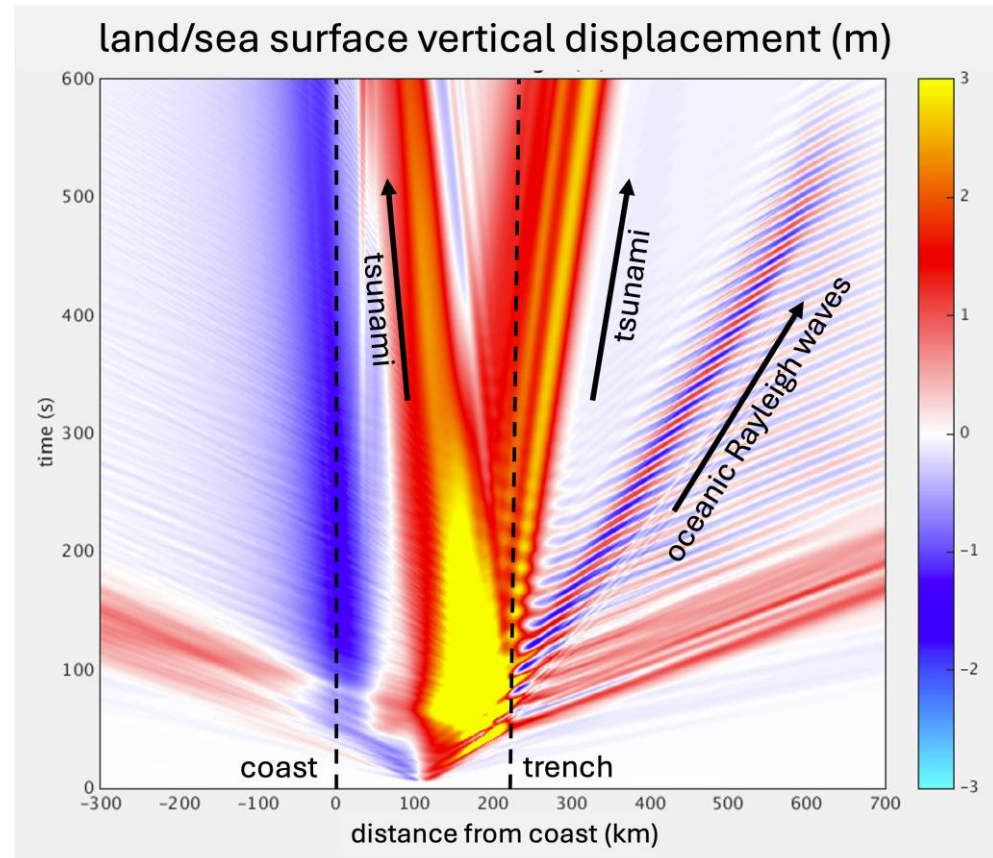
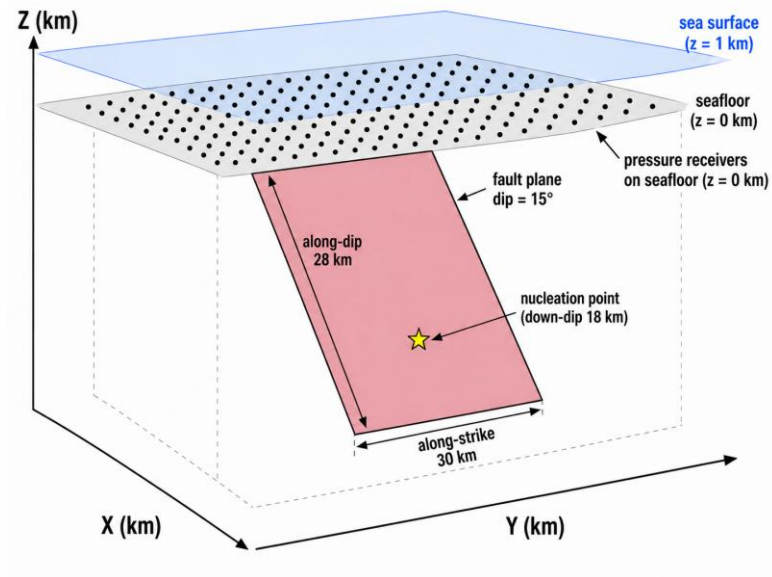


Shallow Rupture Dynamics and Tsunamigenesis: Opportunities and Priorities for Forward and Inverse Modeling

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Institute for Computational and
Mathematical Engineering
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Wenqiang Zhang, Gabe Lotto, Lauren Abrahams
collaborators: Lukas Krenz, Alice Gabriel, Tatsuhiko Saito
TTPV benchmarks: Fabian Kutschera, Shuo Ma, Wenqiang, Alice



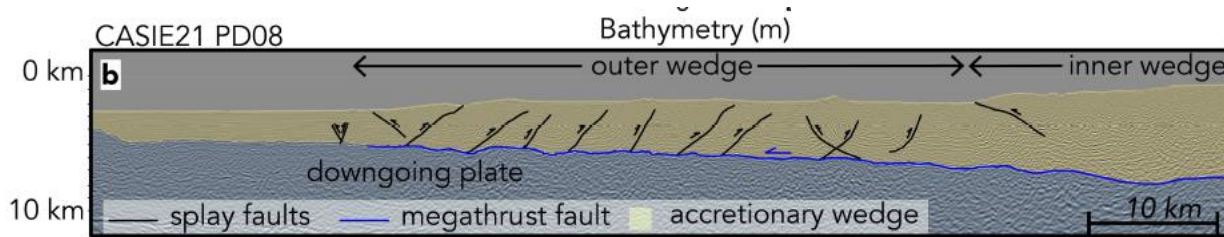
1. Stress and pressure control shallow rupture dynamics –
Need to integrate long-term ($\sim 10^4$ - 10^6 yr) modeling with
dynamic rupture and cycle modeling
2. Tsunami generation physics (+ other wave modes, with
implications for source characterization and warning)
3. Turbulent boundary layers—are we missing something?

Also important, but covered by others:

- rupture dynamics with splays and off-fault yielding
- tsunami directivity and sensitivity to slip heterogeneity and
rupture propagation along-strike (e.g., Williamson et al., 2019
Melgar, 2026)

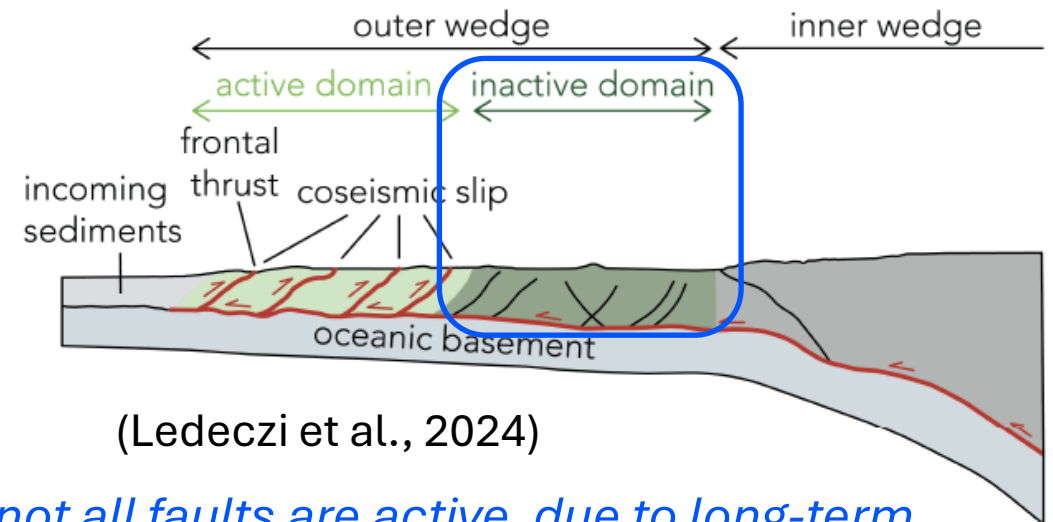
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Splay faults and accretionary prism



Simplest dynamic rupture modeling workflow:

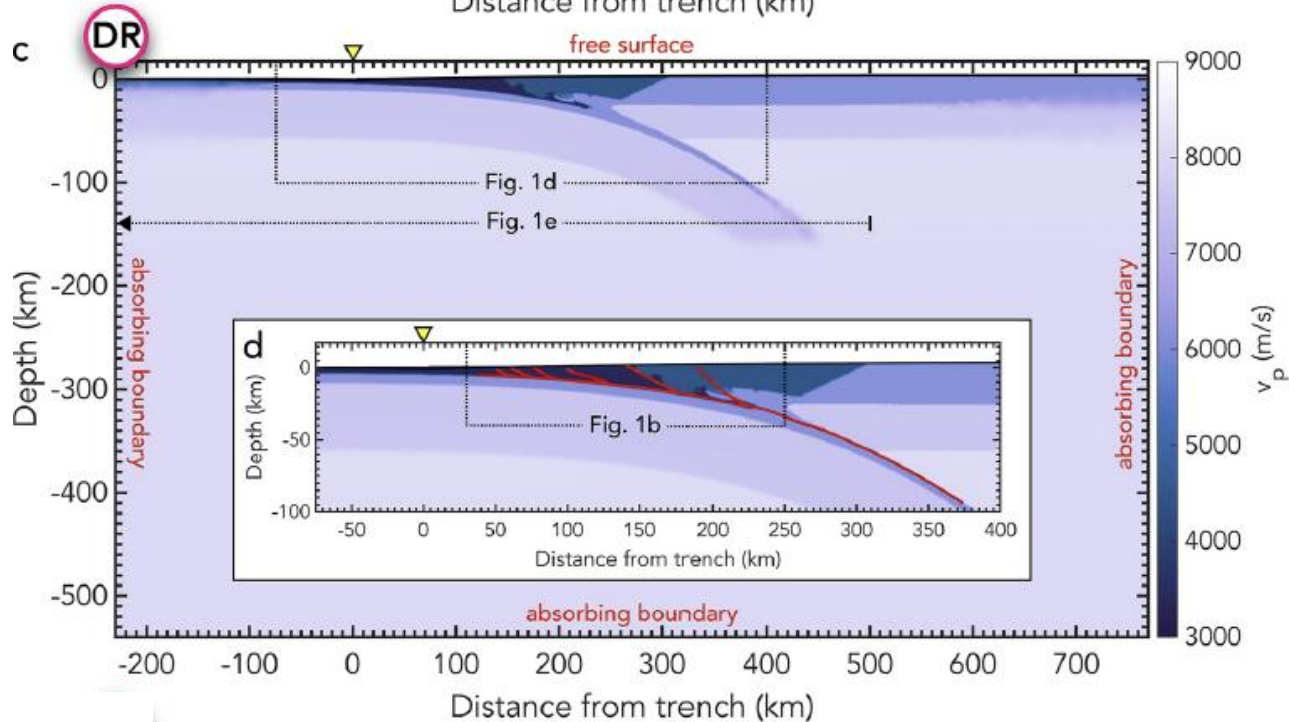
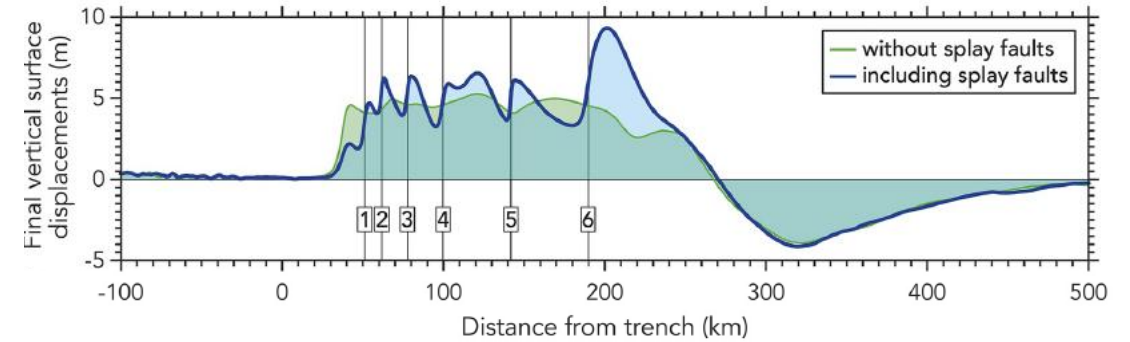
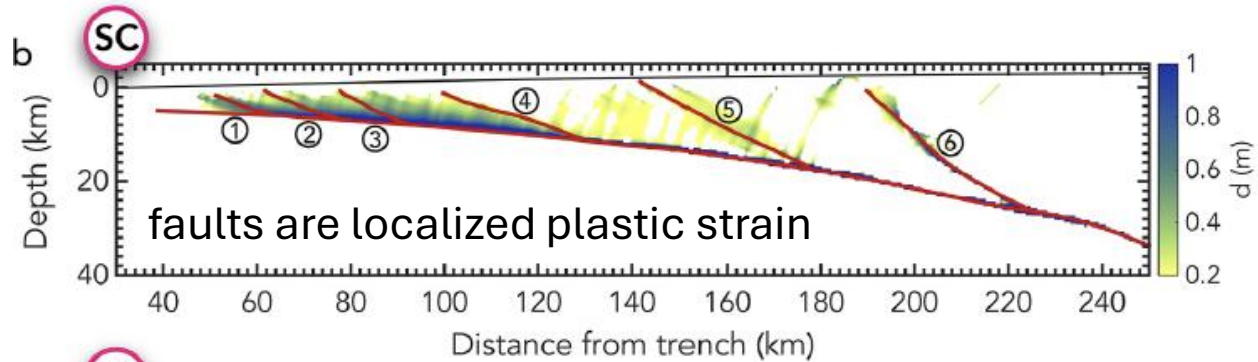
- Add mapped splays to megathrust model
- Critical taper theory to set stress/pressure
- Perform dynamic rupture model



(Ledeczi et al., 2024)

But not all faults are active, due to long-term evolution of stress and fluid pressure

Self-consistent stress from long-term modeling

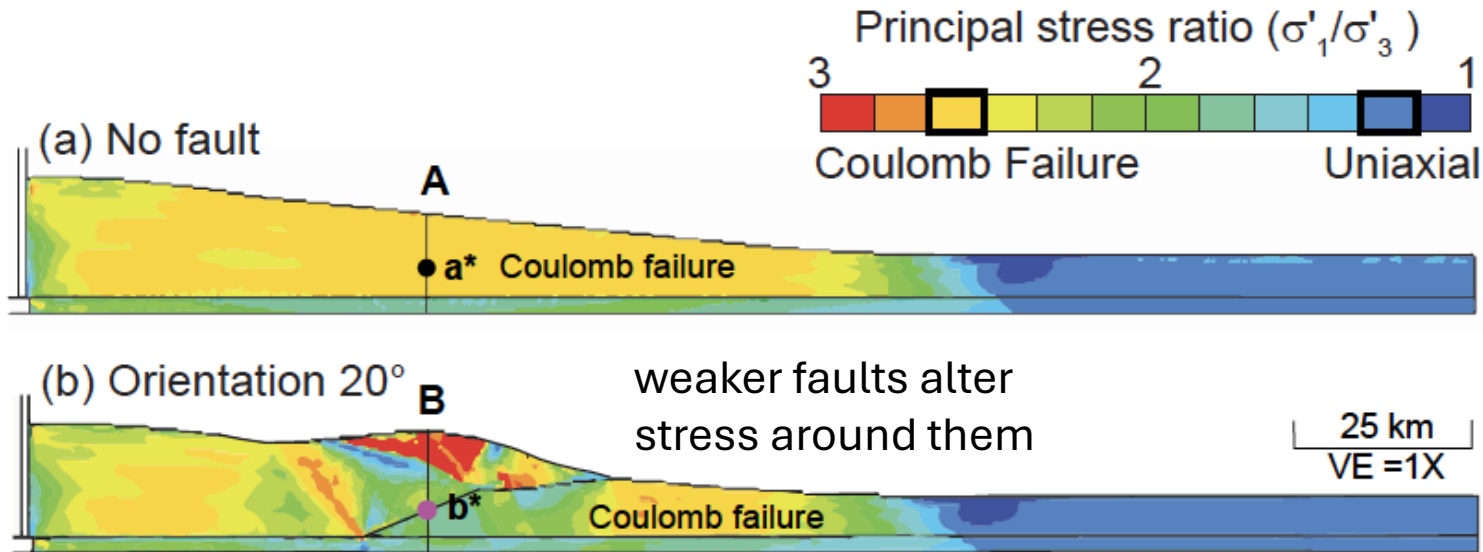


But all 6 splays slipped coseismically – why?

Alternative workflow:

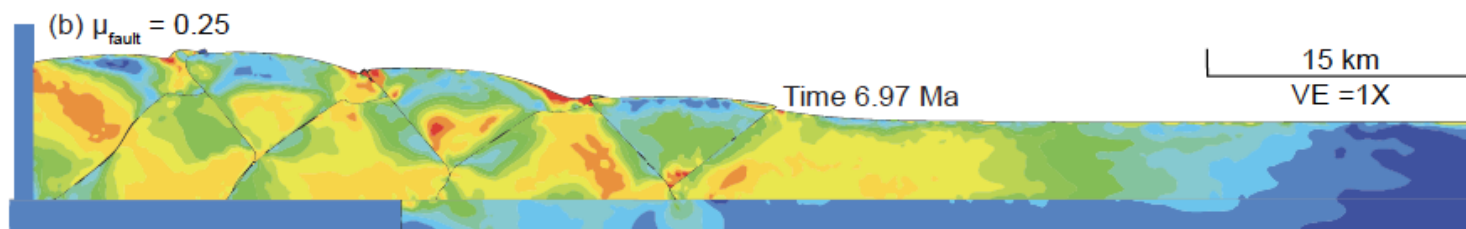
- Long-term geodynamics model for structure, stress, pressure
- Dynamic rupture model

Sedimentation and yielding produce stress states more complex than critical taper theory



(Lopez-Campos et al., 2024)

“Coulomb failure” =
critical taper assumption

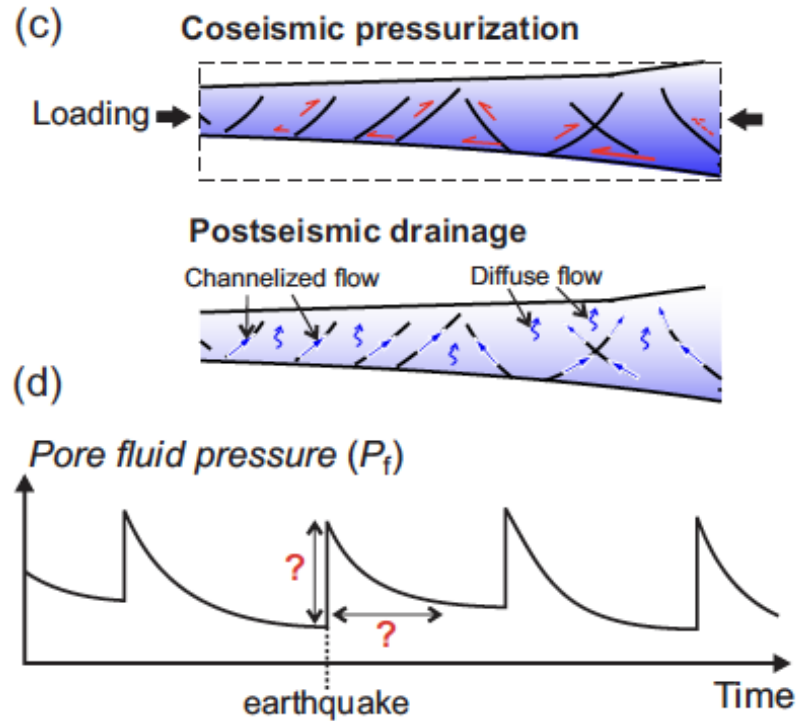


(Lopez-Campos et al., 2025)

Extension to multiple splay
faults that form spontaneously
shows seaward migration of
active faults

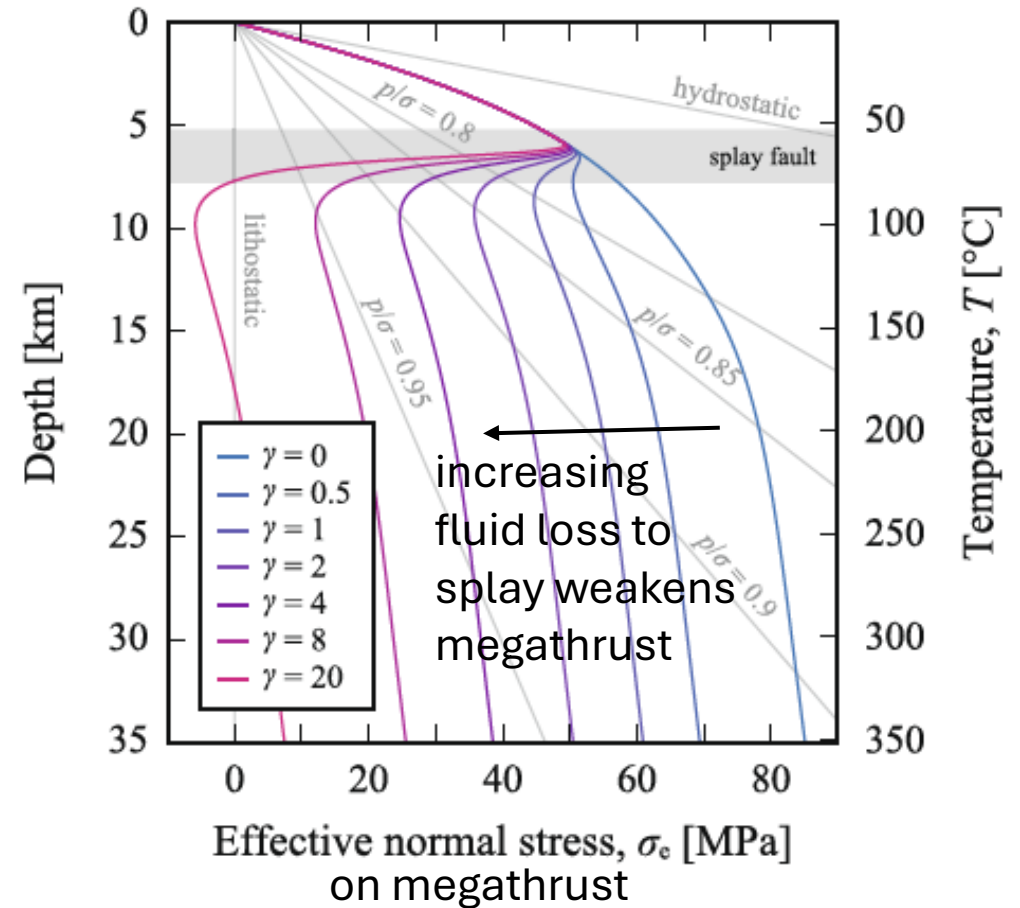
Fluids require more attention

...and fluid pressure and transport evolve over earthquake cycle



poroelastic modeling by Sun et al. (2026)

steady state fluid transport model (with flow localized to megathrust and splay), accounting for clay dehydration reaction kinetics

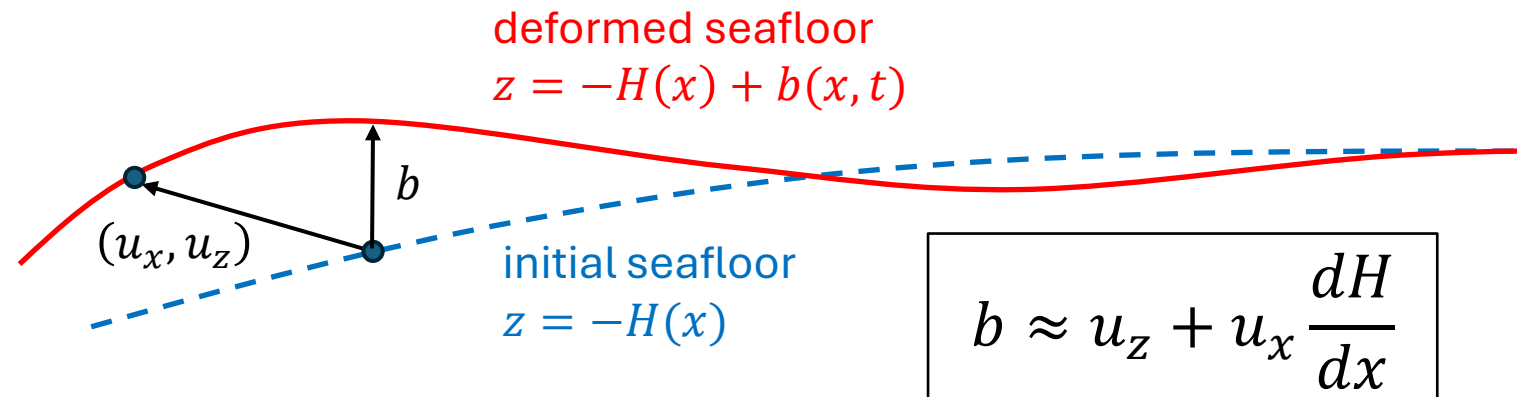


(Kaneki & Noda, 2023; see also Ozawa et al., 2026, on deeper dehydration and interplay with frictional-viscous transition)

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Tsunami generation from seafloor uplift

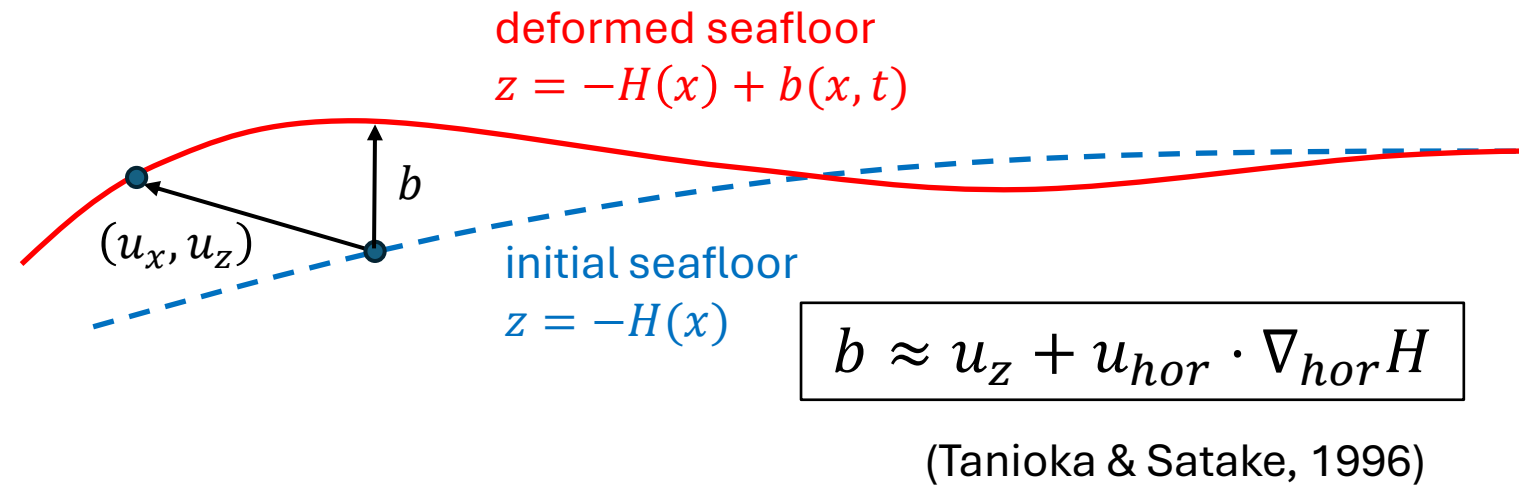
Tsunamis are generated by seafloor uplift, b , not vertical displacement, u_z .



(Tanioka & Satake, 1996)

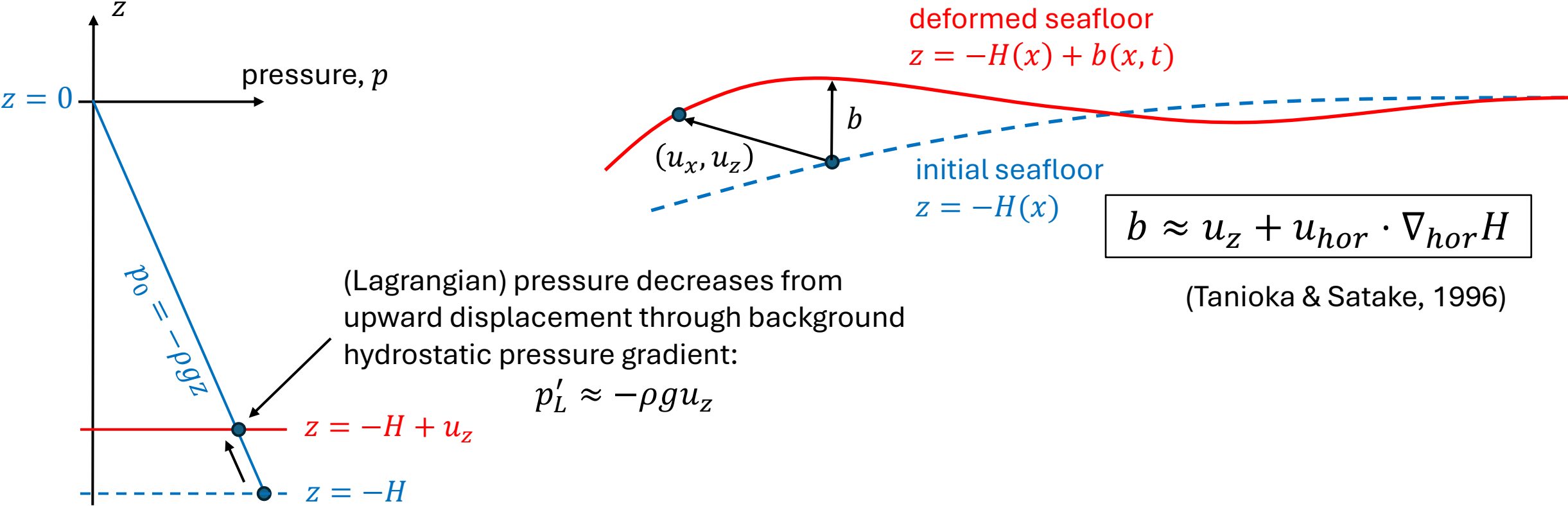
Tsunami generation from seafloor uplift

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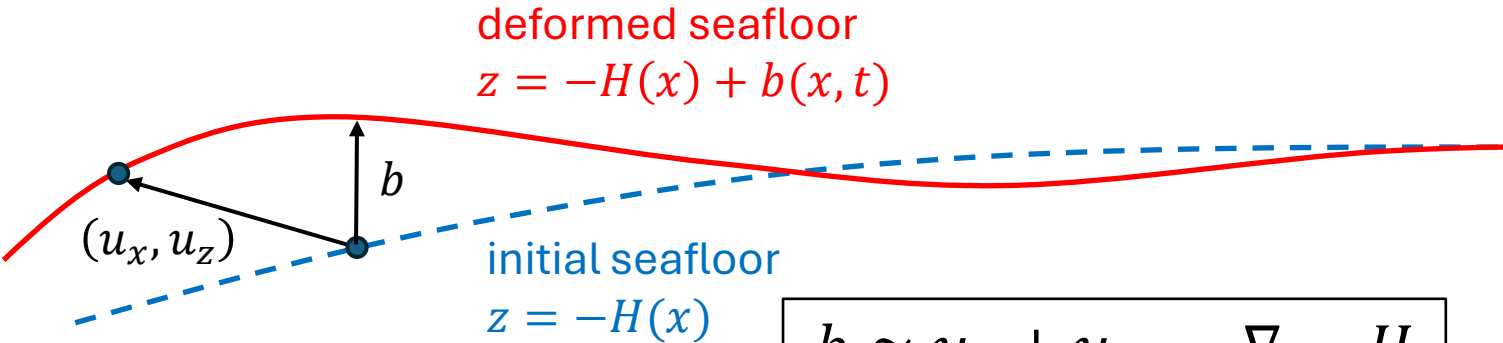
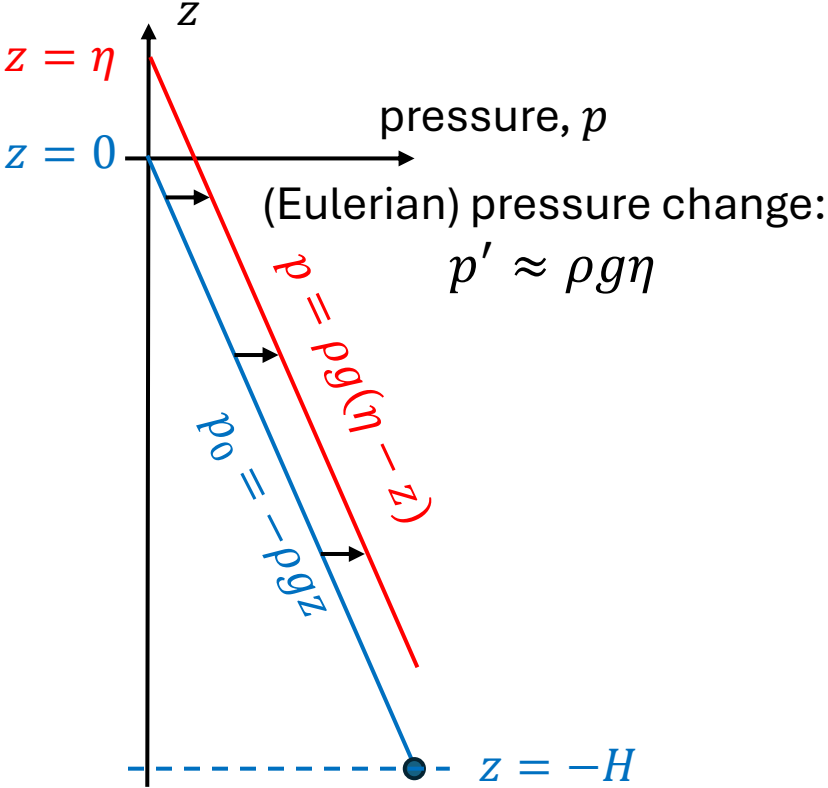
Seafloor pressure changes in an incompressible ocean

What do seafloor pressure sensors measure?



Seafloor pressure changes in an incompressible ocean

What do seafloor pressure sensors measure?



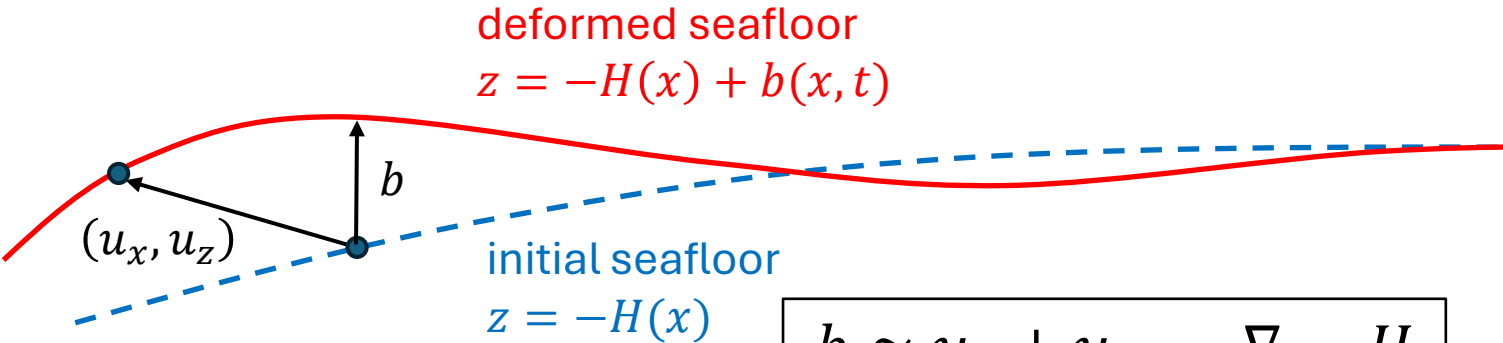
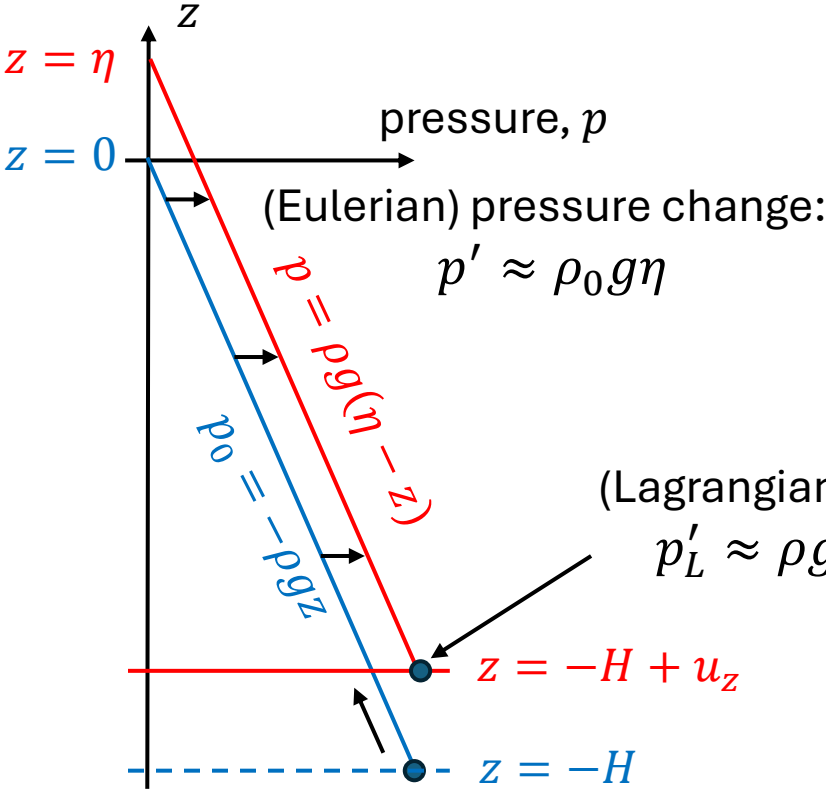
$$b \approx u_z + u_{hor} \cdot \nabla_{hor} H$$

(Tanioka & Satake, 1996)

$p' \approx \rho g \eta$ (hydrostatic) only if negligible vertical acceleration

Seafloor pressure changes in an incompressible ocean

What do seafloor pressure sensors measure?



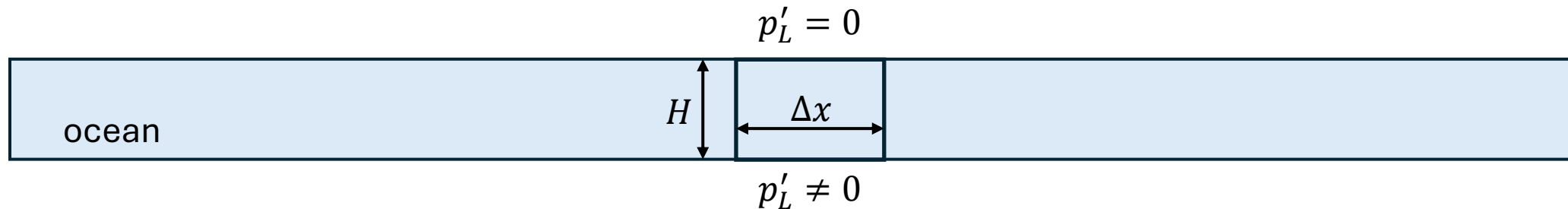
$$b \approx u_z + u_{hor} \cdot \nabla_{hor} H$$

(Tanioka & Satake, 1996)

*Must be careful to use correct pressure—
they have different information content!*

Ocean as a thin mass layer (no gravity case)

At low frequencies ($\omega H/c_0 \ll 1$) and long horizontal wavelengths ($kH \ll 1$), ocean is effectively incompressible and moves vertically as a thin mass layer:



$$\overbrace{\rho \Delta x \Delta y H}^{\text{mass}} \overset{\text{acceleration}}{\downarrow} \frac{\partial^2 u_z}{\partial t^2} \approx \overbrace{(p'_L - 0) \Delta x \Delta y}^{\text{forces from pressure on top and bottom}}$$

$$\Rightarrow \text{seafloor pressure: } p'_L \approx \rho H \frac{\partial^2 u_z}{\partial t^2}$$

sometimes referred to as “dynamic” pressure change to distinguish from “hydrostatic” pressure change

Seafloor pressure to seafloor acceleration

$$p'_L \approx \rho H \frac{\partial^2 u_z}{\partial t^2}$$

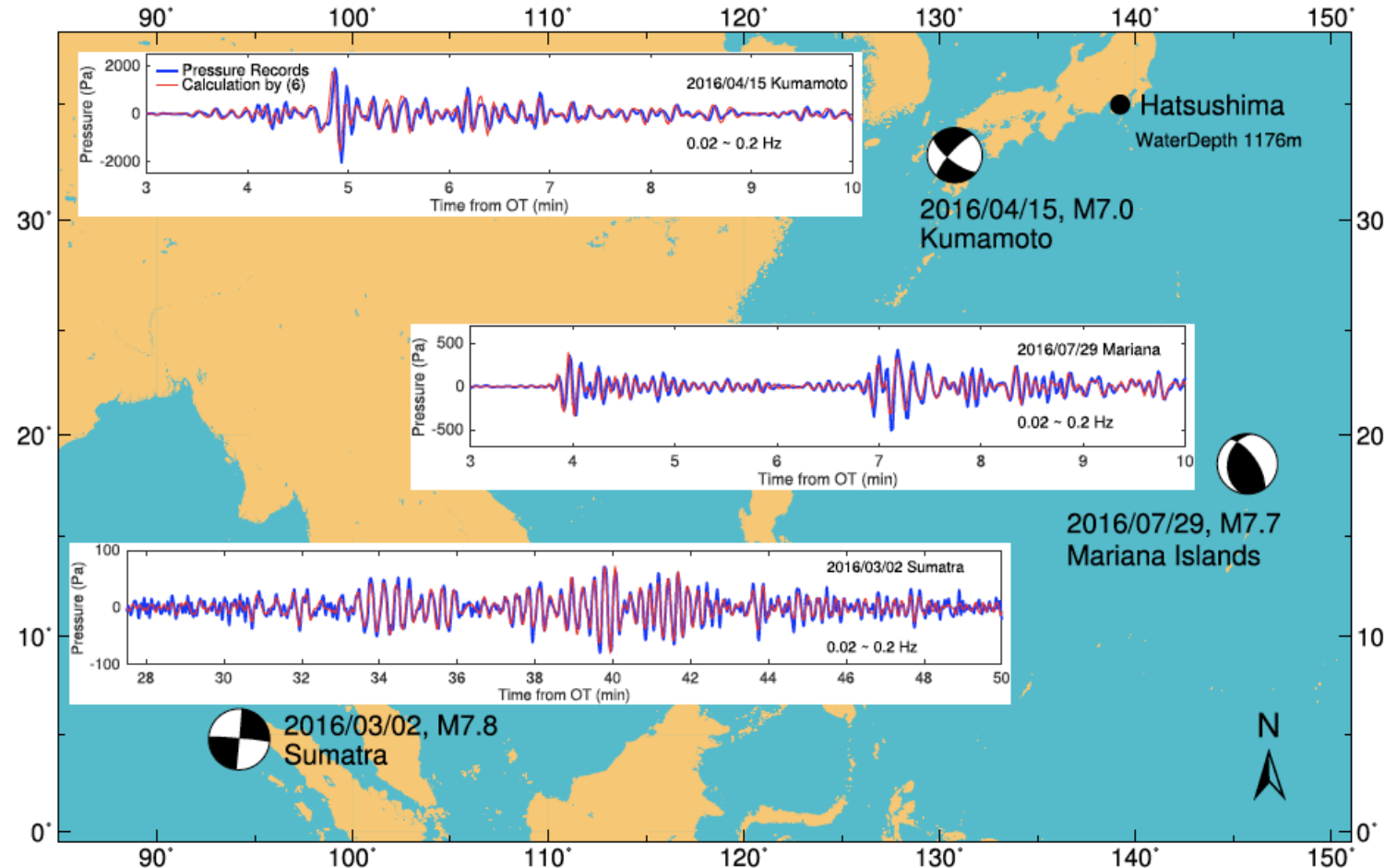
blue = pressure data (0.02 – 0.2 Hz)

red = scaled acceleration from
collocated OBS

these are (low frequency) seismic waves, not
tsunami, so no hydrostatic pressure change

Can we use this to determine seafloor uplift and tsunami generation?

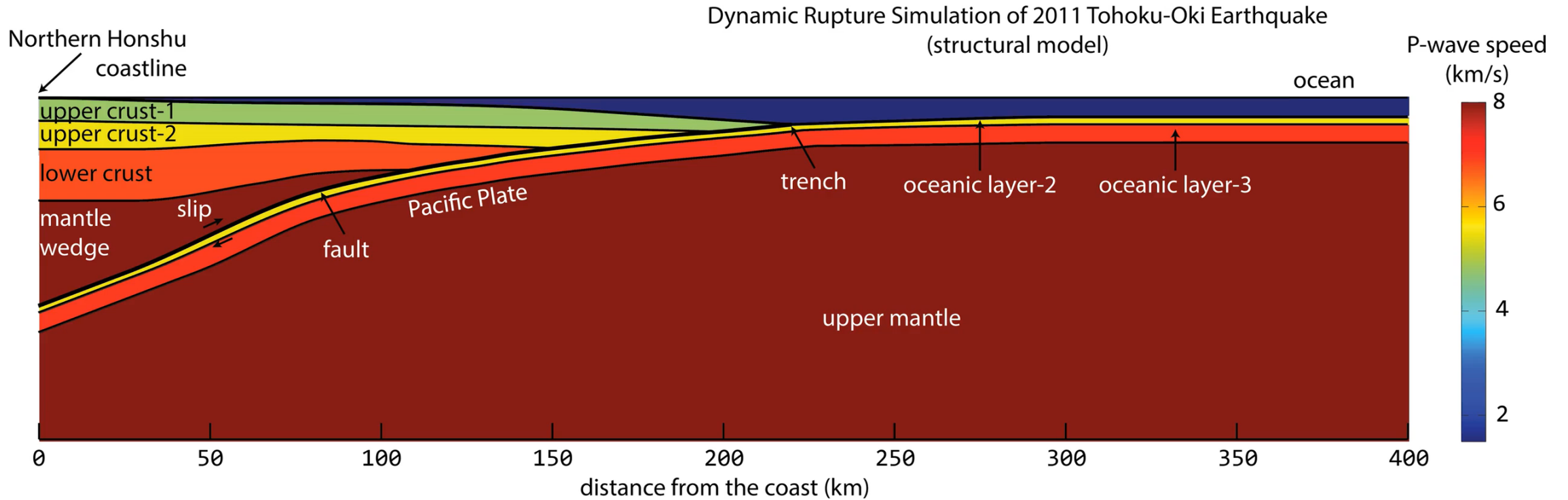
- u_z is not seafloor uplift $b = u_z + u_{hor} \cdot \nabla_{hor} H$
- possibly unstable integration to u_z
(without using hydrostatic pressure changes)
- missing higher frequencies that might be important
- ocean is compressible
(acoustic waves at high frequencies)



(An et al., 2017)

Offshore earthquakes generate complex wavefield

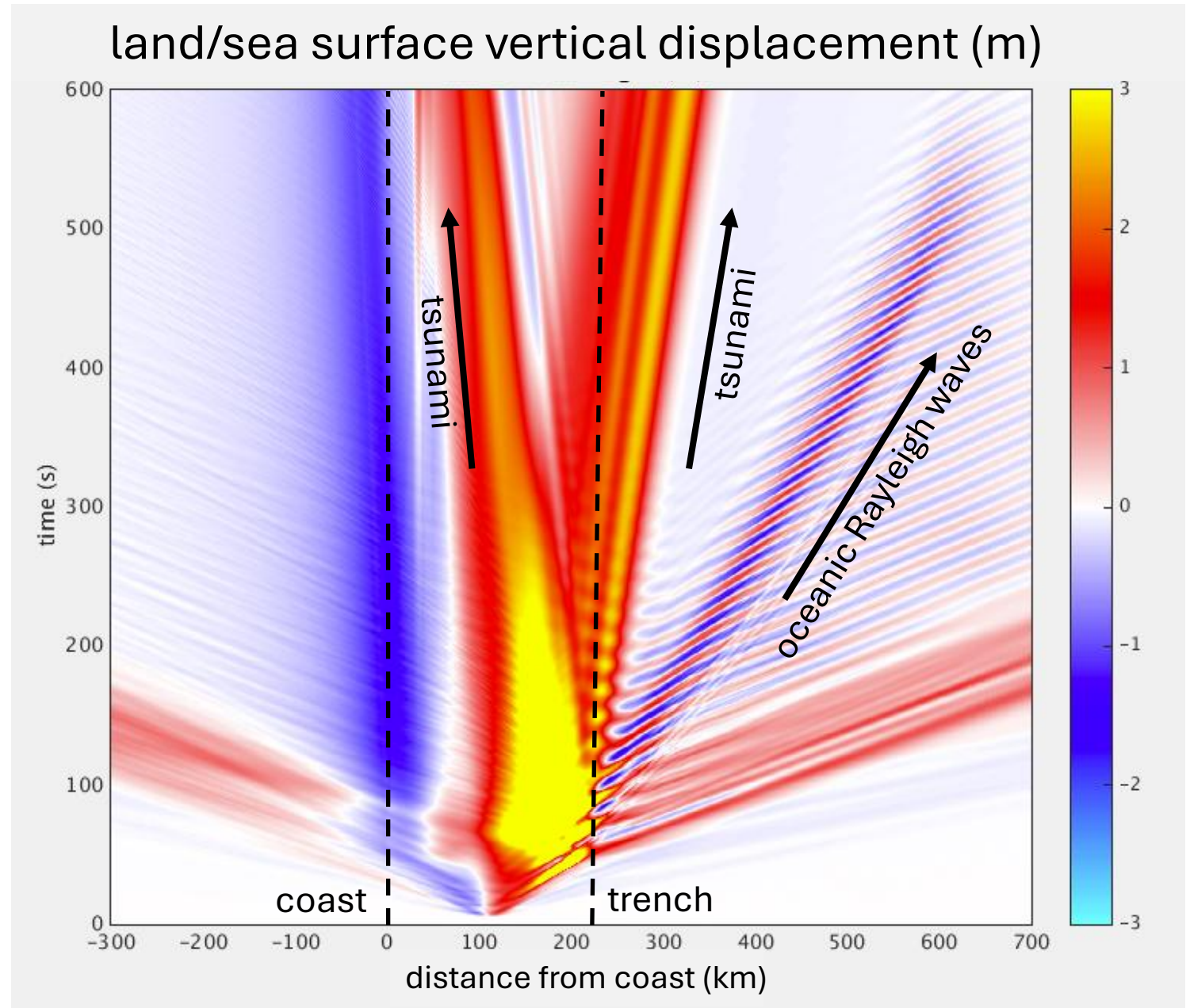
new simulation capabilities for “fully coupled” solid Earth-ocean modeling emerged after 2011 Tohoku-Oki (e.g., Maeda & Furumura, 2013; Lotto & Dunham, 2015)



2D dynamic rupture simulation of Tohoku-Oki (Kozdon & Dunham, 2014)

Offshore earthquakes generate complex wavefield

- tsunami: ~ 200 m/s
- seismic and ocean acoustic waves (usually coupled, not separate types of waves): $\sim 1-6$ km/s
- internal gravity waves in ocean and atmosphere



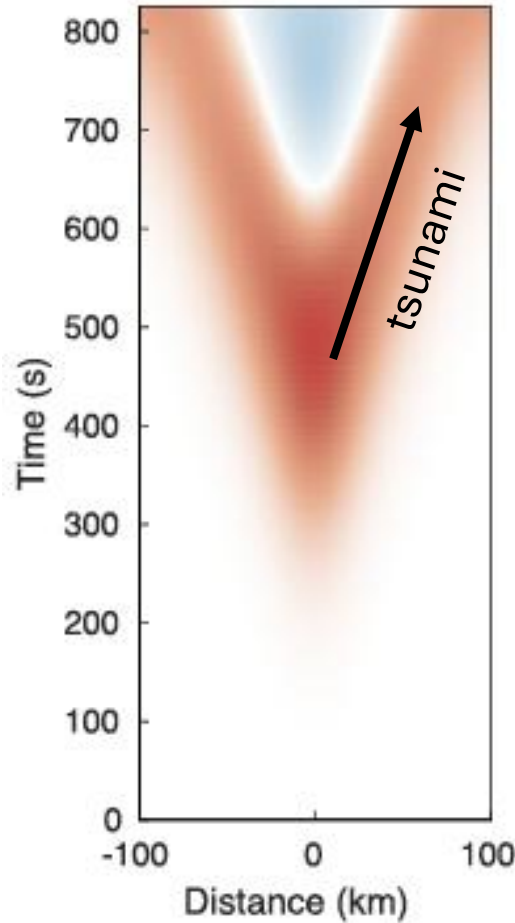
Wave generation depends on source duration and horizontal wavelengths

three examples of imposed Gaussian-shaped seafloor uplift over timescale

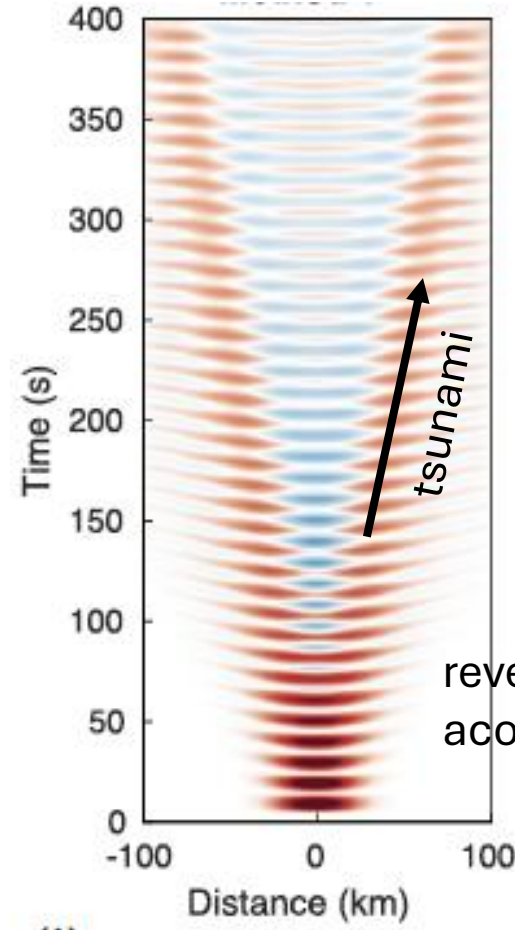
For $e^{i(kx-\omega t)}$ solution, dimensionless parameters:

- $\omega H/c_0$ (frequency * acoustic wave travel time over ocean depth)
- kH (horiz. wavenumber * ocean depth)

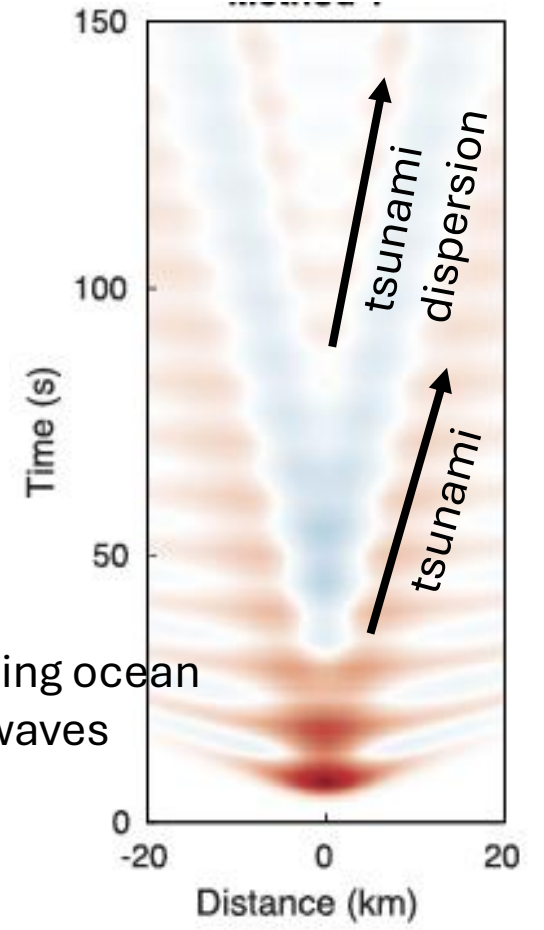
color = sea surface height (& note different axes limits)



long wavelength, long duration
 → only tsunami (nondispersive)



long wavelength, short duration
 → tsunami (nondispersive) and ocean acoustic reverberations



short wavelength, short duration
 → tsunami (dispersive) and ocean acoustic reverberations⁰

Tsunami generation – incompressible case

$$\begin{aligned} \nabla \cdot \mathbf{v} &= 0, & p' - \rho g \eta &= 0, \quad \frac{\partial \eta}{\partial t} = v_z \text{ at } z = 0 \\ \rho \frac{\partial \mathbf{v}}{\partial t} + \nabla p' &= 0 & \frac{\partial b}{\partial t} &= v_z \text{ at } z = -H = \text{const.} \end{aligned}$$

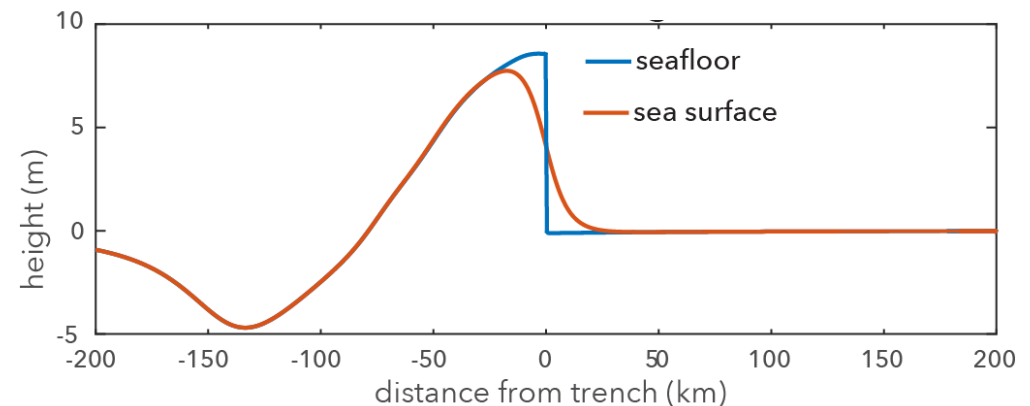
For $e^{i(kx - \omega t)}$ solution, $\hat{\eta}(k, \omega) = T(k, \omega) \hat{b}(k, \omega)$ with $T(k, \omega) = \frac{1}{\cosh(kH) - \left(\frac{gk}{\omega^2}\right) \sinh(kH)}$.

$T^{-1} = 0$ gives dispersion relation $\omega^2 = gk \tanh(kH) \rightarrow gHk^2$ when $kH \ll 1$ (long wavelength).

Tsunami propagation is nondispersive at $c \approx \sqrt{gH}$. Boussinesq approximation adds additional term.

Instantaneous response gives Kajiura (1963) “filter”

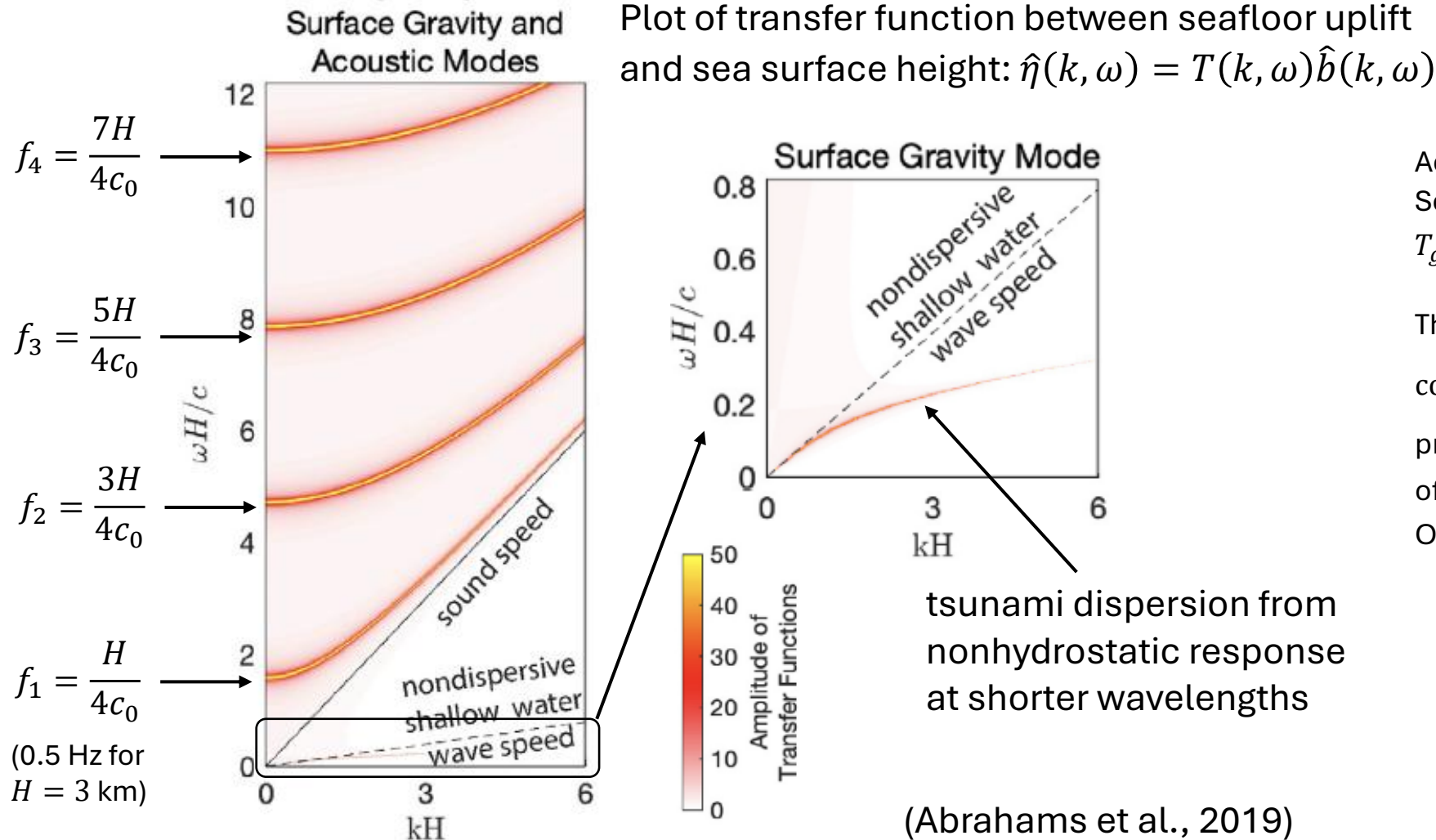
$$T(k, \omega \rightarrow \infty) = \frac{1}{\cosh(kH)}$$



Compressibility adds additional wave modes

Surface gravity wave (tsunami) mode + infinite set of acoustic modes (propagating or evanescent).

Because $\frac{gH}{c_0^2} \approx 0.02 \ll 1$, neglect compressibility for gravity waves and gravity for acoustic waves.



Acoustic modes:

Set $g = 0$. $\hat{\eta}(k, \omega) = T(k, \omega)\hat{b}(k, \omega)$ with $T_{g=0}(k, \omega) = \frac{1}{\cos(\sqrt{\omega^2/c_0^2 - k^2H})}$.

This gives dispersion relation

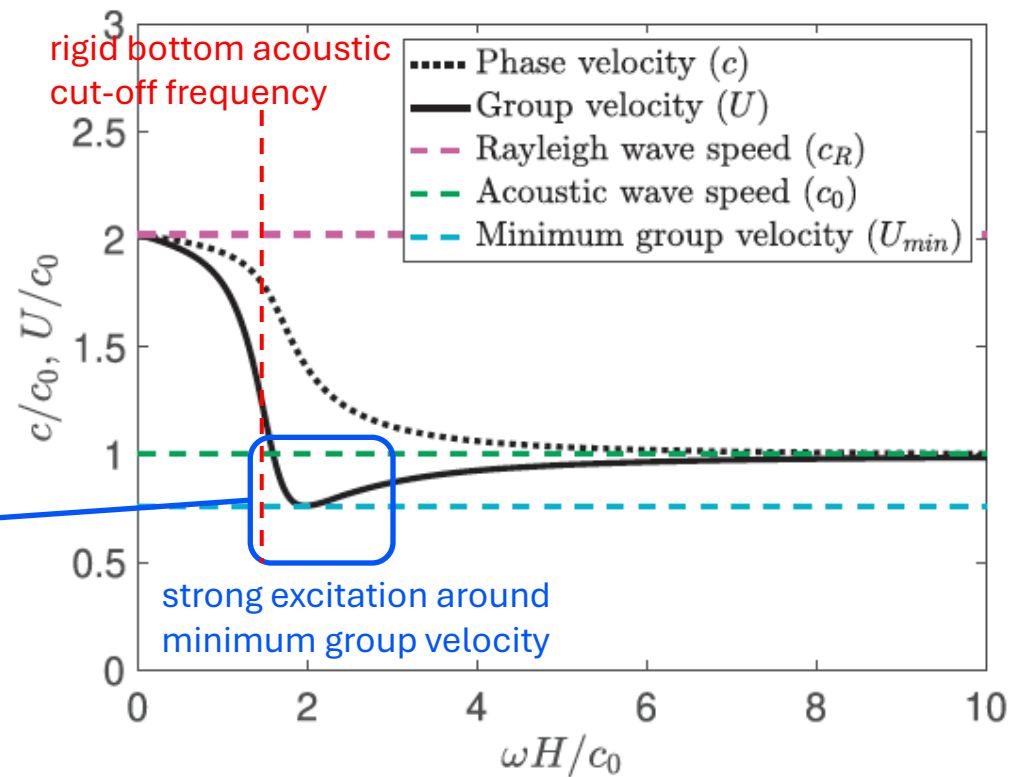
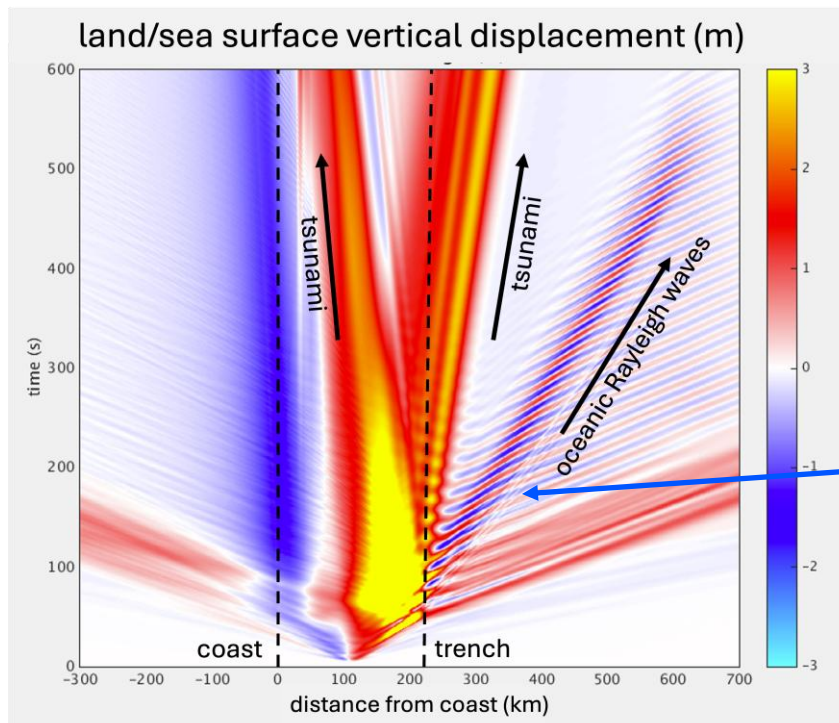
$\cos(\sqrt{\omega^2/c_0^2 - k^2H}) = 0$, which has

propagating wave solutions only above cut-off frequencies $\omega_n = (n - \frac{1}{2})\frac{\pi c_0}{H}$, $n = 1, 2, \dots$

Otherwise, waves are evanescent.

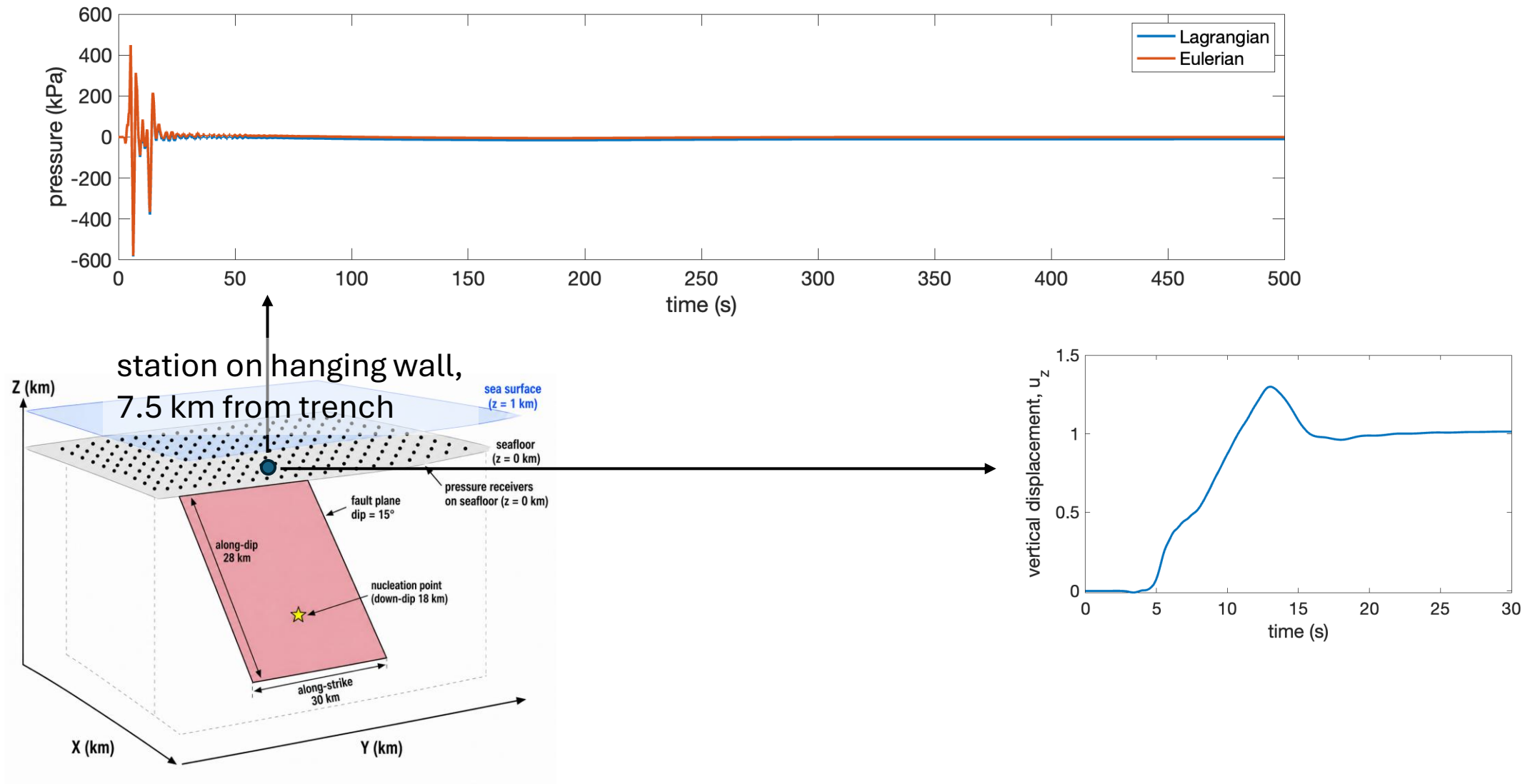
Coupling to elastic solid alters wave modes

First acoustic mode becomes “oceanic Rayleigh wave,” which is propagating for all frequencies (no cut-off frequency). When $\frac{\omega H}{c_0} \ll 1$, ocean becomes negligible and propagation occurs at Rayleigh speed c_R (Biot, 1952; Eyov et al., 2013).

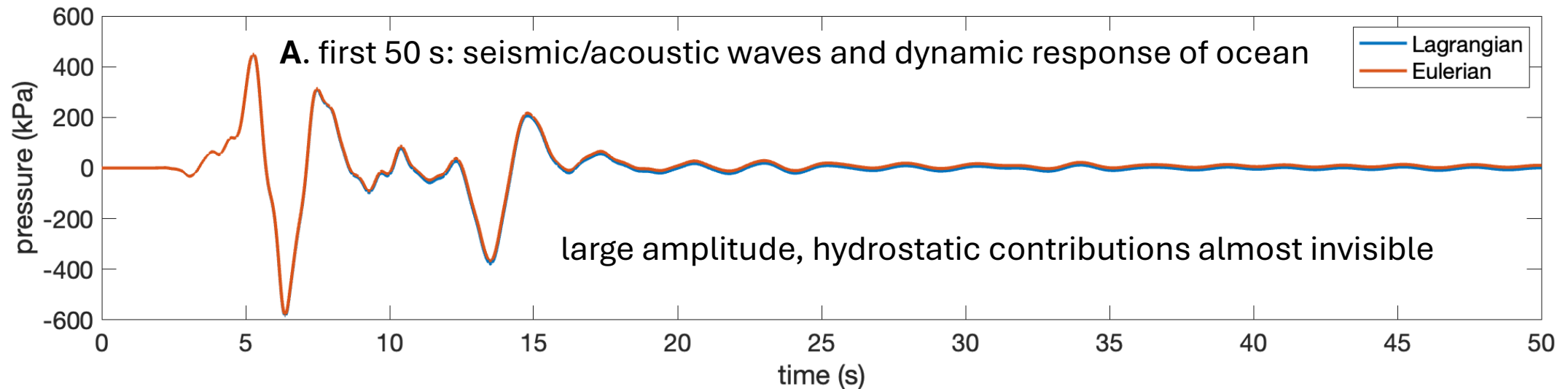
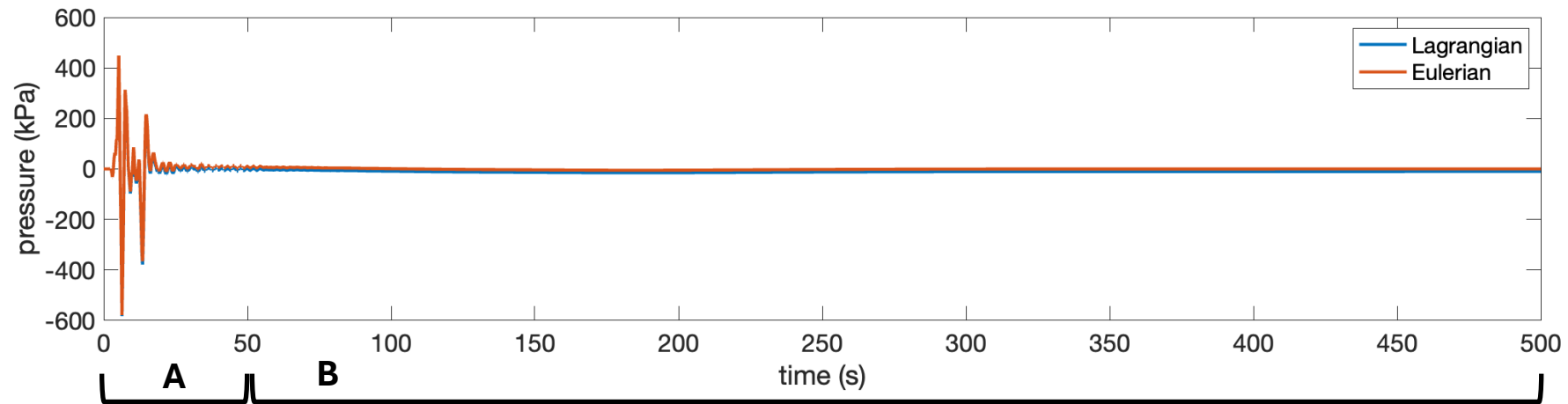


(Abrahams et al., 2019)

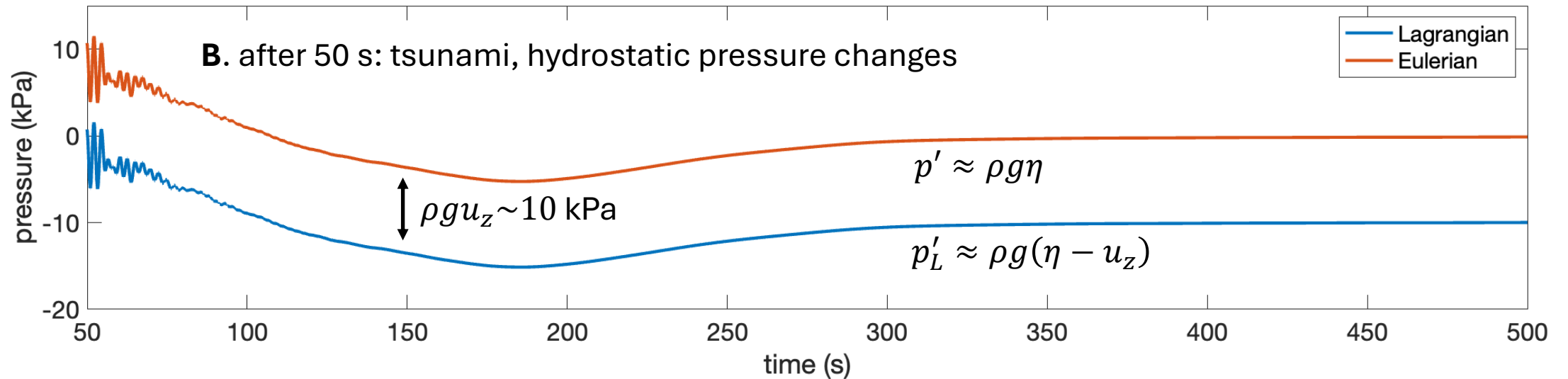
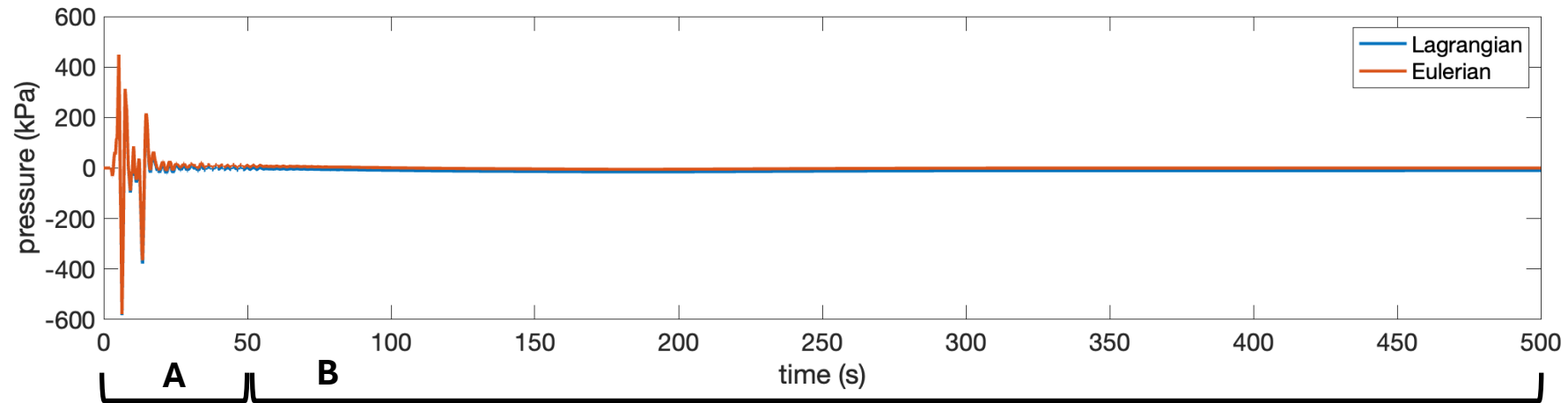
Seafloor pressure in TTPV1 benchmark problem



Lagrangian pressure $p'_L = p' - \rho g u_z$, p' includes tsunami (hydrostatic, $kH \ll 1$), dynamic (vertical acceleration), acoustic waves from compressibility

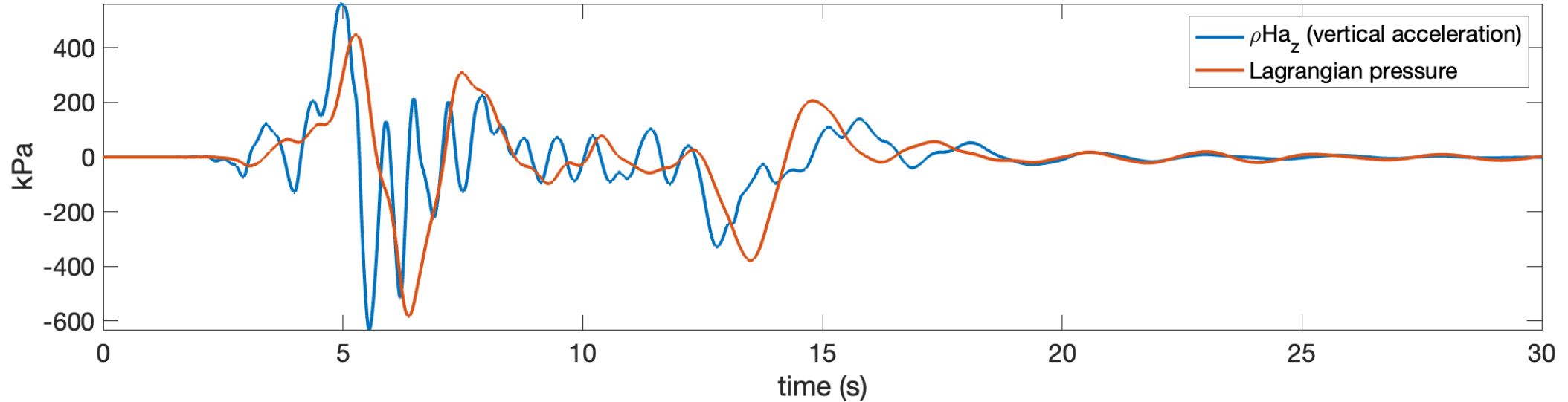


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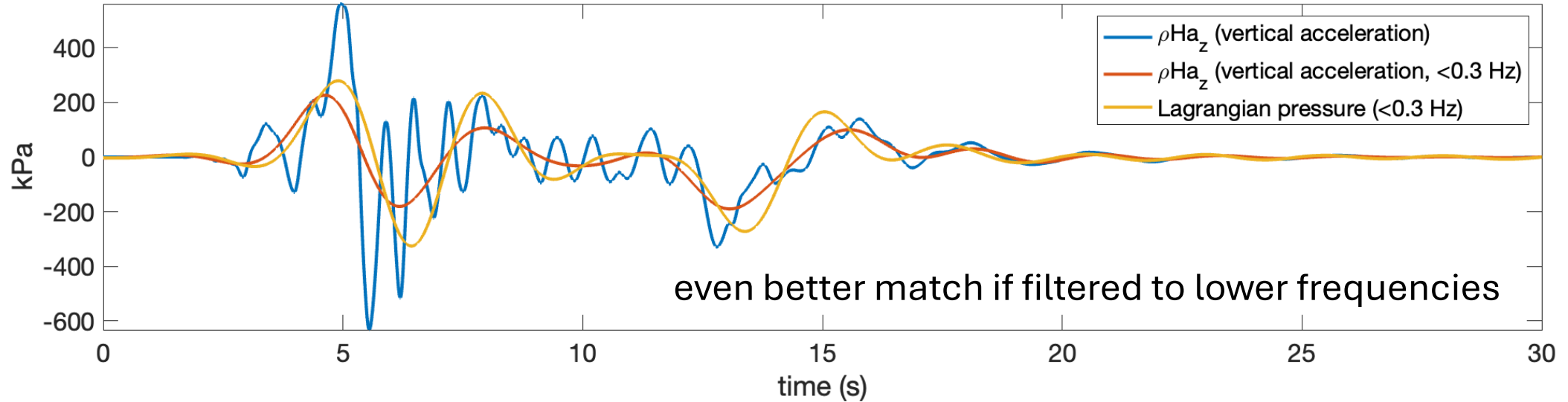
Dynamic pressure proportional to seafloor acceleration at low frequencies $\left(\frac{\omega H}{c_0} < 1\right)$

$$p'_L \approx \rho H \frac{\partial^2 u_z}{\partial t^2}$$



Dynamic pressure proportional to seafloor acceleration at low frequencies $\left(\frac{\omega H}{c_0} < 1\right)$

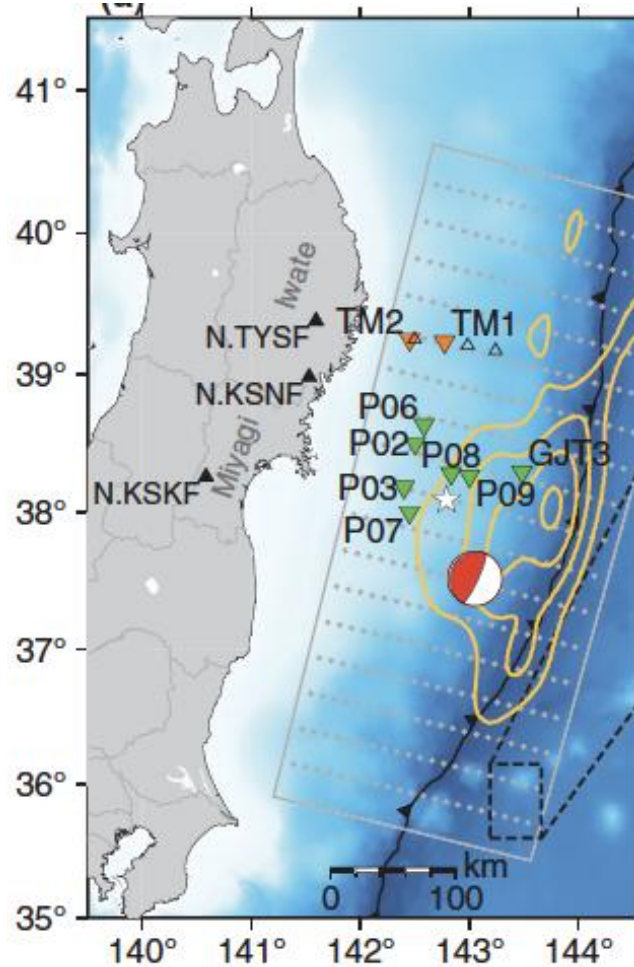
$$p'_L \approx \rho H \frac{\partial^2 u_z}{\partial t^2}$$



...but double integration to vertical displacement u_z is unstable – we really need to use hydrostatic pressure to determine static u_z

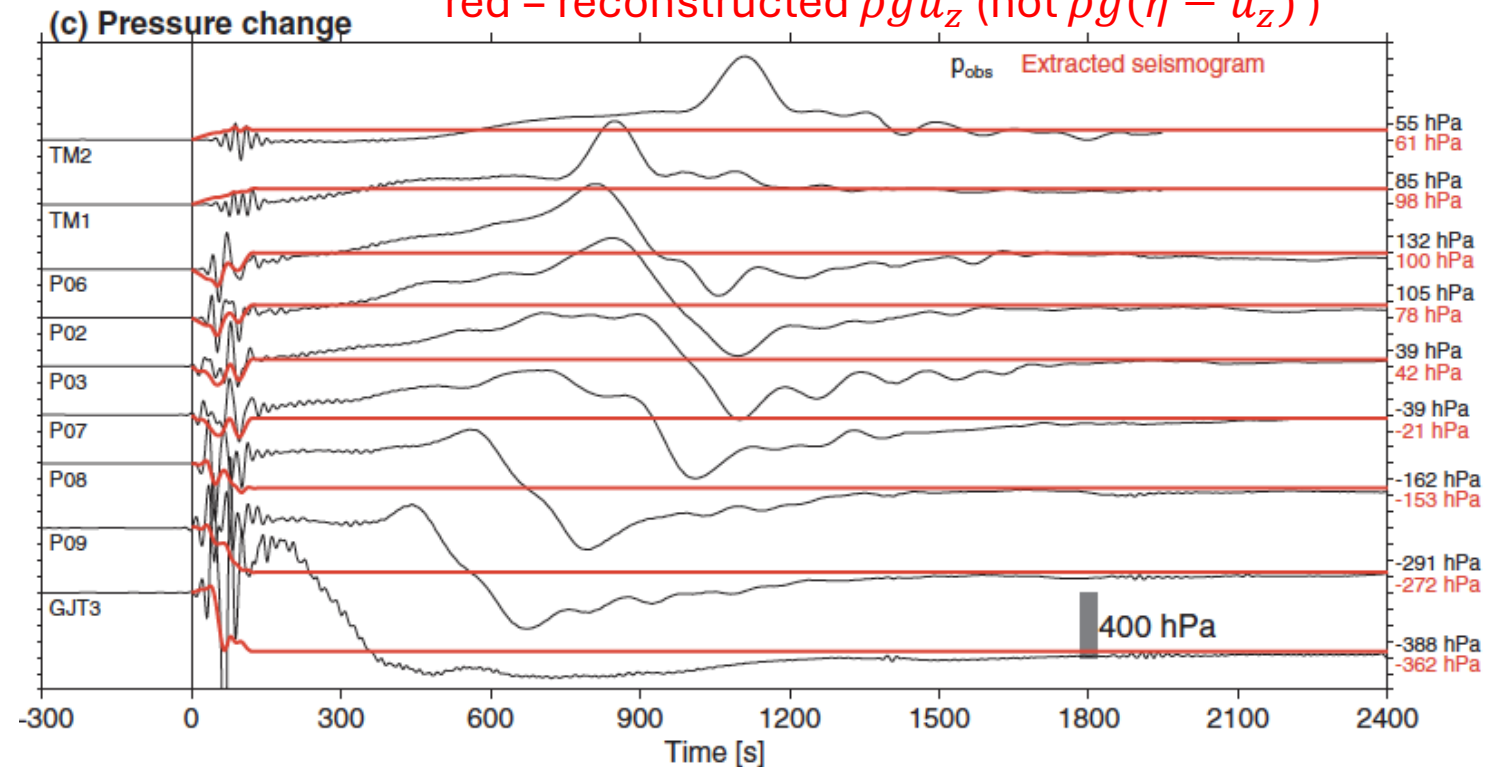
Extracting seafloor displacement and tsunami generation from pressure

least squares problem for parameterized $u_z(t)$, using both dynamic and hydrostatic pressure, $p'_L \approx \rho g(\eta - u_z) + \rho H \partial^2 u_z / \partial t^2$, and tsunami model $\eta = G * u_z$ (assumes $b \approx u_z$)



black = Lagrangian pressure, p'_L (< 0.05 Hz)

red = reconstructed $\rho g u_z$ (not $\rho g(\eta - u_z)$)



(Kubota et al., 2021)

Extracting seafloor displacement and tsunami generation from pressure

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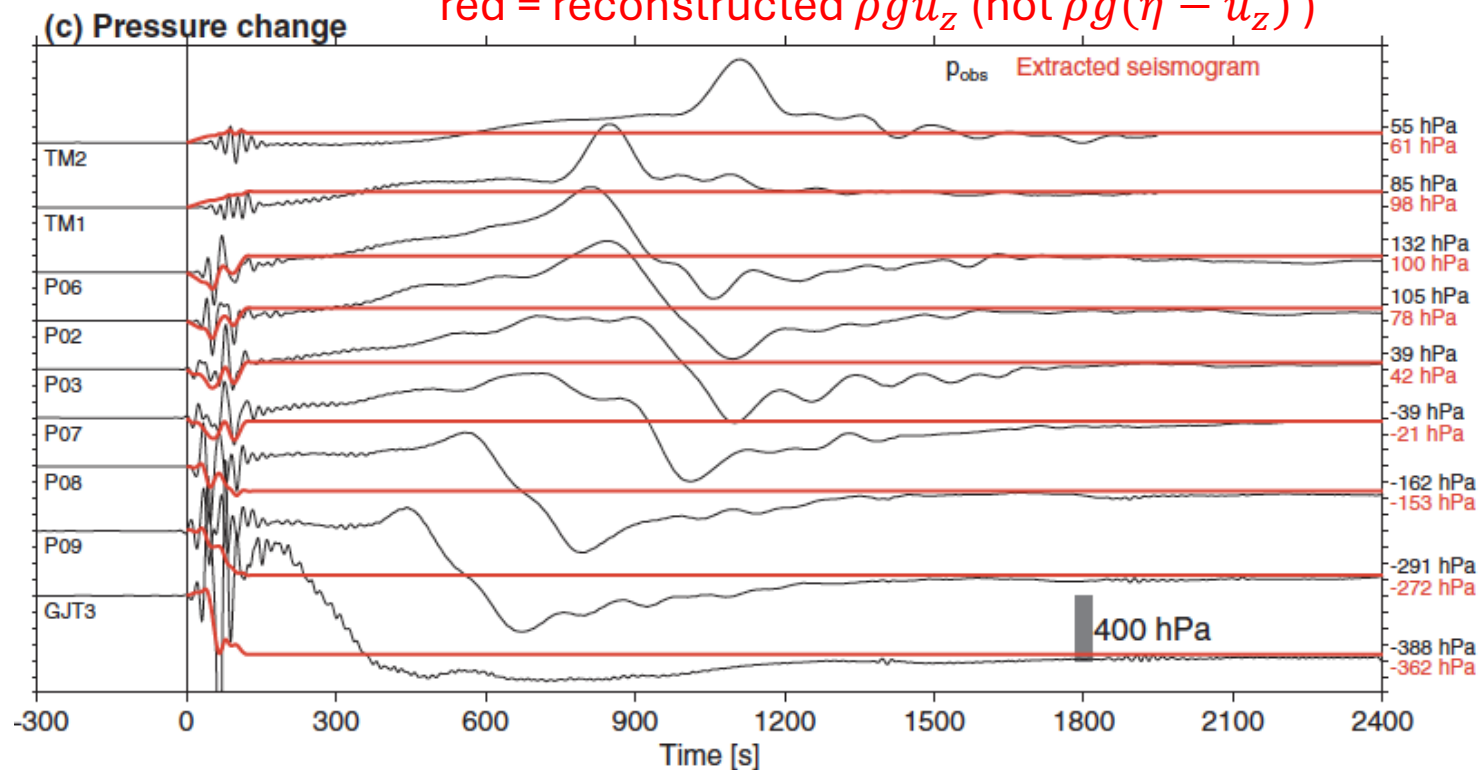
- This method purposefully low-pass filters to remove compressibility and acoustic waves. Is there additional information in these waves to help constrain tsunami generation? (adjoint sensitivity analysis may be useful—see Wenqiang’s poster)

- This method neglects horizontal displacement contribution to tsunami generation:

$$b = u_z + u_{hor} \cdot \nabla_{hor} H$$

black = Lagrangian pressure, p'_L (< 0.05 Hz)

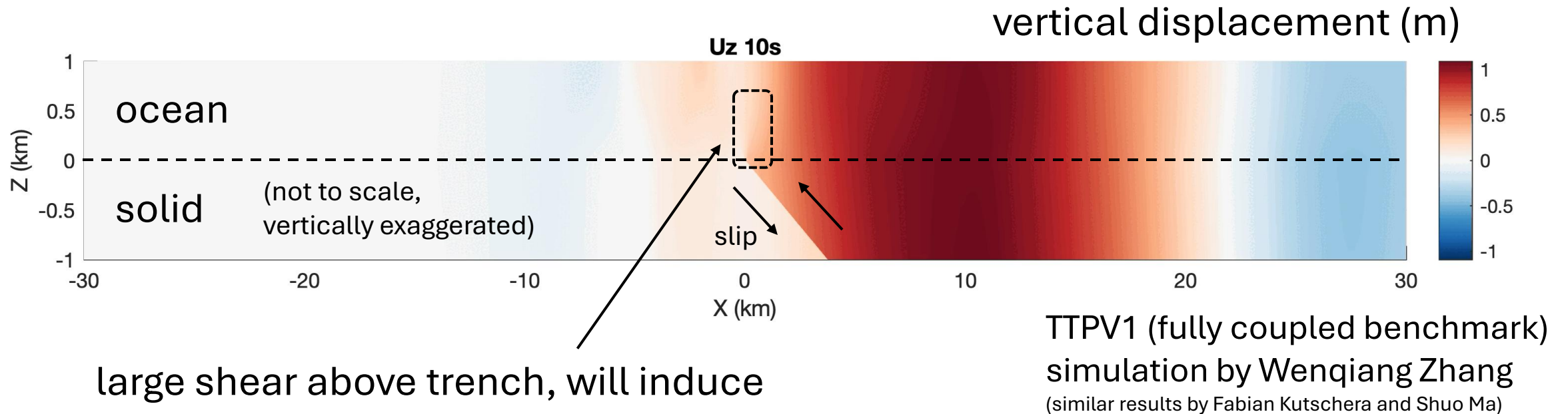
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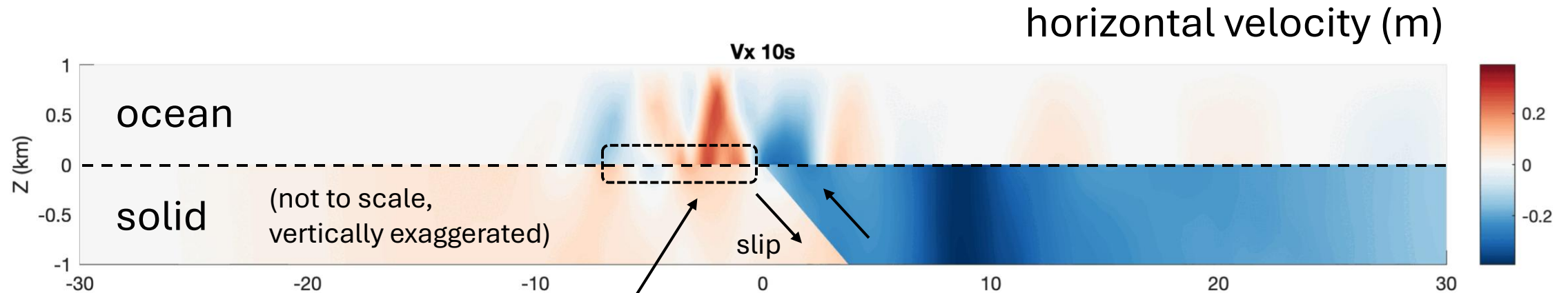
Is linear potential theory (for inviscid, irrotational fluid) still valid for surface-breaking ruptures?



large shear above trench, will induce turbulence through (neglected) nonlinear advection-related terms in governing equations

...but maybe this is limited to narrow boundary layers, so correction is negligible? – requires nonlinear hydrodynamics modeling (RANS or LES with sub-grid turbulence closure) or at least estimates using simple eddy diffusion model

Turbulence might also complicate interpretation of high frequency seafloor pressure measurements



TTPV1 (fully coupled benchmark)
simulation by Wenqiang Zhang
(similar results by Fabian Kutschera and Shuo Ma)

large shear (and turbulent boundary layer)
along seafloor – can this develop over
timescales of seismic/acoustic waves?
how large are turbulent pressure fluctuations?

1. Stress and pressure control shallow rupture dynamics –
Need to integrate long-term ($\sim 10^4$ - 10^6 yr) modeling with dynamic rupture and cycle modeling
2. Tsunami generation physics (+ other wave modes, with implications for source characterization and warning)
Need to better understand seafloor pressure, perhaps using adjoint sensitivity analysis
3. Turbulent boundary layers—are we missing something?
Nonlinear hydrodynamic modeling of tsunami generation

special thanks to the CRESCENT DET group, whose ideas and feedback have been so useful!