Wedge Plasticity, Impulsive Tsunami, and Large Runup Along the Sanriku Coast of Japan

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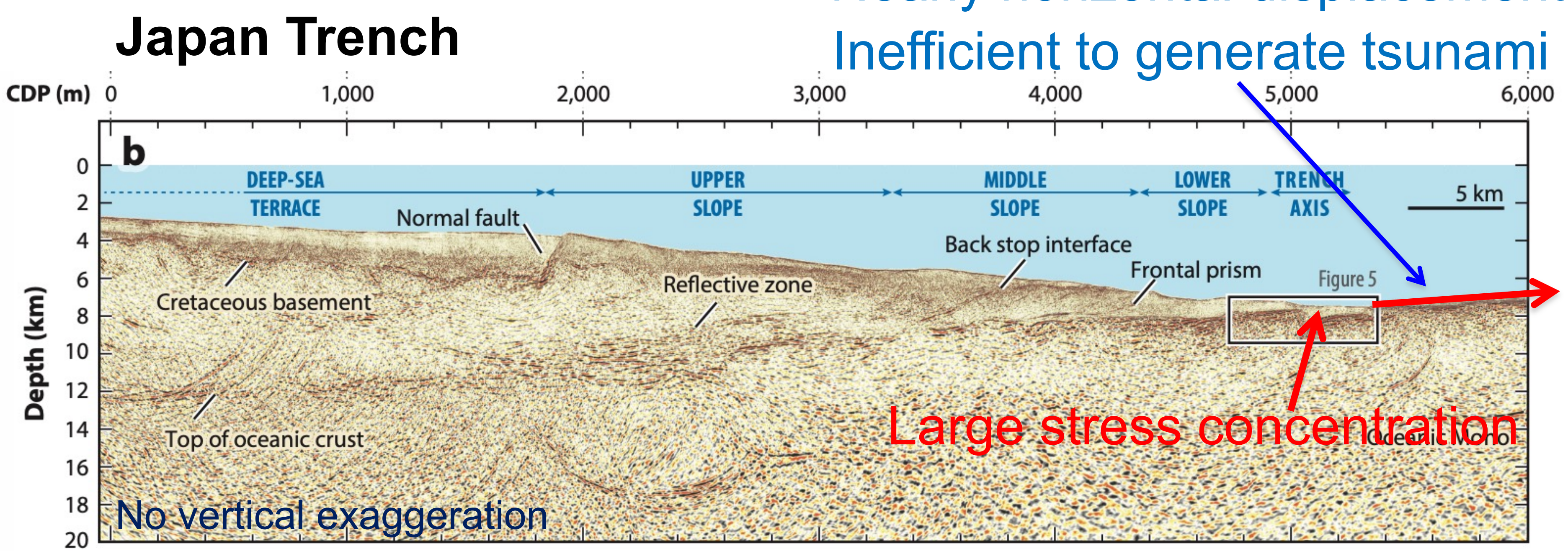
Mechanism for Tsunami Generation: Large Shallow Slip



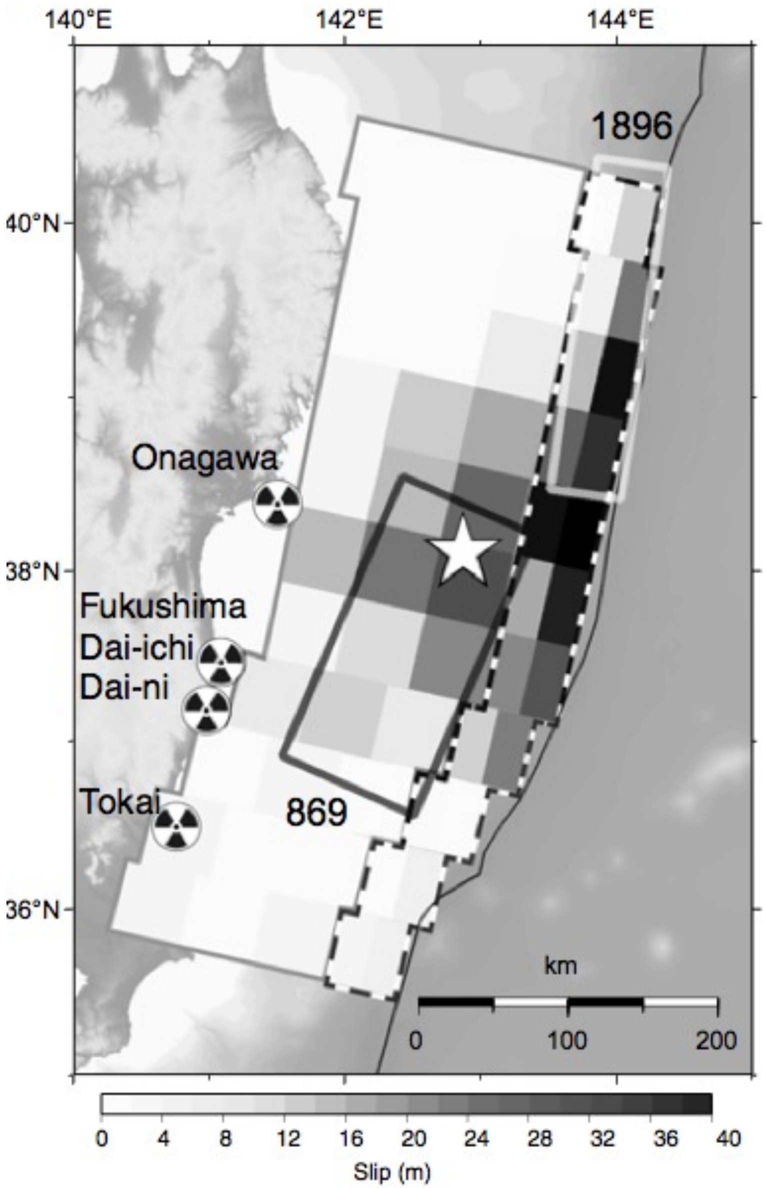
Kodaira et al. (2012)

Elastic dislocation theory gives

$$\text{uplift} \approx \text{slip} \times \sin(\text{dip})$$

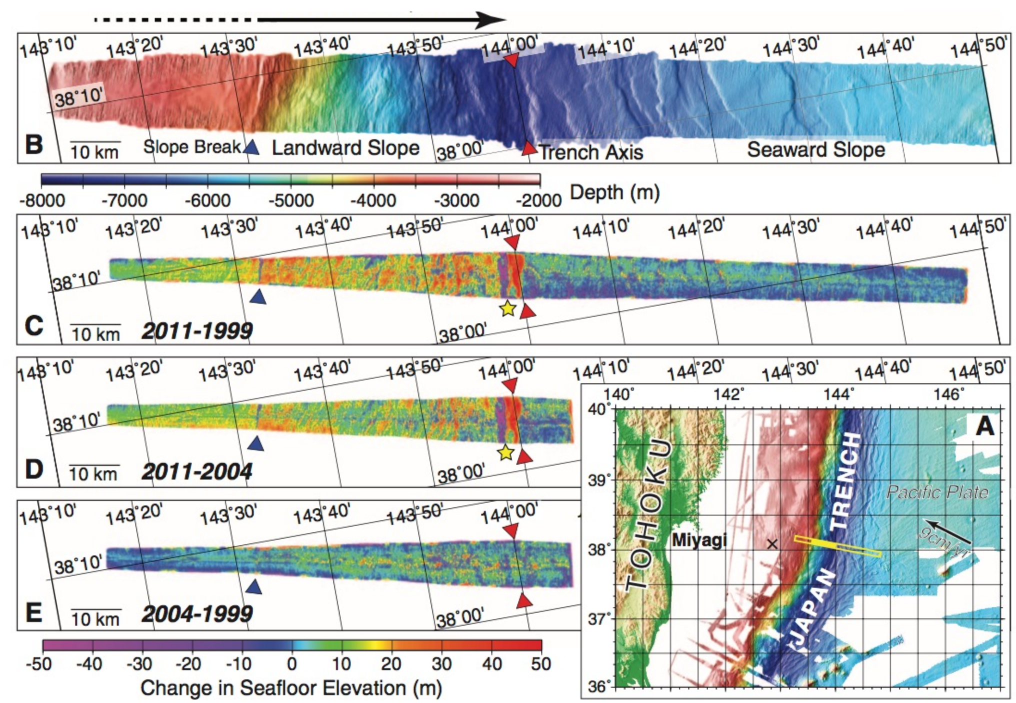
Shallow fault dip ——?——> large slip

Large Near-Trench Slip in the 2011 Tohoku Earthquake



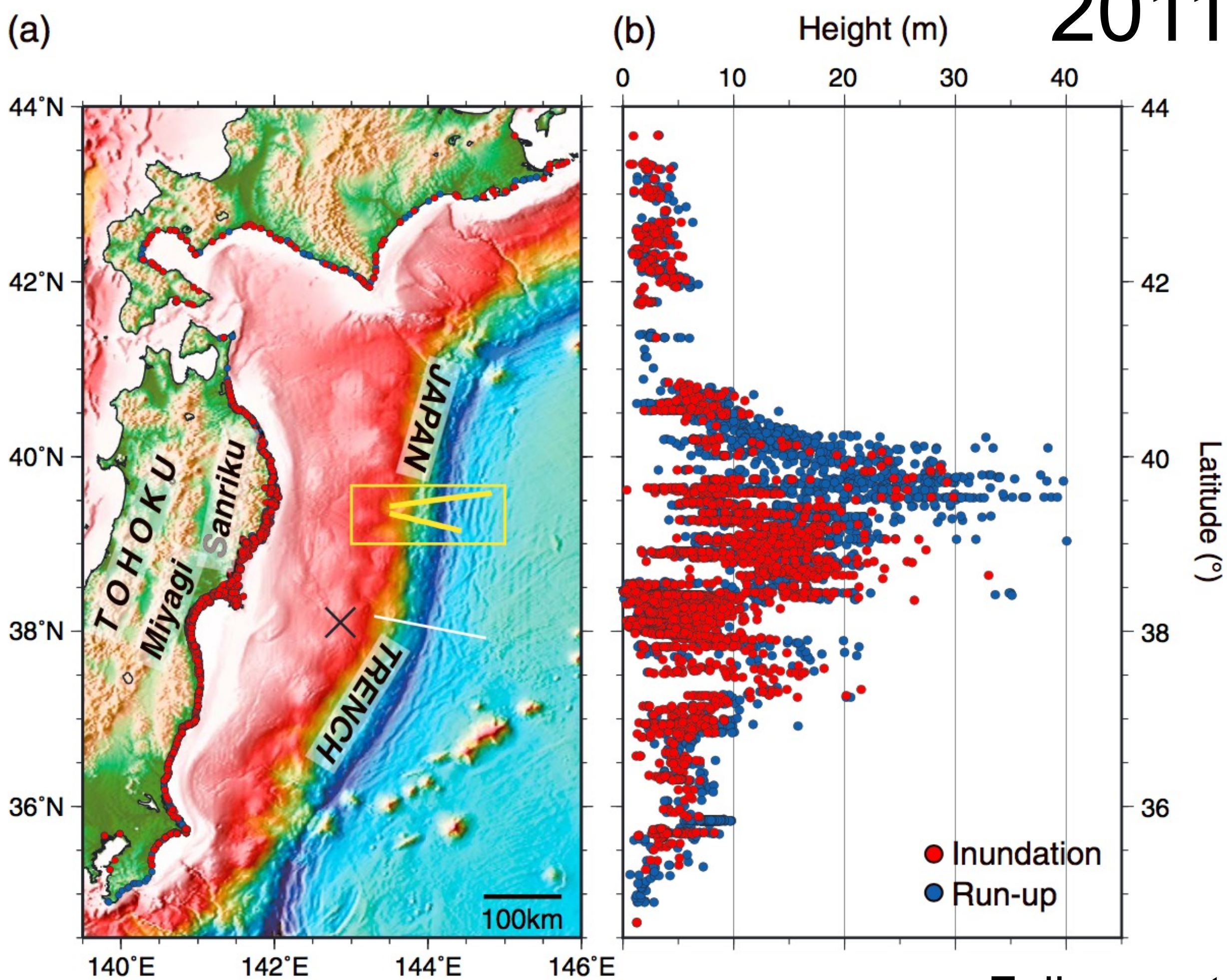
Satake et al. (2013)

50 m horizontal displacement



Fujiwara et al. (2011)

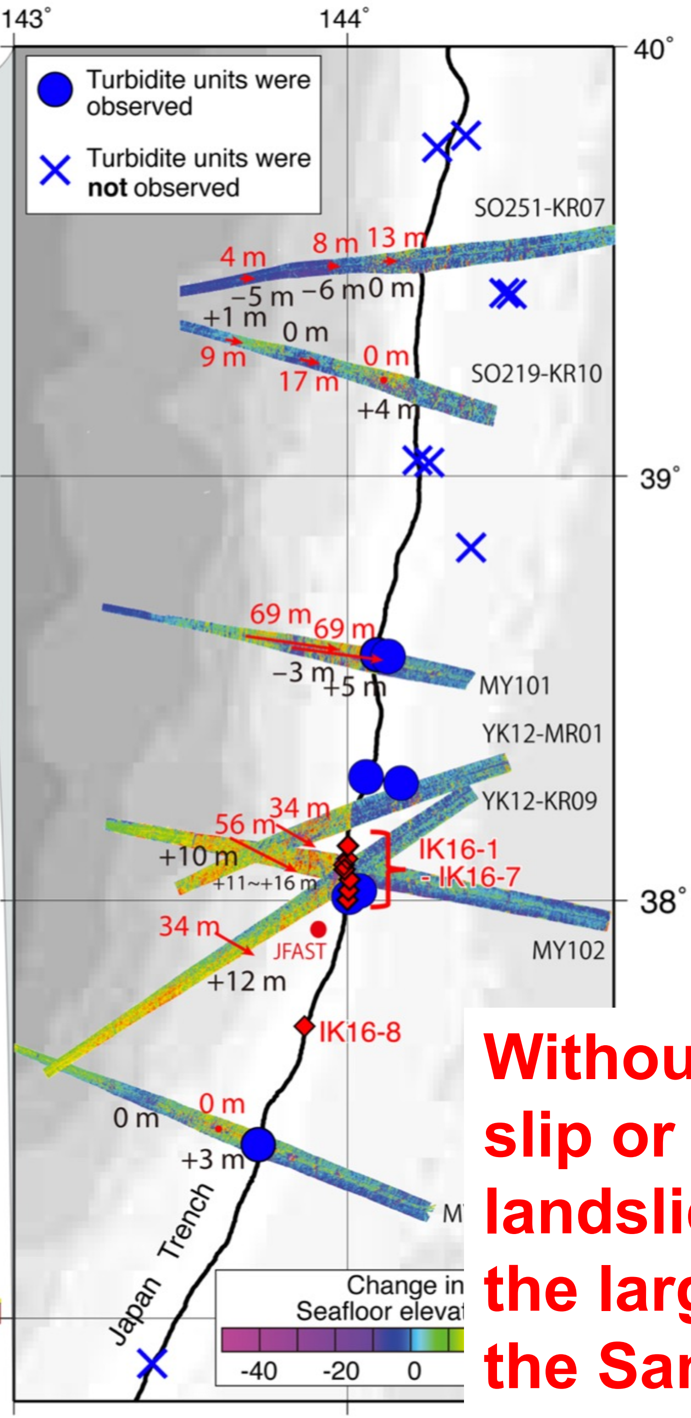
2011 Tohoku Tsunami

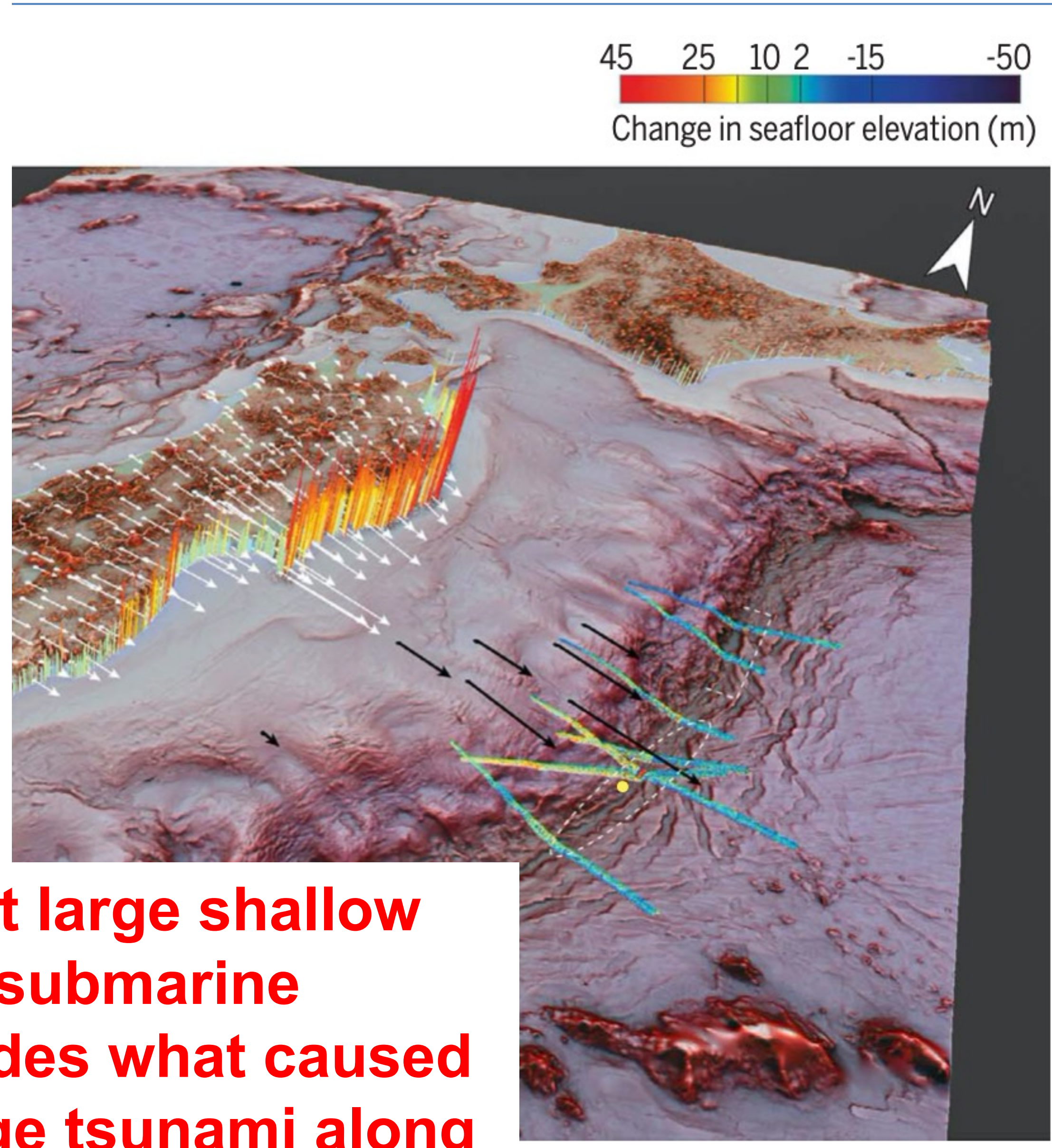


The largest runup occurred along the Sanriku coast (>100 km north of the epicenter).

Fujiwara et al., GRL (2017)

Bathymetry before and after the earthquake in the northern Japan trench indicates <u>no large slip near the trench or submarine landslides</u>.

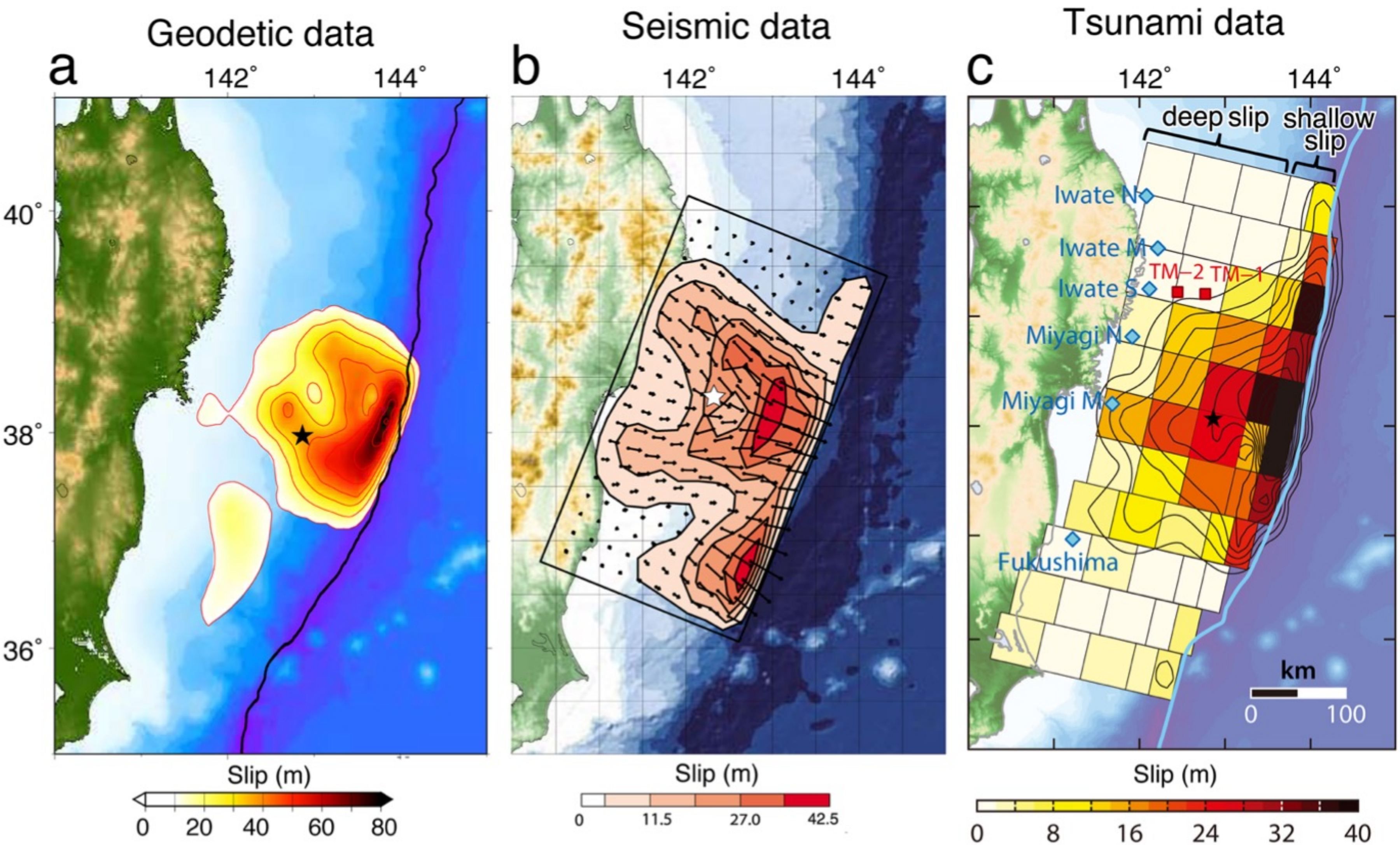




Without large shallow slip or submarine landslides what caused the large tsunami along the Sanriku coast?

Kodaira et al. (2021)

Representative Slip Models of the 2011 Tohoku Earthquake

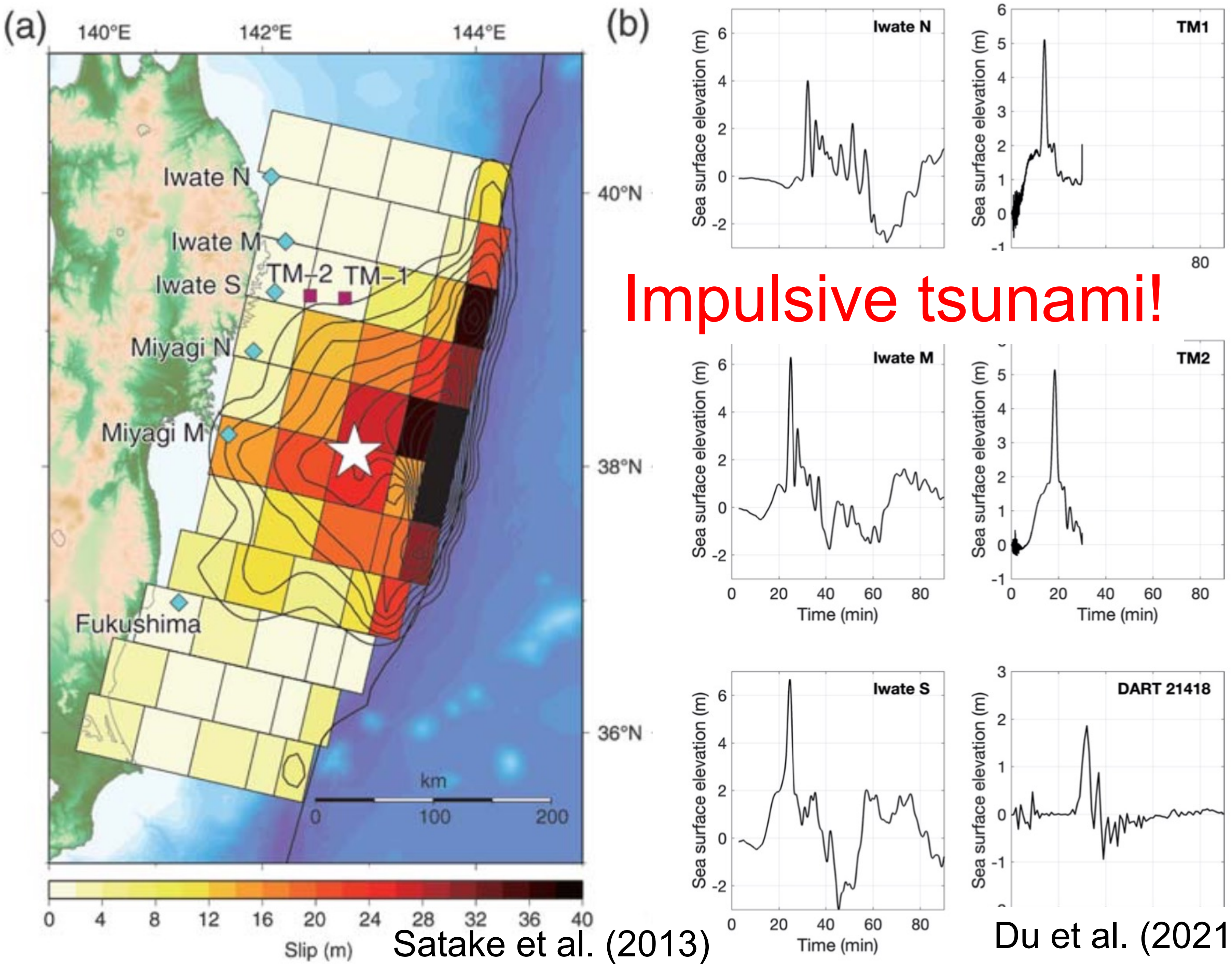


Iinuma et al. (2012)

Lay et al. (2011)

Satake et al. (2013)

From Uchida and Bürgmann (2021)

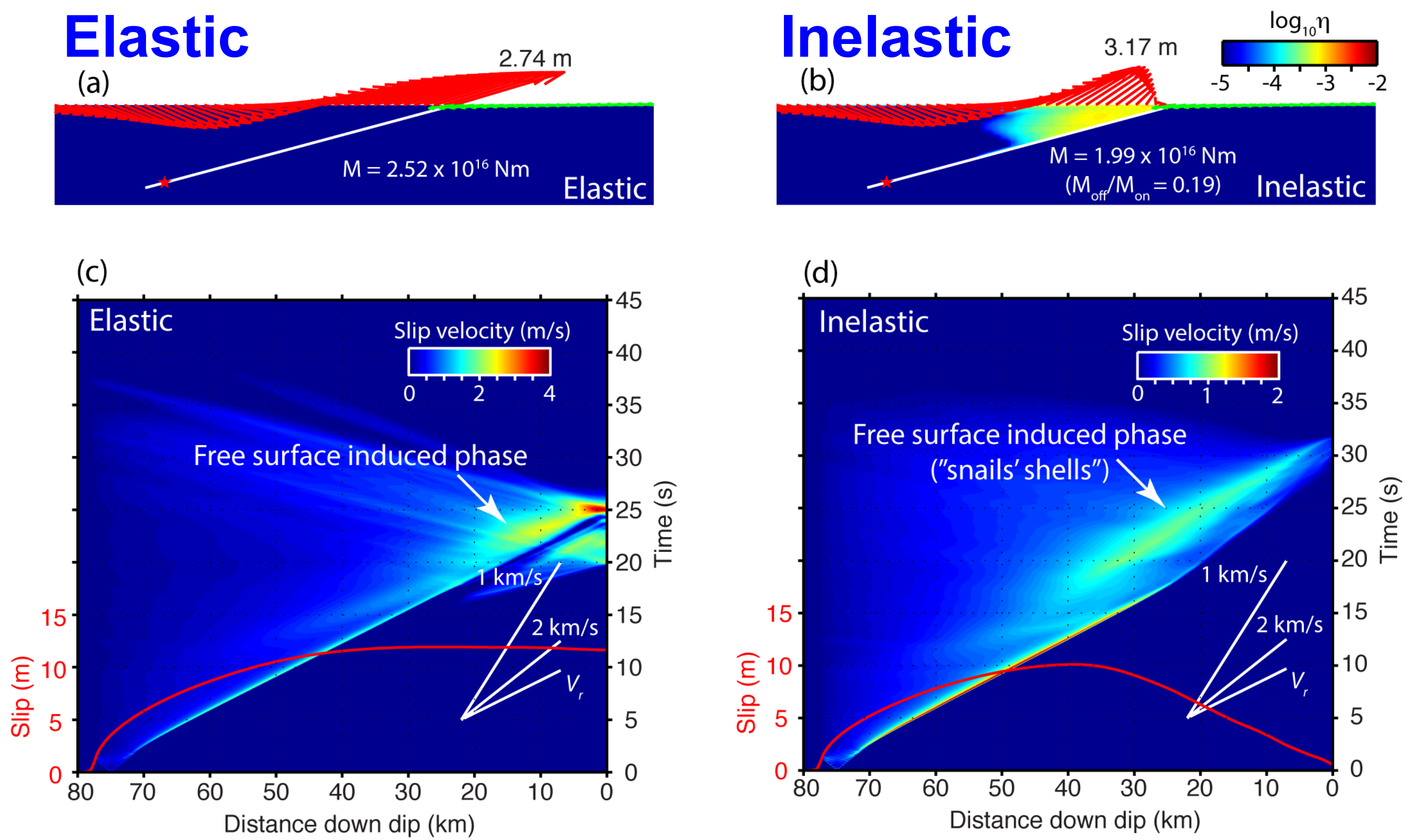


Impulsive tsunami!

Satake et al. (2013)

Du et al. (2021)

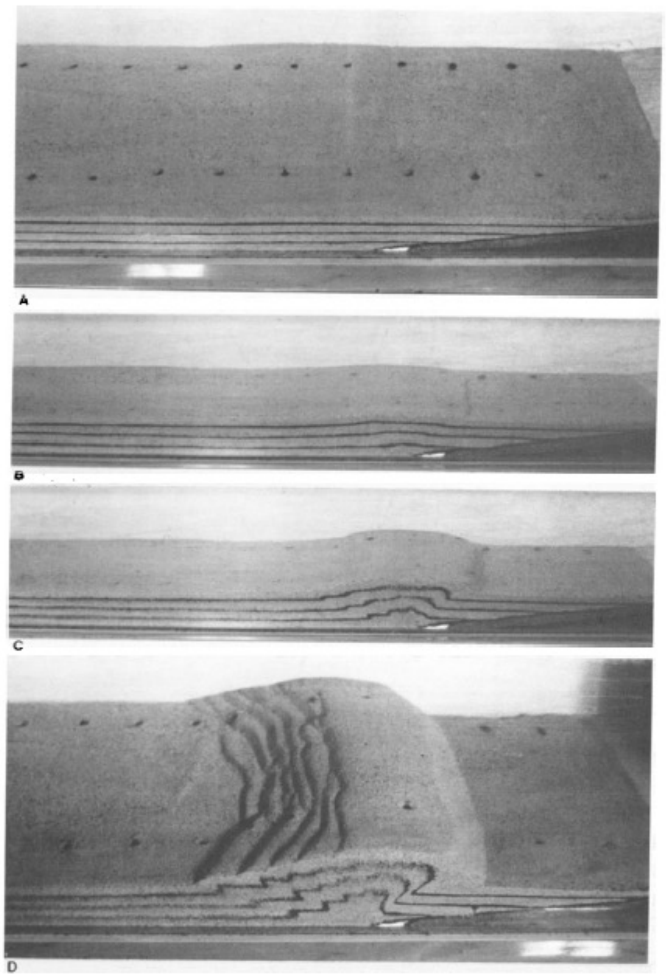
2D Models Incorporating Inelastic Wedge Deformation



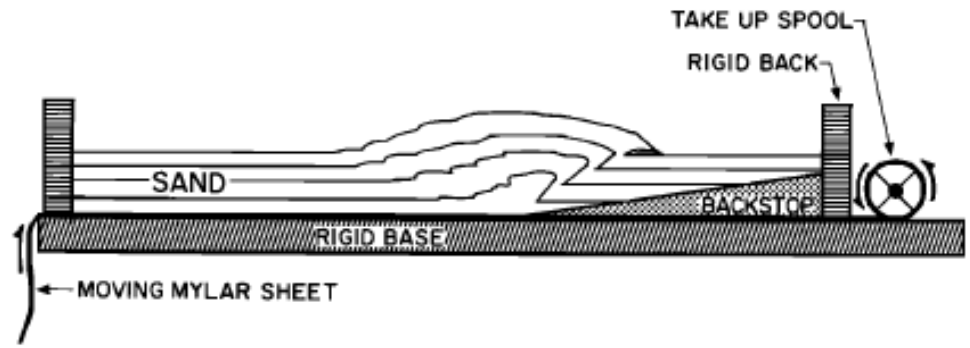
- Inelastic deformation generates tsunami efficiently with diminishing slip on the fault
- Inelastic deformation is a large energy sink that can lead to slow rupture velocity, deficiency in high-frequency radiation, and low energy-to-moment ratio

Ma (2012)
Ma and Hirakawa (2013)

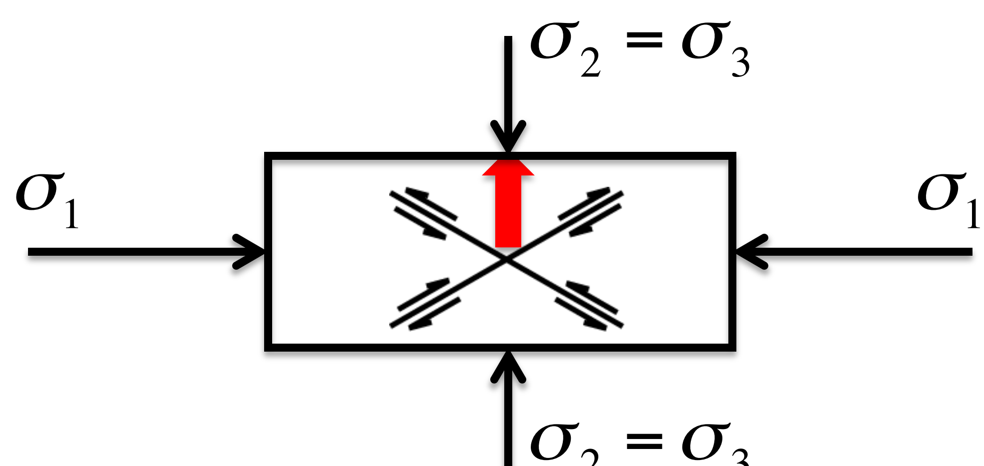
Understanding Inelastic Deformation



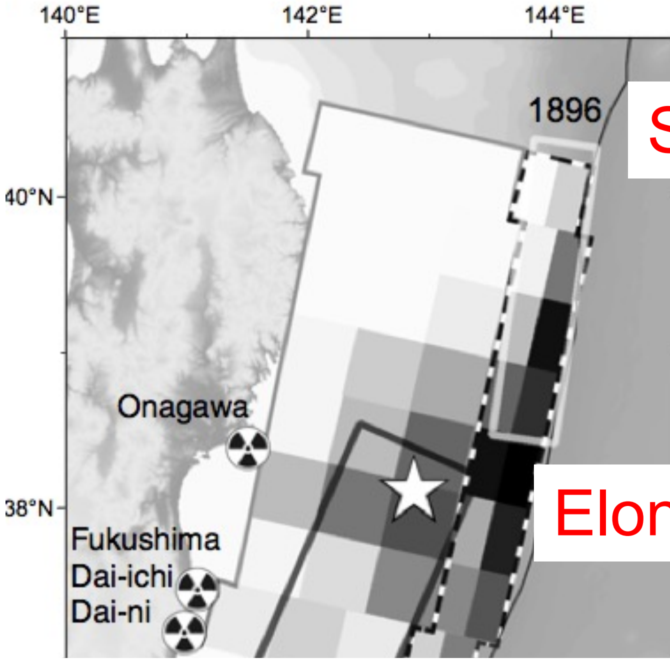
Byrne et al. (1988)

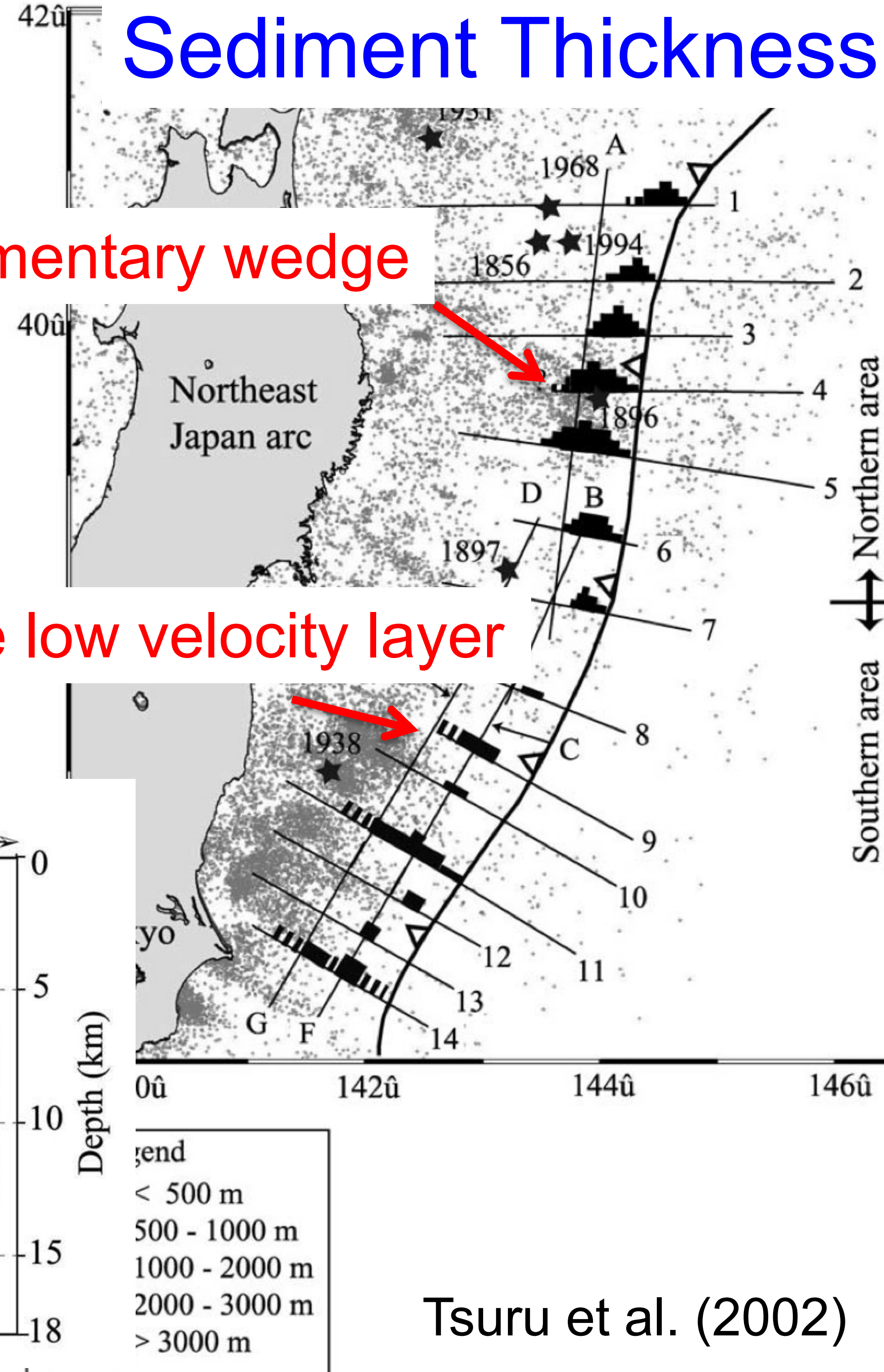


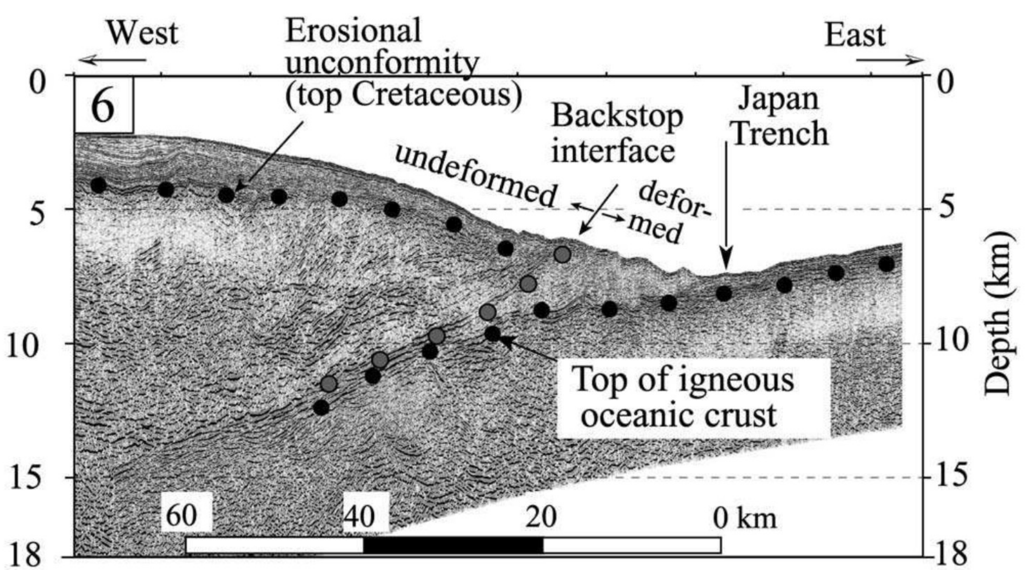
Tri-axial experiment



Sediment Thickness







Tsuru et al. (2002)

Drucker-Prager Yield Criterion

$$\sqrt{\frac{1}{2}s_{ij}s_{ij}} \leq c\,cos\phi - \frac{\sigma_{kk}^{*}}{3}sin\phi$$

Shear stress *Yield stress*

The Closeness-to-Failure

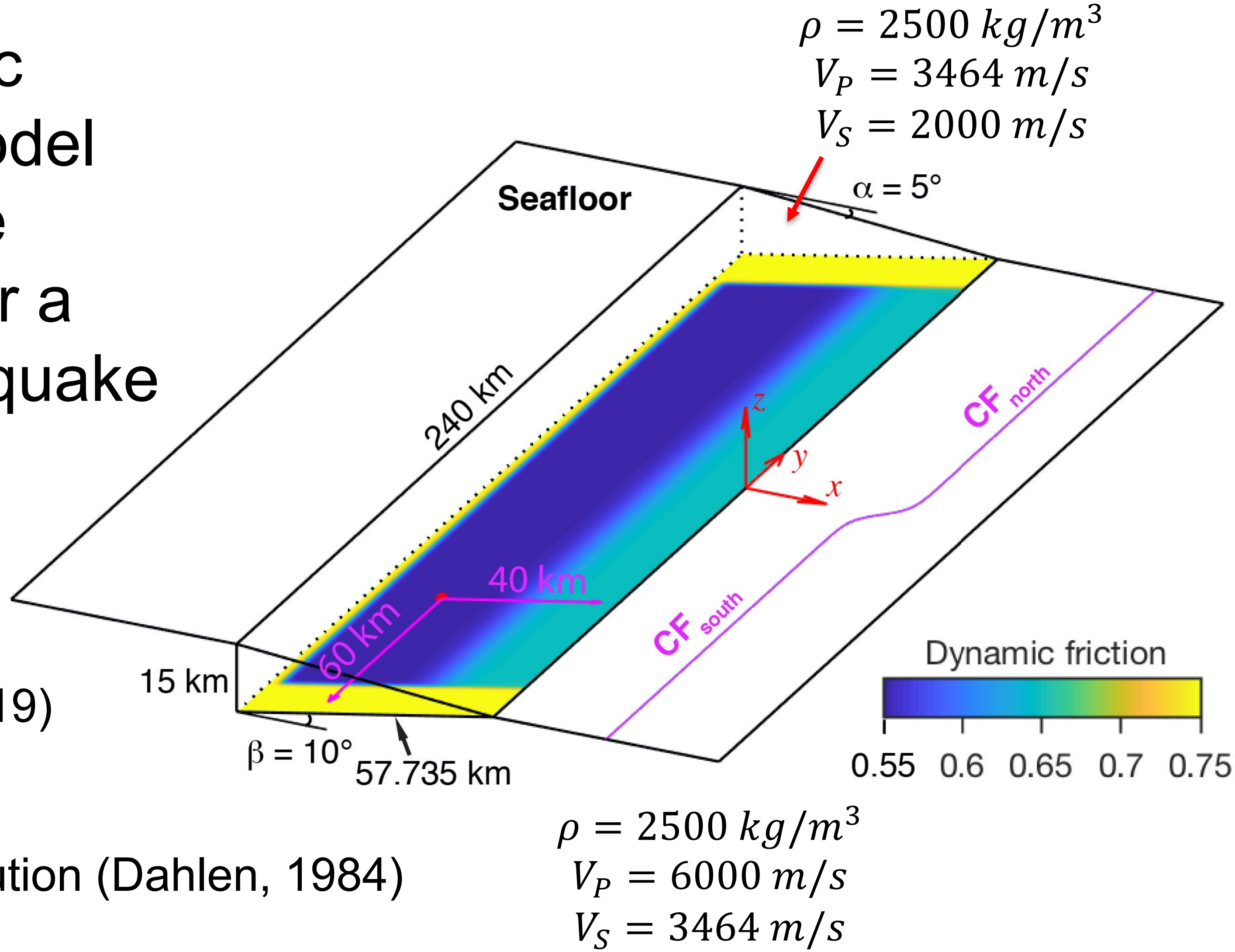
$$CF = \frac{Shear\ stress}{Yield\ stress}$$

s_{ij}: deviatoric stress tensor
c: cohesion (variable, determined by *CF*)
ϕ: internal friction angle

Undrained parameters:

Skempton's coefficient: $B = 0.6$
Biot's coefficient: 0.5

3D Dynamic Rupture Model with Wedge Plasticity for a M_w 8 Earthquake



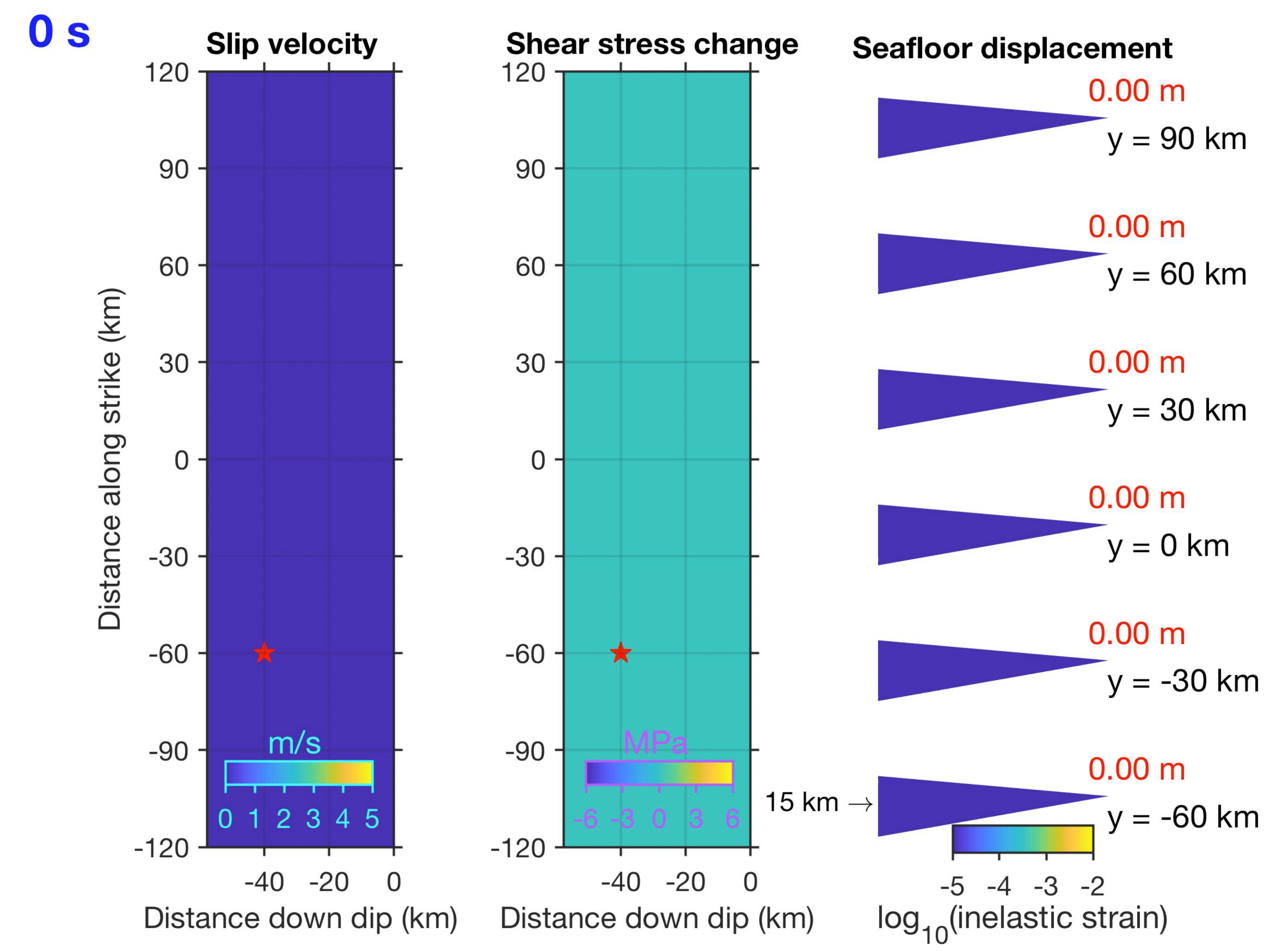
Ma and Nie (2019)

Critical stress solution (Dahlen, 1984)

Element size: 250 m

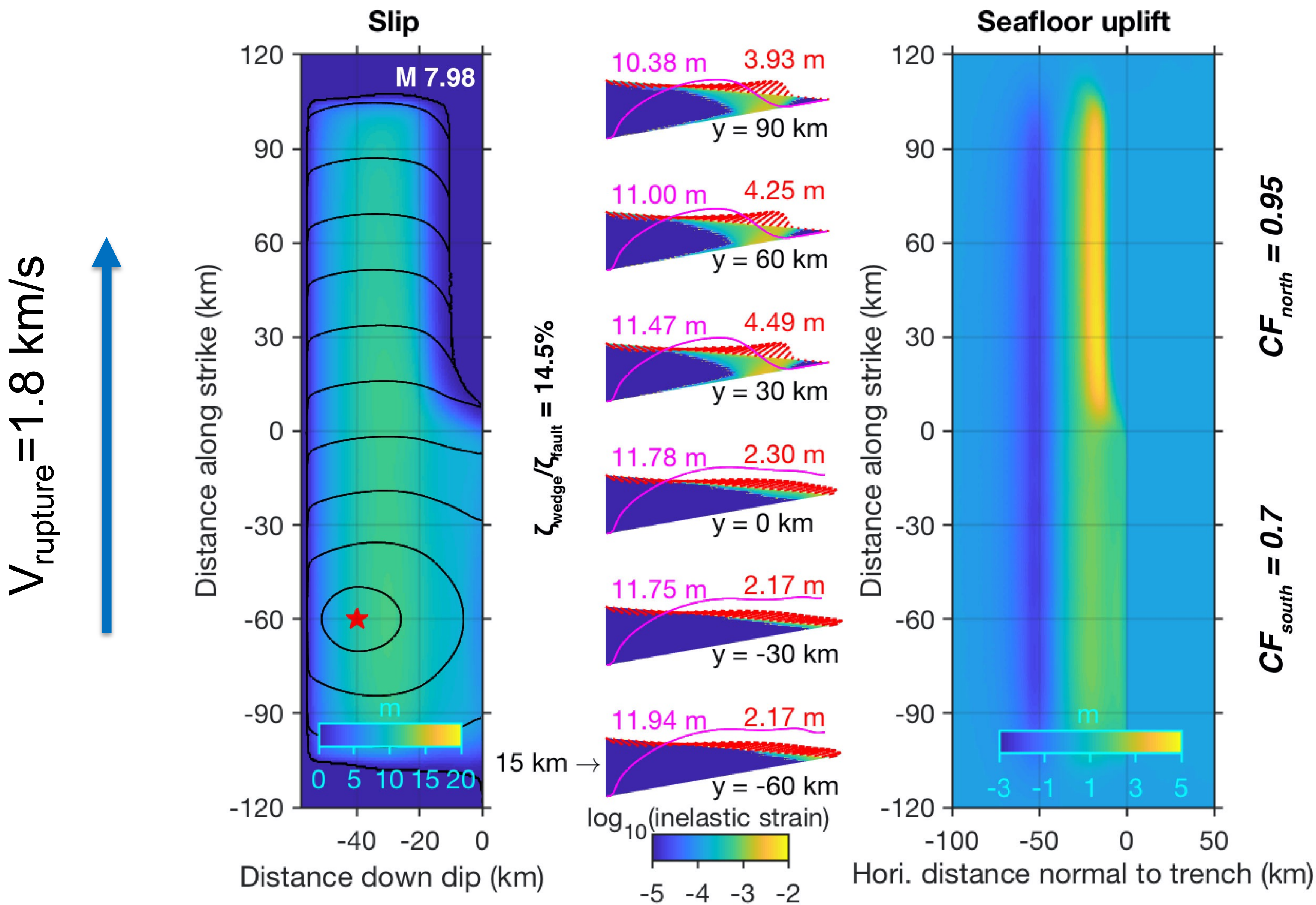
The time-weakening friction

Initial friction: 0.6
Static friction: 0.75
Characteristic weakening time: 0.375 s

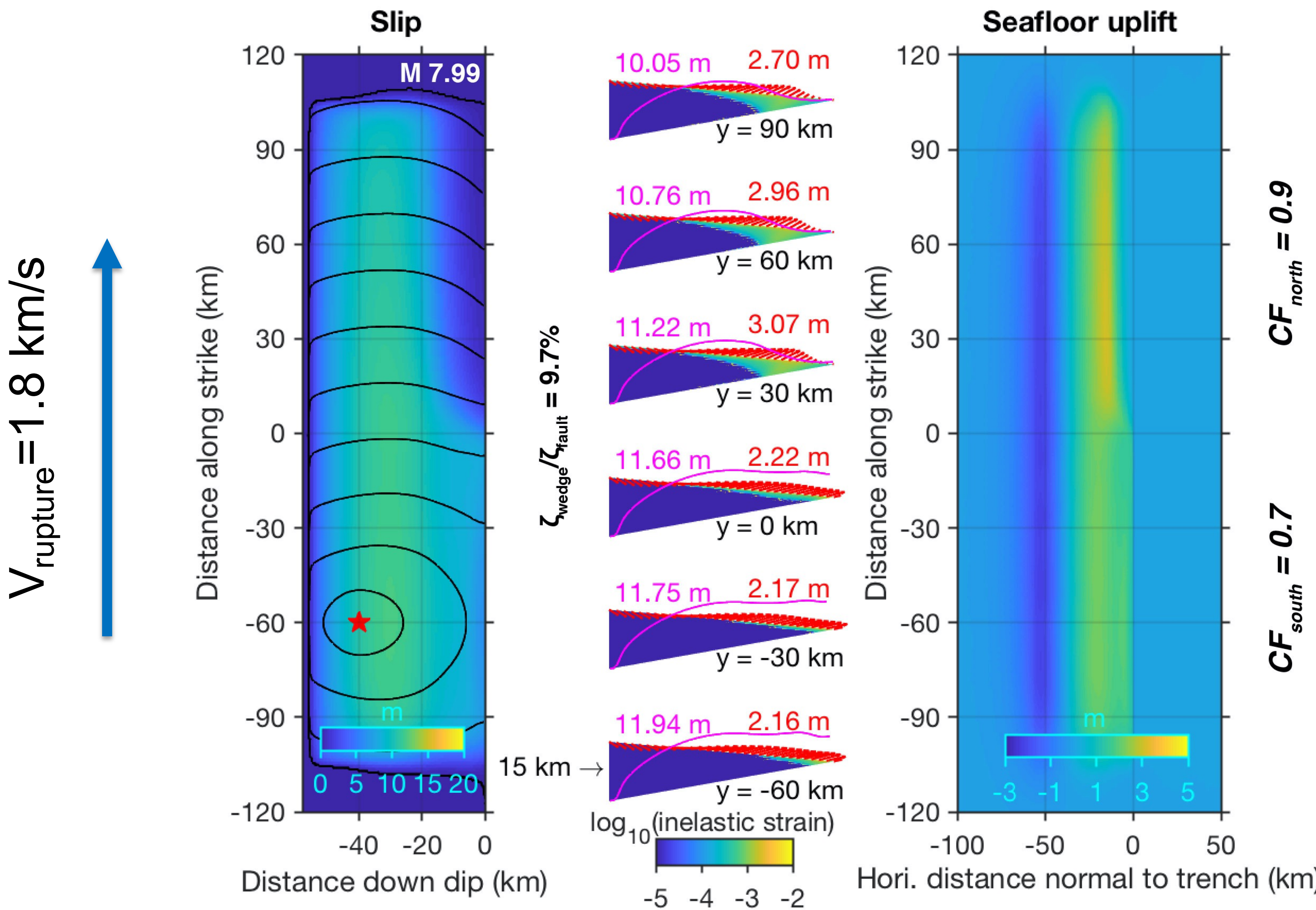


0 s
Slip velocity
Shear stress change
Seafloor displacement
Distance along strike (km)
120
90
60
30
0
-30
-60
-90
-120
m/s
0 1 2 3 4 5
MPa
-6 -3 0 3 6
-40 -20 0
Distance down dip (km)
0.00 m
y = 90 km
0.00 m
y = 60 km
0.00 m
y = 30 km
0.00 m
y = 0 km
0.00 m
y = -30 km
0.00 m
y = -60 km
15 km →
-5 -4 -3 -2
log10(inelastic strain)

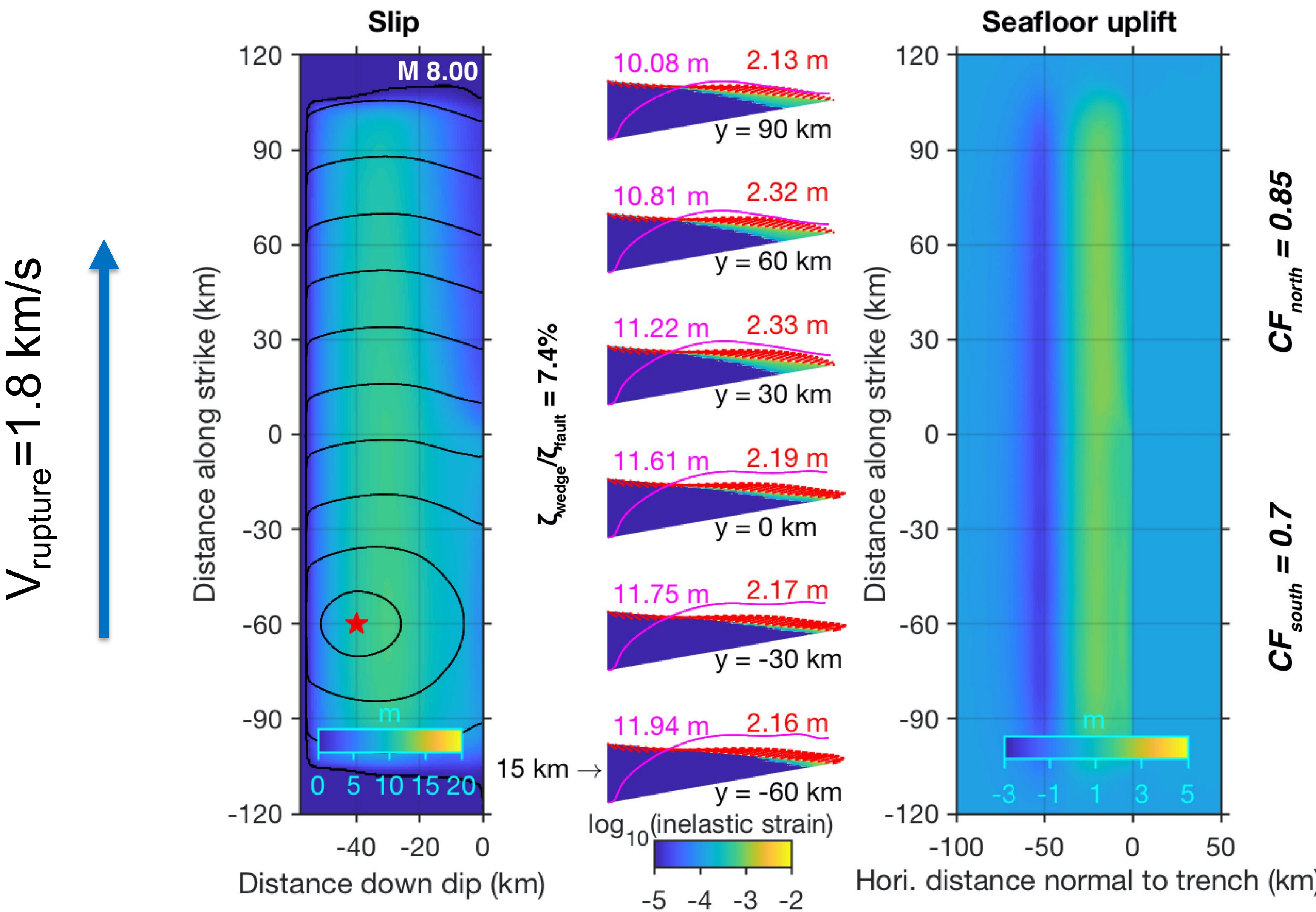
Final Slip and Seafloor Displacement



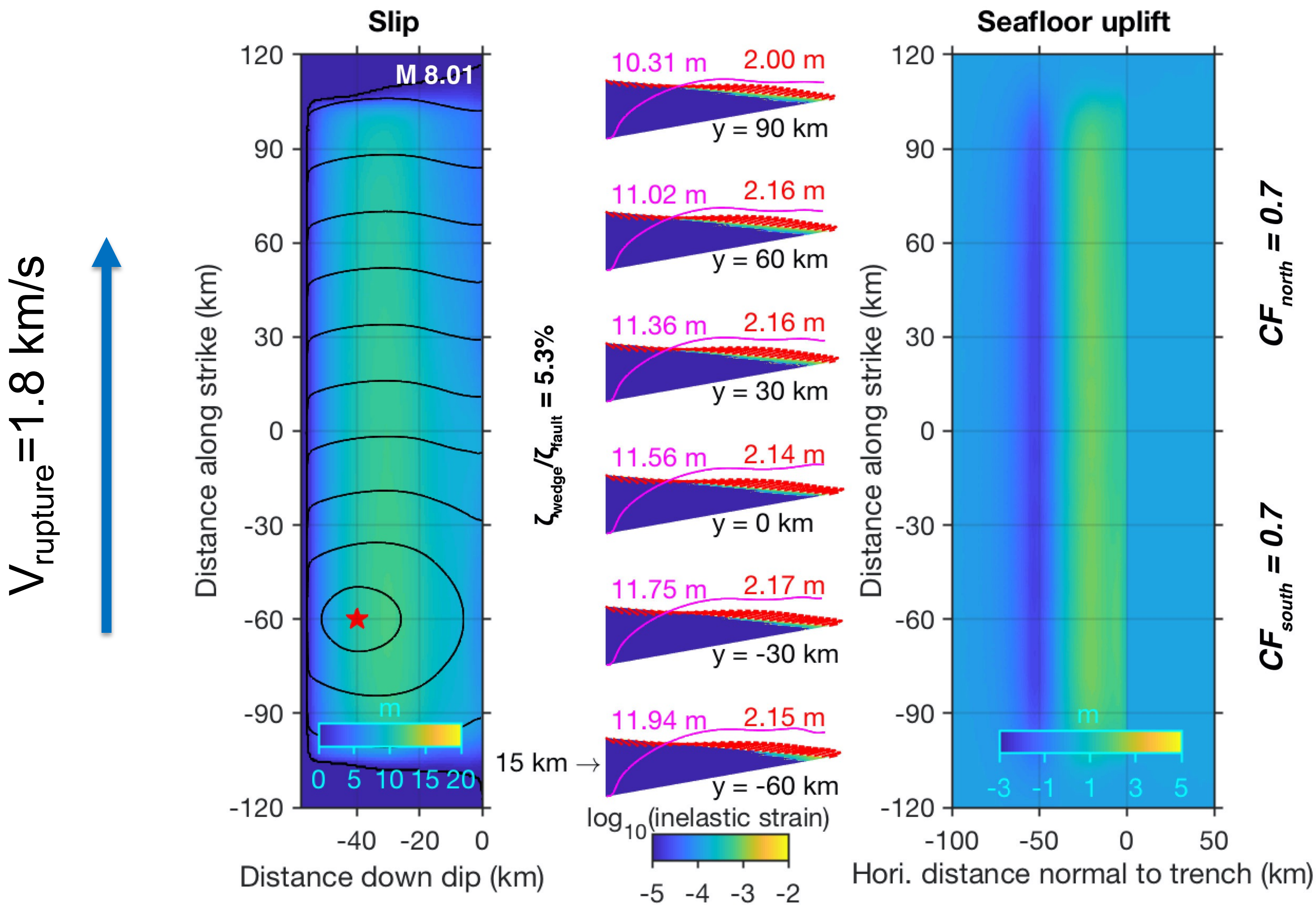
Final Slip and Seafloor Displacement



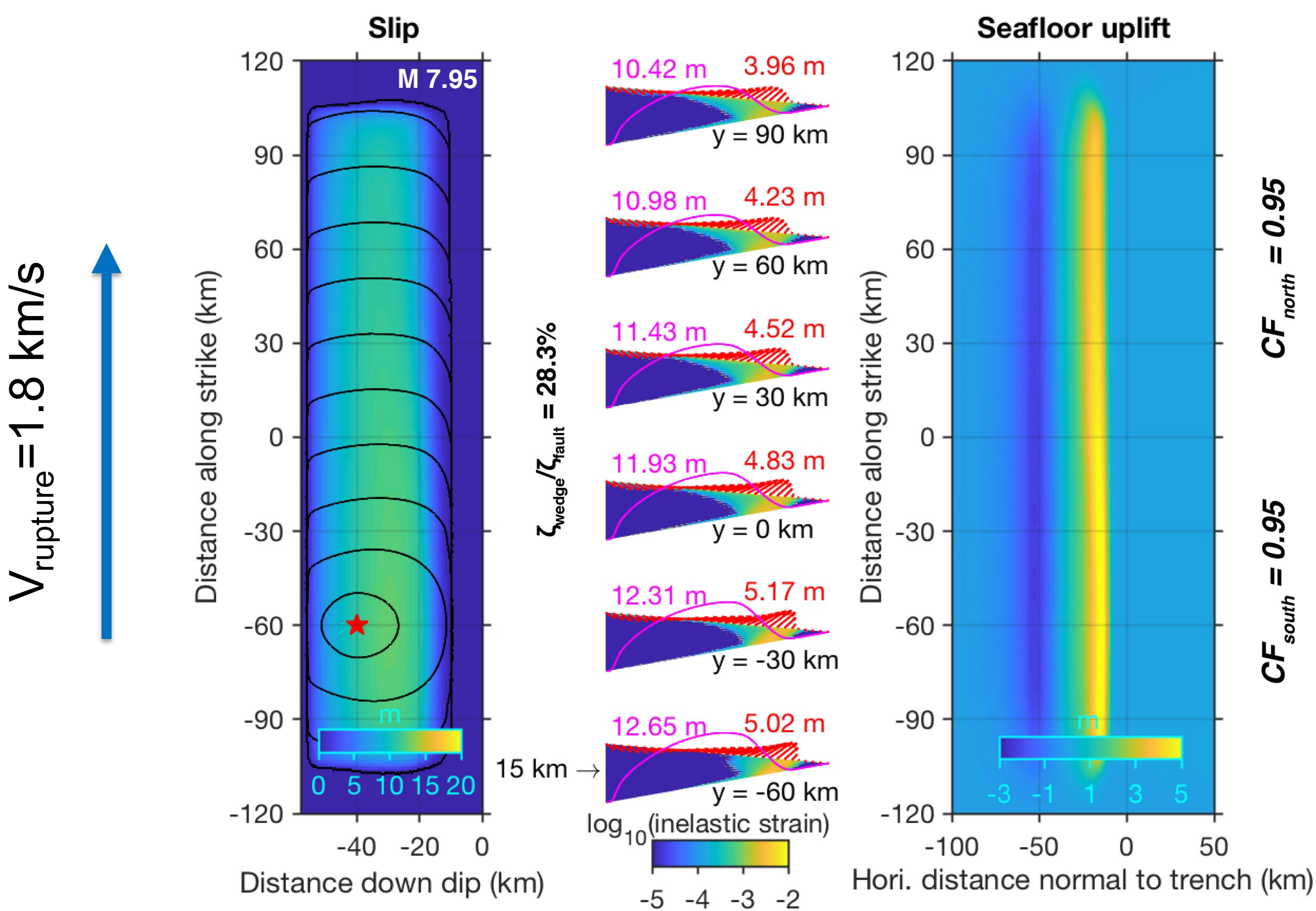
Final Slip and Seafloor Displacement



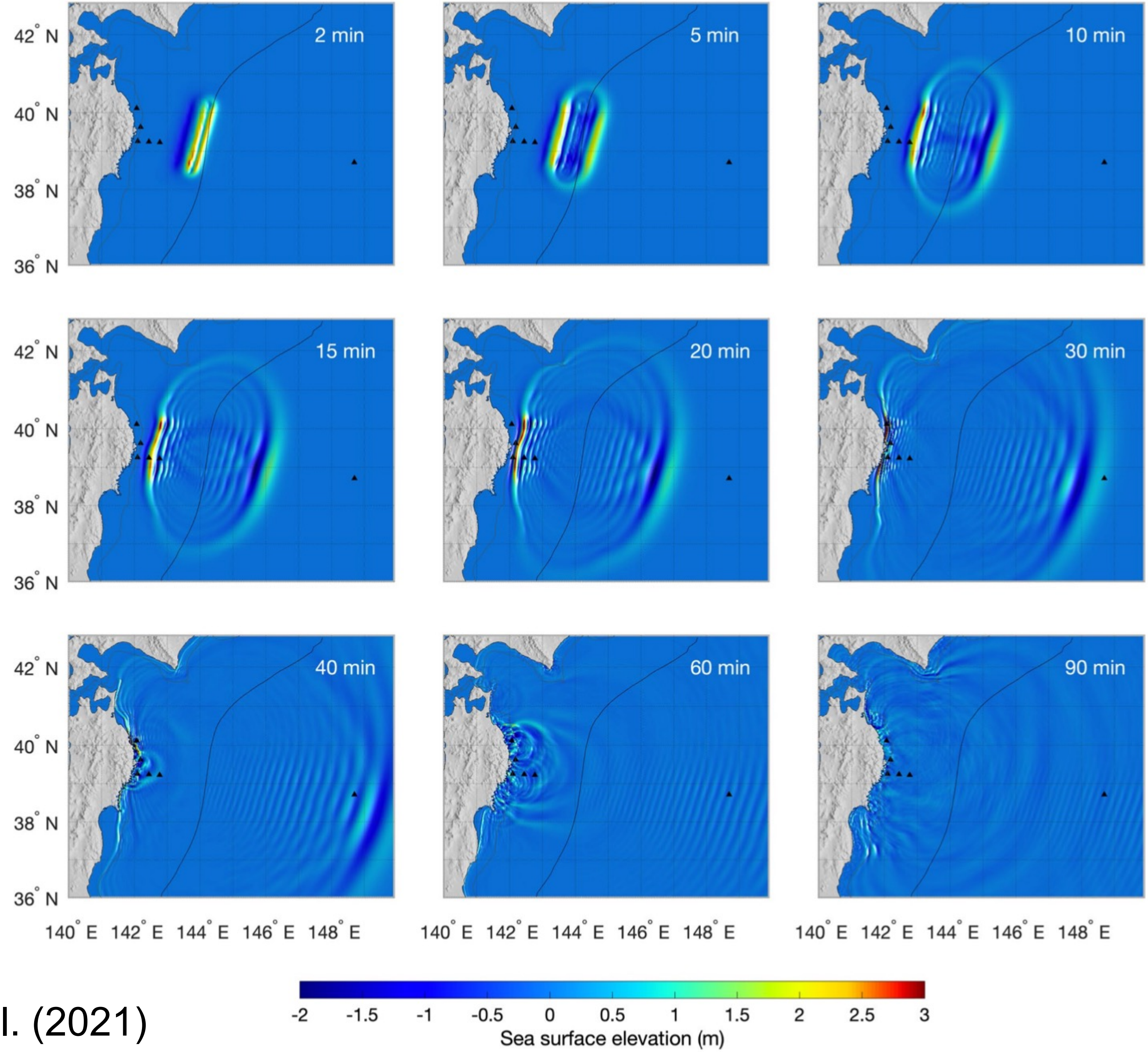
Final Slip and Seafloor Displacement



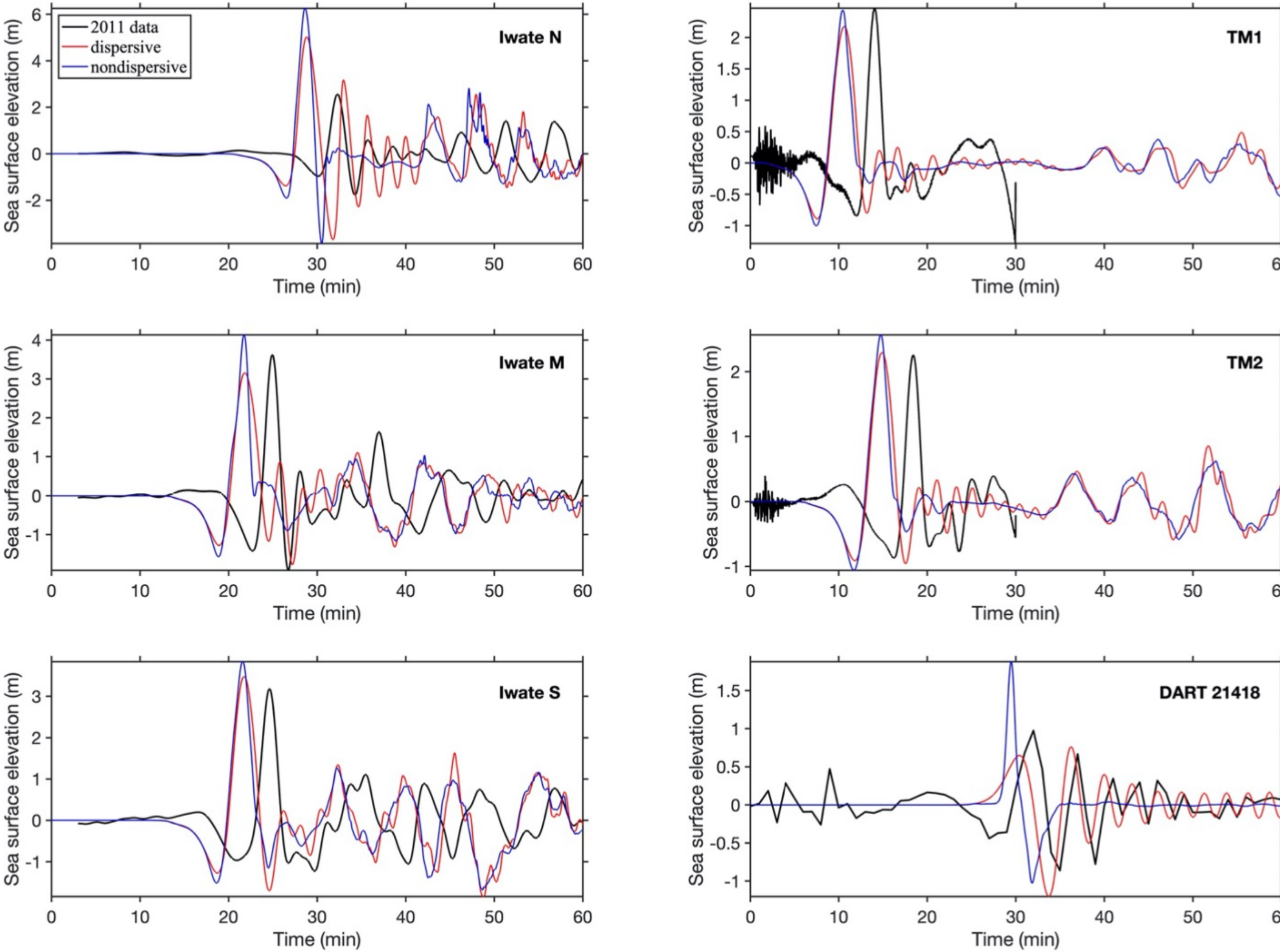
Final Slip and Seafloor Displacement



Simulation of the 1896 Sanriku Tsunami by Solving the Nonlinear Boussinesq Equation

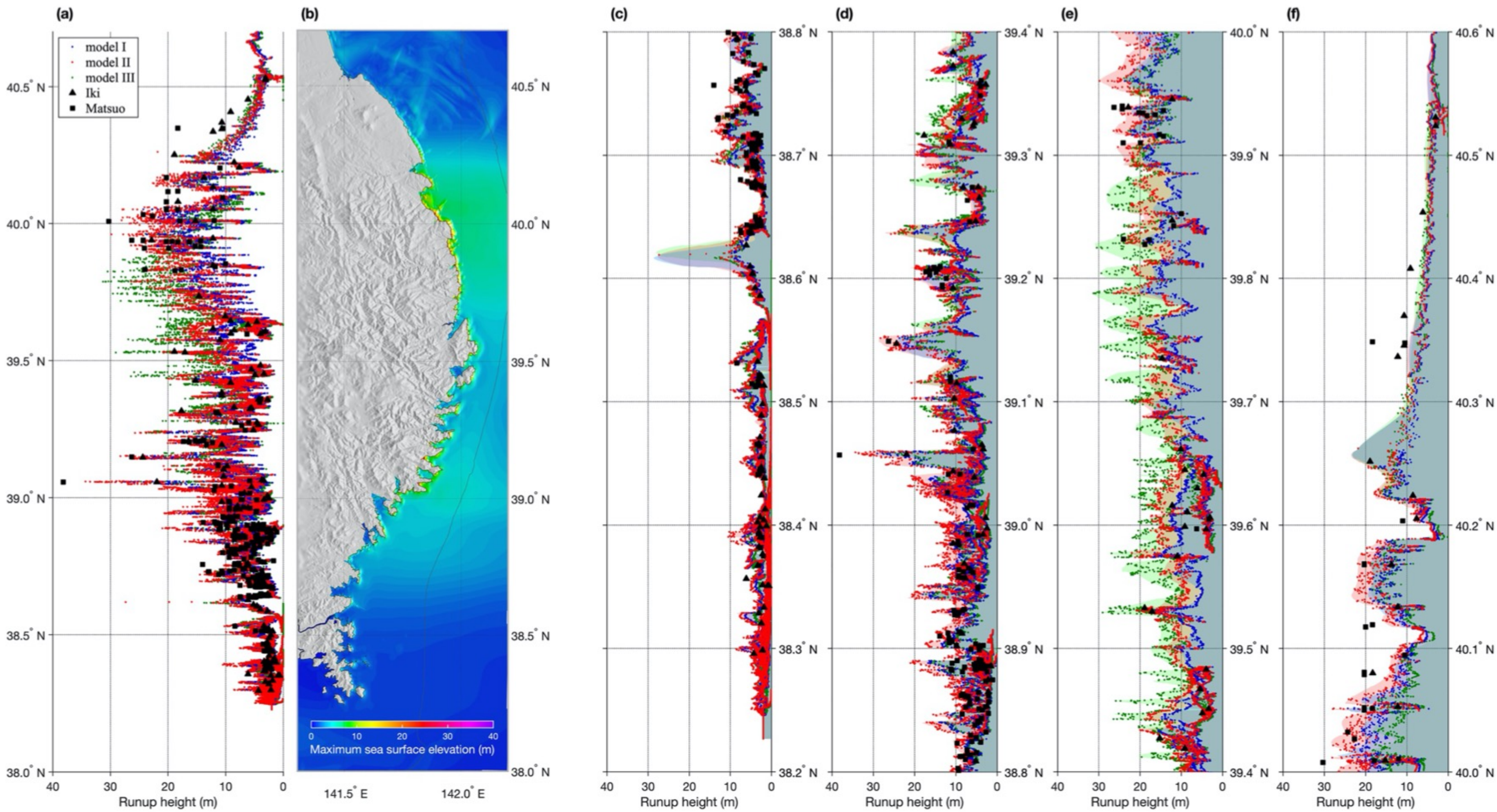


Du et al. (2021)


2011 data
dispersive
nondispersive
Iwate N
TM1
Iwate M
TM2
Iwate S
DART 21418
Sea surface elevation (m)
Time (min)

Du et al. (2021)

Runup Comparison: Models vs. 1896 Sanriku Data



Remarkable fit without any model tuning

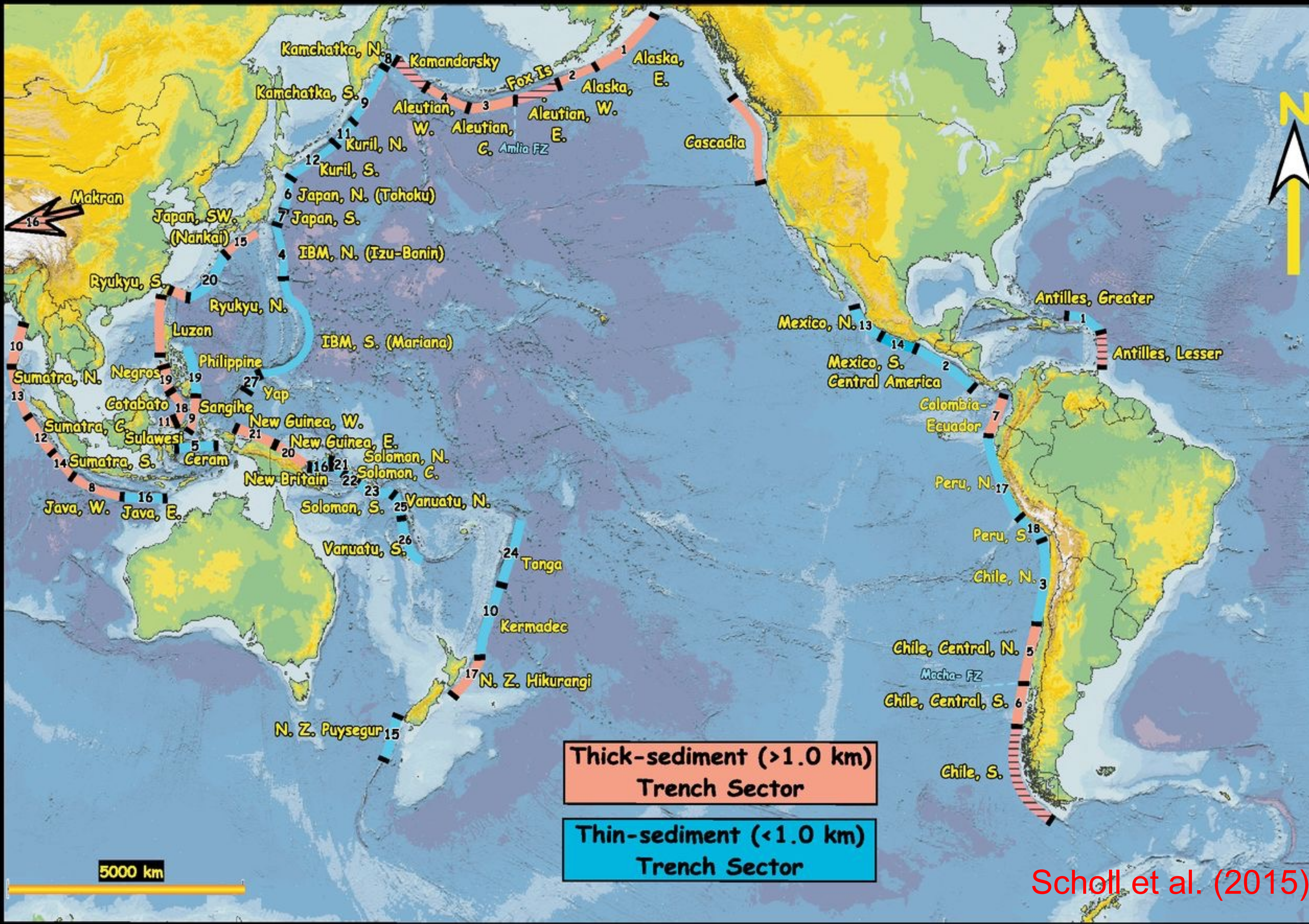
Du et al. (2021)

An Alternative View on the Generation of the 2011 Tohoku Tsunami

Wedge plasticity provides a self-consistent mechanism for

- Efficient tsunamigenesis landward from trench with diminishing near-trench slip on the plate interface, consistent with the bathymetry observations in the northern Japan Trench
- Depletion in high-frequency seismic radiation
- Impulsive tsunami
- Large runup along the Sanriku coast (largely due to impulsive tsunami)

The physics of tsunamigenesis is *critical* in tsunami hazard assessments and early warnings in the Japan Trench and worldwide.



Scholl et al. (2015)

More details of this work can be seen in:

Du, Y., Ma, S., Kubota, T., and Saito, T. (2021), Impulsive tsunami and large runup along the Sanriku coast of Japan produced by an inelastic wedge deformation model, *Journal of Geophysical Research,* 126, https://doi.org/10.1029/2021JB022098.

Ma, S., and Nie, S. (2019), Dynamic wedge failure and along-arc variations of tsunamigenesis in the Japan Trench margin, *Geophysical Research Letters*, 46., https://doi.org/10.1029/2019GL083148.

More discussions of wedge plasticity in tsunamigenesis are given in:

Wilson, A., and Ma, S. (2021), Wedge plasticity and fully coupled simulations of dynamic rupture and tsunami in the Cascadia subduction zone, *Journal of Geophysical Research,* 126, https://doi.org/10.1029/2020JB021627.

Ma, S., and E. T. Hirakawa (2013), Dynamic wedge failure reveals anomalous energy radiation of shallow subduction earthquakes, *Earth and Planetary Science Letters*, 375, 113 – 122, doi: 10.1016/j.epsl.2013.05.016.

Ma, S. (2012), A self-consistent mechanism for slow dynamic deformation and tsunami generation for earthquakes in the shallow subduction zone, *Geophysical Research Letters,* 39, L11310, doi:10.1029/2012GL051854.