

# Imaging earthquakes from optical remote sensing brings constraints on deformation localization and the related shallow slip deficit

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**Jet Propulsion Laboratory**  
California Institute of Technology



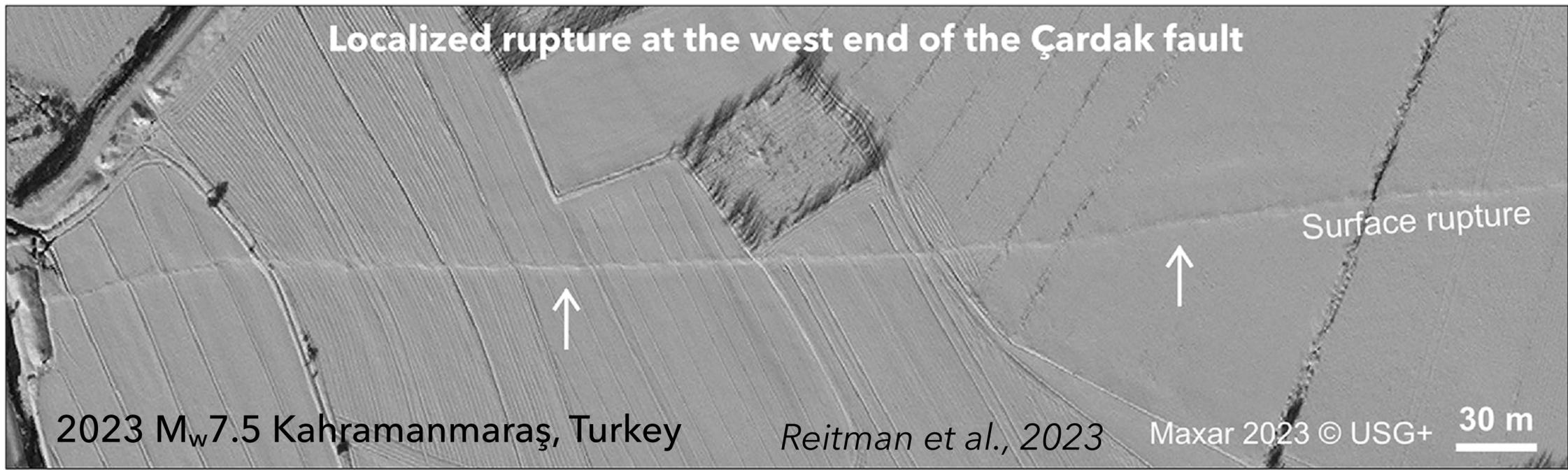
**Berkeley**  
UNIVERSITY OF CALIFORNIA



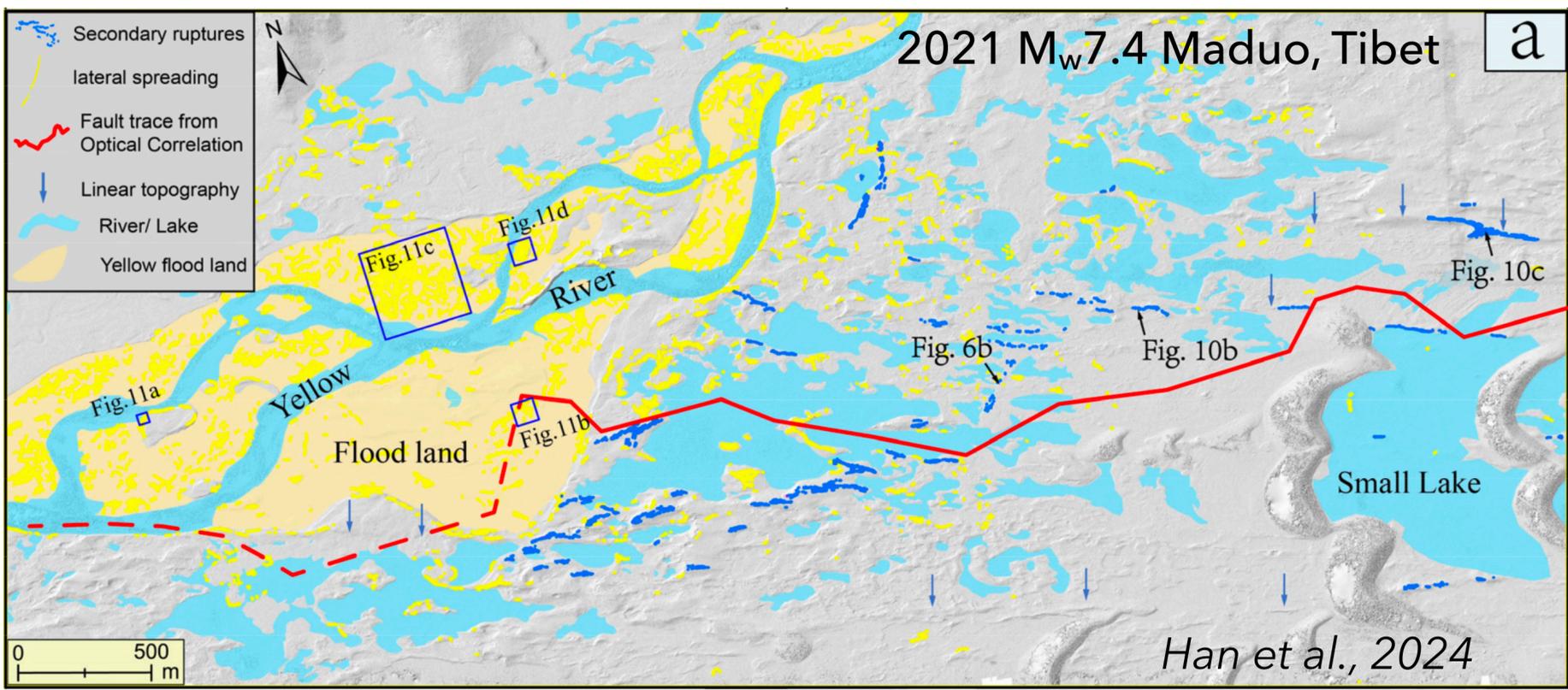
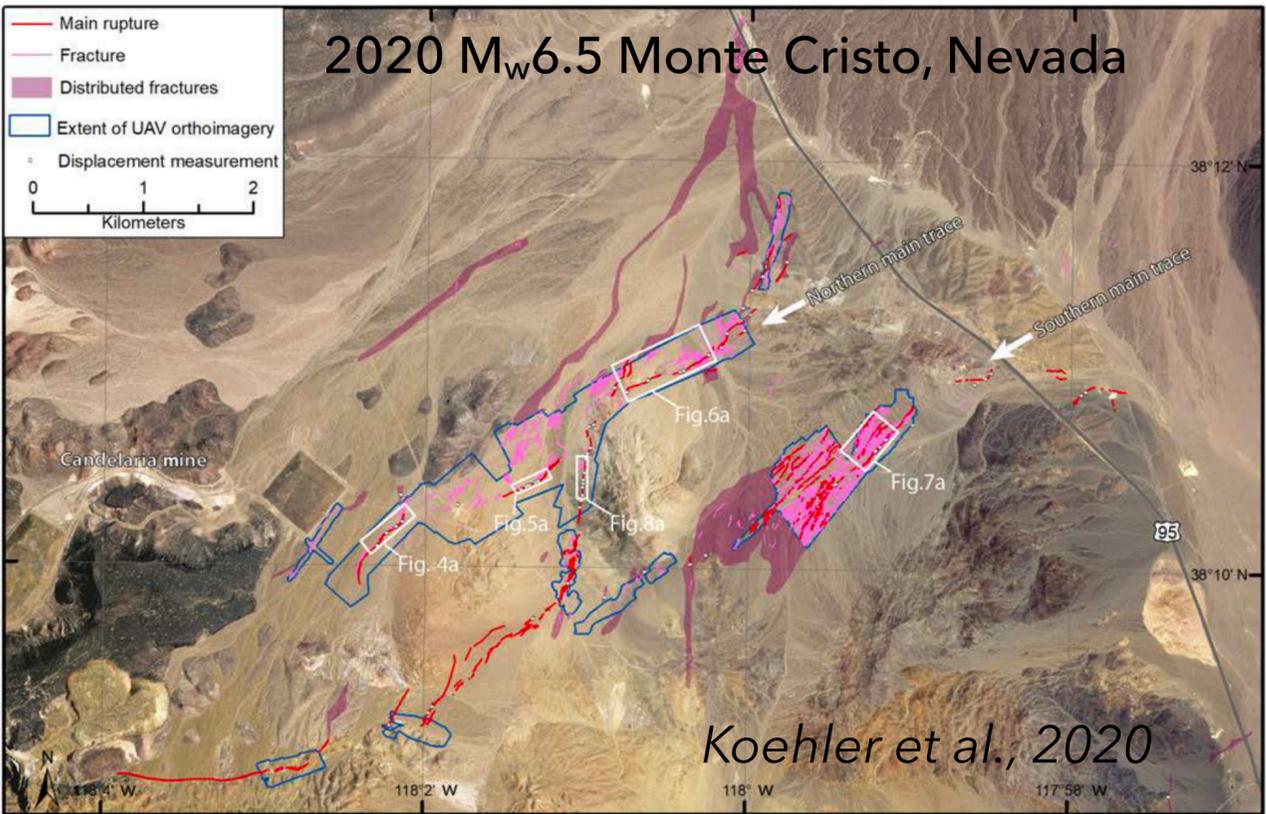
**Caltech**



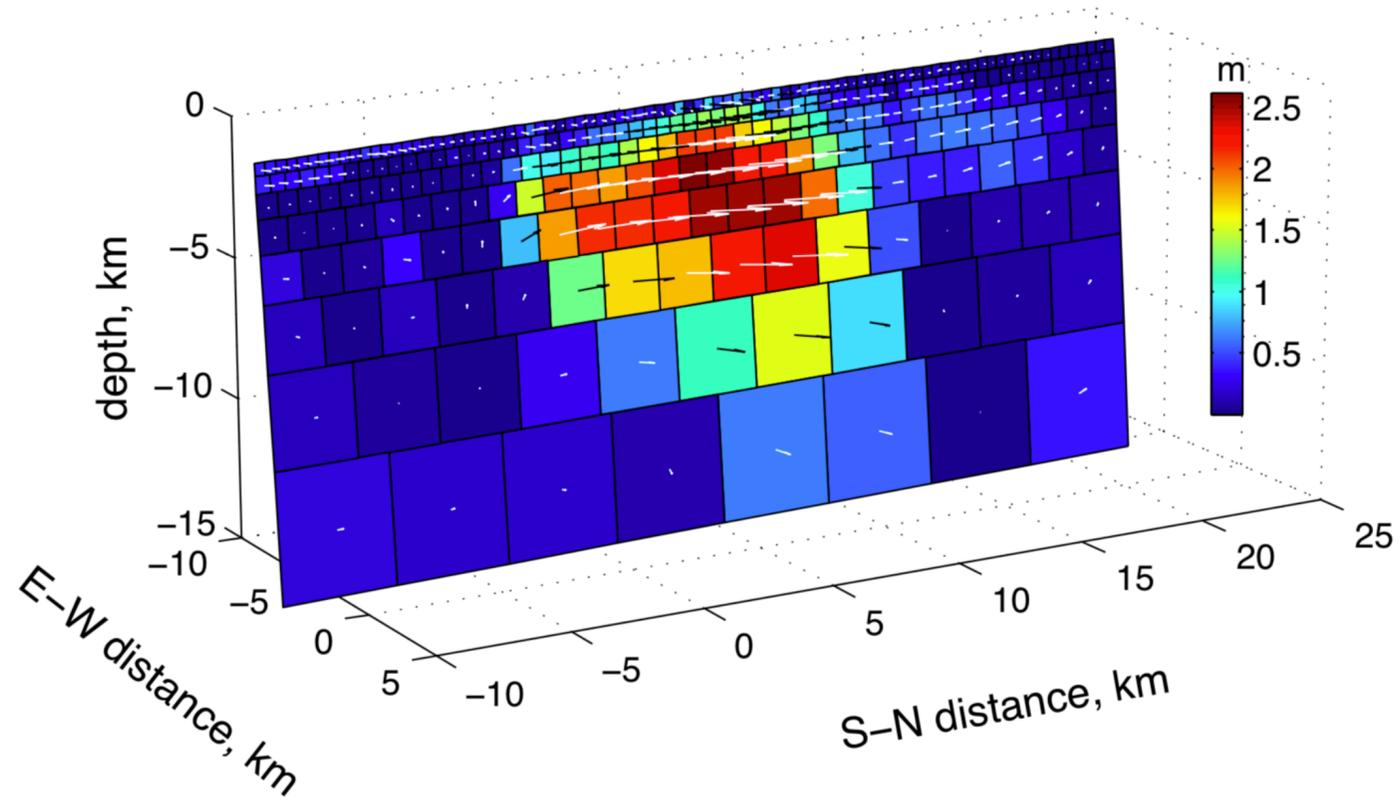
# What controls the localization of surface deformation during earthquakes?



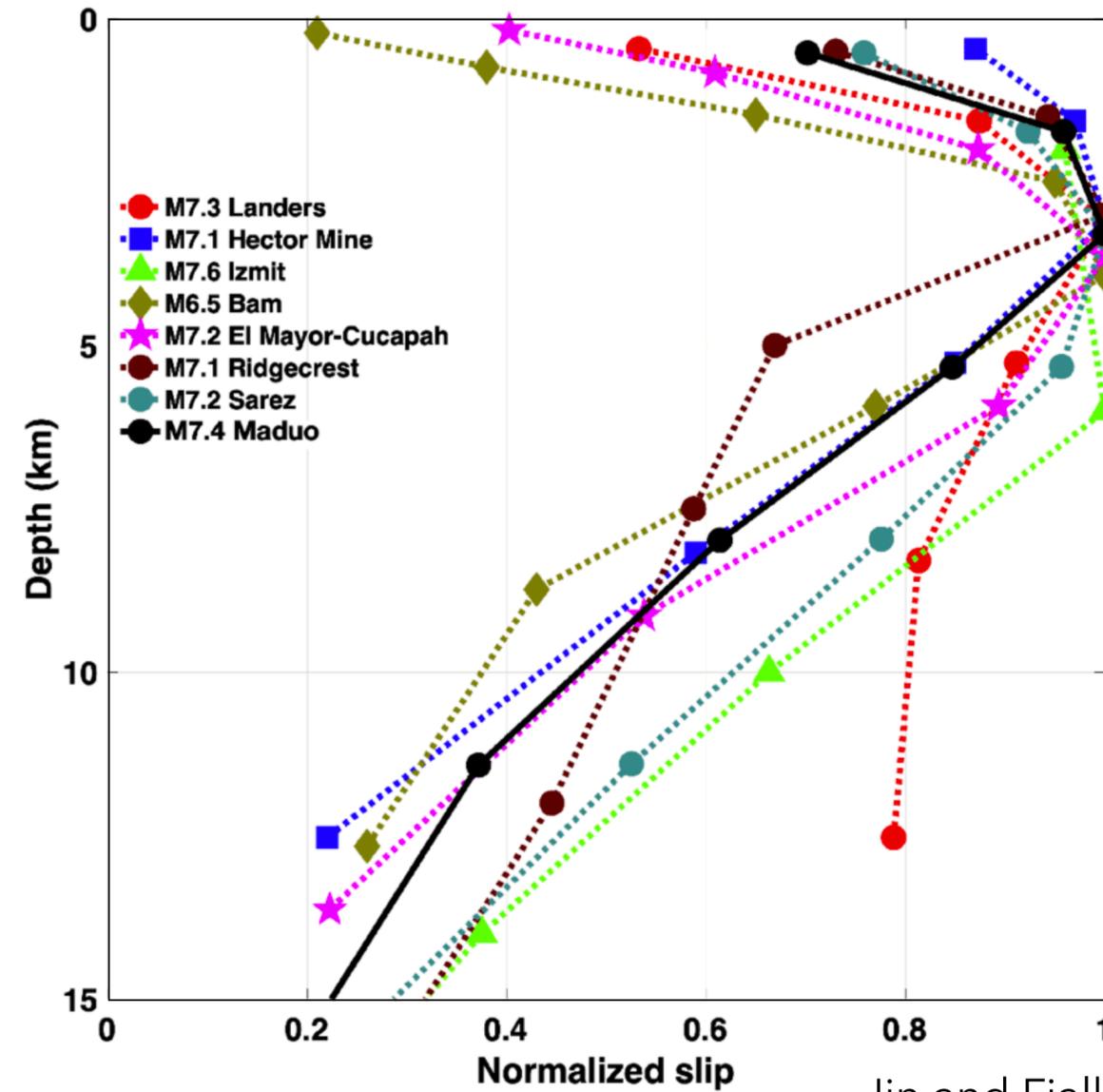
→ lithology, fault geometry, fault maturity, earthquake magnitude, rupture velocity?



# How does it relate to the so called "Shallow Slip Deficit"?



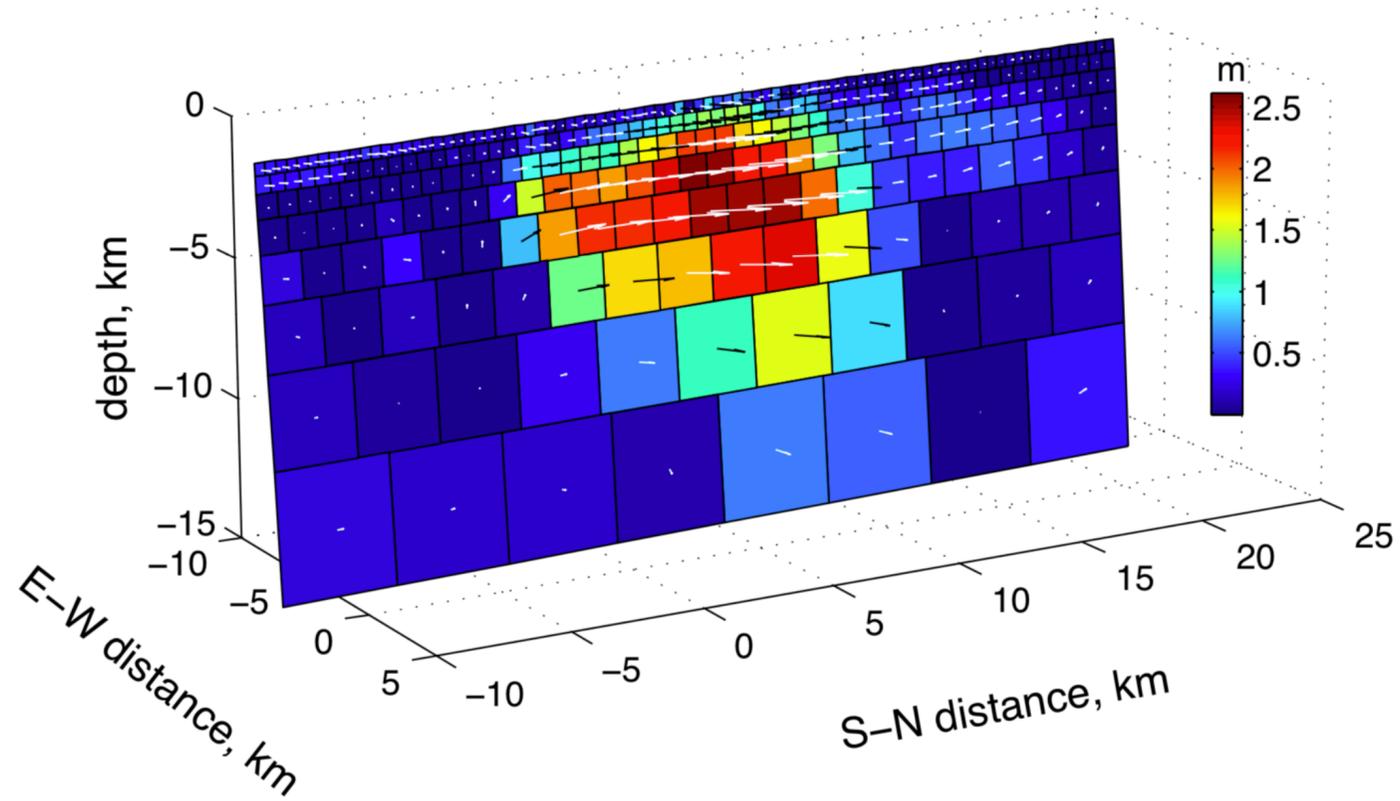
Rupture model of the 2003 Bam,  $M_w$ 6.5, Iran, earthquake (Fialko et al., 2005)



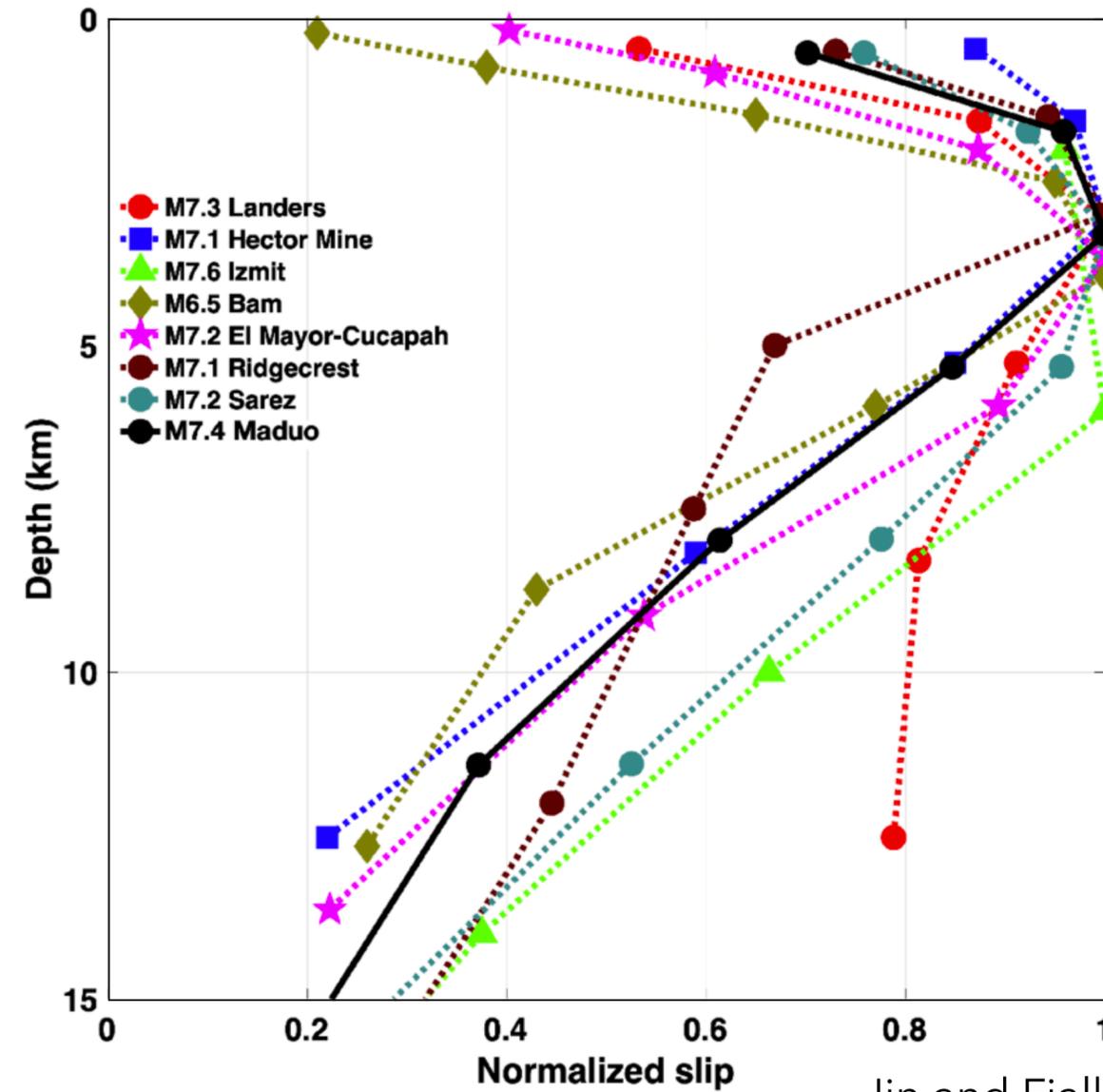
Jin and Fialko (2021)

→ *Modeling artifacts?*  
*Shallow afterslip? Other earthquakes? Bulk yielding?*

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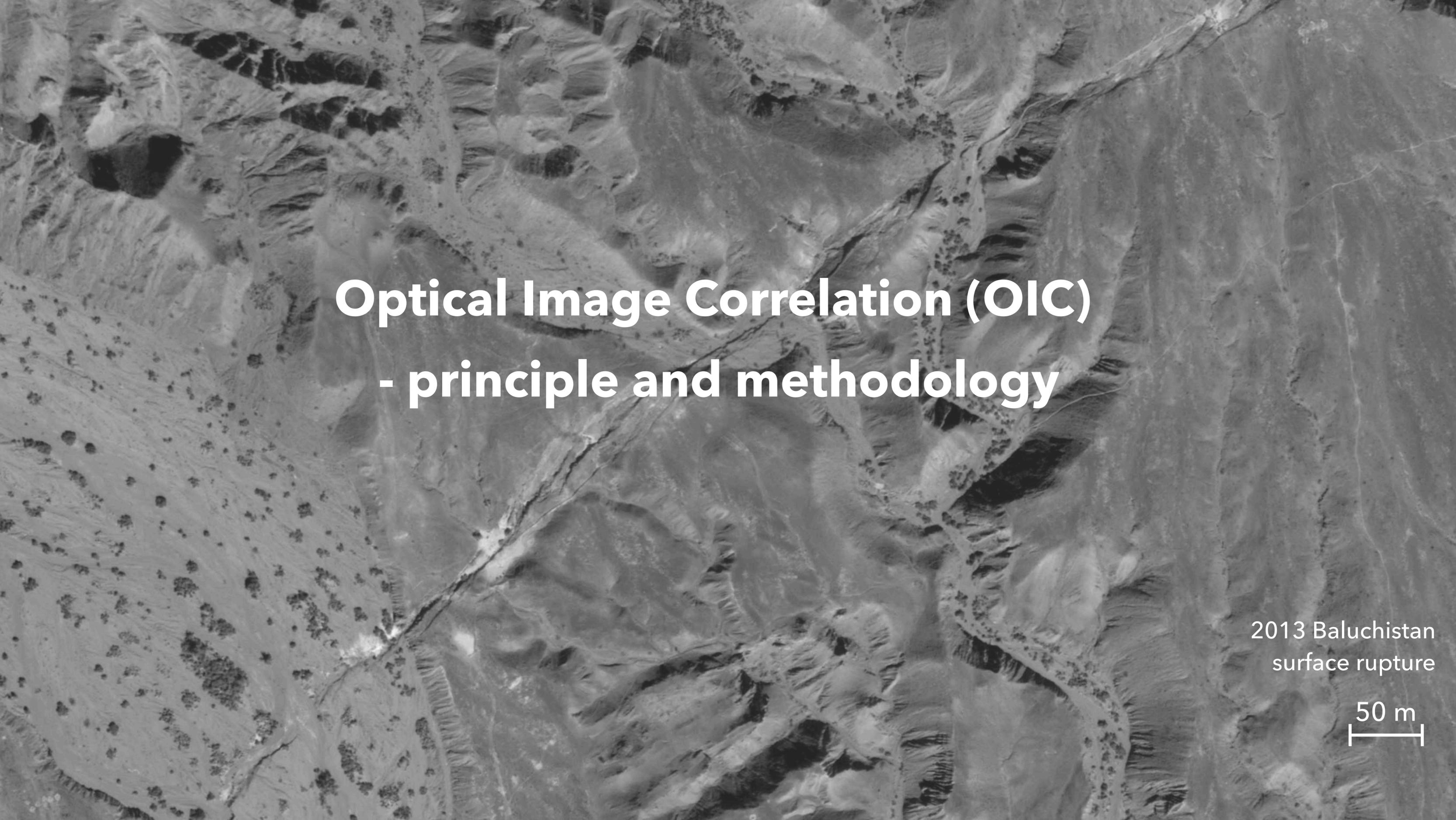
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→ *Modeling artifacts?*  
*Shallow afterslip? Other earthquakes? Bulk yielding?*

+ *other implications such as rupture energy budget, fault long term strain budget, rupture arrest...*



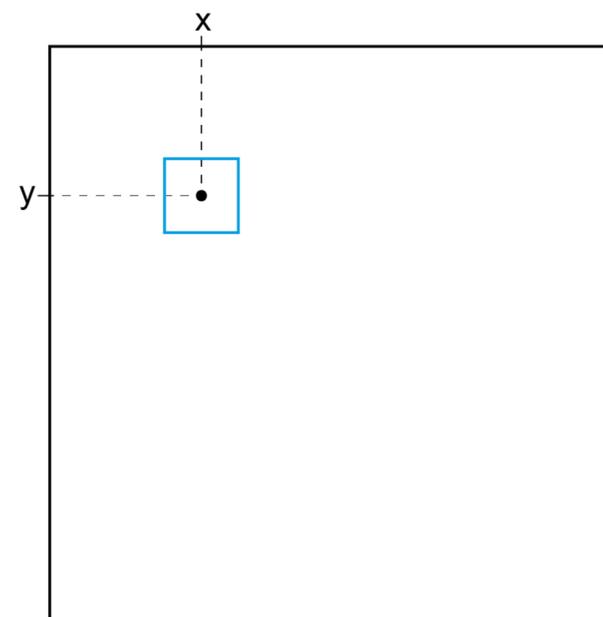
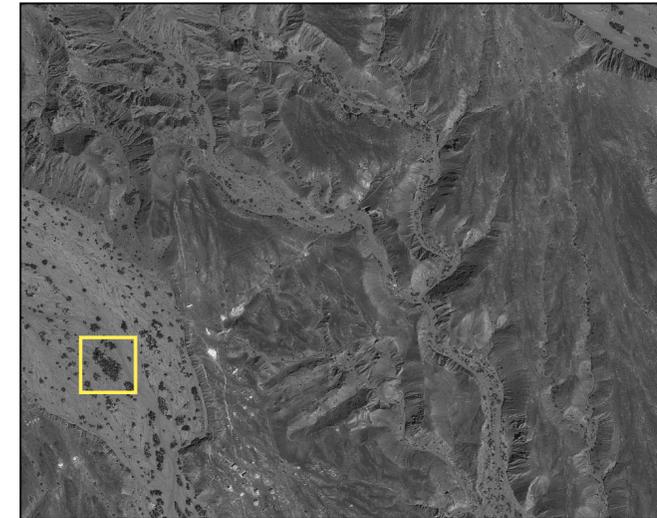
# Optical Image Correlation (OIC) - principle and methodology

2013 Baluchistan  
surface rupture

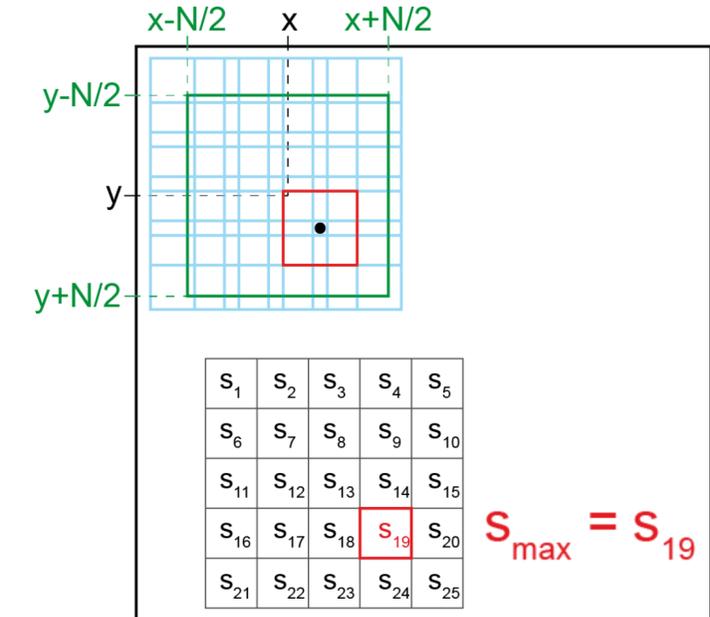
50 m  
|-----|

# Optical image correlation (OIC) measures the displacement between pixels of pre- and post-earthquake orthoimage

- Benefits from the high-resolution of satellite optical sensors (0.3-15 m)
- No decorrelation close to the faults
- sub-pixel correlation ( $\sim 1/10$ th of px)

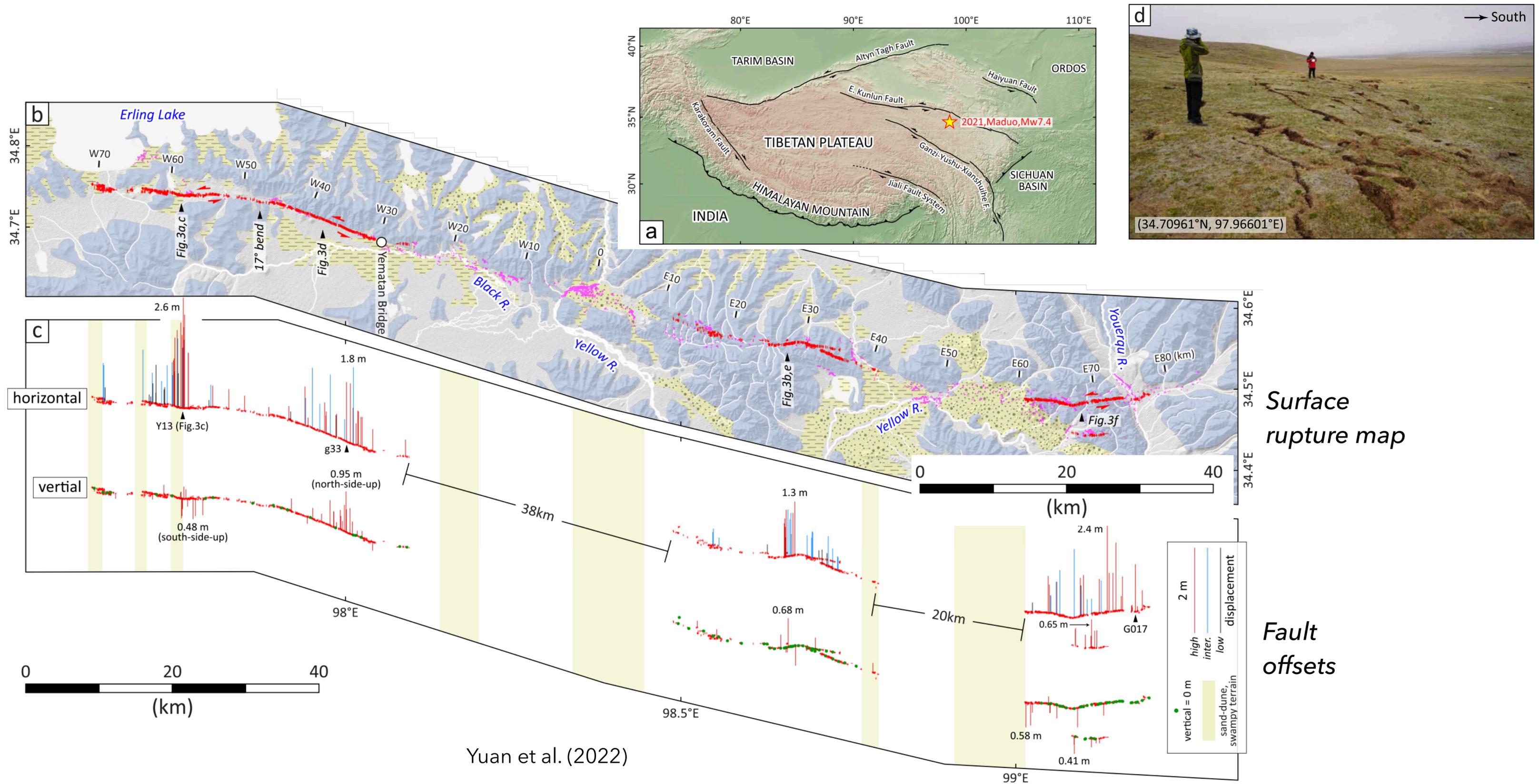


Ortho-image 1



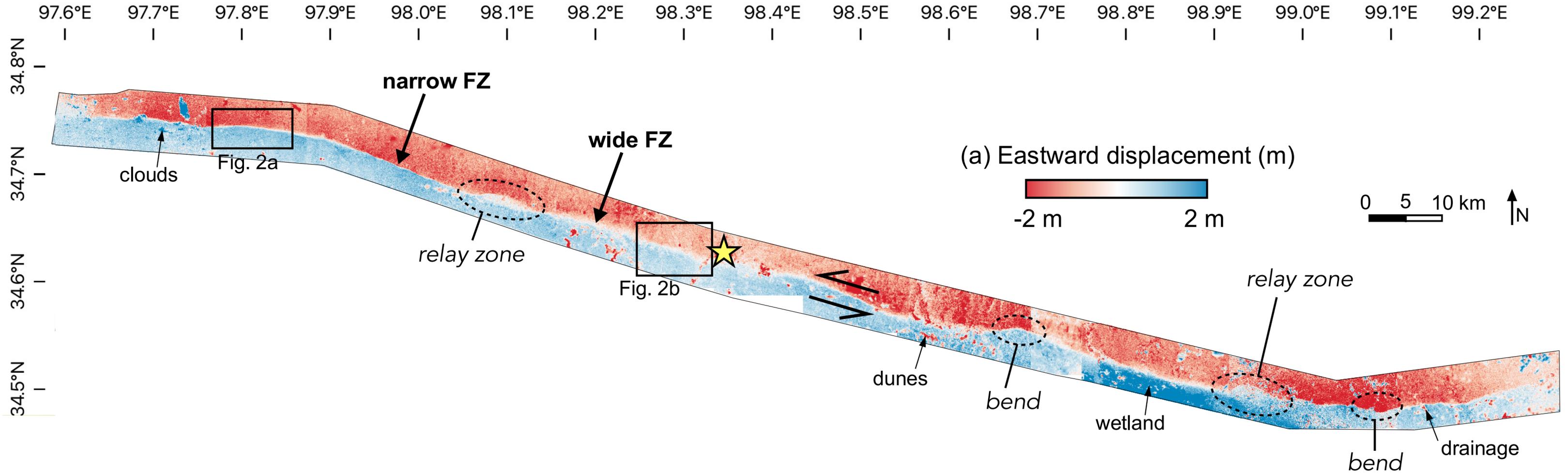
Ortho-image 2

# The 2021 $M_w$ 7.4 Maduo, Tibet, earthquake



Yuan et al. (2022)

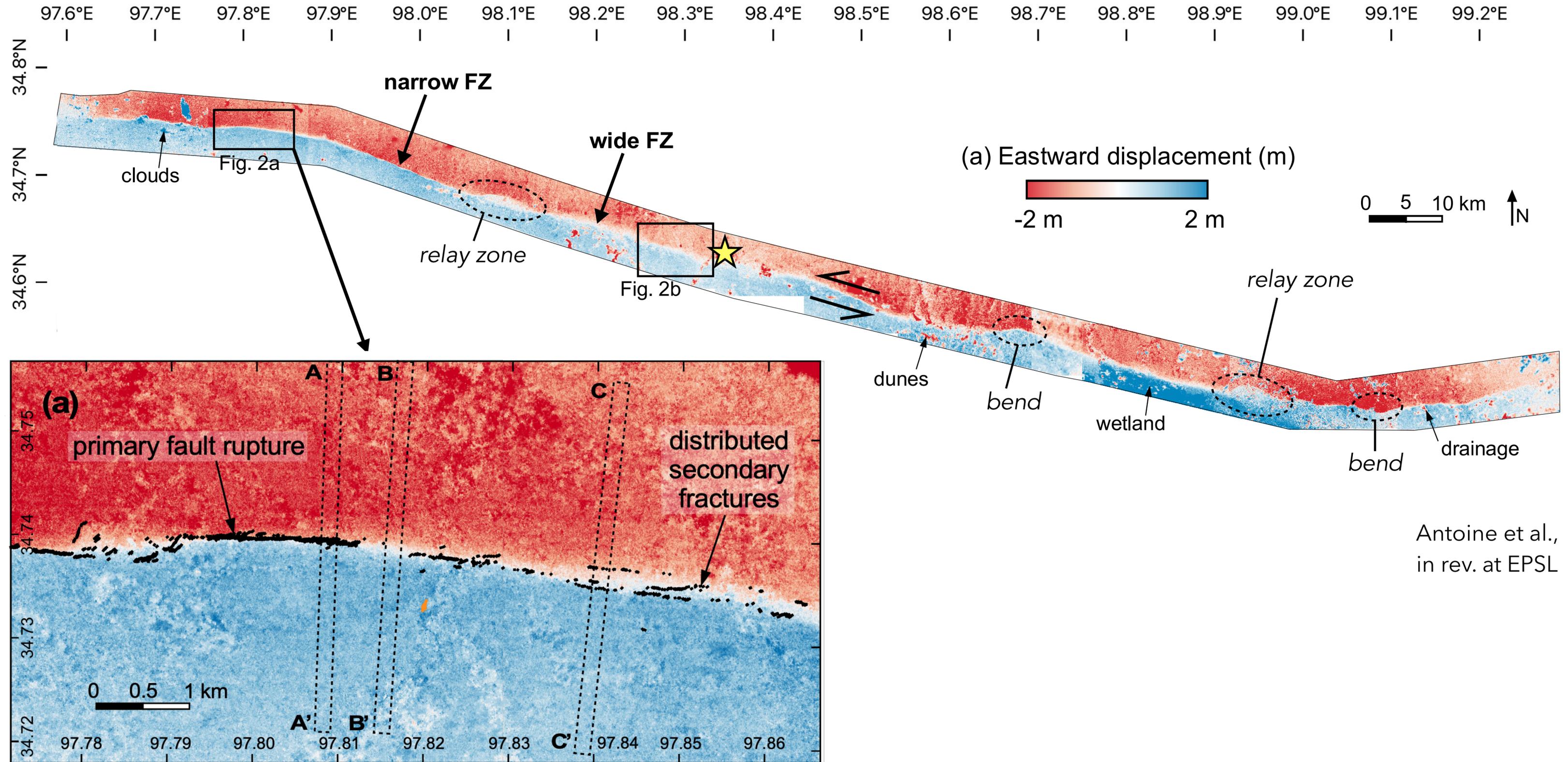
# Near-fault horizontal displacement field (0.5 m ground resolution)



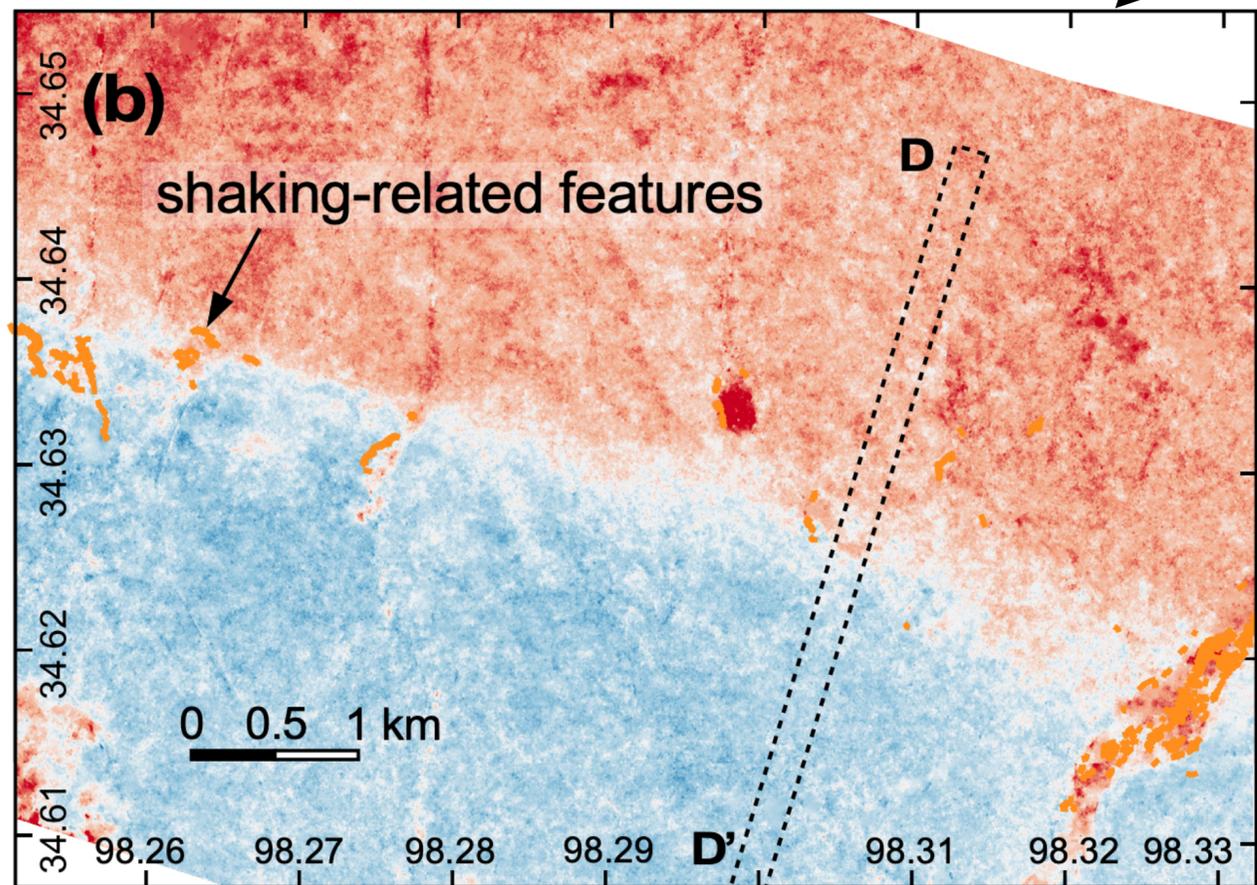
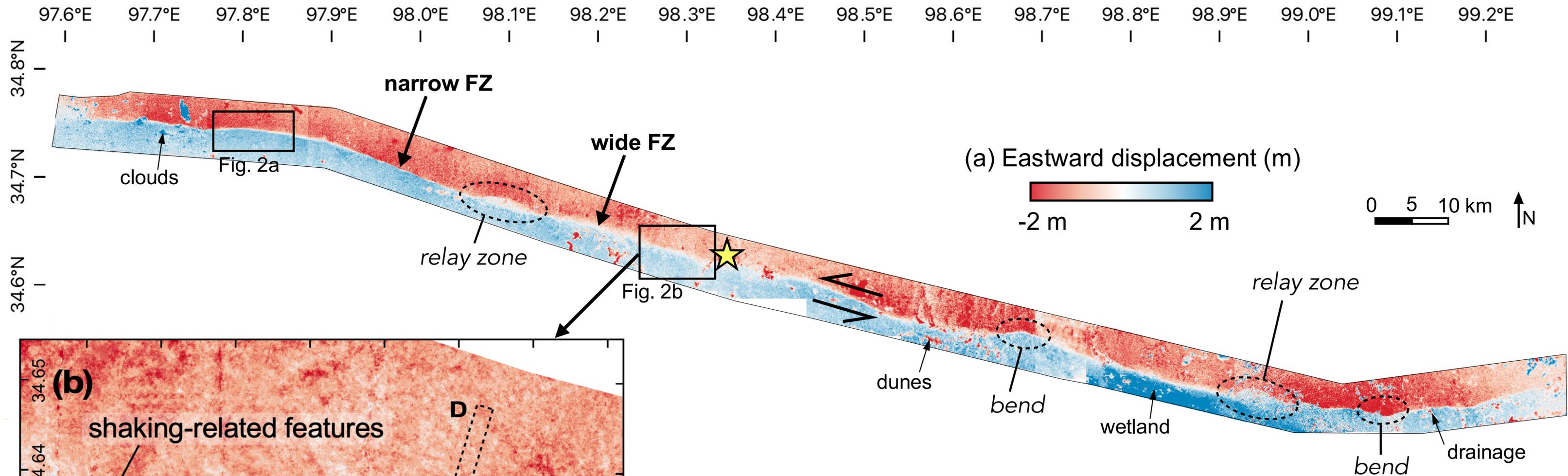
→ pre-event SPOT6/7 (1.6 m)  
post-event Pleiades (0.5 m)

Antoine et al.,  
in rev. at EPSL

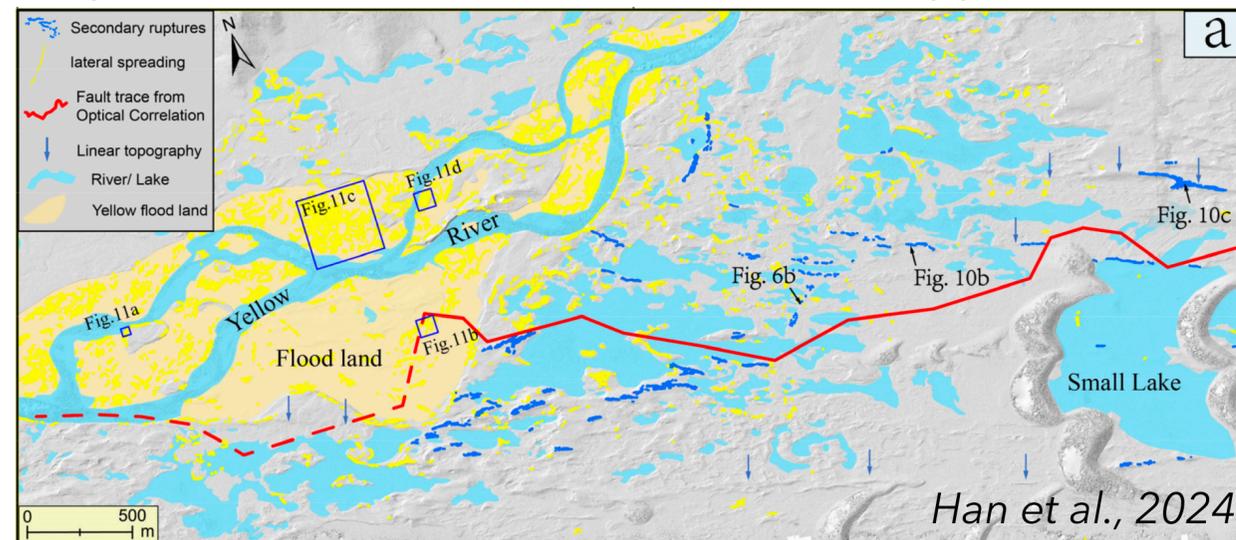
# Localized deformation in regions of surface faulting



# Diffuse deformation along the rupture gaps

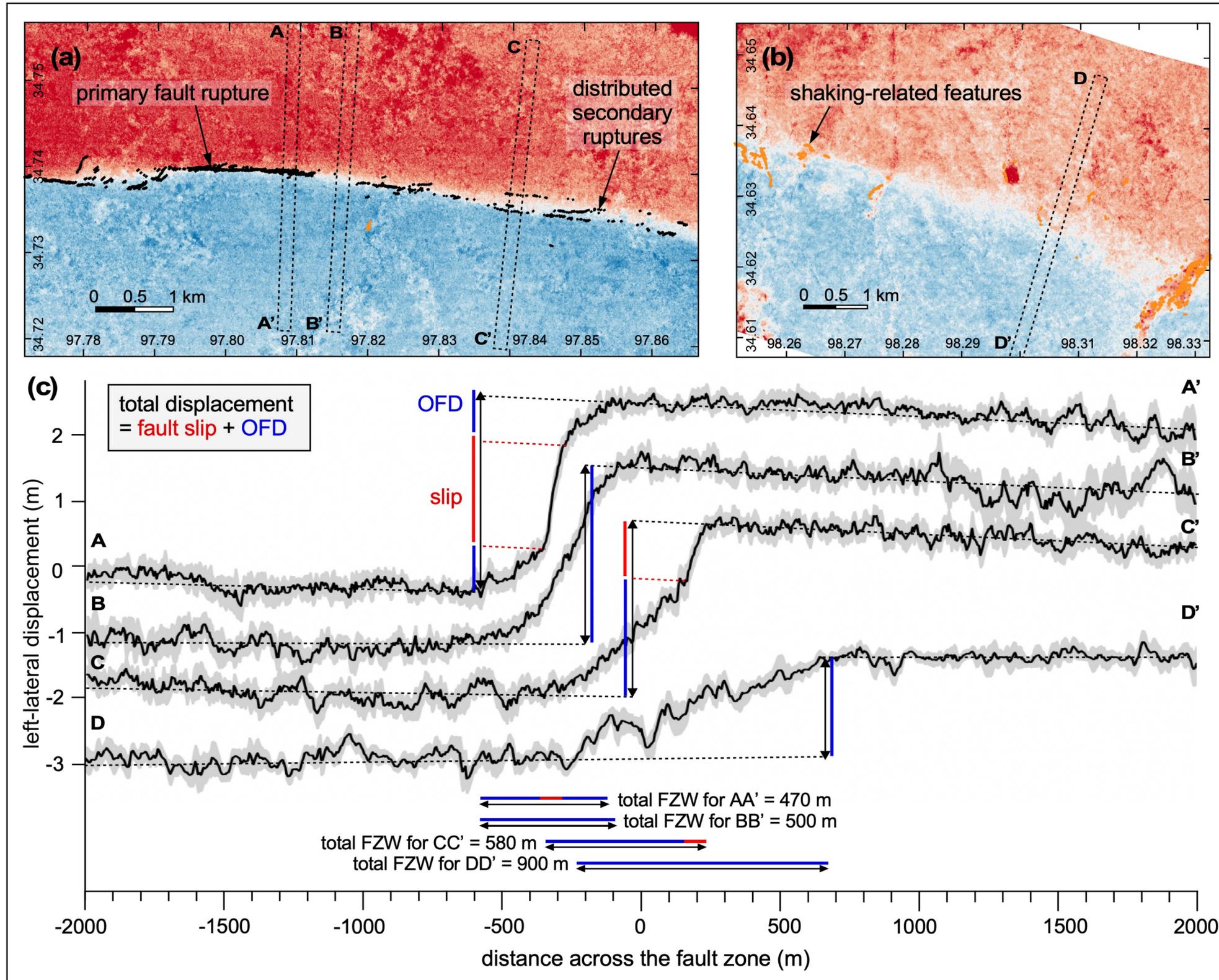


Only few en-echelon fractures could be mapped:



Antoine et al.,  
in rev. at EPSL

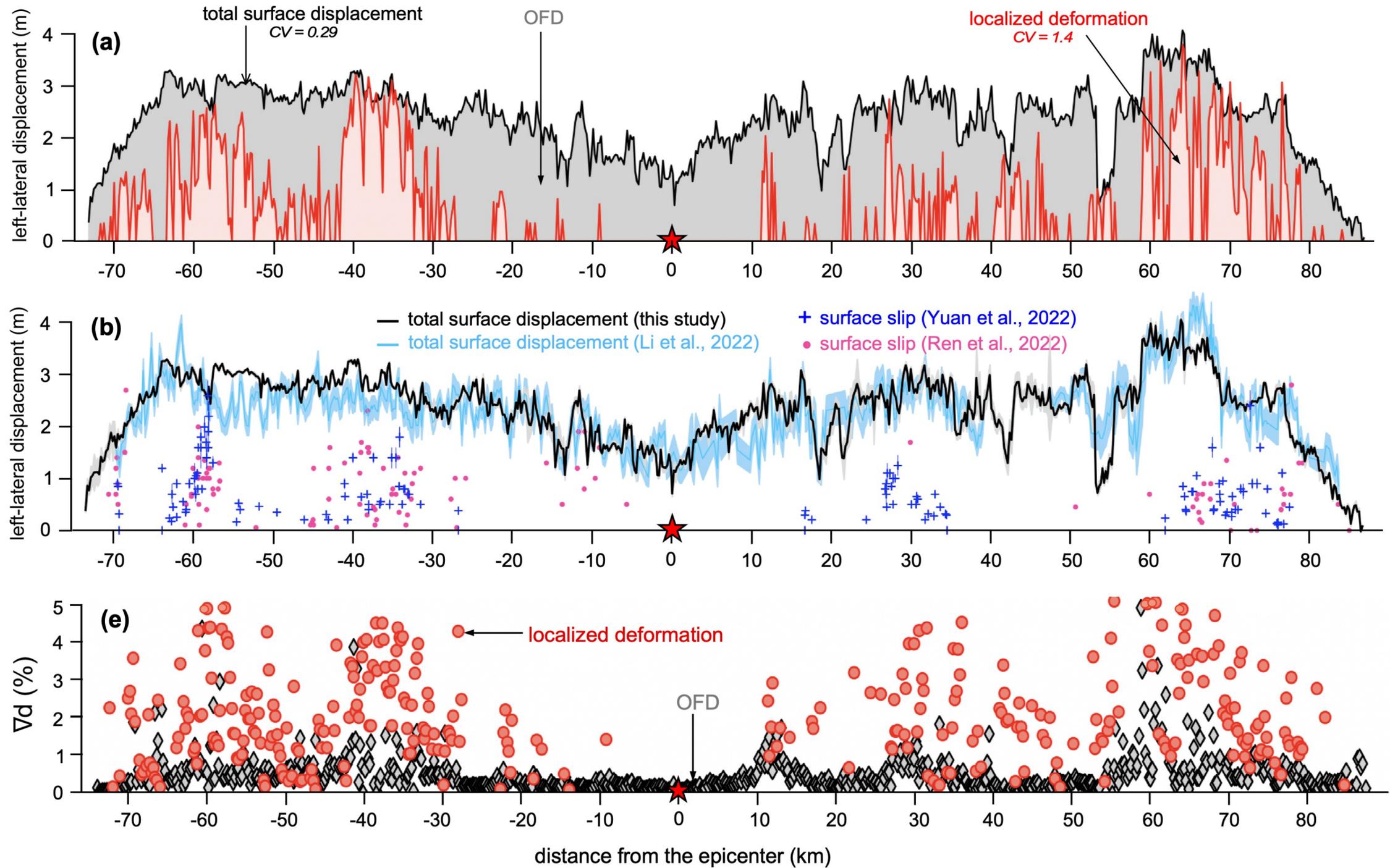
# We use profiles to measure the deformation across the rupture zone



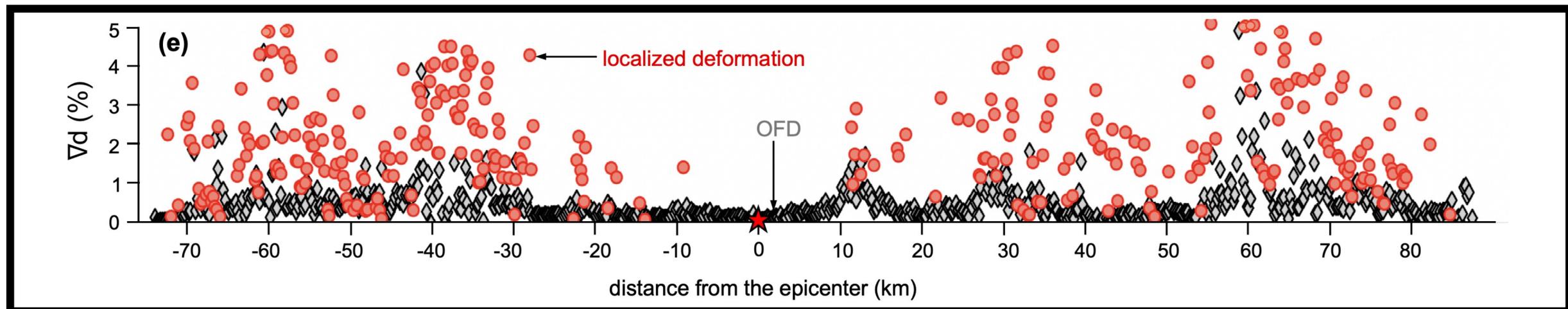
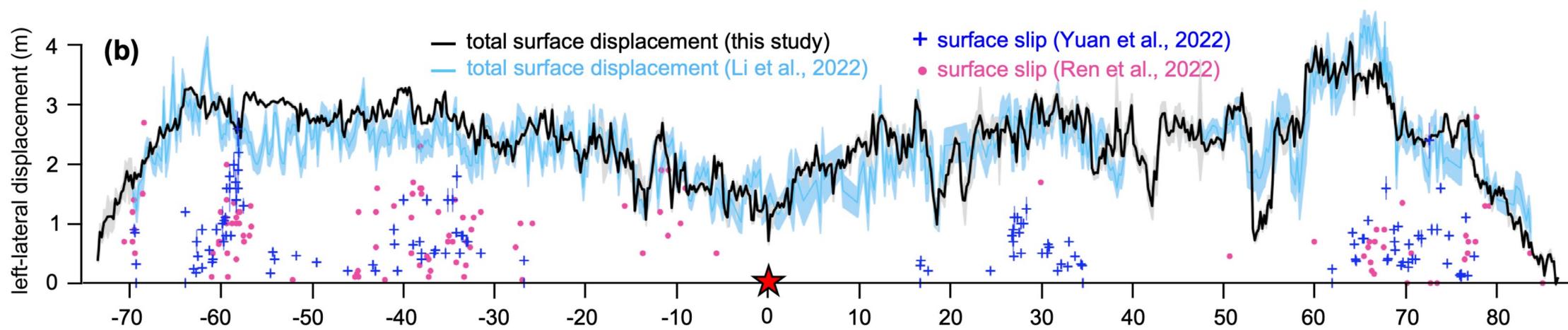
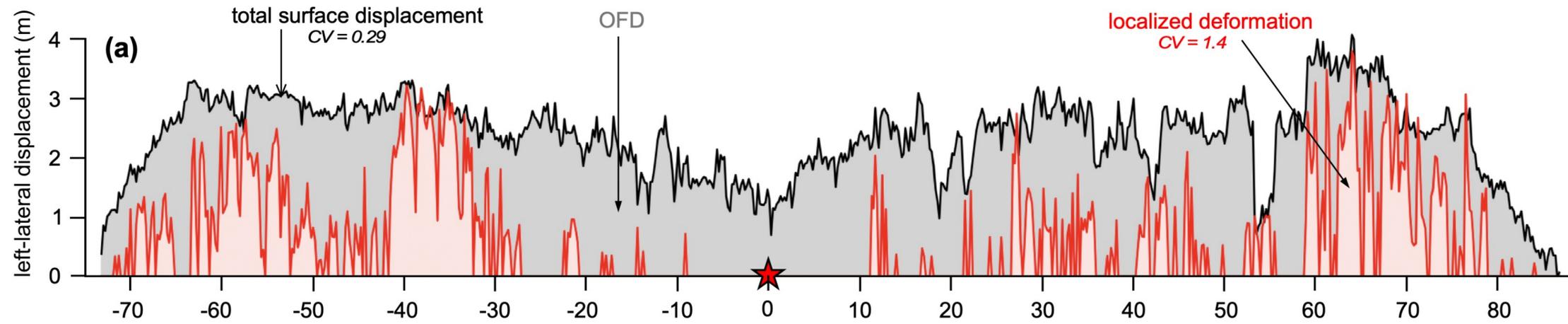
- Localized deformation correlates with mapped surface faults

- Off-fault deformation extends up to >1 km from the center of the fault zone

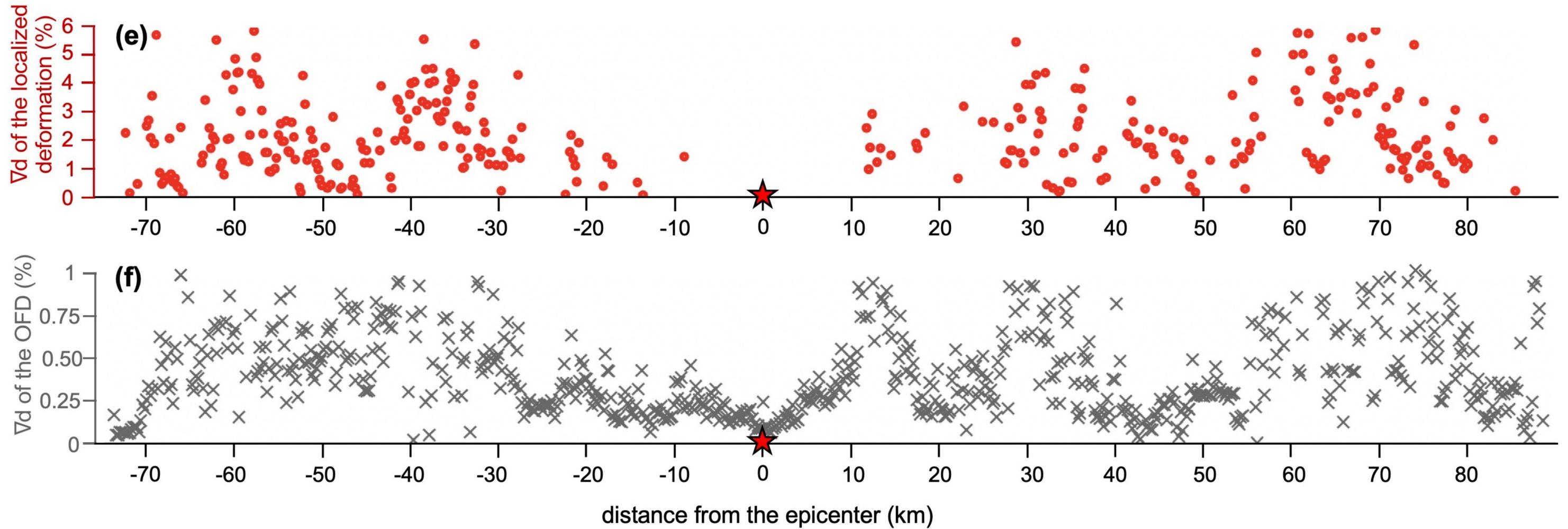
# Surface displacement budget: OFD=74% of the surface deformation



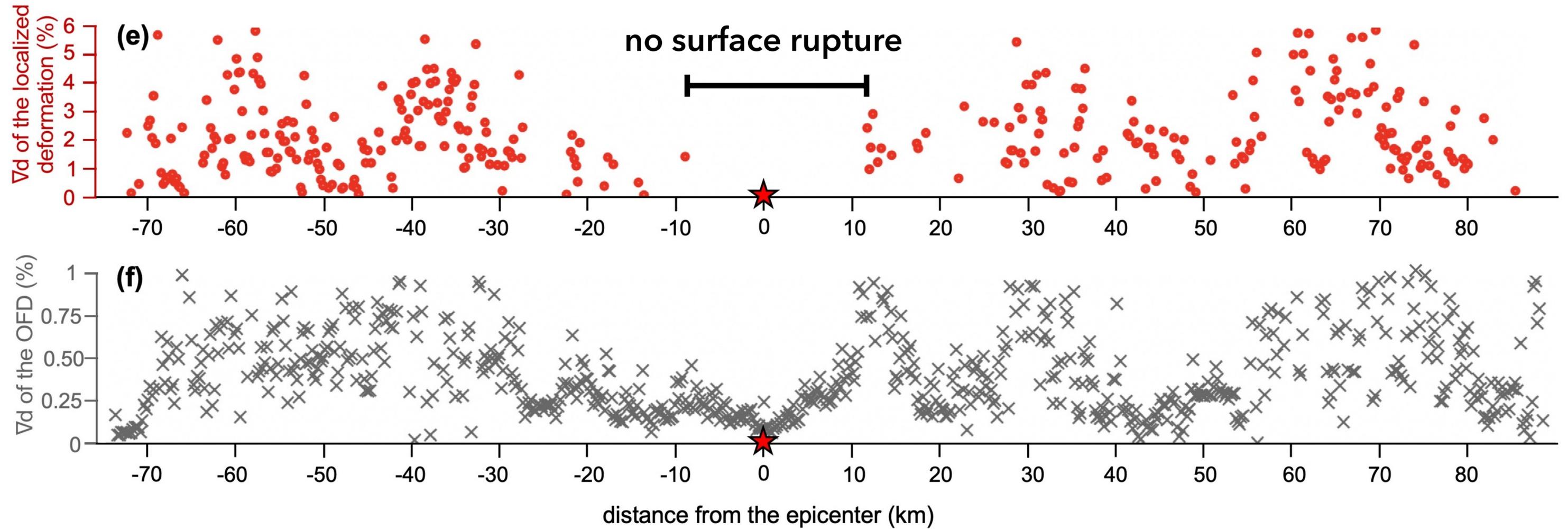
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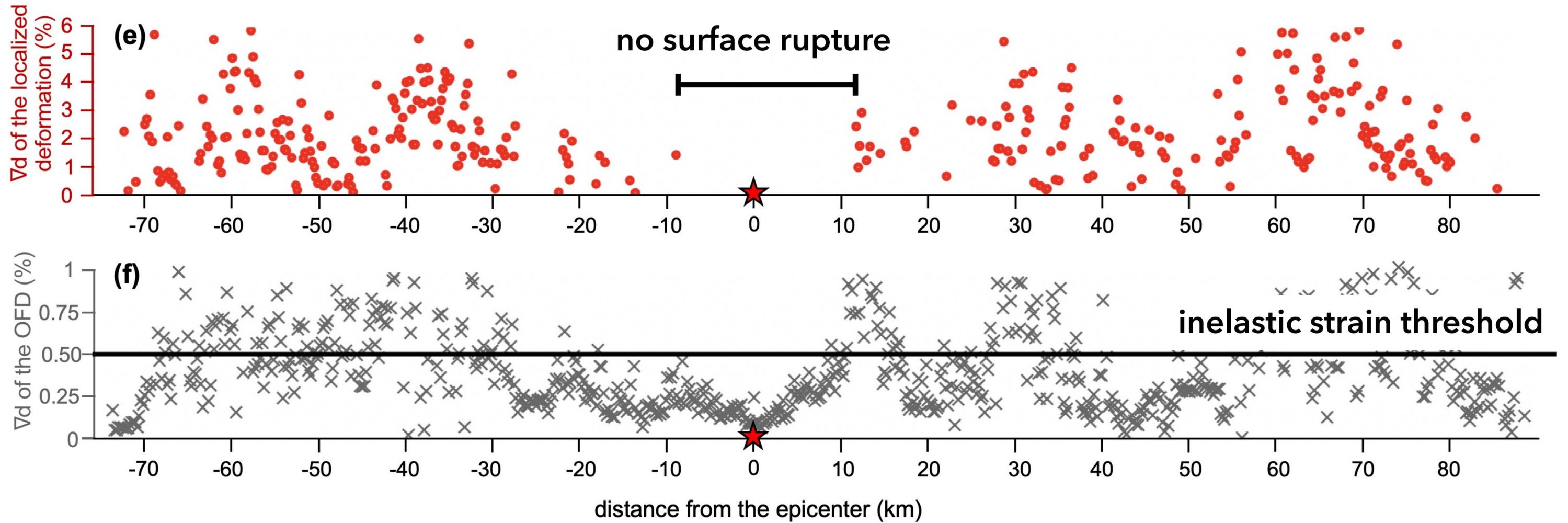
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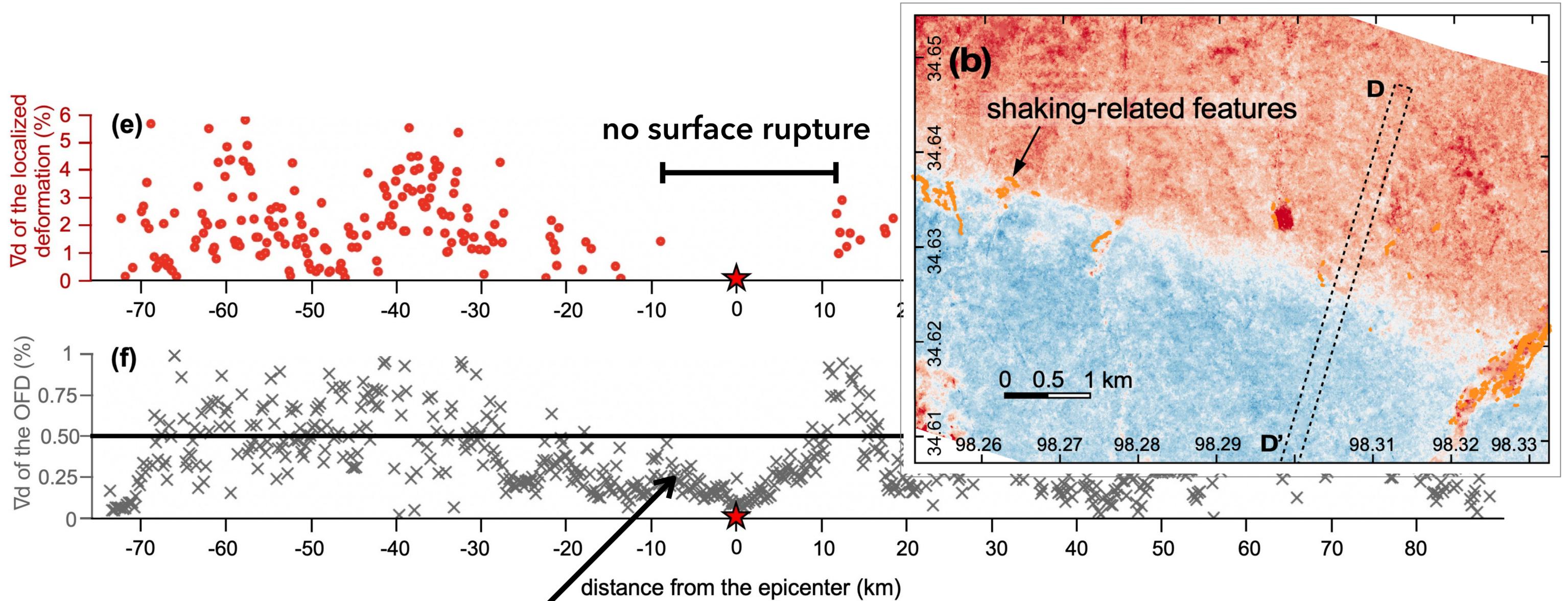
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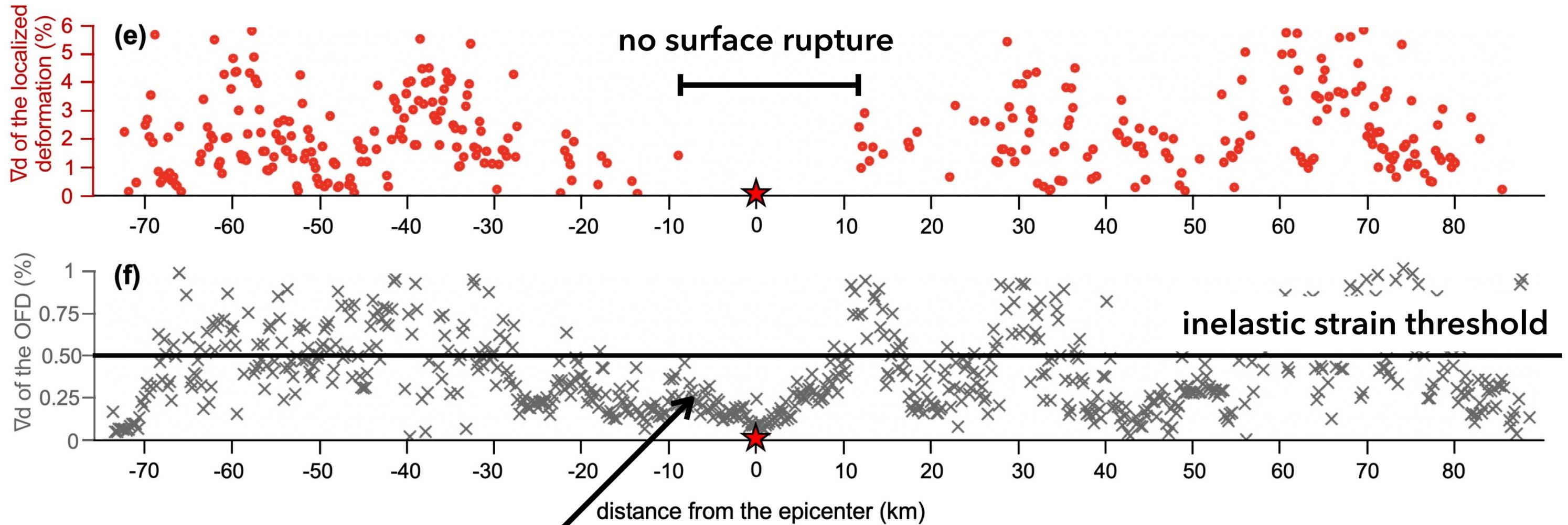


# Surface displacement budget: OFD=74% of the surface deformation



can inelastic deformation occur at such low strains (<0.5%)?

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can inelastic deformation occur at such low strains (<0.5%)?

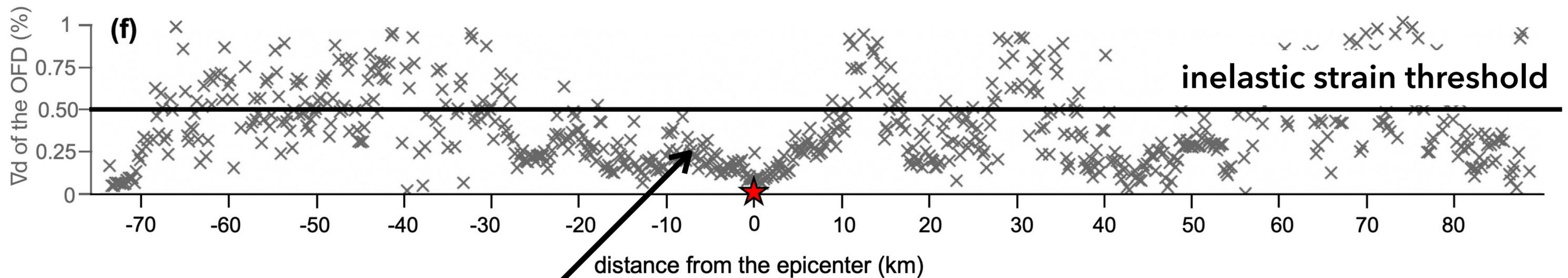
# Surface displacement budget: OFD=74% of the surface deformation

1) traces of distributed shear fractures at the surface

2) no additional post-seismic deformation

(afterslip <20 cm included in the diffuse deformation ;  
occurs within the bulk or at the subsurface)

3) no detectable creep



can inelastic deformation occur at such low strains (<0.5%)?

# Bulk yielding is compatible with measured strain and geomechanical conditions, on principle



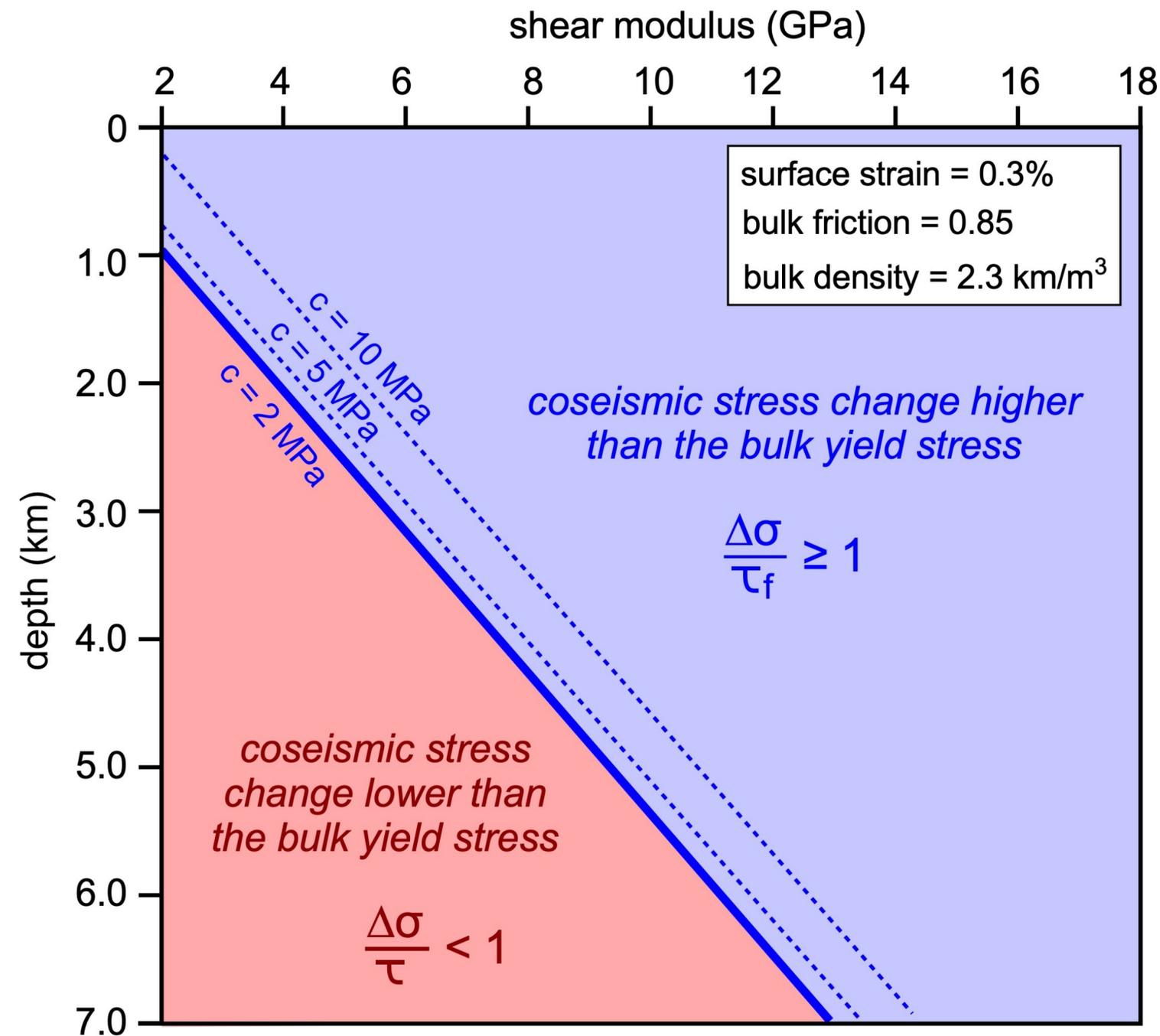
Rishav Mallick (JPL-EOS)

→ Estimate a Mohr-Coulomb type of failure threshold

$$\Delta\sigma = 2 \times \mu \times \Delta\varepsilon$$

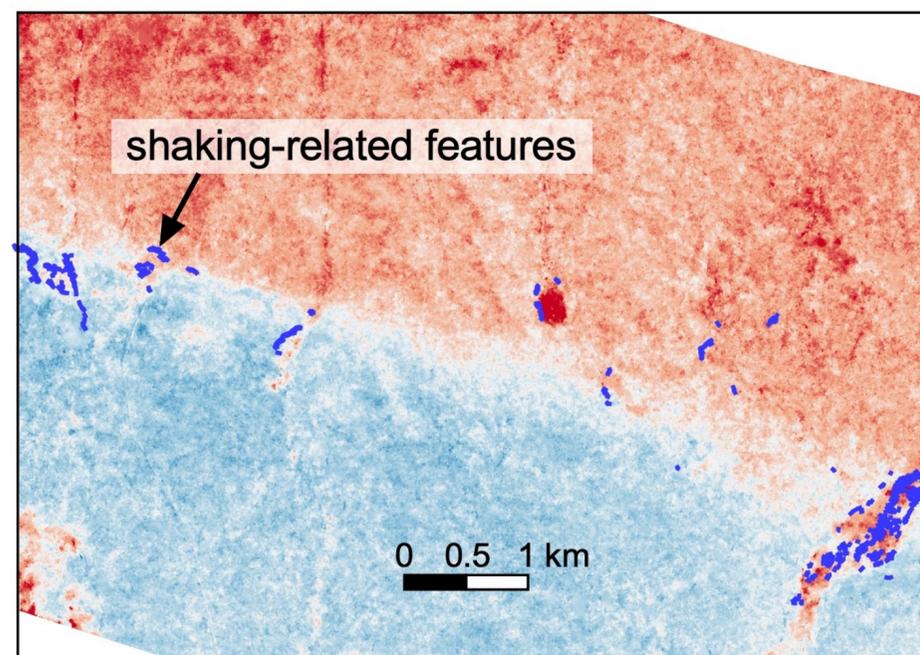
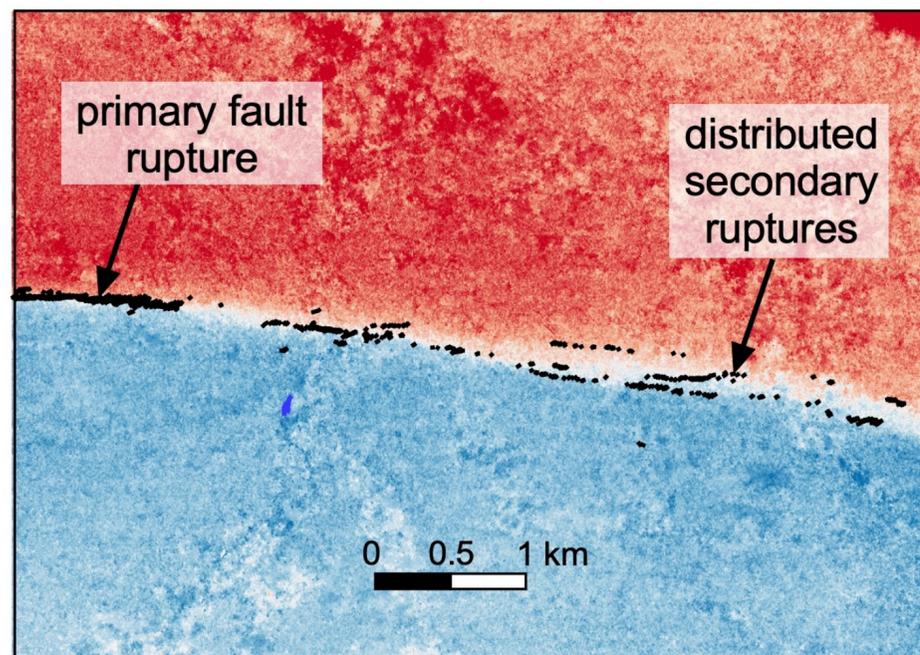
$$\tau_f = c + f \times P_z$$

(depth-dependent yield strength)



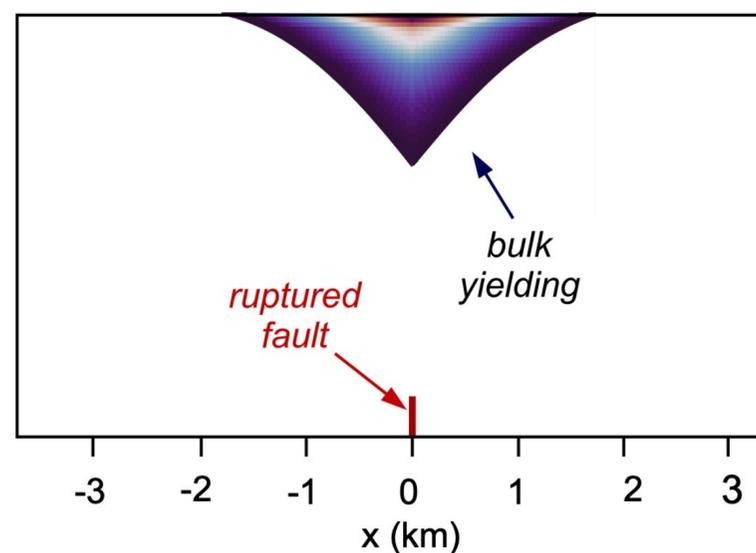
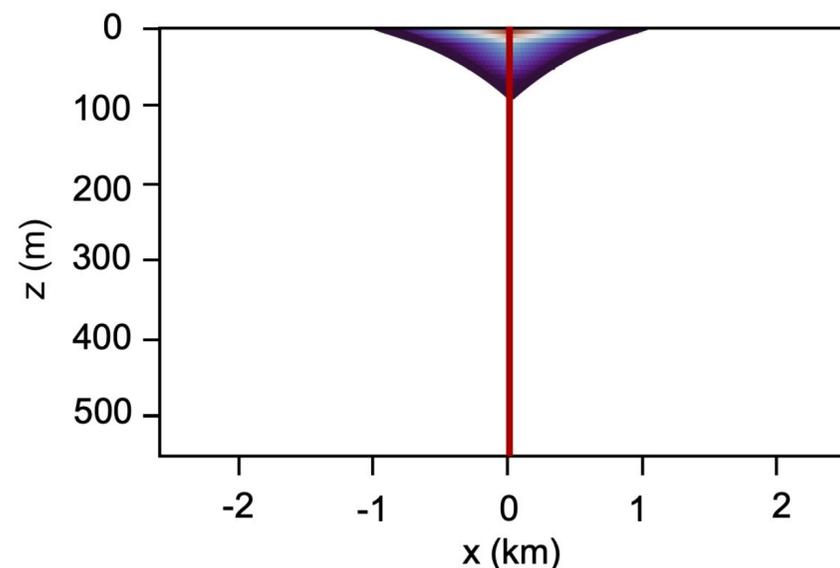
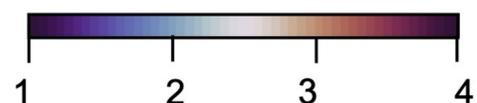
**(a) surface observations of the deformation from optical image correlation**

East-West displacement (m)



**(a) prediction of the off-fault inelastic strain**

failure criterion = coseismic stress change / bulk shear strength



# We estimate the 2D distribution of the failure criterion for given slip distributions

*Singularity-free Boundary Element Approach (BEMCS, Mallick and Meade, 2024)*

$$c = 2\text{MPa}$$

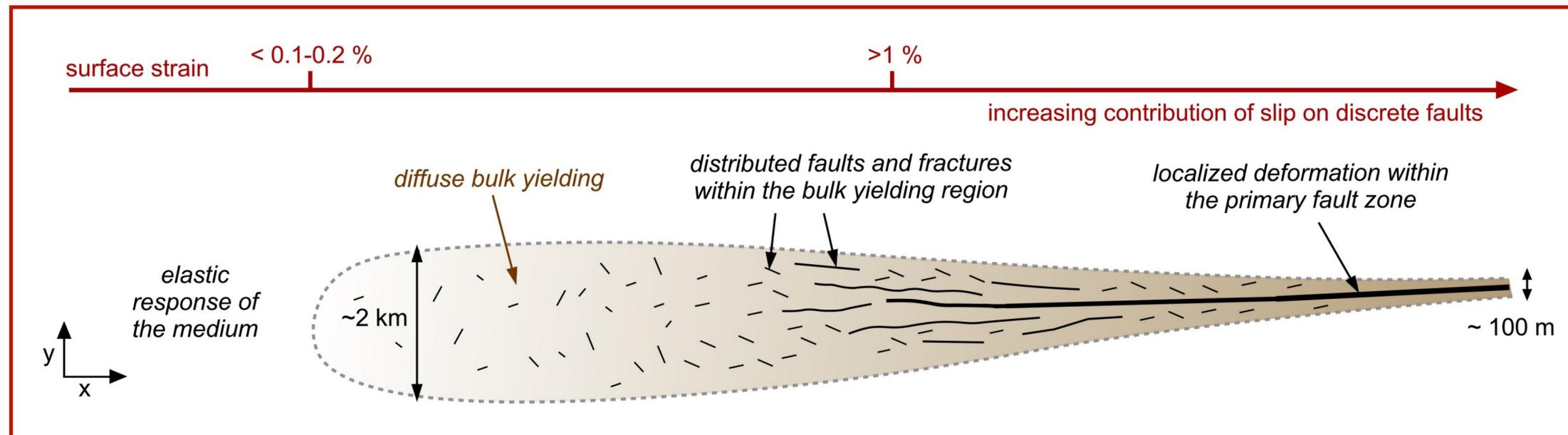
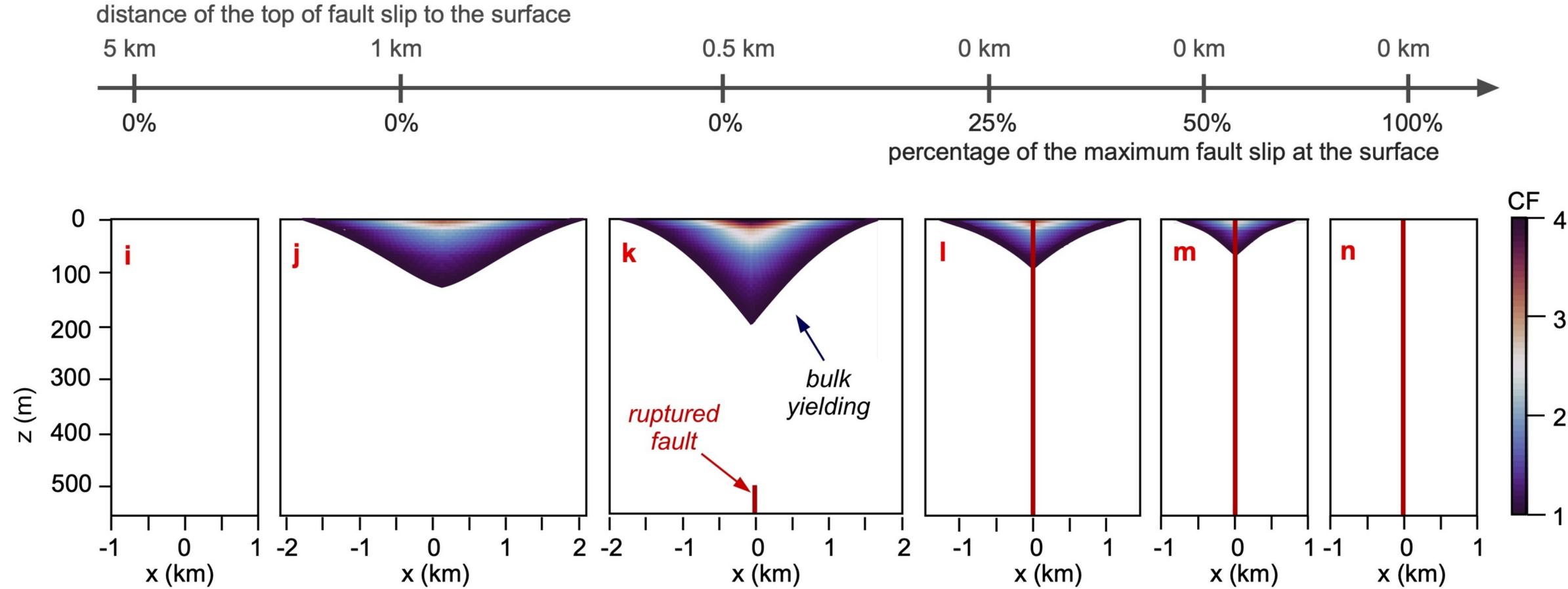
$$f = 0.85$$

$$\mu = 10\text{ GPa}$$

*slip distribution at depth is given in Zhao et al. (2023)*

Antoine et al., in rev. at EPSL

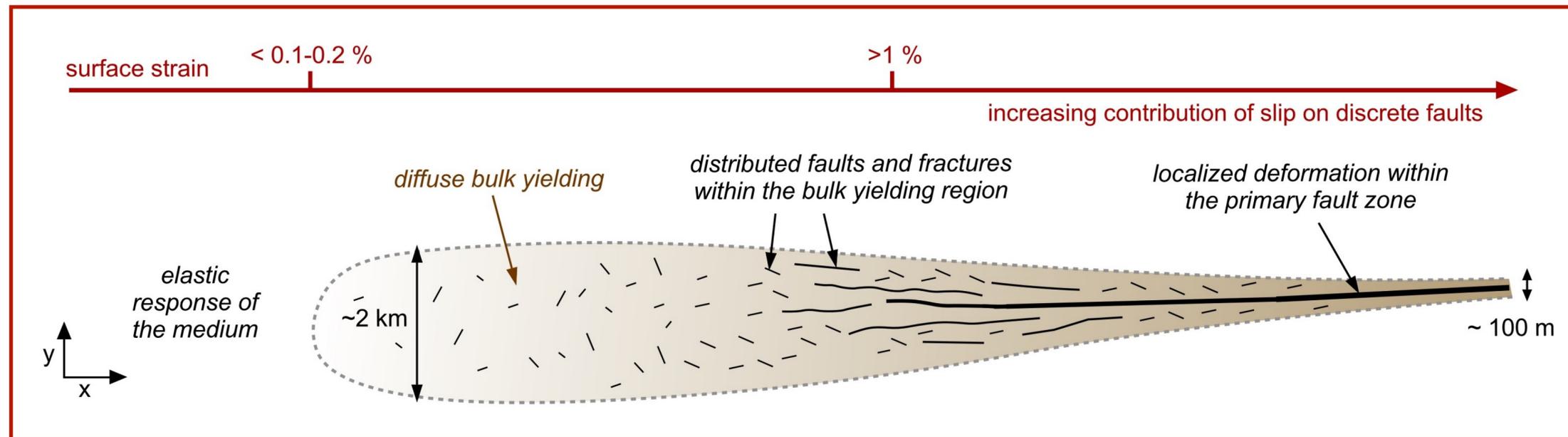
# Surface deformation localizes as shallow slip increases



Antoine et al.,  
in rev. at EPSL

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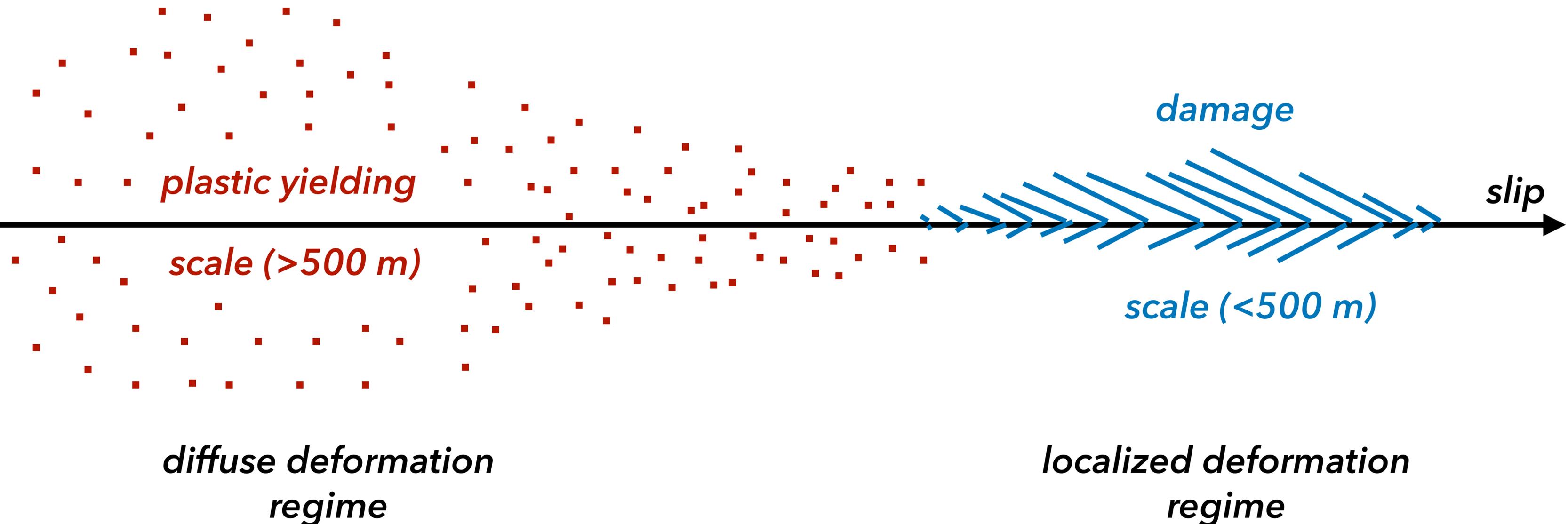
→ *contrary to common descriptions of increasing damage with slip (geological observations, numerical models)*



Antoine et al., in rev. at EPSL

# Surface deformation localizes as surface slip increases

→ *contrary to common descriptions of increasing damage with slip*  
*(geological observations, numerical models)*



$$D \propto M_w$$

**Can we generalize this model to earthquakes of different magnitudes?**

→ *What are the implications for the earthquake rupture process, fault zone structural evolution, and seismic hazard assessment?*

**2020 Mw6.5 Monte Cristo, Nevada, United States**

	Data	Measurements ; comments	References
Surface slip	field ; InSAR ; GNSS	lateral and vertical offsets up to 0.20 and 0.10 m respectively, with a majority of them in the range 4-6 cm ; shallow (0-3 km) afterslip ranges between 0.1 and 0.3 m	Dee et al., 2021; Hammond et al., 2021; Koehler et al., 2021; Li et al., 2021; Sethanant et al., 2023
Coseismic slip at depth	GNSS ; InSAR	peak average slip of ~0.55 m at ~7 km depth	Sethanant et al., 2023
SSD		80-90%	Sethanant et al., 2023
Surface creep	N/A	N/A	N/A
Possible processes accounting for the SSD	InSAR and GNSS data report a wide shear zone with associated displacements up to ~0.35-40 (Hammond et al., 2021). Field studies also report a ~800 m shear deformation region (Koehler et al., 2021).		

**2004 Mw6.4 Al Hoceima, Morocco**

	Data	Measurements ; comments	References
Surface slip	field	distributed fracturing, mainly tension cracks, vertical offsets up to 0.25 m, but no clear lateral surface slip ; no post-seismic deformation documented	Azelarab et al., 2004; Tahayt et al., 2009; van der Woerd et al., 2014
Coseismic slip at depth	InSAR ; seismic data	Slip up to 2-2.5 m at 8-12 km depth, and no slip at the surface	Akoglu et al., 2006; Biggs et al., 2006; Çakir et al., 2006; Stich et al., 2005
SSD	Field and models	100%	Previous publications
Surface creep	N/A	N/A	N/A
Possible processes accounting for the SSD	Possible 5±5 cm of surface diffuse shear (Tahayt et al., 2009). Centroid depth of fault slip is ~8 km, which is greater than, for example, the 2003 Bam earthquake (~ 5km; e.g., Funning et al., 2005; Wimpenny et al., 2017), supporting the hypothesis of lesser surface shear and greater elastic loading of the shallow crust for this event.		

**2017 Mw6.5 Jiuzhaigou, China**

	Data	Measurements ; comments	References
Surface slip	field	No surface rupture	Han et al., 2018; Li et al., 2020
Coseismic slip at depth	InSAR	peak average slip of ~1.2 m at ~7 km depth	Li et al., 2020; Tang et al., 2021
SSD	Field and models	100%	Previous publications
Surface creep	N/A	N/A	N/A
Possible processes accounting for the SSD	Considering the lack of clear surface rupturing for this event as well as the >5 km width of the across fault displacement signal, it is likely that SSD for this event is associated with elastic loading of the shallow crust. This is supported by the large depth of the rupture, down to 15 km, inferred in the kinematic slip inversions.		

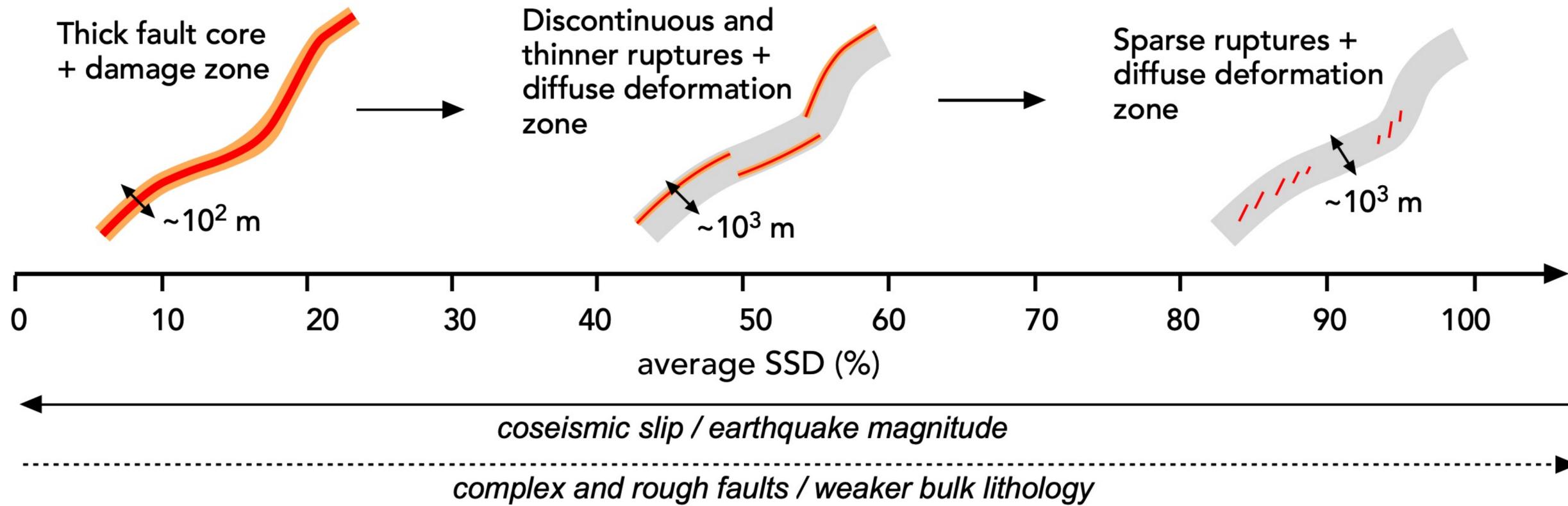
**2020 Mw6.4 Petrinja, Croatia**

	Data	Measurements ; comments	References
Surface slip	field ; InSAR	Average coseismic slip is ~10 cm, with maximum offsets up to 38 cm ; maximum afterslip of 5-10 cm one year after the event	Baize et al., 2022
Coseismic slip at depth	InSAR, field, GNSS	peak average slip of ~0.9 m at ~2-4 km depth	Henriquet et al., 2022; Xiong et al., 2022b
SSD		~57 to 67% in the models ; up to 89% when comparing the models to the field values	
Surface creep	N/A	N/A	N/A
Possible processes accounting for the SSD	Difference between the civilian benchmarks measurements (Henriquet et al., 2022) and the field rupture mapping (Baize et al., 2022) suggests the presence of distributed surface deformation. The shallow depth of maximum slip (~2 km), and the high seismic intensities in the near-field (Markušić et al., 2021) support the hypothesis of shallow inelastic off-fault deformation, diffuse and/or distributed).		

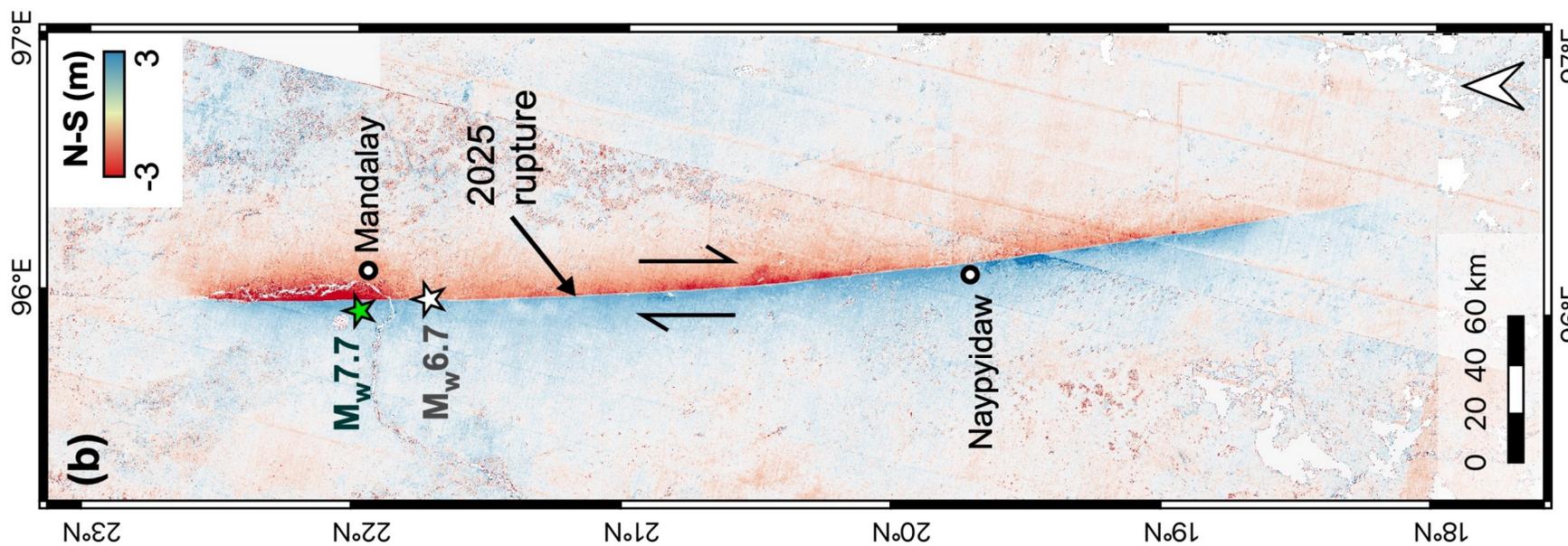
**2003 Mw6.5 Bam, Iran**

	Data	Measurements ; comments	References
Surface slip	field ; InSAR	distributed surface fractures, but not obvious slip associated with this event nor cumulated strike-slip motion along the activated fault systems ; shallow post-seismic (< 5km) deformation is 0.10-0.15 m.	Fielding et al., 2009; Talebian et al., 2004; Wimpenny et al., 2017
Coseismic slip at depth	InSAR	peak average slip of ~1.7-1.8 m at ~4-6 km depth. All models report ~1 m slip in the shallow crust, which is an over-estimation due to low model resolution and high-regularization.	Fialko et al., 2005; Funning et al., 2005
SSD		~78% ; possibly a lower endmember estimation due to the high-slip inferred in the shallow crust in the inversions compared to the field data.	
Surface creep		~0 m	
Possible processes accounting for the SSD	A 500 m-wide surface shear zone is detected in optical data (Binet and Bollinger, 2005), and is associated with an average coseismic surface displacement of 0.77 m. Added to the ~10-15 shallow afterslip detected within this shear zone, it yields a total diffuse surface displacement of ~0.87-0.92 m, accounting 43-55% of the SSD.		

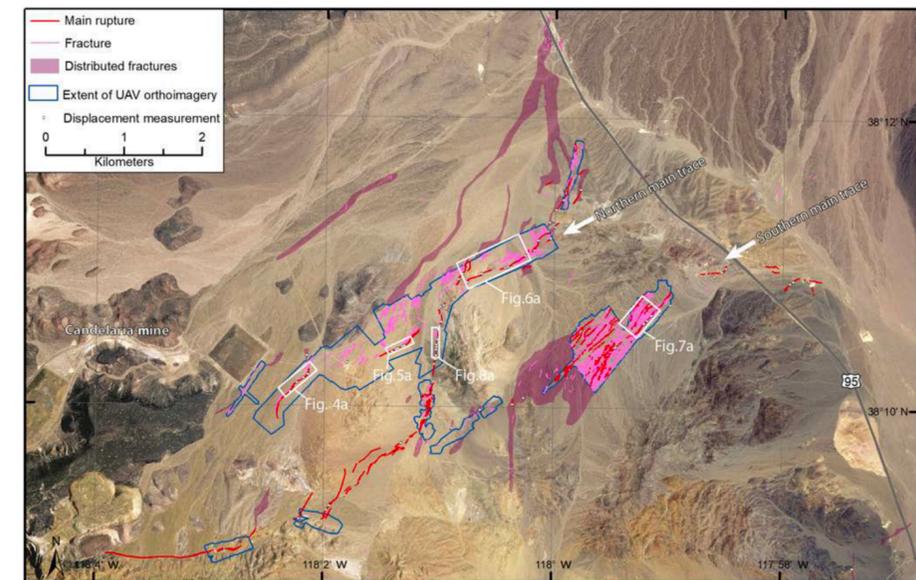
# Localization of the surface deformation with earthquake magnitude



Antoine et al., 2024



2025 Mandalay earthquake (Antoine et al., 2025)



2020  $M_w$  6.5 Monte Cristo, Nevada (Koehler et al., 2020)