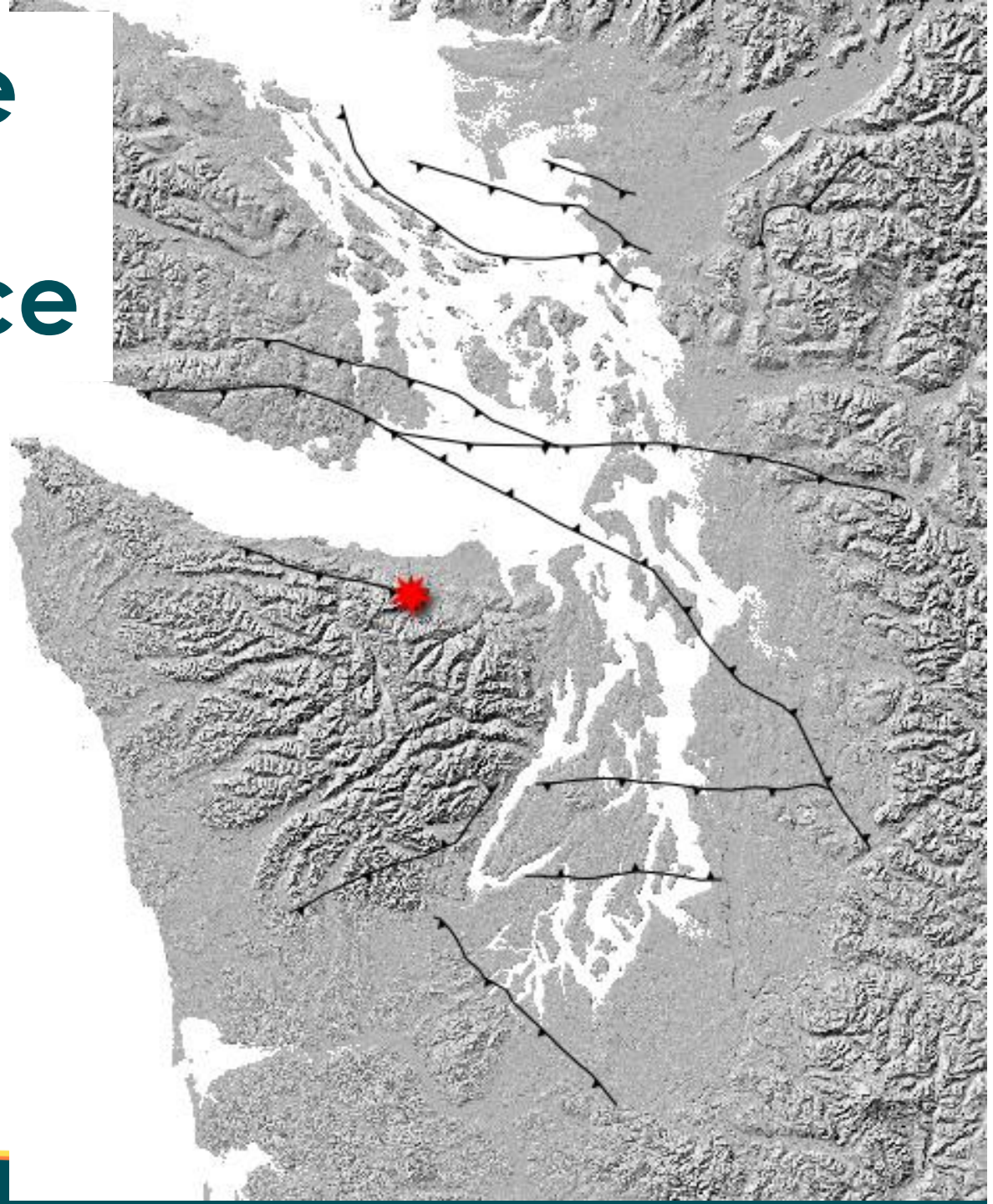

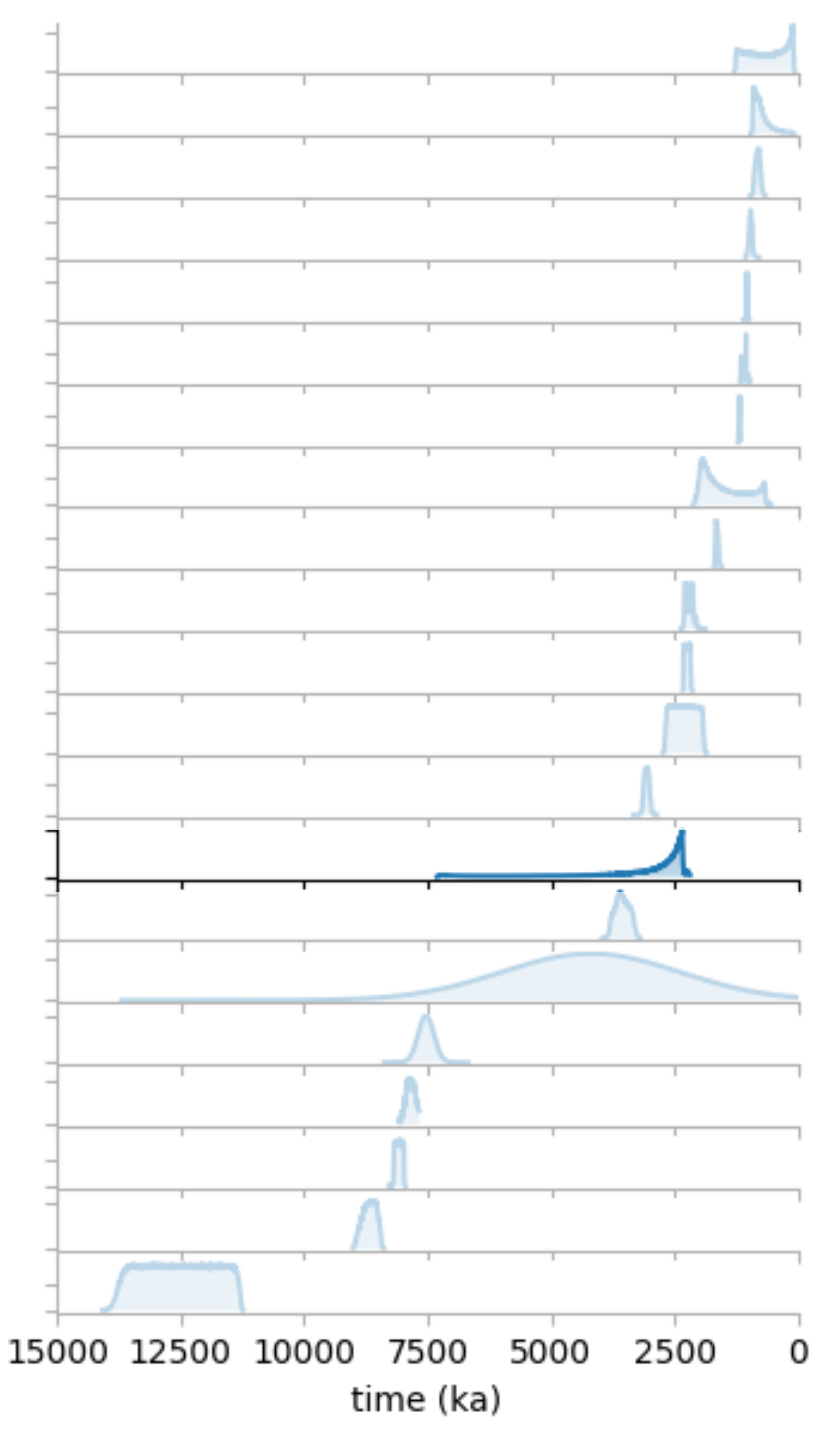

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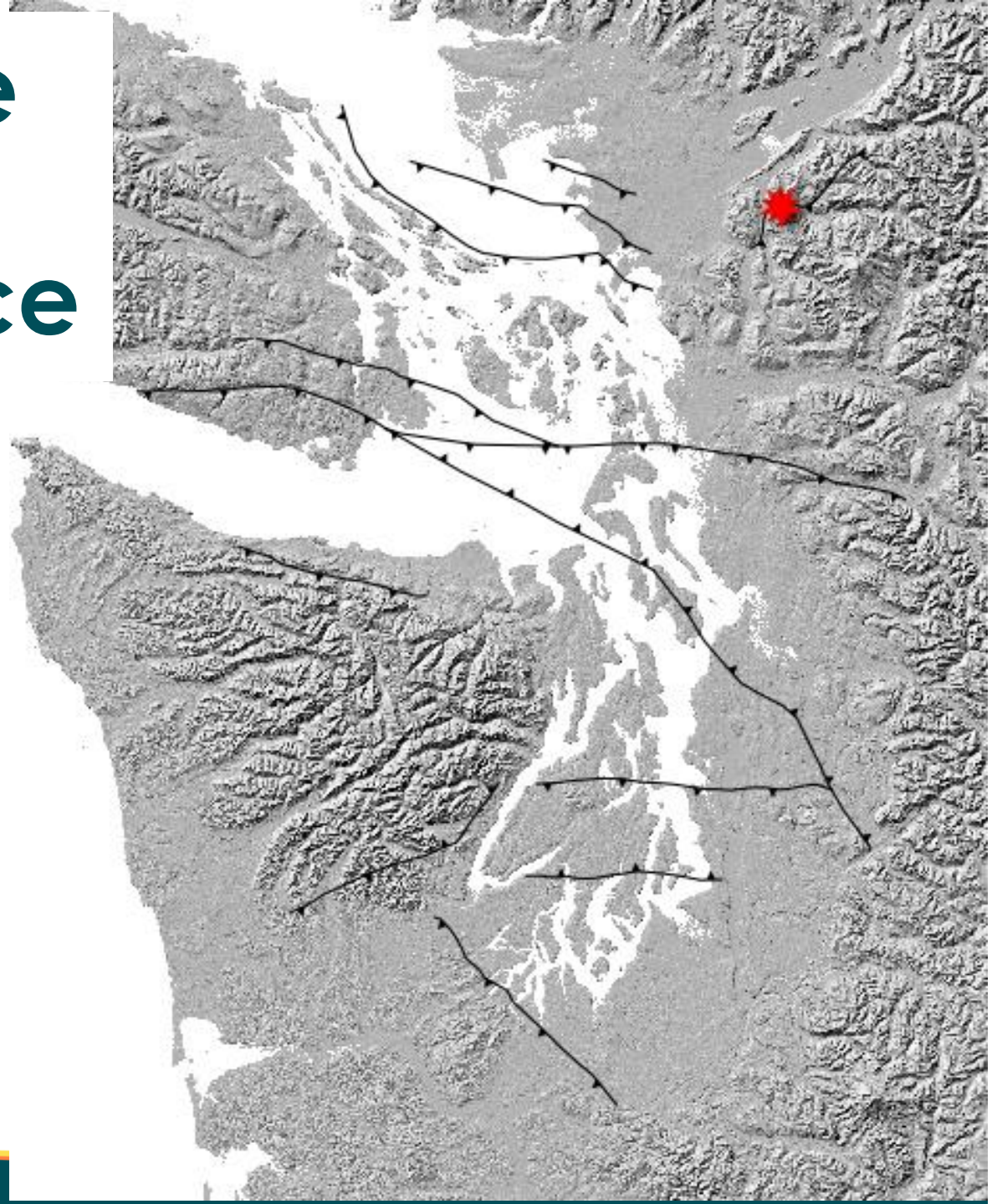

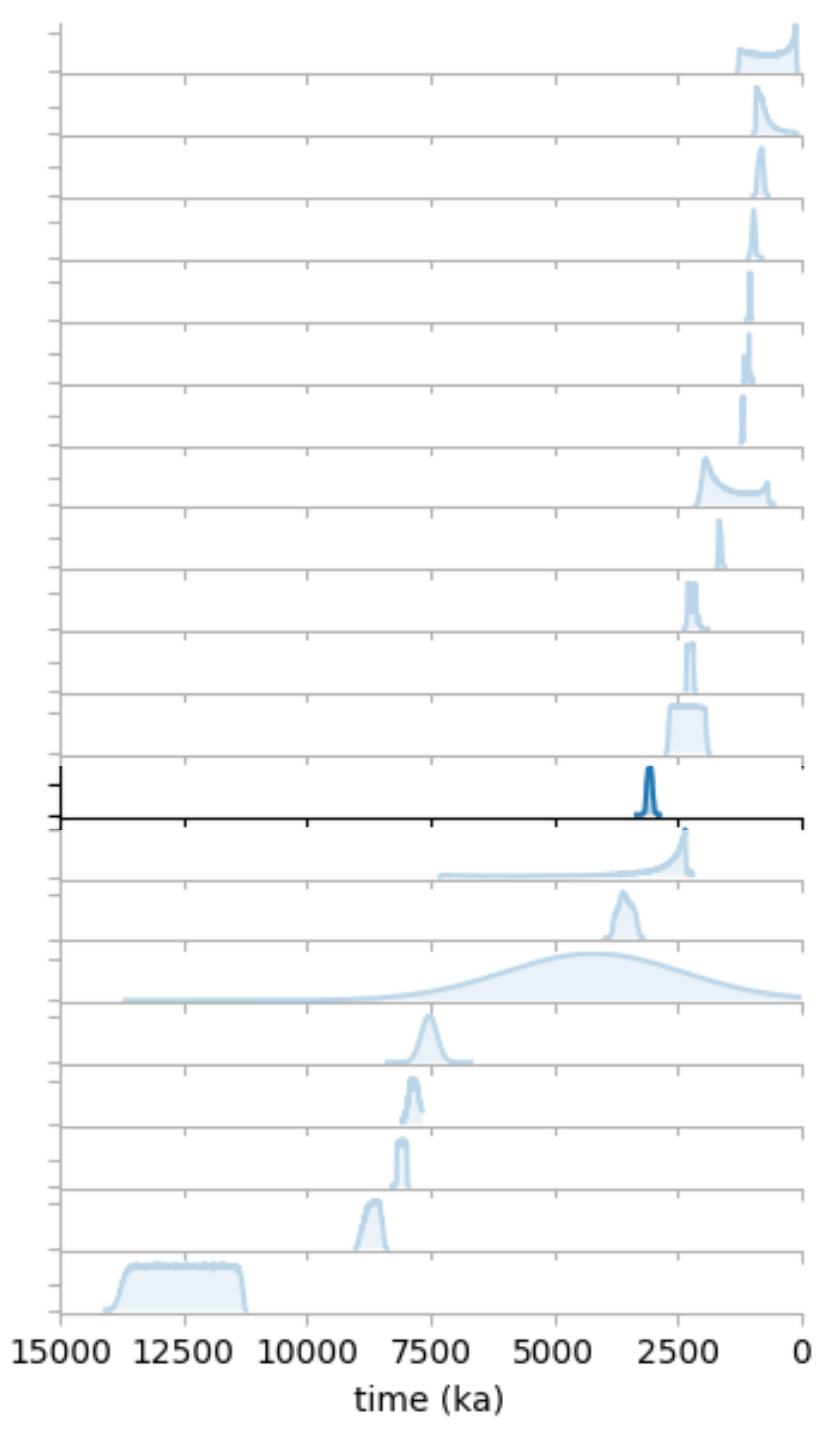

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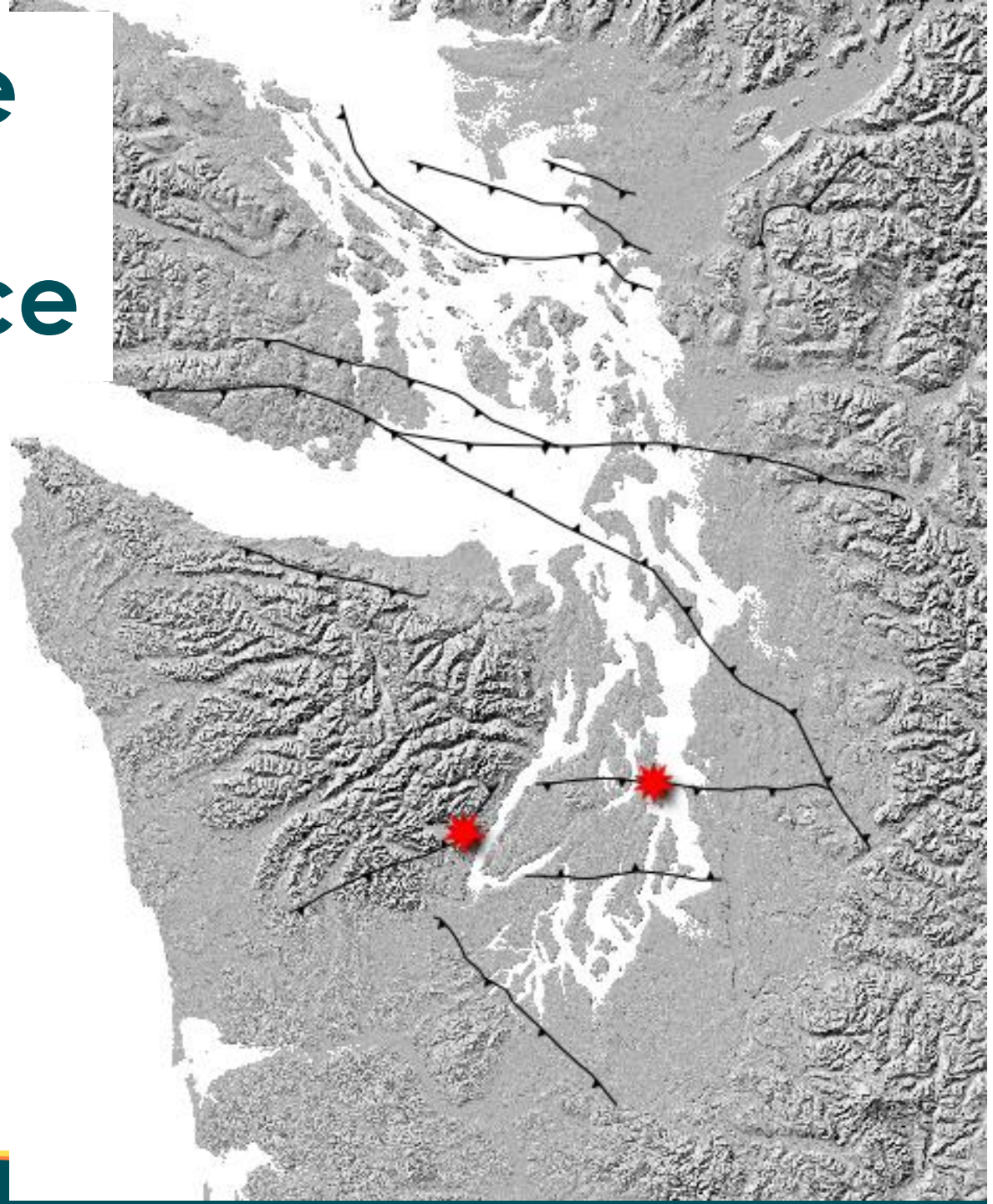

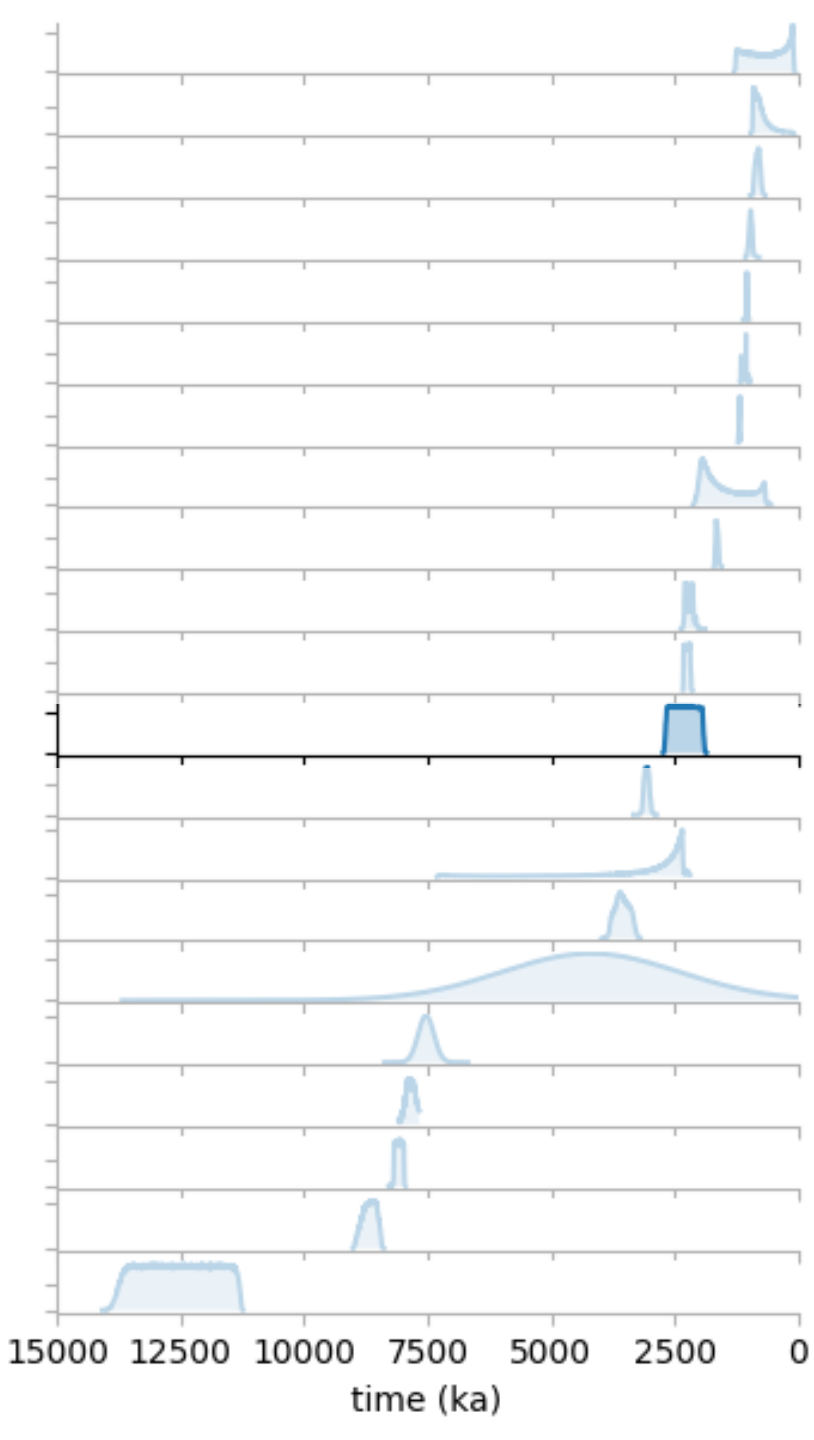

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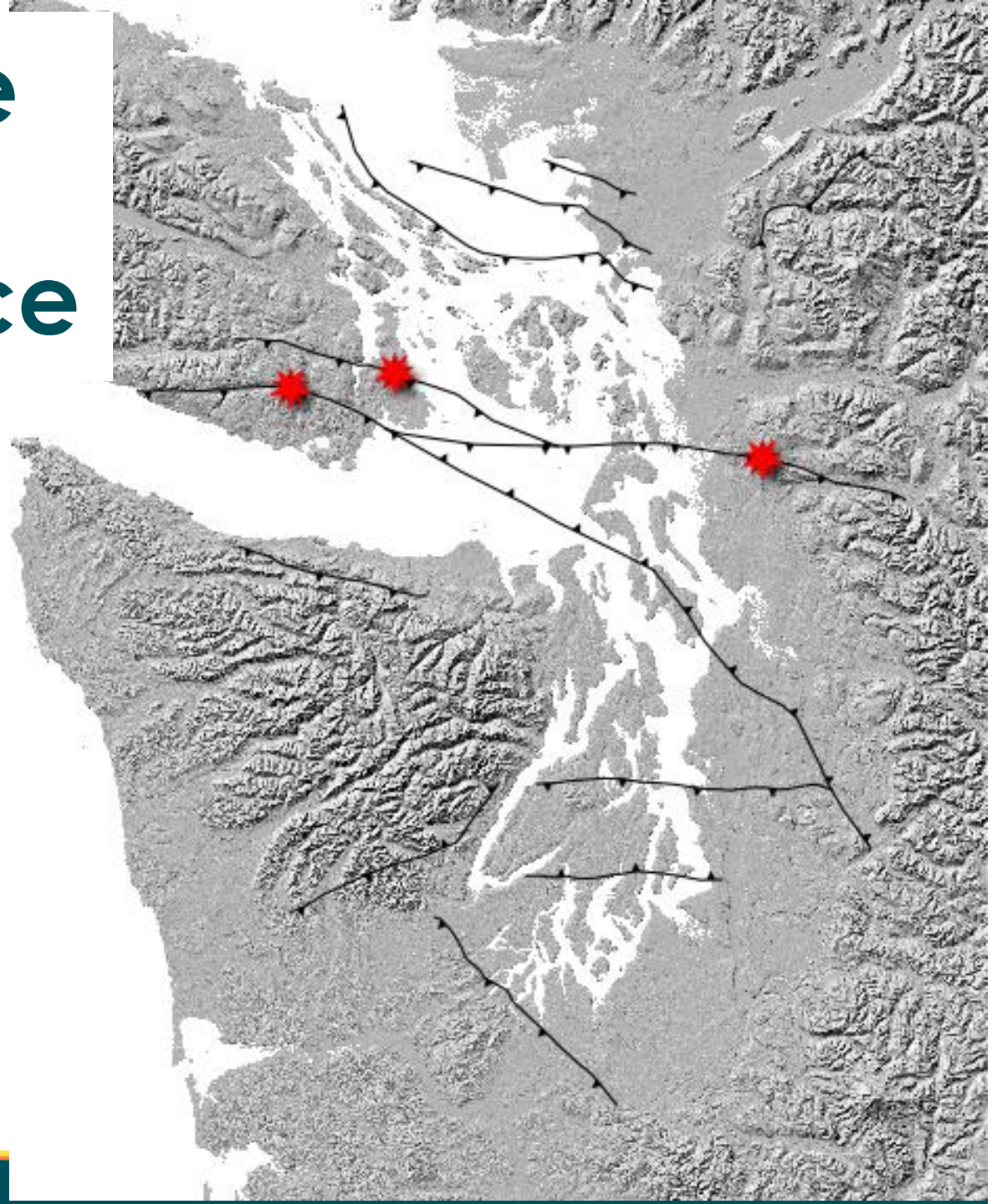

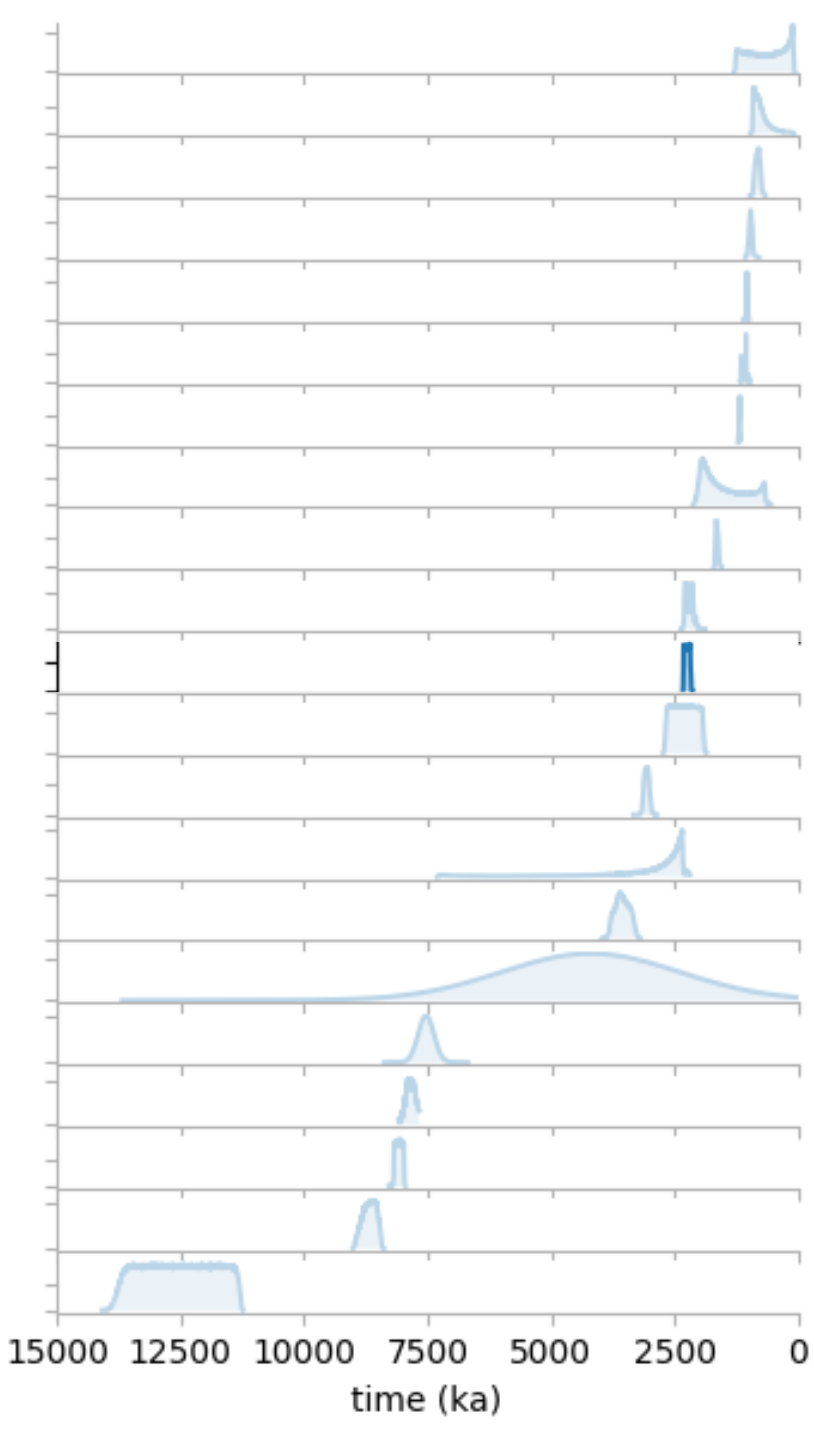

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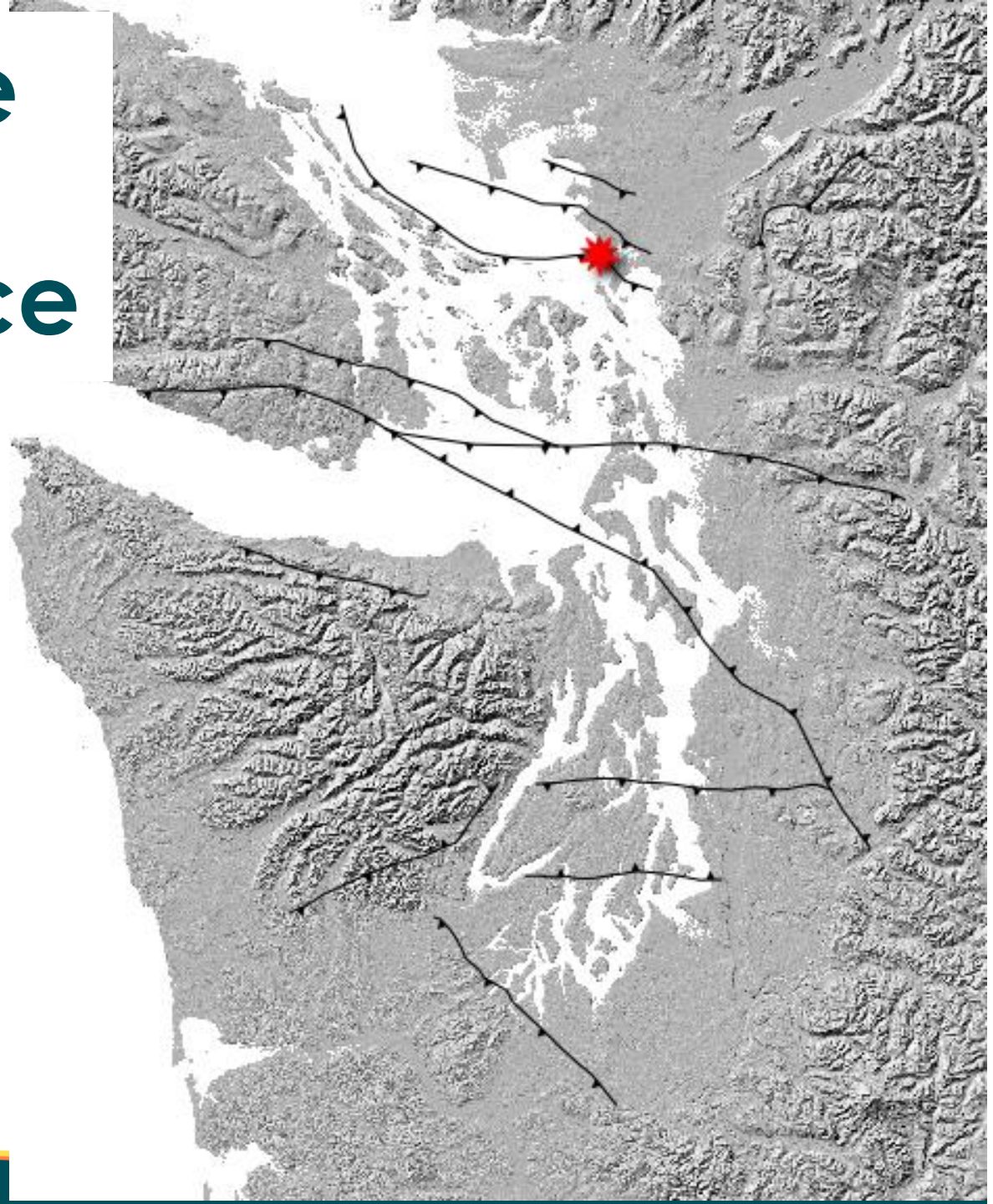

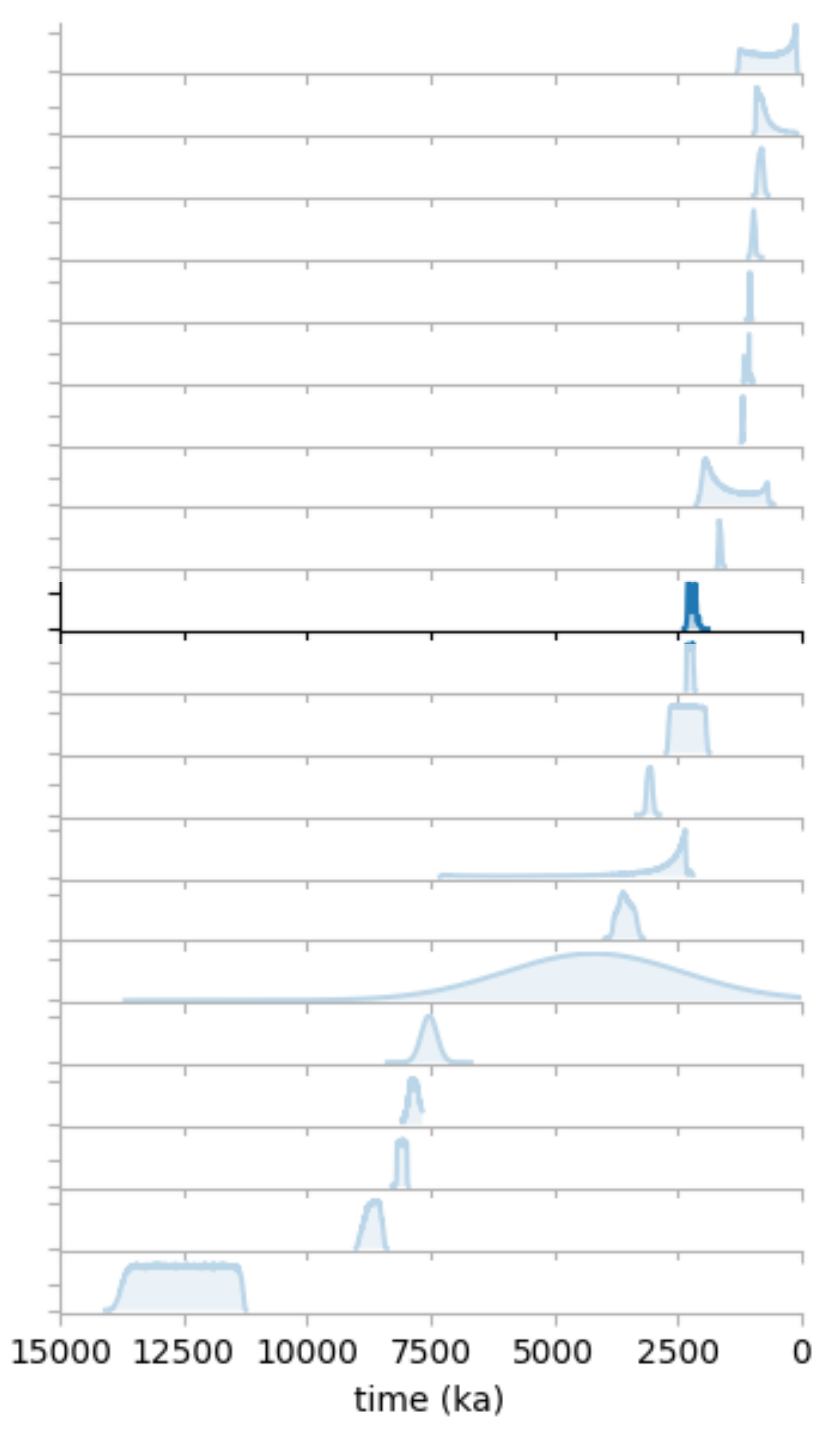

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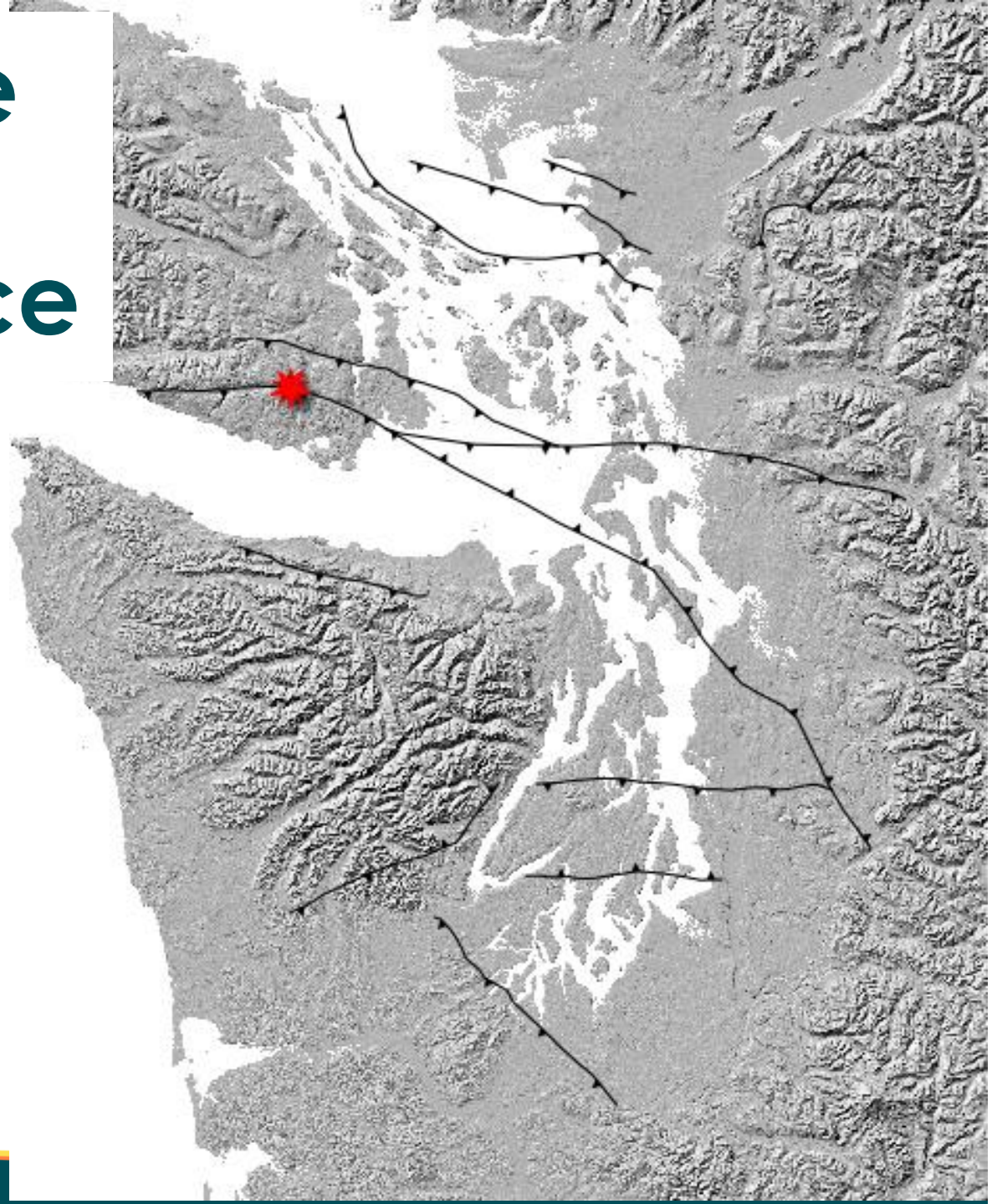

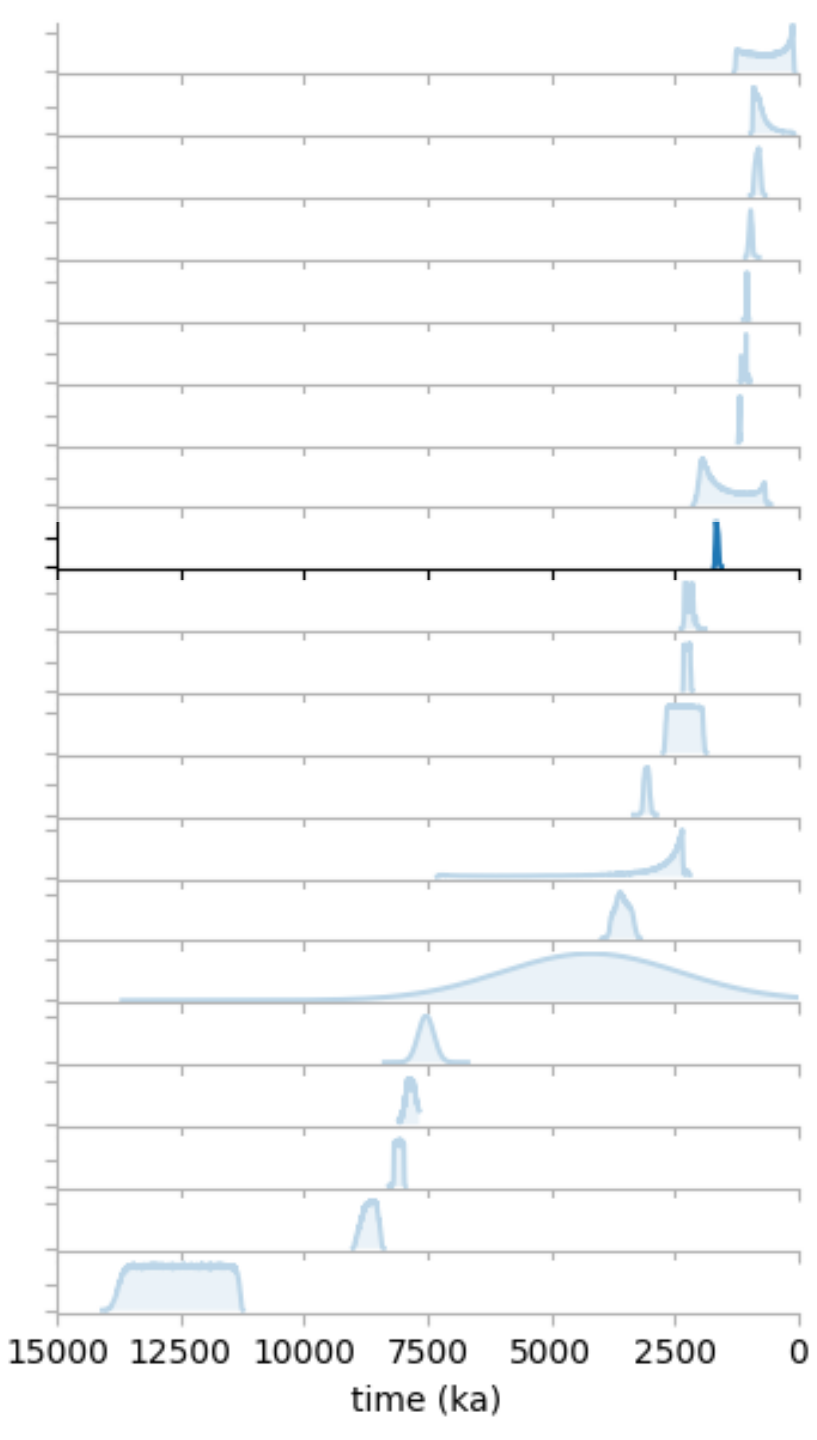

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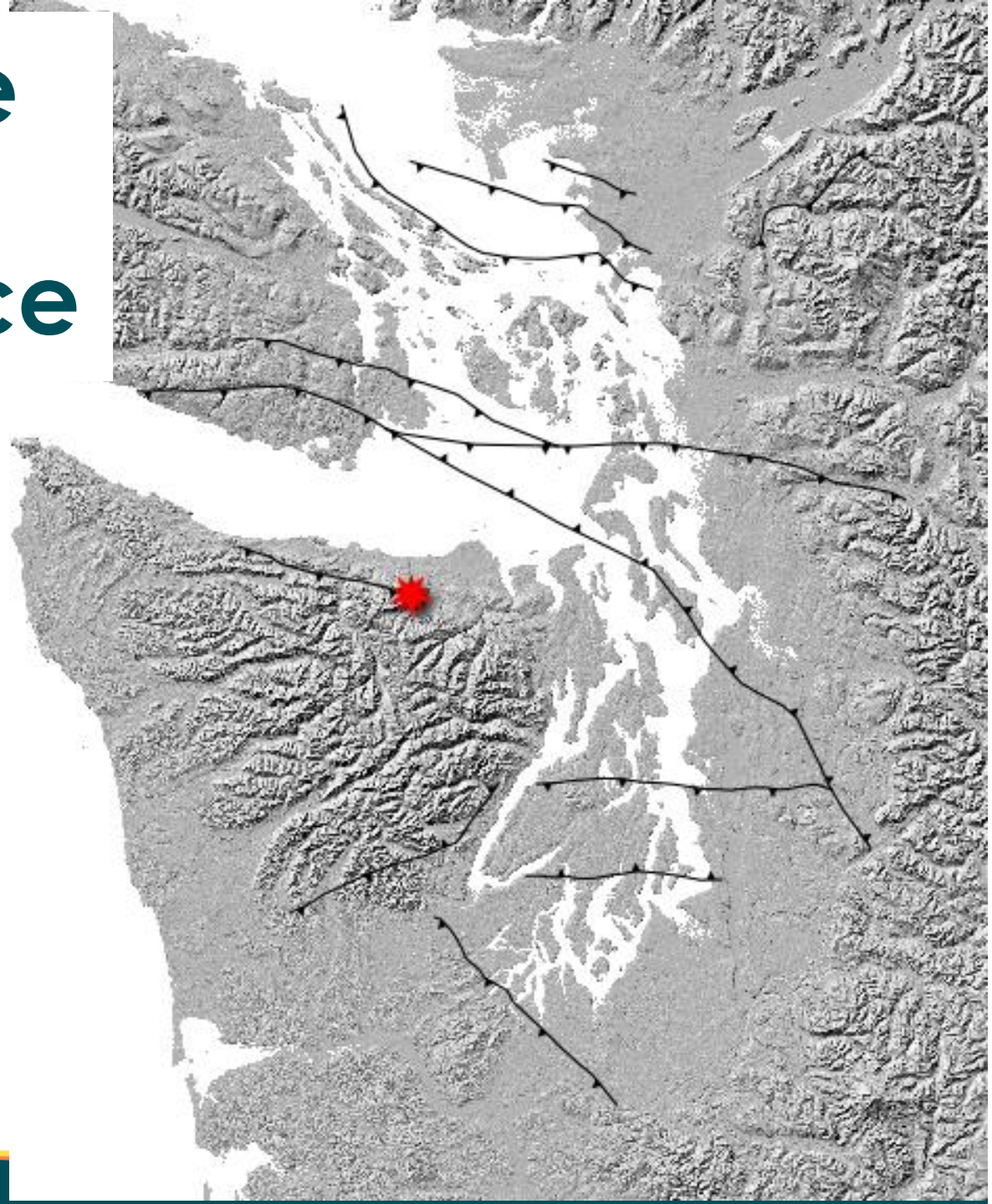

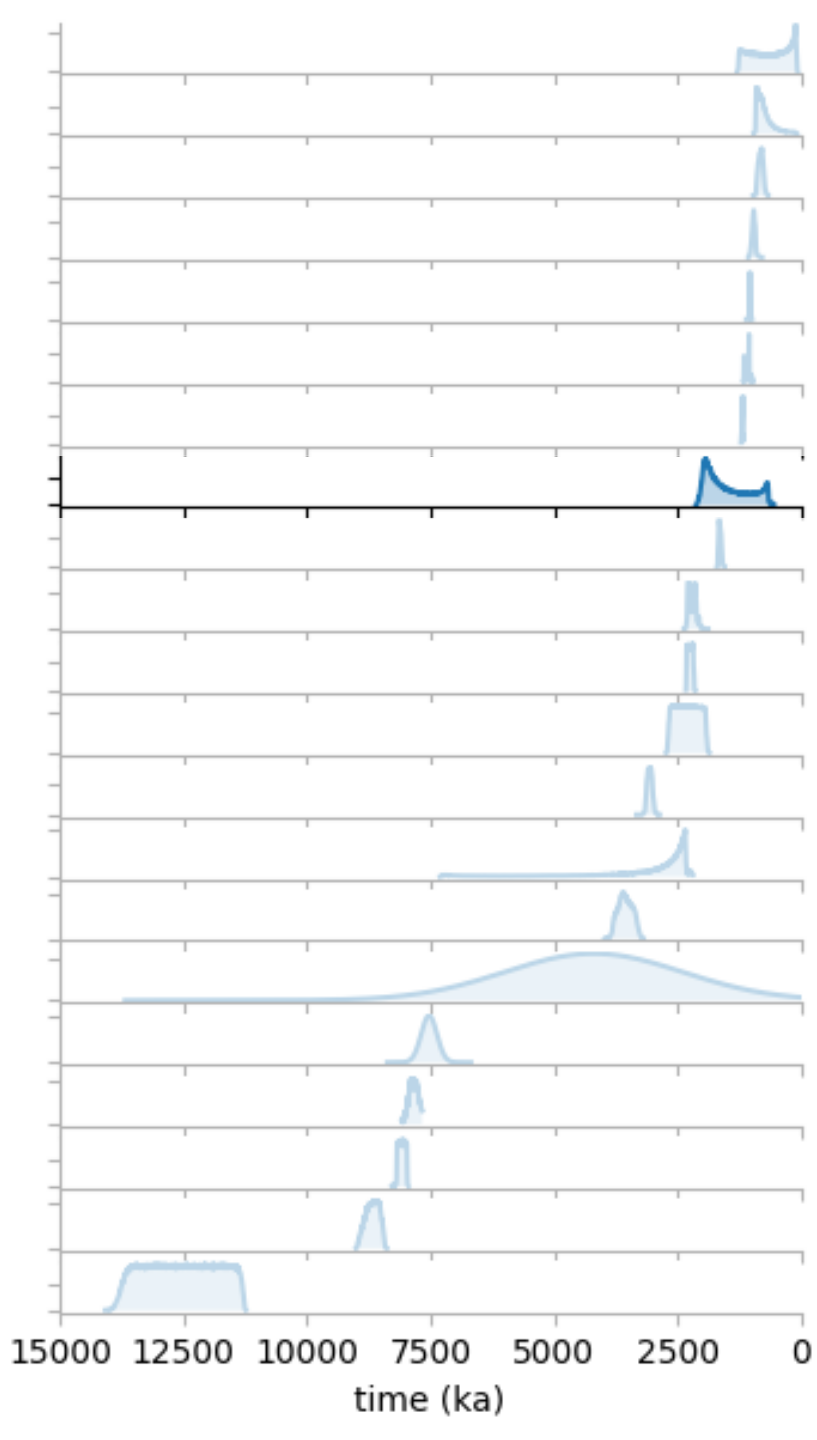

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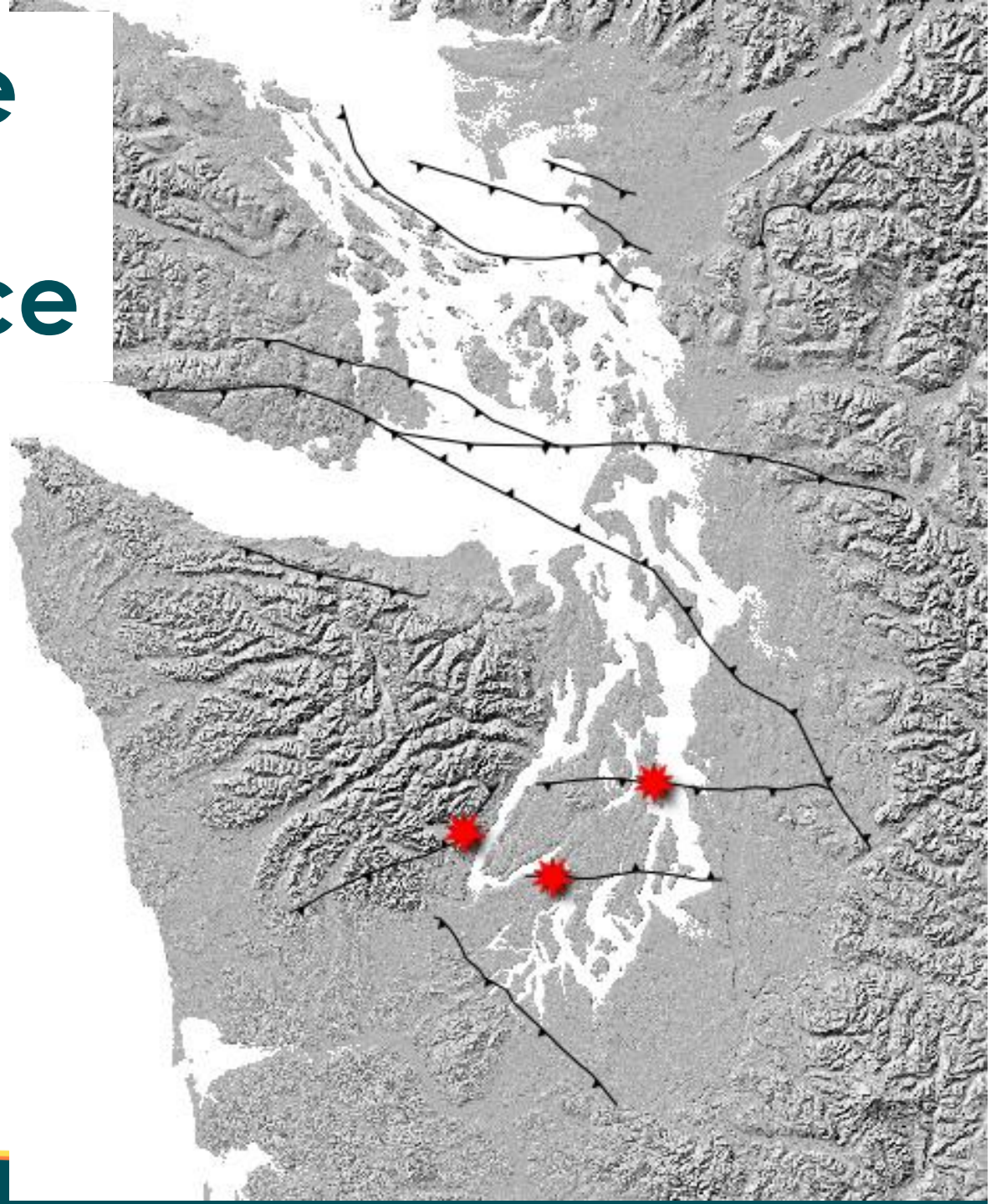

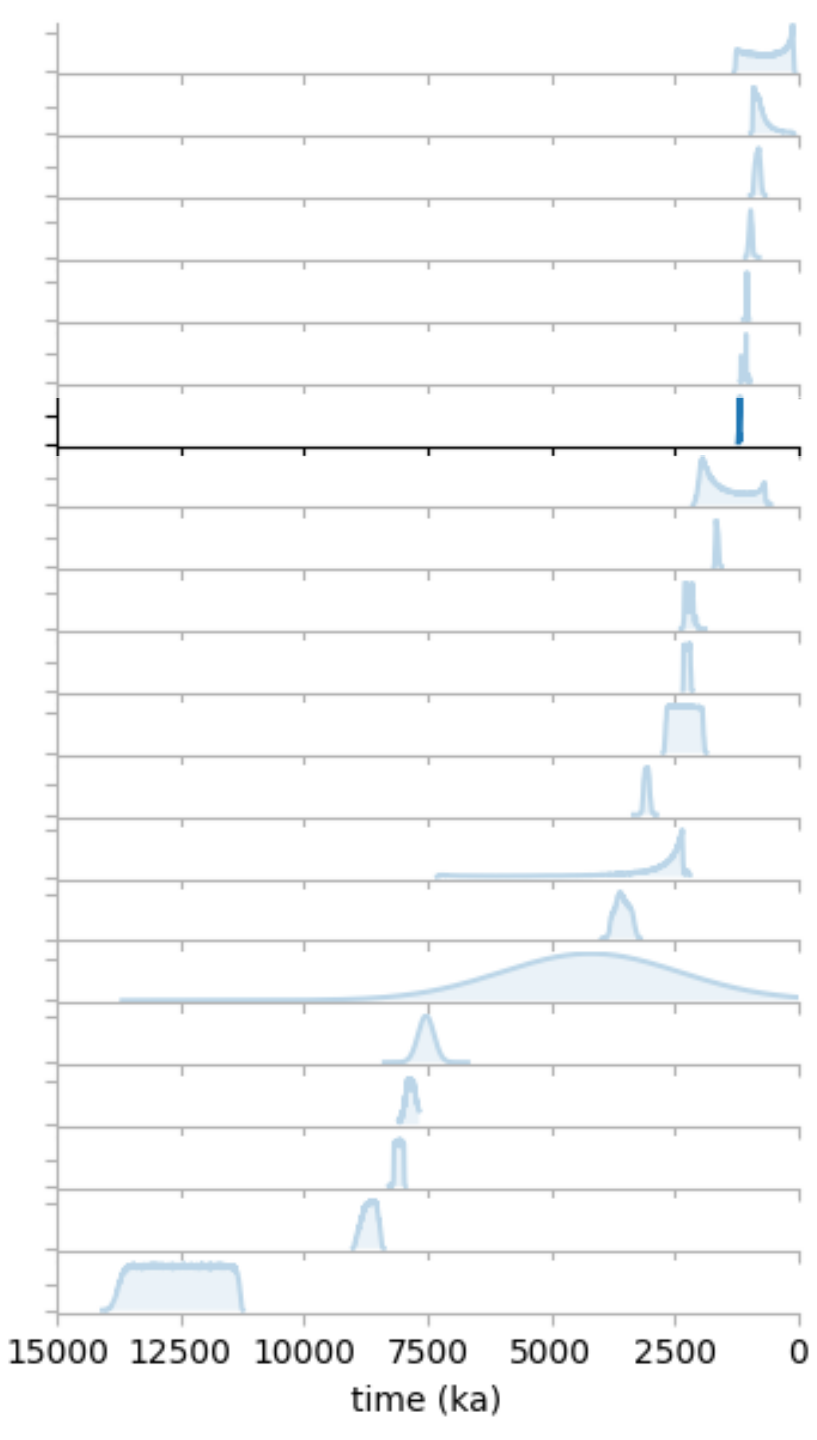

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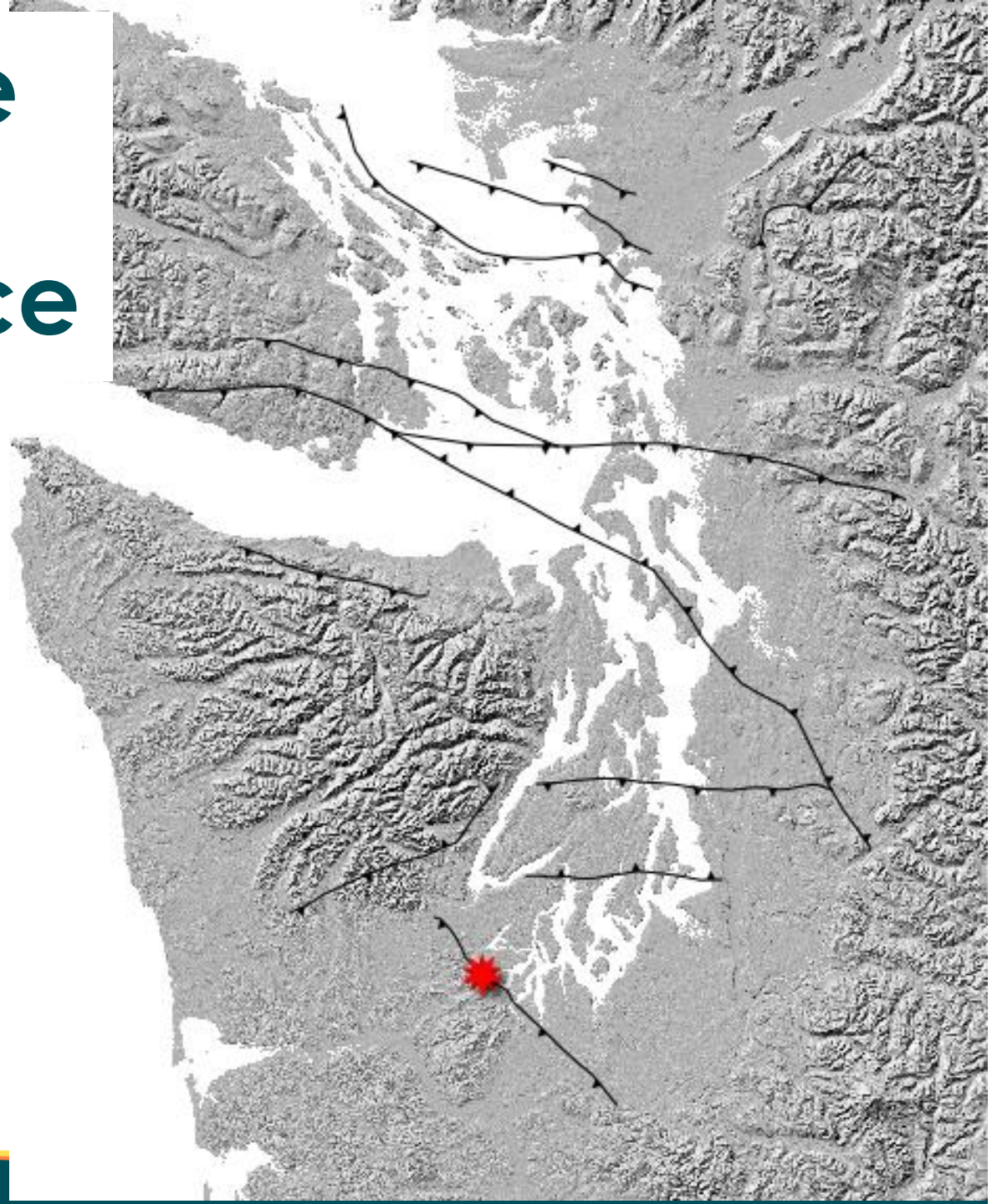

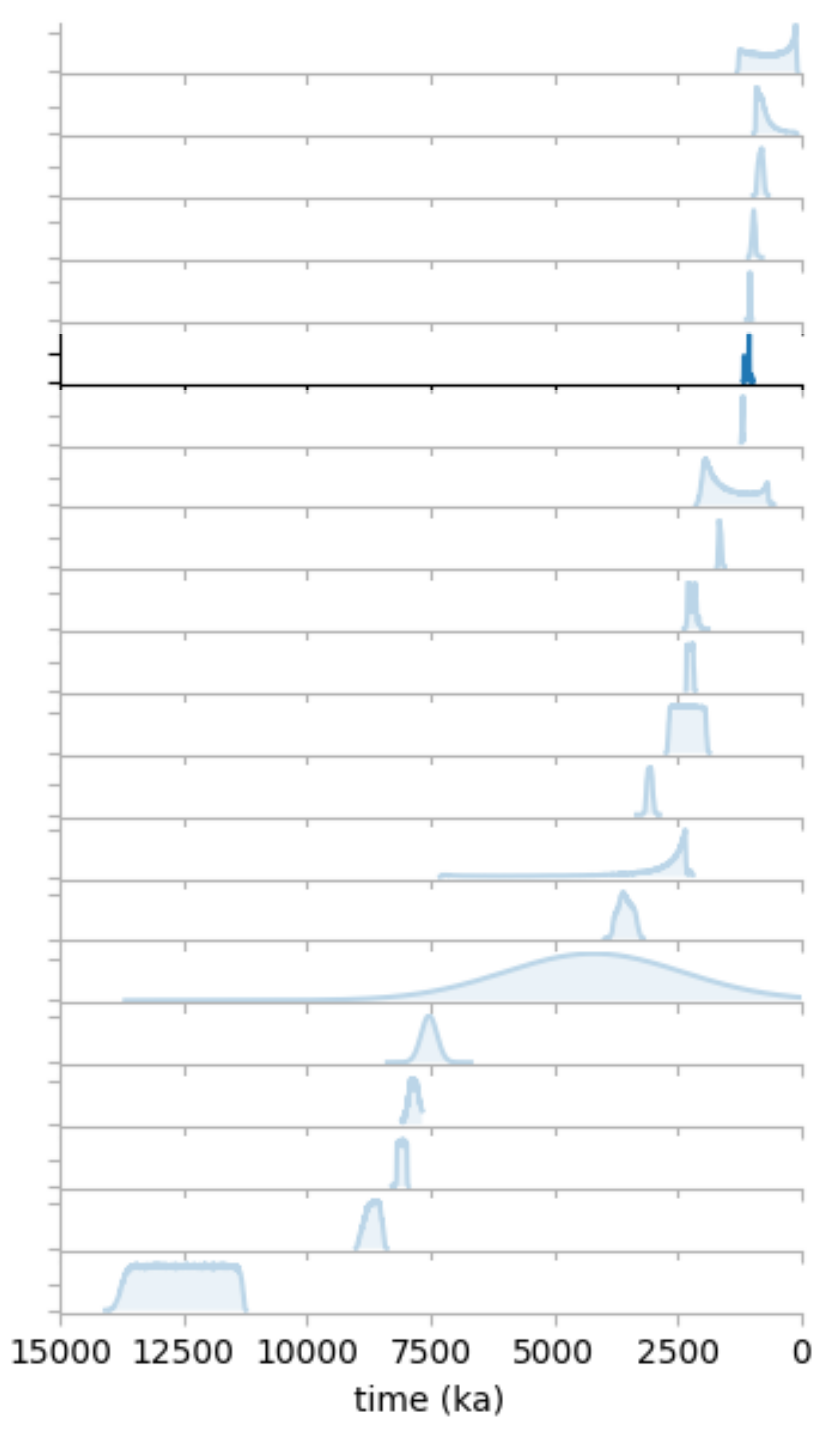

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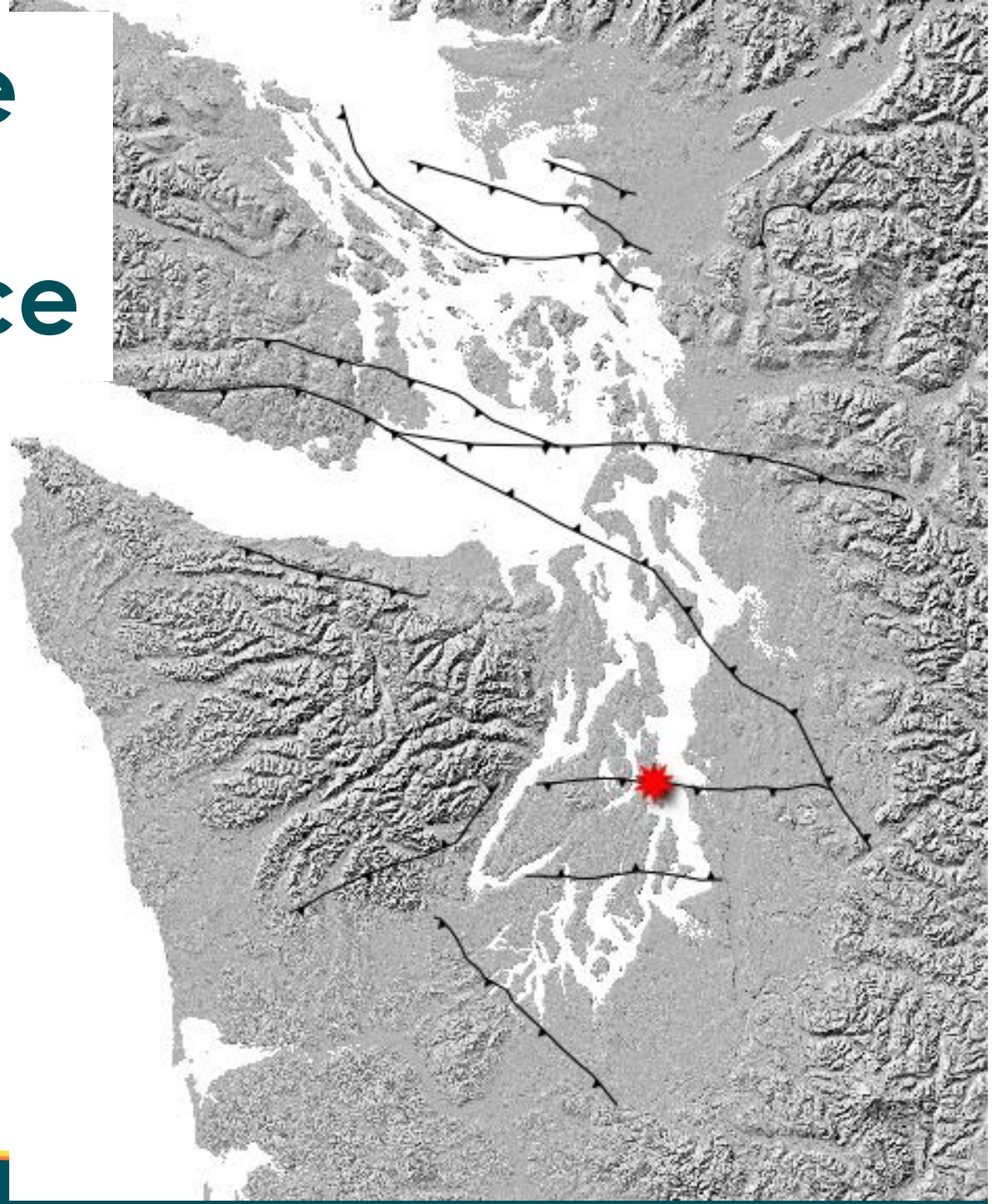

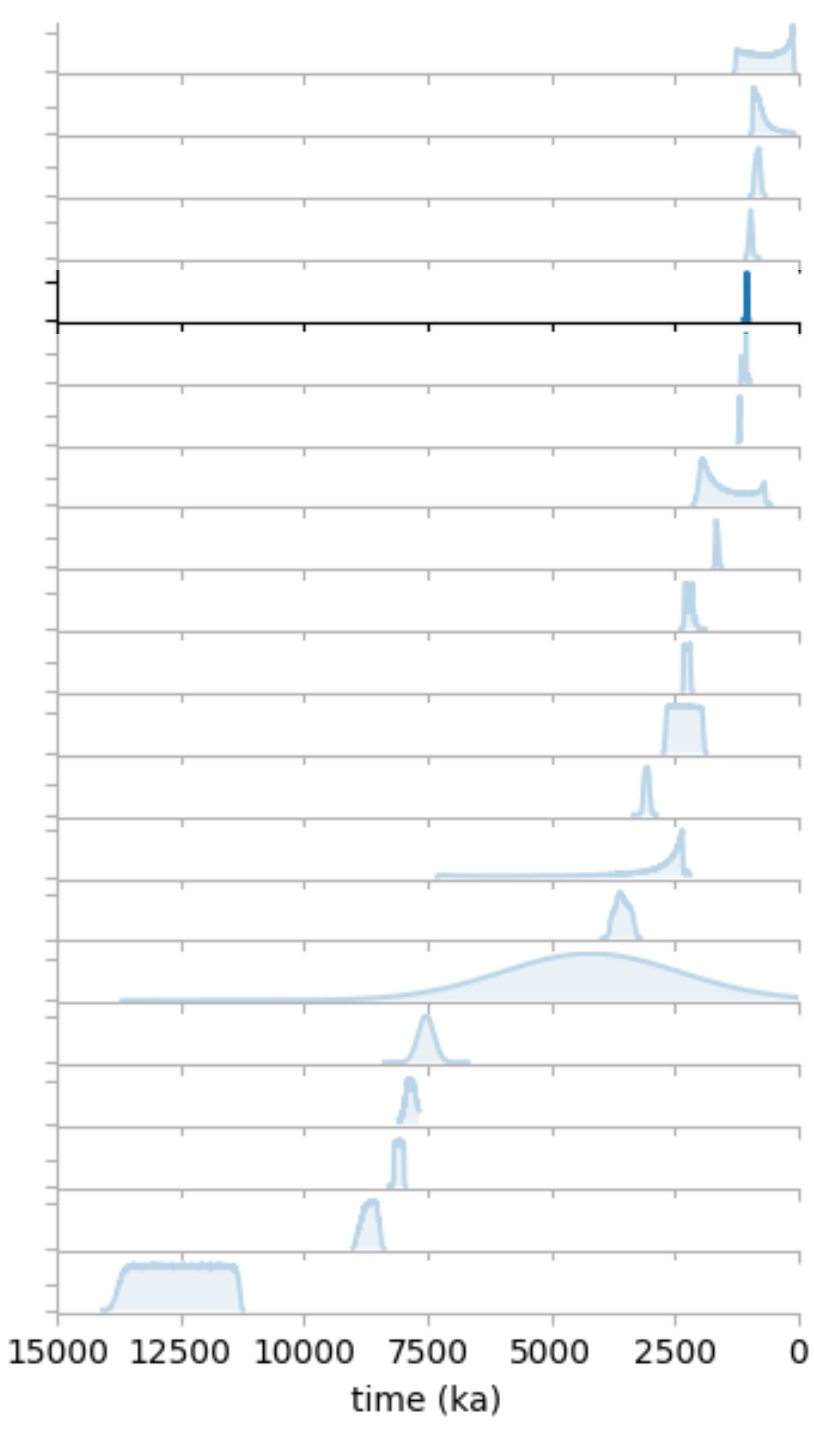

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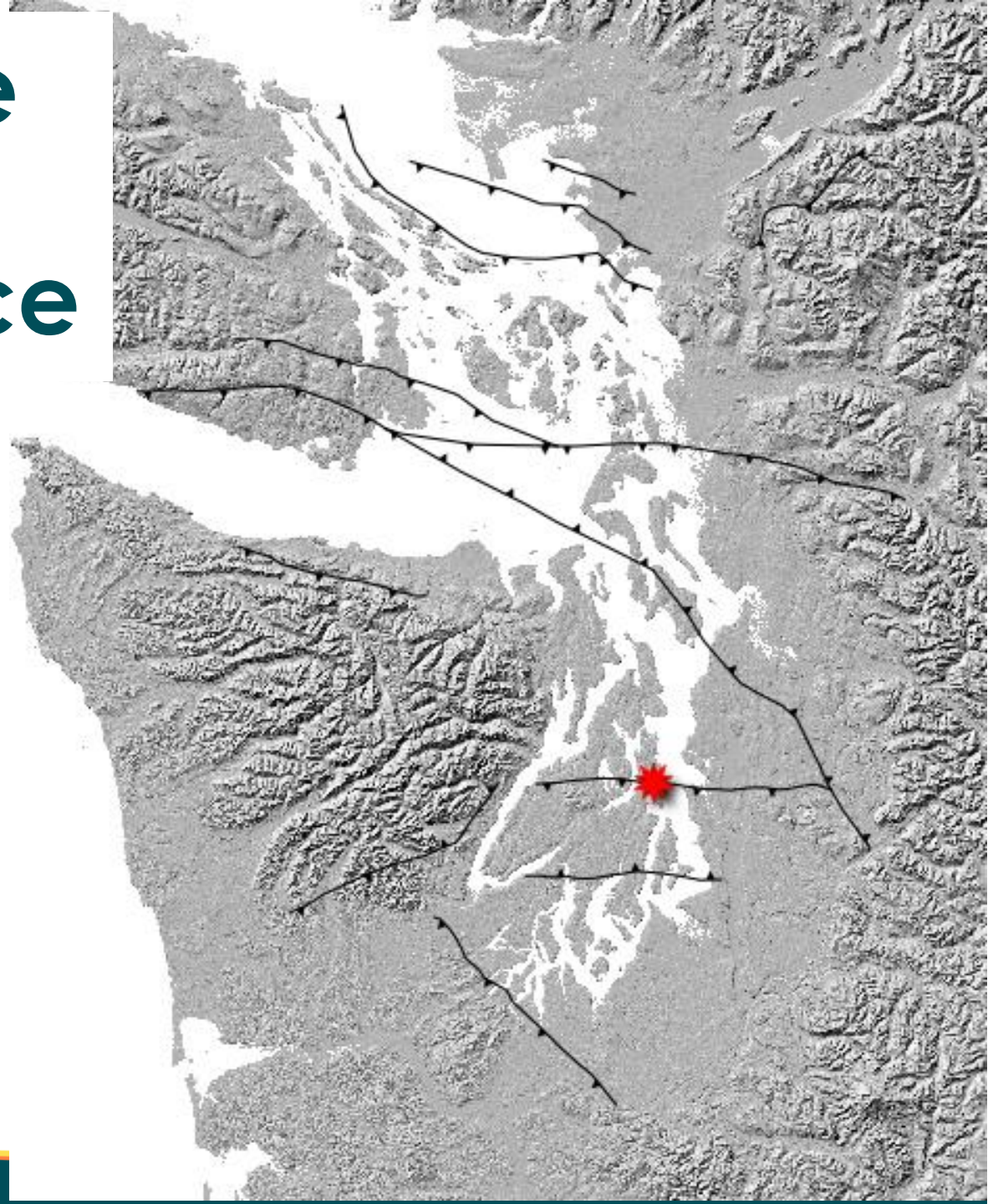

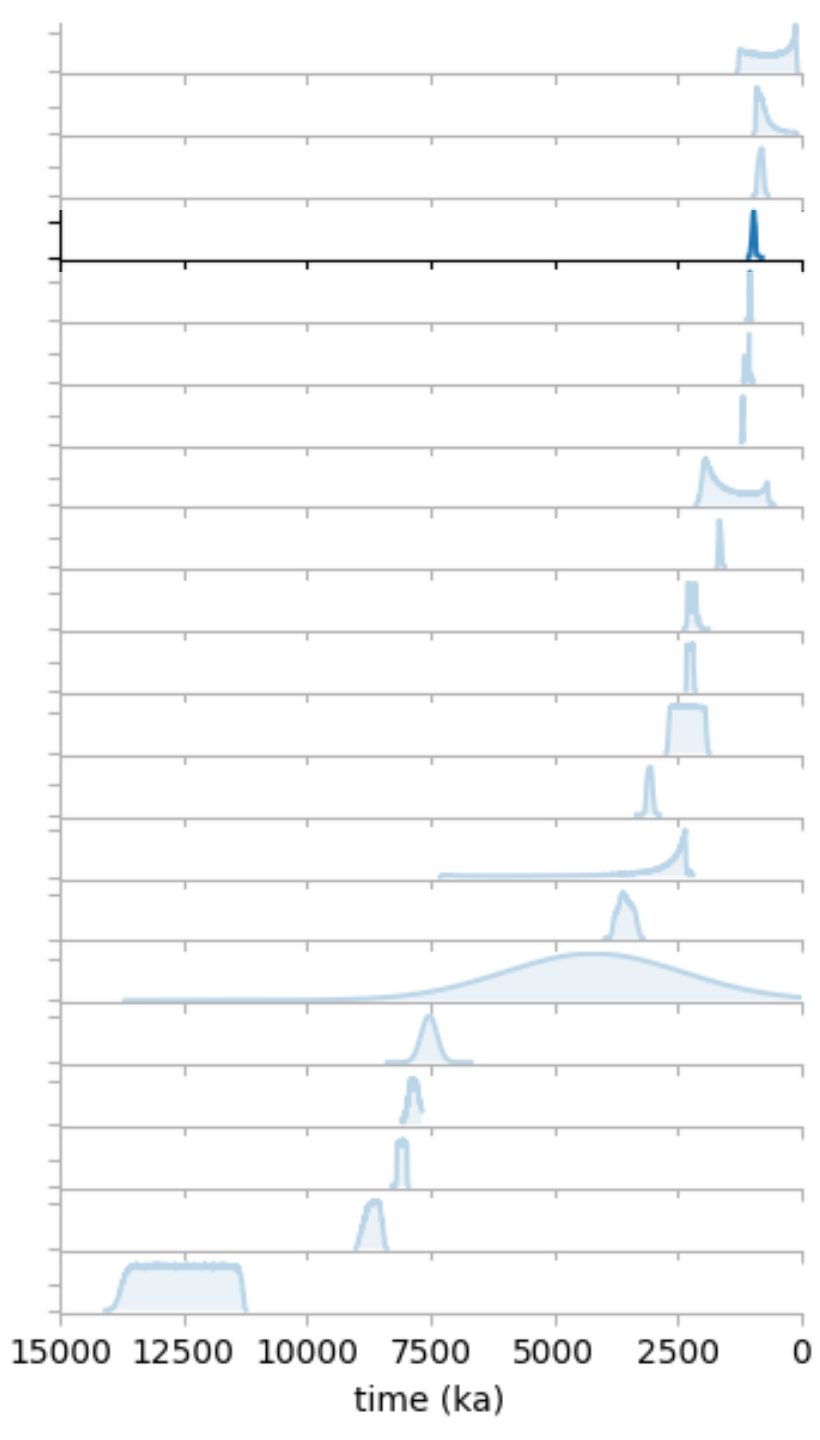

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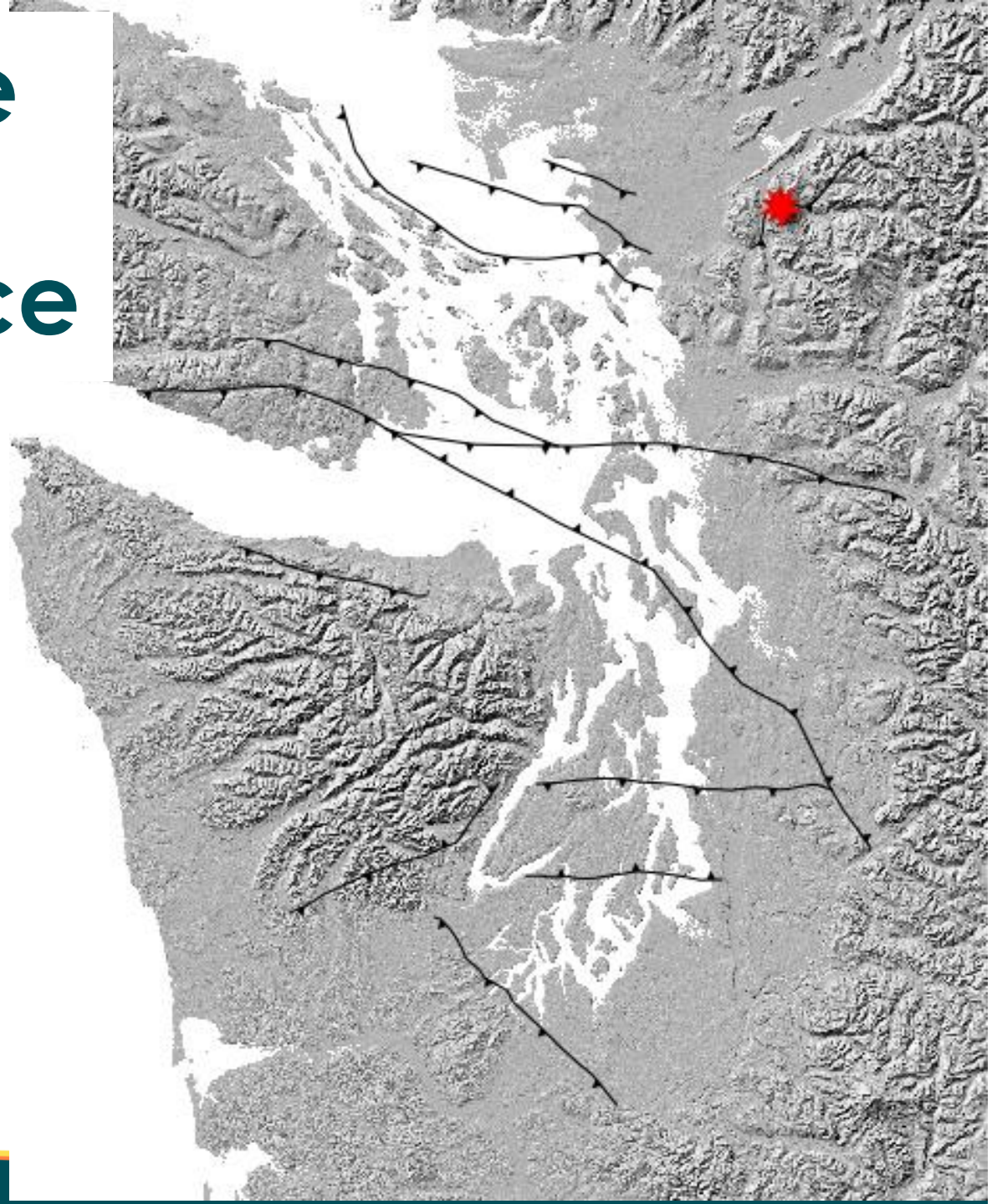

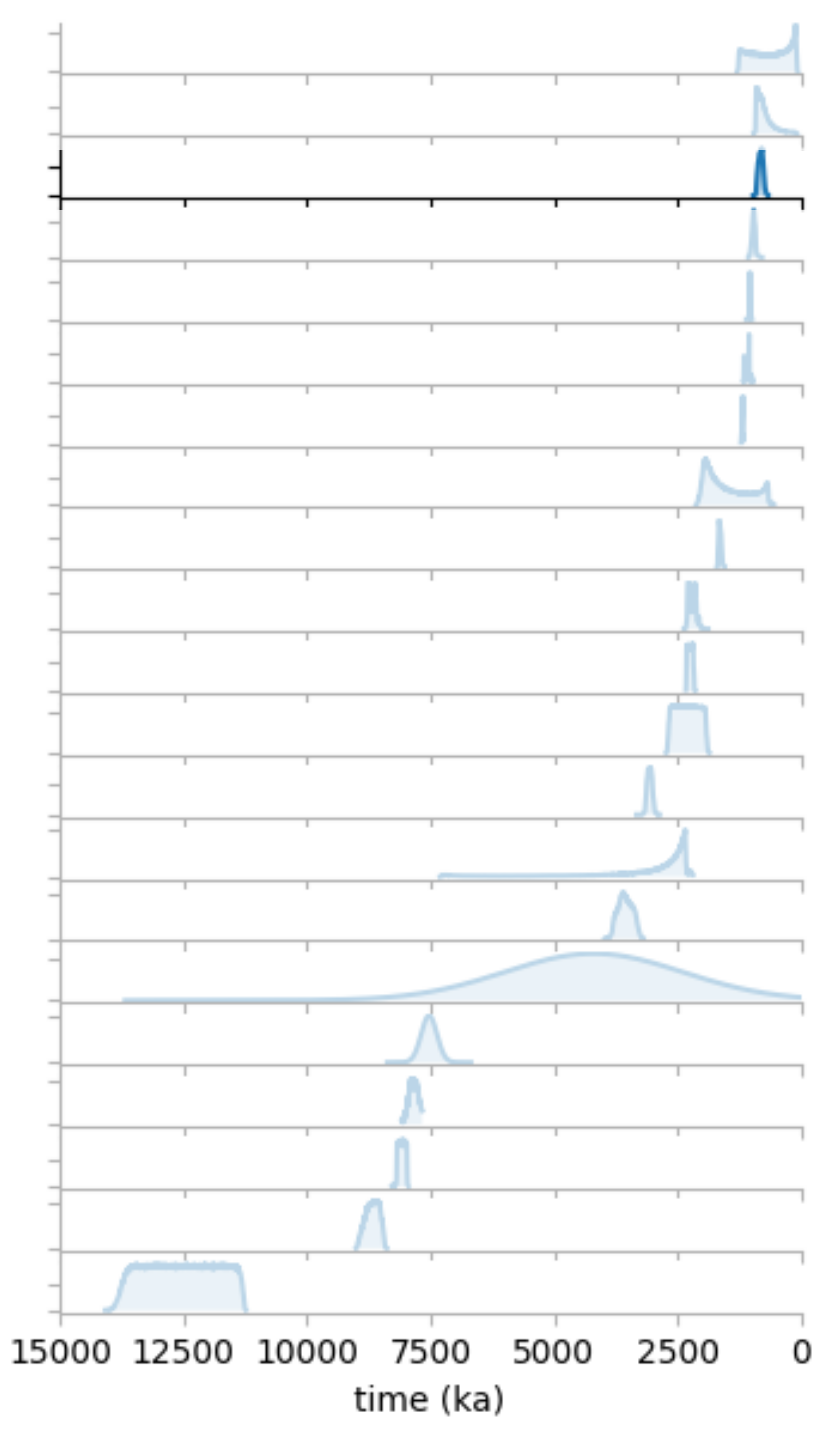

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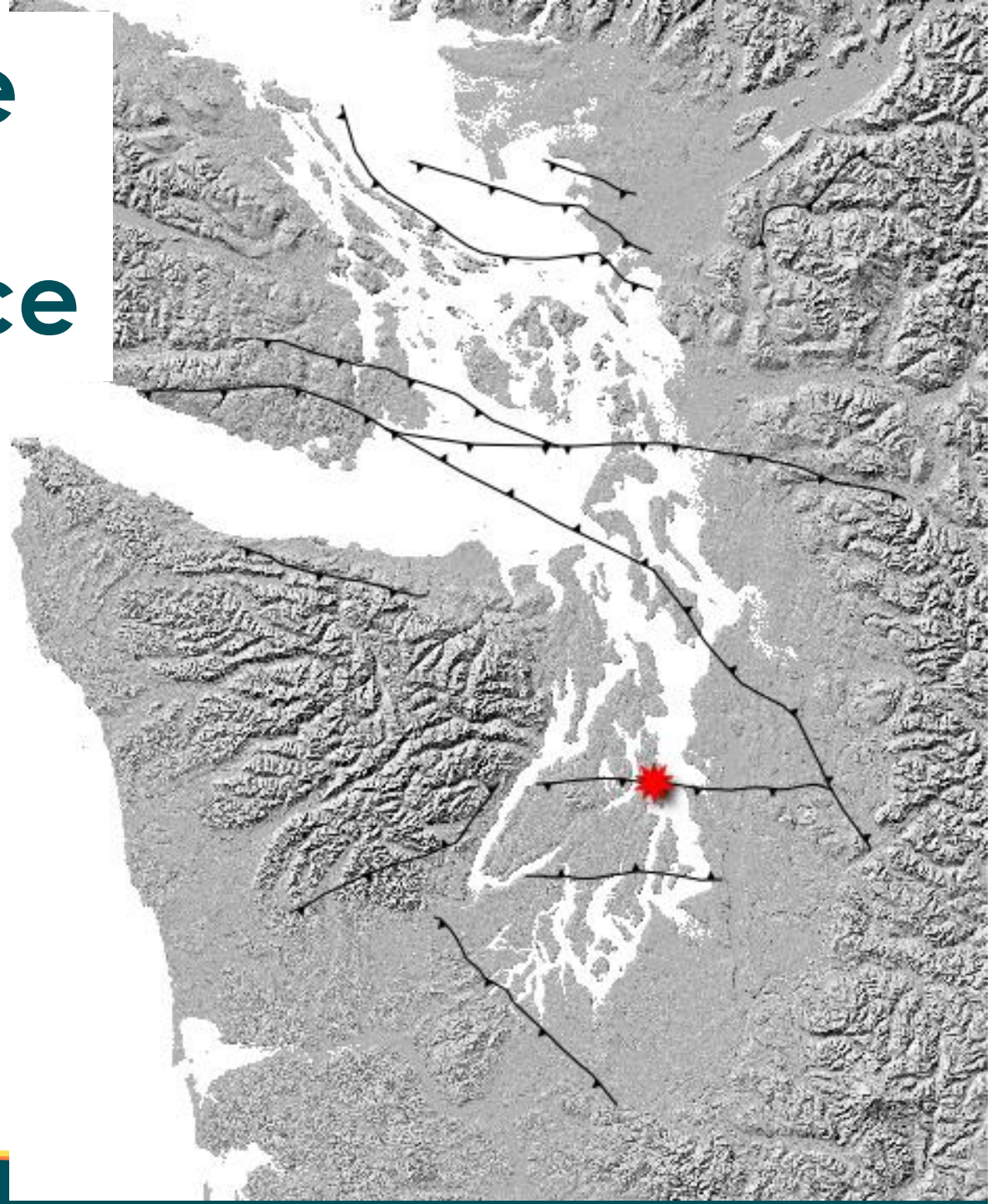
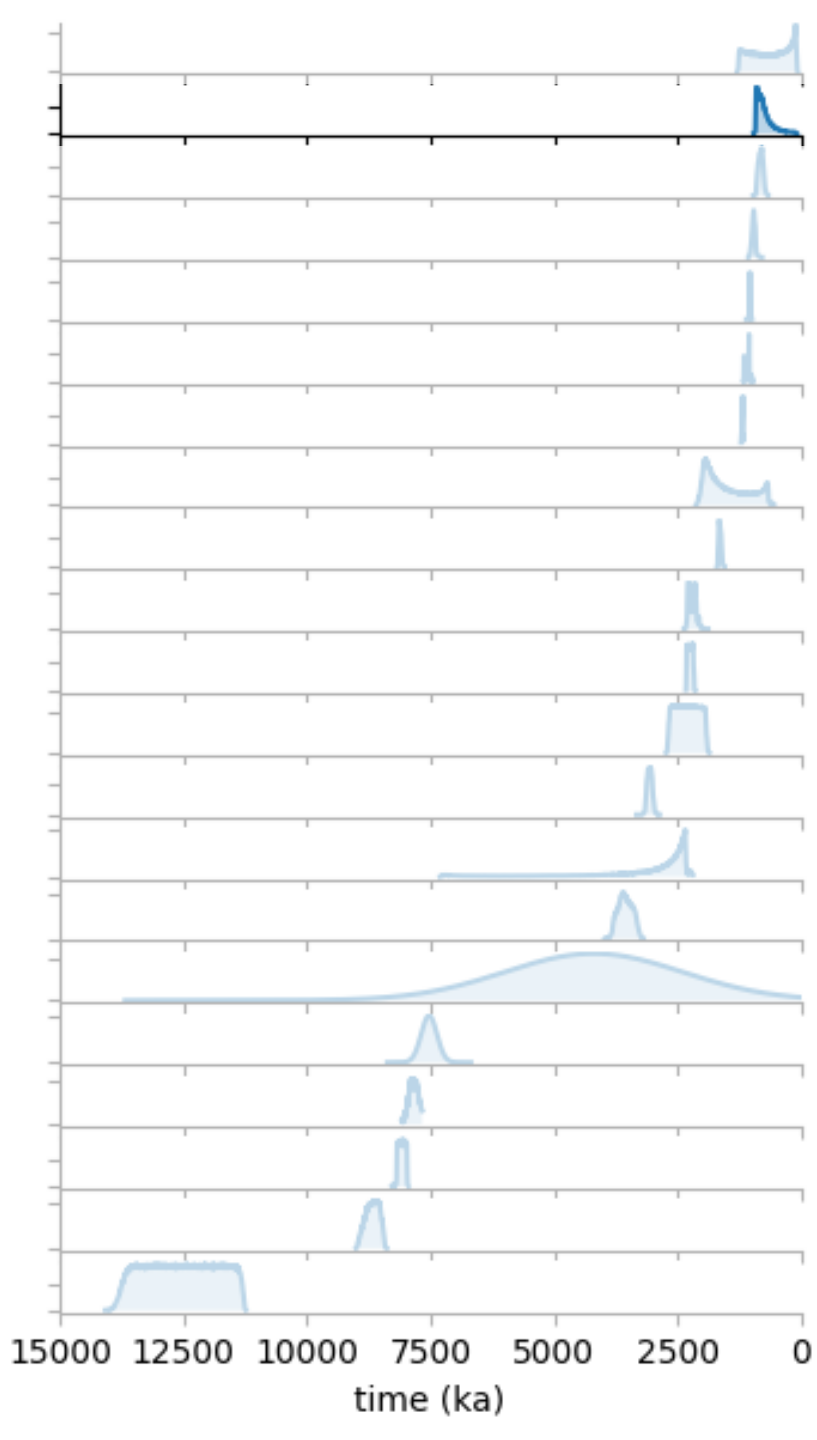
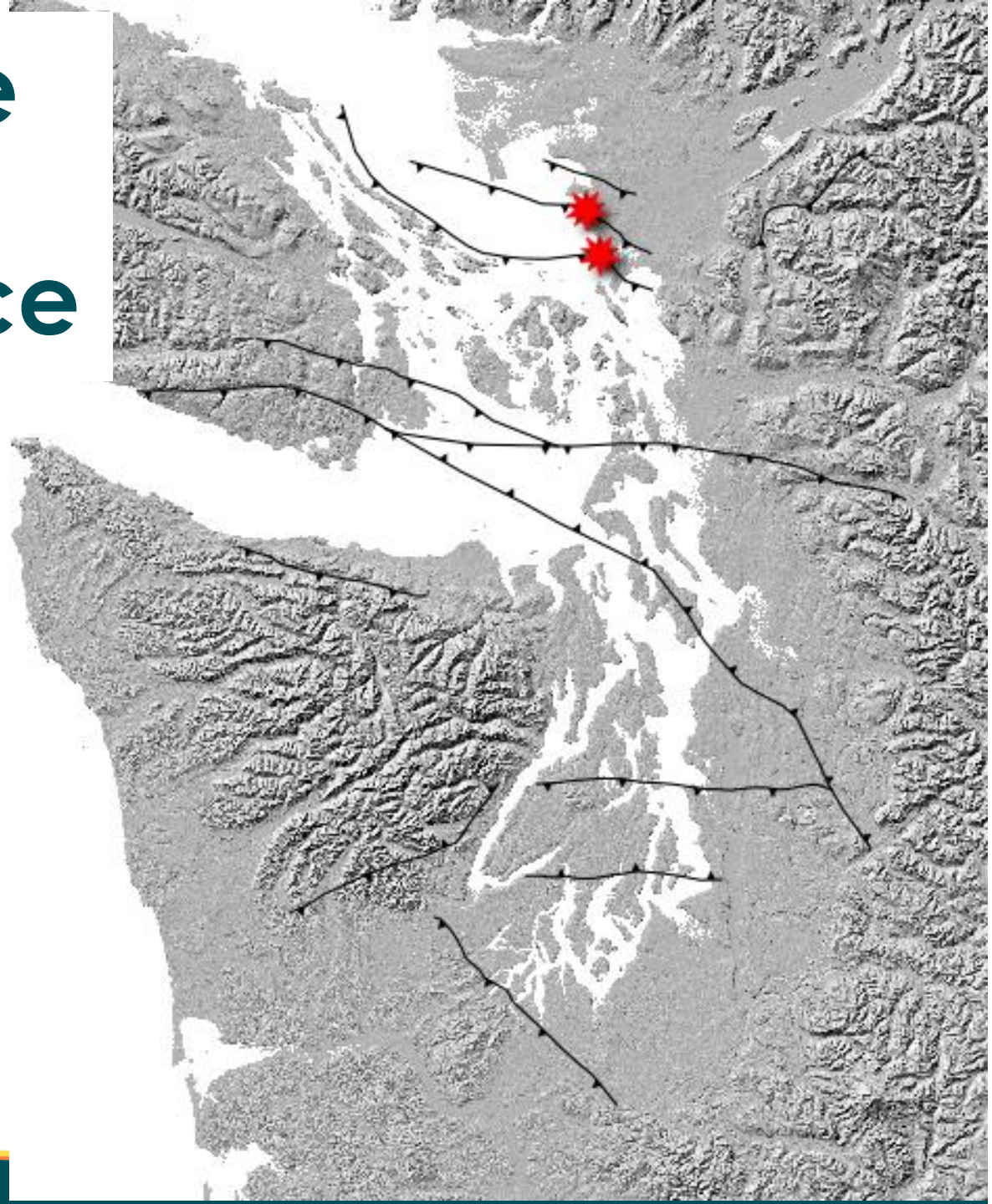
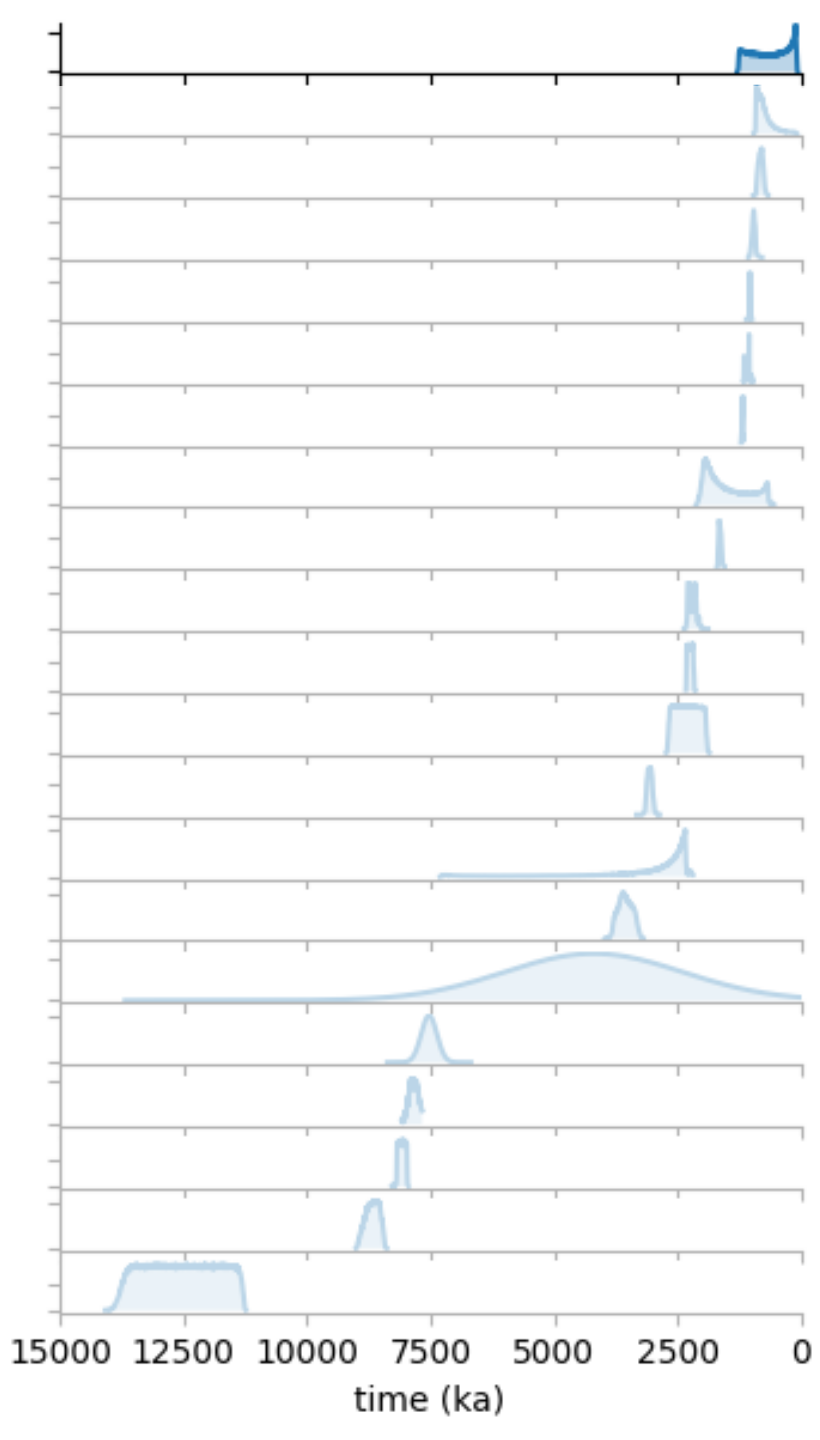




Example event sequence





All Possible Event Sequences

Event-Time graph can be searched through to find all possible event sequences.

This yields **19,404** sequences for the current dataset.

Associating ruptures with sequences

Each trench event has some number of compatible.

Number of ruptures per event in **example sequence**:
[7, 4, 1, 2, 2, 2, 2, 2, 3, 7, 7, 4, 3, 2, 2, 2, 2, 2, 34, 20, 20]
(This is **687,852,748,800** possibilities)

Total number of possibilities for all sequences:
4.6×10^{21}

Must be able to **filter** to get anything workable

Filter by likelihood

Event likelihood:

- Integral of time PDF (<1 for overlapping PDFS)

Rupture likelihood:

- Geometric and kinematic criteria (plausibility)
- Compatibility between rupture magnitude (from area) and observed offset (from paleoseismology per trench event)

Most likely rupture found for each paleoseismic event (single or multiple trench events)

Most Likely EQ History

Sequence likelihood:

- Normalized product of rupture/eq likelihoods (normalized so that sum of all trench events for each observation is 1)

Most likely earthquake history:

- Single-fault ruptures for all events, except:
- Joint Saddle Mountains fault, Tacoma fault, and central-western Seattle fault (no Vasa Park/eastern section) for 923 CE M7.4-7.8 event

What's next?

Probabilistic, likelihood-based magnitudes and recurrence distributions

Statistical spatiotemporal patterns of occurrence (clustering, triggering, supercycles, etc.)

Hypothesis generation?

4.625×10^{21} – 1 possible other histories to consider…

Thanks!

- Thanks to paleoseismologists

- Data modified from compilation in Styron and Sherrod (2021) (many authors and studies), Harrichhausen et al. (2021), Haricchausen et al. (2023)

- Software (Fermi: multifault ruptures, Hyphae: topological event histories) supported by GEM Foundation

- Thanks to CRESCENT for opportunity, yall for listening