Role of fault maturity on relationship of surface displacement and rupture length

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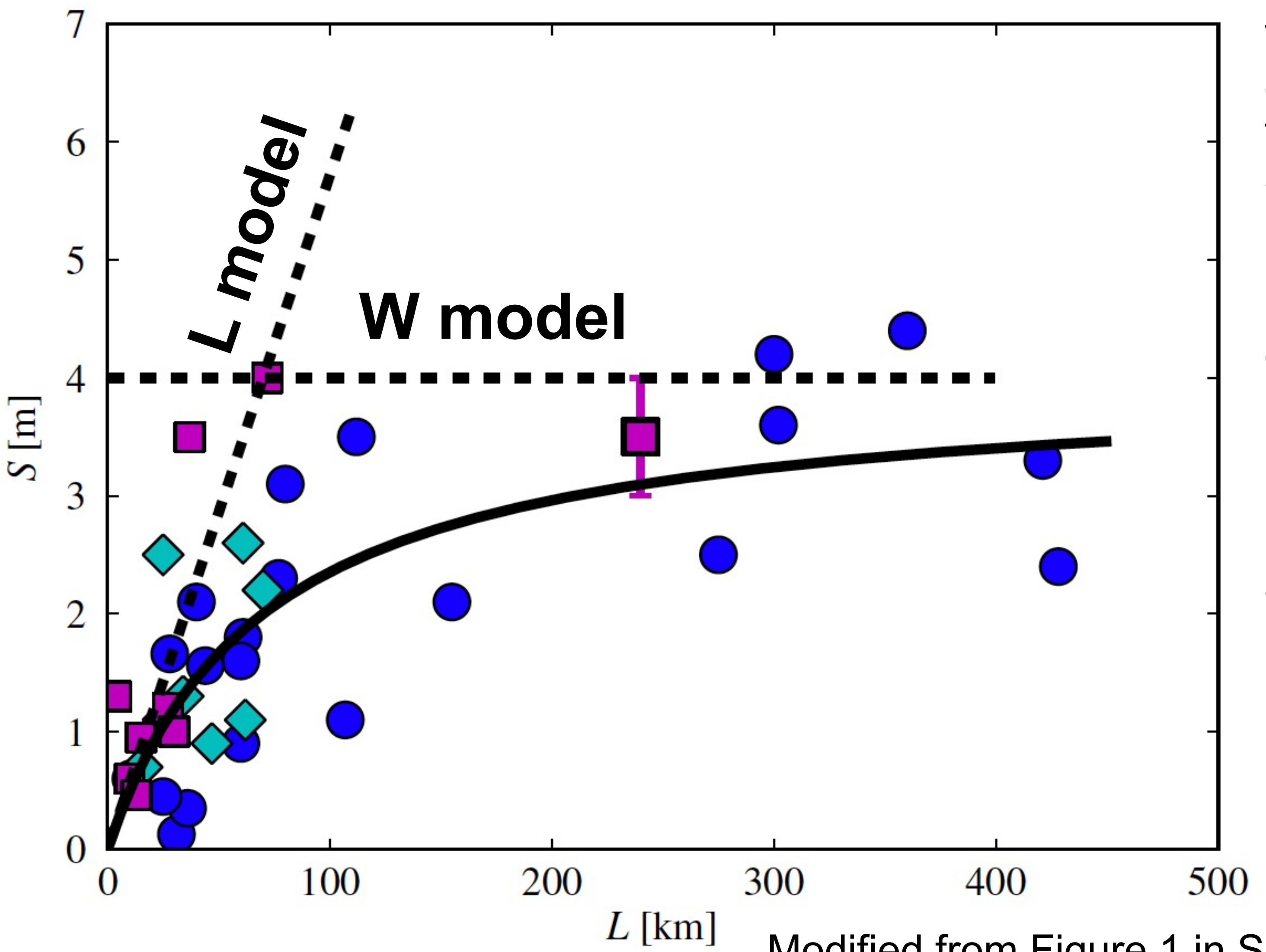
Motivation: surface displacement vs length



We investigate whether the slip of large earthquakes can continue to increase with the rupture length far beyond the seismogenic depth (L model, as described by Sholtz, 1982).

Studying the relationship of surface displacement and rupture length can:

1. have important implications for earthquake mechanism.

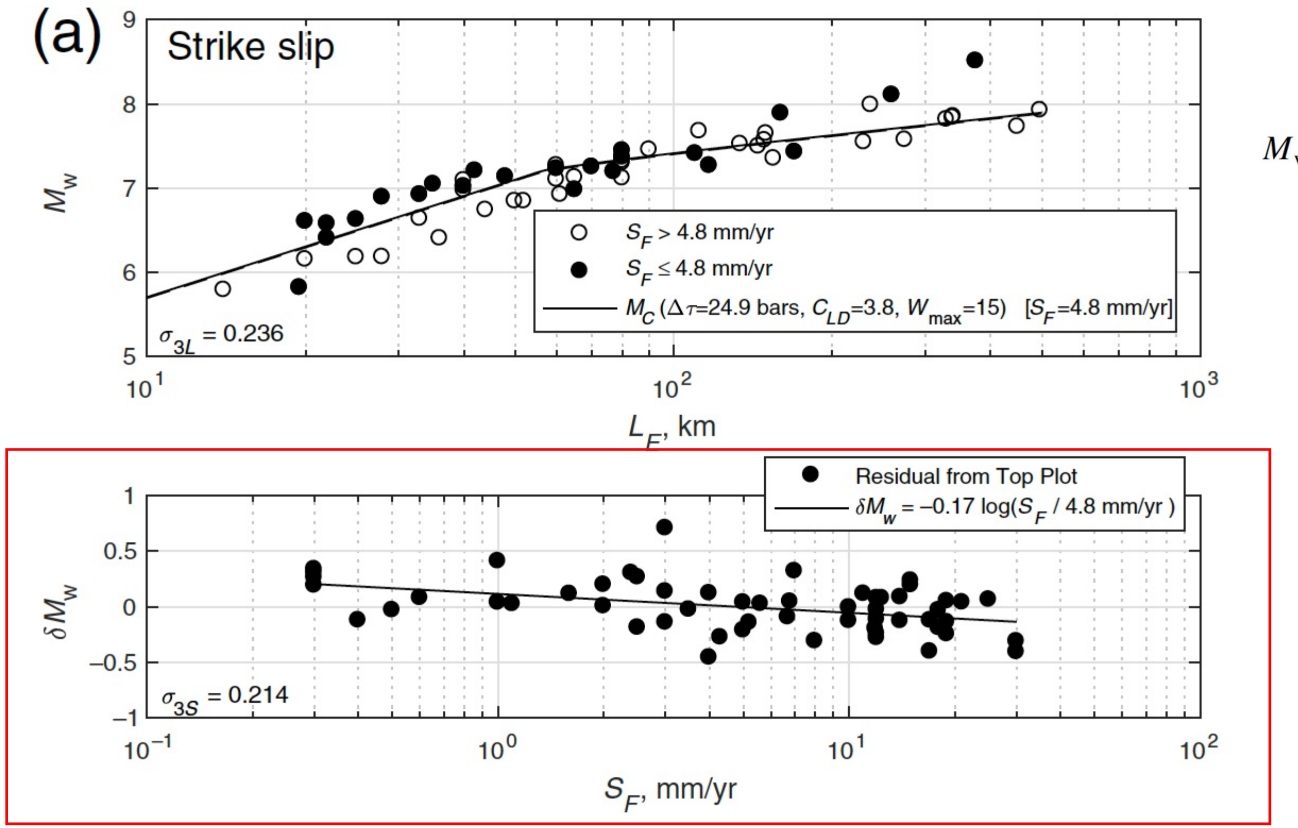
2. contribute to improved earthquake rupture forecast.

Modified from Figure 1 in Shaw (2013).

Whether does considering geological slip rate help model the data?

Fault-Scaling Relationships Depend on the Average Fault-Slip Rate

by John G. Anderson, Glenn P. Biasi,* and Steven G. Wesnousky



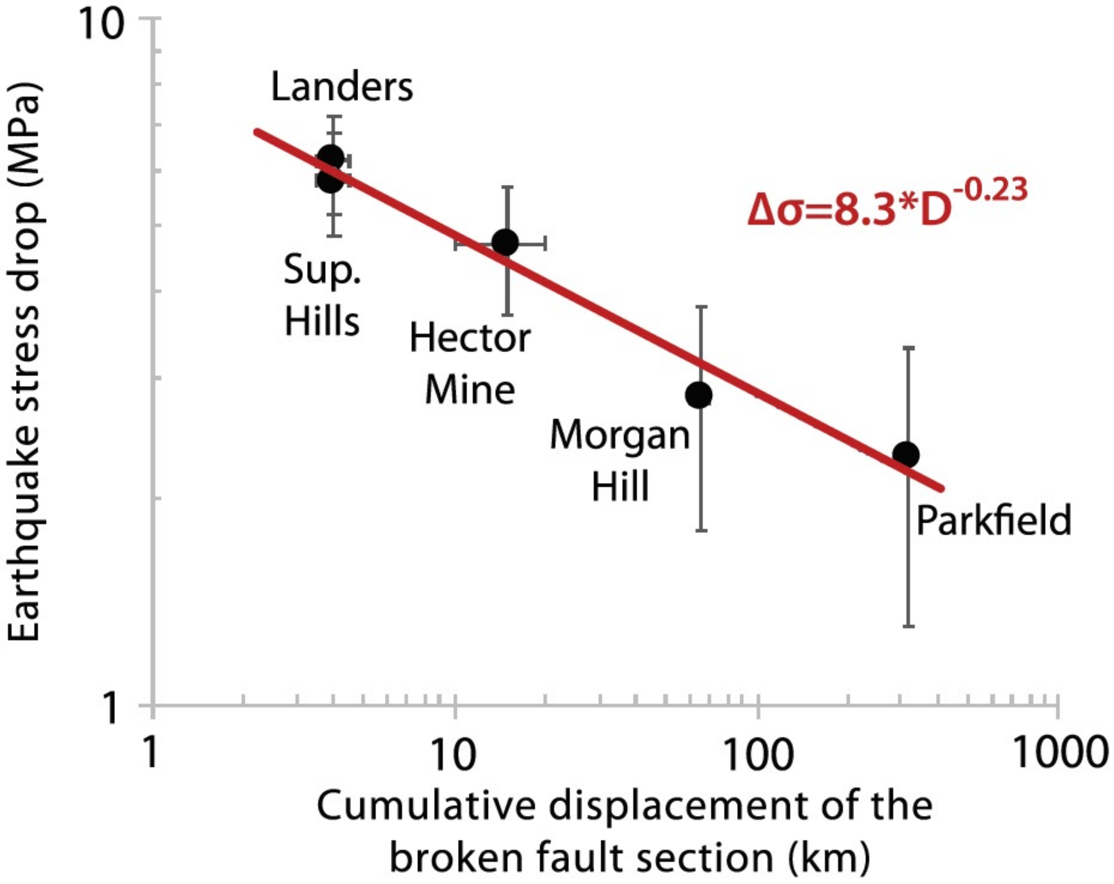
$$M_w = \begin{cases} 2\log L_E + \frac{2}{3}\log \Delta\tau_C + \frac{2}{3}\left(\log \frac{2\pi}{C_{LW}^2 C(\gamma)} - 16.1\right) + c_2 \log\left(\frac{S_F}{S_0}\right) & \frac{L_E}{C_{LW}} < W_{\max} \\ \frac{2}{3}\log L_E + \frac{2}{3}\log \Delta\tau_C + \frac{2}{3}\left(\log \frac{2\pi W_{\max}^2}{C(\gamma)}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

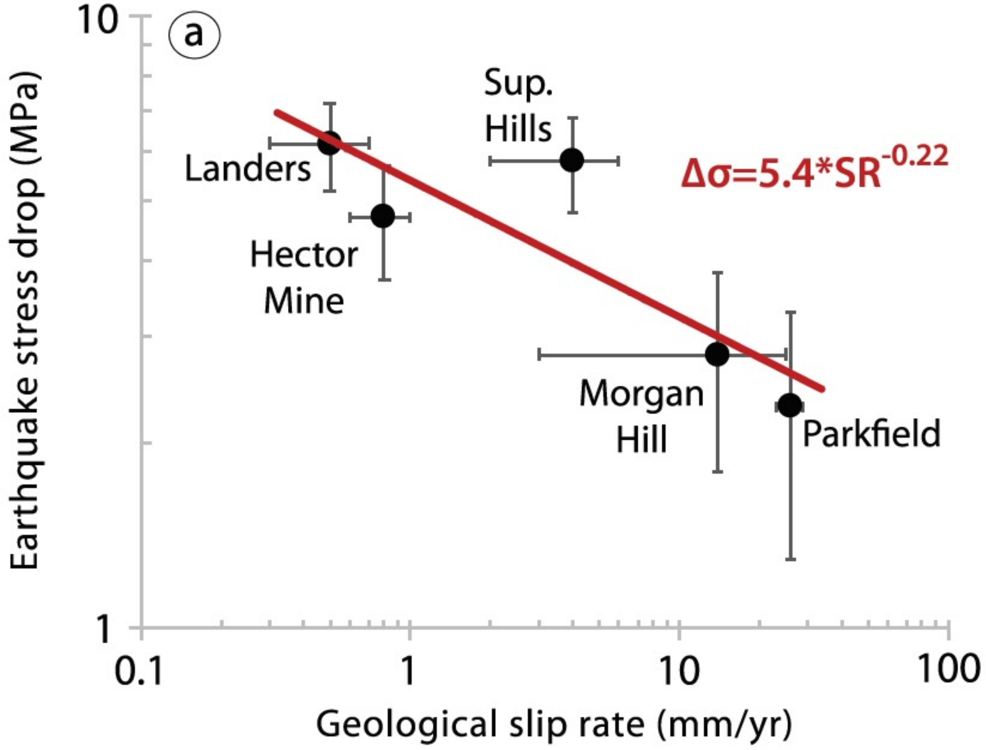
This term may infer the stress drop has a dependence of geological slip rate

Seismological support

The Shear Deformation Zone and the Smoothing of Faults With Displacement

Clément Perrin[1,2], Felix Waldhauser[1], and Christopher H. Scholz[1]





Derive SR-dependent surface displacement model

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

Small circular fault

Long rectangular fault

Modified from Shaw (2013)

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

SR-dependent stress drop

Three models

Model-I: SR dependent stress drop and unknown saturation length

$$\log(S) = \begin{cases} A_1 + A_2\log(SR) - \log(\frac{7}{3L}) & L \le L_{max} \\ A_1 + A_2\log(SR) - \log(\frac{4}{3L} + \frac{1}{L_{max}}) & L > L_{max} \end{cases}$$

Model-II: SR independent stress drop and unknown saturation length

$$\log(S) = \begin{cases} B_1 - \log(\frac{7}{3L}) & L \le L_{max} \\ B_1 - \log(\frac{4}{3L} + \frac{1}{L_{max}}) & L > L_{max} \end{cases}$$

Model-III: 4MPa and 5km width (black solid line in Figure 1)

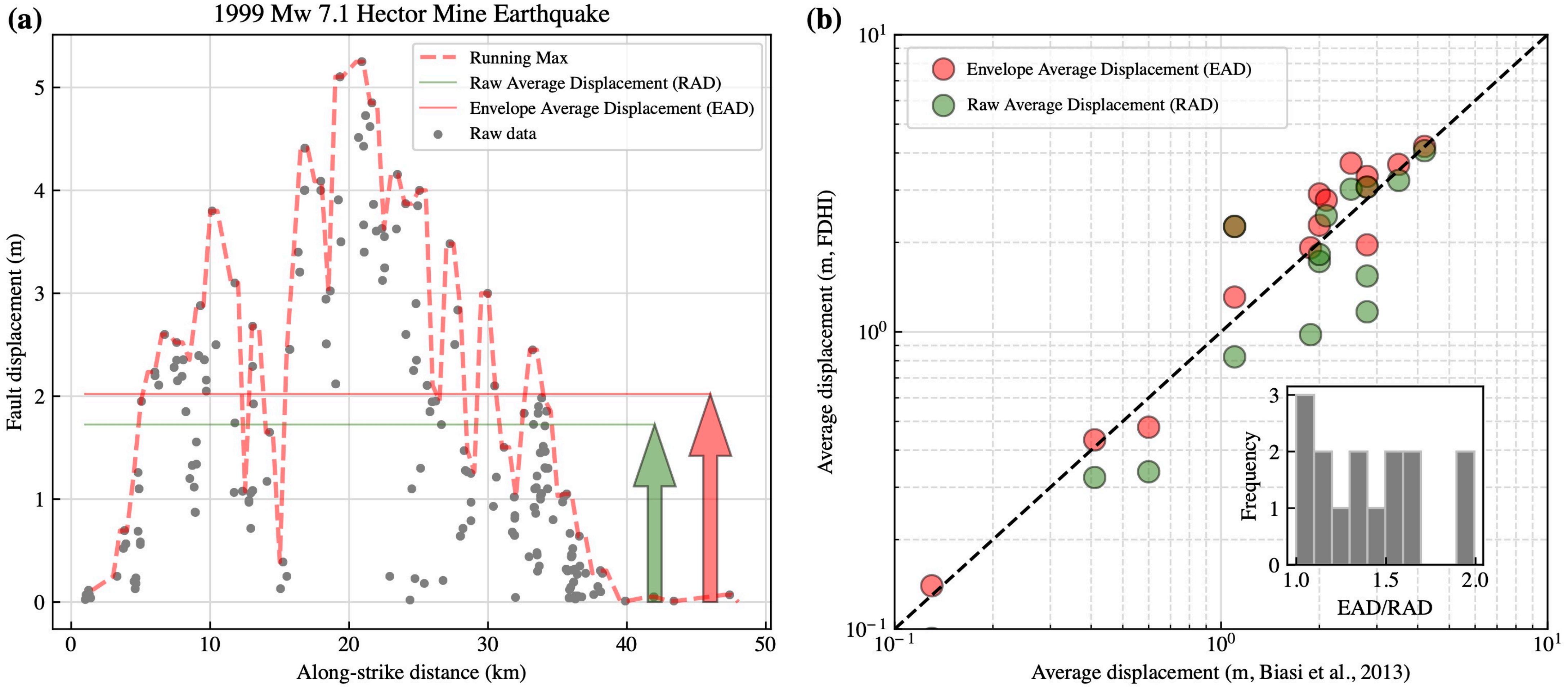
$$\log(S) = \begin{cases} \log(4/30) - \log(\frac{7}{3L}) & L \le 30\ \text{km} \\ \log(4/30) - \log(\frac{4}{3L} + \frac{1}{30}) & L > 30\ \text{km} \end{cases}$$

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).

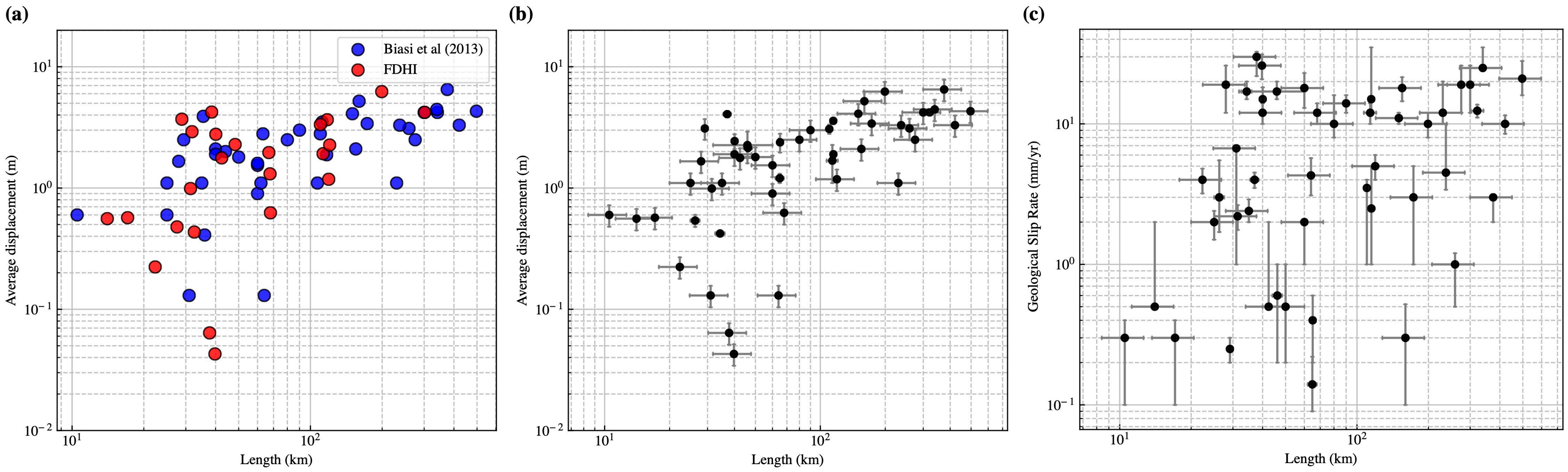
Country list	Earthquake name list			
China, Iran, Japan, Mexico, Mongolia, New Zealand, Nicaragua, Pakistan, Philippines, Russia, Turkey, USA	Name	Year	Name	Year
	Ridgecrest sequence	2019	Luhuo	1973
	Kumamoto	2016	Tonghai	1970
	Napa	2014	Borrego Mtn	1968
	Balochistan	2013	Parkfield	1966
	Darfield	2010	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		

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.

Consider uncertainty in regression



In this study, we also consider uncertainties of average displacement, rupture length and geological slip rate. Uncertainties of these quantities are obtained from multiple estimates for a given event or are set to 20% of the estimate if only one set of measurements is available.

Regression method

We use 3 distinct models for our data. For each earthquake, average displacement (*S*), rupture Length (*L*) and slip rate (*SR*)are uniformly chosen from the range of uncertainties with the preferred value set as the median.

We solve for 10,000 randomized combinations of *S, L* and *SR* for coefficients (*A1, A2, Lmax, B1*) by using a segmented linear regression technique.

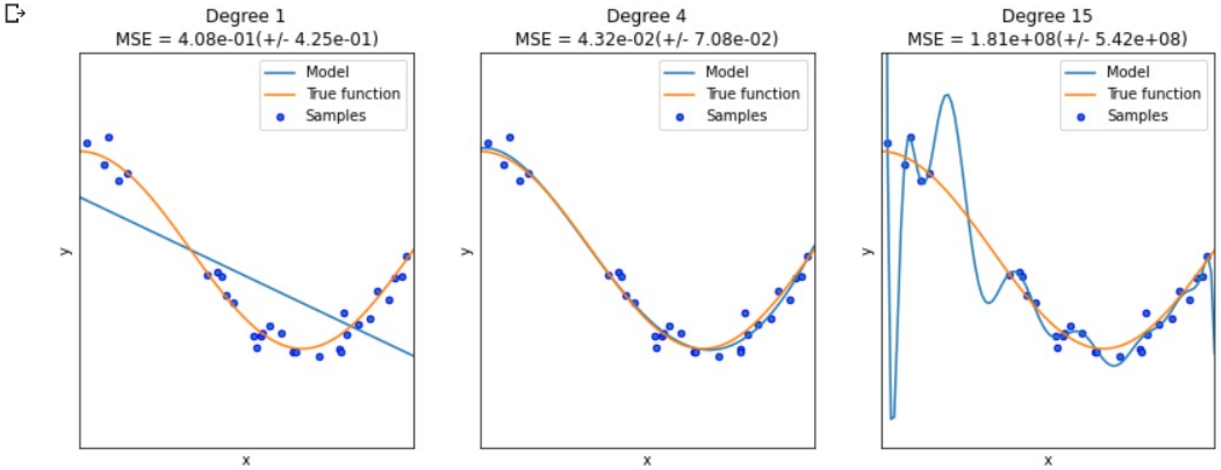
If the preferred value is not the average of min and max, the probability distribution for randomized value of L is as follows (50% between min and preferred):

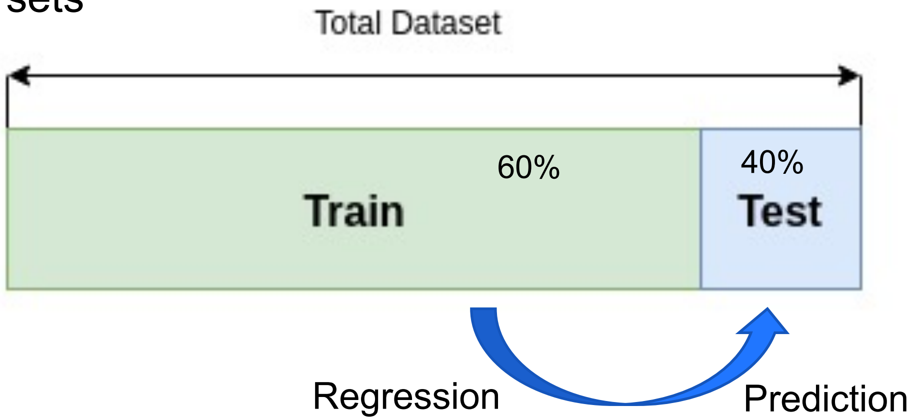
$$p(L_E) = \begin{cases} \frac{1}{(L_E^{\mathrm{pref}} - L_E^{\mathrm{min}})} & \text{(caseA)} \\ \frac{1}{(L_E^{\mathrm{max}} - L_E^{\mathrm{pref}})} & \text{(caseB)}, \end{cases}$$

Regression result

For model 1, we first test whether the SR dataset improve modeling or overfit data by adding a regression parameter

(1) Use random SR
(2) Cross-validation: Split data into training and testing sets





Accuracy = MSE(test)/MSE(train)

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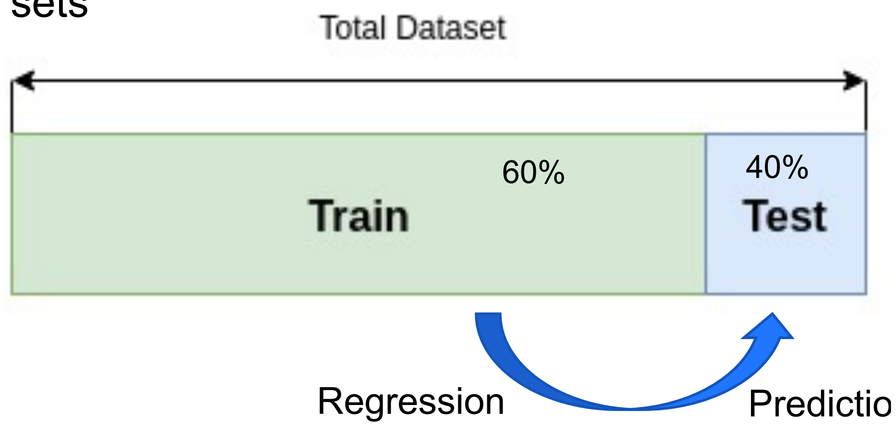

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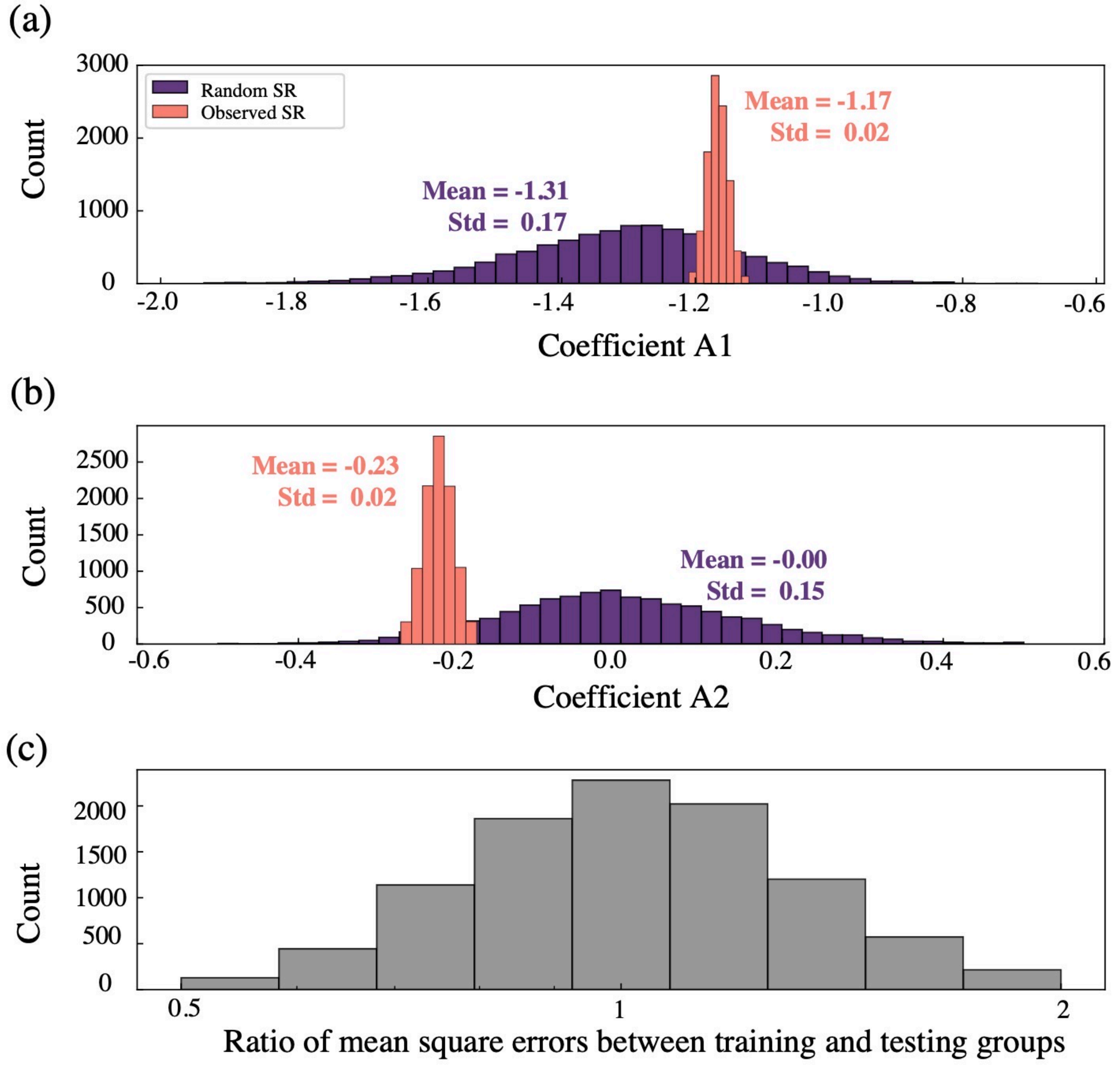
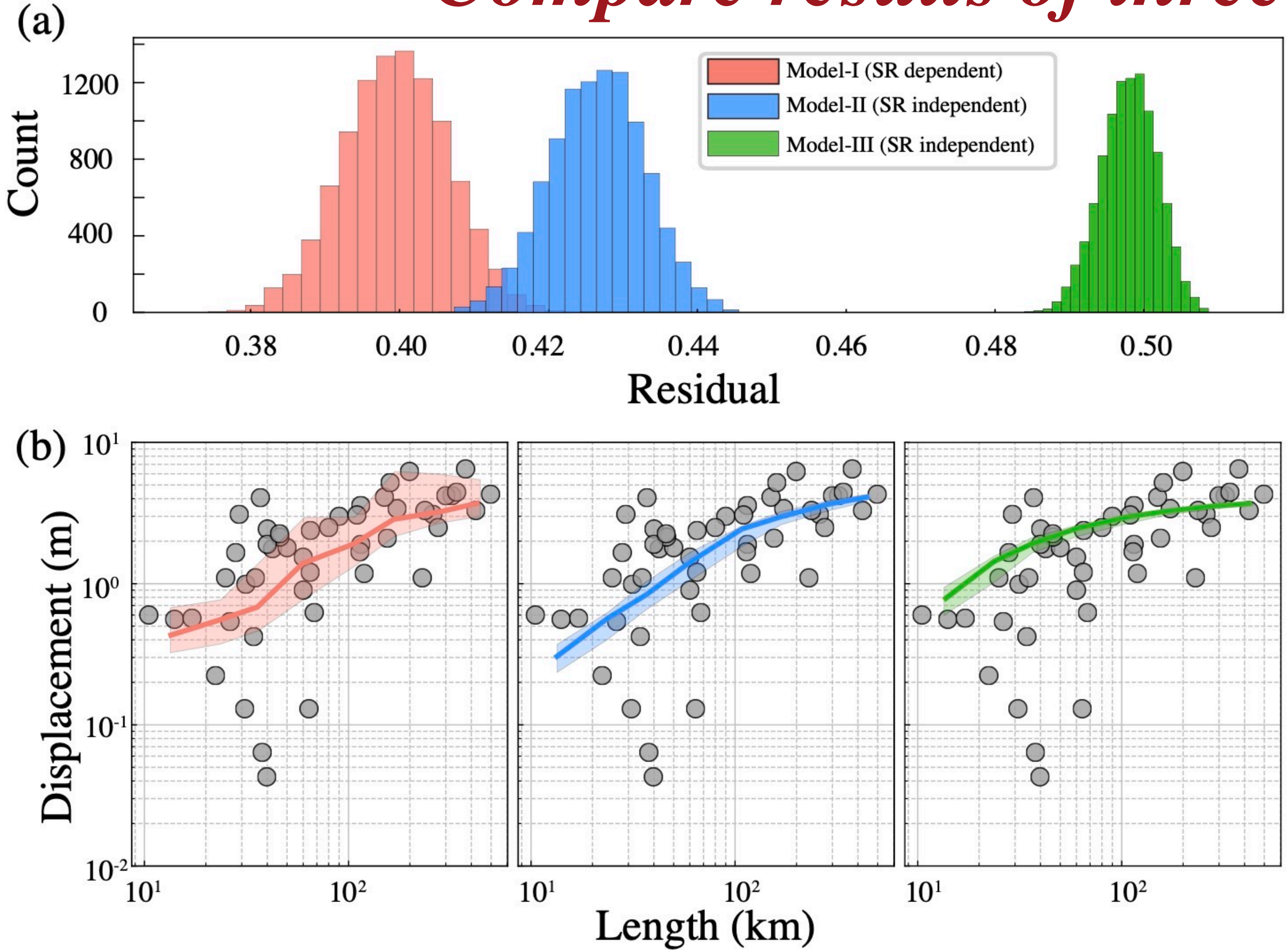


Compare results of three models



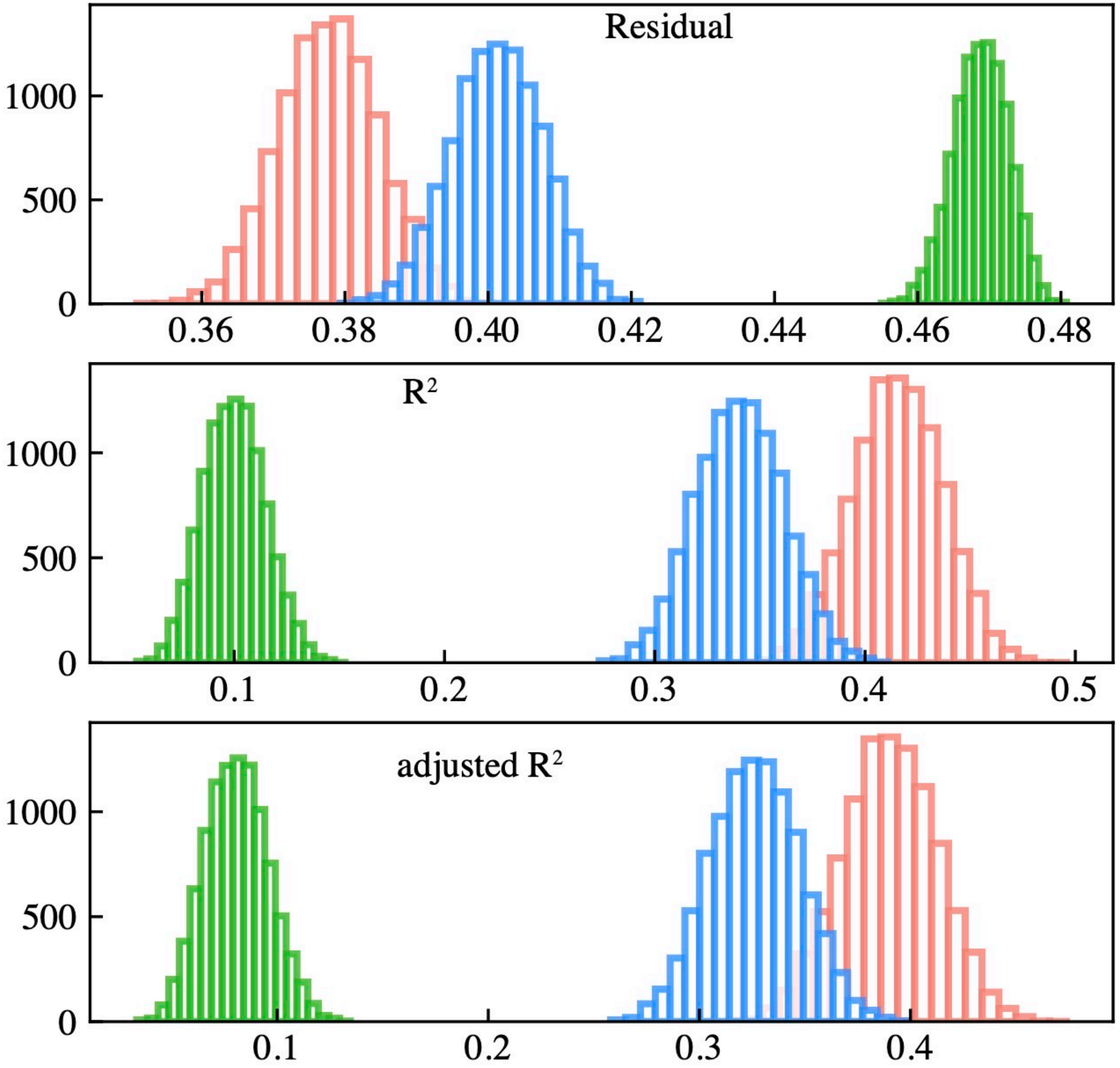
$$\sigma^j = \left\{ \frac{1}{N} \sum \left(S_i^j - \hat{S}_i^j \right)^2 \right\}^{1/2}$$

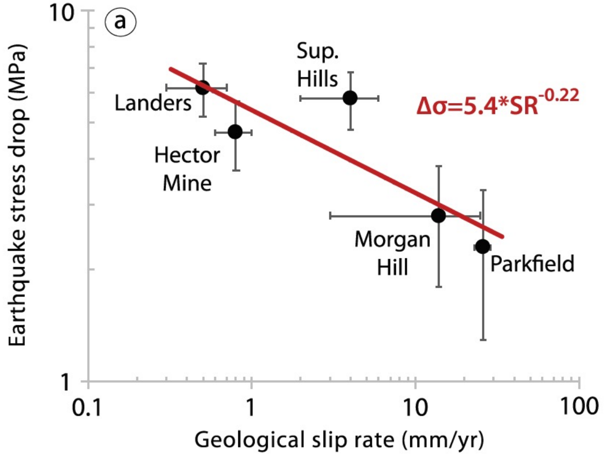
i : event index
j : realization index
S_i^j : observed displacement resampled within the uncertainty range for i^th event and j^th realization
$\hat{S}_i^j$: Predicted displacement for i^th event and j^th realization

Note: S_i^j is the logarithm of displacement if in log-scale regression

Predictions (5%, 50% and 95%) for the three models based on the 10,000 realizations

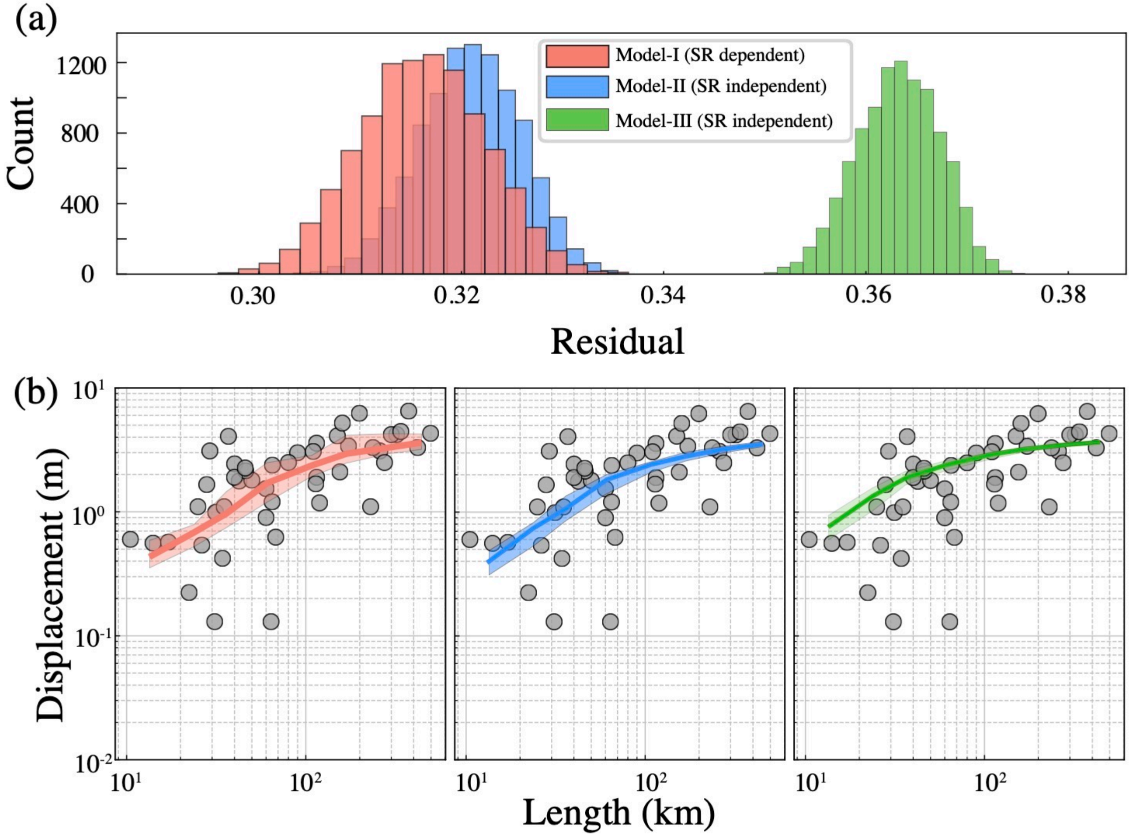
3 metrics for model comparison

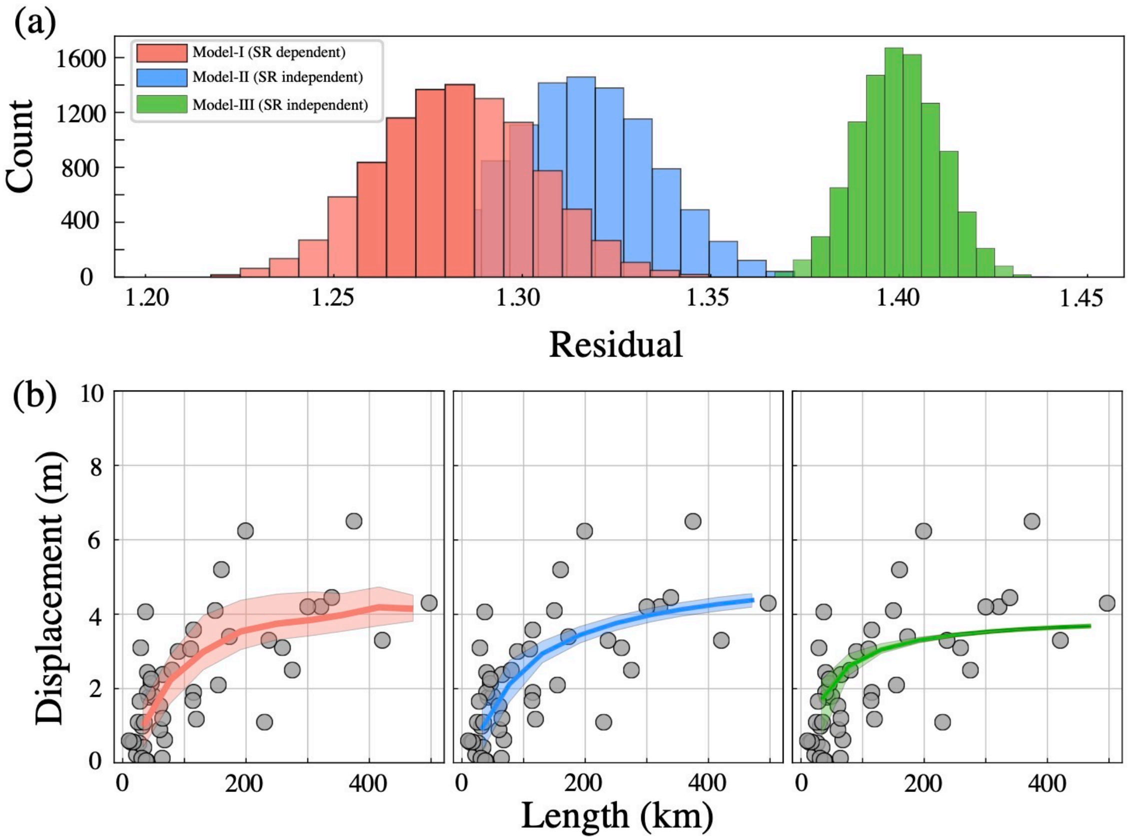




Compare with results without events on creeping faults and from linear-scale regression

All events in log-log scale:	Events excluding creeping events (2 Parkfield):	All events in linear scale:
$A_1 = -1.17 \pm 0.02$	$A_1 = -1.14 \pm 0.01$	$A_1 = -1.11 \pm 0.02$ ~2MPa
$A_2 = -0.23 \pm 0.02$	$A_2 = -0.10 \pm 0.02$	$A_2 = -0.08 \pm 0.02$ SR dependence

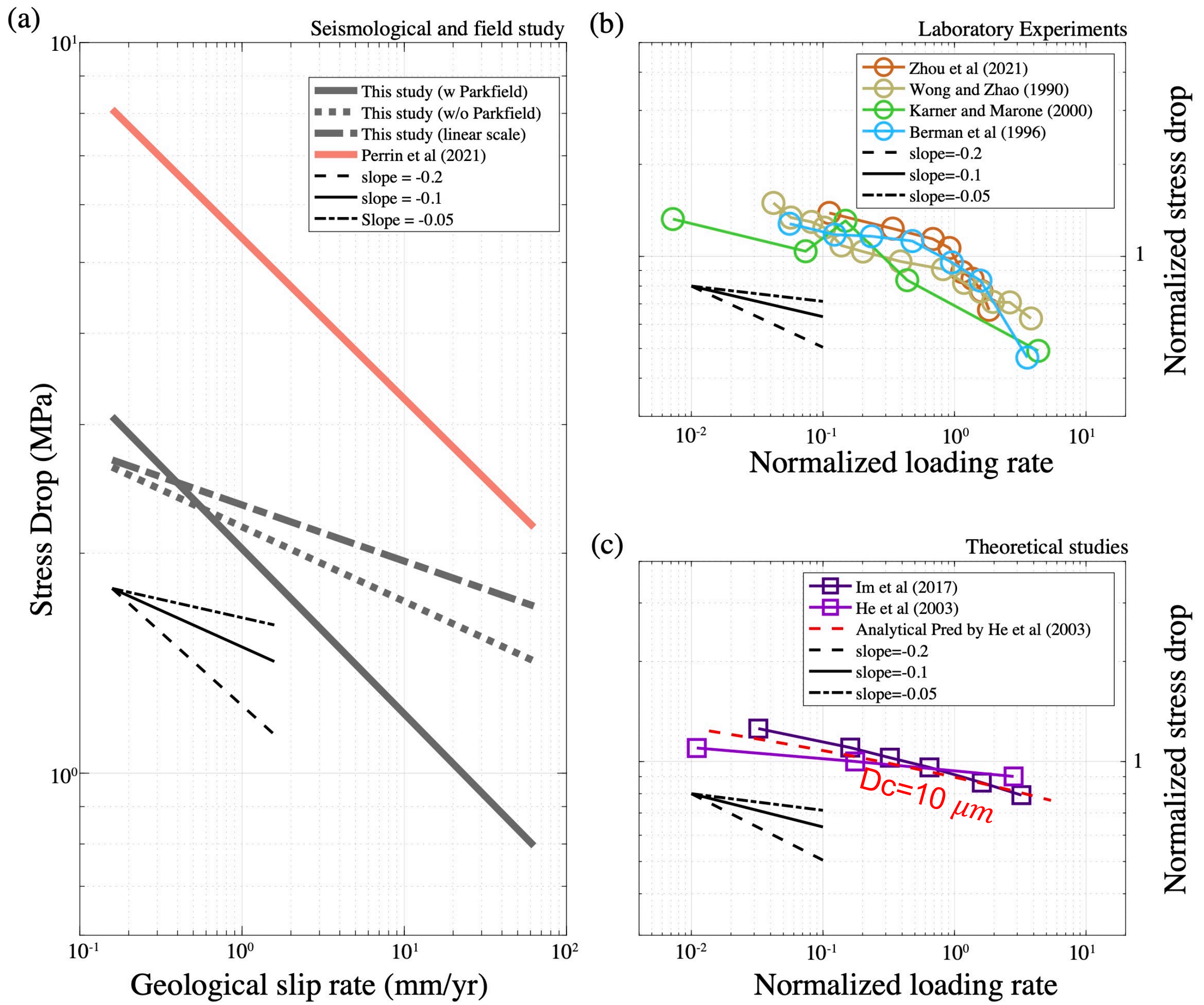




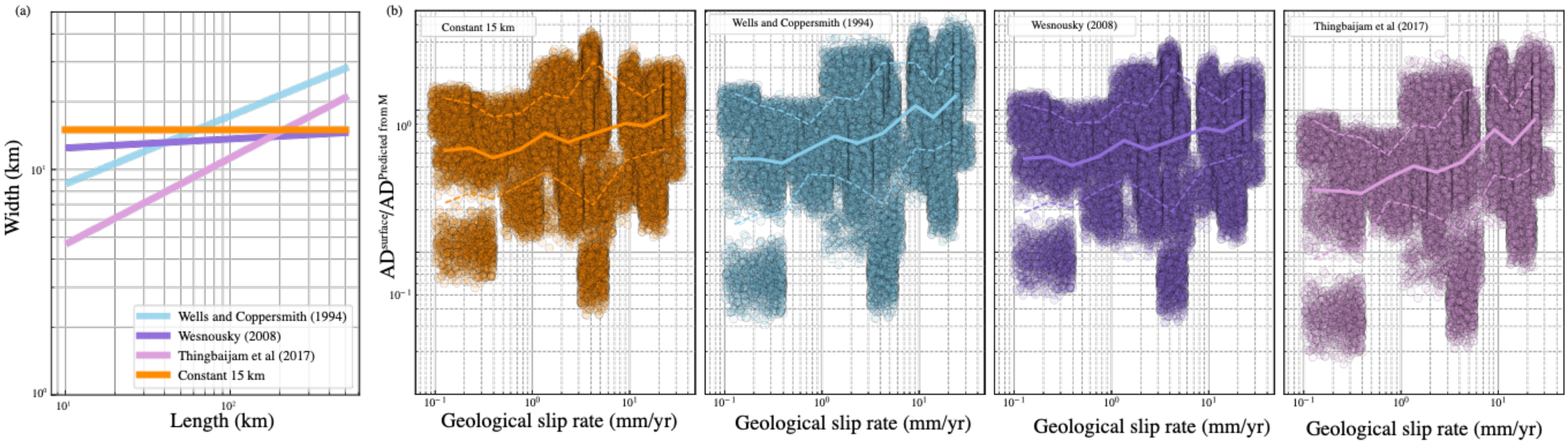
Whether are these parameters physically plausible?

The exponent A_2 s in the range of 0.08-0.23 ± 0.02 (std), which are well consistent with the seismological observations, lab experiments and theoretical predictions.

(a) Comparison of stress drop with geological slip rate between the model-I in this study and that derived from seismological data in Perrin et al (2021). (b) Comparison of normalized stress drop with normalized loading rate among numerical simulations (lower group), lab experiments (middle group), seismological and field observations (upper group).



Fault maturity vs Surface displacement localization

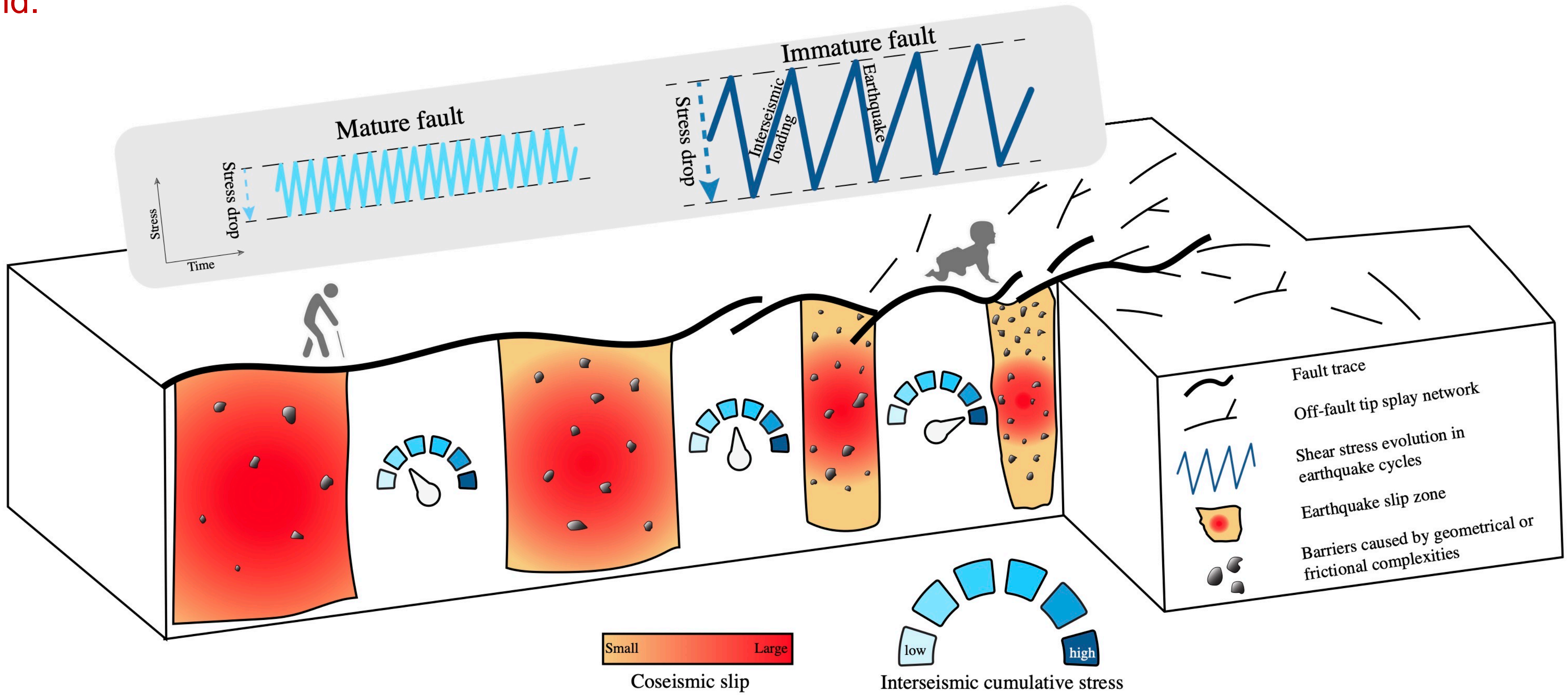


Relationship between the ratio of surface average (*S*) and fault-plane average (estimated from magnitude) displacements with fault maturity based on the seismogenic width models.

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.

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 model implementing slip rate dependent stress drop better models the surface displacement data.
- The exponent from the regression (0.08-0.23) is 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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