Wedge Inelasticity as a Mechanism for Efficient Tsunami Generation and Weak High-Frequency Radiation in Shallow Subduction Zones

Implications for tsunami earthquakes, observability, and shallow source physics

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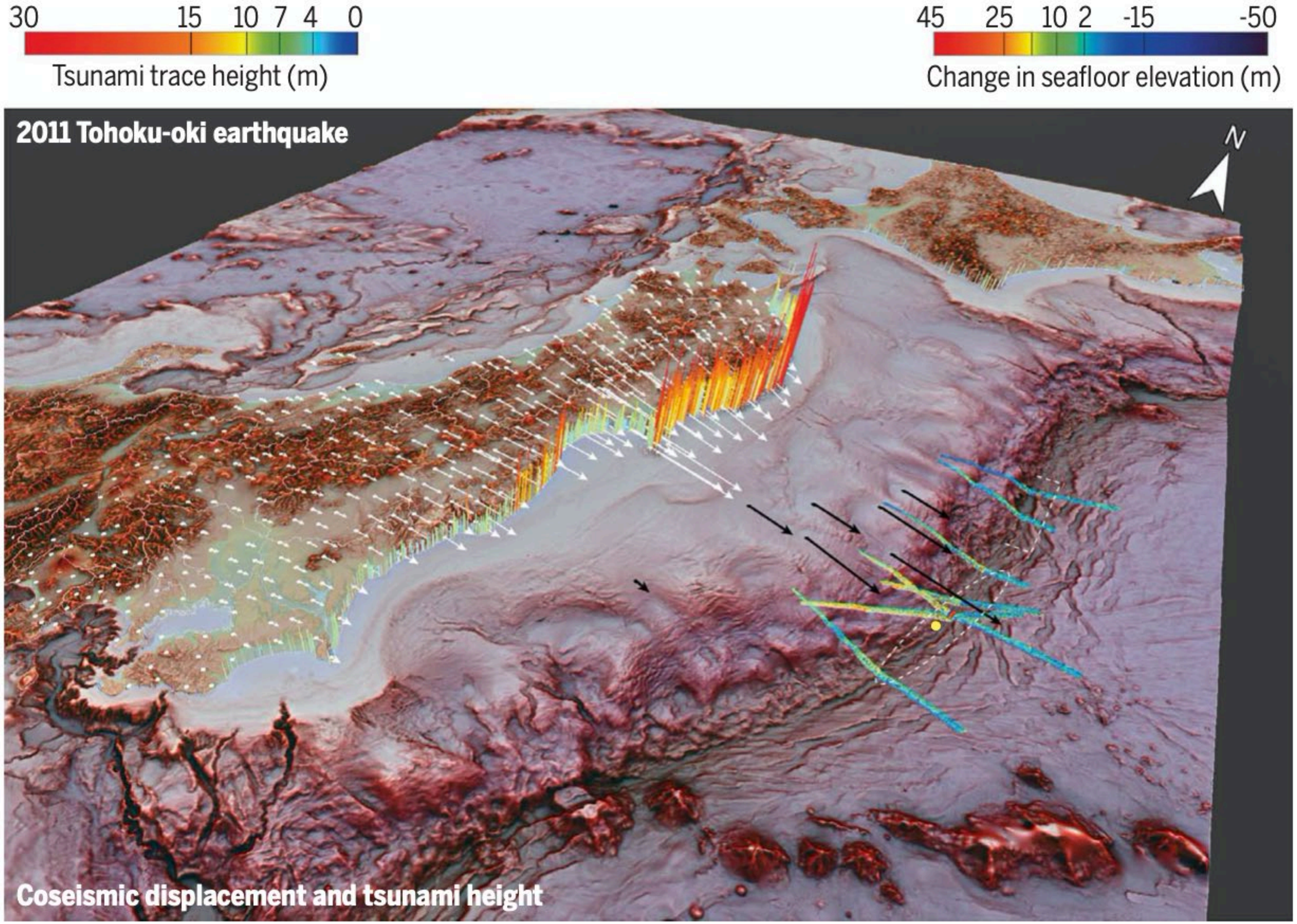
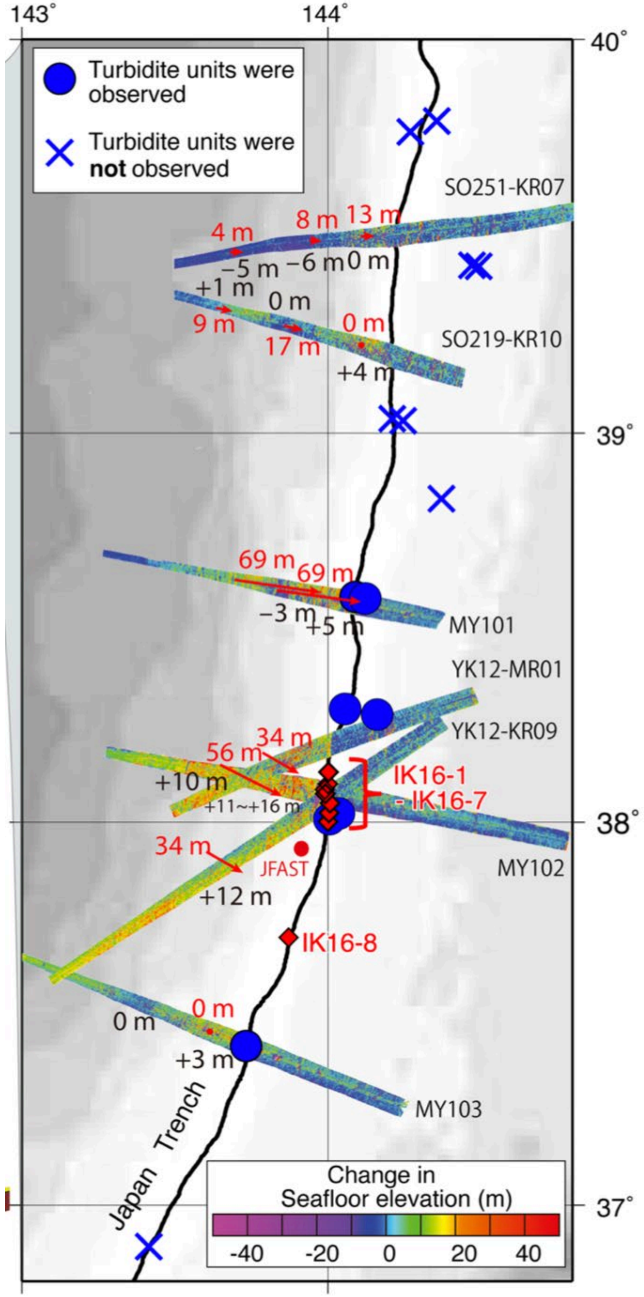
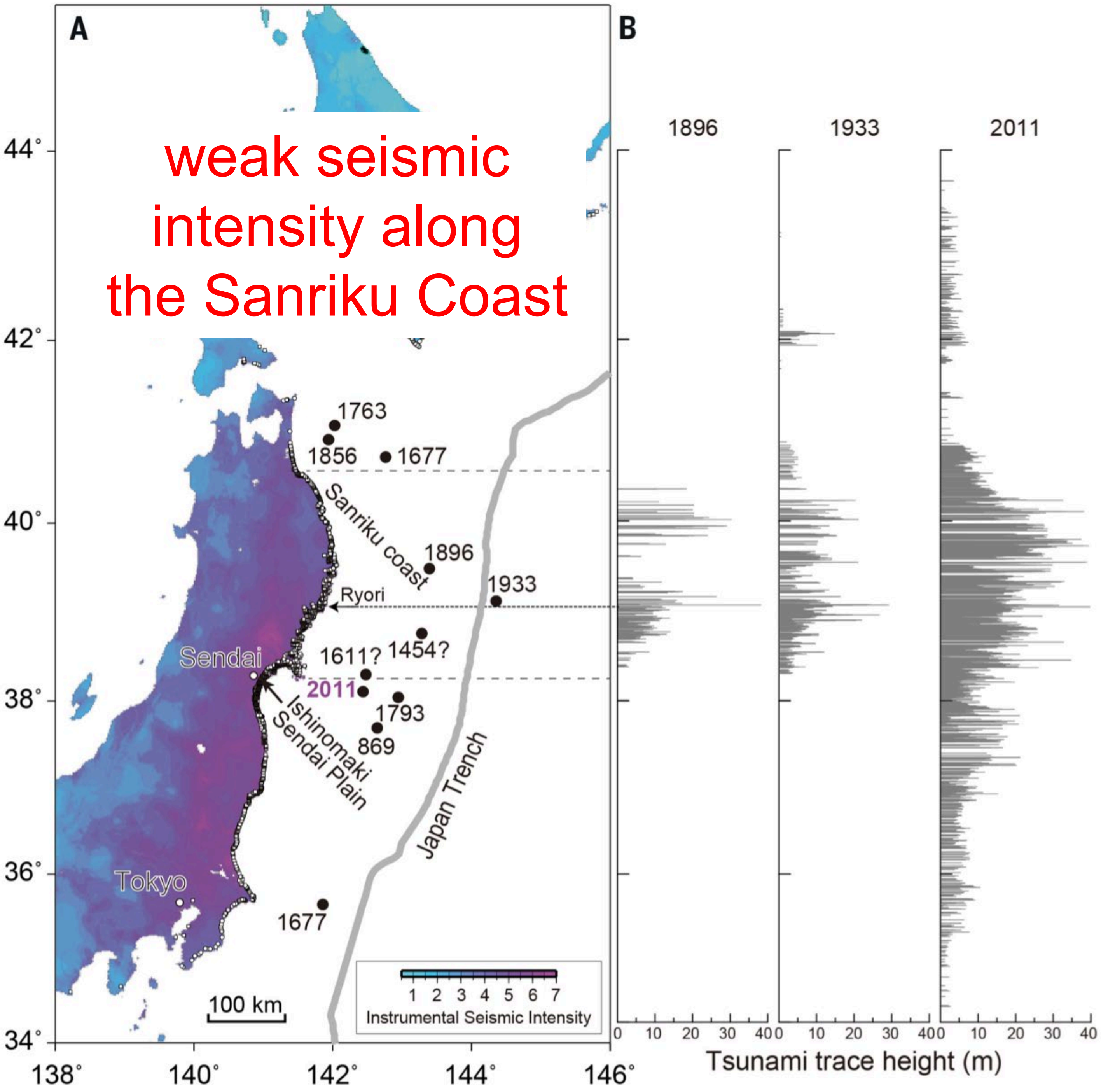
2011 Tohoku-Oki: Northern Japan Trench Anomaly





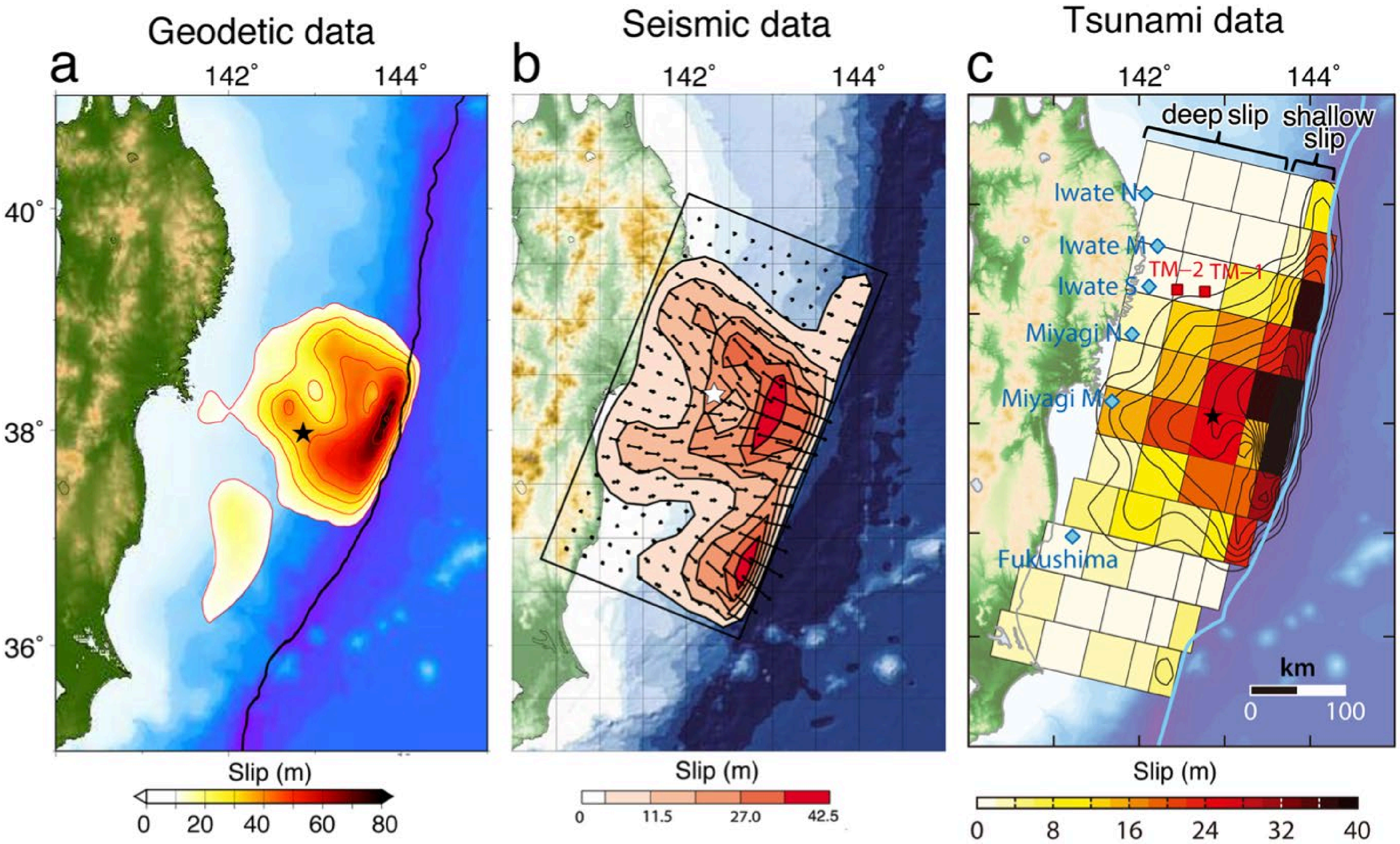
Historic Large Tsunamis in the Japan Trench



weak seismic intensity along the Sanriku Coast

Kodaira et al. (2021)

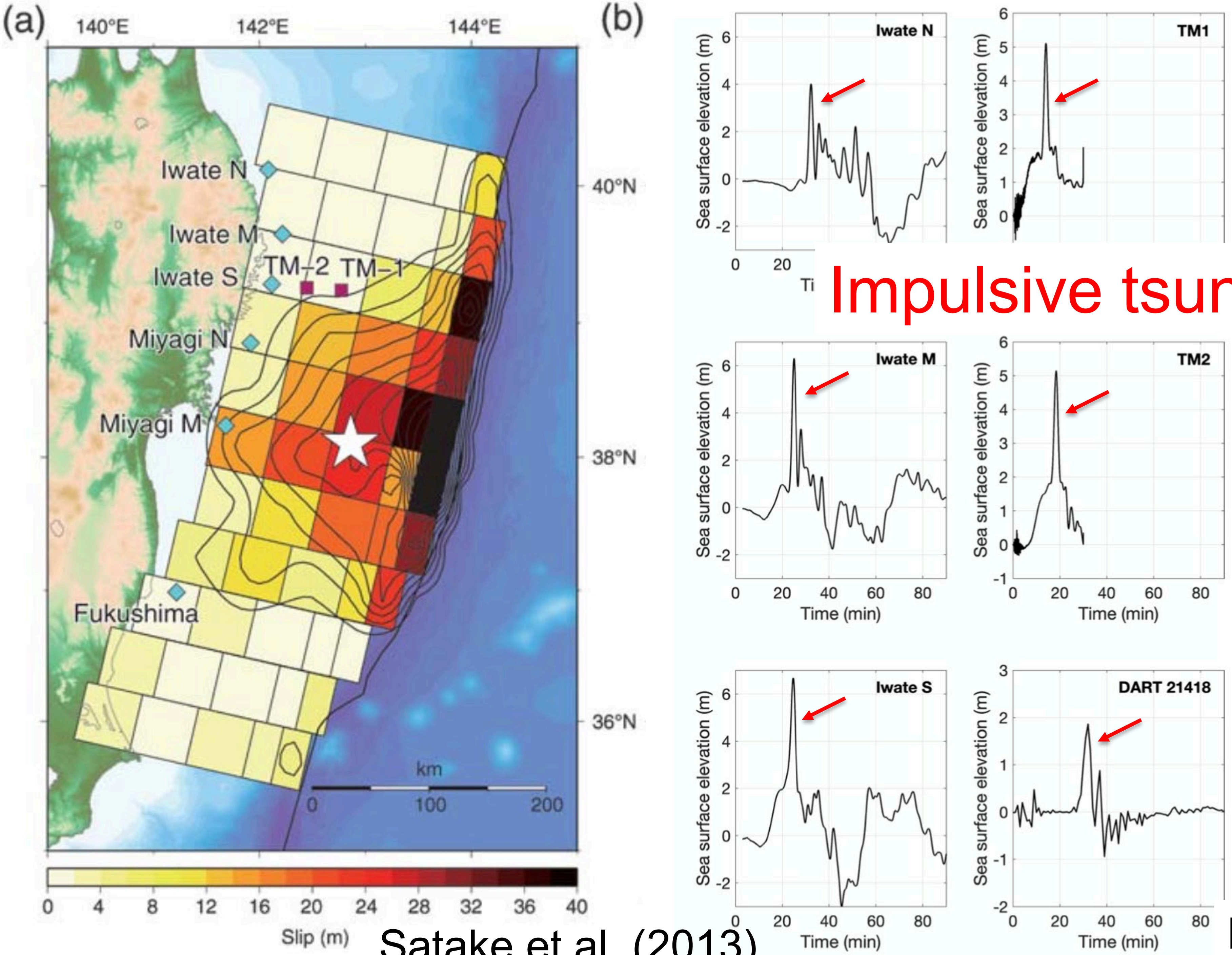
Representative Slip Models of the 2011 Tohoku Earthquake



Iinuma et al. (2012)

Lay et al. (2011)

Satake et al. (2013)

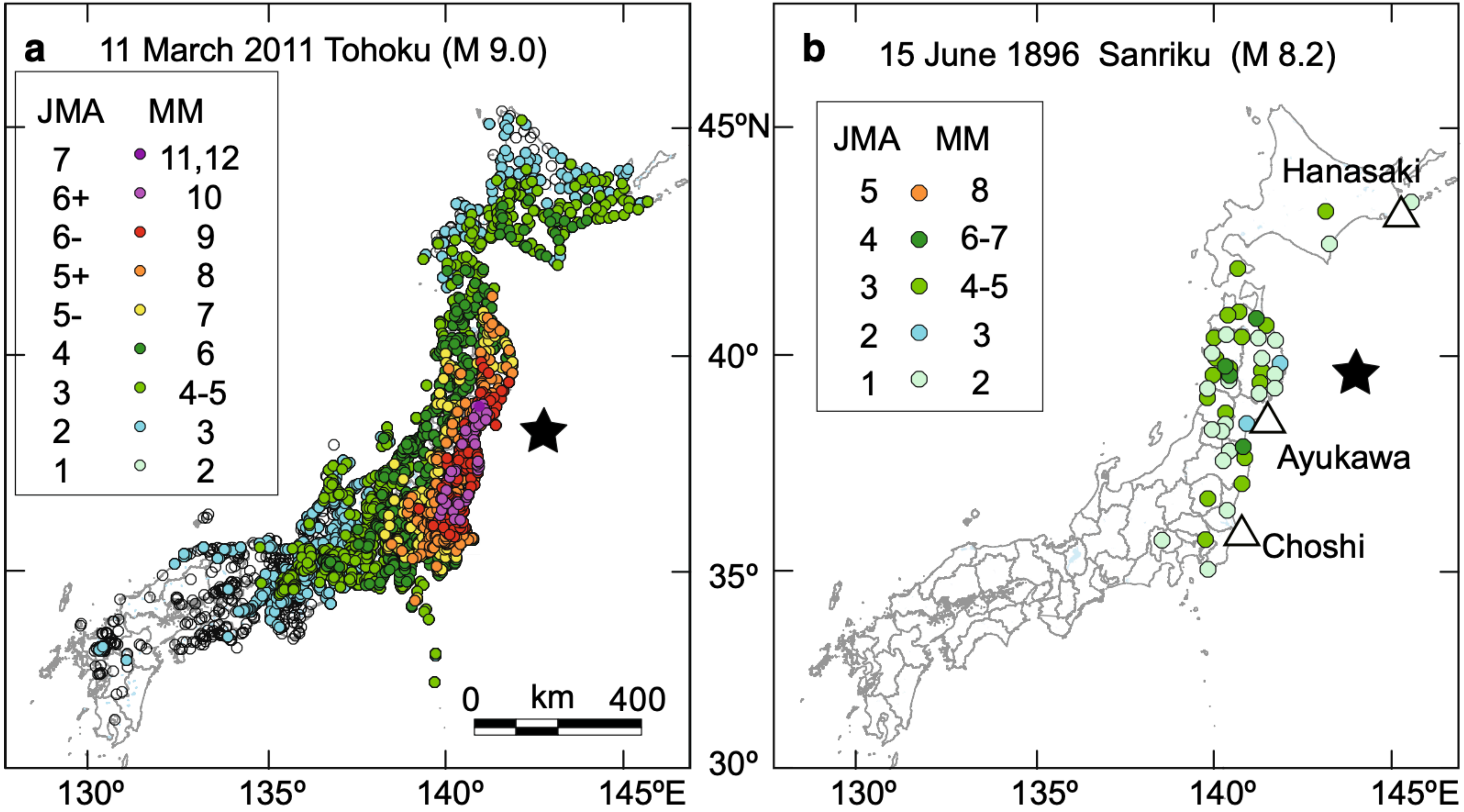


Impulsive tsunami pulse

Satake et al. (2013)

Du et al. (2021)

1896 Sanriku Tsunami Earthquake

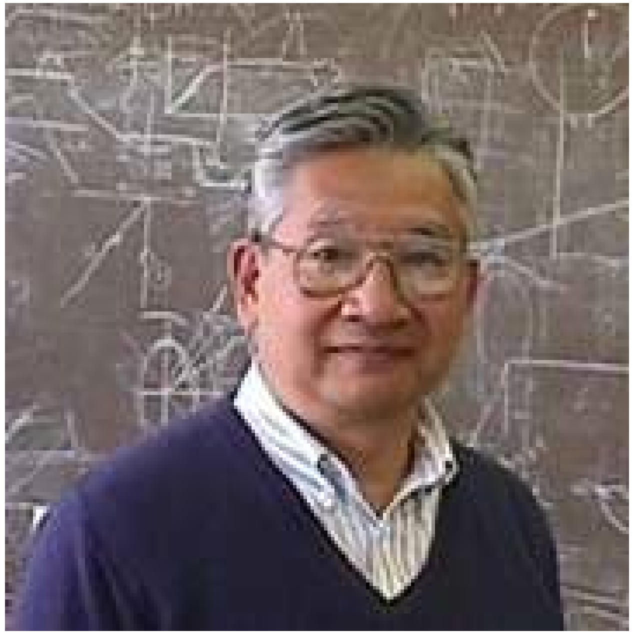


Satake et al. (2017)

Persistent Puzzle About Tsunami Earthquakes

Identified by Hiroo Kanamori in 1972

- Large tsunami
- Depleted high-frequency radiation



- Occur in upper 15 km – a frictionally stable (velocity-strengthening) or conditionally unstable regime
- Slow rupture velocity and/or long rupture duration
- Low energy-to-moment ratio

A Central Question

Can a common shallow-source process simultaneously explain:

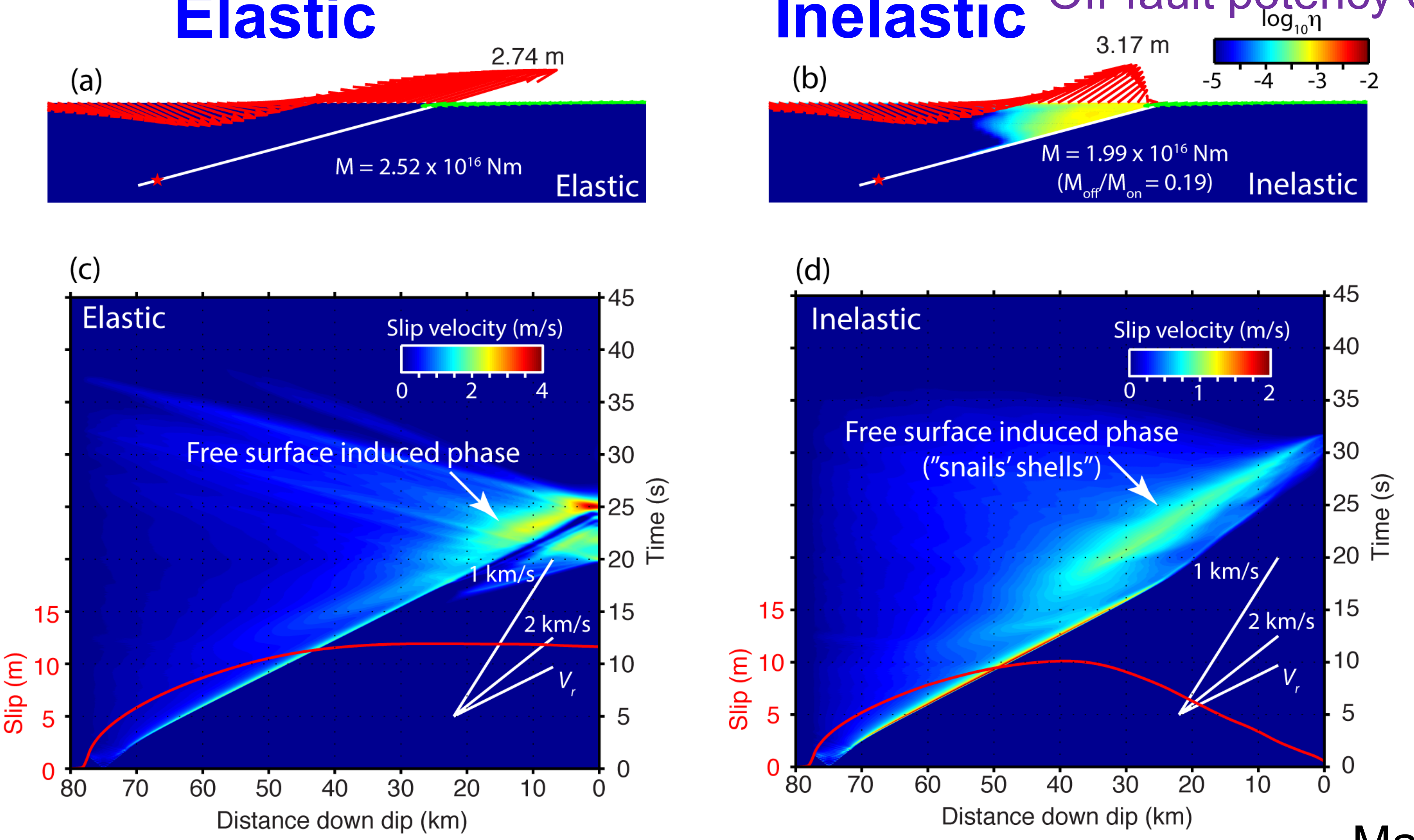
- Efficient Tsunami Generation
- Depleted HF Radiation
- Low Radiated Energy
- Localized Seafloor Uplift

2D Models Incorporating Inelastic Wedge Deformation

Elastic

Inelastic

Off-fault potency density



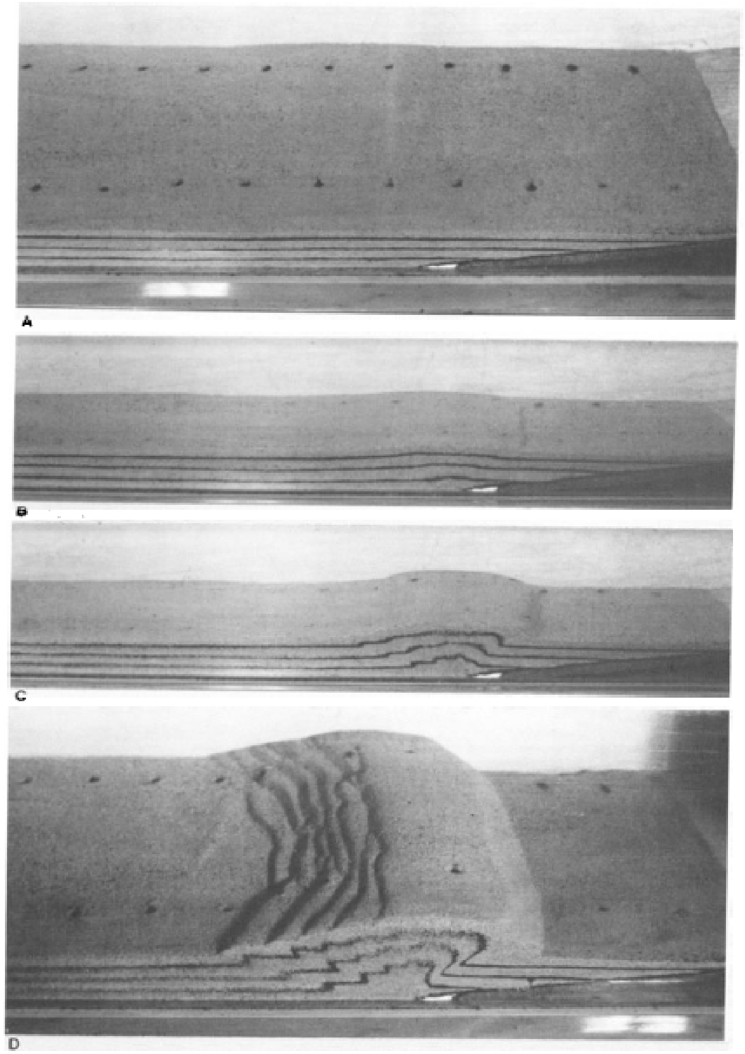
Earlier 2D dynamic rupture models showed that shallow inelastic deformation can simultaneously:

- enhance tsunami generation efficiency
- dissipate energy
- suppress high-frequency radiation

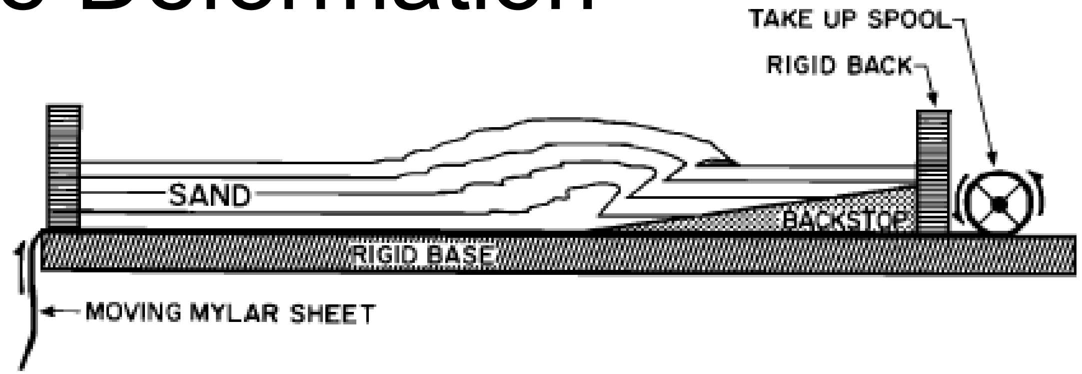
Ma (2012)

Ma and Hirakawa (2013)

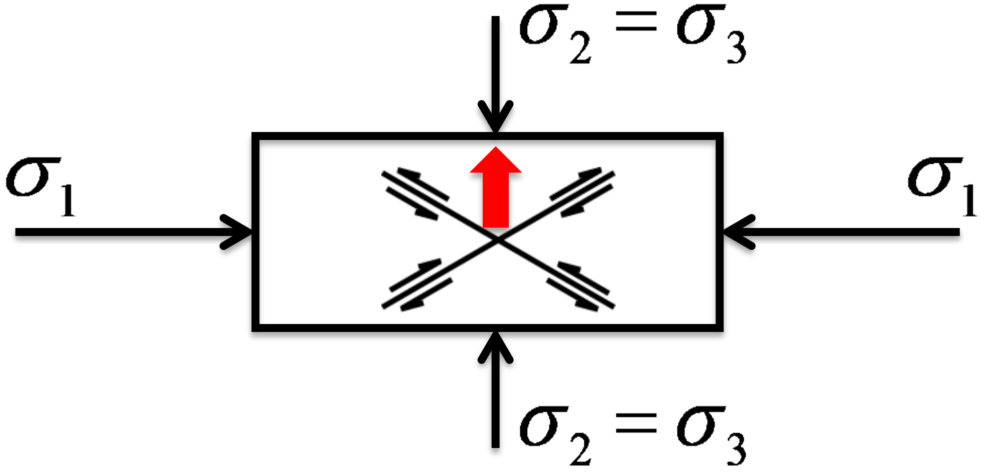
Granular Materials Under Shear and Compression Develop Irreversible Deformation



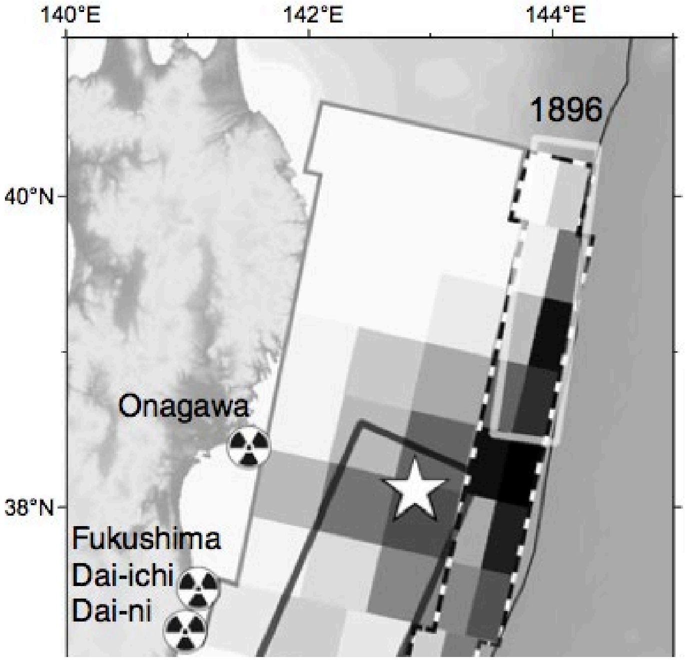
Byrne et al. (1988)

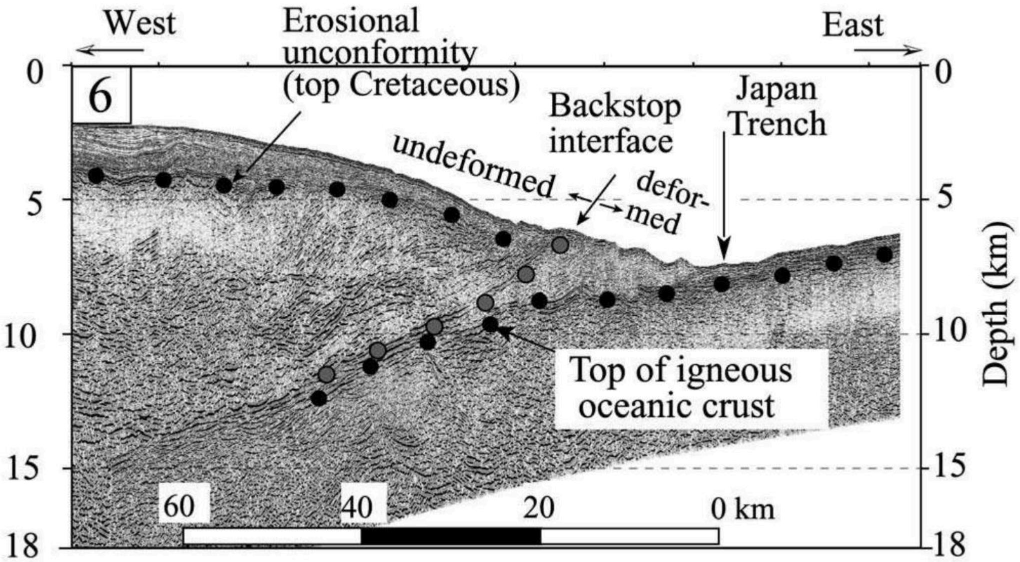


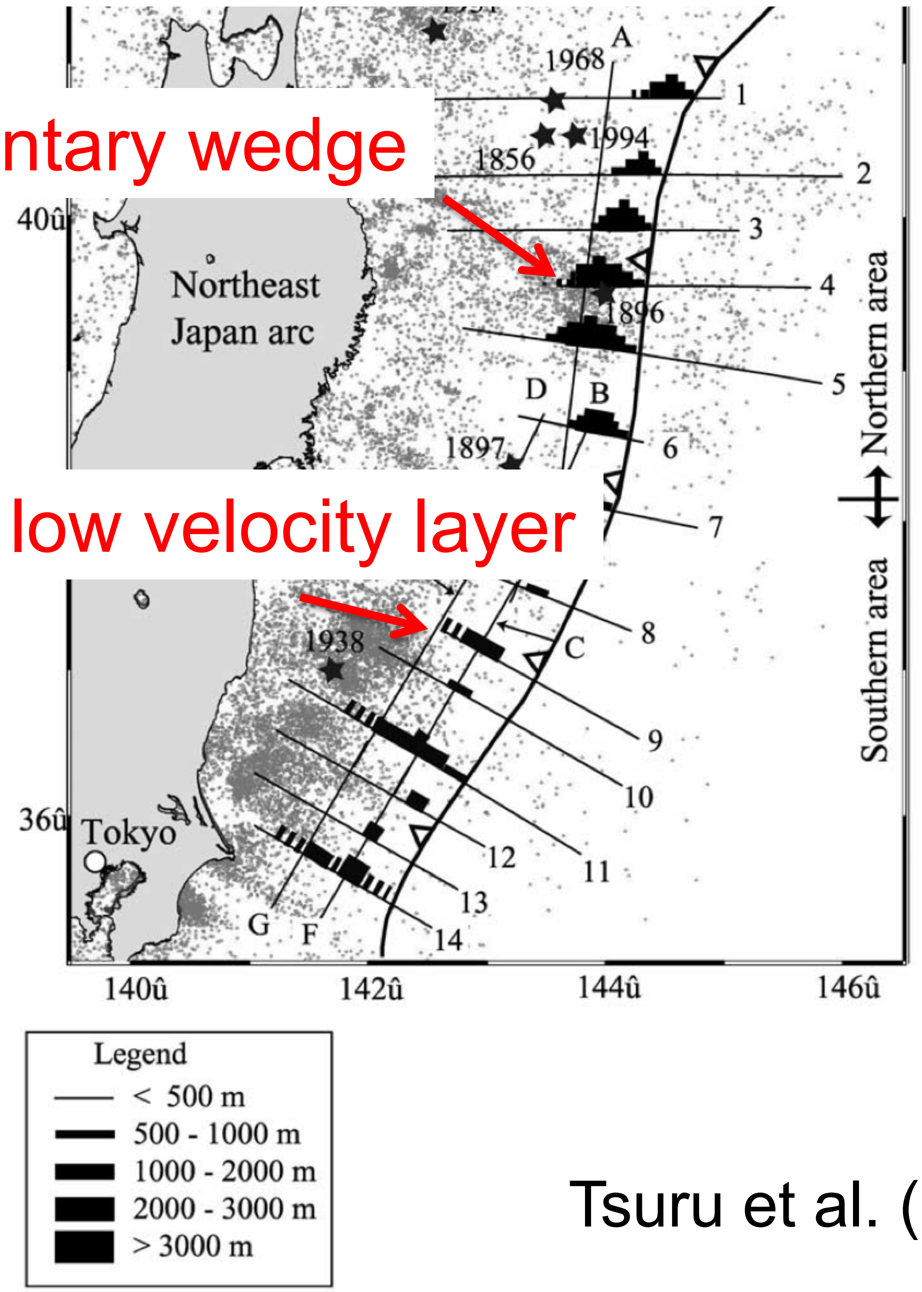
Tri-axial experiment



Sediment Thickness





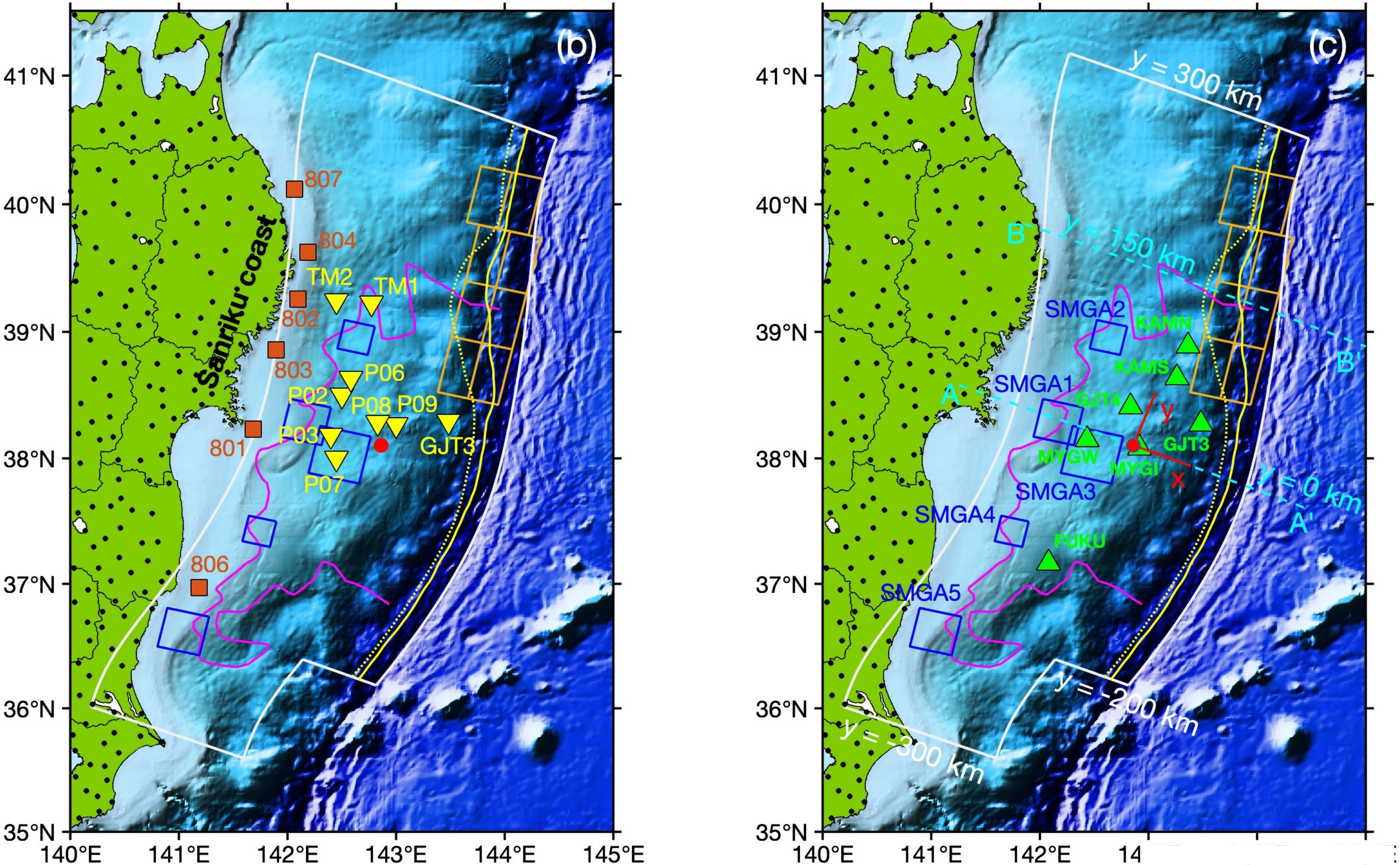


Sedimentary wedge

Elongate low velocity layer

Tsuru et al. (2002)

A Minimalist Dynamic Rupture Model of the 2011 Tohoku-Oki Earthquake



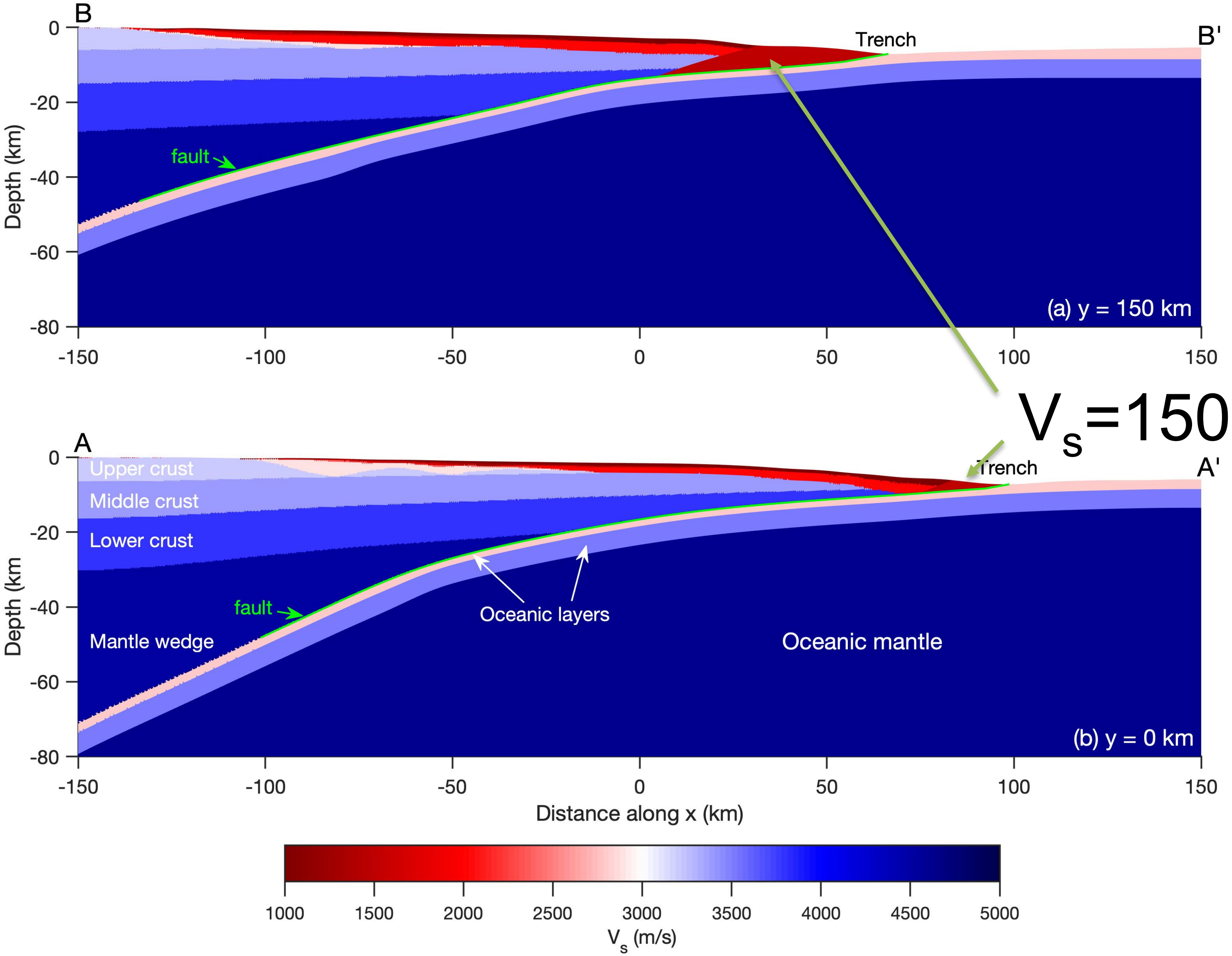
Ma (2023)

Magenta curve: Coseismic rupture extent (Kato & Igarashi, 2012)

SMGAs: Strong ground motion generation areas (Kurahashi & Irikura, 2013)

Orange subfaults: 1896 Sanriku earthquake rupture zone (Satake et al., 2017)

Japan Integrated Velocity Structure Model (JIVSM)



V_s=1500 m/s

Model Framework

Dynamic rupture
Rate-state friction
Plastic yielding
Realistic regional and trench structure

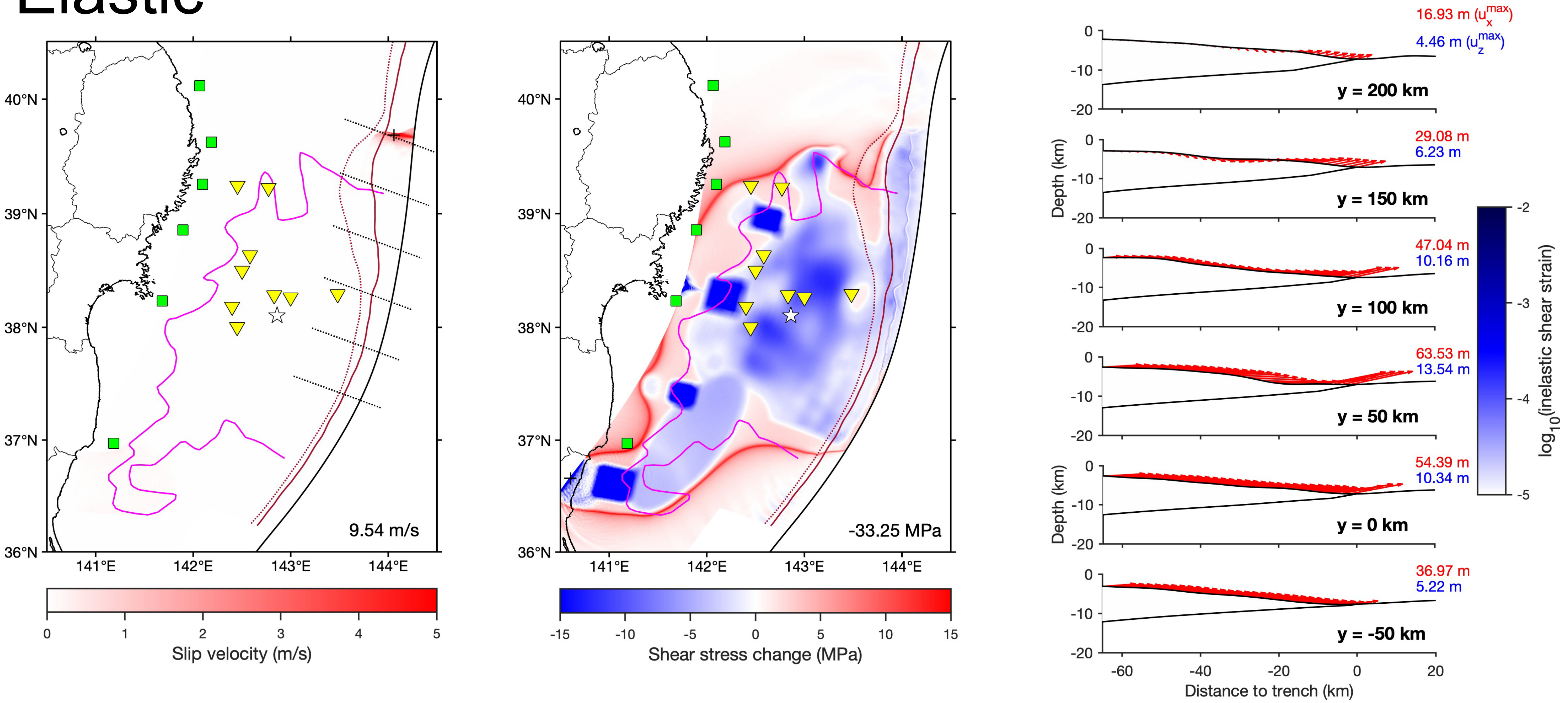
→

Shallow off-fault yielding modifies:

- rupture propagation
- tsunami generation
- radiated energy

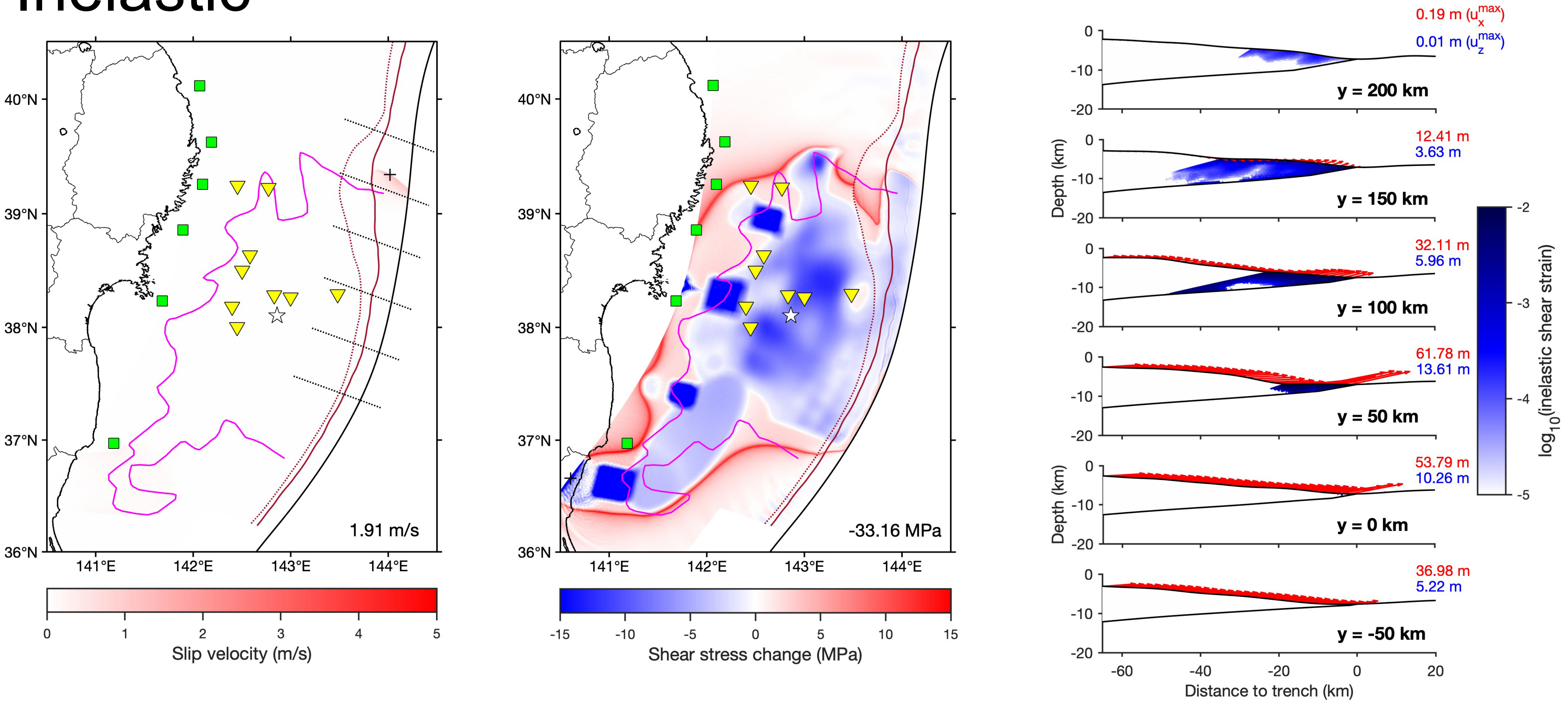
Rupture snapshot (time = 122 s)

Elastic



Rupture snapshot (time = 122 s)

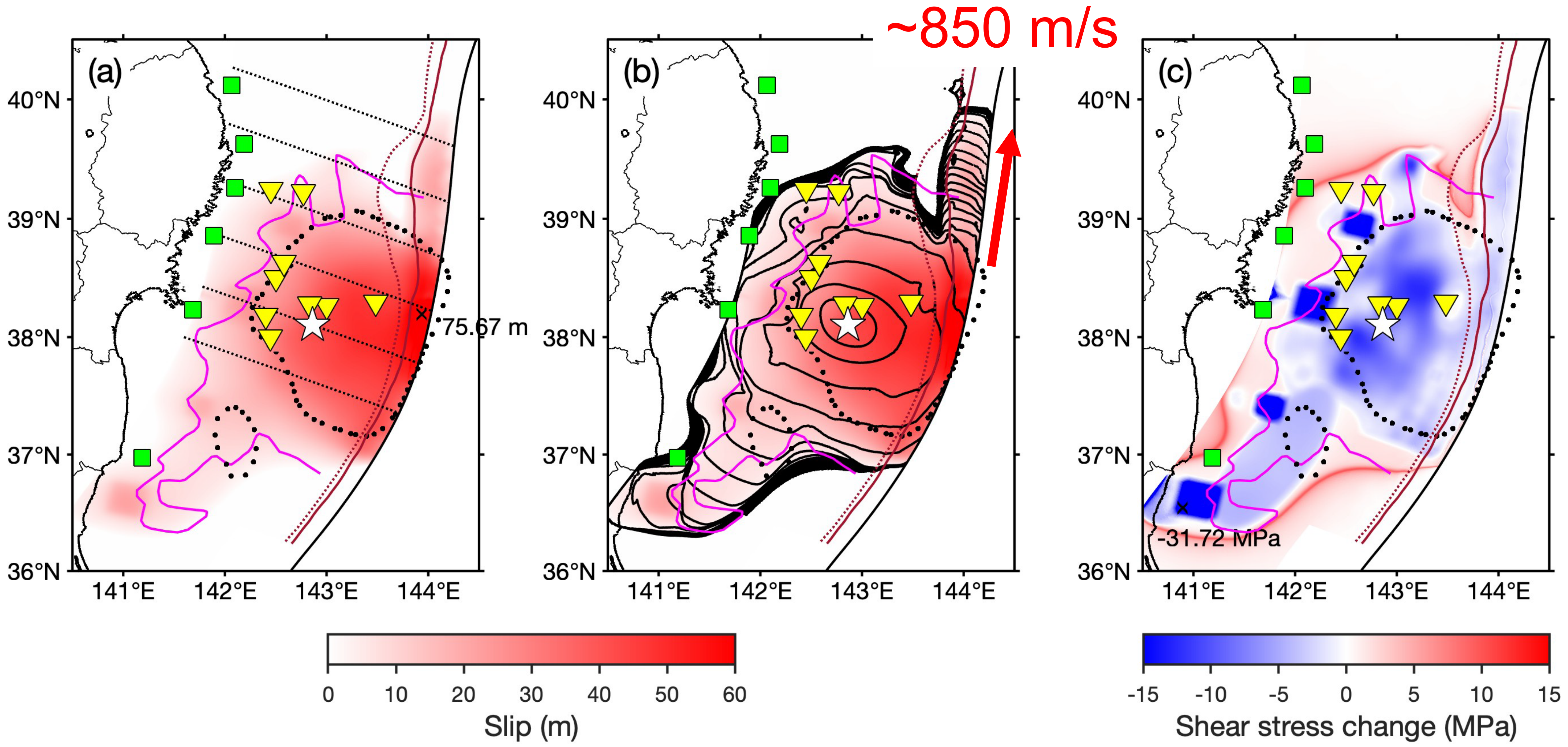
Inelastic



Slip

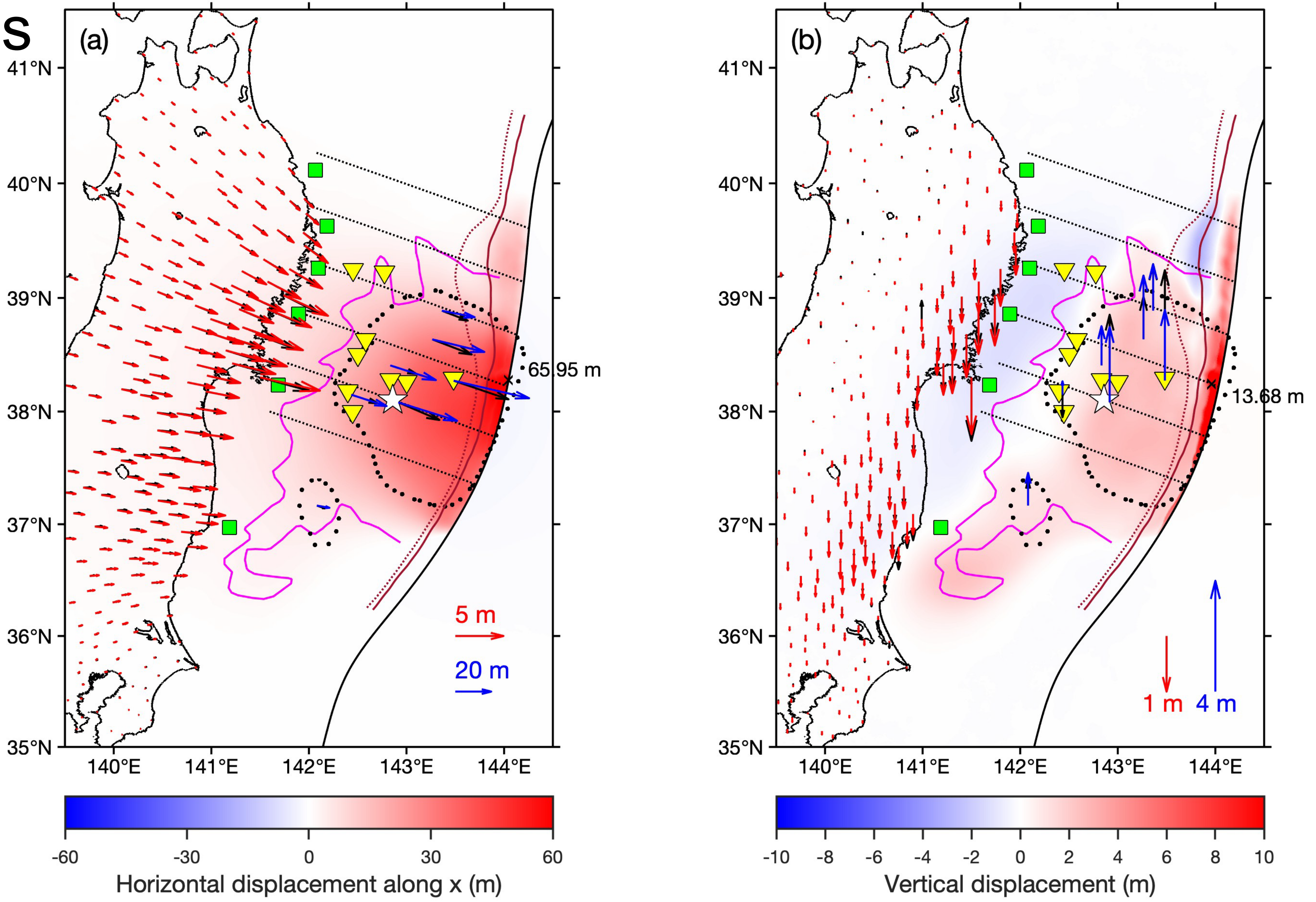
Rupture time

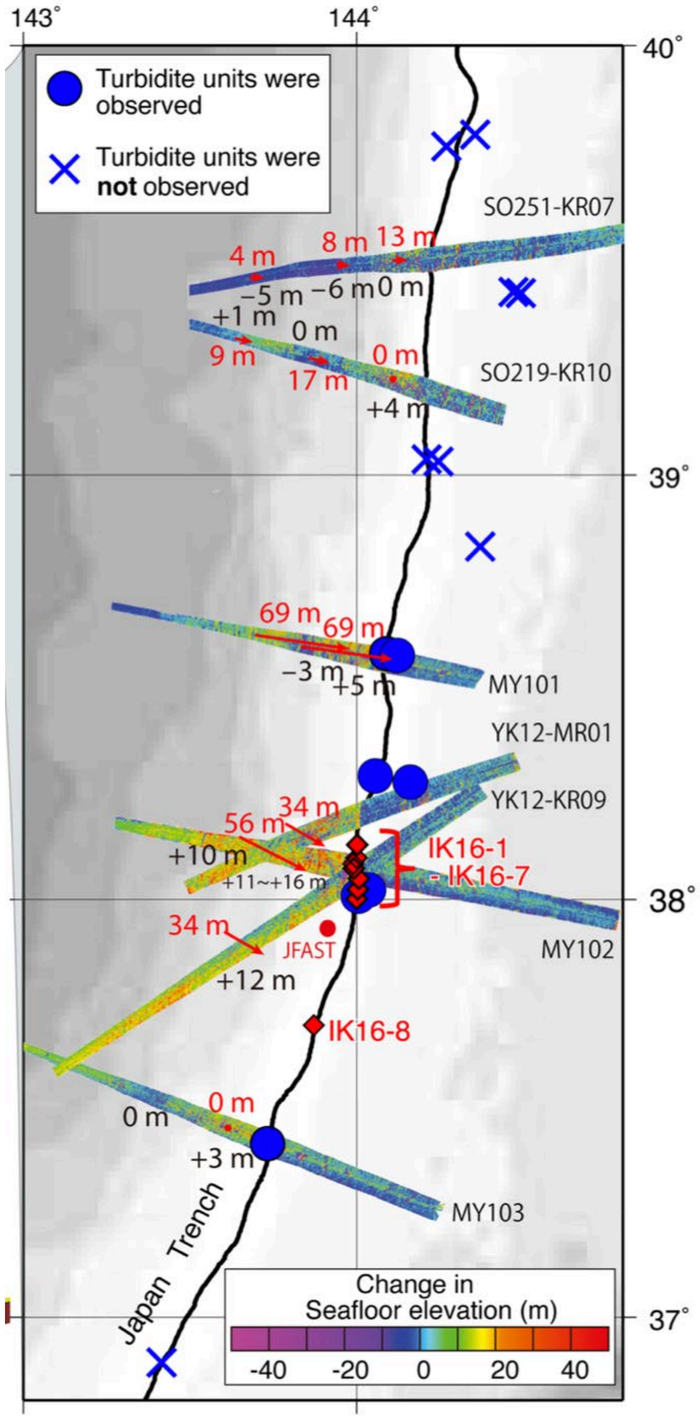
Shear stress change



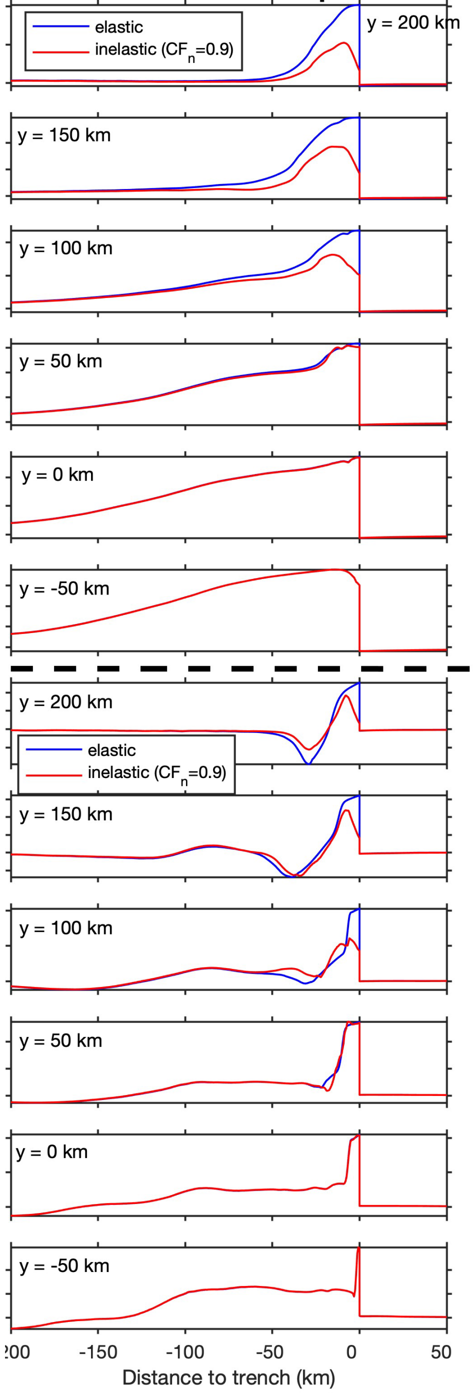
~850 m/s

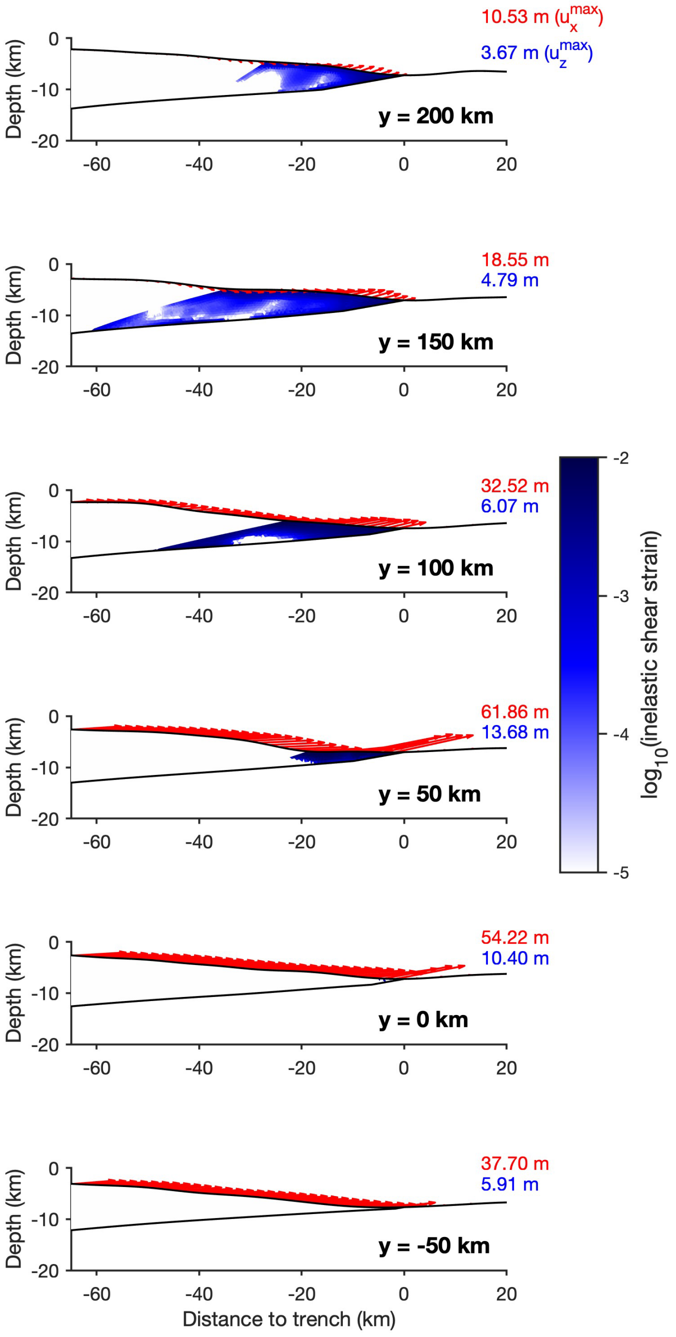
Comparisons with GPS Data

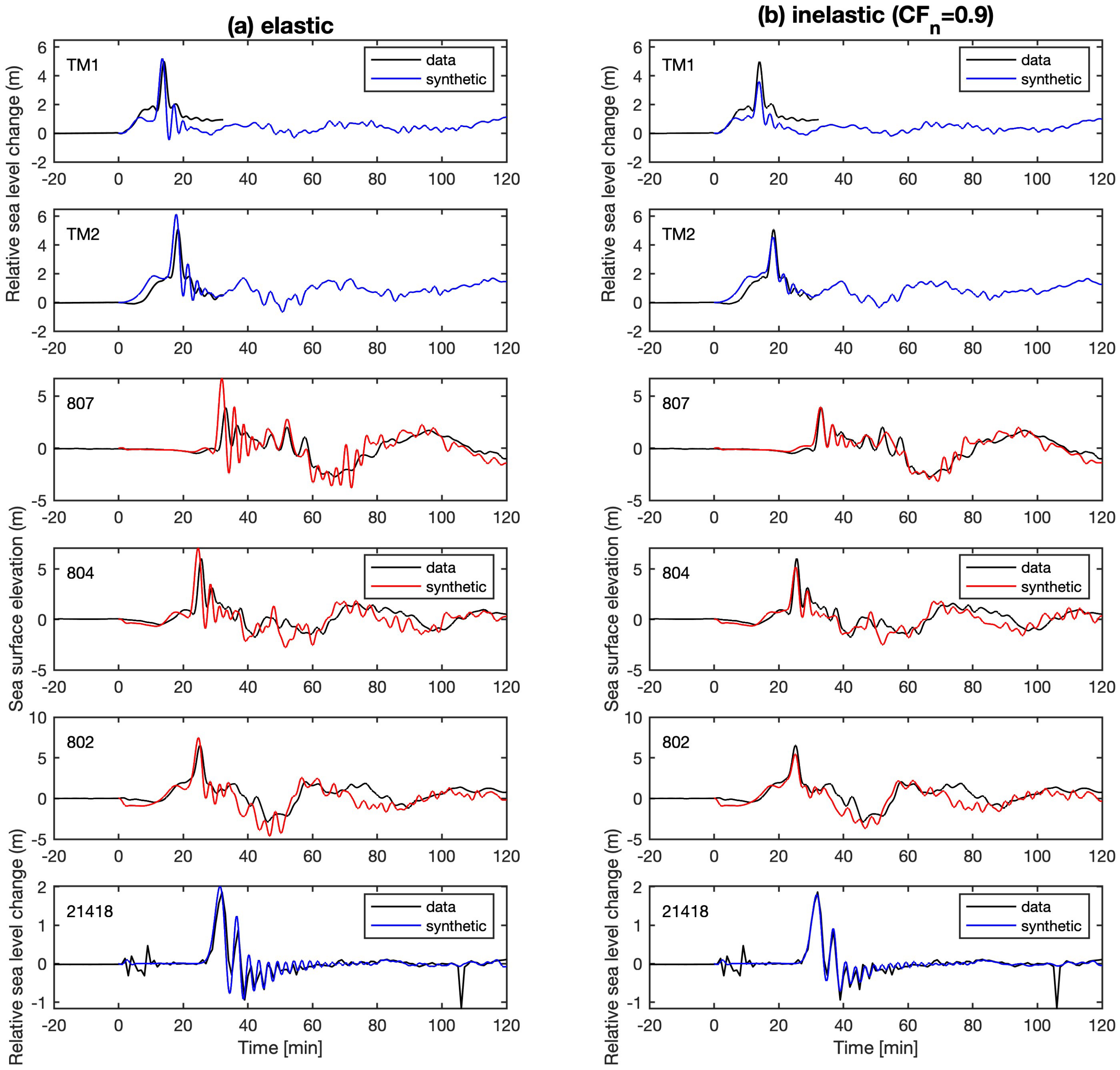


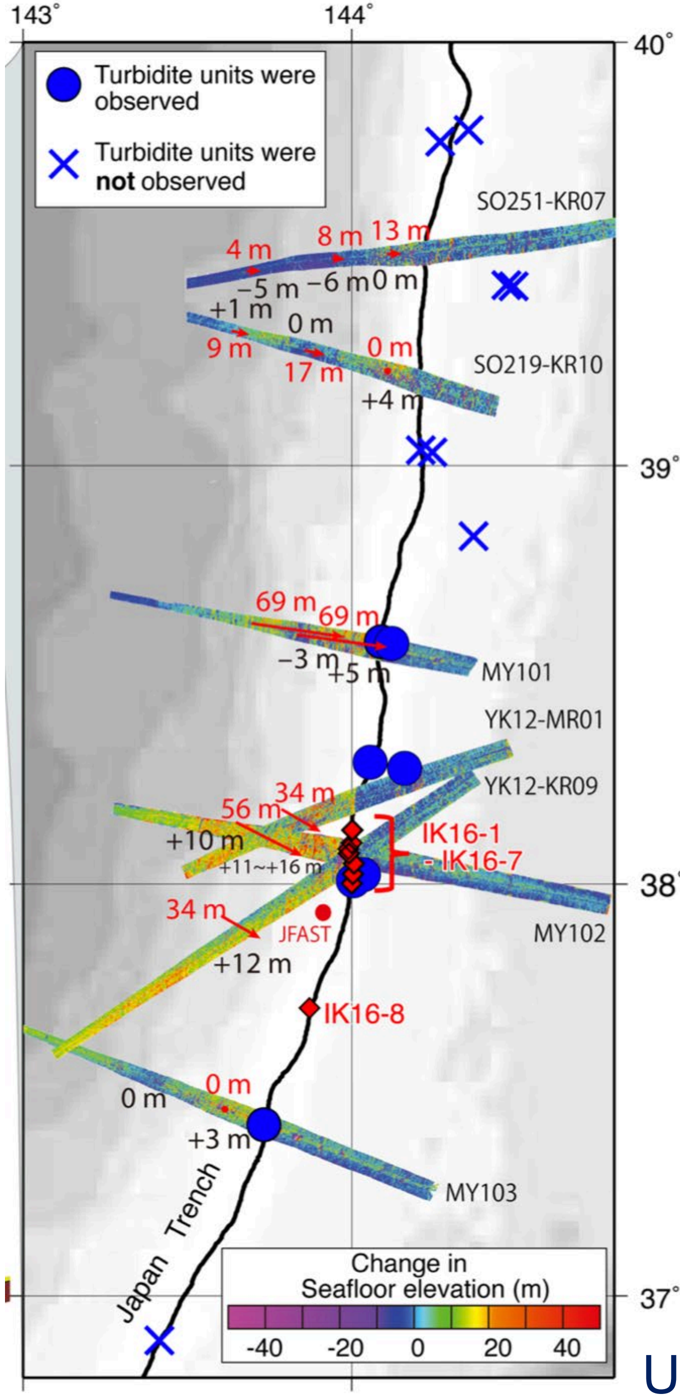


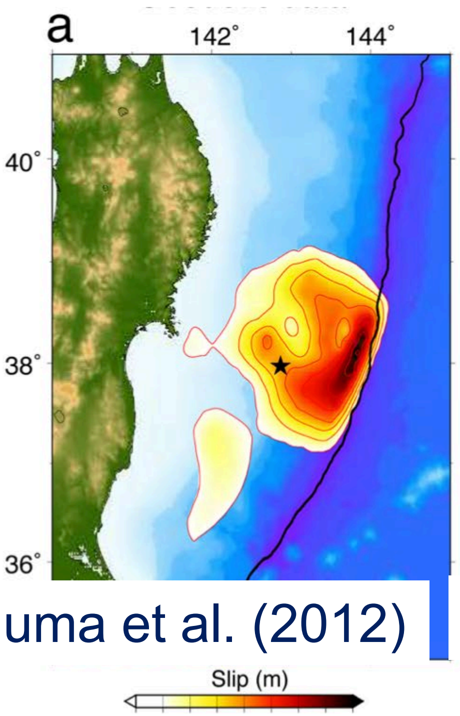
orizontal and vertical displacements



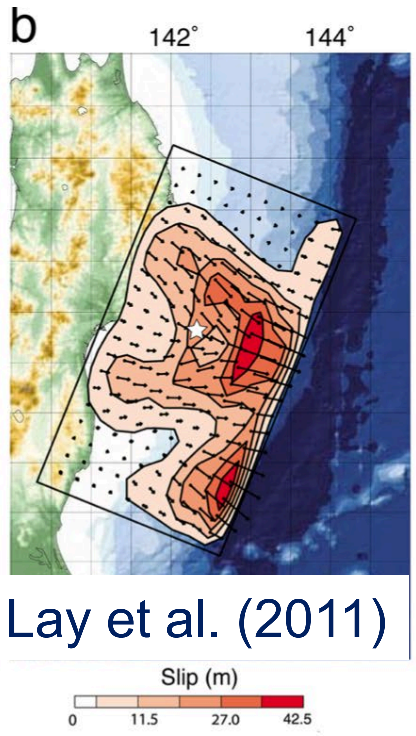



(a) elastic
(b) inelastic (CF_n=0.9)
TM1
TM2
807
804
802
21418
data
synthetic
Relative sea level change (m)
Sea surface elevation (m)
Time [min]
-20
0
20
40
60
80
100
120

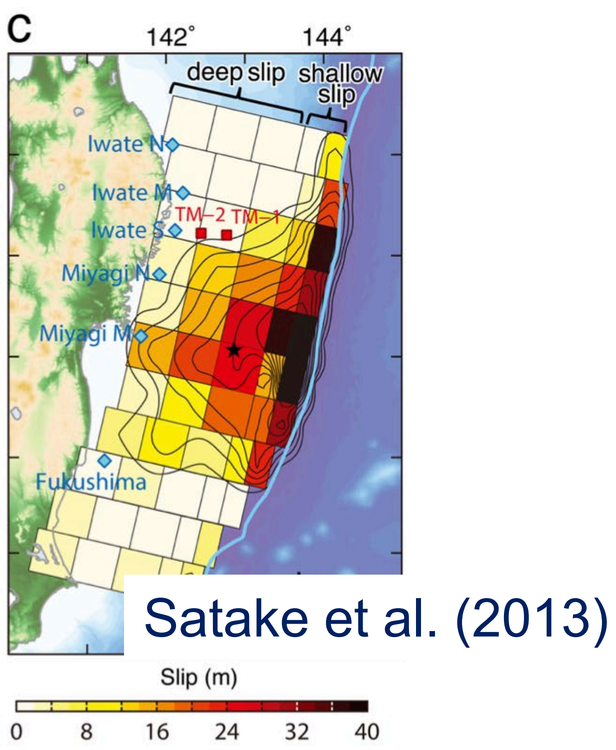




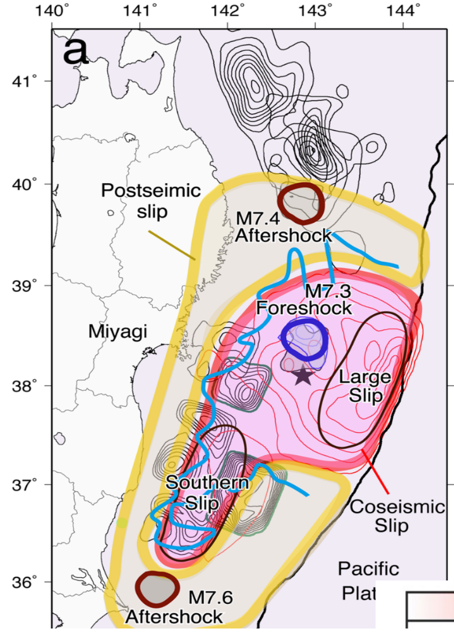
Iinuma et al. (2012)



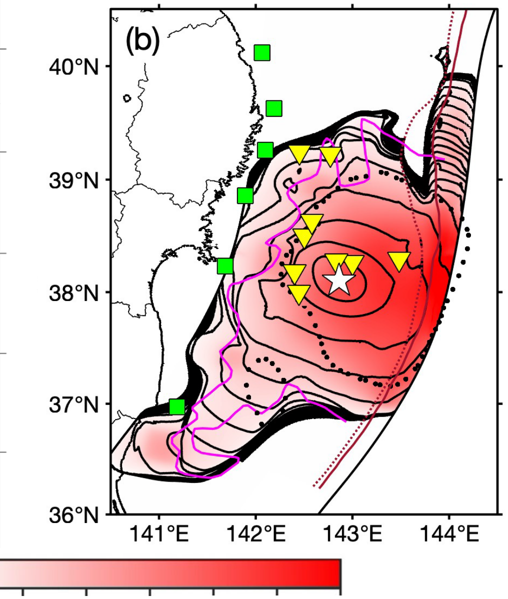
Lay et al. (2011)



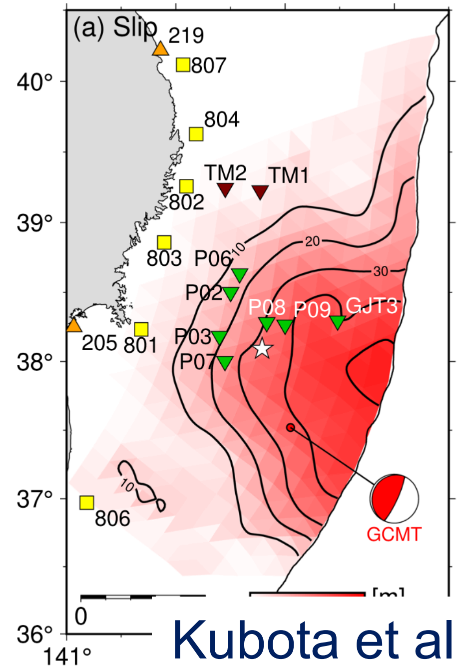
Satake et al. (2013)



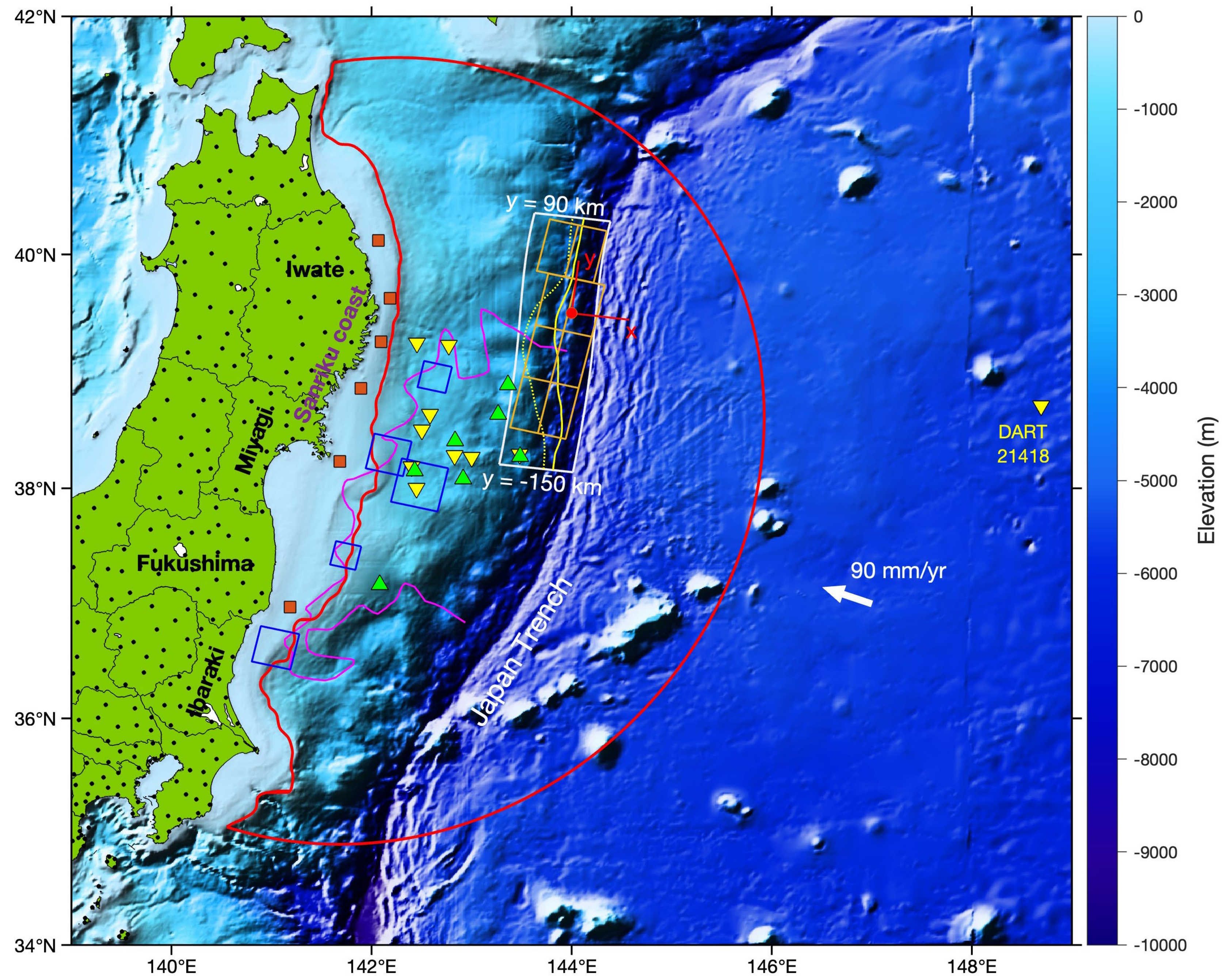
Uchida and Bürgmann (2021)



Ma (2023)



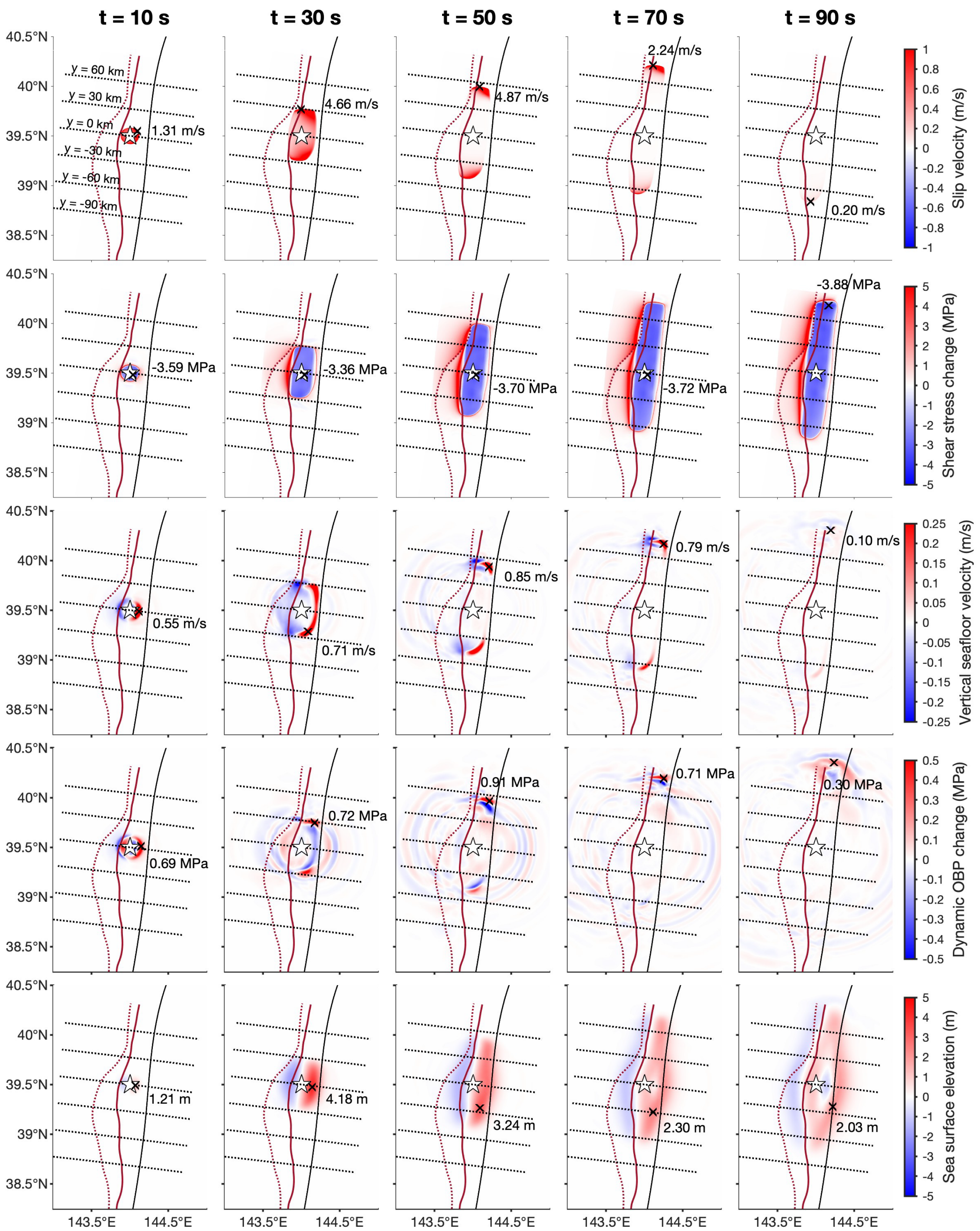
Kubota et al. (2022)



Modelling the 1896 Sanriku Earthquake

Du and Ma (2025)

Rupture Snapshots



Slip velocity

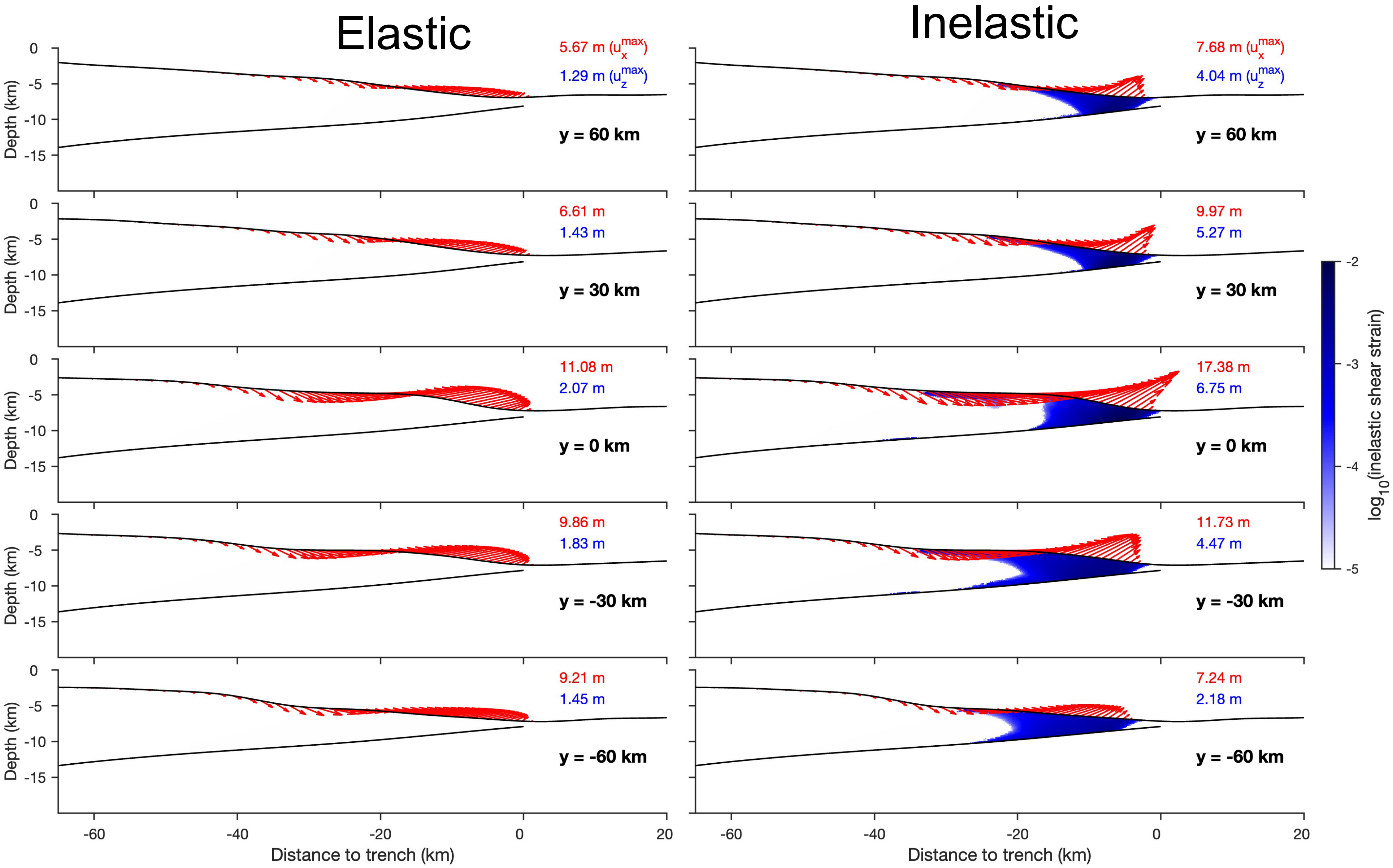
Shear stress change

Vertical seafloor velocity

Ocean bottom pressure change

Sea surface elevation

Comparison of Final Seafloor Displacement

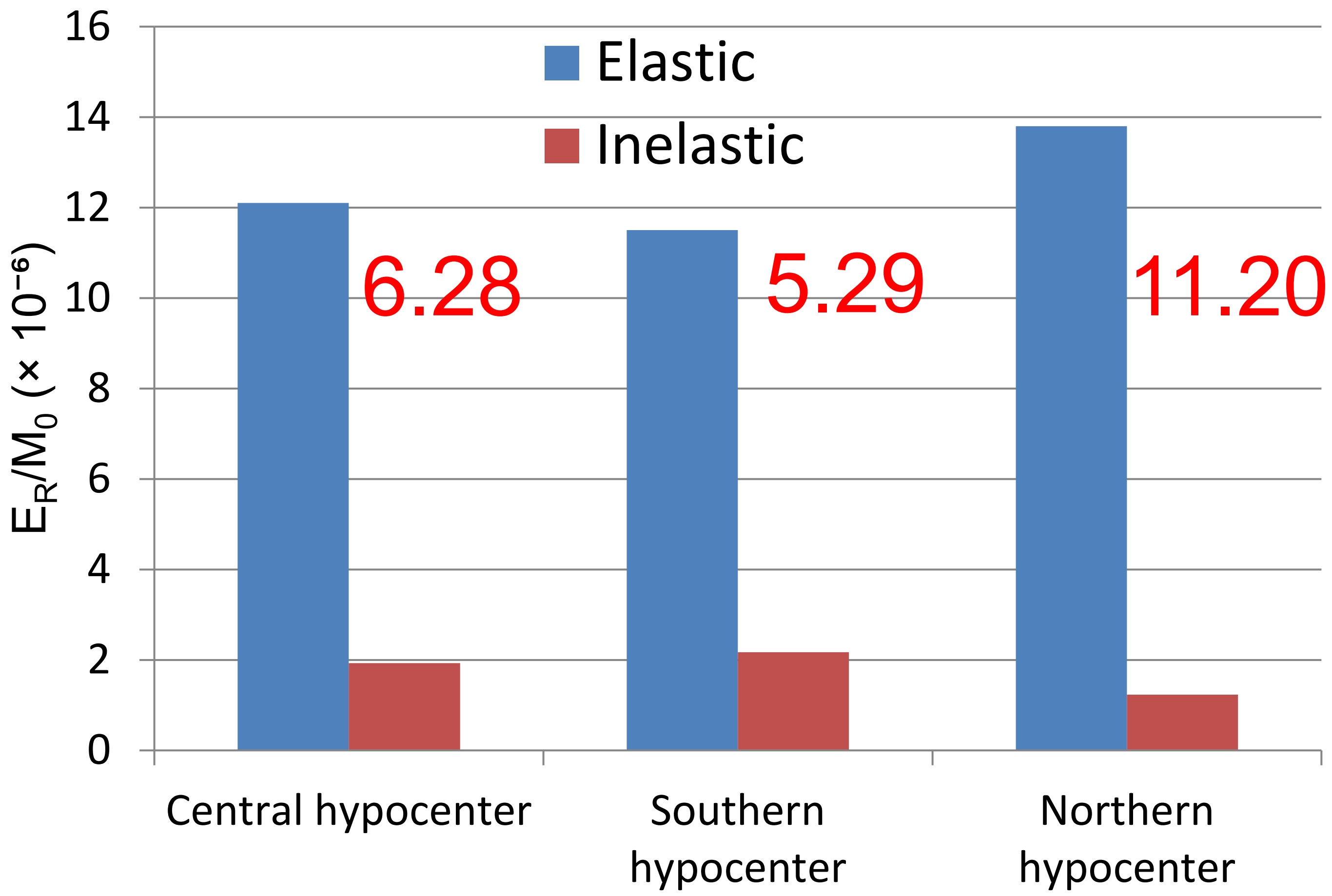


Elastic

Inelastic

Moment-Scaled Radiated Energy

Strong shallow yielding substantially reduces radiated energy.



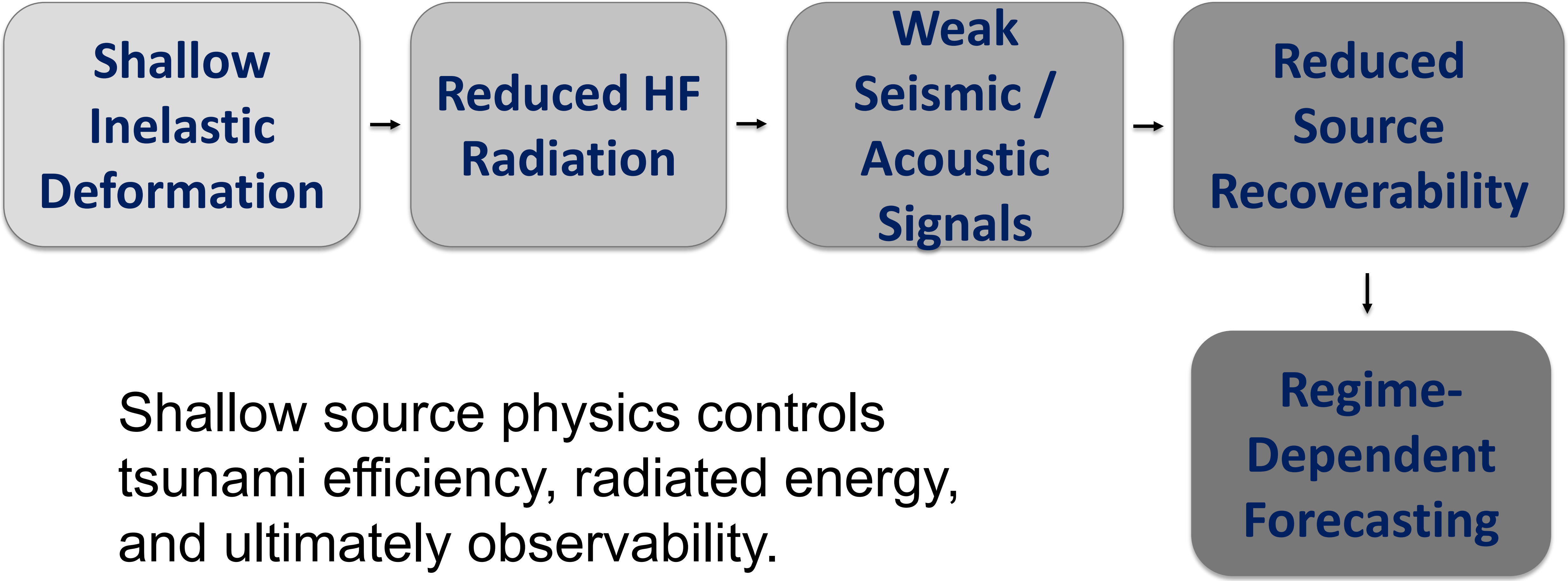
Key interpretation

- Inelastic deformation acts as a major energy sink
- Reduced E_R/M_0 is consistent with tsunami-earthquake behavior

Strong shallow yielding produces dissipation-dominated rupture behavior.

Source Physics Controls Observability

Some tsunami-generating earthquakes may be intrinsically difficult to recover.



Shallow Inelastic Deformation → **Reduced HF Radiation** → **Weak Seismic / Acoustic Signals** → **Reduced Source Recoverability**

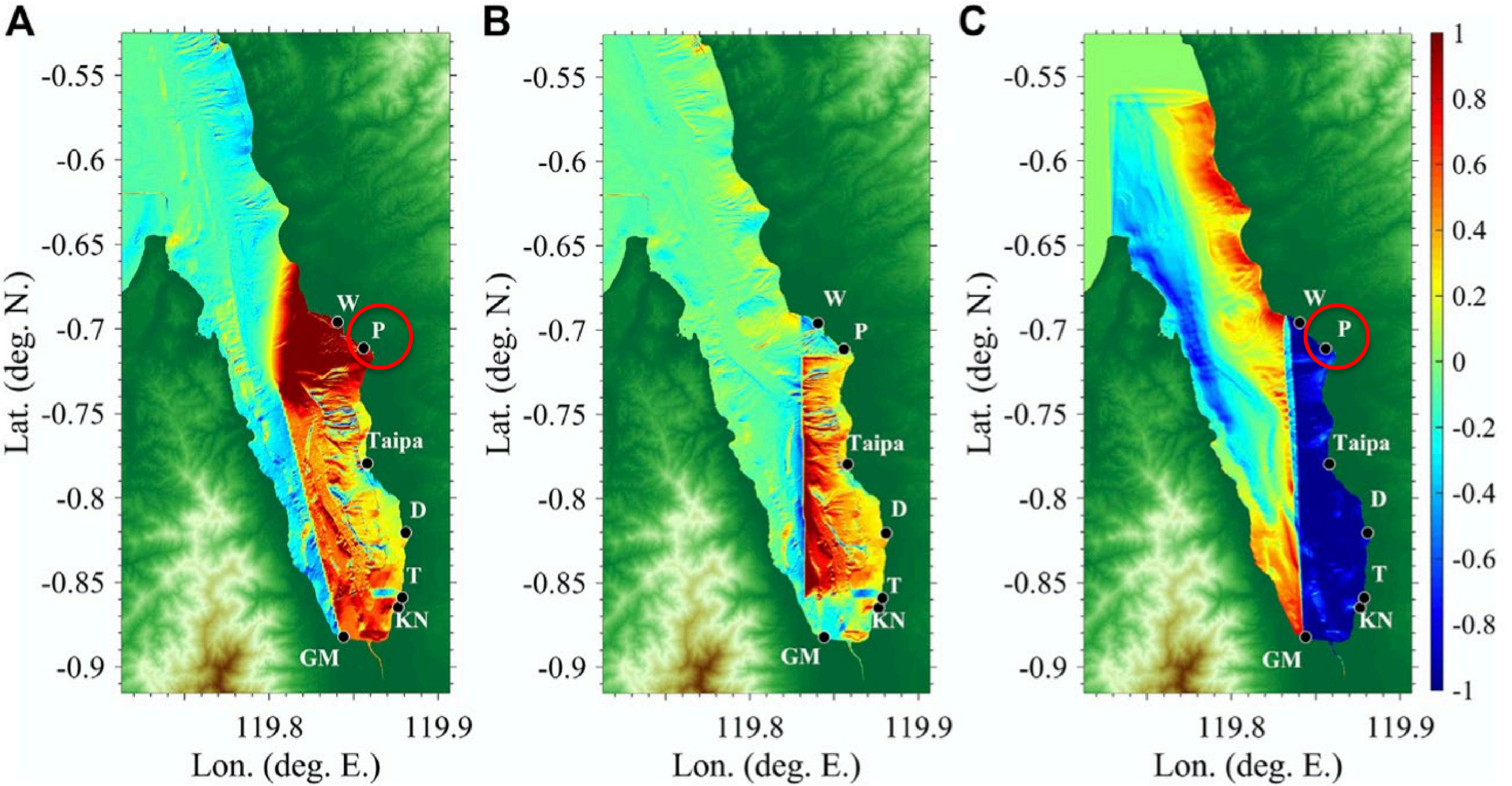
↓

Regime-Dependent Forecasting

Shallow source physics controls tsunami efficiency, radiated energy, and ultimately observability.

Beyond subduction megathrusts

2018 M_W 7.5 Palu Earthquake

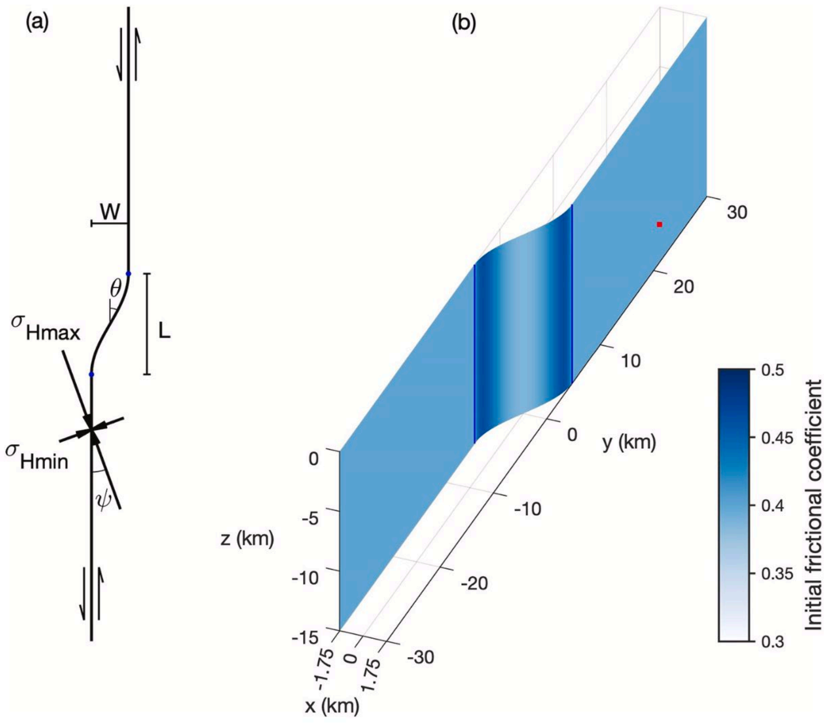


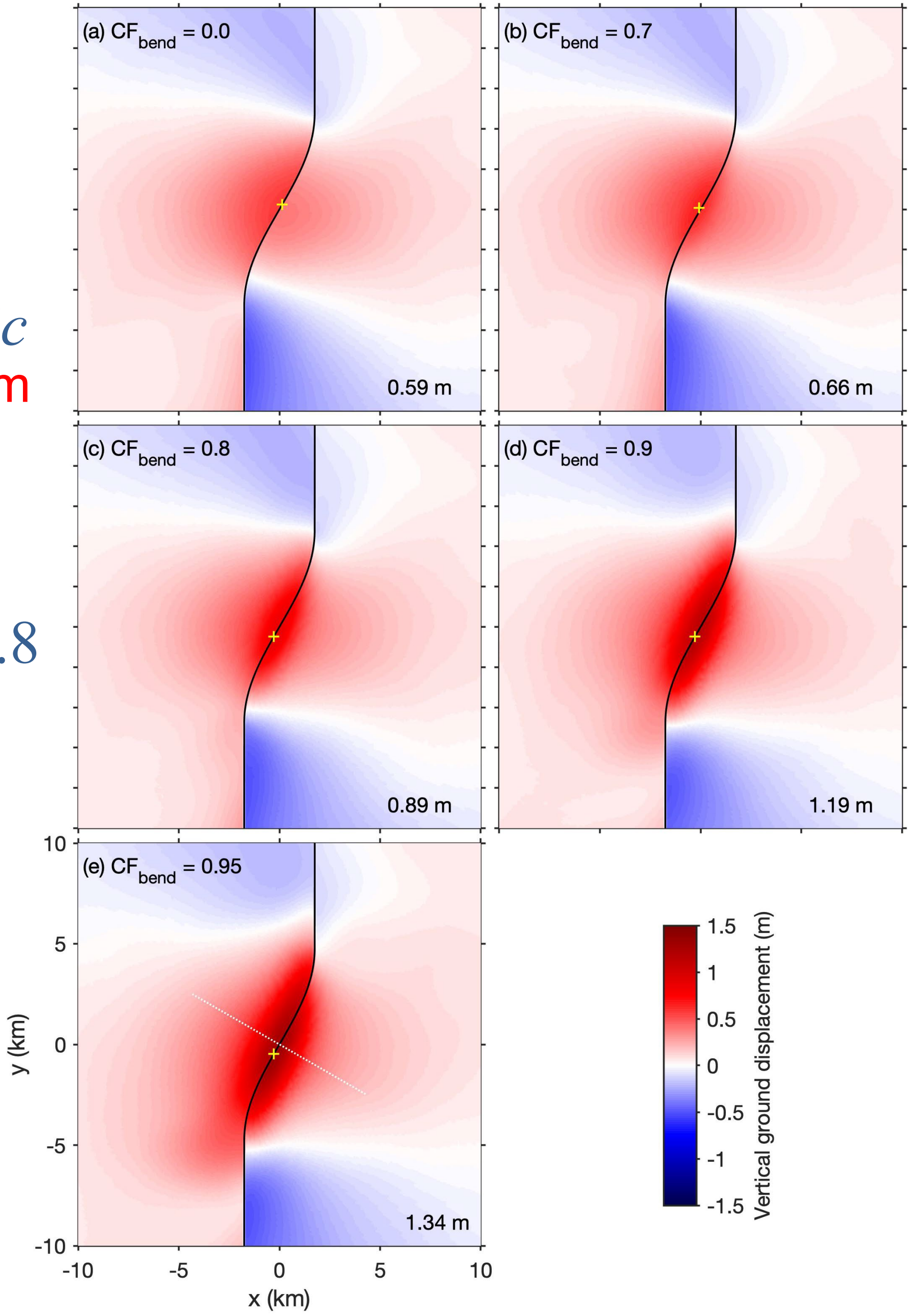
Jamelot et al. (2019) Socquet et al. (2019) Ulrich et al. (2019)

A key constraint is that Pantoloan tidal station recorded little uplift or subsidence.

Schambach et al. (2021)

Efficient uplift at restraining bends due to inelastic off-fault deformation





Elastic
0.59 m

$CF_{bend} = 0.7$
0.66 m

$CF_{bend} = 0.8$
0.89 m

$CF_{bend} = 0.9$
1.19 m

$CF_{bend} = 0.95$
1.34 m

Ma (2022)

Take-Home Messages

- Inelastic wedge deformation may fundamentally alter tsunami generation efficiency and energy partitioning.
- The same mechanism suppresses high-frequency radiation and limits observability.
- Integrating inelastic deformation into future source frameworks is an important DET research direction.

Thank you