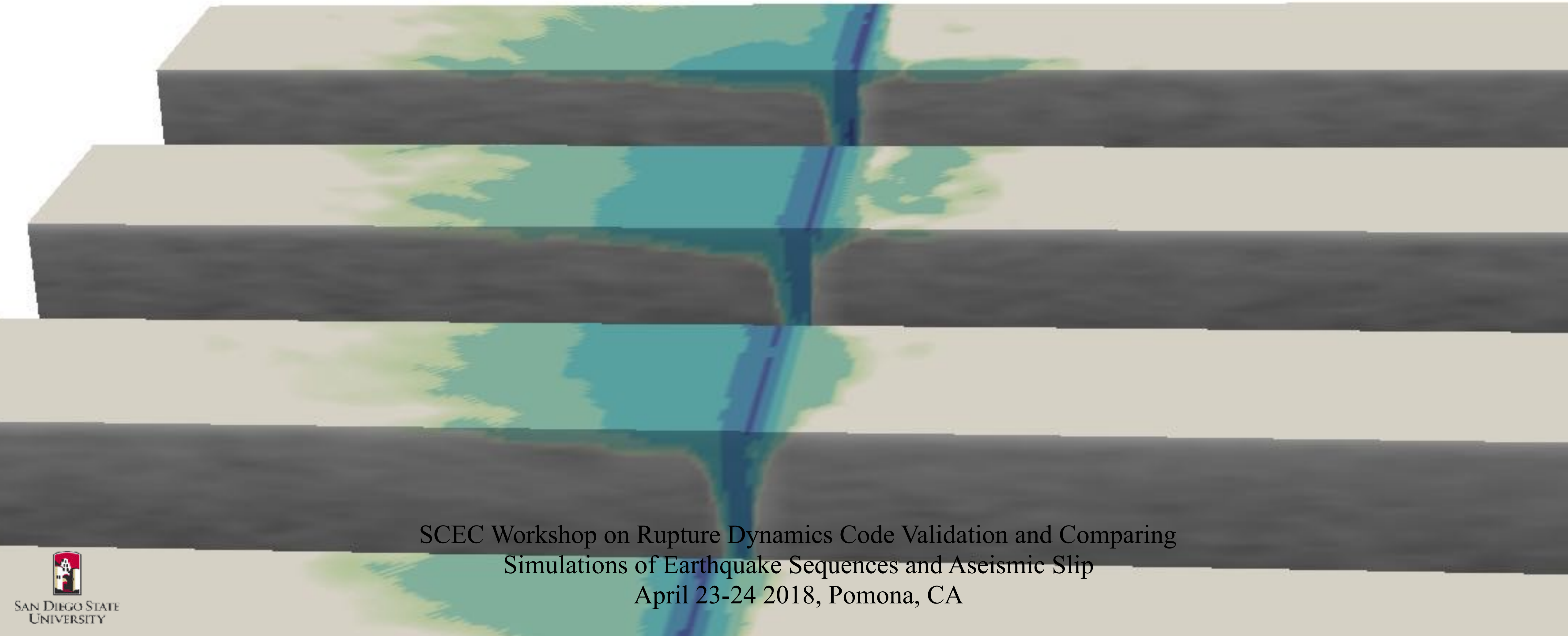


Off-fault Deformation and Shallow Slip Deficit from Dynamic Rupture Simulations with Fault Zone Plasticity

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



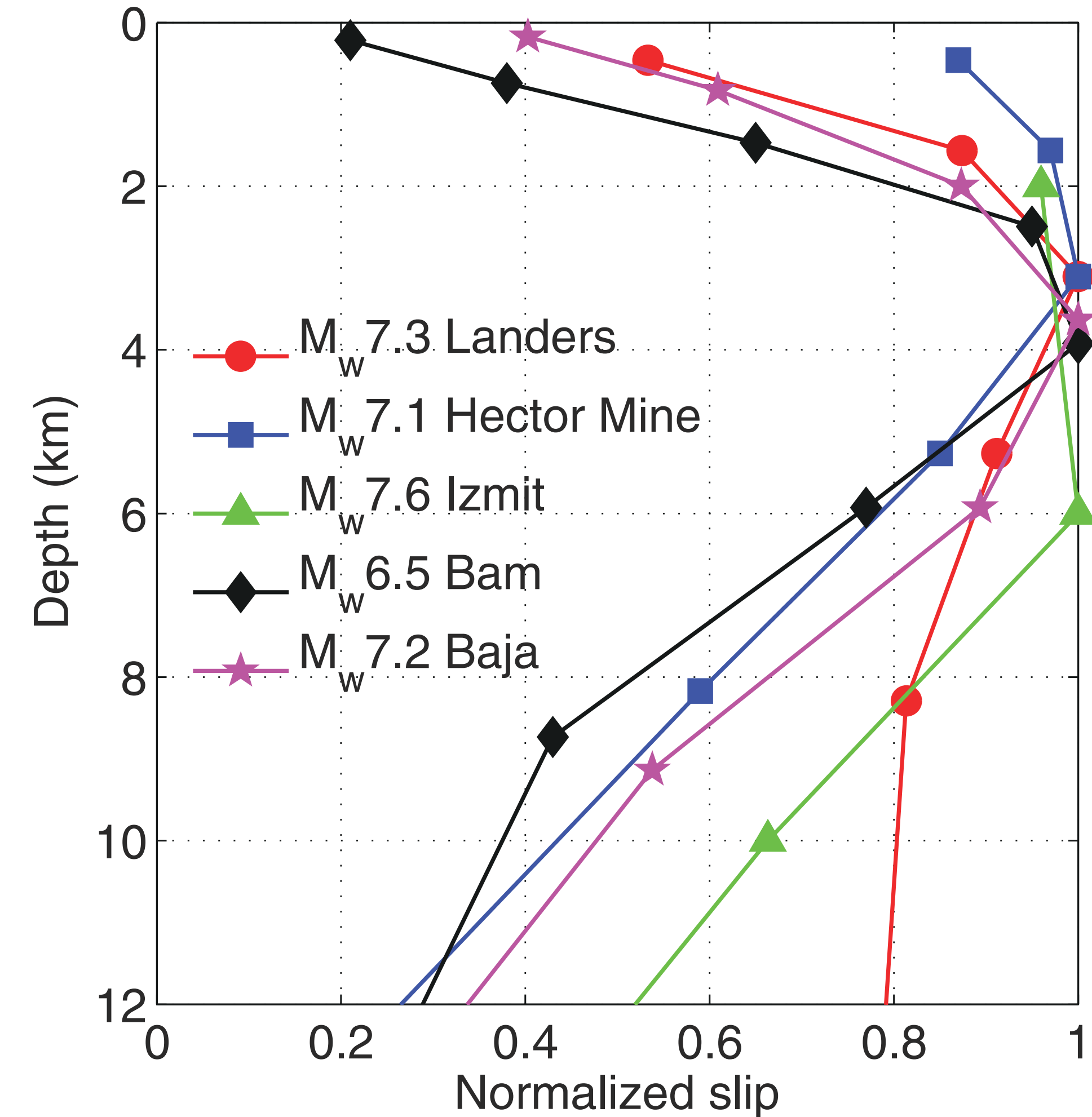
SCEC Workshop on Rupture Dynamics Code Validation and Comparing Simulations of Earthquake Sequences and Aseismic Slip

April 23-24 2018, Pomona, CA



Shallow Slip Deficit and Surface Deformation

- *Co-seismic slip at the surface is generally lower than slip at depth:*
 - Surface slip measured in the field is less geodetically inferred slip at depth
 - Inversions of INSAR and GPS data yield more slip at 4—5 km depth than at surface

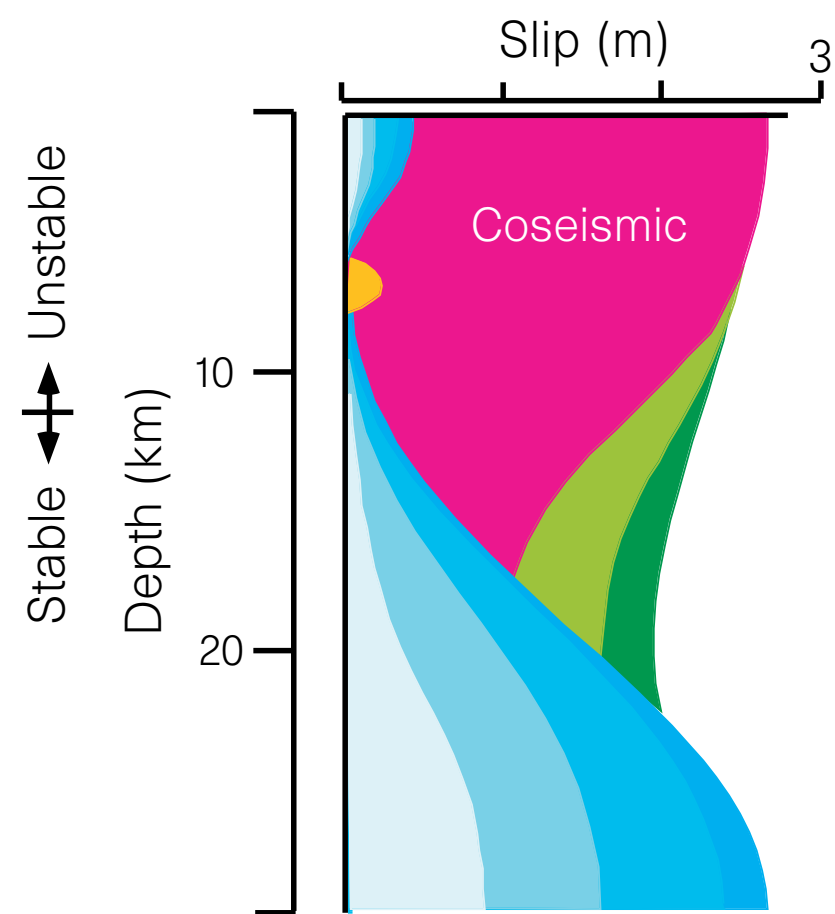


Fialko *et al.* (2005)

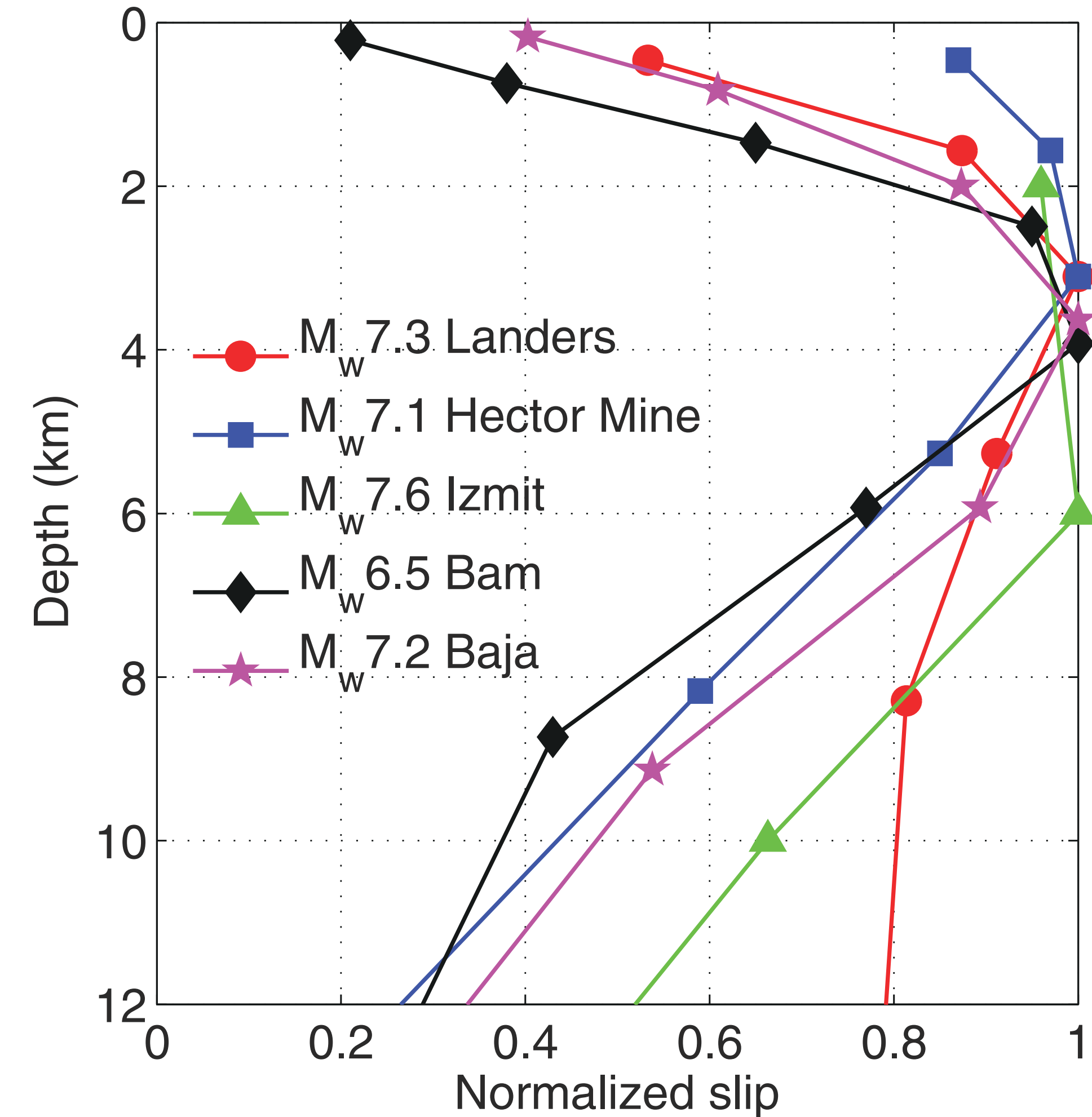
Kaneko & Fialko (2011)

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- *Explanations for this Shallow Slip Deficit:*
 - Interseismic fault creep



Scholz (1998)



Fialko *et al.* (2005)

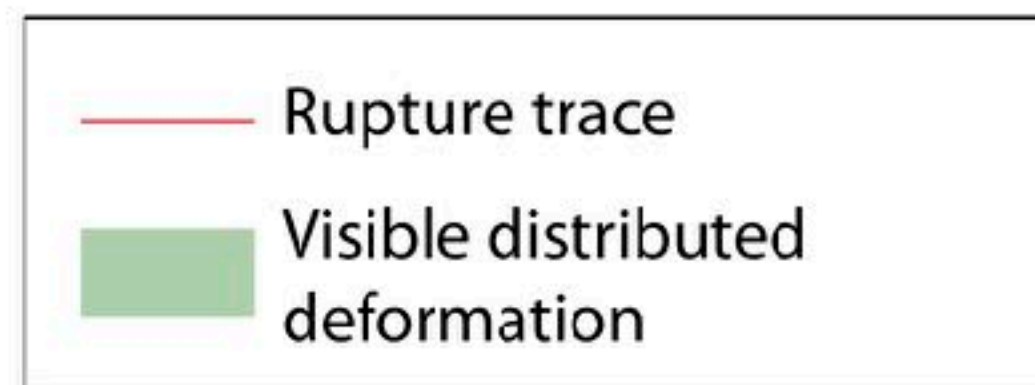
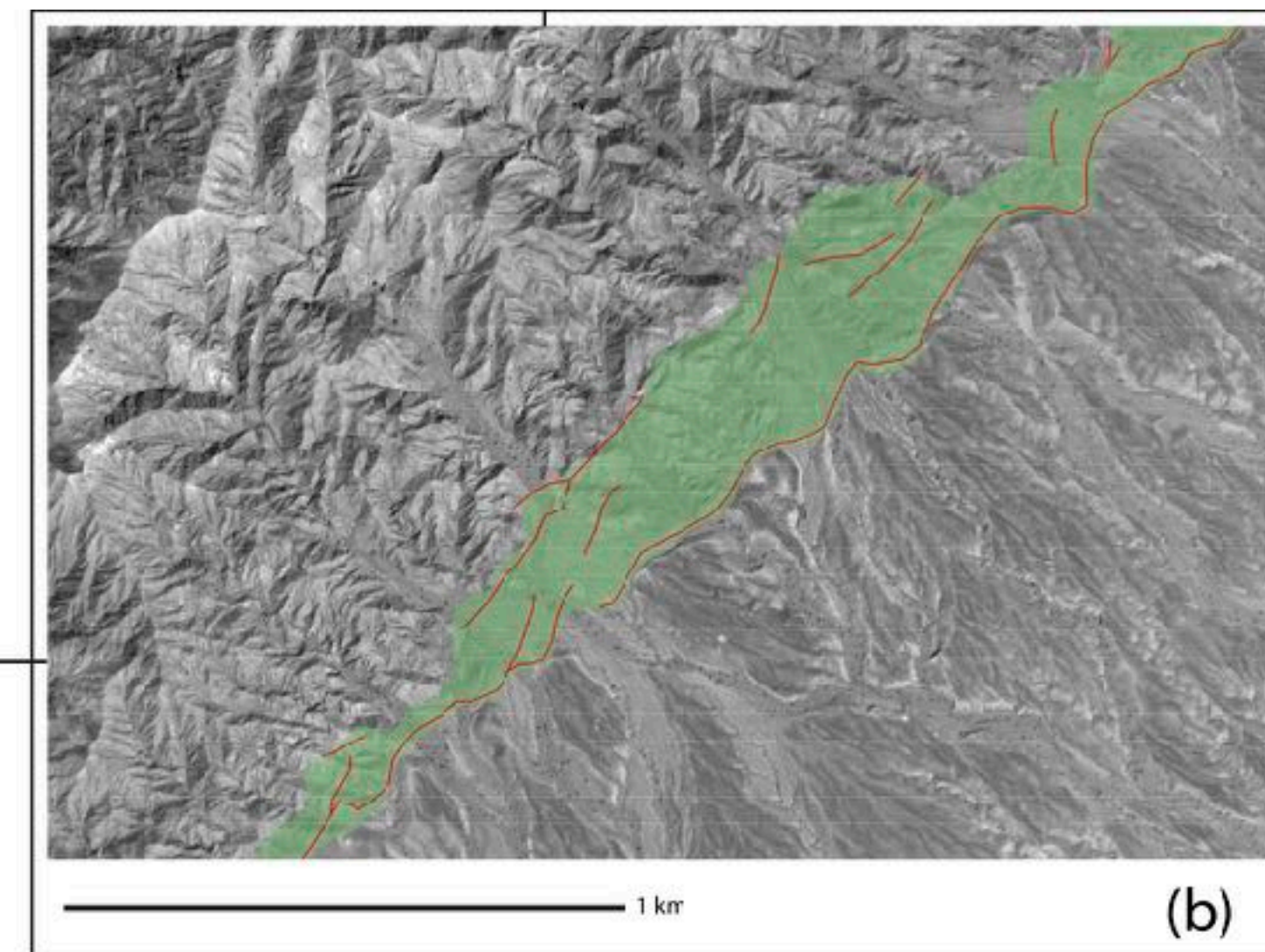
Kaneko & Fialko (2011)

Shallow Slip Deficit and Surface Deformation

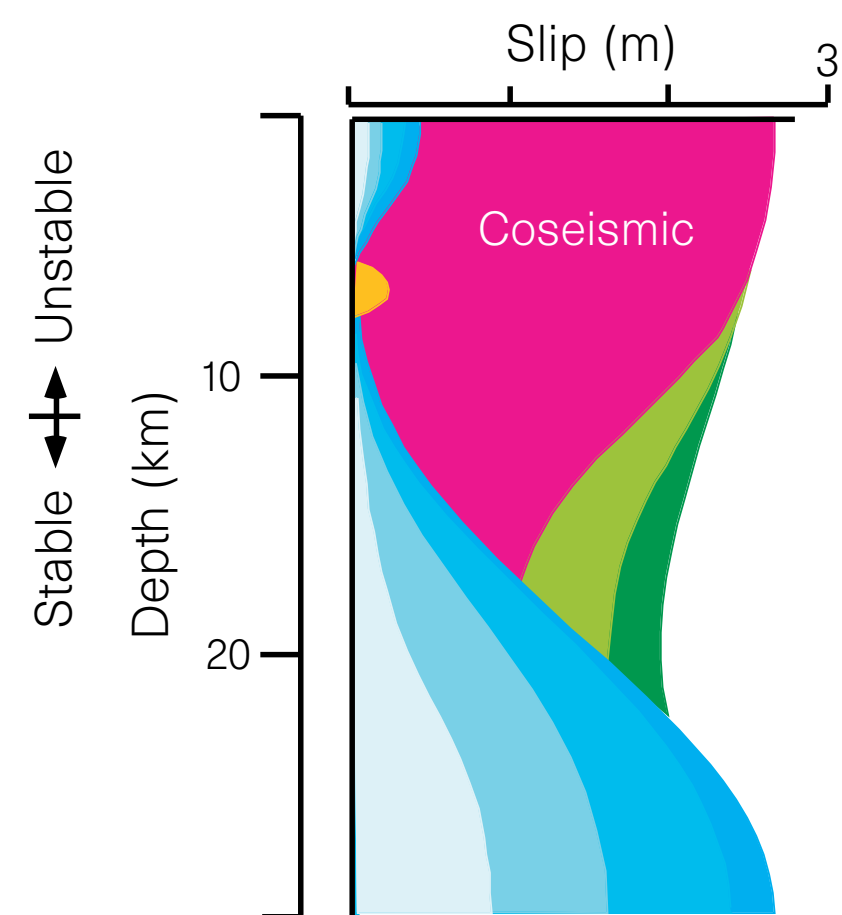
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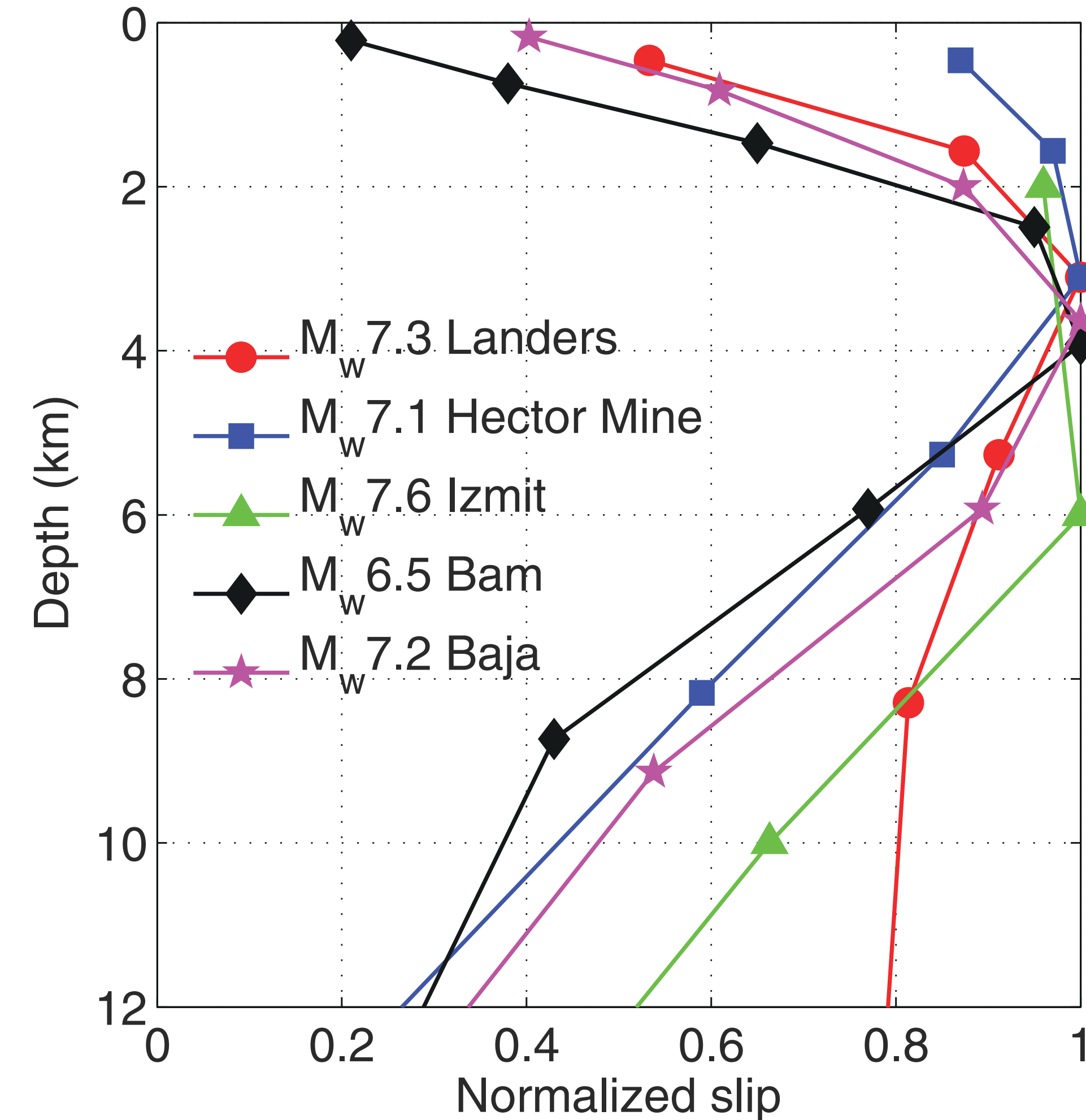
- Interseismic fault creep
- Distributed off-fault deformation



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



Scholz (1998)



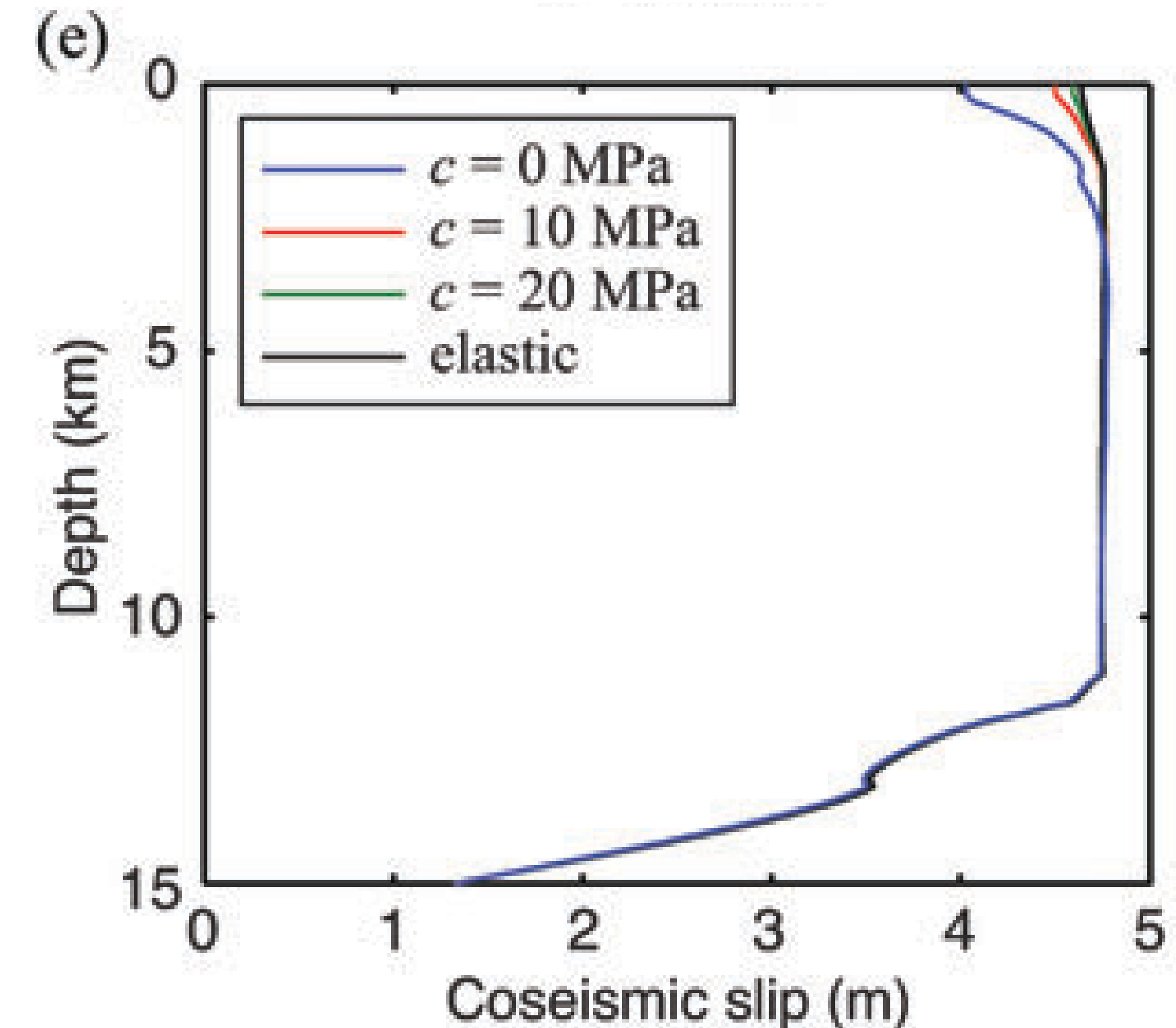
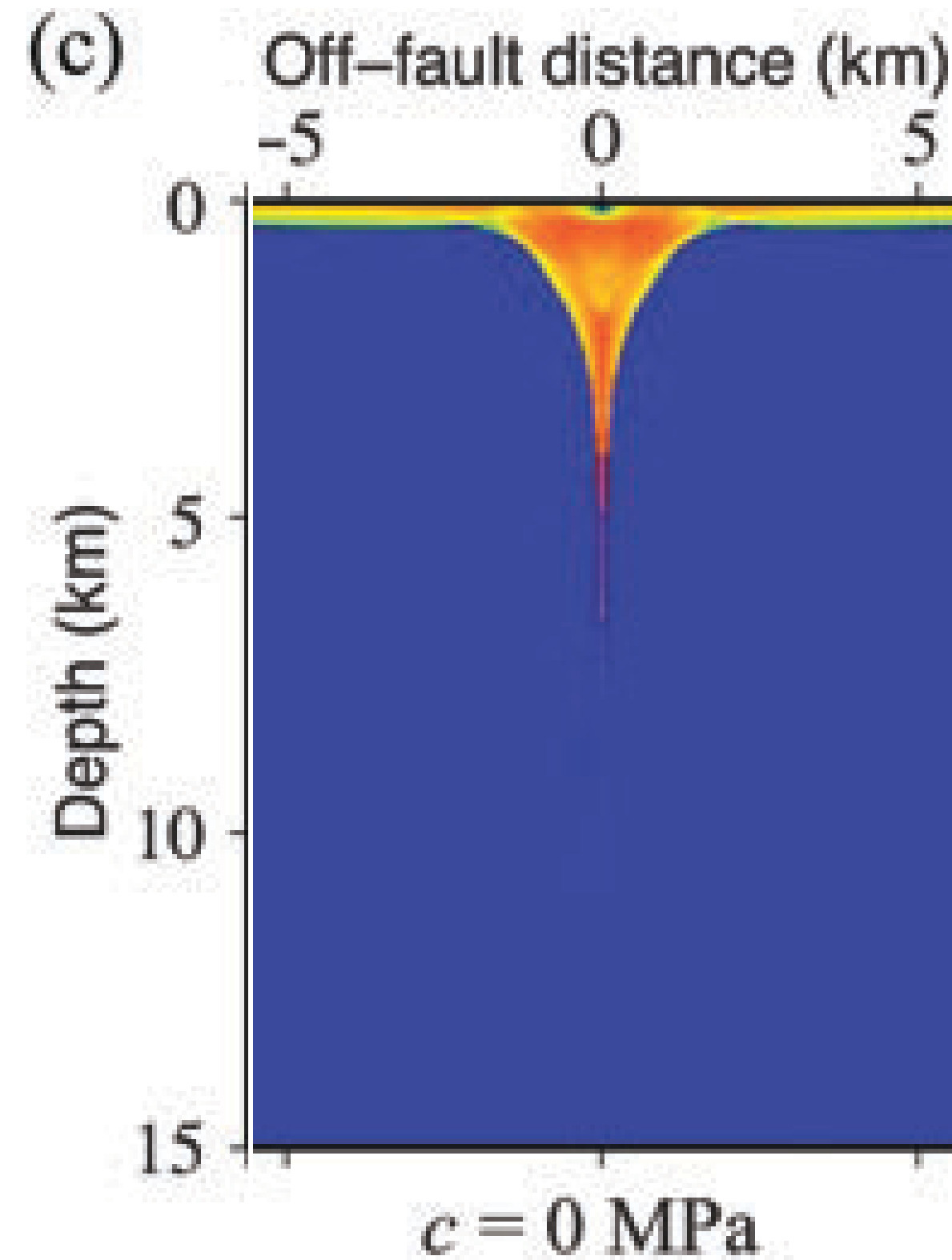
Fialko *et al.* (2005)
Kaneko & Fialko (2011)

Shallow Slip Deficit and Surface Deformation

- 2D dynamic rupture simulations with plasticity (Kaneko & Fialko, 2011) predict a Shallow Slip Deficit (SSD) of up to 15%
- SSD proportional to inelastic deformation
- 2—4 times lower than observed SSD

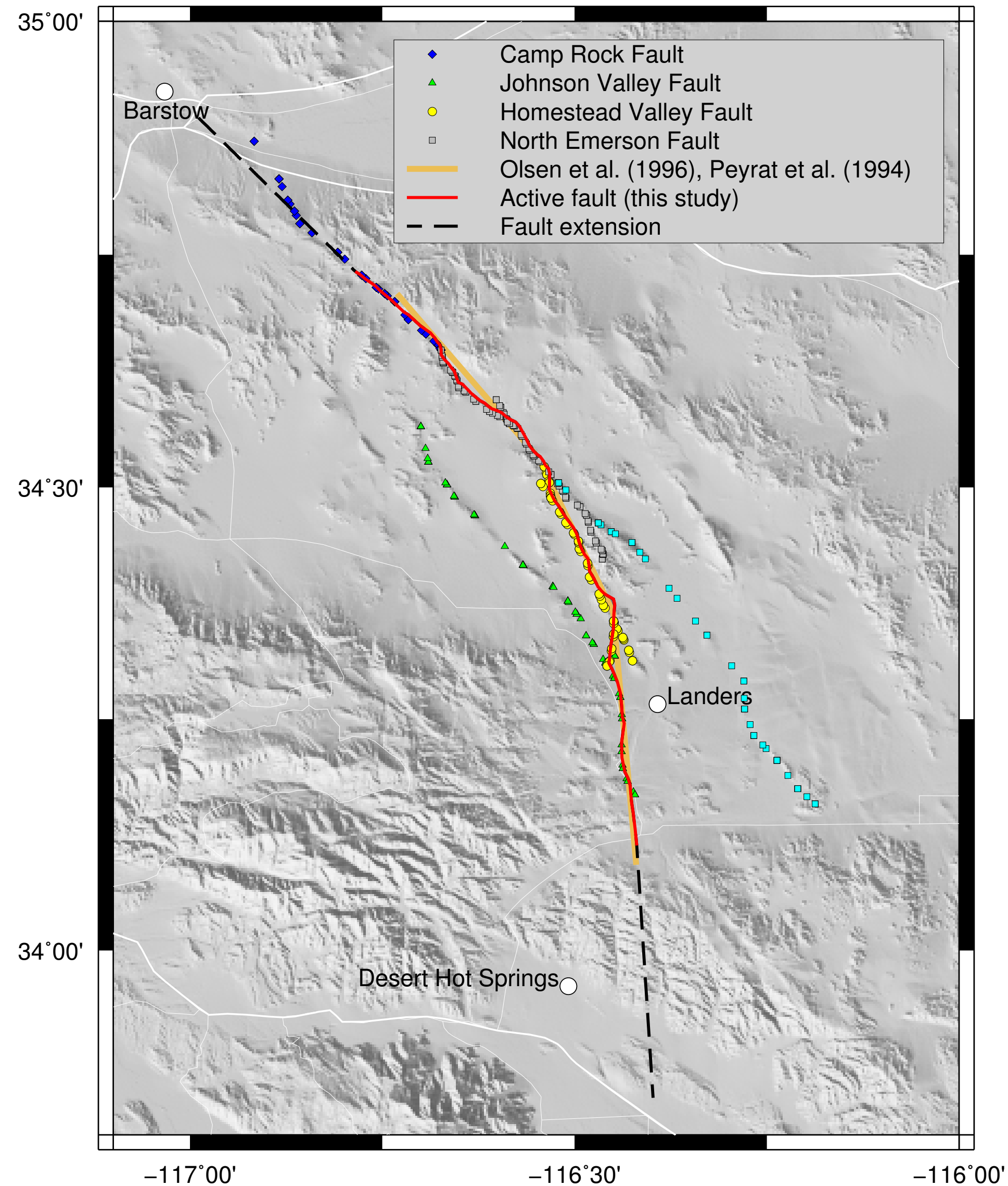
Scope

- Perform 3D nonlinear dynamic rupture simulations for observed earthquake with documented SSD
- Sensitivity of SSD to rock strength
- Compare simulated deformation patterns with observations



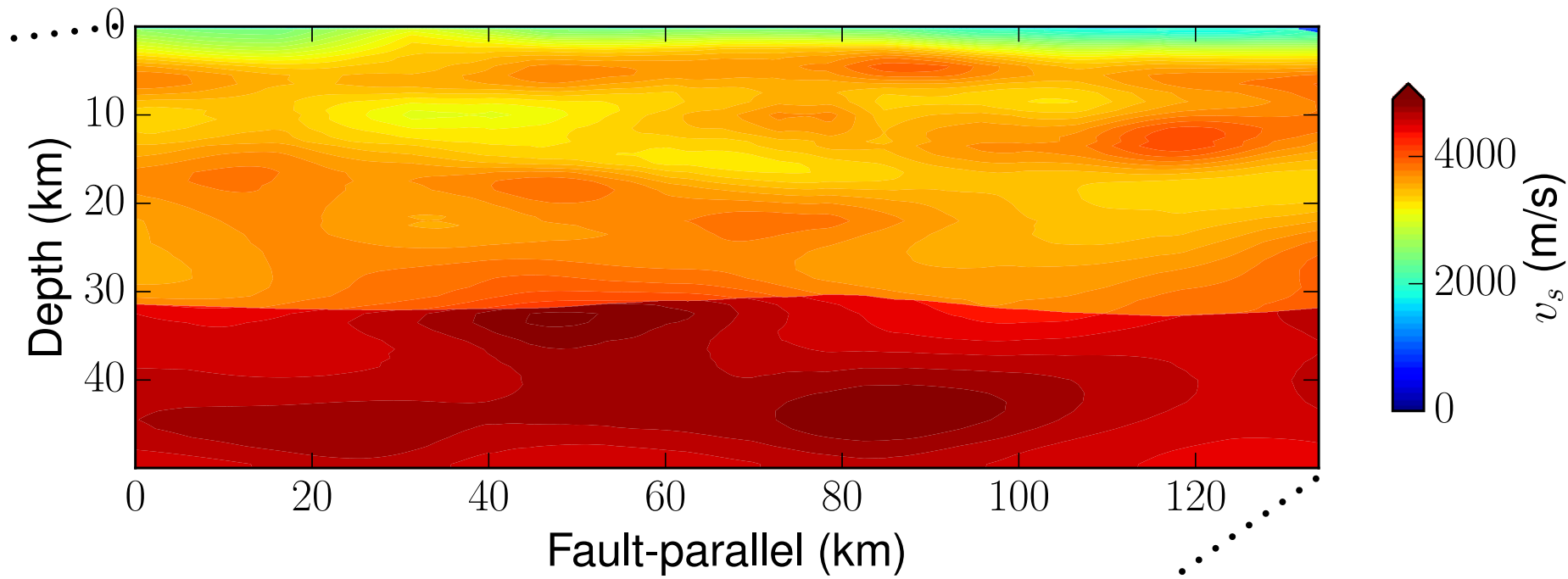
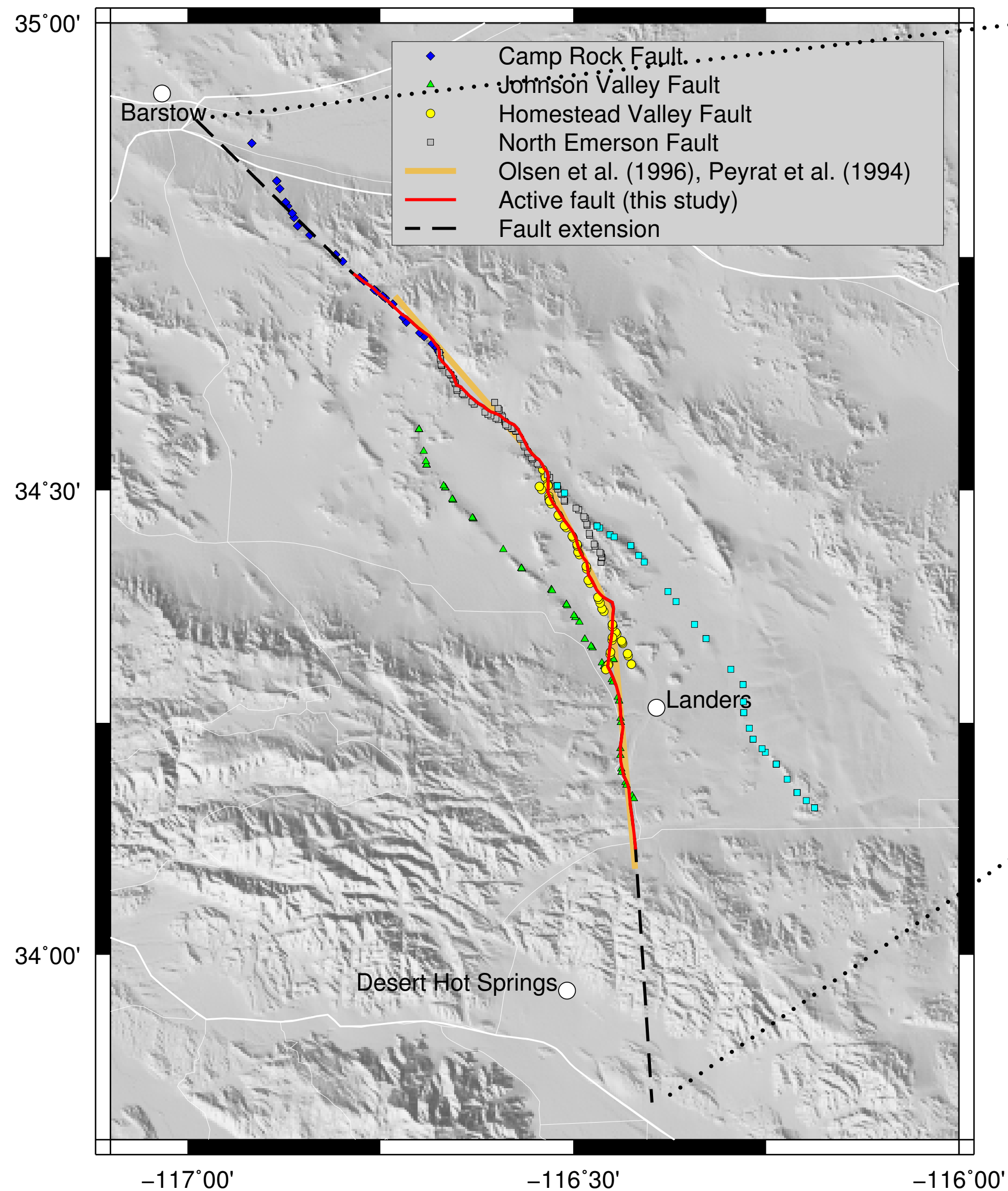
from Kaneko & Fialko (2011)

Dynamic Rupture Simulation of M 7.3 Landers Earthquake



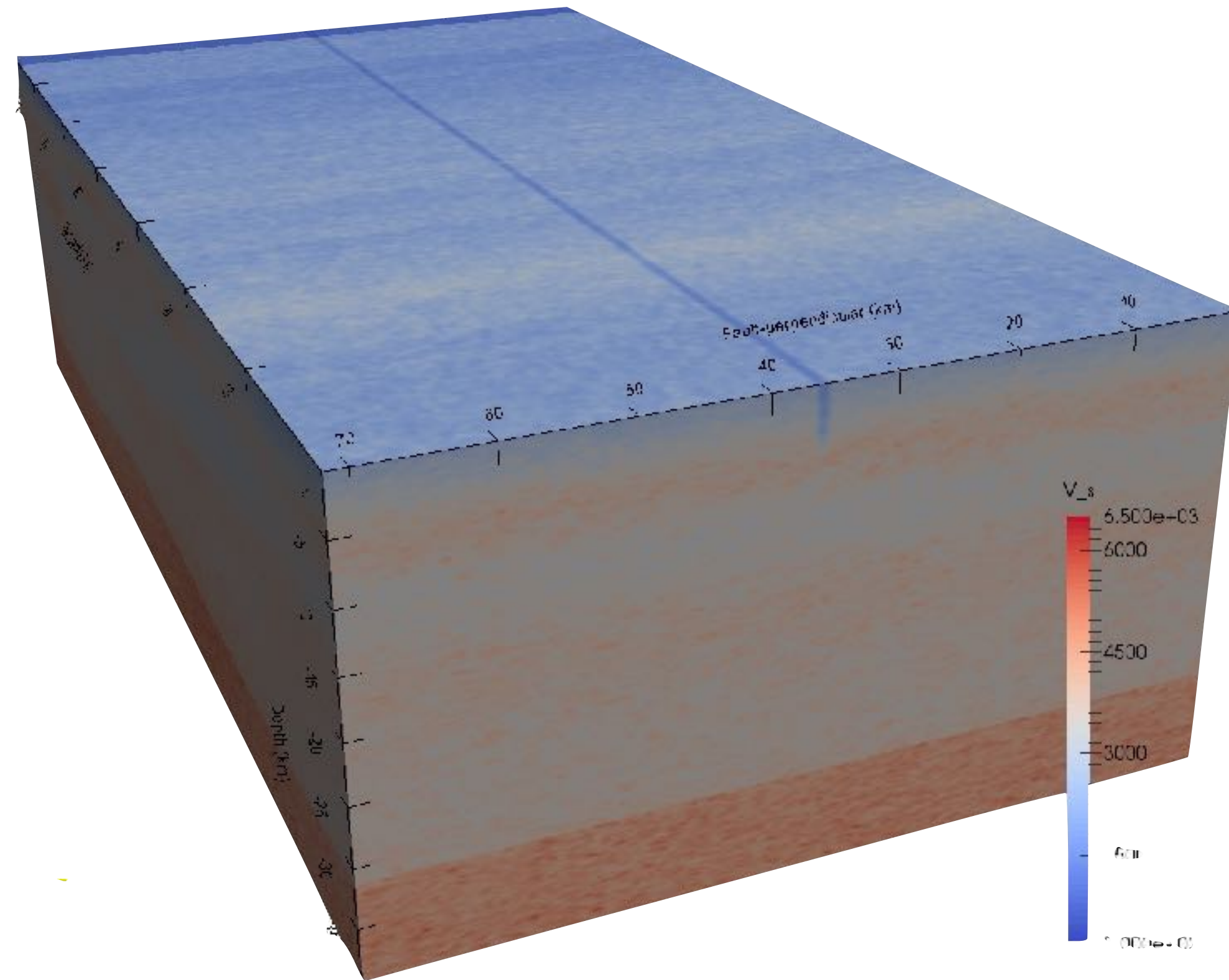
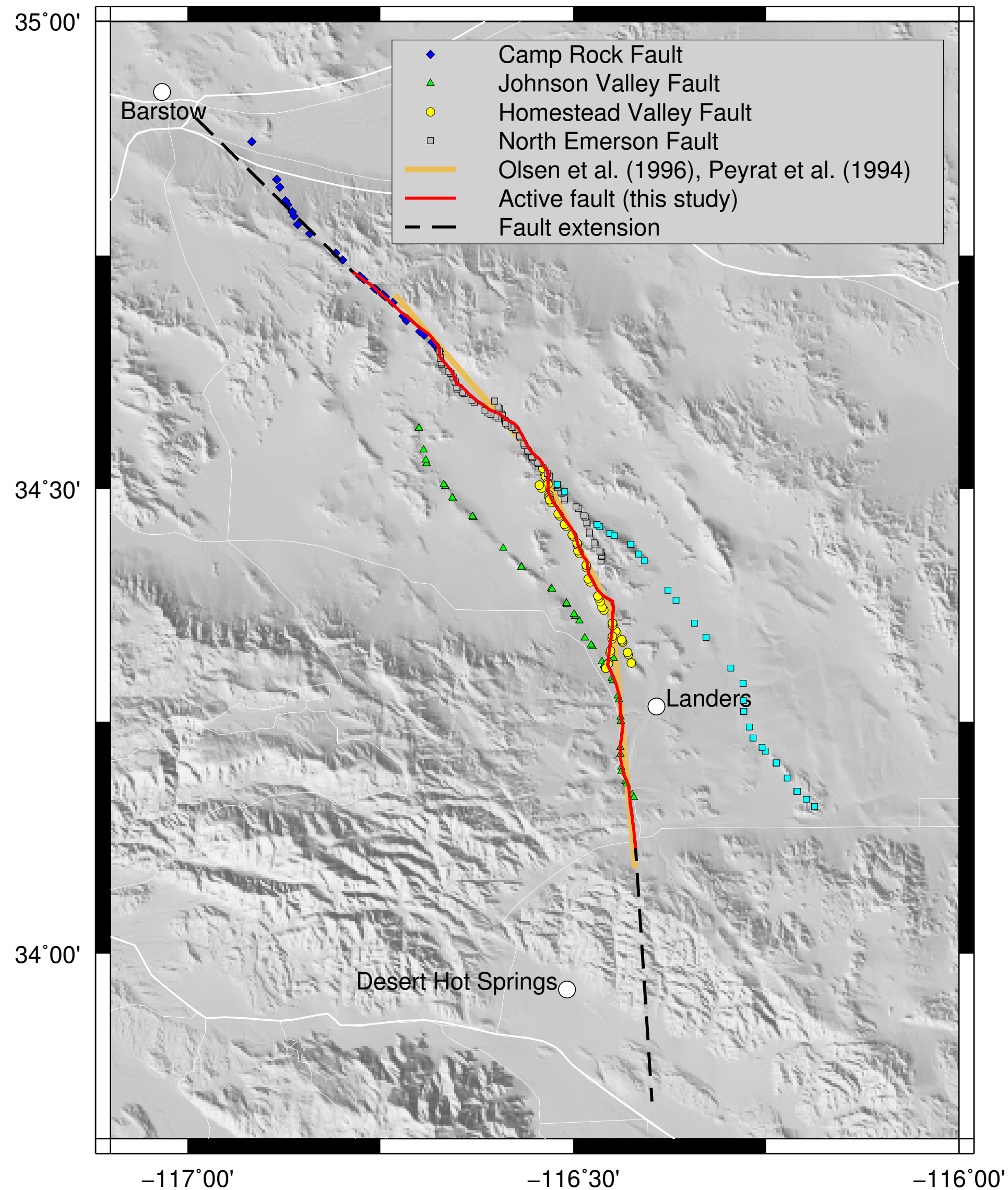
- AWP-ODC staggered-grid split-node finite difference code (Dalguer & Day, 2007) using slip-weakening fault friction
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Dynamic Rupture Simulation of M 7.3 Landers Earthquake



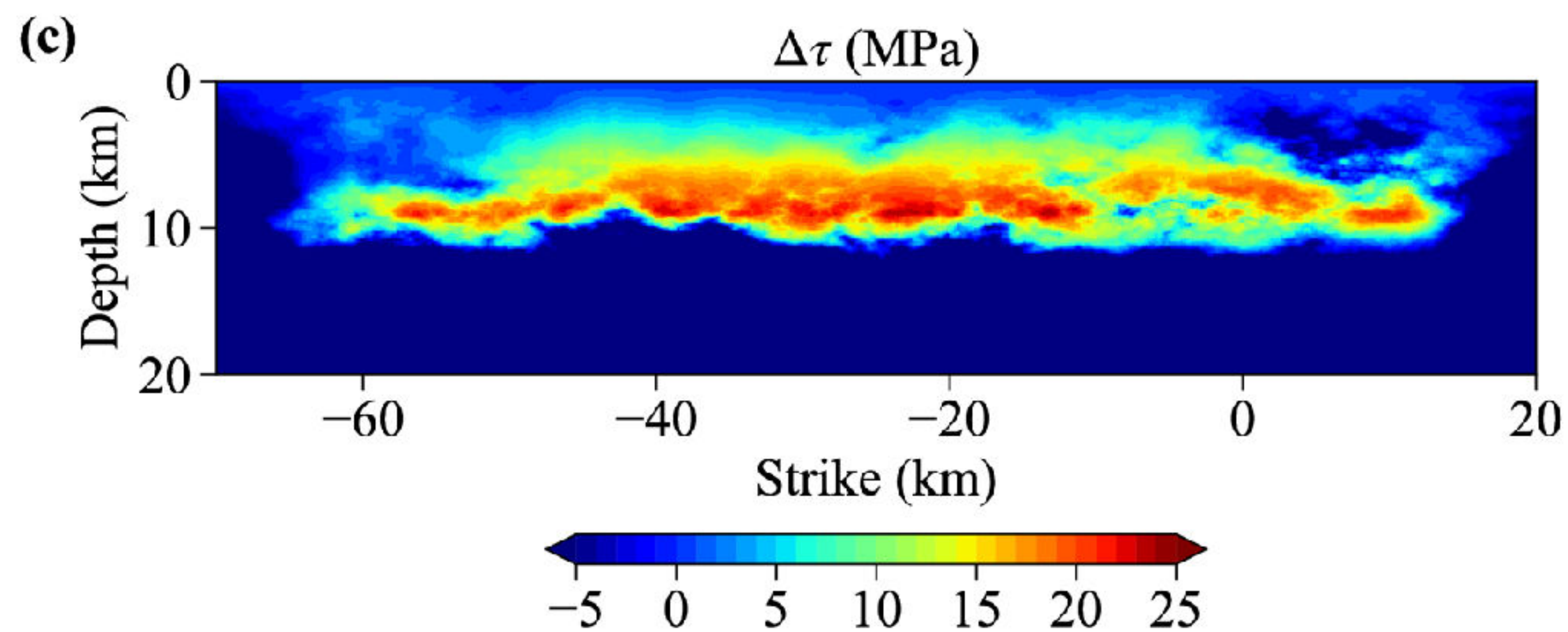
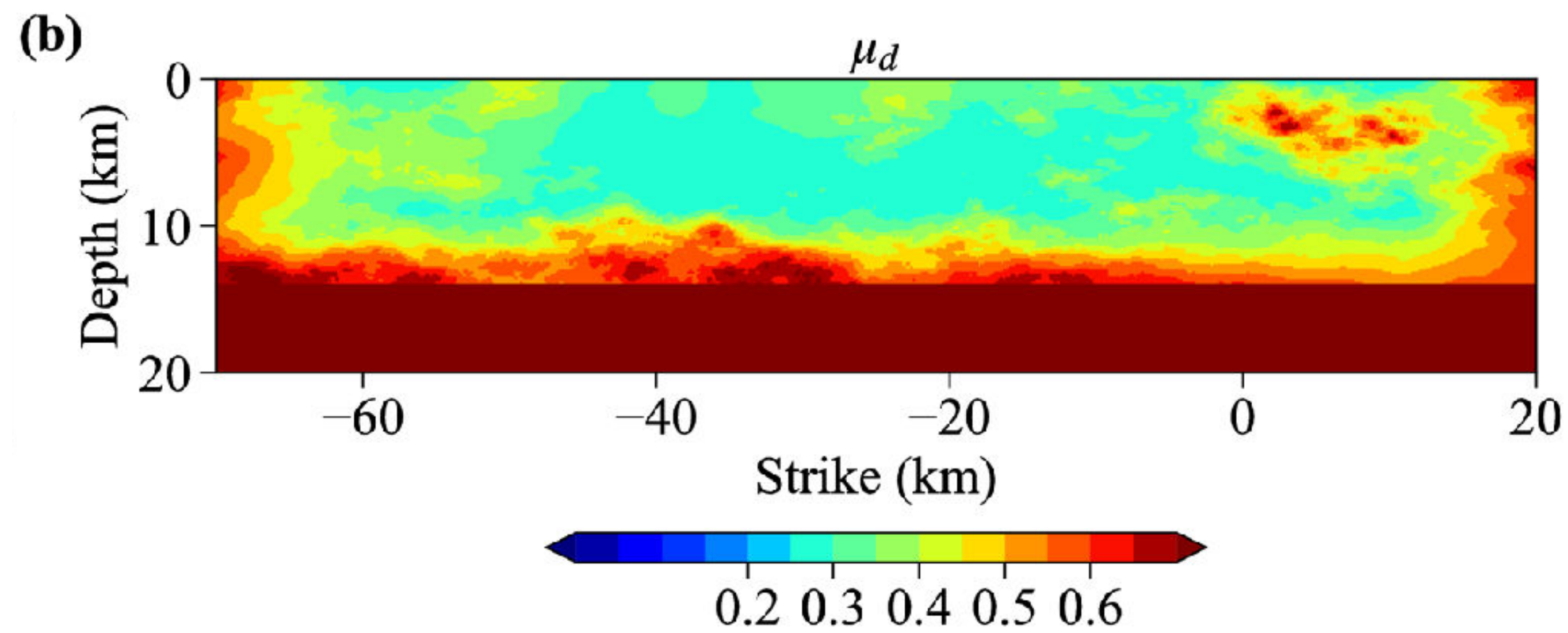
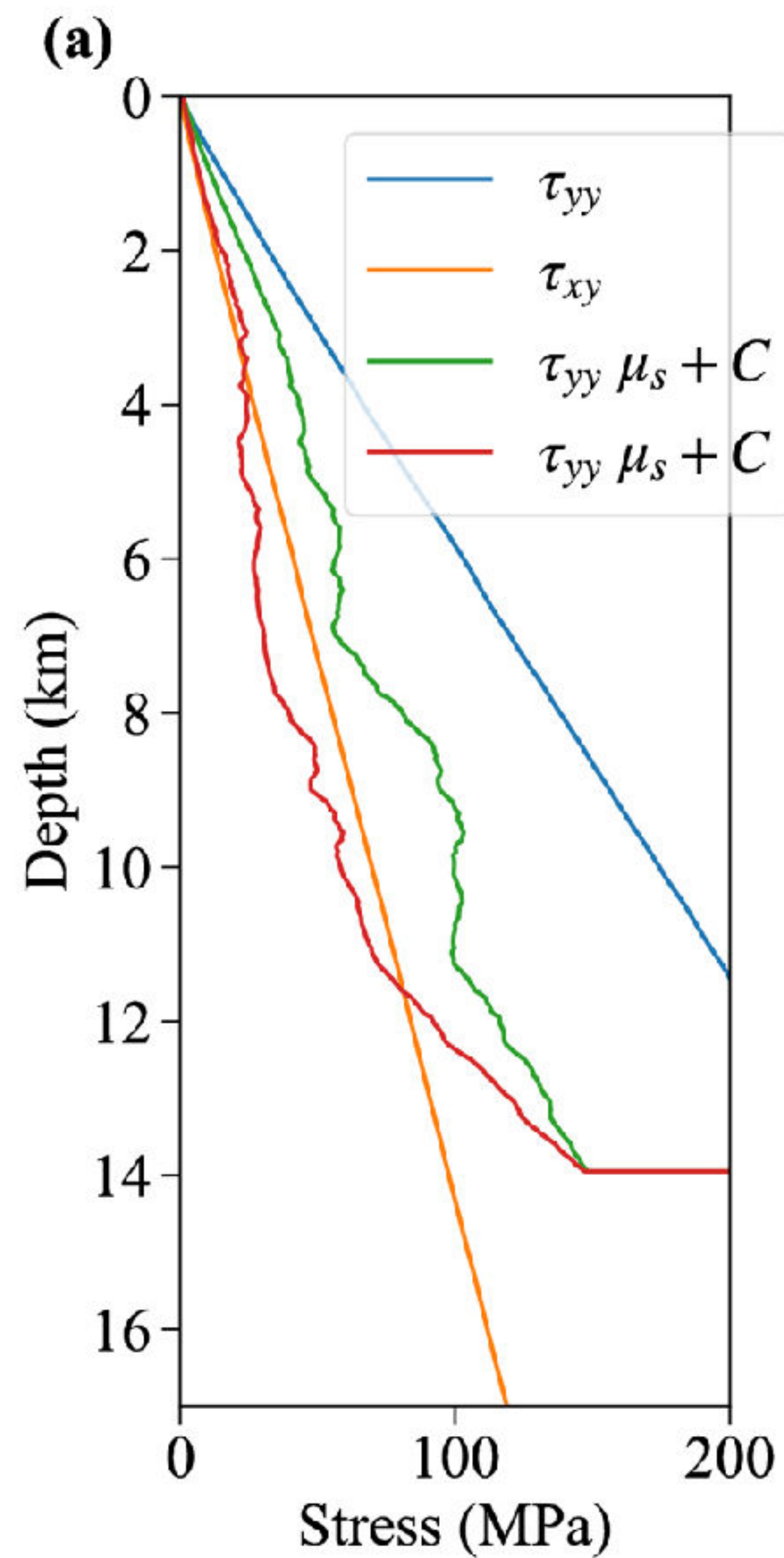
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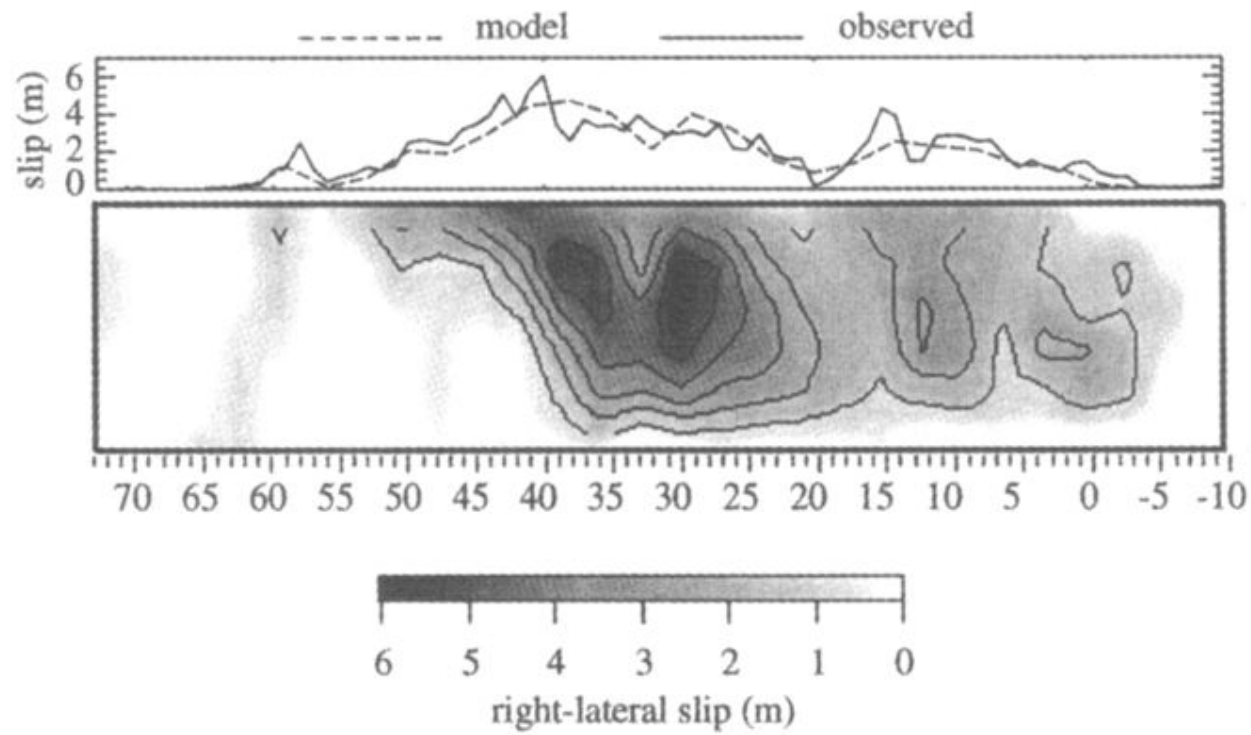
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Definition of Initial Stress

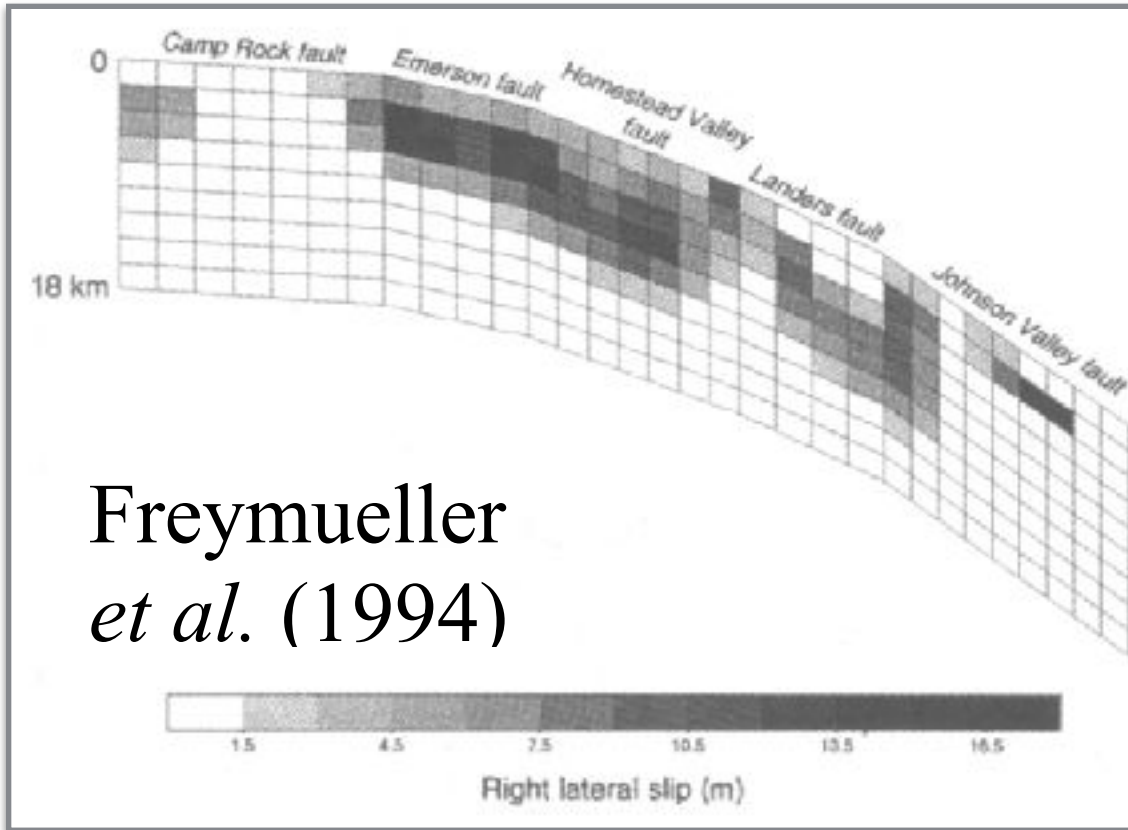


Source Models of 1992 M 7.3 Landers Earthquake

Cohee & Beroza (1994)

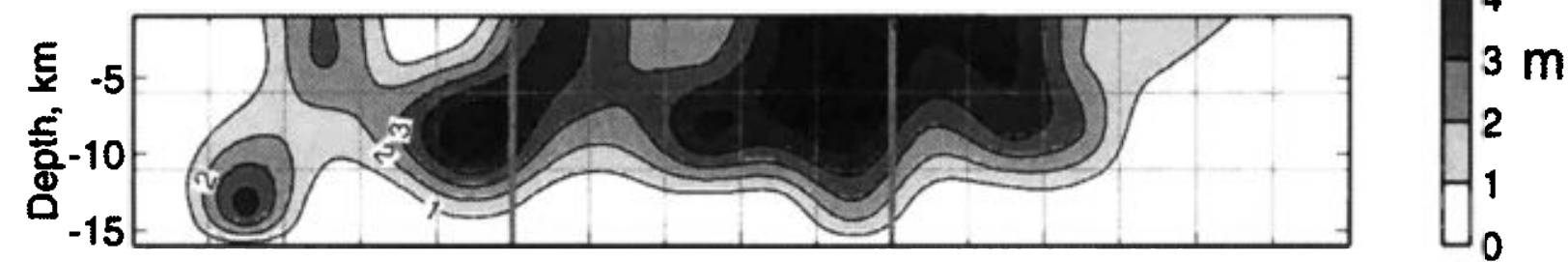


Freymueller
et al. (1994)

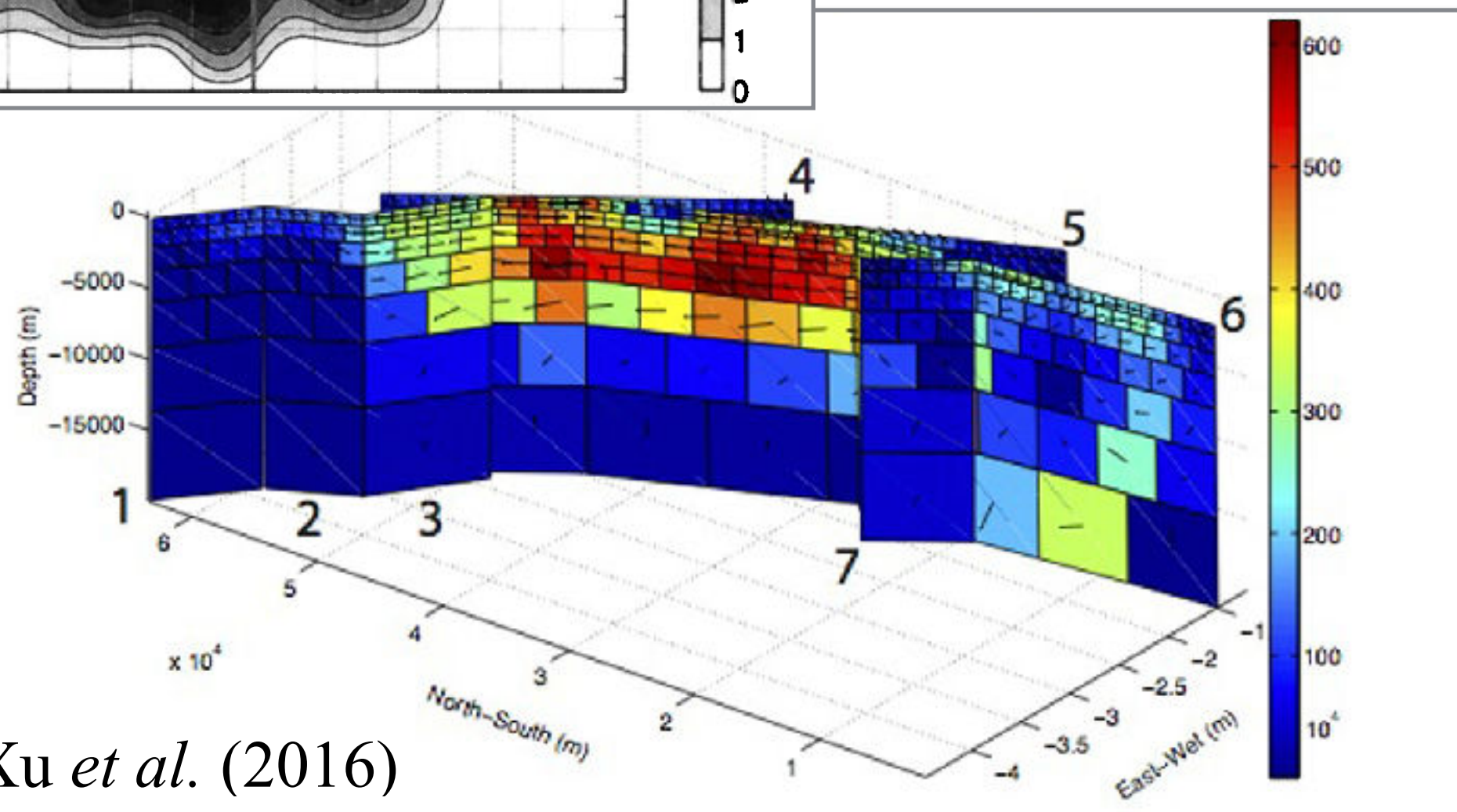


Hernandez *et al.* (1999)

Slip amplitude, m

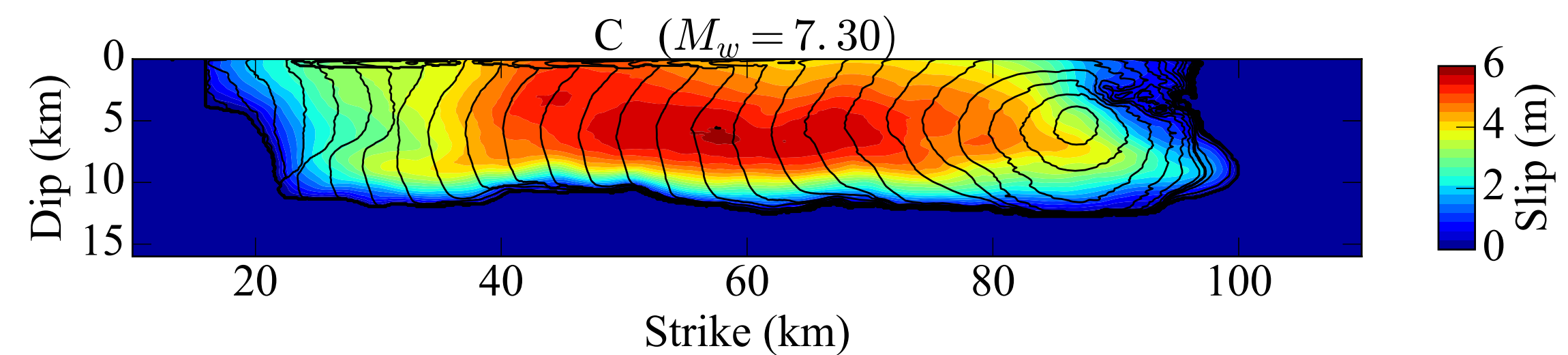
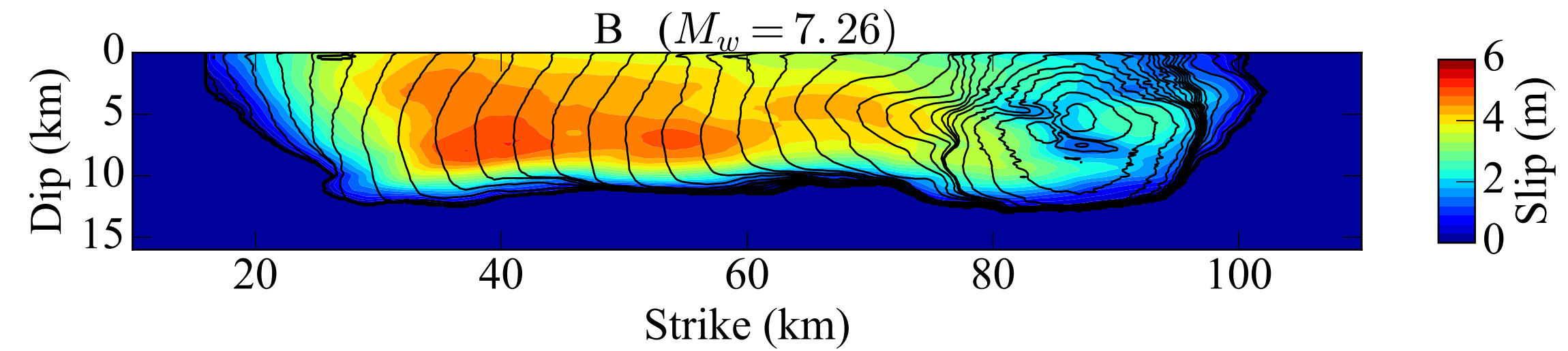
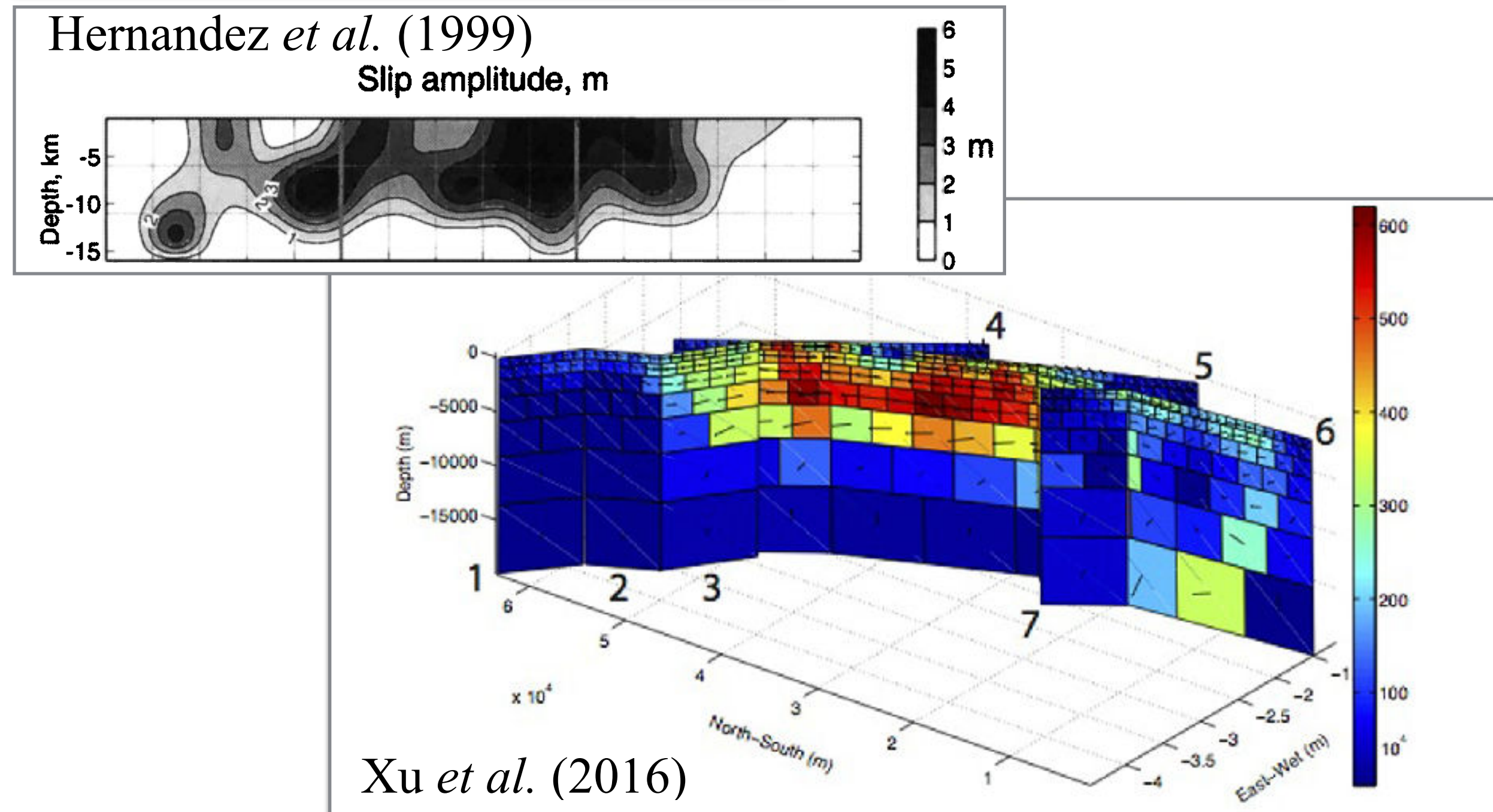
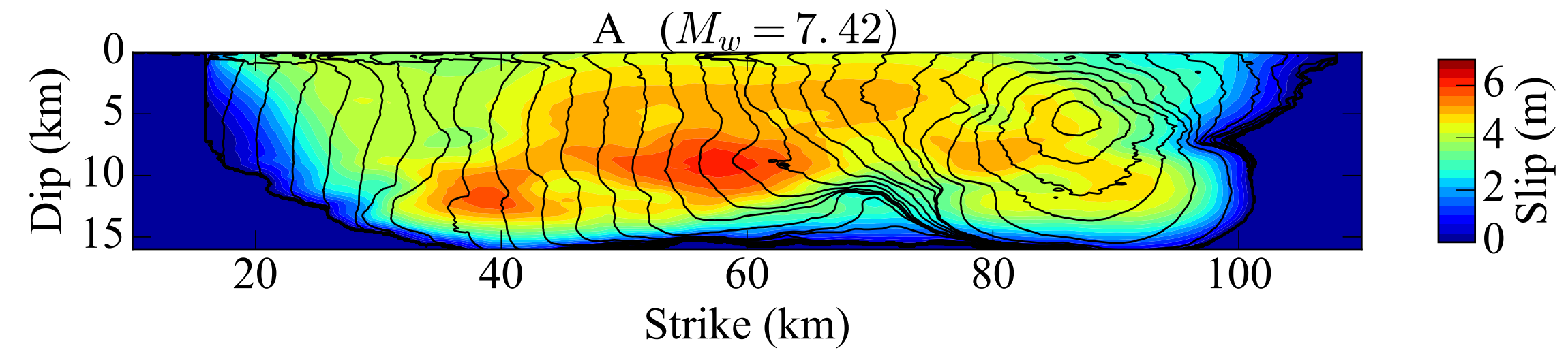
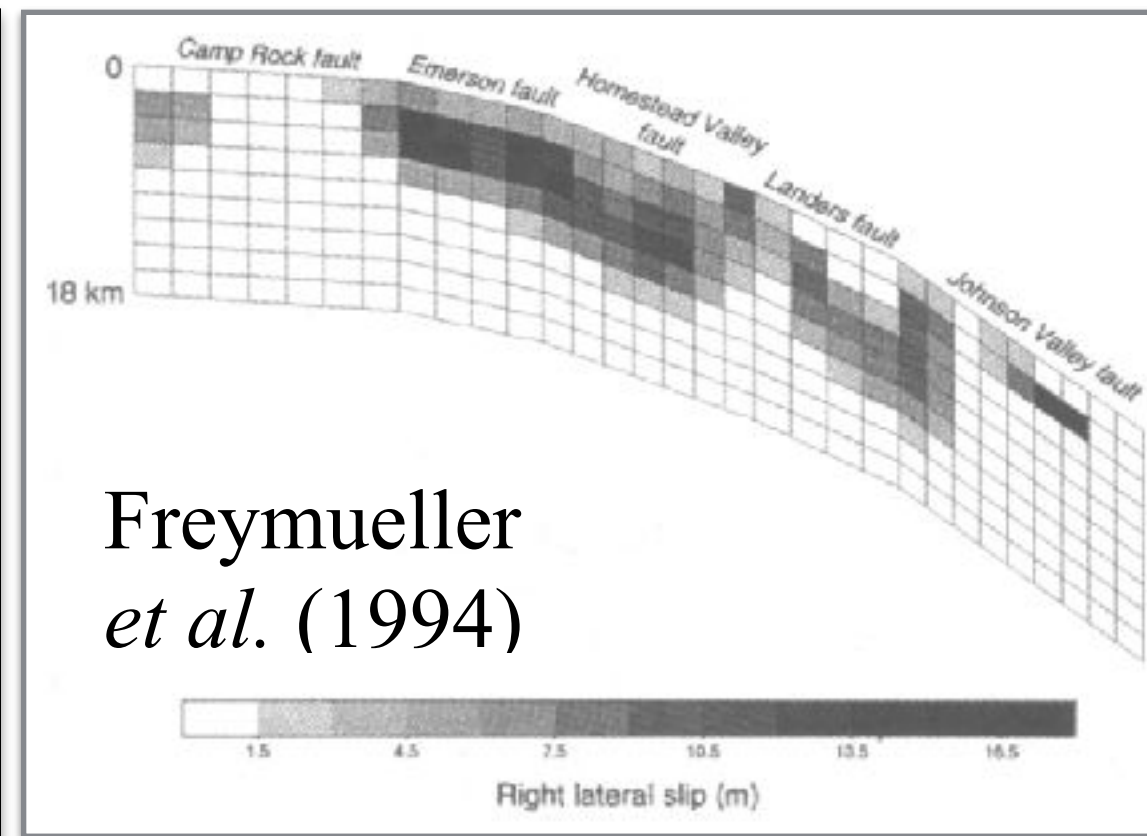
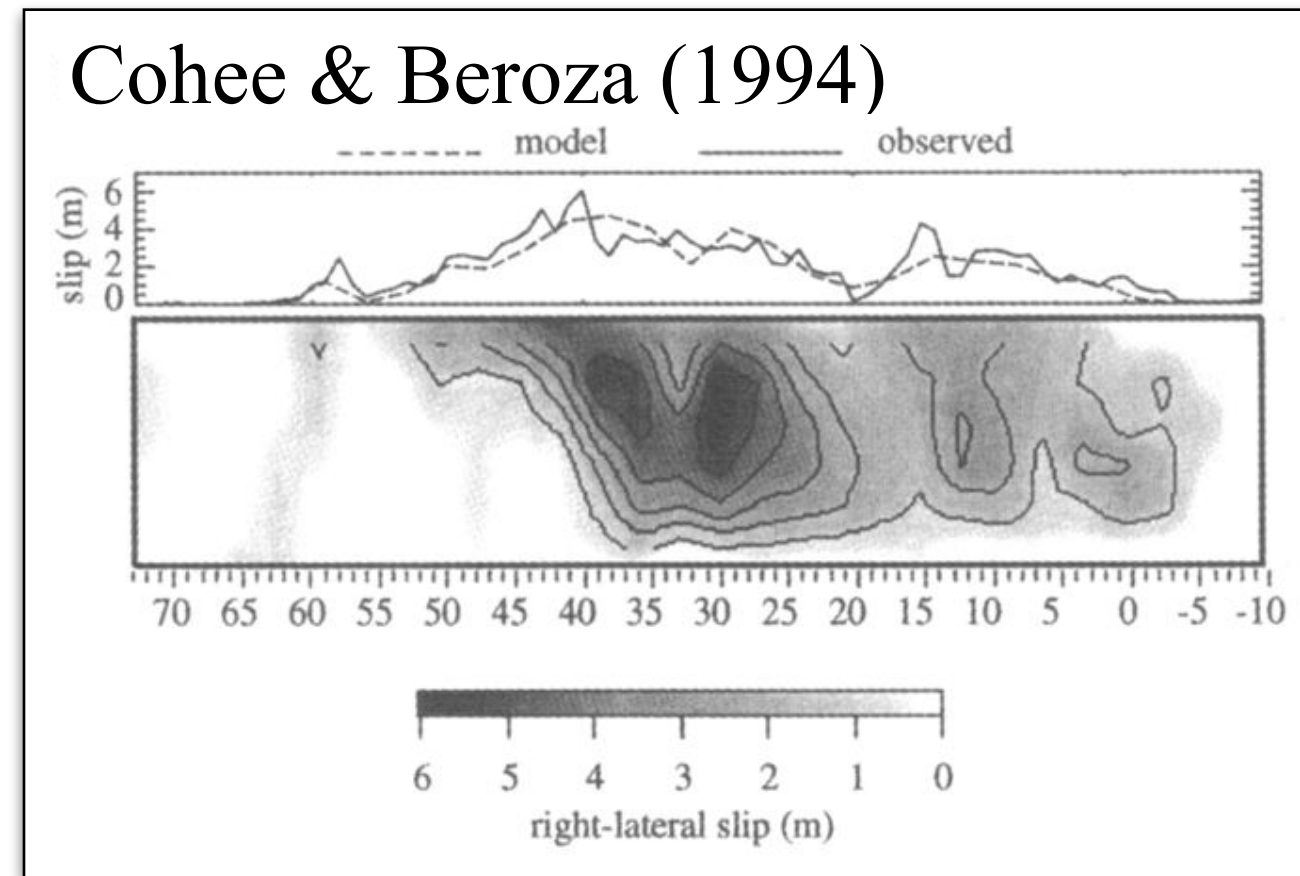


Xu *et al.* (2016)

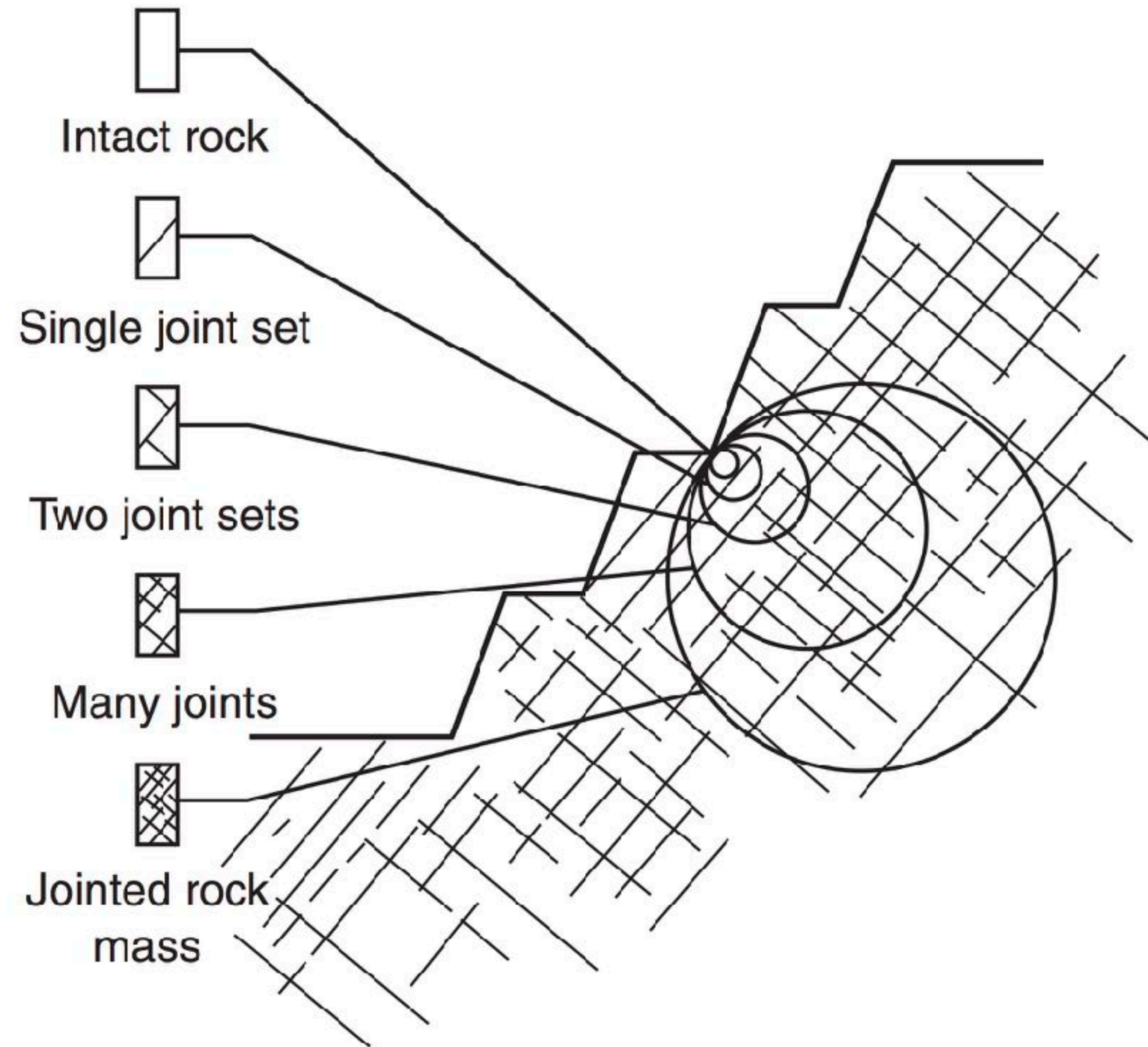


Source Models of 1992 M 7.3 Landers Earthquake

Dynamic Rupture Models

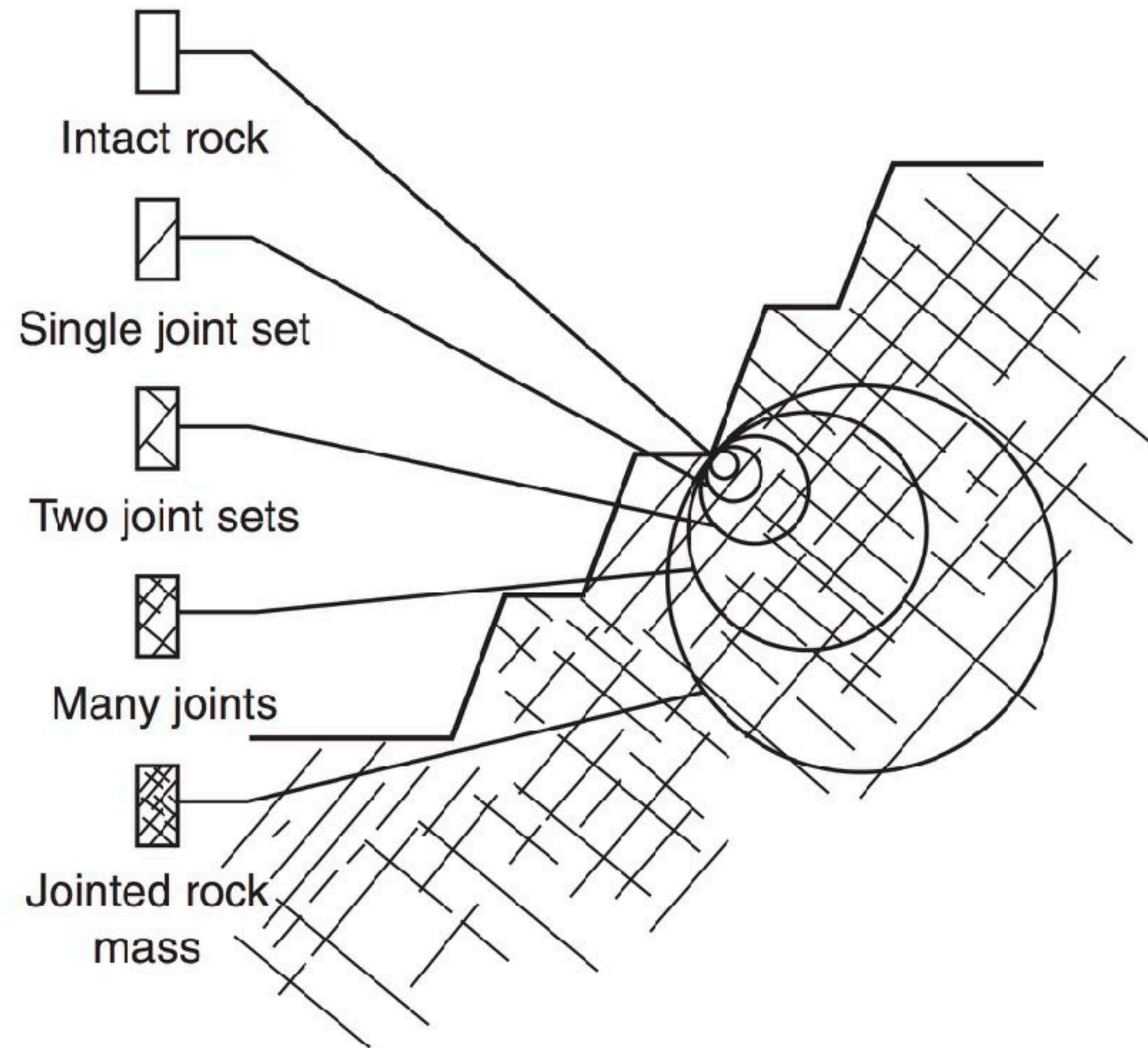


How to Define Rock Strength in Dynamic Rupture Simulations?



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

How to Define Rock Strength in Dynamic Rupture Simulations?

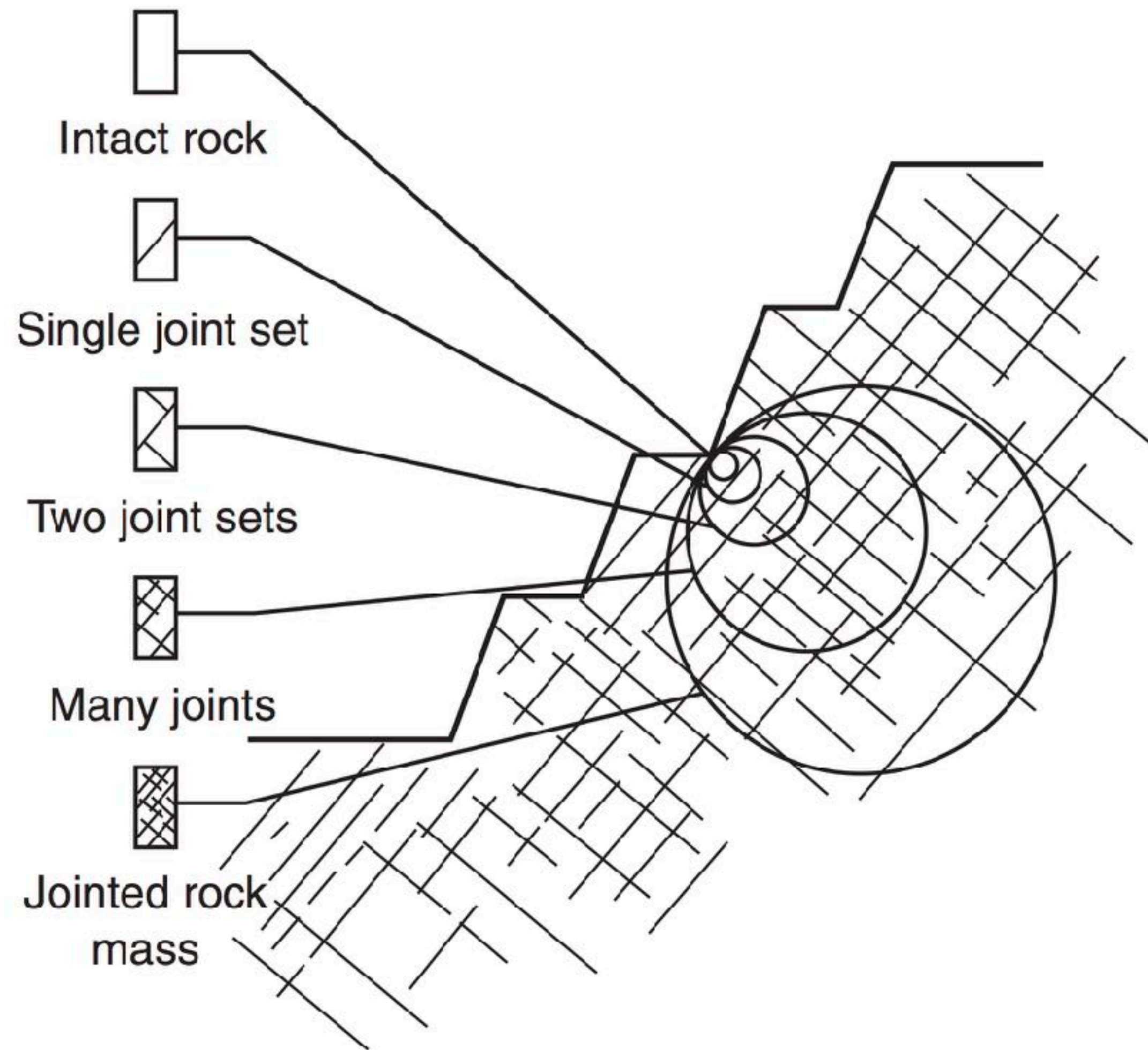


Hoek Brown failure criterion for fractured rock

- Accounts for reduction of shear strength caused by presence of joints
- Uses *Geological Strength Index (GSI)* to describe degree of fracturing

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

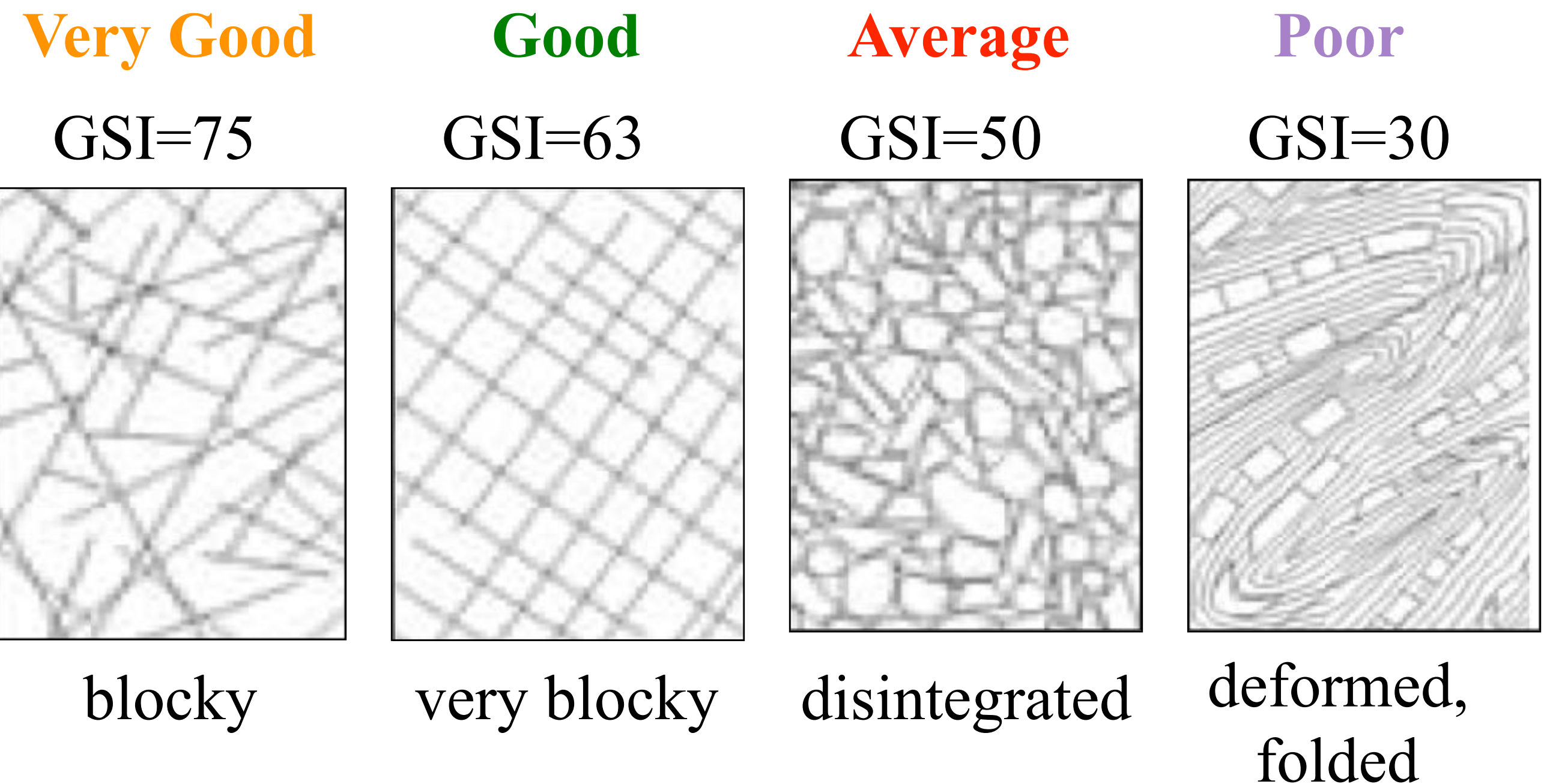
How to Define Rock Strength in Dynamic Rupture Simulations?



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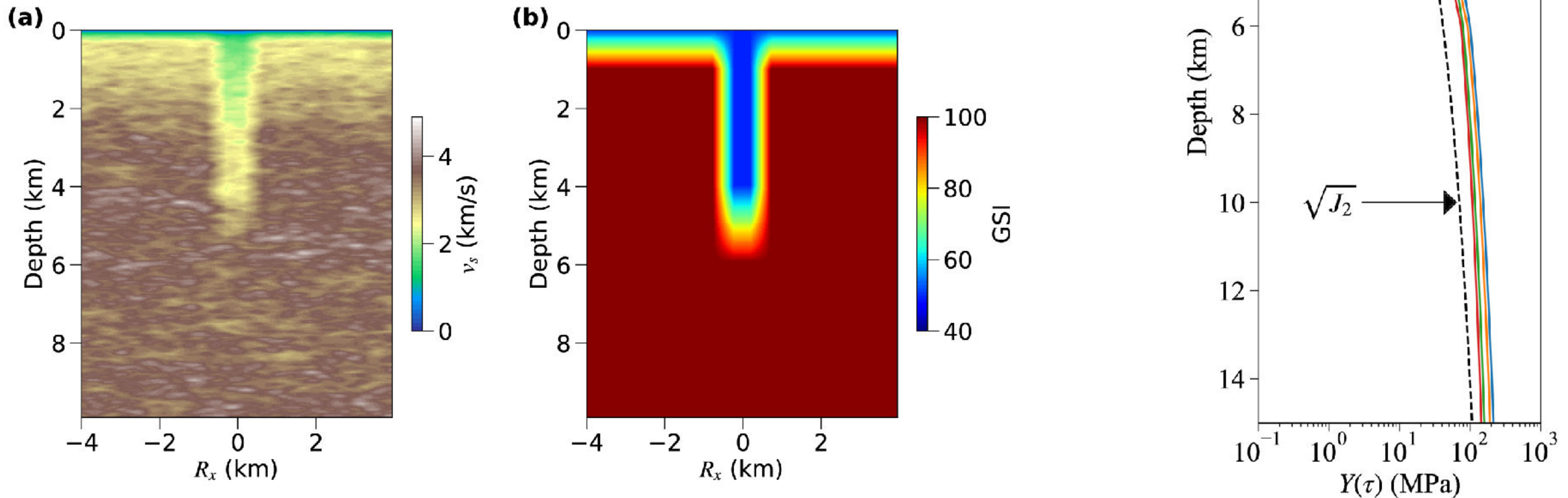
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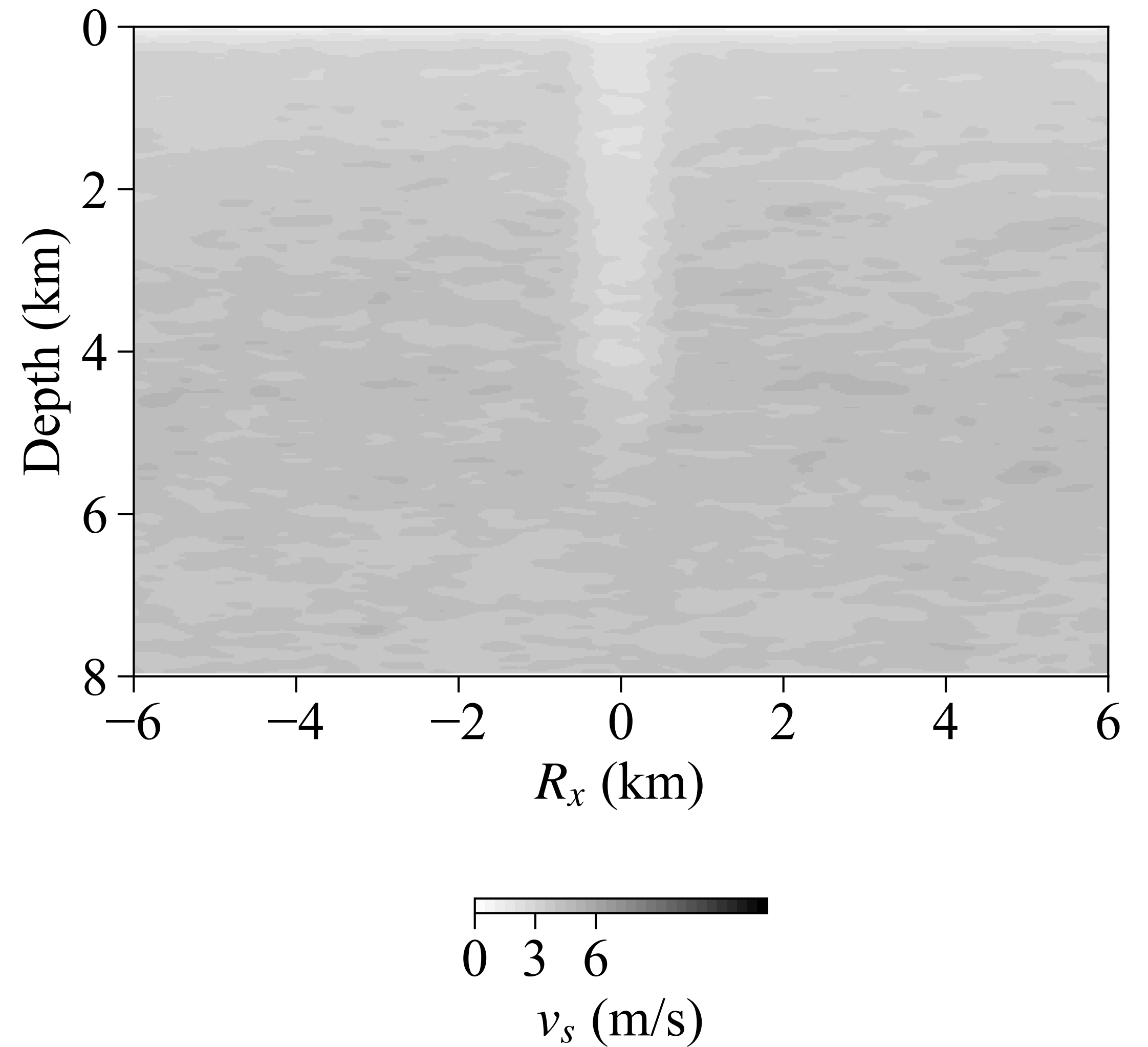
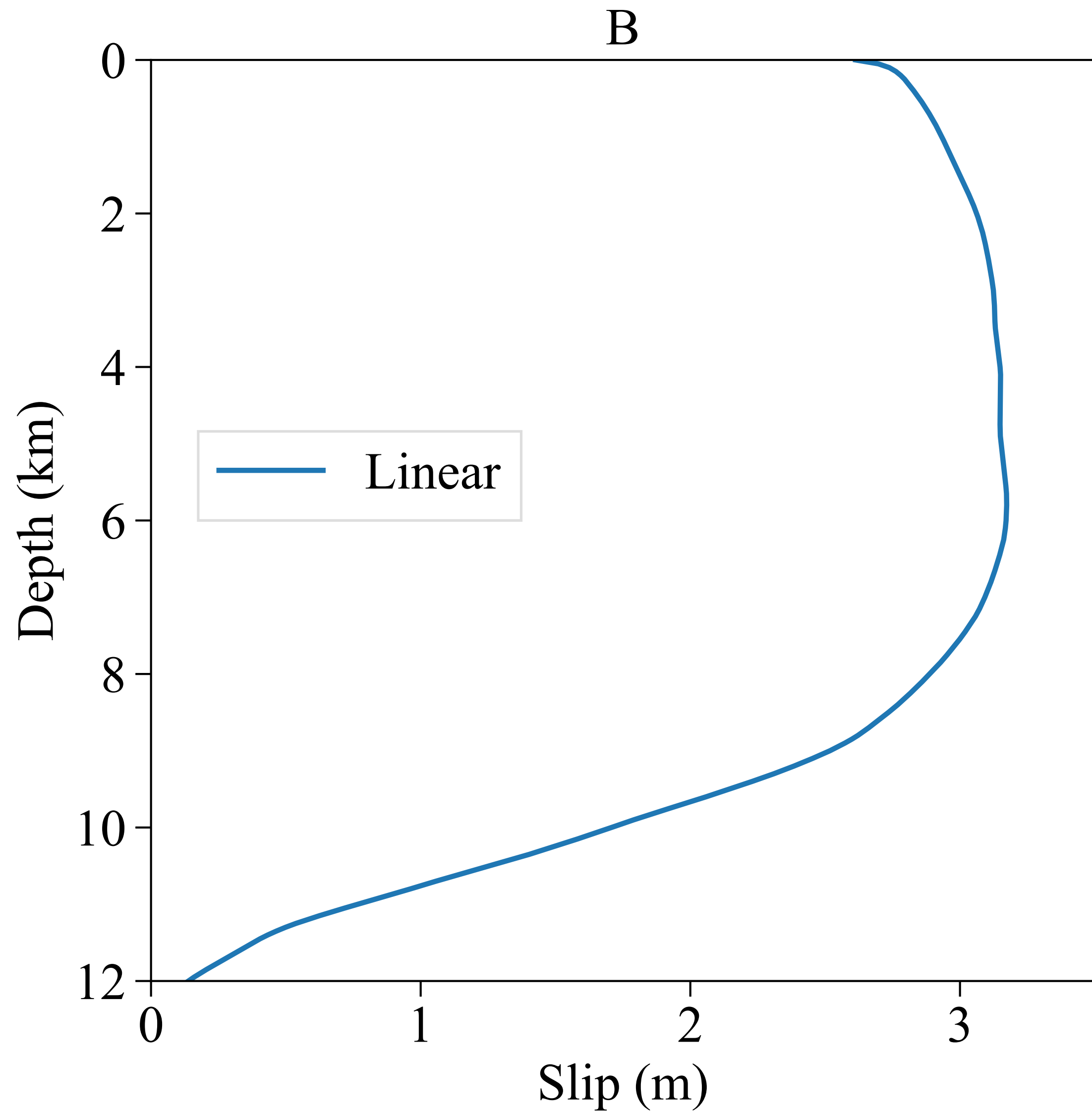
Definition of Four Rock Strength Models

Low-velocity zone (LVZ) around fault:

- Inner damage zone: 450 m wide, 4 km deep
- Outer damage zone: 1,5 km wide, 6 km deep
- GSI=100 outside LVZ and below 1 km depth
- Inside LVZ GSI represents pre-fractured rock

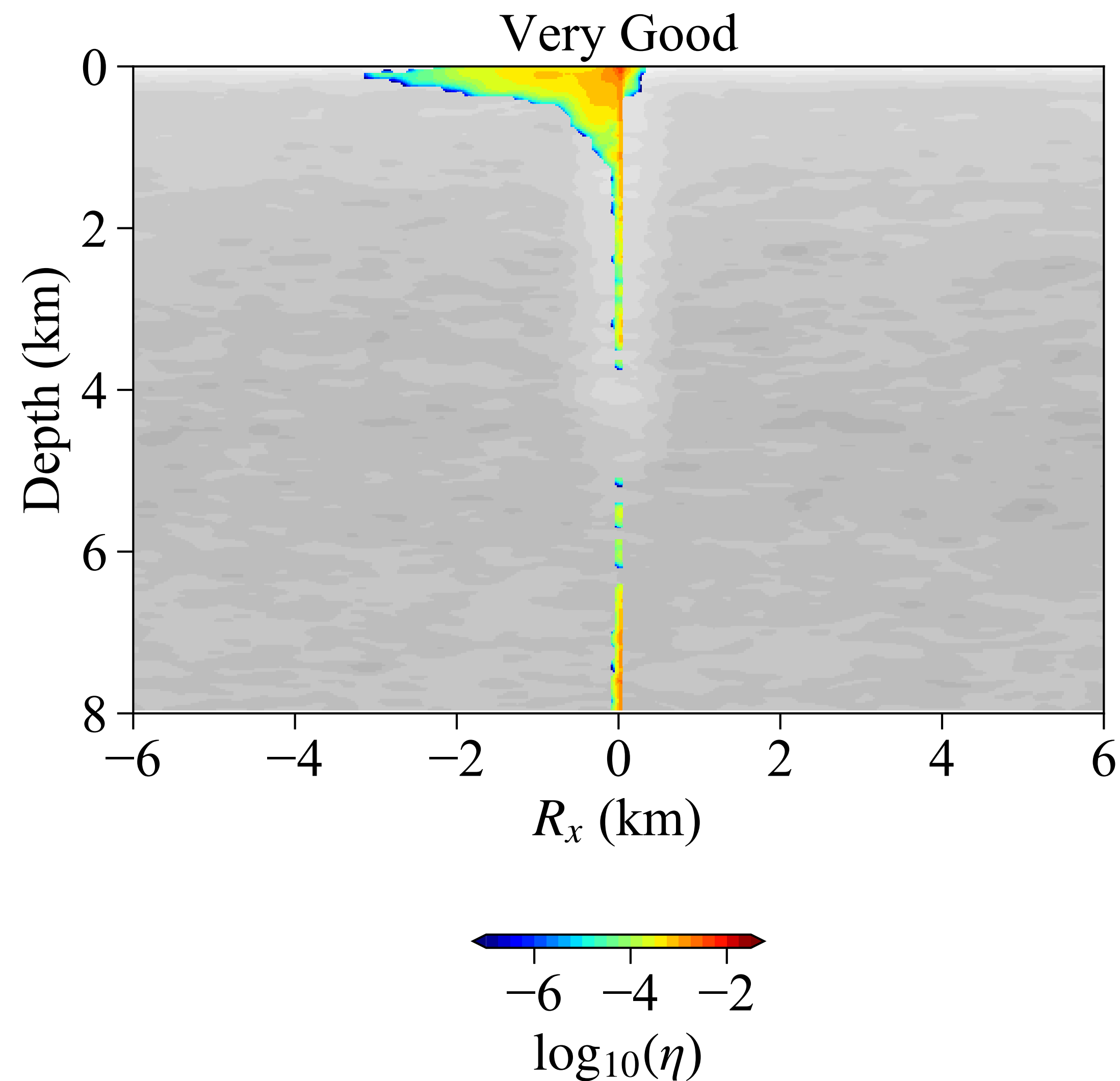
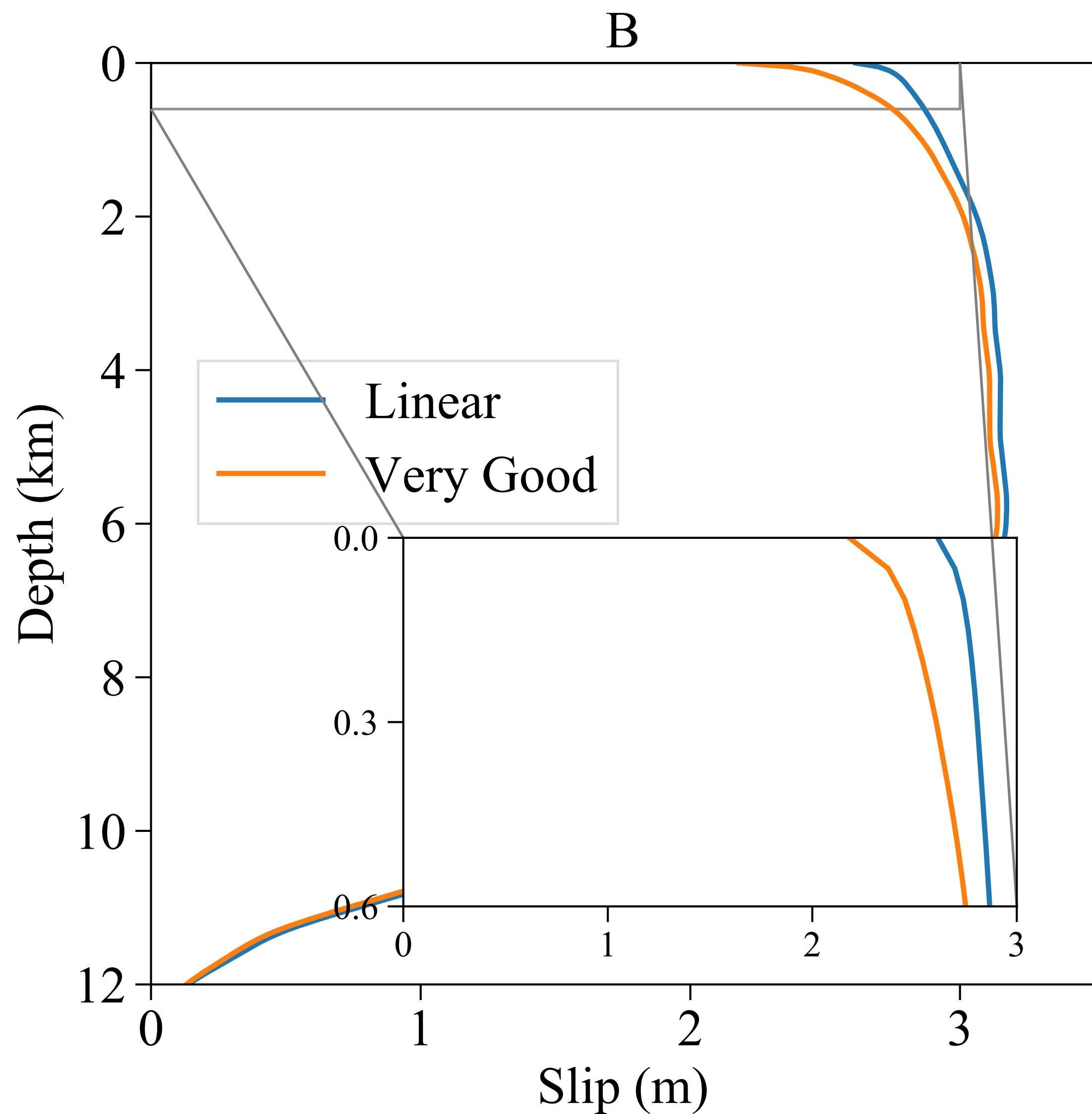


Shallow Slip Deficit from Fault Zone Plasticity

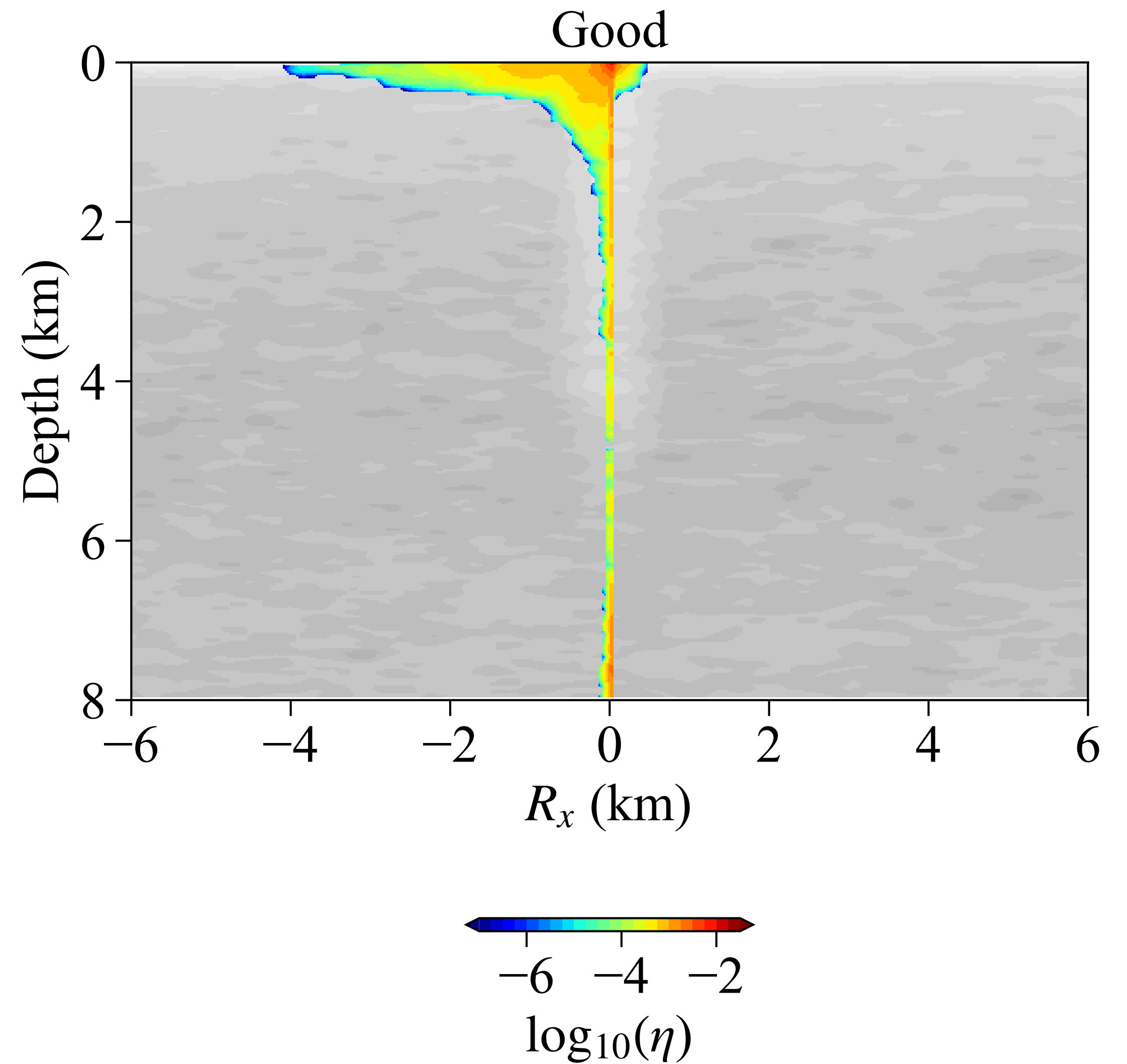
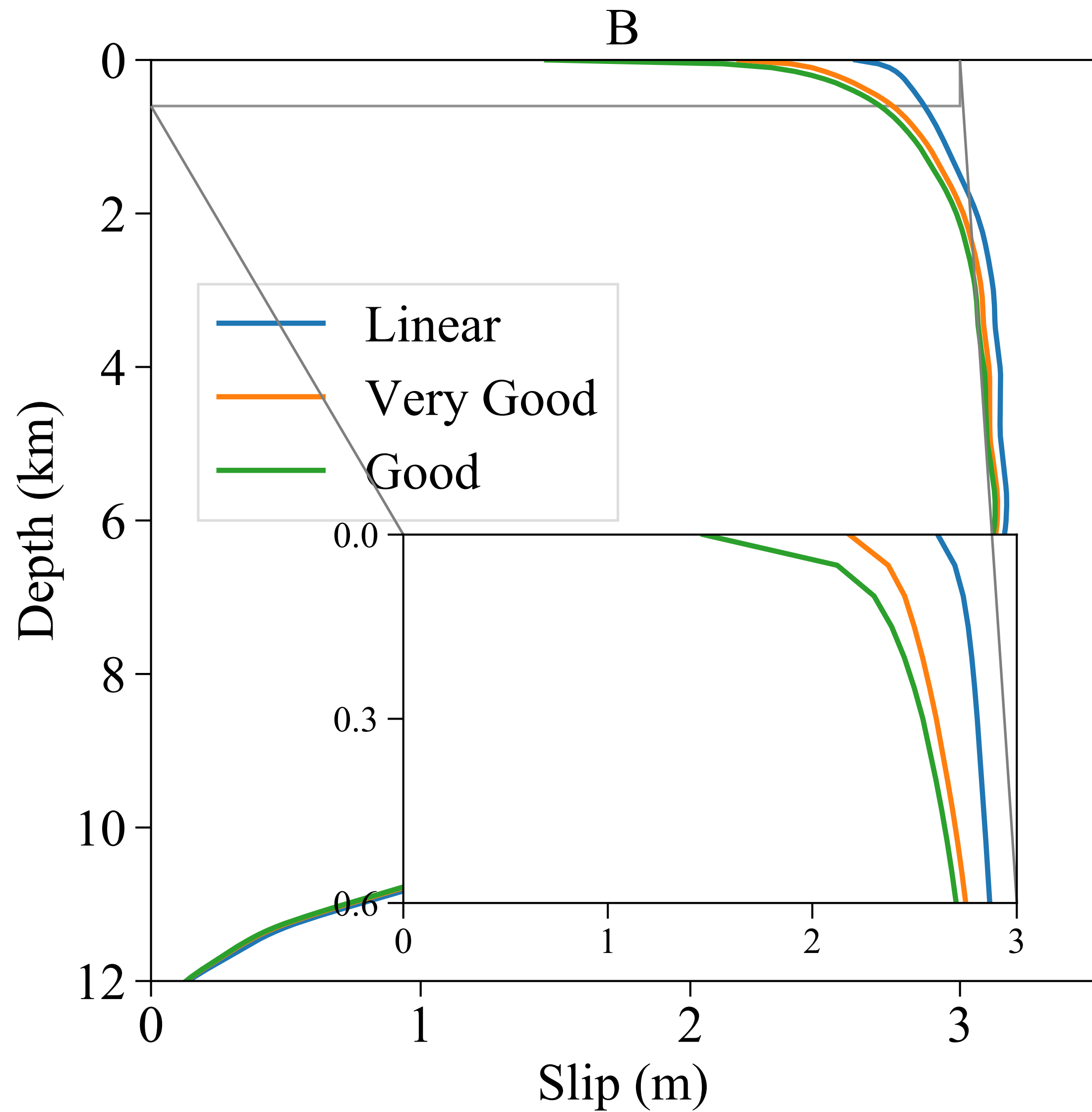


Roten *et al.*, GRL, 2017

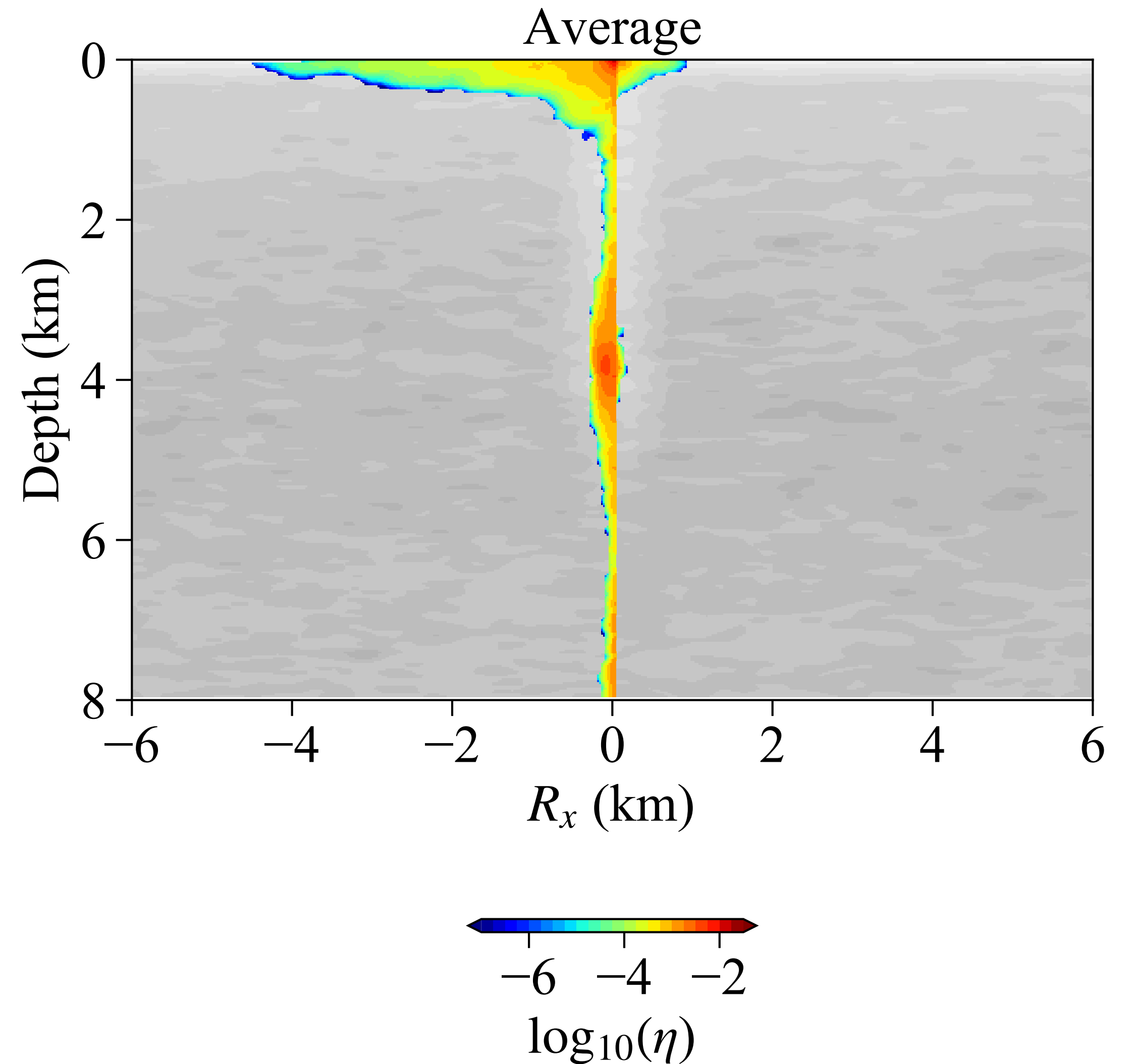
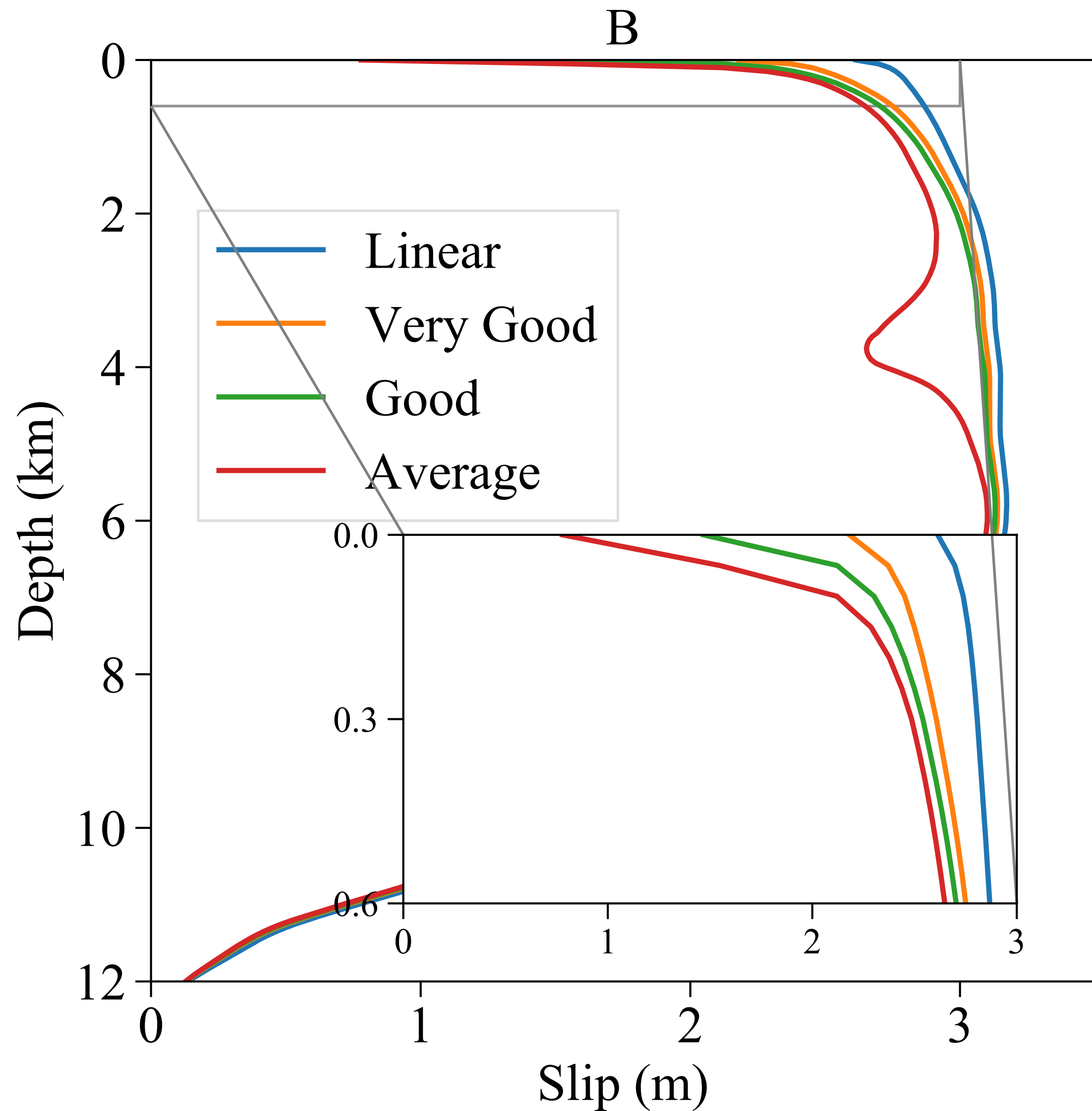
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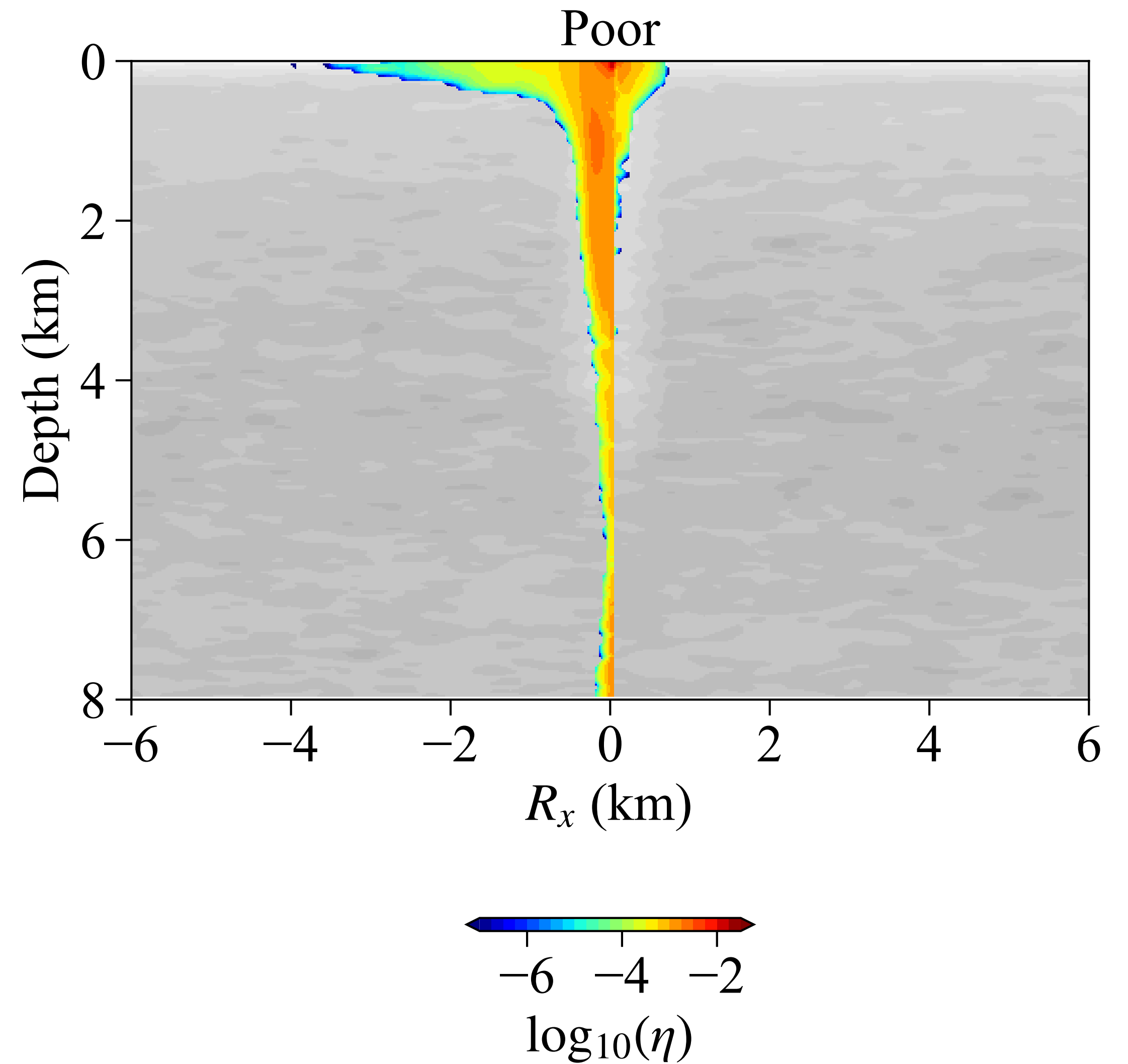
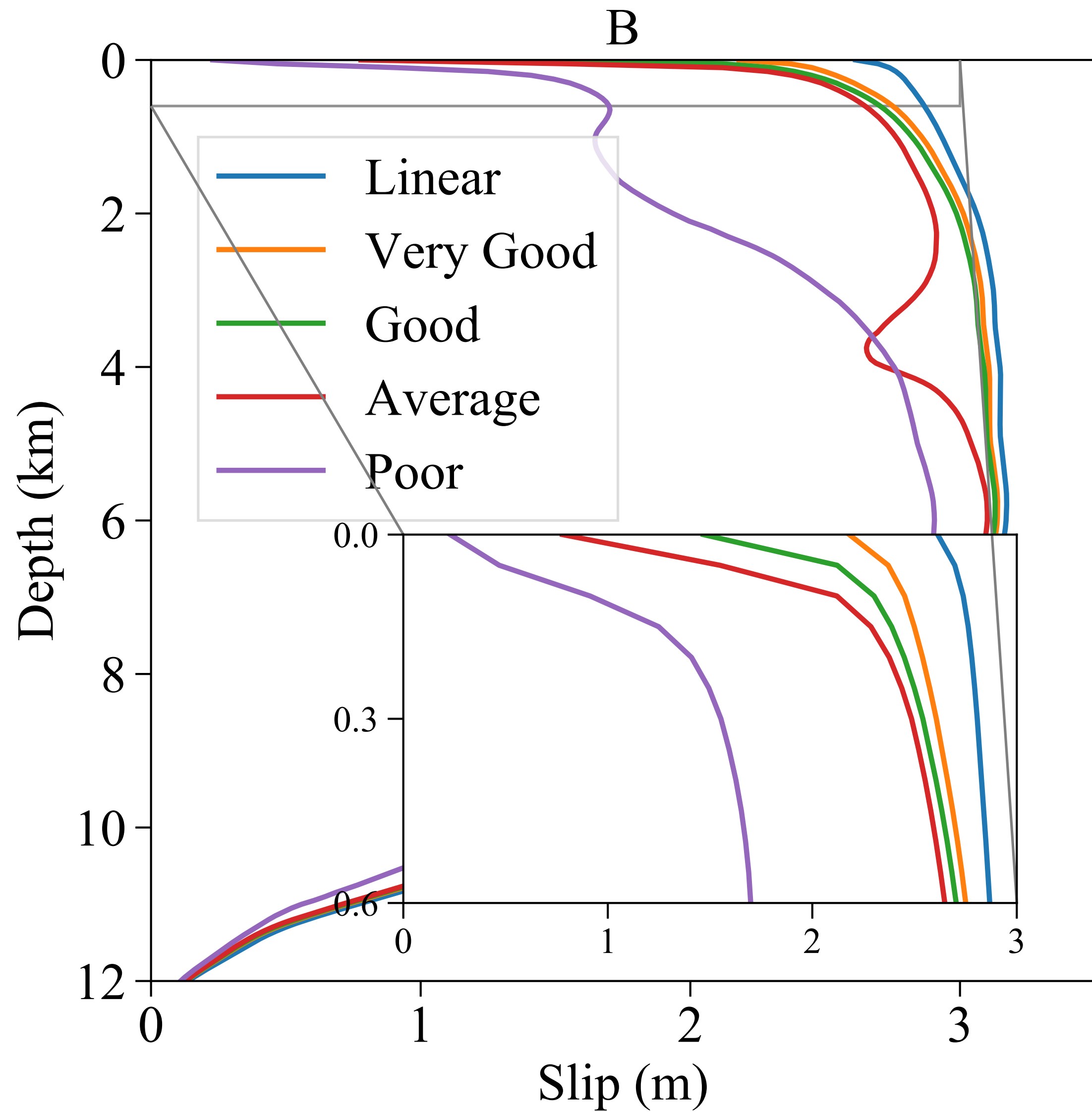
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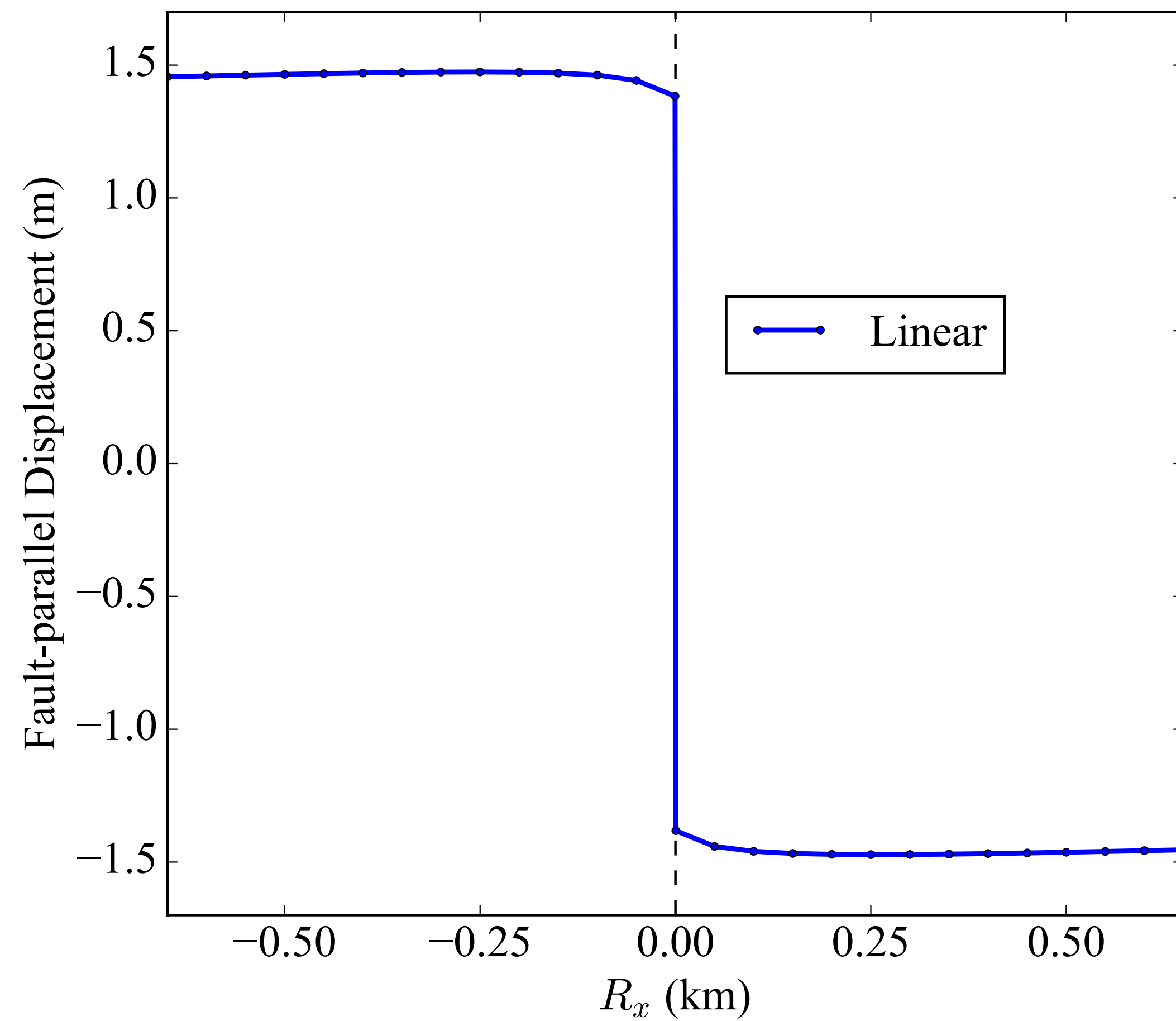


Shallow Slip Deficit from Fault Zone Plasticity



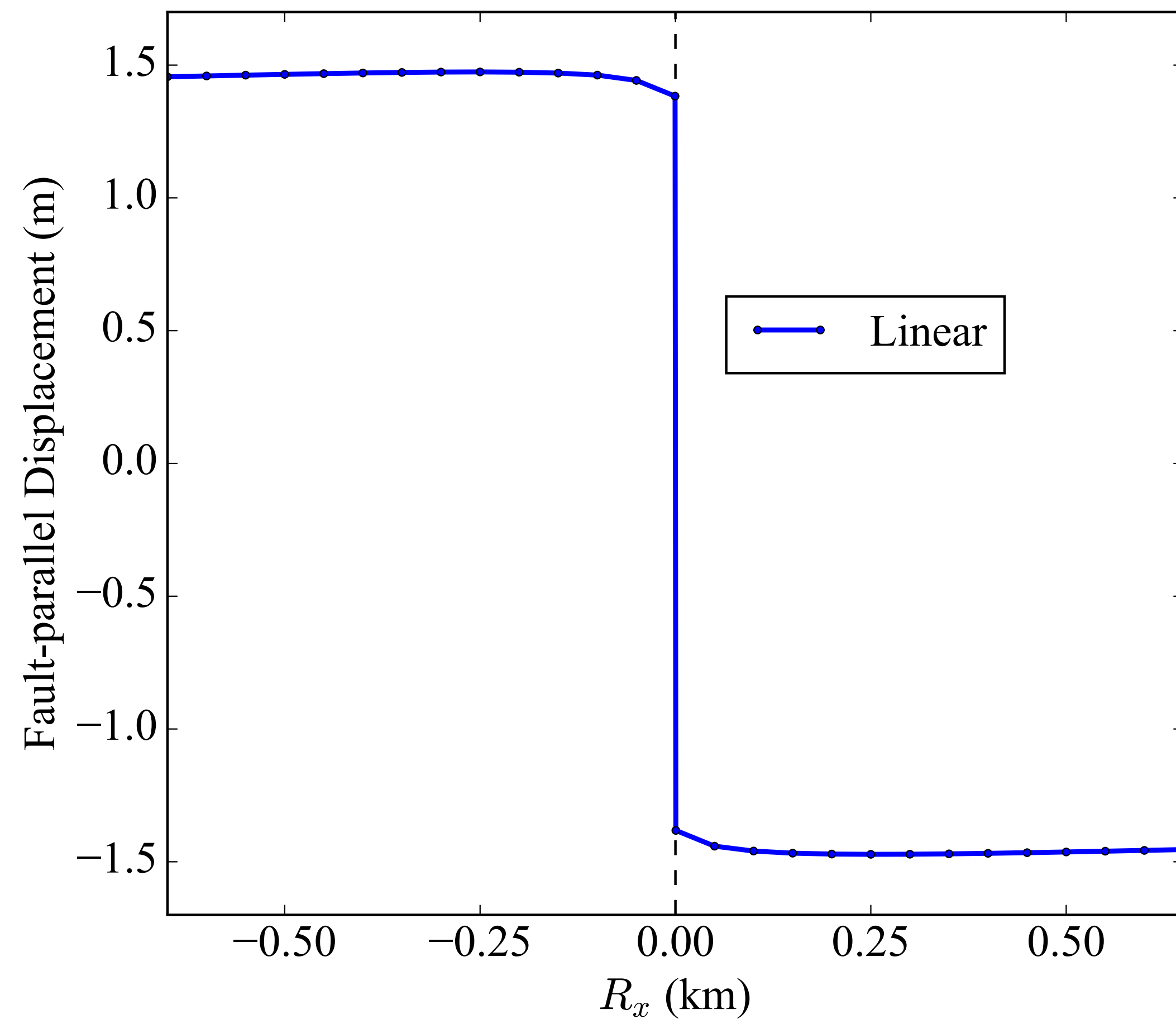
Effect of Plasticity on Shear Zone Width

Average of simulated displacement
(rupture model C)

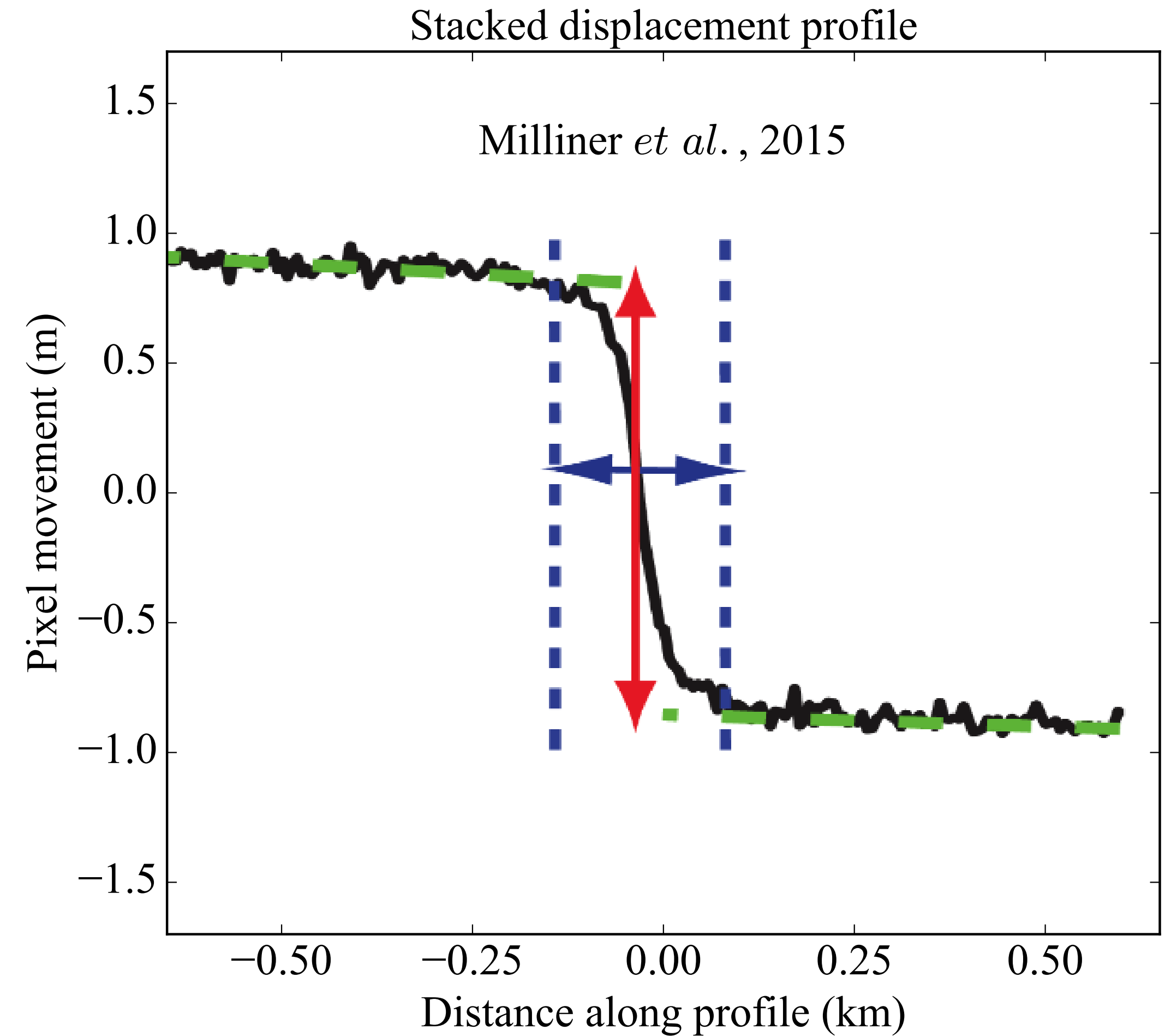


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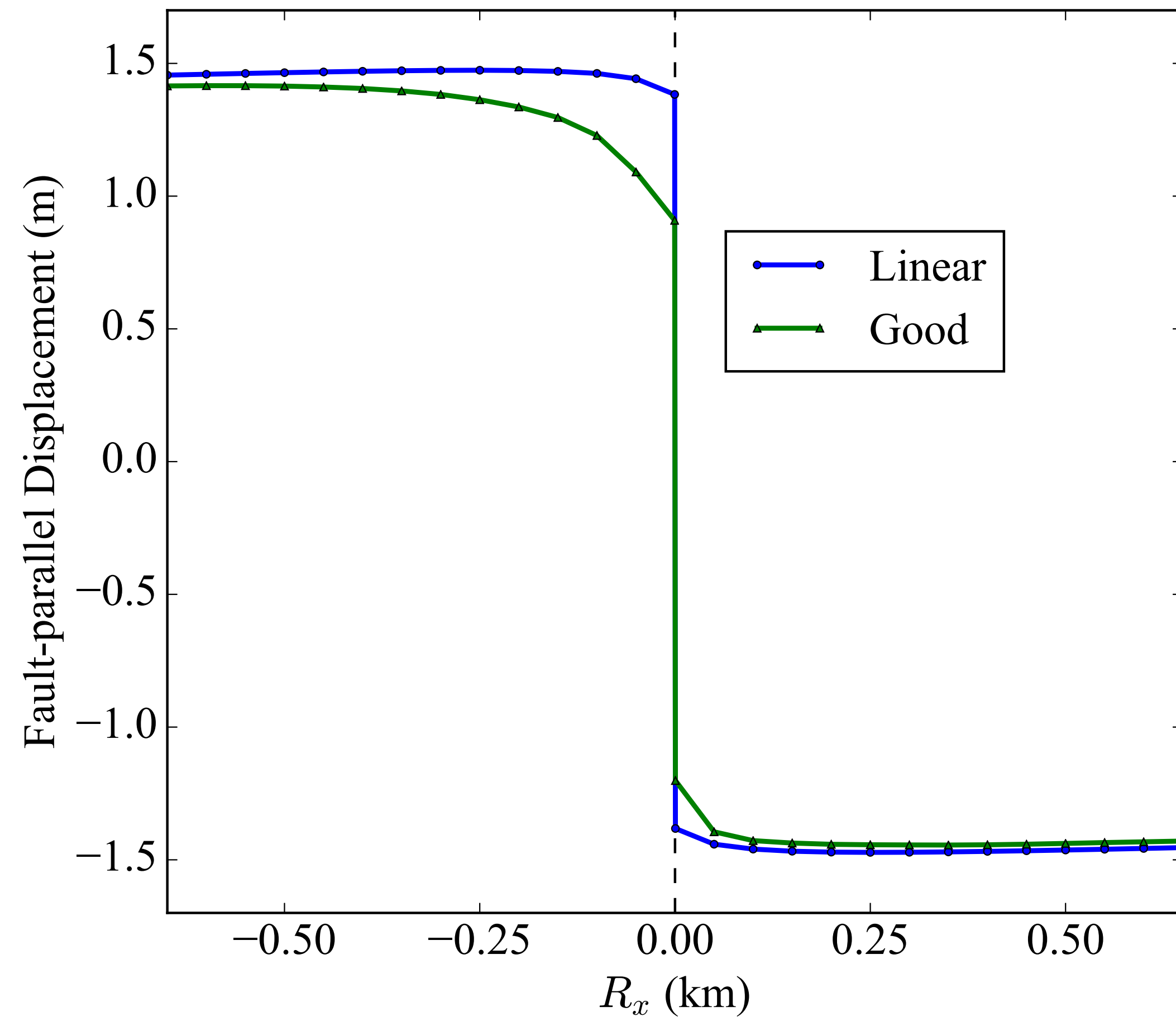


Displacement derived from correlation of
aerial images (COSI-Corr)

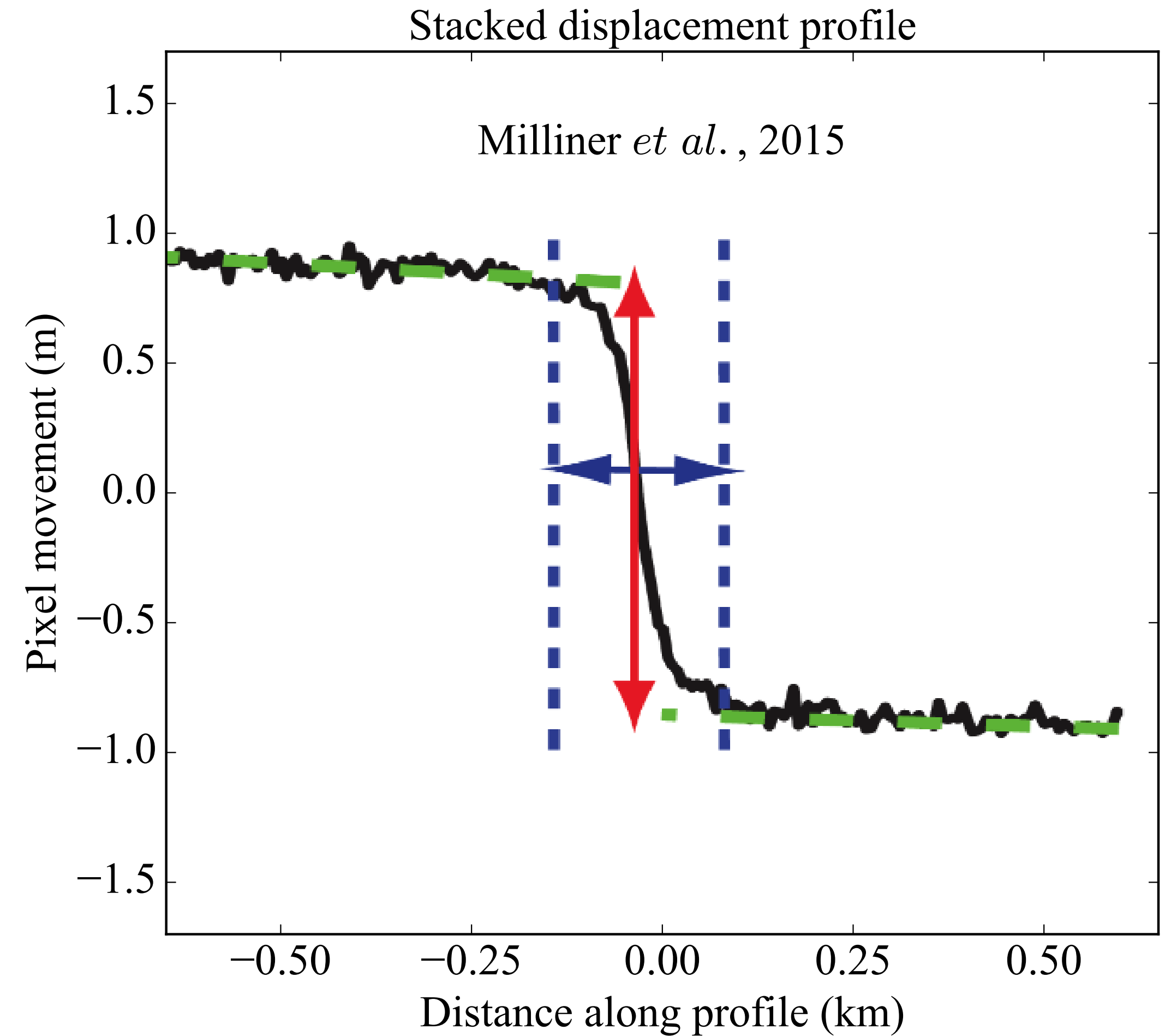


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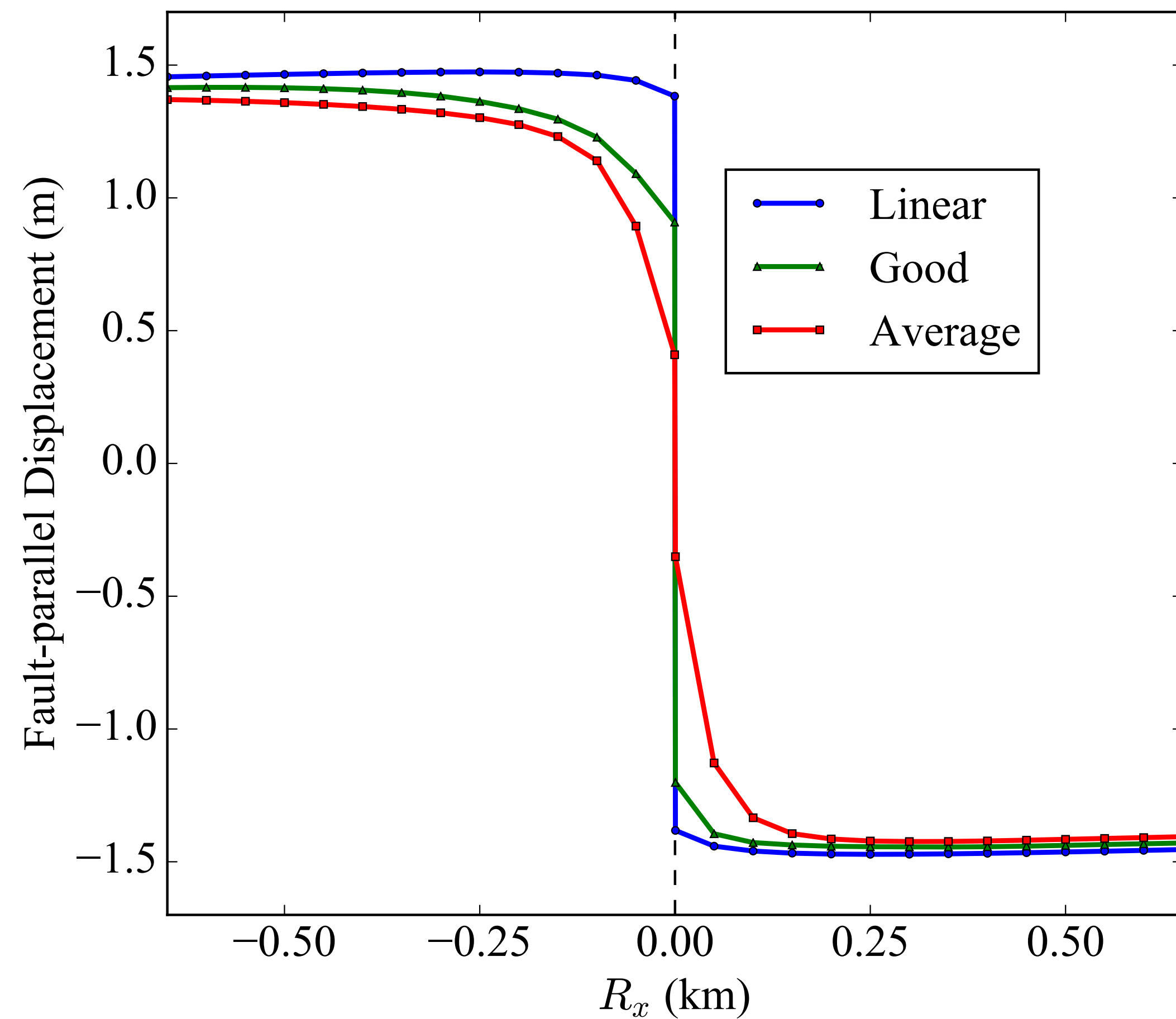


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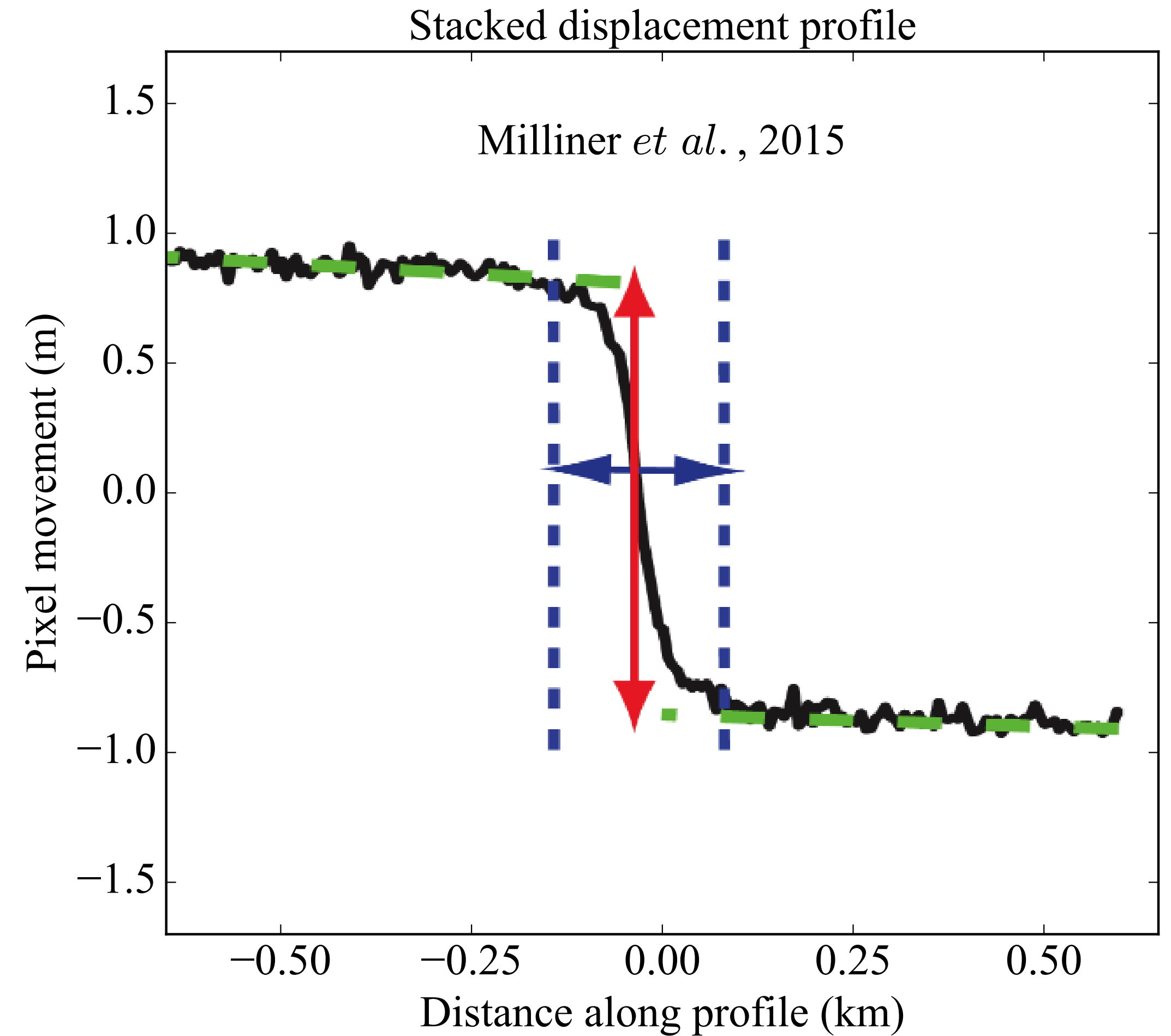


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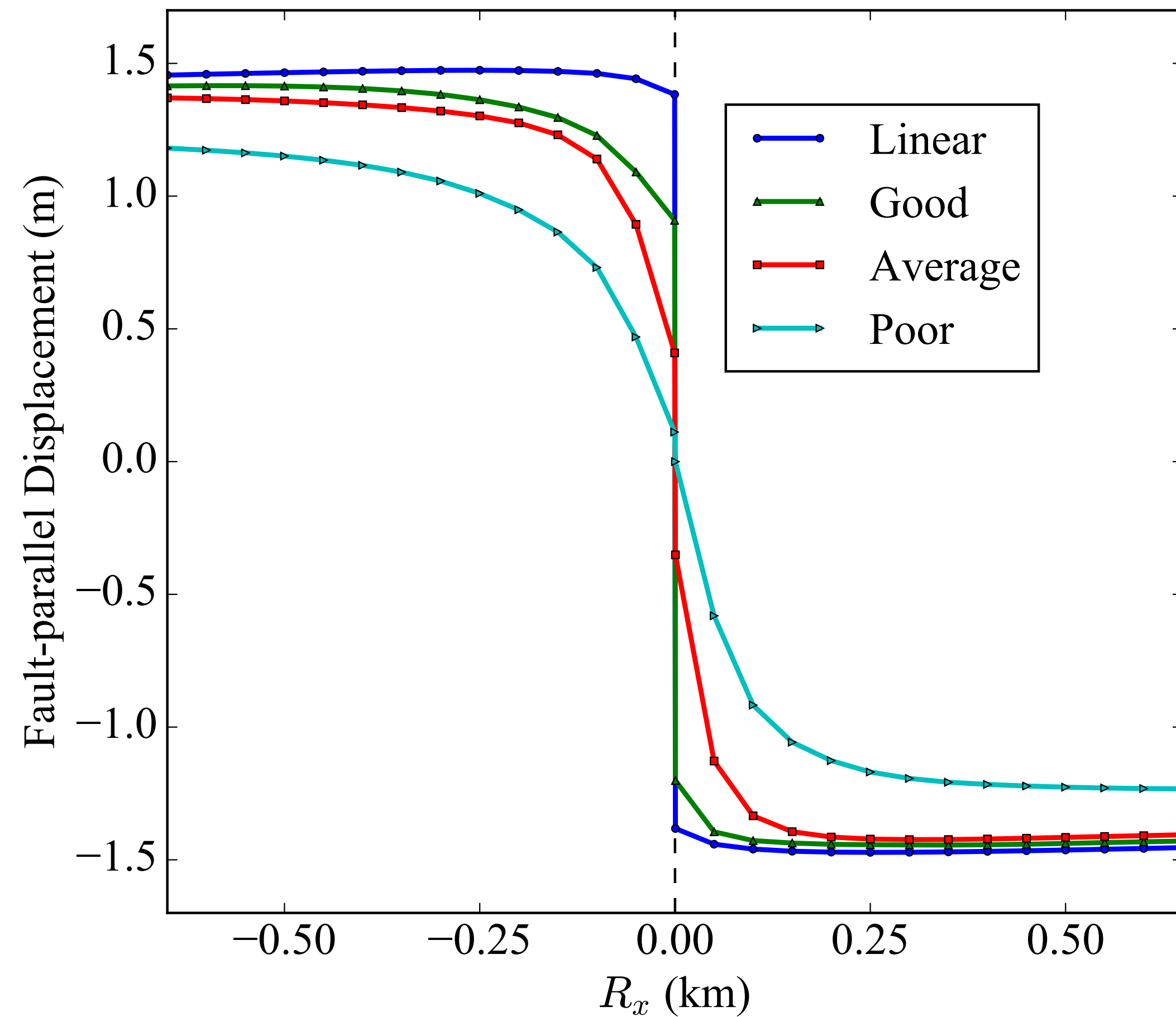


Displacement derived from correlation of
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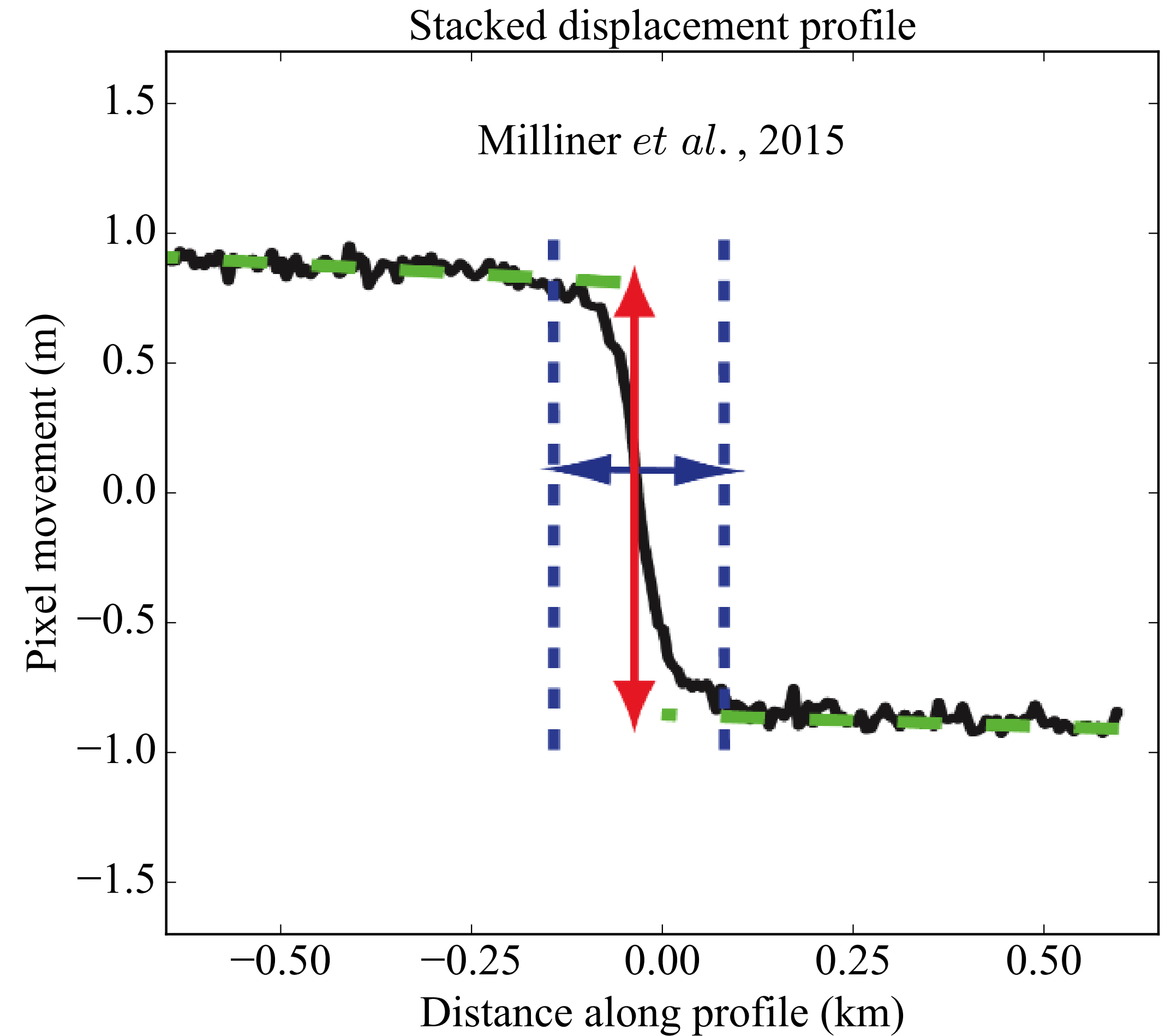


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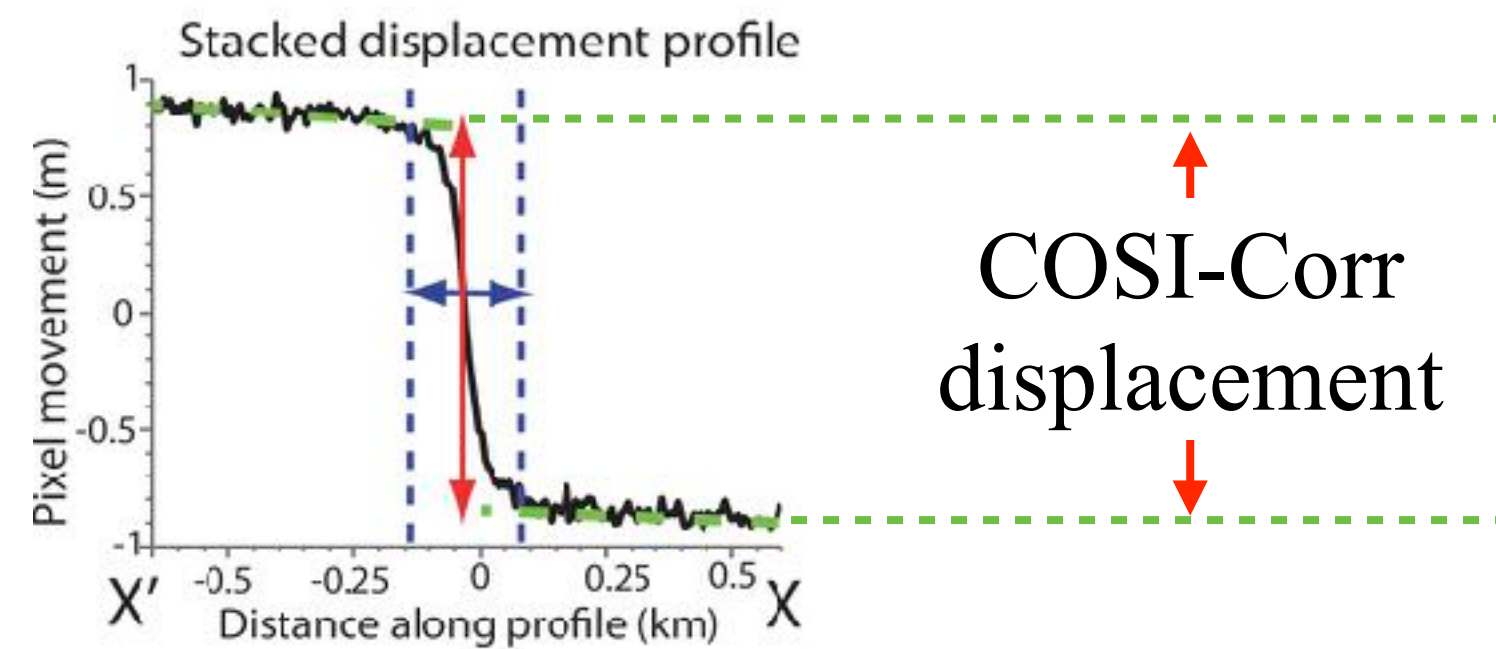
Displacement derived from correlation of
aerial images (COSI-Corr)



Quantifying Off-fault Deformation (OFD)

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

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

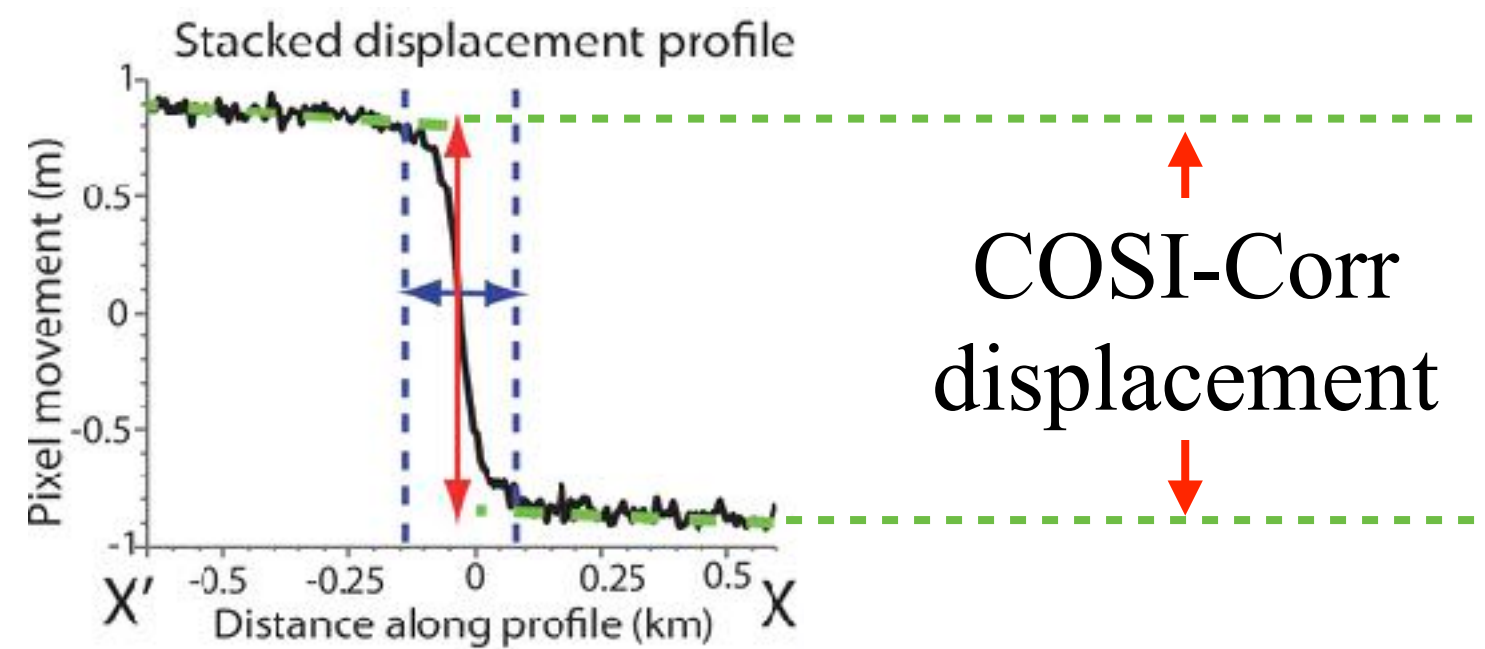


Main fault
strand field
displacement

Quantifying Off-fault Deformation (OFD)

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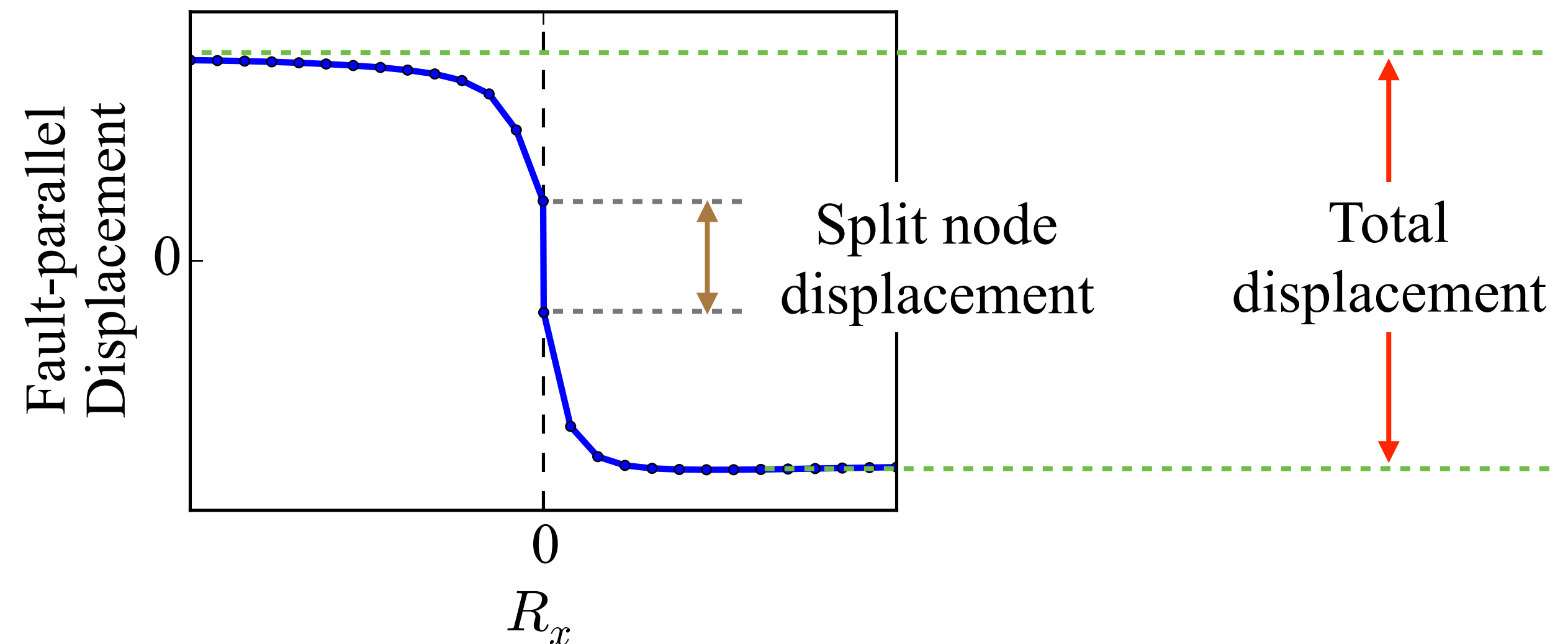
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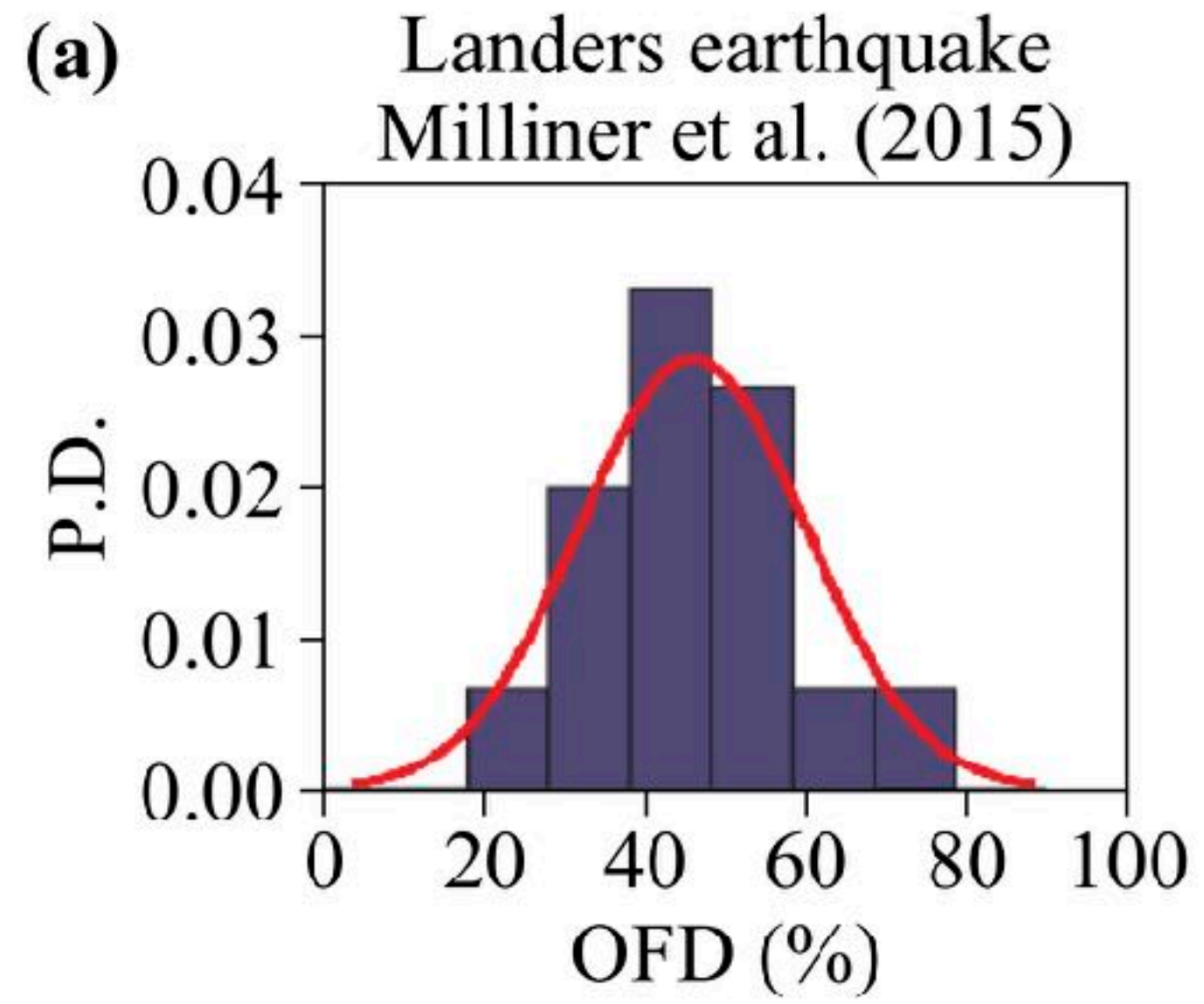
Main fault strand field displacement

Simulated off-fault deformation:

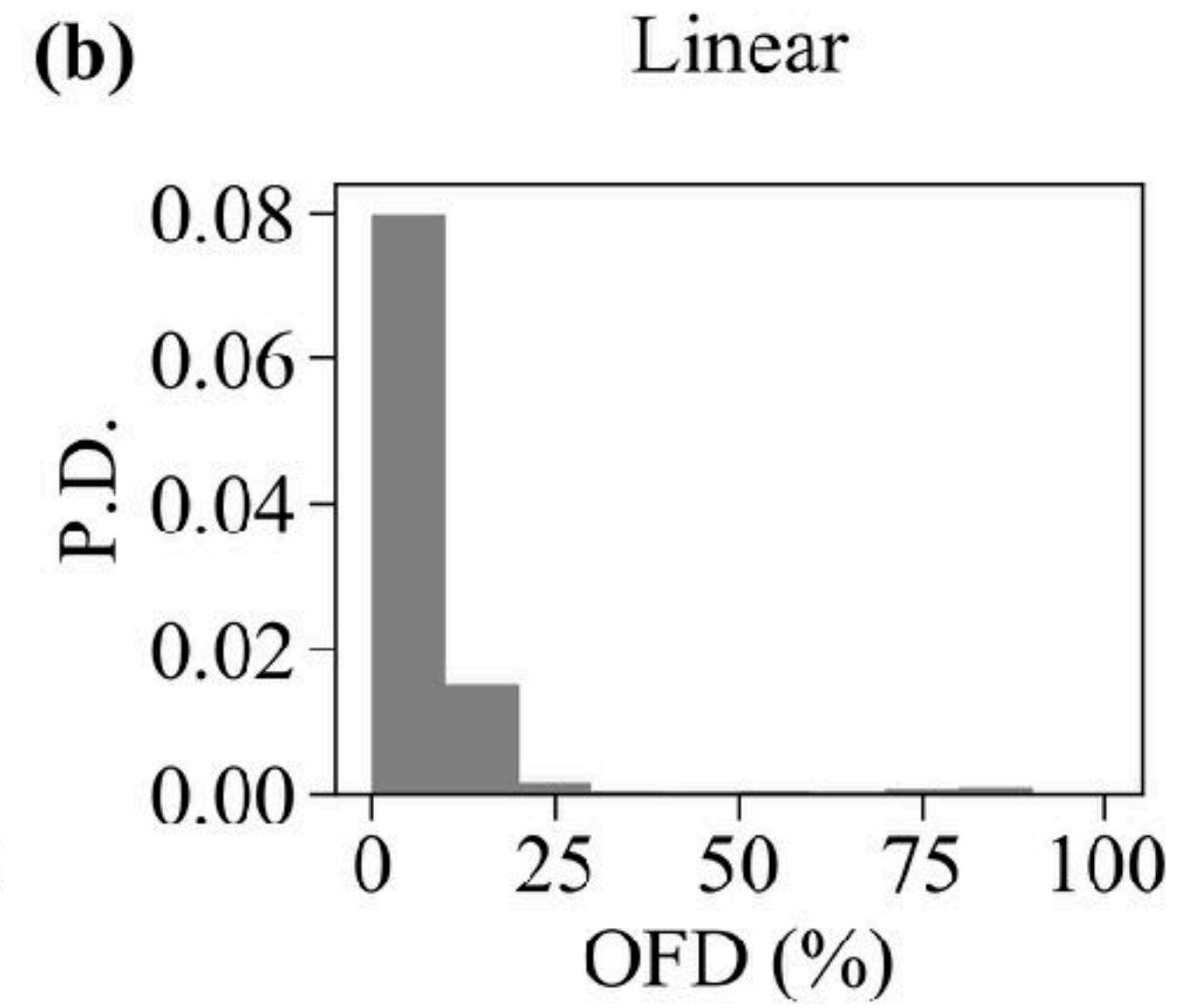
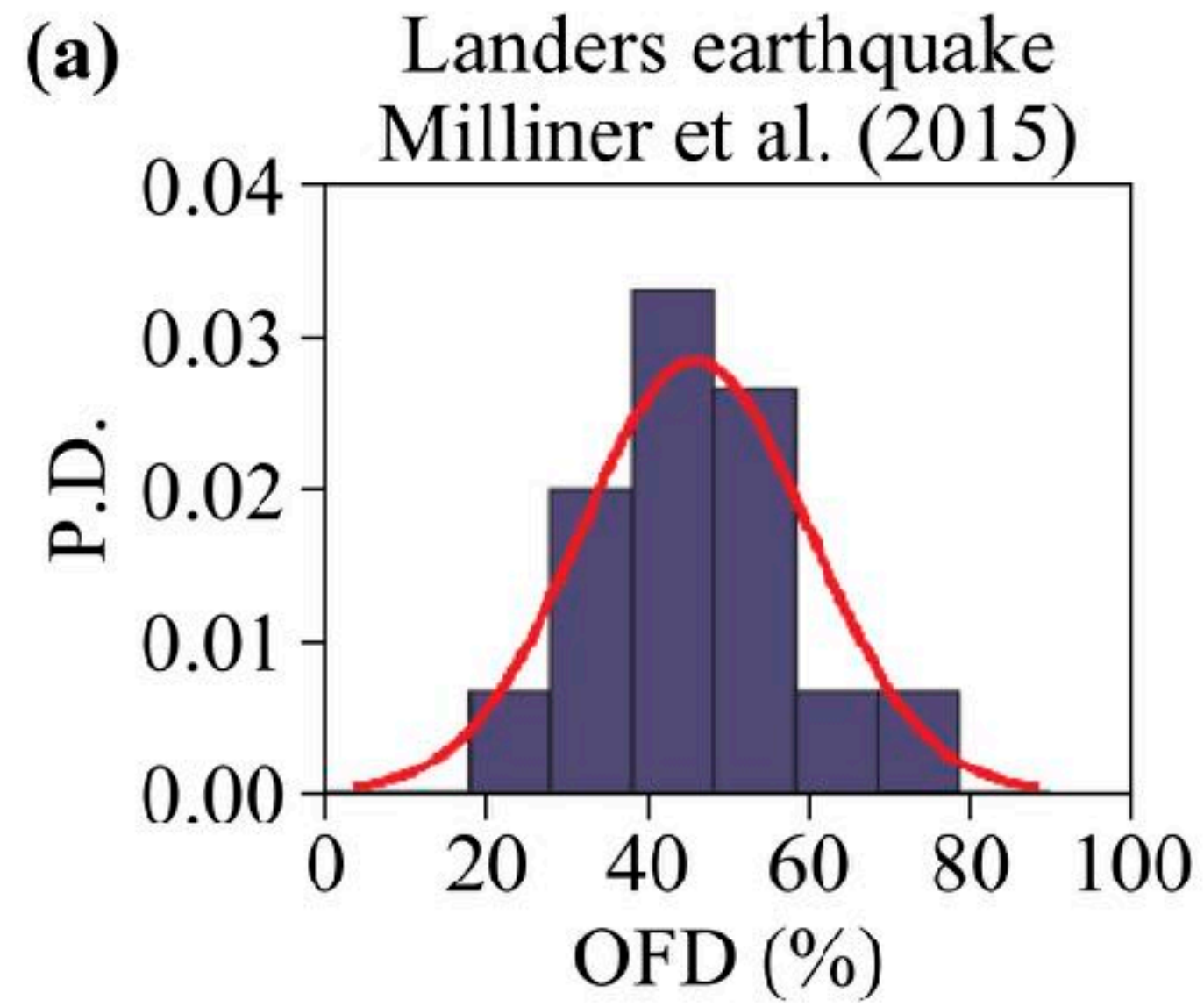
$$\text{OFD} = \frac{\text{Total displacement} - \text{Split node displacement}}{\text{Total displacement}}$$



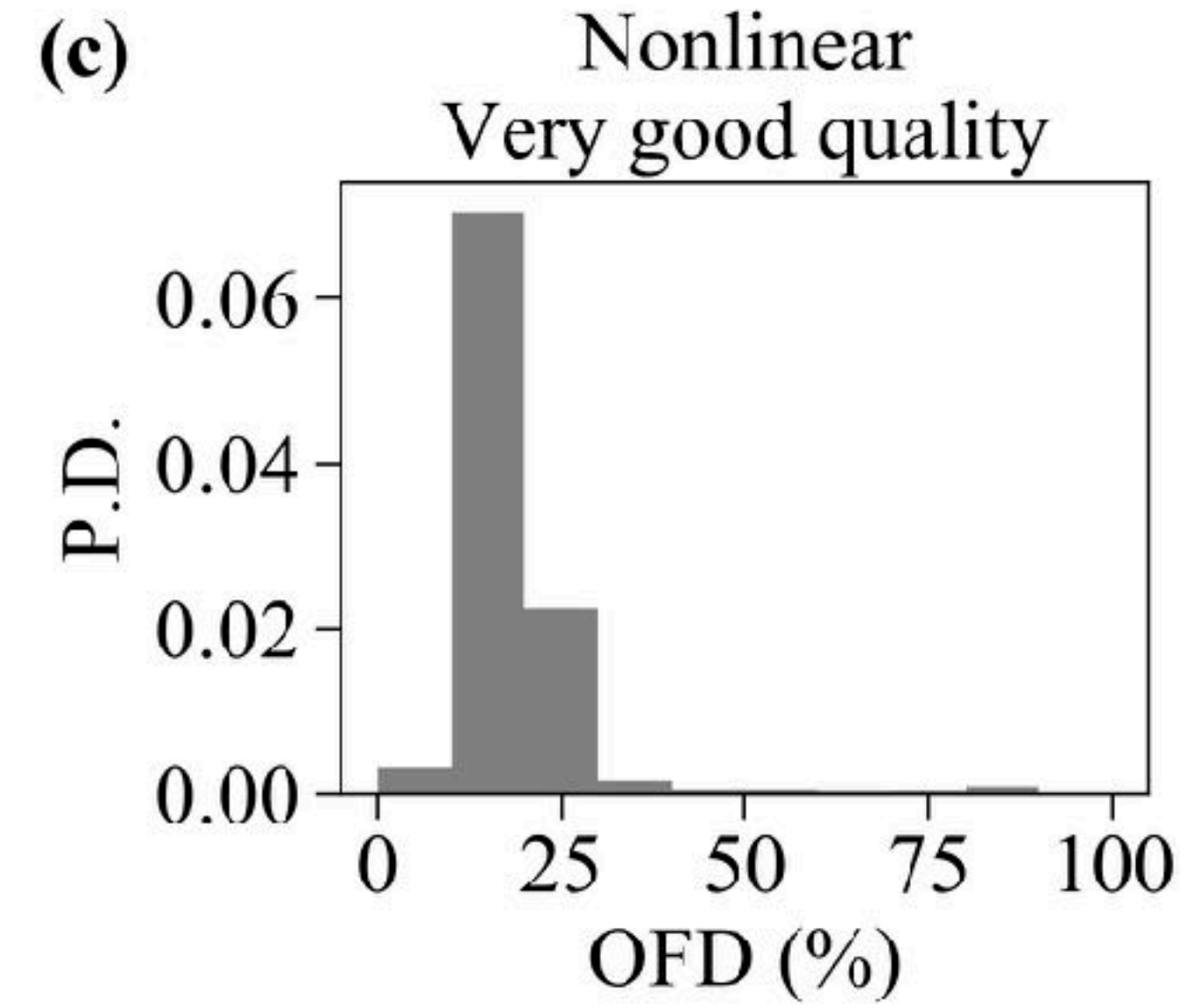
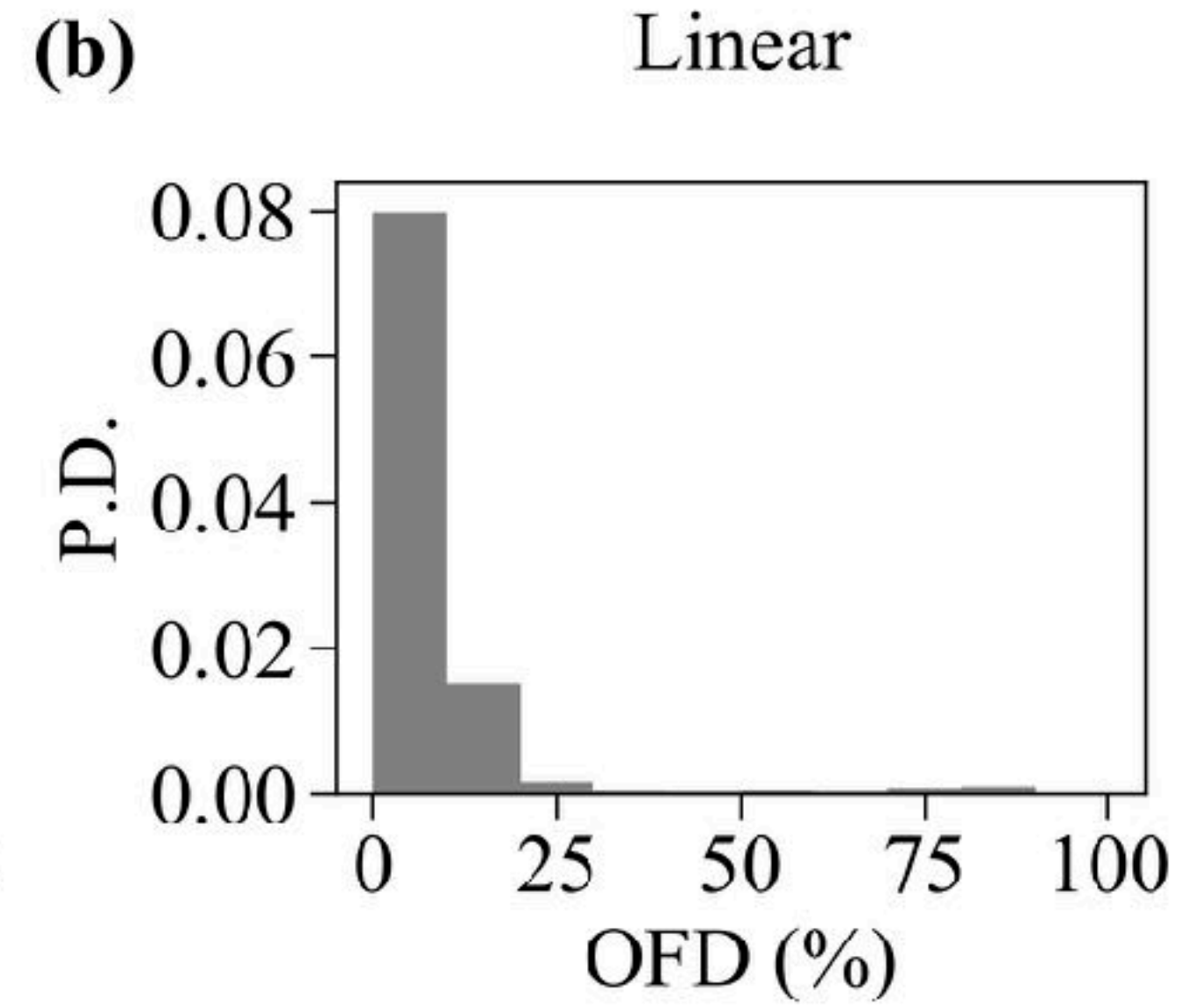
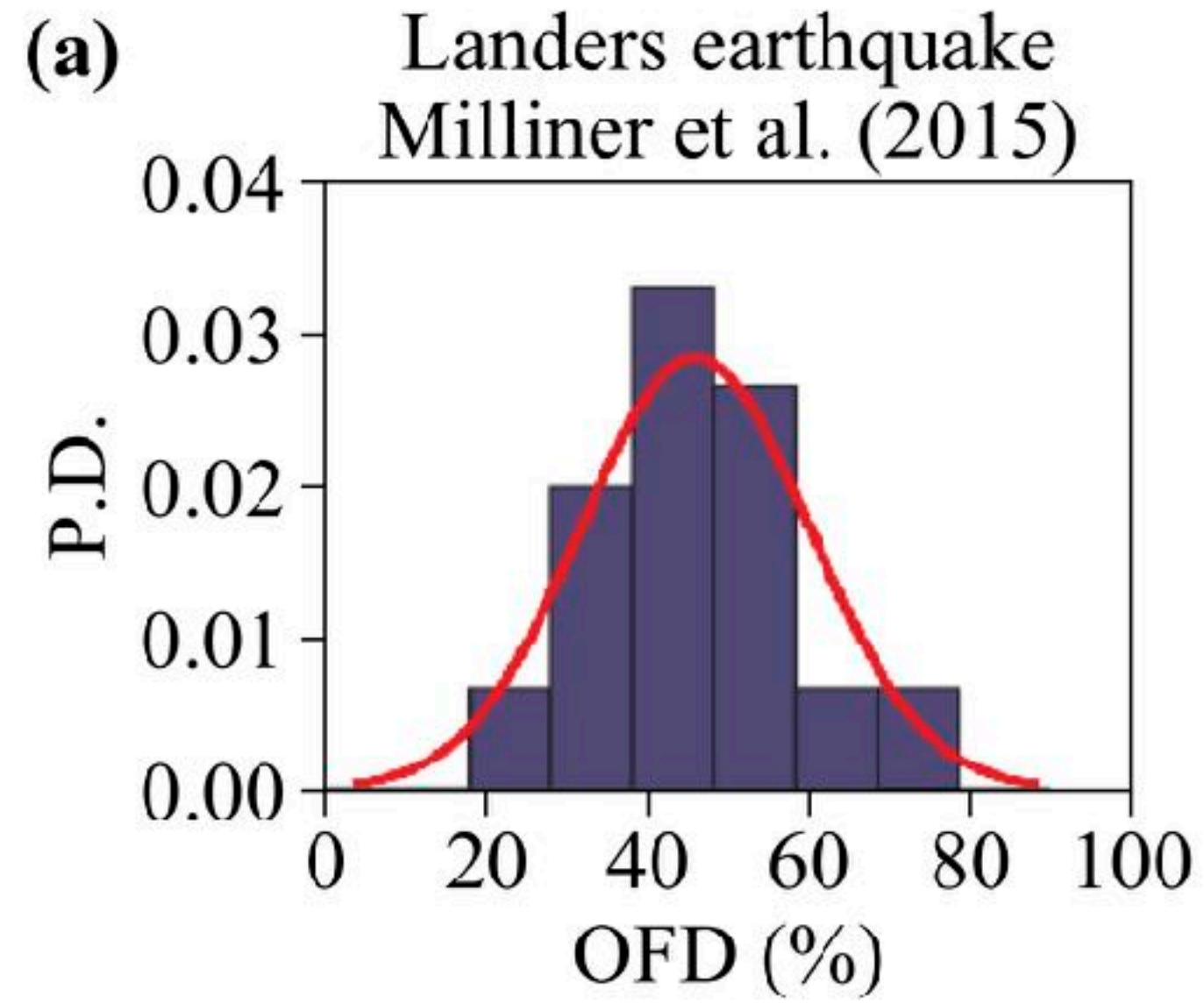
Distribution of Off-fault Deformation



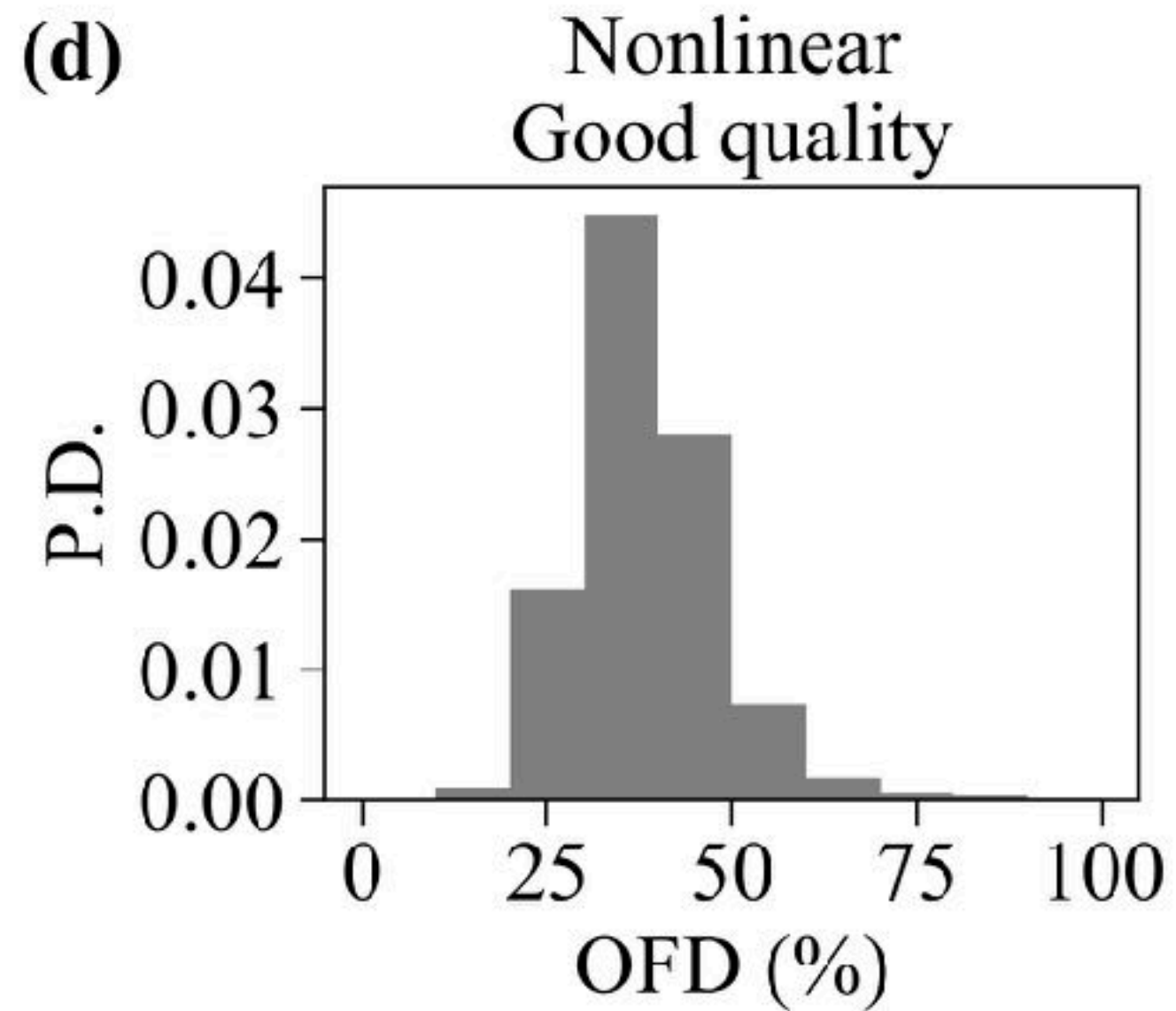
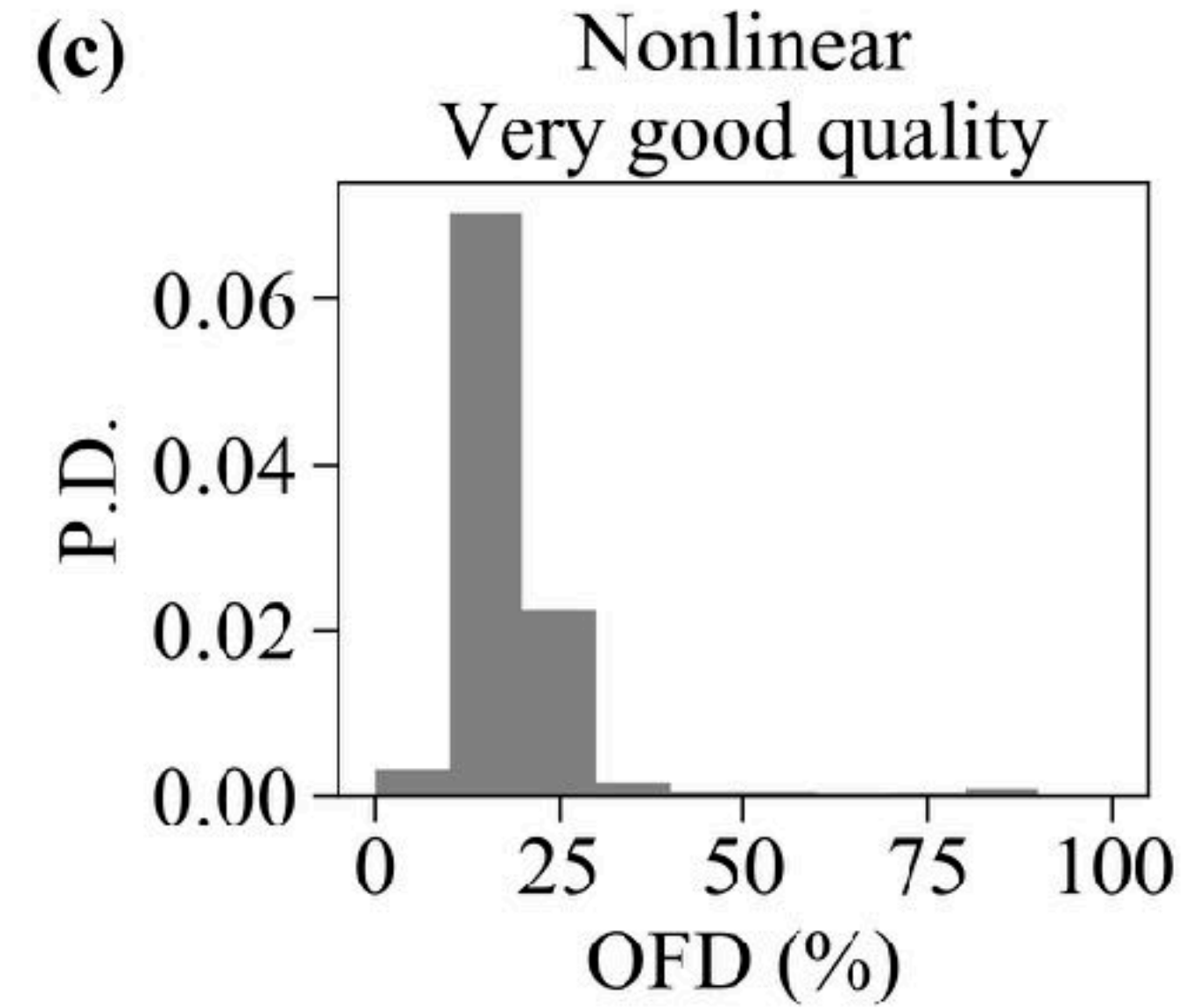
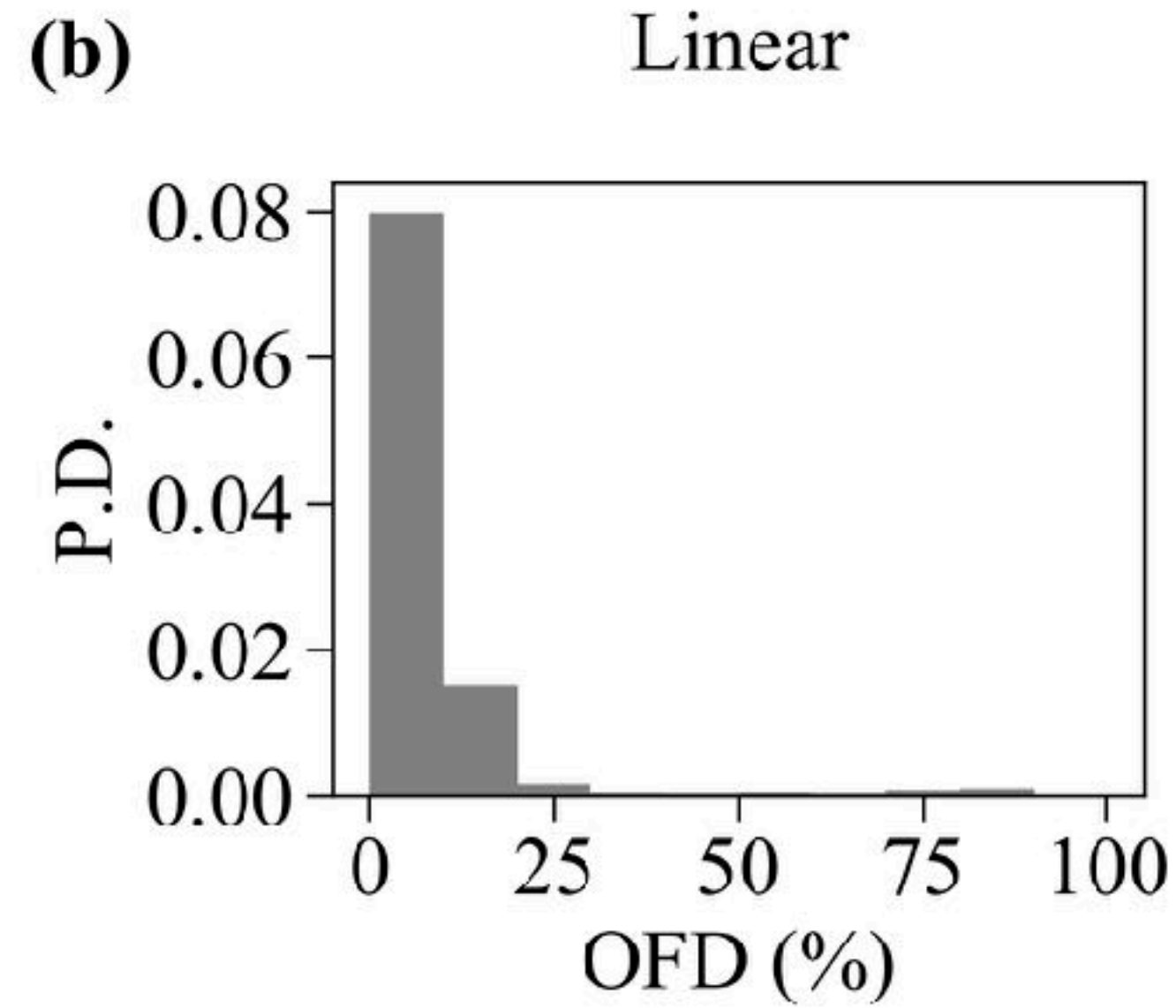
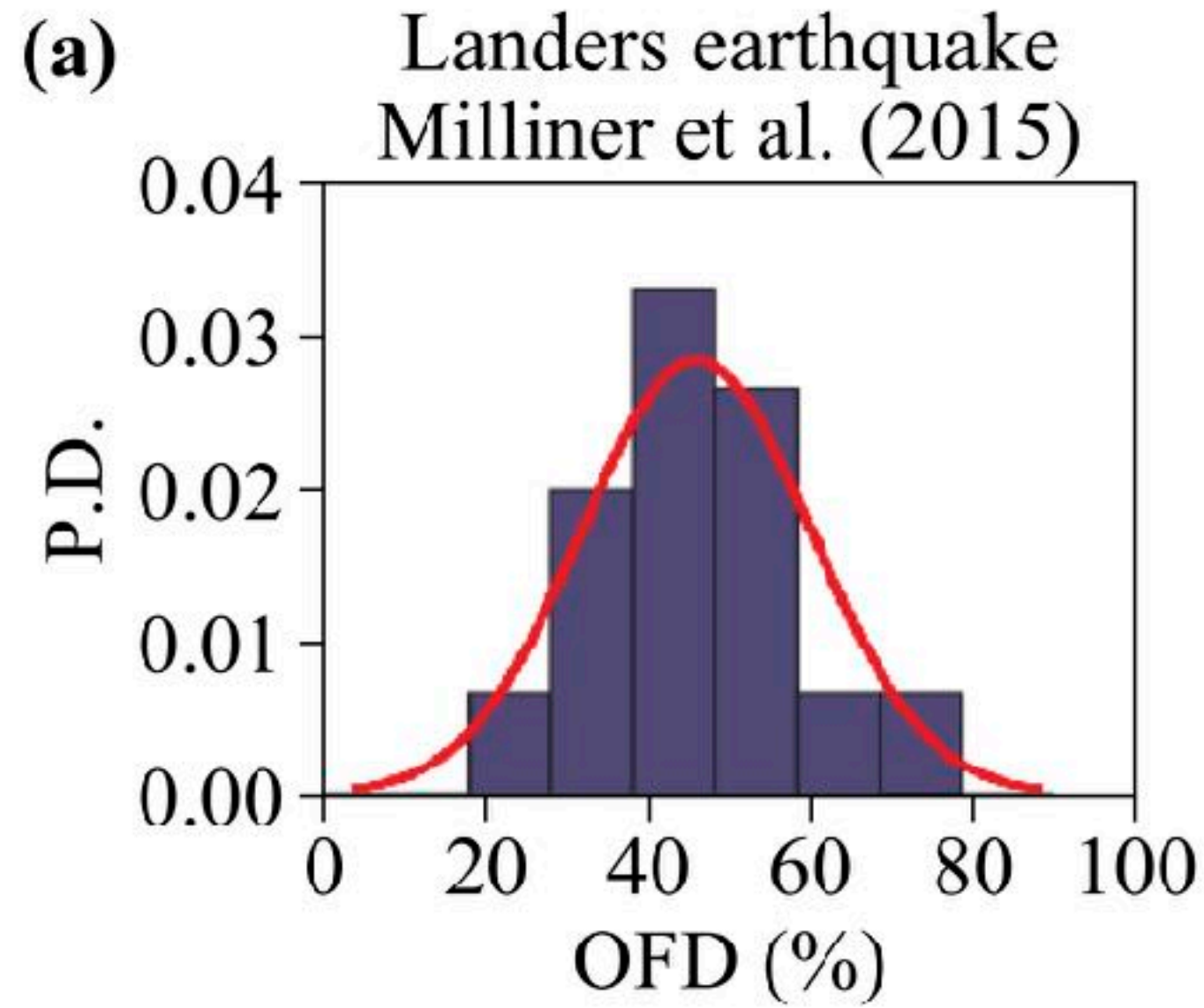
Distribution of Off-fault Deformation



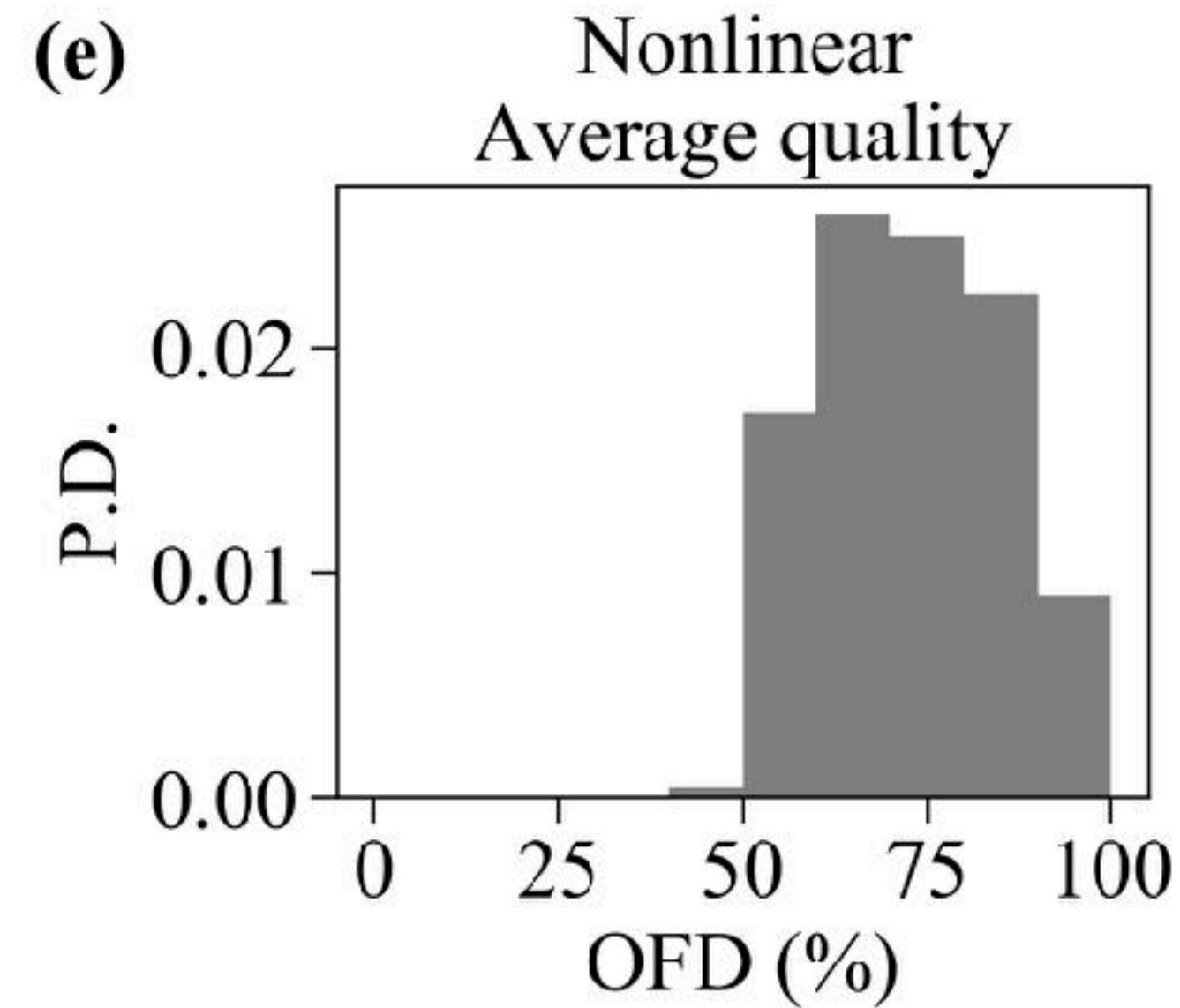
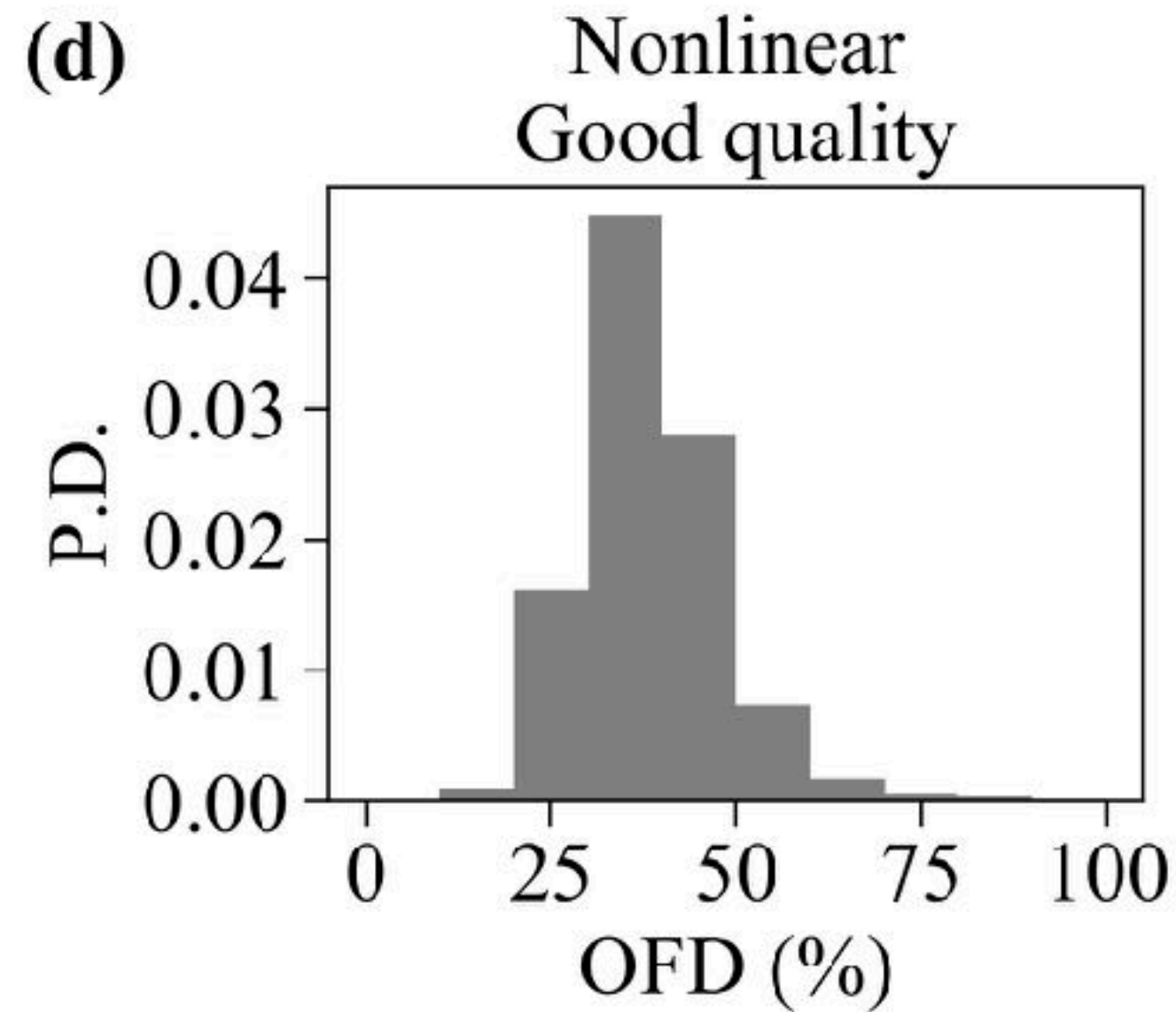
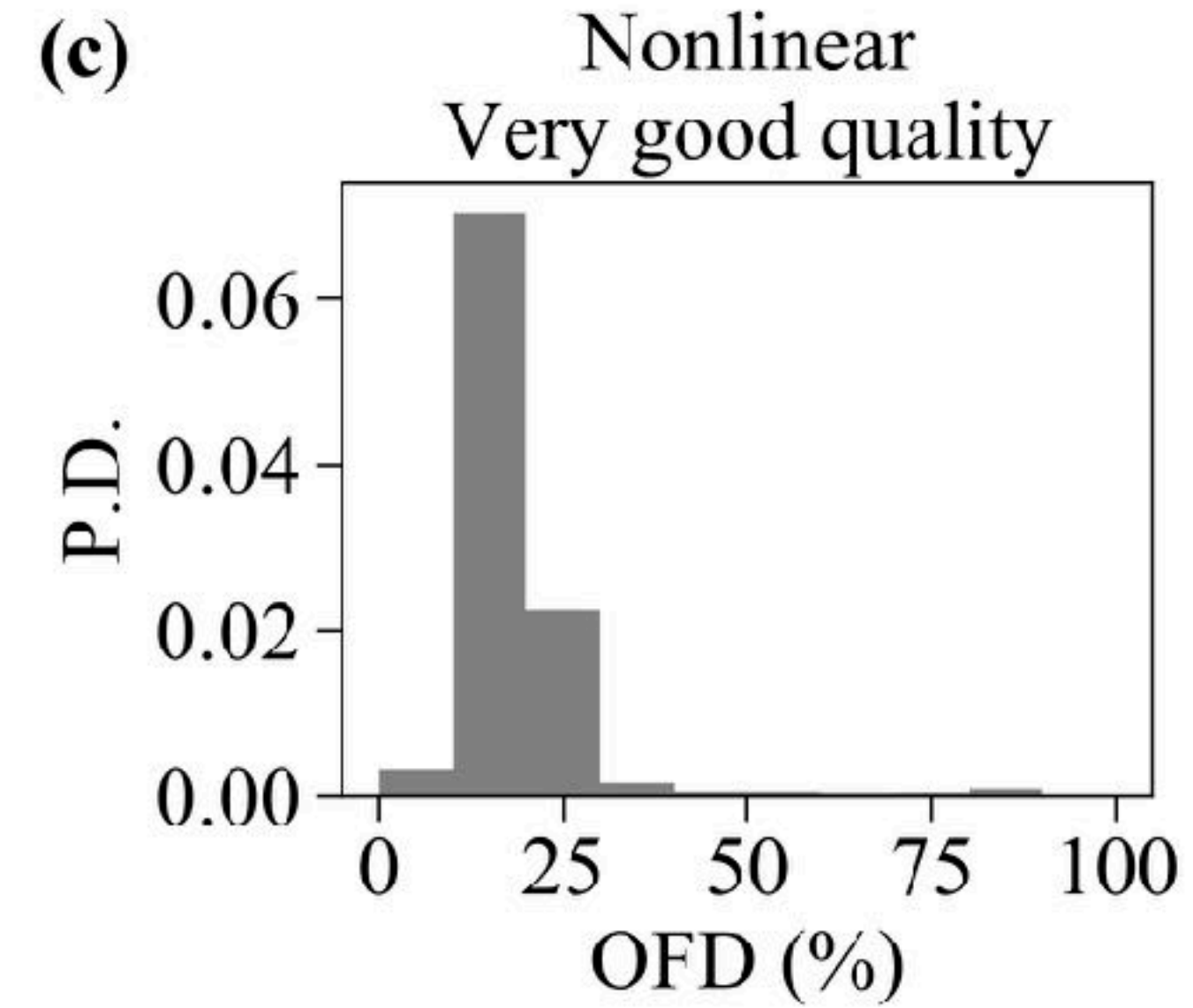
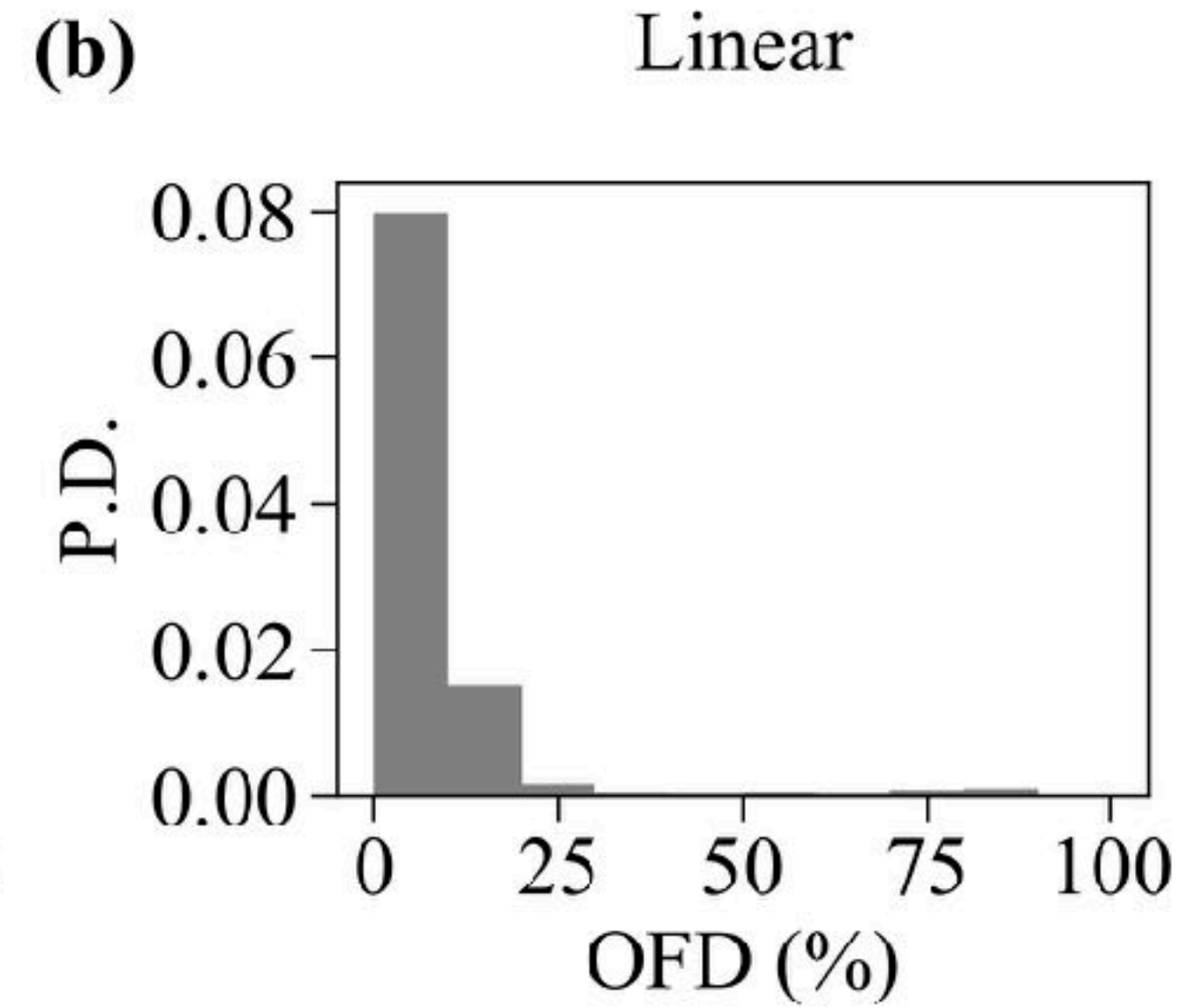
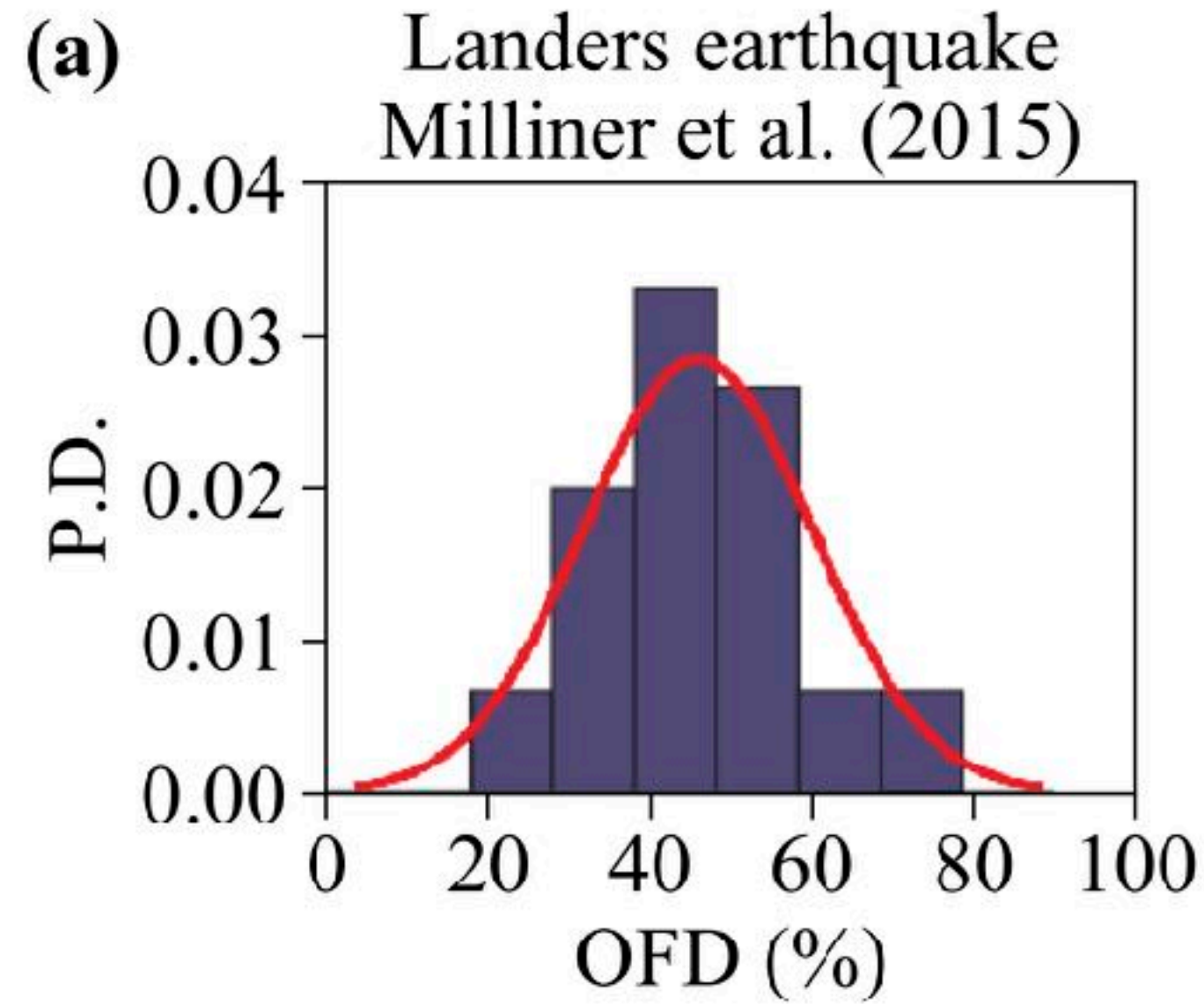
Distribution of Off-fault Deformation



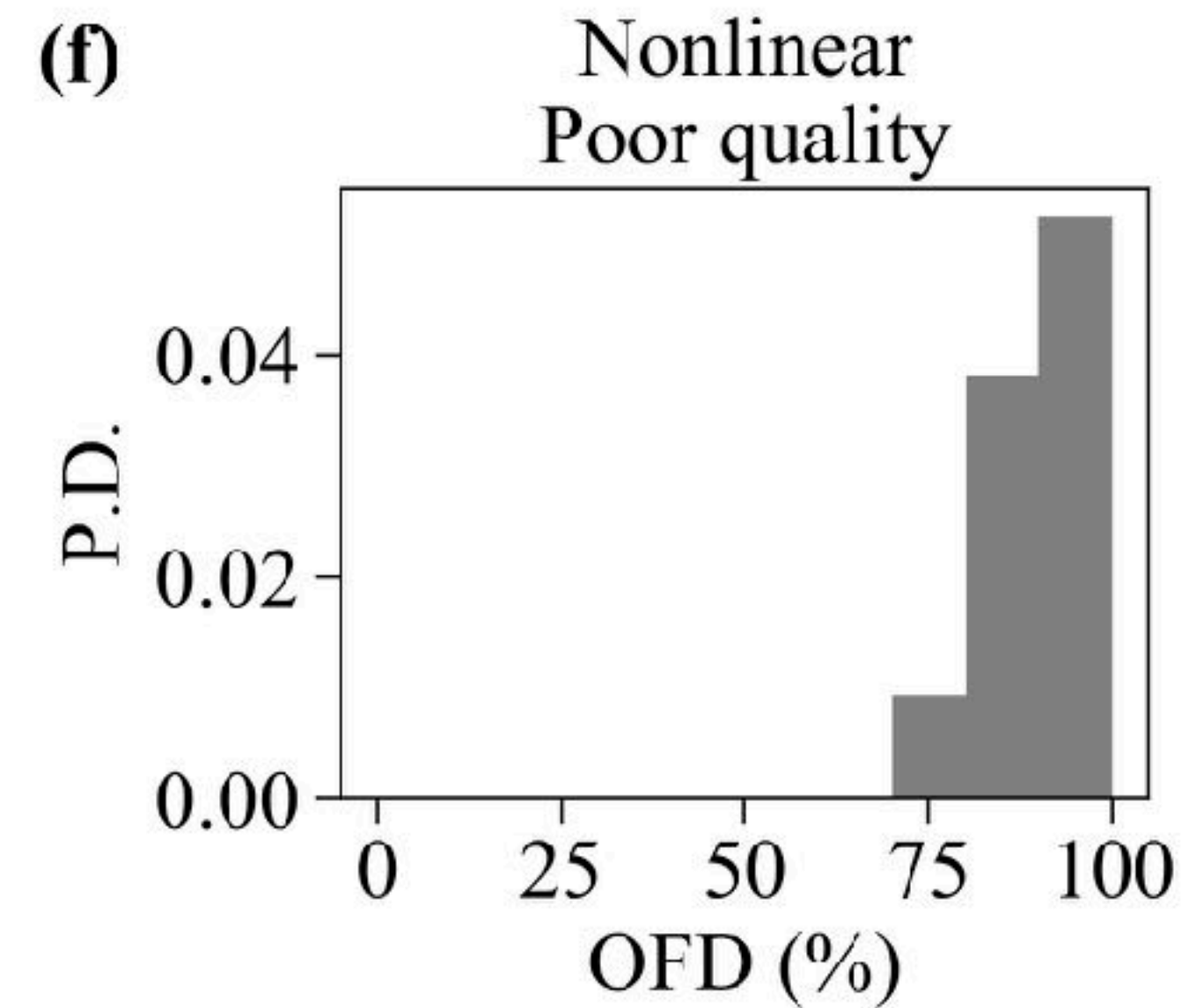
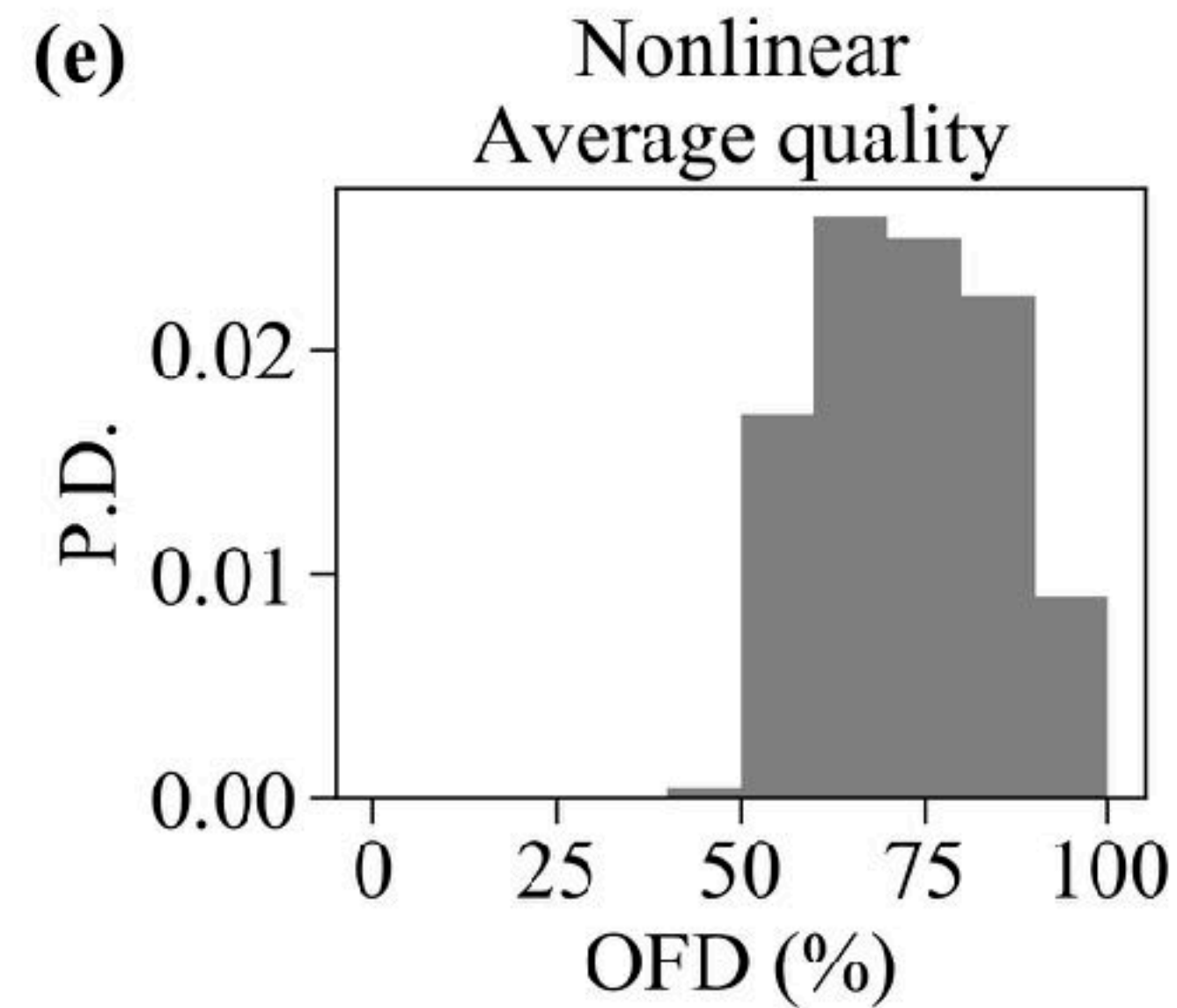
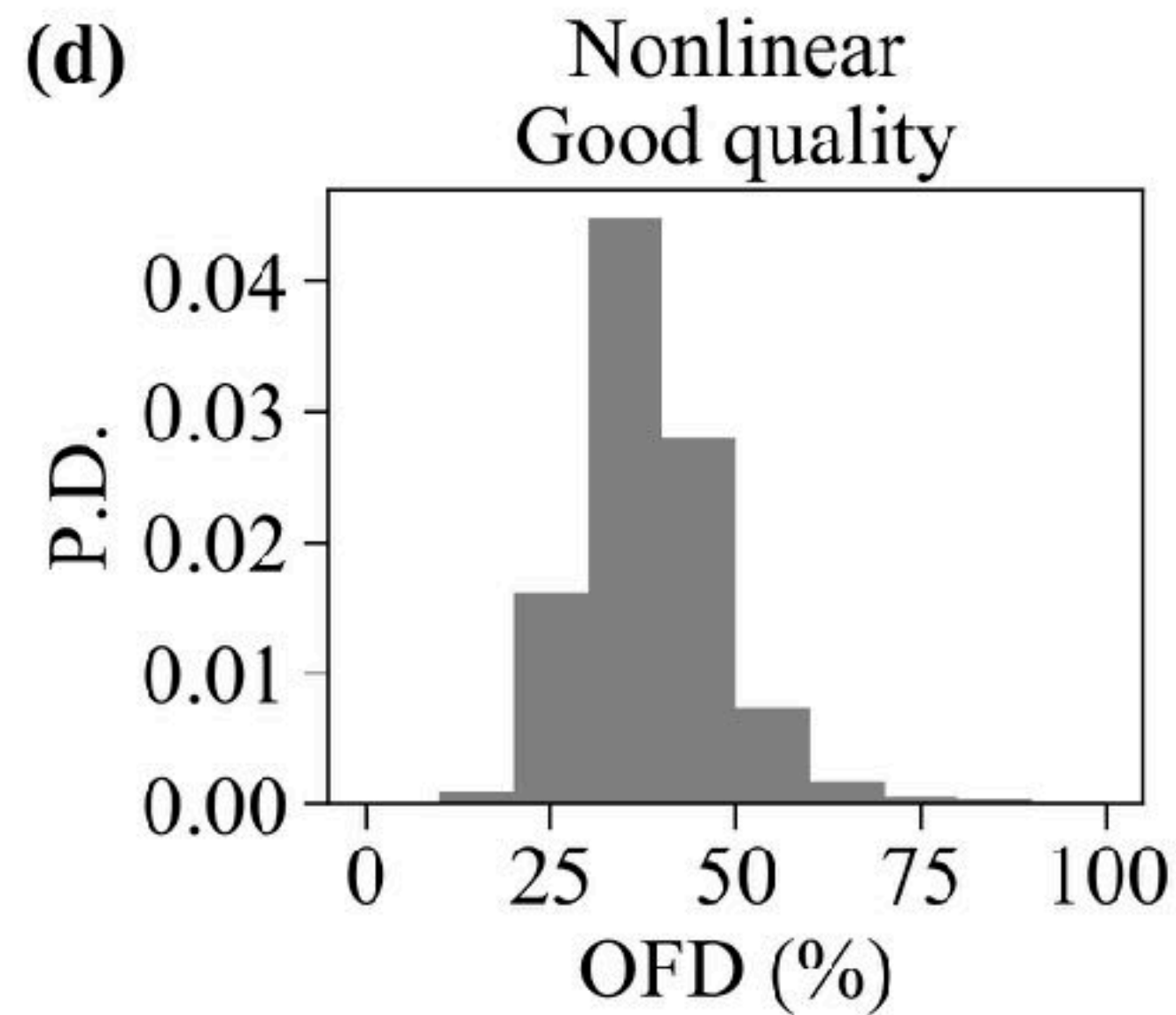
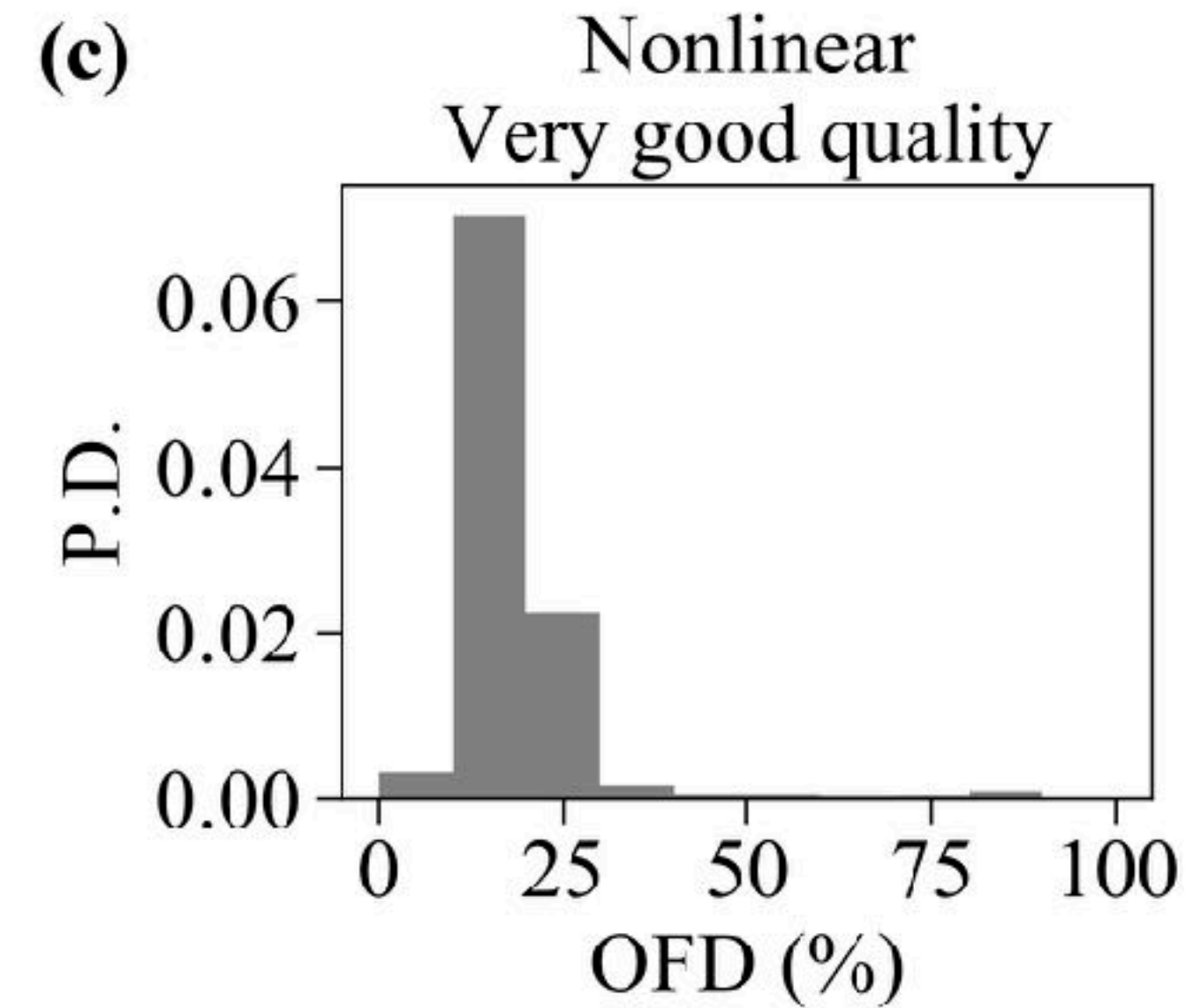
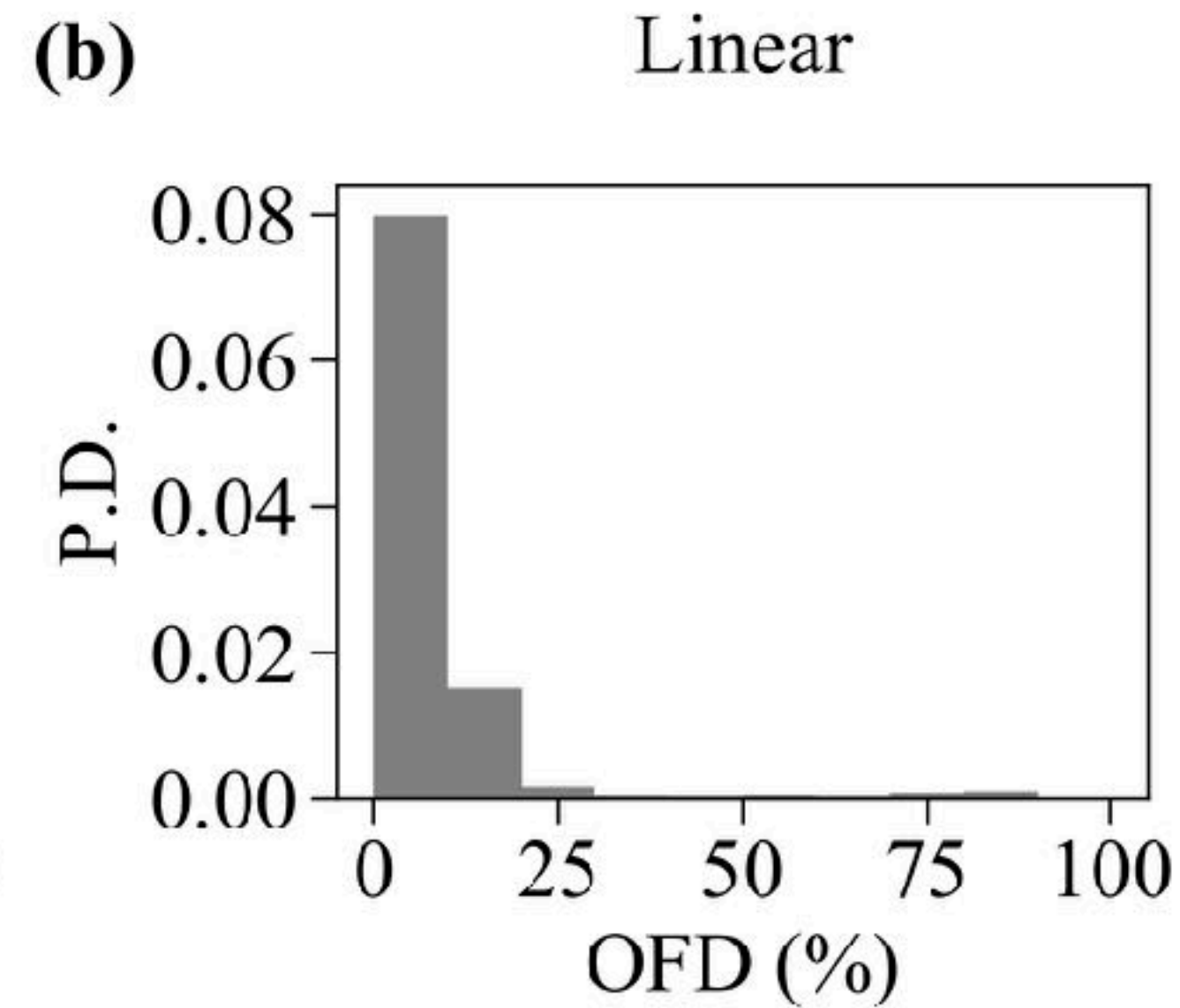
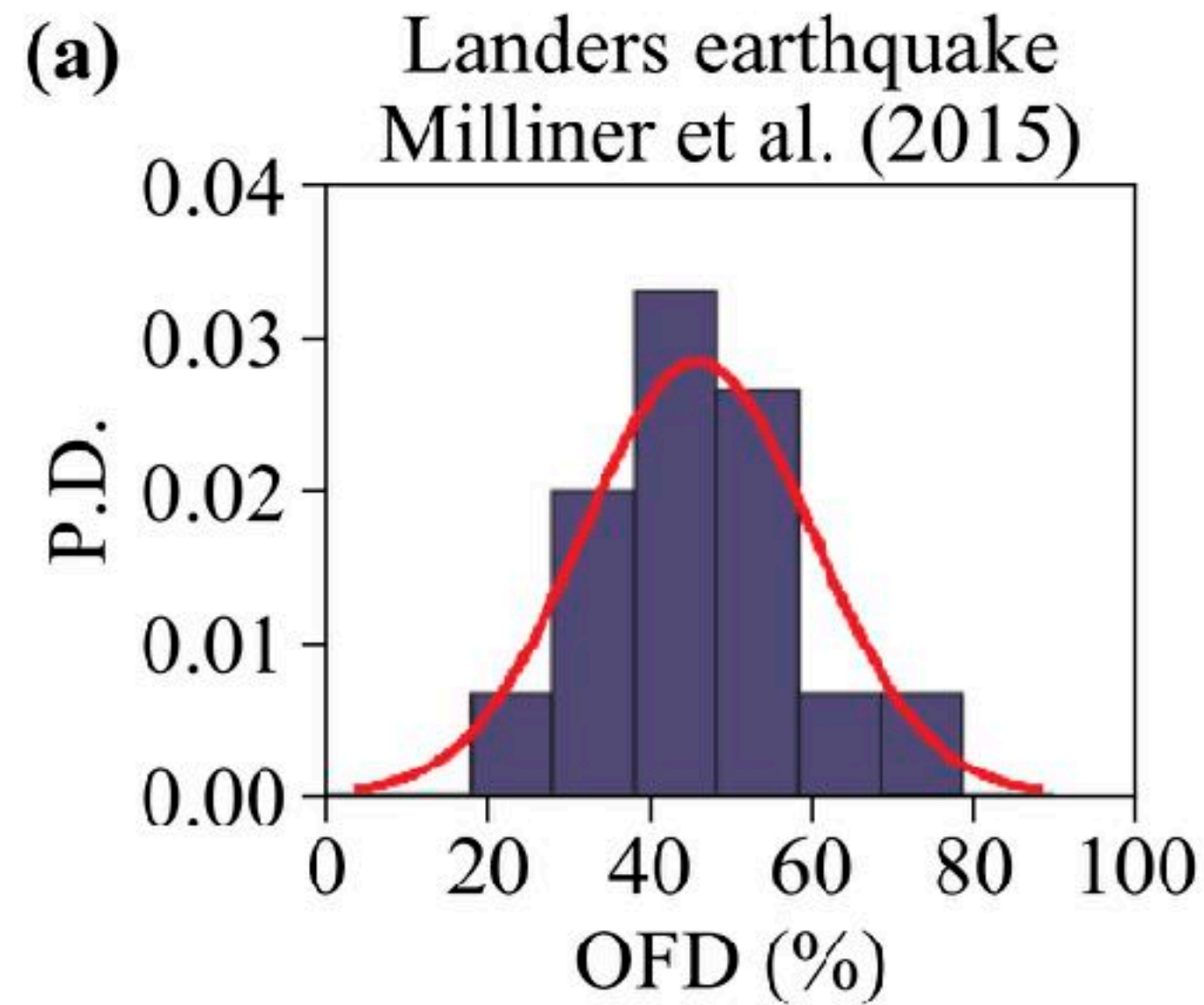
Distribution of Off-fault Deformation



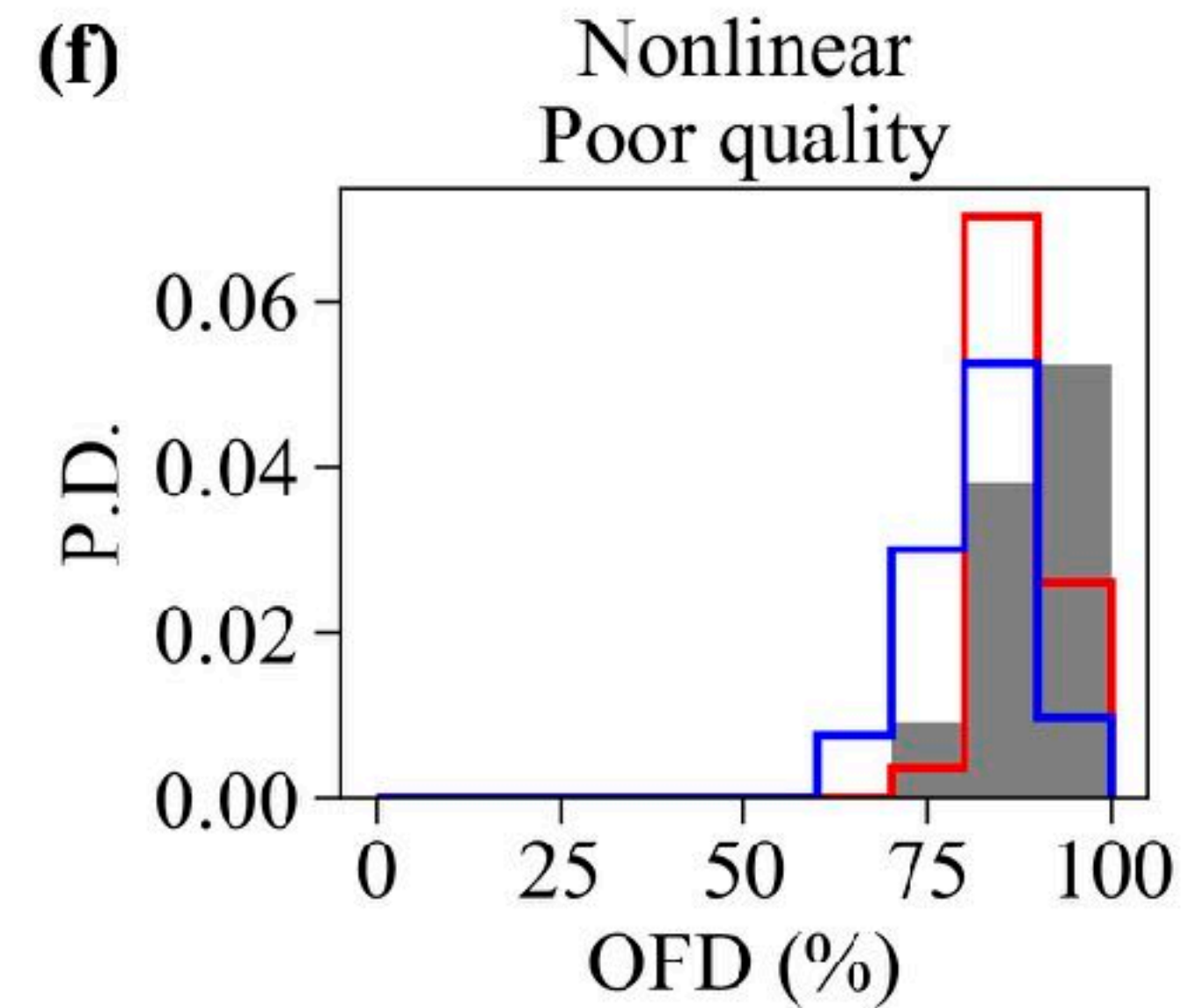
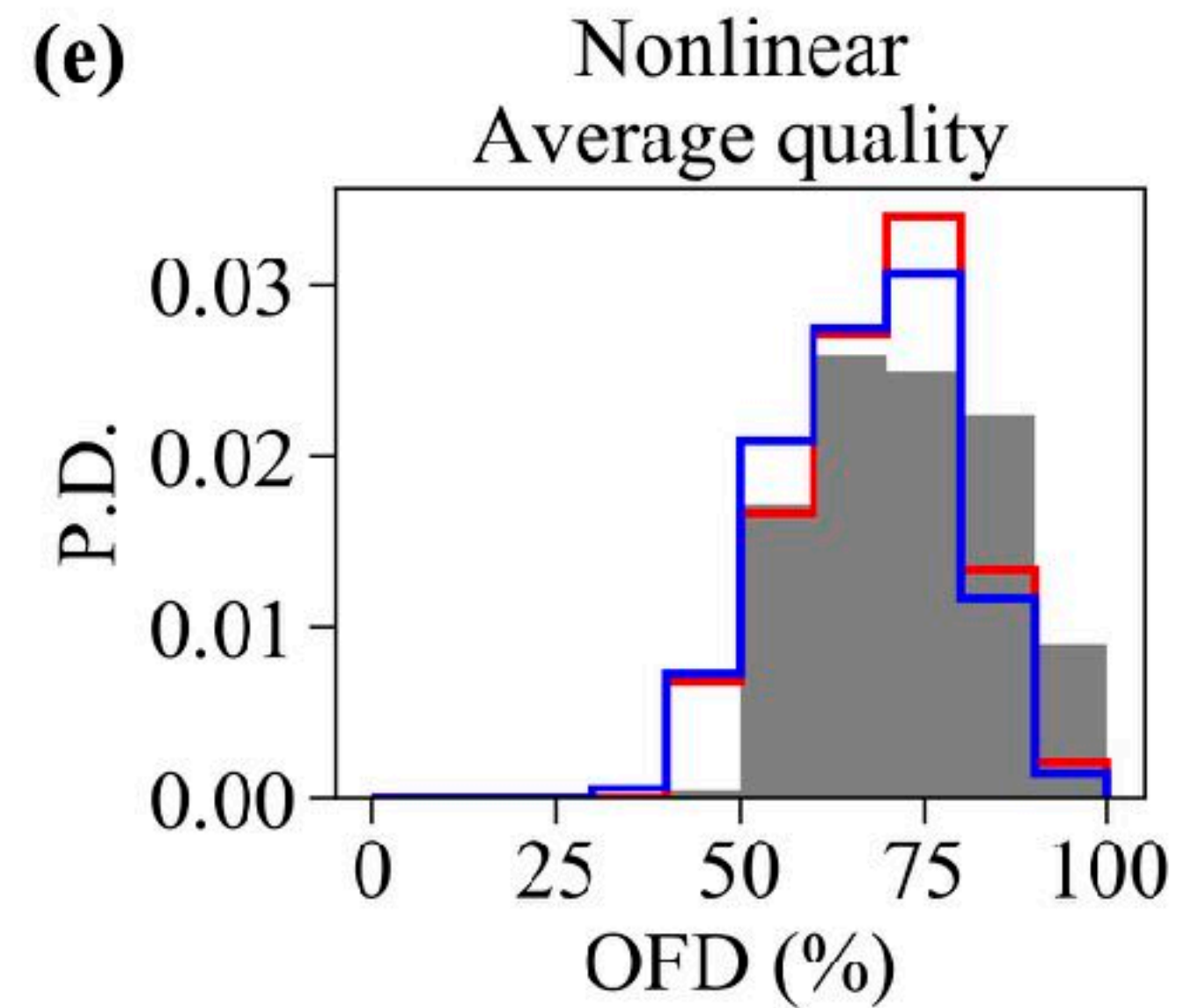
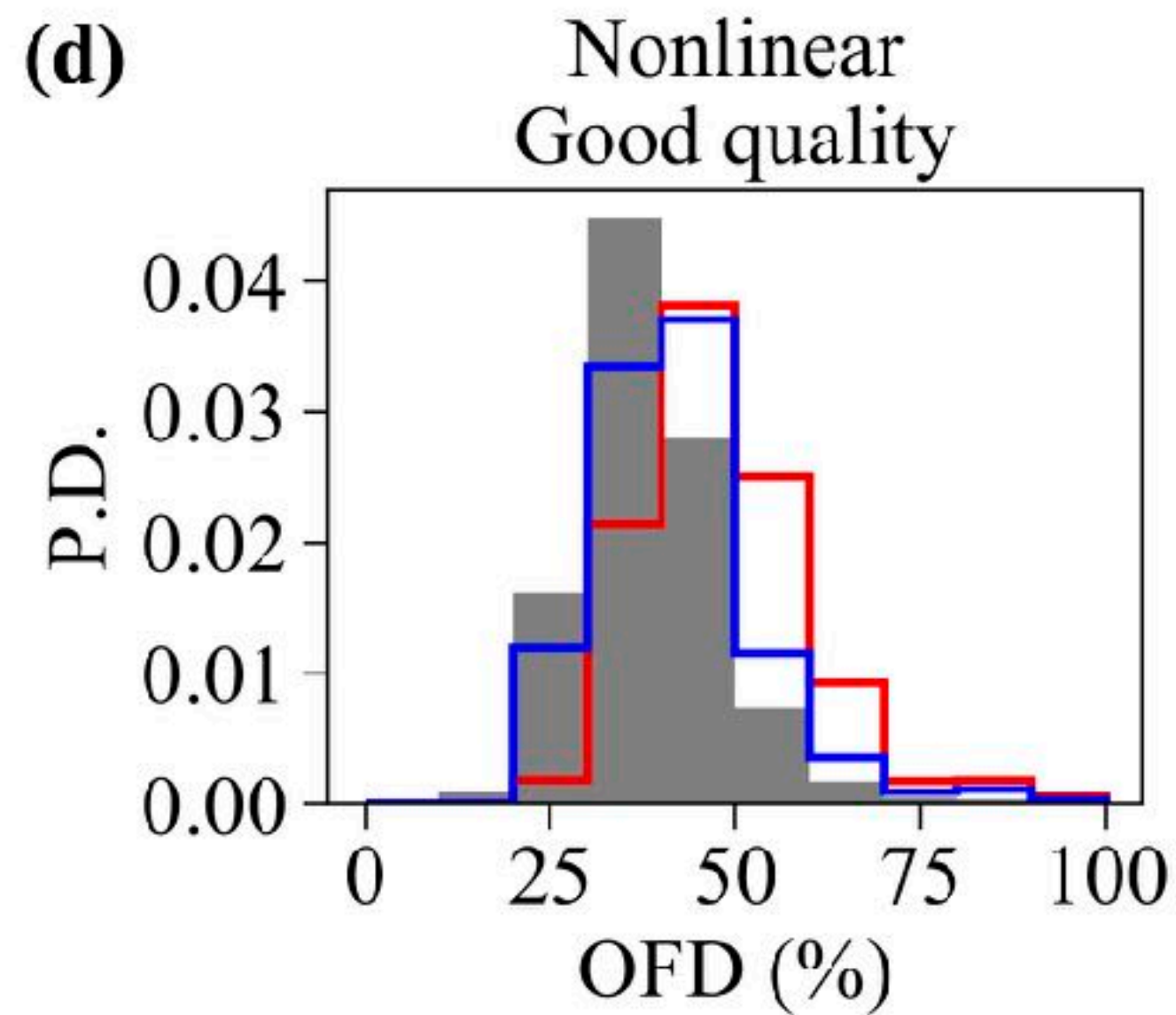
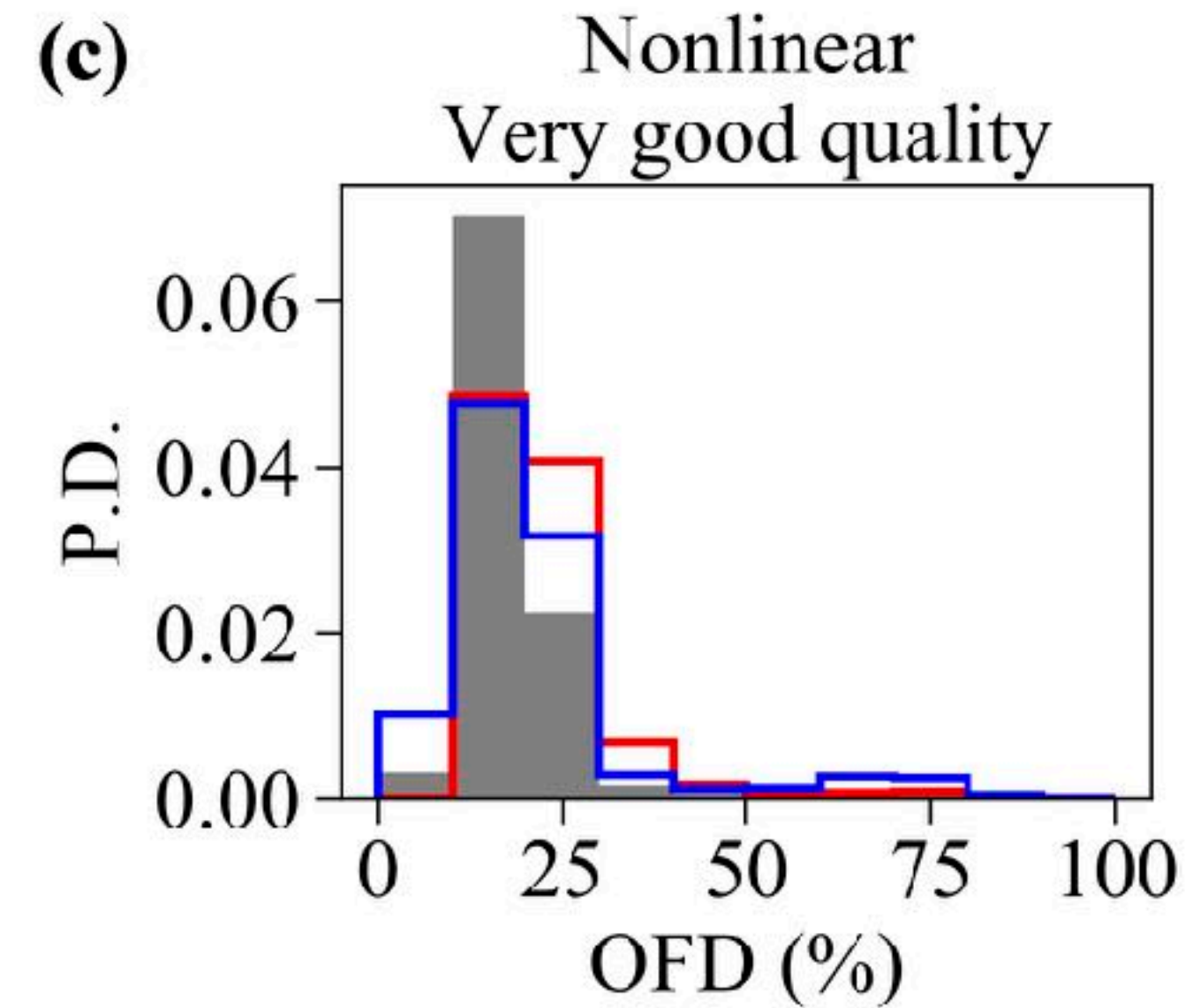
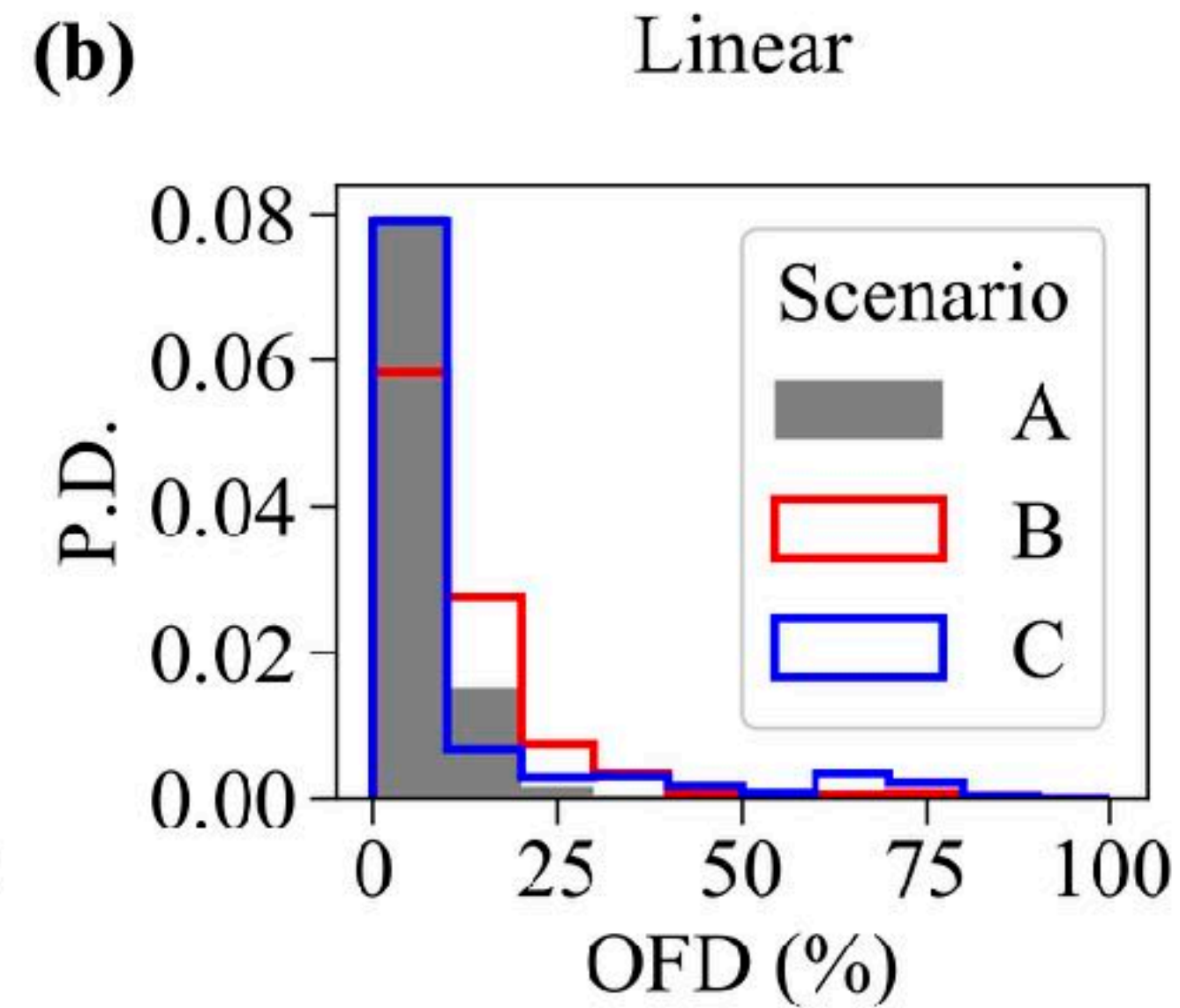
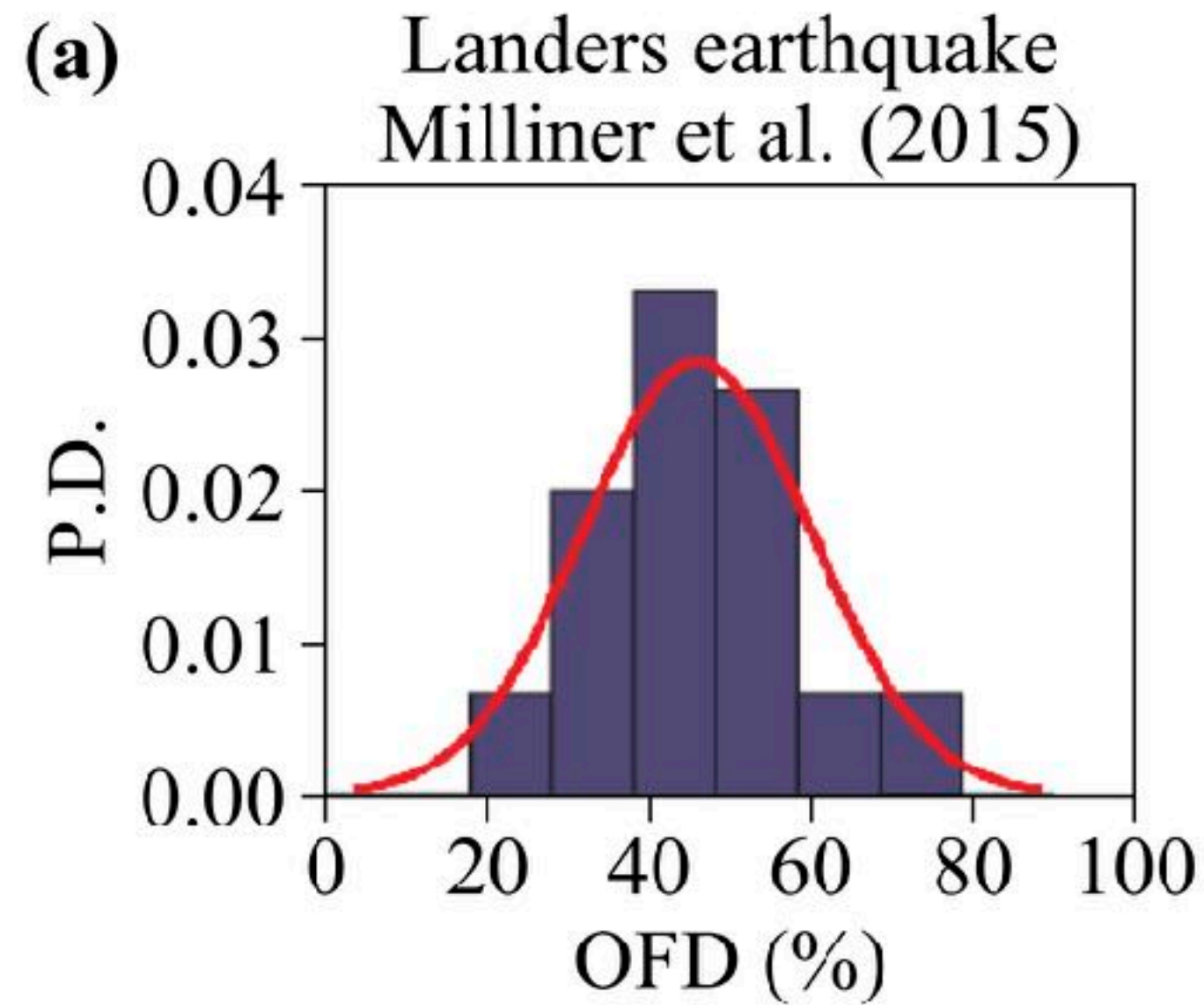
Distribution of Off-fault Deformation



Distribution of Off-fault Deformation



Distribution of Off-fault Deformation



Summary

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

Table 1. Mean Shallow Slip Deficit (SSD, %) and Mean Off-Fault Deformation (OFD, %) $\pm 1\sigma$ Obtained From Three Dynamic Rupture Scenarios (A–C) in the Linear Case and in the Nonlinear Case Using Four Rock Strength Models^a

		Nonlinear				
		Linear	Very Good	Good	Average	Poor
A	SSD	17.3	25.5	44.2	76.8	90.9
	OFD	8.2 ± 11.5	18.0 ± 11.5	38.8 ± 10.9	73.2 ± 12.0	88.8 ± 6.0
B	SSD	17.6	30.5	53.1	74.9	92.1
	OFD	10.0 ± 12.6	22.3 ± 9.4	48.3 ± 11.4	68.7 ± 11.3	87.3 ± 4.2
C	SSD	18.1	31.4	51.2	72.2	93.7
	OFD	9.8 ± 16.8	21.7 ± 14.0	42.2 ± 11.1	67.2 ± 11.7	81.8 ± 6.8

^aBold emphasizes SSD.