Three-Dimensional Numerical Modeling of Sound Propagation and Scattering in the Deep Ocean with Elastic Bottoms

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Motivation

Many research questions in marine seismology and bottom-interacting ocean acoustics require an understanding of elastic wave propagation in complex, three-dimensional environments including the ocean. Bottom rigidity, shear waves and interface waves are important aspects of this research. SPECFEM3D could be extremely useful in addressing these research questions. In this poster we focus on multi-pathing in ocean acoustics caused by scattering from deterministic bathymetry.

Objectives

- To study the interaction of sound with the seafloor and scattering from topographic features
- To investigate and quantify the influence of bottom rigidity (shear and interface waves)
- To quantify the distribution of sound energy within water column, the coupling of energy between the ocean bottom and the water column, and the feasibility of measuring these features using networks of hydrophones and seismometers

Philippine Sea Environment

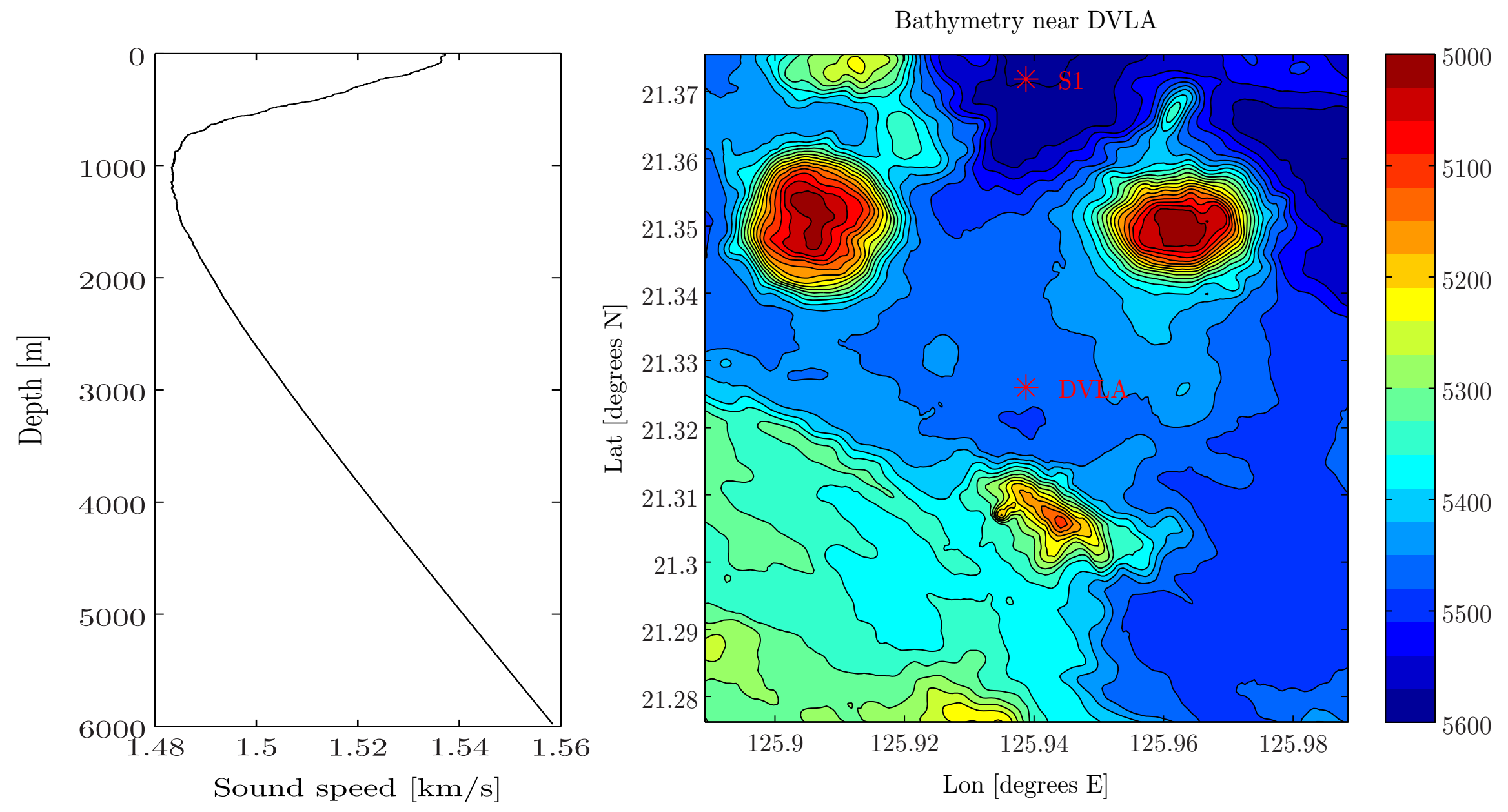

Figure 1. (left panel) Sound speed profile in the water constructed from hydrographic data. (right panel) Bottom topography surrounding the receiving array. The vertical line array of hydrophones is labeled "DVLA". A broadband acoustic source with a center frequency of 10 Hz and a bandwidth of 5 Hz is placed at 37.5 m depth at the location labeled "S1".

Flat bottom simulations, VLA

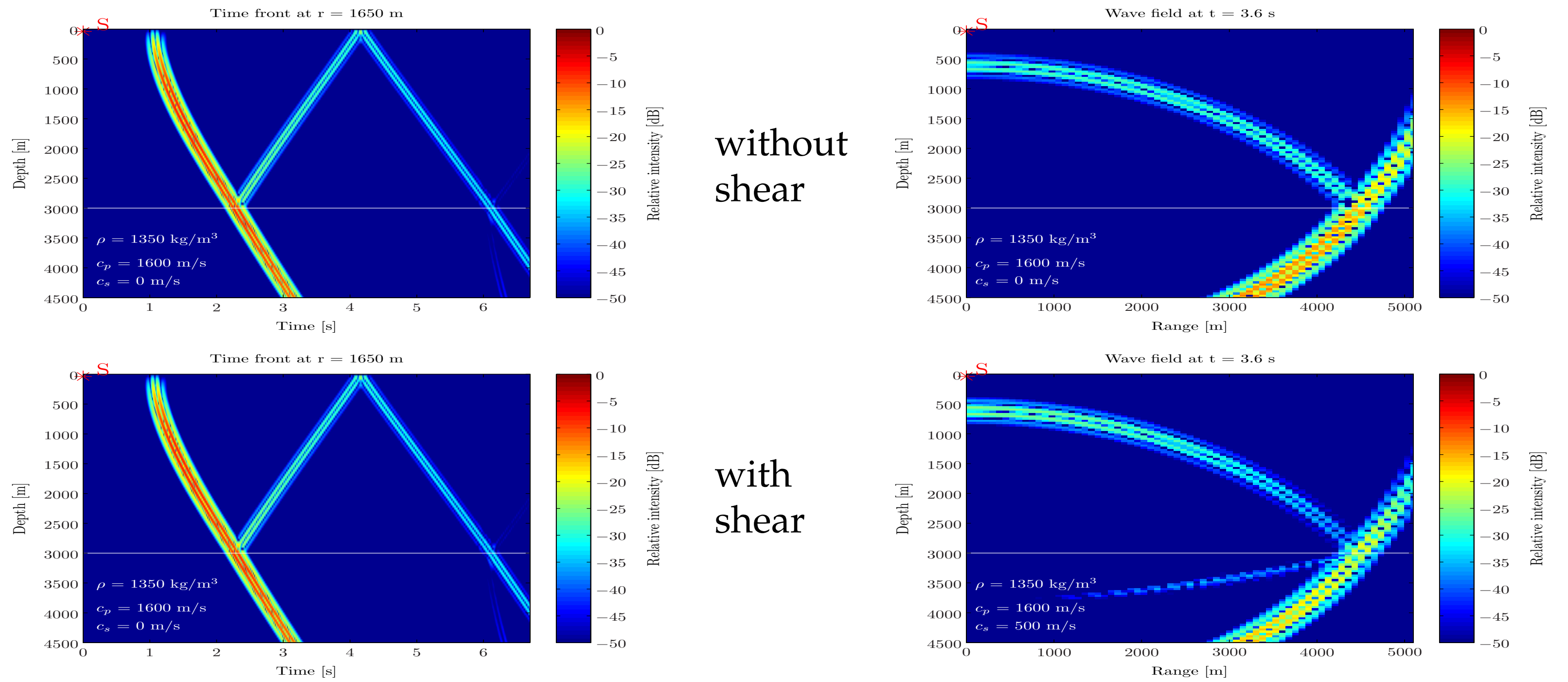

Figure 2. Time fronts (left panels) and snapshots (right panels) of wave fields computed with a fluid ocean bottom (top panels) and a rigid ocean bottom (bottom panels). A significant shear wave is excited in the bottom panels.

S1 to DVLA 3D simulations, VLA

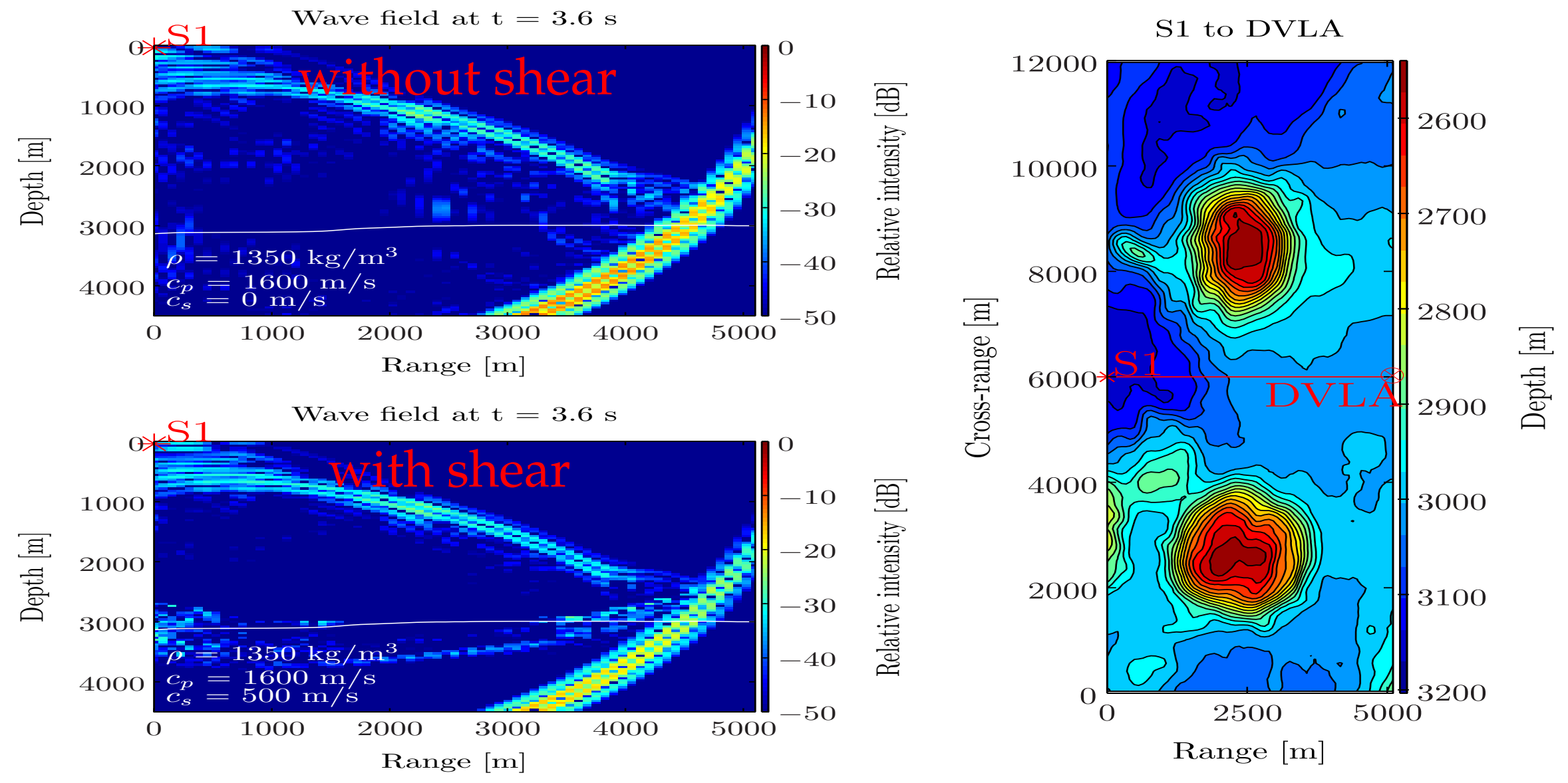

Figure 3. Wave field snapshots produced by the source S1 on the DVLA with a fluid bottom (top left panel) and with a bottom with rigidity (bottom left panel). The bathymetry is shown in the right panel. This is the first time acoustic bottom interaction has been studied in three dimensions with shear wave properties in the bottom. The effects of the out-of-plane seamounts are significant.

Spectral Finite-Element Model SPECFEM3D


COMPUTATIONAL INFRASTRUCTURE FOR GEODYNAMICS (CIG)
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CNRS, INRIA and UNIVERSITY OF PAU (FRANCE)

SPECFEM 3D
Cartesian

User Manual
Version 2.1

- 3D model.
- Finite-element (time domain).
- Solves equations of motion in the weak form (integrated momentum equation with stress-free boundary condition at the earth's surface and absorbing boundary condition at other model boundaries).
- Supports environments with rigidity.
- Supports all interactions between body waves, interface waves (Rayleigh and Stoneley) and guided waves (modes and T-phases).
- Allows heterogeneities at the sub-wavelength scale.
- Designed for parallel computations on a cluster or a supercomputer.

Some problems in marine seismology that would benefit from modeling with SPECFEM3D

- Excitation of Earth's hum by surface- gravity wave loading on coastlines. (0.001-0.03 Hz)
- Inferring crustal rigidity from seafloor compliance. (0.001-0.03Hz)
- Ice shelf excitation by surface gravity waves. (0.01-0.1 Hz)
- The excitation and propagation of microseisms. (0.1-0.5 Hz)
- The T-phase excitation problem. (5-30 Hz)
- Interpreting 3-D multi-channel seismic data over axial magma chambers. (5-100 Hz)

SPECFEM3D vs RAM2D

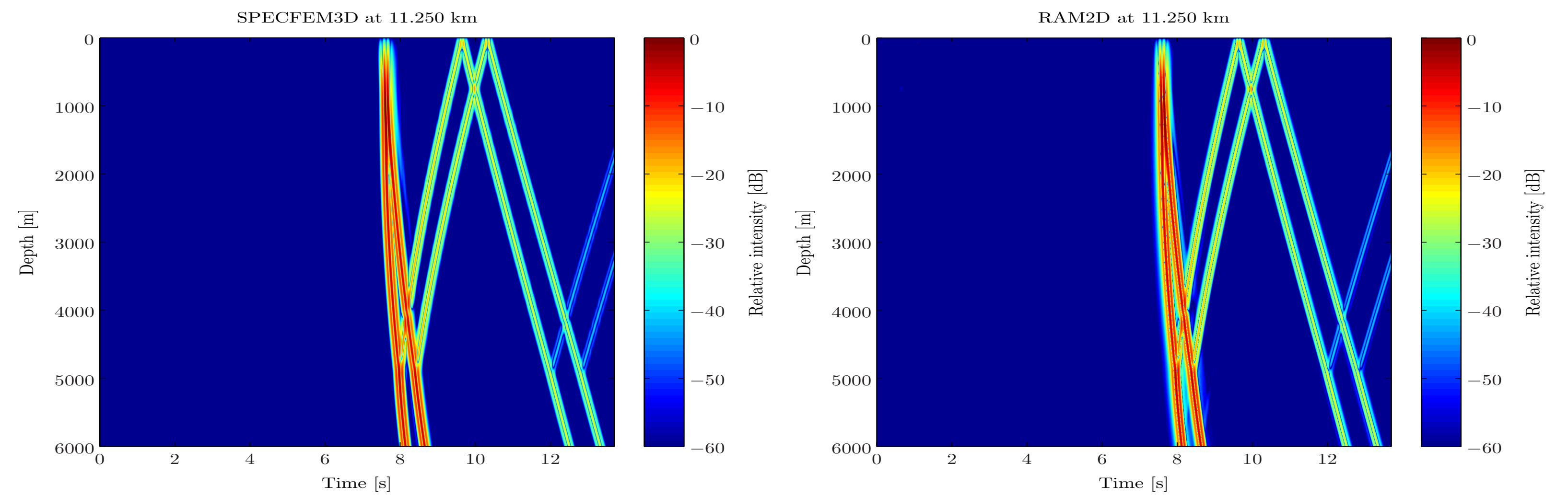

Figure 4. Wave field intensities as functions of arrival time and depth computed using SPECFEM3D (left panel) and RAM (right panel) are shown for a laterally uniform ocean with a constant depth (4950 m). A broadband acoustic source with the same characteristics as in Figure 1 is placed at 750 m depth. The bottom is homogeneous with a density of 1350 kg/m^3 and a compressional velocity of 1.6 km/s. The water column sound speed profile is similar to a "Munk-like" mid-latitude ocean profile (Figure 1, left panel).

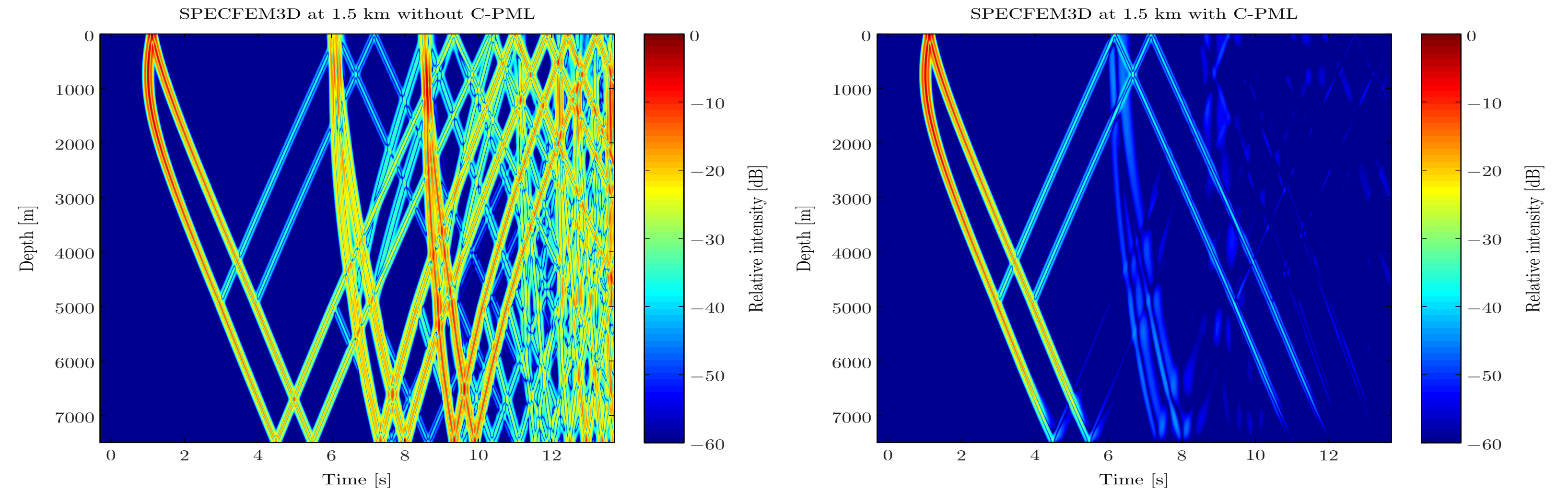

Figure 5. Wave field intensities as functions of arrival time and depth computed using SPECFEM3D without convolutional perfectly matched layer (C-PML) (left panel) and with C-PML (right panel) are shown for a laterally uniform ocean with a constant depth (4950 m). A broadband acoustic source with the same characteristics as in Figure 1 is placed at 750 m depth. The bottom is homogeneous with a density of 1350 kg/m^3 and a compressional velocity of 1.6 km/s. The water column sound speed profile is shown in Figure 1, left panel.

! Reflections from boundaries of the computational domain are efficiently attenuated with C-PML.

Estimating compressional attenuation using "spectral ratio method"

Consider a plane compressional wave, $u(x,t)$, propagating in the x direction in a homogeneous medium. This propagation is described by the well-known one dimensional wave equation

$$\rho(x)\frac{\partial^2 u(x,t)}{\partial t^2} = \frac{\partial}{\partial x}\left(M(x)\frac{\partial u(x,t)}{\partial x}\right) \tag{1}$$

where ρ is the density of the medium and M is the appropriate modulus. For strictly harmonic motion M can be replaced by the complex modulus $M^*(\omega) = \sigma(\omega)/\varepsilon(\omega)$, where σ and ε are stress and strain, respectively. A solution to Equation (1) can be written as a damped wave:

$$u(x,t;\omega) = u_0 \exp(\alpha(\omega)x)\exp(i\omega(t - x/c(\omega))), \tag{2}$$

where $\alpha(\omega)$ is the attenuation coefficient and $c(\omega)$ is the phase velocity.

The internal friction is expressed as

$$1/Q(\omega) = 2c(\omega)\alpha(\omega)/\omega \tag{3}$$

Q is obtained from impulsive source data at two receivers by the "spectral ratio method":

$$\ln\left(\left|\frac{u(x_2,\omega)}{u(x_1,\omega)}\right|\right) = -\alpha(x_2 - x_1);\alpha = mf/(x_2 - x_1);Q = \pi(x_2 - x_1)/(cm) \tag{4}$$

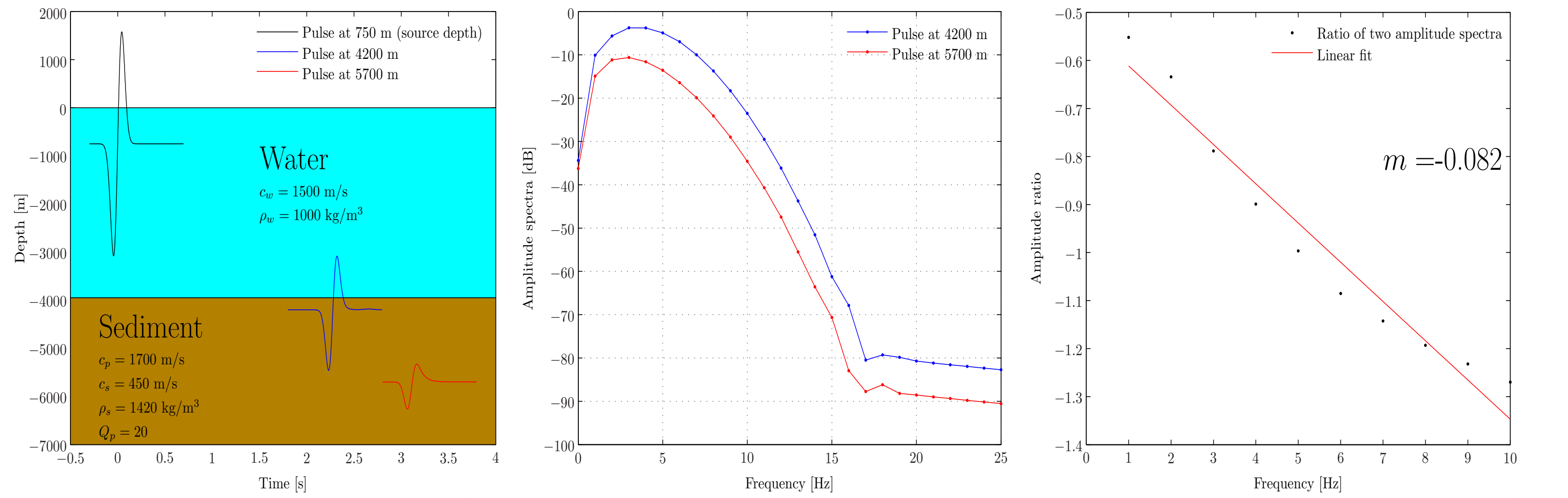

Figure 6. (Left panel) The waveforms at 750 m, 4200 m, and 5700 m depth. (Middle panel) The spectra of the waveforms at 4200 m and 5700 m shown in panel (a). (Right panel) The spectral ratio for the waveforms and a linear fit. The estimate of Q using Equations (4) based on the linear fit to the spectral ratio is 34. The input value in SPECFEM3D is 20.

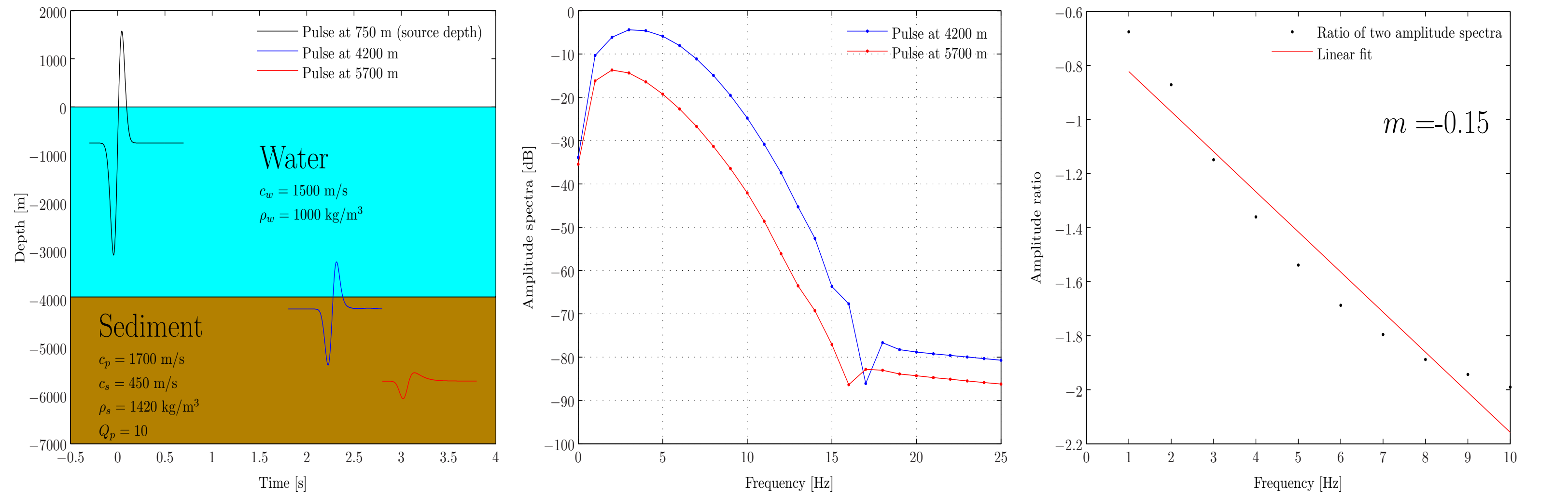

Figure 7. Same as Figure 6, but with the input value of Q=10 in SPECFEM3D. The estimate of Q using Equations (4) based on the linear fit to the spectral ratio is 19.

Conclusions

- 3D topography and bottom rigidity are important considerations in numerical modeling of underwater sound propagation
- SPECFEM3D is a promising technique for numerical modeling of bottom interaction problems in ocean acoustics.
- Convolutional perfectly matched layer efficiently reduces reflections from the boundaries of the computational domain.
- Compressional attenuation recently implemented in SPECFEM3D agrees well with estimates based on "spectral ratio method".

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References.

1. P. Cristini and D. Komatitsch "Some illustrative examples of the use of a spectral-element method in ocean acoustics", J. Acoust. Soc. Am., 131, pp. EL229-EL235, doi: 10.1121/1.3682459 (2012).
2. I. A. Udovydchenkov, R. A. Stephen, T. F. Duda, Y.-T. Lin, and D. Peter, Three-dimensional numerical modeling of sound propagation and scattering in the deep ocean with elastic (shear) bottoms, J. Acoust. Soc. Am., 132, pp. 1973, 164th Meeting of the Acoustical Society of America (2012).