Tsunami earthquakes as transient phenomena

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[1] Recent modeling of tsunami waveforms caused by tsunami earthquakes indicates that fault slip occurred along the subduction boundary close to the trench axis. On the other hand, it is well known that seismicity is generally very low within ca. 50 km from the trench axis, and this has been attributed to the stable frictional sliding properties of the subducted unconsolidated sediments. This makes tsunamigenic slip near the trench difficult to explain. In order to solve this dilemma, I propose that transition from stable sliding to nearly zero friction, with a velocity-weakening property, occurs as a result of areal increase of zones of elevated fluid pressure, which may make fairly rapid seismic slip possible following the breakage of asperities at normal seismogenic depths. This transition can be identified as seismic reflections with negative polarities, which may help to rate hazards for a coming large tsunami earthquake. INDEX TERMS: 7209 Seismology: Earthquake dynamics and mechanics; 7223 Seismology: Seismic hazard assessment and prediction; 7230 Seismology: Seismicity and seismotectonics; 8120 Tectonophysics: Dynamics of lithosphere and mantle—general; 8123 Tectonophysics: Dynamics, seismotectonics

1. Introduction

[2] For a variety of reasons, and disaster mitigation in particular, it is important to understand the occurrence of tsunami earthquakes, for which tsunamis are larger than expected given their surface wave magnitudes. Previous studies have elucidated how tsunami earthquakes occur and proposed various models for their occurrence. Tsunami earthquakes are generally characterized by slow faulting, manifest as a deficiency of short period components of seismic radiation relative to long periods [Kanamori, 1972; Pelayo and Wiens, 1992; Kanamori and Kikuchi, 1993; Polet and Kanamori, 2000]. However, it is also known that slow slip alone is insufficient to explain the small magnitudes compared with anomalously large tsunamis produced by some tsunami earthquakes, such as the 1896 Sanriku and 1946 Aleutian earthquakes [Fukao, 1979; Kanamori and Kikuchi, 1993]. Upheaval by high-angle splay faulting off the main thrust within a weak accretionary prism [Fukao, 1979], landslides caused by shaking [Kanamori and Kikuchi, 1993], and large seismic slip due to low rigidity of sediments along the shallow thrust zone [Geist and Bilek, 2001], have been proposed as mechanisms for the required additional uplift.

[3] On the other hand, recent modeling of tsunami waveforms of tsunami earthquakes based on dislocation theory has revealed that fault slip in several cases occurred very close to the trench axis [Satake, 1994; Piatanesi et al., 1996; Tanioka and Satake, 1996; Johnson and Satake, 1997; Satake and Tanioka, 1999]. Tsunami source areas of historical tsunami earthquakes also show similar features [Ishibashi, 1983, 1986]. These make the involvement of splay faults unlikely. The low rigidity (~10 GPa) of sediments in the shallow portion of the boundary can produce larger slip given the same seismic moment [Geist and Bilek, 2001], however, this produces the same order of stress drop (~1 MPa) as ordinary earthquakes, and how such a stress can be maintained in stable sliding sediments remains unresolved. Furthermore faulting close to the trench axis must occur of very low dips, which makes the uplift less efficient. To compensate this, Seno [2000] proposed that soft sediments near the toe of the trench slope are offscaped by a sudden horizontal movement of the backstop over the decollement (the detachment surface between offscaped and subducted sediments), causing an inelastic uplift at the toe. This effect was demonstrated to be potentially effective by numerical simulations of tsunamis of the 1896 tsunami earthquake off the Sanriku coast of northern Honshu [Tanioka and Seno, 2001], the required fault slip of 10 m without sediment deformation was reduced to 6 m.

[4] Above all, the large slip occurring along a shallow part of the subduction boundary remains as the largest enigma regarding tsunami earthquakes. It is known that seismicity is usually sparse within a distance of ca. 50 km of the trench axis [Hirata et al., 1983; Byrne et al., 1988; Scholz, 1998], and this has been attributed to the stable frictional sliding of unconsolidated sediments subducted beneath the decollement and deeper zones [Marone and Scholz, 1988; Scholz, 1998; Hyndman et al., 1997]. This stable sliding property is characterized by a positive a – b value, where a and b are coefficients in the rate and state dependent friction laws [Dieterich, 1979; Ruina, 1983], and a fault zone with this property operates as an absorbing barrier [Tse and Rice, 1986; Boatwright and Cocco, 1996; Kato and Hirawasa, 1999] if seismic faulting occurs at a nearby asperity, making the occurrence of tsunami earthquakes difficult to explain. In this paper, I show first that slip distributions associated with recent large earthquakes off northern Honshu are consistent with the above stable sliding frictional properties, then discuss a possibility of transient effective normal stress and its effects on frictional stability as applied to the occurrence of tsunami earthquakes.

2. Recent Large Earthquakes Off Northern Honshu

[5] In the subduction zone off Sanriku, northern Honshu, close to the rupture zone of the 1896 tsunami event, large (M_s > 7) earthquakes have occurred recently in 1989, 1992, and 1994 (Figure 1, Table 1). Though these events had aftershock areas extending very close to the trench axis, they were not tsunami earthquakes (compare their magnitudes with those of the 1896 event in Table 1). The asperities ruptured in these recent events [Nagai et al., 2001; Yamanaka et al., 2001] were generally located in the deeper part of their aftershock zones (Figure 1, Hino et al. [1999]; Tohoku University [1990]), indicating that only small amounts of seismic slip occurred in the shallow portion near the trench. Moreover, borehole strain meters on the coast and GPS velocities throughout northern Honshu indicate that large amounts of afterslip occurred with a time scale of 1 day to 1 year in the aftershock zones of these events [Kawasaki et al., 1995; Heki et al., 1997]. This behavior, i.e., small slip at the time of an earthquake and large afterslip, is similar to that predicted by the numerical simulation of frictional slip with a stable sliding zone in the shallow portion of the subduction boundary [Kato and Hirawasa, 1999]. These are completely consistent with the idea that a shallow subduction boundary constitutes a fault zone with positive a – b
Provided that these recent events shared the fault zone with the 1896 event (Figure 1), it seems difficult to explain the occurrence of the 1896 event by general factors such as paucity of subducted sediments and so on (see Tanioka and Satake [1996] and Polet and Kanamori [2000] for this kind of explanation). Note also that tsunami earthquakes are very rare; i.e., none of the same subduction zone segments has experienced a tsunami earthquake more than once during historic times.

3. Transient Frictional Stability

In subduction zones, fluids expelled from the subducting plate play important roles in various phenomena such as earthquakes, volcanism, metamorphism and so on. Fluids released by compaction of interstitial and fracture pore spaces or by dehydration of clay minerals migrate along the decollement-thrusts in the accretionary prism. Recent seismic reflection and ocean drilling surveys have revealed that reflection signals along the decollement exhibit substantial spatial variation [Moore and Shipley, 1993; Shipley et al., 1994]. For example, in some places the decollement produces a negative polarity reflection, but not in others, and reflection amplitudes also vary (Figure 2, Shipley et al. [1994]). This is most easily explained by variations in impedance (velocity x density) and thickness of the decollement. Negative polarity reflections usually have their origin in a thin (~10 m) layer of lower impedance than surrounding layers, which is attributed to pore space dilation by overpressured fluids [e.g., Moore and Shipley, 1993]. The fluid pressures of such layers are estimated to be 86 – 98% of the lithostatic pressure [Tobin et al., 1994].

The existence of elevated fluid pressures requires sealing and fluid infiltration, which will dissipate with time unless an effective seal can be continually maintained; thus high pore pressures themselves must be an indication of transience. This was confirmed by measurements in the holes of ODP Leg110 near the toe of the Barbados accretionary prism. Fisher and Houslows [1990], using shapes of geotherms and geochemical anomalies, showed that flows through the horizontal conduits had a transient nature with a time constant of decades to thousands of years. This indicates the high and/or low fluid pressures seen in Figure 2 may not be a permanent but rather transient characteristic of the fault zone; a wide area along the decollement might be covered by negative polarity reflections temporarily.

The effective normal stress in such an area would change significantly as the pore fluid pressure is elevated to a substantial fraction of the lithostatic pressure. The reduced effective stress would substantially decrease the friction on the fault zone. In the numerical studies of the mechanical behavior of a series of asperities intervened by high pore pressure compartments, Lockner

Table 1. Magnitudes of Earthquakes off Sanriku Coast, N. Japan

<table>
<thead>
<tr>
<th>Date</th>
<th>Ms</th>
<th>Mw</th>
<th>Mt</th>
</tr>
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<tbody>
<tr>
<td>1989 11 02</td>
<td>7.4</td>
<td>7.4</td>
<td>7.5</td>
</tr>
<tr>
<td>1992 07 18</td>
<td>7.1</td>
<td>6.9</td>
<td>7.2</td>
</tr>
<tr>
<td>1994 12 28</td>
<td>7.5</td>
<td>7.7</td>
<td>7.7</td>
</tr>
<tr>
<td>1896 06 15</td>
<td>7.2</td>
<td>8.0</td>
<td>8.6</td>
</tr>
</tbody>
</table>

Ms is the surface wave magnitude determined by International Seismological Centre; Mw is the moment magnitude from the Harvard centroid moment tensor catalogue; Mt is the tsunami magnitude [K. Abe, personal comm., 2001], except for the 1896 event of which parameters are taken from Tanioka and Satake [1996] and Tanioka and Seno [2001].
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Figure 3. (a) A cross-section illustrating DSRs (Deep Strong Reflectors) and the decollement beneath the Nankai accretionary prism off Shikoku [simplified from Park et al., 2001]. The DSRs and part of the decollement have negative seismic reflection polarities which may indicate elevated pore fluid pressures. (b) DSRs [Park et al., 2001], coseismic slip zones of the 1944 Tonankai and 1946 Nankai earthquakes [Ando, 1982], tsunami source and inundation areas accompanied with the 1605 Keicho earthquake [Ishibashi, 1983]. The seismic intensity at Kyoto at the time of the 1605 event was negligible, but the tsunami disaster was extensive to have killed more than two thousands of people [Ishibashi, 1983].

4. Mechanism of Tsunami Earthquakes

[9] Considering the peculiar nature of faulting associated with tsunami earthquakes that it breaks the shallowest portion of the subduction boundary and the possibility of transience of frictional properties along such a part of the boundary, I propose that a tsunami earthquake occurs when overpressured zones along the shallow portion cover a considerable areal extent and asperities in the seismogenic zone at depths break simultaneously, since the zones may make fairly rapid seismic slip following the breakage of asperities. The overpressured zones may not be necessarily connected with each other but be separated into compartments by impermeable seals as discussed by Lockner and Byerlee [1995].

[10] Off Sanriku, northern Honshu, strong reflectors along the plate interface, indicated by “F” in Figure 1, have been observed by refraction-reflection surveys [Fujie et al., 2000] to the south of the 1992 earthquake aftershock zone. The north-south dimension of the reflectors is about 30 km, coincident with an area of extremely low seismicity, which is indicated by the dashed line in Figure 1. If this reflective zone stems from elevated fluid pressures as Fujie et al. [2000] suggested and becomes pervasive over the shallow portion of the plate boundary along the Japan Trench, a tsunami earthquake, such as the 1896 event, may eventually happen, in association with the breakage of asperities in the deeper seismogenic zone, such as that of the 1992 event.

[11] In the Nankai Trough, great earthquakes have recurred every 100–200 years. Among those great earthquakes, the 1605 Keicho earthquake is a unique tsunami earthquake, which had small seismic intensities on land but caused disastrous tsunamis (Figure 3b, Ishibashi [1983]). From the seismic reflection surveys, Park et al. [2001] delineated reflections with negative polarities Beneath the Nankai accretionary prism 20–60 km landward of the frontal thrust (Figures 3a, 3b), which are located deeper than the negative polarity decollement near the frontal thrust [Moore and Shipley, 1993]. These DSRs (Deep Strong Reflectors) are distributed seaward of the co-seismic fault zone of the 1946 Nankai earthquake [Ando, 1982] (Figure 3b). Park et al. [2001] interpreted the DSRs as indicating elevated fluid pressures. A tsunami earthquake would happen when the sporadic DSRs shown in Figure 3b become pervasive over a wider area along the trough, connected to the negative polarity decollement in the shallow portion, and simultaneously asperities in the deeper seismogenic zone break. The 1605 Keicho earthquake might have been such an event. With the fact that usual great earthquakes such as the 1946 Nankai earthquake tend to rupture up-dip along the splay faults ca. 100 km landward from the trough axis [Cummins and Kanda, 2000; Kuramoto et al., 2000], tsunami earthquakes in this region are characterized by the slip close to the trough axis, beyond the splay faults, due to the transience of the frictional property in the shallow part of the subduction boundary.

5. Concluding Remarks

[12] The transient nature of the frictional property along the positive a – b portion of the subduction boundary proposed in this study might be tested by repeated reflection surveys over a target area. If possible, 3-D reflection surveys, such as the ones in the Barbados and the Nankai Trough [Shipley et al., 1994; Kuramoto et al., 2000] are desired. The transient nature of the frictional property proposed in this study might also be applicable to ordinary subduction zone or transform fault earthquakes. If so, the hypothesis could be more easily tested for those events, which have shorter recurrence intervals than tsunami earthquakes.

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References


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