Tsunami early warning using earthquake rupture duration and $P$-wave dominant-period: the importance of length and depth of faulting

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After an earthquake, rapid, real-time assessment of hazards such as ground shaking and tsunami potential is important for early warning and emergency response. Tsunami potential depends on sea floor displacement, which is related to the length, $L$, width, $W$, mean slip, $D$, and depth, $z$, of earthquake rupture. Currently, the primary discriminant for tsunami potential is the centroid-moment tensor magnitude, $M_{w}^{\text{CMT}}$, representing the seismic potency $LWD$, and estimated through an indirect, inversion procedure. The obtained $M_{w}^{\text{CMT}}$ and the implied $LWD$ value vary with the depth of faulting, assumed earth model and other factors, and is only available 30 min or more after an earthquake. The use of more direct procedures for hazard assessment, when available, could avoid these problems and aid in effective early warning. Here we present a direct procedure for rapid assessment of earthquake tsunami potential using two, simple measures on $P$-wave seismograms – the dominant period on the velocity records, $T_d$, and the likelihood that the high-frequency, apparent rupture-duration, $T_0$, exceeds 50-55 sec. $T_0$ can be related to the critical parameters $L$ and $z$, while $T_d$ may be related to $W$, $D$ or $z$. For a set of recent, large earthquakes, we show that the period-duration product $T_dT_0$ gives more information on tsunami impact and size than $M_{w}^{\text{CMT}}$ and other currently used discriminants. All discriminants have difficulty in assessing the tsunami potential for oceanic strike-slip and back-arc or upper-plate, intraplate earthquake types. Our analysis and results suggest that tsunami potential is not directly related to the potency $LWD$ from the “seismic” faulting model, as is assumed with the use of the $M_{w}^{\text{CMT}}$ discriminant. Instead, knowledge of rupture length, $L$, and depth, $z$, alone can constrain well the tsunami potential of an earthquake, with explicit determination of fault width, $W$, and slip, $D$, being of secondary importance. With available real-time seismogram data, rapid calculation of the direct, period-duration discriminant can be completed within 6-10 min after an earthquake occurs and thus can aid in effective and reliable tsunami early warning.

Introduction

After an earthquake, rapid, real-time assessment of hazards such as ground shaking and tsunami potential is important for early warning and emergency response (e.g., Kanamori 2005; Bernard et al. 2006). Effective tsunami early warning for coastlines at regional distances (>100 km) from a tsunamigenic earthquake requires notification within 15 minutes after the earthquake origin time (OT). Currently, rapid assessment of the tsunami potential of an earthquake by organizations such as the Japan Meteorological Agency (JMA), the German-Indonesian tsunami early warning system (GITEWS) or the West Coast and Alaska (WCATWC) and Pacific (PTWC) Tsunami Warning Centers relies mainly on initial estimates
of the earthquake location, depth and moment, $M_0$, or the corresponding moment magnitude, $M_w$. For the regional scale, WCATWC and PTWC issue warning notifications within about 5-10 min after OT for shallow, underwater events using the P-wave moment-magnitude discriminant, $M_{wp}$, (Tsuboi et al. 1995; Tsuboi et al. 1999) if $M_{wp} \geq 7.5$ (e.g., Hirshorn et al. 2009).

$M_0$ is of interest for tsunami warning because the efficiency of tsunami generation by a shallow earthquake is dependent on the amount of sea floor displacement, which can be related to a finite-faulting model expressed by the seismic potency, $LWD$, where $L$ is the length, $W$ the width and $D$ the mean slip of the earthquake rupture (e.g., Kanamori 1972; Abe 1973; Kajiura 1981; Lay and Bilek 2007; Polet and Kanamori 2009). Then, since $M_0 = \mu LWD$, where $\mu$ is the shear modulus at the source, the sea-floor displacement and thus tsunami potential should scale with $LWD = M_0/\mu$. If $\mu$ is taken as constant for all shallow earthquakes, $M_0$ and the corresponding $M_w$ should be good discriminants for tsunami potential; indeed, for a point source, the tsunami wave amplitude is expected to be directly proportional to $M_0$ (Okal 1988).

$M_w$ is found to be a good discriminant for many, past, tsunamigenic earthquakes, but not all, especially not for so-called “tsunami earthquakes”, which, by definition, cause larger tsunami waves than would be expected from their $M_w$ (e.g., Kanamori 1972; Satake 2002; Polet and Kanamori 2009). The discrepancy for these earthquakes can be related to rupture at shallow depth where $\mu$ can be very low, an-elastic deformation such as ploughing and uplift of sediments may occur, and the fault surface may be non-planar with splay faulting into the accretionary wedge (e.g., Fukao 1977; Moore et al. 2007; Lay and Bilek 2007). One or more of these effects can result in an underestimate by $M_0$ or $M_w$ of an effective $LWD$ value by a factor of 4 or more relative to the value needed to explain the observed tsunami waves (Okal 1988; Satake 1994; Geist and Bilek 2001; Lay and Bilek 2007; Polet and Kanamori 2009).

The assessment of tsunami potential using $M_0$ follows an indirect procedure: firstly, an earthquake source model (e.g., hypocenter, $M_0$) is determined from basic observations using a physical theory, earth model and an inversion algorithm, and, secondly, the critical parameters (e.g., $LWD$) that estimate the hazard are (explicitly or implicitly) extracted from this source model. This procedure involve assumptions and algorithms that introduce error and sometimes large processing-time delays. For $M_0$, as noted above, an error in source depth or use of an inappropriate earth model can lead to error in the estimated $LWD$, while obtaining $M_0$ requires inversion of long period seismic waves which introduces a delay of 30 min or more after OT. The use of direct and rapid procedures to constrain critical parameters such as $L, W$ and $D$ and assess tsunami potential could avoid these problems and, in some cases, make possible effective tsunami early warning for coastlines near a tsunamigenic earthquake. Direct procedures are currently used to estimate magnitudes and shaking intensity for earthquake early warning and rapid response (e.g., Wald et al. 1999; Kanamori 2005; Lancieri and Zollo 2008).

Recently, through analysis of teleseismic, P-wave seismograms (30°-90° great-circle distance; GCD), Lomax and Michelini (2009A; LM2009A hereinafter) have shown that a high frequency, apparent rupture-duration, $T_0$, greater than about 50 s forms a reliable discriminant for tsunamigenic earthquakes (Fig. 1). Lomax and Michelini (2009B; LM2009B hereinafter) exploit this result through a direct, “duration-exceedance” (DE) procedure applied to seismograms at 10-30° GCD to rapidly determine if $T_0$ for an earthquake is likely to exceed 50-55 s and thus to be a potentially tsunamigenic earthquake.

Here we present a direct procedure for assessing tsunami potential which combines $T_0$ with a measure of the dominant period on the velocity records, $T_d$. $T_d$ and $T_0$ are simple to measure on observed, P-wave seismograms and can be related to the critical parameters $L, W, D$ and depth needed for assessing tsunami potential. This direct, period-duration procedure gives
improved identification of recent earthquakes which produced large or devastating tsunamis, relative to the use of the $M_w$, teleseismic $T_0$ or DE discriminants.

**Tsunami size, moment magnitude and rupture duration**

We consider a reference set of 117 large earthquakes ($6.4 \geq M_w \geq 9.0$; 101 shallow, under water) since 1992, when high-quality, broadband seismograms became widely available, along with the impact and size of any generated tsunamis (Table S1). This reference set includes most tsunamigenic earthquakes listed in the NOAA/WDC Historical Tsunami Database (http://www.ngdc.noaa.gov/hazard/tsu_db.shtml), most events of $M_w \geq 7$ in the past few years and several events of regional importance.

Lacking a uniform, physical measure of impact for most tsunamis, following $LM2009A,B$, we define a approximate measure of tsunami importance, $I$, for the reference earthquakes based on 0-4 descriptive indices, $i_{\text{effect}}$, of tsunami effects (deaths, injuries, damage, houses destroyed), and maximum water height $h$ in meters from the NOAA/WDC database: $I = i_{\text{height}} + i_{\text{deaths}} + i_{\text{injuries}} + i_{\text{damage}} + i_{\text{houses-destroyed}}$, where $i_{\text{height}} = 4, 3, 2, 1, 0$ for $h \geq 10$, $3$, $0.5$, $0$ m respectively. We ignore earthquakes not in the database if they are aftershocks of large events, otherwise we set $I = 0$. Note that $I$ is approximate since it depends strongly on the available instrumentation, coastal bathymetry and population density in the event region. $I \geq 2$ corresponds approximately to the JMA threshold for issuing a “Tsunami Warning”; the largest or most devastating tsunamis typically have $I \geq 10$.

For a measure of tsunami size, we calculate a representative tsunami wave amplitude at 100km distance from the source, $A_s$, for each event, using the water height readings in the NOAA/WDC database corrected to zero to peak, deep-water amplitudes, $h_a$, and to a distance of 100km using the conservation of energy on the wave front on a spherical surface (e.g., Woods and Okal 1987), $a_s = h_a \sin^{1/2}(\Delta) / \sin^{1/2}(\Delta_{100})$, where $\Delta$ and $\Delta_{100}$ are the angular distances of the height measure from the source and corresponding to 100km, respectively. $A_s$ is the median of the $a_s$ calculated for events with 3 or more water height readings.

As discriminants for tsunami potential, we first consider the Global Centroid-Moment Tensor moment-magnitude, $M_w^{\text{CMT}}$ (Dziewonski et al. 1981; Ekström et al. 2005), and $T_0$ durations calculated from the envelope decay of squared, high-frequency (HF; 1-5 Hz band-pass), P-wave seismograms at teleseismic distance ($LM2009A$). Fig. 2 shows $M_w$, $M_w^{\text{CMT}}$ and $T_0$ compared with the impact and size measures $I$ and $A_s$. The thresholds $M_w^{\text{CMT}} \geq 7.5$ and $T_0 \geq 55$ s (despite a relatively high uncertainty for the $T_0$ values) both identify most of the events with $I \geq 2$ (see also Tables 1 and S1). However, unlike $T_0$, $M_w^{\text{CMT}}$ shows no clear relationship to $I$ or $A_s$; this difference is especially marked for tsunami earthquakes (type T) and back-arc intraplate events (type B). Relative to a possible linear relationship between $A_s$ and $M_0$ (Fig. 2, lower centre), $M_w^{\text{CMT}}$ is too high for some events, and too low for others, notably for T and some B type events. In contrast, $T_0$ tends to increase for events with larger $I$ and $A_s$, including for types T and B, and shows possible agreement with a linear relationship between $A_s$ and $T_0$ (Fig. 2, lower right).

**Faulting dimensions, rupture duration and dominant period**

The $M_0$ (or $M_w^{\text{CMT}}$) discriminant relies on the assumption that tsunami potential is directly related to the $LWD$ or potency, finite-faulting description of the source, while the shortcomings of this discriminant for tsunami and other earthquakes are in part related to depth of rupture. Rupture duration, $T_0$, corresponds well to the tsunami size measures $I$ and $A_s$ because $T_0$ is related to a component of the $LWD$ source, the rupture length $L$: $T_0 \propto L / v_r$, where $v_r$ is rupture velocity. Since $v_r$ scales with $S$-wave velocity and shear modulus, $\mu$, which increase with depth, and since $v_r$ is found to be very low at shallow depth for tsunami
earthquakes (Geist and Bilek 2001; Polet and Kanamori 2009), we may assume \( v_0 \propto z^q \), where \( z \) is some mean rupture depth (e.g., Kajiura 1981) and \( q \) is positive. Then, \( T_0 \propto L/z^q \), showing that \( T_0 \) provides information on both \( L \) and \( z \), and, most importantly, \( T_0 \) grows with increasing \( L \) and decreasing \( z \), two conditions for increased tsunami potential.

The above considerations suggest a general relation for tsunami potential involving \( L, W, D \) and the mean rupture depth, \( z \), of the form \( LWD/z^q \), with \( p \) positive. Such a relationship could be evaluated by combining \( T_0 \), which gives information on \( L \) and \( z \), with additional information on \( W, D \) and \( z \).

Information on \( W, D \) and \( z \) may be provided by the frequency content of the \( P \)-wave seismogram. For example, consider the corner frequency of the \( P \)-wave displacement spectrum, \( f_c \). The corresponding period, \( 1/f_c \), can be related to a linear dimension of the earthquake rupture, typically \( \sqrt{A} \), where \( A \) is the rupture area (e.g., Brune 1970; Madariaga 1976; Madariaga 2009). However, since we consider here large earthquakes with \( L \gg W \) or \( L \gg W \), \( 1/f_c \) is more likely related to \( W \) than to \( L \), e.g. \( W \propto v_r f_c \). For the fault displacement, \( D \), there is controversy whether \( D \propto W \) or \( D \propto L \) for large crustal earthquakes, but for subduction zone, thrust events that concern us most, \( W \) may grow with \( L \) (Scholz 1982), which allows \( D \propto W \) and thus the possibility that \( D \propto v_r f_c \). In addition, tsunami earthquakes and shallow, near trench earthquakes are characterised by a deficiency in high-frequency radiation (e.g., Shapiro et al., 1998; Polet and Kanamori 2000; Polet and Kanamori 2009). Thus a characterisation of the frequency content of the \( P \)-wave seismograms may provide information on \( W, D \) and \( z \), with anomalously low frequencies indicating increased \( W \) or \( D \), or decreased \( z \), and correspondingly increased tsunami potential.

Here we choose to characterise the \( P \)-wave frequency content by its dominant-period, obtained by applying the rapid, time-domain, \( t_c \) algorithm (Nakamura 1988; Wu and Kanamori 2005) to velocity seismograms. Given a \( P \)-wave velocity seismograms, \( v(t) \), \( t_c \), is given by,

\[
\tau_c = 2\pi \sqrt{\frac{\int_{t_1}^{t_2} v^2(t) dt}{\int_{t_1}^{t_2} v^2(t) dt}}
\]

with the integrals taken over the time window \((T_1, T_2)\).

We define the dominant period, \( t_d \), as the peak \( t_c \) value obtained from eq.(1) applied with a 5 s sliding time-window from 0 to 55 s after the \( P \) arrival. This definition of \( t_d \) follows from examination of numerous possible parameter settings with the goal of best discriminating tsunamigenic events. The value of 5 s for the time-window is sufficient to identify if \( t_d \) is greater or less than about 10 s, which we will see below is roughly the critical value for discrimination using \( t_d \) along with \( T_0 \). We use \( P \)-wave seismograms only within the distance range of 5-40° GCD to avoid biases due to distance- and frequency-dependent attenuation, ignored here due to lack of accurate attenuation models for the earthquake source regions. Where the signal is predominantly monochromatic, the obtained \( t_d \) values match well the dominant period of \( P \)-waves found by visual inspection of seismograms (Fig. 1).

We define an event \( T_d \) level as the median of the station \( t_d \) values, with station distribution weighting applied to balance the contribution of sometimes highly heterogeneously distributed (e.g. clustered or isolated) stations. Fig. 3 shows a comparison of event \( T_d \) (median of the station \( t_d \) values) with \( I \) and \( A \). - there is an overall increase in \( T_d \) with respect to increasing \( I \), though much scatter, and an unclear but possibly similar relation between \( T_d \) and \( A \).

To investigate relationships of the form \( LWD/z^q \) for determining tsunami potential we have examined numerous expressions such as \( T_d^2 T_0, T_d T_0^2 \) and \( T_d T_0 \) as discriminants and found that \( T_d T_0 \) gives the best agreement with \( I \) and \( A \). Fig. 3 shows a comparison of \( T_d T_0 \) with \( I \) and \( A \).
The discriminant \( T_dT_0 \) (despite a relatively large uncertainty; see Table S1) has a clearer correspondence to \( I_t \) and \( A_t \) than \( M_w^{\text{CMT}} \) and \( T_0 \) (Fig. 2), including for tsunami earthquakes (type T) and some back-arc intraplate earthquakes (type B). The main contribution to this correspondence comes from the \( T_0 \) values, while the \( T_d \) values, despite their scatter, help to improve the results for larger events and those with \( I_t=0 \). \( T_dT_0 \) also shows possible agreement, as good or better than that of \( T_0 \), to a linear relationship with \( A_t \) (Fig. 3, lower centre). A critical threshold value of \( T_dT_0 = 510 \) s\(^2\) shows improved identification of events with \( I_t \geq 2 \) and of non-tsunamigenic events with \( I_t=0 \) relative to \( M_w^{\text{CMT}} \) and \( T_0 \) (Figs. 2 and 3; Table 1). This result indicates a critical value for \( T_d \) of about 10 s, since the critical threshold for the \( T_0 \) discriminant alone is 55 s.

**Rapid, direct assessment of tsunami potential**

Since moment-based magnitudes such as \( M_w^{\text{CMT}} \) are only available 30 min or later after OT, rapid magnitude estimates such as \( M_{wp} \) are used for tsunami warning. But \( M_{wp} \) performs poorly relative to \( M_w^{\text{CMT}} \), \( T_0 \) or \( T_dT_0 \) for identifying events with \( I_t \geq 2 \) (Fig. 2; Table 1). Other rapid magnitude estimates for large earthquakes (e.g., Hara 2007; \( M_{wpd} \), LM2009A; \( m_{bc} \), Bormann and Saul 2009; \( M_{ws} \), Kanamori and Rivera 2008) may perform nearly as well as \( M_w^{\text{CMT}} \) or \( T_0 \) (e.g., \( M_{wpd} \) in Tables 1 and S1), but are not available until about 15 min or later after OT.

Rapid, real-time determination if \( T_dT_0 \) exceeds a critical threshold (i.e., \( T_dT_0 \geq 510 \) s\(^2\)) would provide important complementary information to initial location, depth and magnitude estimates for early assessment of earthquake tsunami potential. Since \( T_d \) is obtained rapidly (\(<60\) s) after the \( P \) arrival, it remains to rapidly assess \( T_0 \) for an earthquake, in particular if \( T_0 \geq 50-55\) s. Using the duration-exceedance, DE, procedure of LM2009B, we determine if \( T_0 \) for an earthquake is likely to exceed 50-55 s through HF analysis of vertical-component, broadband seismograms. On 1-5 Hz band-pass filtered seismograms we form the ratio of the \( rms \) amplitude from 50-60 s after the \( P \) with the \( rms \) amplitude for the first 25 s after the \( P \) to obtain a station DE level for 50-55 s, \( L_{50} \) (Fig. 1). We define an event DE level, \( L_{50} \), as the median of the station \( L_{50} \) values, with station distribution weighting and ignoring stations at less than 10° GCD to avoid noisy, anomalously long, and S-wave HF signal. If an event DE level \( L_{50} \) is greater (less) than 1.0, then \( T_0 \) is likely (unlikely) to exceed 50-55 s. Based on this study and our previous work (LM2009A,B) with large earthquakes datasets, we estimate that measures from 10-20 stations are needed to obtain stable estimates of \( T_0, L_{50} \) and \( T_d \).

Using \( L_{50} \) as a substitute for \( T_0 \), our discriminant for tsunami potential becomes \( T_dL_{50} \) (i.e., \( T_dL_{50} \geq 8.0 \) s). We apply the \( T_dL_{50} \) discriminant to the reference earthquakes using data up to 10 min after OT from stations up to 30° GCD from each event to simulate the information available in the first minutes after an earthquake occurs. Fig. 3 shows a comparison of \( T_dL_{50} \) with \( I_t \) and \( A_t \), the overall \( T_dL_{50} \) results are listed in Table 1 and all event parameters and results listed in Table S1. A comparison of the \( T_dL_{50} \) and \( T_dT_0 \) discriminants shows similar performance for identifying events with \( I_t \geq 2 \) and \( I_t < 2 \), confirming that the rapidly available \( T_dL_{50} \) measures form reliable proxies for \( T_dT_0 \) using the teleseismic, \( T_0 \) durations.

**Discussion**

The period-duration discriminants \( T_dT_0 \) and \( T_dL_{50} \) correctly identify 77% of tsunamiogenic events with \( I_t \geq 2 \), more than the \( M_w^{\text{CMT}} \) and \( T_0 \) discriminants, with fewer false positive identifications of events with \( I_t < 2 \) (Tables 1 and S1; Figs. 2 and 3). The \( T_dT_0 \) and \( T_dL_{50} \) discriminants miss 11 tsunamiogenic events, all are also missed using the \( M_w^{\text{CMT}} \) discriminant, except for one, an oceanic, strike-slip earthquake, \( I_t = 6 \), \( M_w 7.5 \), 2000.05.04 Sulawesi missed by \( T_dL_{50} \). The events missed by \( T_dT_0 \) and \( T_dL_{50} \) with largest \( I_t \) include two oceanic, strike-slip
events, \( I = 13, M_s^7.1, 1994.11.14 \) Philippines and \( I = 8, M_s^6.7, 2006.03.14 \) Seram Indonesia, a shallow, offshore thrust event, \( I = 8, M_s^6.8, 2003.05.21 \) N Algeria, and a back-arc interplate event, \( I = 9, M_s^6.9, 1995.05.14 \) Timor associated with a landslide-induced tsunami (NOAA/WDC database). There are 7 events for \( T_dT_0 \) and 11 for \( T_dL_50 \) that are falsely identified as likely tsunamiogenic, most of these have \( I = 1 \) and thus produced small tsunamis.

Real-time calculation of the rapid discriminant \( T_dL50 \) does not require accurate knowledge of the earthquake location or magnitude and, for most events, stable \( L_50 \) (LM2009B) and \( T_d \) values are available within 6-10 min after OT. The overall performance of the \( T_dL50 \) discriminant is marginally better than \( M_w^CMT, M_wpds \) and teleseismic \( T_0 \) (Table 1), though these latter three measures are not available until at least 30, 15 and 15 min, respectively, after OT (LM2009A). In contrast, the rapidly available \( M_wp \) discriminant correctly identifies only 52% of tsunamiogenic events with \( I \geq 2 \) (Fig. 2; Table 1), primarily because \( M_wp \) underestimates the size of events with \( M_w^CMT \geq 7.0-7.5 \), particularly tsunami earthquakes and other events with long rupture duration (e.g., LM2009A). The \( T_dL50 \) discriminant also outperforms the energy-to-moment parameter, \( \Theta \), useful for identification of tsunami earthquakes (Newman and Okal 1998), because \( \Theta \) is not a good indicator for tsunamiogenic events in general (LM2009A).

Like \( M_w^CMT \) and \( T_0 \), the period-duration discriminants gives mixed results for identifying the tsunami potential of oceanic, strike-slip events (Type So). Some of these events may be falsely identified as tsunamiogenic (i.e., if they have high magnitude or \( T_0 \)) since the tsunami excitation for a vertical, strike-slip fault is very low relative to other faulting types (e.g., Kajiura 1981). In contrast, other oceanic, strike-slip events may be missed as tsunamiogenic (i.e., if they have moderate magnitude or \( T_0 \)) because their tsunami excitation can be augmented by horizontal displacement of ocean floor topography (Tanioka and Satake 1996), an effect which is somewhat independent of source size \( LWD \) and thus not well quantified by any of the \( M_w^CMT, T_0 \) or \( T_dT_0 \) discriminants.

The \( T_dT_0 \) discriminant identifies better than \( M_w^CMT \) and \( T_0 \) some of the tsunamiogenic, back-arc intraplate earthquakes (Type B). However, the \( T_0, T_d \) and \( T_dT_0 \) values for this event type are generally lower than for other event types with similar tsunamiogenic impact, suggesting that characteristics other than fault length, width or slip affect the tsunami potential for some back-arc intraplate events. For example, some of these events may involve rupture on steeply dipping faults, which could augment the tsunamiogenic strength of these events (e.g., Kajiura 1982), though fault dip is probably not reflected directly in either the \( M_w^CMT \) or \( T_dT_0 \) discriminants.

The improved correspondence to \( I, A_t \) of the period-duration discriminants relative to \( M_w^CMT \) and \( T_0 \), and the sensitivity of these discriminants to specific source types (e.g. \( T, P, So; \) Figs. 2 and 3; Table S1) lend support to the \( L, W, D \) and \( z \) scaling arguments used here. It may be that the \( T_dT_0 \) discriminant inherently avoids underestimate of tsunami potential due to incorrect source depth or earth model, as can occur with the indirect, \( M_0 \) inversion procedure and corresponding \( M_w \) discriminants. Effectively, as shown schematically in Fig. 4, for a fault of fixed potency \( LWD \), as rupture depth decreases the rupture velocity, \( v_r \), also decreases, so \( T_0 \) and \( T_d \), when interpreted as related to \( L/v_r, W/v_r, \) or \( D/v_r \), must increase. Thus the quantity \( T_dT_0 \) increases with decreasing rupture depth, more or less correctly reflecting the increased tsunami potential of the shallowest, underwater earthquakes, including tsunami earthquakes. This behaviour suggests that the \( T_dT_0 \) discriminant captures the “tsunami” faulting model reflecting the observed tsunami waves (Satake 1994), as opposed to the “seismic” faulting model as given by \( M_0 \). In this case \( T_dT_0 \) may also be a valuable aid in defining the finite-faulting description of the source and sea floor displacement for real-time tsunami forecasting.

From the preceding, we can identify the most critical parameters for discrimination of earthquake tsunami potential. The performance of the \( T_dT_0 \) discriminant, though improved by the \( T_d \) values, is dominated by the \( T_0 \) values (e.g., Figs. 2 and 3), and \( T_0 \) for large earthquakes...
is probably related primarily to rupture length, \( L \). Additionally, we have shown that \( T_0 \), \( T_d \) and \( T_dT_0 \) may inherently account for source depth, and that \( T_dT_0 \) may be proportional to \( A_s \). These results imply that knowledge of rupture length, \( L \), and depth, \( z \), alone can constrain well the tsunami potential of an earthquake. Then information on the fault width, \( W \), and slip, \( D \) is of secondary importance, though perhaps provided by \( T_d \) for some event types, or implicitly through scaling relations such as \( W \propto L \) and \( D \propto L \). In this case, and considering the poor match of \( M_w^{CMT} \) to a linear relation between \( A_s \) and \( M_0 \) (Fig. 2), there is the suggestion that tsunami potential is not a simple function of the potency \( LWD \) from the “seismic” faulting model, as is assumed with the use of the \( M_w^{CMT} \) discriminant.

Conclusions

The period-duration discriminant, \( T_dT_0 \), for tsunami potential of an earthquake makes use of two direct, \( P \)-wave measures: dominant period, \( T_d \), on velocity records and HF, apparent rupture duration, \( T_0 \). We have shown empirically that the \( T_dT_0 \) discriminant, perhaps through characterisation of a quasi finite-faulting description of the source and of the source depth, provides more information on tsunami importance, \( I_s \), and tsunami amplitude, \( A_s \), than do other discriminants, including teleseismic \( T_0 \) alone and centroid-moment tensor magnitude, \( M_w^{CMT} \). The \( T_dT_0 \) discriminant correctly identifies 77% of tsunamigenic events (\( I_s \geq 2 \)) in our dataset, while teleseismic \( T_0 \) and \( M_w^{CMT} \) each identify 68% (Table 1). The value of the \( T_dT_0 \) discriminant has relatively large uncertainty, but avoids the possible processing-time delay and error, including underestimate of tsunami potential for shallow earthquakes, of indirect, moment-tensor determinations. Additional improvement in the \( T_dT_0 \) discriminant may follow from further development of the \( T_d \) algorithm or investigation of other procedures for rapidly extracting information on the frequency content of \( P \) waveforms. And the possibility of a linear relationships between \( A_s \) and \( T_dT_0 \) (Fig. 3) suggests that \( T_dT_0 \) or related measures may ultimately prove useful for rapid, quantitative estimates of tsunami wave heights.

Our analysis and the likely, inherent sensitivity of \( T_dT_0 \) to rupture length and source depth, indicate that the tsunami potential for most earthquake types can be well constrained by knowledge of the rupture length, \( L \), and some mean rupture depth, \( z \), while explicit information on the fault width, \( W \), or slip, \( D \), is of lessor importance. Moreover, the results imply that tsunami potential is not a simple function of the potency \( LWD \) as is assumed with the use of the \( M_w^{CMT} \) discriminant. The tsunami potential for many oceanic strike-slip, and back-arc intraplate earthquakes types, however, is not well constrained by any of the discriminants analysed here; further study is warranted to find direct measures and discriminants for these event types, which are occasionally highly tsunamigenic.

For rapid estimation of \( T_dT_0 \), the discriminant \( T_dL_{50} \) combines \( T_d \) with the likelihood that \( T_0 \) exceeds 50-55 s. The \( T_dL_{50} \) assessment can be completed within 6-10 min after OT for most regions using currently available, real-time seismograms and should form a valuable complement to initial estimates of the location, depth and magnitude of an earthquake to improve the reliability of or make possible tsunami early warning.

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References


<table>
<thead>
<tr>
<th>Discriminant</th>
<th>Available (min after OT)</th>
<th>Critical Value</th>
<th>Correctly Identified</th>
<th>Missed</th>
<th>False</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$I_t \geq 2$</td>
<td>$%$**</td>
<td>$I_t &lt; 2$</td>
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<tr>
<td>$M_{CMT}$</td>
<td>30+</td>
<td>7.45</td>
<td>32</td>
<td>68%</td>
<td>40</td>
</tr>
<tr>
<td>$M_{wp}$</td>
<td>3-10</td>
<td>7.45</td>
<td>20</td>
<td>43%</td>
<td>45</td>
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<tr>
<td>$M_{wpd}$ (raw)</td>
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<td>7.45</td>
<td>30</td>
<td>64%</td>
<td>42</td>
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<tr>
<td>$T_0$ (teleseismic)</td>
<td>15+</td>
<td>55</td>
<td>32</td>
<td>68%</td>
<td>42</td>
</tr>
<tr>
<td>$L_{S0}$</td>
<td>6-10</td>
<td>1.0</td>
<td>33</td>
<td>70%</td>
<td>42</td>
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<tr>
<td>$T_dT_0$ (teleseismic)</td>
<td>15+</td>
<td>510</td>
<td>36</td>
<td>77%</td>
<td>47</td>
</tr>
<tr>
<td>$T_dL_{S0}$</td>
<td>6-10</td>
<td>8.0</td>
<td>36</td>
<td>77%</td>
<td>43</td>
</tr>
</tbody>
</table>

* 101 events classified; 47 have $I_t \geq 2$

** percent of all events with $I_t \geq 2$ that are correctly identified
Figure 1

Single-station, period-duration processing examples for (a) 2006.07.17, $M_w7.7$, $T_0=180$ s,
6 Dec 2010

Tsunami early warning using rupture duration and dominant period
$I_t=19$, Indonesia tsunami earthquake, station MY.IP at 15°GCD, and (b) 2009.03.19, $M_w7.6$, $T_0=39$ s, $I_t=1$, Tonga Islands, station AU.NFK at 17°GCD, showing raw, broadband velocity seismogram (trace 0), HF seismogram (trace 1), and $T_d$ period (trace 2). $P$ – automatic $P$ pick; To – teleseismic, HF duration, $T_0$; $t_d,150$ – termination time for calculation of $t_d$ period and $l_{50}$ DE level. Note much longer $T_0$ and larger $t_d$ for the Indonesia tsunami earthquake than for the mildly tsunamigenic, Tonga Islands event of similar magnitude.
Figure 2

Comparison of body-wave moment-magnitude, $M_{wp}$ (left column), centroid-moment tensor magnitude, $M_{w}^{CMT}$ (centre column) and teleseismic, apparent source duration, $T_0$, (right column) with tsunami importance, $I_t$, (upper row) and representative tsunami amplitude at 100km, $A_t$, (lower row). Vertical red lines show the target $I_t \geq 2$ threshold; horizontal red lines show the critical values for the $M_{wp}$, $M_{w}^{CMT}$ and $T_0$ discriminants (Table 1). The $A_t$ and $T_0$ axes use logarithmic scaling. Parallel diagonal lines are indicative of the slope required for a linear relationships between $A_t$ and $M_0$ (lower centre), $A_t$ and $T_0$ (lower right). Event labels show earthquakes type for non interplate-thrust events with $I_t \geq 2$ ($I$–interplate-thrust; $T$–tsunami earthquake; O–outer-rise intraplate; B–back-arc intraplate; U–upper-plate intraplate; So–strike-slip oceanic, S–strike-slip continental, R–reverse-faulting).
Figure 3

Comparison of dominant period, $T_d$ (left column), period-duration, $T_dT_0$, (centre column) and rapid period-duration discriminant, $T_dL_{50}$, (right column) with tsunami importance, $I_t$, (upper row) and representative tsunami amplitude at 100km, $A_t$, (lower row). Vertical red lines show the target $I_t \geq 2$ threshold; horizontal red lines show the critical values for the $T_dT_0$ and $T_dL_{50}$ discriminants (Table 1). The $A_t$, $T_d$, $T_dT_0$ and $T_dL_{50}$ axes use logarithmic scaling. Parallel diagonal lines are indicative of the slope required for a linear relationships between $A_t$ and $T_dT_0$ (lower centre). Event labels as in Fig. 2.
Figure 4

Simplified diagram of a subduction zone mega-thrust (pale green surface) showing two interplate thrust ruptures 1 and 2 with the same seismic potency LWD (dark green patches), but different vertical seafloor displacement (uplift areas shown in red and orange). The long, shallow rupture 1 produces greater total seafloor uplift than the deeper rupture 2. Since $M_0 = \mu \text{LWD}$ and $\mu$ increases with depth (e.g., $\mu \propto z^q$, $q$ positive), $M_0$ will be smaller for rupture 1 than for rupture 2. In contrast, since $L_1 > L_2$, and $v_r$ is lower at shallow depths, $T_0 \propto L/v_r$ will be larger for rupture 1 than for rupture 2. Since $T_d$ may give additional information on $z$, $W$ or $D$, the quantity $T_d T_0$ for rupture 1 can be larger or much larger than for rupture 2, correctly identifying the greater seafloor uplift and tsunami potential of the long, shallow rupture 1.