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Probing frictional properties on seismogenic faults with constraints from near-field data

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- CUHK, RGC, and NSFC/RGC grants

SCEC Dynamic Rupture Group Ingredients Workshop on Fault Friction
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Earthquake and fault friction

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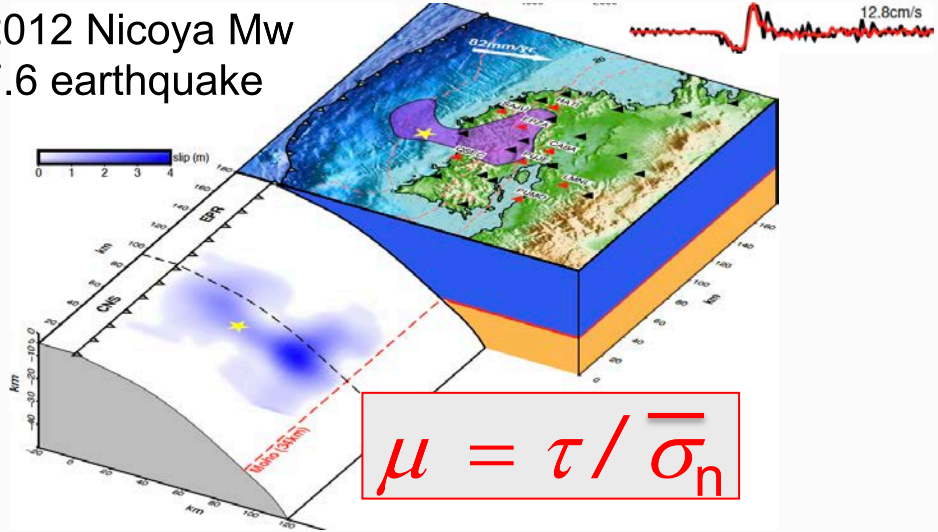
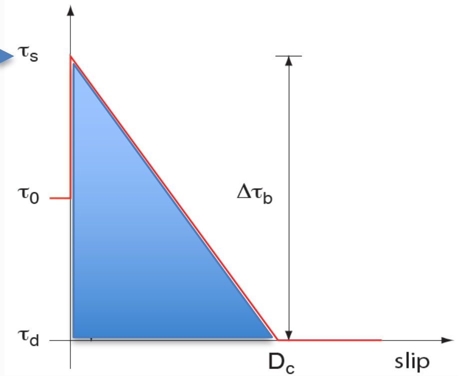
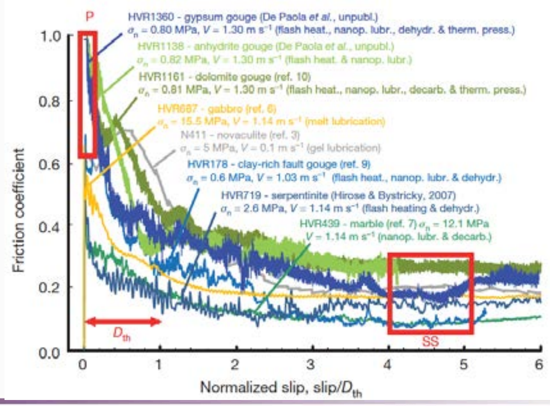
2012 Nicoya Mw 7.6 earthquake



$$\mu = \tau / \overline{\sigma}_n$$

Fault strength



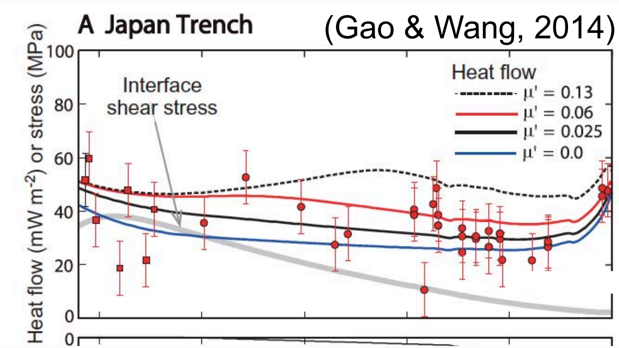


Di Toro et al., 2011

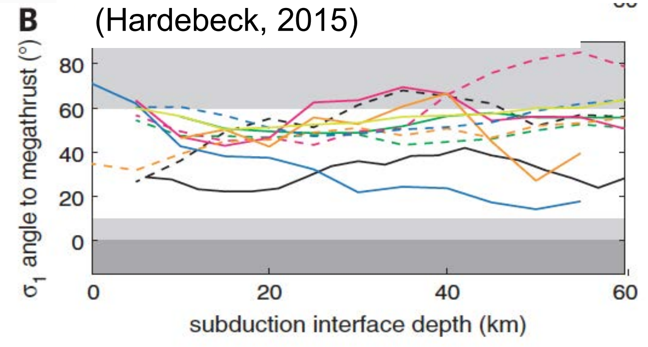
An earthquake occurs when stress exceeds the fault strength. Unfortunately we don't know the stress, strength, and D_0 on seismogenic fault.

Constrain strength on faults

heat flow measurements



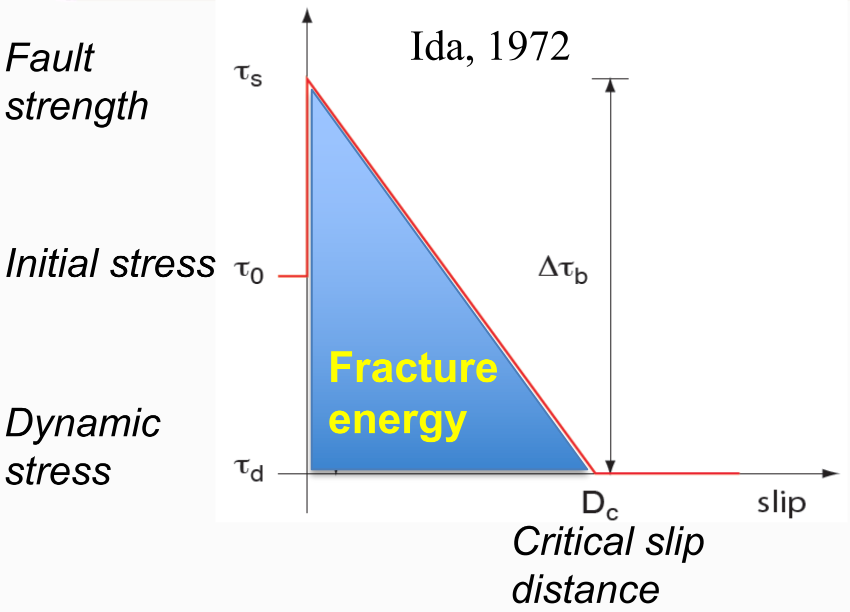
stress orientation: θ 45~60°



Long-term average Apparent friction coefficient : $\mu' < 0.15$

- Experiments of rock samples
- Postseismic drilling measurements (e.g. temperature)
- Seismic studies/Rate-state simulations
- Dynamic source parameters of large earthquakes

Frictional/dynamic source parameters



To determine D_0 requires deriving stress history during coseismic ruptures, which is often approached by the following:

1. Kinematically inferred stress history/D_0 from data.
2. Dynamic model to search for best-fit D_0
3. Near-field measurement of fault-parallel ground displacement (D_0', D_0'')

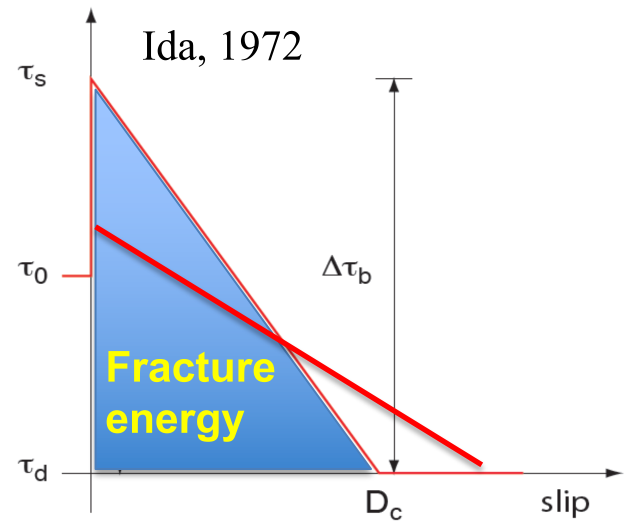
- D_0: 1 – 500 cm
- Scale with final slip $D_0 = k$ u, where k ranges from ~0.1 to ~1 (Tinti et al., 2005)

Trade-off between strength/D_0

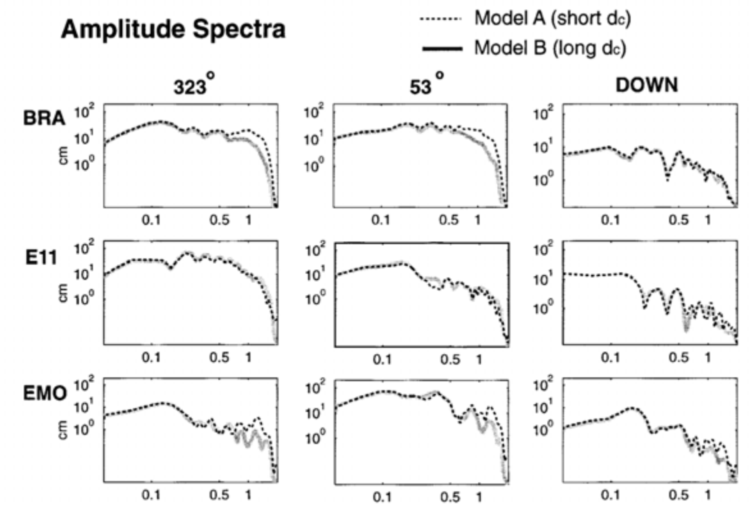
Fault strength

Initial stress

Dynamic stress



Critical slip distance



Guatteri and Spudich, 2000

Previous approaches suffered from the trade-off between the strength and D_0. The product of the two yields fracture energy that can be determined robustly. However, separating them is extremely difficult.

A new method to remove the trade-off

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Journal of Geophysical Research: Solid Earth 2018

RESEARCH ARTICLE
10.1029/2017JB015414

Constraining Frictional Properties on Fault by Dynamic Rupture Simulations and Near-Field Observations

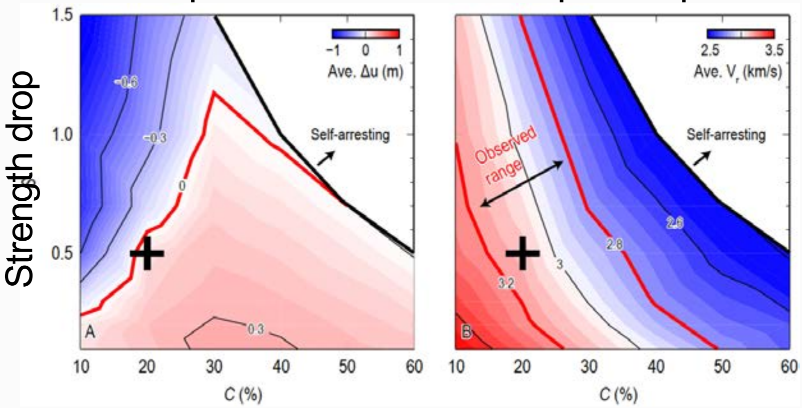
Huihui Weng[1] and Hongfeng Yang[1,2]

Key Points:

A single parameter (e.g. ground velocity) leads to trade-off, while multiple parameters with different trends can remove the trade-off

Slip

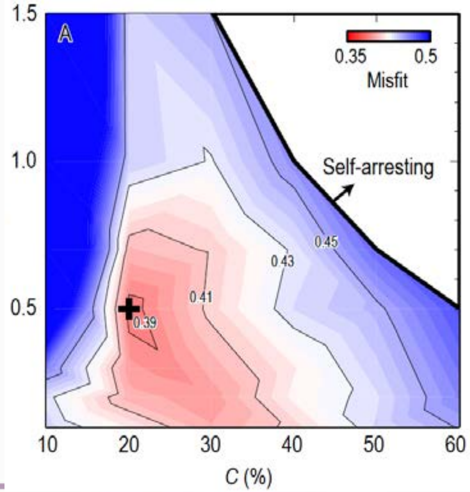
Rupture speed



Slip weakening distance

Slip + Rupture Speed

Using the 2015 Nepal earthquake as an example



Critical distance during the Nepal EQ

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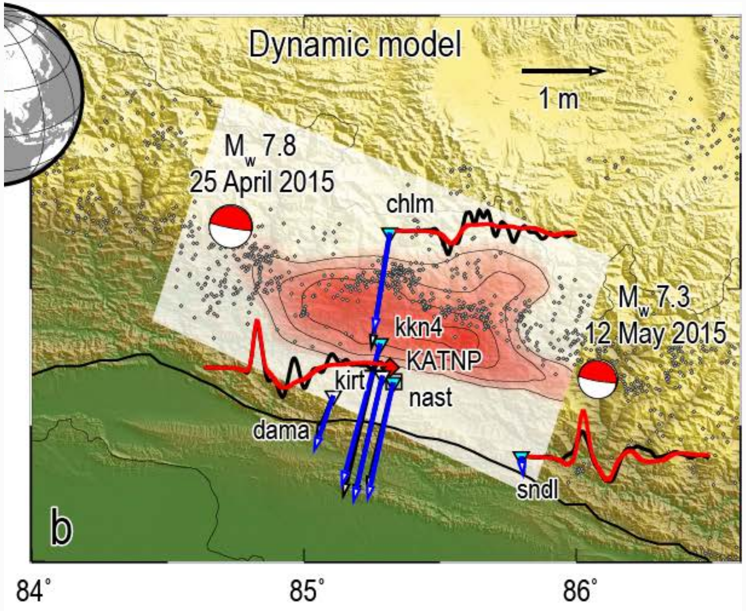
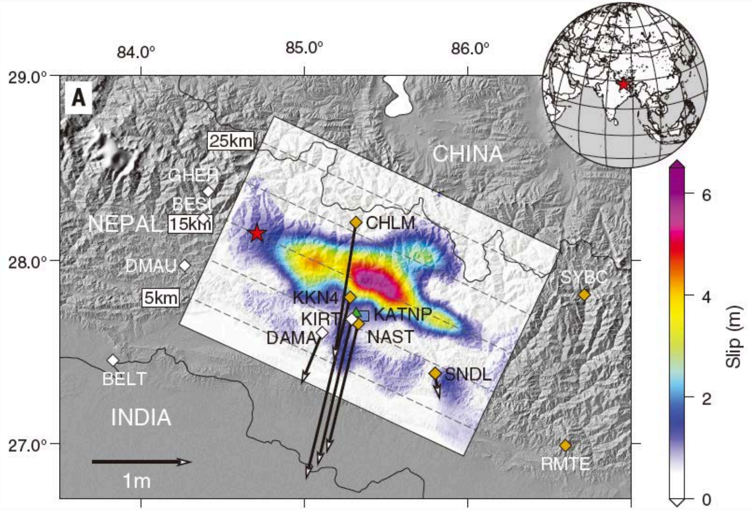


Weng and Yang, 2018, JGR

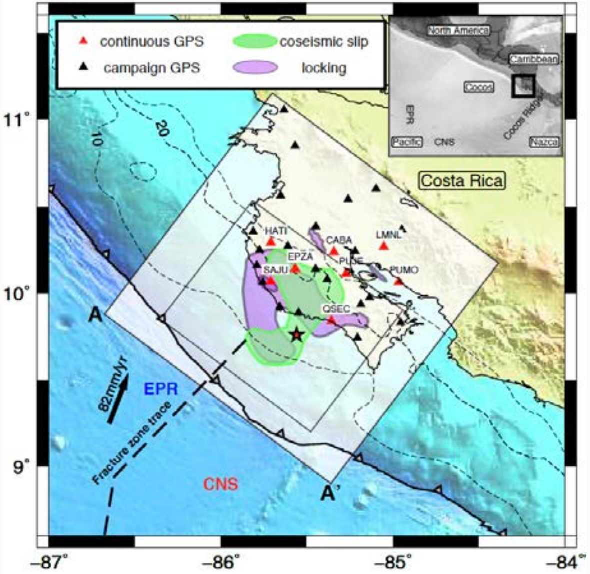


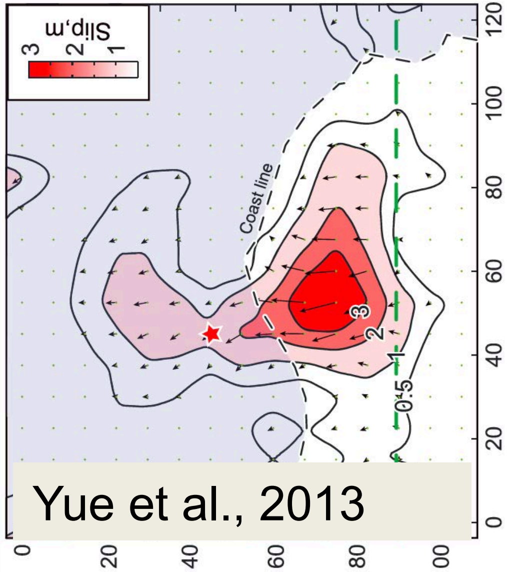
Galetzka, et al., 2015, Science

Average d_0 ~0.6 m, $\overline{\tau_s - \tau_d} = 4.8$ MPa

D_0 = 5 m (???)

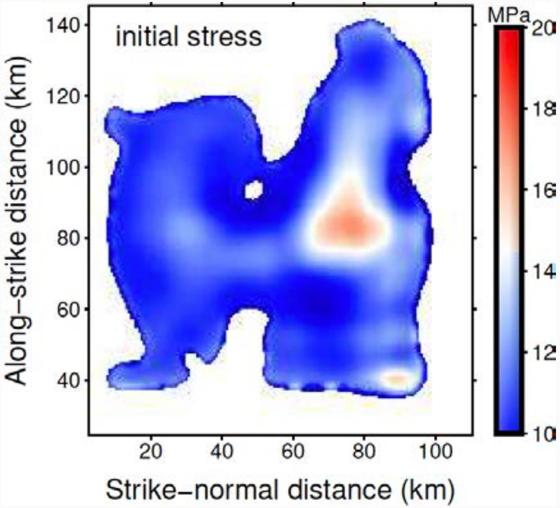
The 2012 M_w 7.6 Nicoya earthquake





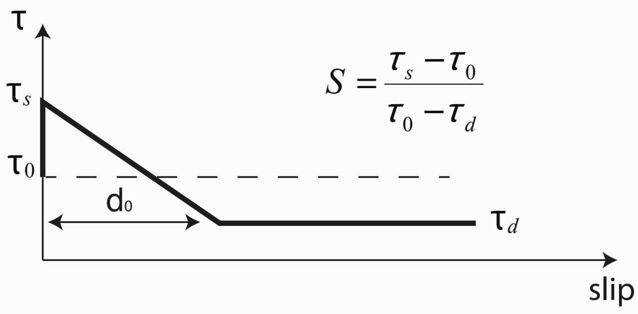
Yue et al., 2013

Initial stress



- Anticipated by locking models
- Well recorded by near field measurements (high/low rate GPS + strong motion)

Dynamic rupture parameters



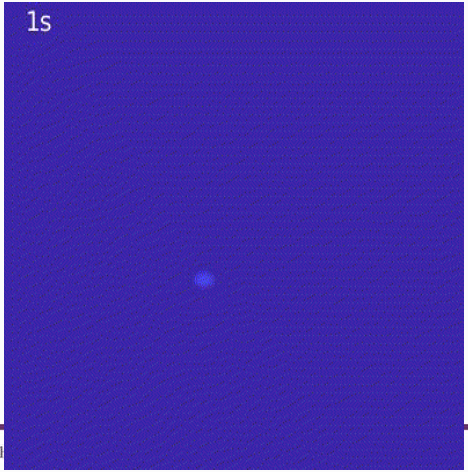
$$S = \frac{\tau_s - \tau_0}{\tau_0 - \tau_d}$$

$$d_0 = Cu$$

$$\overrightarrow{\tau_d} = Constant$$

$$\overrightarrow{\tau_0} = B\overrightarrow{\Delta\tau} + \overrightarrow{\tau_d}$$

$$\tau_s = (1 + S)(|\overrightarrow{\tau_0}| - |\overrightarrow{\tau_d}|) + |\overrightarrow{\tau_d}|$$



Kinematic slip was used to calculate static stress drop, assuming a constant dynamic/final stress

We start with an assumed effective normal stress, and then search for the best-fit value to determine strength (S) and d_0 (C)

Comparison of data and synthetic

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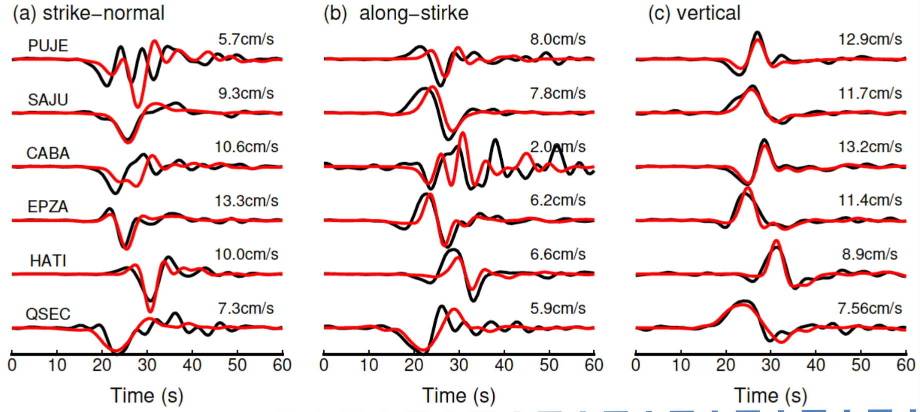
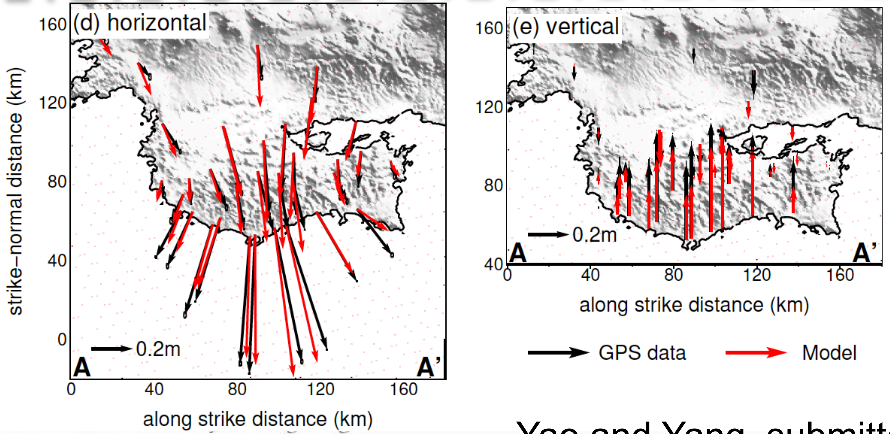


Both amplitudes and shapes match very well with data. Slightly worse on horizontal components.



Synthetics match well with campaign GPS data

For each run, we quantify the misfit between synthetic static (displacement) and high-rate GPS (velocity) and data

Yao and Yang, submitted

Heterogeneous or homogeneous D_0

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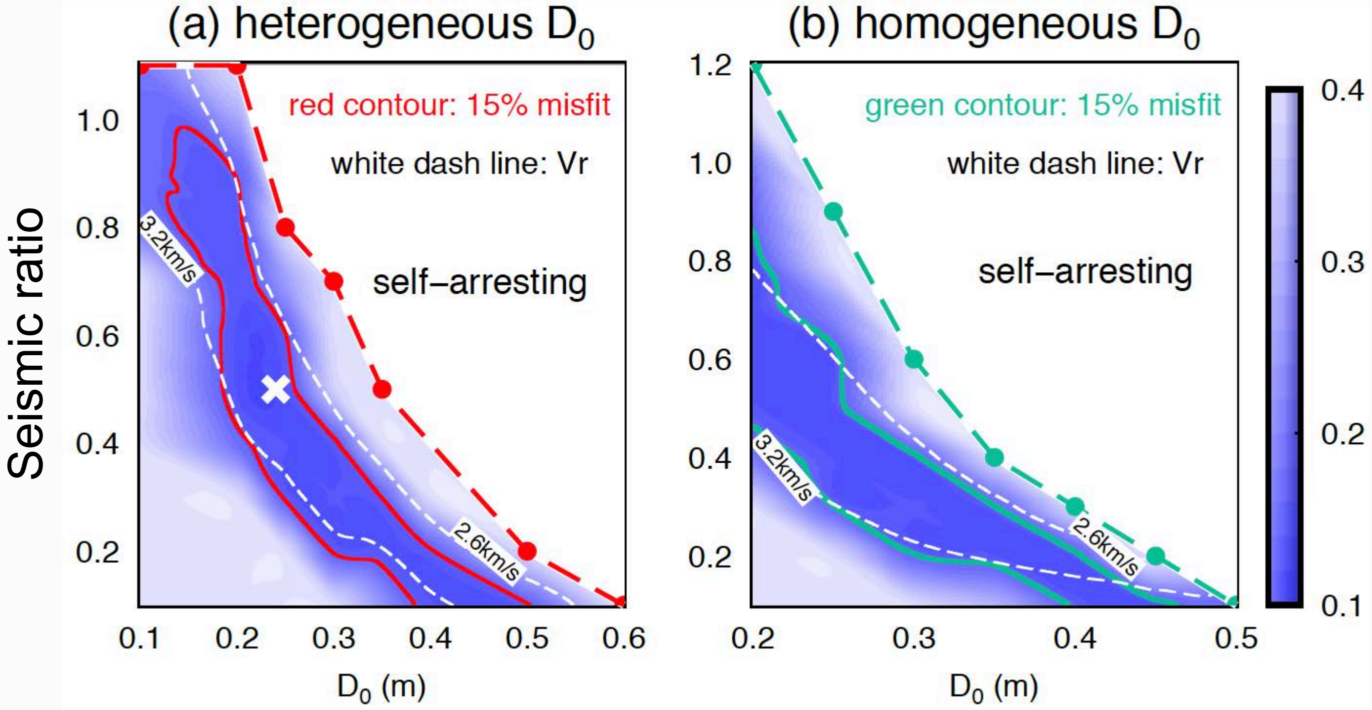
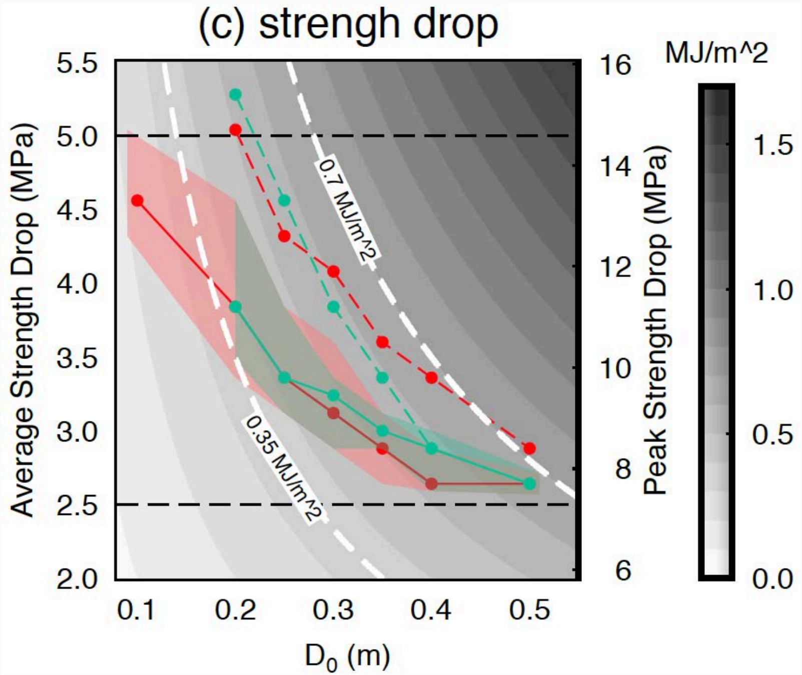


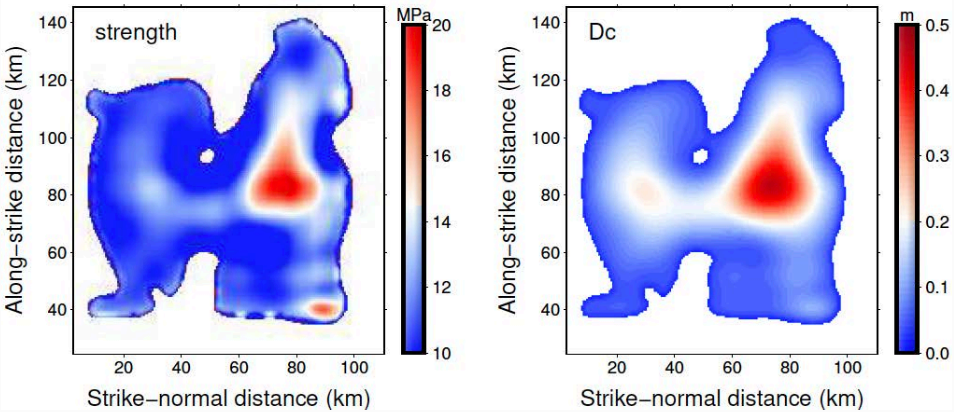
Although heterogeneity of friction should exist on faults, near-field data may not be able to distinguish. Here we tested cases with heterogeneous and homogenous distribution of D_0, the average value is close.

The best-fit model yields D_0=0.12 u ($\overline{D_0}$ =0.25 m), S = 0.4 ($\overline{\tau_s - \tau_d} = 3.4$ MPa)

Yao and Yang, submitted

Low strength





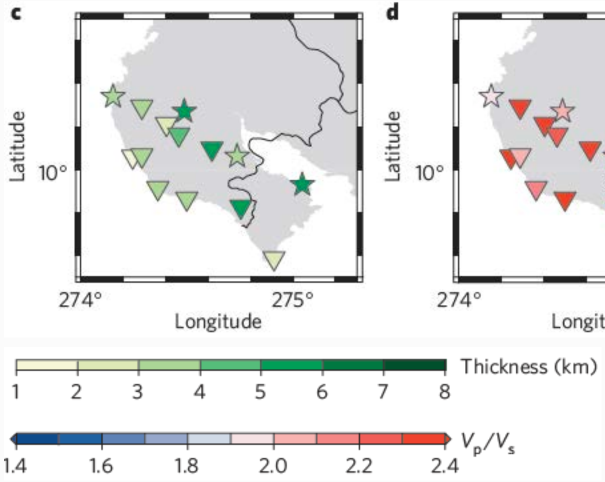
Average strength drop <5 MPa

D_0 is scaled with slip and thus displays same pattern as final slip. The peak value is 0.5 m. By assuming the dynamic friction coefficient of 0.2 or lower, strength is estimated to be lower than 7.5 MPa on average, indicating near-lithostatic pore pressure on the megathrust.

Yao and Yang, submitted

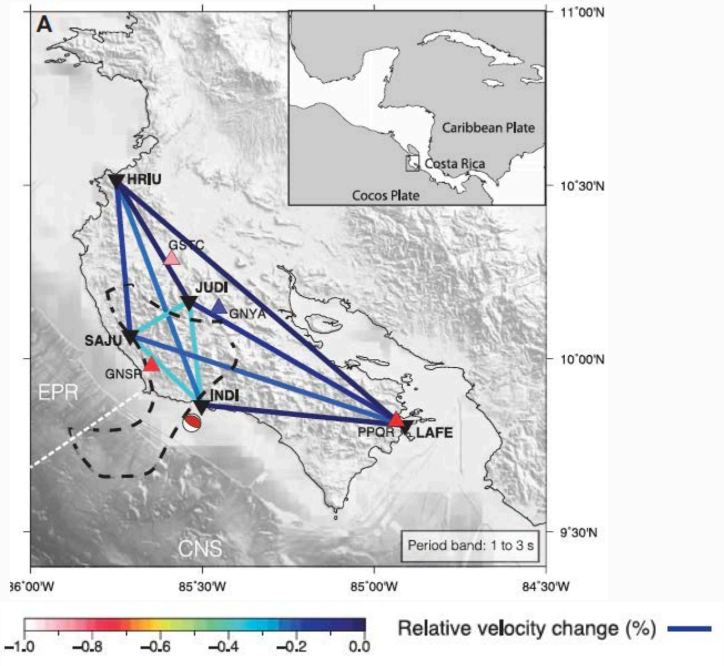
Seismic observations indicate high P

High vp/vs by RF



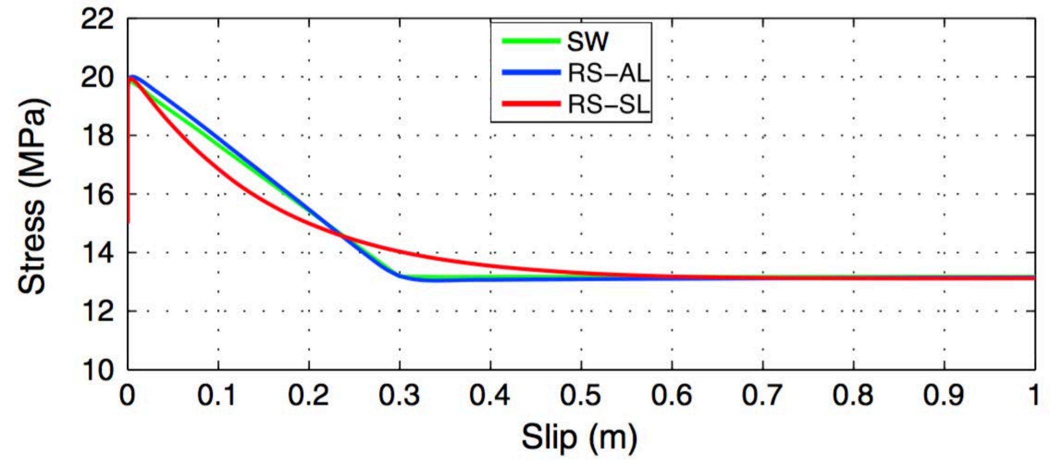
Audet and Schwartz, 2013

Coseismic velocity reduction: NCC



Chaves and Schwartz, 2016

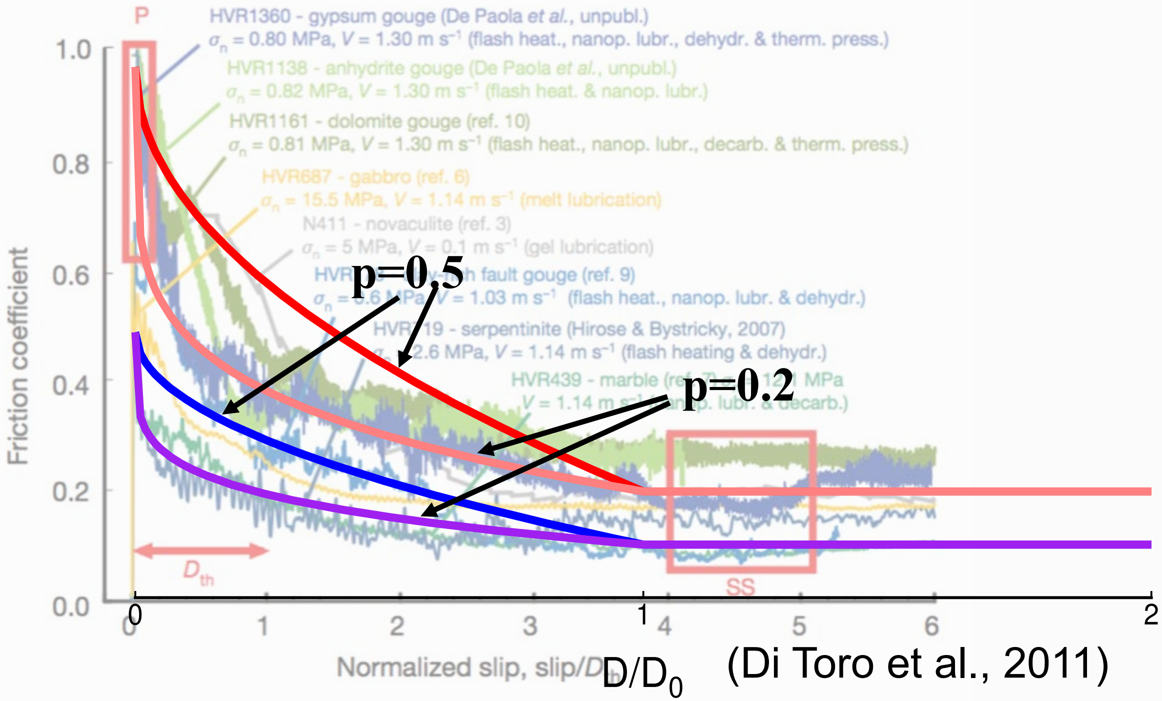
Slip-dependent vs rate-dependent



(Ryan and Oglesby, 2014)

- Although featuring different parameterizations, RS laws exhibit slip weakening under seismic slip rates;
- Dynamic rupture simulations using rate- and state-dependent friction law can obtain similar rupture process with simulations using linear slip-weakening law under the same **fracture energy**;
- Under the same fracture energy, RS friction laws with higher initial weakening rates at small slip lead to more energetic rupture fronts and consequent higher rupture speeds compared to the SW law. The differences are slight on planar faults, but can be significant on nonplanar faults

Slip weakening curves from laboratory experiments



(Di Toro et al., 2011)

Power law slip-weakening law:

$$f = f_s - (f_s - f_d)\left(\frac{D}{D_0}\right)^p$$

Fracture energy:

$$G = \sigma_n (f_s - f_d) D_0 p/(p+1)$$

- For linear slip-weakening: p=1
- From laboratory experiments, the range for the exponent p is 0.2-0.5.

$\overline{D_0}$ =0.25 m

$\overline{\tau_s - \tau_d}$ = 3.4 MPa

Assuming that fracture energies are well constrained by dynamic rupture simulations using the linear slip-weakening law, considering the range for exponent p of 0.2-0.5, the product of D_0 and strength drop can be underestimated by a factor of 1.5-3.

Slip weakening curves from laboratory experiments

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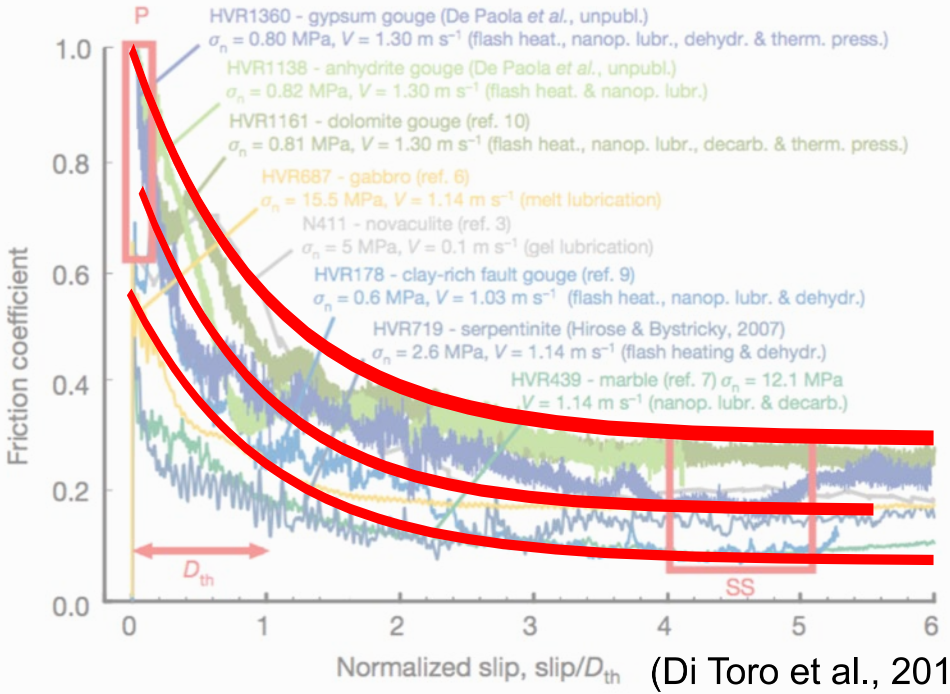


(Di Toro et al., 2011)

Exponential slip-weakening law:

$$f = f_d + (f_s - f_d)exp(\frac{ln(0.05)D}{D_0})$$

Fracture energy:

$$G \doteq 0.33\sigma_n(f_s - f_d)D_0$$

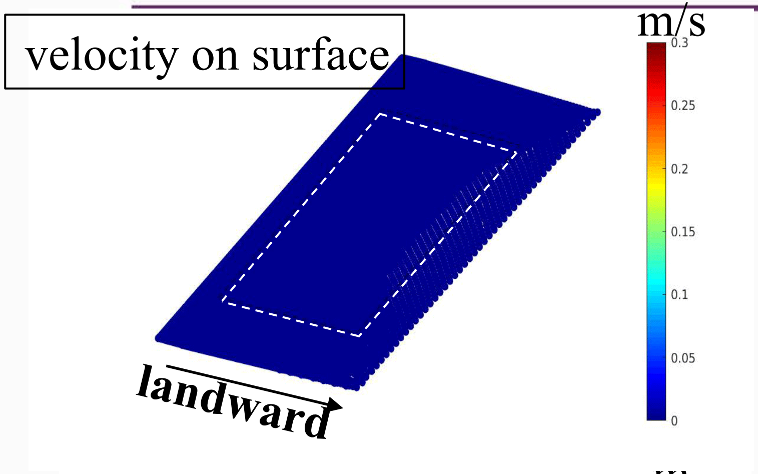
(Mizoguchi et al., 2007)

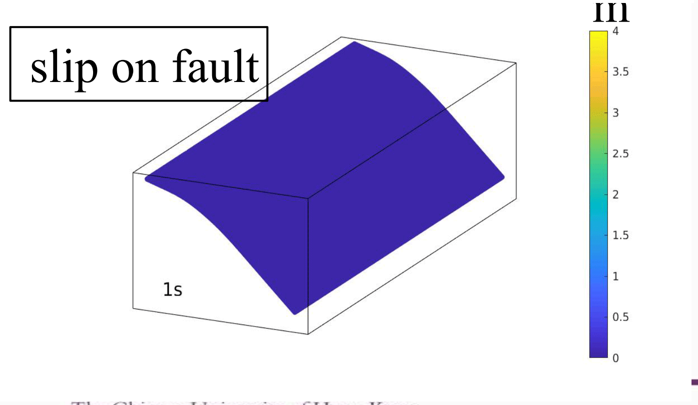
$\overline{D_0} = 0.25$ m

$\overline{\tau_s - \tau_d} = 3.4$ MPa

Assuming that fracture energies are well constrained by dynamic rupture simulations using the linear slip-weakening law, considering the exponential slip-weakening law, the product of D_0 and strength drop can be underestimated by a factor of 1.5.

Conclusions





1. We derive frictional parameters (strength drop and D_0) on seismogenic faults
2. Based on constraint from near-field ground displacement and velocity recordings, the best-fit model yields an average D_0 of 0.25 m (peak 0.5 m) and strength of ~7.5 MPa (maximum 20 MPa) for the Nicoya EQ. D_0 of 0.6 m for the Nepal EQ.
3. Small difference between heterogeneous and homogeneous distribution of D_0
4. Slightly underestimate comparing to non-linear slip weakening law

Ongoing efforts – higher frequency

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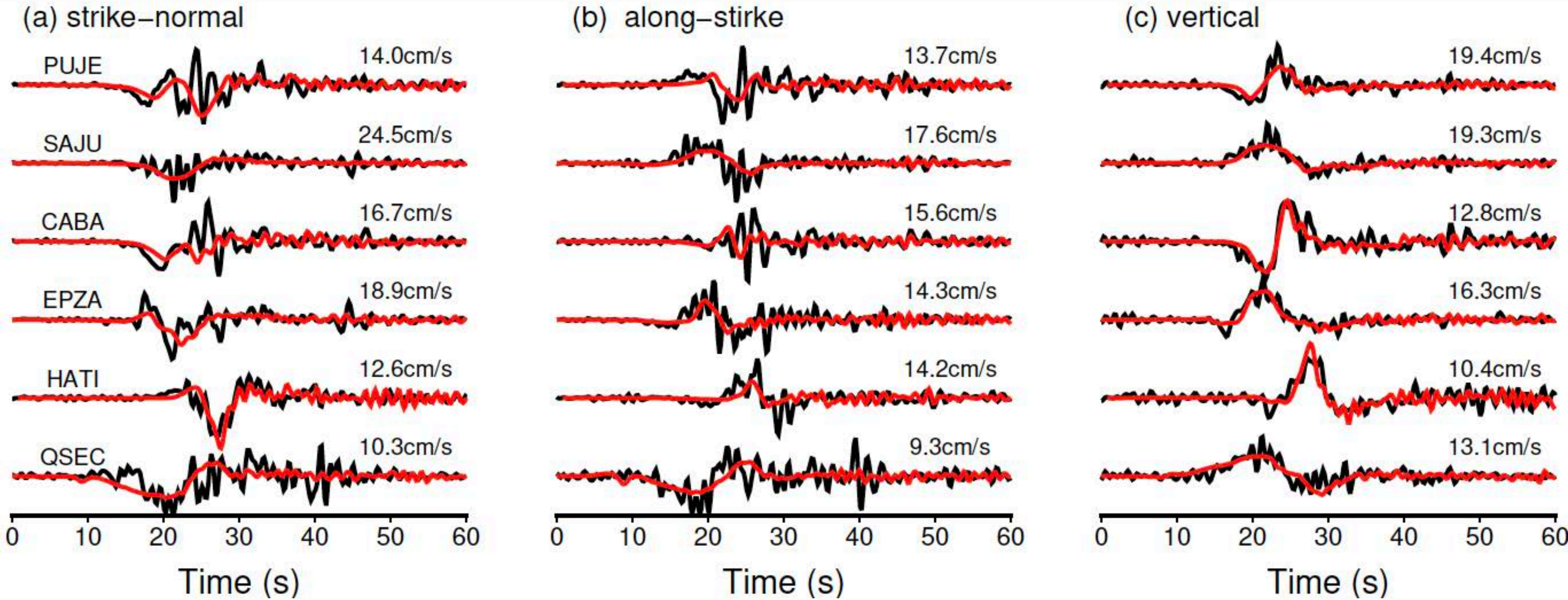

Yao and Yang, in prep.