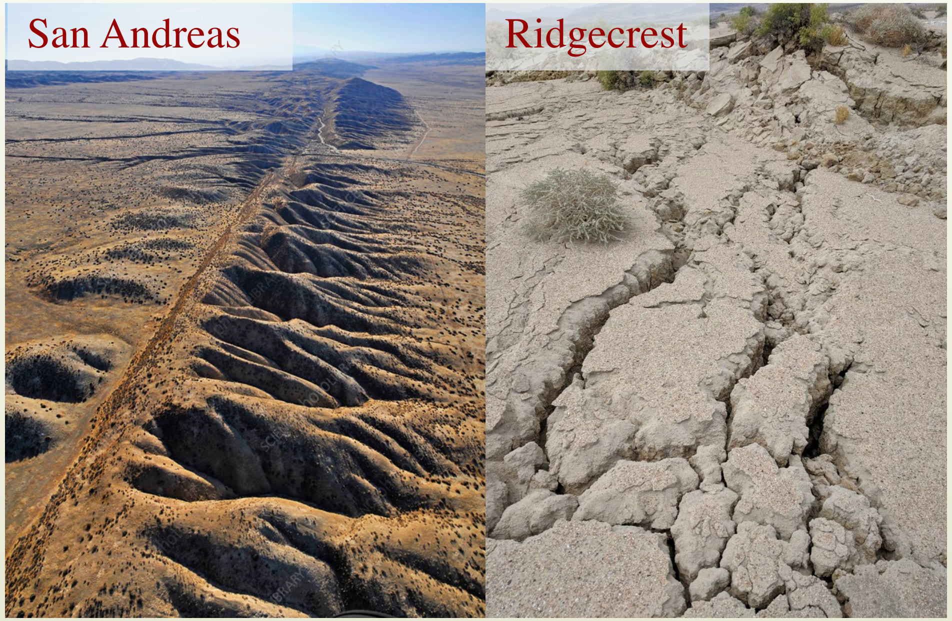
SC/EC



How does the fault maturity impact seismic hazard?

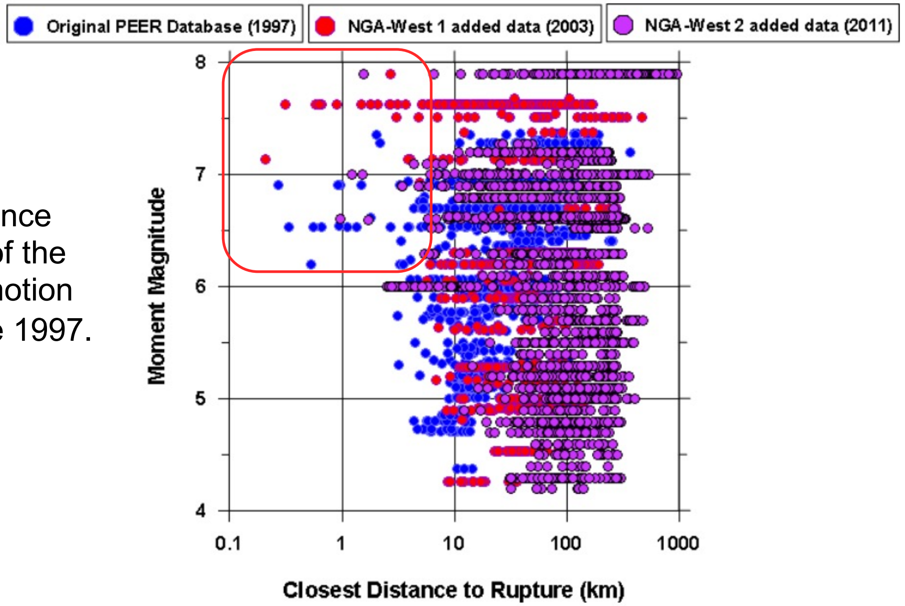
Physical connection of the stress drop (earthquake) with geological the geological slip rate (fault) and implications for seismic hazard

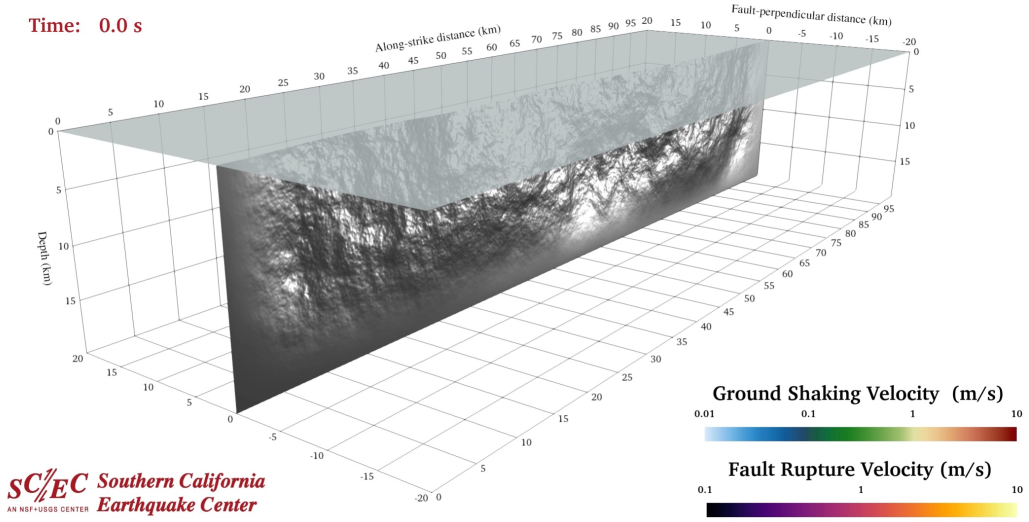
Yongfei Wang

Challenges for accurately predicting seismic hazard

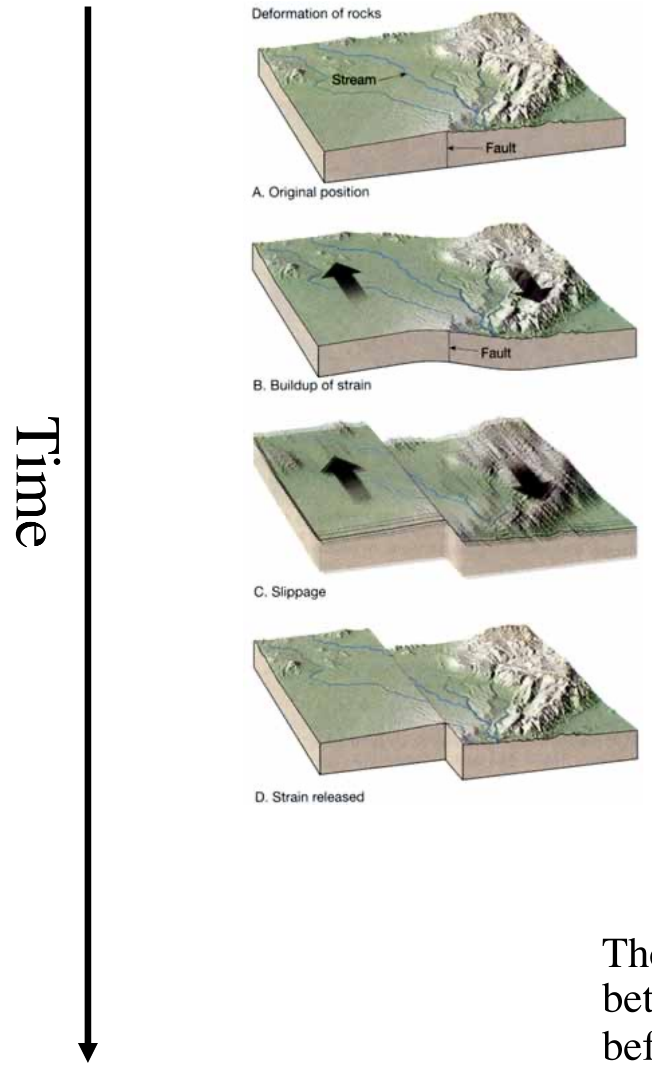
- Traditional probabilistic seismic hazard analysis (**PSHA**) relies on empirical ground-motion model and existing data.
- **Limitation**: recorded ground motions are very sparse for sites very close to fault in large earthquakes. (**Large uncertainty**)
- **Solution**: **Physics-based simulation** is an attractive alternative to provide data and reduce variability by using physics-constrained laws (**CyberShake**). Model events we haven't seen.
- The **uncertainties** of physics-based simulation can be potentially **reduced** as **more knowledge** about earthquakes is gained.

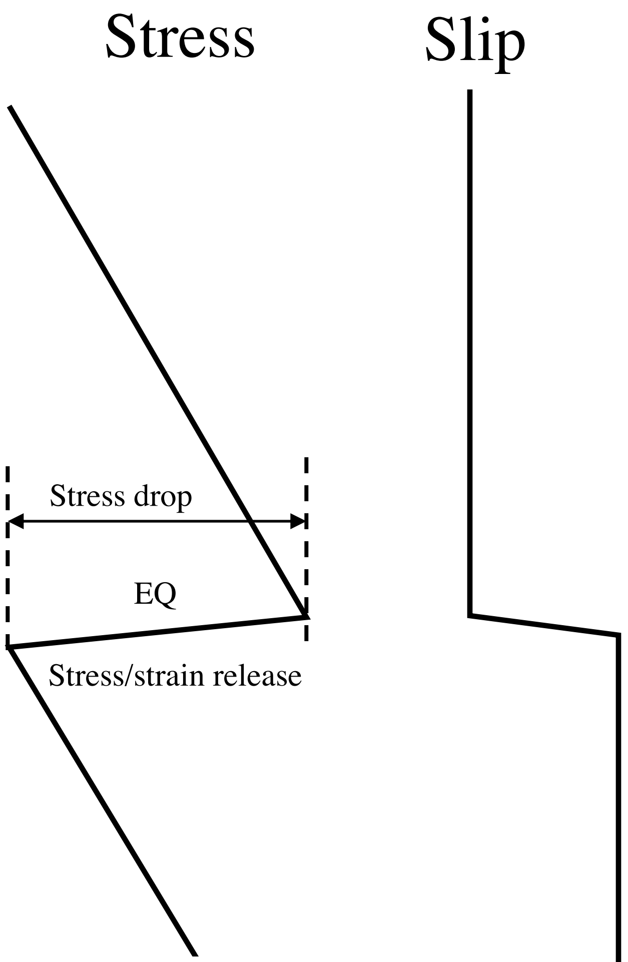
Magnitude-distance representation of the PEER ground motion databases since 1997.



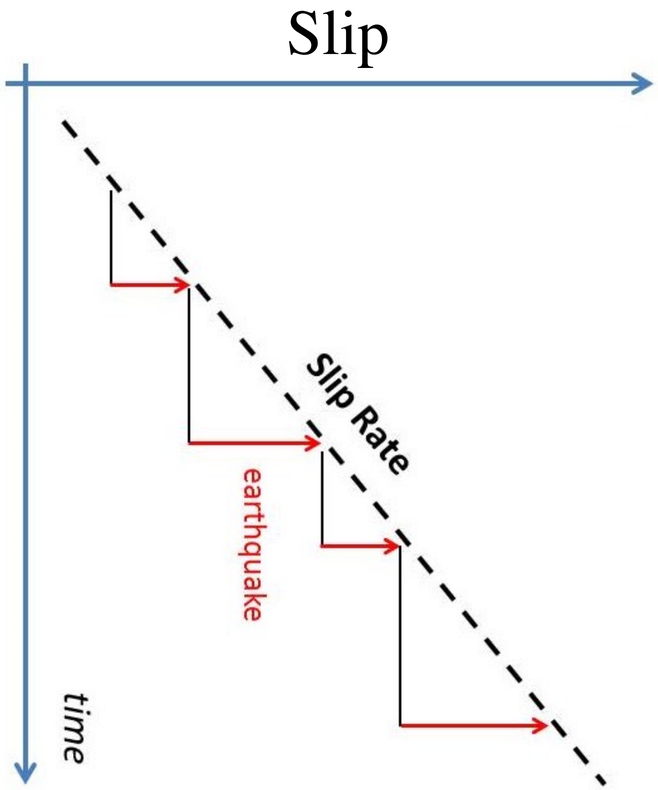


Earthquake, stress drop and slip rate





The stress drop is the difference between the stress across a fault before and after an earthquake

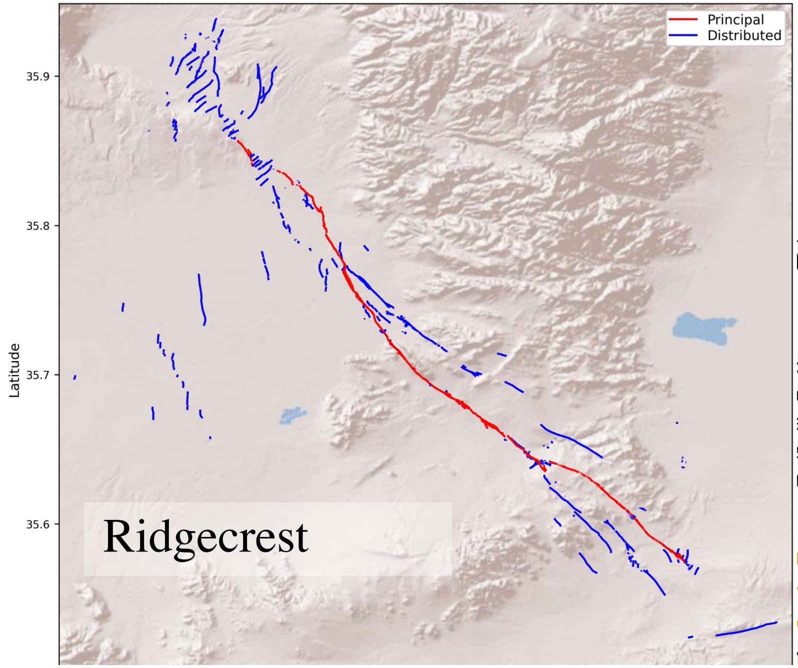


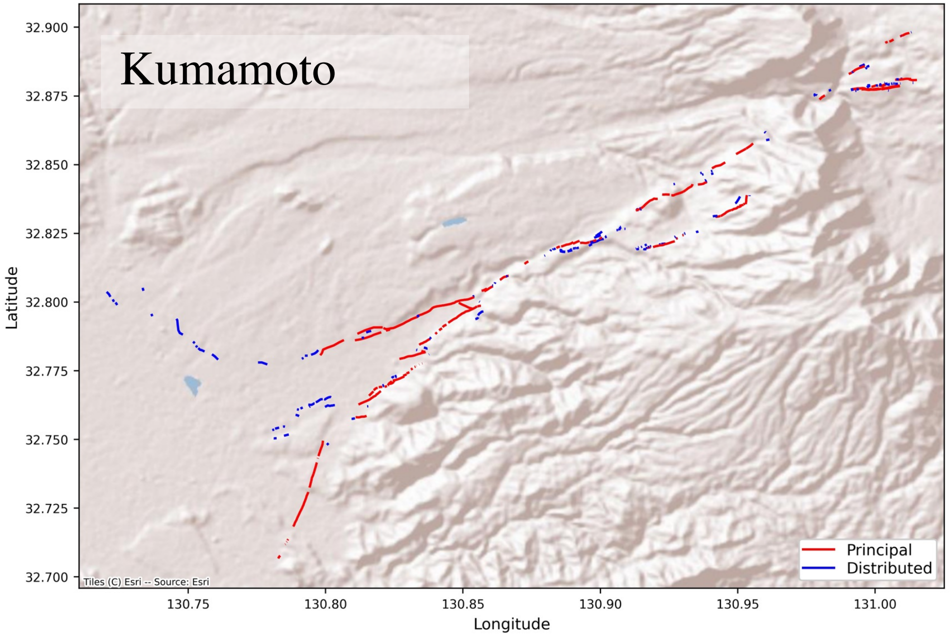
Slip rate is how fast the two sides of a fault are slipping in a long-term period.

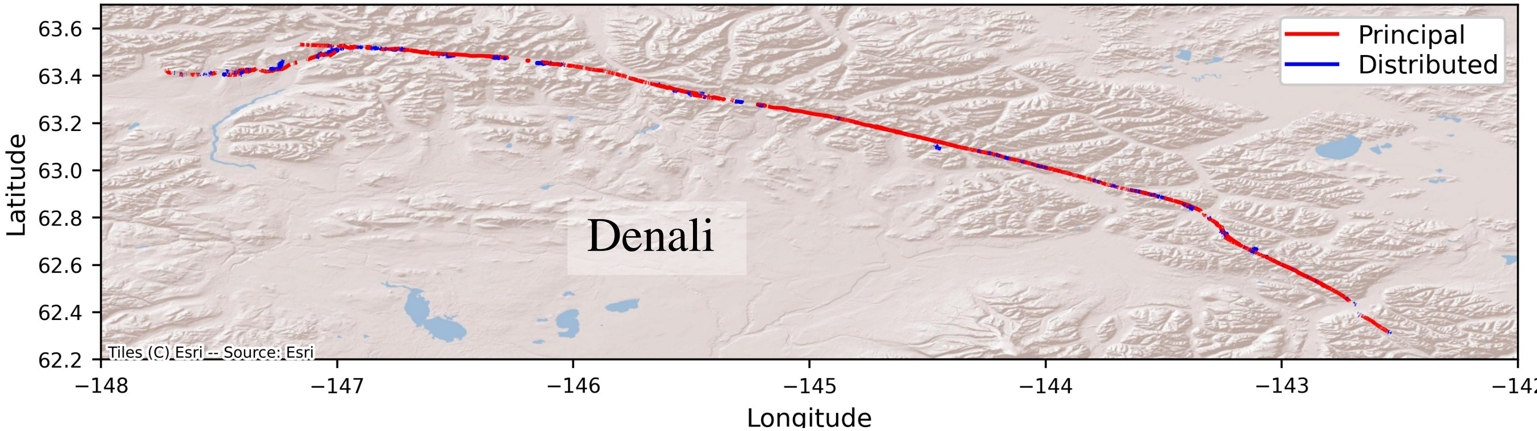
fault maturity (4D fault zone)?

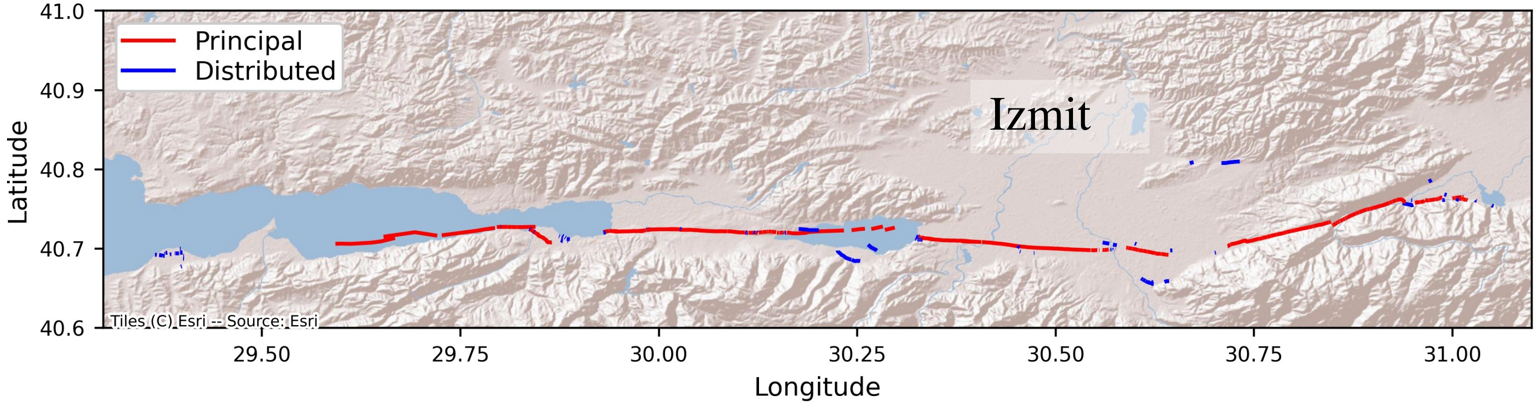
vith time (4^{th} D)

perities
e intersegment z
e
to non-planarity
mage zone



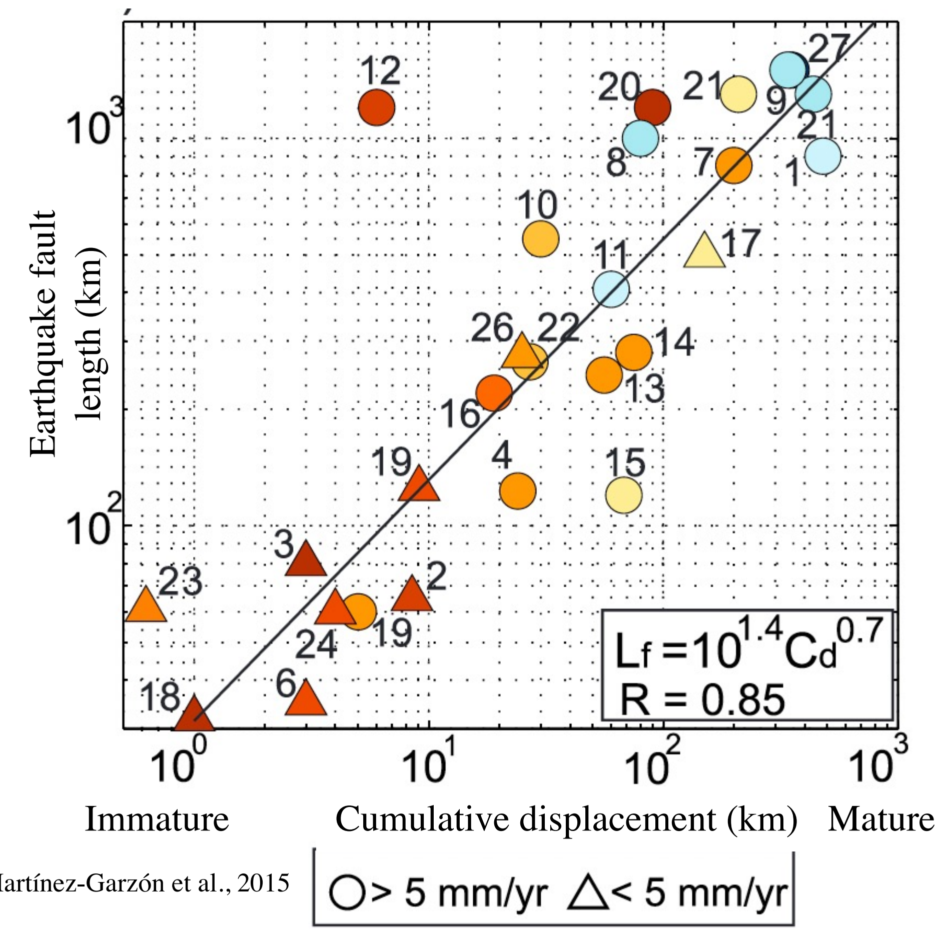






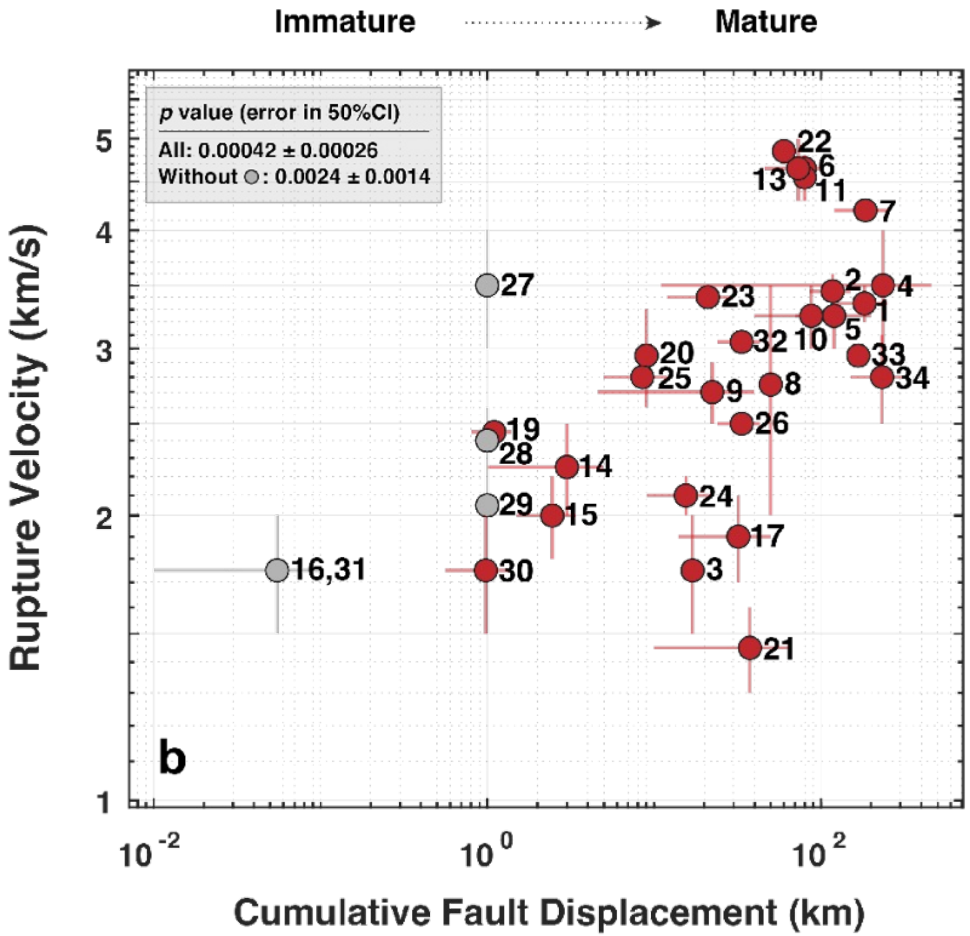
Some already found evidences of the fault maturity

Earthquake length vs fault maturity



Martínez-Garzón et al., 2015

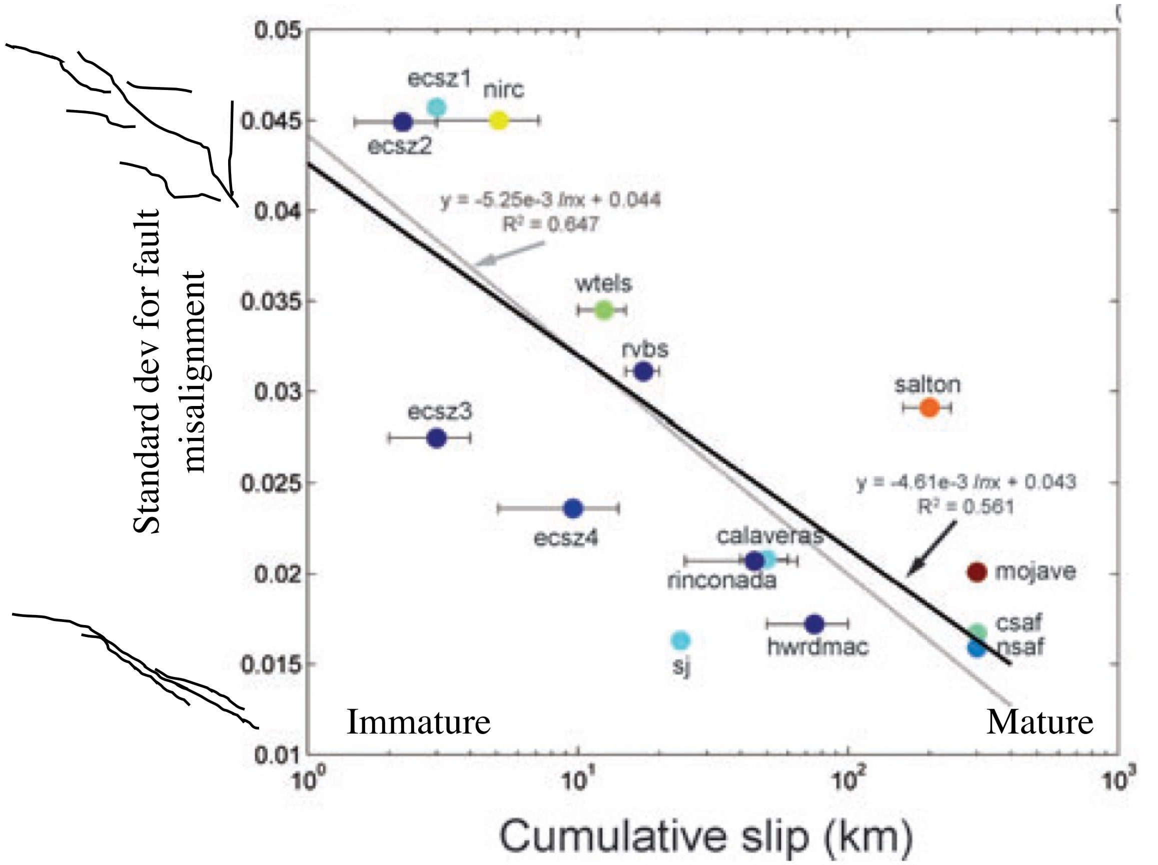
Rupture speed vs fault maturity



Guo et al., (preprint) 2022

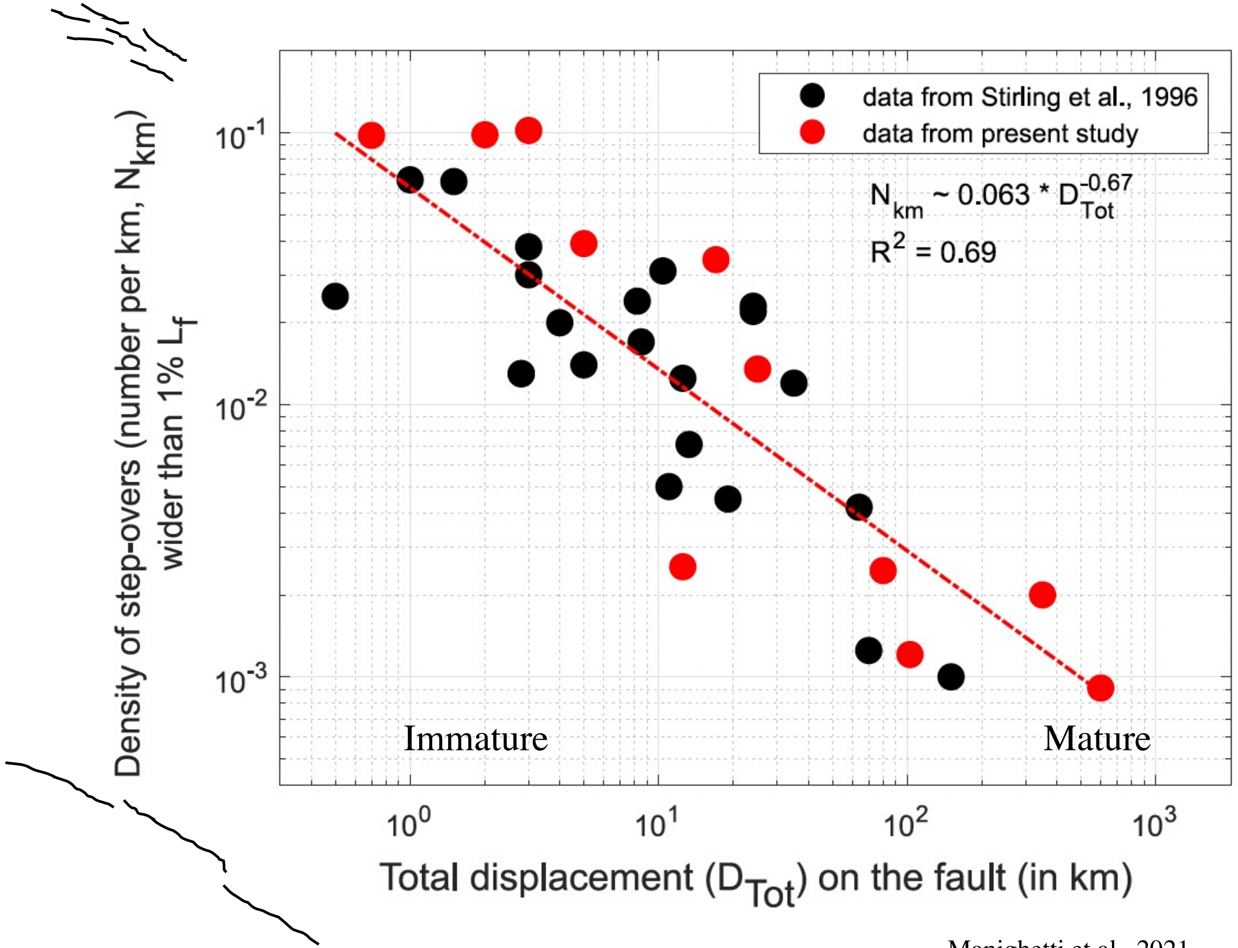
Some already found evidences of the fault maturity

Fault geometry vs fault maturity



Wechsler et al., 2010

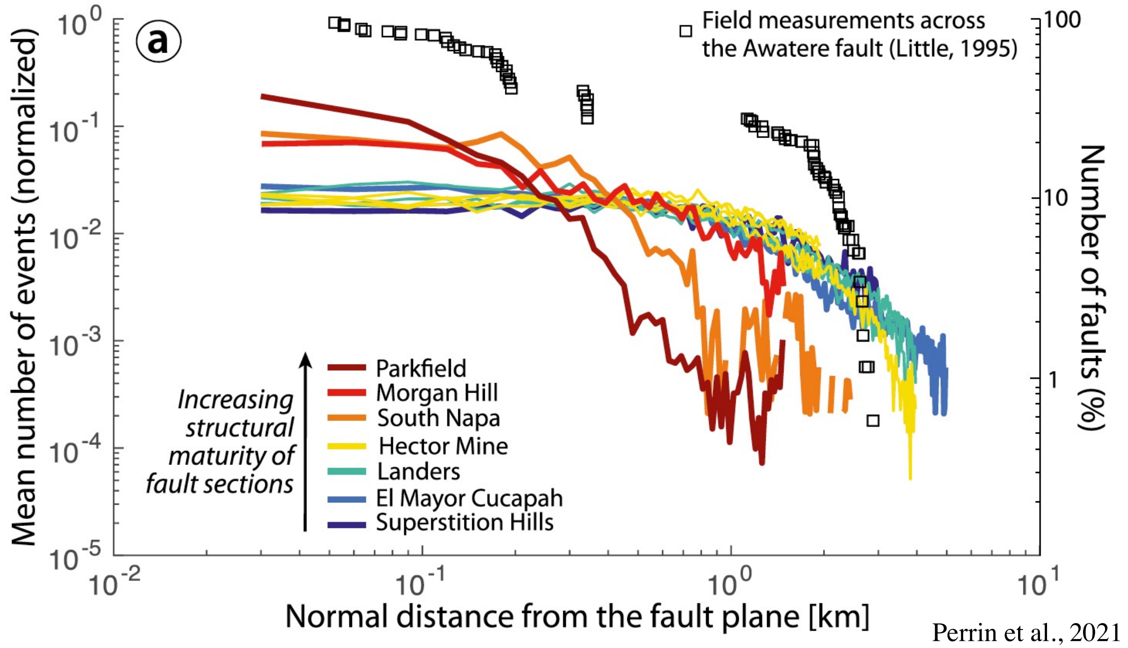
Fault step-over vs fault maturity



Manighetti et al., 2021

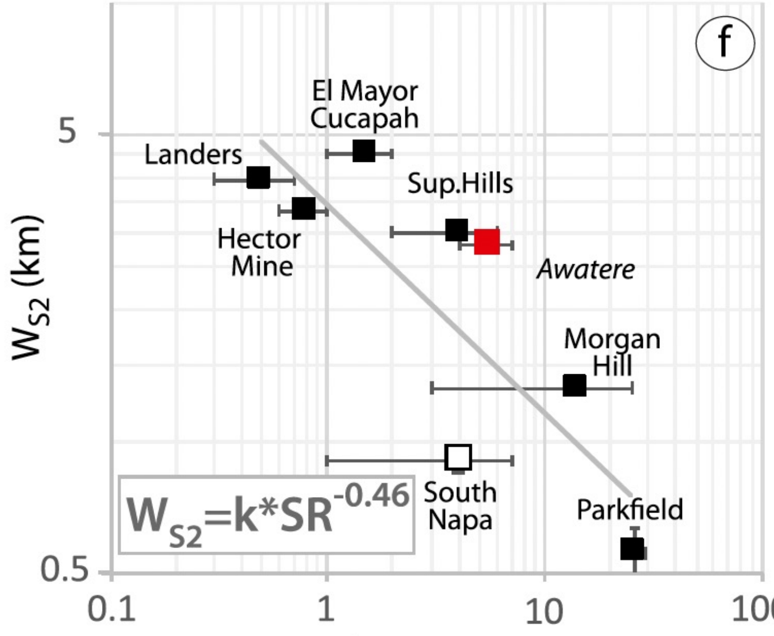
Some already found evidences of the fault maturity

Localization of aftershocks vs fault maturity



Perrin et al., 2021

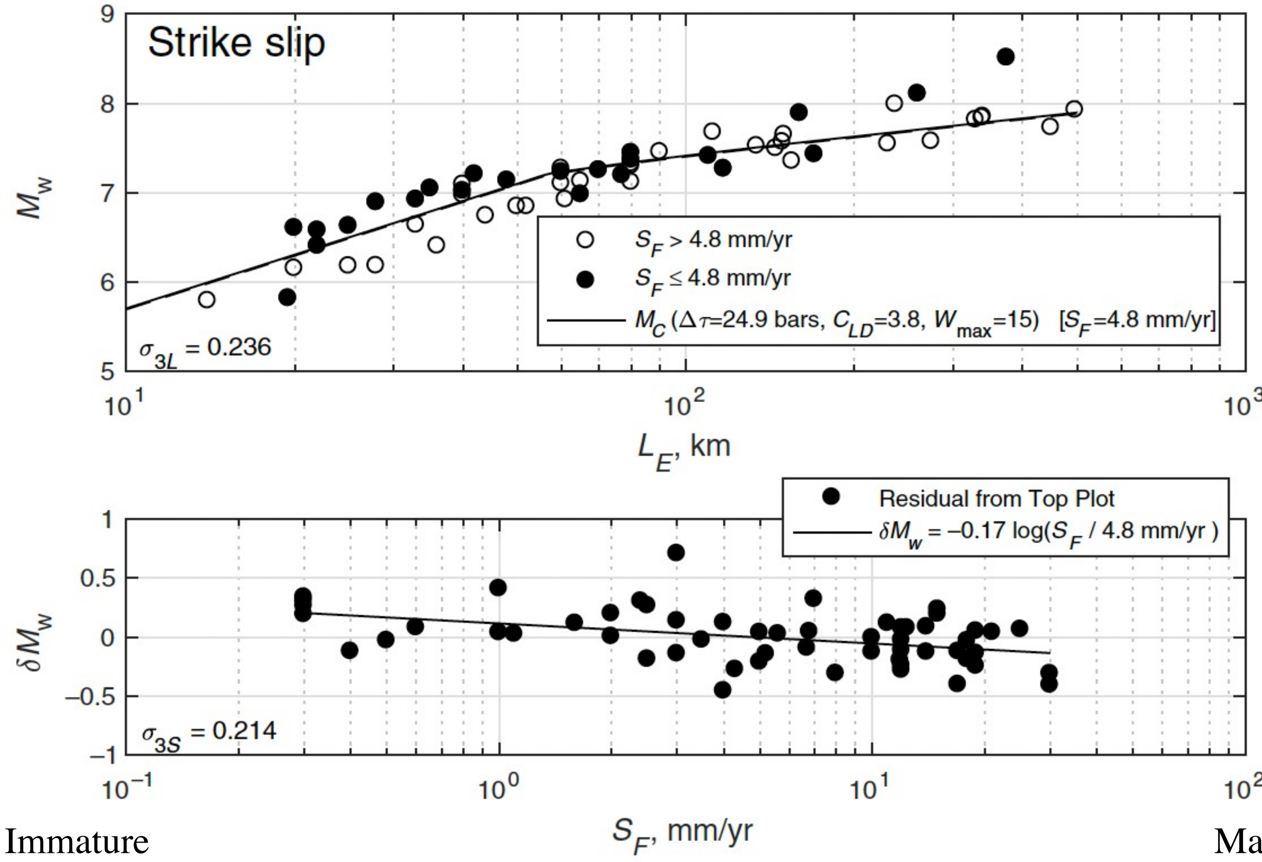
Shear zone width vs fault maturity (geological slip rate)



More mature faults => the more localized fault zones

Some already found evidences of the fault maturity

Magnitude vs fault maturity



Immature

Mature

Anderson et al., 2017

Constant stress drop assumption

δM_w

$$M_w = \begin{cases} 2\log L_E + \frac{2}{3}\log\Delta\tau_C + \frac{2}{3}\left(\log\frac{2\pi}{C_{LW}^2 C(\gamma)} - 16.1\right) + c_2\log\left(\frac{S_F}{S_0}\right) & \frac{L_E}{C_{LW}} < W_{\max} \\ \frac{2}{3}\log L_E + \frac{2}{3}\log\Delta\tau_C + \frac{2}{3}\left(\log\frac{2\pi W_{\max}^2}{C(\gamma)} - 16.1\right) + c_2\log\left(\frac{S_F}{S_0}\right) & \frac{L_E}{C_{LW}} \geq W_{\max}, \end{cases}$$

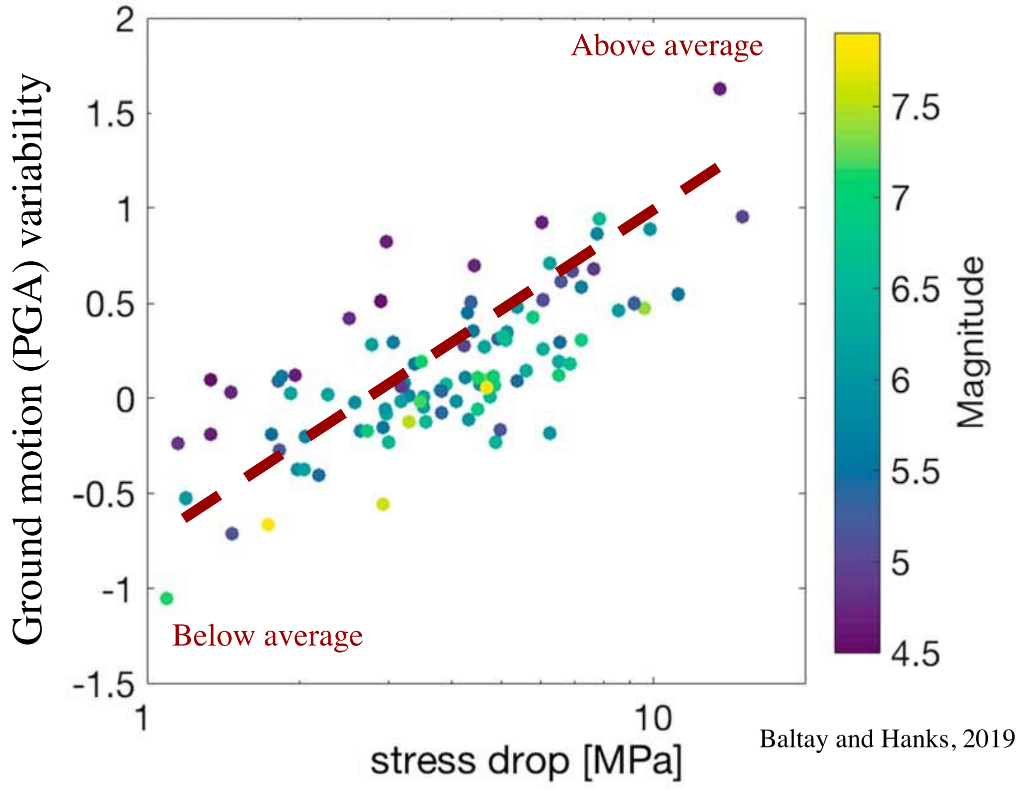
SF: geological slip rate

Mw-L slope changed caused by fault aspect ratio transition (from circular to elongated rectangular fault)

Does it suggest stress drop is also relevant to fault maturity?

Stress drop is important to seismic hazard but poorly constrained

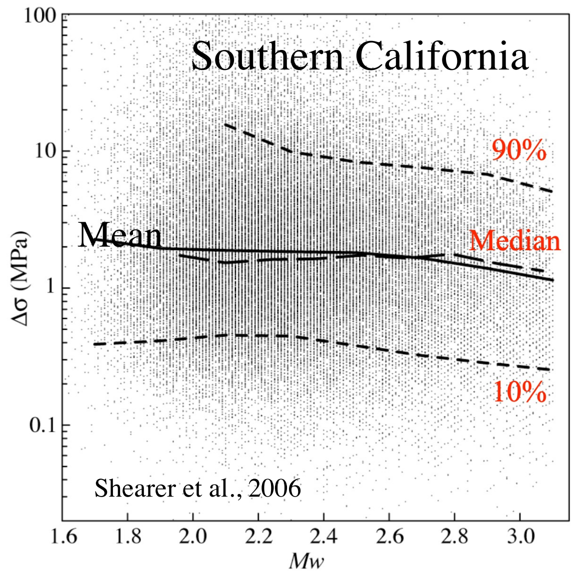
- Stress drop is a very important earthquake source property and a key input parameter for physics-based simulation.
- Stress drop has a big impact on ground motion intensity (large stress drop leads to large ground motion)
- A well constrained stress drop in simulations can improve predictions of ground motions simulations.
- How to constrain stress drop (what knowledge) and set up a stress drop for a future earthquake?



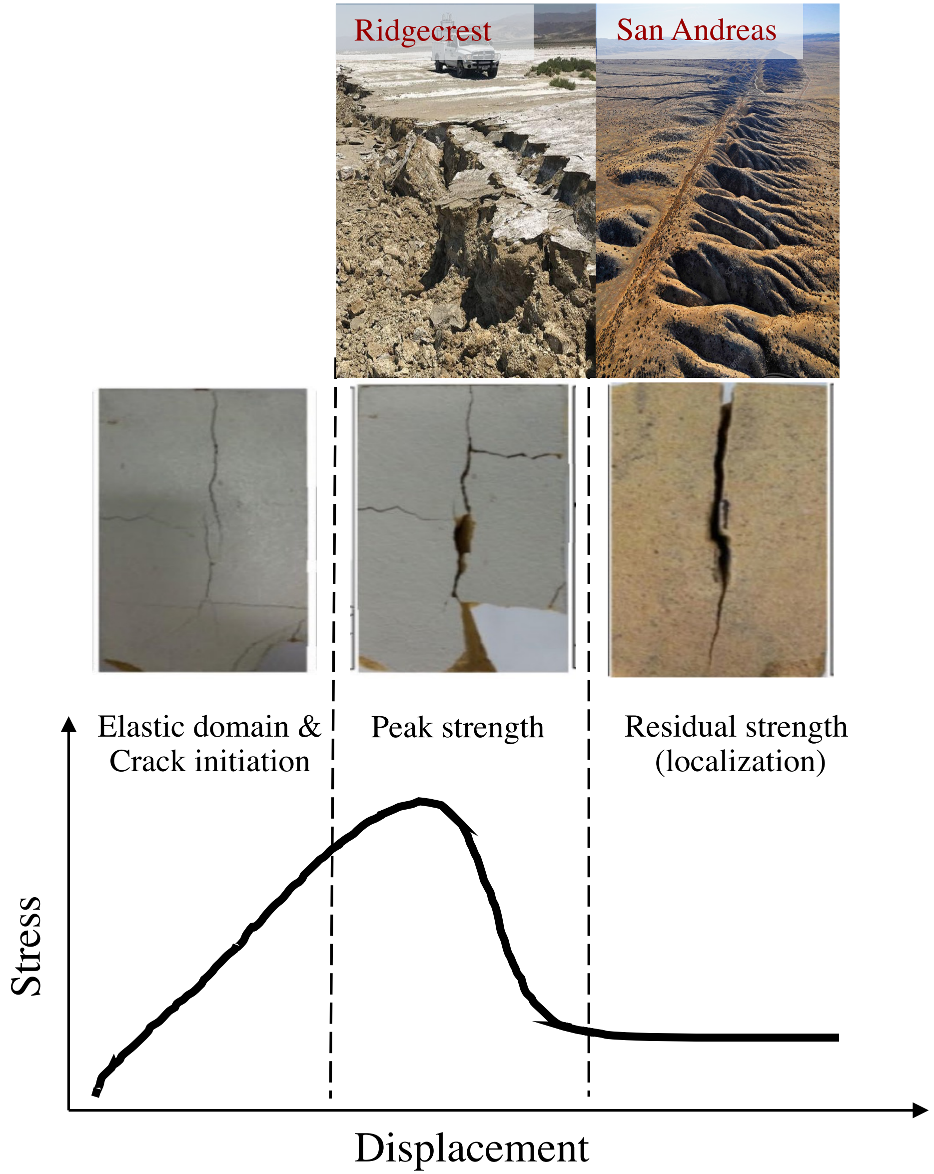
Baltay and Hanks, 2019

Stress drop: constant or fault specific?

- Generally, stress drop is believed to be constant with M (~3MPa), but with a large uncertainty.



- How can we use knowledge of material mechanics to help constrain stress drop for fault displacement modeling?



Fault Displacement Hazard Initiative (FDHI)

- A community-based research project
  - Led by UCLA and involving over 25 researchers and practitioners
  - Analogous to NGA project for ground motion
- With the goals to:
  - Develop a more comprehensive **database** measured worldwide and
  - Develop new fault displacement **models** to be used for PFDHA
- Our SCEC physics-based simulation within FDHI supported by:

PG&E

STATE OF CALIFORNIA ENERGY COMMISSION SINCE 1975

TACC TEXAS ADVANCED COMPUTING CENTER

U.S. DEPARTMENT OF ENERGY INCITE LEADERSHIP COMPUTING

Cal Poly

Caltech

SCEC AN NSF+USGS CENTER

UC Irvine

UCLA

UC Santa Barbara

USC

Fault Displacement Hazard Initiative Database

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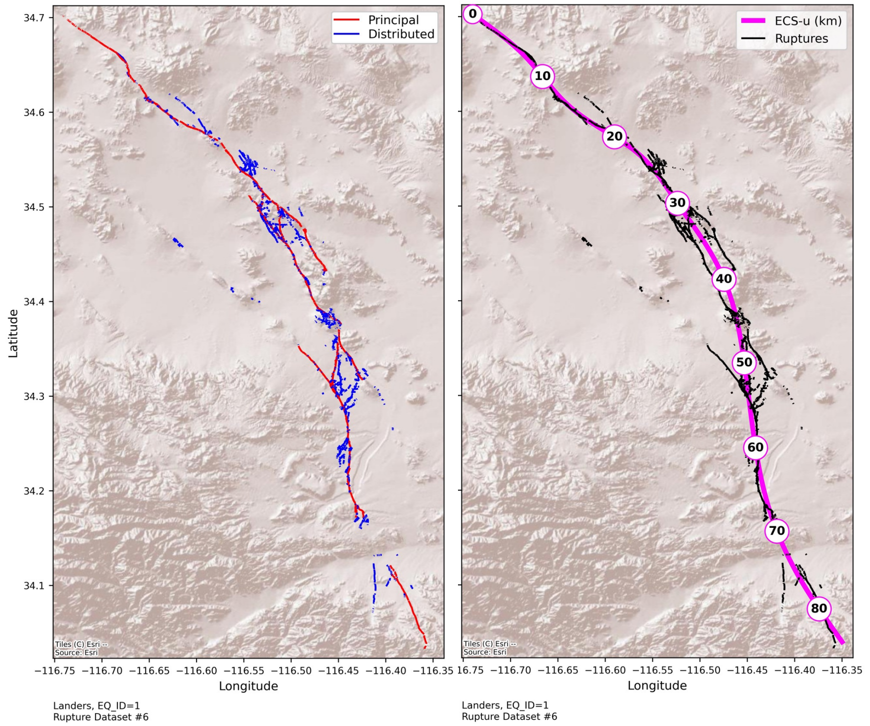
DOI: 10.34948/N36P48

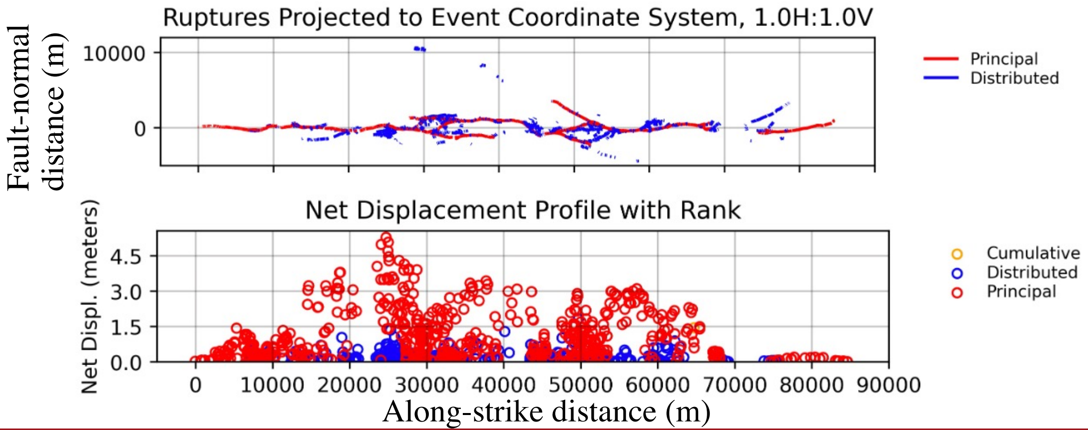
University of California, Los Angeles (headquarters)

The B. John Garrick Institute for the Risk Sciences
UCLA ENGINEERING

FDHI database

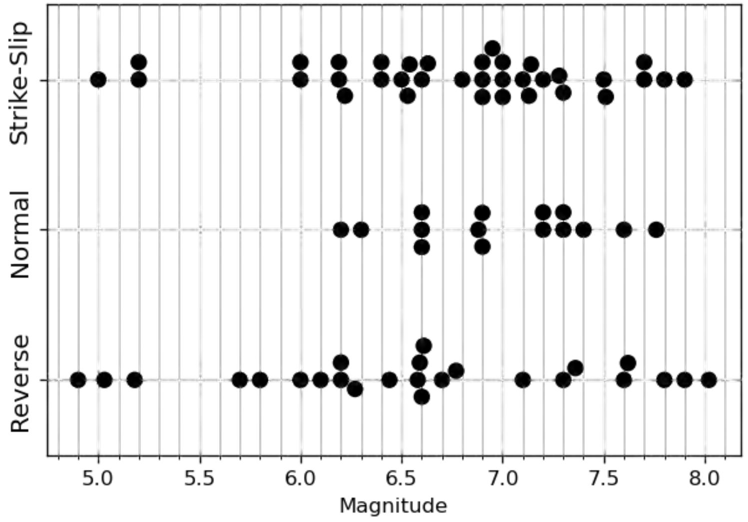
Landers earthquake





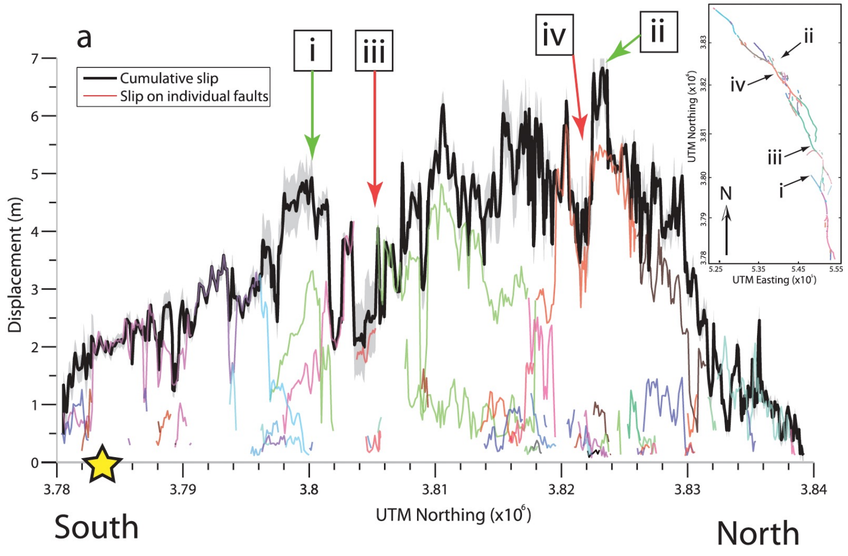
Contents:

- 75 earthquakes (1872 – 2019)
- M 4.9 – 8.0
- 45% SS, 20% NM, 35% RV
- > 40,000 measurements:
  - Principal and distributed displacements
  - Data from multiple survey techniques (field mapping and optical imaging)
  - Reference fault traces developed for “aggregated” displacements



Is the stress drop related to the fault maturity?

For fault displacement hazard, we use fault displacement data (average displacement and rupture length) and geological slip rate as a proxy of fault maturity to test it



E.g., Landers

Stress drop

Rupture length

Average displacement on the fault trace

$$S = \begin{cases} \dfrac{\Delta\sigma}{\mu}\dfrac{3L}{7} & L \le L_{max} \quad \text{Small circular fault} \\[2ex] \dfrac{\Delta\sigma}{\mu}\dfrac{1}{\dfrac{4}{3L}+\dfrac{1}{L_{max}}} & L > L_{max} \quad \text{Long rectangular fault} \end{cases}$$

Modified from Shaw (2013)

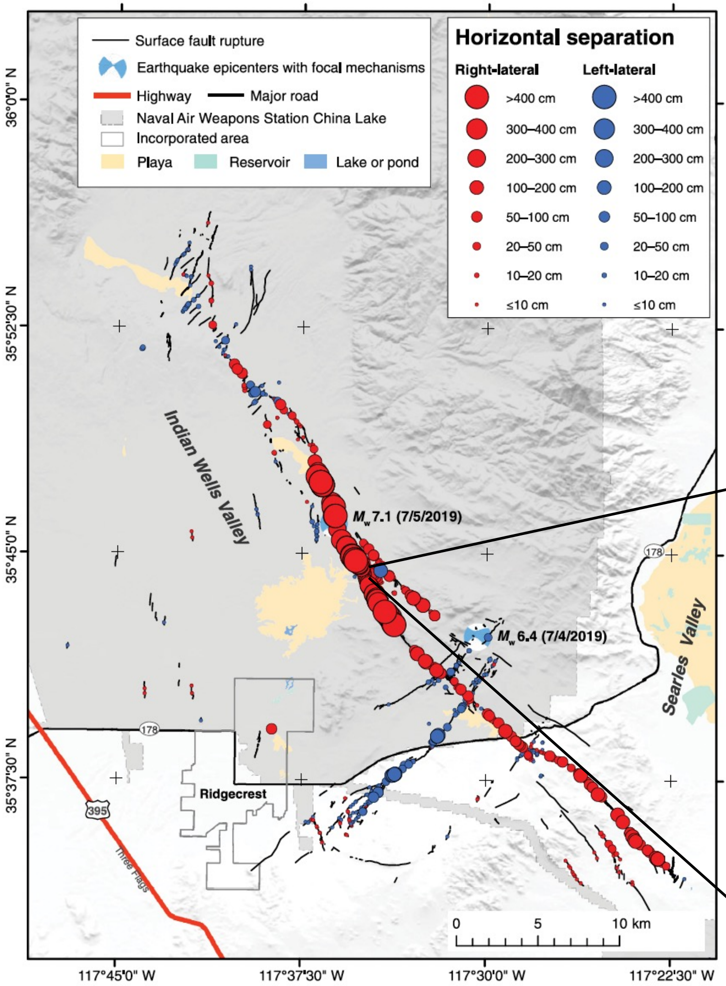
Prepare data

We aggregate the fault displacement databases of Biasi et al. (2013) and from the Fault Displacement Hazard Initiative (Sarmiento, et al., 2019), along with the slip rate dataset of Anderson et al. (2017), which together include 48 strike-slip earthquakes (Table 1).

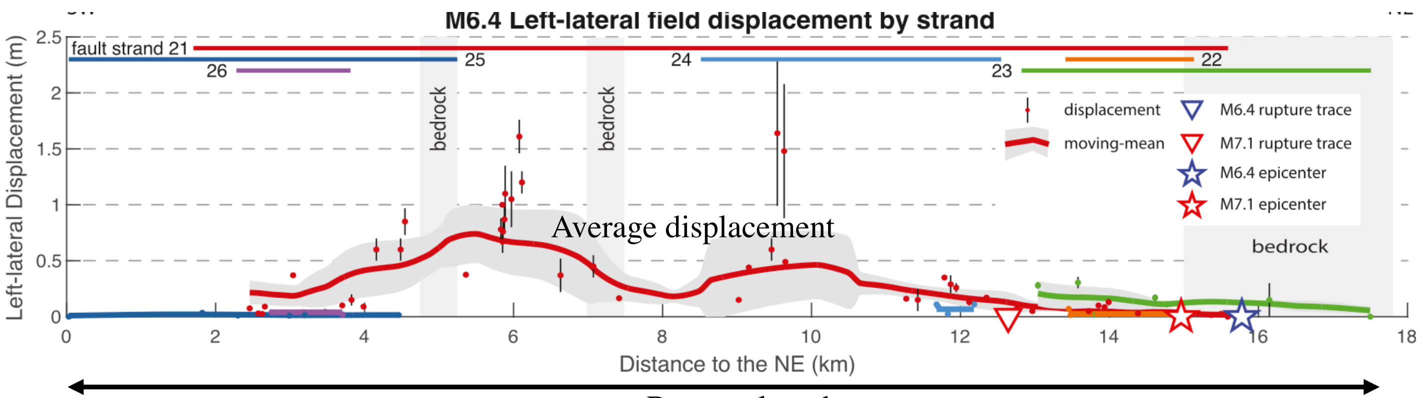
Country list	Earthquake name list			
China, Iran, Japan, Mexico, Mongolia, New Zealand, Nicaragua, Pakistan, Philippines, Russia, Turkey, USA	Name	Year	Name	Year
	Ridgecrest sequence	2019	Luhuo	1973
	Kumamoto	2016	Tonghai	1970
	Napa	2014	Borrego Mtn	1968
	Balochistan	2013	Parkfield	1966
	Darfield	2010	Alake Lake	1963
	Yushu	2010	Gobi-Altai	1957
	El Mayor Cucapah	2010	San Miguel	1956
	Parkfield	2004	Fairview Peak	1954
	Chuya	2003	Gerede-Bolu	1944
	Denali	2002	Tosya	1943
	Kunlun	2001	Tottori	1943
	Duzce	1999	Niksar-Erbaa	1942
	Hector Mine	1999	Imperial Valley	1940
	Izmit	1999	Erzincan	1939
Table 1: List of used earthquakes in this study	Fandoqa	1998	Tuosuo Lake	1937
	Manyi	1997	Fuyun	1931
	Zirkuh	1997	NorthIzu	1930
	Sakhalin Island	1995	Luoho-Qianjiao	1923
	Landers	1992	Haiyuan	1920
	Luzon	1990	San Francisco	1906
	Superstition Hill	1987	Bulnay	1905
	Sirch	1981	Owens Valley	1872
	Imperial Valley	1979	Fort Tejon	1857
	Motagua	1976		

Estimation of stress drop from fault displacement

Ridgecrest EQ



Ponti et al., 2020



Gold et al., 2021

Fault displacement measured from fields

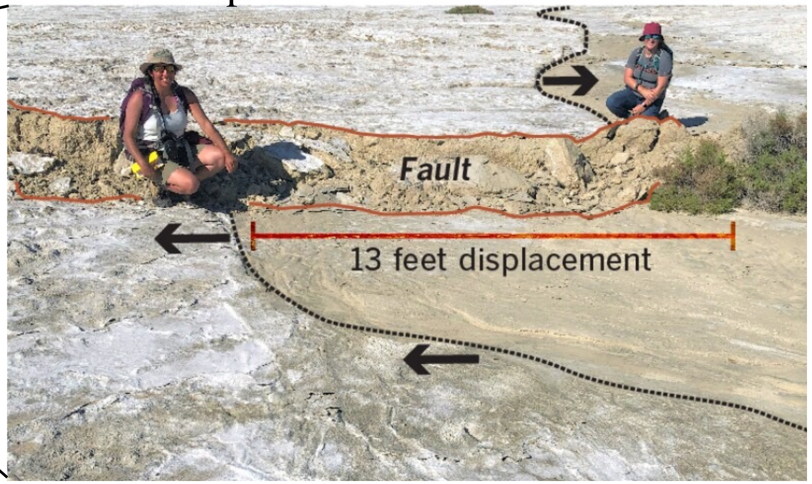


Photo by Brian Olsen, CGS

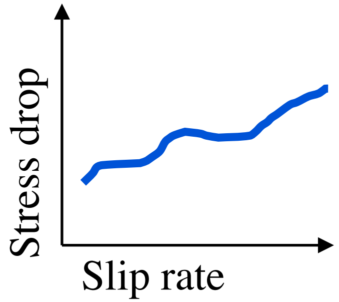
$$S = \begin{cases} \dfrac{\Delta\sigma}{\mu}\dfrac{3L}{7} & L \le L_{max} \\ \dfrac{\Delta\sigma}{\mu}\dfrac{1}{\frac{4}{3L}+\frac{1}{L_{max}}} & L > L_{max} \end{cases}$$

Assumption: stress drop is a function of slip rate

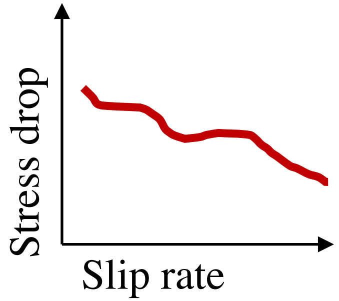
Borrowing relations from Anderson et al. 2017 and Perrin et al. 2021, we reorganize terms and propose

$$\Delta\sigma = c_1 SR^{c_2}$$

- If $c_2 = 0$, stress drop is constant/independent of slip rate.
- If $c_2 > 0$, stress drop is positively correlated with slip rate



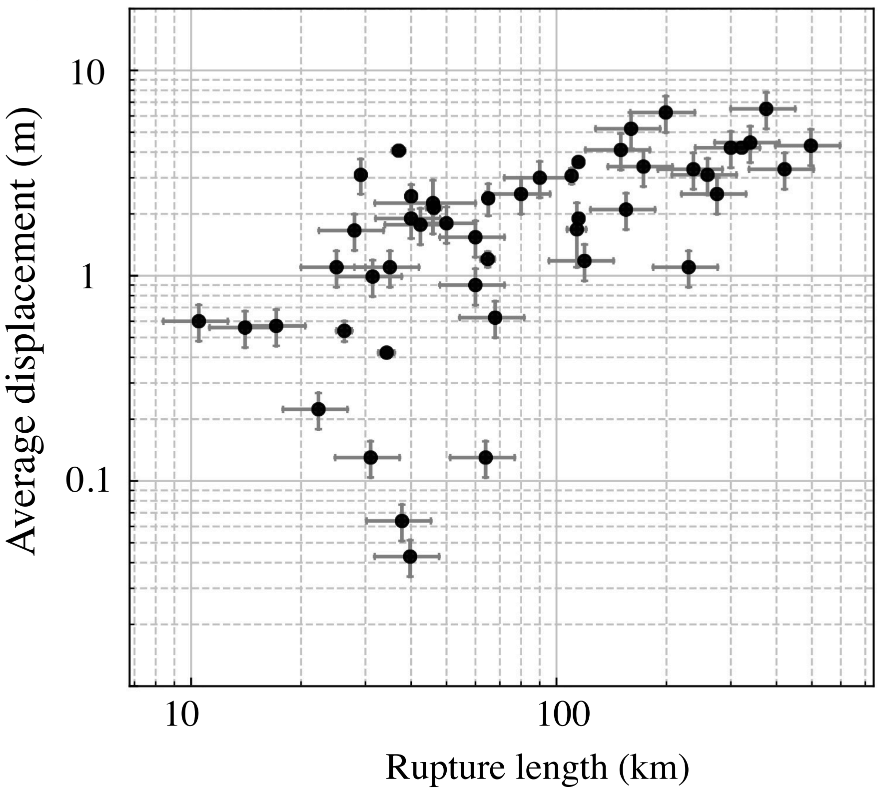
- If $c_2 < 0$, stress drop is negatively correlated with slip rate

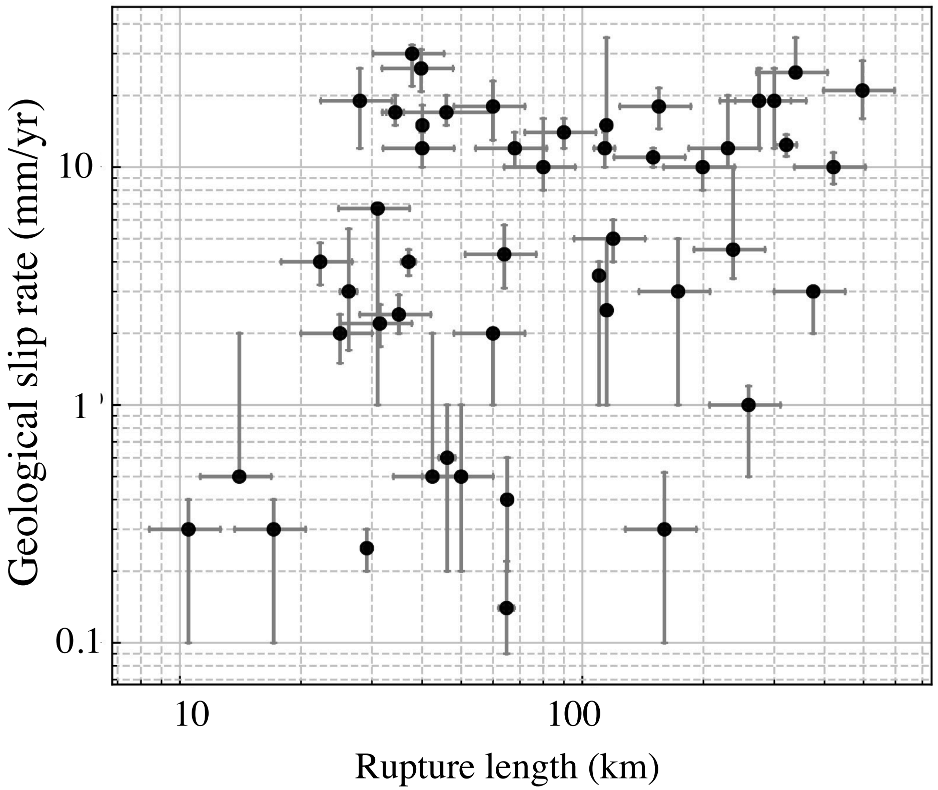


Linear regression for c_1 and c_2

Data (48 historical strike-slip earthquakes)

$$\Delta\sigma = c_1 S R^{c_2}$$

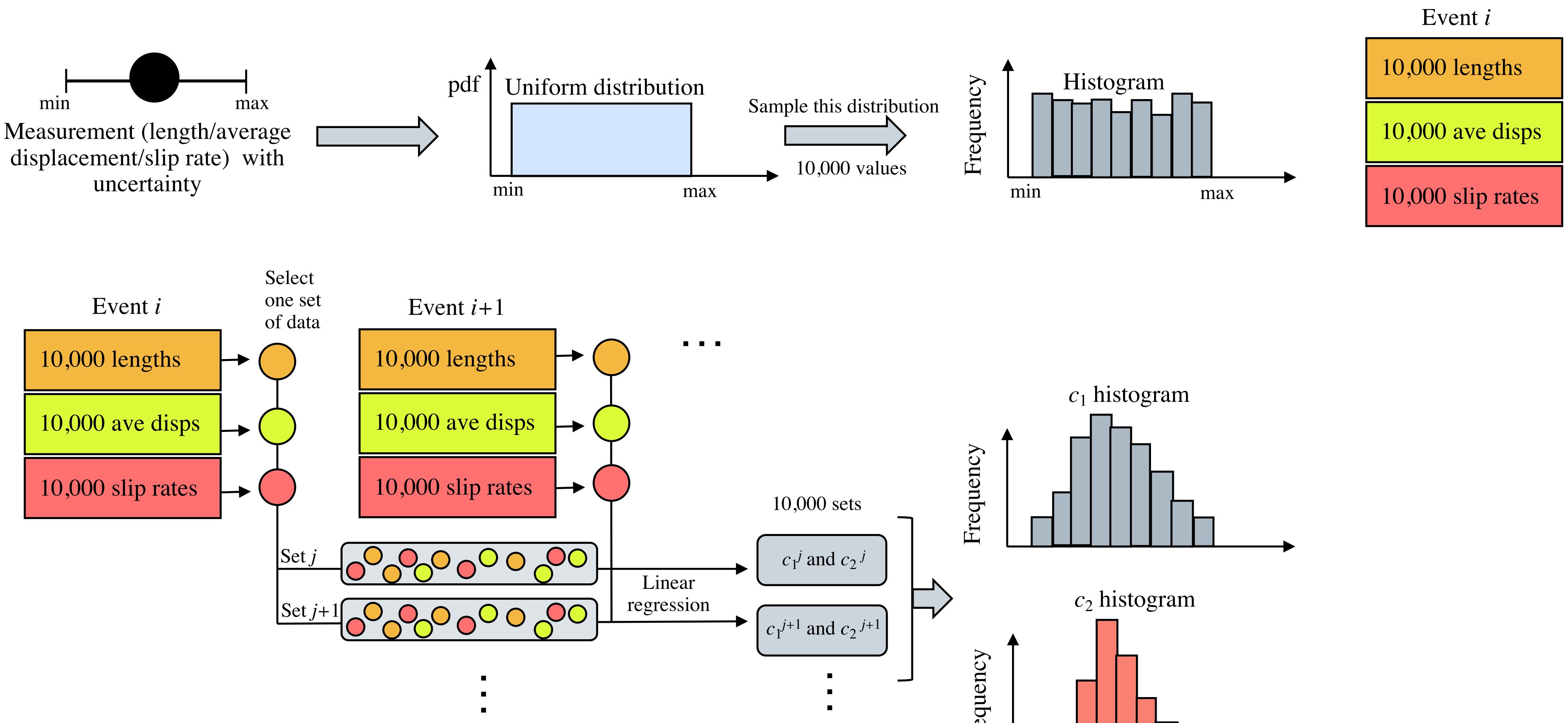




Data from FDHI (Sarmiento et al. 2020), Biasi et al. 2013, Anderson et al. 2017, USGS

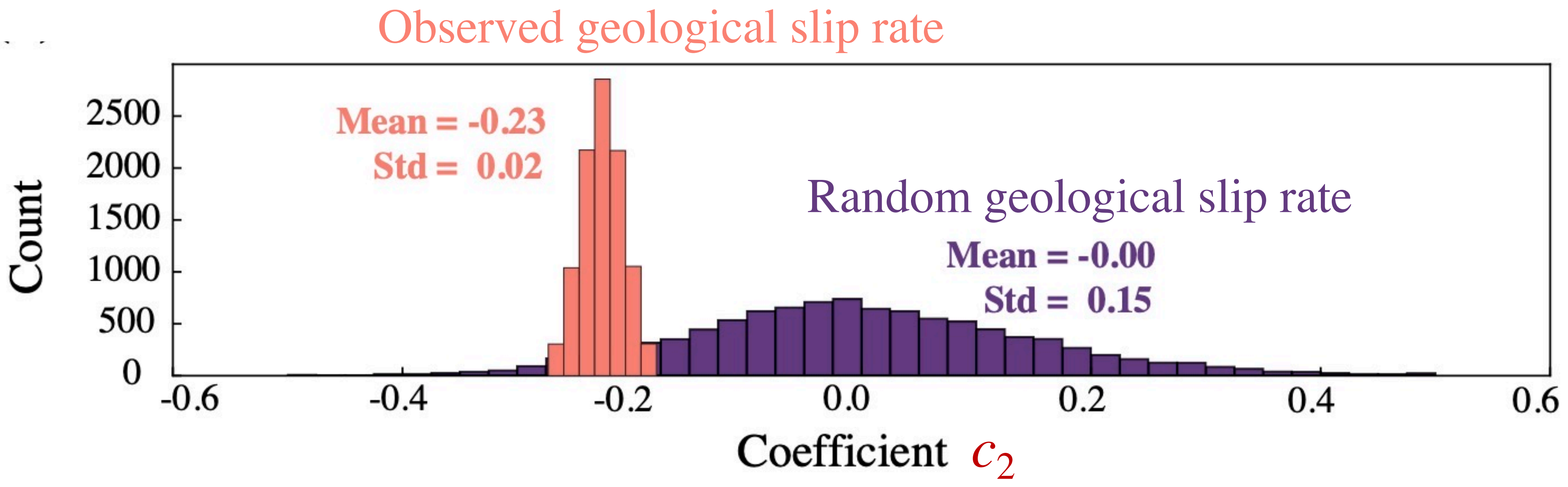
Monte Carlo sampling of uncertainty

For each earthquake



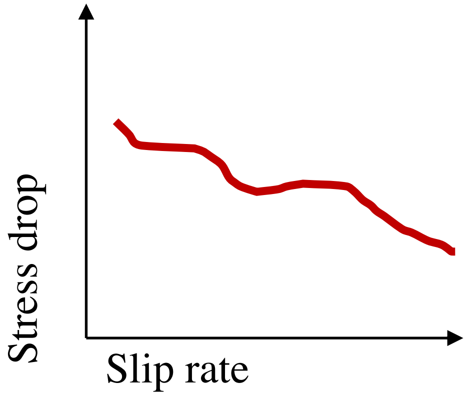
We build a dataset from 10,000 realizations that cover the ranges of uncertainty

Regression results (Monte Carlo simulation)

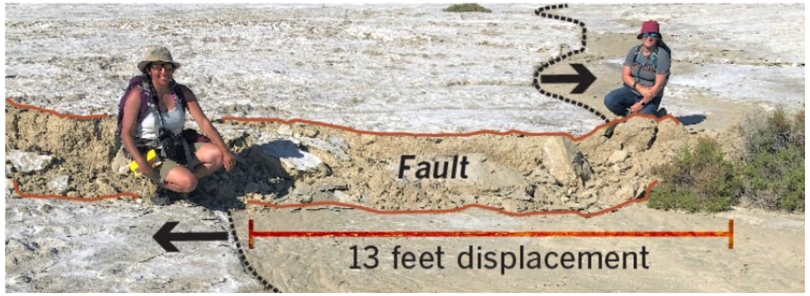


- Results indicate c_2 is ~ -0.23, suggesting the stress drop decreases with slip rate

$$\Delta\sigma = 2.0 * \mathrm{SR}^{-0.23}$$

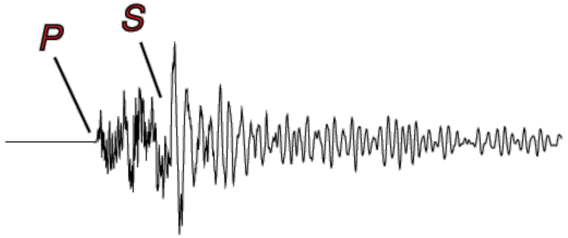


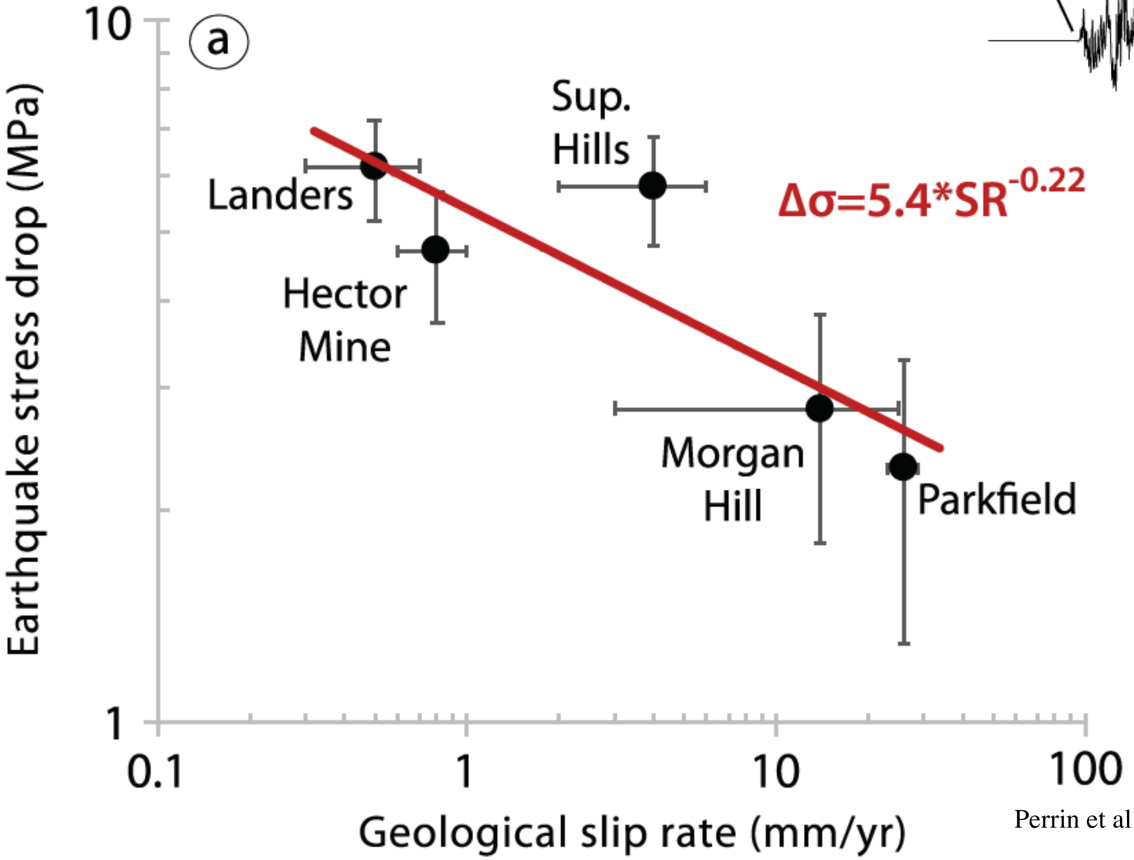
Comparison with other data types



$$\Delta\sigma = 2.0 * SR^{-0.23}$$

Stress drop obtained from completely different seismological data and method (seismic wave)





Perrin et al., 2021

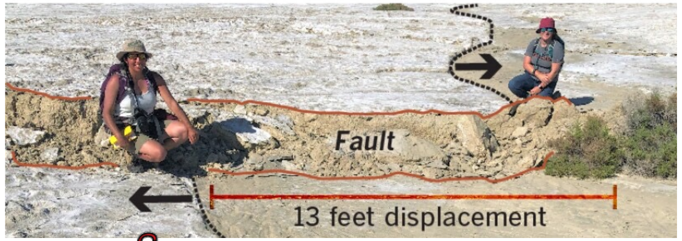
Comparison with other data types

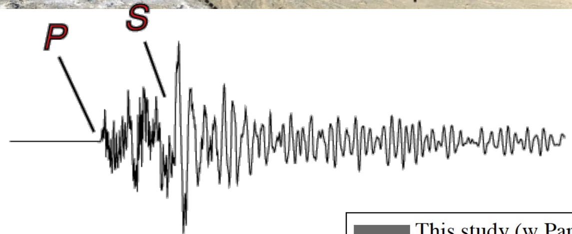
We test assumptions for regression and obtain a range of exponent c_2 values:

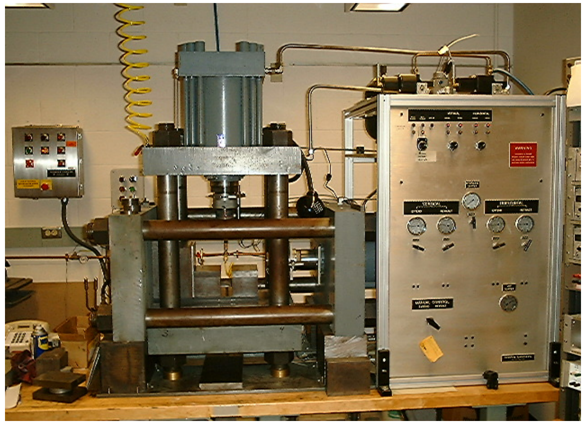
-0.08 to -0.23

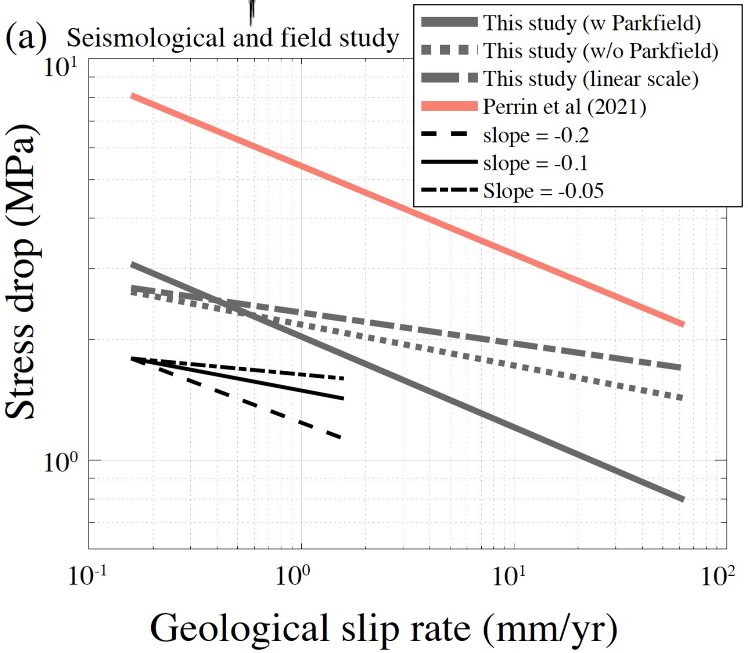
showing the same negative correlation and trend.

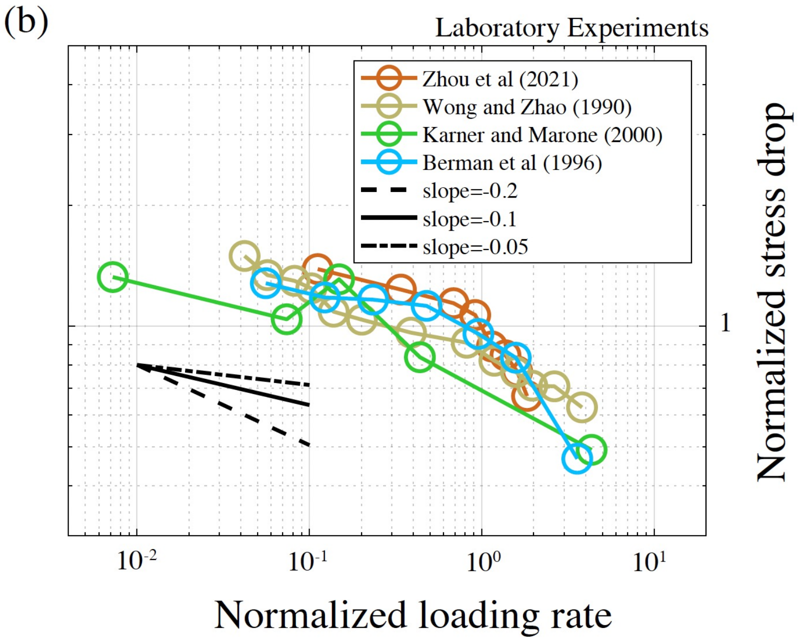
The range of exponents (slopes in plot) is also supported by those in lab experiments.



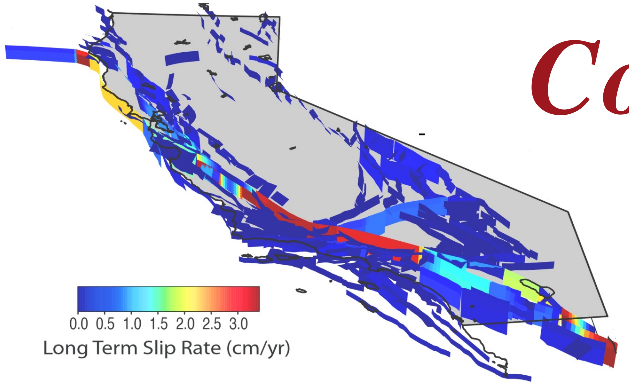






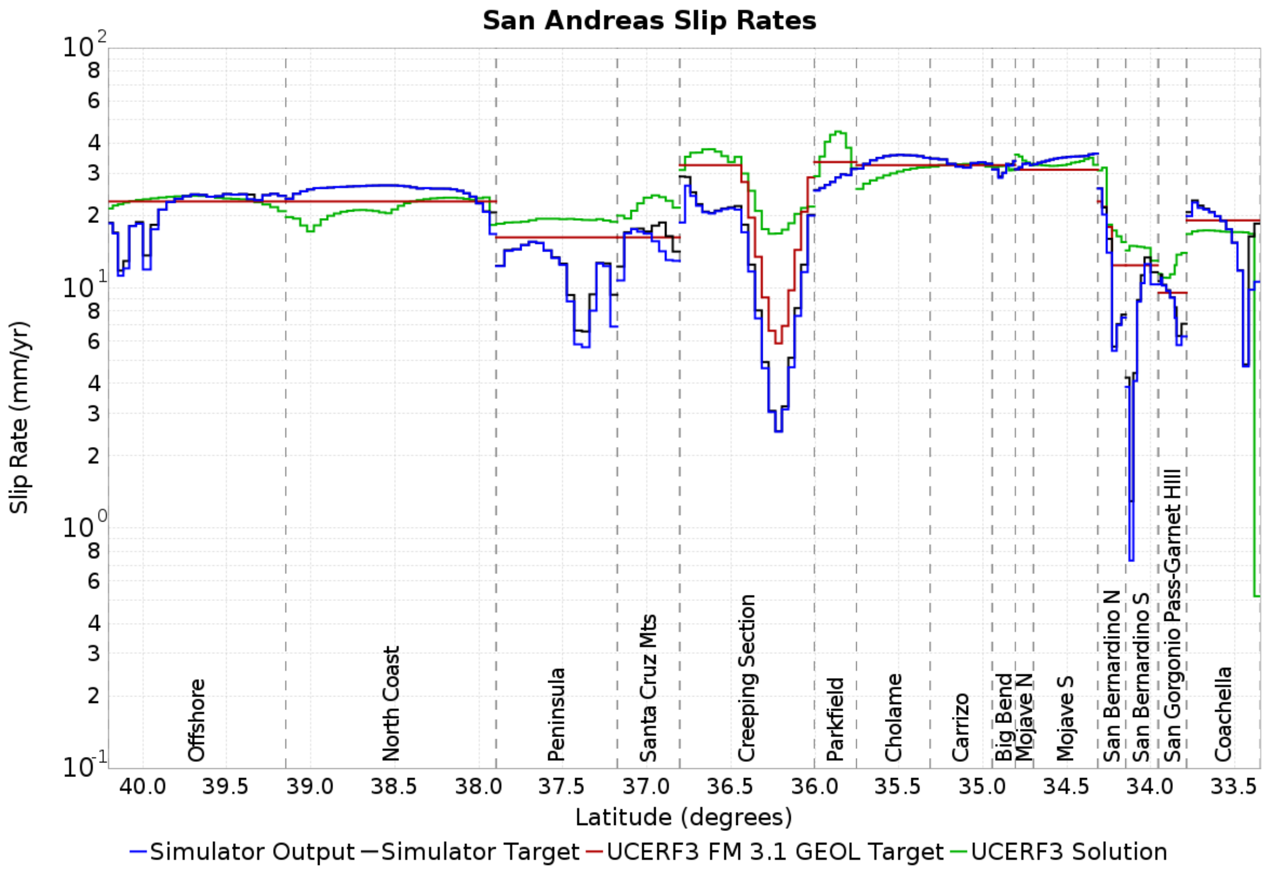


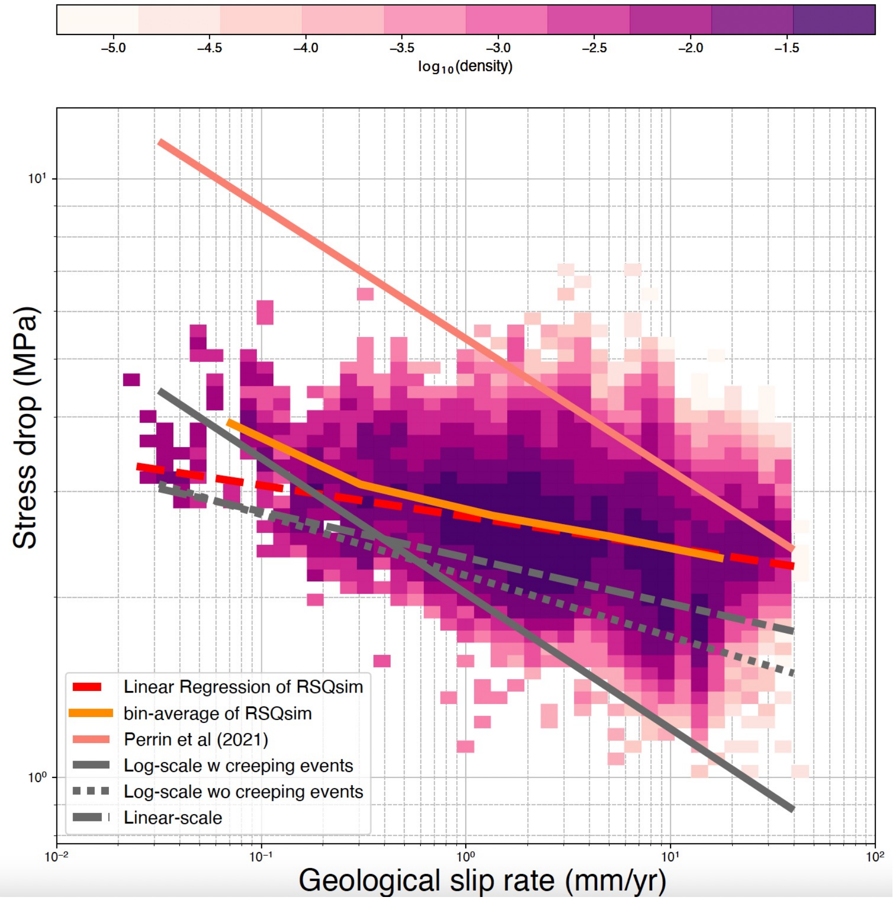
Comparison with other data types



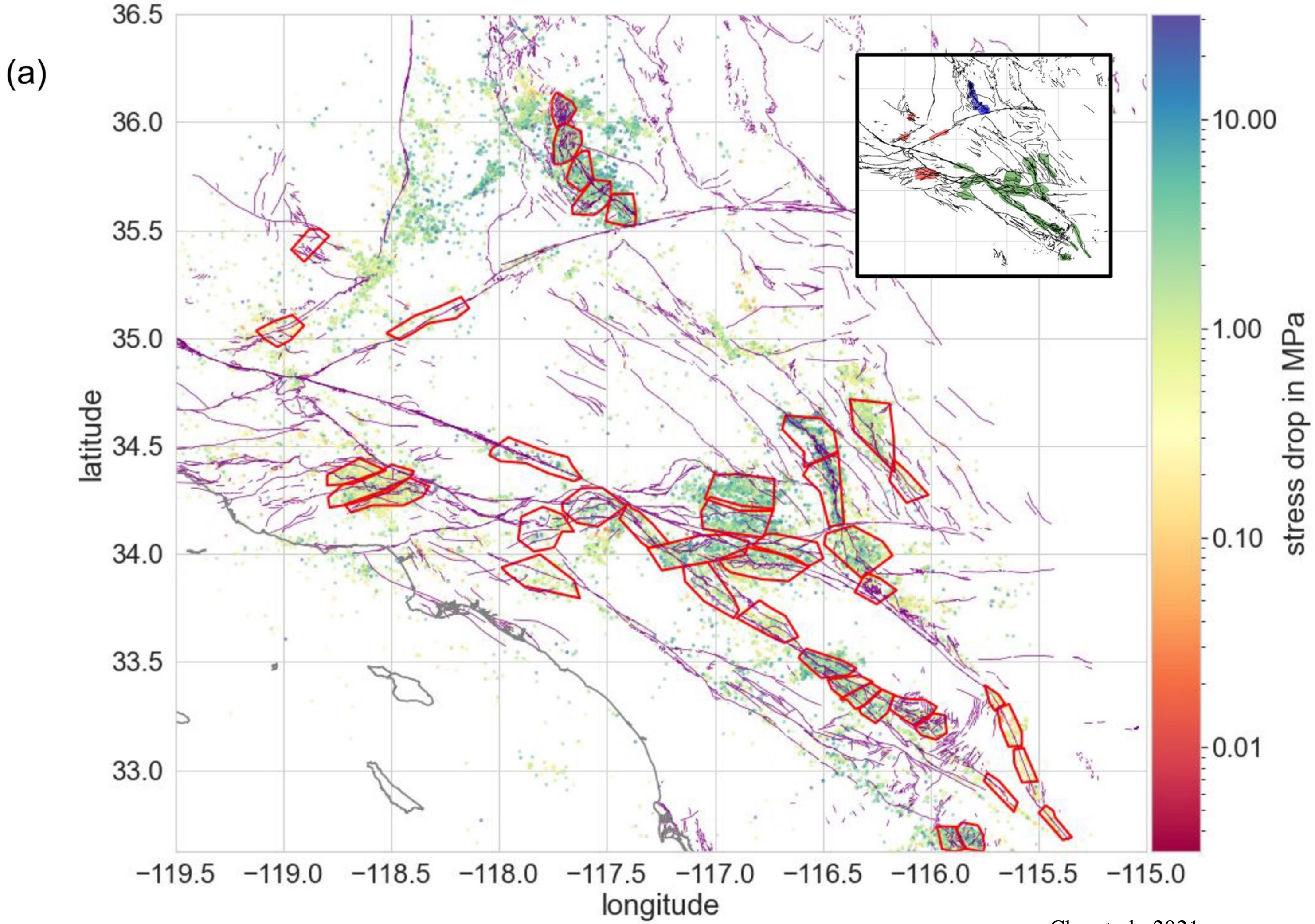
RSQSim simulations catalog *(Thanks to B. Shaw & K. Milner)*

- Rate and state physics-based earthquake simulator
- RSQSim catalog contains 13,487,320 events (M>6.5) in 779,523 years over all California Fault Model

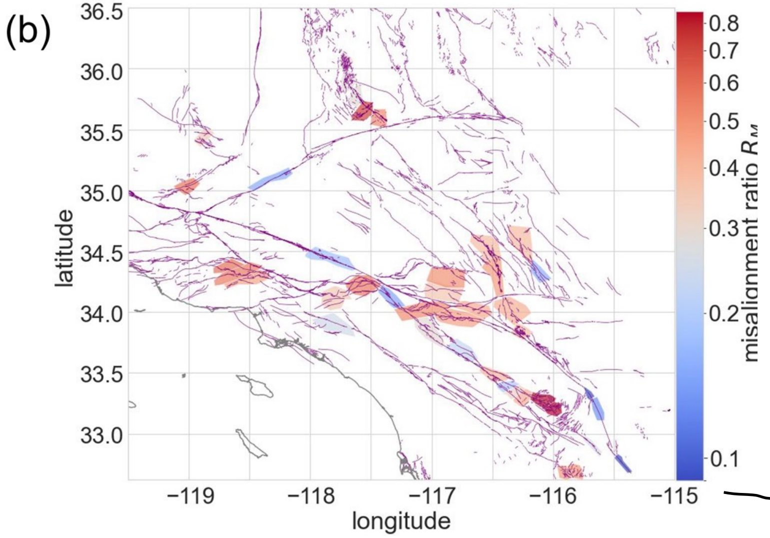




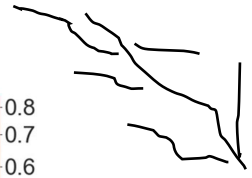
Another qualitative evidence



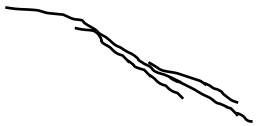
Chu et al., 2021

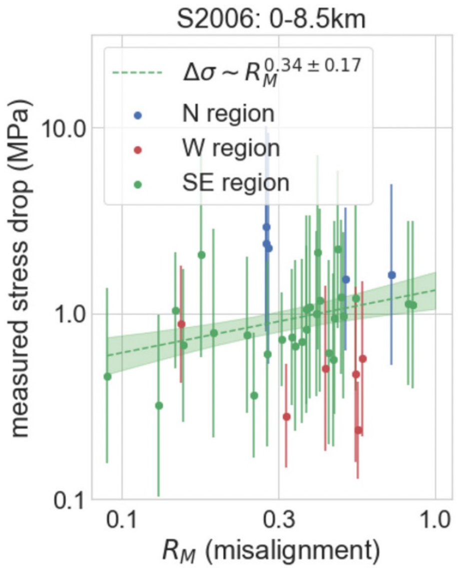


Immature



Mature



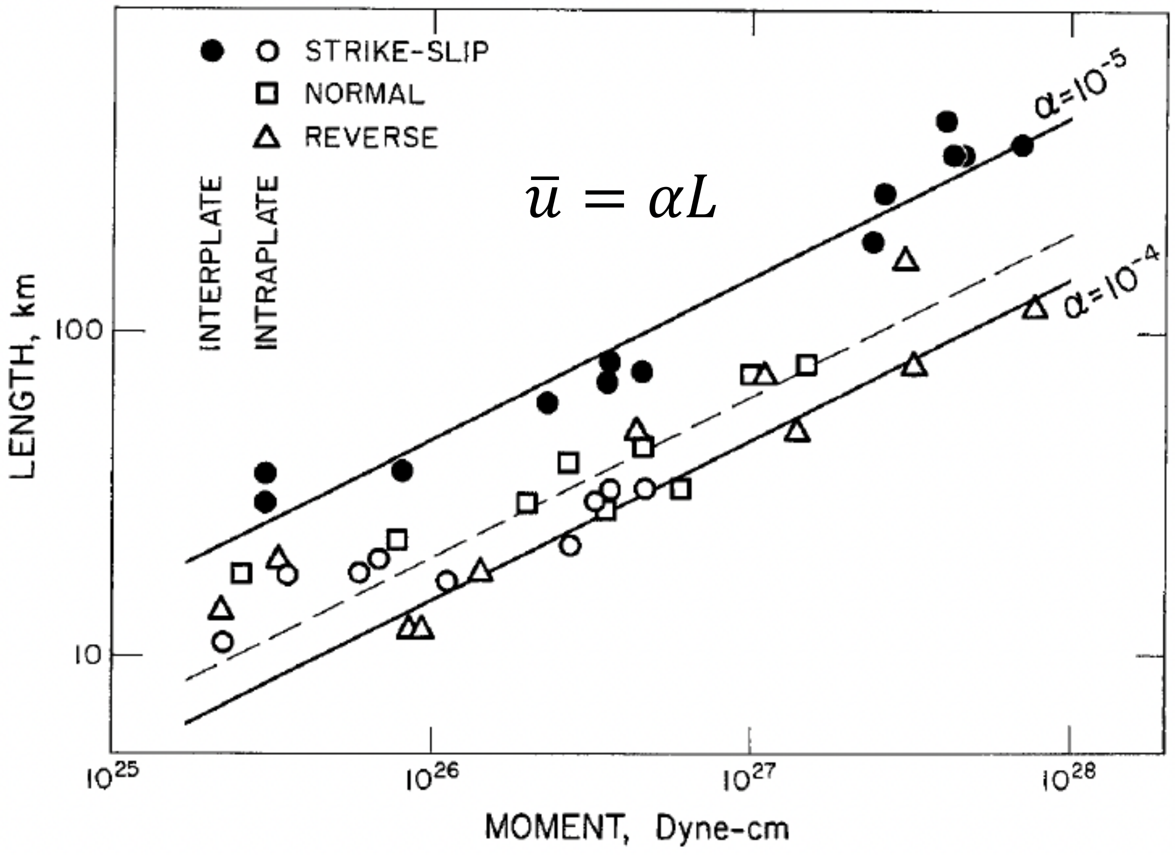


Stress drop found correlated with fault geometrical complexity that is also found inversely correlated with geological slip rate

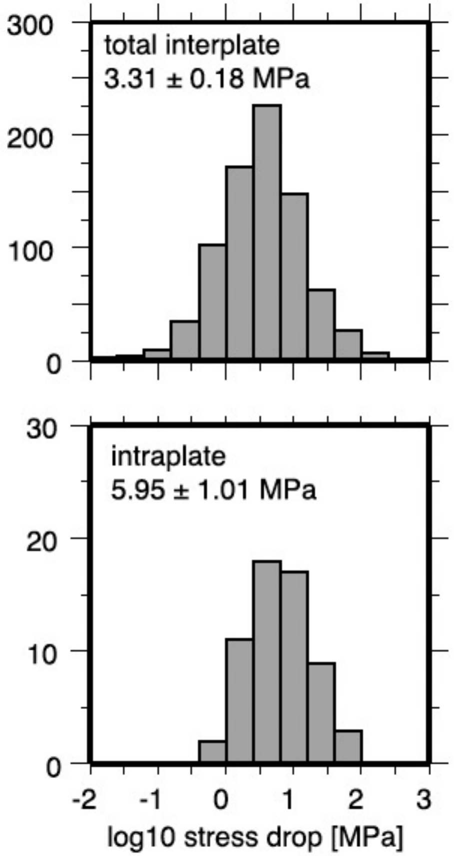
Another qualitative evidence

Differentiate stress drops of intra- and inter-plate earthquakes

Interplate fault:
~10-100 mm/yr
Intraplate fault:
~0.1-10 mm/yr

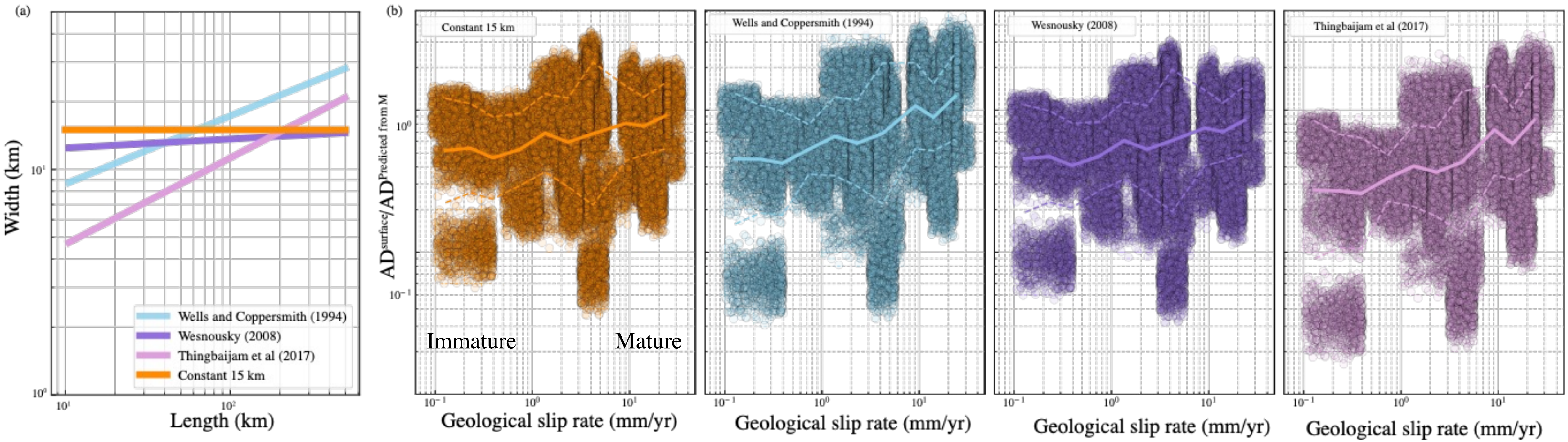


Scholz et al., 1986



Allmann and Shearer., 2009

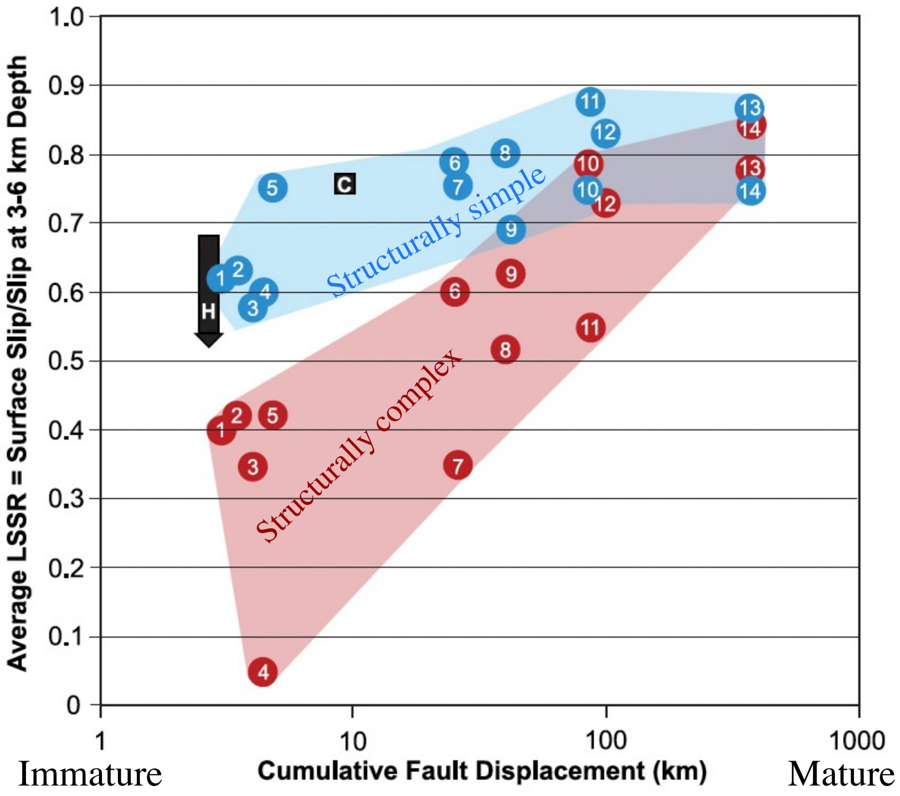
Fault maturity vs Slip along depth



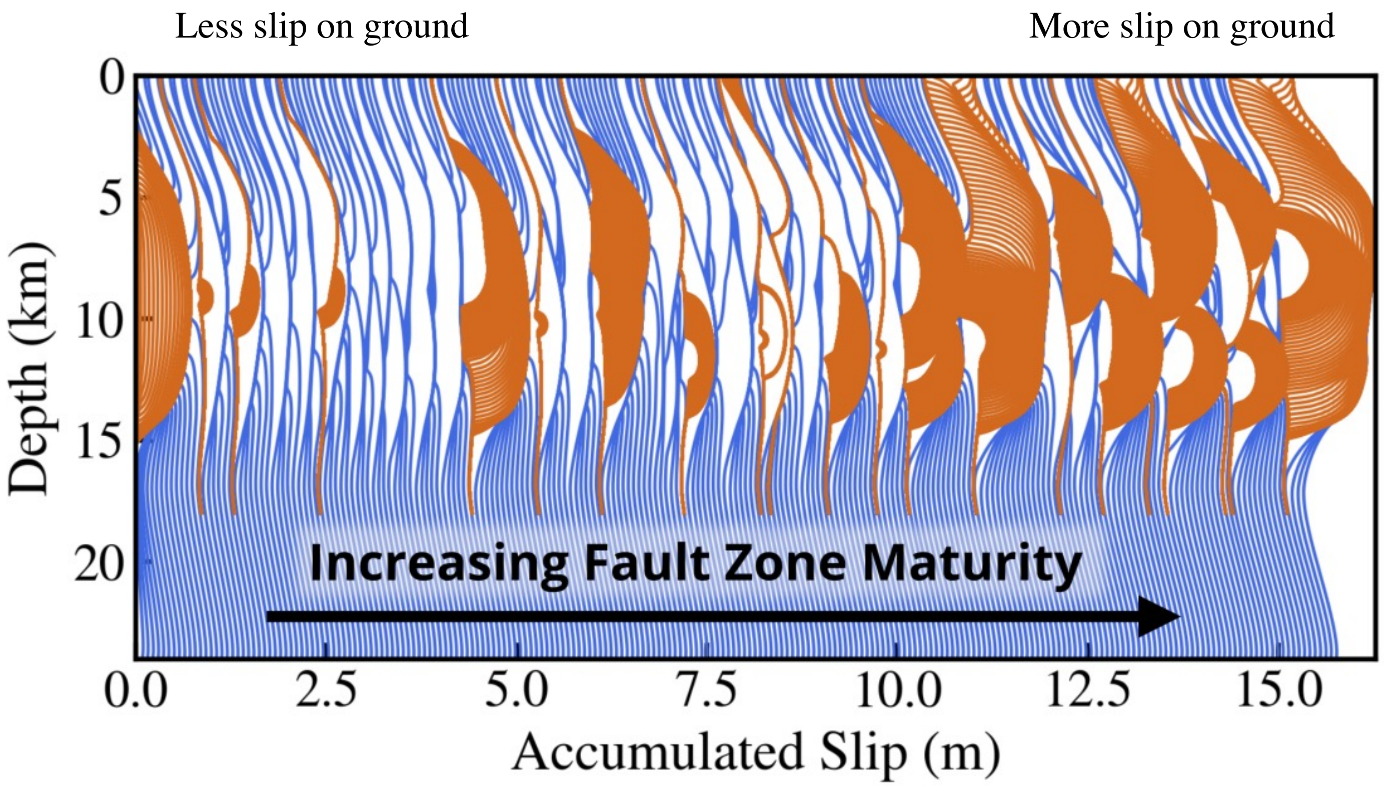
Relationship between the ratio of surface average (S) and fault-plane average (estimated from magnitude) displacements with fault maturity based on the seismogenic width models.

Surface displacement localization is correlated with the fault maturity, implying a mature fault has a larger partition of slip on the surface regardless of seismogenic width model used in inferring fault-plane average displacement

Supported by some evidences



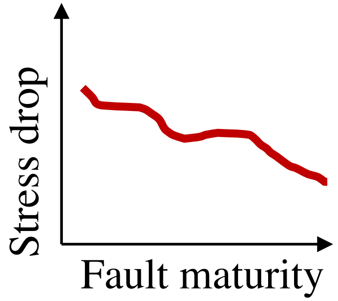
Dolan and Haravitch, 2014

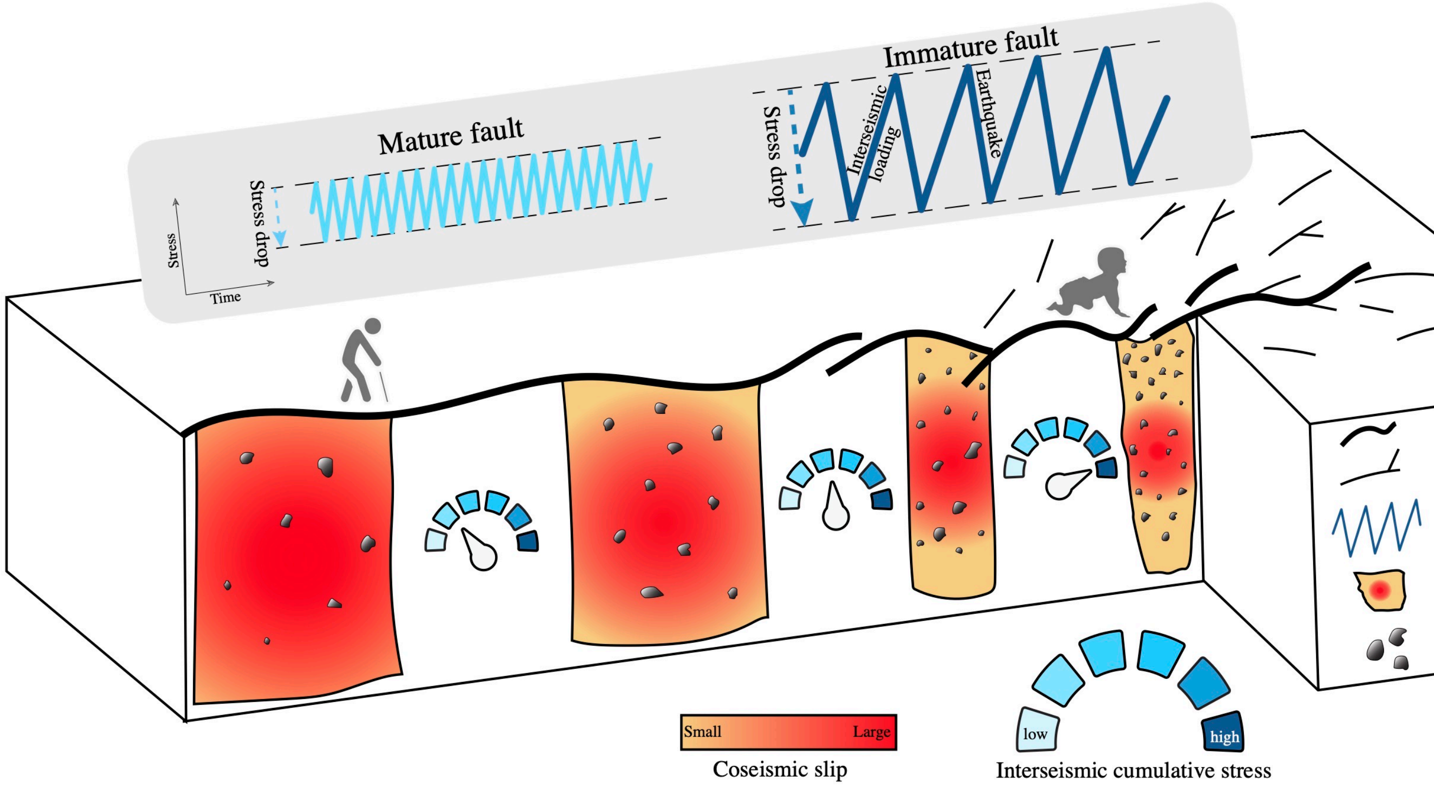


Thakur and Huang, 2021

Take-home messages

- Stress drop has a power-law relationship with the geological slip rate (Fault maturity): A mature fault has a smaller stress drop.
- The exponent from the regression (0.08-0.23) is physically plausible and supported by broad cross-scale evidences (seismology, lab experiment and numerical simulation).
- Surface displacement localization is also related with fault maturity: A mature fault has a larger portion slip on the ground.





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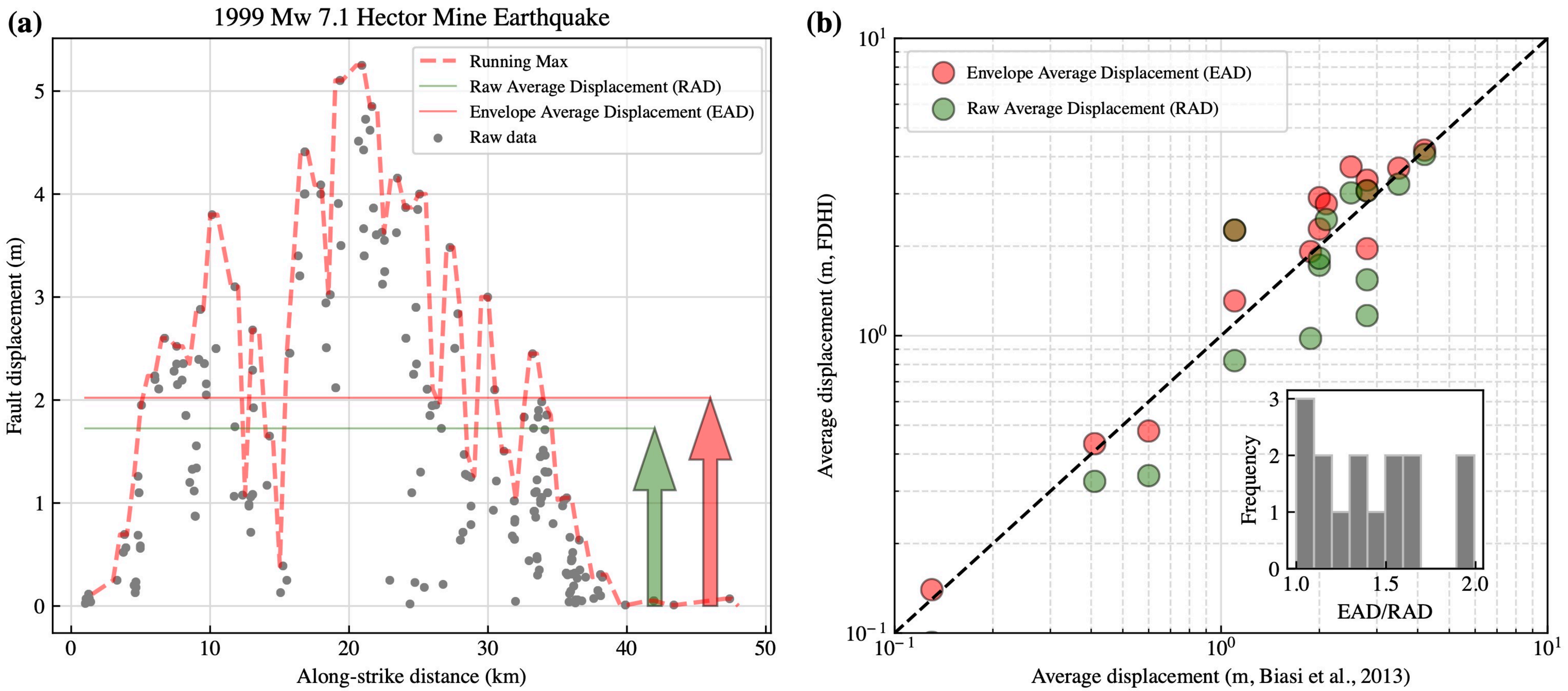
Consistently combine Biasi et al (2013) and FDHI



We adopt the definition of envelope average displacement (EAD) from Biasi et al. (2013) and apply it to the FDHI data; we compare those estimates for the same events, confirming that there is no systematic bias between the datasets.