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# Constraining shallow slip and tsunami excitation in megathrust ruptures using seismic and ocean acoustic waves recorded on ocean-bottom sensor networks

Jeremy E. Kozdon[a,*], Eric M. Dunham[b,c]

[a] Department of Applied Mathematics, Naval Postgraduate School, Monterey, CA, USA
[b] Department of Geophysics, Stanford University, Stanford, CA, USA
[c] Institute for Computational and Mathematical Engineering, Stanford University, Stanford, CA, USA

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ABSTRACT

Great earthquakes along subduction-zone plate boundaries, like the 2011 magnitude 9.0 Tohoku-Oki, Japan, event, deform the seafloor to generate massive tsunamis. Tsunami wave heights near shore are greatest when excitation occurs far offshore near the trench, where water depths are greatest and fault slip is shallow. The Tohoku event, featuring over 30 m of slip near the trench, exemplifies this hazard. Unfortunately the rupture process that far offshore is poorly constrained with land-based geodetic and even most seafloor deformation measurements, and seismic inferences of shallow slip are often nonunique. Here we demonstrate, through dynamic rupture simulations of the Tohoku event, that long-period guided waves in the ocean (specifically, leaking oceanic P-wave modes known as PL waves) can resolve the shallow rupture process and tsunami excitation near the trench. With predicted pressure changes of ∼0.1–1 MPa along most of the seafloor landward of the trench, and periods of several seconds, these PL waves should be observable with ocean-bottom pressure sensors and/or seismometers. With cabled sensor networks like those being deployed offshore Japan and in other subduction zones, these waves could be used to rapidly quantify shallow slip and near-trench seafloor uplift and improve local tsunami early warning systems.



## 1. Introduction

In subduction zones like the Japan Trench, the site of the 2011 $M_w$ 9.0 Tohoku-Oki earthquake, coastal communities only have tens of minutes following a megathrust earthquake before the leading tsunami waves reach shore. In contrast, seismic waves, propagating an order of magnitude faster than tsunamis, arrive within about a minute. This travel-time difference provides an opportunity for local tsunami early warning systems. For earthquakes smaller than about $M_w$ 8, a point source characterization of the earthquake in terms of magnitude, focal mechanism, and depth using seismic waves suffices to reliably estimate tsunami excitation (Hirshorn and Weinstein, 2009). For great earthquakes ($M_w > 8$), the spatial distribution of slip across the fault and the finite rupture duration begin to influence tsunamigenesis. Real-time slip inversions, such as those based on high-rate geodetic data (Blewitt et al., 2009; Ohta et al., 2012), can help predict tsunami wave heights. However, resolving the near-trench region ∼100–200 km offshore, where tsunami excitation was largest in the Tohoku event (Sato et al., 2011; Ito et al., 2011; Kido et al., 2011; Fujiwara et al., 2011; Maeda et al., 2011), is challenging or even impossible using only land-based data (Ohta et al., 2012).

The resolution limits of land-based data can be overcome, of course, by placing instruments offshore, and the current revolution in seafloor geodesy and seismology holds much promise. Perhaps most relevant to local tsunami early warning systems are cabled sensor networks (Monastersky, 2012; Uehira et al., 2012; Saito, 2013), consisting of ocean-bottom pressure sensors and/or seismometers. These networks are directly linked to shore via fiber optic cables, thereby enabling real-time access to the data stream. Pressure sensors provide a rather direct measurement of tsunami wave heights as the waves pass overhead through the linear relation between pressure and the height of the water column under effectively hydrostatic conditions. Retrospective tsunami forecasts utilizing such data for the Tohoku event suggest that reliable

* Corresponding author.
*E-mail addresses:* jekozdon@nps.edu (J.E. Kozdon), edunham@stanford.edu (E.M. Dunham).

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estimates of wave heights can be obtained in about 20 min (Tsushima et al., 2011).

The pressure changes carried by the tsunami itself are neither the largest-amplitude nor the first-arriving signals from megathrust events at seafloor locations. Rapid seafloor uplift also excites seismic waves and ocean sound waves that propagate an order of magnitude faster than tsunamis. These include T waves, which are high-frequency (>2 Hz) sound waves trapped within the low-velocity SOFAR channel in the ocean. Despite initial optimism regarding their potential use for tsunami warning (Ewing et al., 1950), T waves appear to be too sensitive to small-scale details of the source process to reliably estimate the overall, lower-frequency earthquake source properties controlling tsunami excitation (Okal et al., 2003).

In addition to purely acoustic modes in the ocean, like T waves, offshore earthquakes also generate various guided waves involving motions of both the ocean and underlying solid. These include oceanic Rayleigh waves (Biot, 1952; Yamashita and Sato, 1976; Eyov et al., 2013) and leaking P-wave modes (also known as oceanic PL waves) (Oliver and Major, 1960; Phinney, 1961; Haddon, 1987), which are the subject of this work. We demonstrate, through simulations of the Tohoku earthquake, that PL waves excited by megathrust events are remarkably sensitive to shallow slip and seafloor uplift near the trench. The waves propagate toward shore at about 6 km/s (about 30 times faster than tsunami waves) and carry oscillatory pressure changes, at periods of several seconds, between 0.1 and 1 MPa across most of the seafloor landward of the trench. Acoustic organ-pipe reverberations in the ocean above the trench are also quite sensitive to near-trench motions. These various waves could be recorded by the same pressure sensor networks deployed for monitoring tsunamis, provided that the sampling rate and dynamic range of the instruments permit recording such signals without aliasing or clipping. These data could potentially be used to more rapidly and accurately infer tsunami wave heights.

## 2. Dynamic rupture simulations

We identified the link between PL waves and tsunami excitation through dynamic rupture simulations of the Tohoku earthquake (Kozdon and Dunham, 2013). Dynamic rupture simulations simultaneously solve for the slip history and seismic and acoustic wavefields that are consistent with the fault friction law, initial stresses, and the momentum balance and material response of the solid Earth and overlying compressible ocean. Using a dynamic, rather than kinematic, rupture model is not essential to study PL-wave excitation and propagation from megathrust events, but does provide an additional level of self-consistency in the source process.

The full details of our rupture models are given in Appendix A, and briefly summarized here. Because the Tohoku rupture extended nearly 500 km along strike and only 200 km down-dip we neglect variations in the along-strike direction. This renders the model two-dimensional, and allows us to focus on the up- and down-dip rupture growth that dominated most of the rupture process, particularly in the first minute or so (Ide et al., 2011; Yue and Lay, 2011). The method and model parameters are largely the same as those in the simulations of Kozdon and Dunham (2013), but with improvements to the structural model that are described below. Also, in contrast to our previous study, all simulations now have an ocean layer. The solid Earth response is linear elastic and the ocean is treated as a linear acoustic medium. We neglect gravitational restoring forces in the momentum balance, except in setting the initial tractions on the fault surface as described subsequently. The geometry and off-fault material properties (Fig. 1a) are based on the structural model of Miura et al. (2005). In our original simulations (Kozdon and Dunham, 2013), we directly used the nonplanar seafloor bathymetry and material interfaces observed along a seismic line extending off the Miyagi coast (Miura et al., 2005). The present model has smoother interfaces and bathymetry. The new bathymetry averages over along-strike bathymetric variations to provide a more representative profile. This proves useful when estimating the contribution to tsunami excitation from horizontal displacement of a sloping seafloor (Tanioka and Satake, 1996). The material properties are piecewise constant (see layer names in Fig. 1a) with values given in Table 1. The property values within each layer are identical to those in Kozdon and Dunham (2013); only the geometry is slightly altered.

We use a rate-and-state friction law in which fault shear resistance evolves with slip toward a steady state strength that is either an increasing or decreasing function of fault slip velocity (e.g., Rice et al., 2001). These behaviors are known as velocity-strengthening and velocity-weakening, respectively; the latter is necessary for unstable slip and earthquake nucleation while the former is usually associated with aseismic sliding. The depth dependence of frictional properties determines where and how fault slip occurs. We initially developed these simulations to study how frictional properties along the shallowest portion of the plate interface influence the ability of ruptures to reach the trench, finding that surface-breaking rupture is possible even through >30-km-long velocity-strengthening segments (Kozdon and Dunham, 2013).

In this work, we focus on a set of four simulations. All simulations have velocity-weakening friction on the central, seismogenic part of the plate interface, and transition to velocity-strengthening below 46.5 km depth. The latter is well-constrained by comparison to static displacement data on land and on the seafloor (Kozdon and Dunham, 2013). The models have different frictional properties on the upper part of the fault extending 30 km landward from the trench. That distance corresponds approximately to the length of the frontal prism, or deformed zone, at the trench (Tsuru et al., 2002). We label the four simulations based on the value of the rate-and-state $b-a$ parameter on the shallow fault as follows: velocity-weakening ($b-a=0.004$), neutrally stable ($b-a=0$), velocity-strengthening ($b-a=-0.004$), and extreme velocity-strengthening ($b-a=-0.008$). The central seismogenic zone has $b-a=0.004$. For the purposes of this exposition, the reader may simply view these as alternative source models with different amounts of slip near the trench.

We set initial effective normal stress on the upper section of the fault as the difference between lithostatic total normal stress and hydrostatic pore pressure. Below a certain depth we assume that pore pressure begins to track the lithostatic gradient, thus saturating the initial effective normal stress on the fault at a constant value $\bar{\sigma}_{\max}$ below that depth. The maximum effective stress $\bar{\sigma}_{\max}$ is the sole tunable model parameter that we select, in each of our four models, to obtain a reasonable fit to the onshore and offshore displacements. The values of $\bar{\sigma}_{\max}$ for the four models, from velocity-weakening to extreme velocity-strengthening, are $\bar{\sigma}_{\max}=$ 25 MPa, 30 MPa, 40 MPa, and 45 MPa, respectively. The corresponding values of $(b-a)\bar{\sigma}_{\max}$ in the central seismogenic zone are 0.1, 0.12, 0.16, and 0.2 MPa, respectively.

The resulting slip profiles (Fig. 2a) are nearly identical between the four models at depth, but differ substantially over the final $\sim$50 km near the trench. This reflects a trade-off between the average stress drop at depth, which increases with increasing $\bar{\sigma}_{\max}$, and the effective length of the seismogenic zone, which decreases as the upper part of the fault becomes more velocity-strengthening. Also shown in Fig. 2 are fits to an onshore high-rate GPS displacement time series and to static seafloor displacement measurements. With the exception of the seafloor measurements closest to the trench (Ito et al., 2011), which are subject to large