An interpretation of tsunami earthquake based on a simple dynamic model: Failure of shallow megathrust earthquake

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[1] The 2011 Tohoku earthquake demonstrated that extremely large seismic slip can occur at shallow plate interfaces in subduction zones. The large slip area for the Tohoku earthquake included the source region of a tsunami earthquake. We performed dynamic rupture simulations using simplified fault models and the mechanism of thermal fluid pressurization. We found that small fluctuations of initial shear stress near a trench, within 1 MPa, lead to differences in seismic moment release greater than two orders of magnitude. In addition, we performed another experiment varying rupture nucleation sizes and obtained similar acute sensitivities of parameters. Moderate slip events with trapezoidal (flat-topped) source time functions appear to occupy a transition position, between shallow megathrust earthquakes with surface rupture and smaller ordinary earthquakes without surface rupture. We interpret this result as representing the differences in interplate slip between shallow megathrust earthquakes, tsunami (moderate) earthquakes, and non-tsunami (ordinary) earthquakes, on the basis of seismic observations. **Citation:** Mitsui, Y., and Y. Yagi (2013), An interpretation of tsunami earthquake based on a simple dynamic model: Failure of shallow megathrust earthquake, *Geophys. Res. Lett.*, *40*, 1523–1527, doi:10.1002/grl.50266.

1. Introduction

[2] The Tohoku earthquake of 11 March 2011 (Mw 9.0) caused a massive tsunami along the Pacific coast of Japan. The tsunami was excited by ocean-bottom deformation near the Japan Trench that was mainly due to extremely large slip (50 m or more) in the shallow part of the plate boundary (e.g., *Ito et al*. [2011]; *Yagi and Fukahata* [2011]). Some research have noted a deficiency of high-frequency wave radiation from this shallow slip patch, relative to deeper parts of the plate interface (*Ide et al*. [2011]; *Simons et al*. [2011]). However, using a hybrid back-projection method, *Yagi et al*. [2012] reported that large amounts of seismic energy were released from the shallow slip patch in the frequency band 0.1–0.5 Hz. This finding implies that an episode of smooth and rapid slip near the Japan Trench occurred during the 2011 Tohoku earthquake. Moreover, by analyses of low-frequency spheroidal modes of the Earth, *Okal* [2012] proposed that the 2011 Tohoku earthquake did not exhibit significant slow components to its source.

[3] A previous tsunami earthquake (Mw $\sim$ 8.0), the Meiji Sanriku earthquake of 15 June 1896, occurred in a source region near the Japan Trench estimated by tsunami simulation (*Tanioka and Satake* [1996]). In their source model, the ruptured area extended from around 39.5°N (epicenter) to 38.5°N along the Japan trench with uniform slip of about 5 m. By contrast, for the 2011 megathrust event, many inversion studies using seismic wave, tsunami, static land deformation, and seafloor deformation (e.g., *Ide et al*. [2011], *Yagi and Fukahata* [2011], *Gusman et al*. [2012], *Iinuma et al*. [2012]) implied that a northern limit of a large slip area on the order of 20 m were located approximately 39.0°N, and some of them around 39.5°N. Although the source models of the earthquakes involve uncertainty (especially tsunami inversion models including effects of splay faults or seafloor landslides (*Grilli et al*. [2012])), the source area of the 1896 tsunami earthquake overlapped the large slip area of the 2011 megathrust earthquake at least partly. The question is raised whether this region behaved differently. In addition, Mw 7-class non-tsunami (ordinary) earthquakes had occurred in the region such as those of 19 January 1981 (*Hatori* [1981]), 18 July 1992 (e.g., *Seno* [2002]), and 9 March 2011 (*Shao et al*. [2011]). The estimated source regions of the interplate earthquakes are illustrated in Figure 1.

[4] A tsunami earthquake is one that excites a tsunami of a size larger than expected from its surface wave magnitude (*Kanamori* [1972]). Some megathrust earthquakes might involve components of tsunami earthquakes (e.g., *Seno and Hirata* [2007]), but, hereinafter, we use a term "shallow megathrust earthquake" for the Tohoku-type megathrust earthquake. Mechanisms proposed for the large tsunami excitation of tsunami earthquakes include upward branching of the coseismic rupture from the plate interface on splay faults (*Fukao* [1979]), seafloor landslides (*Kanamori and Kikuchi* [1993], *Ward* [2001]), and unusually large sediment uplift (*Seno* [2000], *Tanioka and Seno* [2001]). All of them follow shallow slips at plate interfaces. Using seismic inversions, *Bilek and Lay* [2002] compiled source time functions of six recent tsunami earthquakes in the world and showed that these have trapezoidal shapes (the peak value of the source time function remaining steady for a long time) rather than the triangular shapes of the source time functions of simple earthquakes. This characteristic seems widely common in tsunami earthquakes (an exception is the 1994 Java earthquake with an impulsive source time function, which might be associated with a seamount subduction (*Abercrombie et al*. [2001])). In the following, we discuss typical tsunami earthquakes with trapezoidal source time

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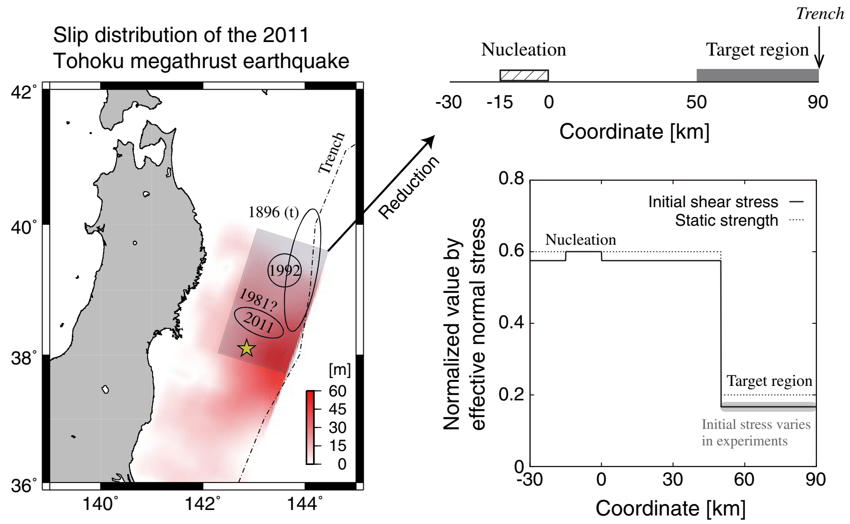

Figure 1. (Left) Source regions of the previous tsunami earthquake in 1896 (*Tanioka and Satake* [1996]), and non-tsunami (ordinary) earthquakes in 1992 (e.g., *Seno* [2002]) and 2011 (2 days prior to the megathrust earthquake; *Shao et al*. [2011]). One more non-tsunami earthquake in 1981 occurred at almost the same area as the 2011 non-tsunami earthquake (*Hatori* [1981]). The color contour represents slip distribution of the 2011 Tohoku megathrust earthquake, estimated by *Yagi and Fukahata* [2011]. (Right) In-plane model fault and parameter distribution for the initial shear stress τ_{sh} and the static strength τ_{fs} normalized by the effective normal stress $\sigma - p_0$.

functions at shallow parts. We also assume that the 1896 tsunami earthquake had such a source time function on the plate interface.

[5] We focus on slip behavior at plate interfaces during tsunami earthquakes and shallow megathrust earthquakes. For the shallow source faults of tsunami earthquakes, *Bilek and Lay* [2002] proposed a frictional framework of conditional stability (*Boatwright and Cocco* [1996]) as property transition from stable sliding to stick-slip behavior, and *Seno* [2002] suggested such transition due to temporal evolution of pore fluid pressure. For shallow megathrust earthquakes, *Mitsui et al*. [2012a] modeled an earthquake cycle at the Tohoku subduction zone with a huge coseismic slip in the shallow part of the rupture zone near the trench, owing to a dynamic weakening mechanism of thermal pressurization (TP) of pore fluid. In their modeling, the TP mechanism is effective only for shallow megathrust earthquakes, depending on the stress state in the shallow part of the rupture zone, which is central to the triggering of shallow megathrust earthquakes. In fact, strong correlations between tidal phase and occurrence of microearthquakes were observed during the decade prior to the 2011 Tohoku earthquake (*Tanaka* [2012]), which implies that the stress state was critical or nearly so. *Noda and Lapusta* [2013] performed a state-of-the-art conceptual simulation with the similar weakening mechanism in a 3D full space. Such a model with a TP mechanism can also reproduce the moment release rate of the 2011 Tohoku earthquake (*Mitsui et al*. [2012b]) and could explain its normal-fault-type aftershock sequences around the Japan trench (*Asano et al*. [2011]; *Yagi and Fukahata* [2011]).

[6] In this paper, we apply the TP mechanism in a numerical analysis of the differences in interplate slip behavior between non-tsunami (ordinary) earthquakes, tsunami earthquakes and shallow megathrust earthquakes. Using a simplified model of dynamic rupture, we focus mainly on the effect of the stress state in the shallow part of the fault plane.

2. Simplified Fault Model

[7] We solve the dynamic rupture problem by a boundary integral equation method in the frequency domain (*Geubelle and Rice* [1995]). Fault motion at each point depends on shear stress τ_{sh} and frictional strength τ_{fs}, where τ_{fs} is equal to $\mu(\sigma - p)$. μ is a frictional coefficient, σ is normal stress, and p is pore fluid pressure. For the frictional coefficient μ, we assume a velocity- and state (time) -dependent law (*Ampuero and Ben-Zion* [2008]) to cause self-healing pulses of slip during dynamic rupture (*Heaton* [1990]). The pore pressure p increases owing to the TP mechanism of frictional heating, thermal diffusion, and fluid diffusion (*Sibson* [1973], *Bizzarri and Cocco* [2006]) from the initial value p_0. The details of the assumptions, equations, and parameters are described in Section 1 of the auxiliary material. In the following, we try five other cases varying two parameters as listed in Table 1: ϖ is hydraulic diffusivity, and A is a non-dimensional material parameter characterizing the pressurization degree.

[8] We consider an analogue fault model for the shallow part of the megathrust earthquake rupture zone, as shown in Figure 1. We focus on slip and stress evolution in a target region (40 km from a trench) in a case in which a pulse-like rupture propagates from a deeper hypocenter, with the following assumptions. (1) The target region has a lower

Table 1. Hydraulic Diffusivity ϖ and Material Parameter A for Cases 1 to 6

Case	ϖ [m^2/s]	A
1	2.0×10^{-5}	0.025
2	5.0×10^{-6}	0.025
3	1.0×10^{-3}	0.1
4	2.0×10^{-4}	0.04
5	1.0×10^{-4}	0.03
6	5.0×10^{-5}	0.02

static strength and initial stress than the deeper part reflecting the existence of weak clay minerals (*Byerlee* [1978], *Moore and Saffer* [2001], *Kimura et al.* [2012]). Furthermore, we assume the TP mechanism to be effective in this target region, because clay minerals tend to have low static permeability that promotes efficient TP (e.g., *Faulkner et al.* [2010]). (2) We treat the end of the target region as a free end to represent the trench, using a mirror method to reduce the strain to zero there. The other end of the model fault is a fixed condition. (3) The effective normal stress $\sigma - p_0$ is a uniform 60 MPa, a reasonable value because several kilometers of sea-water exerts hydrostatic pressure of tens of MPa in addition to accretionary wedges on subduction plate interfaces, even around trenches.

[9] We perform numerical experiments by changing the initial shear stress in the target region between 9 MPa (normalized value 0.15) and 10 MPa (normalized value 0.167) at 0.2 MPa intervals, where the normalized values are done by the initial effective normal stress $\sigma - p_0$. The other parameters are shown in Figure 1: normalized static strength in the target region is 0.2, normalized initial stress and static strength in the nucleation area are 0.6, and normalized initial stress and static strength in other regions are 0.575 and 0.6, respectively.

3. Results

[10] Figure 2 shows calculated values of moment release in the target region, where moment release (2D) is defined as the product of the rigidity, the slip amount at each grid cell, and the slip area. We found that small differences in the initial shear stress, less than 1 MPa, led to differences in moment release greater than two orders of magnitude. Such nonlinear behavior is a characteristic of dynamic models with strongly weakening friction (*Noda et al.* [2009]). In our experiments, the behavior depends on the parameters regarding TP (Cases 1–6). Smaller hydraulic diffusivity ϖ or larger A leads to larger event via effective TP (e.g., *Bizzarri and Cocco* [2006]).

[11] We can group the calculation results into three types: shallow megathrust earthquakes with the largest moment release, moderate earthquakes, and smaller "ordinary" earthquakes that do not rupture the trench. The moderate earthquakes appear to occupy a transitional position between the shallow megathrust earthquakes and the ordinary earthquakes.

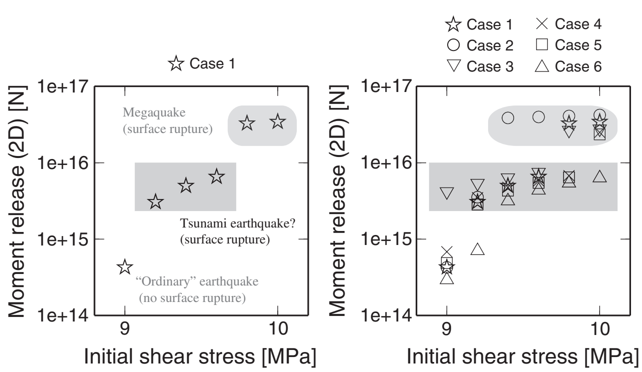

Figure 2. Calculated moment release (2D) at different initial shear stresses in the target region for (left) Case 1 and (right) all cases. The results can be grouped in three types: shallow megathrust earthquakes, moderate earthquakes (possible tsunami earthquakes), and smaller "ordinary" earthquakes without surface rupture.

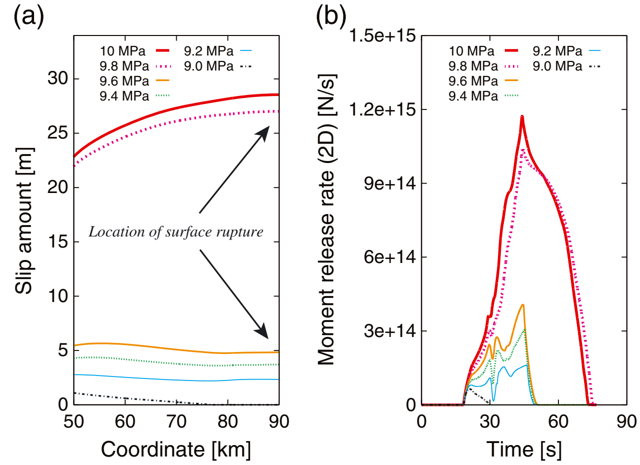

Figure 3. (a) Calculated final slip amount and (b) source time function with different initial shear stresses in the target region for Case 1. Note that only the moderate (tsunami) earthquakes with initial stresses of 9.2, 9.4, and 9.6 MPa, have trapezoidal rather than triangular source time functions.

[12] Figure 3 presents the final slip distribution and source time function (moment release rate) in the target region using Case 1 as a prime example. It is notable that the moderate earthquakes have trapezoidal source time functions whereas the larger and smaller events have triangular source time functions. The trapezoidal source time functions of the moderate events are results of the pulse-like rupture propagation. Because the slip velocity and slip area for the pulse-like rupture are relatively constant, the moment release rate remains steady for a long time, approximately given by product of the rigidity, the slip velocity, and the slip area. The characteristics of the trapezoidal source time functions correspond to tsunami earthquakes as compiled by *Bilek and Lay* [2002], therefore, we interpret the moderate earthquakes as tsunami earthquakes. The moderate earthquakes tend to have rather smaller values of stress drop than the megathrust earthquakes (see Section 2 of the auxiliary material).

[13] We do not consider some elements at shallow subduction parts such as low-rigidity layer or low dip angle. Low-rigidity layer may not affect moment release so much, differently from peak ground velocity (*Kaneko et al.* [2008]). Low dip angle tends to restrain rupture termination via free surface effects (*Oglesby et al.* [1998]). Whether the omitted effects break our interpretation or not will be the focus of future works.

4. Discussion

4.1. Implications for Long-Term Fault Behavior

[14] As Figure 1 showed, the shallow part of the Tohoku subduction zone has been the site of all three types of large interplate earthquakes. The near-trench huge slip area of the 2011 megathrust earthquake was located around the southern

edge of the source fault of the 1896 tsunami earthquake. We do not know whether the portion had been locked strongly or slipped slowly before the megathrust earthquake. Either way, once dynamic fault-weakening occurred, the thrust earthquake led to a megathrust one (*Mitsui et al.* [2012a]).

[15] Another subduction plate interface in Japan, the Nankai Trough region, has recorded historical Mw 8-class earthquakes (e.g., *Ando* [1975]; *Ishibashi* [2004]). The magnitudes of these earthquakes have varied considerably, as some of them probably also ruptured adjoining (along-strike) seismogenic segments. Indeed, it is unclear whether any tsunami earthquakes or shallow megathrust earthquakes with extremely large slip near the trench have occurred in the Nankai Trough, but some researchers have proposed that the 1605 Keicho earthquake was a tsunami earthquake, and the following 1707 Hoei earthquake was one of the greatest earthquakes in this region (see *Ishibashi* [2004]). We speculate that this sequence might be analogous to the 1896 tsunami earthquake and subsequent 2011 megathrust earthquake in the Tohoku subduction zone.

[16] Slip behavior in shallow parts of subduction zones is very common in the compilation of *Lay et al.* [2012], although they simply interpreted shallow parts as source regions of tsunami earthquakes. According to our numerical experiments, the peculiar slip behavior in shallow parts (e.g., *Bilek and Lay* [2002], *Lay et al.* [2012]) results from a relatively weak contribution of the dynamic frictional weakening. In addition to that, our study reveals a sensitive dependence of stress conditions in shallow subduction zones on earthquake magnitudes and other defining characteristics (shallow megathrust, tsunami, or ordinary earthquakes). This concept does not conflict with the possible complex earthquake sequences at the actual plate interfaces, and the possible critical stress state in the near-trench region prior to the 2011 Tohoku earthquake (*Tanaka* [2012]).

4.2. Effect of Triggering Intensity

[17] One may consider that shallow megathrust earthquakes are combinations of deeper large earthquakes and shallower tsunami earthquakes (e.g., *Fujii et al.* [2011]). This is similar to the interpretation by *Kanamori and McNally* [1982] that the 1906 M8.8 Columbia earthquake was produced by a combination of smaller M8-class events. Our result basically supports this concept. Our result also suggests that the dynamic frictional weakening in the shallower part plays a crucial role in the interaction between the deeper and the shallower parts.

[18] In our numerical model, the triggering intensity from the deeper part can affect the TP activation in the shallower part. To demonstrate this point, we perform another experiment. We set three models of rupture nucleation (Models A, B, and C) for the Case 5 parameters with the initial stress of 9 MPa in the near-trench target region. Model A is the same nucleation of the width of 15 km as the previous experiments, Model B is a larger nucleation of the width of 25 km, and Model C is also a larger nucleation beside the target region. Figure 4 shows the nucleation models and calculated moment release rate. Model B results in a megaquake simply because of the greater triggering intensity for TP than Model A. By contrast, Model C leads to a tsunami earthquake despite the same nucleation size as Model B. It implies that near-trench nucleation favors tsunami earthquake at least for these parameter settings.

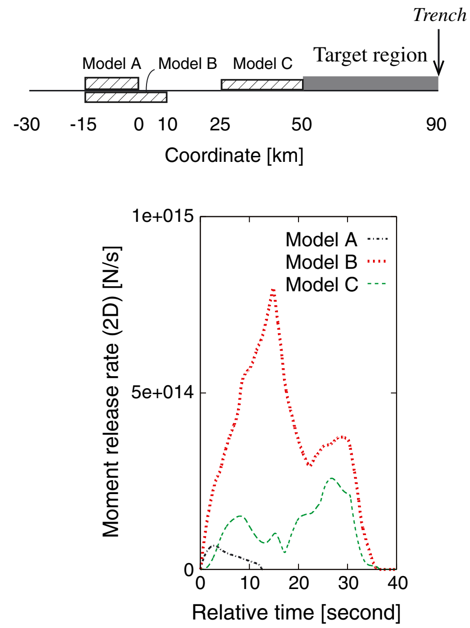

Figure 4. Nucleation Models A–C and calculated moment release rate (2D) in the target region for the Case 5 parameters with the initial stress of 9 MPa. The horizontal axis in the lower figure represents relative time from a rupture arrival at the target region.

[19] Such a sensitivity regarding nucleation may also strongly affect earthquake cycles. For instance, stress accumulation around the hypocenter of the 2011 Tohoku earthquake before its occurrence (e.g., *Kato et al.* [2012]) could drastically change the final magnitude of the megathrust earthquake via dynamic fault weakening, as revealed by *Mitsui et al.* [2012b].

5. Conclusion

[20] Using a simplified dynamic rupture simulation, our study illuminated the influence of initial shear stress near trenches on shallow interplate earthquakes. The differences between shallow megathrust earthquakes, tsunami (moderate) earthquakes with trapezoidal source time functions and small stress drop in near-trench areas, and non-tsunami (ordinary) earthquakes appear to originate from the slight differences in stress conditions as well as hydraulic properties within fault zones. We suggest that the interplate fault slips of some tsunami earthquakes are transitional phenomena between shallow megathrust and ordinary earthquakes.

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