Hydroacoustic Waves from Megathrust Ruptures

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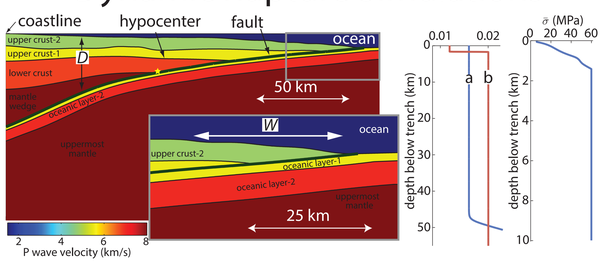
Abstract

The occurrence of shallow coseismic slip in megathrust ruptures enhances seafloor uplift and tsunami excitation. Shallow slip also excites hydroacoustic waves in the ocean, which can be recorded on ocean bottom pressure sensors. We are exploring the possibility of using hydroacoustic waves, which arrive at near-shore sensors ~10 min prior to tsunami waves, for local tsunami early warning systems. To study this problem, we conduct two-dimensional dynamic rupture models of megathrust events. The simulations employ rate-and-state friction on the fault, realistic material structure (including fault and seafloor topography), and an ocean layer. The models presently capture seismic and hydroacoustic waves, and ongoing work will permit us to simultaneously model surface gravity waves (tsunamis). Preliminary results indicate pronounced excitation of ~10 s hydroacoustic reverberations in the ocean layer that appear as a dispersed wavetrain on seafloor pressure records. These modes involve motions of both the fluid and solid; at ~10 s period they have phase velocities close to the Rayleigh wave speed in the solid and group velocities close the sound wave speed in the ocean. Pressure signals at locations landward of the trench have amplitudes that correlate well with the amplitude of shallow slip and seafloor uplift (and presumably tsunami wave heights). Specific models of the 2011 Tohoku earthquake predict dynamic pressure changes ~0.1 to 1 MPa associated with these hydroacoustic waves at offshore stations; such waves were likely recorded on ocean bottom pressure sensors during that event.

Dynamic Rupture Simulations



Modeling objective: Match onshore 1-Hz GPS displacements and static seafloor deformation

Model parameters:

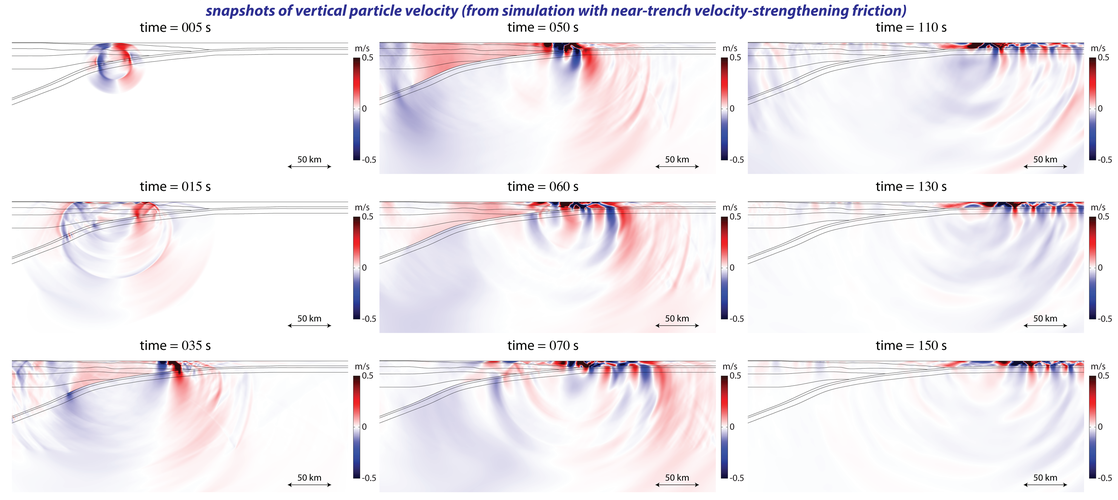
- Frictional properties near trench (over width *W*): control shallow slip and near-trench seafloor uplift
- Maximum effective normal stress: controls average stress drop (and overall slip)
- Depth *D* of seismogenic zone: well-constrained by data (down-dip velocity-strengthening transition)

Dynamic rupture model details:

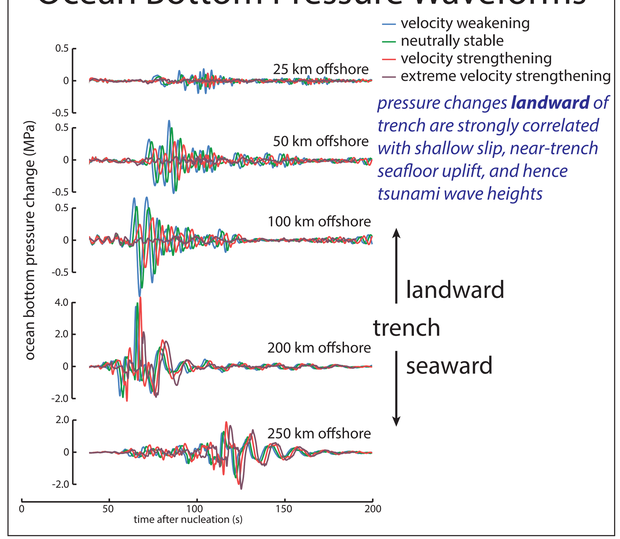
- Two-dimensional plane-strain linear elastic rock response
- Realistic geometry and material structure, including compressible ocean (based on Miura et al., Tectonophys., 2005)
- Rate-and-state friction (slip law), no dynamic weakening
- Depth-dependent frictional properties and prestress (pore pressure gradient becomes lithostatic at depth, giving constant effective normal stress)
- Poroelastic buffering of effective normal stress changes on fault

Hydroacoustic Wave Excitation and Propagation

snapshots of vertical particle velocity (from simulation with near-trench velocity-strengthening friction)

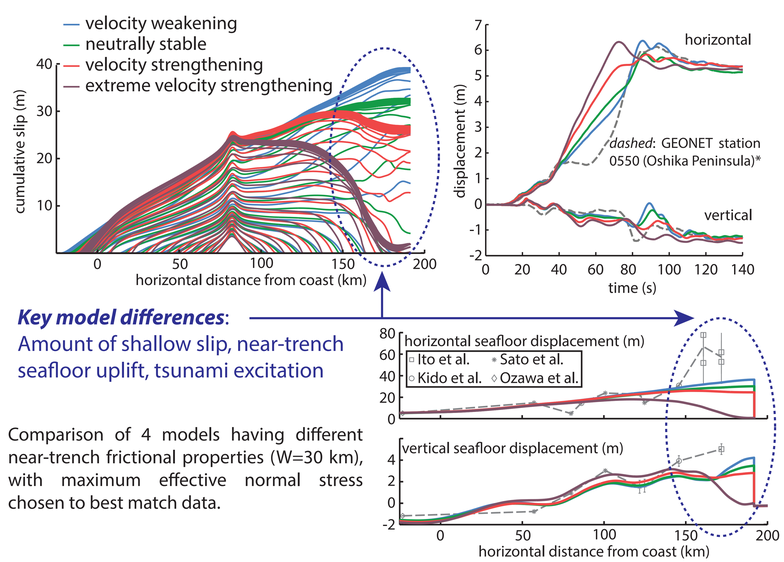


Ocean Bottom Pressure Waveforms



*pressure changes **landward** of trench are strongly correlated with shallow slip, near-trench seafloor uplift, and hence tsunami wave heights*

Constraints on Tohoku Rupture History from Onshore 1-Hz GPS and Seafloor Displacements

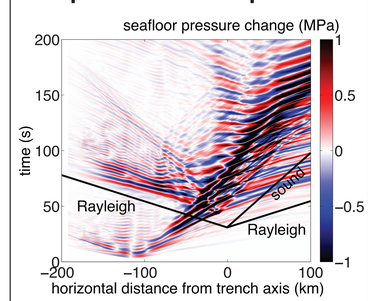


Key model differences:
Amount of shallow slip, near-trench seafloor uplift, tsunami excitation

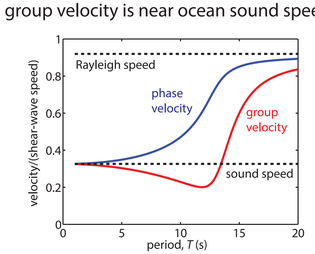
Comparison of 4 models having different near-trench frictional properties (W=30 km), with maximum effective normal stress chosen to best match data.

*The onshore 1-Hz GPS data (station number 0550 of GEONET operated by Geospatial Information Authority of Japan) were provided by Shinichi Miyazaki (personal communication, April 2012), who purchased the original RINEX data from Nippon GPS Data Service Corporation and processed them using the precise point positioning strategy with phase ambiguities resolved using GIPSY-OASIS software (Zumberge et al., 1997); station position errors were modeled as a white noise process.

Dispersion Properties



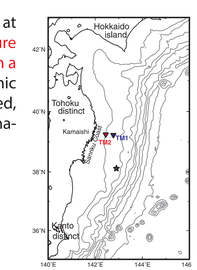
Propagation is dispersive, involving coupled motions of ocean and solid Earth. At T ~ 10 s (peak excitation, fundamental hydroacoustic mode), phase velocity is near Rayleigh wave speed of solid while group velocity is near ocean sound speed.

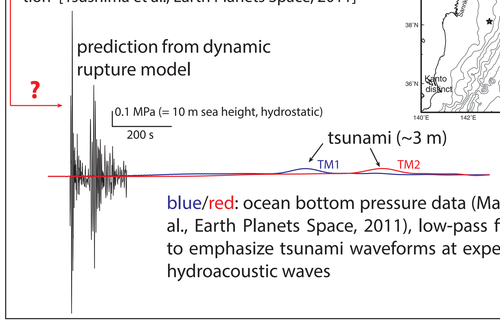


Dispersion curves for 5 km ocean over uniform elastic half-space.

Tohoku Predictions and Data

"...when the 2011 Tohoku earthquake occurred, at the OBPG station TM1 a very large pressure fluctuation (~80 m in equivalent water depth) with a period of ~10 s which was probably due to seismic waves and/or water column oscillation was recorded, in addition to the tsunami and/or seafloor deformation" [Tsushima et al., Earth Planets Space, 2011]





blue/red: ocean bottom pressure data (Maeda et al., Earth Planets Space, 2011), low-pass filtered to emphasize tsunami waveforms at expense of hydroacoustic waves

Future Directions

A modification of the free surface boundary condition will permit us to *model surface gravity waves* (tsunamis and dispersive shorter-wavelength ocean waves), in the linearized limit. We can then quantify the relationship between hydroacoustic wave amplitudes and tsunami wave heights. Such relations might be used as part of local tsunami early warning systems based on real-time data from cabled ocean bottom pressure sensor networks.