Fringe 15-19 June 2026, Kraków, Poland

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New Insights into the Earthquake Factory from InSAR

Sigurjón Jónsson[1], Jihong Liu[1], Bo Li[1], Xing Li[2], Yann Klinger[3] and P. Martin Mai[1]

[1] King Abdullah University of Science and Technology (KAUST)
[2] University of Texas at Austin
[3] Institut de Physique du Globe de Paris (IPGP)

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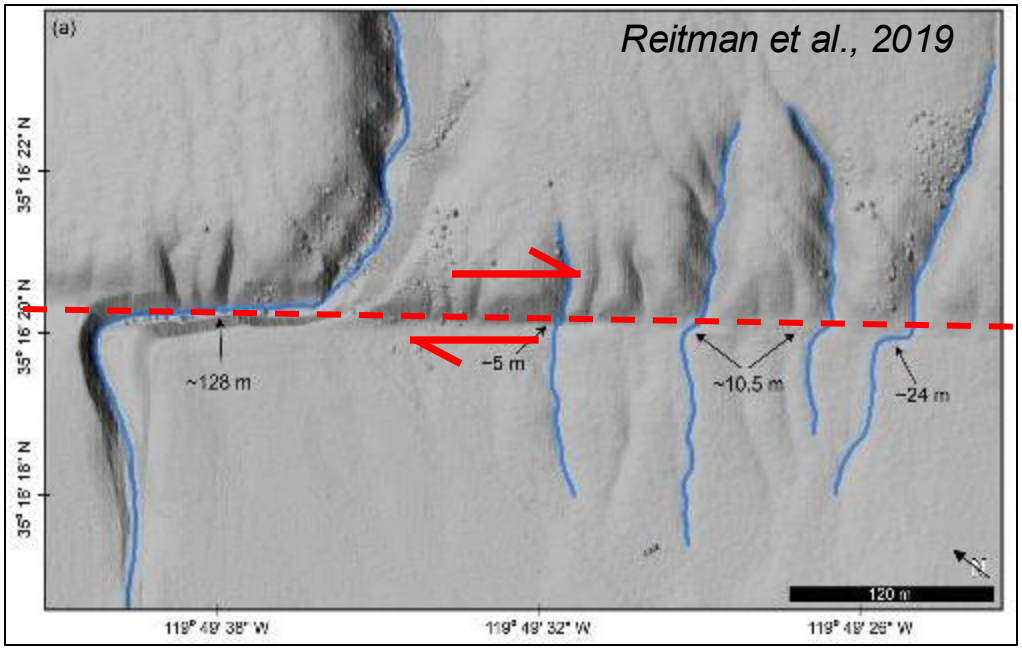
Are paleo-seismological results systematically biased?

Paleo-seismology

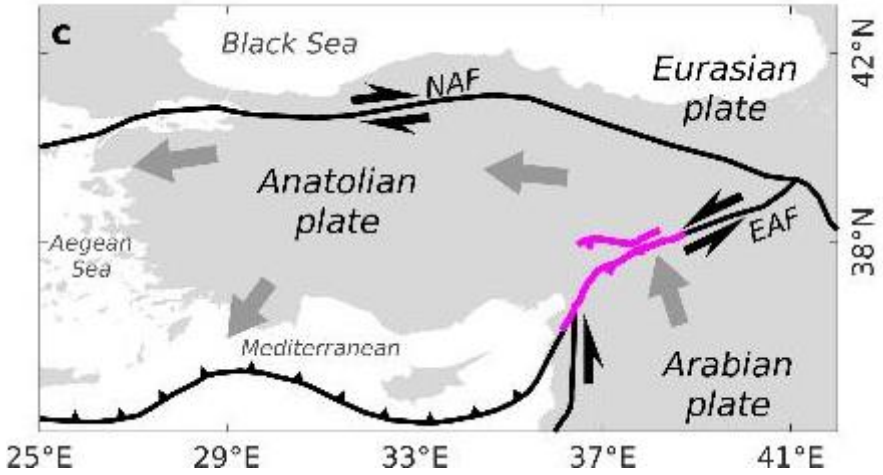
- Paleo-seismology aims to determine fault slip rates

- This is often done with geomorphological mapping and dating of offset stream channels

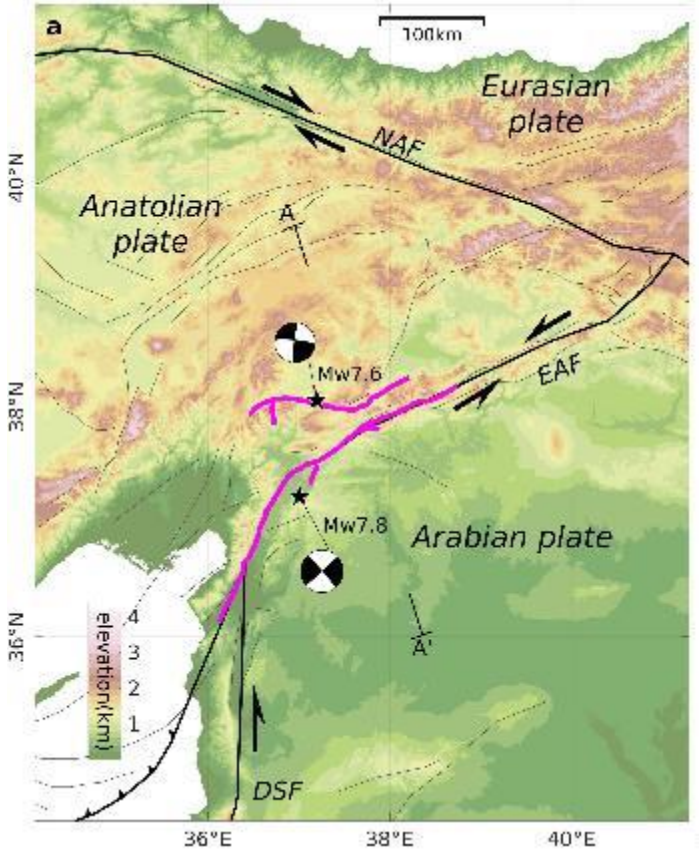


- Fault slip rates provide crucial information for earthquake hazard assessments around the world

The 2023 Türkiye Earthquake Doublet

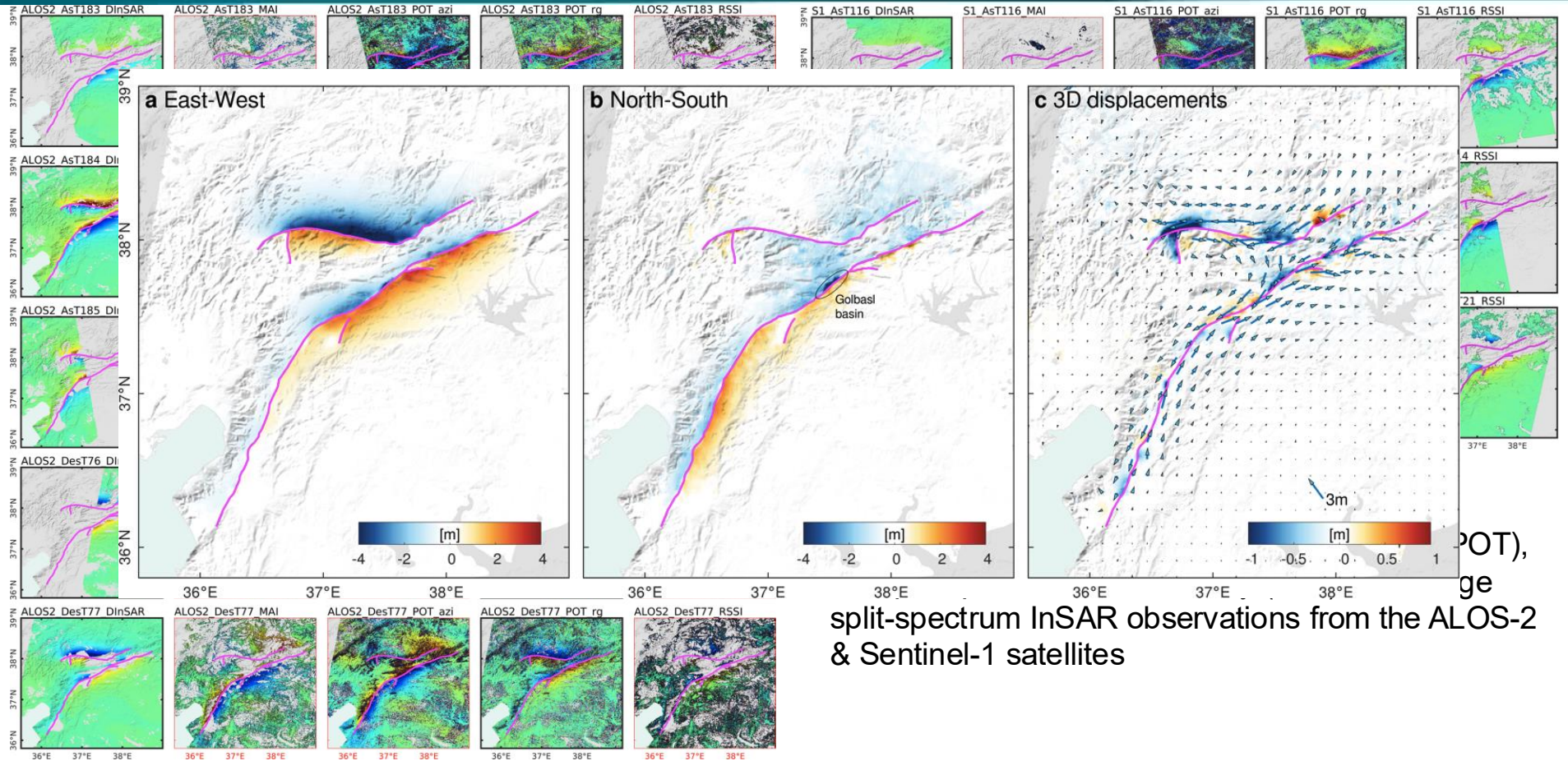


- Magnitude 7.8 & 7.6 Earthquakes on and near the East Anatolian Fault (EAF) on 6 February 2023
- Westward movement of the Anatolian plate, north motion of Arabia
- About 350 km and 160 km long surface ruptures in the two earthquakes



Liu, J., S. Jónsson, X. Li, W. Yao & Y. Klinger, *Nature Communications 16:1286,* 2025

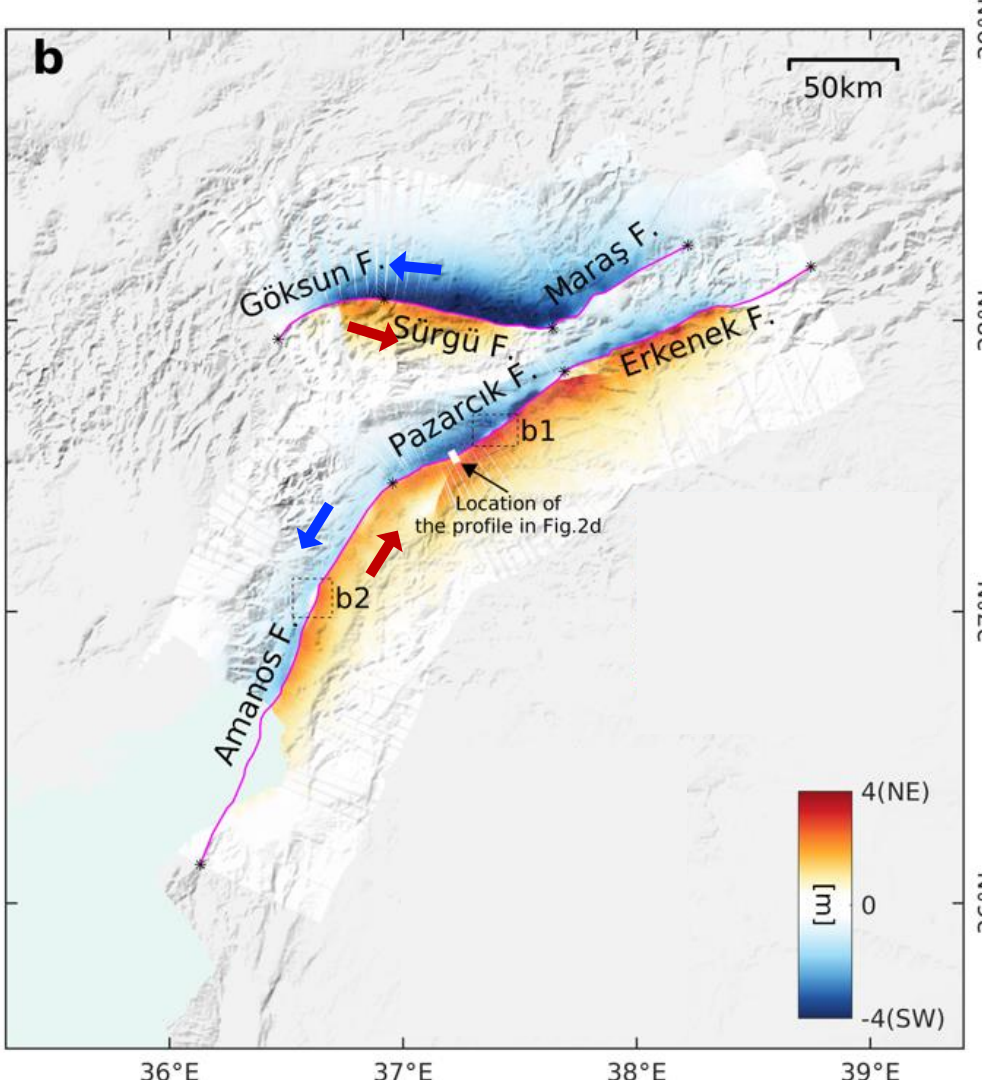
Multiple coseismic ALOS-2 and S1 datasets



POT),
ge
split-spectrum InSAR observations from the ALOS-2 & Sentinel-1 satellites

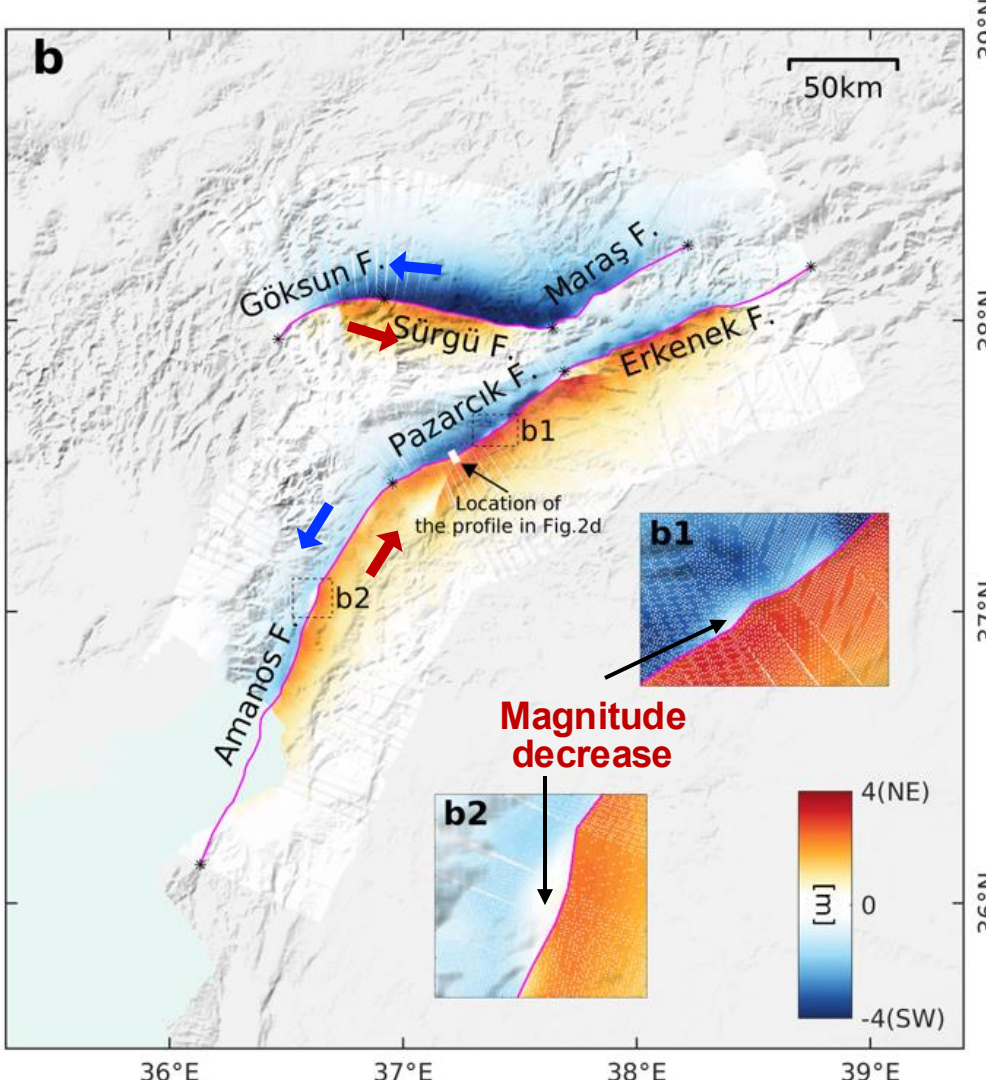
Fault-Parallel Displacements

- Color scale shows fault-parallel disp. from -4 m to 4 m

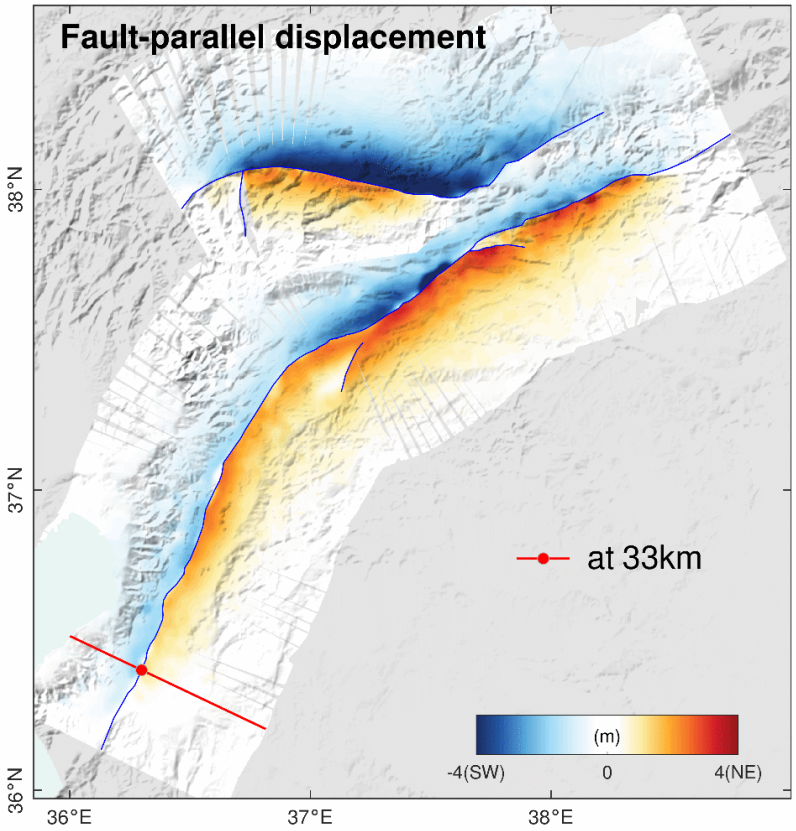


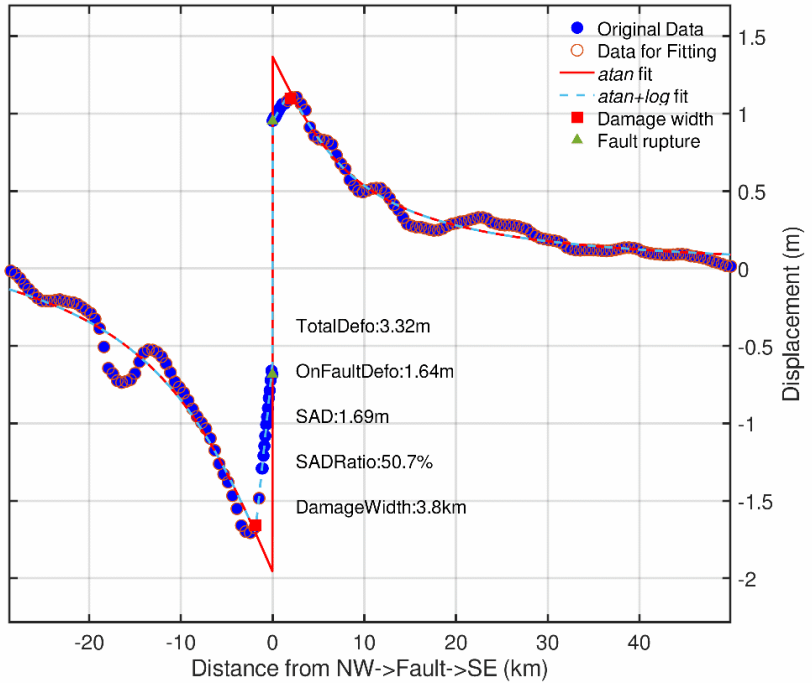
Fault-Parallel Displacements

- Color scale shows fault-parallel disp. from -4 m to 4 m
- Displacements **decrease** towards the fault!

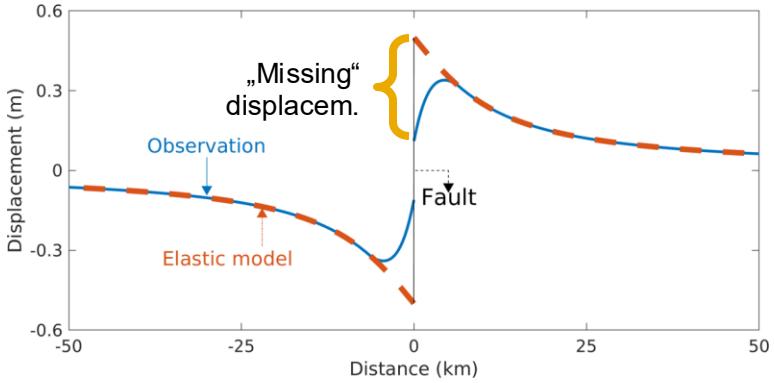


Fault-parallel displ. decrease towards the fault!

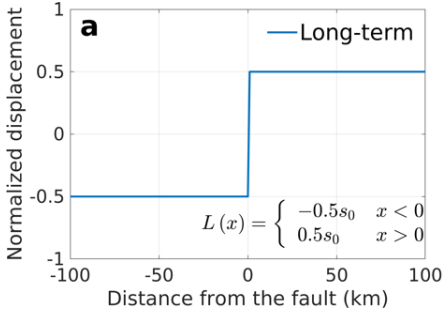


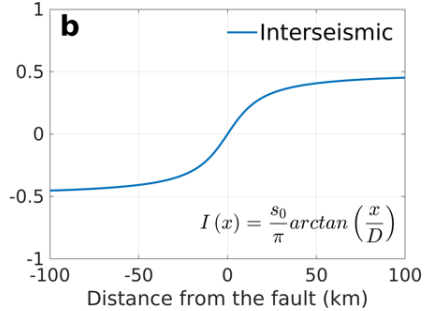


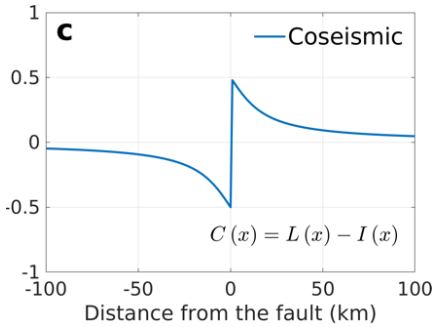
Estimating the „missing“ surface displacements



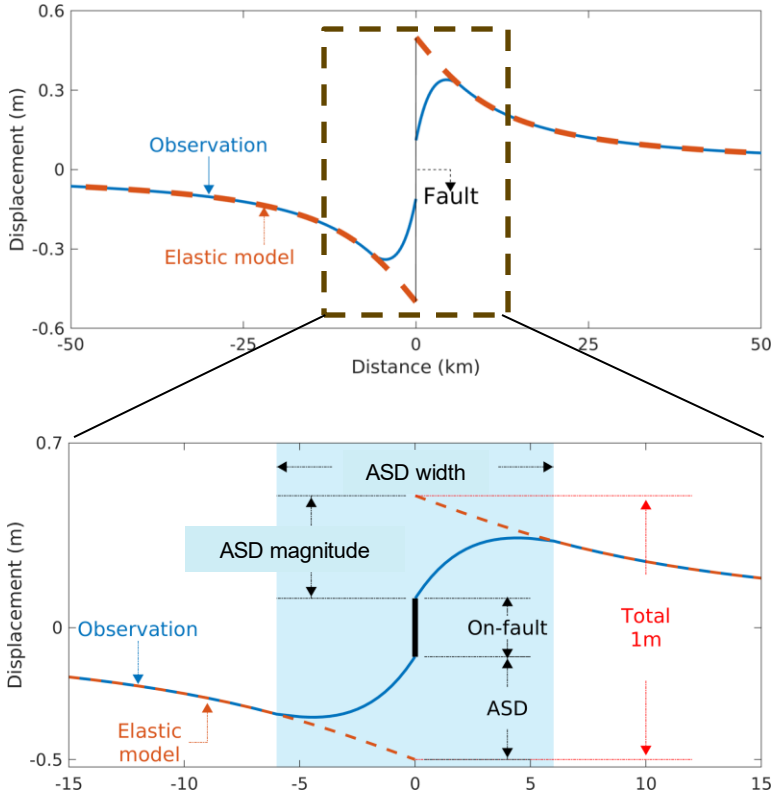
➢ We get this from an **elastic model**

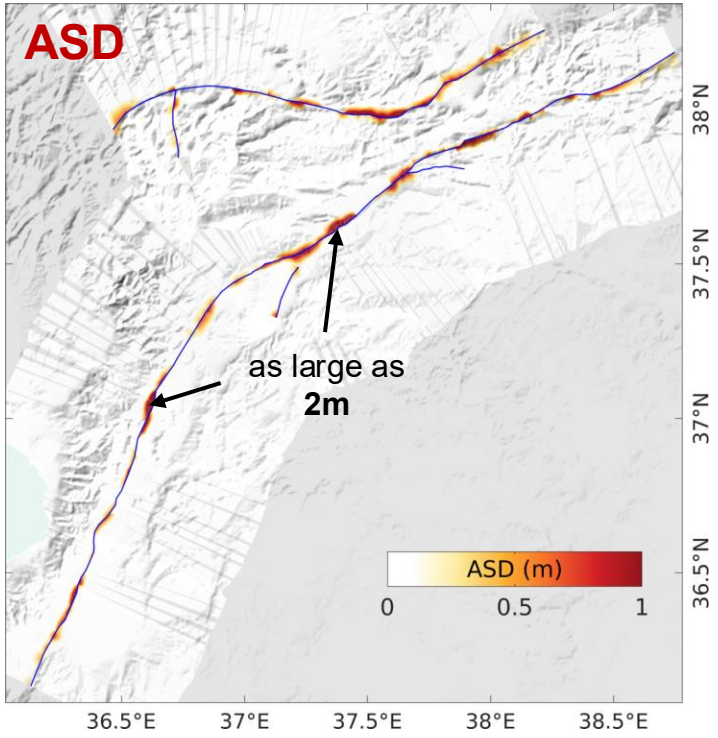






We define Absent Surface Displacement or ASD

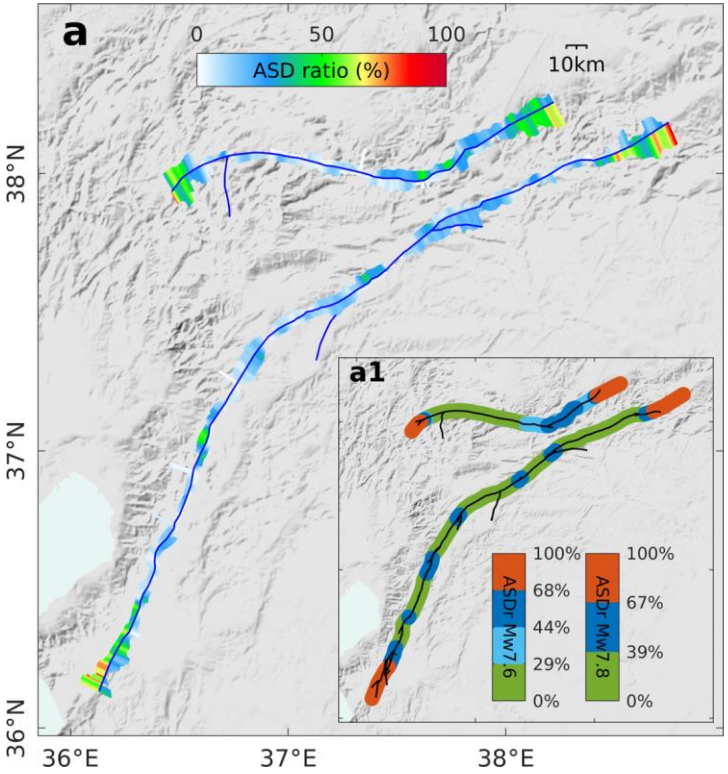




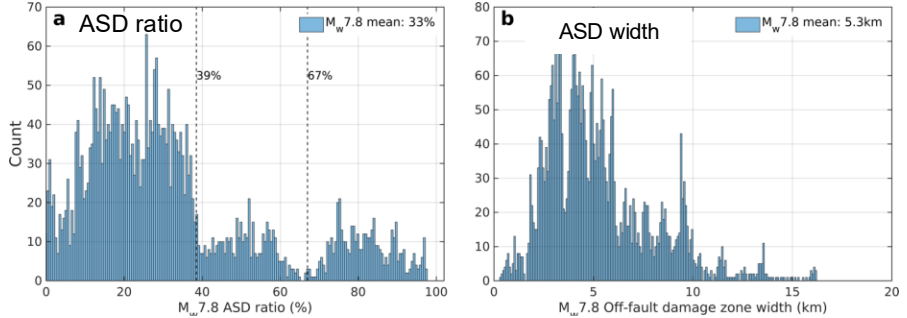
We determine both **ASD magnitude (m)** and **ASD width (km)**

Absent surface displacement ratio (ASDr)

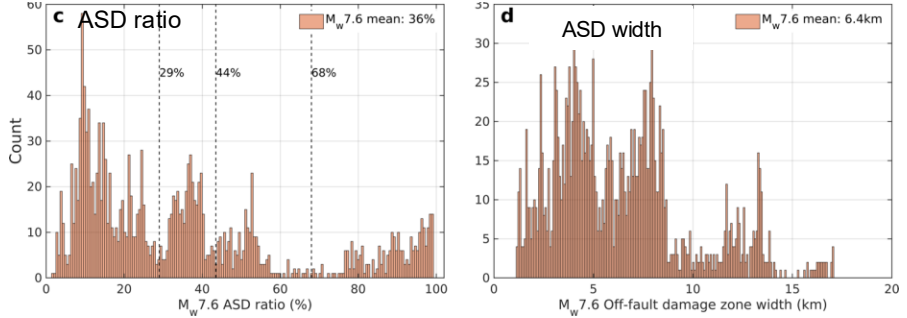
$$ASDr = \frac{ASD}{Total\ displacement} \times 100\%$$



Mw7.8 (33%, 5.3km)



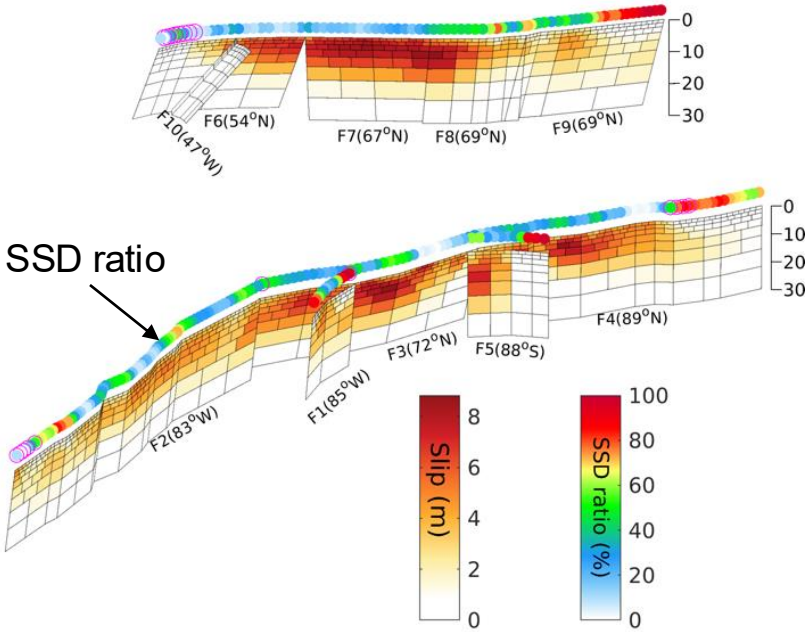
Mw7.6 (36%, 6.4km)

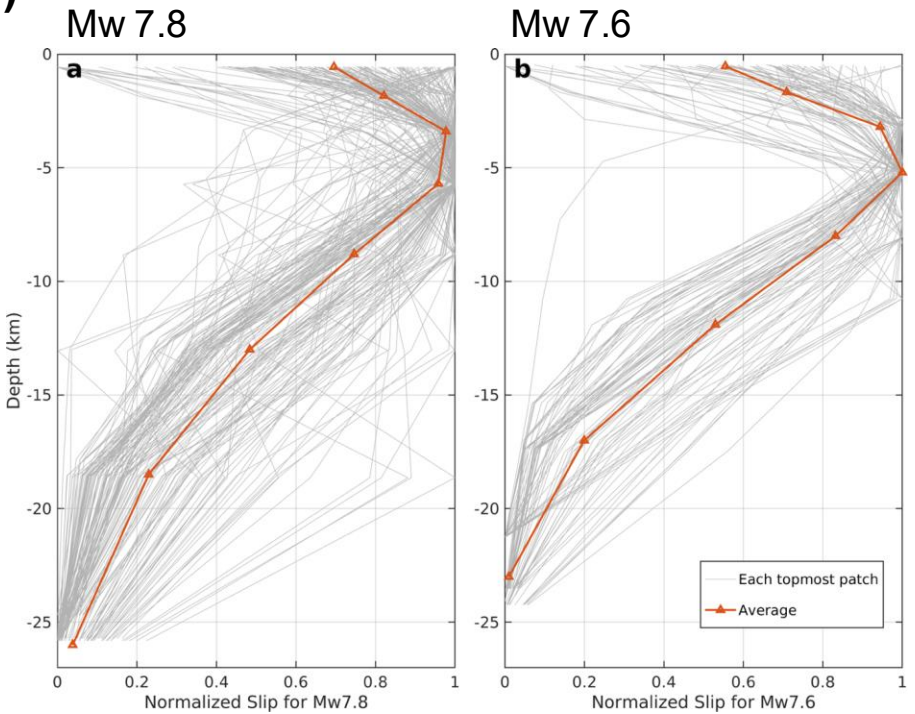


Stronger ASD near geometrically complex fault sections than around straight fault segments

Shallow Slip Deficit (SSD)

Modeling the coseismic deformation yields fault-slip reduction towards the surface – the so-called **shallow slip deficit (SSD)**

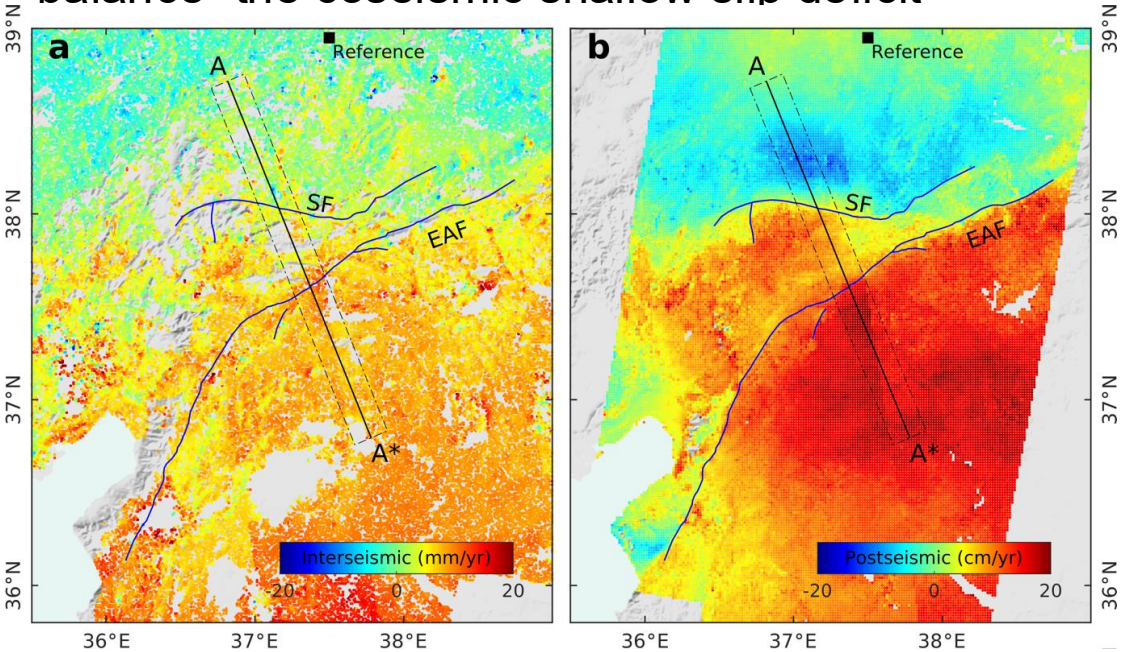




$$\text{SSD ratio} = 1 - \frac{\text{topmost slip}}{\text{maximum slip at depth}}$$

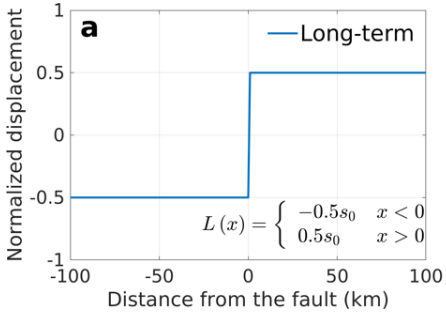
Shallow Slip to account for SSD?

For full plate motion between tectonic plates:
We need postseismic or interseismic shallow fault slip to "balance" the coseismic shallow slip deficit

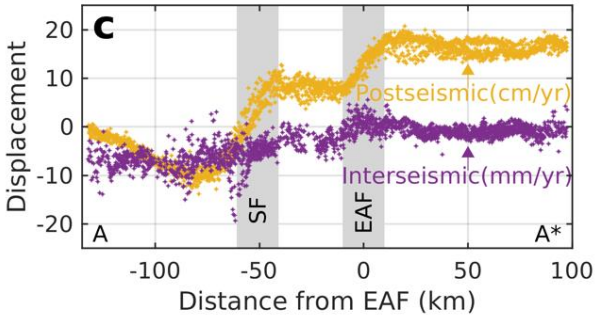


Interseismic rate
(~5 years before)

Postseismic rate
(10 months after)



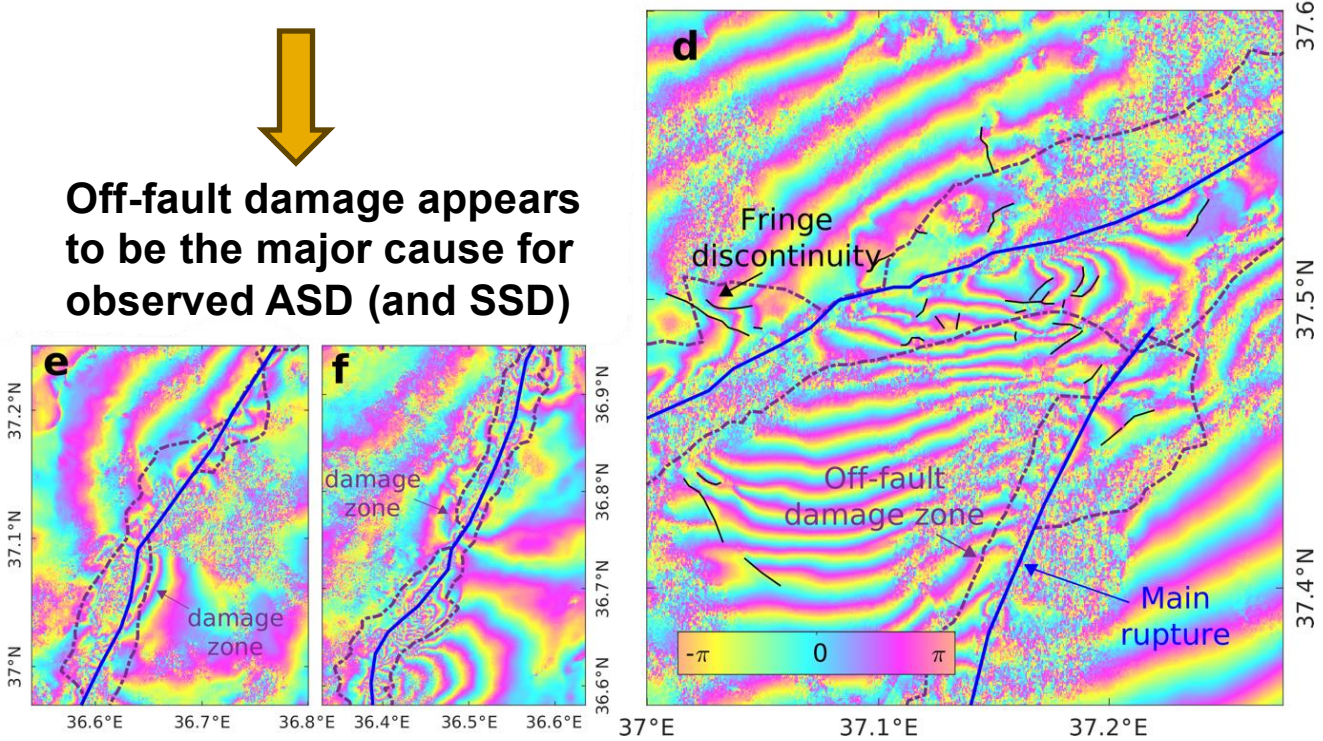
No significant shallow slip



Can Off-Fault Damage explain the ASD?

Evidence in distorted fringes and fringe discontinuities near faults in SAR interferograms

Off-fault damage appears to be the major cause for observed ASD (and SSD)



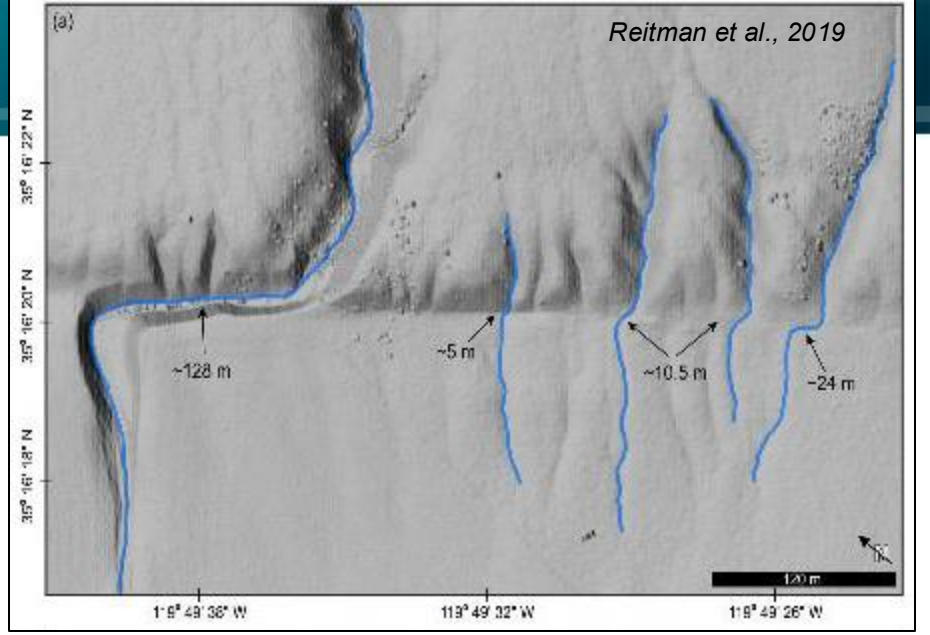
ALOS-2 interferograms:

Regular fringes in far-fault regions due to elastic deformation

Therefore, the absent surface deformation (ASD) is **permanent off-fault damage**

Implications

- Faults move less at the surface than the tectonic plate rate
- Paleo-seismological rates tend to be systematically underestimated
- But are they underestimated by 35%?
- Straight fault sections often have less ASD, more like 0-20%



- Bottom line is that off-fault damage leads to **systematic underestimation** of fault slip rates in paleo-seismology and thus underestimation of earthquake hazard

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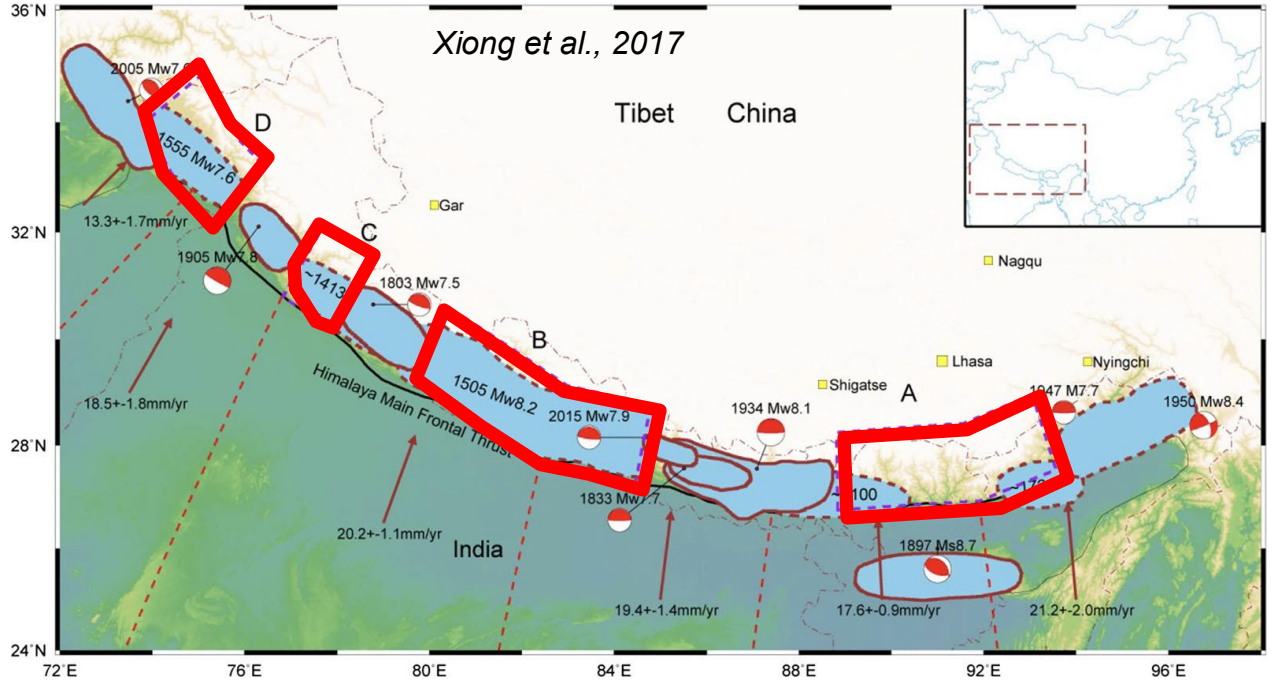
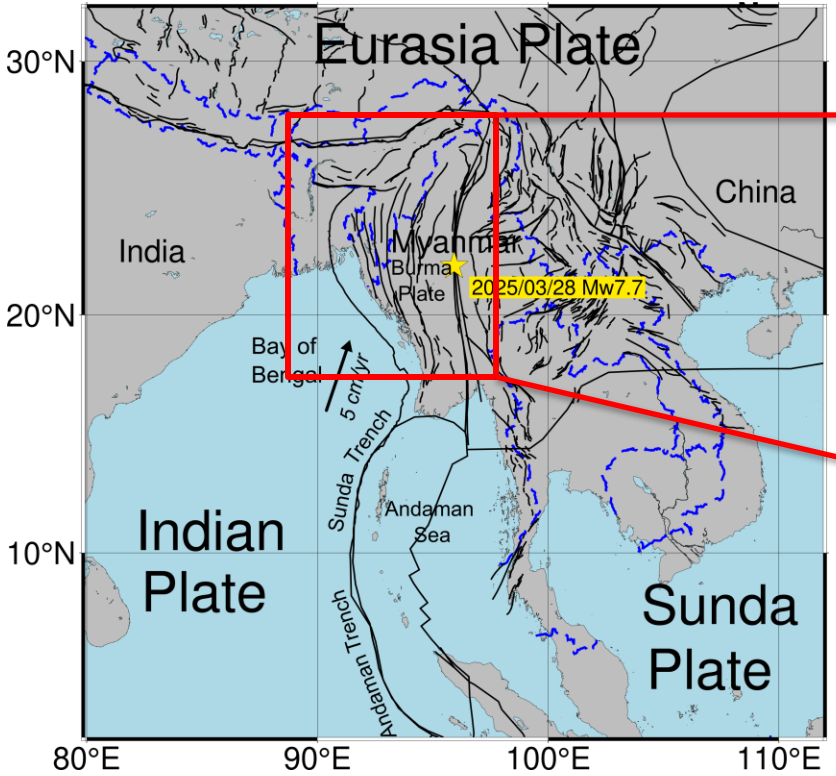
Is the Seismic Gap Hypothesis dead?

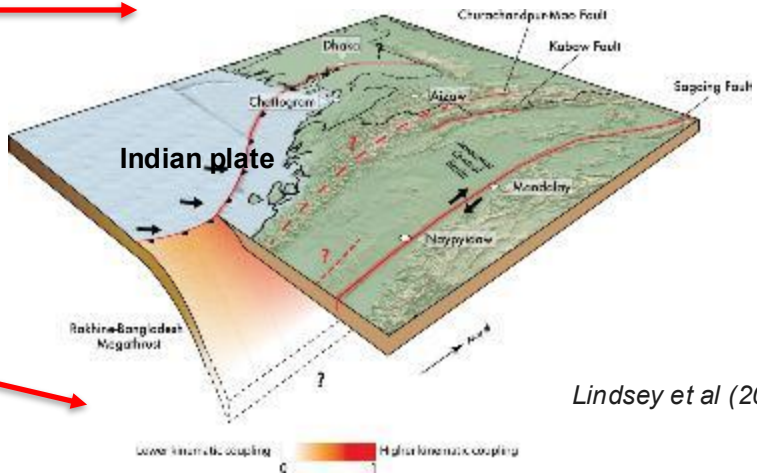
Seismic Gaps



- **Seismic gap** is a section of an active fault that has not experienced a large earthquake for a long time compared to neighboring sections
- Provide approx. locations and size of the next anticipated major earthquakes

The 2025 Mandalay earthquake



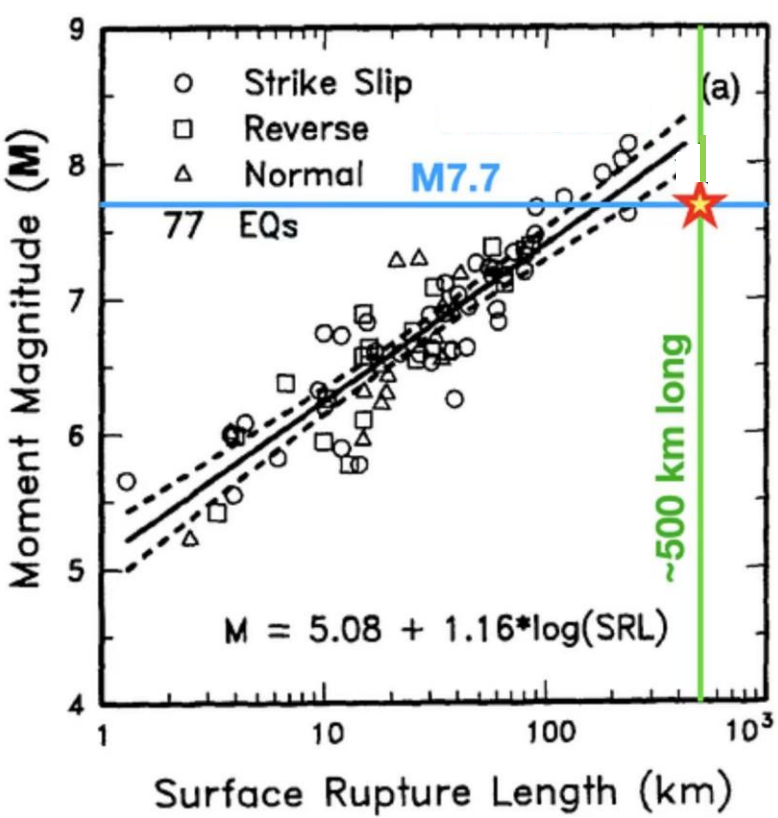


Lindsey et al (2023)

Perspective view of the plates and the slip partitioning onto major active structures.

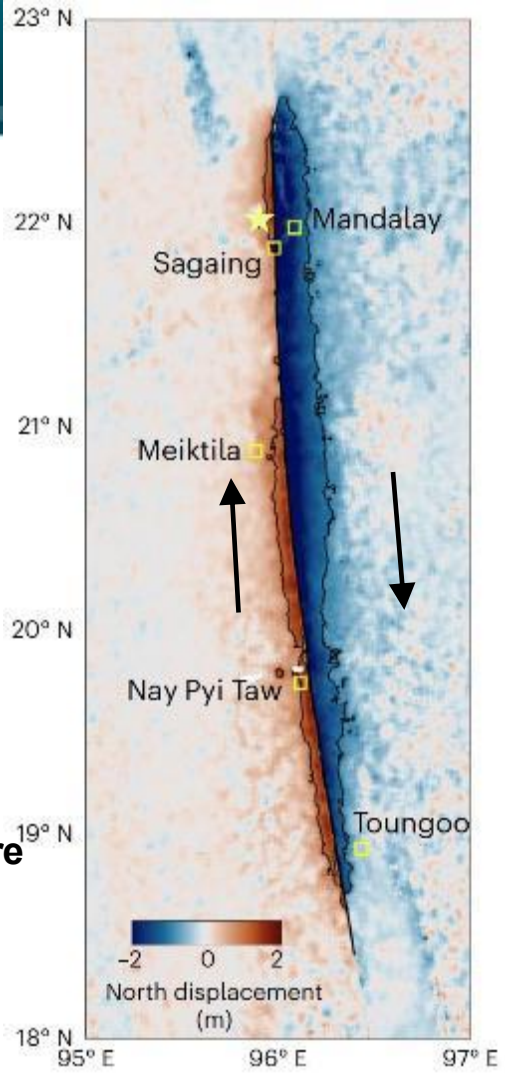
Li, B., S. Jónsson, C. Suhendi, J. Liu, D. Li, A. Delorme, Y. Klinger & P.M. Mai, *Nature Geoscience 18,* 1287-1295, 2025.

Unusual earthquake!



Wells and Coppersmith (1994)

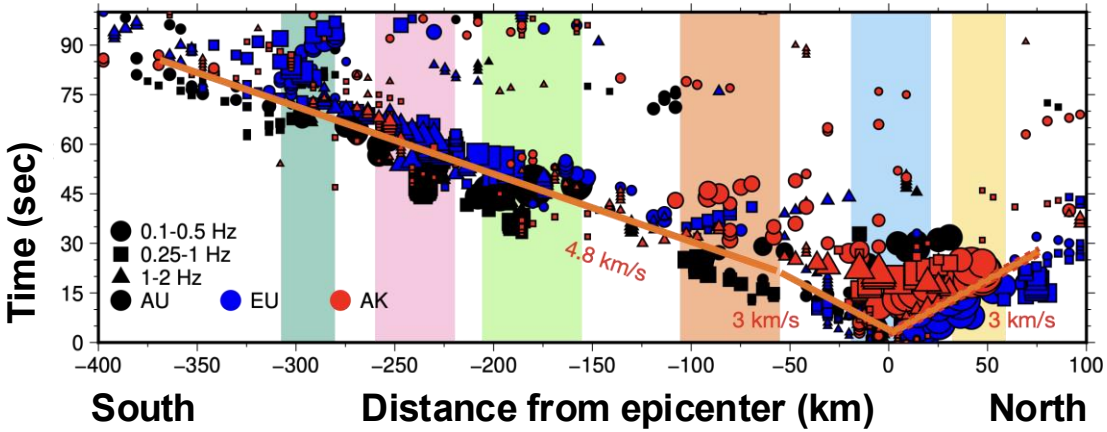
North – South displacements



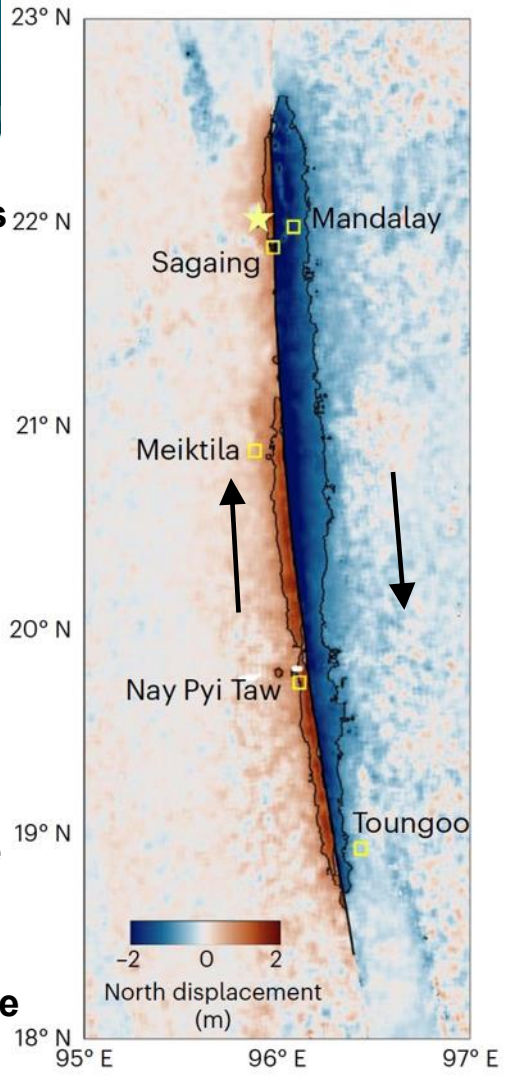
- **Straight, simple fault, asymmetric and local deformation**
- **Very long surface rupture of 460 km**

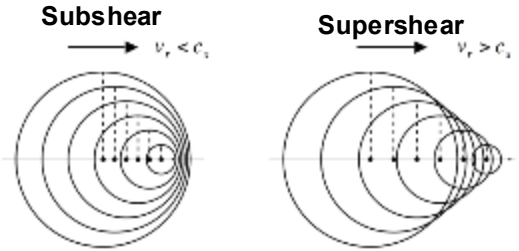
Unusual earthquake!

Back-projection results - different arrays



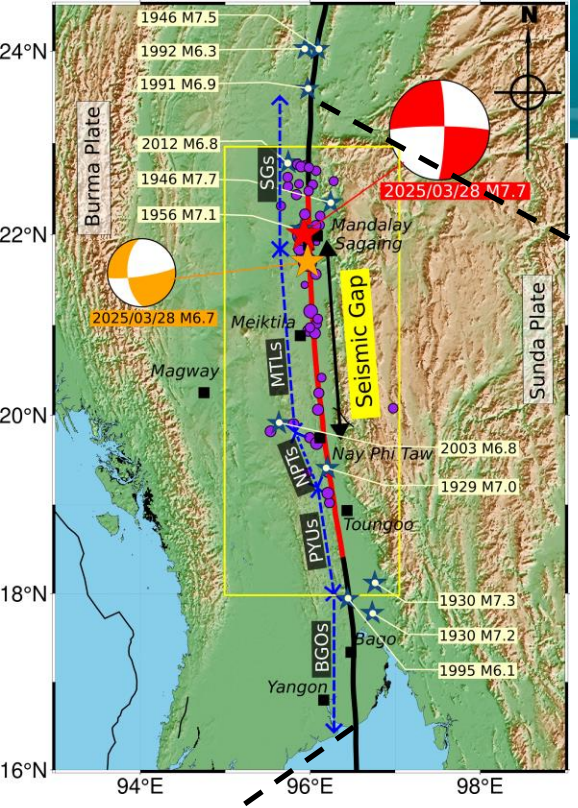
North – South displacements



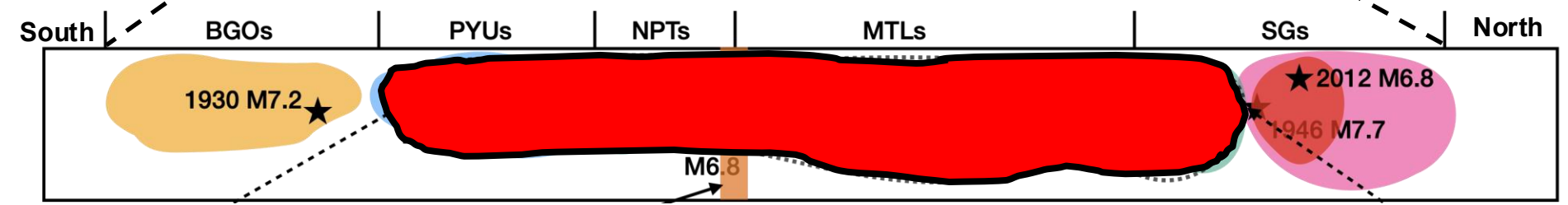


- **Straight, simple fault**, asymmetric and local deformation
- **Very long** surface rupture of 460 km
- **Super-shear rupture** velocity along much of the fault rupture, or ~350 km

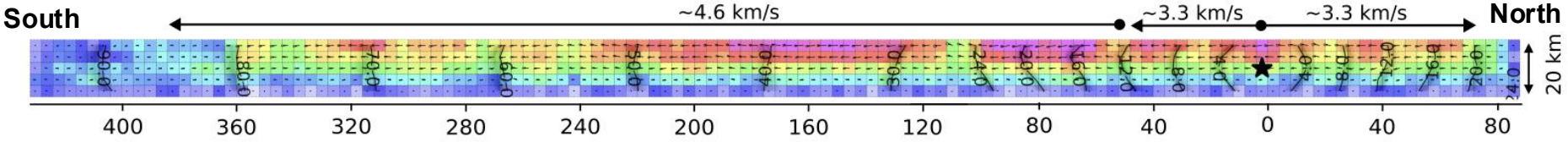
Ruptured a Seismic Gap



- Mandalay earthquake expected
- Seismic gap on Meiktila segment (MTLs) of the Saigang fault
- Last earthquake in 1839
- **However, the 2025 earthquake went far beyond the seismic gap!**
- How could this happen?

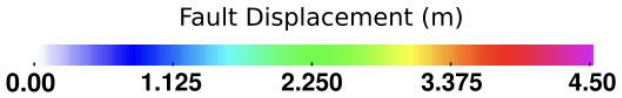


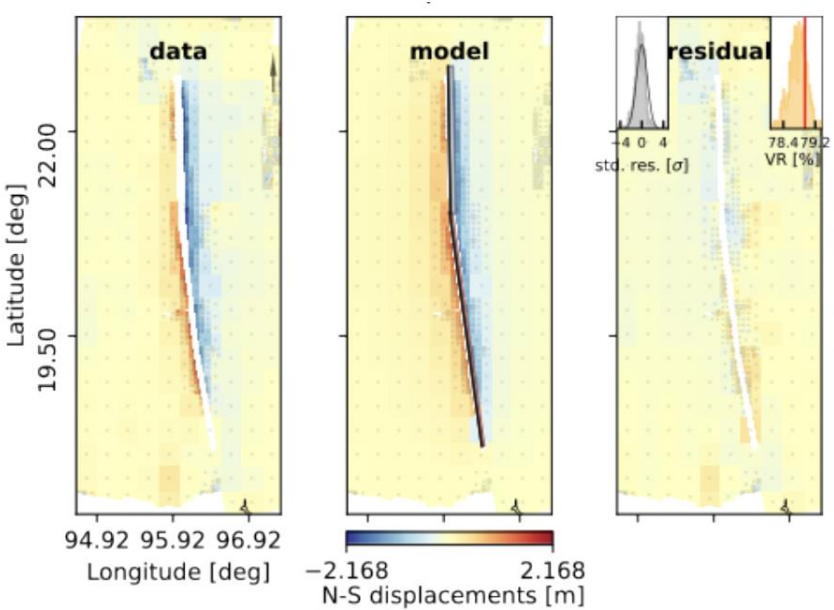
Kinematic Fault Slip Estimation



Finite-fault Slip

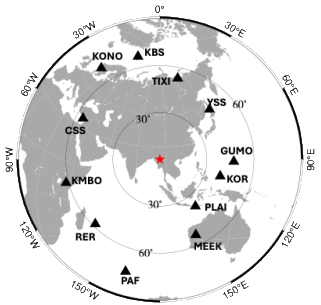
650 subfaults, of 4 x 4 km²

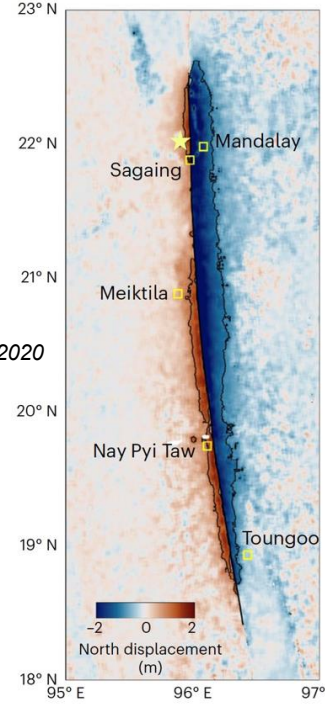




BEAT
BAYESIAN EARTHQUAKE ANALYSIS TOOL

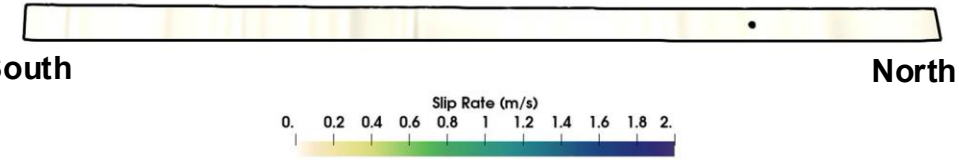
Vasyura-Bathke et al. 2020



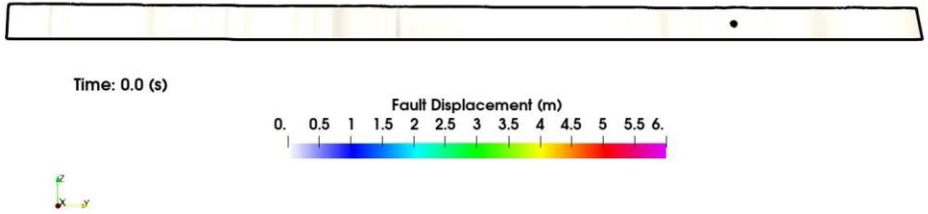


Dynamic Modeling

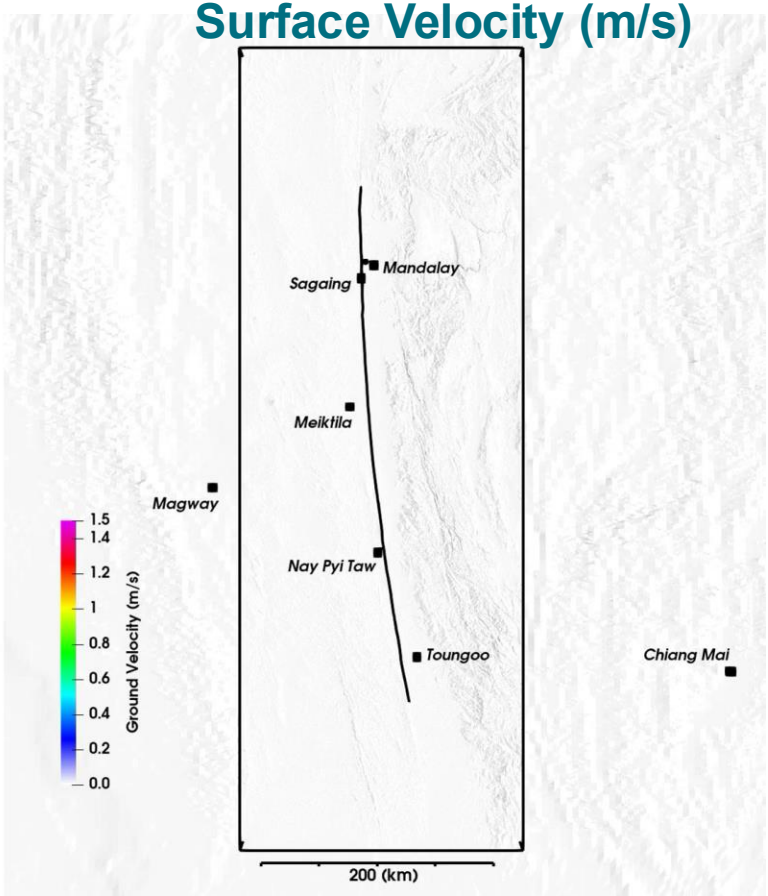
Slip Rate



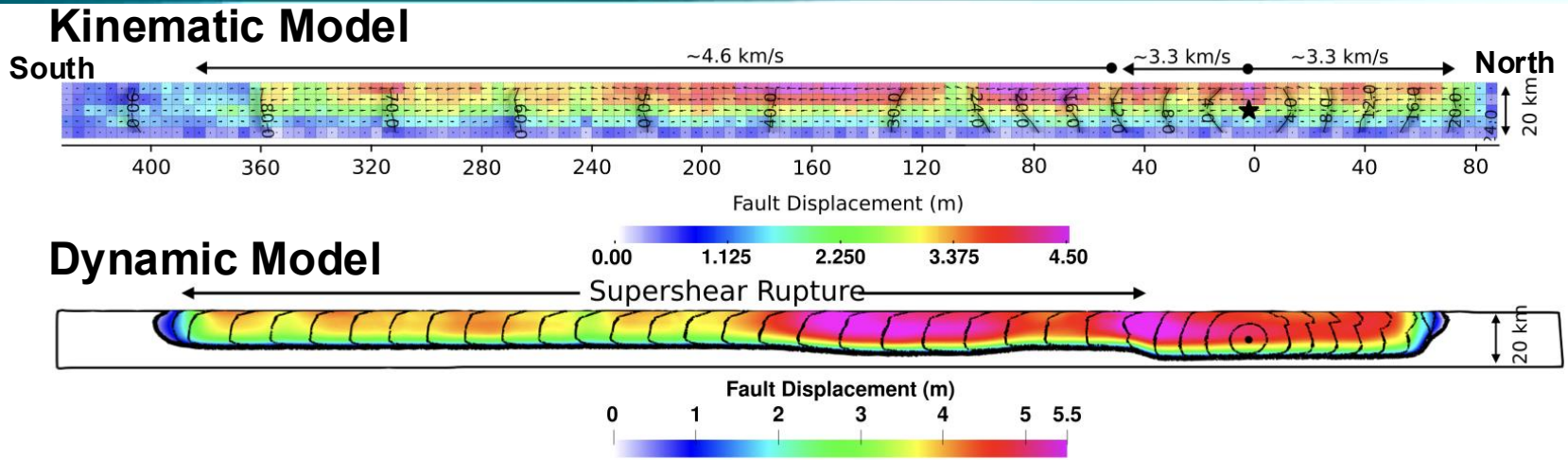
Fault Displacement



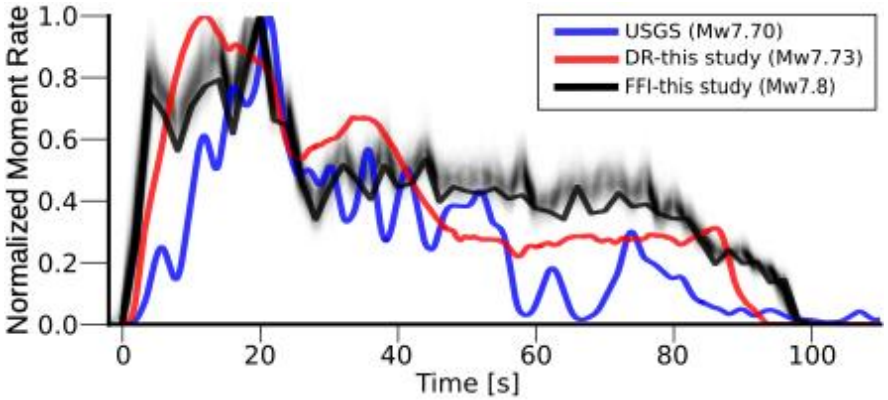
Surface Velocity (m/s)



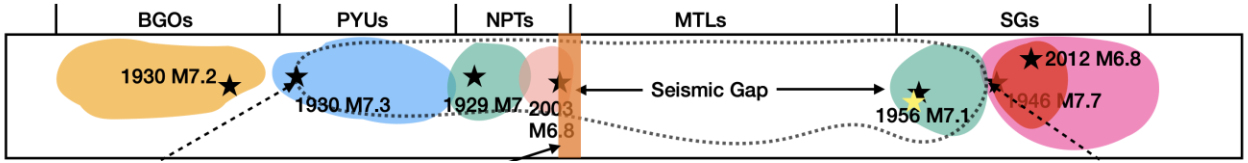
Kinematic vs. Dynamic Modeling



- **Consistent two-phase rupture process**
- **Coherent slip pattern**



But why did it rupture beyond the seismic gap?



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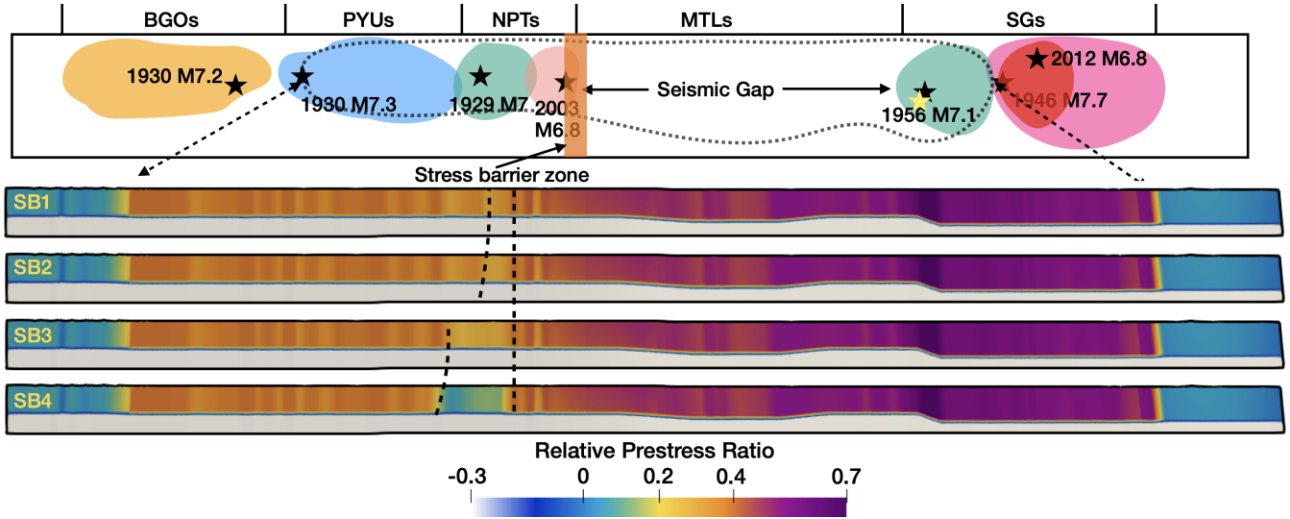
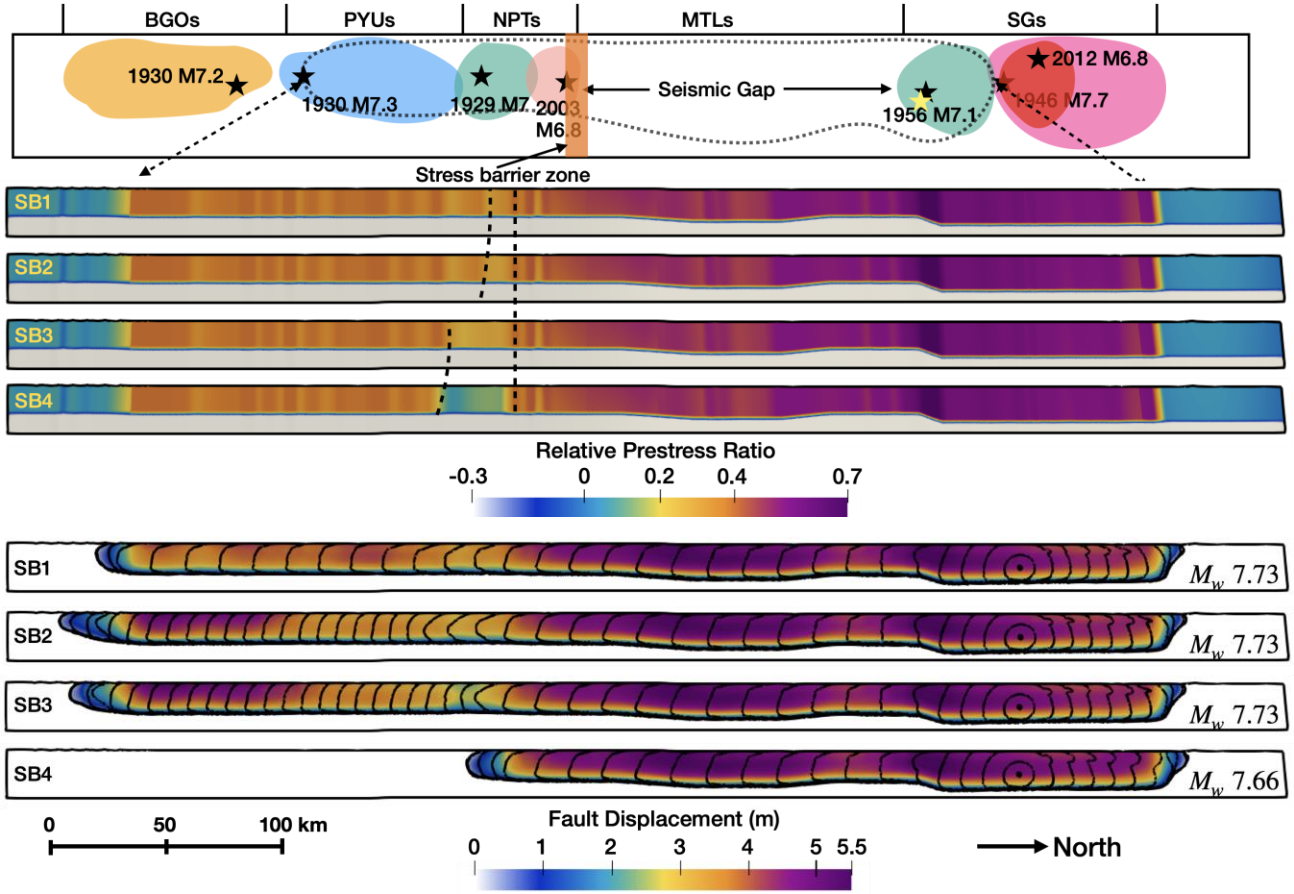


SB1—>SB4: increased stress barrier zone width and decreased prestress loading

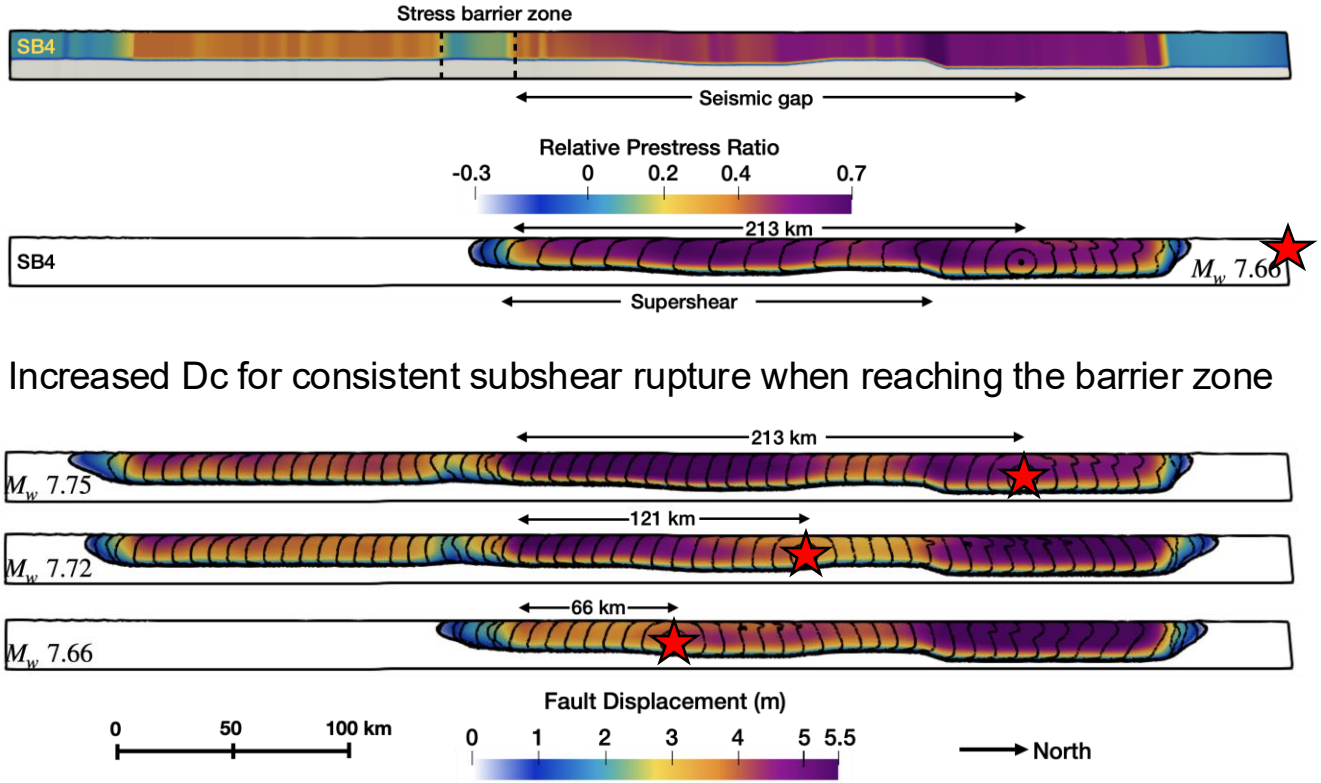
SB1: 9 km width, relative prestress ratio 0.28-0.34
SB2: 11 km width, relative prestress ratio 0.27-0.34
SB3: 23 km width, relative prestress ratio 0.23-0.32
SB4: 33 km width, relative prestress ratio 0.05-0.30

But why did it rupture beyond the seismic gap?



Sustained southward supershear rupture indicates a weak barrier zone

It is not the super-shear velocity

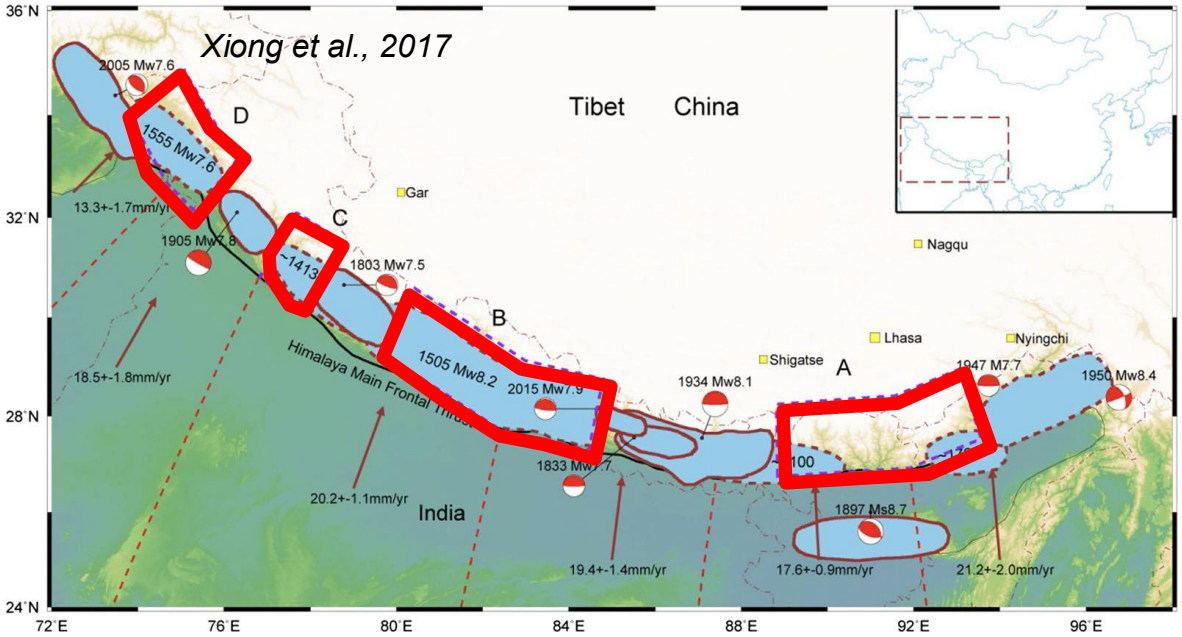


- Given the same prestress conditions, subshear ruptures demonstrate a higher potential to breach the stress barrier than supershear ruptures!

- **Nucleation location far from the gap boundary** produces more dynamic stress loading, critical in driving the rupture beyond the seismic gap

Implications

- Seismic gaps do not necessarily reflect the size of future earthquakes
- Ruptures may cascade into adjacent fault segments, producing unexpectedly large and potentially more destructive events.



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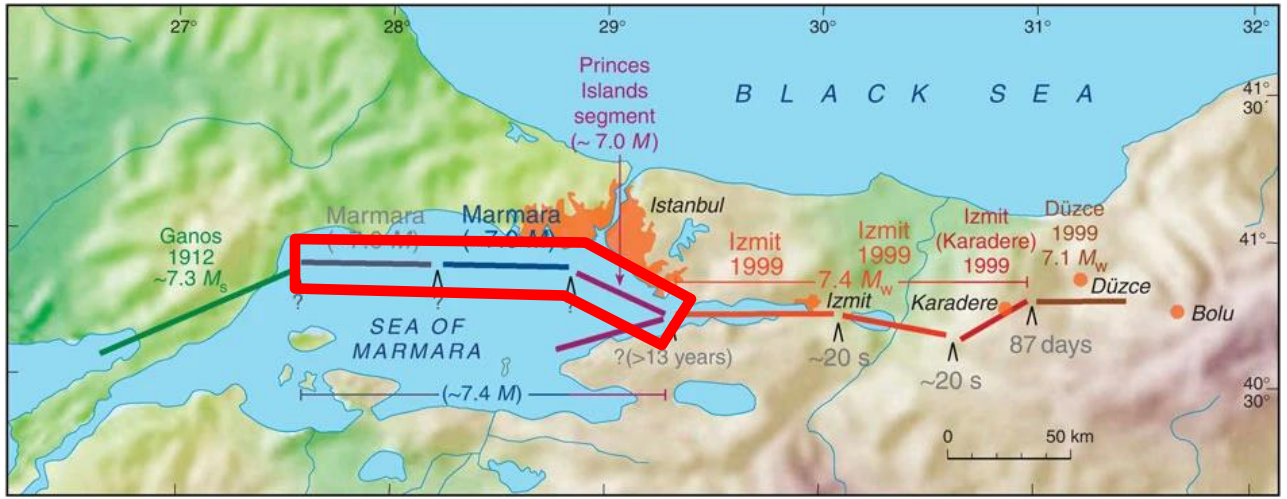
- Ruptures may cascade into adjacent fault segments, producing unexpectedly large and potentially more destructive events.

Marmara Sea (North Anatolian Fault Zone)



(Bohnhoff et al., 2013)

Conclusions

- Large earthquakes produce significant off-fault damage beyond 5 km from the fault -> on-fault slip rates lower than tectonic plate motion
- This means that paleo-seismological slip rates tend to underestimate seismic hazard
- Earthquakes can go far beyond expected magnitude into fault sections we did not expect to rupture soon
- Seismic gaps do not necessarily reflect well the size of future major earthquakes

Bo Li
bo.li.3@kaust.edu.sa

Jihong Liu
jihong.liu@kaust.edu.sa

Published papers for further details

- Li, B., S. Jónsson, C. Suhendi, J. Liu, D. Li, A. Delorme, Y. Klinger & P.M. Mai, Seismic gap breached by the 2025 M_w7.7 Mandalay (Myanmar) earthquake, *Nature Geoscience 18,* 1287-1295*,* 2025.
- Liu, J., S. Jónsson, X. Li, W. Yao & Y. Klinger, Extensive off-fault damage around the 2023 Kahramanmaraş earthquake surface ruptures, *Nature Communications 16:1286,* 2025
- Liu, J., S. Jónsson, X. Li, W. Yao & Y. Klinger, interplate rheological contrast revealed by asymmetric deformation after the 2023 Kahramanmaraş earthquakes, *Nature Communications 17:3182*, 2026

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