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A fast and simple diagnostic method for identifying tsunamigenic earthquakes

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Abstract. An analysis of regional broadband seismograms of moderate and large subduction-zone earthquakes in Mexico shows that earthquakes which occur near the trench are abnormally depleted in high-frequency radiation. This observation leads to a simple and fast method to assess regional tsunami potential from earthquakes which occur along the Pacific coast of Mexico. A significant advantage of the method is that a single broadband seismograph is sufficient for the purpose. The method is based on the ratio of the total energy to the high- frequency energy (between 1 and 5 Hz), ER, computed from the seismograms. For earthquakes with the same seismic moment, ER is an order of magnitude greater for a source area near the trench as compared to those near the coast. The same seismograms are used to compute energy magnitude, M_E, which is tied to the moment magnitude, M_W. A regional tsunami may be expected along the coast if $M_E \geq 6.5$ and ER corresponds to a source near the trench. If, however, ER corresponds to a near-coast source, then M_E may have to be greater than about 7.3 for a tsunami of similar size to occur along the coast. The method holds promise for a fast regional tsunami warning in many Pacific basin countries which lack an adequate seismic network.

Introduction

Tsunami warning systems are based on the magnitude and the location of an earthquake. A large magnitude earthquake with a location near a subduction zone is potentially a tsunamigenic event. The amplitude of the tsunami is proportional to the seismic moment (Abe, 1979) which, in turn, is proportional to the long-period radiation from the source. Thus, the appropriate magnitudes for tsunami warning are those which are based on long- period seismic waves, e.g., the moment magnitude M_W (Kanamori, 1977), and the mantle-wave magnitude, M_M (Talandier and Okal, 1989). Shindele et al. (1995) have shown that M_M can be determined using regional ($7° < \Delta < 20°$) broadband records with the sufficient precision for a tsunami warning. In this case, the first warning can be issued 10-20 minutes after the occurrence of an earthquake. However, such a warning system is of little use at those distances where the tsunami may arrive within less than 10 minutes. Therefore, at close distance, tsunami warning systems rely on magnitude and location estimated from seismograms recorded as close as possible to the source (Uchiike and Hosono, 1995). The estimated magnitudes are often based on relatively short-period seismic waves and may reach a saturation and underestimate the seismic moment and tsunami potential of the event. In this report, we present a novel approach for regional tsunami warning in Mexico which is based on seismograms from just one broadband station. The method holds promise for other regions along the Pacific basin facing tsunami hazard.

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Spectra of subduction earthquakes in Mexico

A broad-band seismological station is located in the campus of the Universidad Nacional Autonoma de Mexico (UNAM) in Mexico City, about 250 km inland from the closest point of the subduction zone along the Pacific coast (Fig. 1). Seismograms from this station are routinely used to determine a magnitude called M_E. This magnitude is computed from radiated seismic energy (Singh and Pacheco, 1994) and is tied to M_W (Kanamori, 1977). An examination of seismograms recorded at UNAM shows that the events with epicenter near the trench are deficient at high frequencies as compared to those which are located near the coast (Fig. 2).

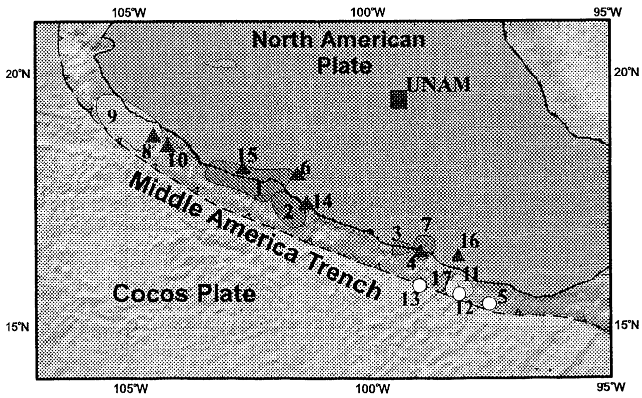

Figure 1. Map of Mexico showing contour of aftershock areas (if known) or epicenters of events listed in Table 1. Solid triangle: near-coast epicenter; open circle: near-trench epicenter; solid rectangle: UNAM location.

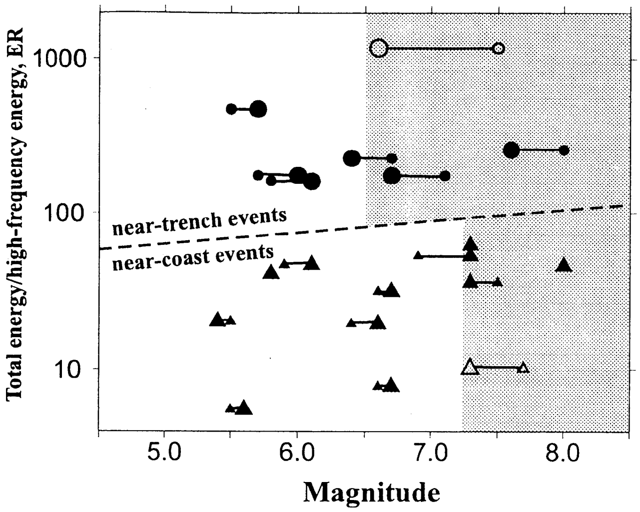

Figure 2. Vertical component velocity seismograms of events 17 and 4 recorded at UNAM. (b) Fourier velocity spectra of the traces shown in (a). The shaded region indicates the frequency band used in computing high-frequency energy.

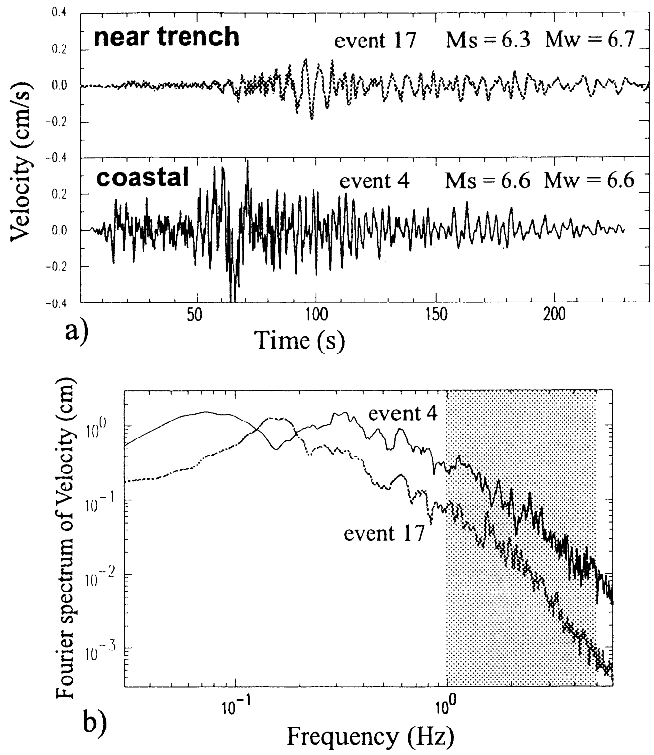

Figure 3. The ratio, ER, of total energy to the high-frequency energy plotted as a function of magnitudes. For the two Peruvian events (18 and 19) M_S replaces M_E. Small symbol: M_W; large symbol: M_E or M_S. Solid circle: near-trench Mexican events; open circle: the Peruvian near-trench event number 18. Solid triangle: near-coast Mexican events; open triangle: the Peruvian near-coast event number 19. The gray area indicates the M_E and ER pair which merit regional tsunami warning.

This observation forms the basis of the tsunami warning system reported here. Table 1 lists some well-located events which include earthquakes near the trench as well as near the coast (Fig. 1). The distances to the sources lie between 300 and 550 km. The ratio of the total energy to the high-frequency energy, ER, was computed using the following relation:

$$ER = \frac{\int_0^{\infty} [V_N^2(f) + V_E^2(f) + V_Z^2(f)]df}{\int_1^{\infty} [V_N^2(f) + V_E^2(f) + V_Z^2(f)]df} \quad (1)$$

In this relation, Vi (f) is the Fourier spectrum of the i-th component of the velocity seismogram normalized to a distance of 400 km. For the normalization we assumed that (a) the signals are surface waves so that the geometrical spreading is given by $R^{-0.5}$, and (b) the anelastic attenuation is given by $e^{\frac{-\pi f R}{\beta Q(f)}}$, where R is the hypocentral distance, β is the shear-wave speed, and $Q(f)$ is the quality factor. In correcting the spectra, we have chosen $\beta = 3.75$ km/s and $Q(f) = 273 f^{0.067}$ which is appropriate for the region (Ordaz and Singh, 1992). In actual computation of ER, the upper limit of the integrals has been taken as 5 Hz, which ensures that spectra are above noise for all events considered in Table 1. The lower limit in the numerator is taken as the smallest frequency below which the spectra is dominated by noise. It is different for each event. We have arbitrarily set the lower limit in the denominator as 1 Hz.

The plot of ER as a function of magnitudes M_E and M_W (Fig. 3) divides the data in two distinct groups. The events with source areas near the trench have ER values which are about an order of magnitude greater than for areas near the coast. Therefore, the magnitude and the ER value of an event provide a strong discriminant between a source area close to the trench and one near the coast.

Table 1. Source parameters of earthquakes analyzed in the study.

N	date	lat	long	M_S	M_W	M_E	ER
1	85.09.19	18.1	-102.7	8.1	8.0	8.0	45.9
2	85.09.21	17.6	-101.8	7.6	7.5	7.3	35.8
3	89.04.25	16.6	-99.5	6.8	6.9	7.3	53.1
4	93.10.24	16.5	-99.0	6.6	6.6	6.7	31.5
5	93.11.13	15.7	-99.0	5.4	5.7	6.0	173
6	94.12.10	18.0	-101.6	6.2	6.4	6.6	19.5
7	95.09.14	17.0	-99.0	7.2	7.3	7.3	62.4
8	95.09.06	18.8	-104.5	5.3	5.8	5.4	40.8
9	95.10.09	18.8	-104.5	7.4	8.0	7.6	258
10	95.10.12	18.7	-104.2	5.5	5.9	6.1	46.6
11	96.02.25	15.6	-98.3	6.9	7.1	6.7	174
12	96.02.26	15.7	-98.2	5.0	5.5	5.7	472
13	96.03.19	15.5	-97.6	5.2	5.8	6.1	160
14	96.07.15	17.5	-101.1	6.5	6.6	6.4	7.75
15	97.01.16	18.1	-102.9		5.5	5.4	20.2
16	97.01.21	16.4	-98.2		5.5	5.4	5.55
17	97.07.19	16.0	-98.2	6.3	6.7	6.4	227
18	96.02.21	-9.6	-79.6	6.6	7.5		1180
19	96.11.12	-15.	-75.7	7.3	7.7		10.1

Detection of 'tsunami earthquakes'

The discrimination between near-coast and near-trench earthquakes is important since large and great events which occur near the trench may also be the so called 'tsunami earthquakes' (Kanamori, 1972). These earthquakes generate anomalously large tsunami for their surface-wave magnitude, M_S, and are characterized by a large disparity between M_S and M_W (Kanamori and Kikuchi, 1993). Tsunami earthquakes may be caused by slow slip through the base of the accretionary prism (Pelayo and Wiens, 1992; Satake, 1994), on steeply dipping faults in the accretionary prism (Fukao, 1979), slumping of sediments near the trench (Ma *et al.*, 1991), or rupture reaching the ocean floor in nonaccreting margins where the sediments are subducted along a plate interface (Kanamori and Kikuchi, 1993). We note that all of these mechanisms involve a source area near the trench. Therefore, it seems possible that for large and great earthquakes the $M_E - ER$ discrimination may be equivalent to the M_W-M_S discrimination. A test of the above hypothesis is provided by recent tsunami earthquakes recorded by broad-band stations located at distances less than 7°.

Firstly we compare two great earthquakes of Mexico: 1985 Michoacan (event 1) and 1995 Colima-Jalisco (event 9). The ER value of the 1995 event (Fig. 3) suggests a near-trench location. This is confirmed by the aftershock area (Pacheco *et al.*, 1997) (Fig. 1). On the other hand, the ER value for the 1985 earthquake corresponds to a near-coast location (Fig. 3). Again this is in agreement with the aftershock area (UNAM Seismology Group, 1986). Because of the larger value of ER for the 1995 earthquake a larger tsunami should be expected for this event as compared to the 1985 event. Indeed this was the case: in the epicentral region of the 1995 earthquake, the tsunami heights were between 3 and 10 m (Borrero *et al.*, 1997). For the 1985 earthquake, the corresponding tsunami heights were between 1 and 5 m (Abe *et al.*, 1986; Farreras, 1997).

The 1995 earthquake propagated towards NW (e.g., Pacheco *et al.*, 1997), away from UNAM, whereas the 1985 earthquake ruptured in the SW direction, toward UNAM (e.g., UNAM Seismology Group, 1986). The Doppler effect predicts high-frequencies enrichment in the direction of rupture propagation as compared to the opposite direction. Therefore, it may appear that this effect can explain the difference in the ER values of the two earthquakes. To investigate this possibility, we have performed two types of tests: one based on recorded data and the other based on simulations using an empirical Greens function technique. We selected large ($M_W \geq 7$) events which occurred along the Mexican subduction zone and whose direction of rupture propagation is well known. For each event, we analyzed records of two broadband stations, located roughly at the same epicentral distance, one in the direction of the rupture propagation and the other one opposite to it. In the other test, we simulated seismograms at UNAM from an M_W=8.0 earthquake in the Colima-Jalisco region, applying an empirical Greens function (EGF) technique proposed by Kanamori *et al.* (1993). We used a foreshock of event 9 as an EGF (1995.10.06; $M_W = 5.8$). The source was represented by a sum of 20 subevents with randomly distributed seismic moments and locations. We calculated synthetic seismograms at UNAM for the cases of the rupture propagation away from the station and toward the station. In all the observed and the simulated cases, the total energy in the forward direction was found to be greater that in the opposite direction. However, the high-frequency energy (1-5 Hz) radiation was nearly isotropic. As a consequence, the ER value in the direction of the rupture propagation was found to be two times greater than in the opposite direction. It follows that the directivity did not accentuate but diminished the difference in the ER values of the 1995 and 1985 earthquakes. It is also worth emphasizing that the difference in the value of ER due to source directivity is smaller than the difference due to offshore and onshore location of the earthquake. Thus, we expect that the directivity would not mask the depth effect even in the most unfavorable case of rupture propagating away from UNAM.

A further confirmation of the predictive value of the method comes from two 1996 Peruvian earthquakes of 21 February (event 18) and 12 November (event 19). Because of the M_W-M_S disparity, the first event is clearly a tsunami earthquake. We analyzed broadband seismograms from the IRIS station of NNA, which is lo-

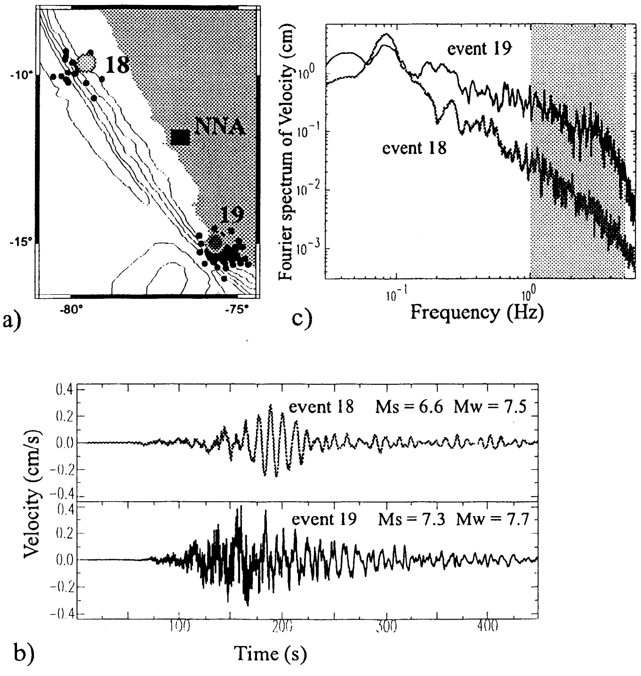

Figure 4. (a) Map of Peru showing the mainshocks and aftershocks of events 18 and 19. (b) Vertical component velocity seismograms of events 18 and 19 recorded at NNA. Note that event 18 located near the trench is depleted in high frequencies as compared to event 19. (c) Fourier velocity spectra of the traces shown in (b).

cated roughly at a distance of 400 km from both events (Fig. 4a). An examination of the seismograms shows that the first event is deficient in higher frequencies as compared to the second event (Fig. 4). The ER value of the first event is about 120 times greater than the second one (Table 1). The plot of ER values of these two events in Fig. 3, suggests that source areas of the first and second events are near the trench and near the coast, respectively. This is in agreement with the aftershock locations as listed in NEIC bulletins and plotted in Fig. 4a. The first earthquake with a large ER value corresponding to a near-trench event, suggests a larger tsunami potential than the second earthquake. In fact, while the first event caused damage and deaths from a regional tsunami, only minor local tsunami was reported during the second event.

Our results show that tsunami earthquakes remain deficient at very short periods (≤ 1 s). This deficiency may result from a combination of a slow rupture during these earthquakes and a high attenuation of seismic waves in the sediments near the source region.

Conclusions

The proposed method to discriminate between near-coast and near-trench subduction earthquakes can be applied for a fast identification of tsunami earthquakes and an estimation of the associated tsunami hazard. An important advantage of this method is that it requires only one, suitably located, broadband seismograph. Therefore, it can also be economically and technically feasible in many countries which are vulnerable to tsunami but can ill afford a sophisticated seismic network. The available data suggests a preliminary strategy for issuing an alert: a regional tsunami may be expected along the Pacific coast of Mexico if $M_E \geq 6.5$ and ER corresponds to a source near the trench. However, M_E may have to be greater than about 7.3 for a tsunami of similar size to occur along the coast if ER corresponds to a near- coast source. We note that the determination of M_E and ER takes less than about 5 minutes after the origin of the earthquake if we use the records from the broadband station of UNAM, located in Mexico City. This is few minutes less than the time it takes for the tsunami to strike the coast in the epicentral area.

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