A study of the generation mechanism of the ocean gravity waves excited by seismic surface waves, based on the comparison of the numerical experiments results and observation data

KAGAWA UNIVERSITY

JAMSTEC

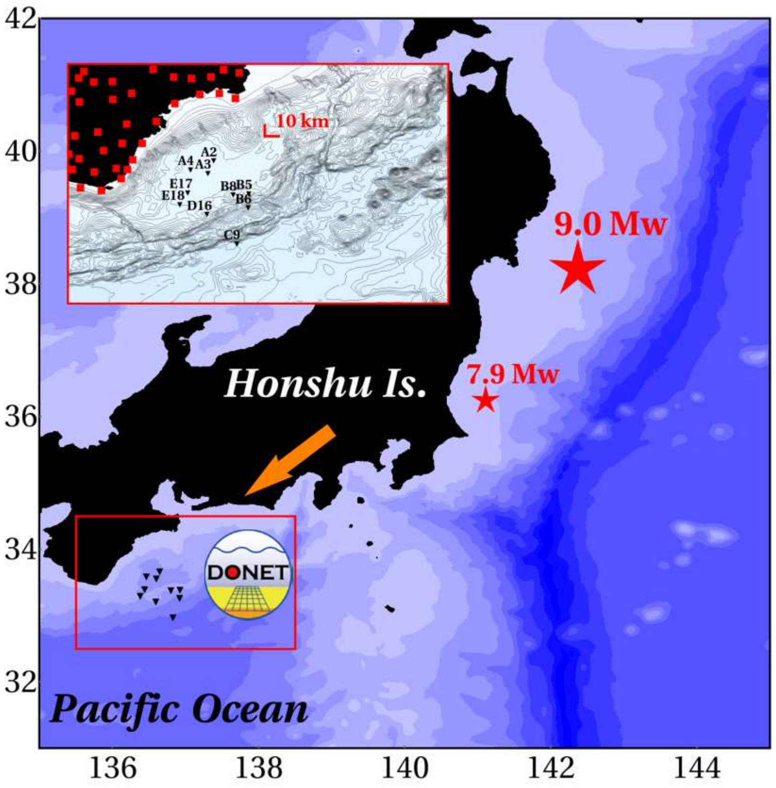
Kirill A. Sementsov
Mikhail A. Nosov
Sergey V. Kolesov

Vyacheslav A. Karpov
Hiroyuki Matsumoto
Yoshiyuki Kaneda

EGU General Assembly

06/05/2020

Introduction

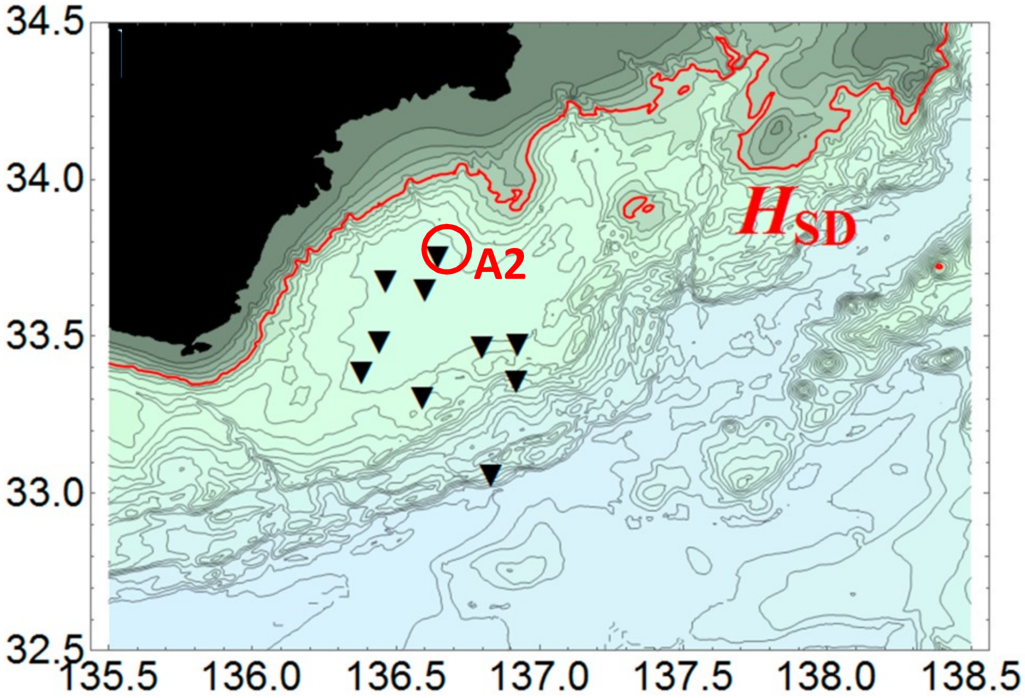


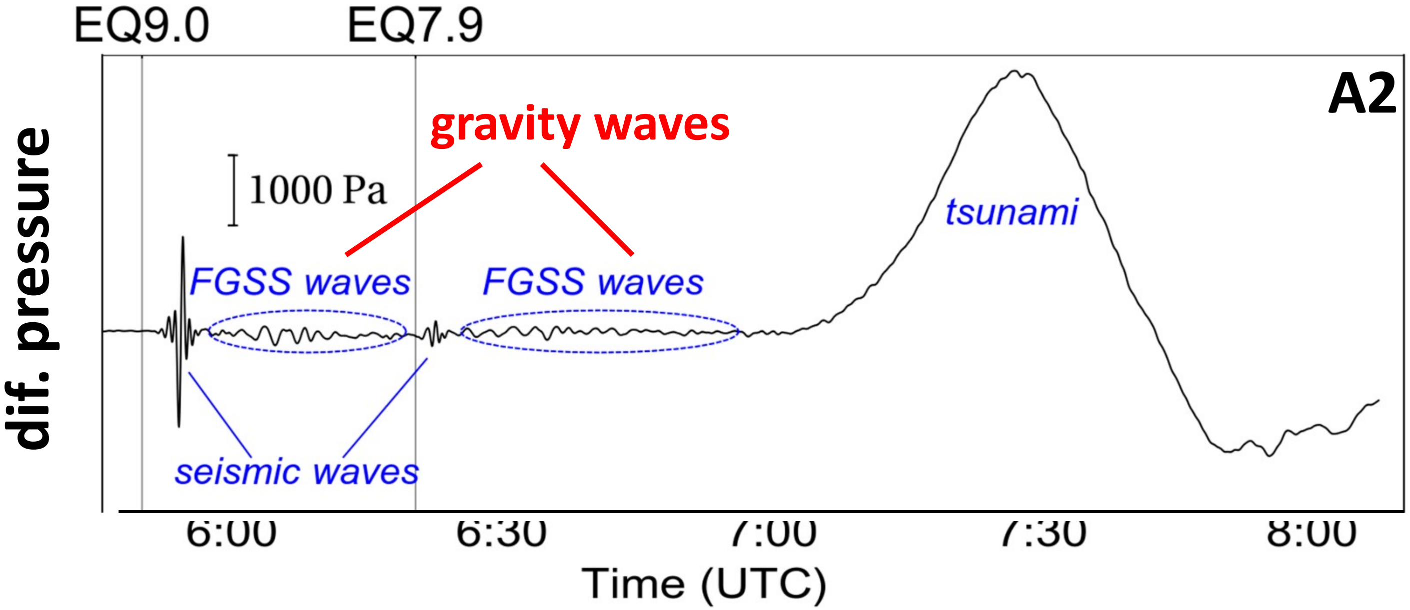
The DONET is a submarine cabled real-time seafloor observatory network for precise earthquake and tsunami monitoring. Ten DONET observatories were in operation during the 2011 Tohoku-Oki event near the Pacific coast of Honshu Island. Each observatory was equipped with an ocean bottom pressure gauge (PG) and a three-component ocean bottom seismometer (OBS). A comparative analysis of the PG and OBS records revealed that shortly after seismic surface waves traversed the DONET region, free gravity waves were observed within the water layer. We call these **F**ree **G**ravity waves excited by **S**urface **S**eismic waves **FGSS waves**.

Sementsov, K. A., Nosov, M. A., Kolesov, S. V., Karpov, V. A., Matsumoto, H., & Kaneda, Y. (2019). Free gravity waves in the ocean excited by seismic surface waves: Observations and numerical simulations. Journal of Geophysical Research: Oceans, 124. https://doi.org/10.1029/2019JC015115

Introduction

The period of these gravity waves excited by surface seismic waves (FGSS waves) was approximately 170 *s*, the peak-to-peak amplitude was approximately 3.5 *cm*, the length was on the order of 22 *km*, and the phase velocity was 134 *m/s*.





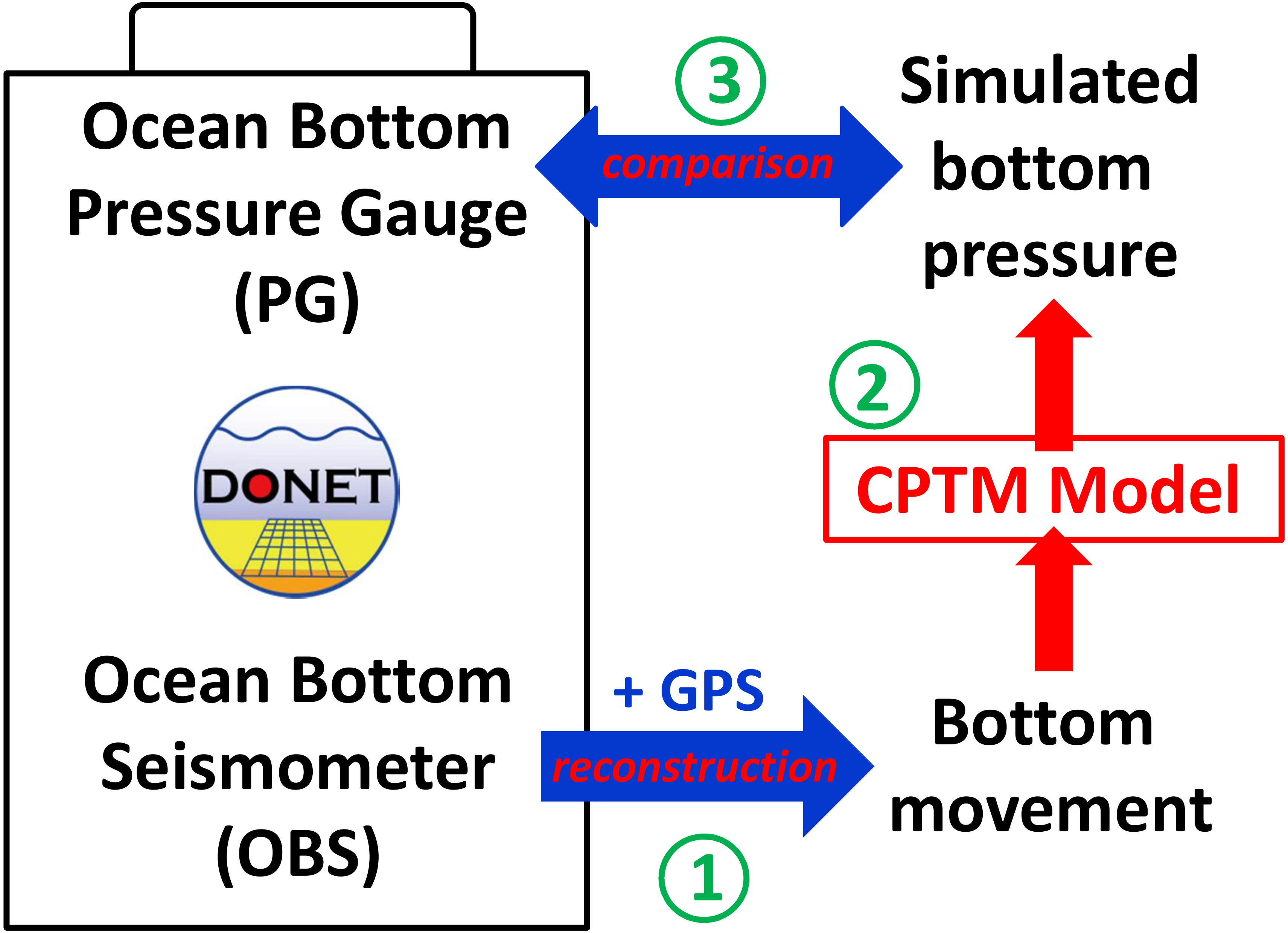
DONET
A2 station
PG record
(low-frequency component
$f < 0.025\ Hz$)

Aims of this study

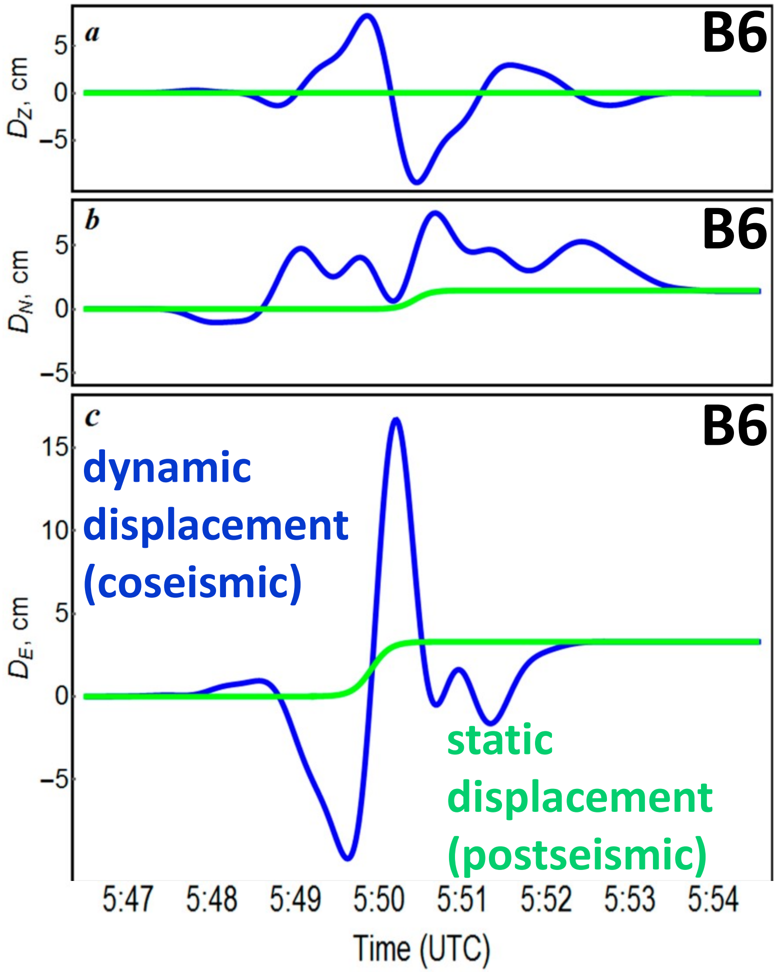
1. To reproduce the observed FGSS waves in the DONET region using Combined Potential Tsunami Model (CPTM)
2. To reveal the generation mechanism of these FGSS waves using the numerical experiments

I. Numerical reproduction of the FGSS waves using the Combined Potential Tsunami Model (CPTM)

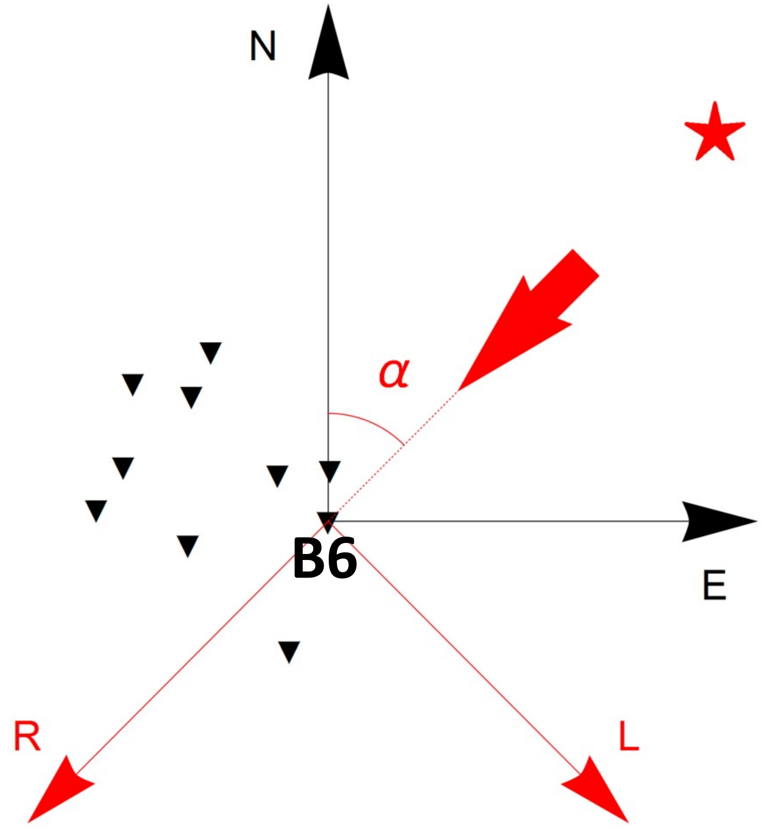
Scheme of the numerical reproduction



1. Reconstruction of bottom movement



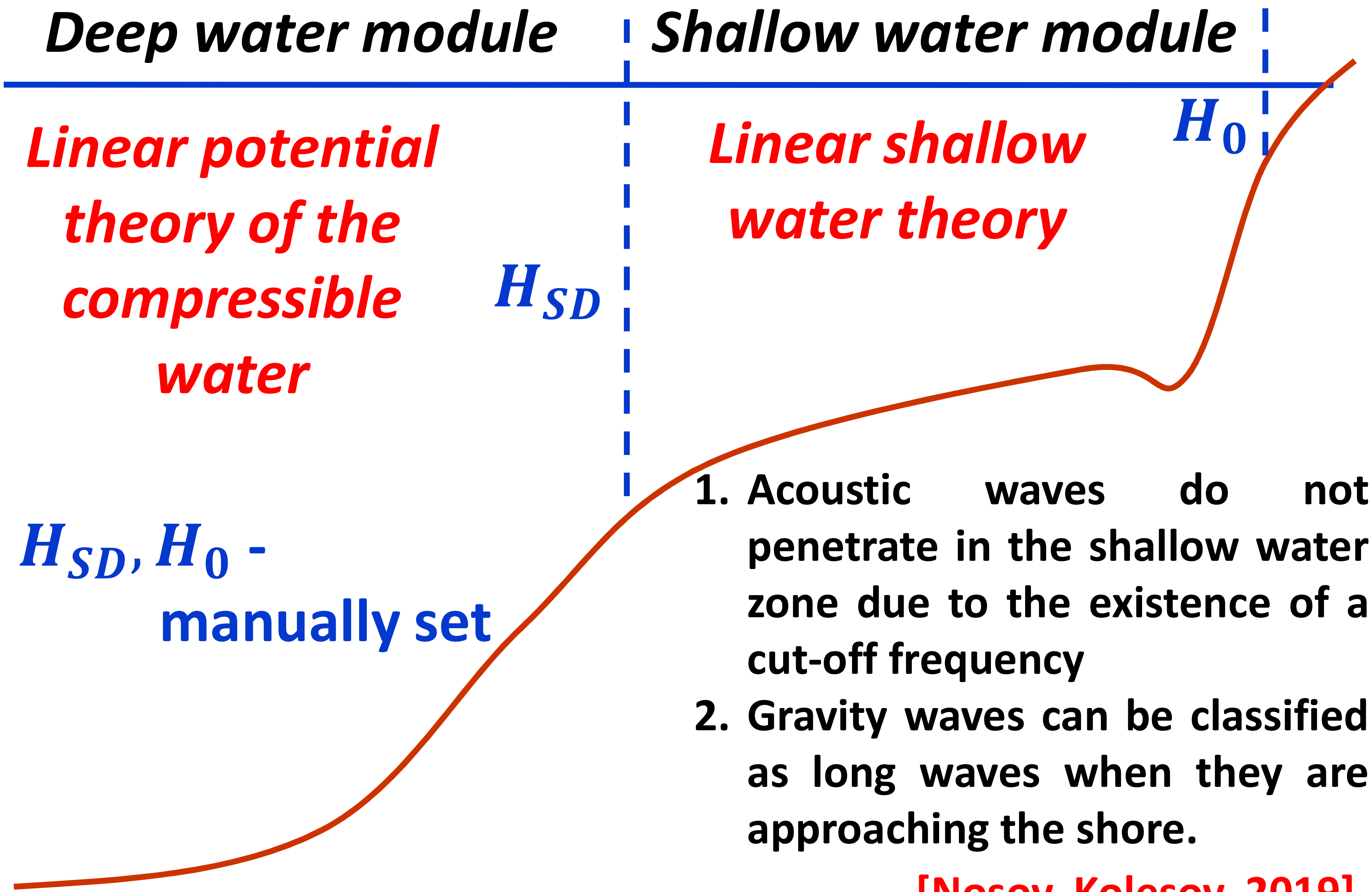
We calculate the **bottom displacement profiles** by the two-fold integration of DONET bottom accelerations over time **[Graizer, 2010]**



We assume that seismic wave is **plane** and **nondispersive.** We calculate the **slowness vector** of seismic wave propagation using the array of DONET acceleration records (for Z, NS and EW components)

[Fukao et al., 2018]

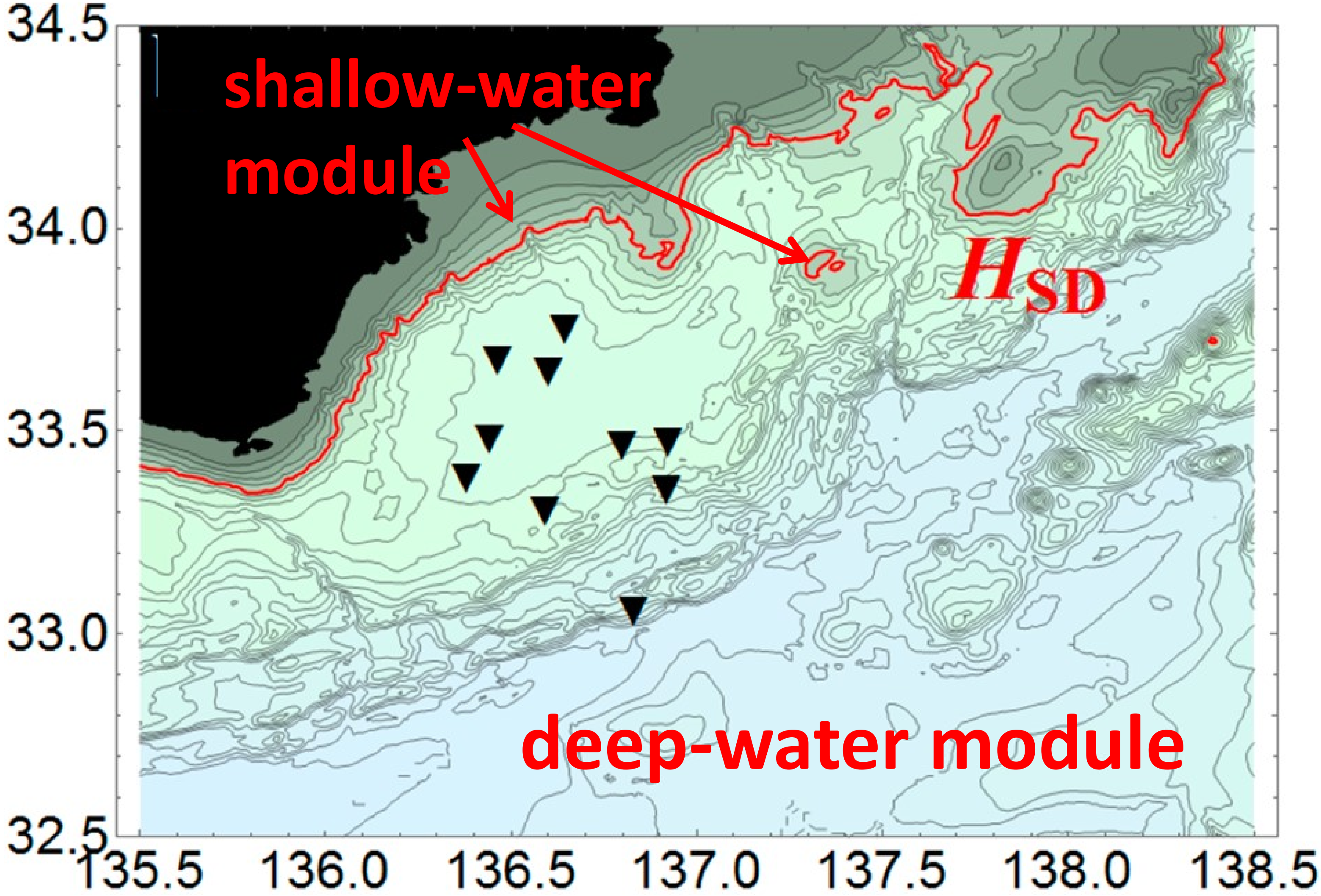
2. CPTM model: principal scheme



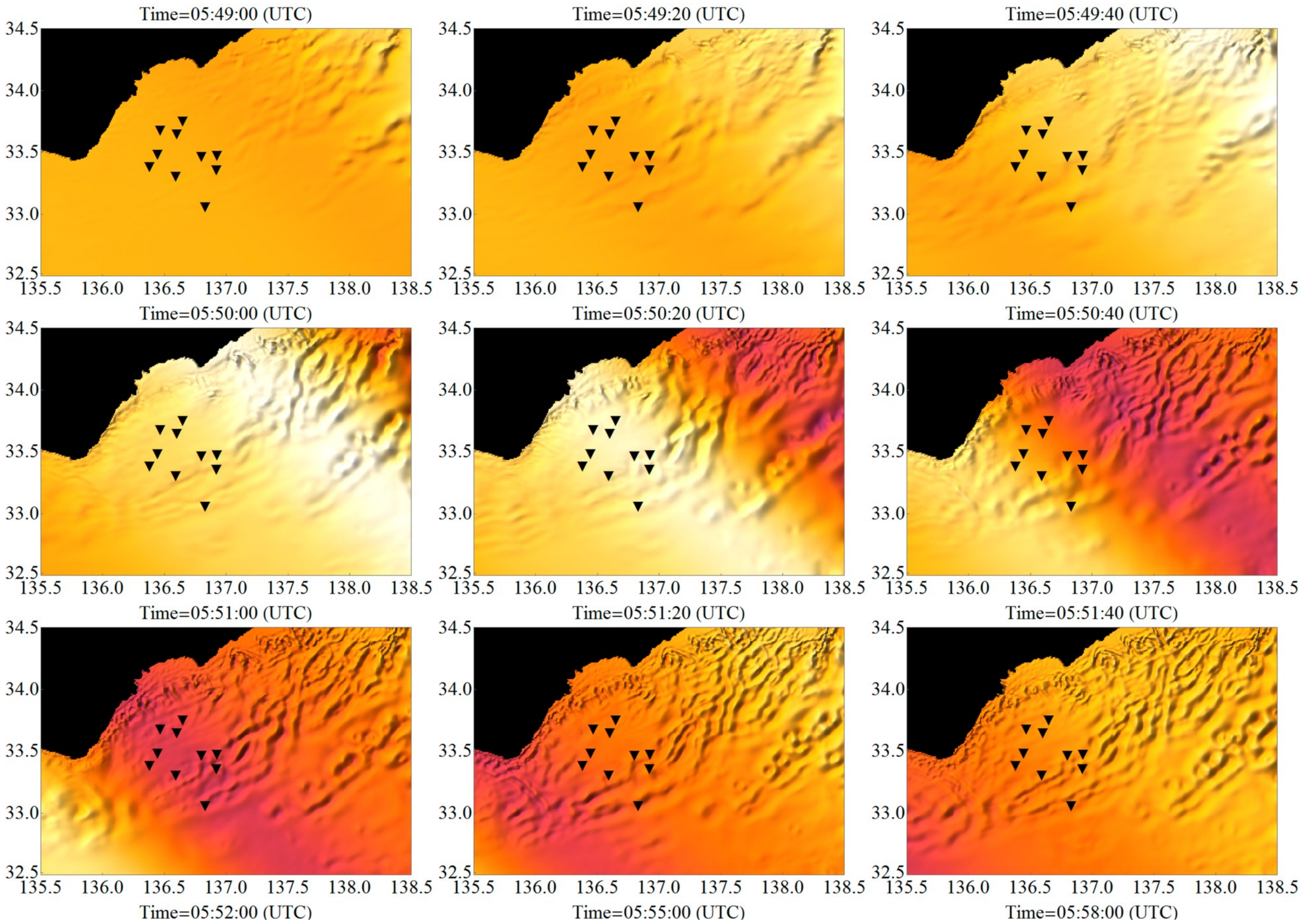
1. Acoustic waves do not penetrate in the shallow water zone due to the existence of a cut-off frequency
2. Gravity waves can be classified as long waves when they are approaching the shore.

[Nosov, Kolesov, 2019]

2. CPTM model: simulation domain

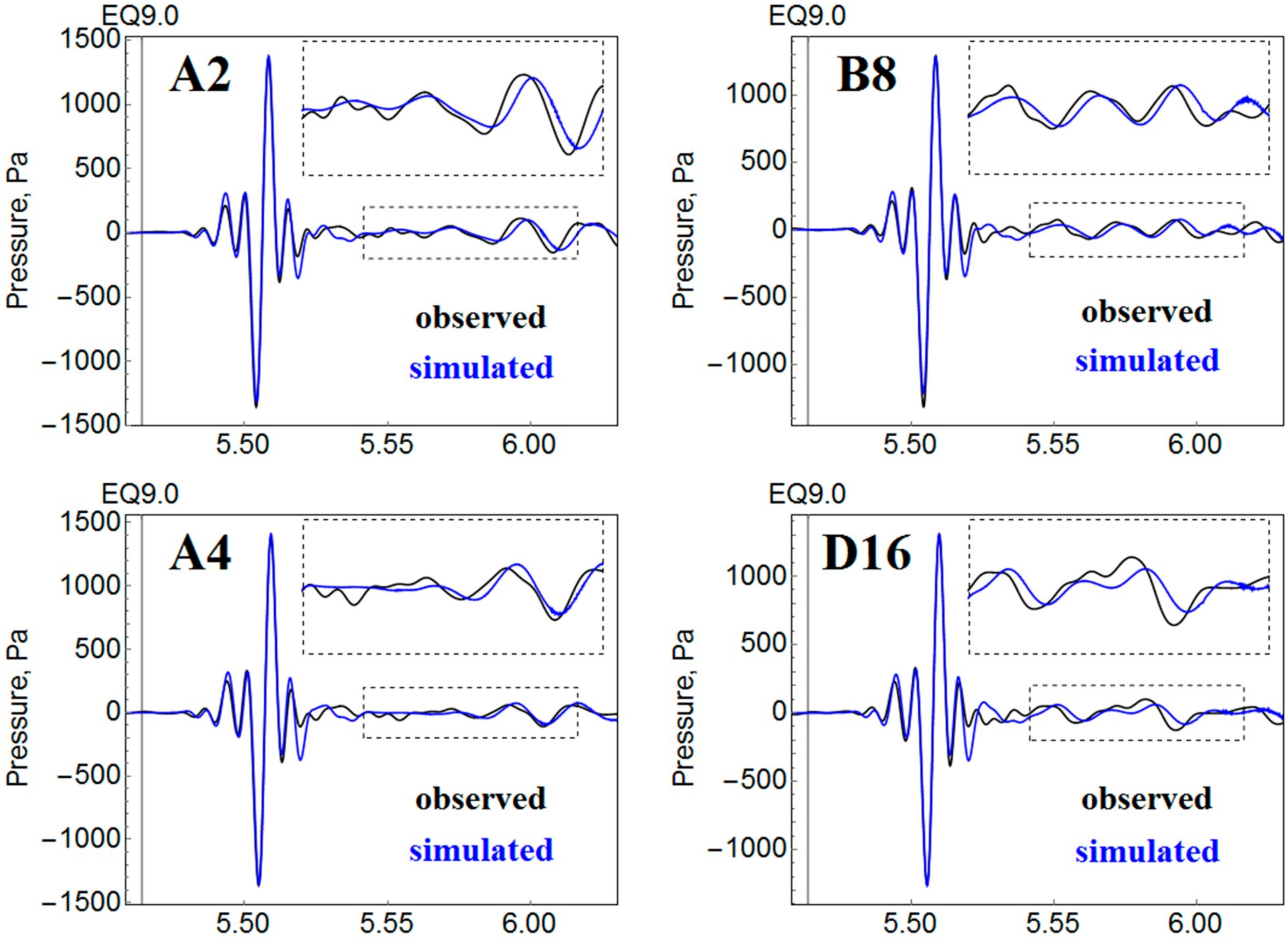


3. Simulation results



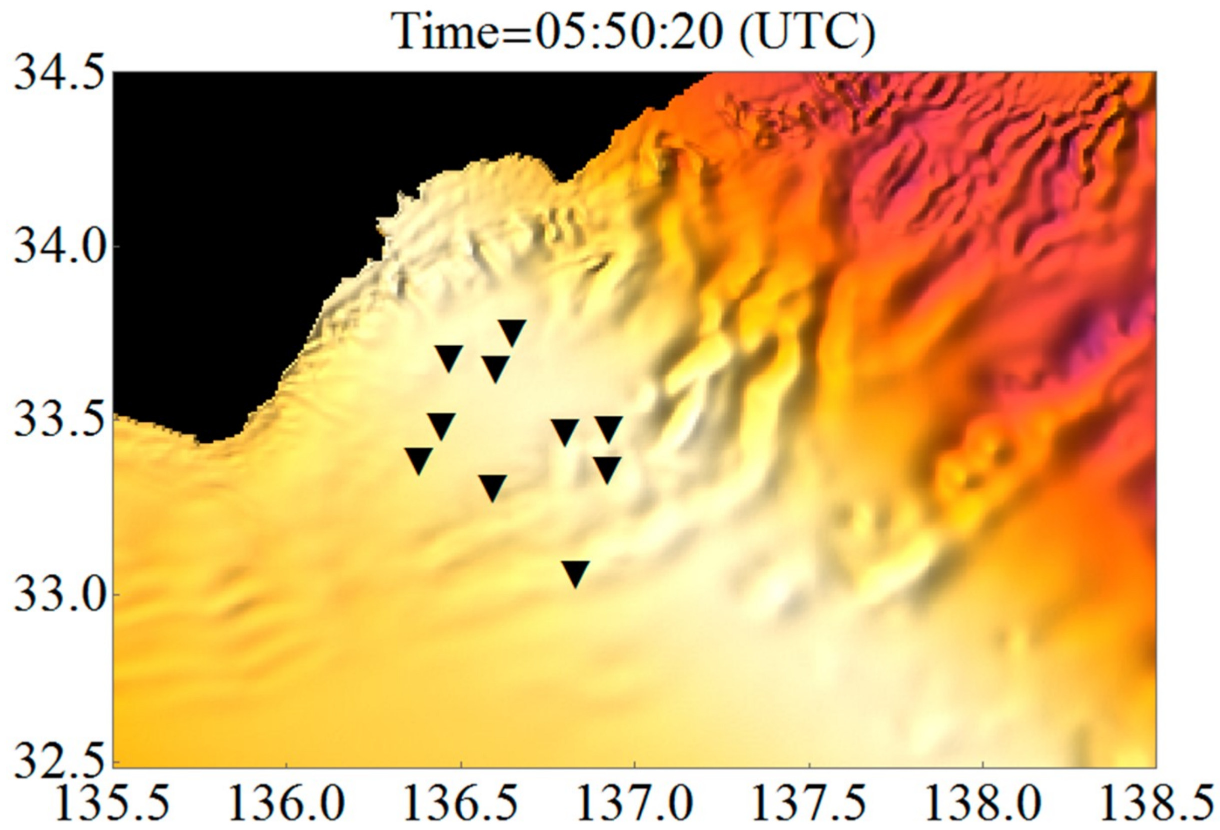
vertical displacement of the water surface

3. Simulation results

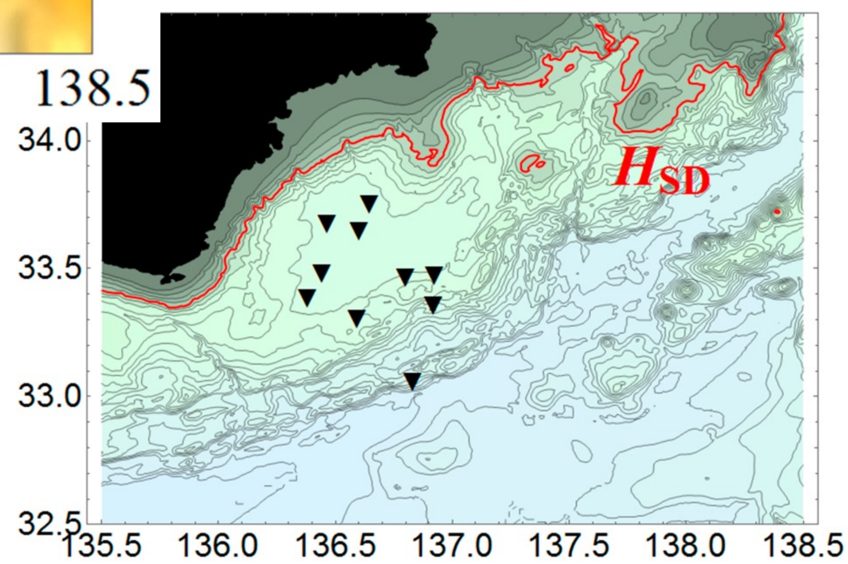


II. FGSS waves generation mechanism: numerical experiments

FGSS waves generation mechanism



Gravity waves are excited directly above the submarine slopes!



Numerical experiments

$$\frac{\partial^2 F}{\partial t^2} - c^2 \Delta F = 0$$

$$z = 0: \quad \frac{\partial^2 F}{\partial t^2} + g\frac{\partial F}{\partial z} = 0$$

$$z = -H: \quad \frac{\partial F}{\partial \vec{n}} = \vec{U} \cdot \vec{n}$$

$$\frac{\partial^2 F}{\partial t^2} - g(\nabla \cdot H \nabla F) = = -g\left(U_x \frac{\partial H}{\partial x} + U_y \frac{\partial H}{\partial y} + U_z\right)$$

$$\vec{U} = U_x\vec{i} + U_y\vec{j} + U_z\vec{k}$$

vector of the bottom deformation velocity

$\vec{n}$

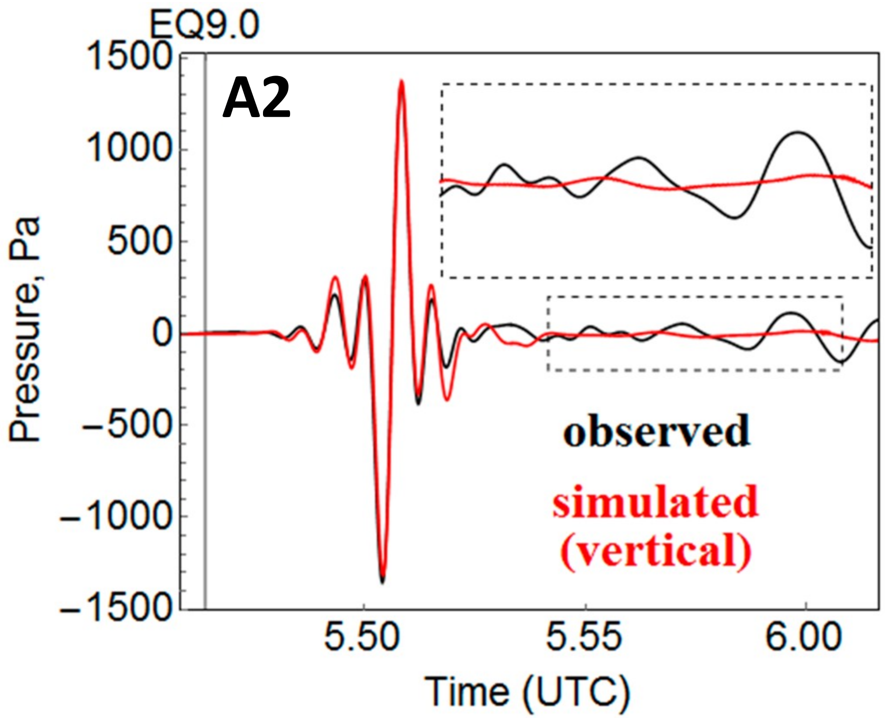
Experiment 1:

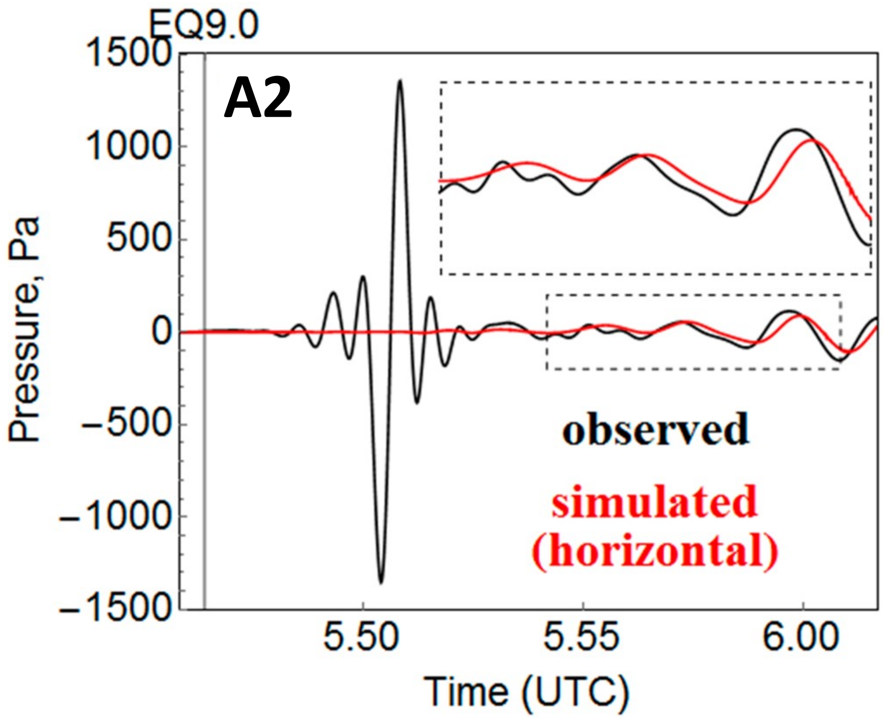
$$\vec{U} = \cancel{U_x\vec{i}} + \cancel{U_y\vec{j}} + U_z\vec{k}$$

Experiment 2:

$$\vec{U} = U_x\vec{i} + U_y\vec{j} + \cancel{U_z\vec{k}}$$

Numerical experiments: results





Vertical bottom movements generates only forced oscillations!

Horizontal, rather than vertical, bottom movements play a key role in the gravity waves generation!

FGSS waves generation mechanism

1. Gravity waves are excited directly above the submarine slopes
2. Horizontal, rather than vertical, bottom movements play a key role in the FGSS waves generation

Theoretical estimates
2D, shallow water theory

$$\frac{\partial^2 F}{\partial t^2} - g\left(\frac{\partial}{\partial x}(H\frac{\partial F}{\partial x})\right) = -g(U_x\frac{\partial H}{\partial x} + U_z)$$

Case 0: horizontal bottom, $\vec{U} = U_x\vec{i} + \cancel{U_z\vec{k}}$

Case 1: horizontal bottom, $\vec{U} = \cancel{U_x\vec{i}} + U_z\vec{k}$

Case 2: submarine slope, $\vec{U} = \cancel{U_x\vec{i}} + U_z\vec{k}$

Case 3: submarine slope, $\vec{U} = U_x\vec{i} + \cancel{U_z\vec{k}}$

Theoretical estimates: 2D, shallow water theory

Case 1: horizontal bottom, $\vec{U} = U_z \vec{k}$

2D, Shallow water theory

$\eta = D_z = f(x - vt), t \geq 0$ - vertical bottom displacement

Cauchy problem:

$$\frac{\partial^2 \xi}{\partial t^2} - c^2 \frac{\partial^2 \xi}{\partial x^2} = \frac{\partial^2 \eta}{\partial t^2}, \quad t > 0$$

$$t = 0: \quad \xi = 0, \quad \partial \xi / \partial t = -vf'$$

$$c = \sqrt{gH}$$

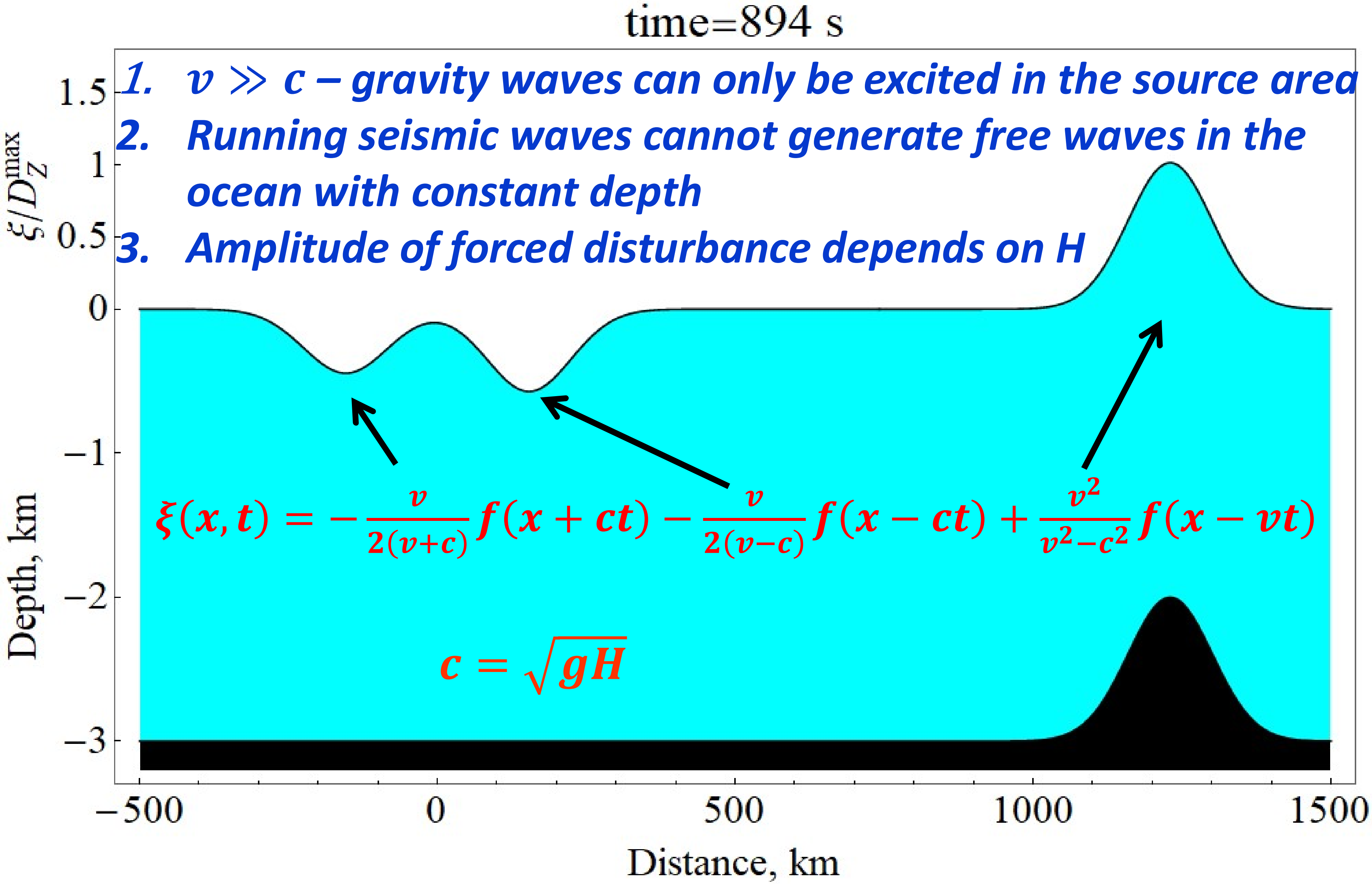
Solution:

$$\xi(x,t) = \frac{v^2}{v^2 - c^2} f(x - vt) - \frac{v}{2(v-c)} f(x - ct) - \frac{v}{2(v+c)} f(x + ct)$$

[Tinti et al., 2001]

Theoretical estimates: 2D, shallow water theory

Case 1: horizontal bottom, $\vec{U} = U_z \vec{k}$



1. $v \gg c$ – *gravity waves can only be excited in the source area*
2. *Running seismic waves cannot generate free waves in the ocean with constant depth*
3. *Amplitude of forced disturbance depends on H*

$$\xi(x,t) = -\frac{v}{2(v+c)} f(x+ct) - \frac{v}{2(v-c)} f(x-ct) + \frac{v^2}{v^2-c^2} f(x-vt)$$

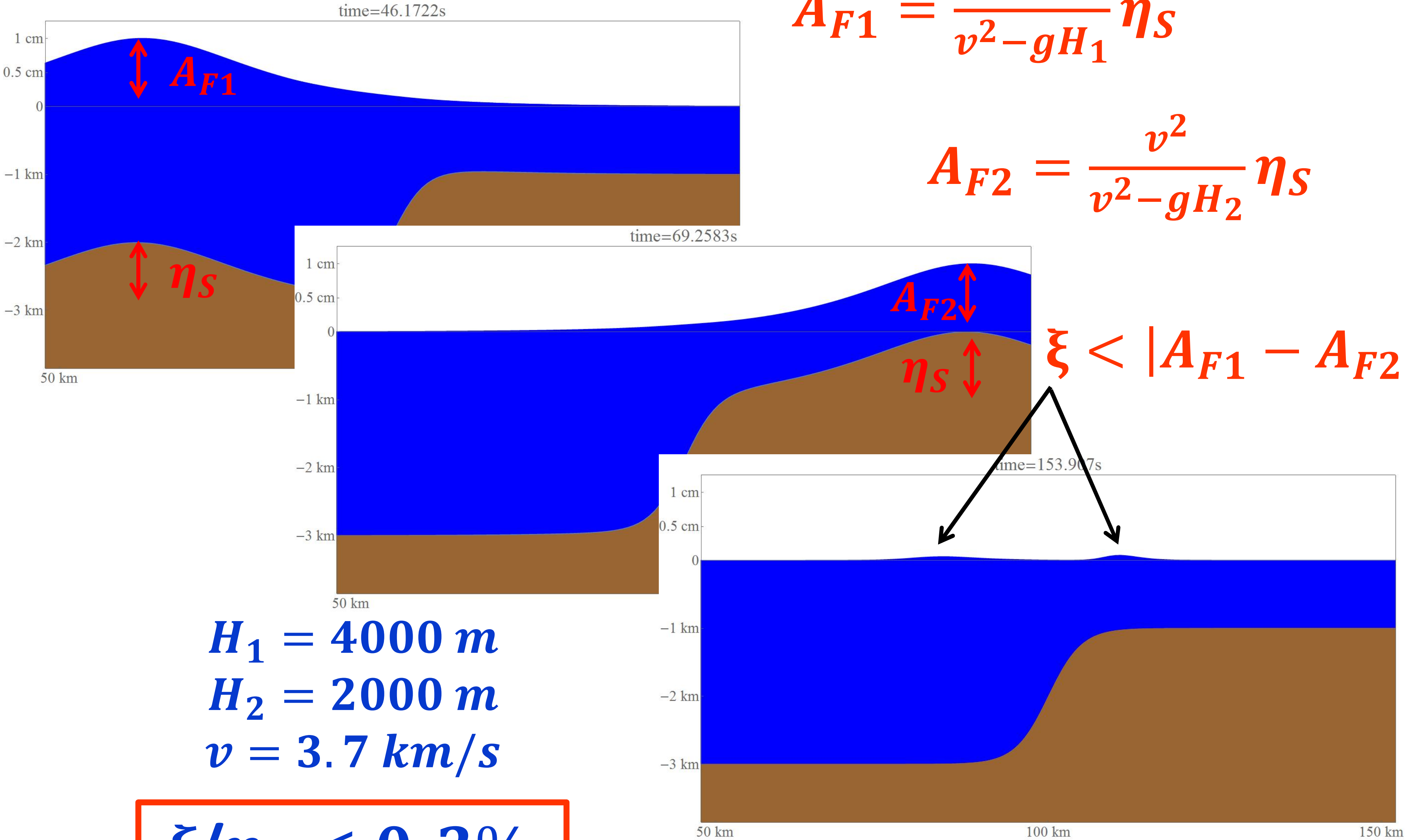
$$c = \sqrt{gH}$$

Theoretical estimates: 2D, shallow water theory

Case 2: submarine slope, $\vec{U} = U_z\vec{k}$

$$A_{F1} = \frac{v^2}{v^2 - gH_1}\eta_S$$

$$A_{F2} = \frac{v^2}{v^2 - gH_2}\eta_S$$



$$\xi < |A_{F1} - A_{F2}|$$

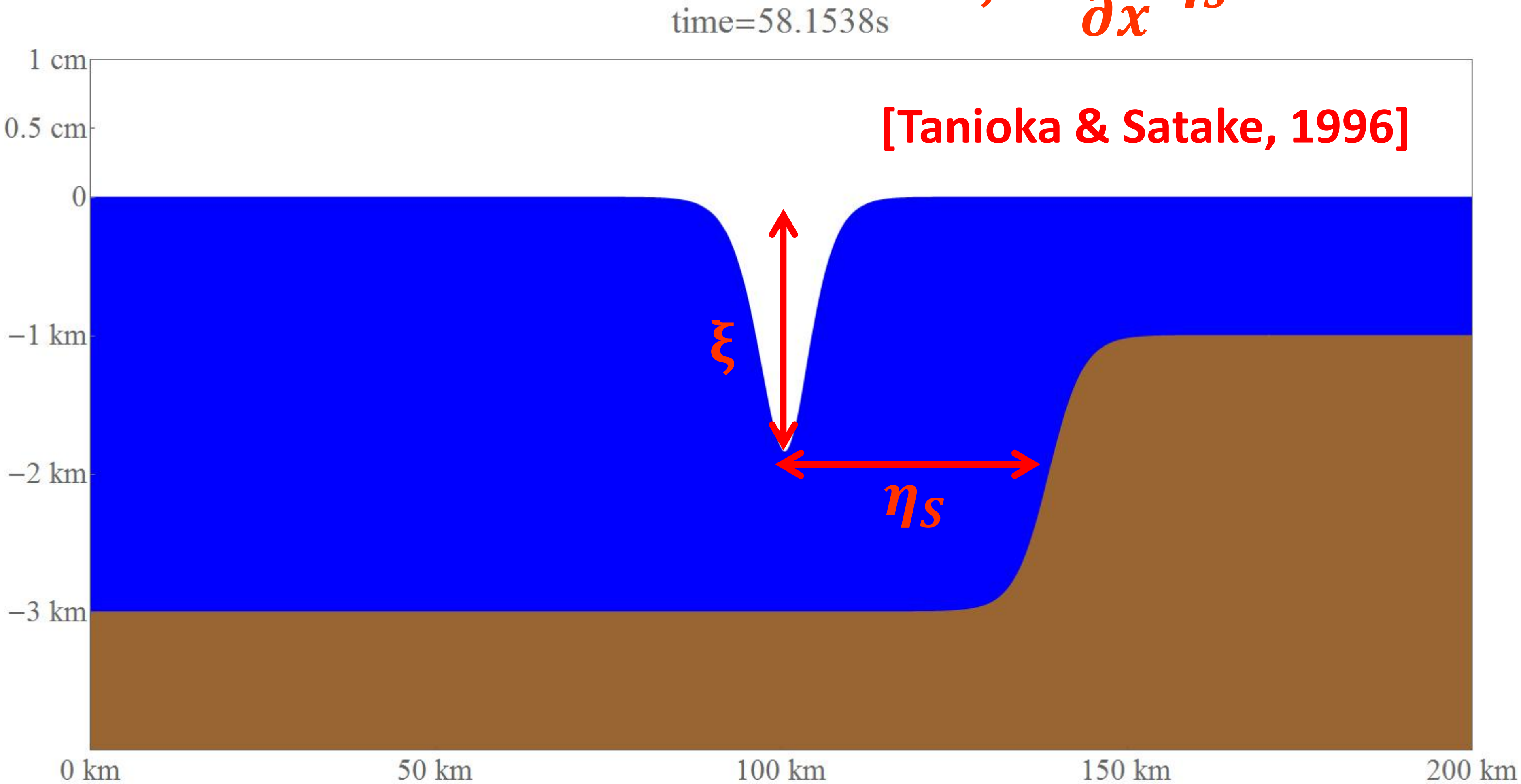
$$H_1 = 4000\ m$$
$$H_2 = 2000\ m$$
$$v = 3.7\ km/s$$

$$\boxed{\xi/\eta_S < 0.2\%}$$

Theoretical estimates: 2D, shallow water theory

Case 3: submarine slope, $\overrightarrow{U} = U_x \vec{i}$

$$\xi < \frac{\partial H}{\partial x} \eta_s$$



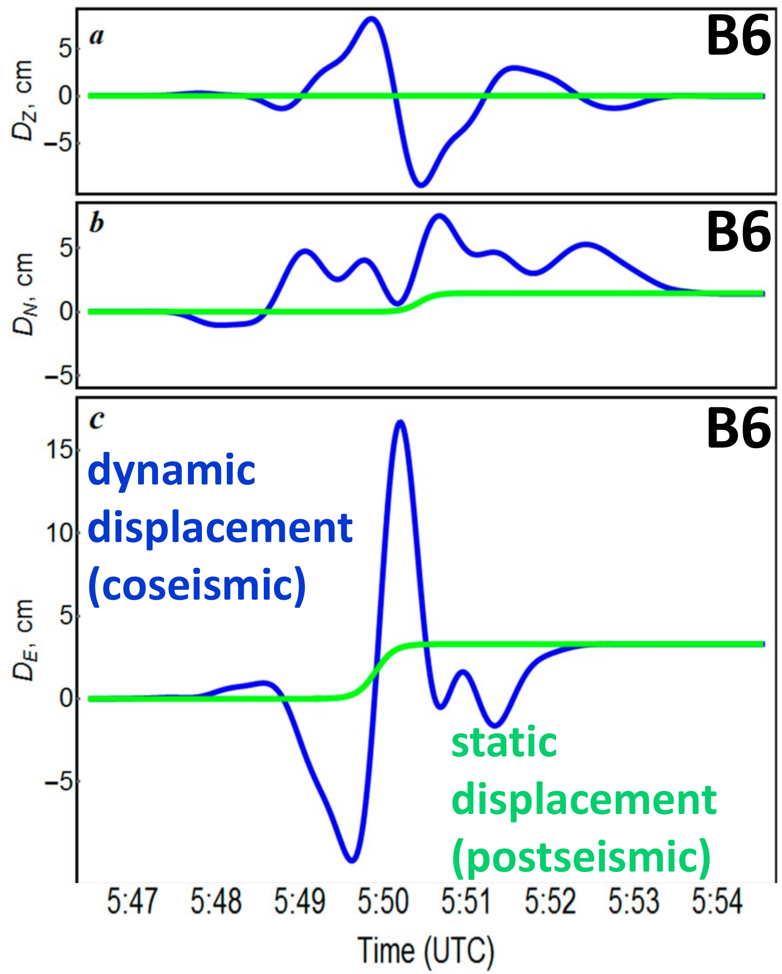
$\xi/\eta_s \sim 10\ \%$
(for DONET area)

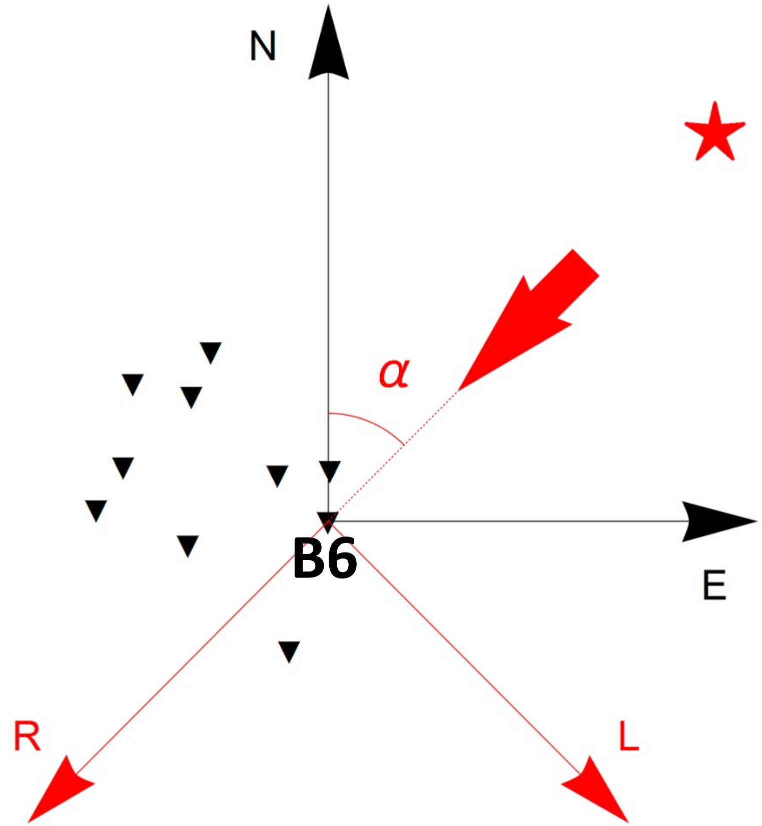
FGSS waves generation mechanism

1. Gravity waves are excited directly above the submarine slopes
2. Horizontal, rather than vertical, bottom movements play a key role in the FGSS waves generation

What is more important for gravity waves generation: dynamic amplitude of bottom deformation during the passage of seismic surface waves or static displacement of the bottom after the passage of seismic surface waves?

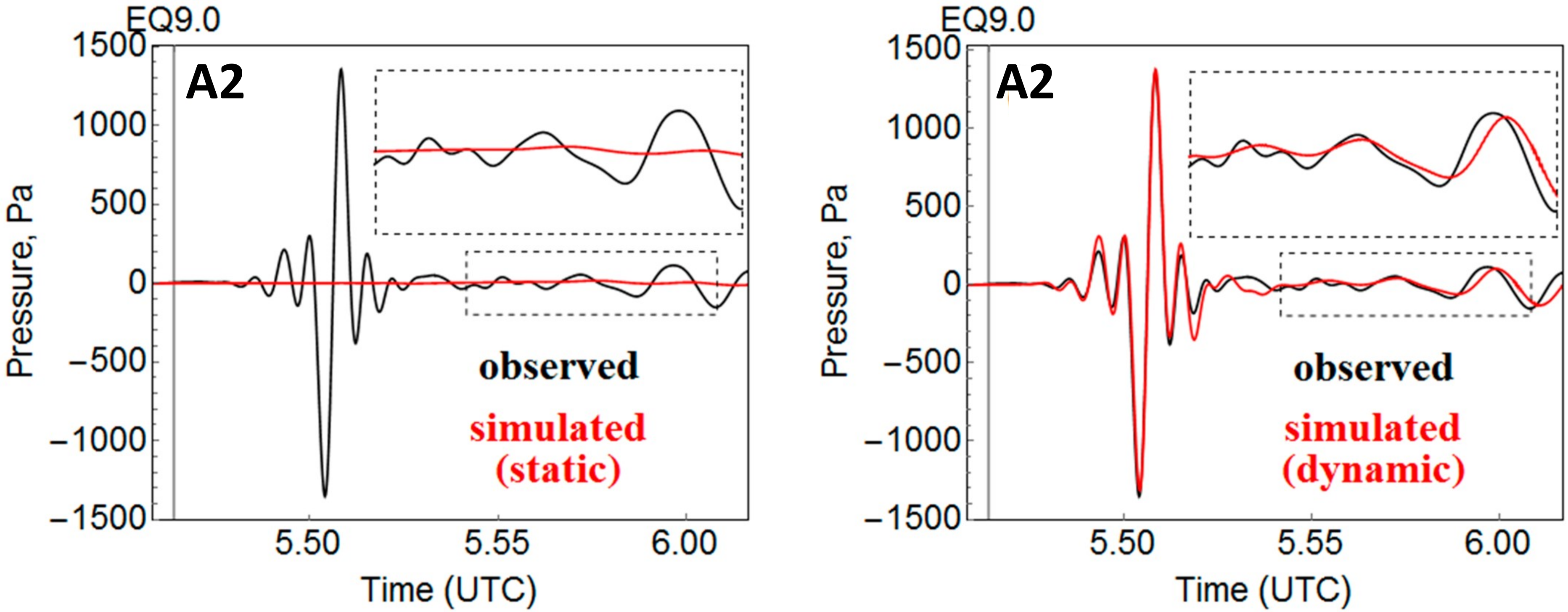
Static displacement or dynamic displacement ?





We calculate the **bottom displacement profiles** with the use of GPS data

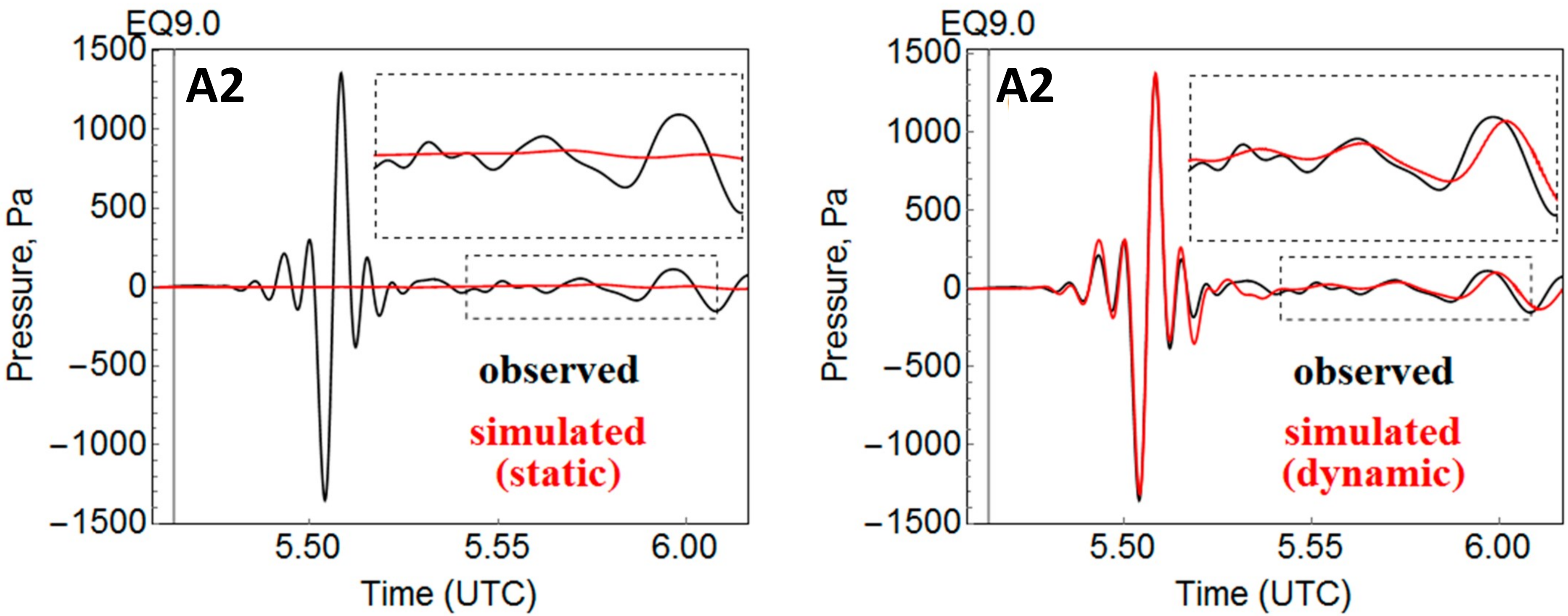
Static displacement or dynamic displacement ?



$$\xi = \frac{\partial H}{\partial x}\eta_x + \frac{\partial H}{\partial y}\eta_y$$

[Tanioka & Satake, 1996]

Static displacement or dynamic displacement ?



The amplitude of the excited gravity waves is determined by the amplitude of the dynamic horizontal bottom motions, while the contribution of horizontal static bottom displacements is insignificant

FGSS waves generation mechanism

1. Gravity waves are excited directly above the submarine slopes
2. Horizontal, rather than vertical, bottom movements play a key role in the FGSS waves generation
3. The amplitude of the excited gravity waves is determined by the amplitude of the dynamic horizontal bottom motions, while the contribution of horizontal static bottom displacements is insignificant

Conclusion

1. Combined 3D/2D potential tsunami model (CPTM) well reproduces the movement of the water layer in the DONET region during 2011 Tohoku Earthquakes

2. Numerical experiments allowed us to reveal the generation mechanism of the free gravity waves excited by the surface seismic waves

Sementsov, K. A., Nosov, M. A., Kolesov, S. V., Karpov, V. A., Matsumoto, H., & Kaneda, Y. (2019).
Free gravity waves in the ocean excited by seismic surface waves: Observations and numerical simulations.
Journal of Geophysical Research: Oceans, 124.
https://doi.org/10.1029/2019JC015115


Thank you!