Surface Fault Rupture Hazard:
Advancing Earthquake-Induced Ground Deformation Modeling

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SCEC SiERRa Workshop

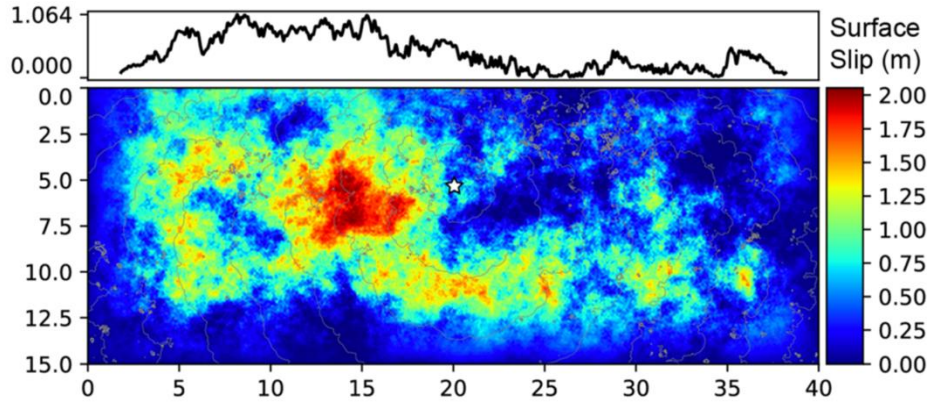
Tuesday, October 20th, 2026

University at Buffalo
The State University of New York

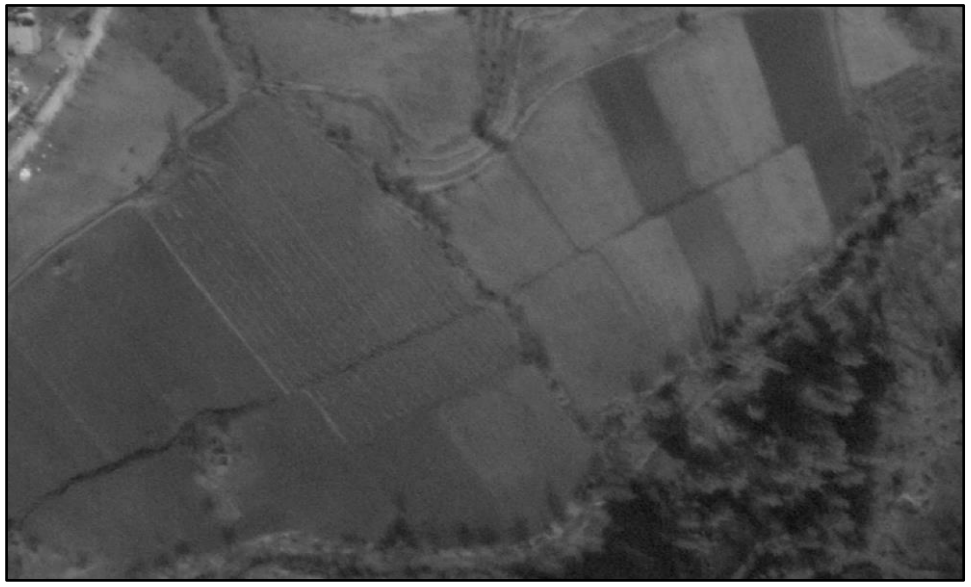
Motivation – Fault Rupture

Fault rupture is another source of primary earthquake hazard

- Occurs when the rupture front interests with the free surface



Kinematic rupture simulations
(Savran and Olsen, 2020)

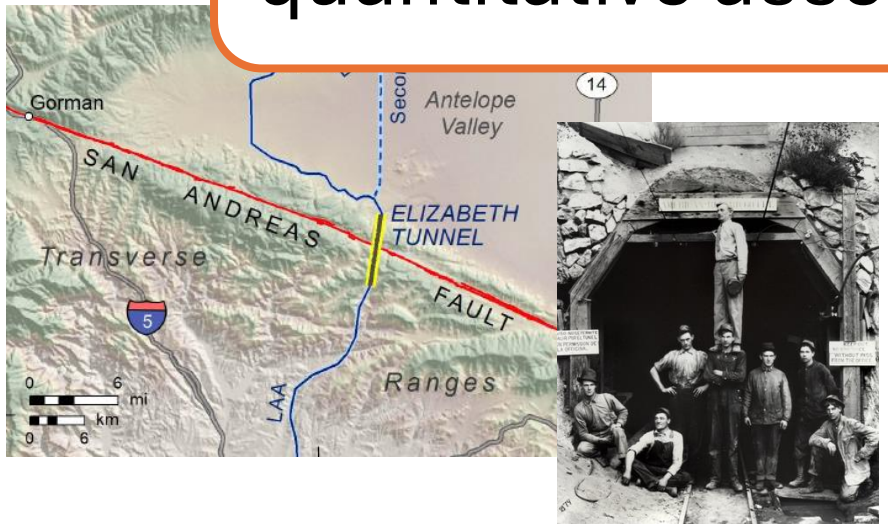


M7.8 Pazarcik earthquake fault rupture (Reitman et al, 2023)

Fault Rupture Mitigation Strategies

- Typically, avoidance is the most effective strategy
- Certain civil infrastructure systems, constrained by geometry
- A

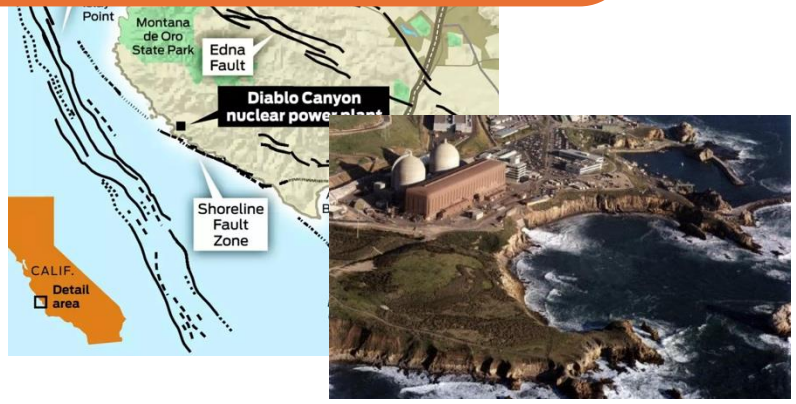
Infrastructure design under these conditions requires quantitative assessment of fault displacement hazards.



San Andreas Fault Crossing
Elizabeth Tunnel, Los Angeles Aqueduct



UC Berkely Stadium
Hayward Fault



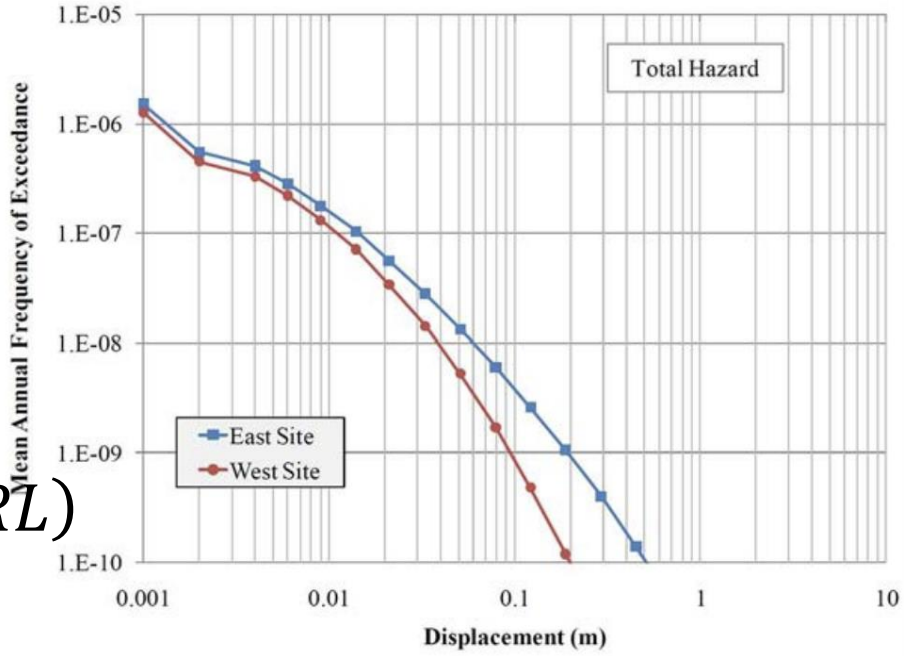
Distributed Fault Displacement
Shoreline Fault Zone
Diablo Canyon Nuclear Power Plant

Probabilistic Fault Displacement Hazard

$$Haz(D > z) = \sum_{eq=1}^{N_{eq}} \nu(eq) P(SR|M) P(D > z|M, x/L, SRL)$$

Components:

- Activity Rate: $\nu(eq)$
  How often earthquakes happen?
- Probability of Surface Rupture: $P(SR|M)$
  Will the rupture reach the surface?
- Fault Displacement Model: $P(D > z|M, x/L, SRL)$
  How large is the displacement?



What do we mean with D?

Definitions: Fault Displacement Types

Principal displacement:

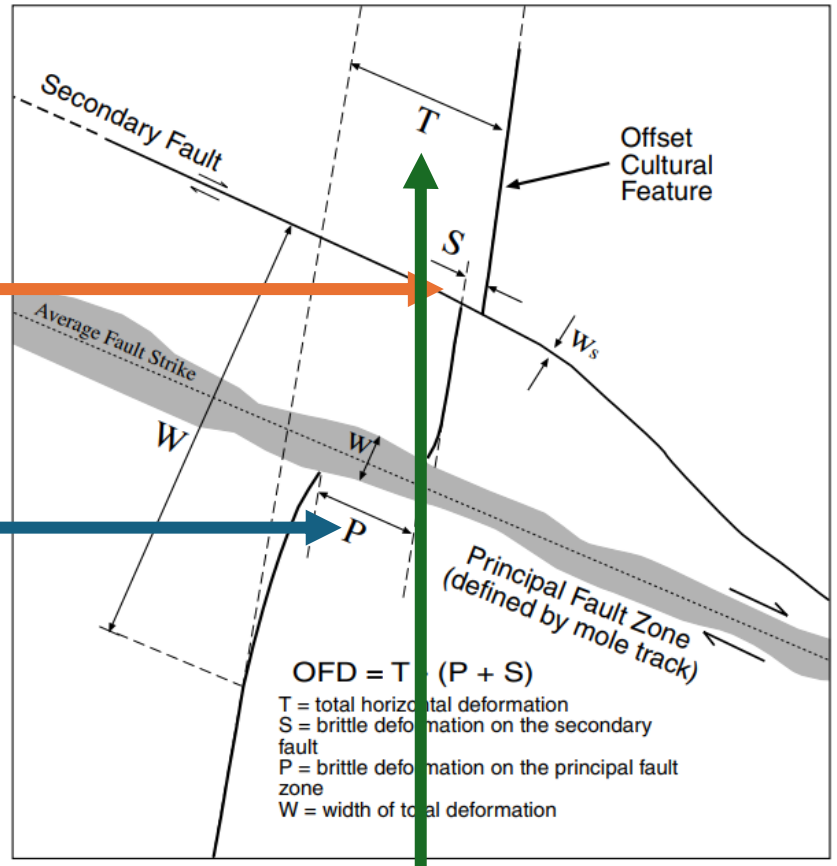
- localized along the main fault trace
- large-amplitude brittle slip
- associated with seismogenic slip

Distributed displacement:

- occurs away from the main fault trace
- smaller-amplitude brittle deformation
- Aften associated with induced slip

Total displacement:

- sum of principal and distributed components



Adopted from Sammiento et al 2024

Definitions: Aggregate Versus Discrete

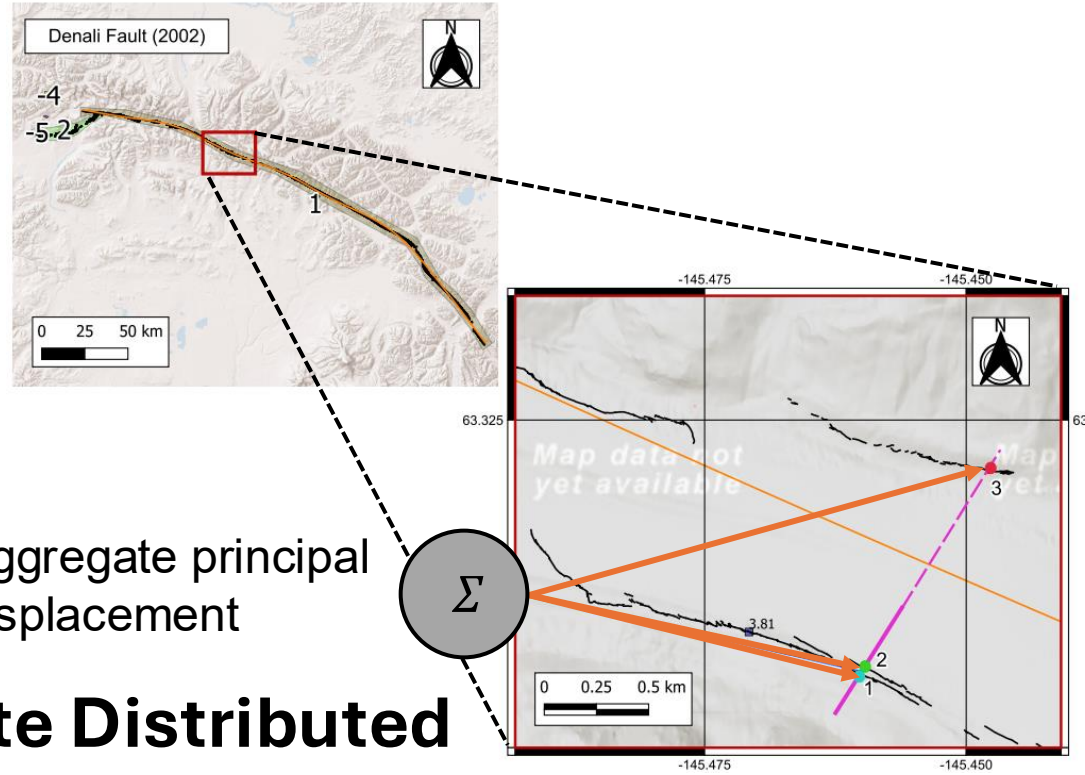
Aggregate displacement is the cumulative displacement from all overlapping ruptures.

Aggregate Principal:

- Sum of overlapping principal slip

Aggregate Distributed:

- Sum of overlapping distributed slip



Aggregate principal displacement

Σ

Total = Aggregate Principal + Aggregate Distributed

Evolution of Fault Displacement Models

First generation (2003–2011)

- E.g., Youngs et al., 2003; Petersen et al., 2011; Moss & Ross, 2011
- FDM based on limited surface-rupture and simplified geometries

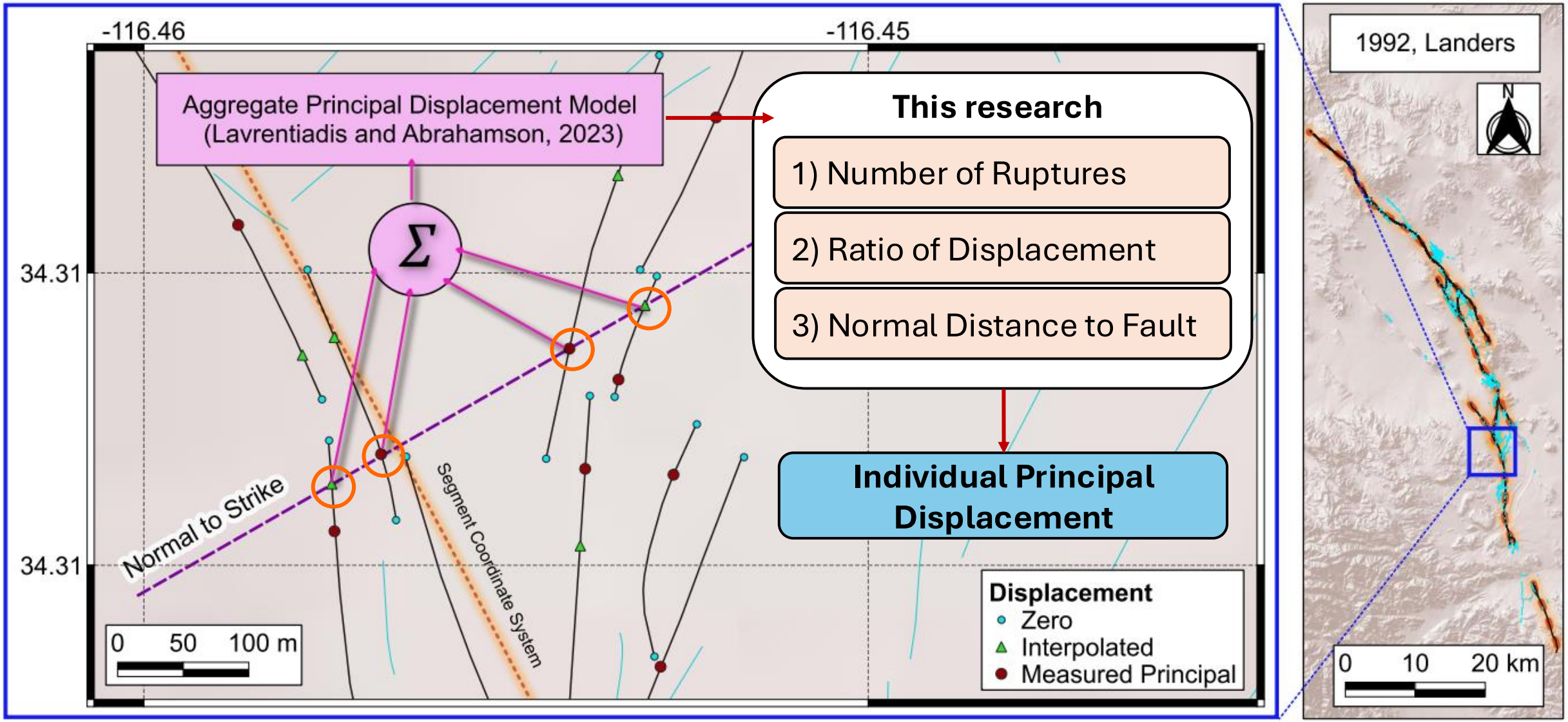
FDHI (2023–2025)

- E.g., Lavrentiadis & Abrahamson, 2023; Kuehn et al., 2024; Moss et al., 2024; Chiou et al., 2025
- Expanded datasets and improved characterization of aggregate displacements

Current research:

- Characterization of individual fault displacements
- Quantification of the influence of geological conditions on fault rupture

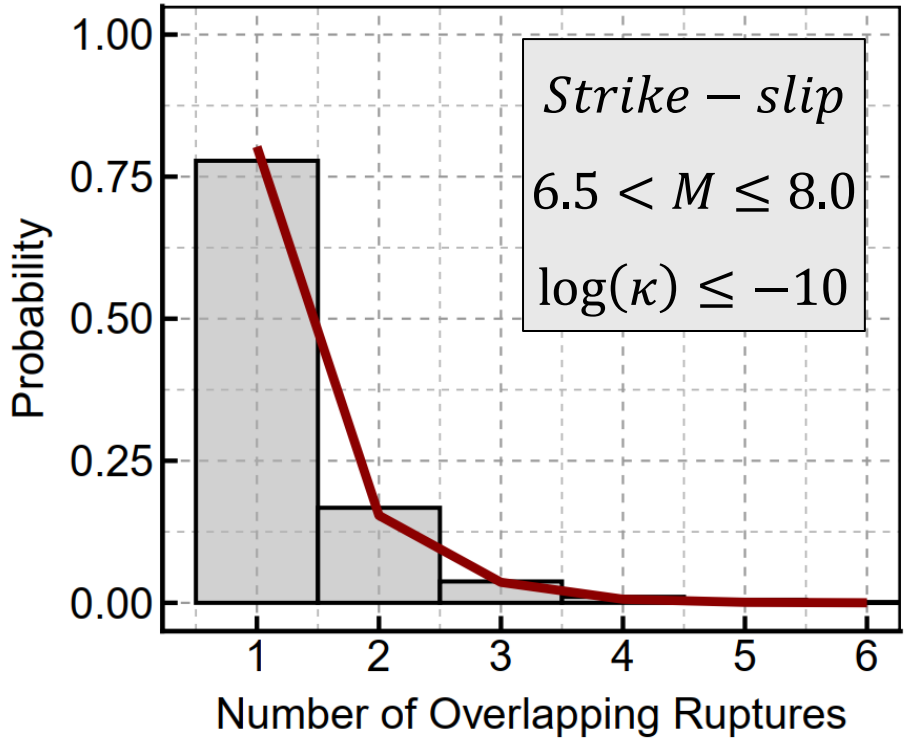
Characterization of Individual Principal Displacements

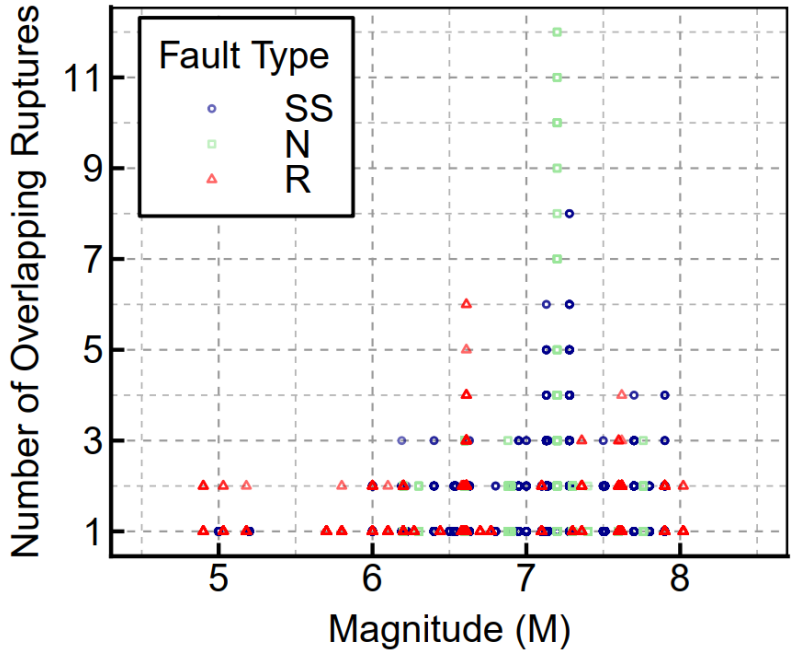


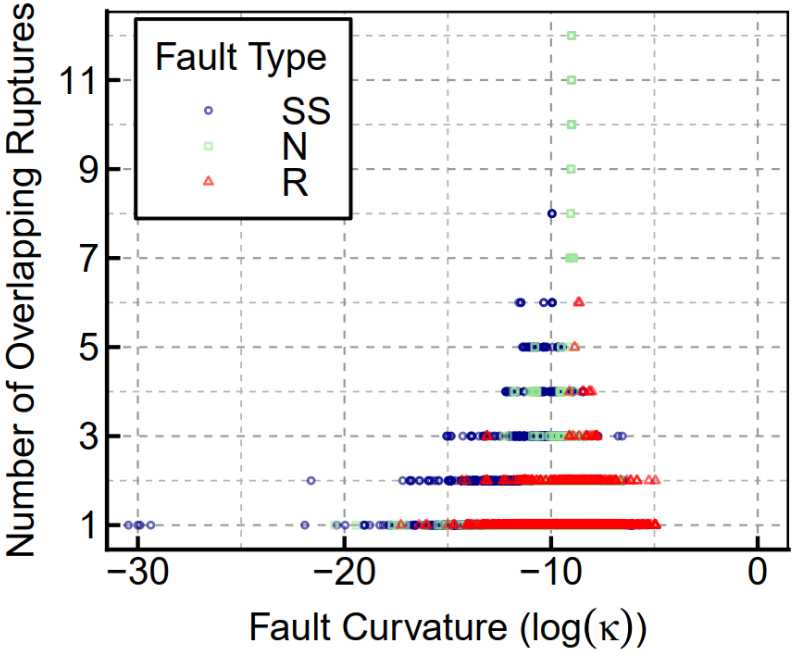
1. Number of Overlapping Ruptures

A hurdle model:

- Bernoulli distribution for $N_{p,tot} = 1$
- Poisson distribution for $N_{p,tot} > 1$







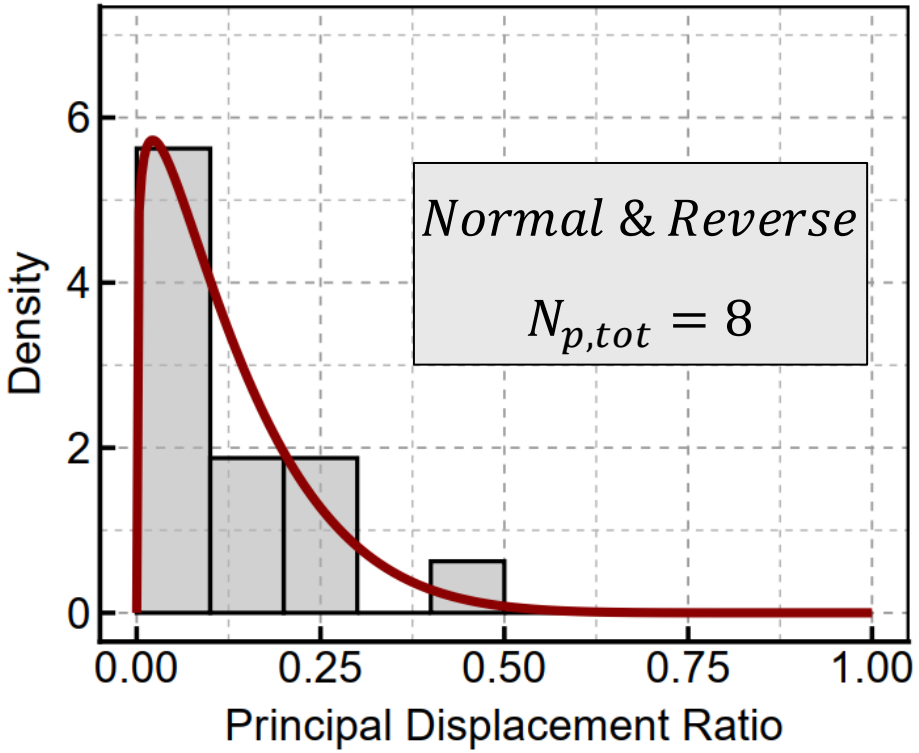
2. Amplitude Ratio of Displacement

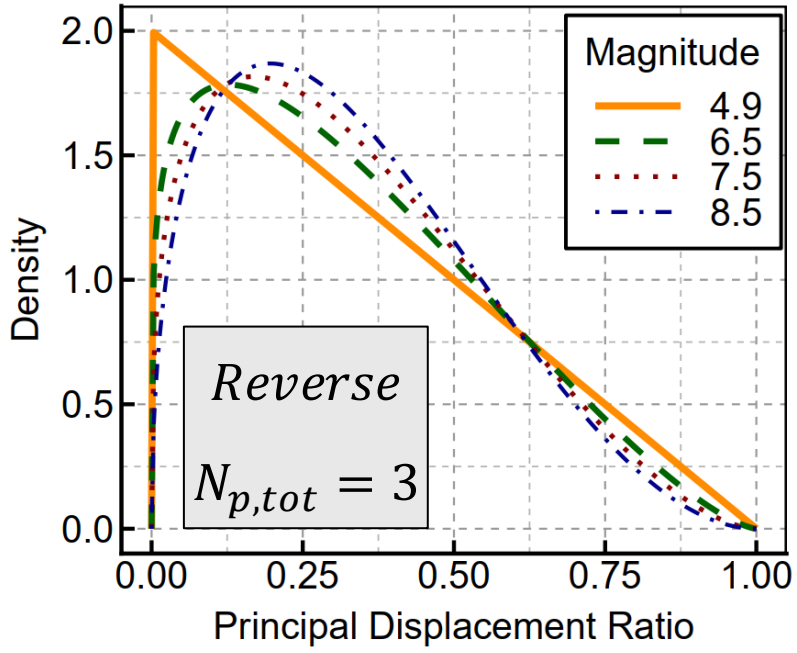
Ratio of principal displacement to aggregate principal displacement

$$ratio\ (r_p) = \frac{D_p}{D_{p,agg}}$$

Beta distribution as a function of:

- Number of overlapping ruptures $N_{p,tot}$ → $E[r] = \frac{1}{N_{p,tot}}$
- Magnitude M

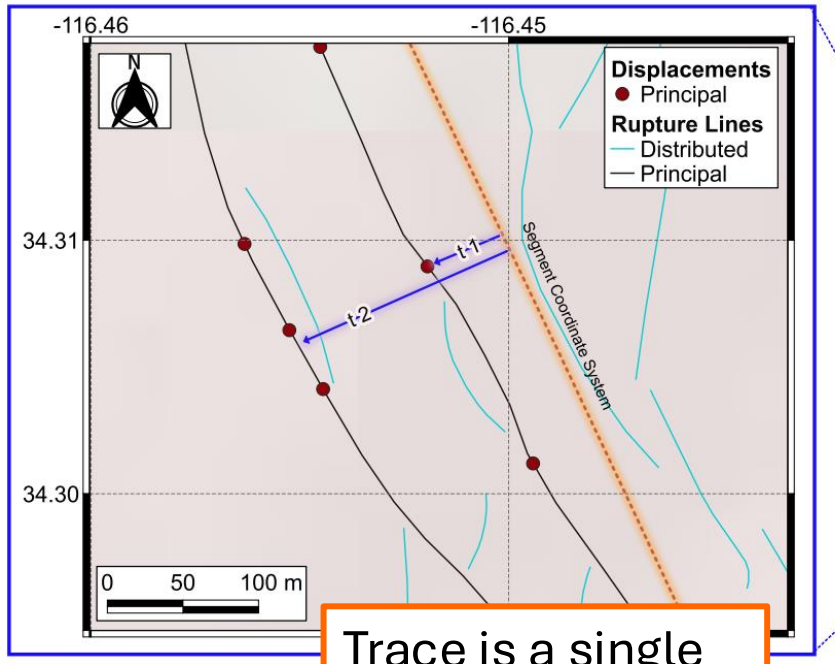




3. Rupture Crossing

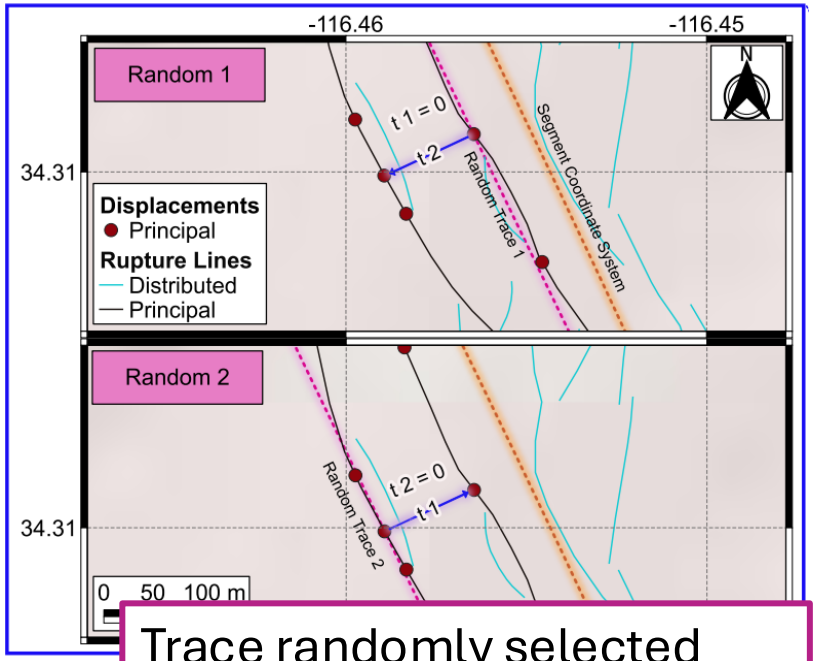
Three alternative rupture-location models are proposed.

SCS Trace



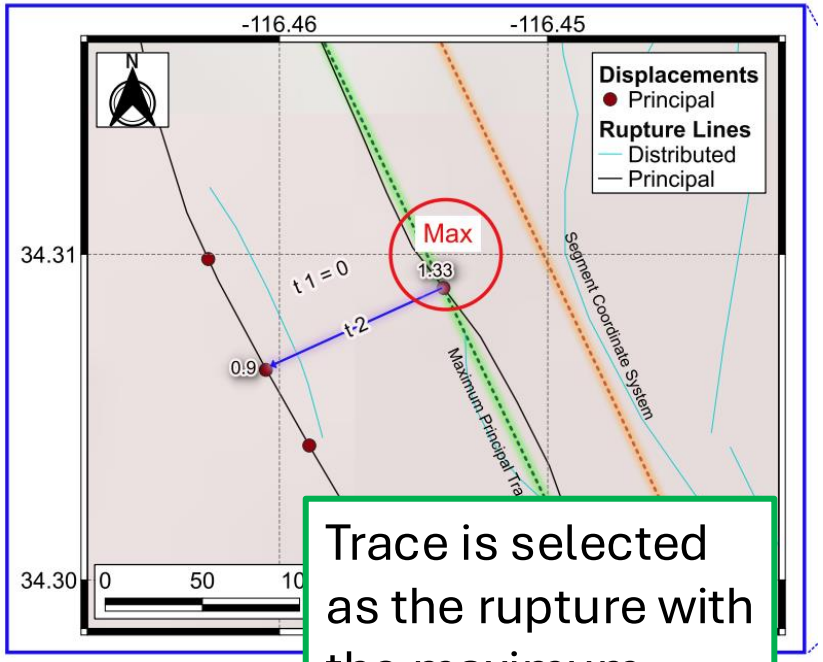
Trace is a single straight line for each segment

Random Trace



Trace randomly selected from overlapping principal rupture strands.

Maximum Principal Displacement

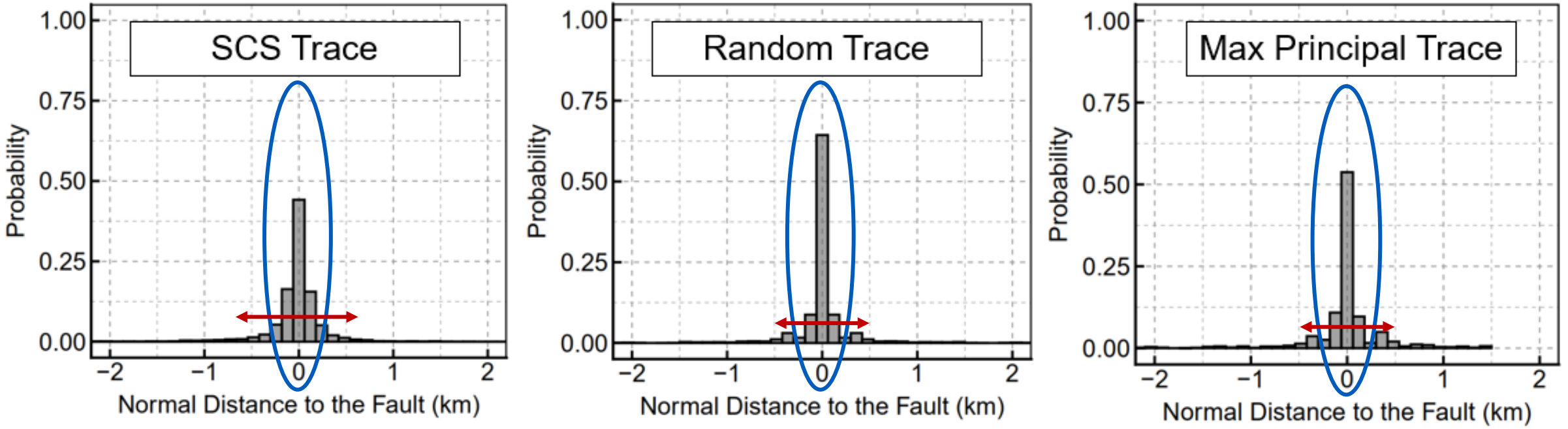


Trace is selected as the rupture with the maximum principal displacement.

3. Rupture Crossing

Different trace definition: different normal distance distribution

- Concentration near zero
- Spread of displacement around the fault

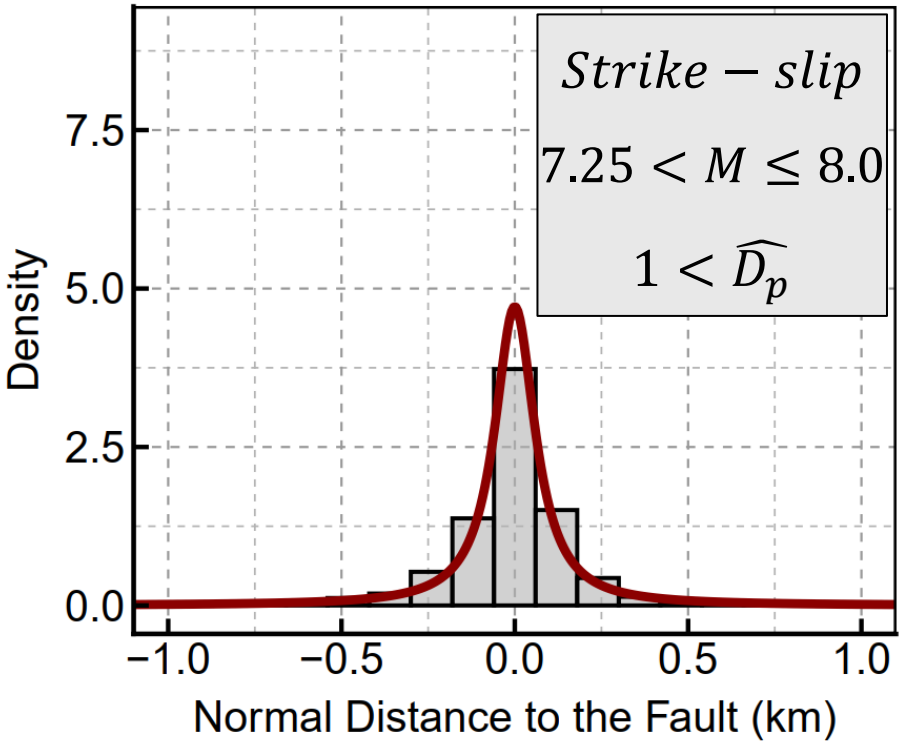


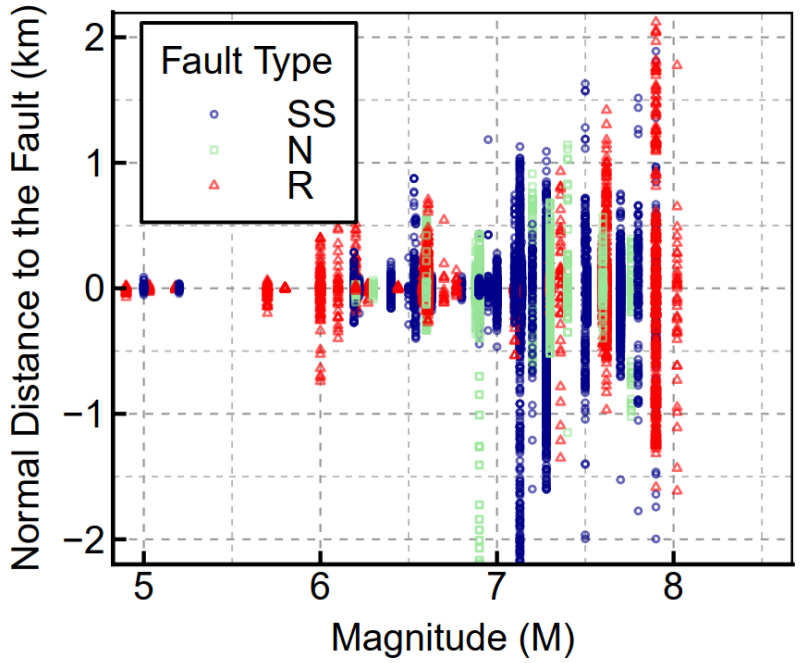
3. Rupture Crossing

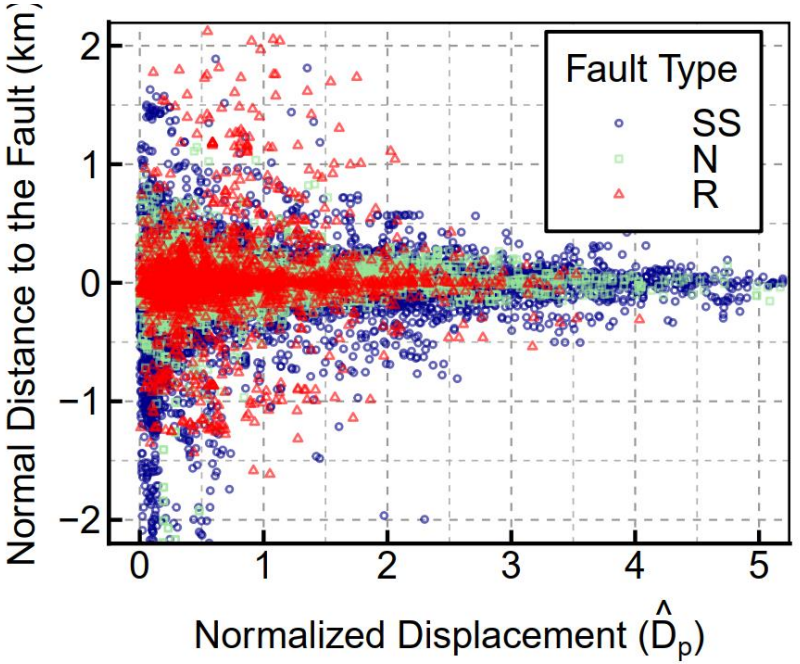
A Single or mix of two t Student's t distribution with spread varying with:

- Magnitude M
- Displacement $\widehat{D_p}$

$$\widehat{D_p} = \frac{D_p}{\overline{D}_{p,agg}(M, SOF, \frac{u}{SRL})}$$







Characterization of Individual Distributed Slip

Aggregate Distributed Displacement

Lavrentiadis & Abrahamson 2023

$$X = D_{tot}^{0.3} \sim N(\mu_{tot}, \sigma_{tot})$$

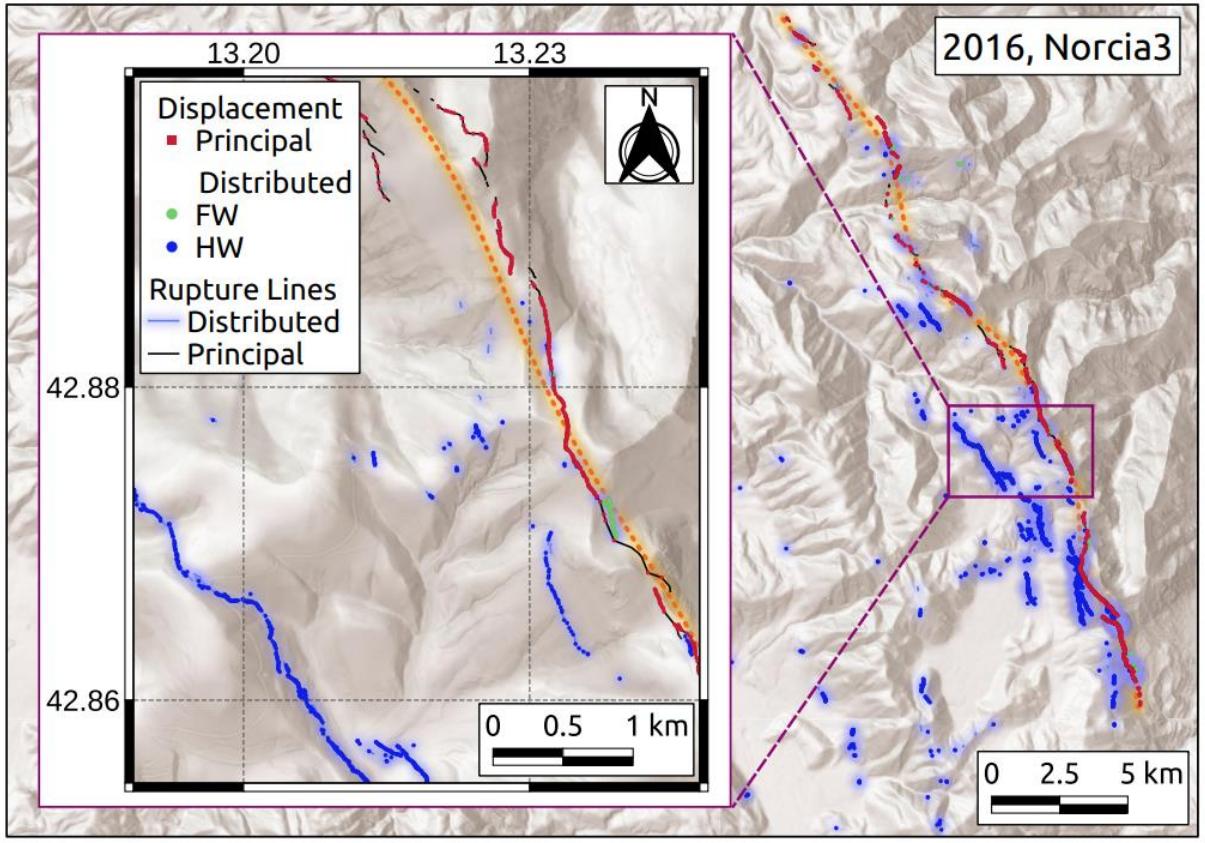
$$Y = D_{p,agg}^{0.3} \sim N(\mu_p, \sigma_p)$$

$$D_{d,agg} = D_{tot} - D_{p,agg}$$

This research

1) Number of Ruptures
2) Ratio HW/FW Displacement
3) Ratio Individual Displacement
4) Normal Distance to Fault

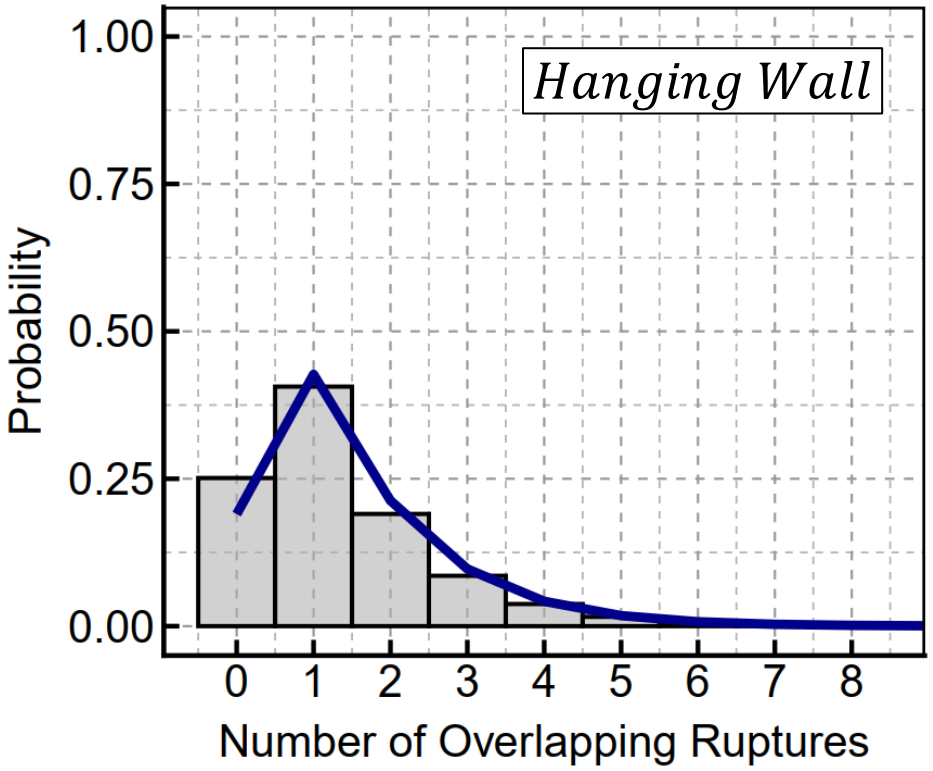
Individual Distributed Displacement

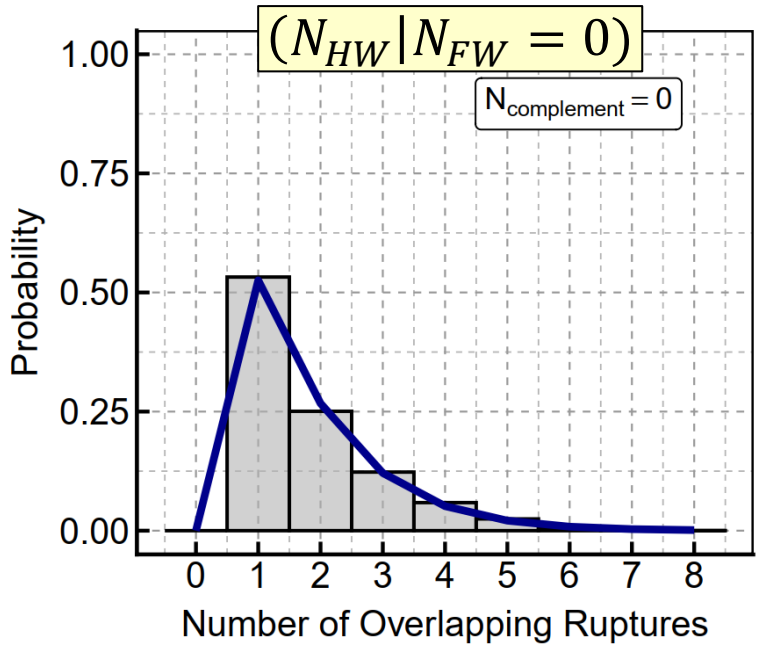


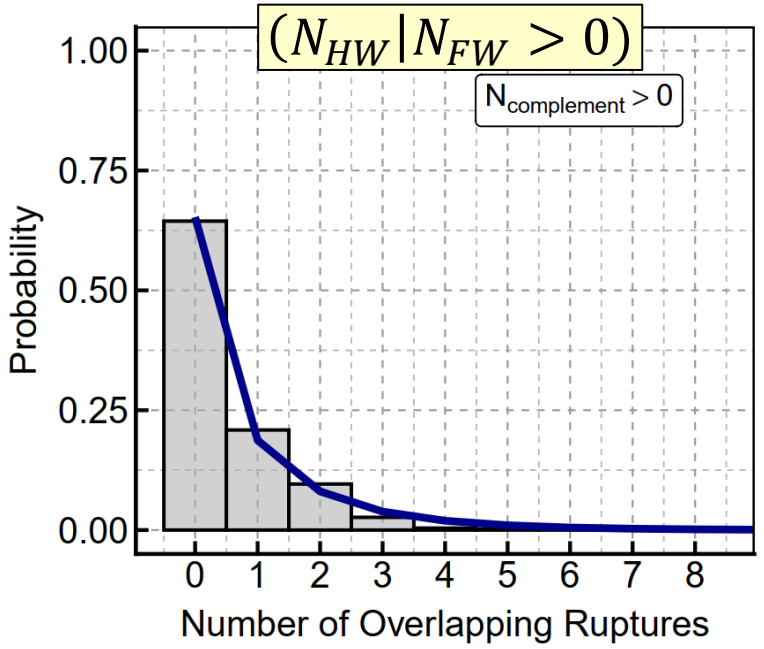
1. Number of Overlapping Ruptures

Mixture Negative Binomial distribution:

- Zero truncated ($N_{complement} = 0$)
- Regular ($N_{complement} > 0$)







2. HW/FW Share of Aggregate Displacement

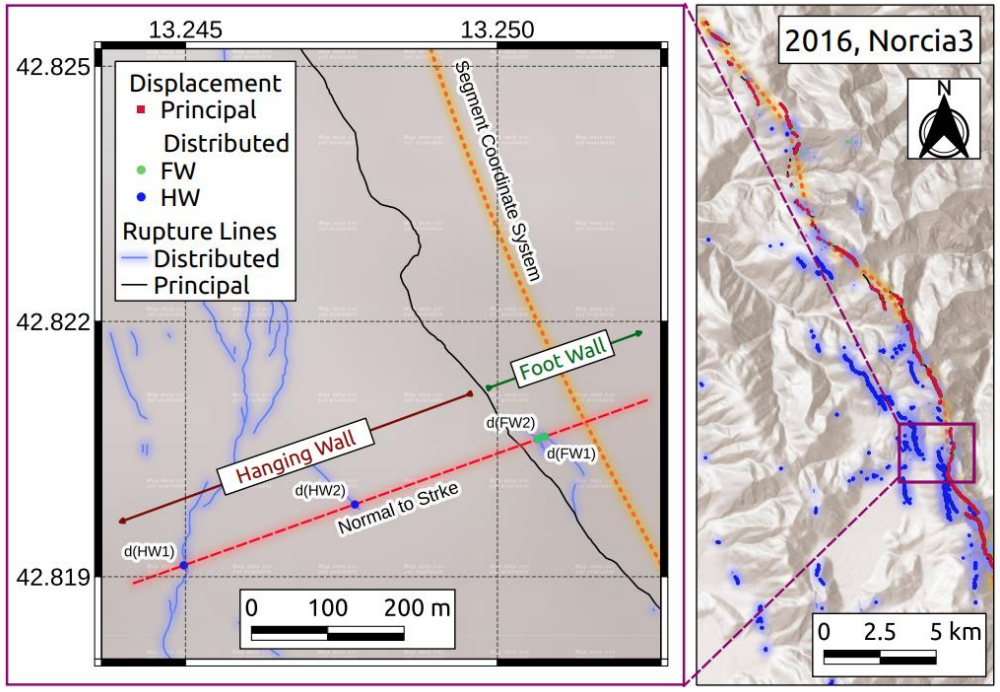
What share of the displacement in on the hanging wall and foot wall?

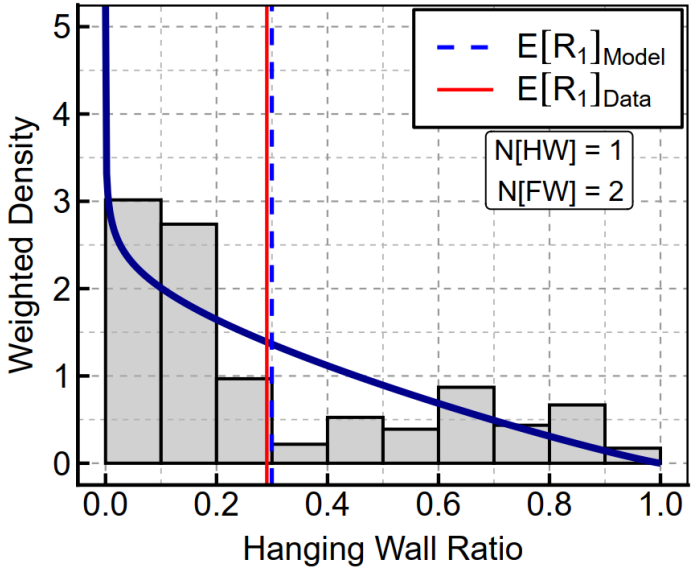
A Dirichlet distribution:

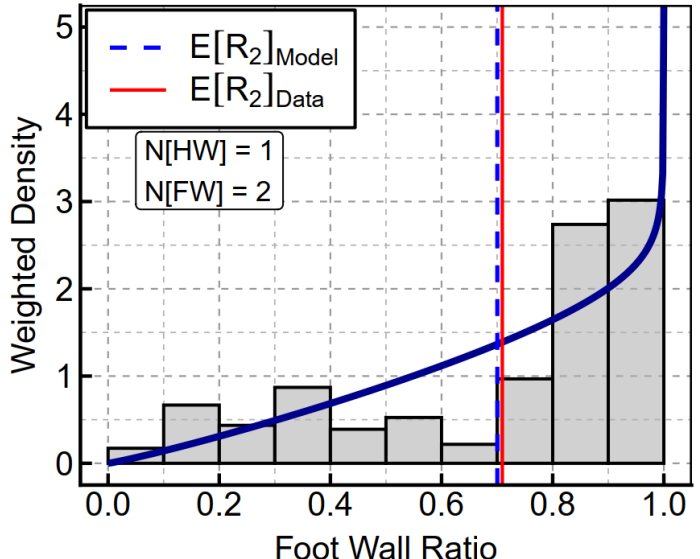
$$r'_d \sim Dir(N_{d1,tot}, N_{d2,tot}, SOF)$$

$$r'_d(\text{side } 1) + r'_d(side\ 2) = 1$$

$$Side\ ratio\ (r'_d) = \frac{D_{d,agg(side)}}{D_{d,agg}}$$







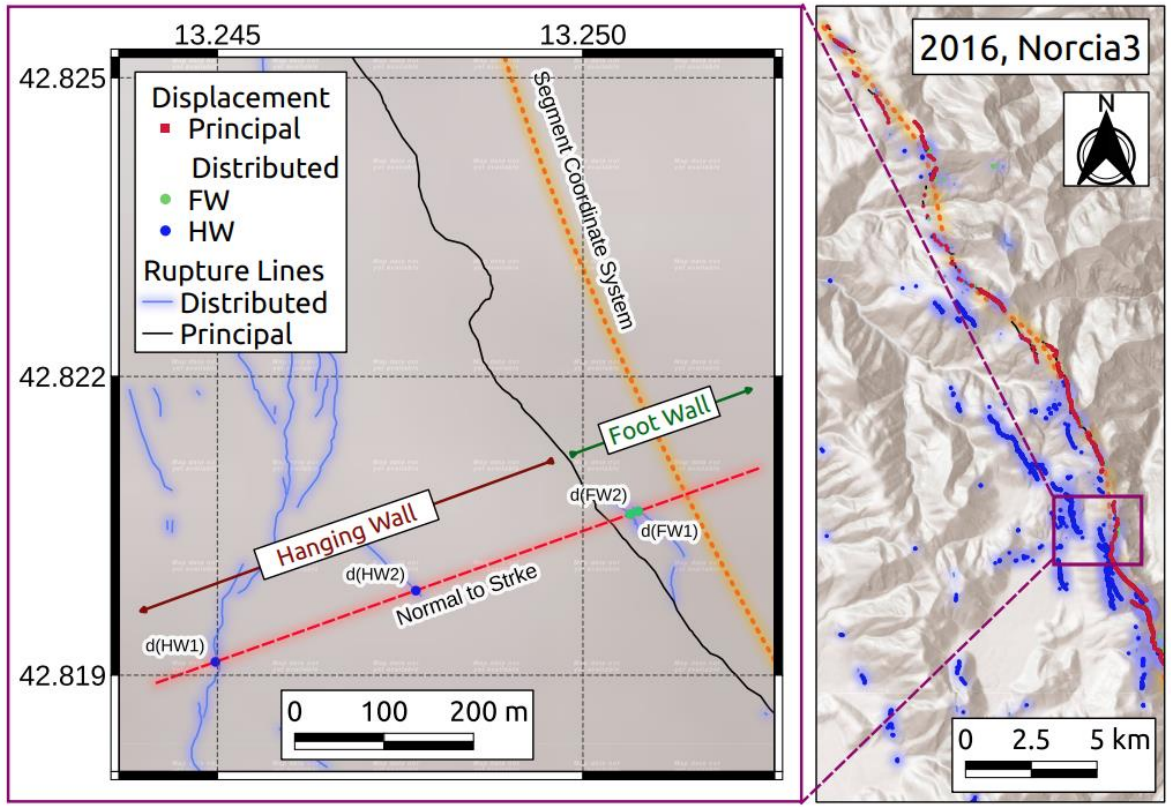
3. Amplitude Ratio of Displacement Per Side

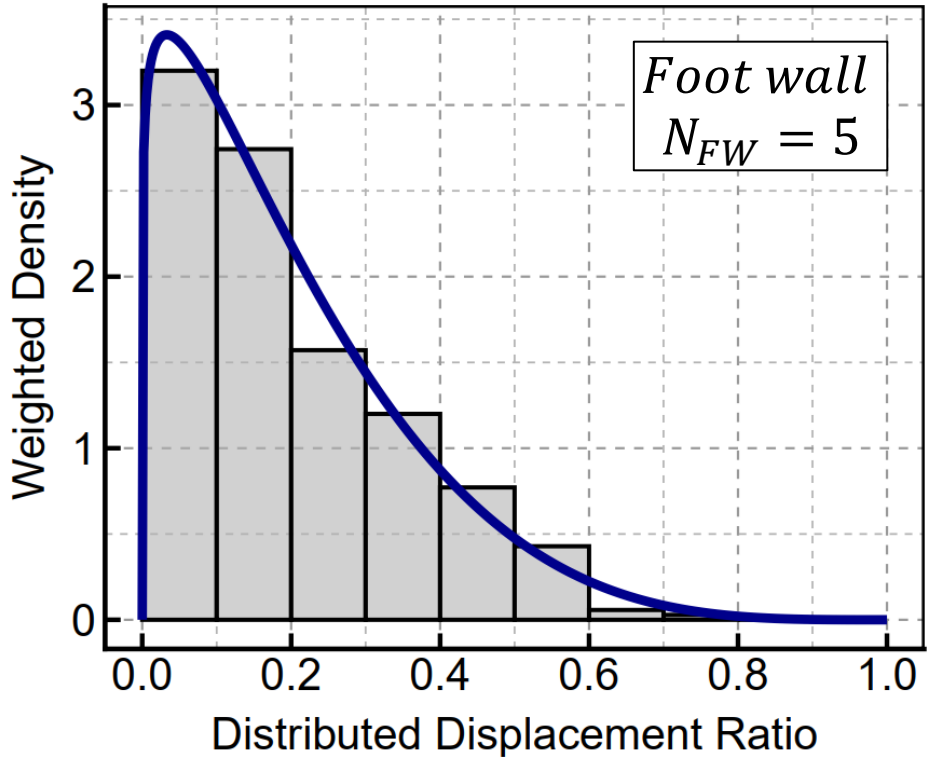
Ratio of principal displacement to aggregate principal displacement

$$ratio\ (r_{side}) = \frac{D_d}{D_{d,agg(side)}}$$

Beta distribution as a function of:

- Number of overlapping ruptures on the side $N_{crossed\ (side)}$ ⟶ $$E[r] = \frac{1}{N_{crossed\ (side)}}$$



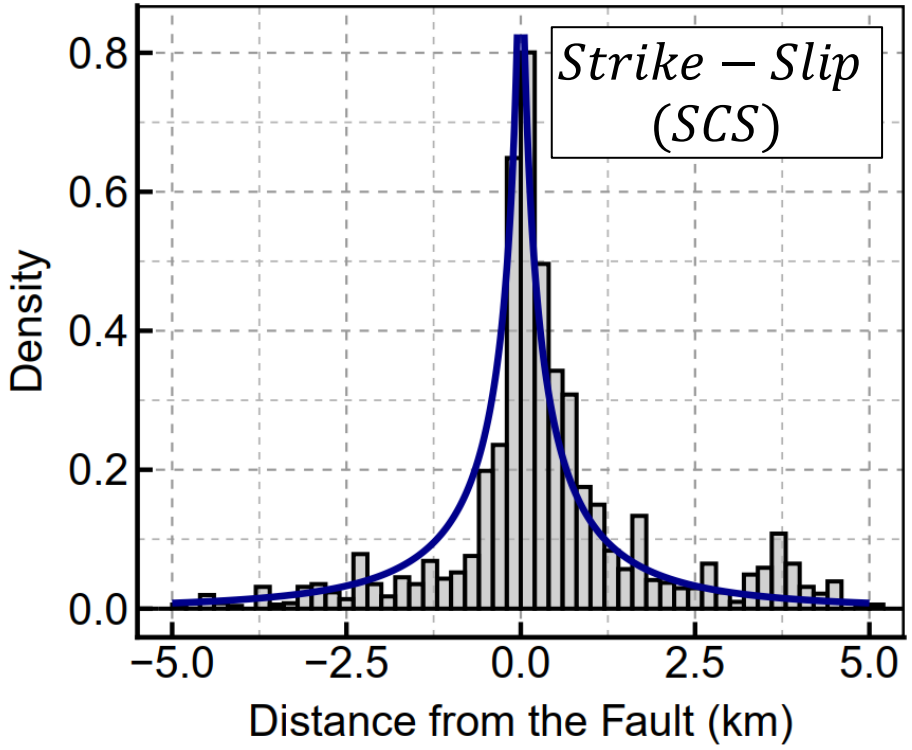


4. Normal Distance to the Fault

Normal distance to the fault:

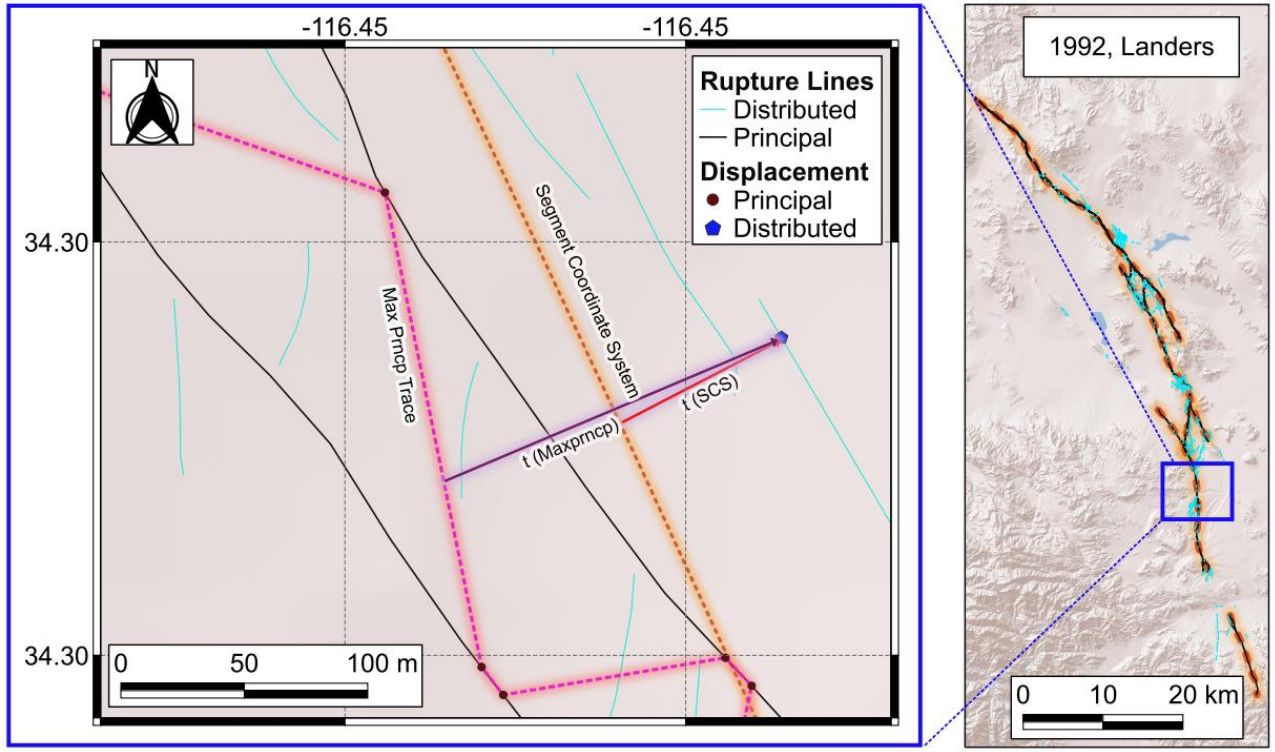
A Power Normal Distribution:

$$f(t) \sim N(t^{\theta}, \mu, \sigma)$$



Uncertainty of fault trace

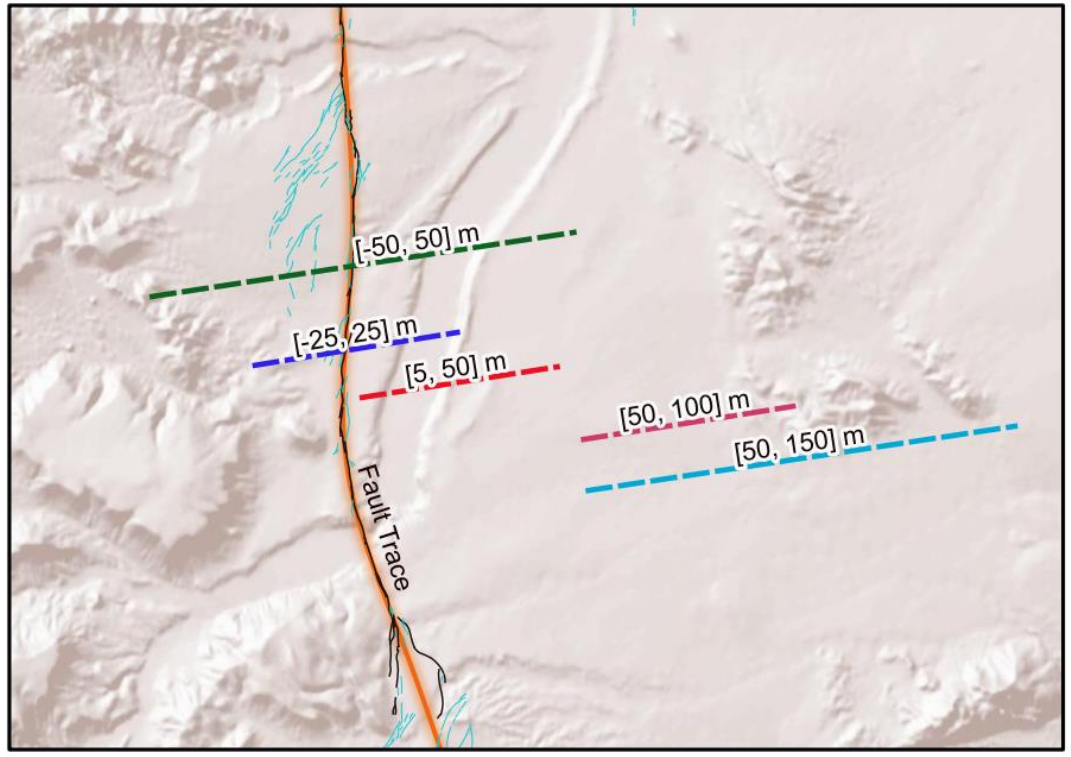
1. Segment Coordinate System (SCS)
2. Maximum Principal Displacement Trace

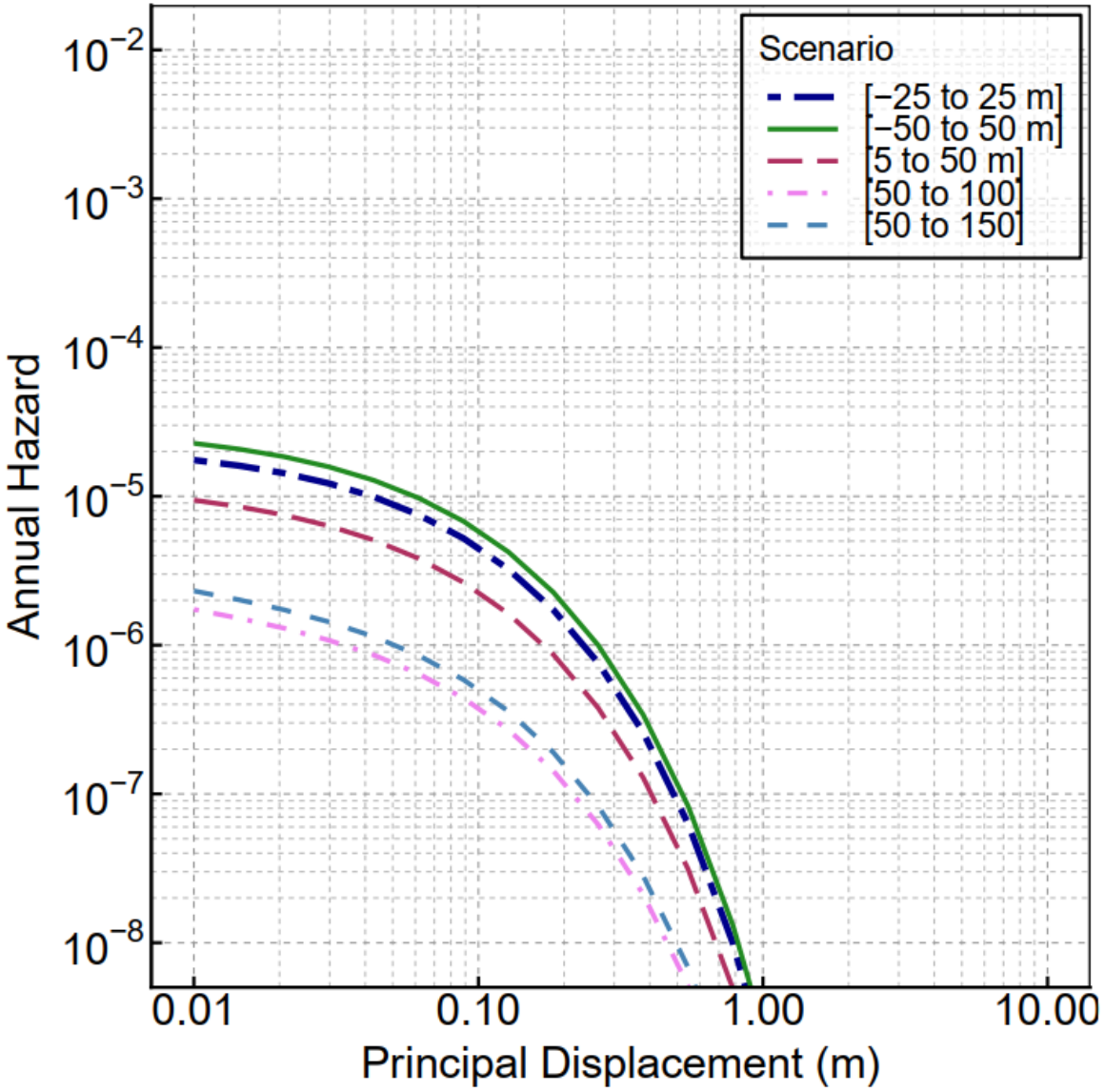


International Atomic Energy Agency (IAEA) Benchmark

Effect of infrastructure length and distance to the fault

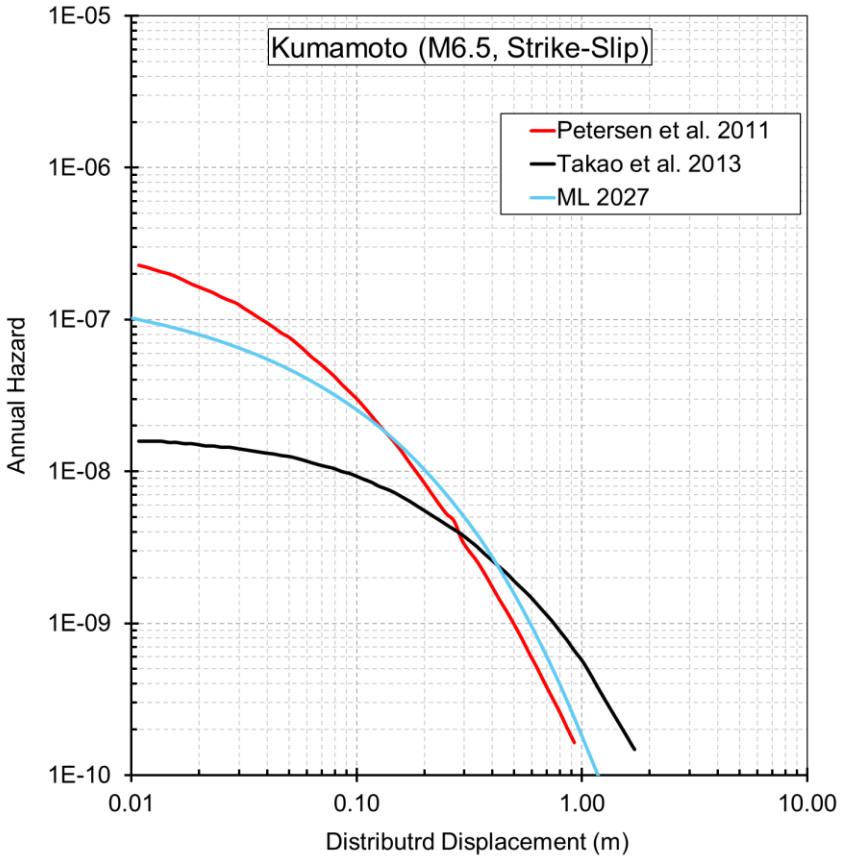
- Wider structures: higher hazard
- Proximity dominates

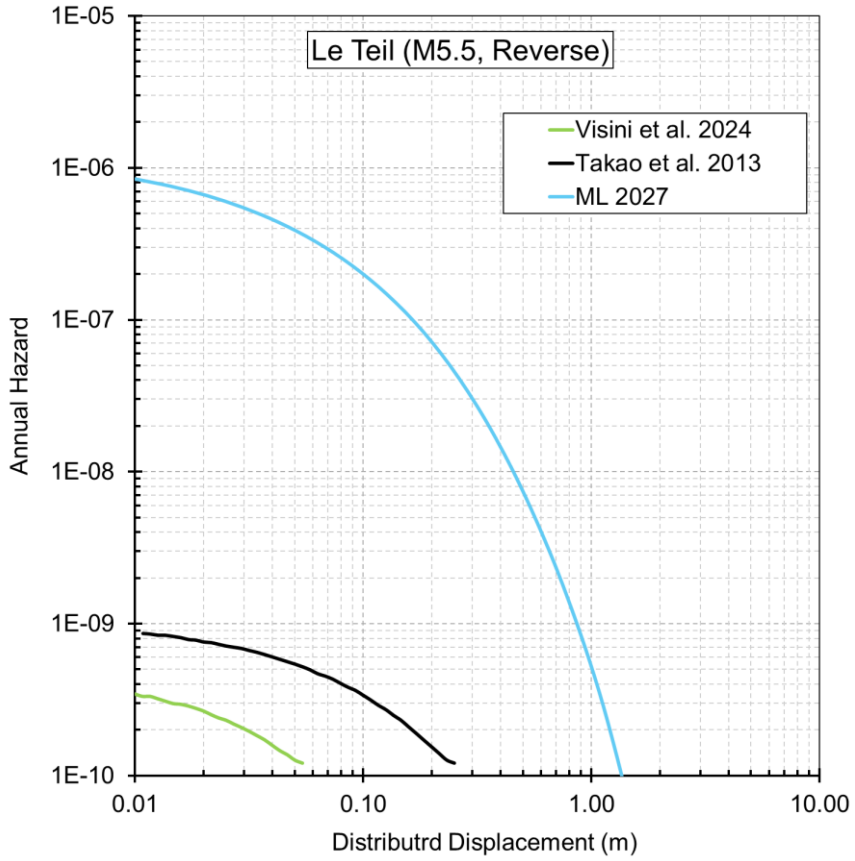


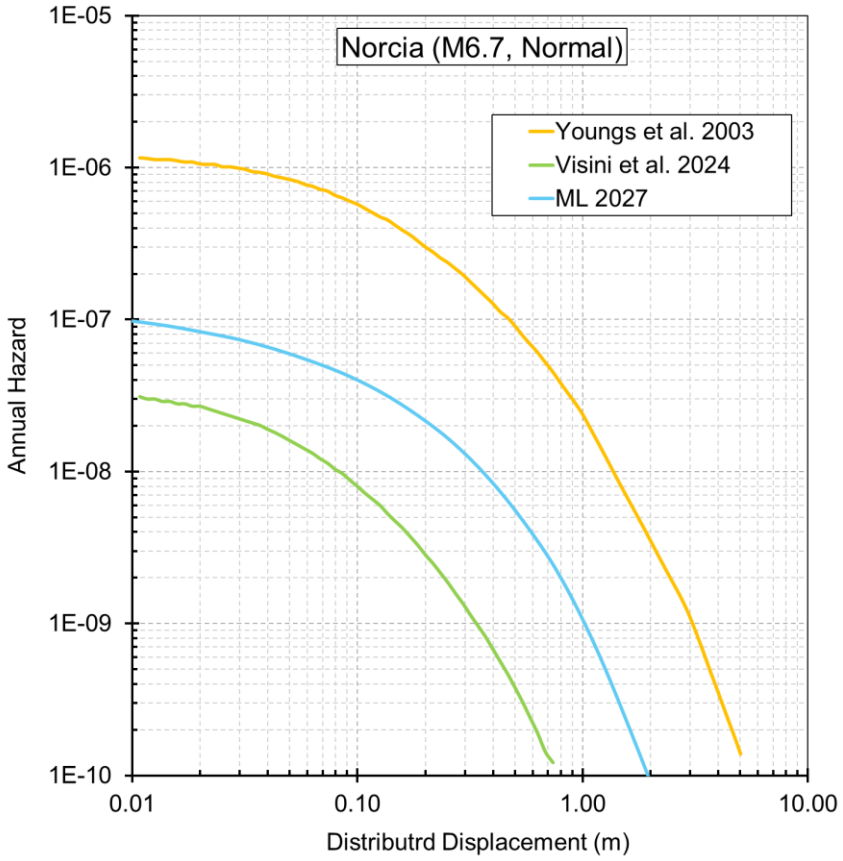


International Atomic Energy Agency (IAEA) Benchmark

- Distributed Displacement







Final Remarks

Conclusions:

- Developed a unified fault-displacement model for aggregate, principal, and distributed rupture
- Extended fault-displacement hazard assessment to individual rupture strands and distributed deformation
- Incorporated fault complexity into displacement scaling

Collaborators:

- Saba Marmarchinia – CSEE PhD Candidate



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- School of Engineering and Applied Sciences