

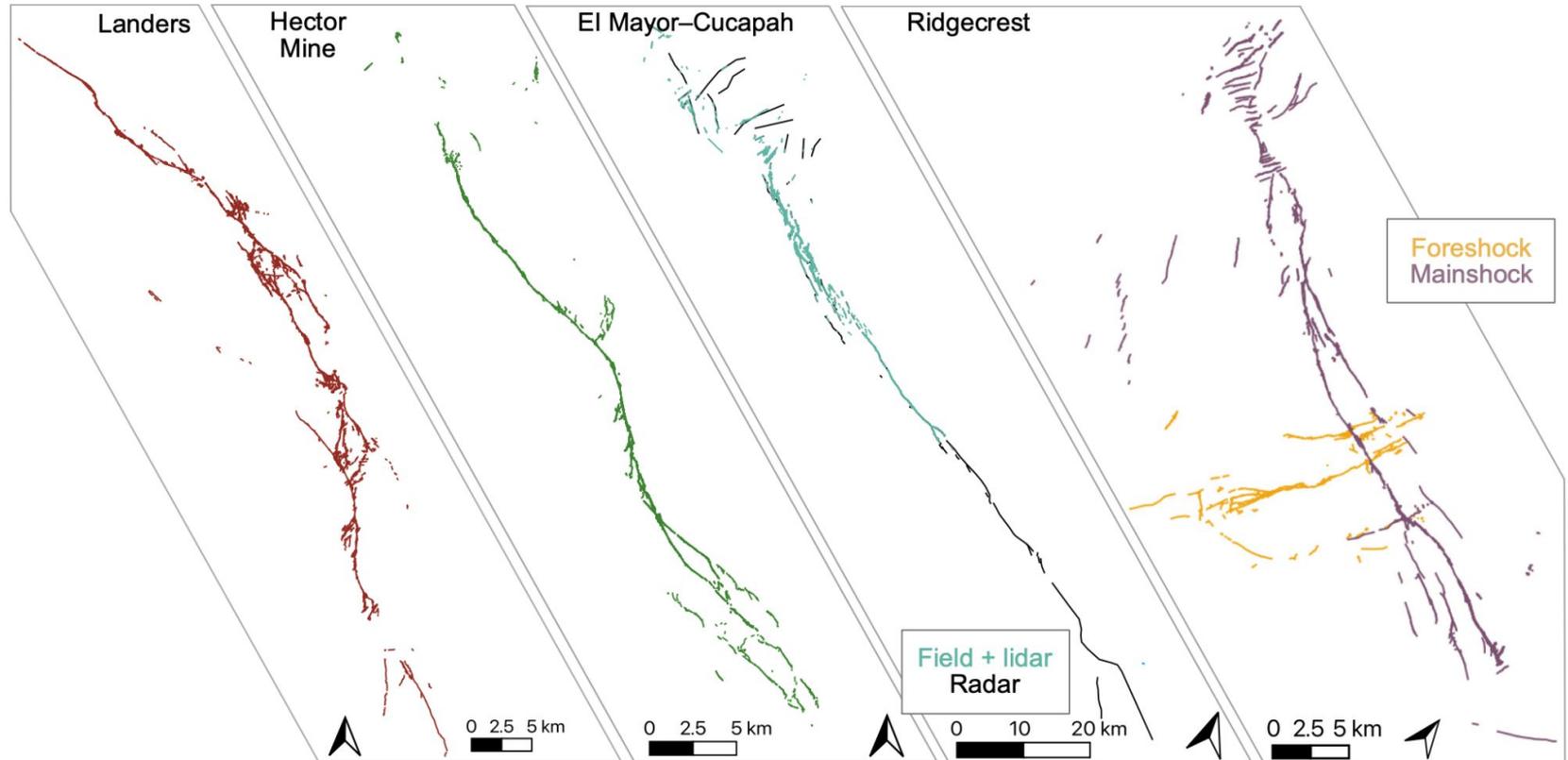
Lessons from global strike-slip surface ruptures for California's next big earthquake



Alba M. Rodriguez Padilla (Utah State University)
With contributions from Travis Alongi, Mike Oskin,
Emily Brodsky, Kelian Dascher-Cousineau, Vanessa
Herrera, and Sophia White

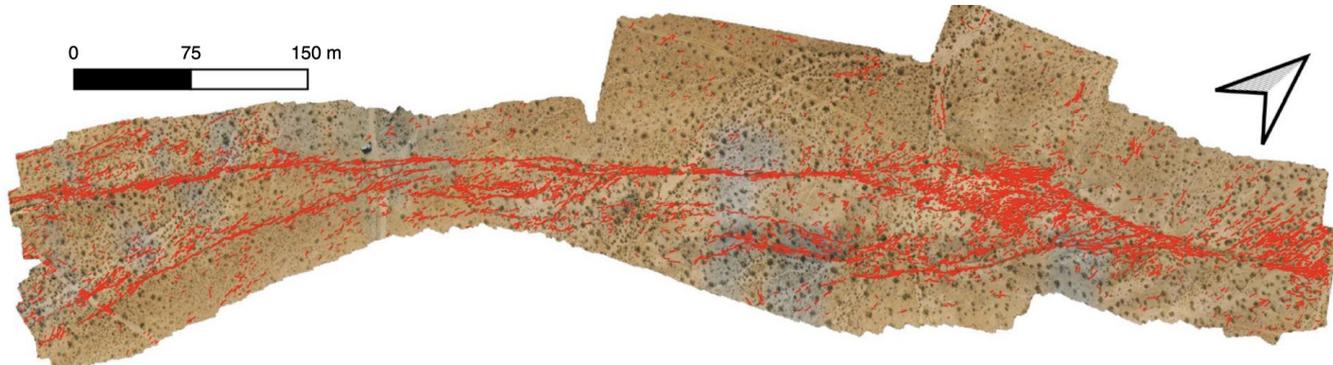
Cruikshank et al., unpublished

39 well-mapped surface rupturing strike-slip earthquakes



Leveraging the global record of surface rupturing strike slip earthquakes to answer:

1. How does fault geometry influence ruptures?
2. Where do faults go fast?
3. Where will the bulk deform during earthquakes?



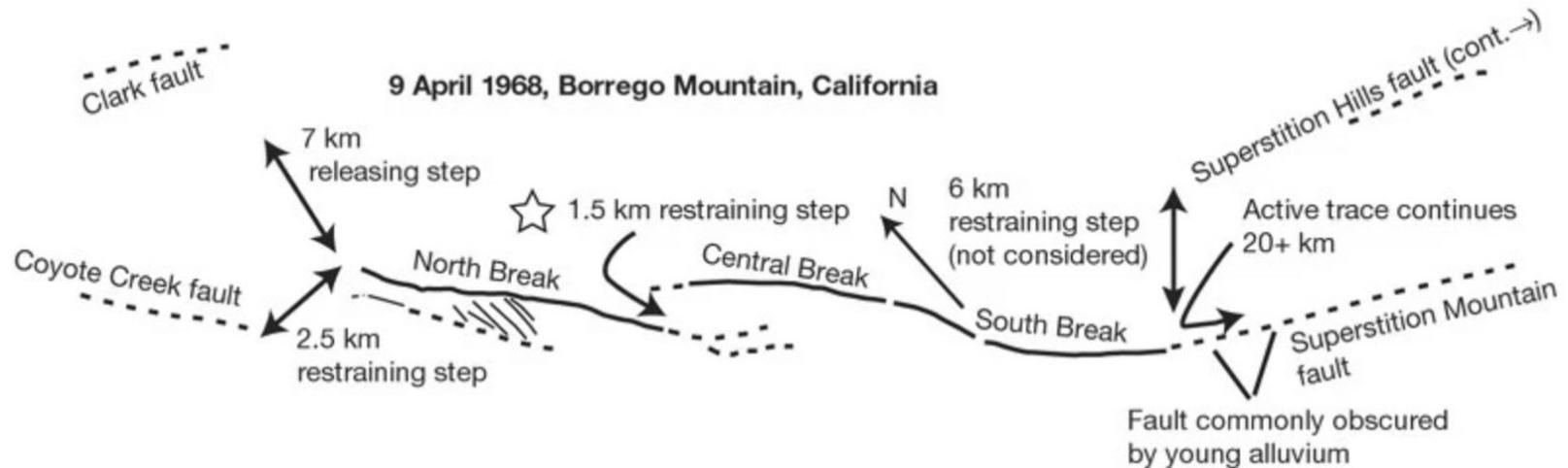
Leveraging the global record of surface rupturing strike slip earthquakes to answer:

When are surface observations representative of processes at depth?

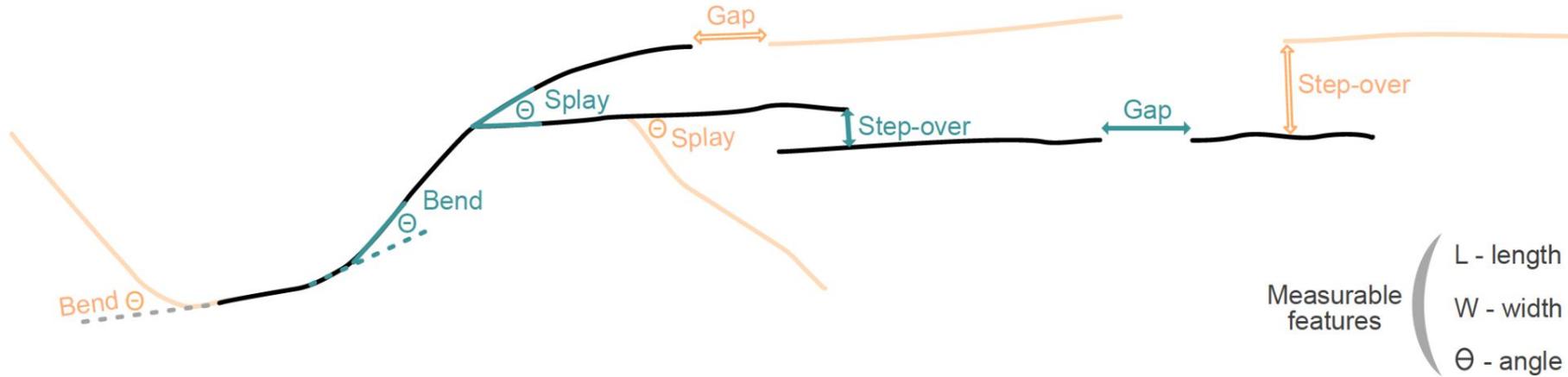


1. How does fault geometrical complexity influence ruptures?

The **end-points of earthquake ruptures are not random**: events terminate at zones of geometrical complexity on faults 90% of the time (Wesnousky, 2006; Wesnousky and Biasi, 2016, 2017, 2021)



Types of fault geometrical complexity at 500 m - 1 km scale



Rodriguez Padilla et al., GRL, 2024

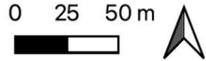
Black = faults active during the earthquake, orange = regional faults not active during the earthquake
Teal = breached (earthquake passed), orange = unbreached (earthquake did not pass)

Characterizing angles and lengths

Double bend



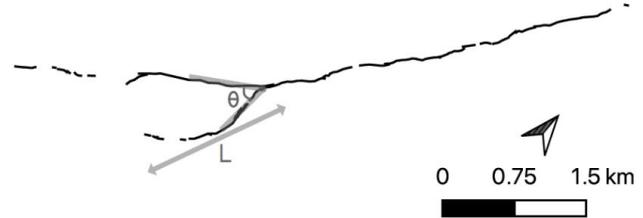
Single bend



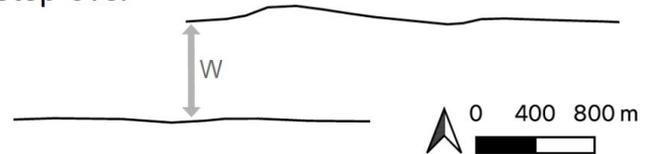
Gap



Splay

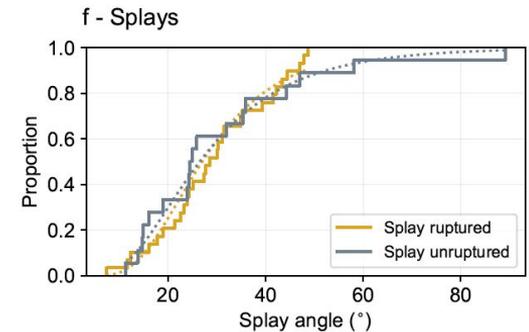
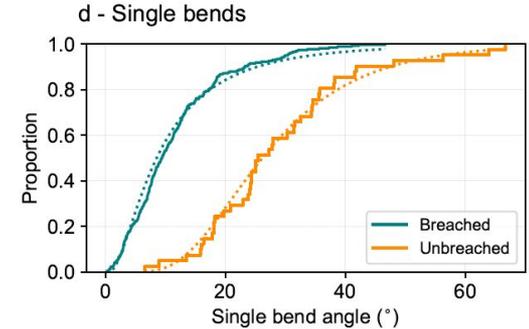
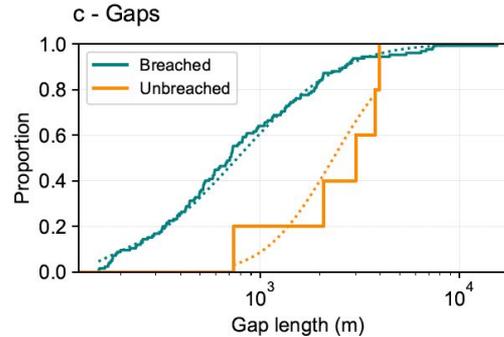
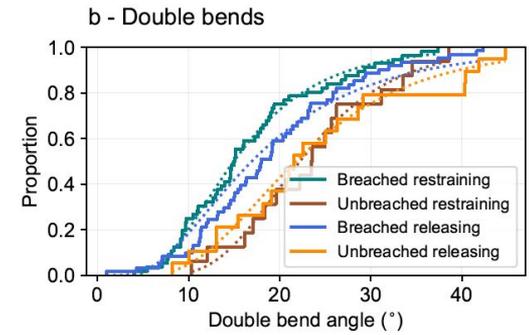
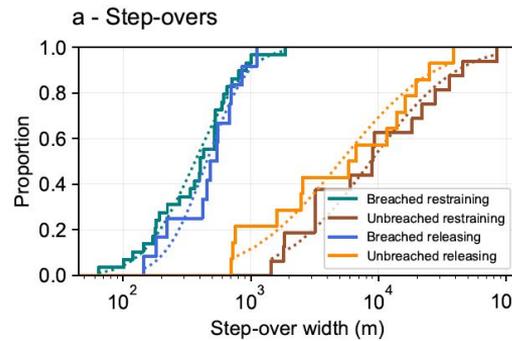


Step-over



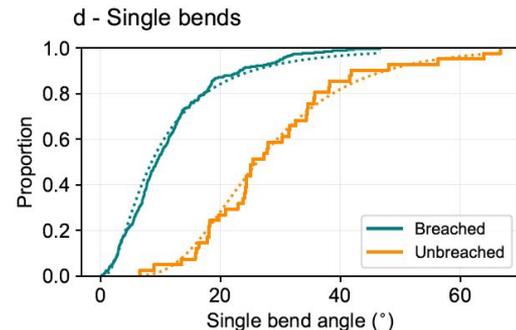
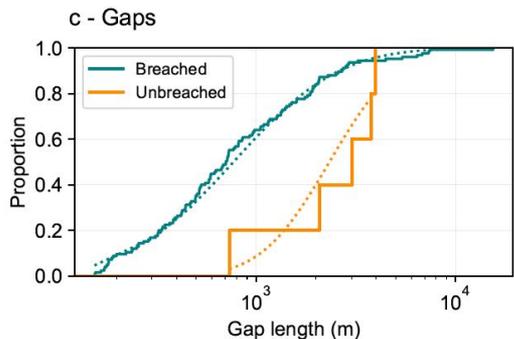
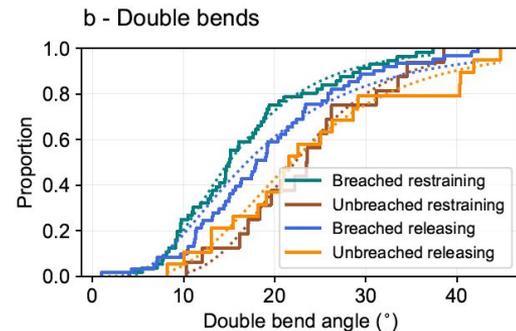
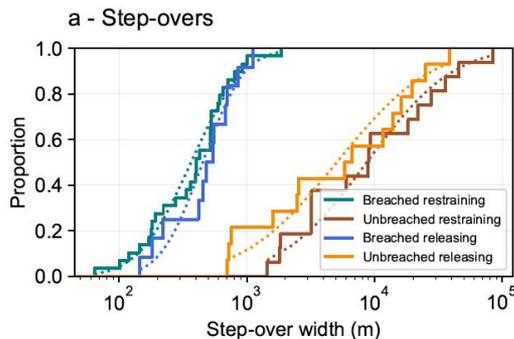
Black = faults active during the earthquake
Grey = measured attributes for each feature type

Are **breached** and **unbreached** populations for each geometrical feature distinct?



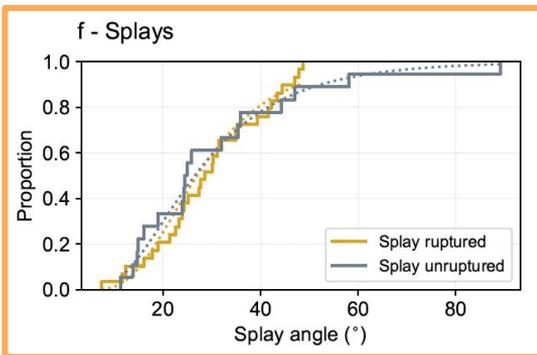
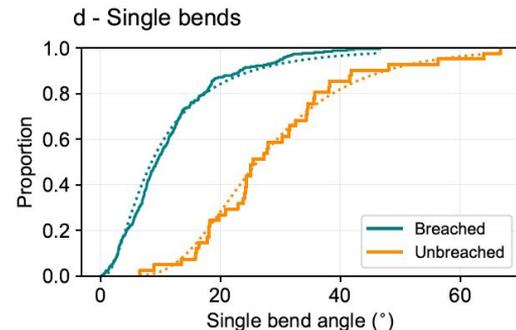
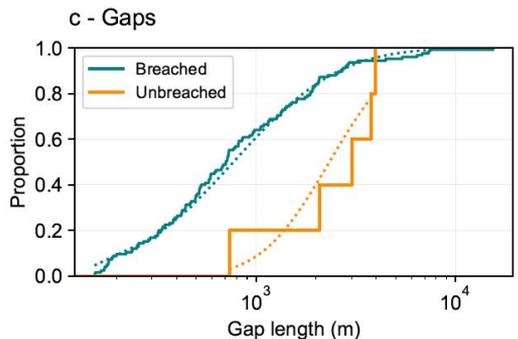
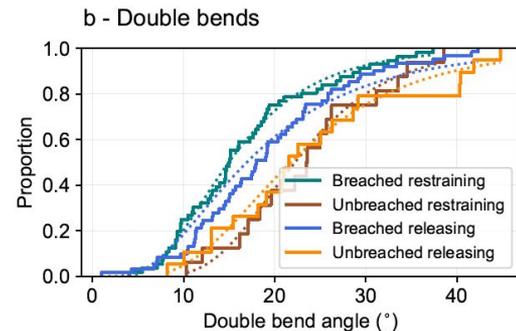
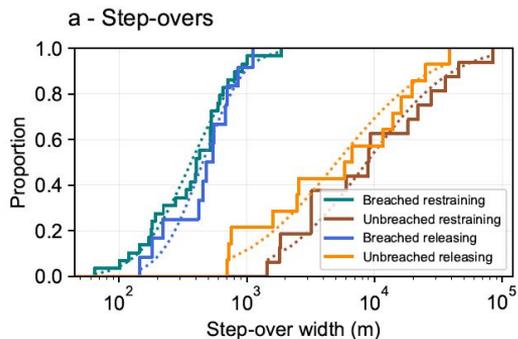
Which geometrical features can promote rupture arrest?

Step-overs, bends, and gaps influence the rupture process, as they have statistically distinct breached and unbreached populations



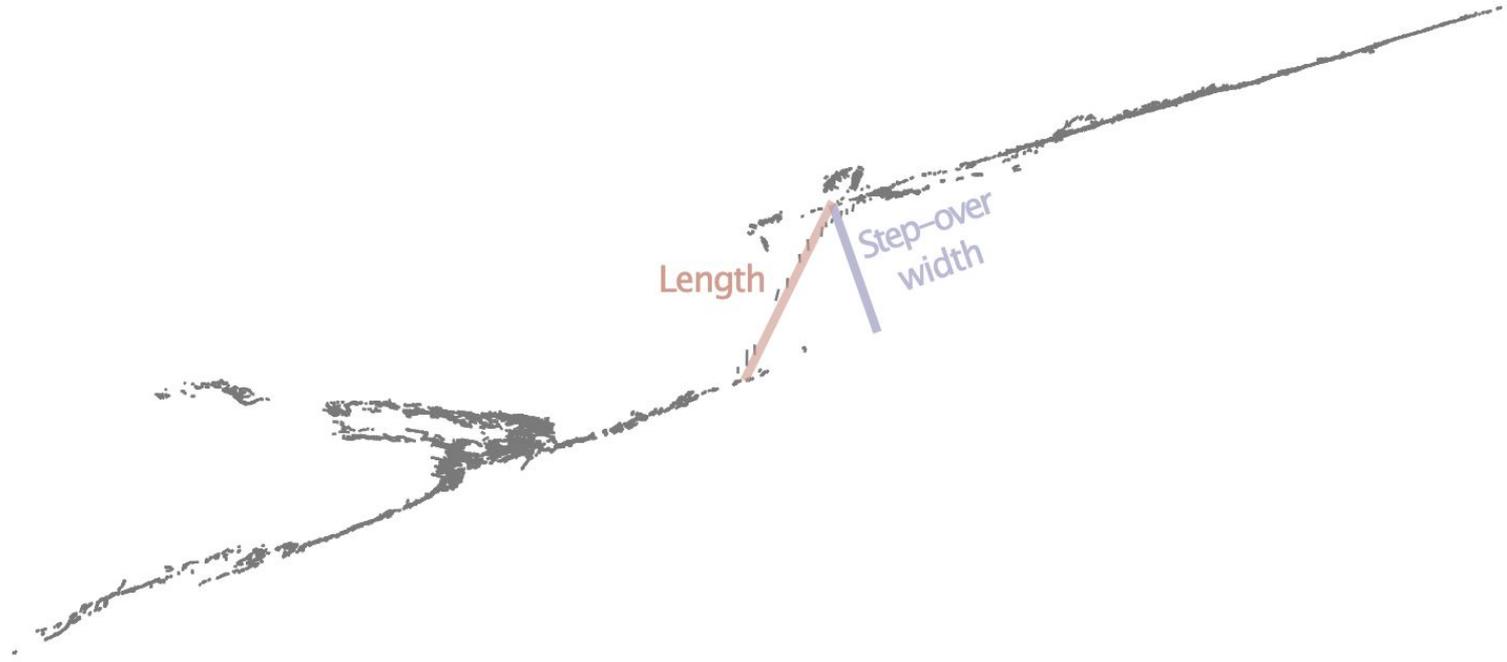
Which geometrical features can promote rupture arrest?

Splays do not have distinct breached and unbreached populations. Likely to represent shallow complexity without depth-extent at the mapping scale.

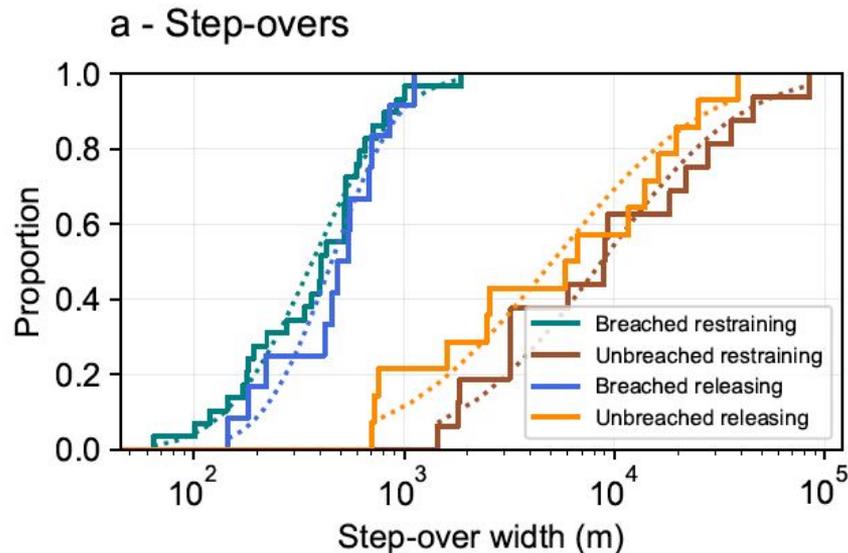
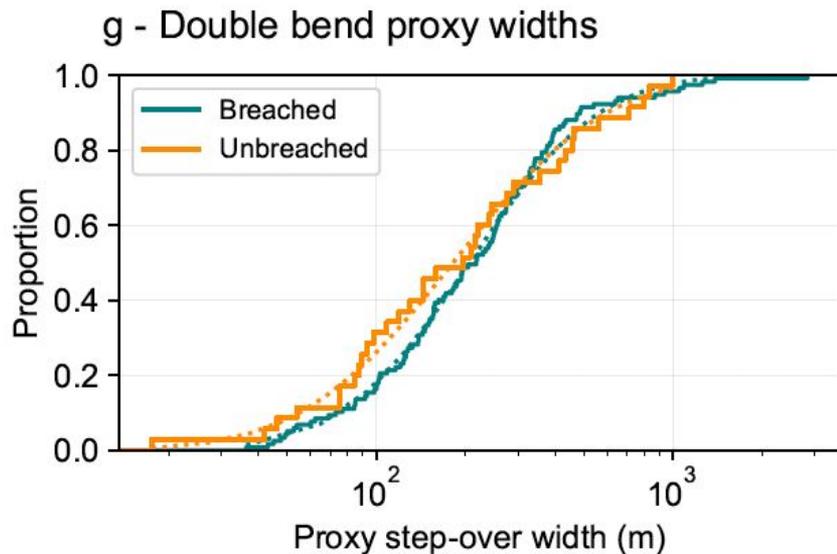


Geometrical evolution as a link to depth extent

Step-overs evolve into double bends over time



Double bend from the 2014 Yutian earthquake

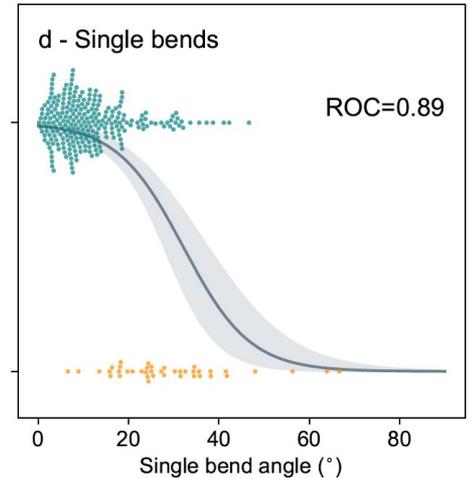
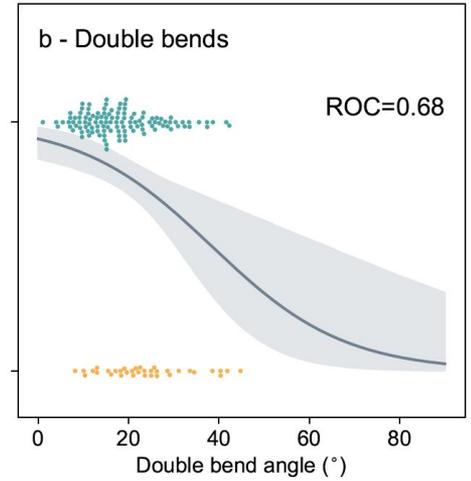
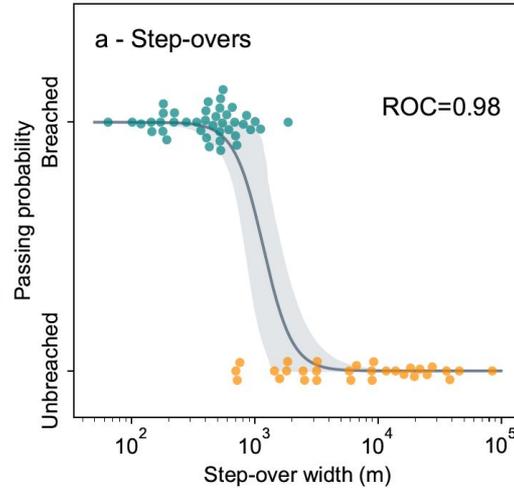


Unlike step-overs, double bend proxy widths are not clearly correlated with rupture propagation or arrest. Suggests **once linkage is achieved, it persists to at least some portion of the seismogenic zone.**

Not all zones of geometrical complexity are equal

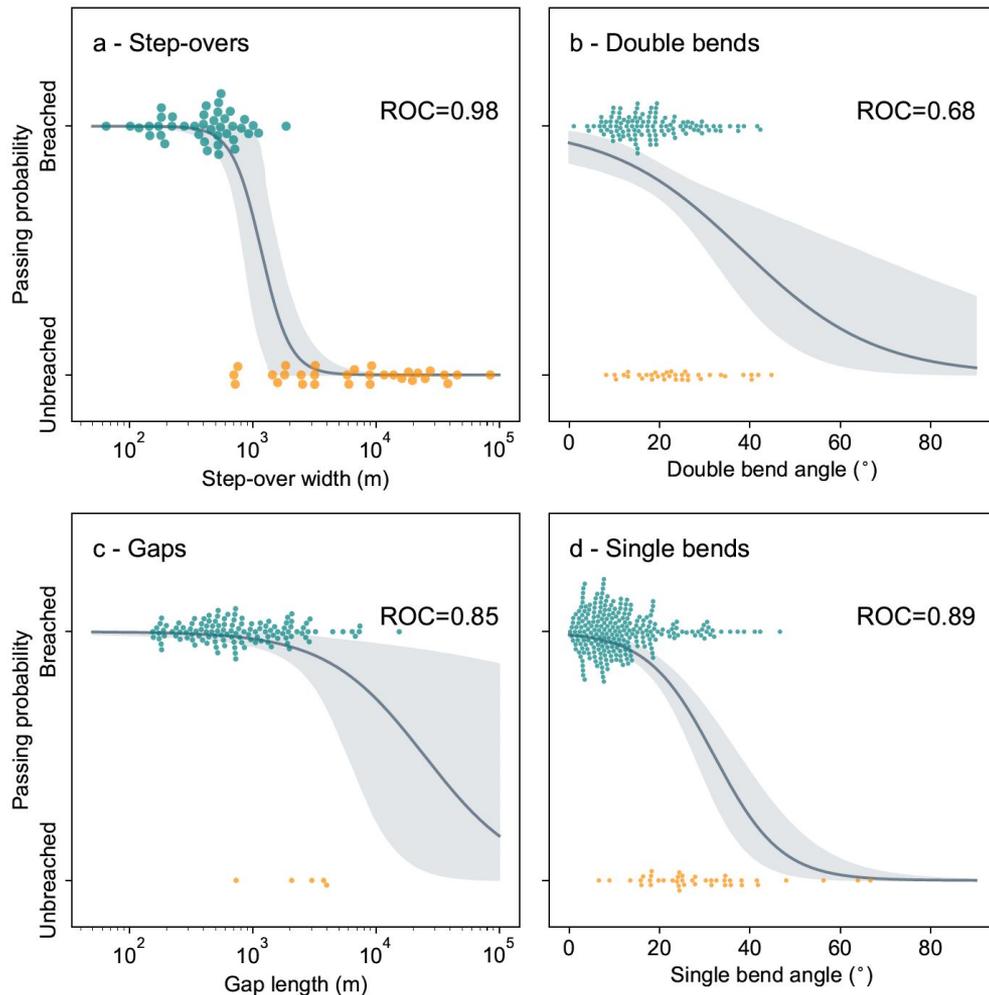
There is a **limiting step-over size** for rupture propagation

Step-overs are better at arresting ruptures than bends



Not all zones of geometrical complexity are equal

Gaps likely represent breaks in surface rupture while the fault continues to slip at depth



Constraints on the dynamics of rupture growth and arrest

Earthquake propagation is a competition between energy feeding the rupture and energy dissipated during propagation

Energy
sources

pre-stress

rupture
dynamics

Energy
sinks

fracture

energy
radiation

friction

Constraints on the dynamics of rupture growth and arrest

80% of the observed rupture termini are at zones of **geometrical complexity suggesting they behaved as barriers**

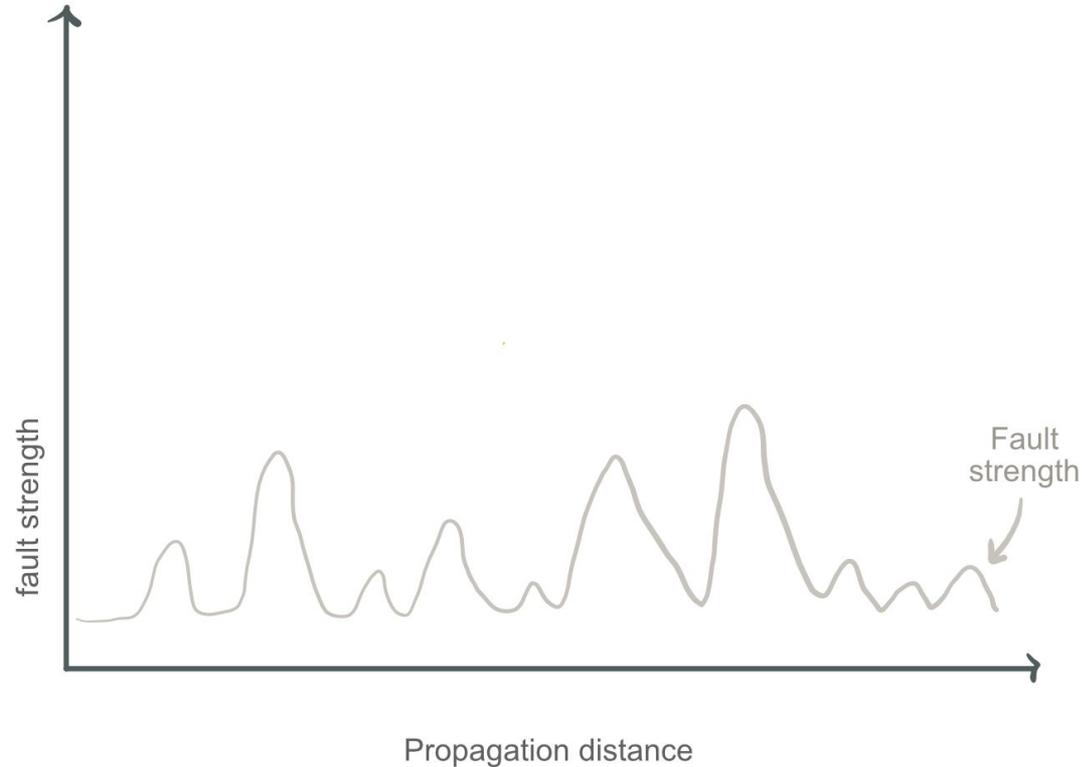
High frequency of arrest at barriers suggests **breaching barriers is a first-order source of energy dissipation** during rupture



Surface rupture of the 1968 Borrego earthquake, CA

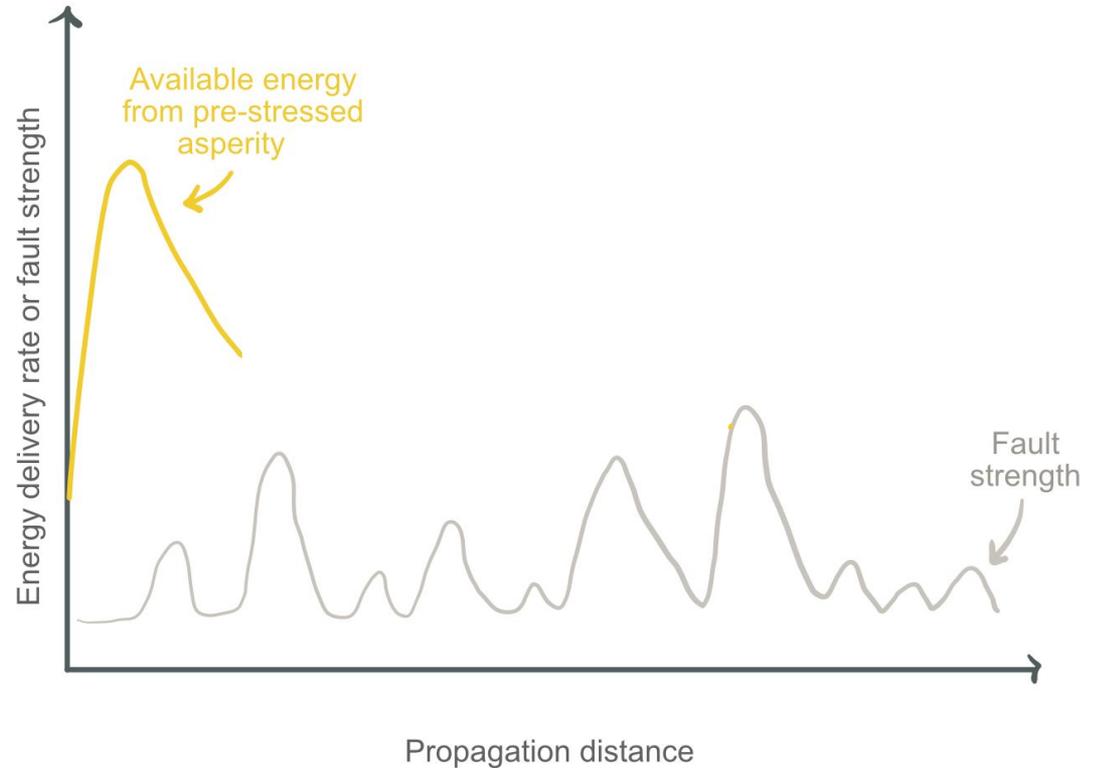
Constraints on the dynamics of rupture growth and arrest

The pre-existing
distribution of potential
barriers partially
controls fault strength

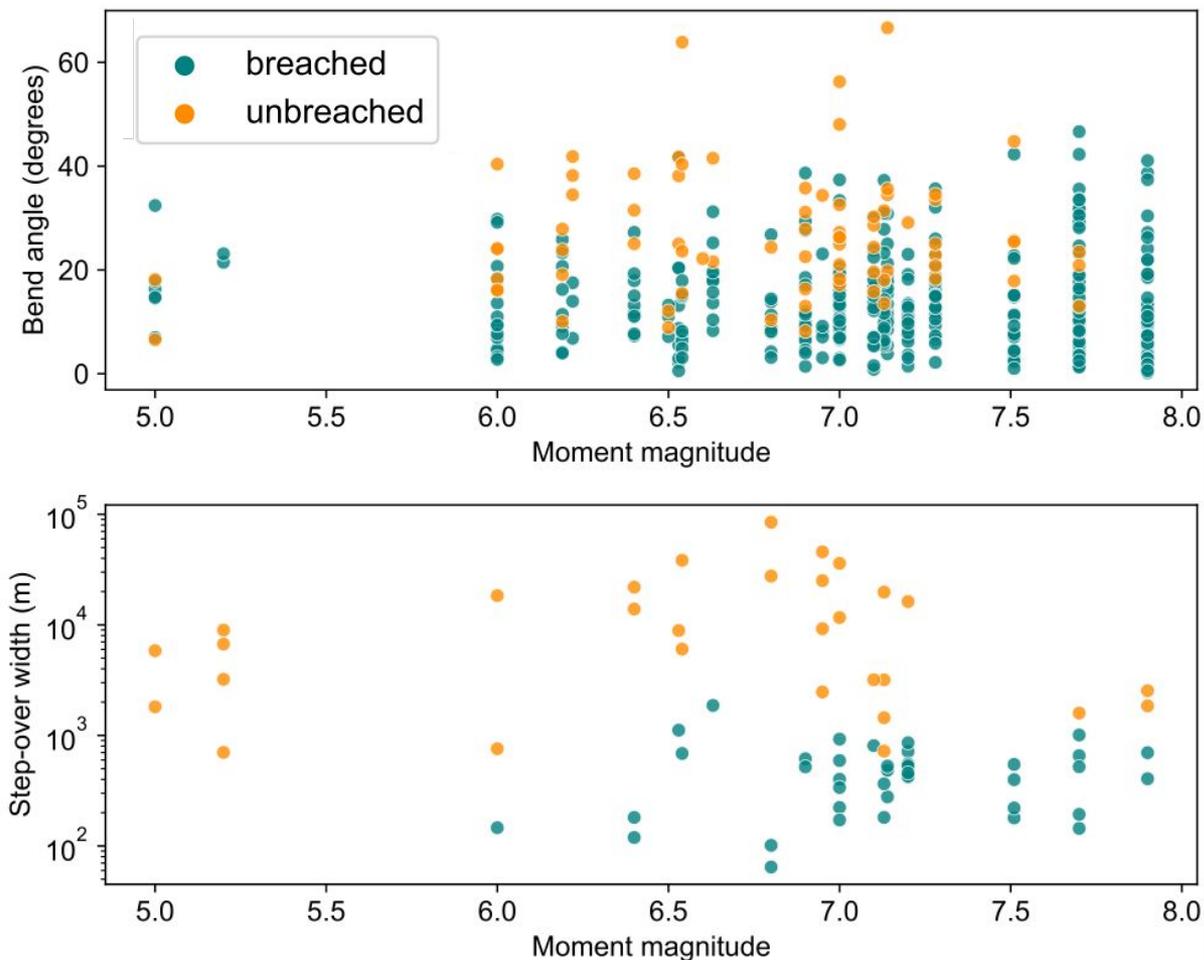


Constraints on the dynamics of rupture growth and arrest

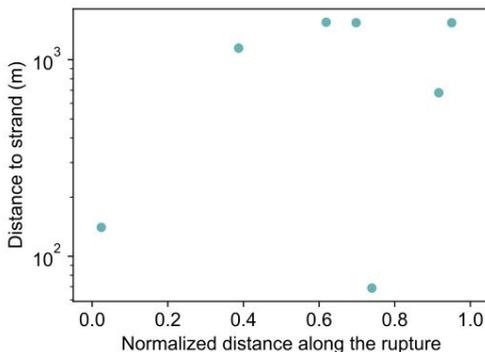
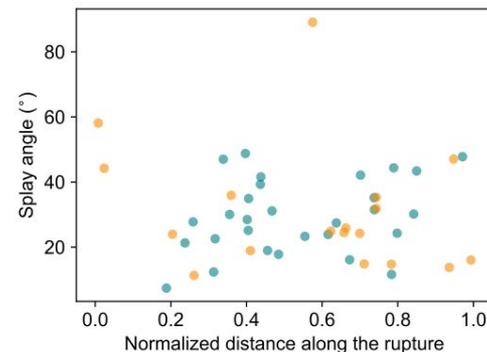
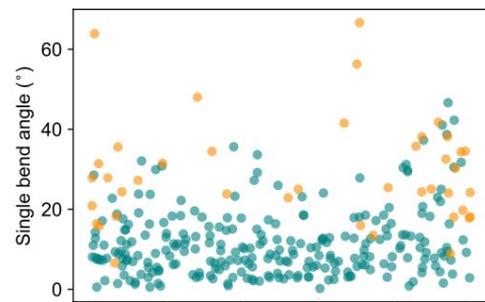
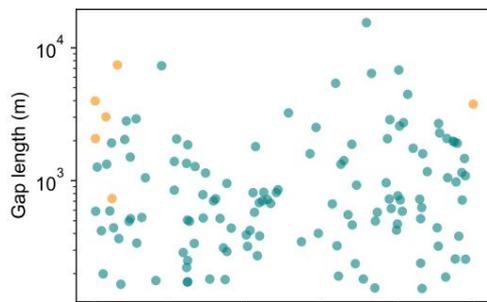
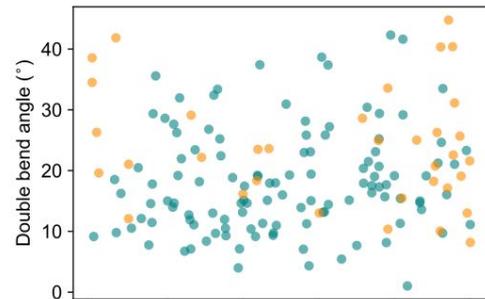
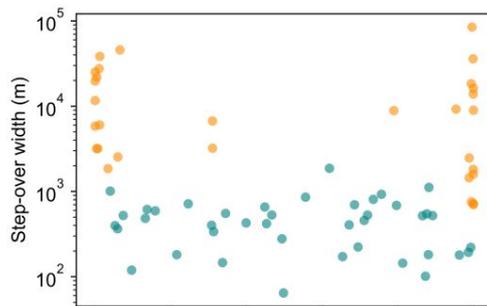
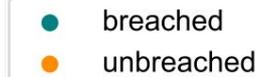
Ruptures had enough energy to grow into a **surface rupturing event**



No correlation
between
geometrical
complexity size
and moment
magnitude

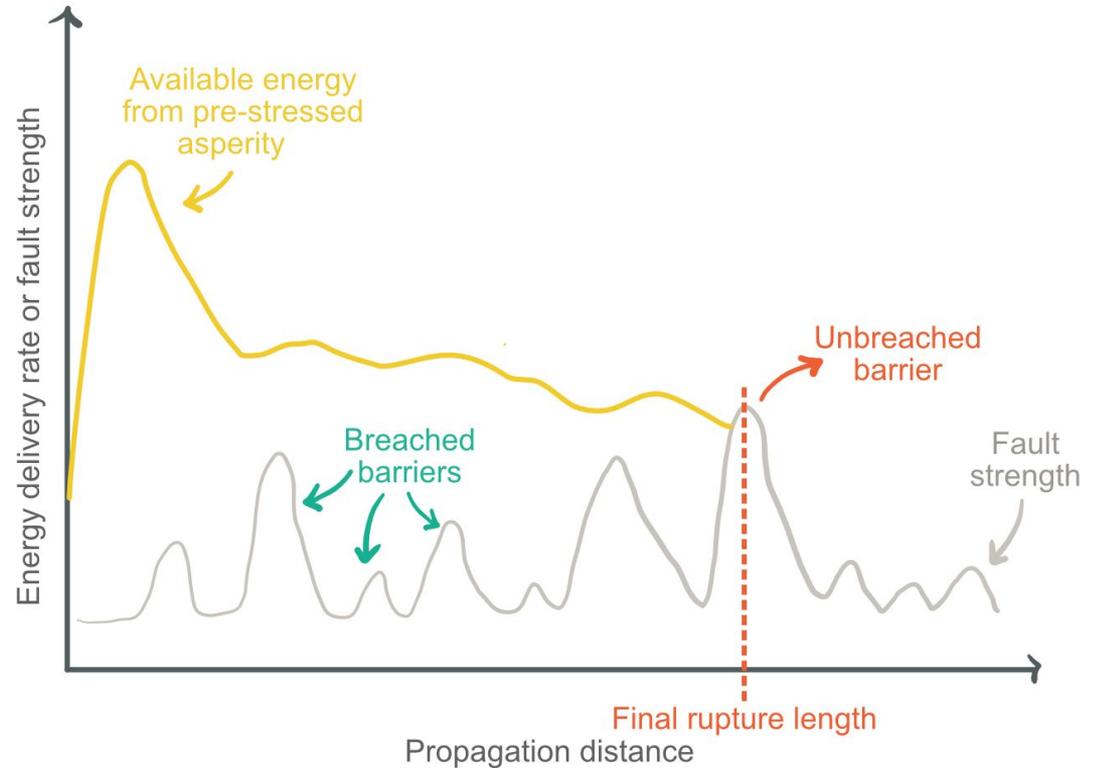


No correlation
between
geometrical
complexity size and
position along the
rupture

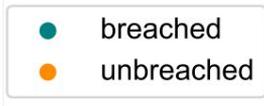
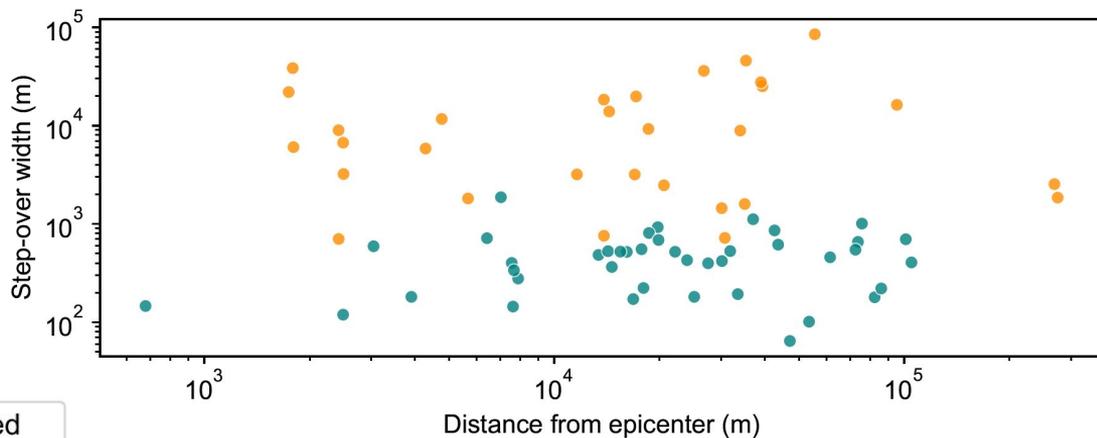
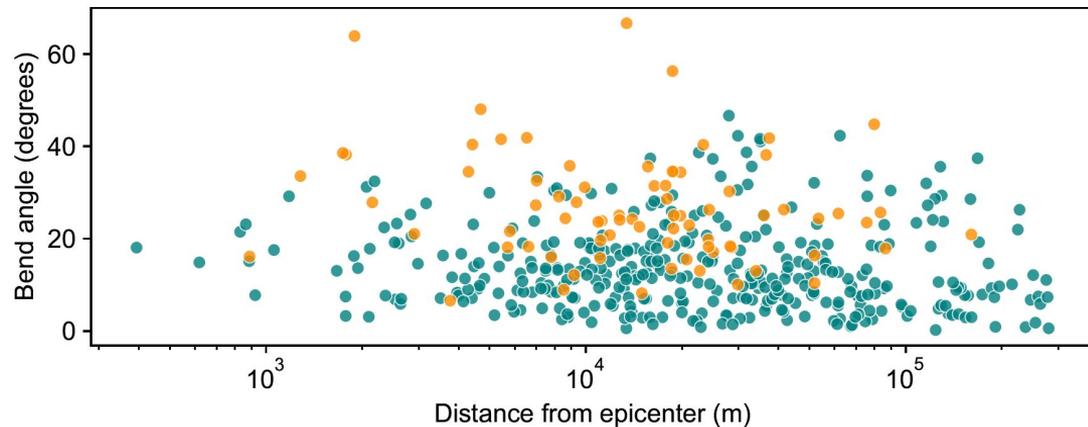


Constraints on the dynamics of rupture growth and arrest

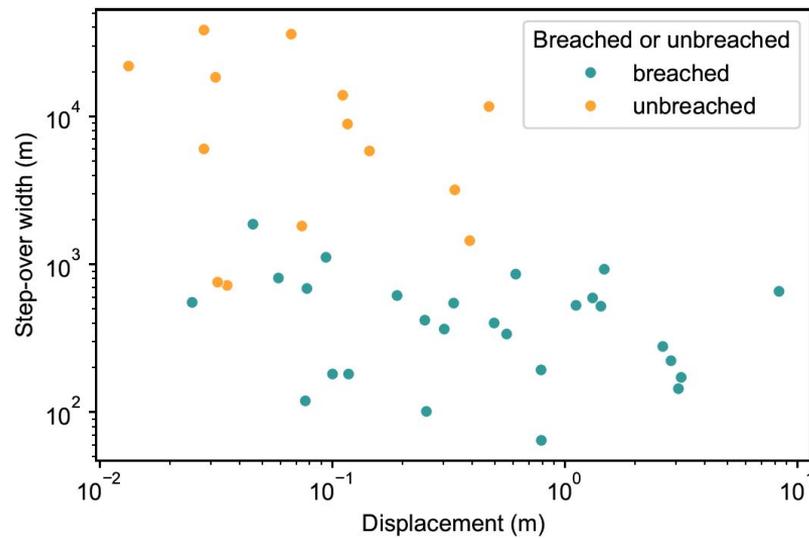
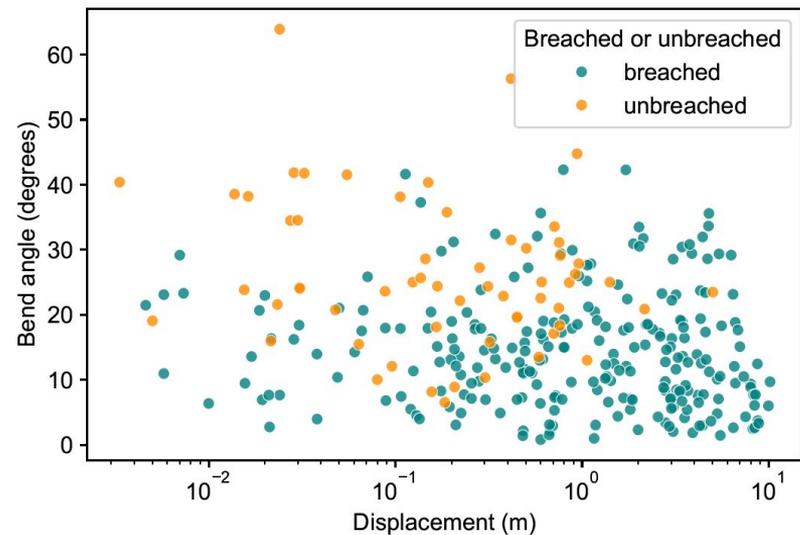
The energy delivery rate remains ~constant as the rupture propagates and is comparable across events



No correlation
between
geometrical
complexity size
and distance to
epicenter

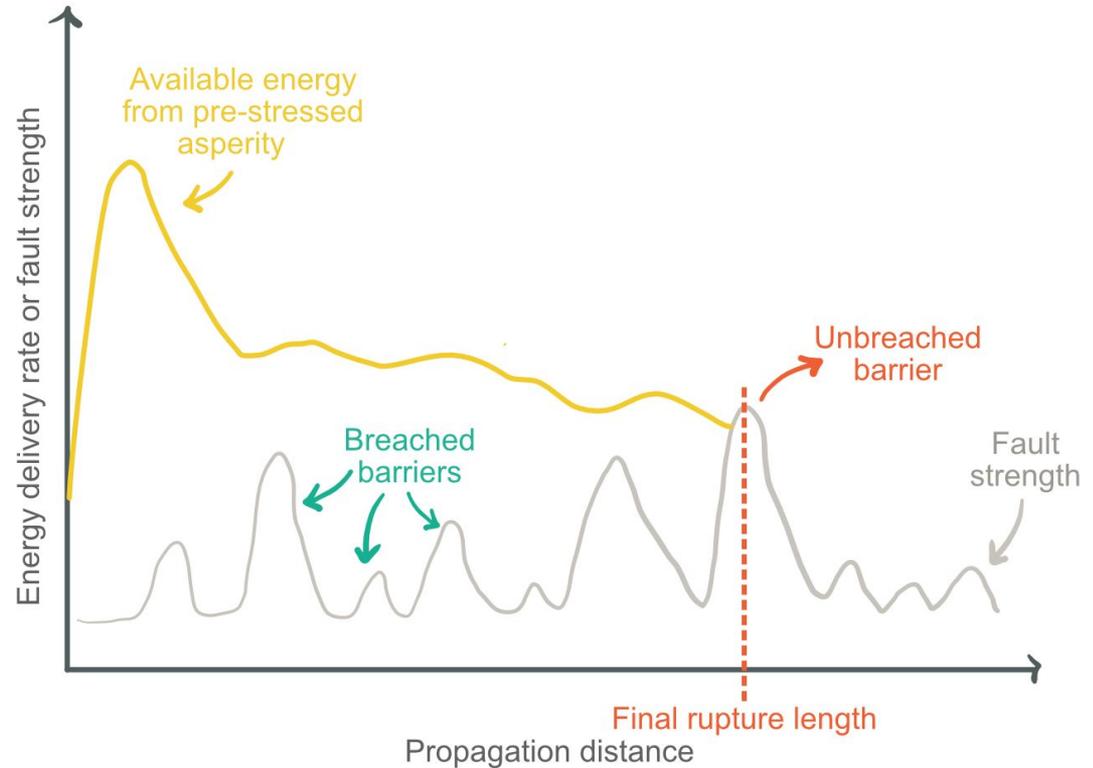


No correlation
between
geometrical
complexity size and
displacement



Constraints on the dynamics of rupture growth and arrest

Fluctuations in energy supply are similar to fluctuations in energy dissipation.

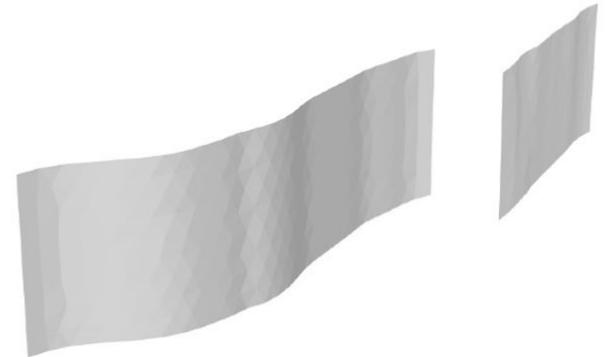
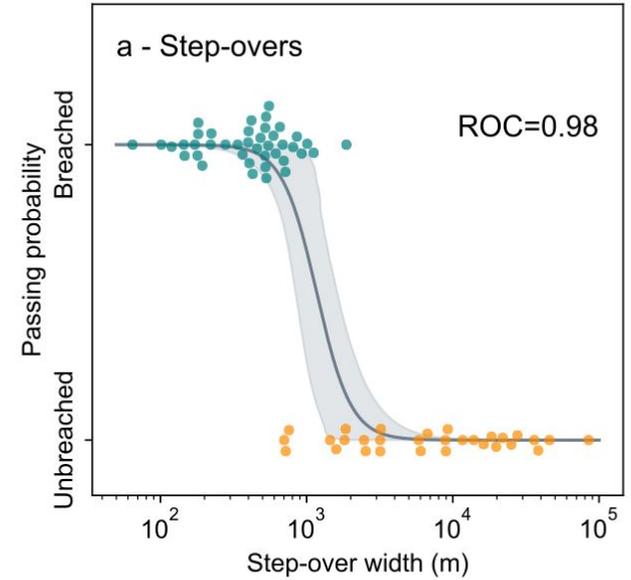


Take home messages:

Features that consistently arrest rupture are likely to extend into the seismogenic zone.

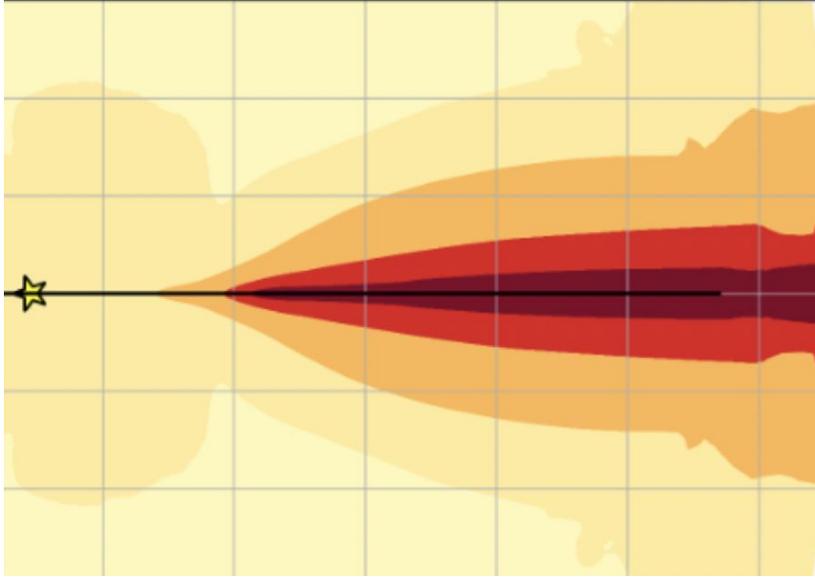
Frequent rupture arrests at zones of geometrical complexity suggest breaching these features is an important mechanism of energy dissipation during rupture propagation.

The lack of correlation between geometrical complexity size and magnitude, displacement, or position, suggest low variability in energy supply and dissipation during rupture.

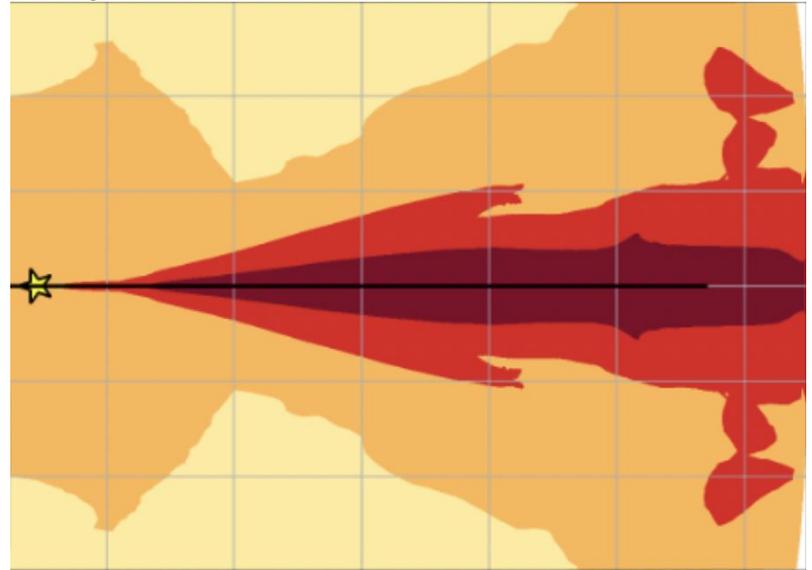


2. Where do faults go fast?

Subshear



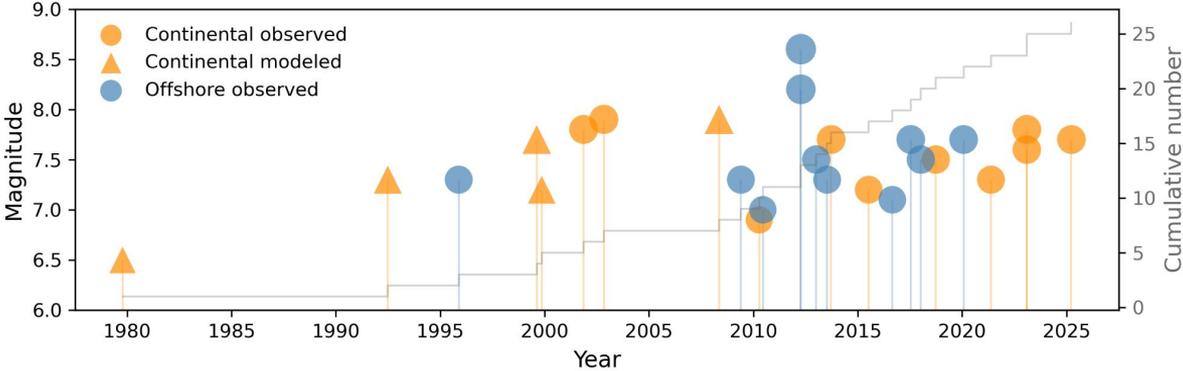
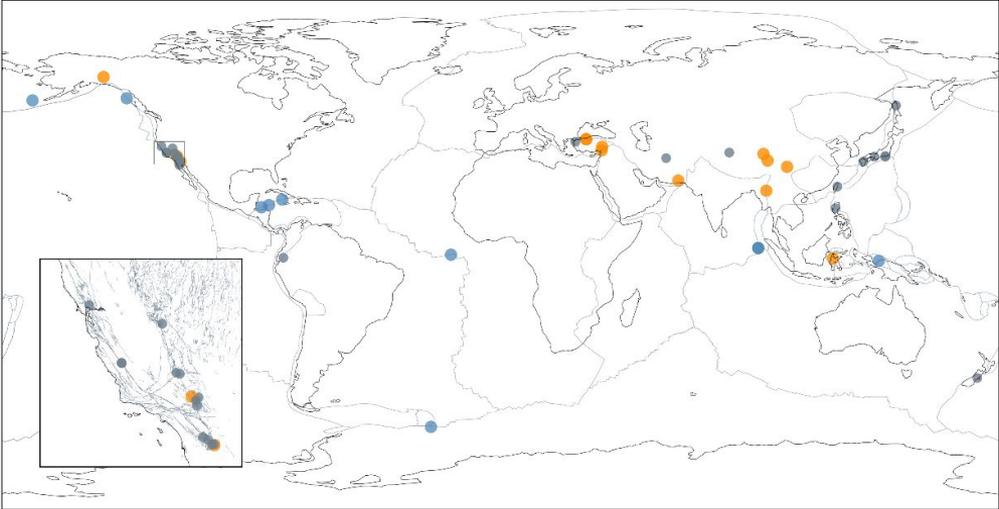
Supershear



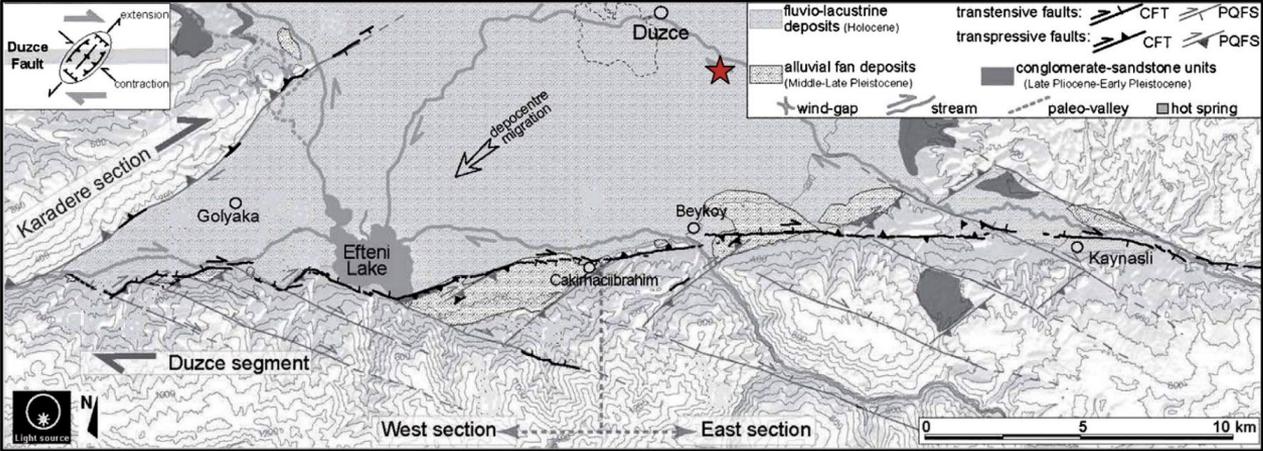
Elbanna et al., 2025

Supershear rupture speeds generate stronger and more widespread ground shaking

The record of supershear earthquakes continues to grow



Supershear rupture is often inferred on long, straight fault segments, yet fault geometry has not systematically compared between sub- and supershear ruptures.

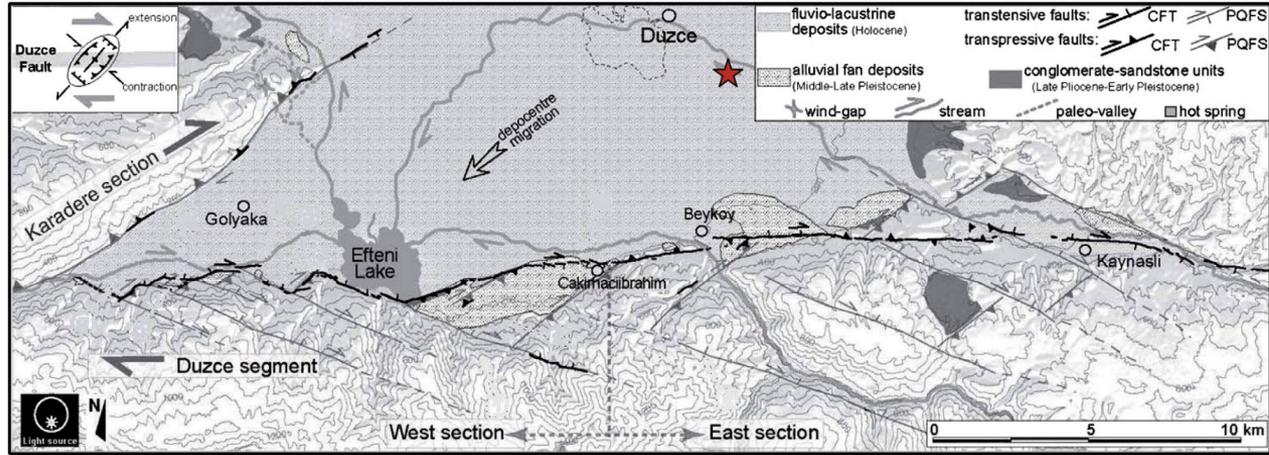


staircase trajectory
sub-Rayleigh

straight trajectory
supershear



Fault geometry is **stable over geologic timescales**, if a relationship between geometry and rupture speed exists, it holds **predictability**



staircase trajectory
sub-Rayleigh

straight trajectory
supershear



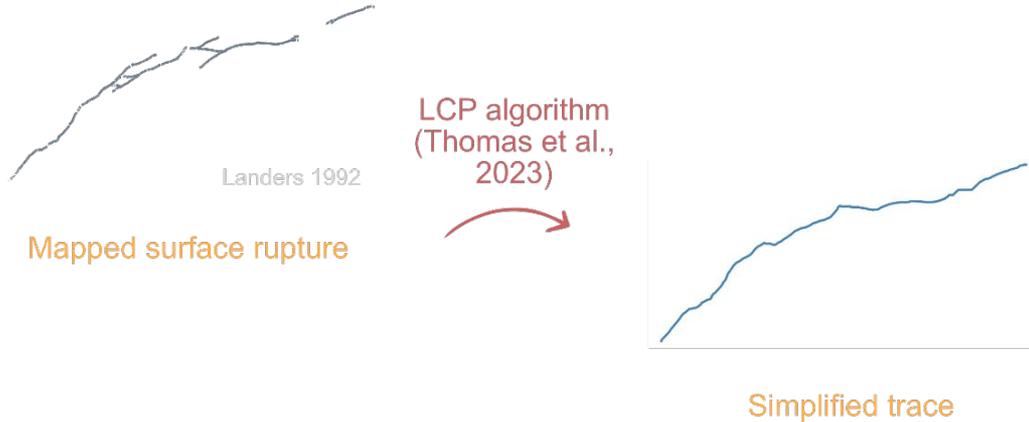
Bouchon et al., 2010

Characterization of the roughness of 39 strike-slip surface ruptures



Mapped surface rupture

Characterization of the roughness of 39 strike-slip surface ruptures



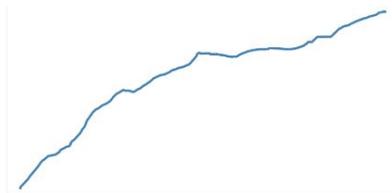
LCP simplification keeps seismogenic structure complexity while limiting high-frequency surface noise

Characterization of the roughness of 39 strike-slip surface ruptures



Mapped surface rupture

LCP algorithm
(Thomas et al.,
2023)



Simplified trace

$$\alpha = \frac{H_{\text{RMS}}}{L}$$

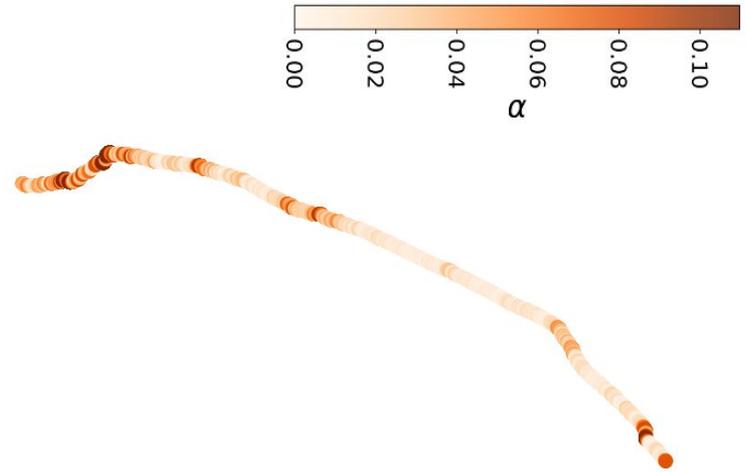
RMS fault roughness
(Candela et al., 2007;
Bruhat et al., 2017)



Fault roughness along
strike, over 5 km window (L)

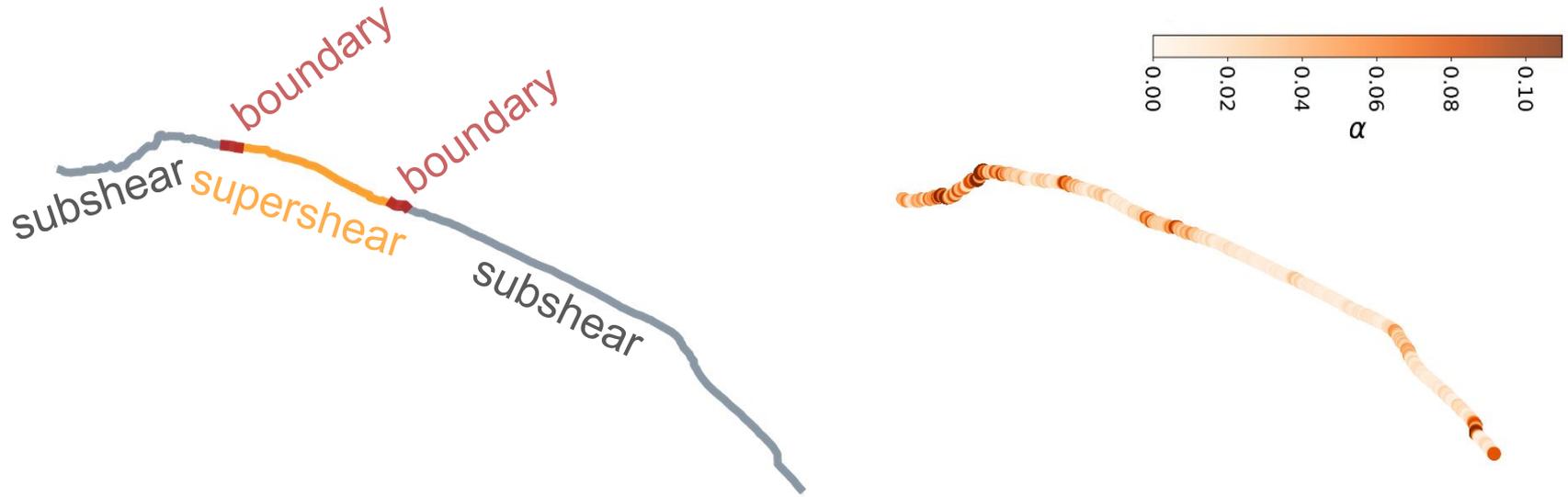
Windowing in roughness calculation further limits mapping variability

Roughness distribution for surface rupture: Denali



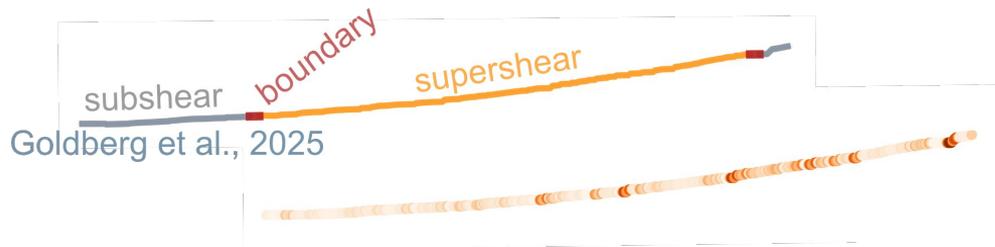
Darker orange = rougher parts of fault

Mining extent of supershear for each event from the literature

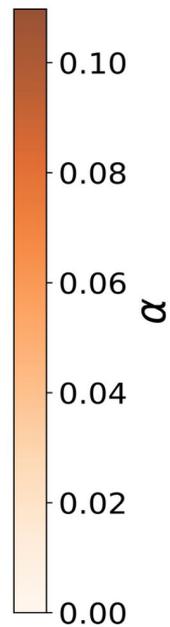


Supershear segment extent characterized from variety of data: near-field seismology, backprojection, or inferred from dynamic rupture models

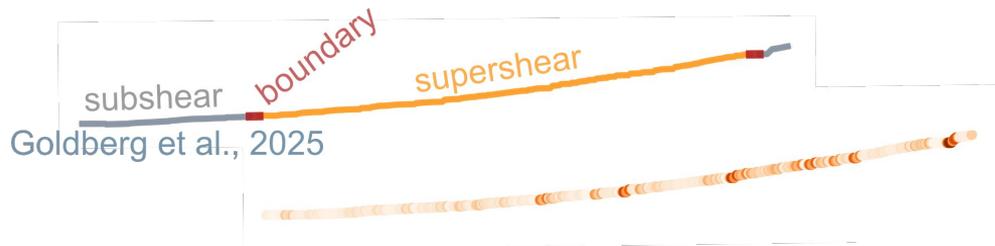
Myanmar



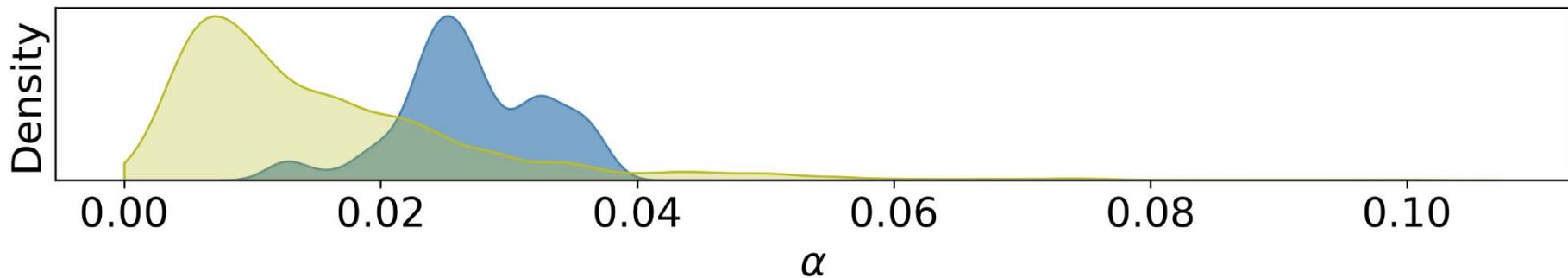
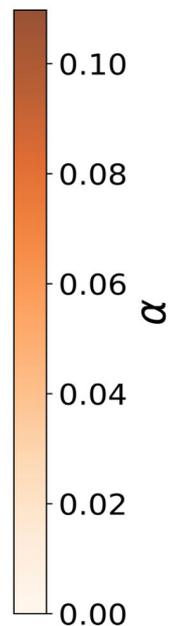
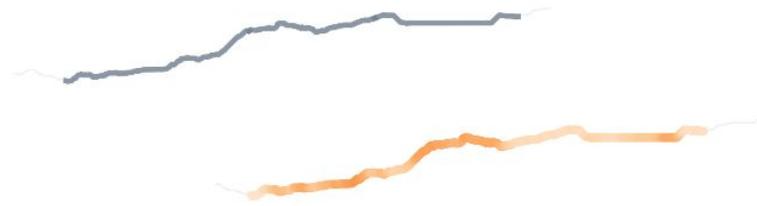
Chalfant Valley

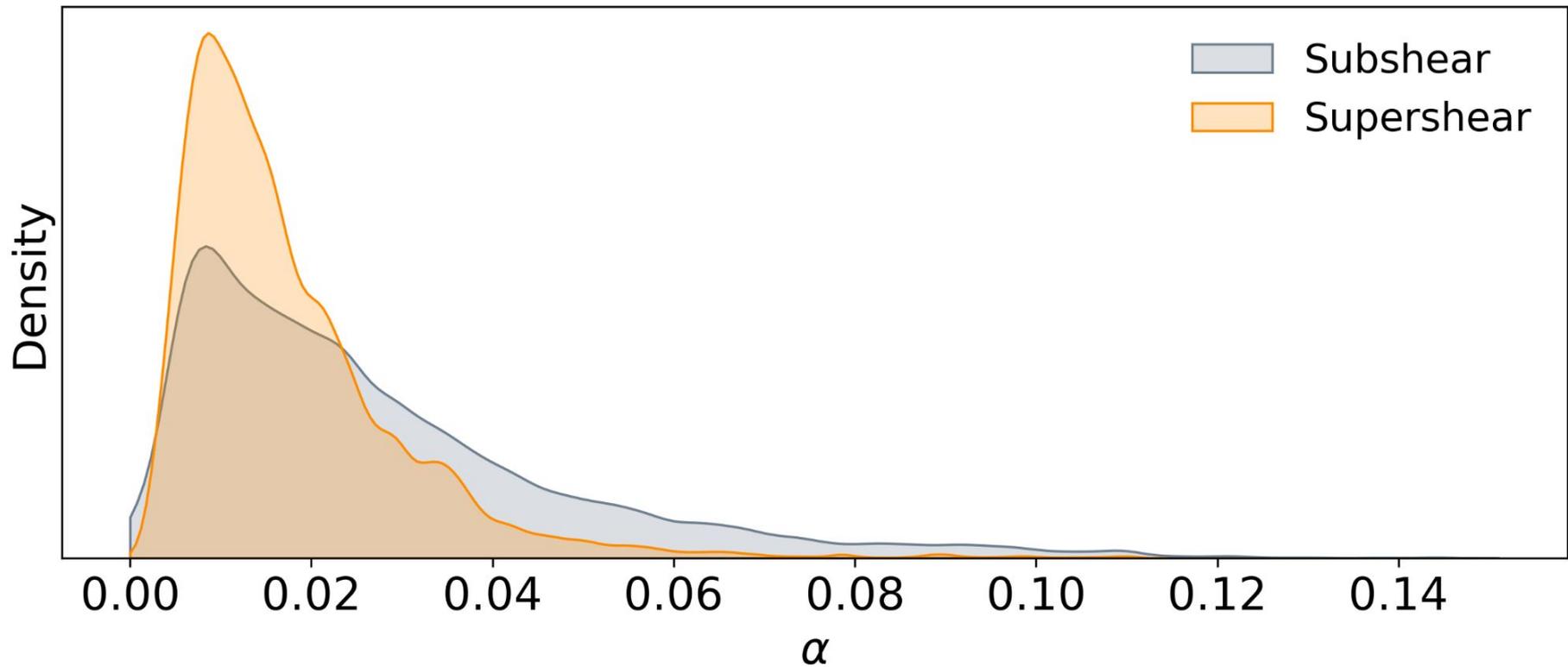


Myanmar



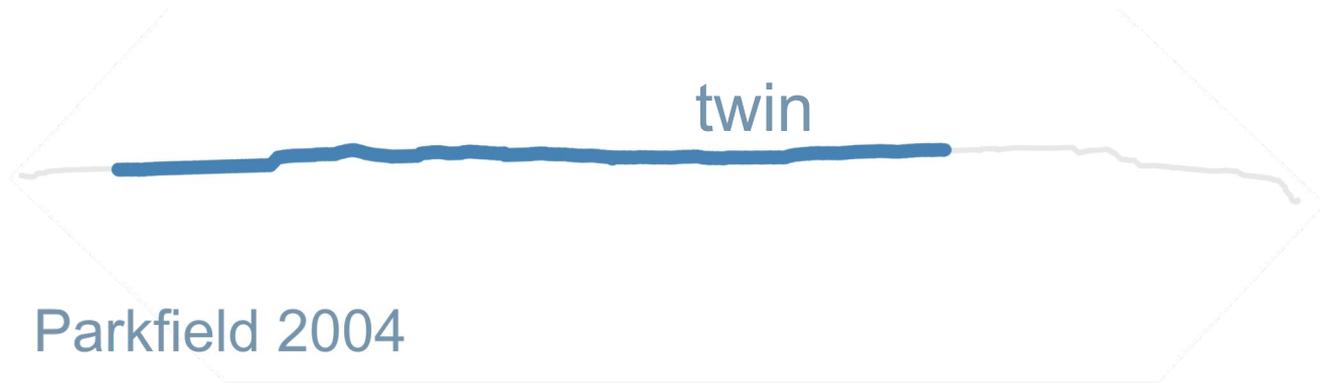
Chalfant Valley



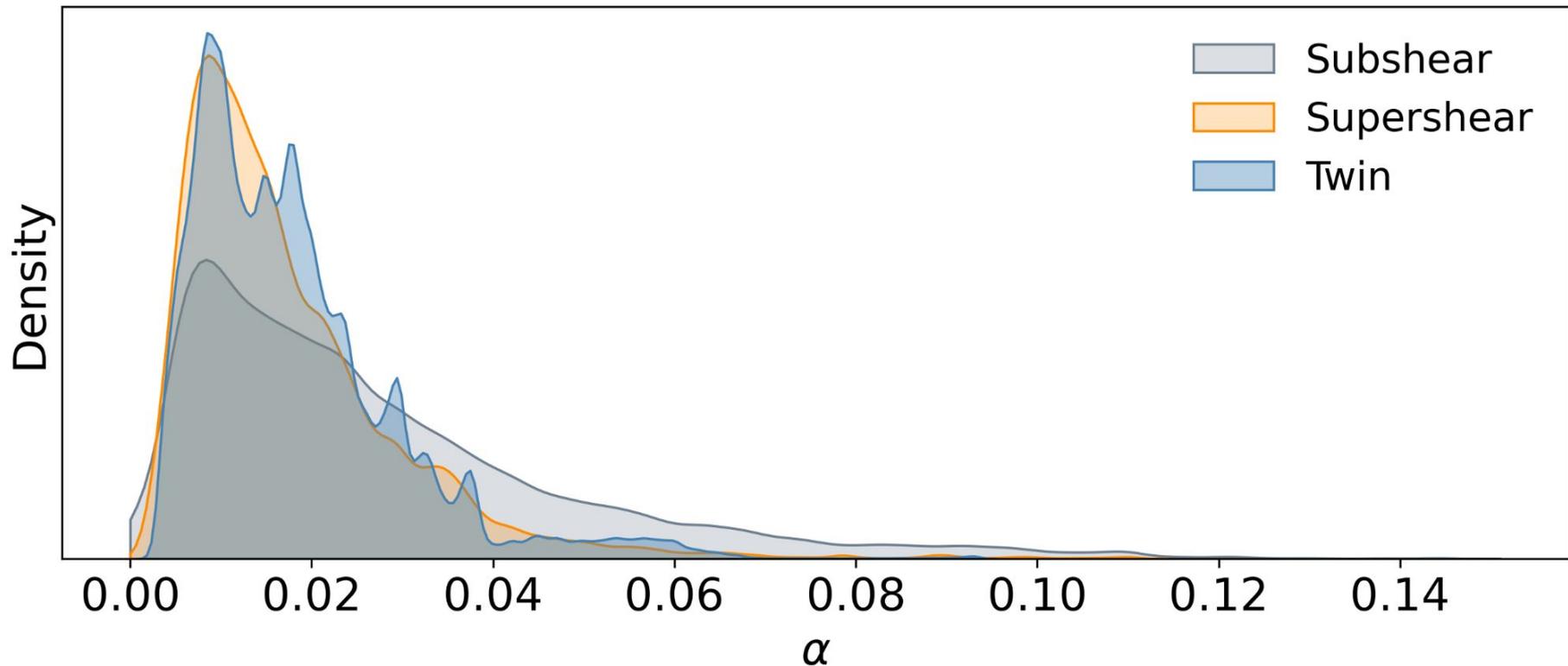


Supershear segments are smoother than subshear segments, but there is substantial overlap in their populations.

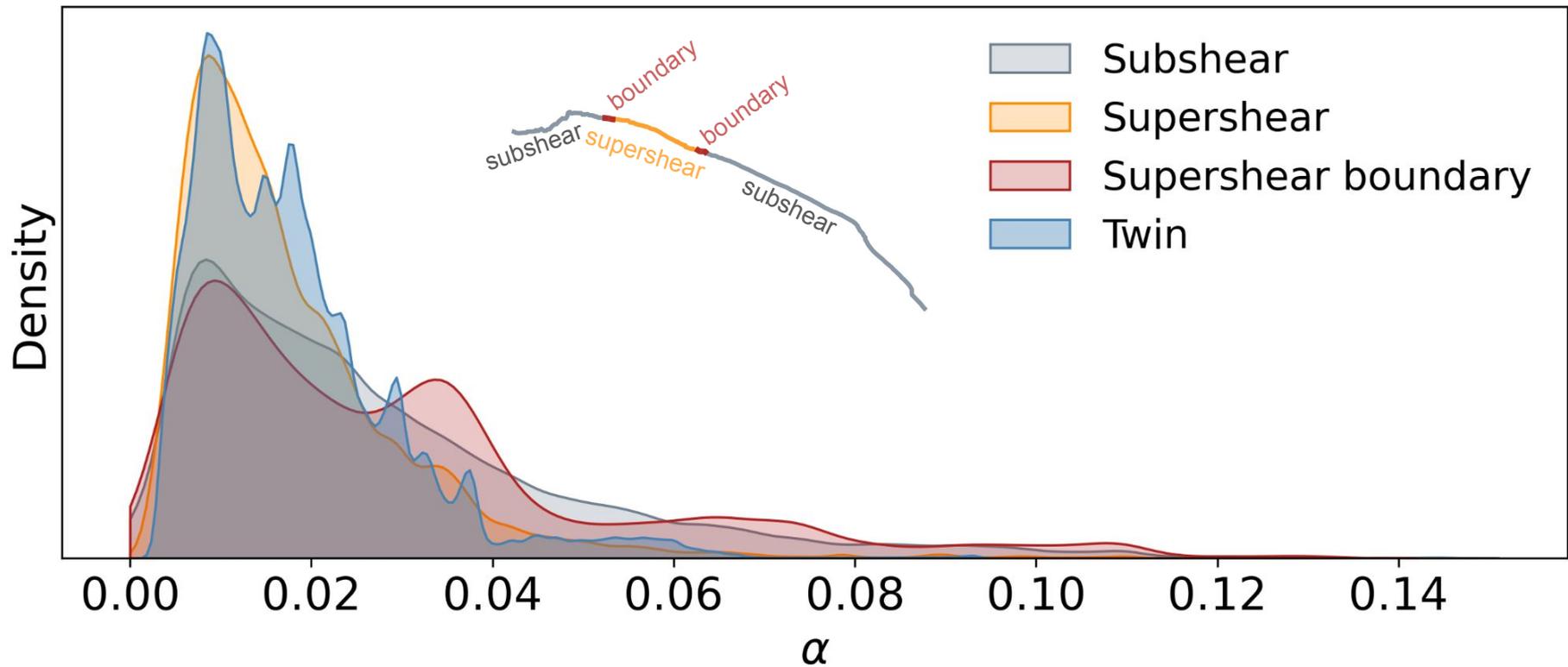
Template matching of supershear segments: searching for **twins** with comparable length and roughness, but subshear speeds



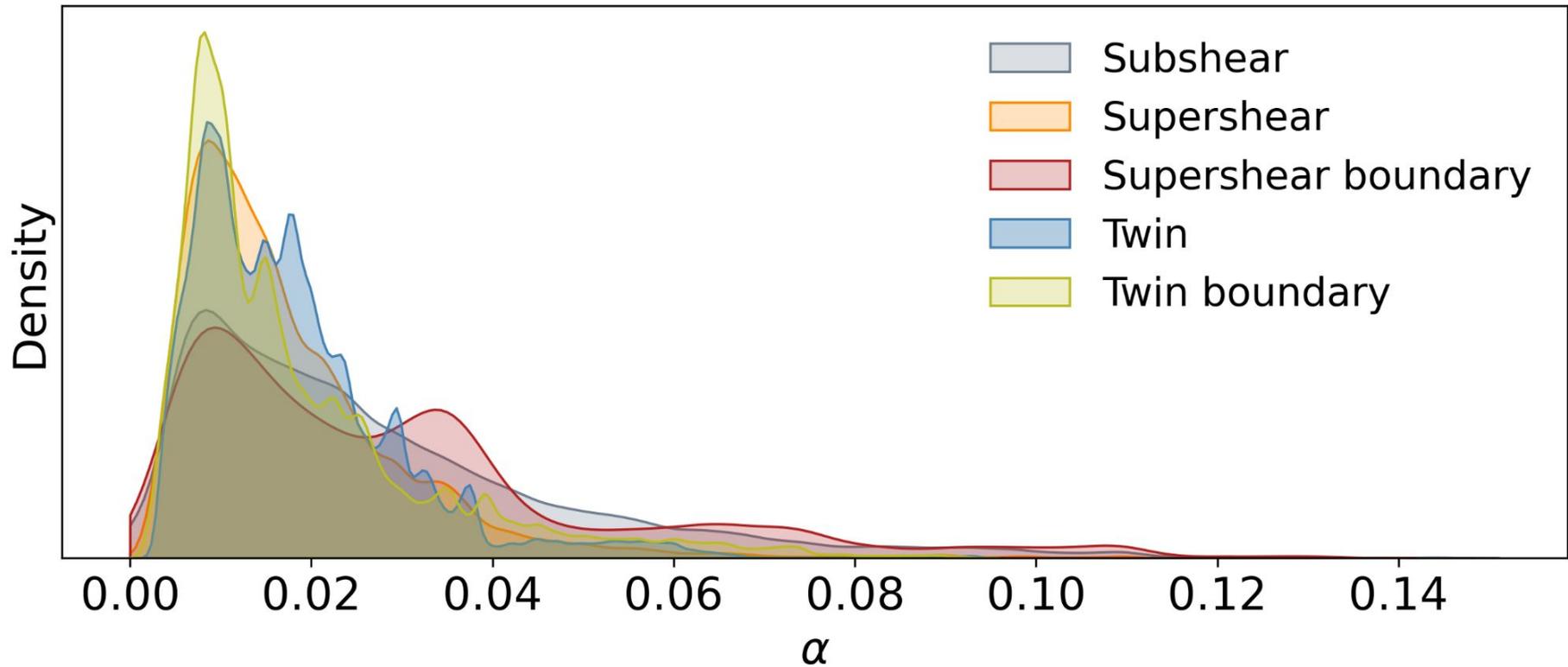
These twins may provide insights into why some segments achieve and sustain intersonic rupture.



A portion of subshear segments have lengths and roughness comparable to supershear segments; many of these occur on events that went supershear on a different segment. **Smoothness is a necessary but insufficient condition for reaching and sustaining supershear speeds.**

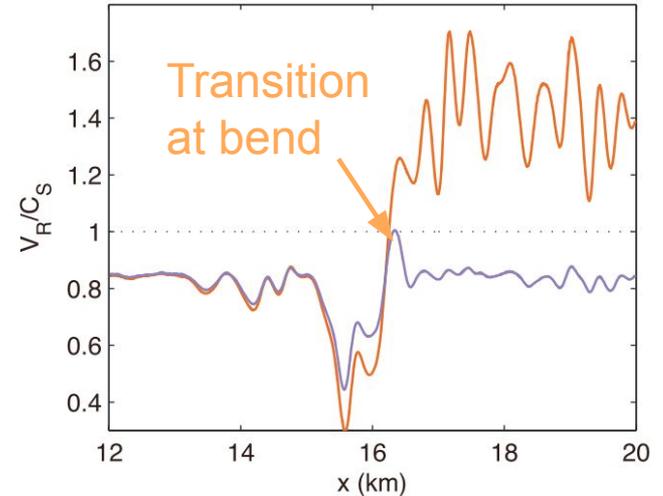
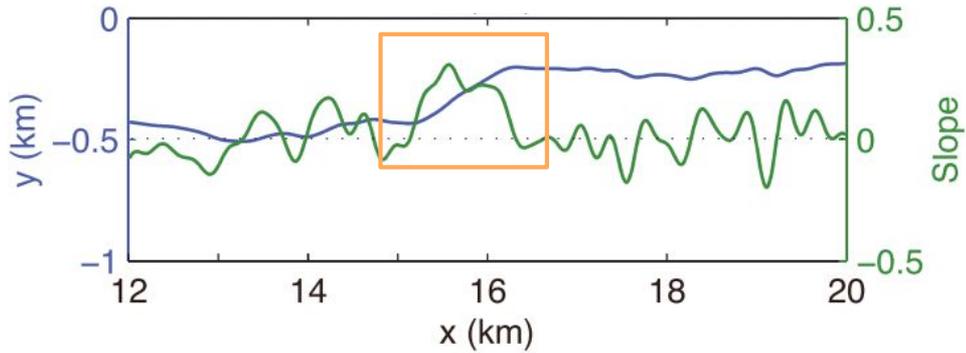


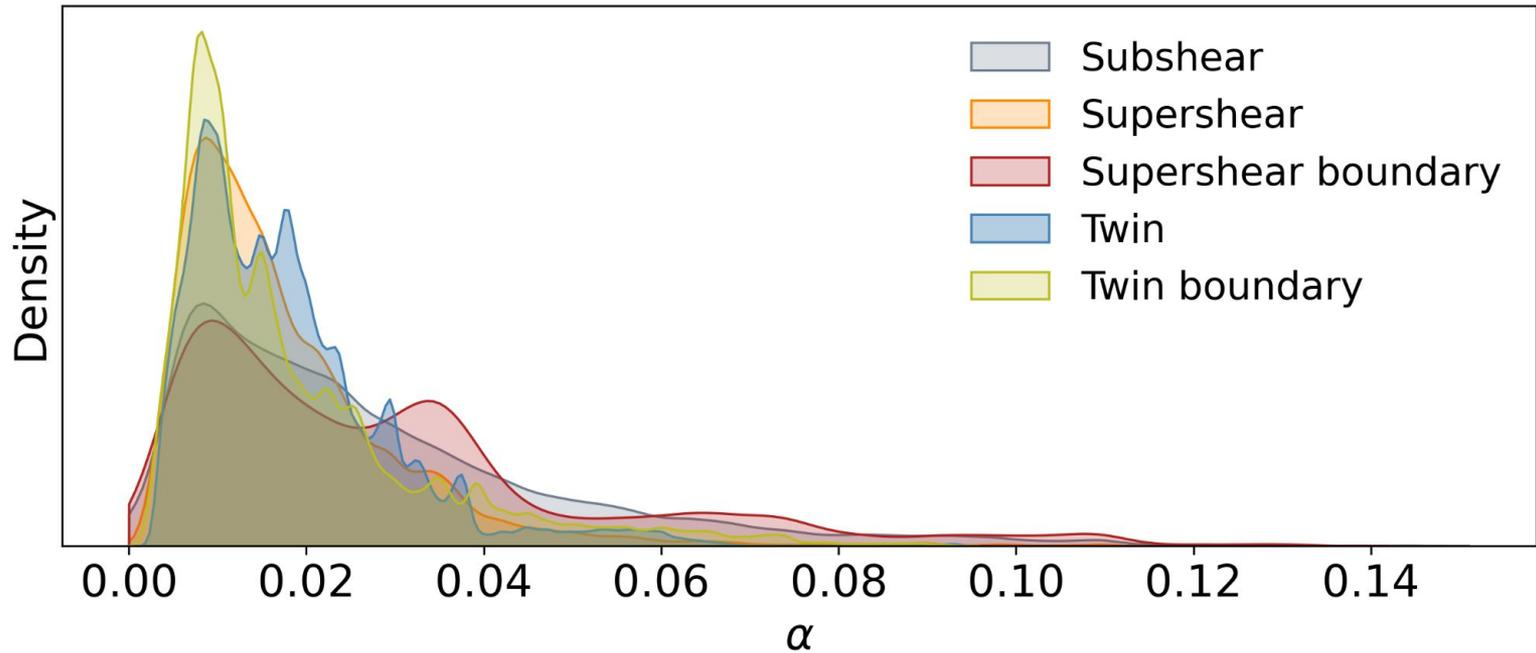
Supershear segment boundaries are much rougher than supershear and subshear segments.



The boundaries of the twin segments are comparable in roughness to the twins and the supershear segments, and much **smoother than the supershear boundaries.**

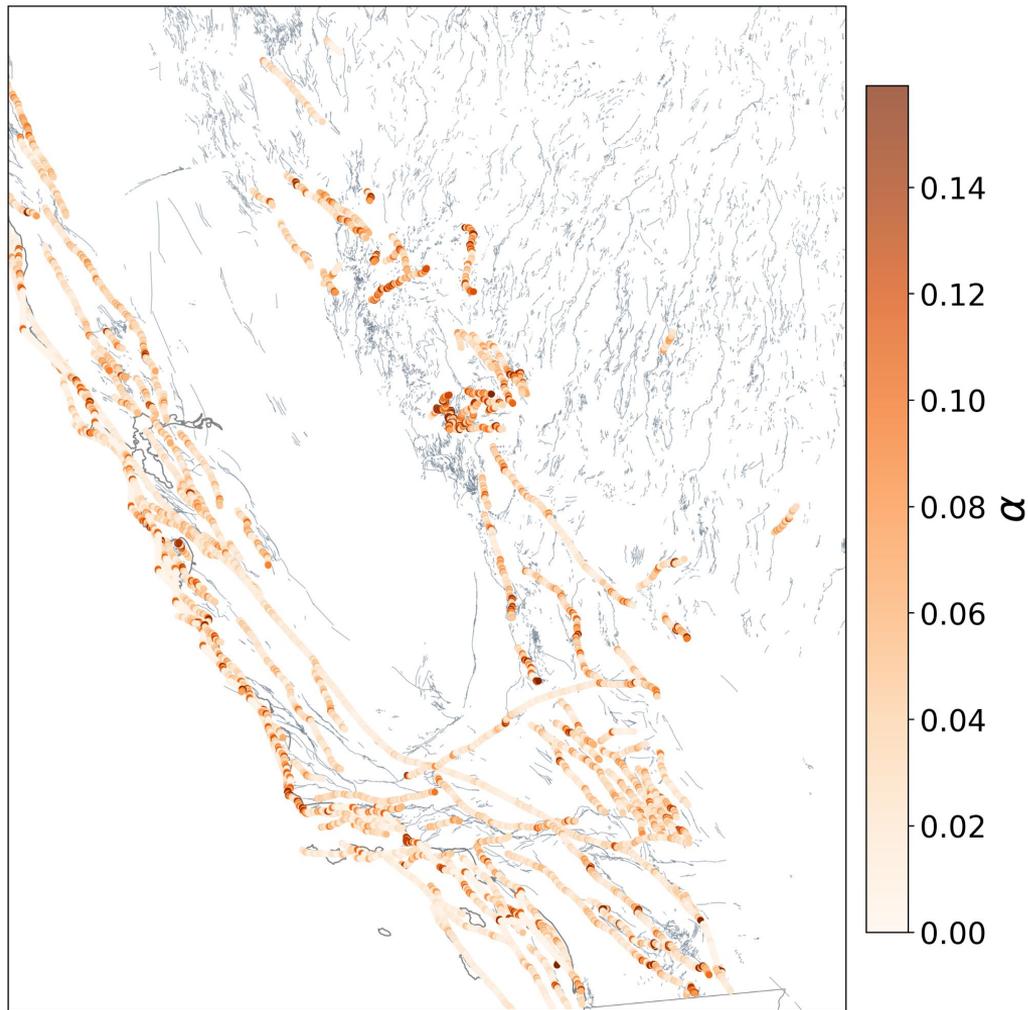
Models show **geometrical complexity** on faults can trigger the **transition to supershear rupture speeds**



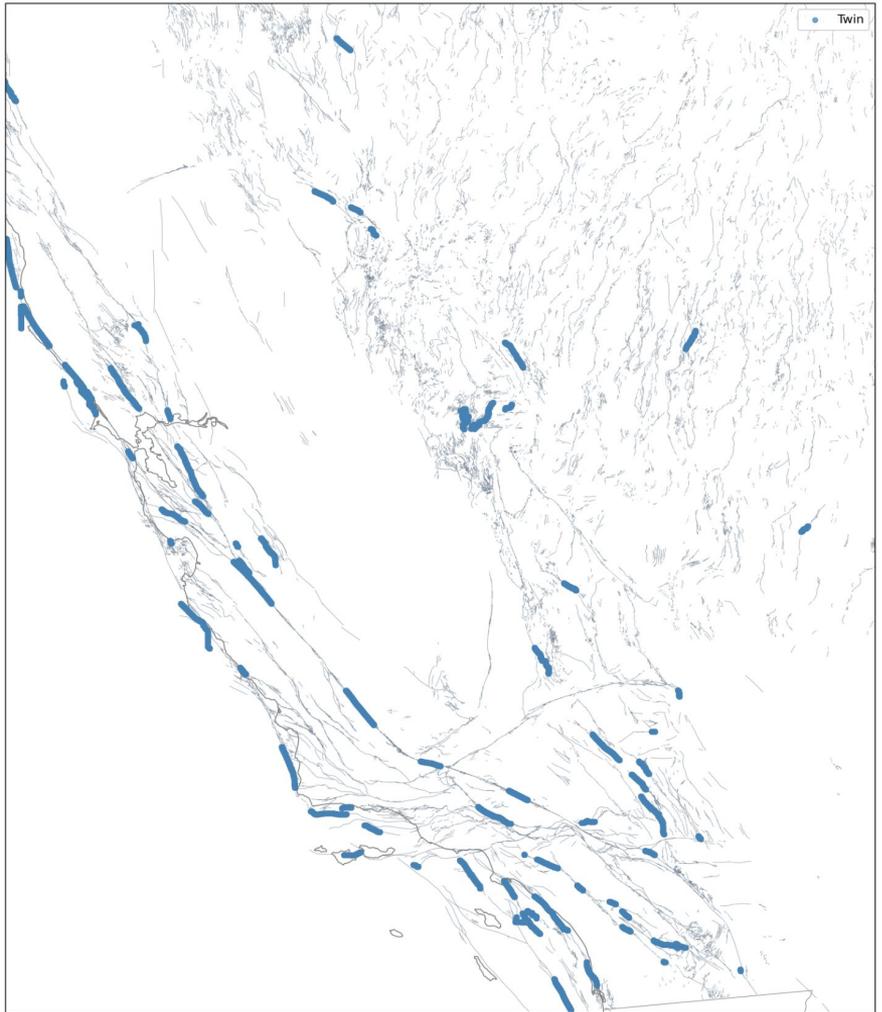


Supershear boundaries being distinctly rough lends **observational support to the supershear transition at geometrical complexity mechanism** that emerges in models.

Supershear in SCEC's home turf?

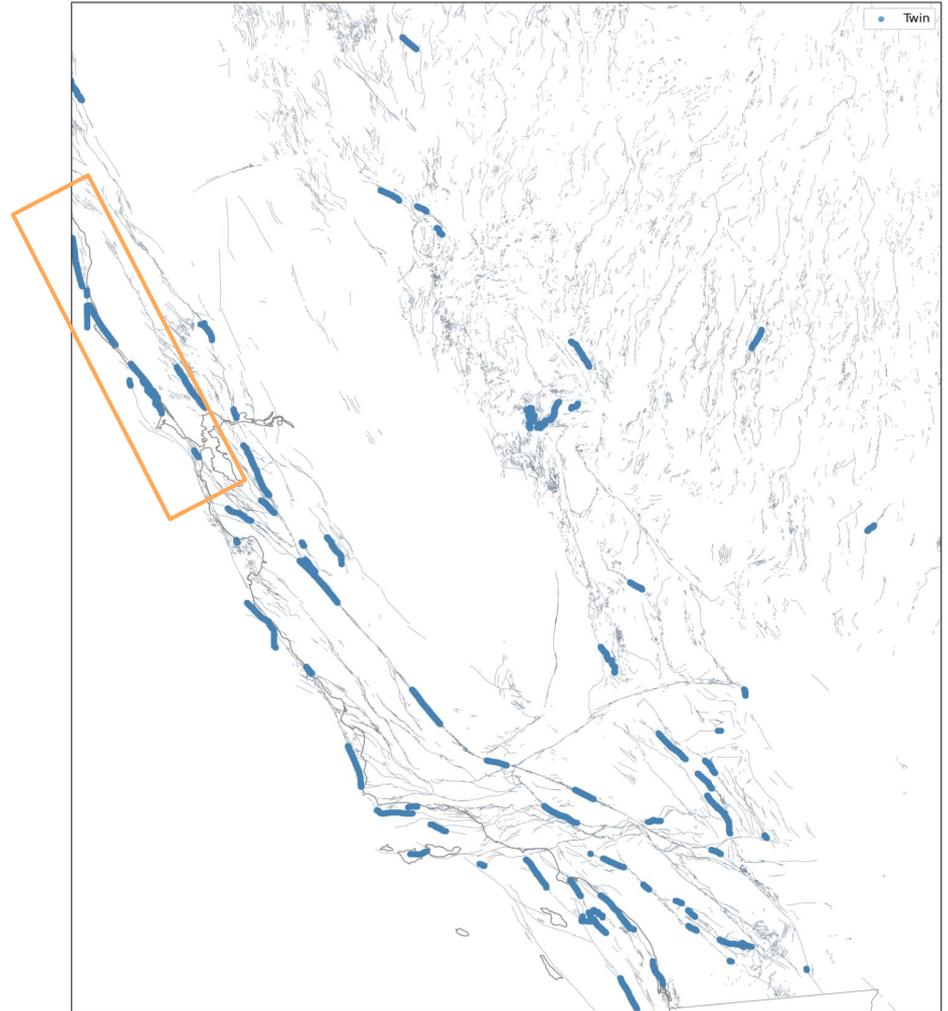


SCEC's supershear twins



Applications to future large strike-slip events in CA

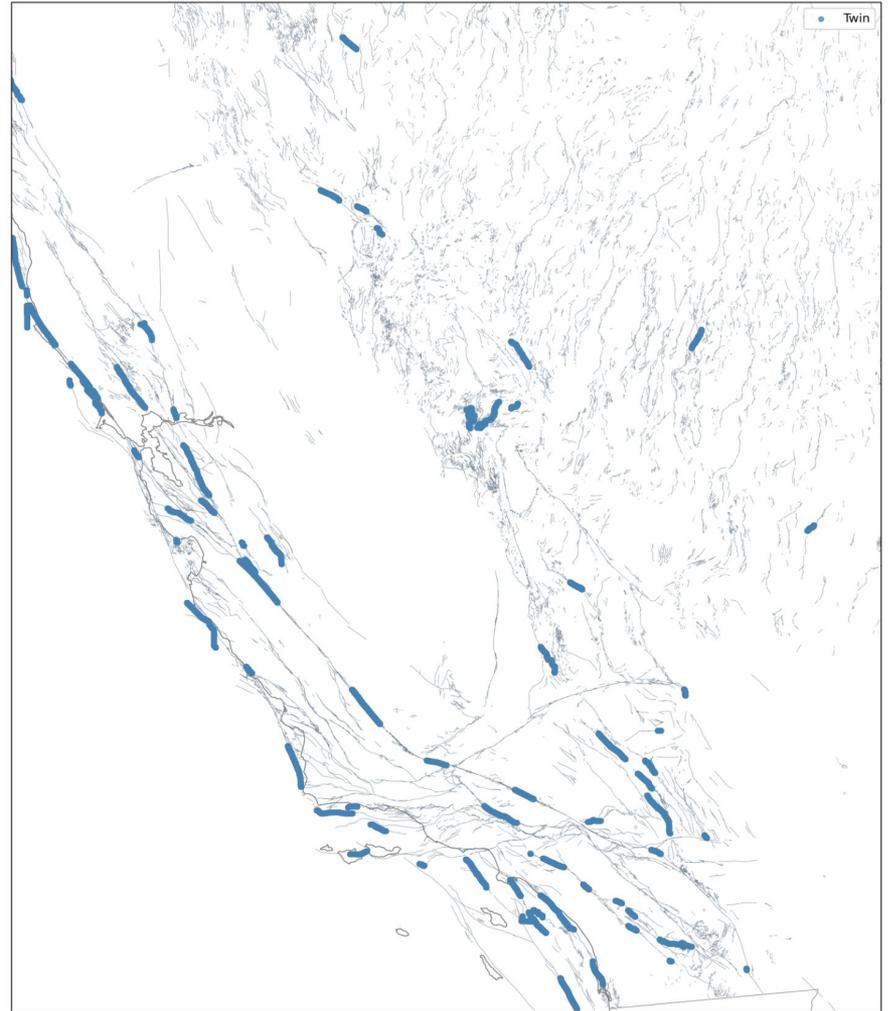
Parts of the San Andreas that ruptured in 1906, proposed to have gone supershear (Song et al., 2008) are highlighted as potential supershear segments in this analysis too.



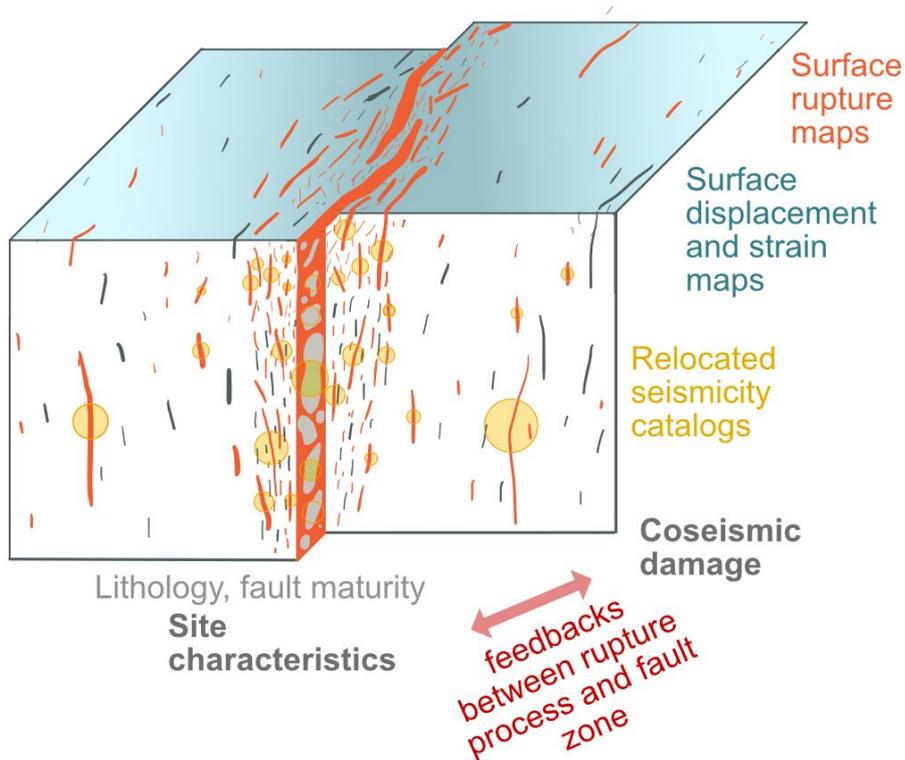
Applications to future large strike-slip events in CA

Many potential supershear segments occur offshore.

Continental-oceanic lithosphere contrast favors simplicity in fault geometry. BUT artificial simplicity can also emerge from lower-resolution datasets for offshore mapping.

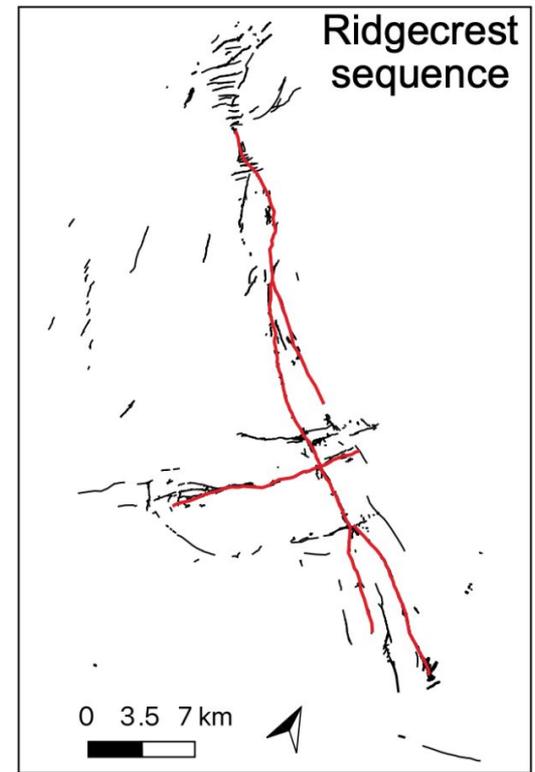
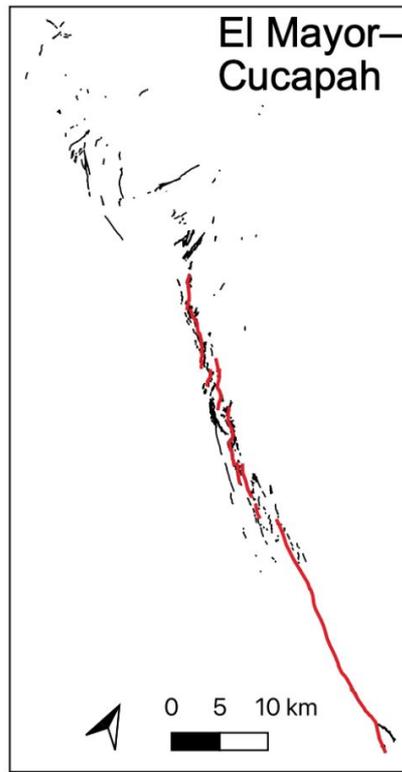
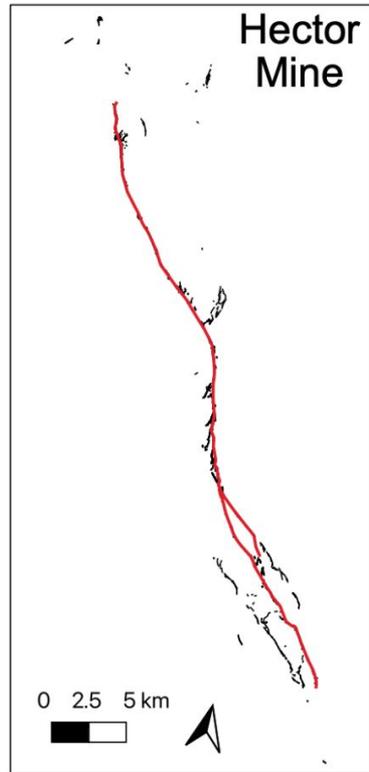
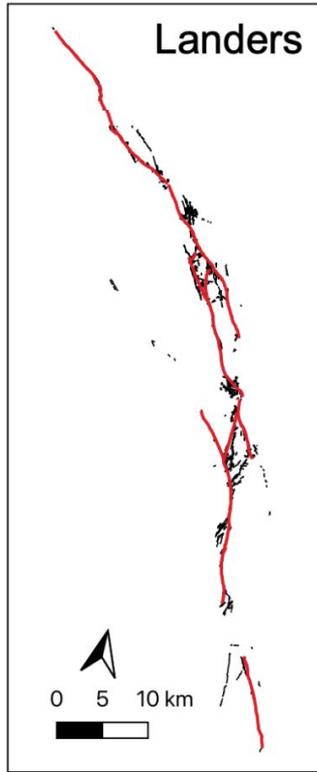


Large earthquakes illuminate fault zone architecture at the surface and depth

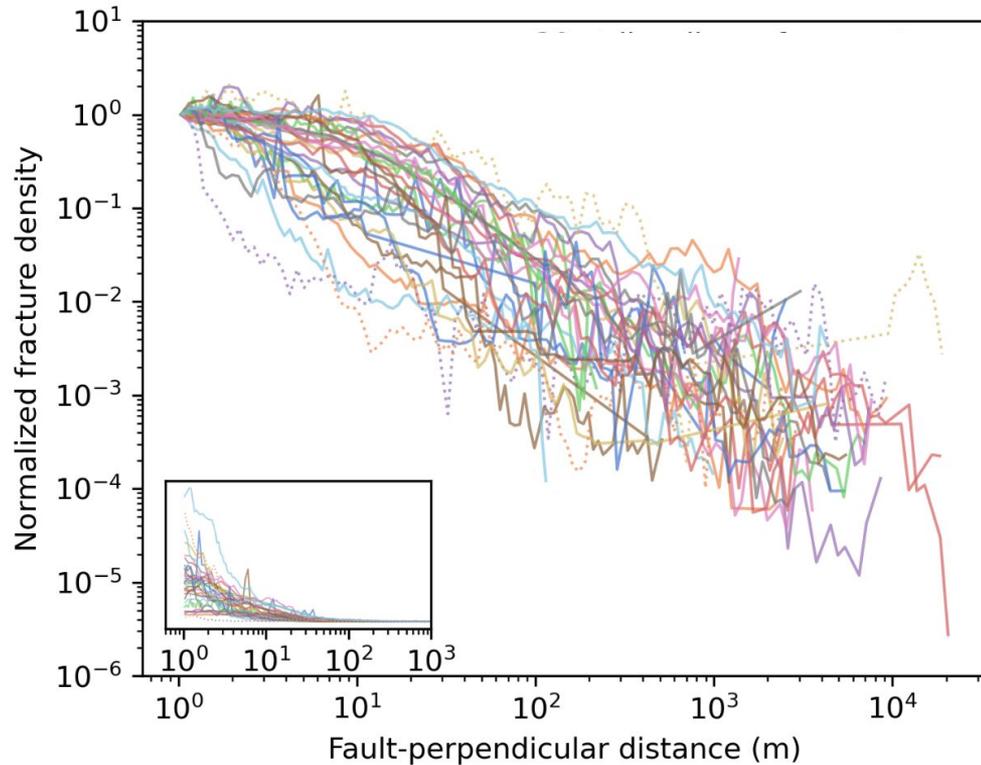


1. Probe 3D fault zone architecture
2. Probe physics of how shallow crust deforms

What is the distribution of off-fault damage in the form of fracturing at the surface?

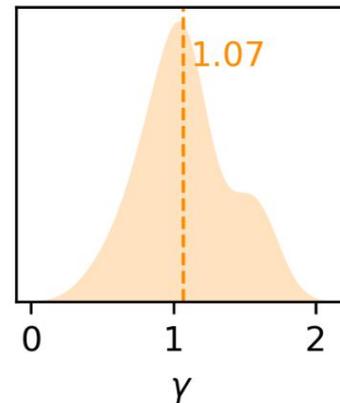
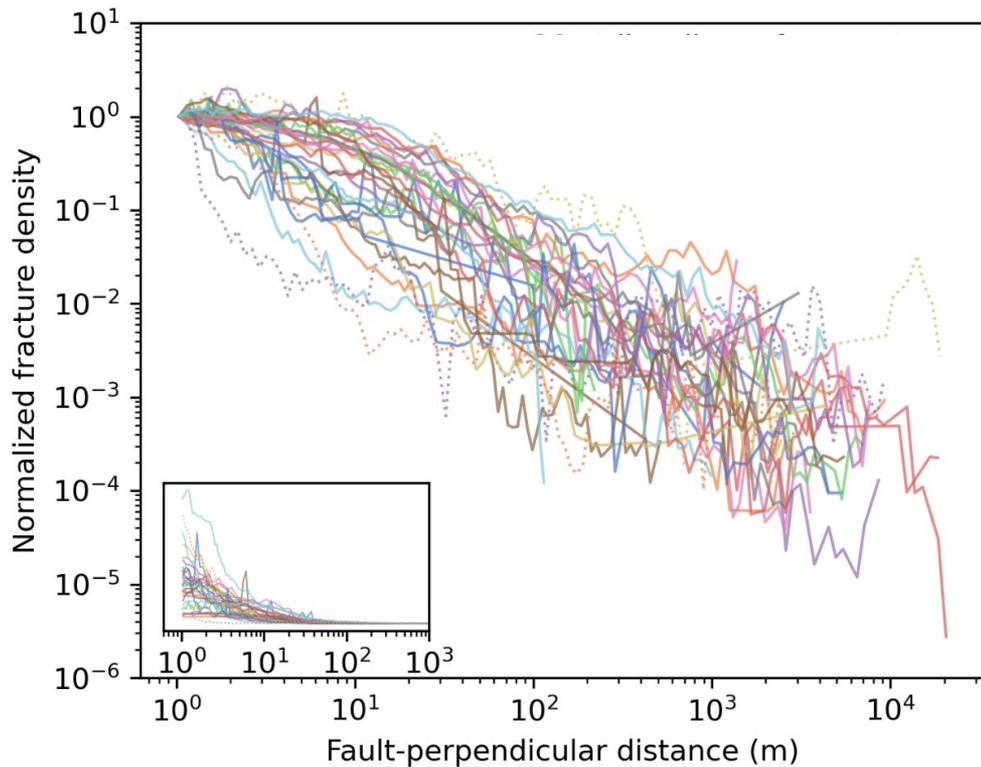


What is the distribution of off-fault damage in the form of fracturing at the surface?



Consistent
non-linear decay in
fracture density with
distance across ~ 30
events

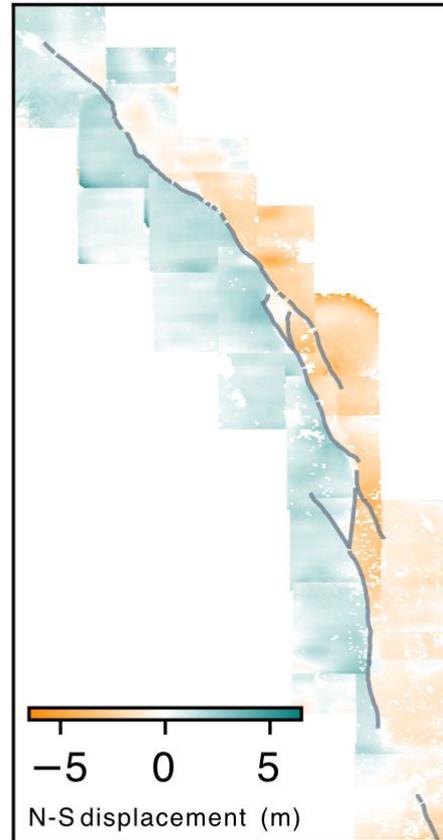
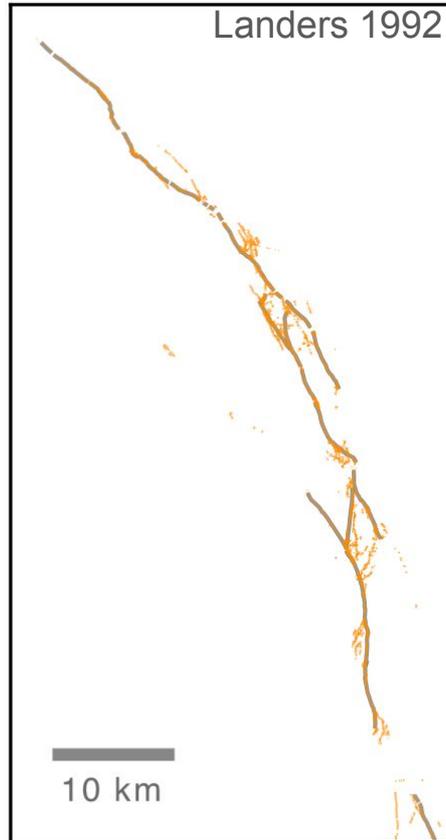
The spatial distribution of fractures around faults follows an inverse power-law with exponent ~ 1



Power-law exponent

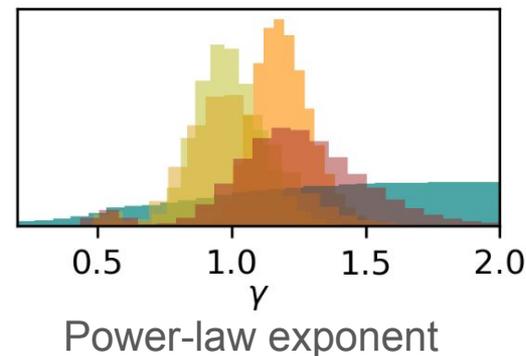
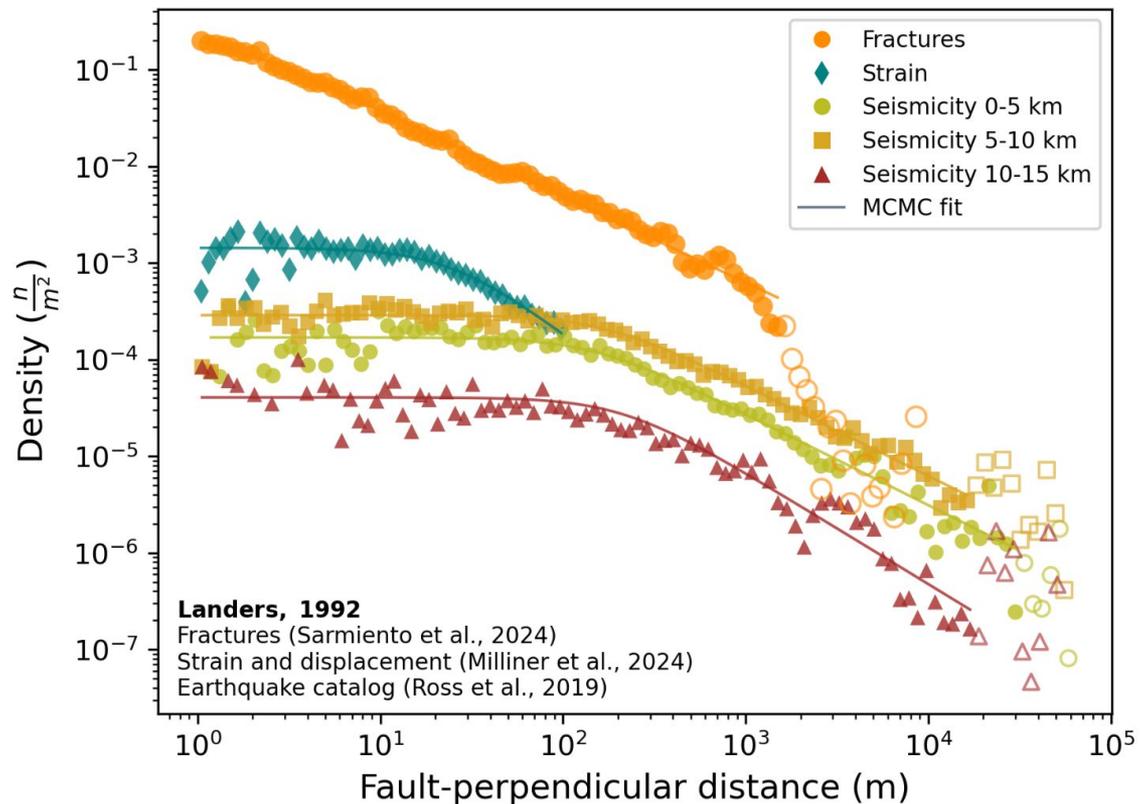
Same process
dominates yielding over
km scale around fault?

Different datasets available after a specific earthquake can probe the **architecture of the fault zone at the surface and depth.**



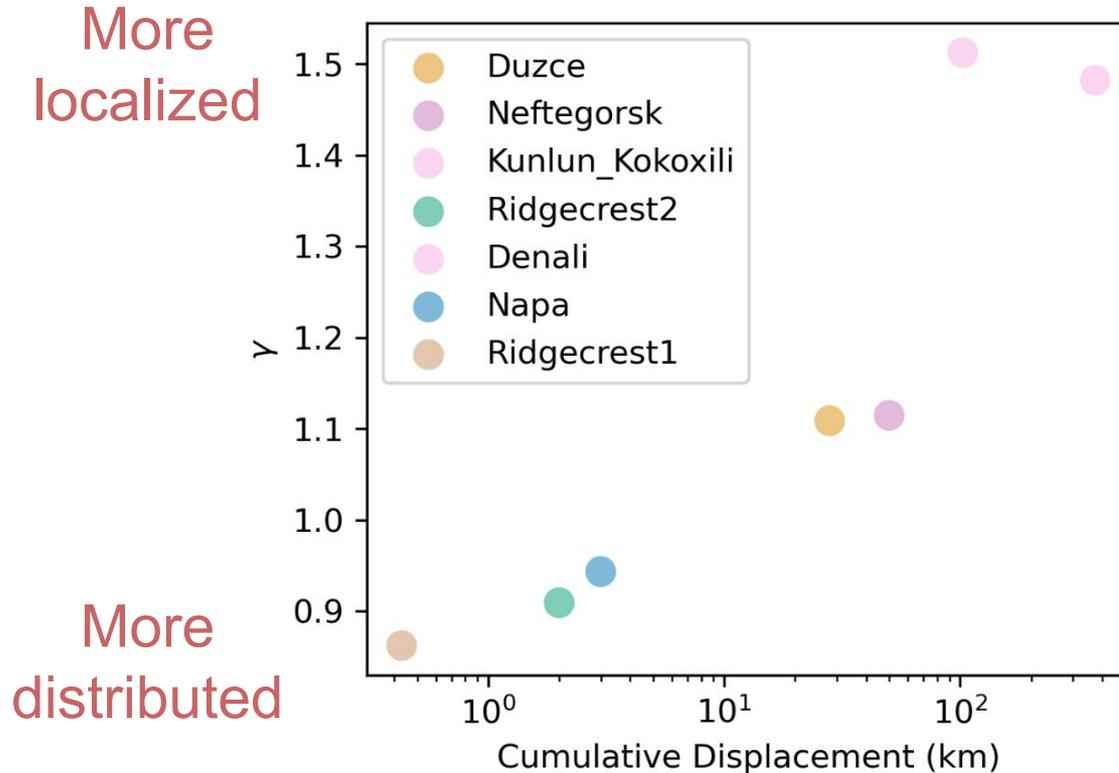
Similarity of fracture, strain, and aftershock distributions at different depths suggest a tabular fault zone where **surface deformation is representative of processes at depth.**

1992 Landers earthquake



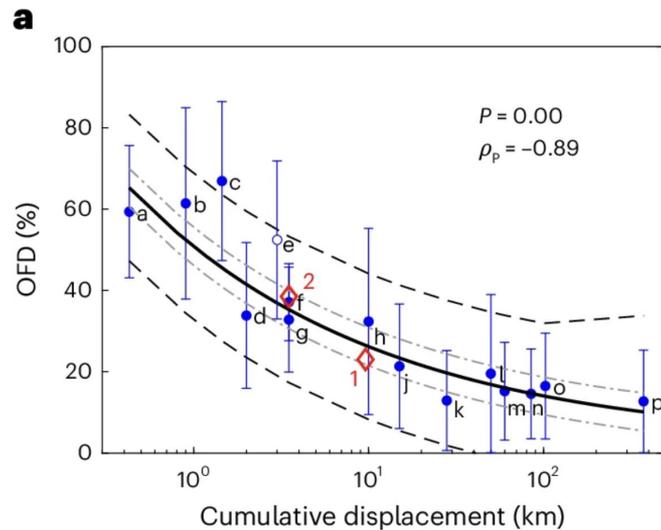
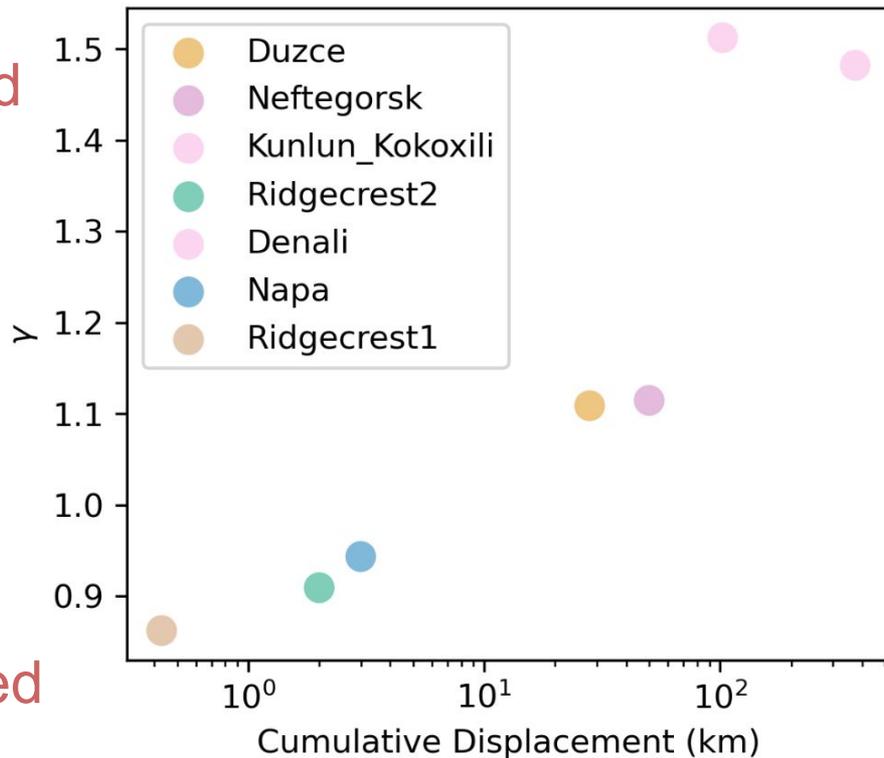
Same process dominates yielding over km scale around fault over 15 km depth range?

Fracture distribution localizes with increasing cumulative displacement



Fracture distribution localizes with increasing cumulative displacement

More localized

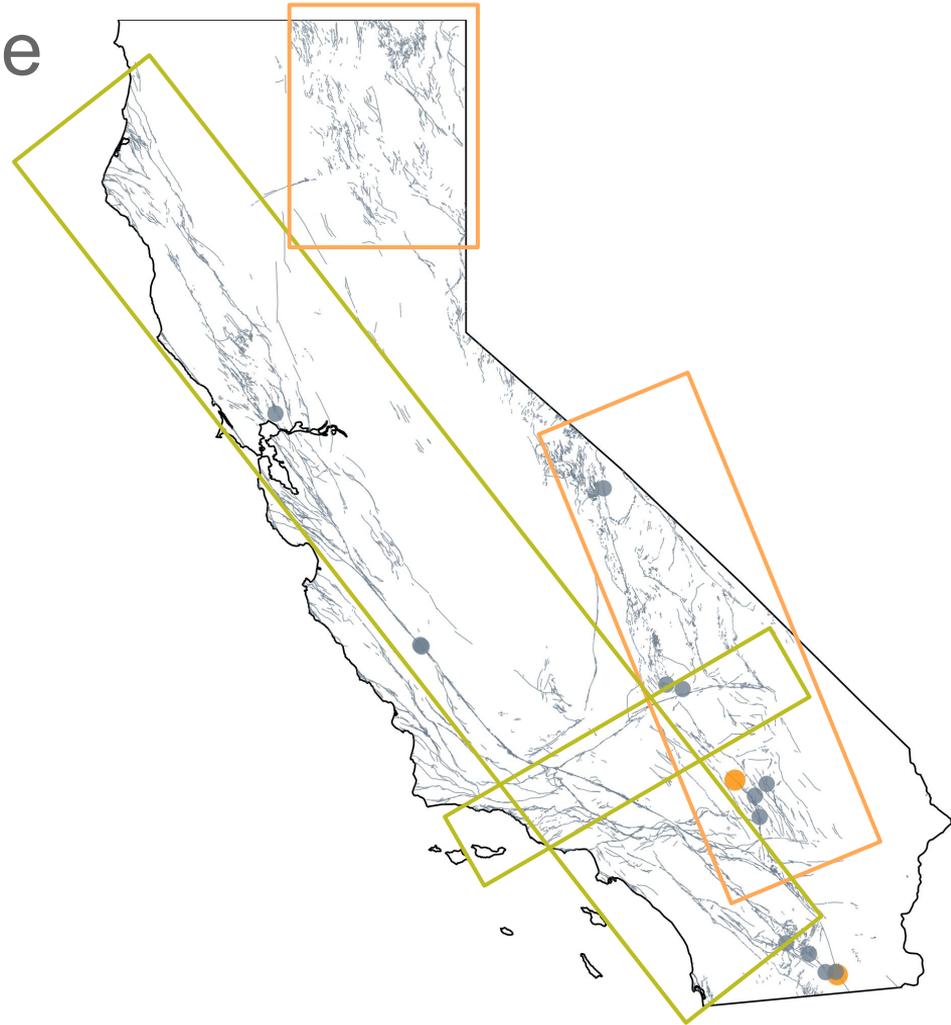


Milliner et al., 2025

Applications to future large strike-slip events in CA

Mature fault zones:
expect localized
deformation

Immature fault
zones: expect widely
distributed
deformation



Take home messages:

Surface rupture maps may be used to probe rupture dynamics and fault zone physics

Surface data can be used to infer processes at depth, but doing so requires caution (scale, feature and problem type, resolution)



Surface rupture of the 1968 Borrego earthquake, CA

Are you interested in these problems or know a student or postdoc that may be?

The Earthquake Science Group at Utah State University is recruiting!

Reach out if you are interested: alba.rodriquez@usu.edu |

<https://absrp.github.io/>

Winter on USU campus, USU

Fall in Logan Canyon, Getty



Are you interested in these problems or know a student or postdoc that may be?



<https://qanr.usu.edu/geo/earthquake-science>



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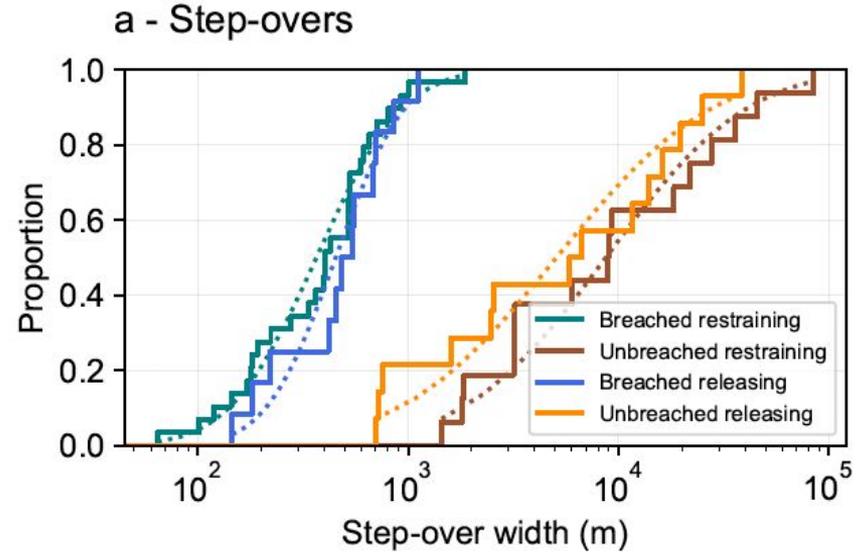


Dr. Srisharan Shreedharan

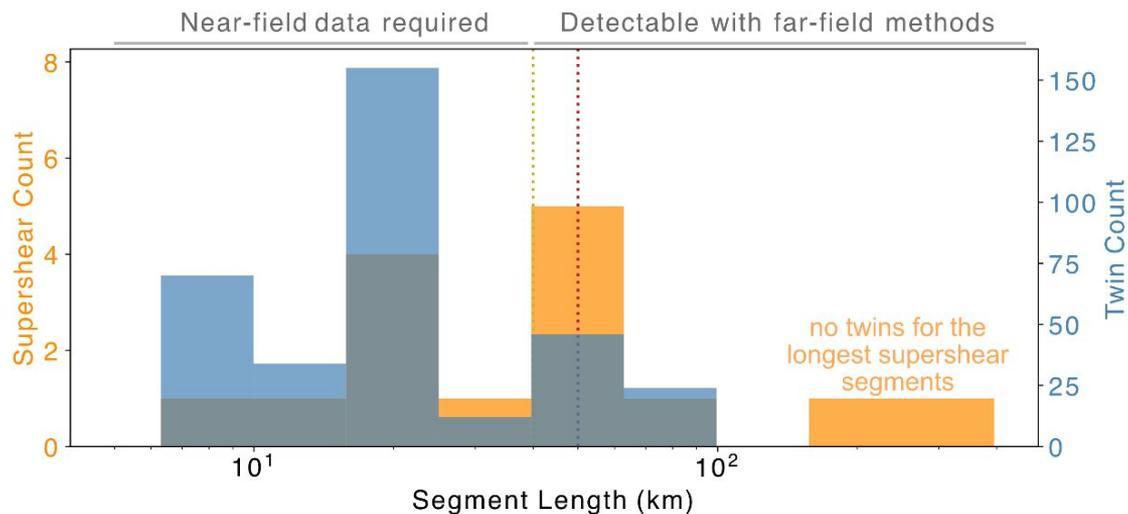
Assistant Professor
Geomechanics and Geophysics
srisharan.shreedharan@usu.edu
[CV](#)
[Research Website](#)

Back-up slides

Restraining and releasing features are statistically indistinguishable, in contrast with behavior in numerical models.



Many of the twin segments are too short to be detectable with far-field methods. Could some have gone supershear and been undercounted? Examination of individual segments and corresponding near field-data is needed.



Observational limits

Backprojection
resolution limit

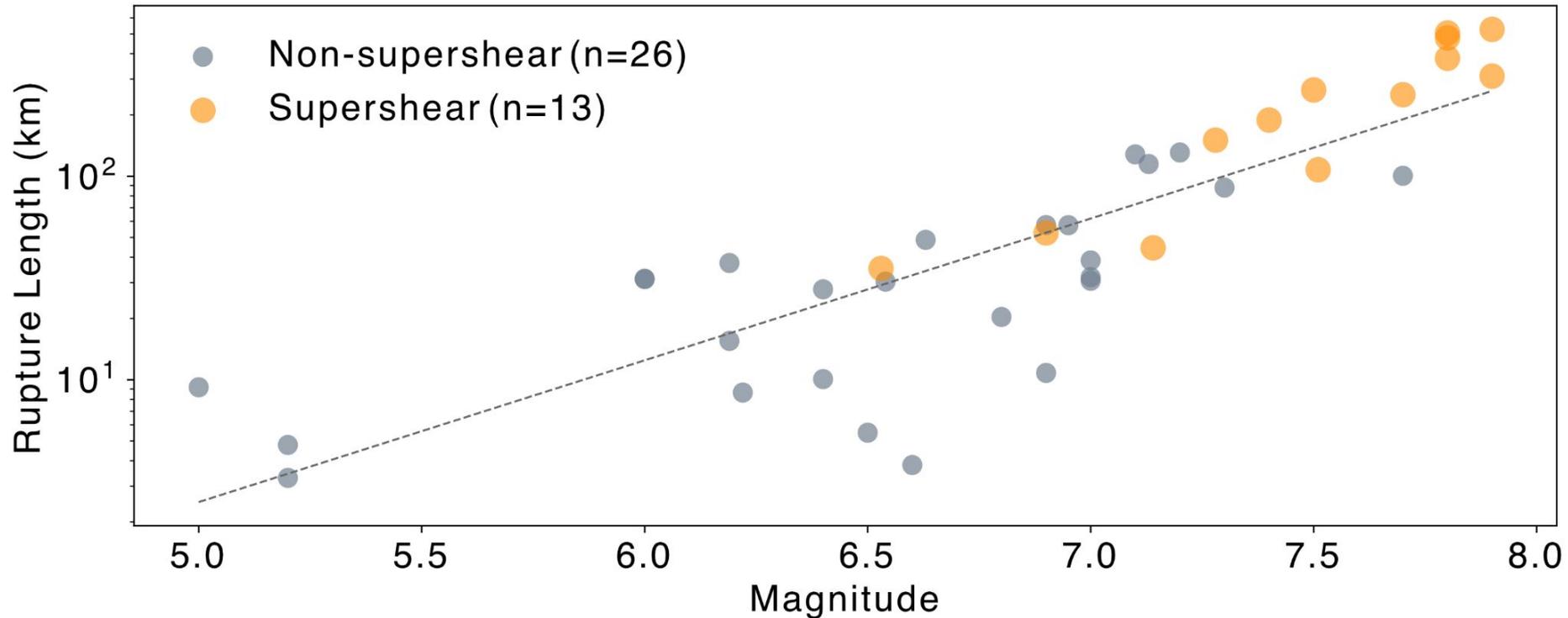
Far-field Mach cone
resolution limit

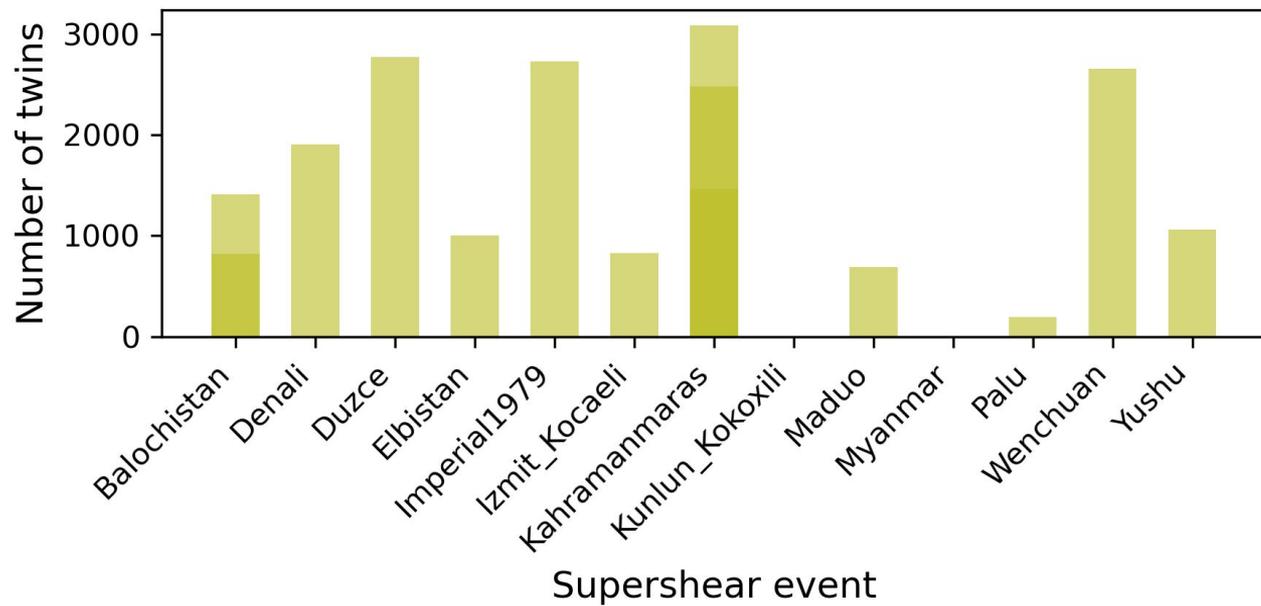
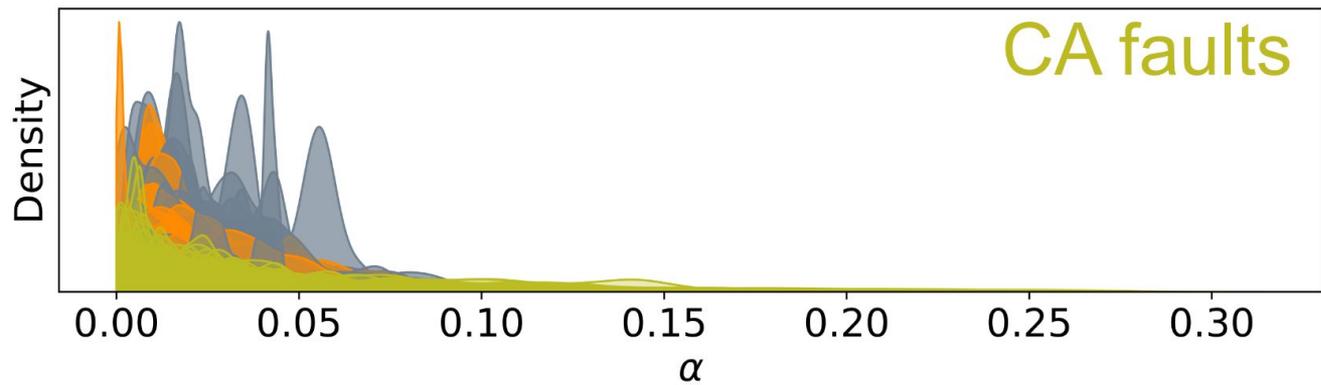
Supershear segment
length > ~50 km

Supershear segment
length > ~40 km

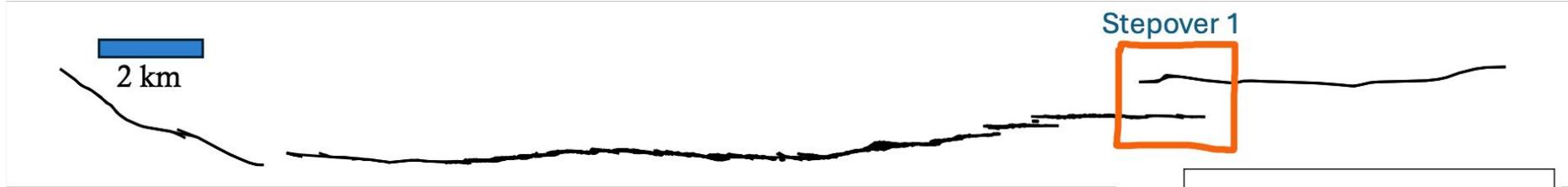
Bao (2022)

Magnitude is the biggest predictor of probability of supershear rupture speeds occurring on fault



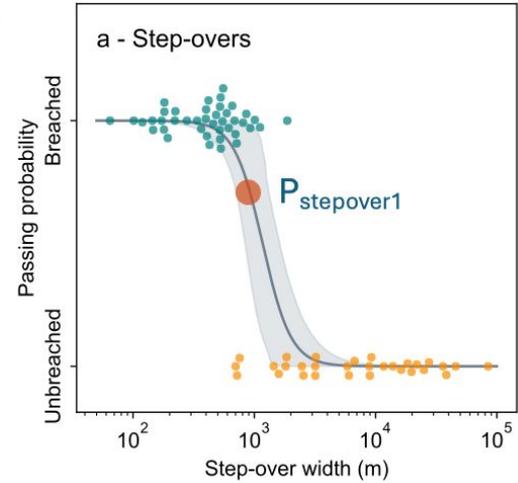


How do zones of geometrical complexity influence earthquake surface rupture length?



Event likelihood:

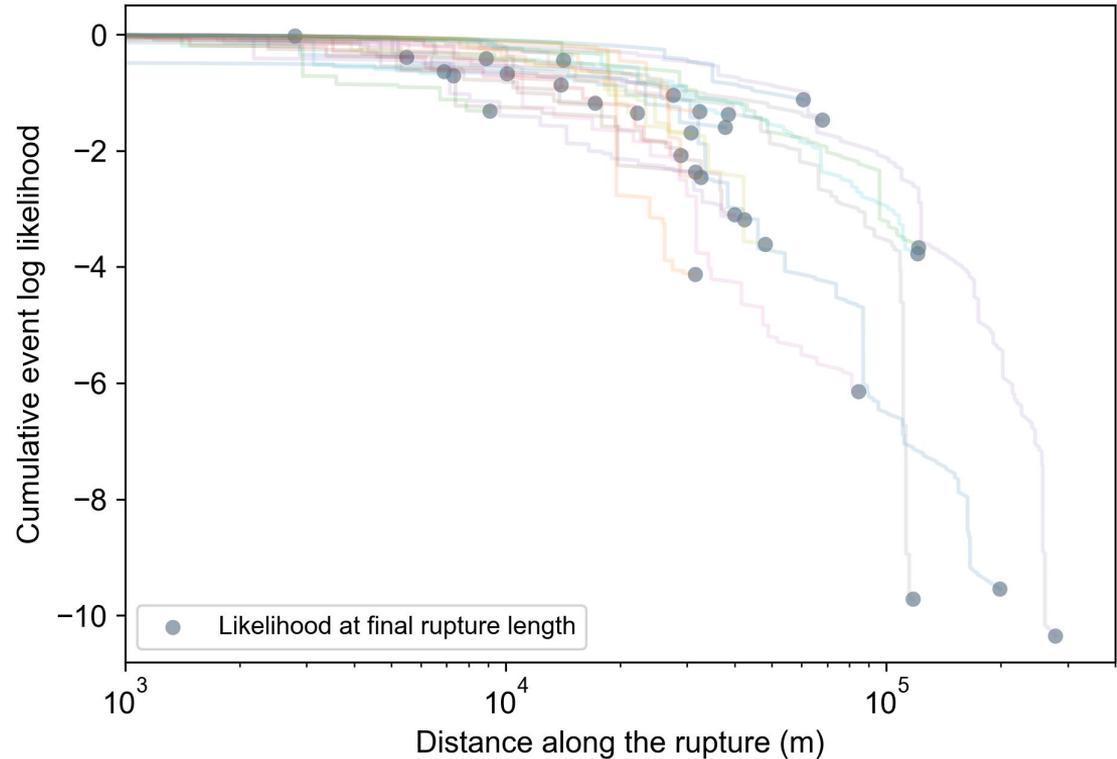
$$P_{\text{event}} = P_{\text{stepover1}} P_{\text{straight}} P_{\text{stepover2}} P_{\text{bend1}} P_{\text{bend2}} P_{\text{stepover3}} \dots$$



How do zones of geometrical complexity influence earthquake surface rupture length?

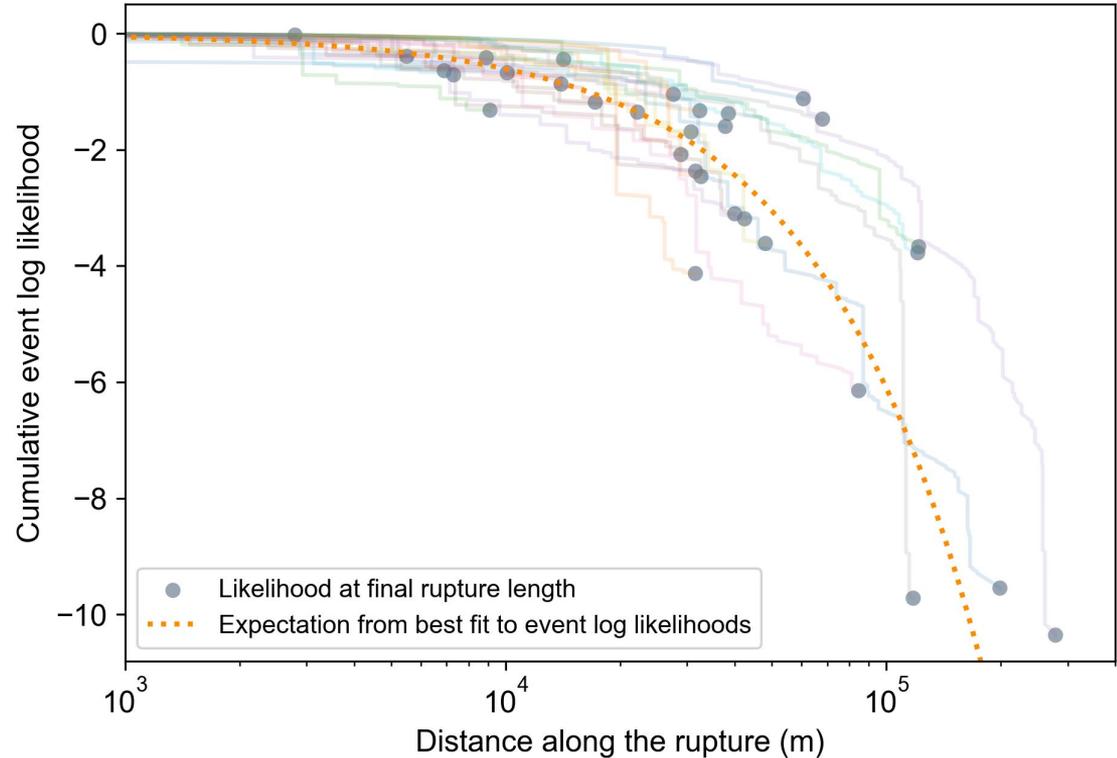
Event likelihood and its evolution along the surface rupture of each event.

Each dot = final event likelihood.



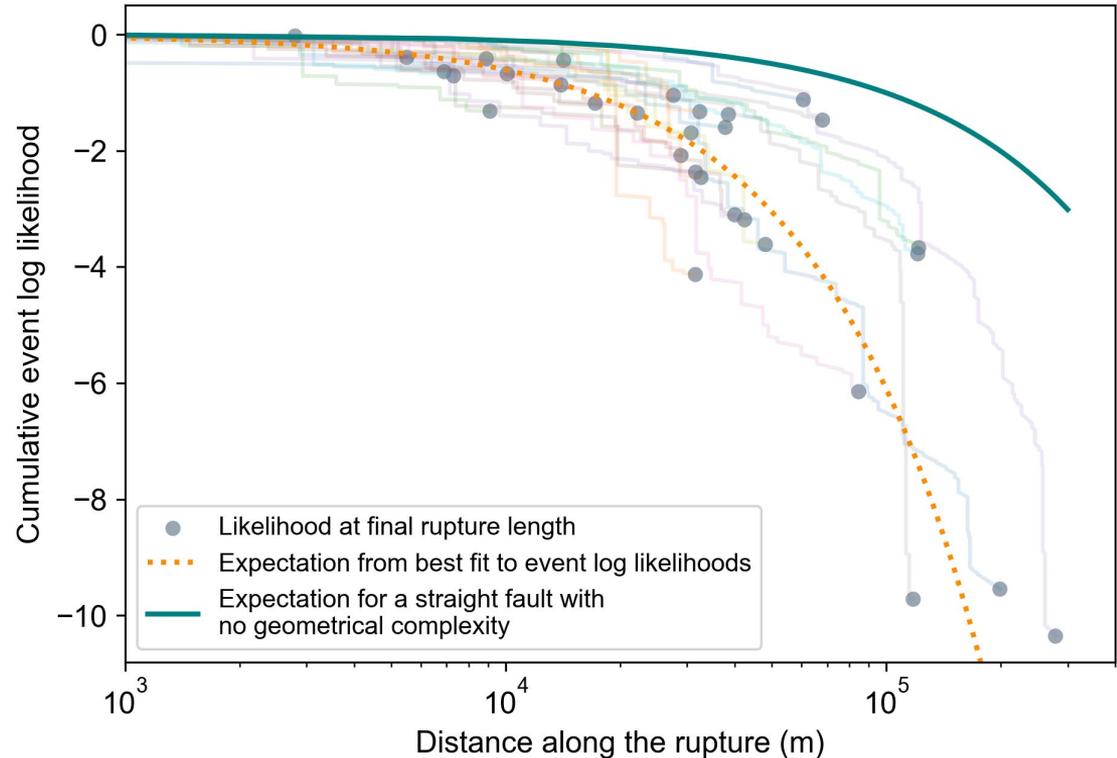
How do zones of geometrical complexity influence earthquake surface rupture length?

Final likelihoods modeled as exponential.



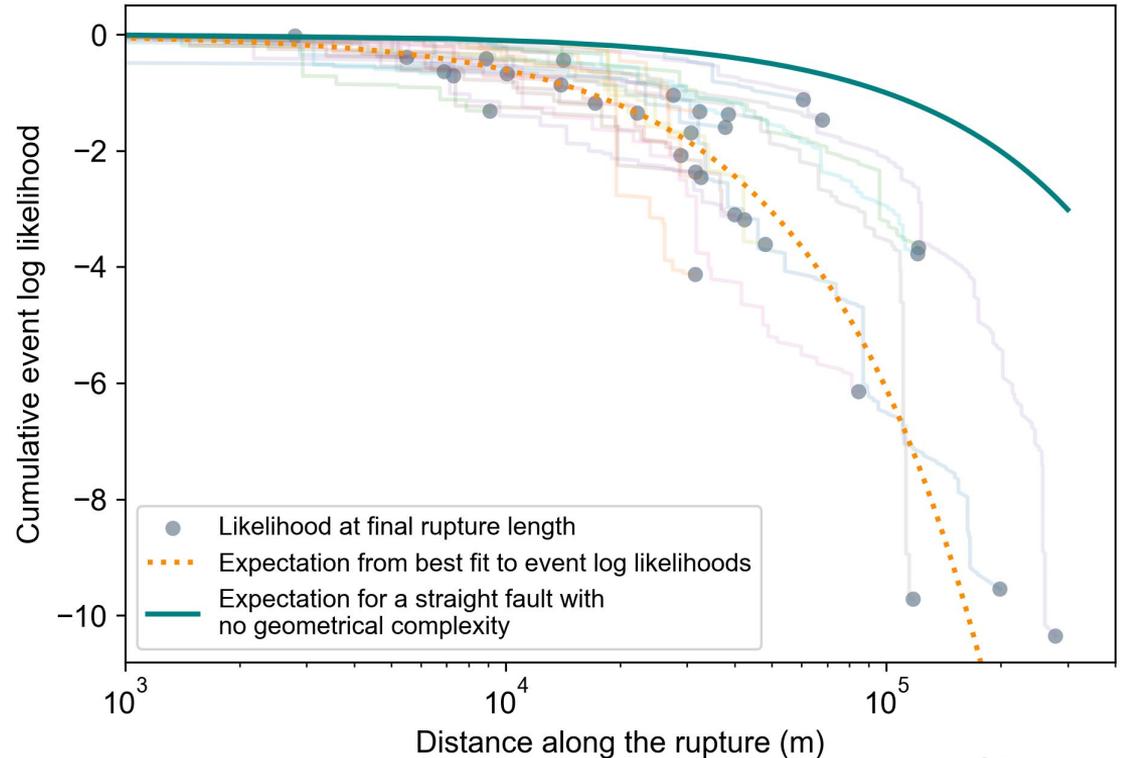
How do zones of geometrical complexity influence earthquake surface rupture length?

Small events have likelihoods comparable to prediction from straight fault model.

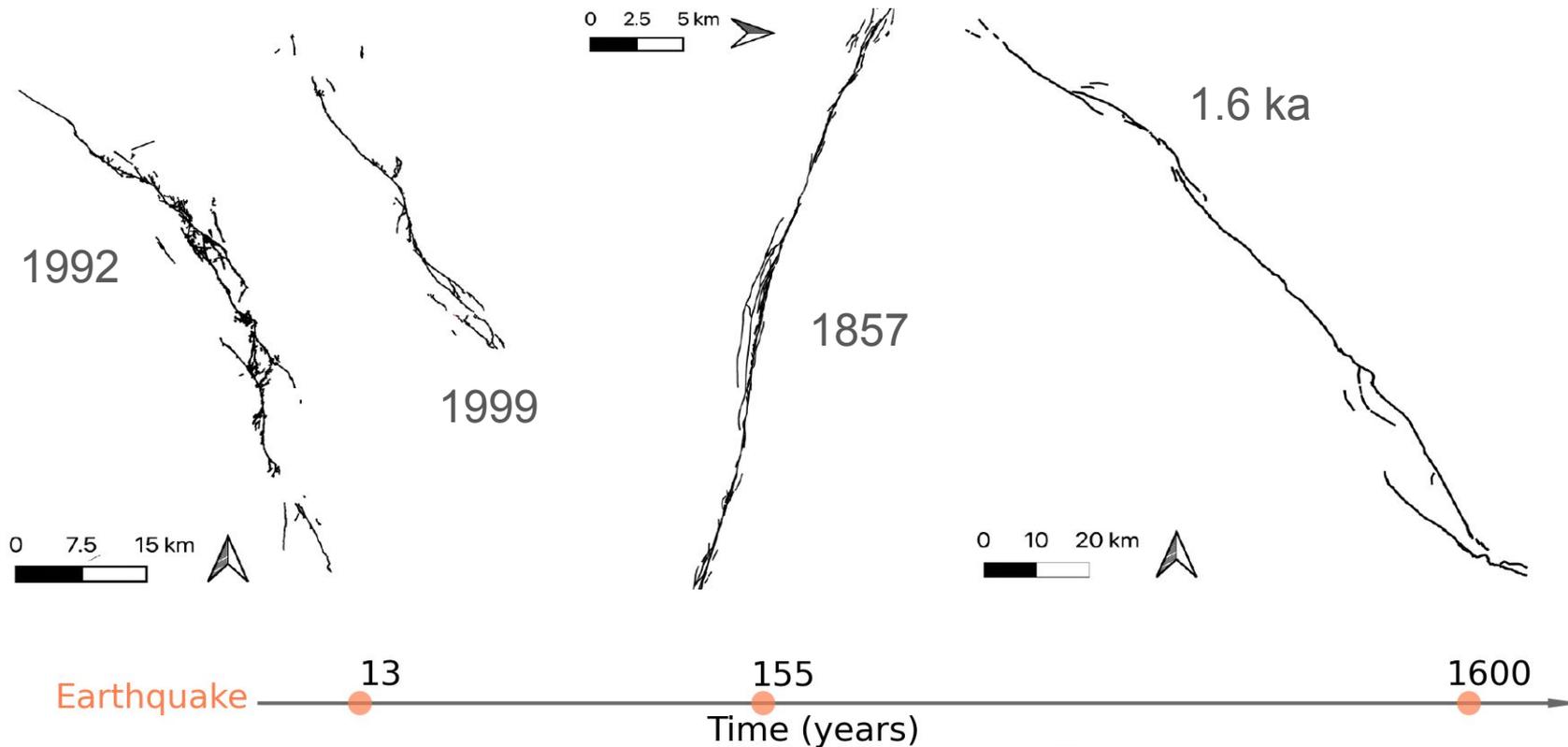


How do zones of geometrical complexity influence earthquake surface rupture length?

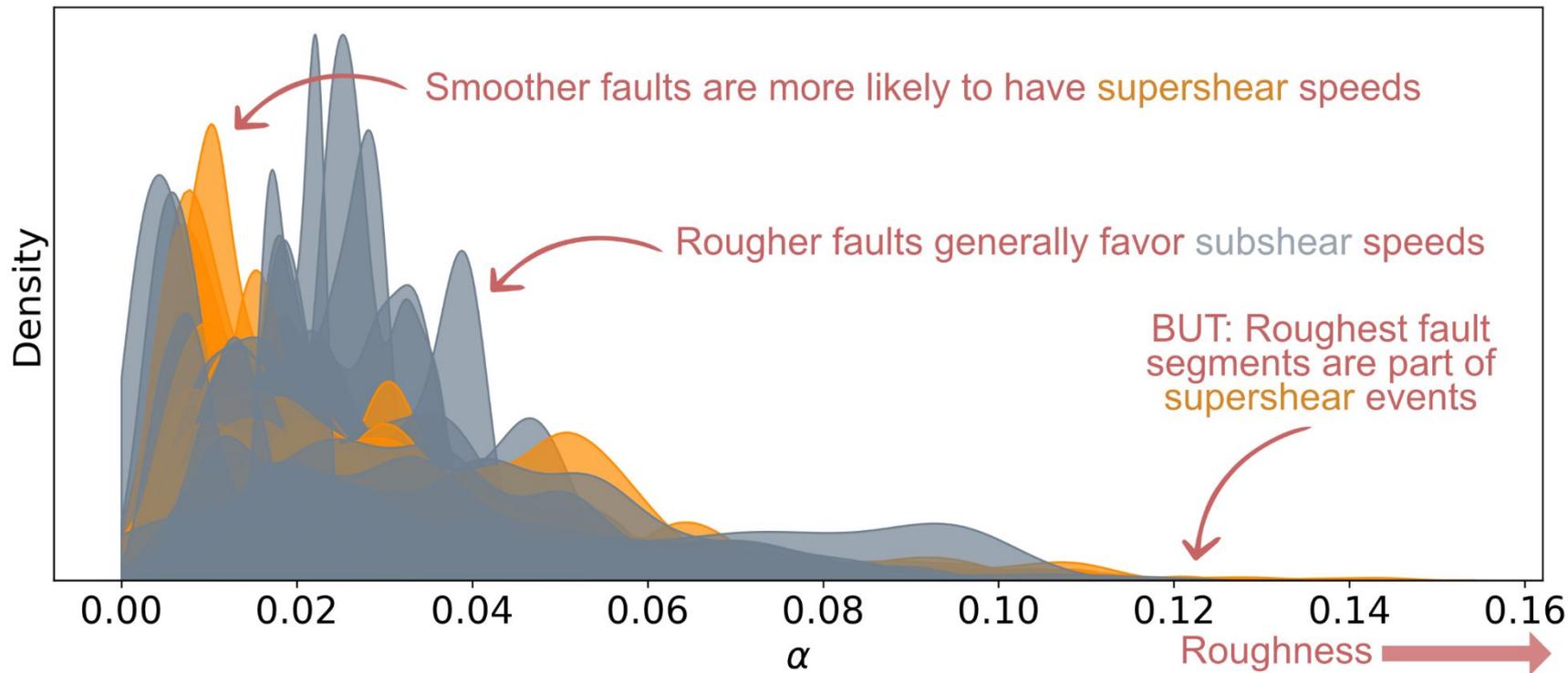
Presence of geometrical complexity contributes to low likelihood of large earthquakes



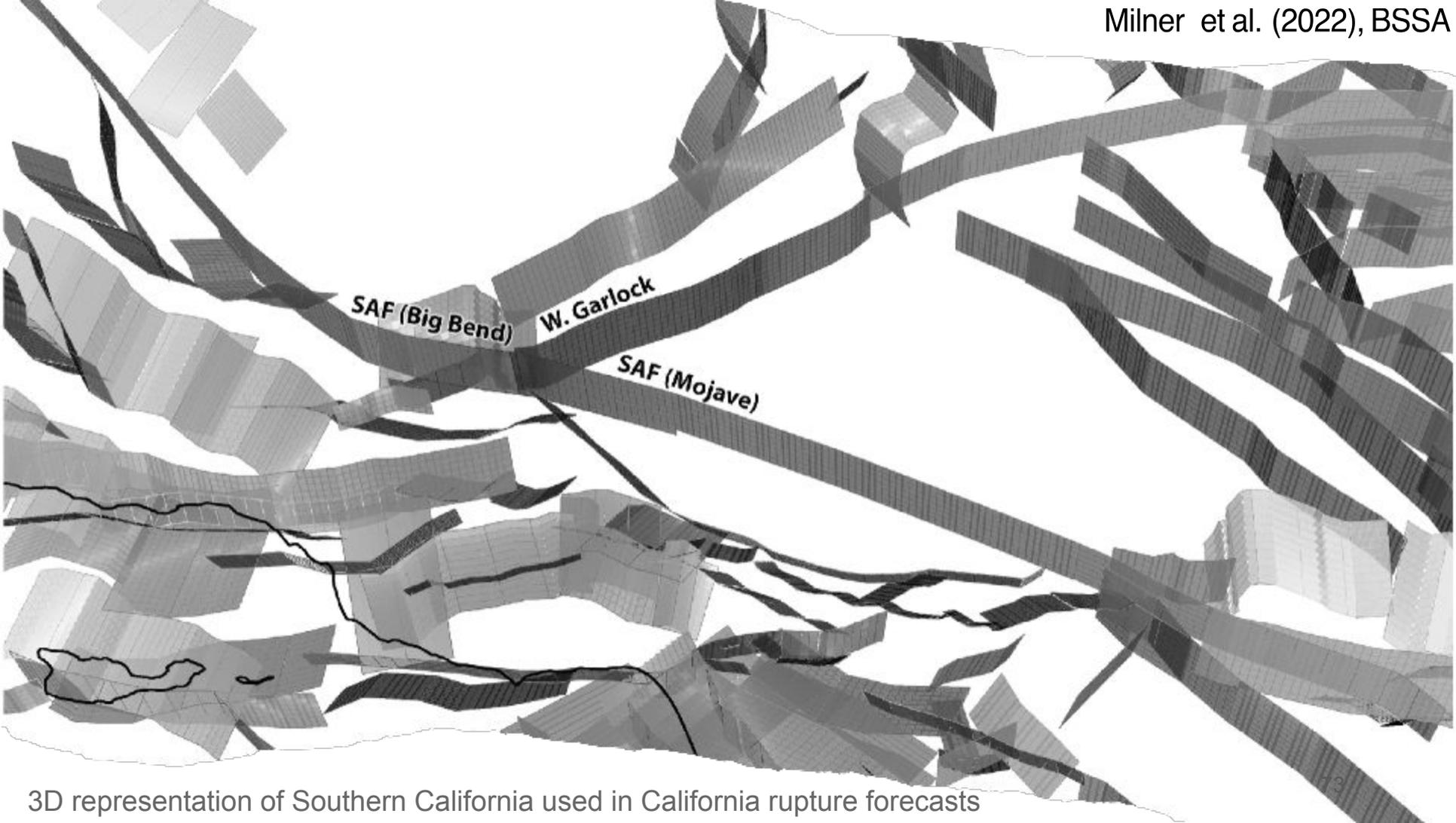
The mappable expression of a fault in the landscape **depends on the time elapsed since the most recent earthquake**



Zuckerman et al. (in review)



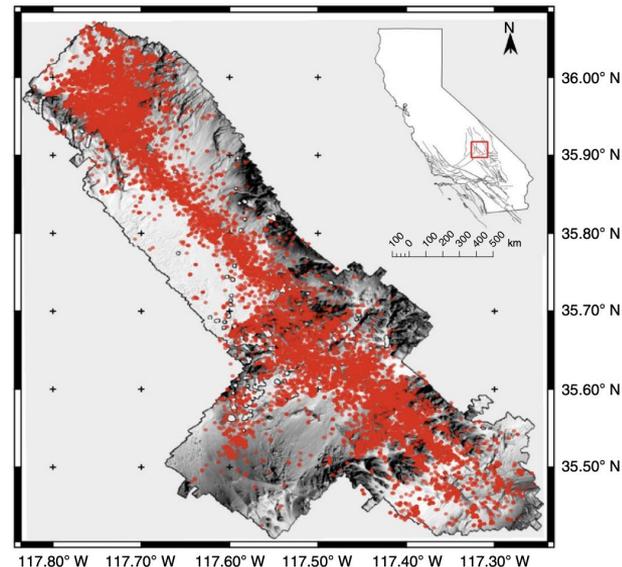
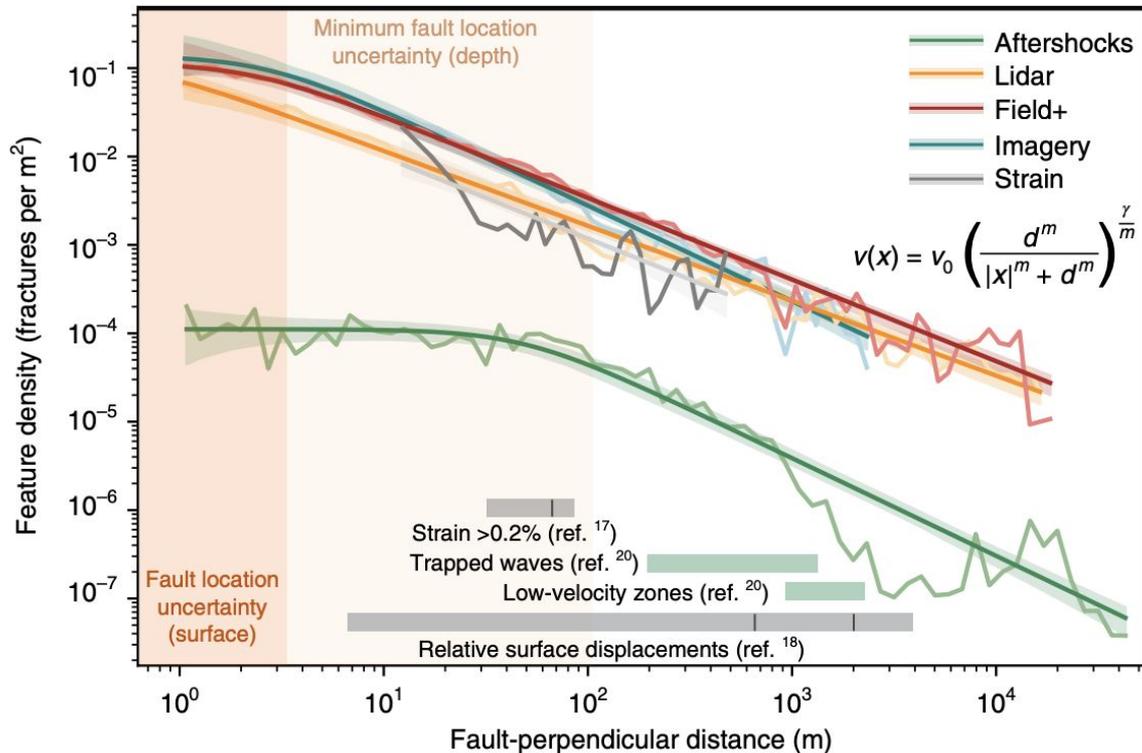
Supershear events have comparatively lower fault roughness, although some of the roughest fault segments occur for these events as well.



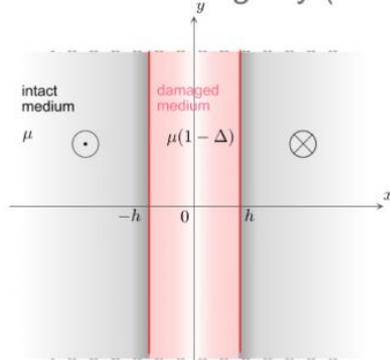
3D representation of Southern California used in California rupture forecasts

Similarity of fracture, strain, and aftershock distributions at different depths suggest a tabular fault zone where **surface deformation is representative of processes at depth.**

2019 Ridgecrest earthquakes



Single to multi-cycle tabular zone of reduced rigidity (elastic)



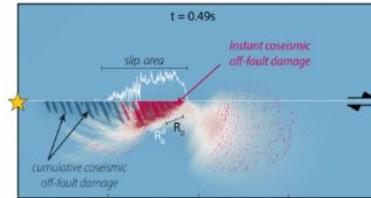
Idini and Ampuero (2020)

2000-2020

Single rupture, spontaneous crack nucleation under plasticity law



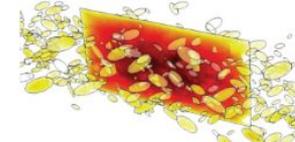
Okubo et al. (2019)



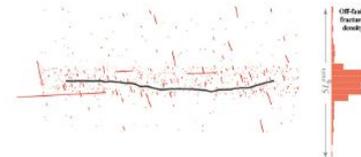
Ferry et al. (2025)

2015-2025

Single rupture to multi-cycle, discrete crack networks of length, orientation, and spatial distribution based on limited field and remote sensing observations



Gabriel et al. (2024)

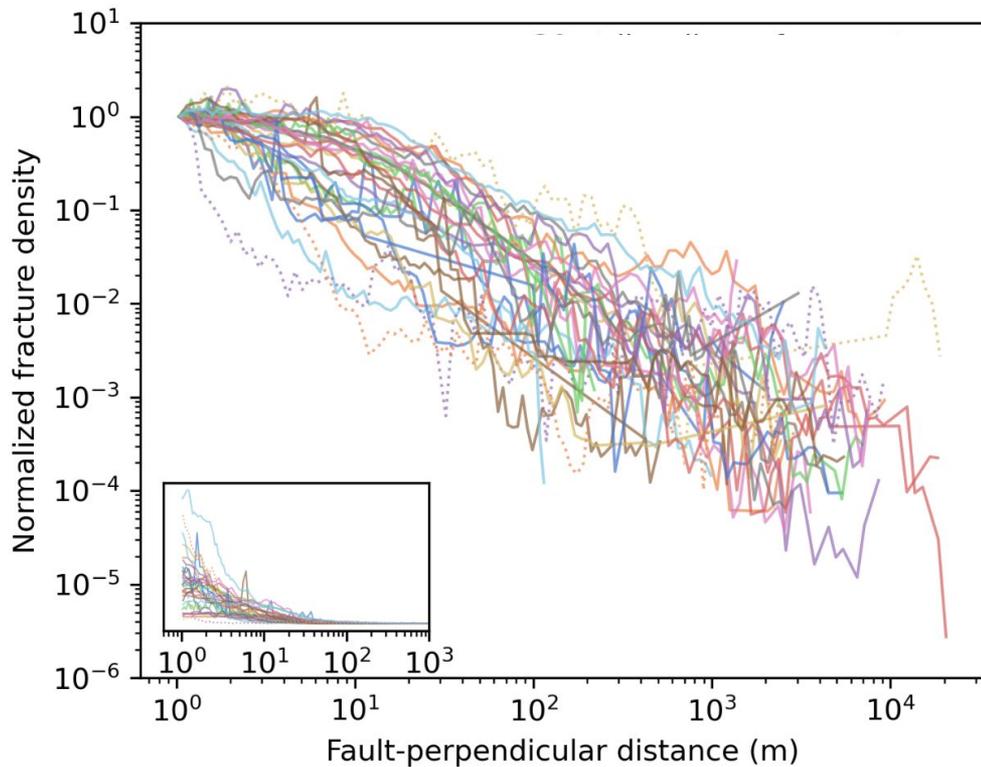


Almakari et al. (2025)

2024-

Evolution of fault zone architecture in numerical models

Lower magnitude events are not well described by this relationship



Turkey & California faults with similar earthquake potential

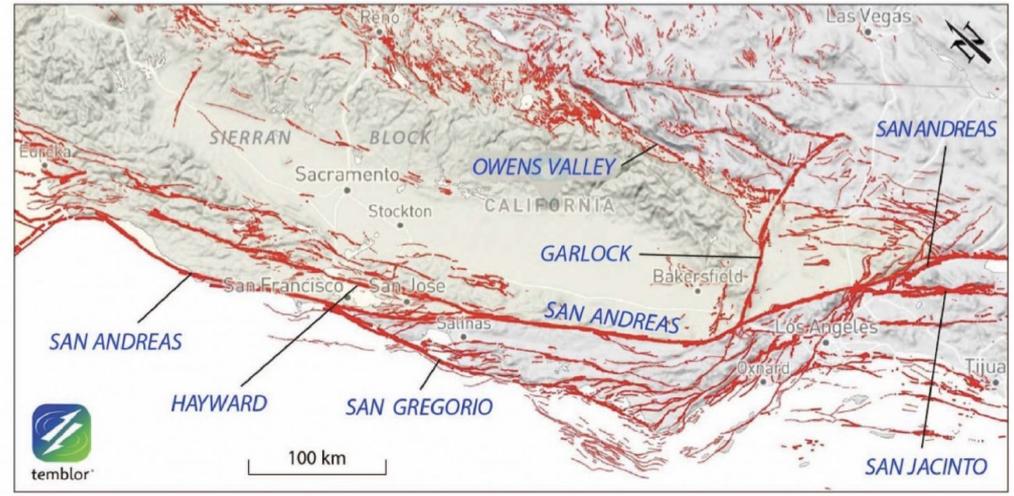
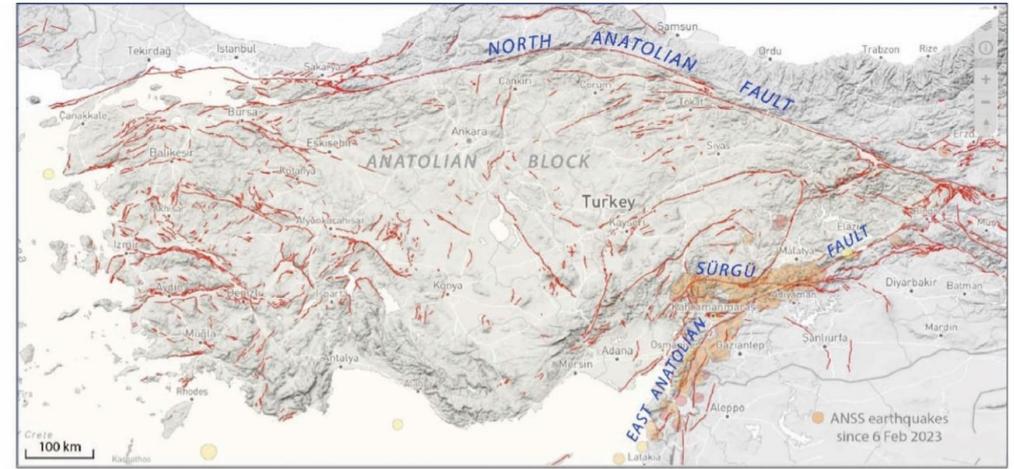
North Anatolian:
San Andreas

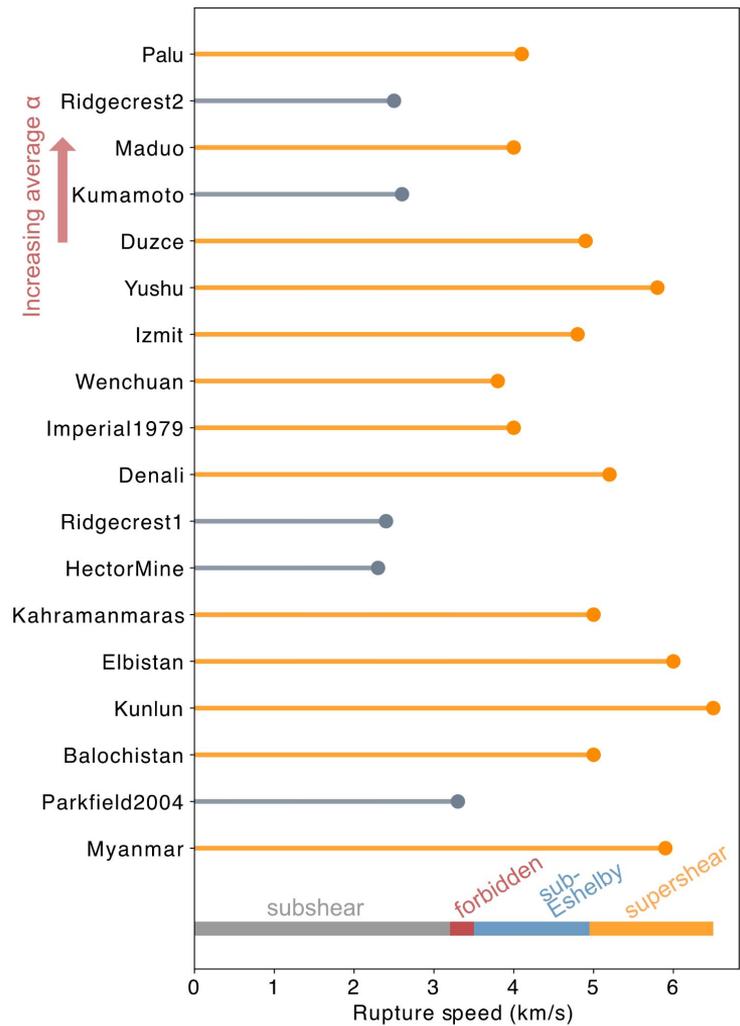
East Anatolian:
Hayward-Rodgers
Creek

San Gregorio
San Jacinto

Owens Valley-White
Mountains

Sürgü-Çardak:
Garlock





Earthquakes are often not confined to a single fault

