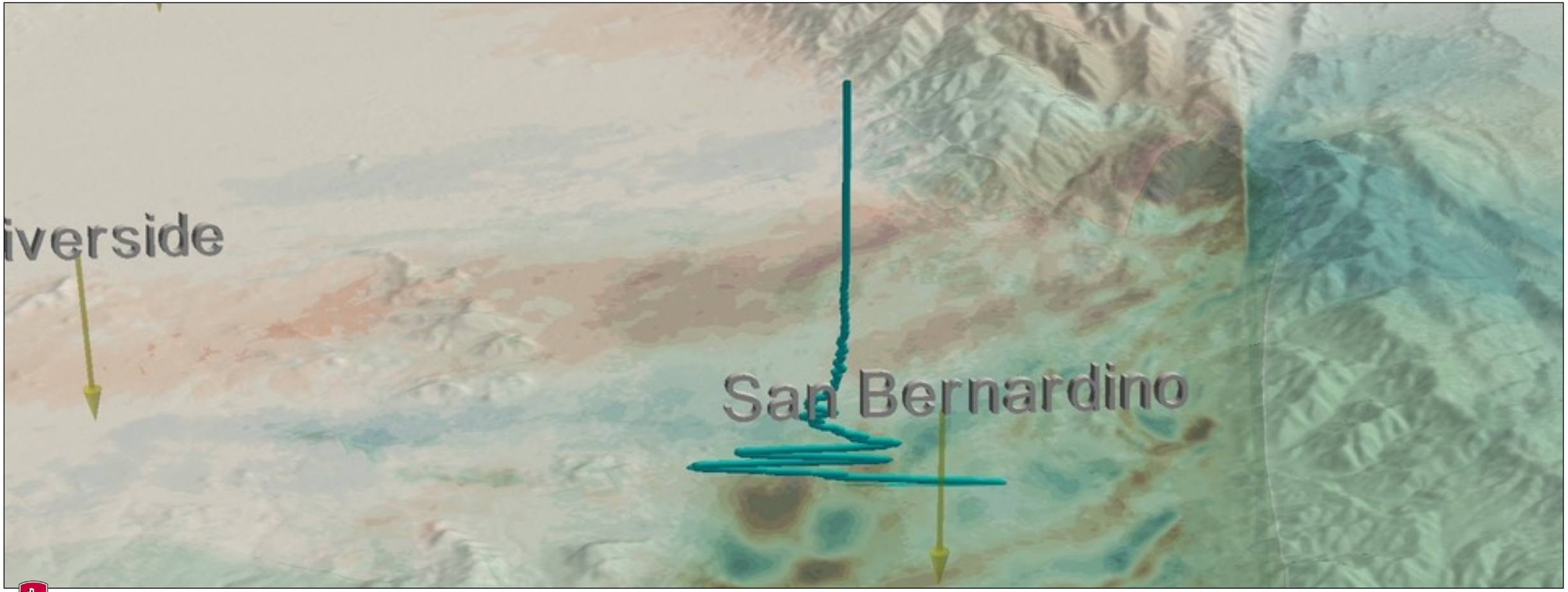
The Role of Fault Zone Plasticity in Controlling Extreme Ground Motions

Daniel Roten (SDSU), Kim B. Olsen (SDSU), Steven M. Day (SDSU)

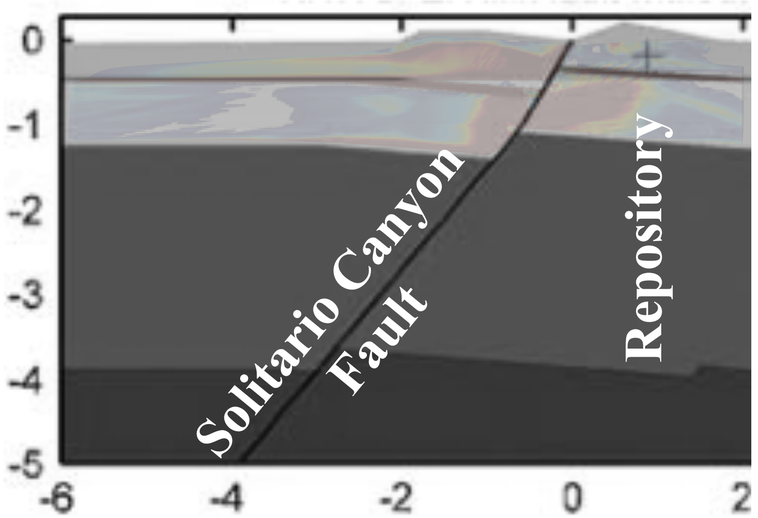


San Diego State University

PSHA Workshop, 5—7 September 2017, Lenzburg, Switzerland

Fault Zone Plasticity and Distributed Deformation

- Stresses at rupture front exceed strength of crustal rock, leading to permanent deformation near the fault
- Physical Limit to peak ground velocity (Andrews, 2007; Duan & Day, 2010)



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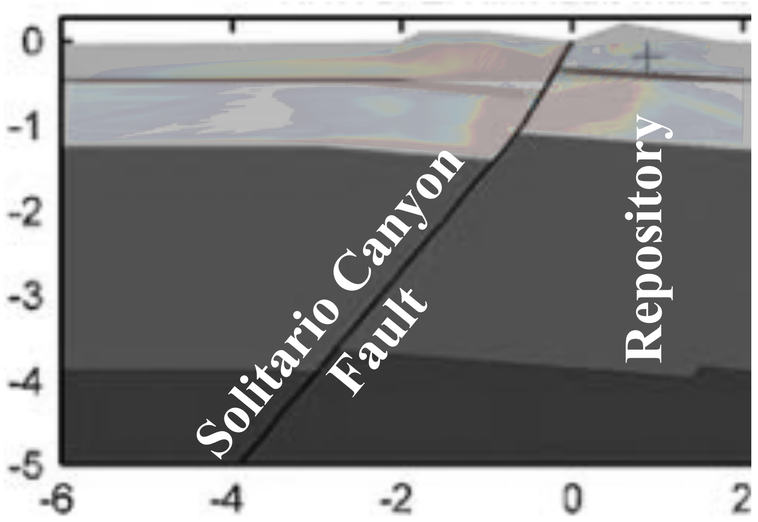

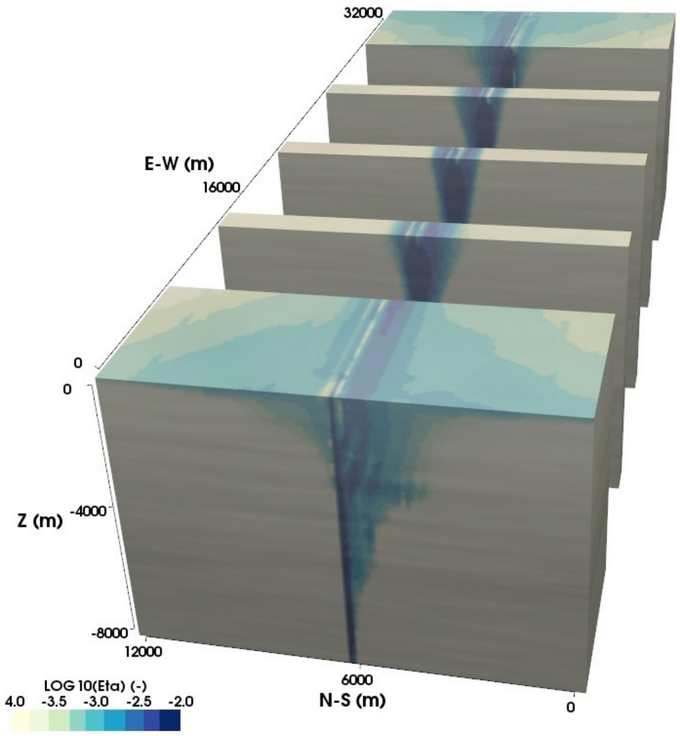

- Formation of a flower-like damage zone (Ma, 2010)

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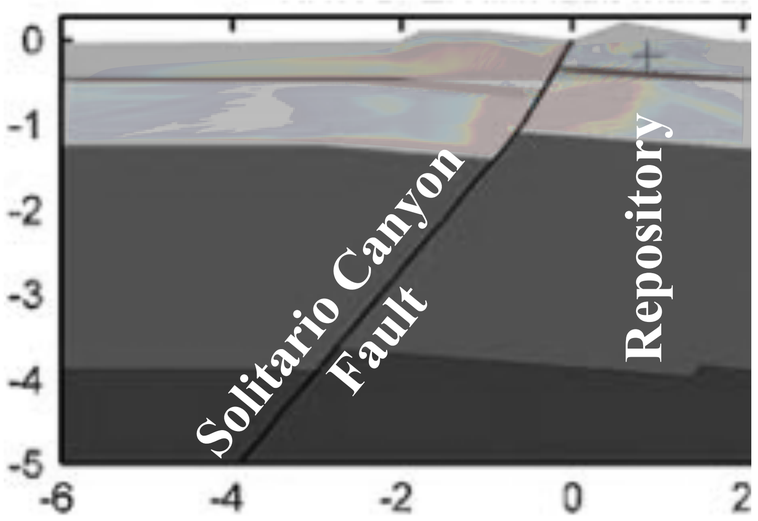

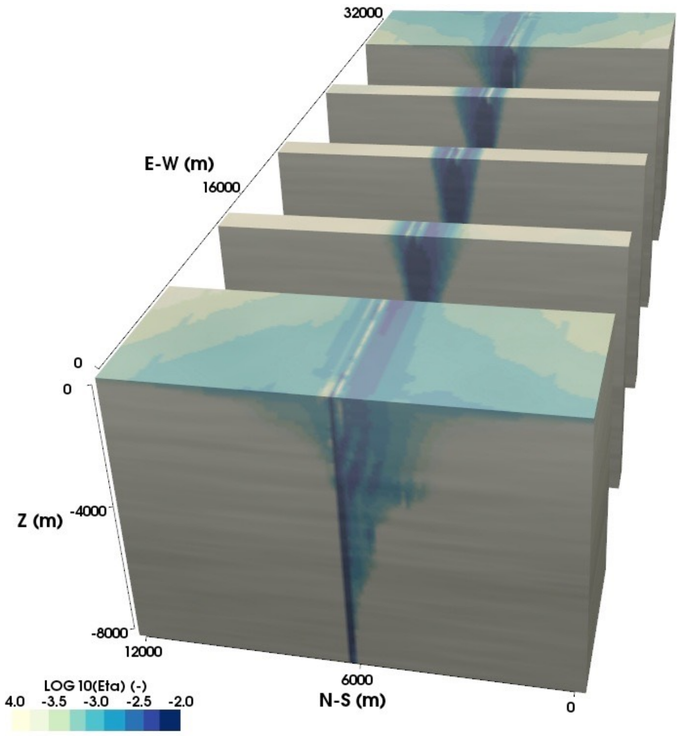

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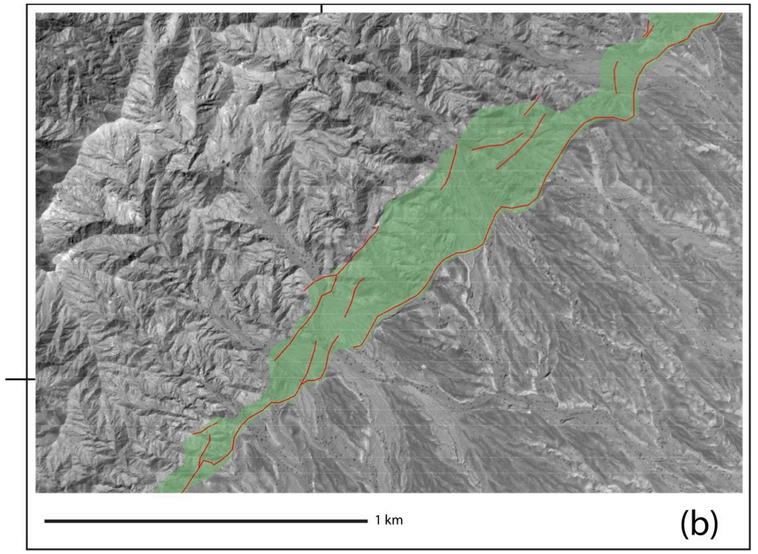
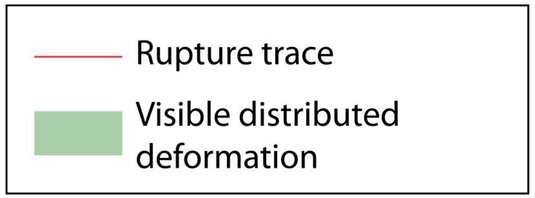
- Plastic yielding leads to distributed surface deformation

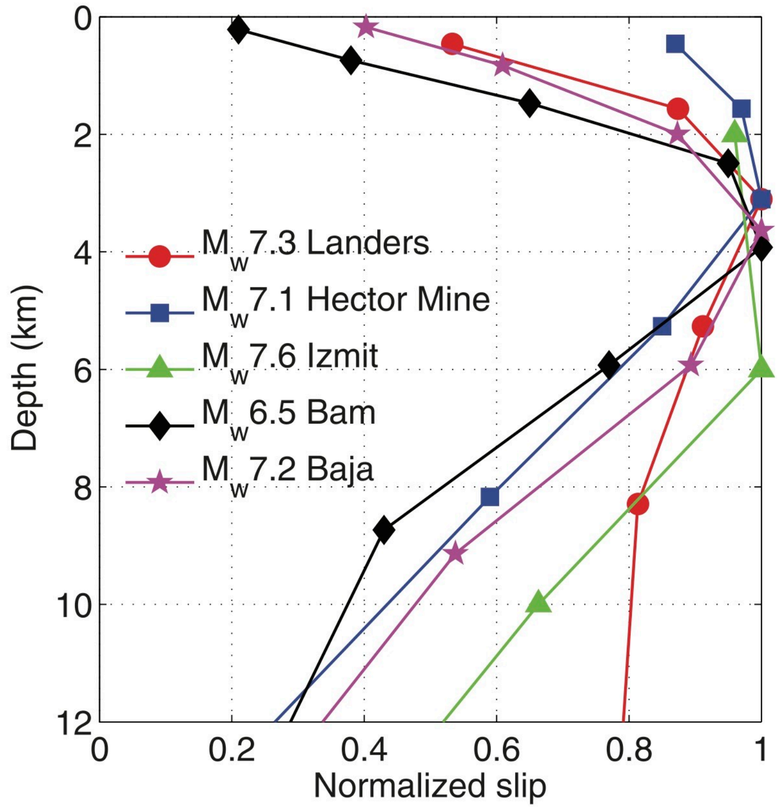




M 7.7 Balochistan (Pakistan) earthquake (Zinke *et al.*, 2014)

Fault Zone Plasticity and Distributed Deformation

- Distributed deformation may explain *Shallow Slip Deficit* (SSD, i.e. decrease of slip towards the free surface).



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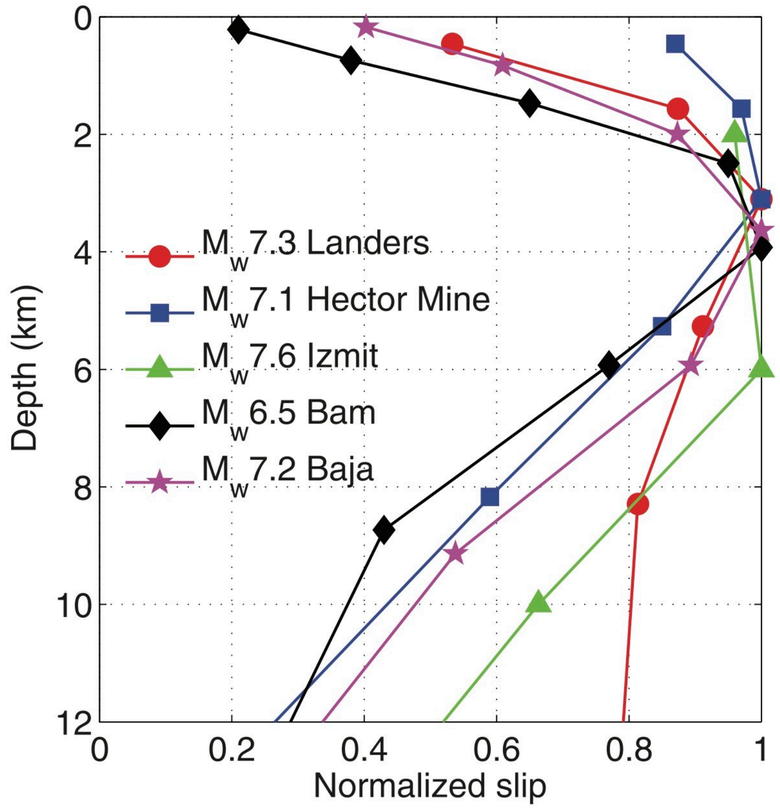

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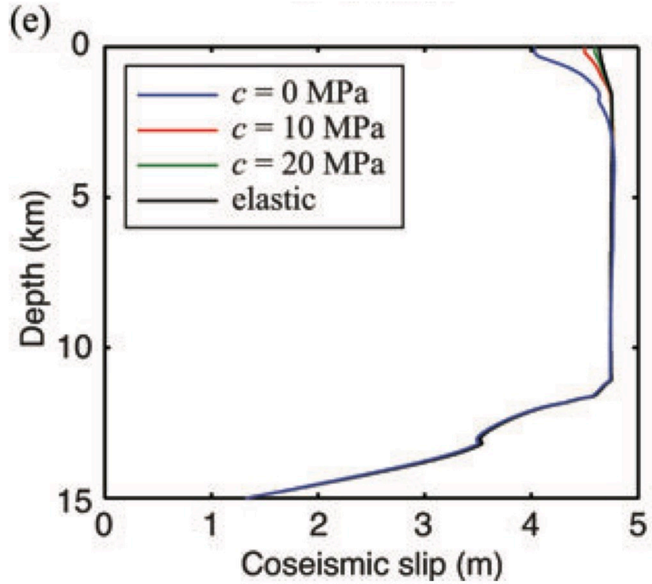
- 2D dynamic rupture simulations from Kaneko & Fialko (2011) predict a Shallow Slip Deficit of up to 15%
- 2—4 times lower than observed SSD (30—60%)



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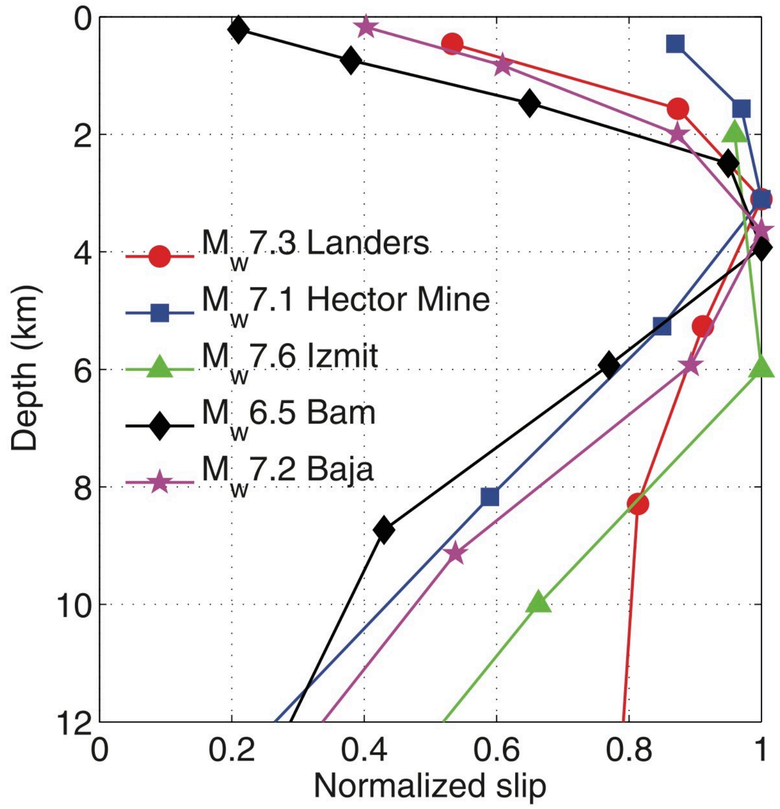

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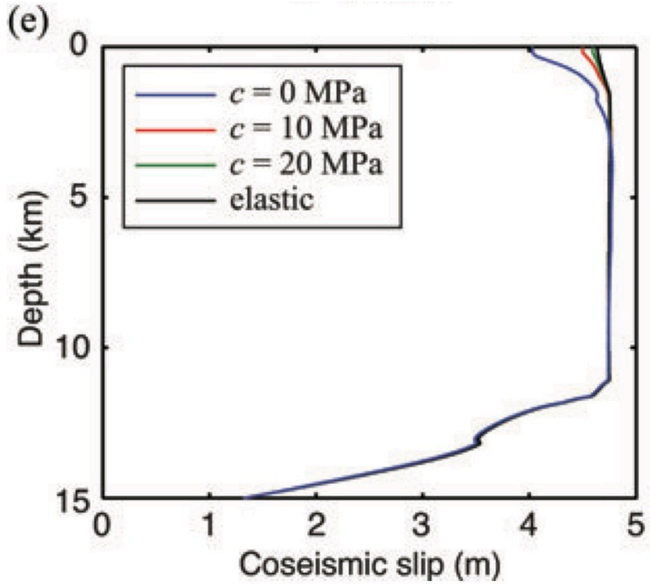
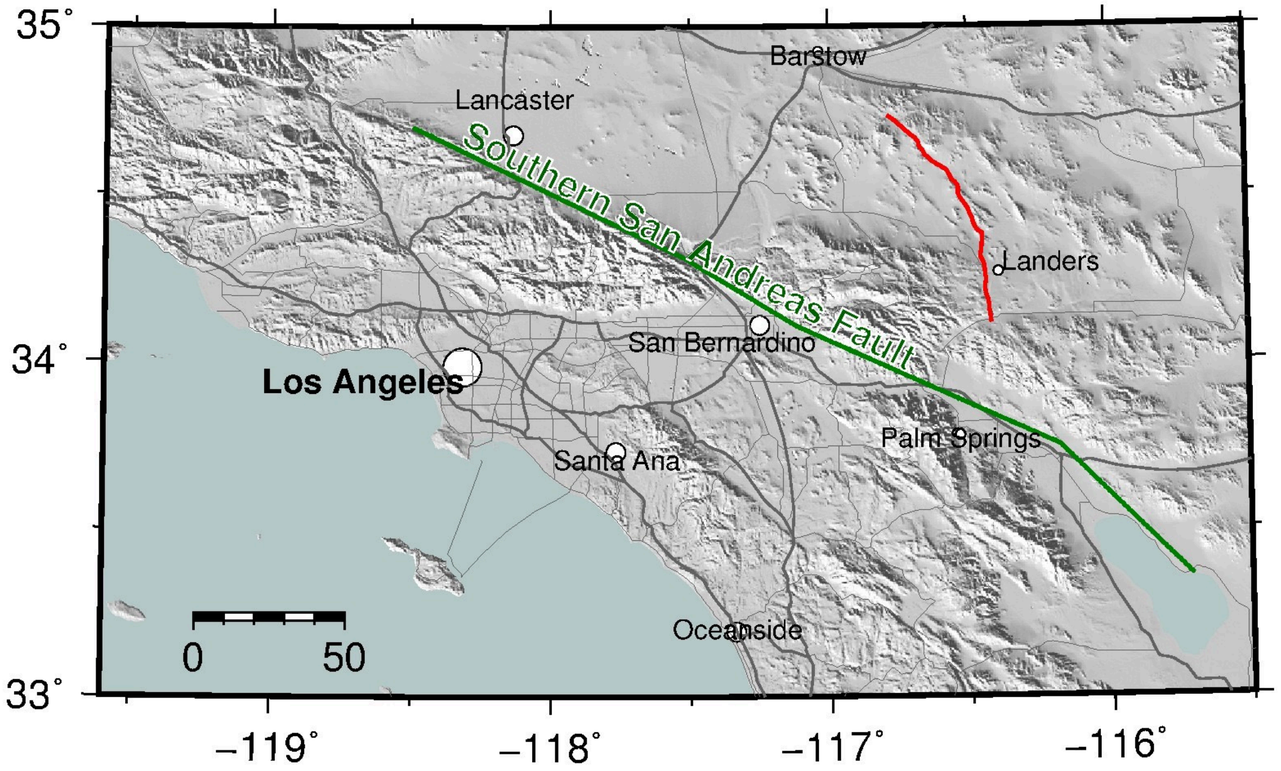


Scope of this study:

Perform 3D nonlinear dynamic rupture simulations to

1. Reproduce SSD and surface deformation observed during past earthquakes
2. Predict how this nonlinearity affects ground motions in future earthquake scenarios

Dynamic Rupture Simulations with Fault Zone Plasticity



- AWP-ODC staggered-grid split-node FD code (Dalguer & Day, 2007) with slip-weakening fault friction
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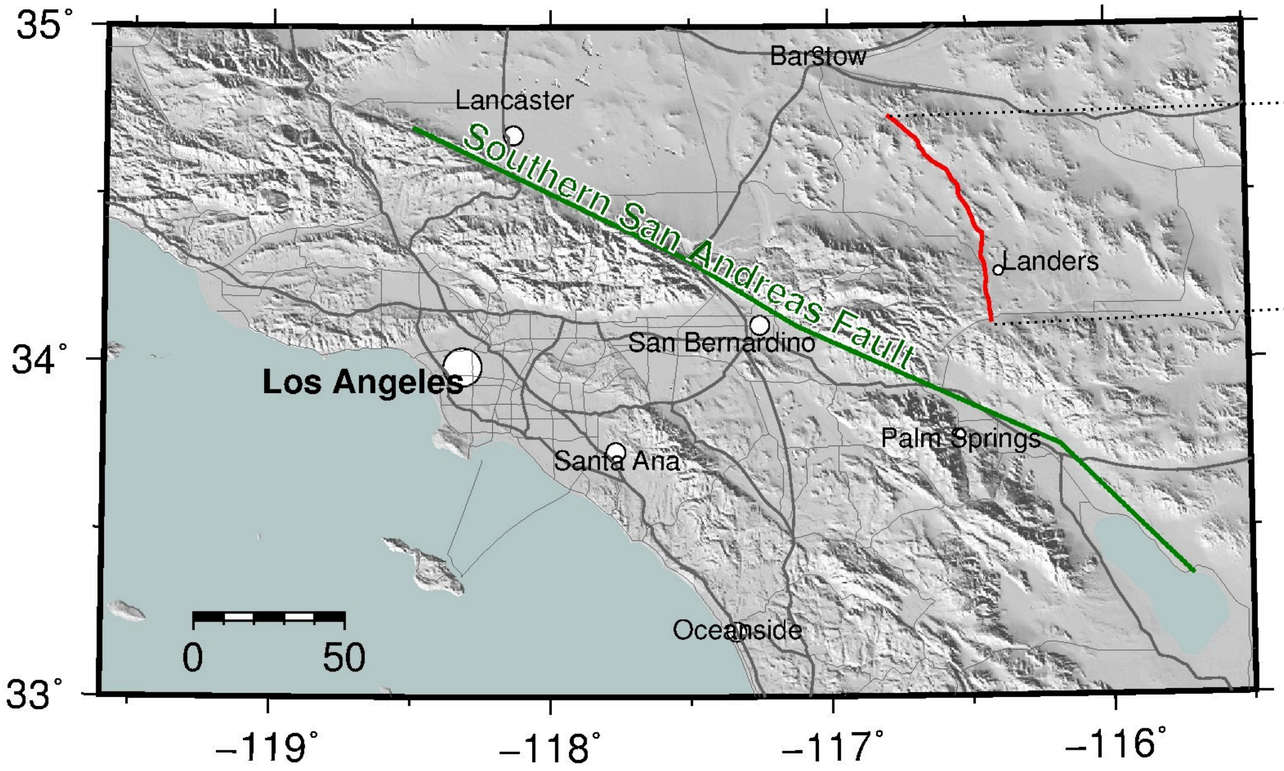
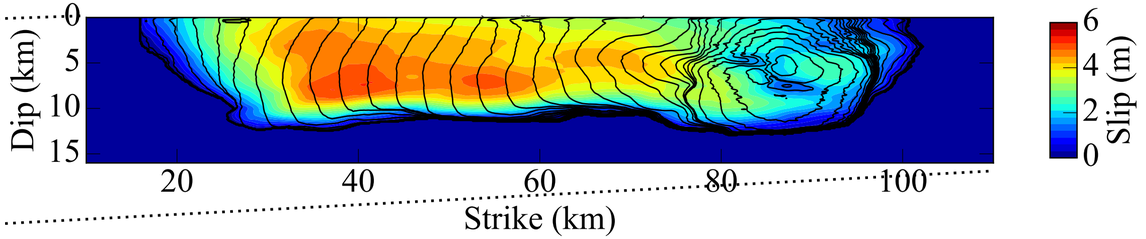


M 7.3 Landers Earthquake



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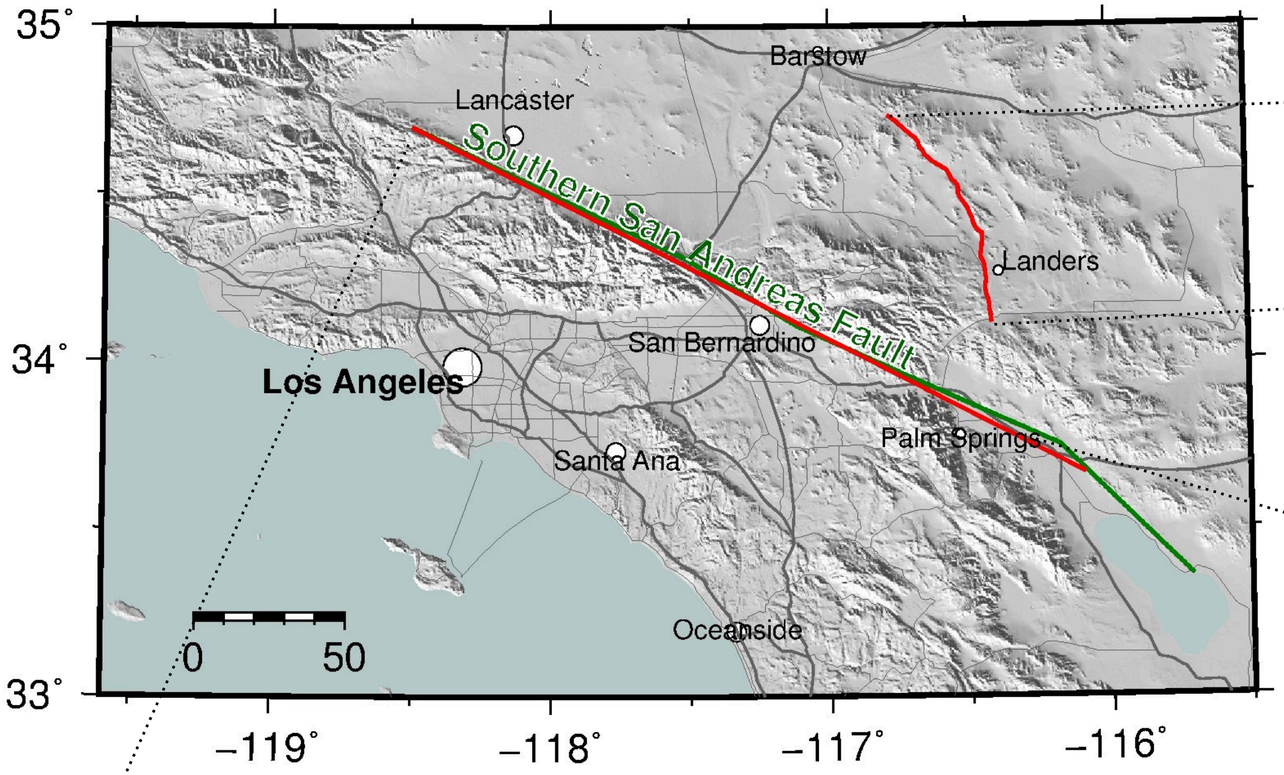

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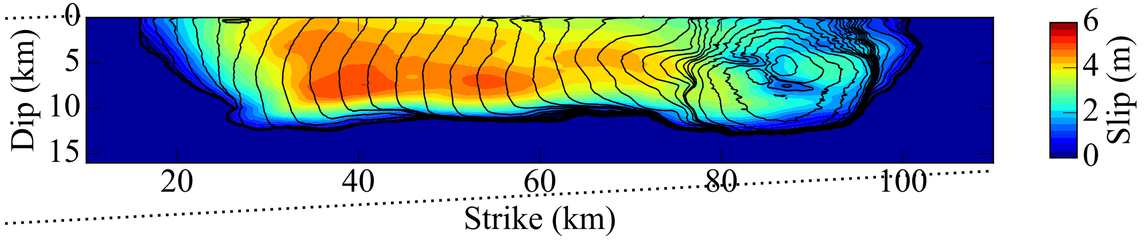

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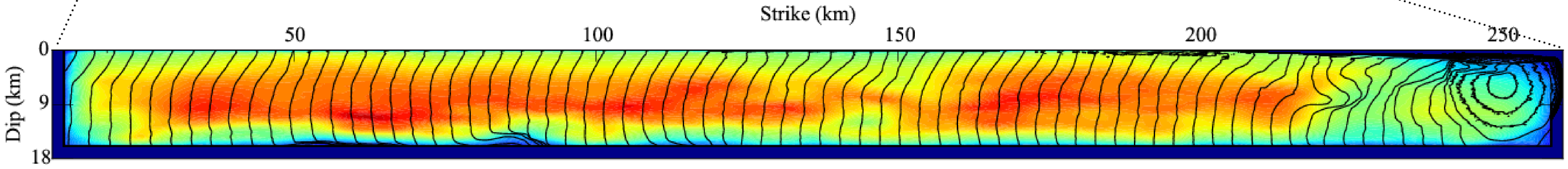
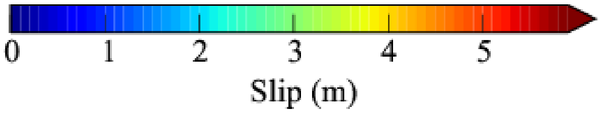
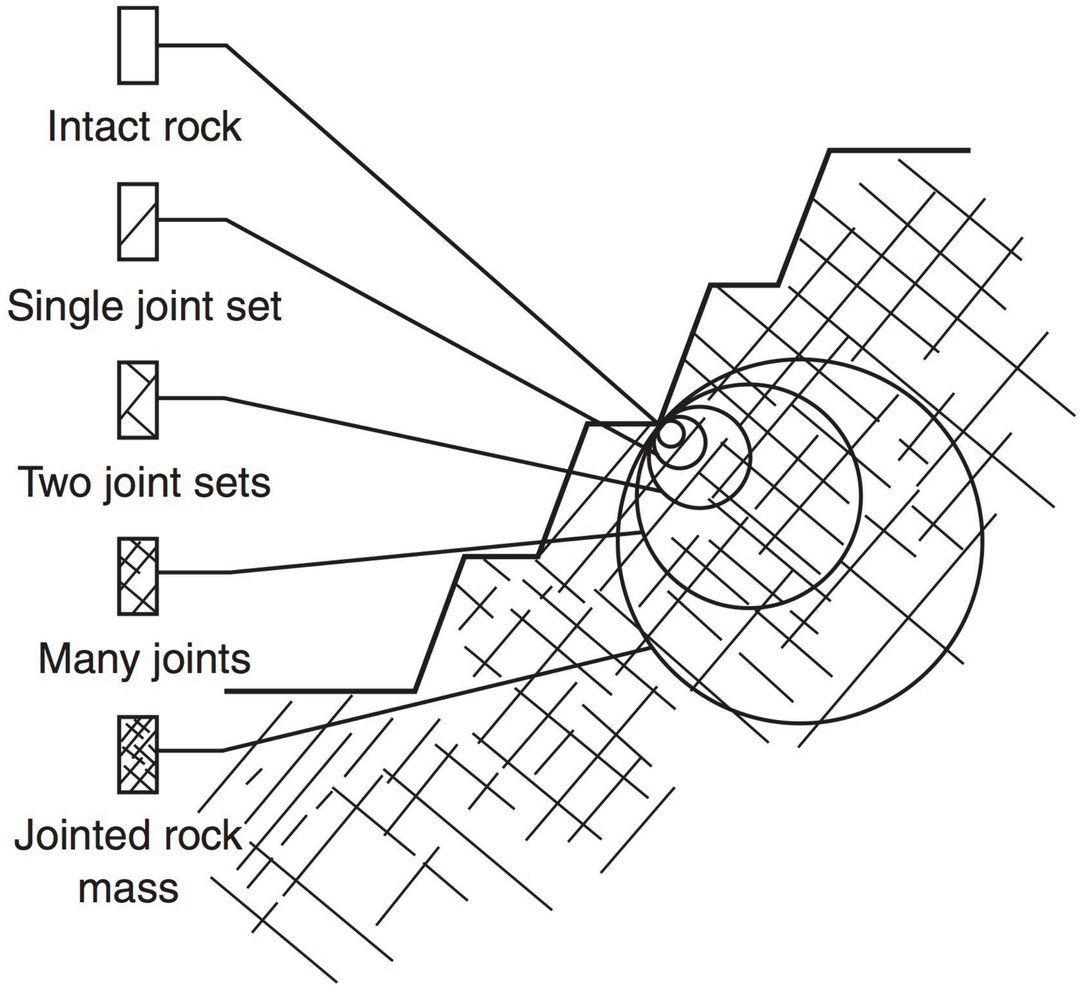




M 7.7 Southern San Andreas Scenario

How to Define Rock Strength in Dynamic Rupture Simulations?



Scale dependence of rock strength
(Wyllie & Mah, 2005)

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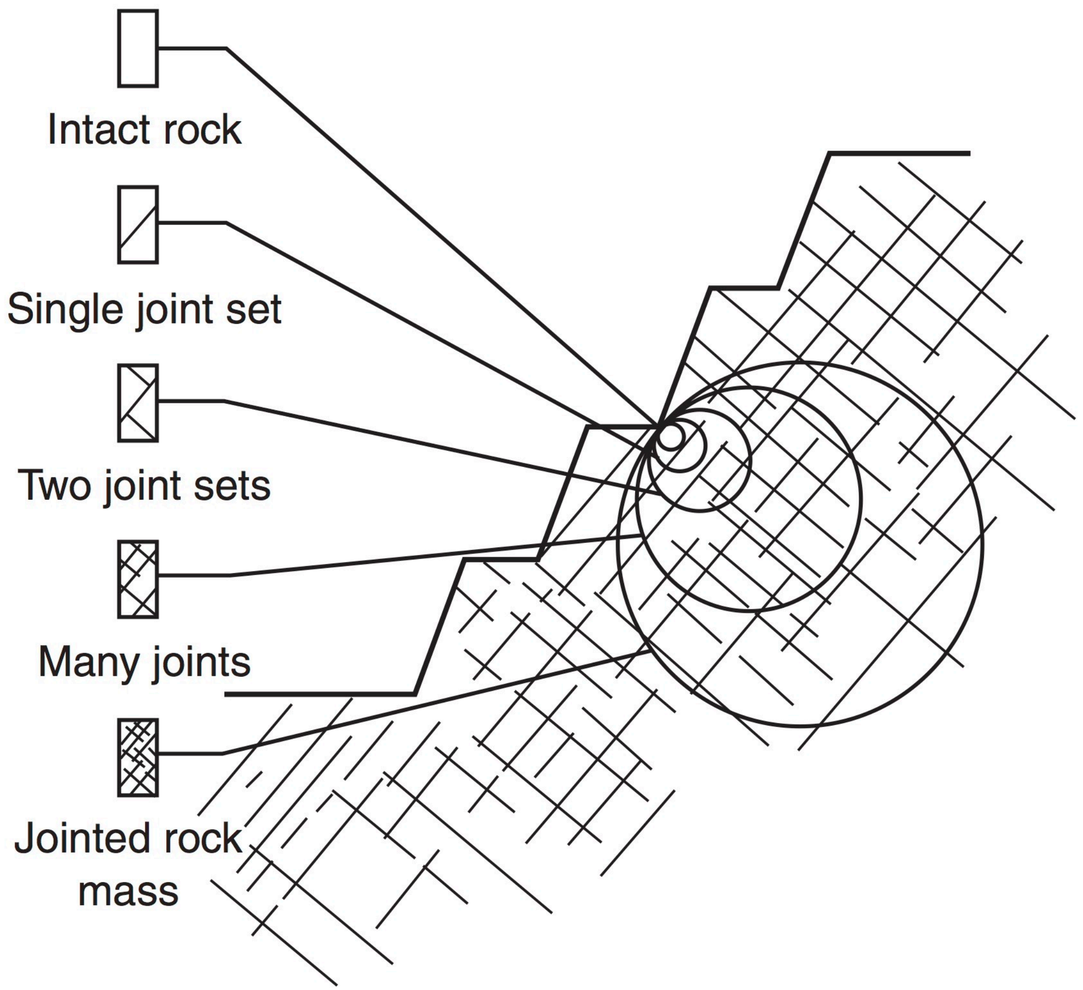

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- Uses *Geological Strength Index (GSI)* to describe degree of fracturing

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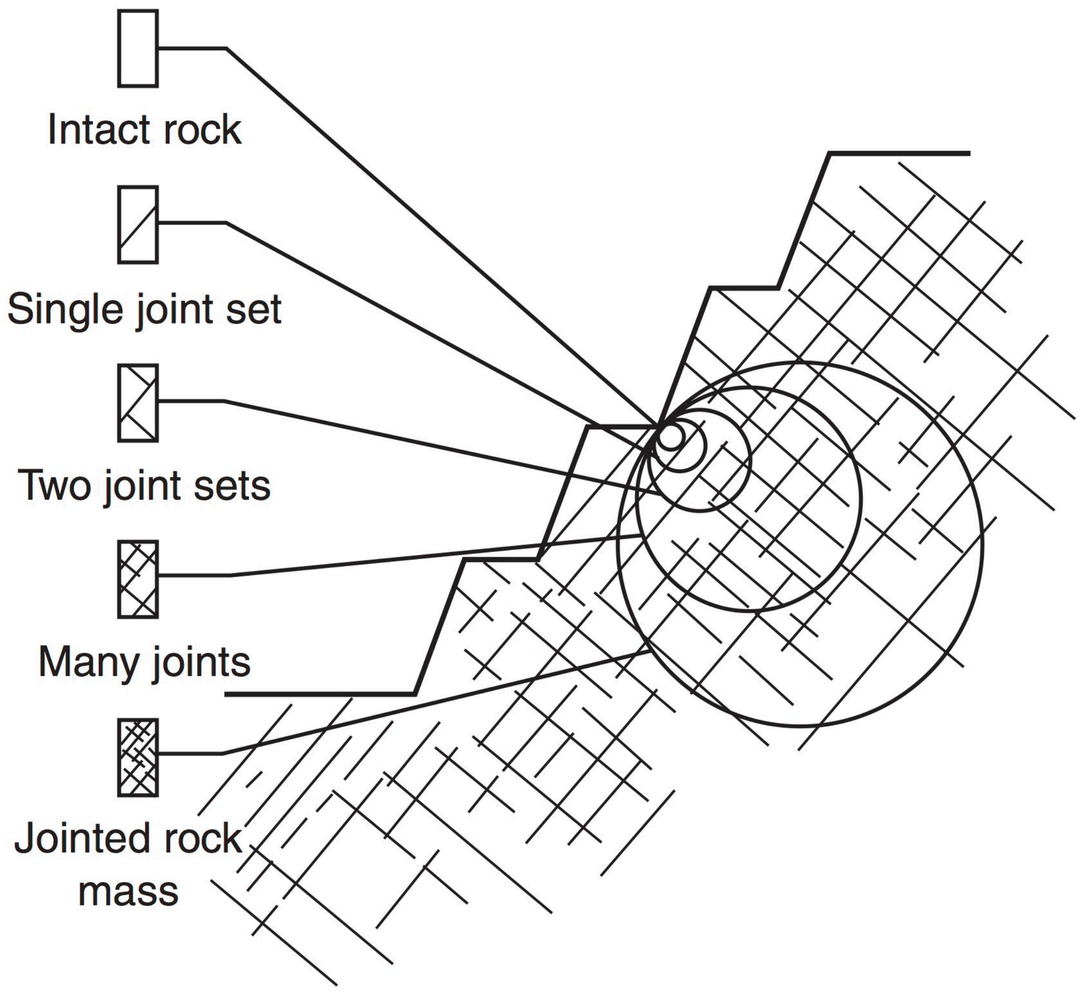

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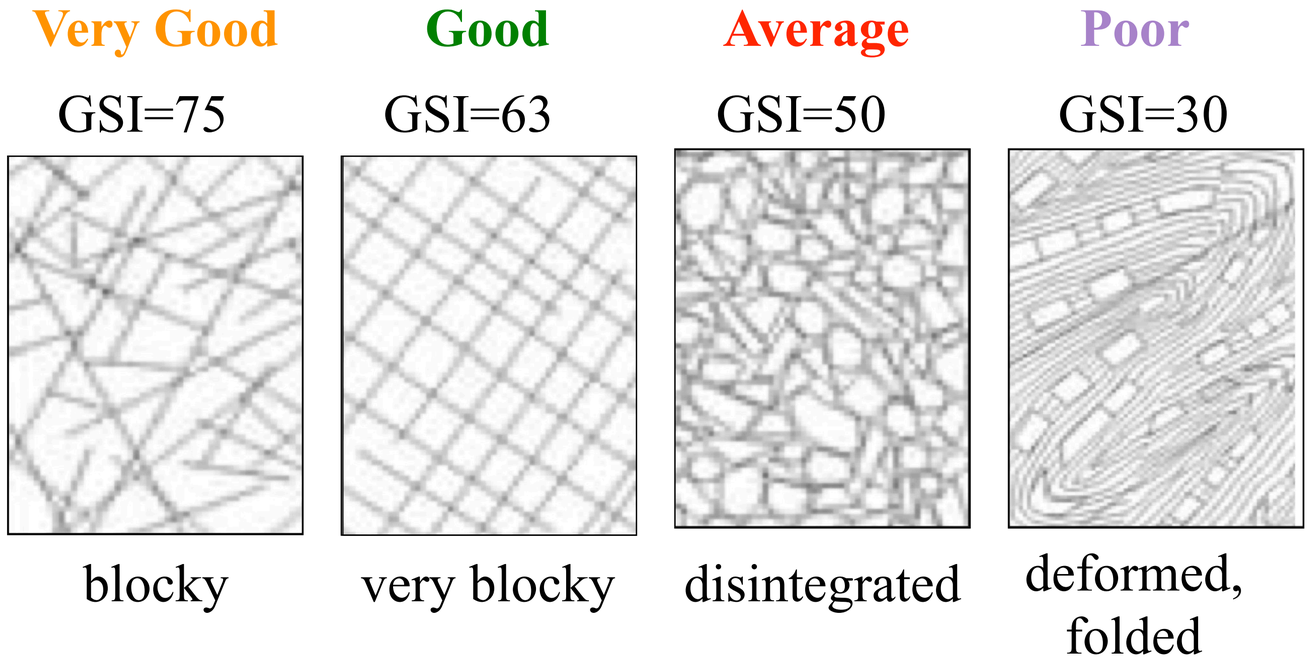
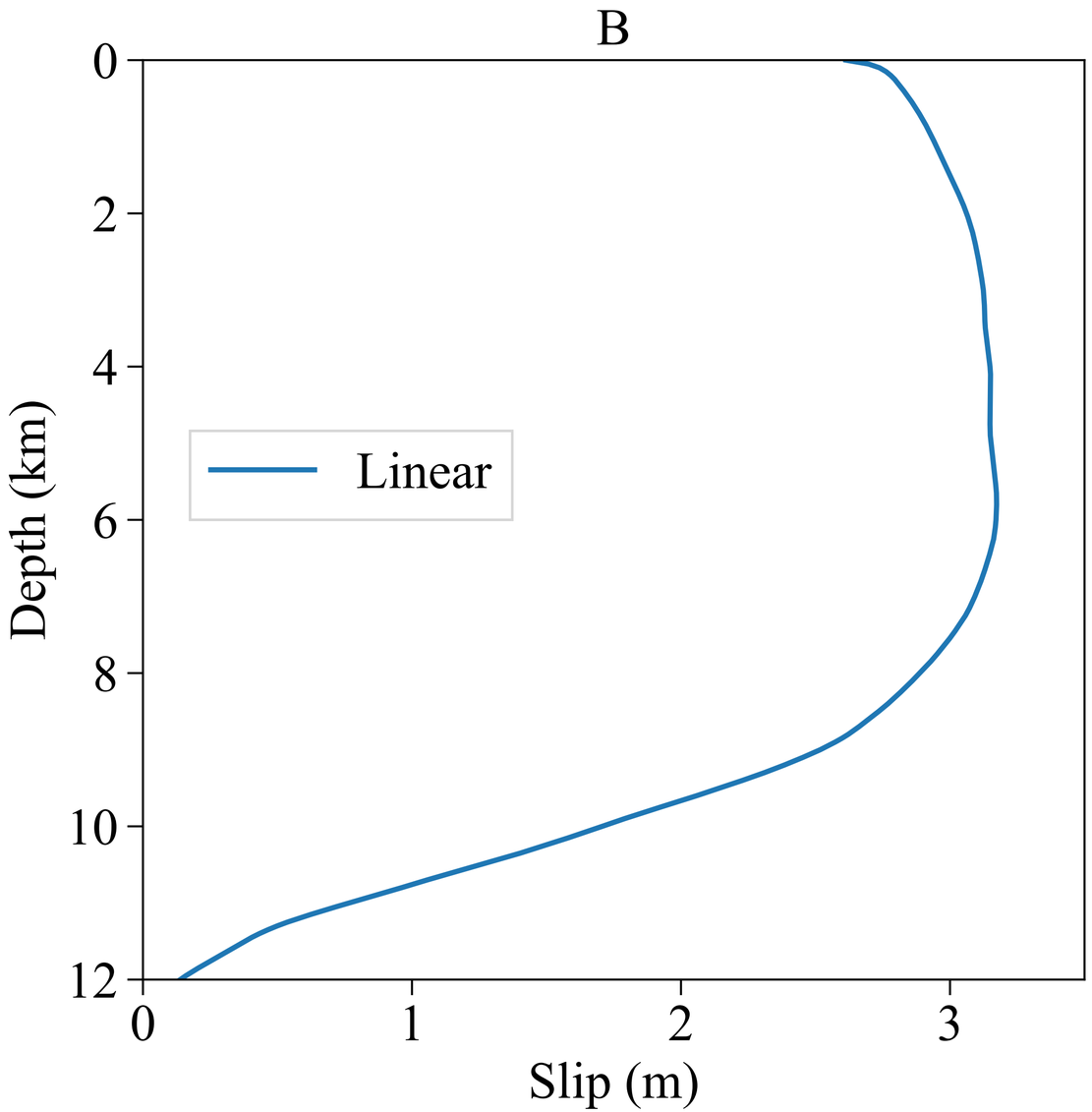
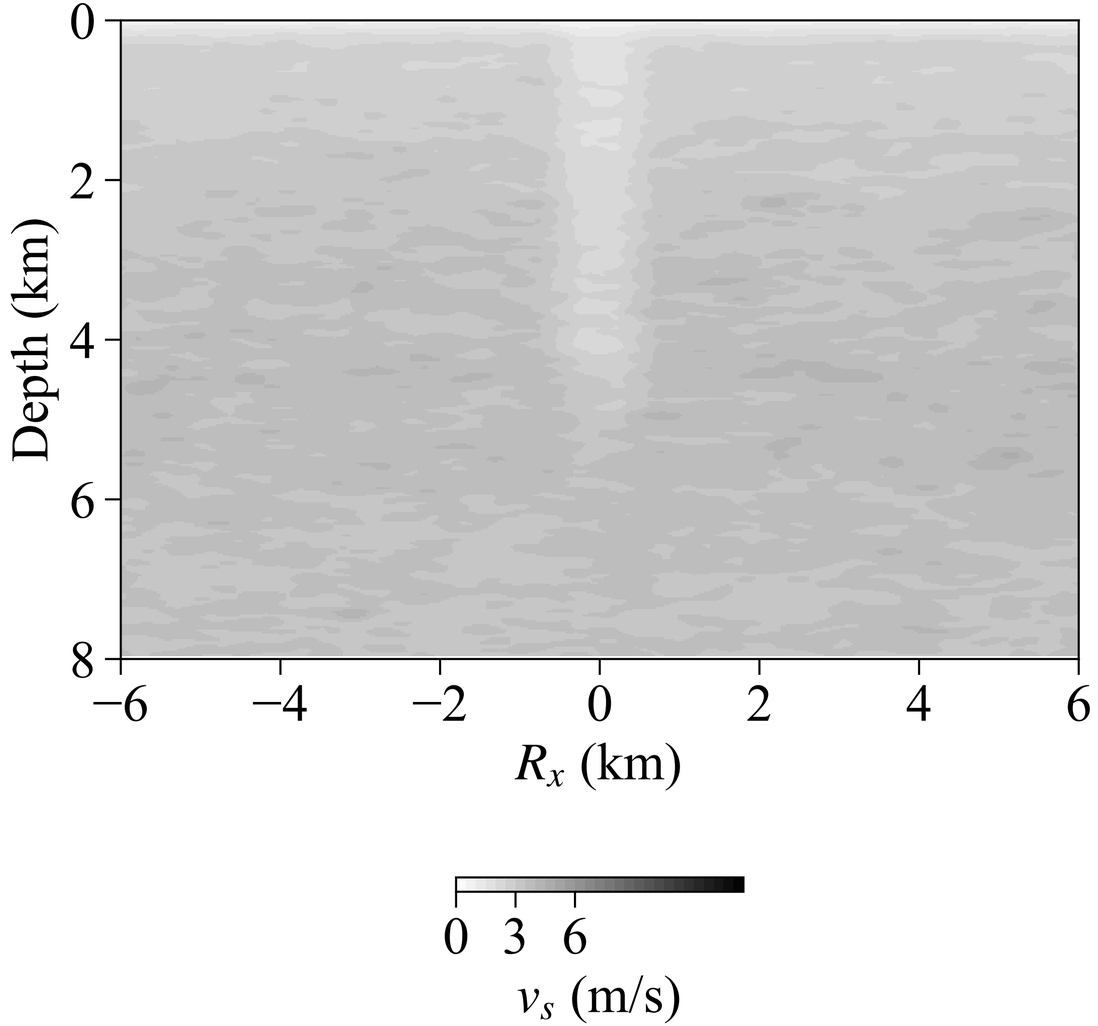


Shallow Slip Deficit from Fault Zone Plasticity





Roten *et al.*, GRL, 2017

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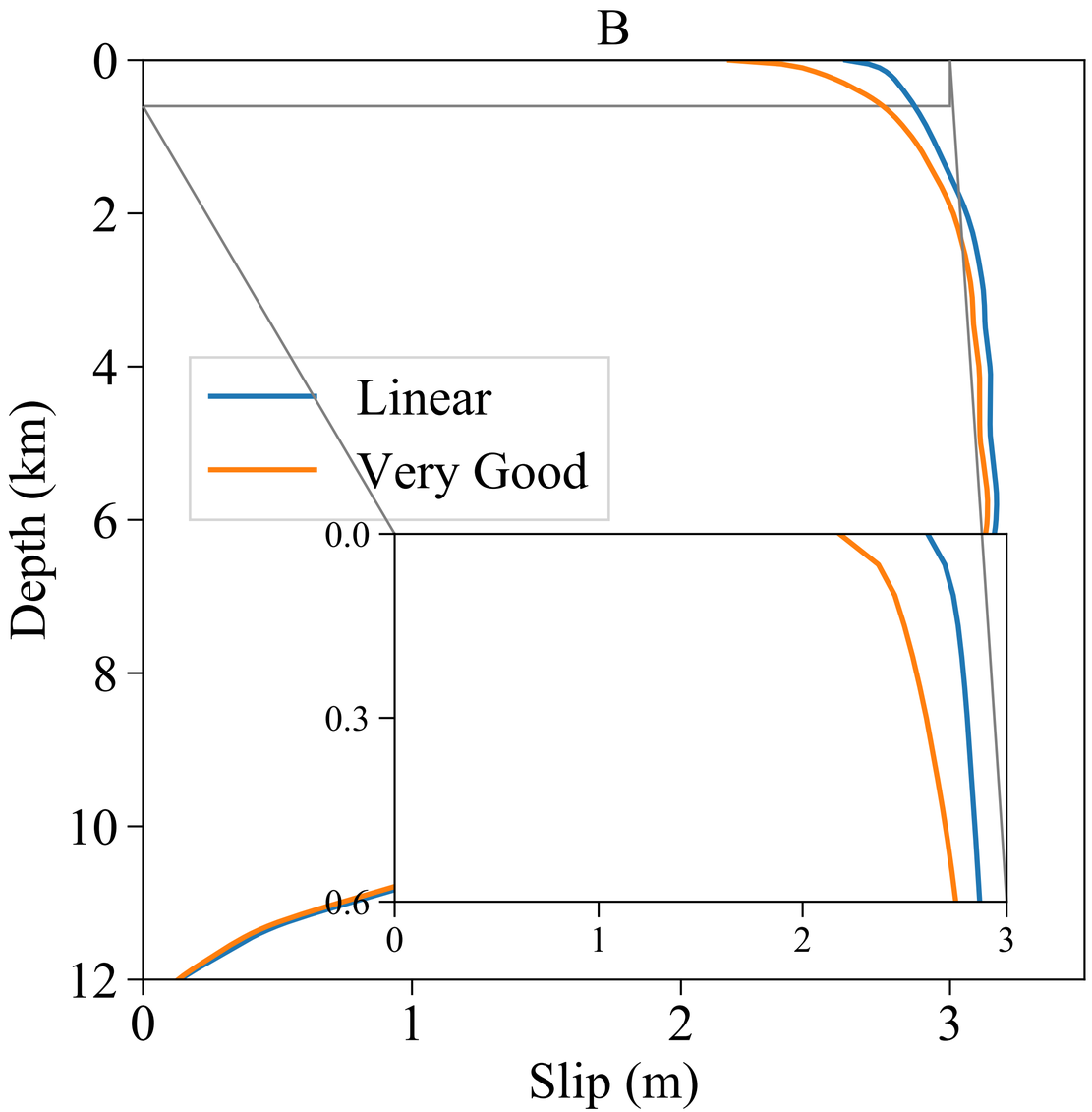

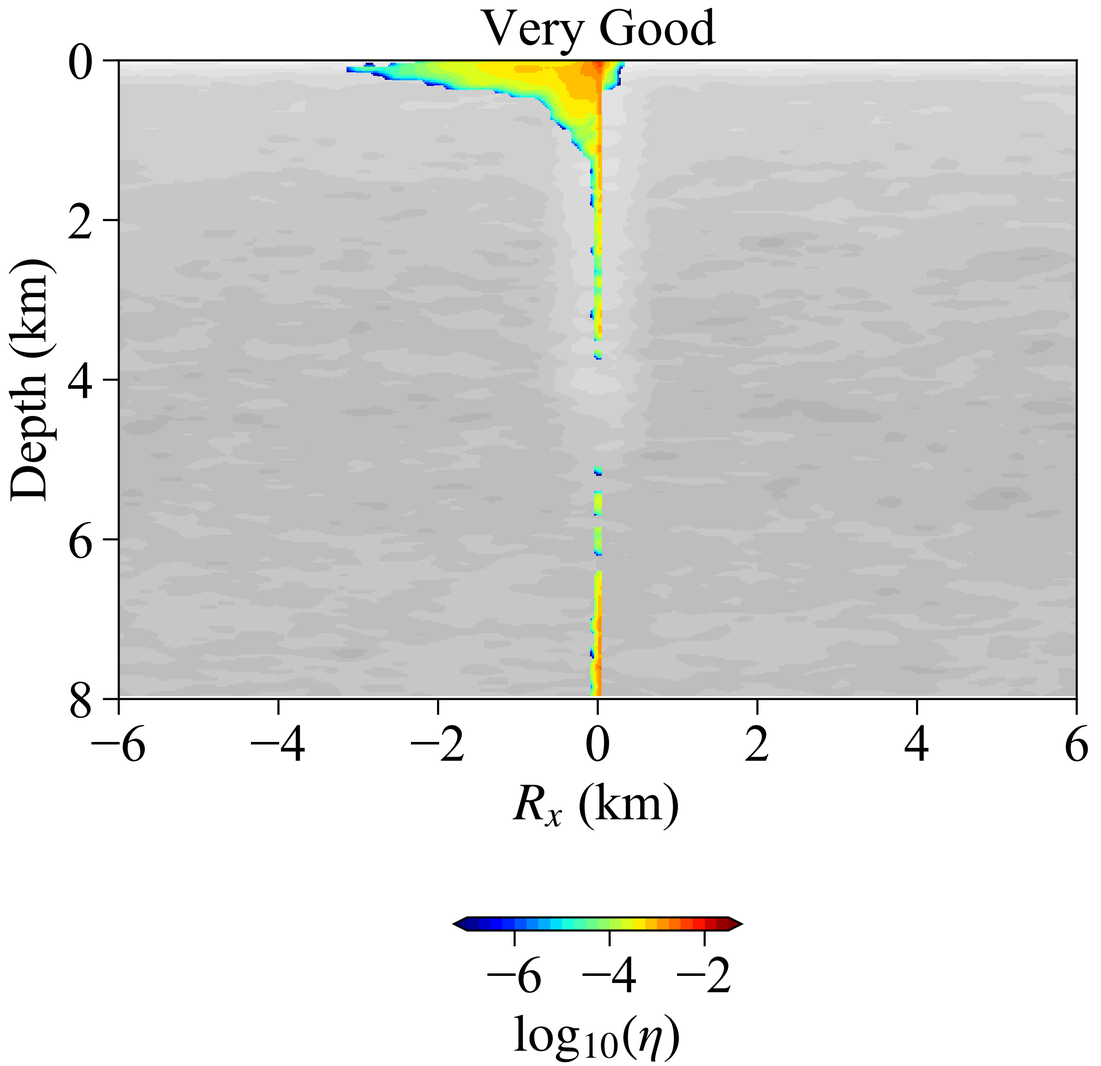

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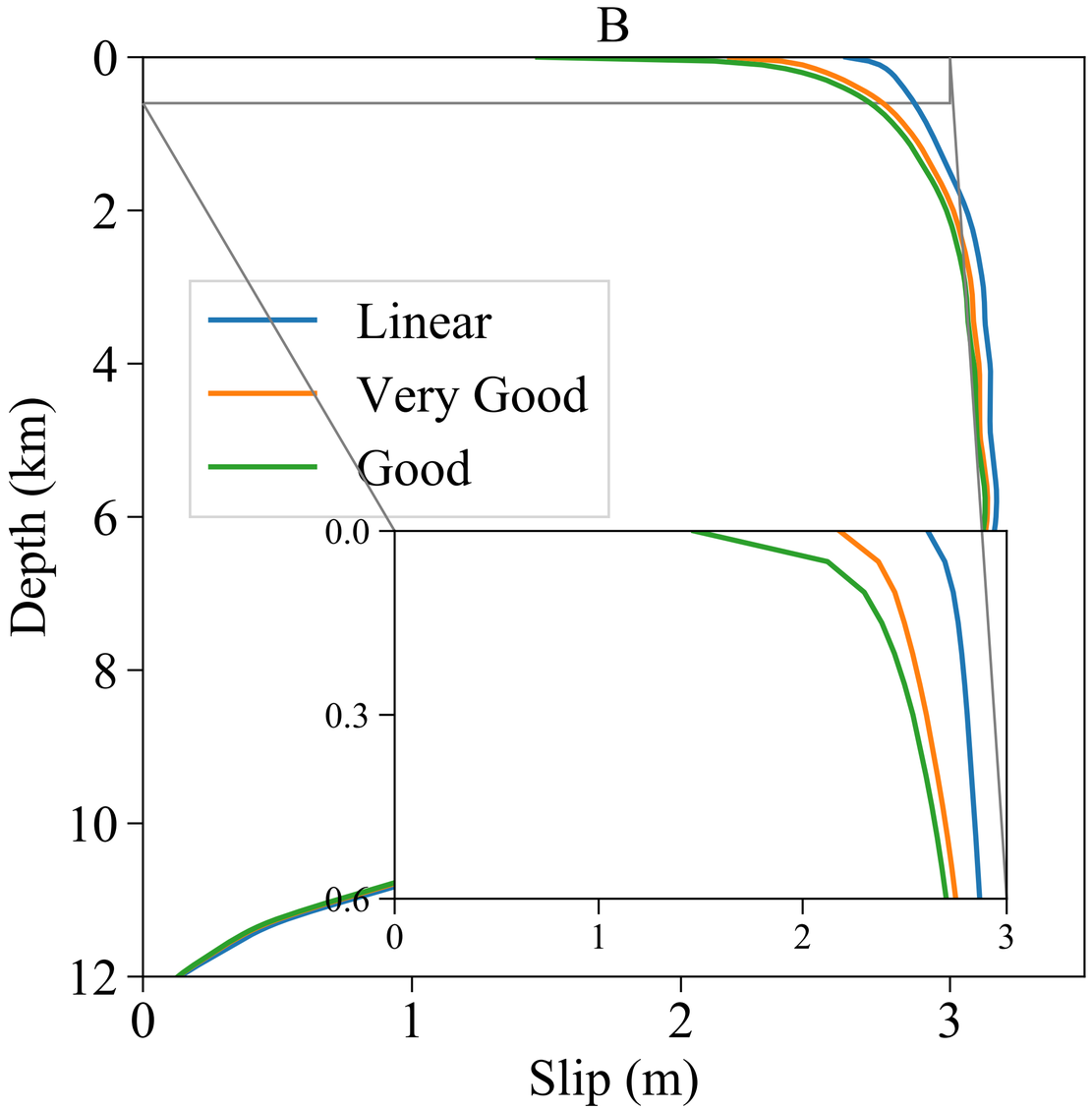

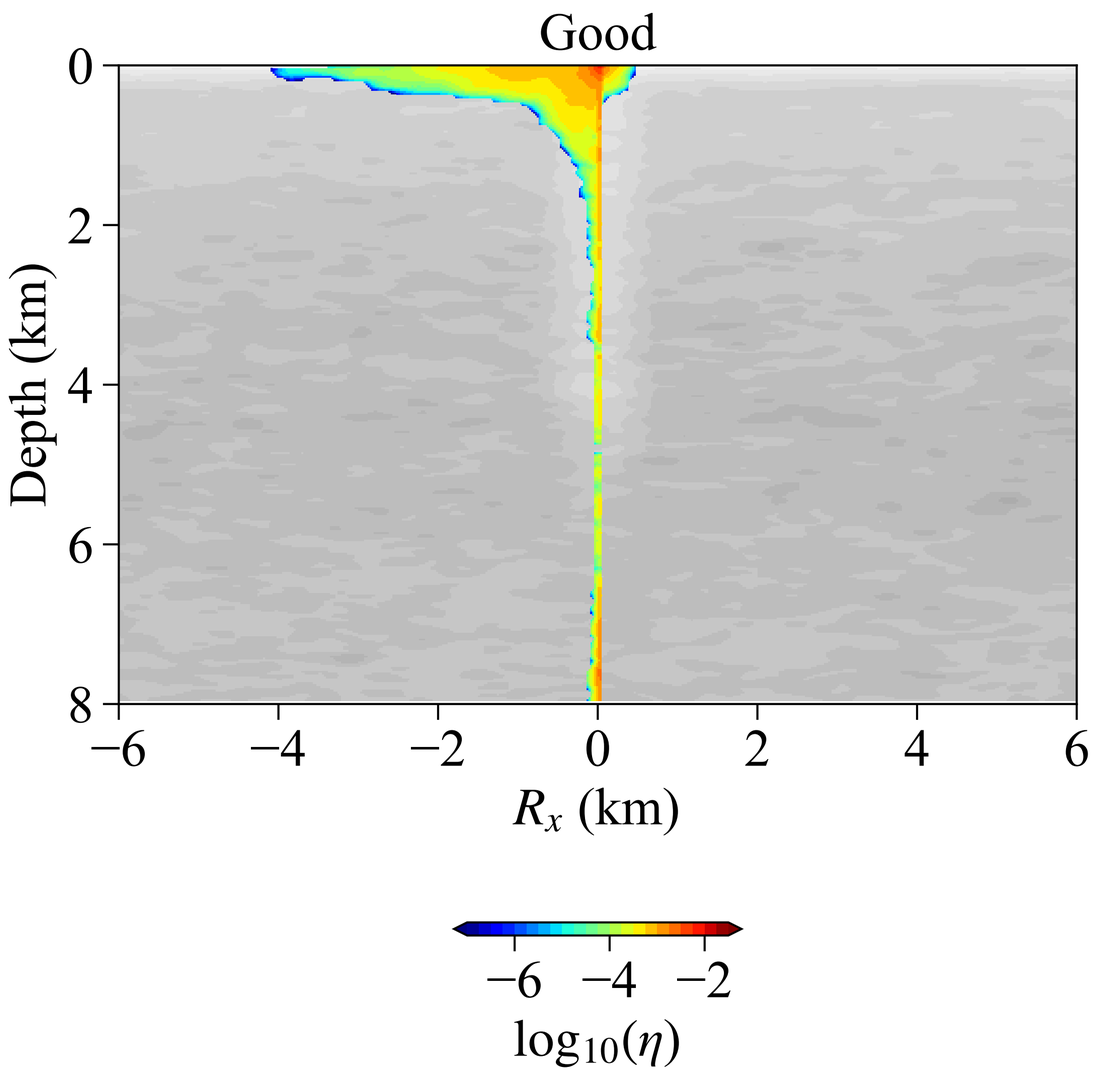

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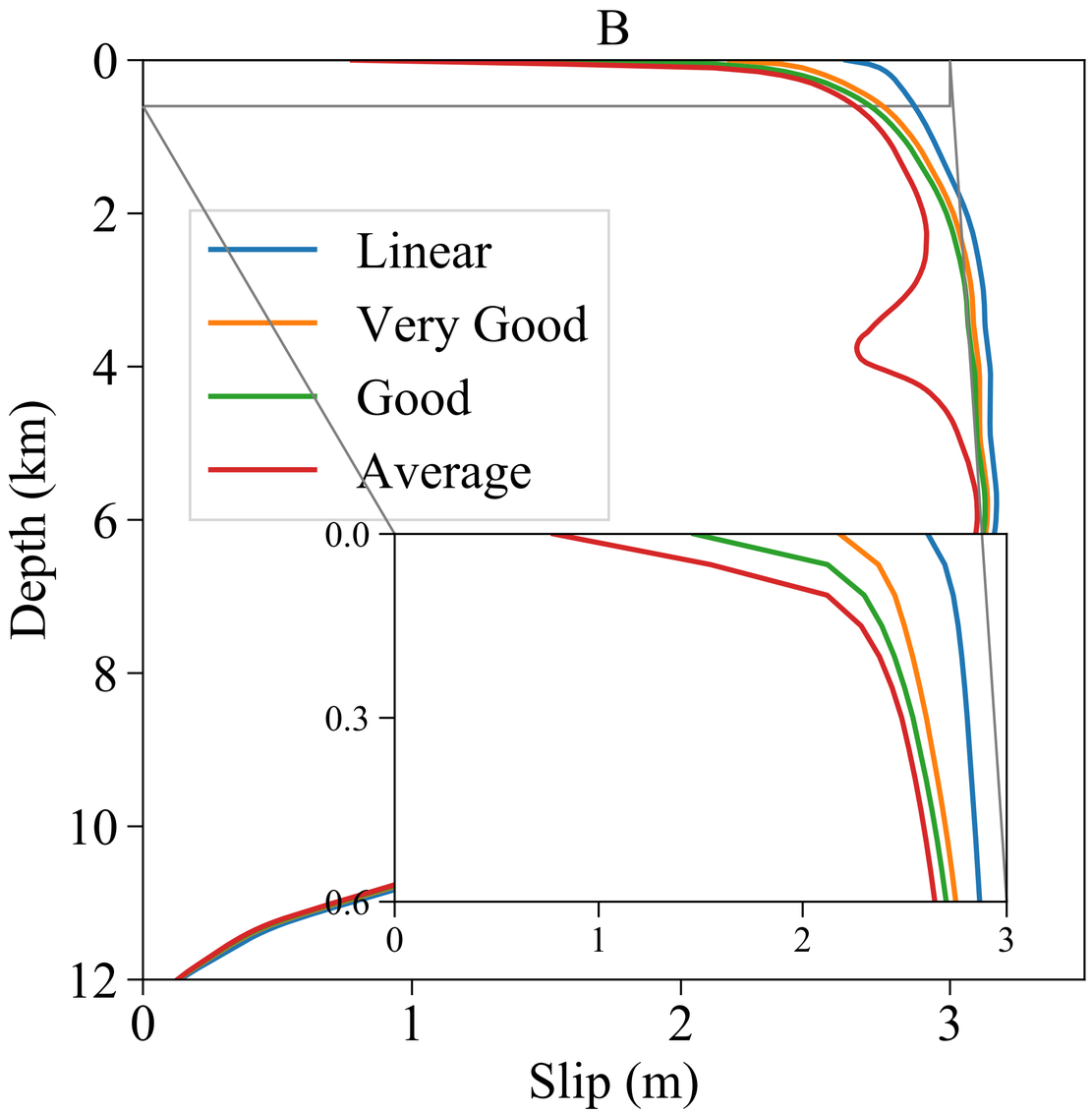

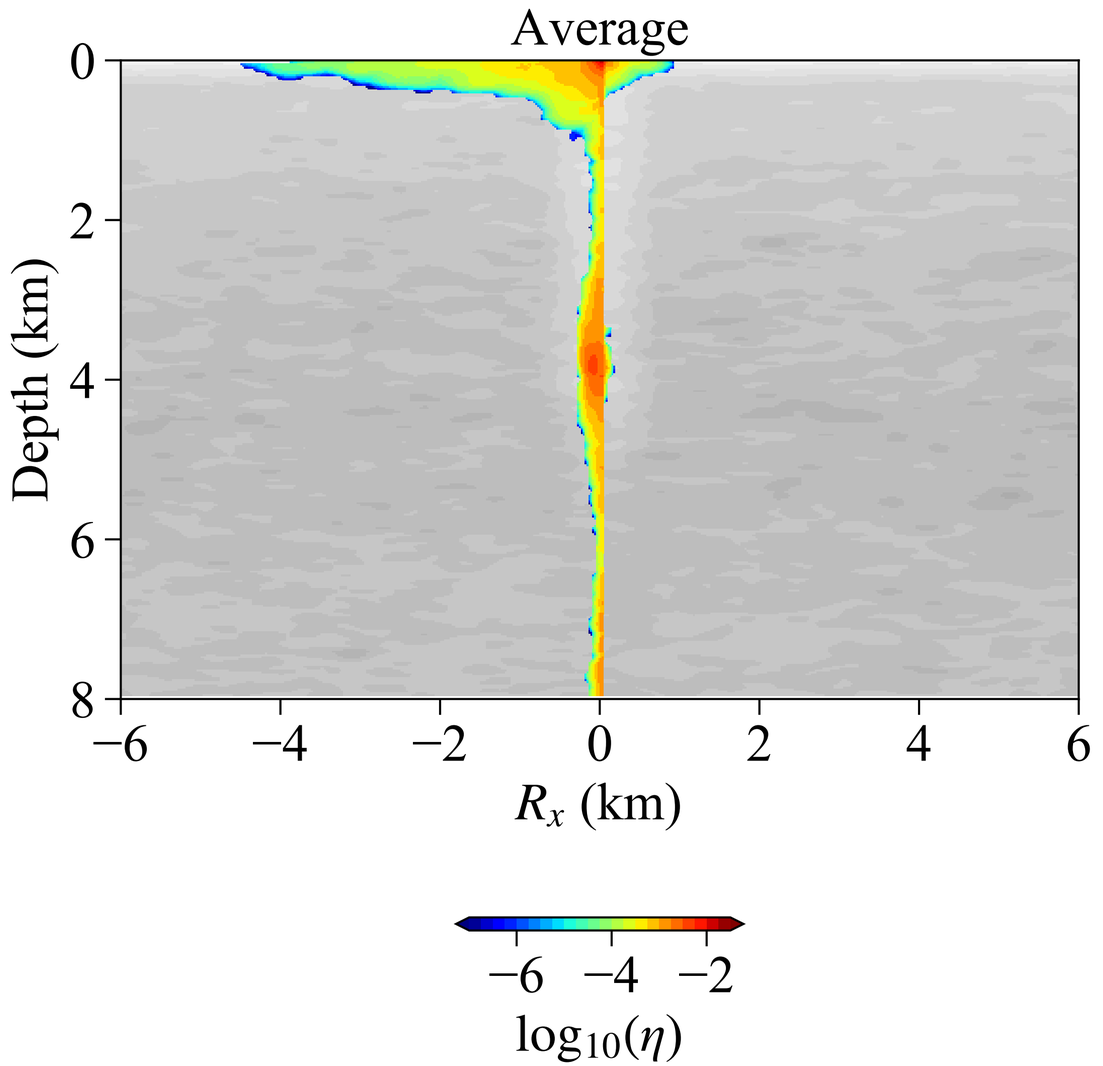

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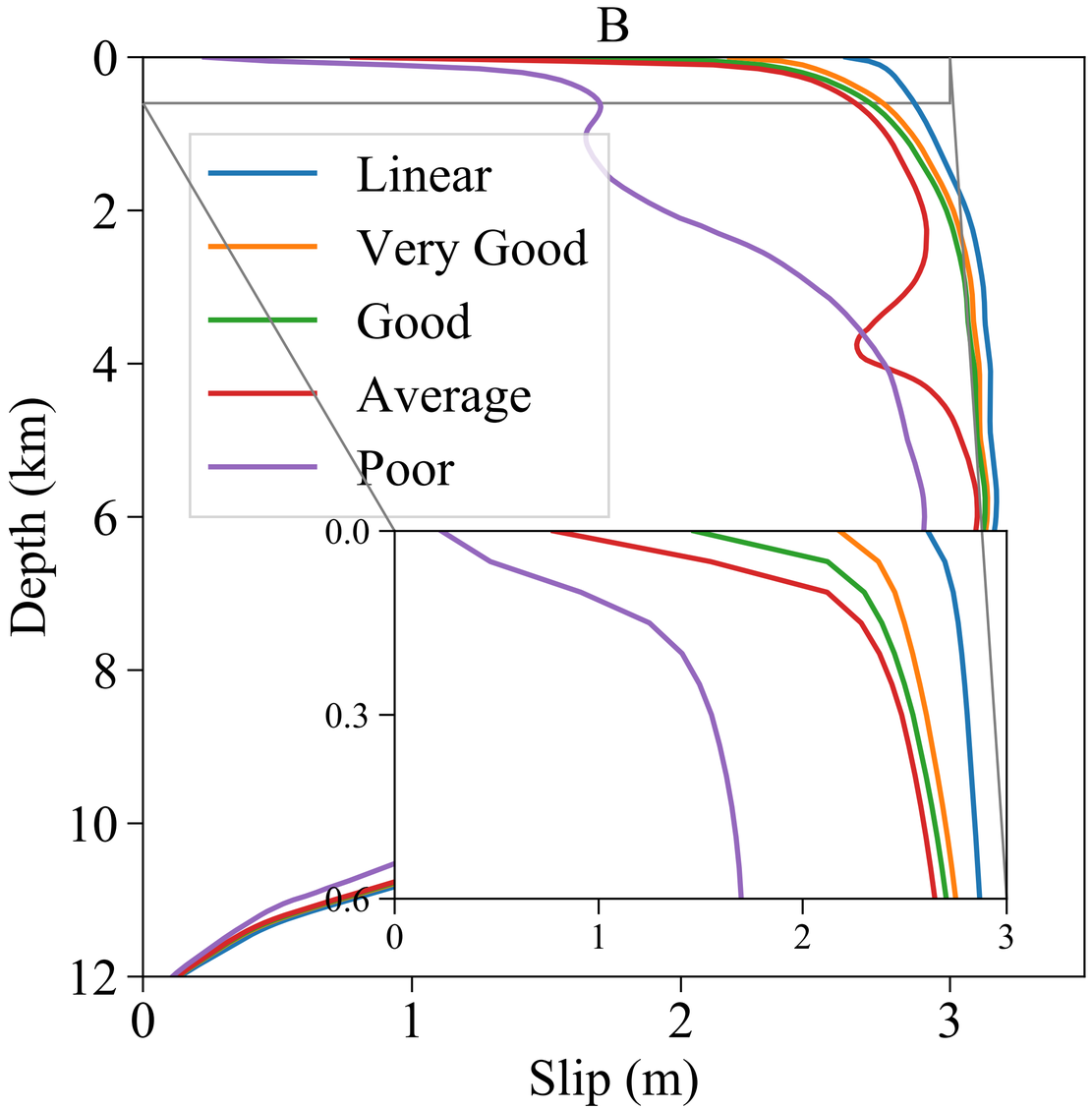
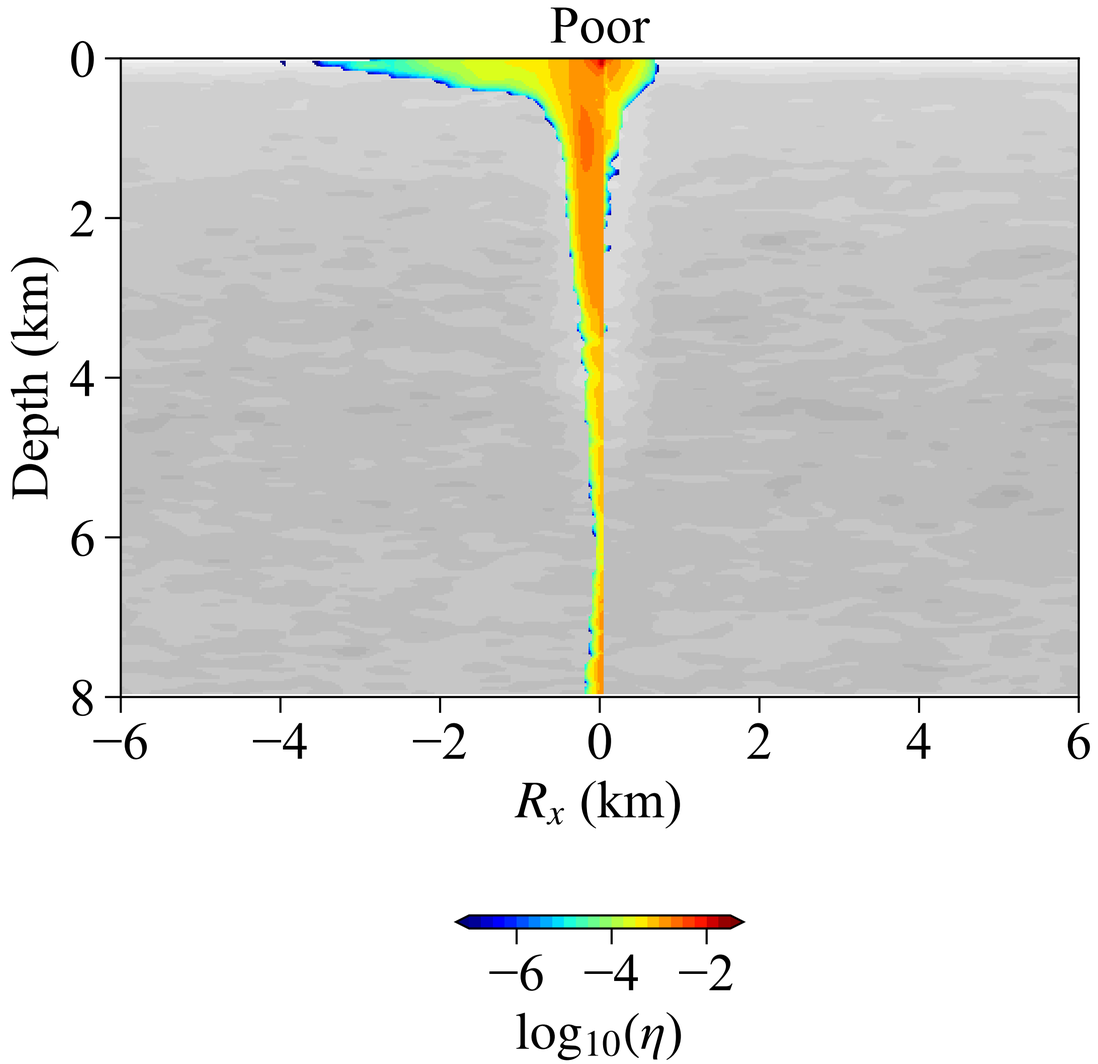
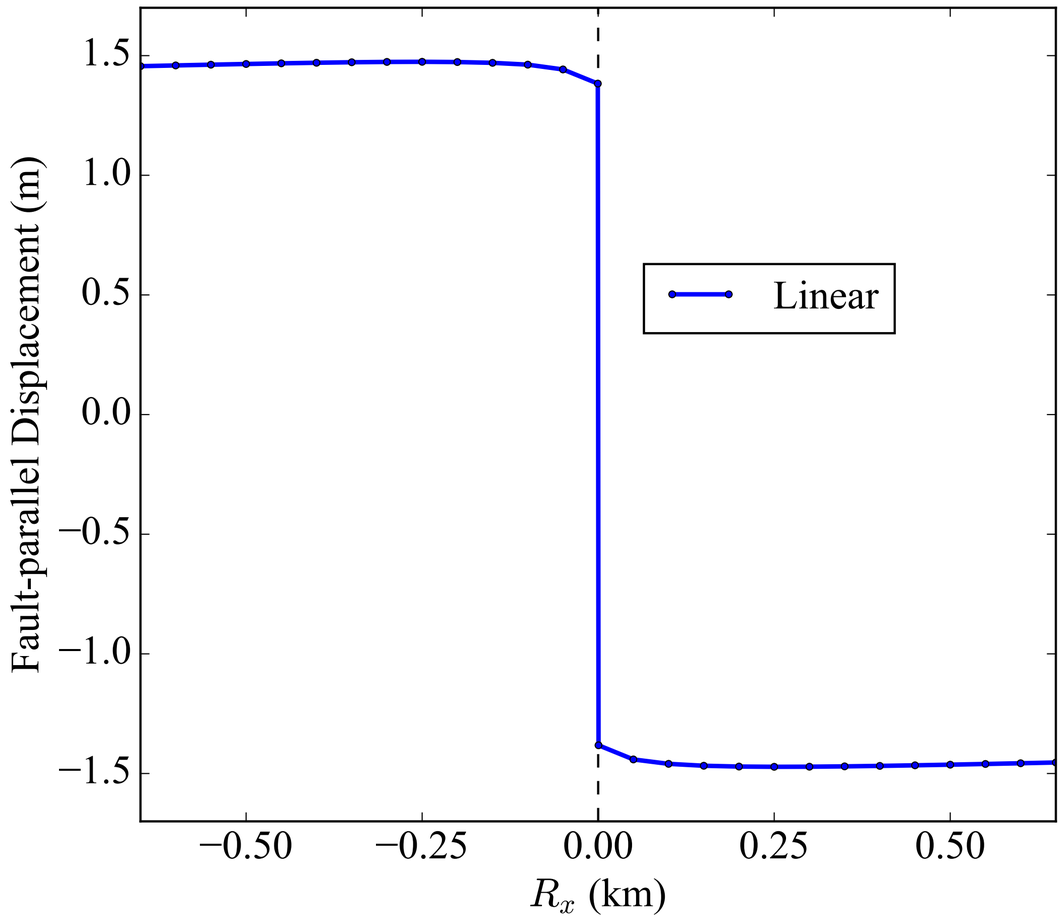




Roten *et al.*, GRL, 2017

Effect of Plasticity on Shear Zone Width

Average of simulated displacement
(rupture model C)



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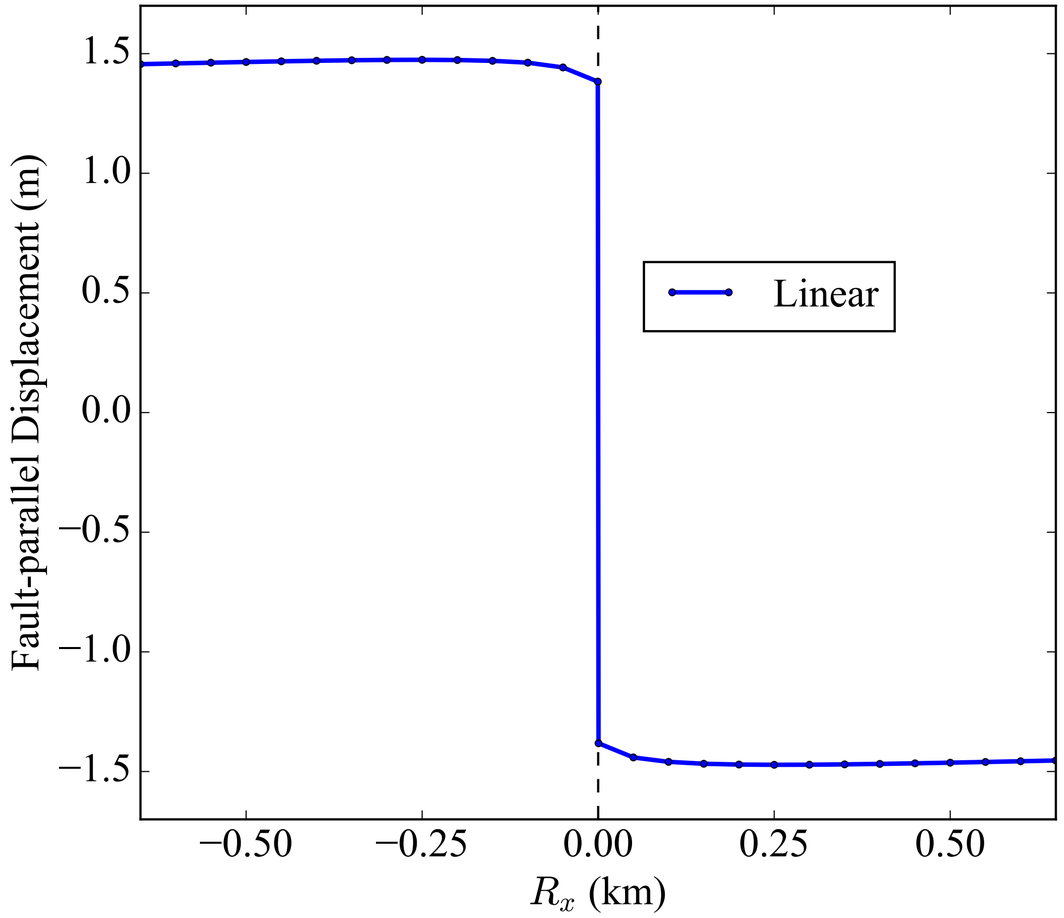
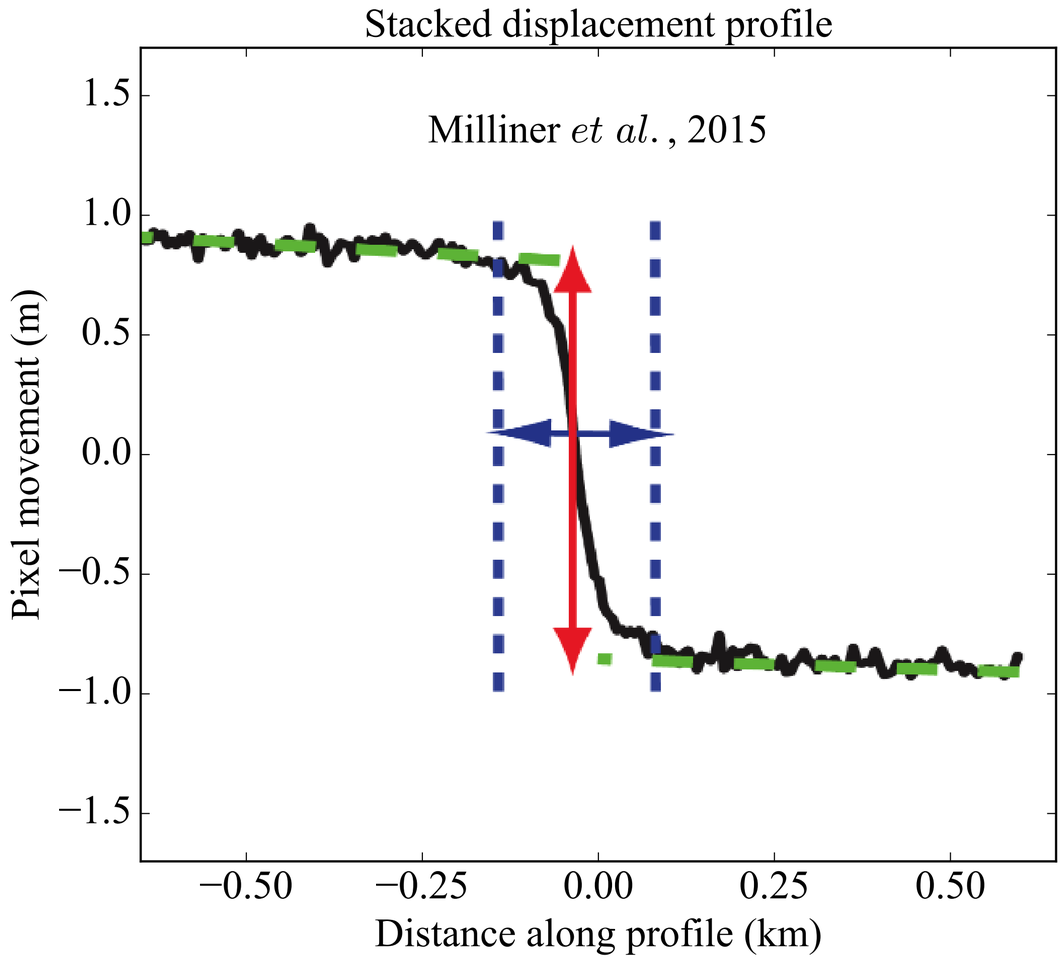


Displacement derived from correlation of aerial images (COSI-Corr)



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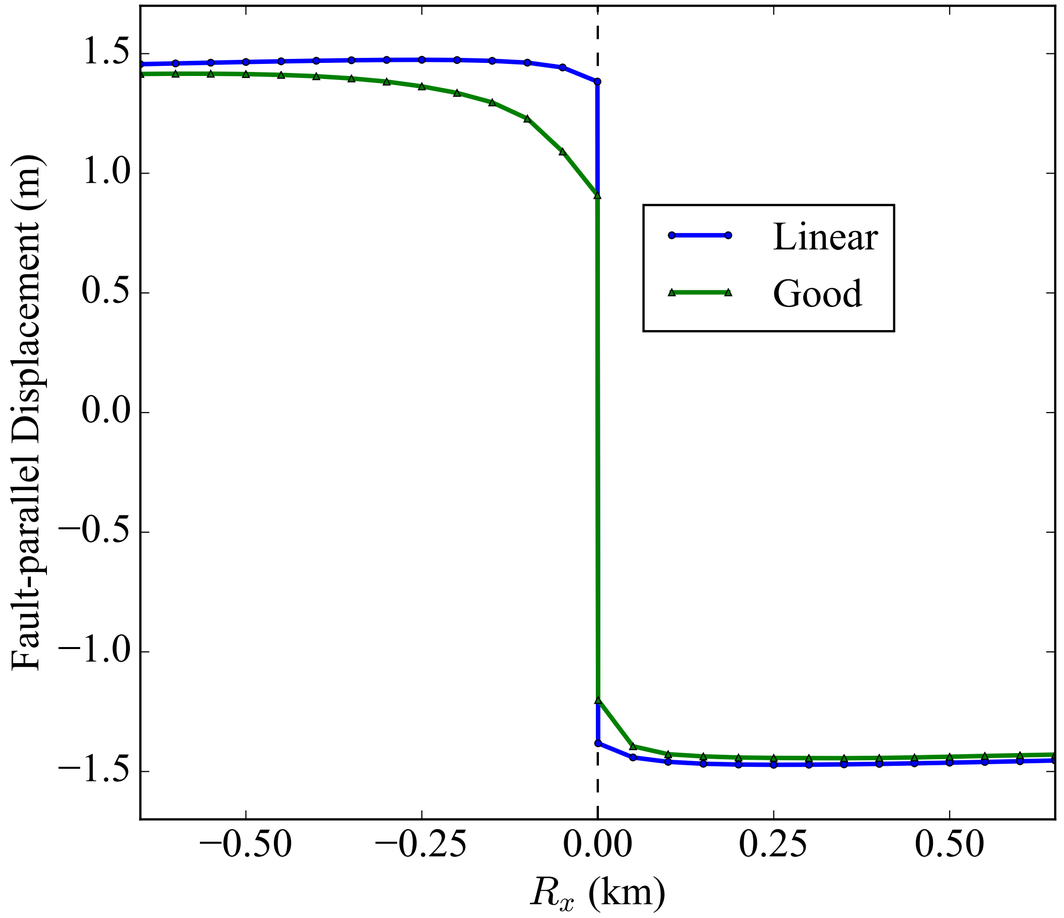

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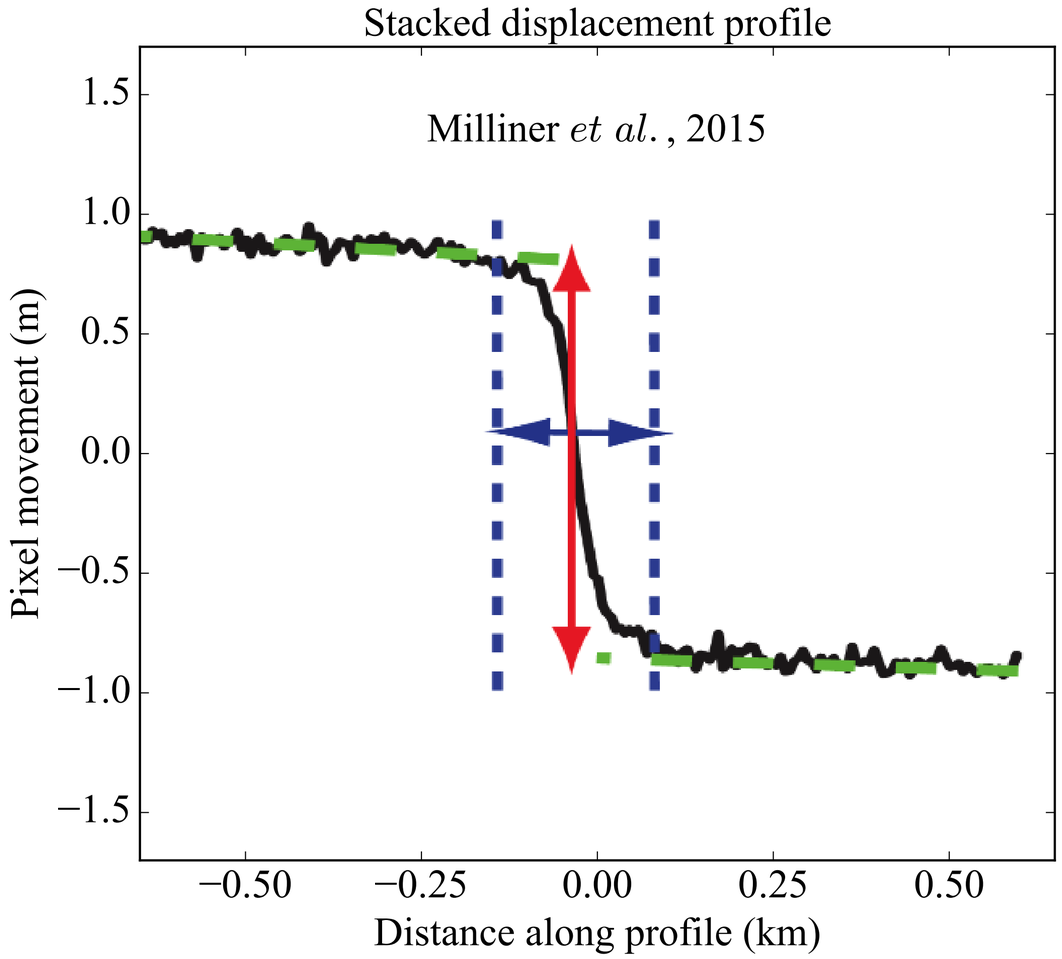

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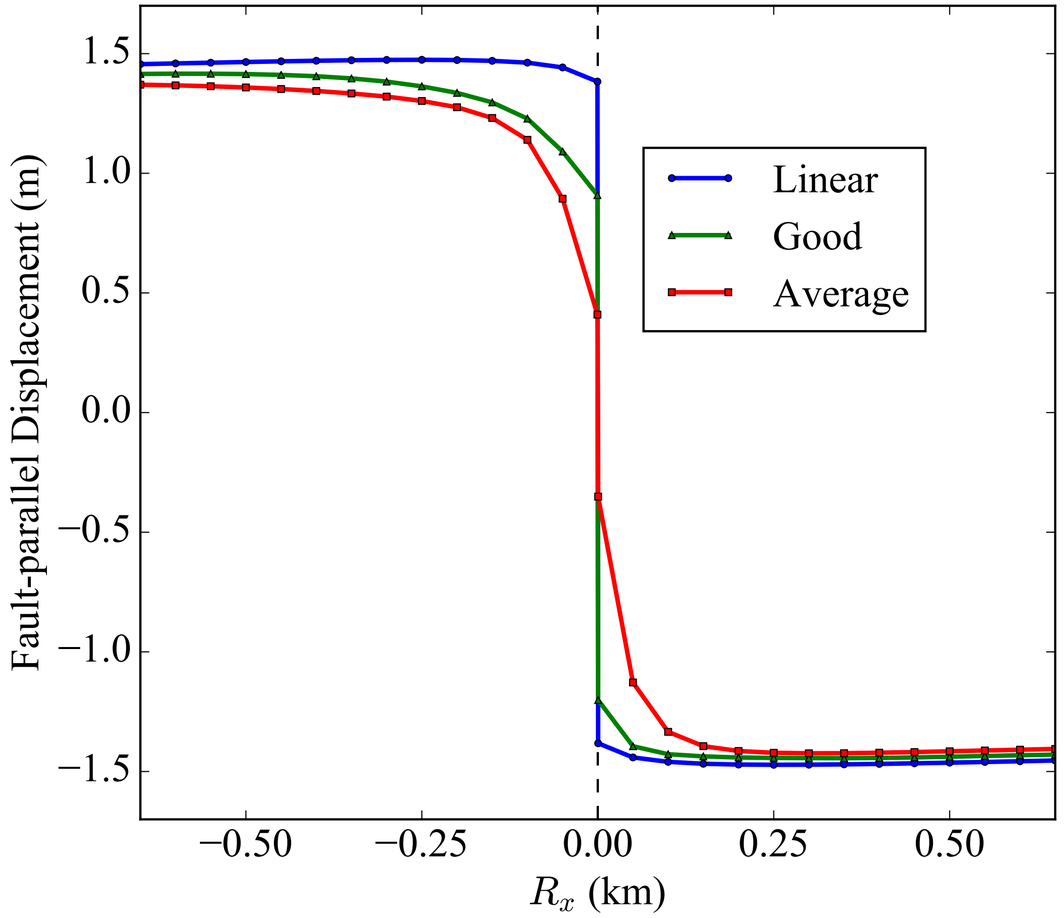

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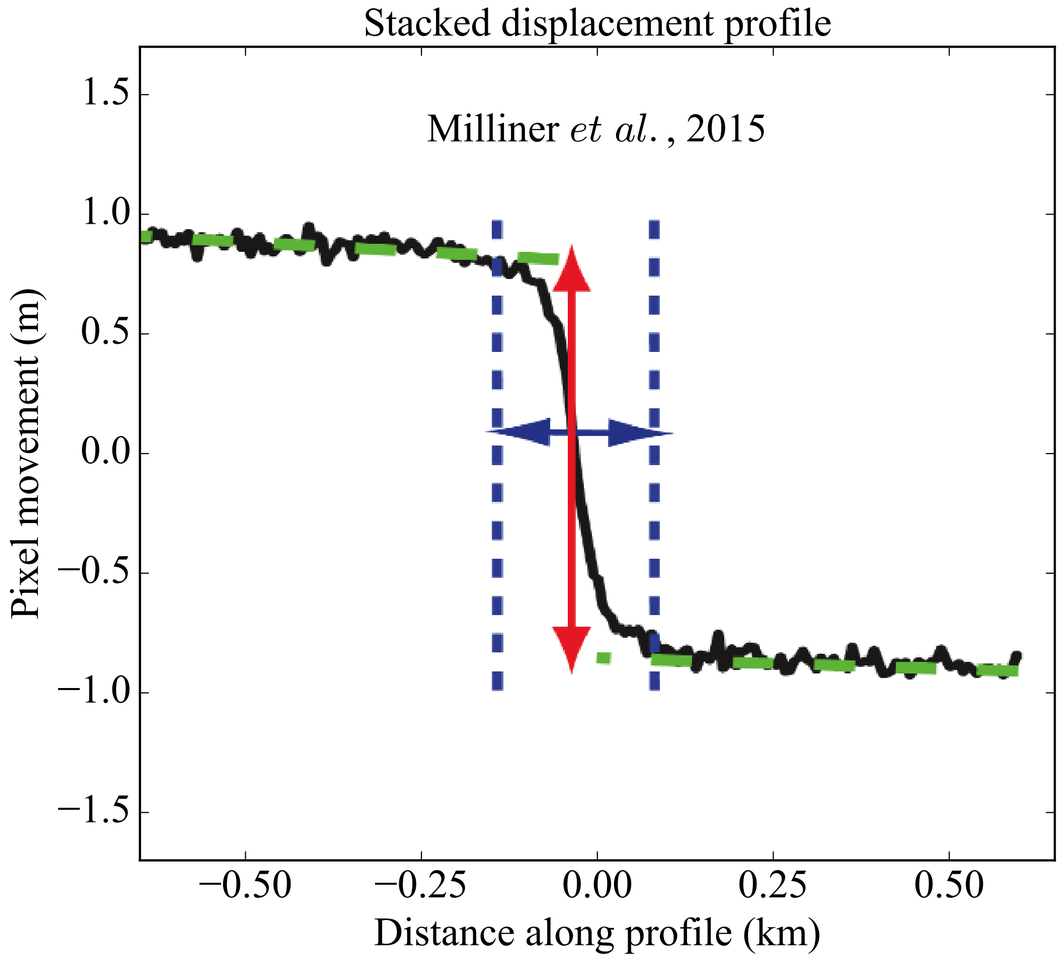

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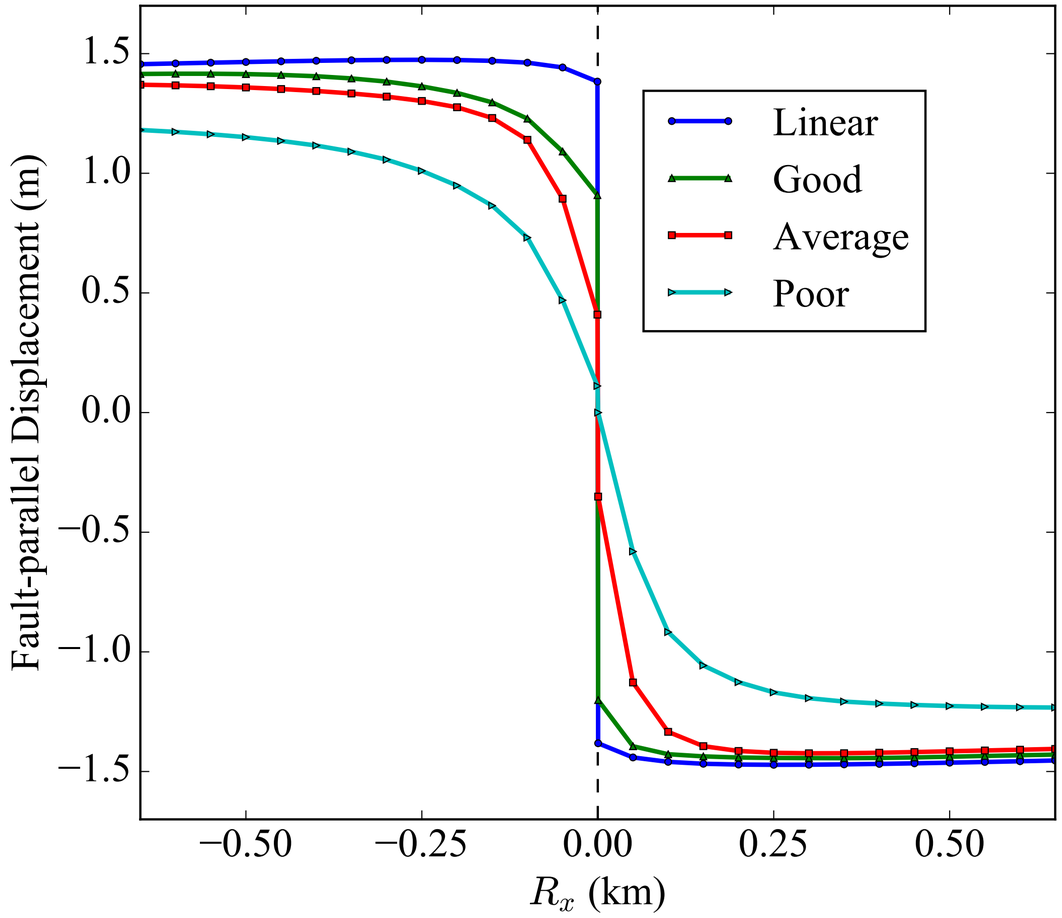

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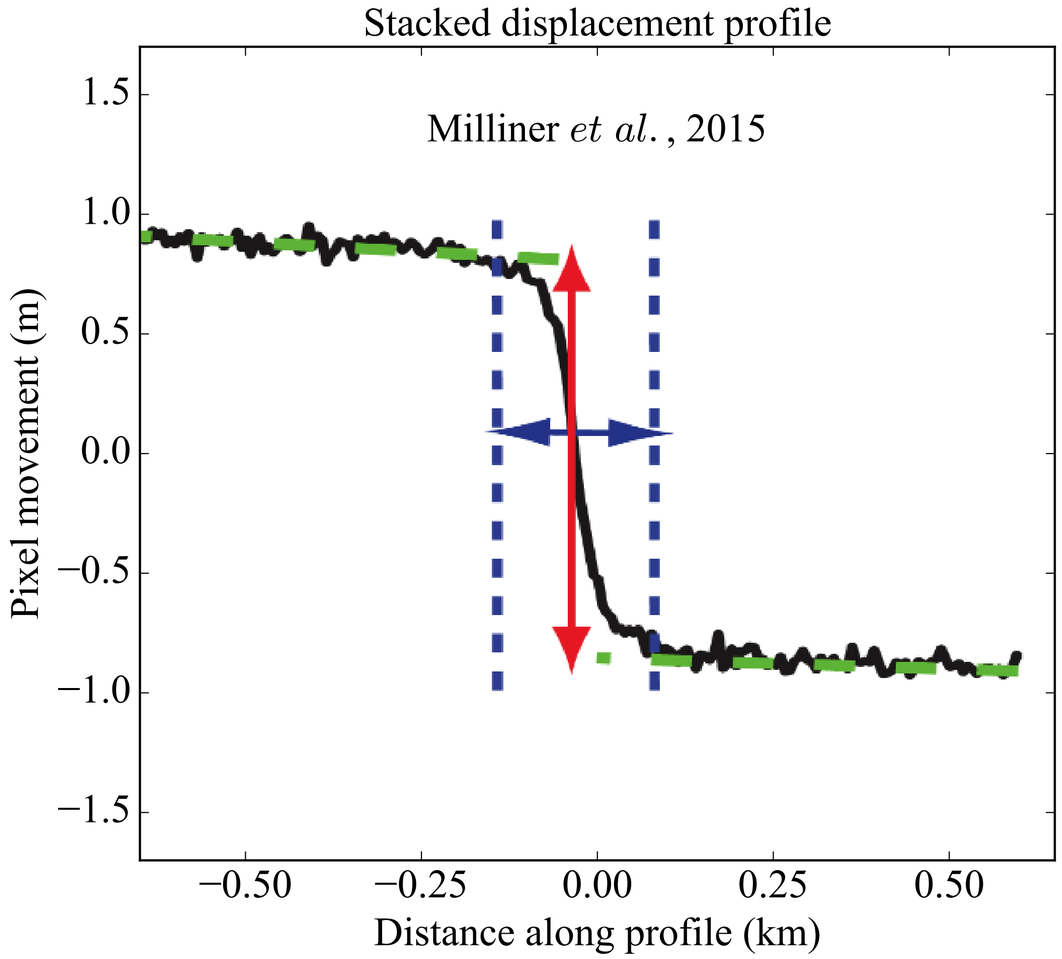
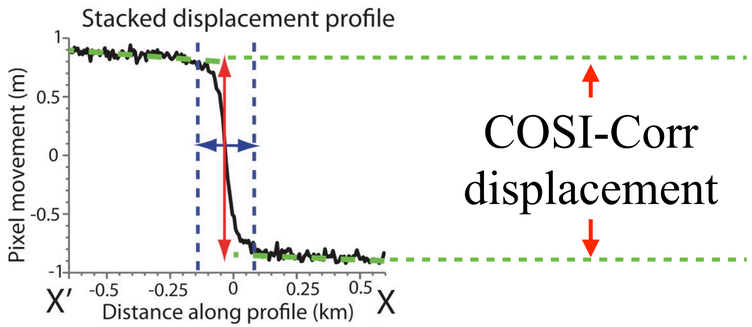
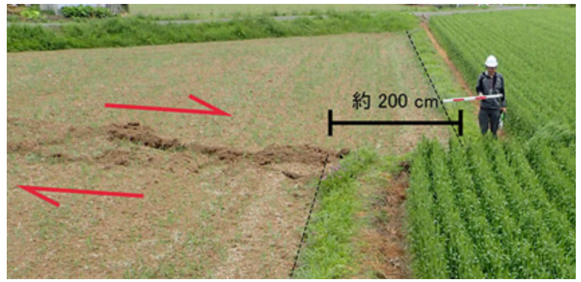


Quantifying Off-fault Deformation (OFD)

Observed off-fault deformation (Milliner *et al.*, 2015):

$$\text{OFD} = \frac{\text{COSI-Corr displacement} - \text{field displacement}}{\text{COSI-Corr displacement}}$$





Main fault strand field displacement

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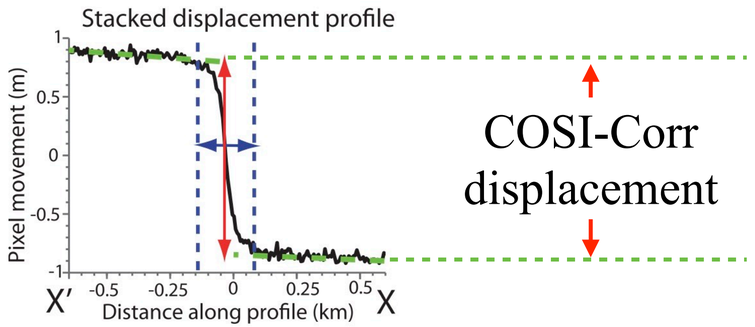
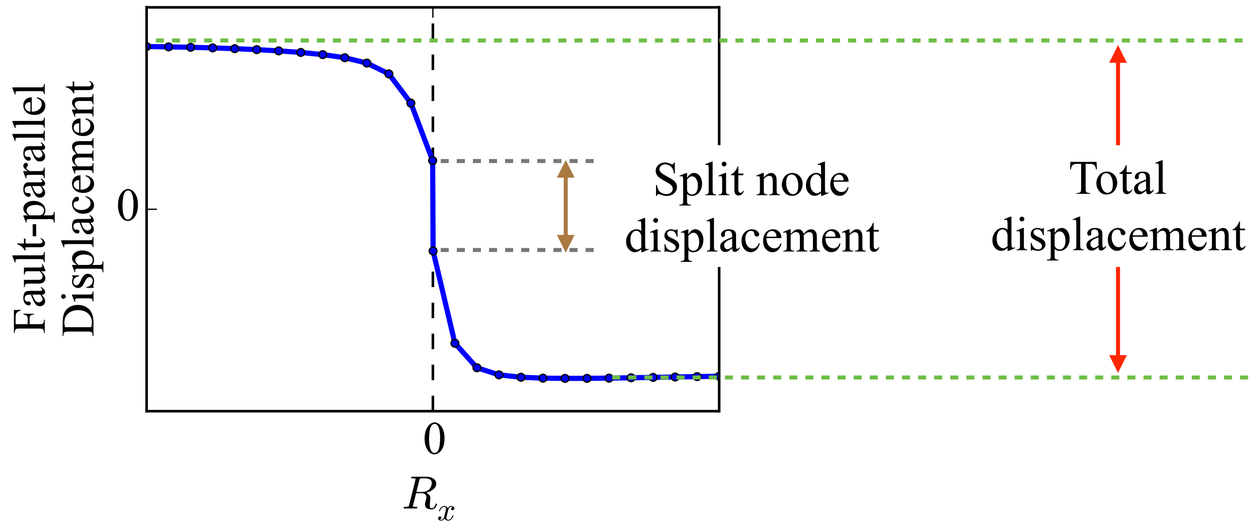


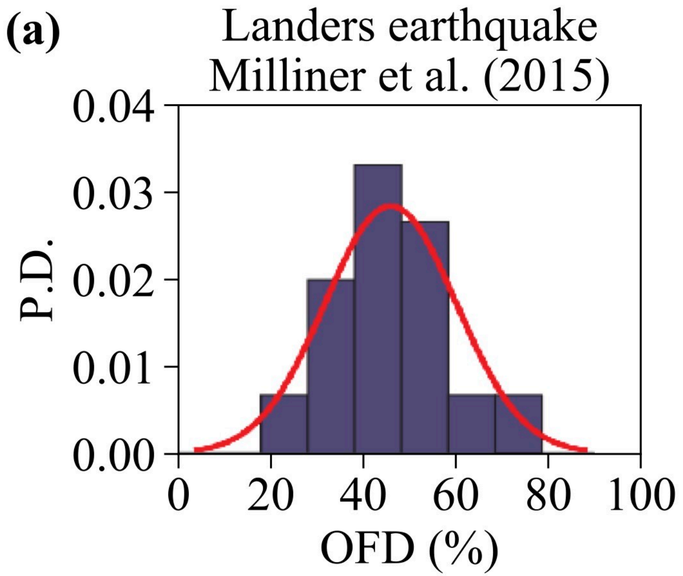
Main fault strand field displacement

Simulated off-fault deformation:

$$\text{OFD} = \frac{\text{Total displacement} - \text{Split node displacement}}{\text{Total displacement}}$$



Distribution of Off-fault Deformation



Roten *et al.*, GRL, 2017

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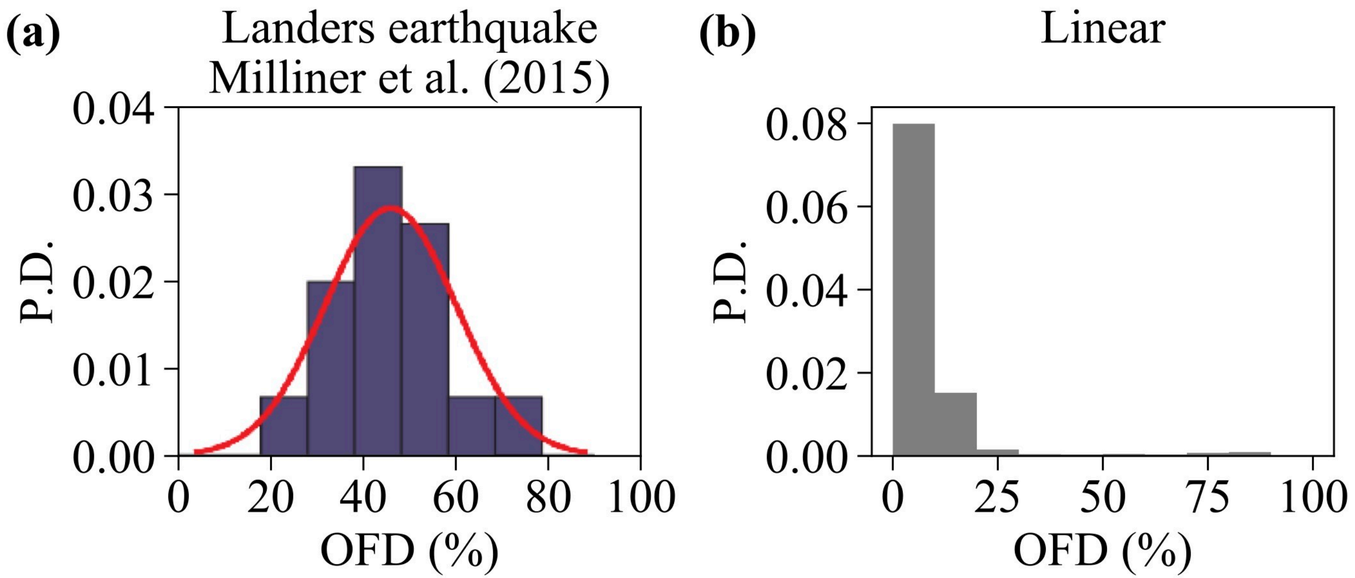

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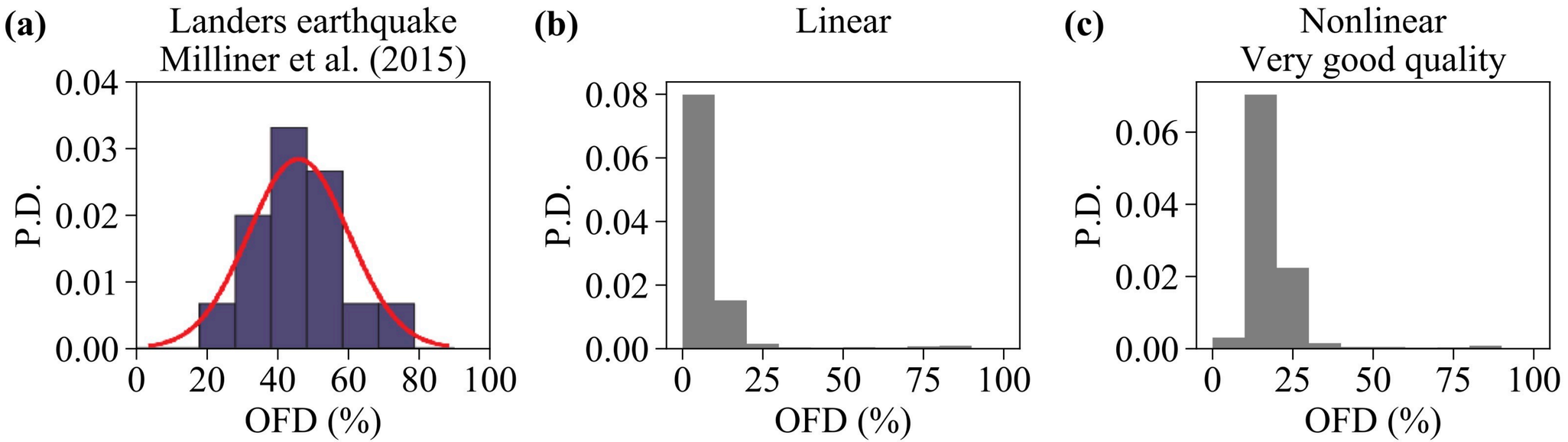
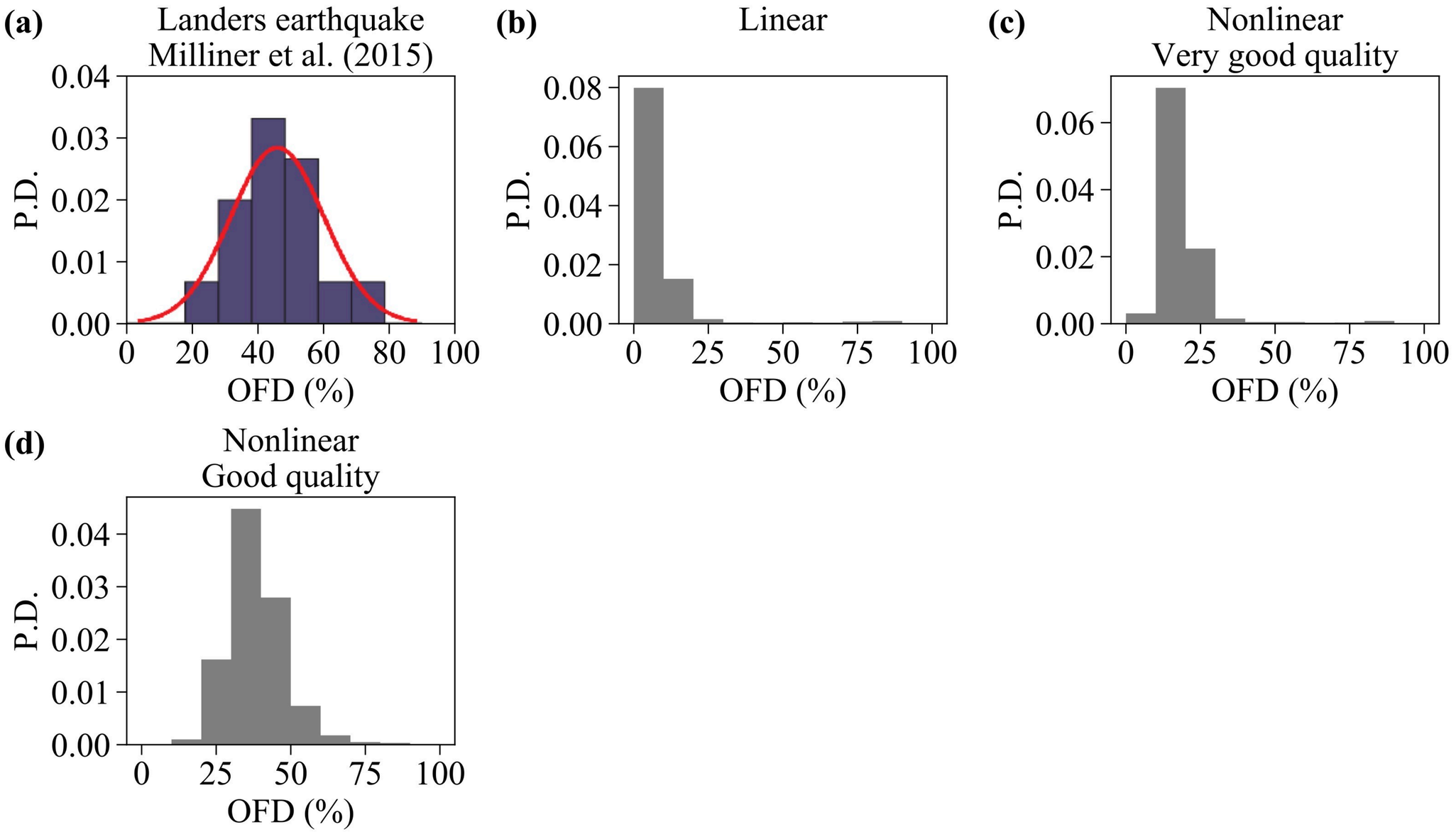


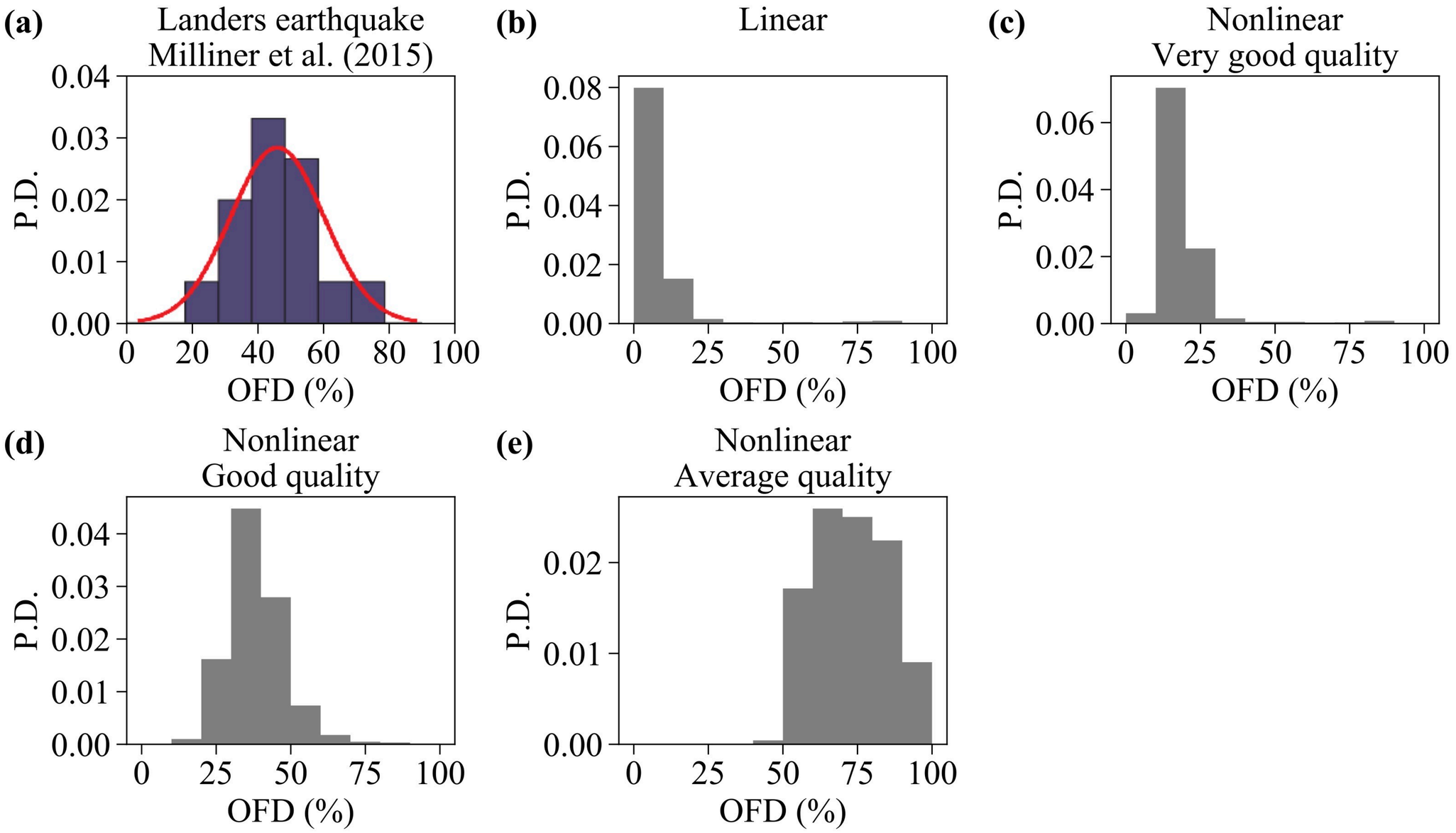
Roten *et al.*, GRL, 2017

Distribution of Off-fault Deformation



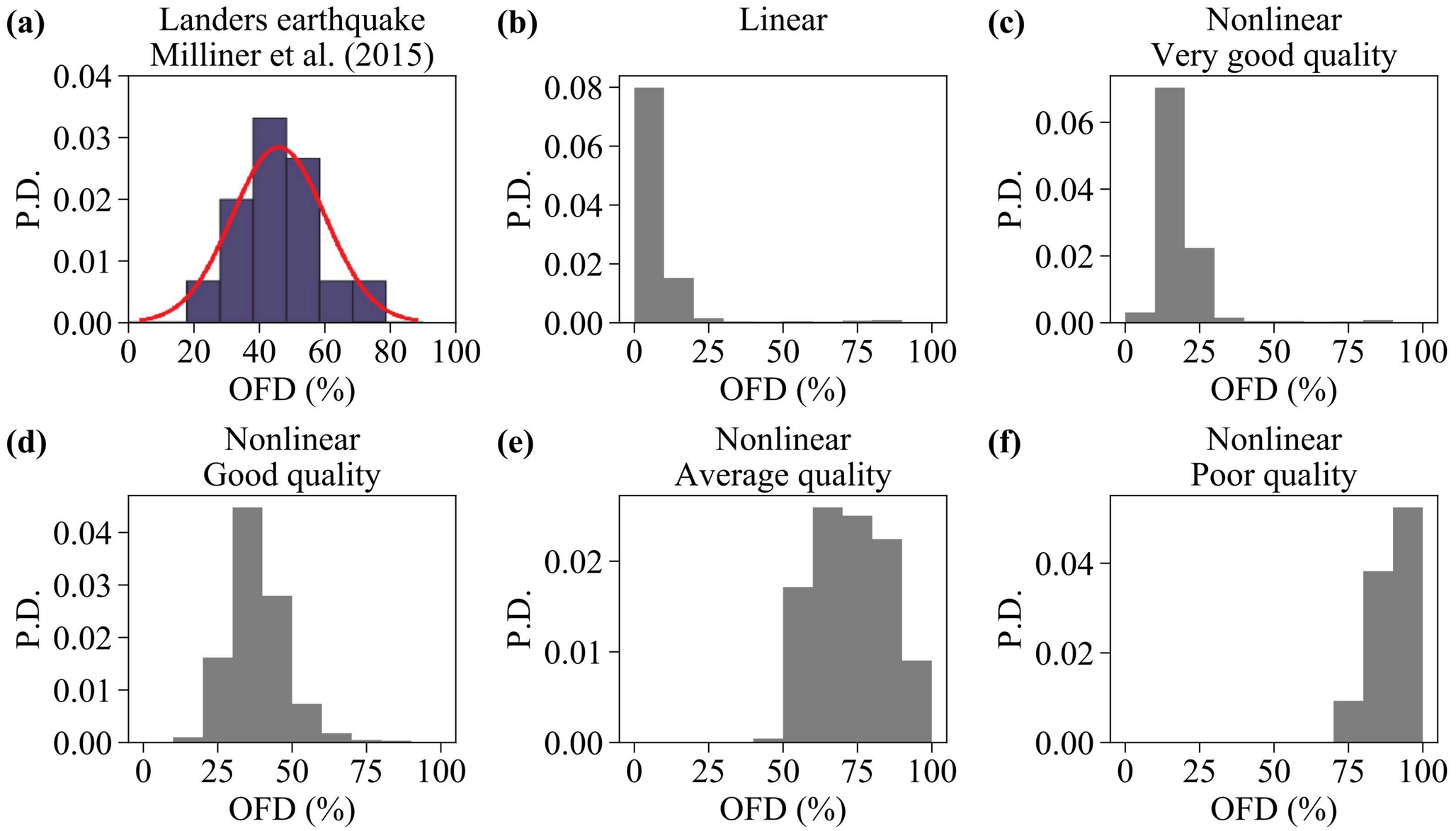
Roten *et al.*, GRL, 2017

Distribution of Off-fault Deformation



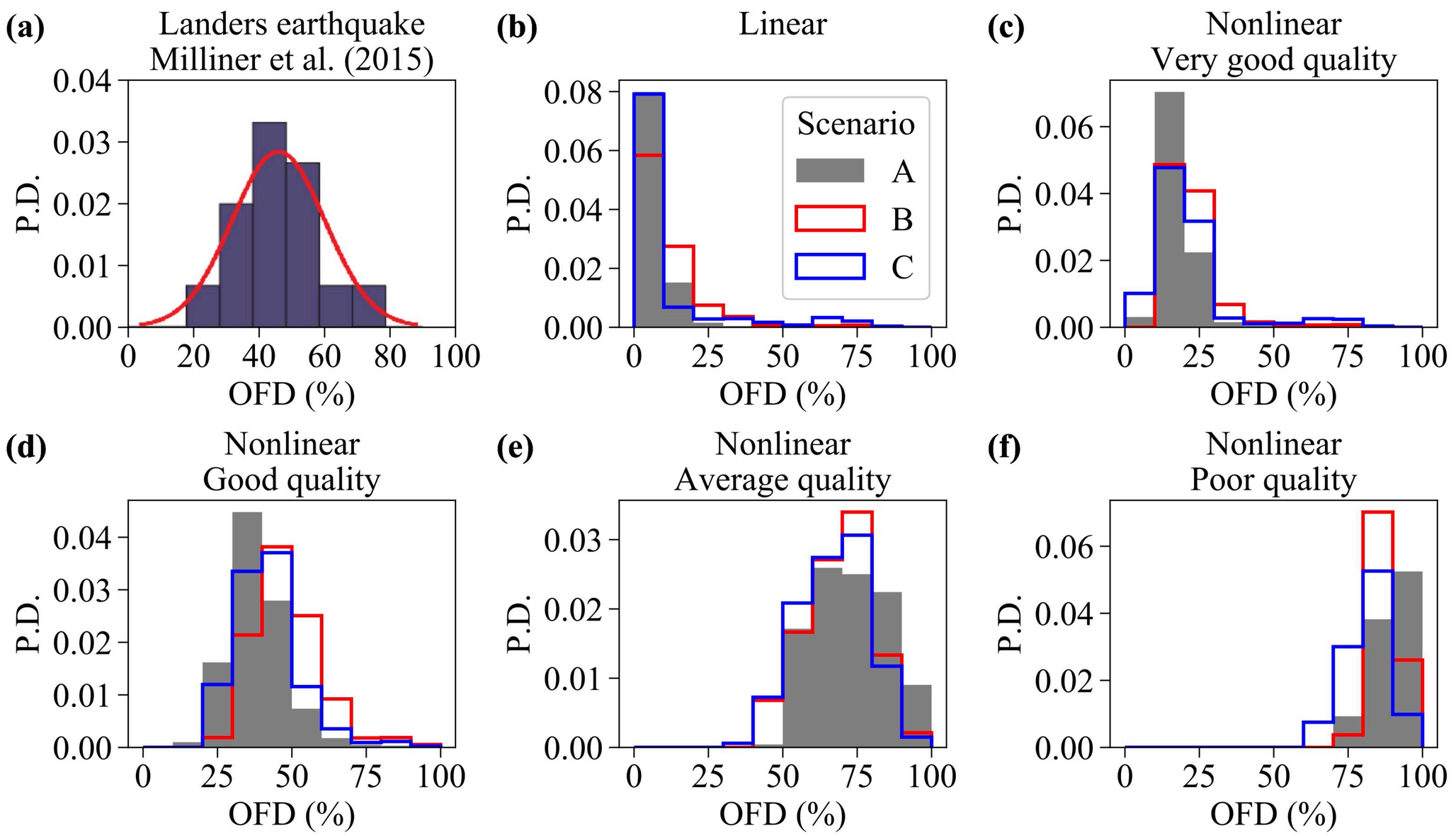
Roten *et al.*, GRL, 2017

Distribution of Off-fault Deformation



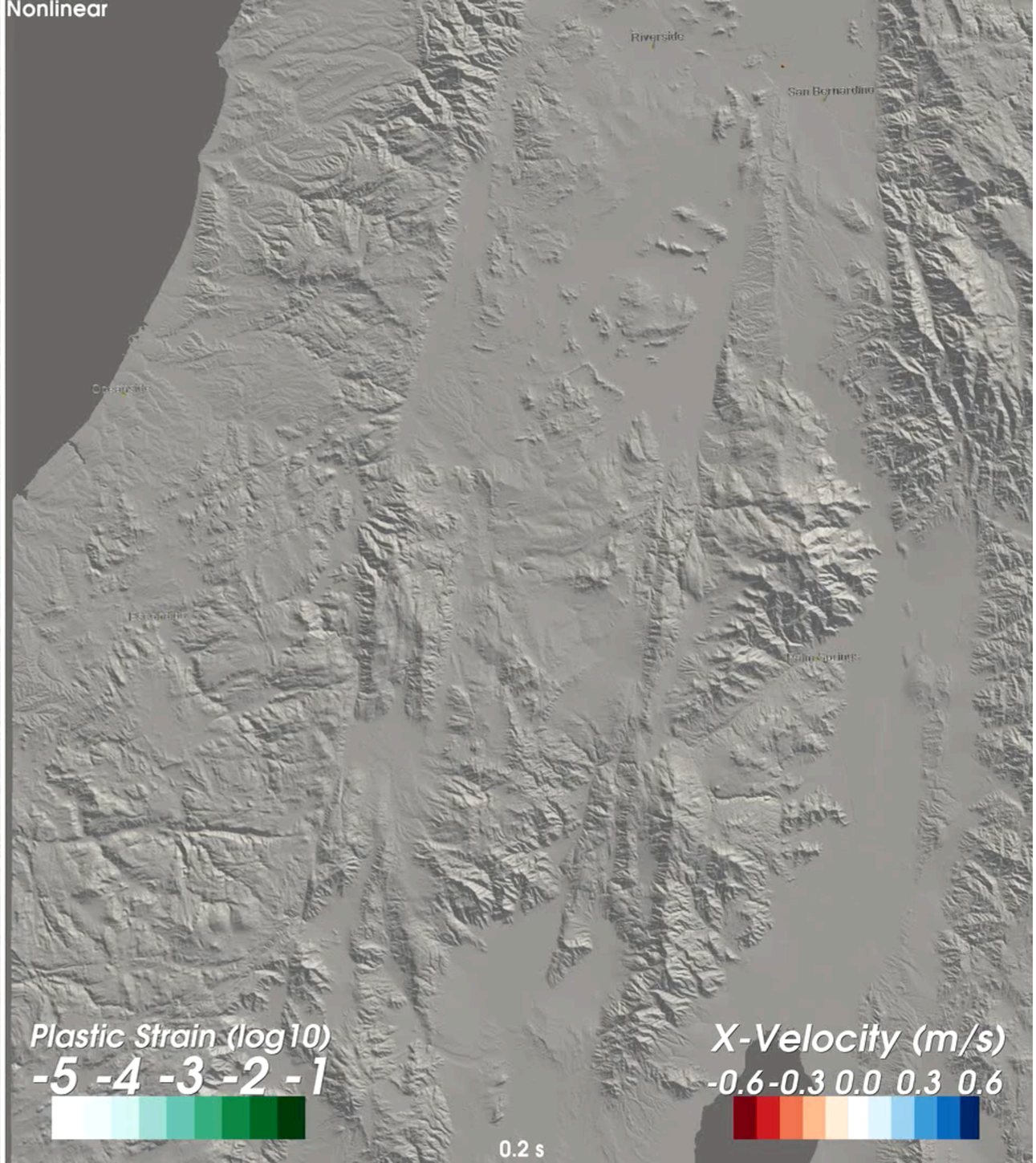
Roten *et al.*, GRL, 2017

Distribution of Off-fault Deformation

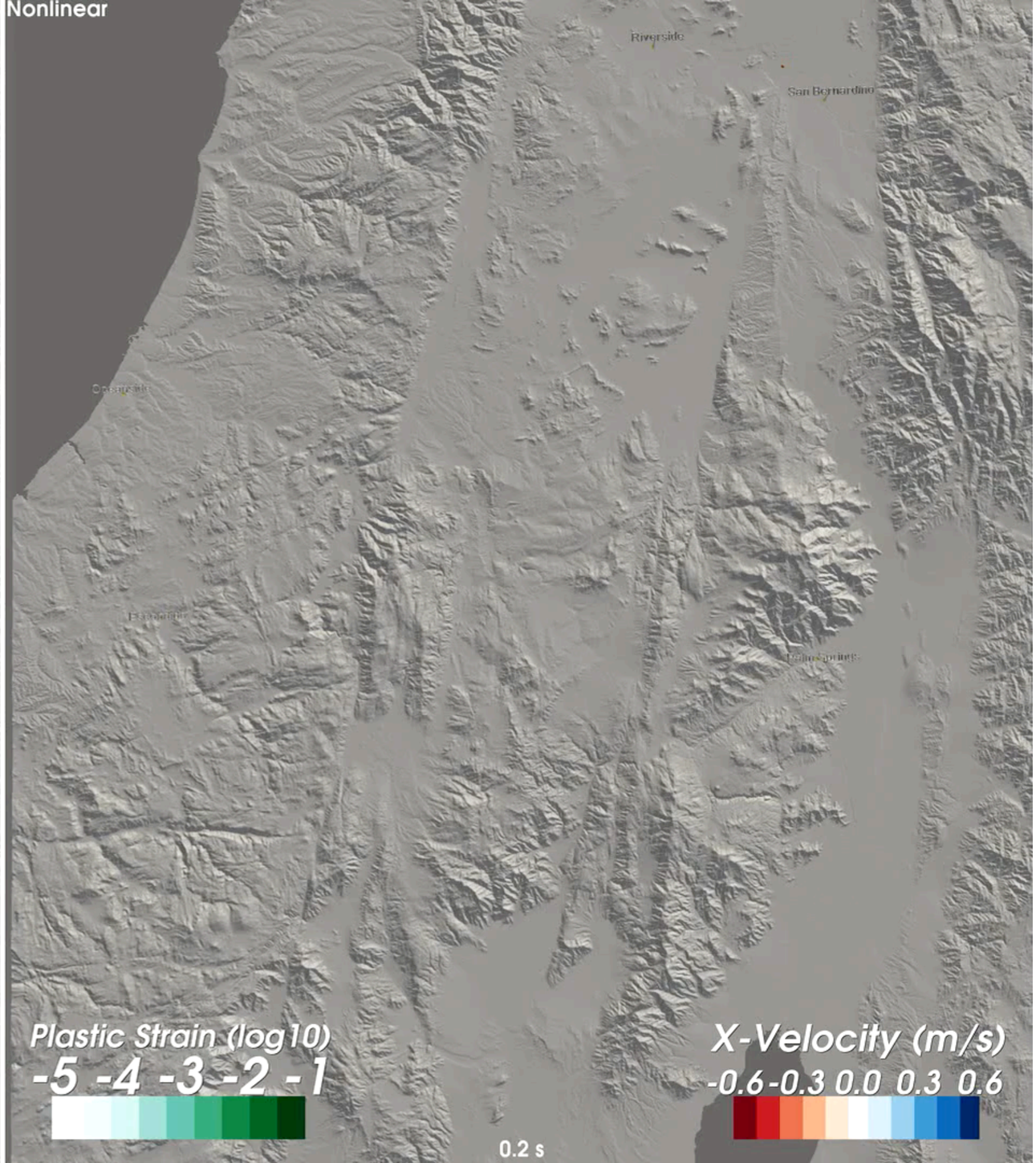


Roten *et al.*, GRL, 2017


Linear
Riverside
San Bernardino
Oceanside
Escondido
Palm Springs
X-Velocity (m/s)
-0.6 -0.3 0.0 0.3 0.6
0.2 s


Nonlinear
Riverside
San Bernardino
Oceanside
Escondido
Palm Springs
Plastic Strain (log10)
-5 -4 -3 -2 -1
X-Velocity (m/s)
-0.6 -0.3 0.0 0.3 0.6
0.2 s


Linear
Riverside
San Bernardino
Oceanside
Escondido
Palm Springs
X-Velocity (m/s)
-0.6 -0.3 0.0 0.3 0.6
0.2 s


Nonlinear
Riverside
San Bernardino
Oceanside
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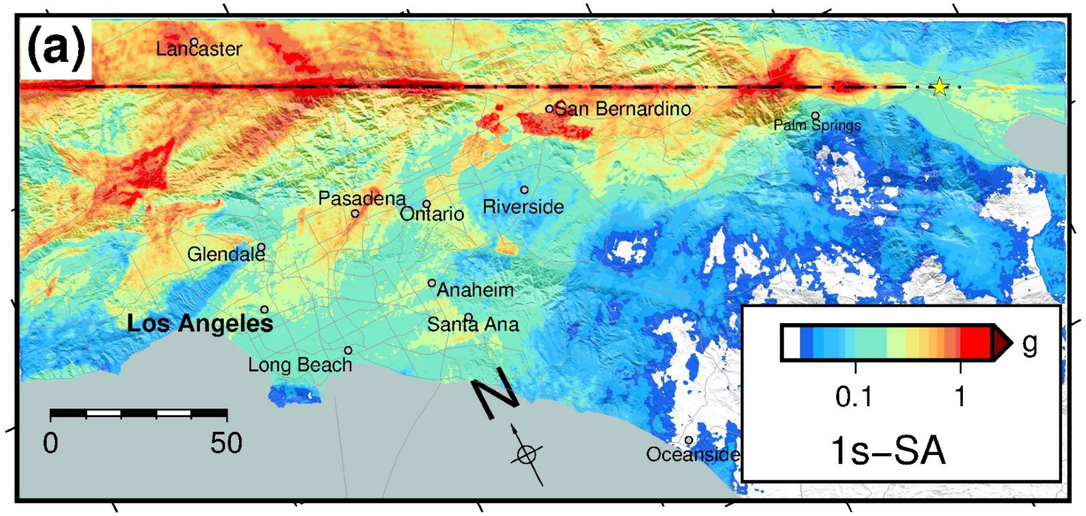
Palm Springs
Plastic Strain (log10)
-5 -4 -3 -2 -1
X-Velocity (m/s)
-0.6 -0.3 0.0 0.3 0.6
0.2 s

Southern San Andreas Scenarios with Plasticity

Spectral Acceleration at 1s (1s-SAs): Linear



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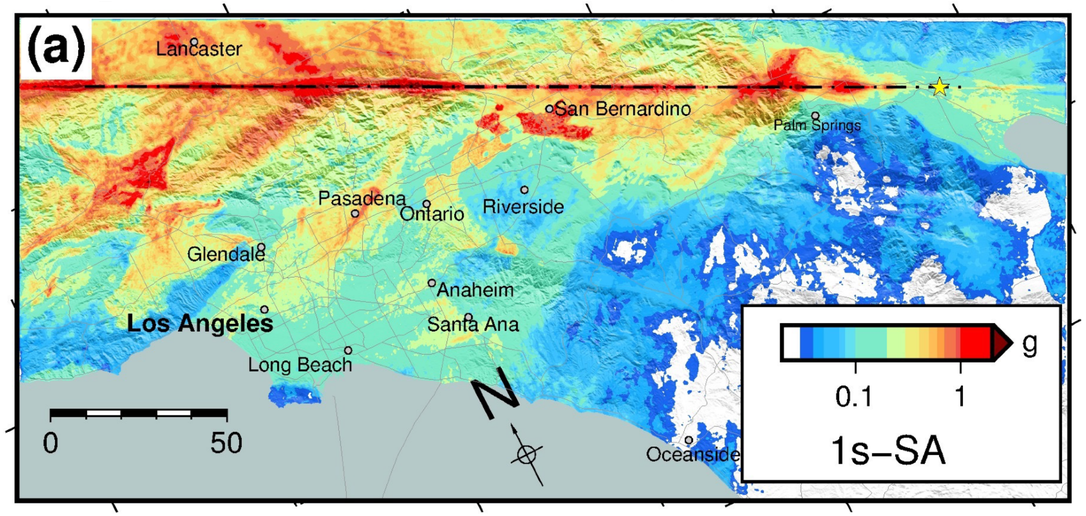
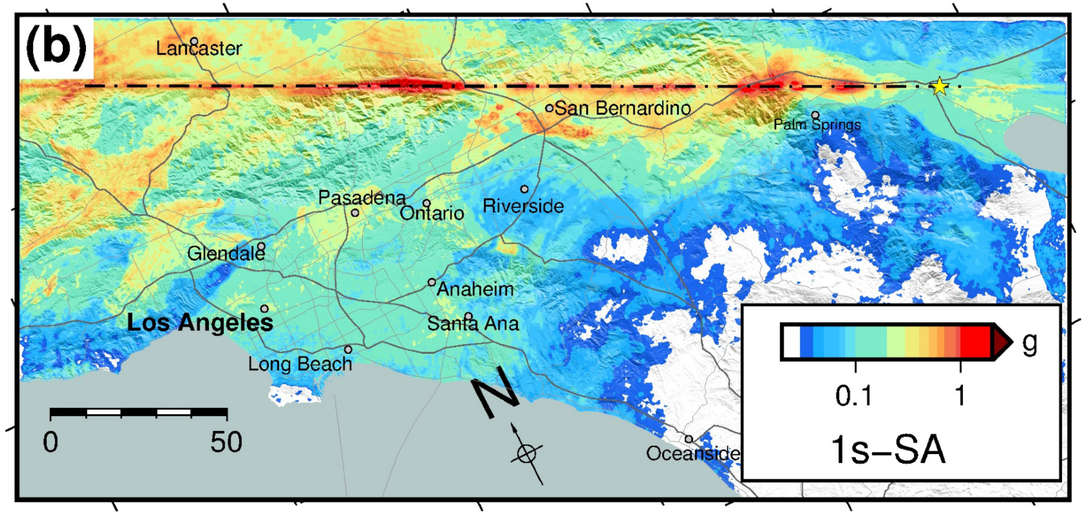


1s-SAs: Nonlinear, Good—Average Quality Rock



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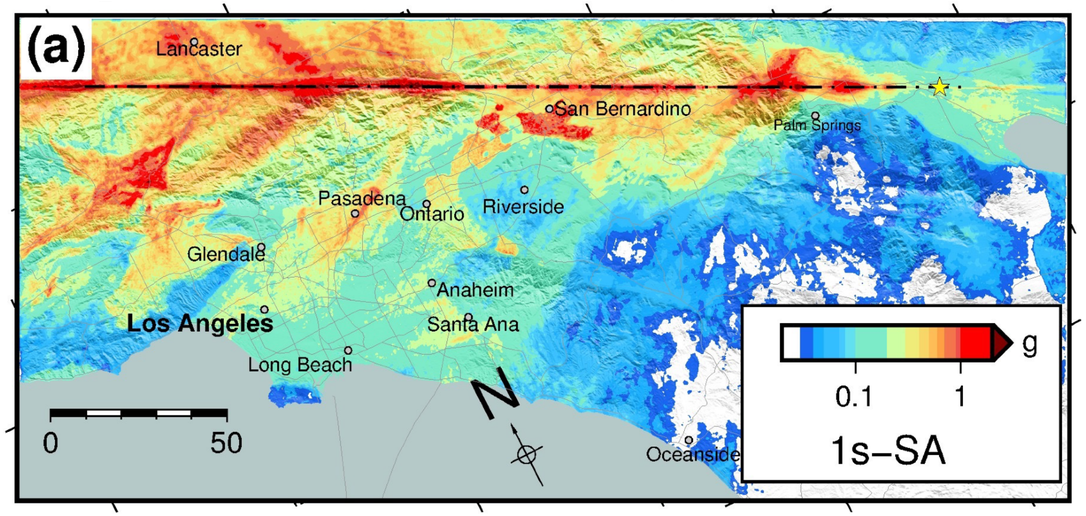
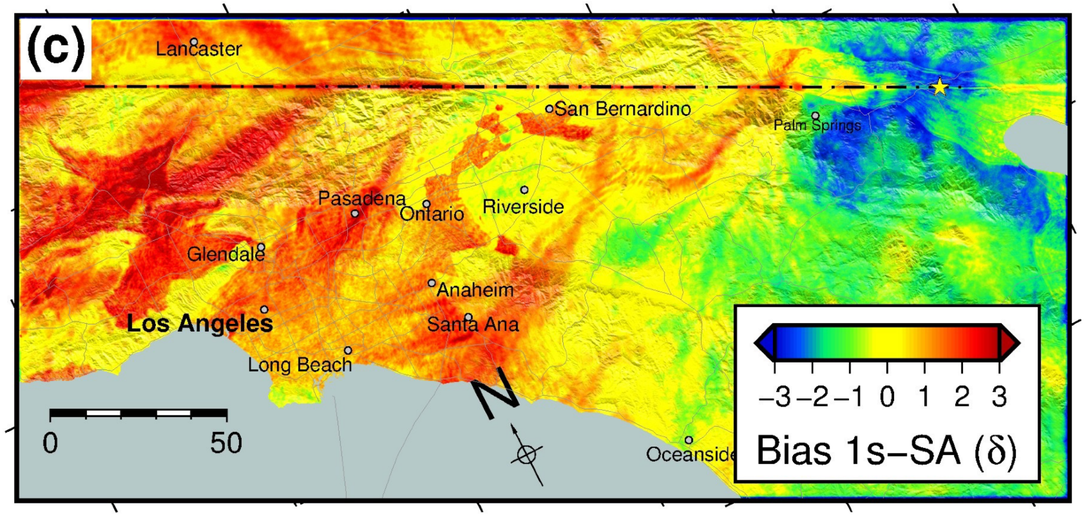


Bias between linear 1s-SA and BSSA14 GMPE



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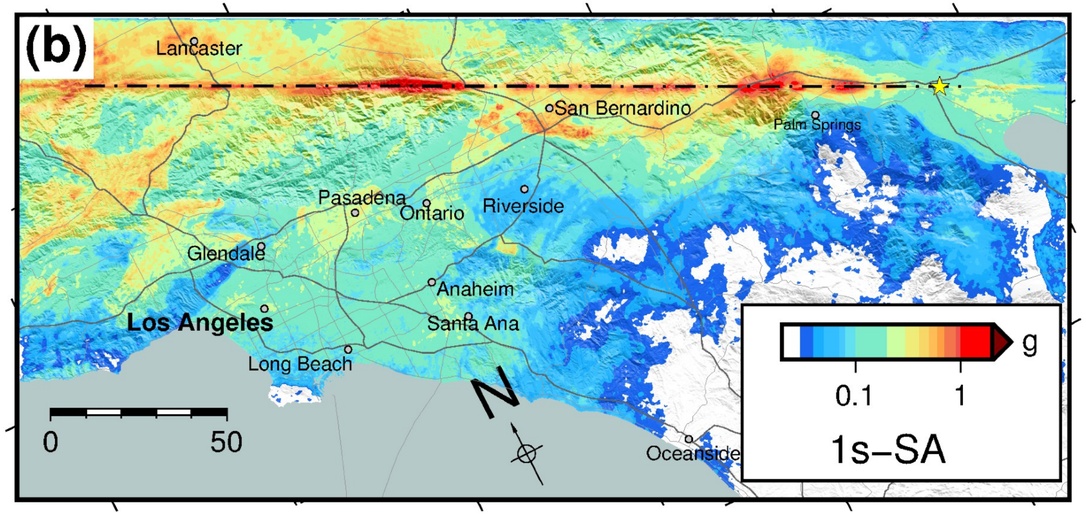

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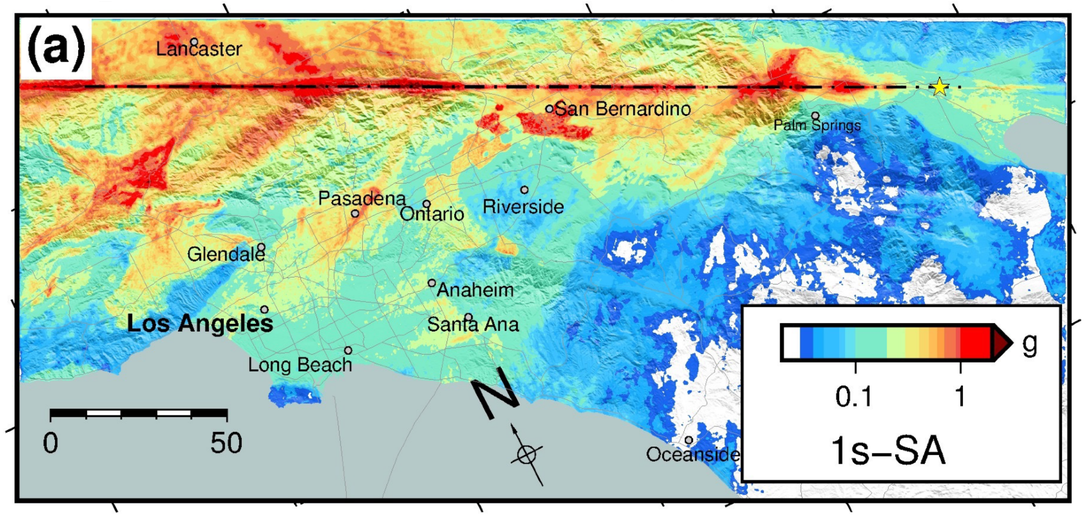

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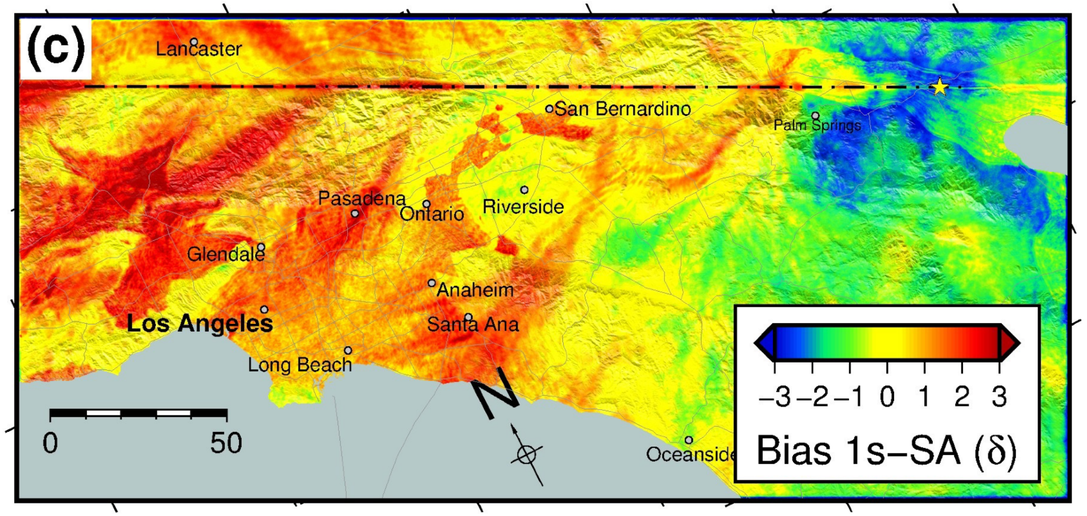
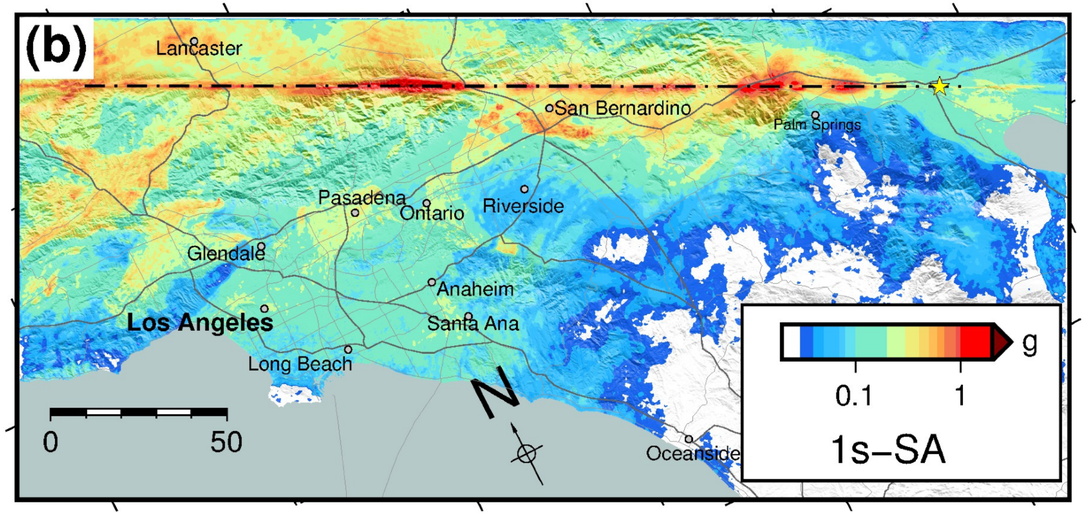
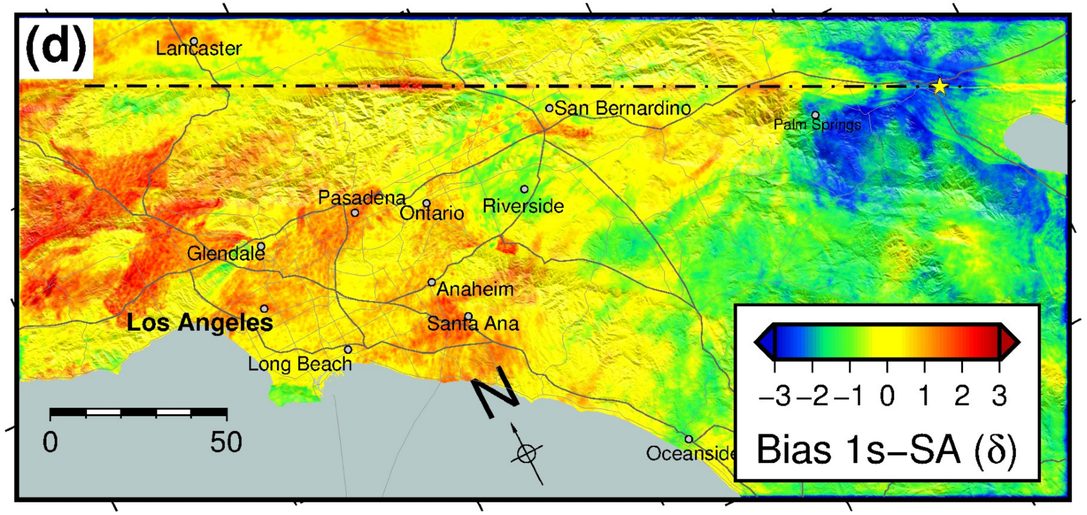


1s-SAs: Nonlinear, Good—Average Quality Rock



Bias between nonlinear 1s-SA and BSSA14 GMPE



Southern San Andreas Scenarios with Plasticity

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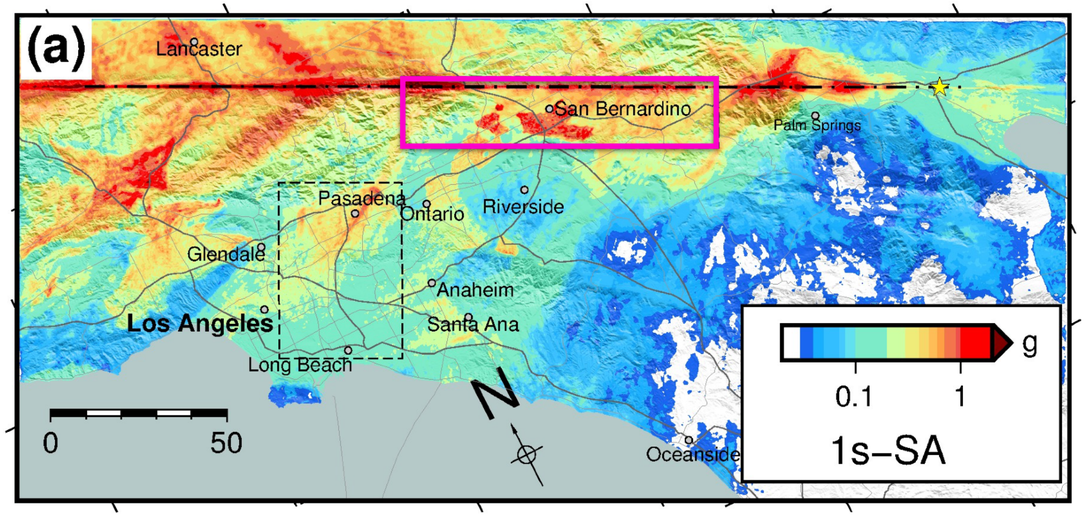
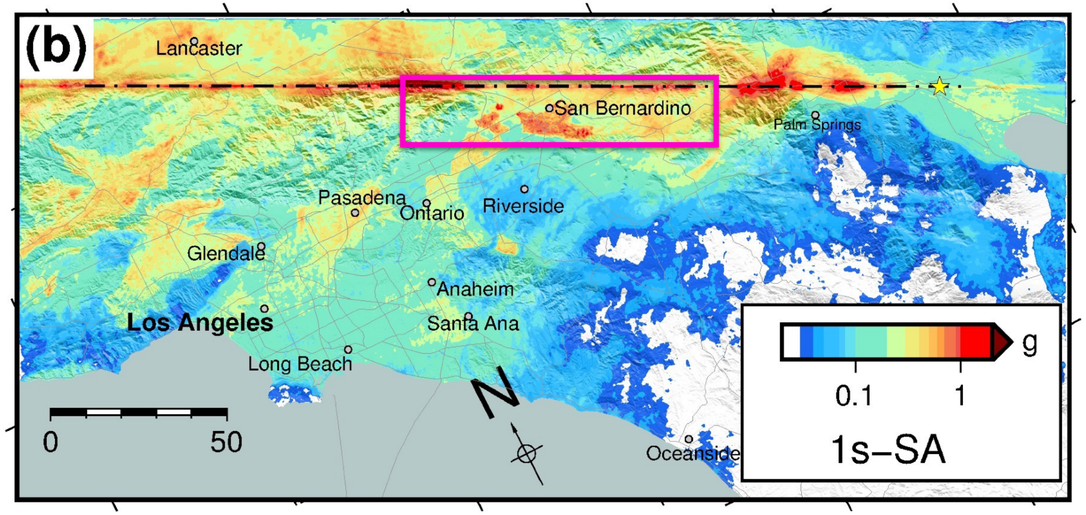
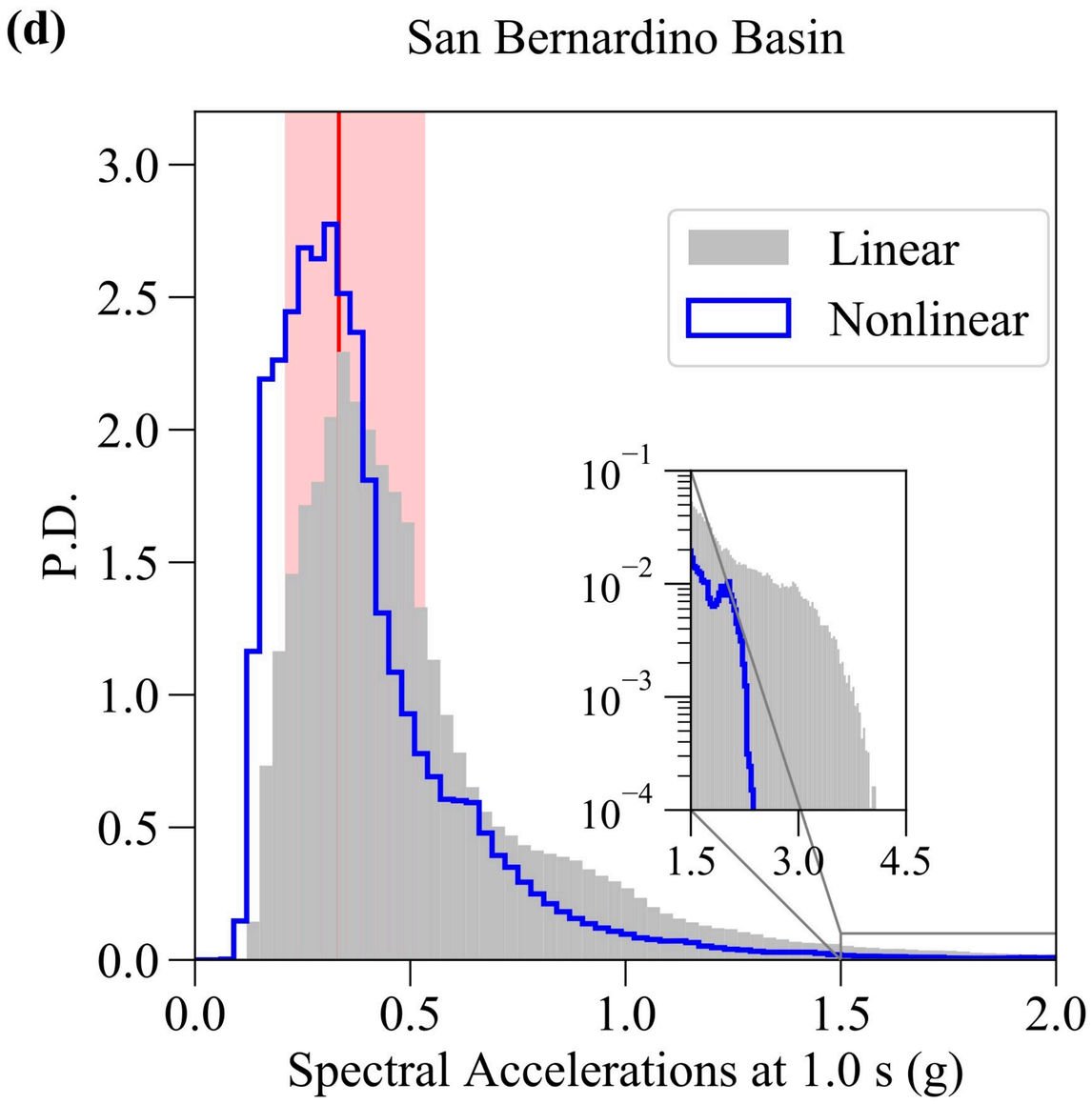


1s-SAs: Nonlinear, Good — Average Quality Rock





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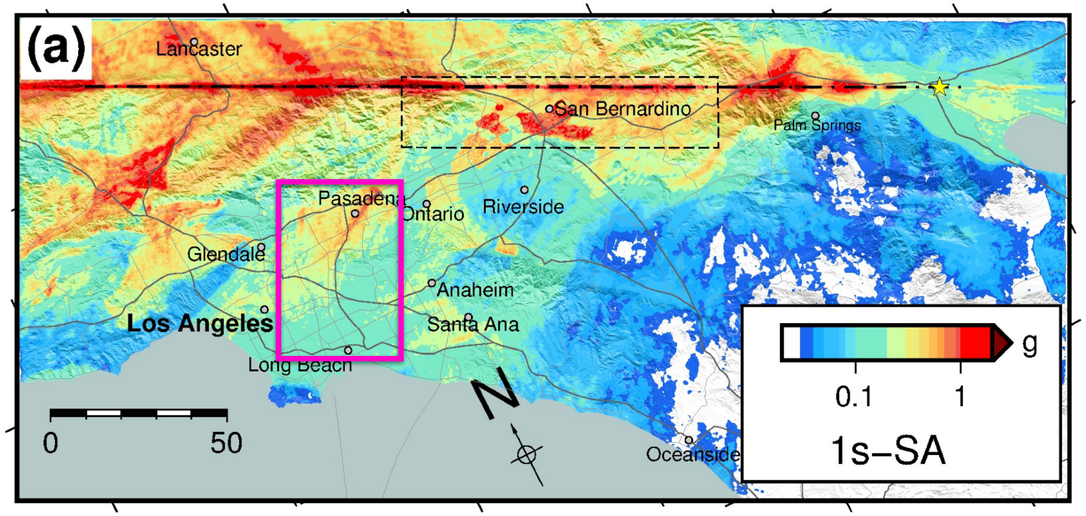
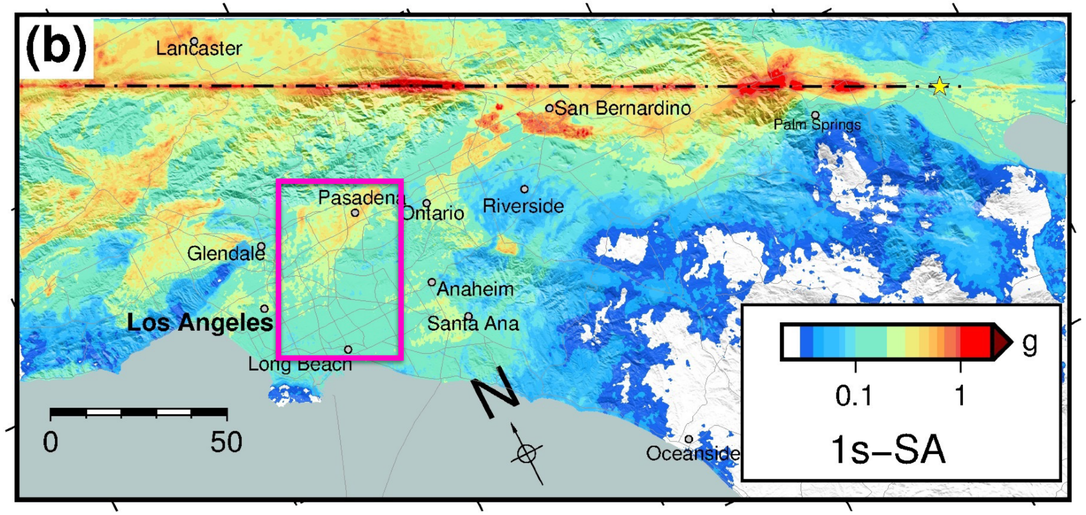
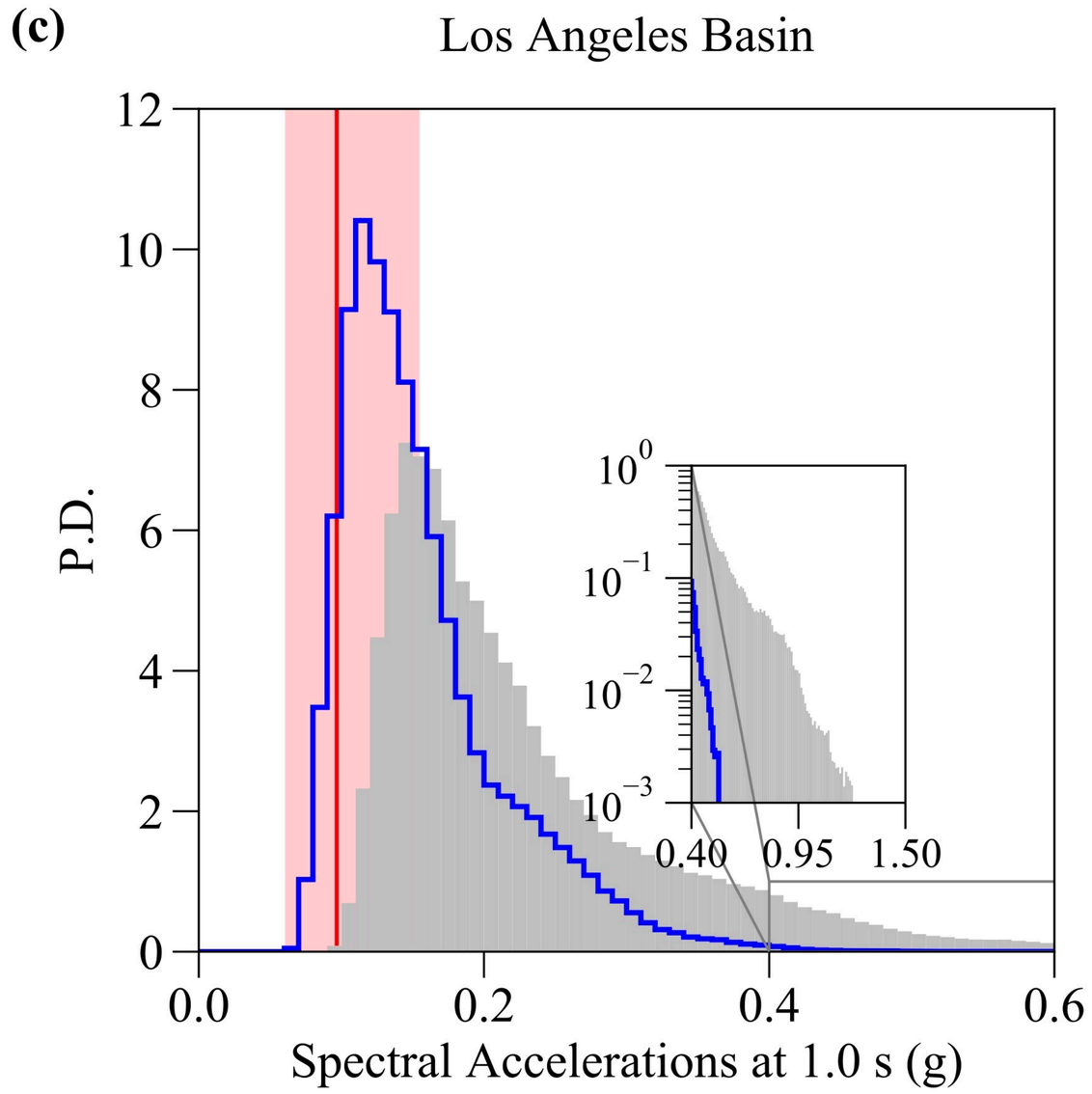


1s-SAs: Nonlinear, Good — Average Quality Rock

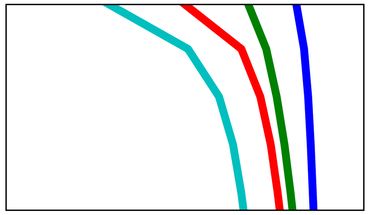


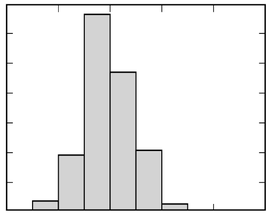


Summary and Conclusions

Landers earthquake simulations

- 3D dynamic rupture simulations of the M 7.3 Landers earthquake underpredict SSD and OFD in the *linear* case.
- However, *nonlinear* simulations for moderate quality rock reproduce both the inferred SSD of 30—60% and the observed OFD of 46 ± 10%.
- Fault zone plasticity is needed to generate dynamic rupture simulations that are consistent with observations





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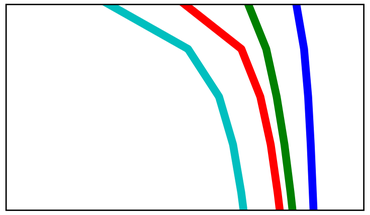

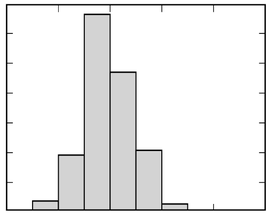

Southern San Andreas scenario

- Simulated spectral accelerations obtained for a linear medium overpredict GMPEs by more than one standard deviation at near-fault locations.
- SAs obtained from nonlinear simulation are more consistent with GMPEs.
- Plasticity acts by truncating the tail of the frequency distribution, reducing the occurrence of extreme ground motions.
- Ground motions are sensitive to strength of rocks in the fault damage zone, which underlines the need to properly prescribe strength parameters for deterministic ground motion prediction.