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A Theoretical Comparison of Tsunamis from Dislocations and Landslides

EMILE A. OKAL[1] and COSTAS E. SYNOLAKIS[2]

Abstract—We use simple physical models to evaluate and compare the orders of magnitude of the energy generated into a tsunami wave by seismic dislocations and underwater slumps. We conclude that the two sources can generate tsunamis of comparable total energy. However, the slumping source is shown to be fundamentally dipolar in nature, which results in a low-frequency deficiency in the far-field. These simple conclusions corroborate the interpretation of the 1998 Papua New Guinea tsunami as being generated by an underwater slump.

Key words: Tsunamis, landslides, seismic sources.

1. Introduction

We present in this paper a number of theoretical discussions of the excitability of tsunami waves by both earthquakes sources (modeled as dislocations occurring in an elastic medium) and underwater landslides or slumps. We are motivated by the recent investigations of the catastrophic tsunami of 17 July 1998 in Papua New Guinea (hereafter, PNG), which suggest that its source was an underwater slump involving 4 km^3 of sedimentary material and occurring 13 mn after the mainshock (OKAL, 2002a; SYNOLAKIS *et al.*, 2002). Because they take place under water and are generally not witnessed directly, slumps remain very poorly known and only a few exceptional cases have been the subject of specific investigations, such as the 1929 Grand Banks slump (HASEGAWA and KANAMORI, 1987) or the Suva landslide of 1953 (HOUTZ, 1962). In both instances, the rupture of telegraphic cables provided the key evidence for slumping.

Our approach is to use very simple physical models of the deformation of the ocean floor to obtain the principal properties of the tsunamis generated by the two kinds of sources, with an aim at understanding the fundamental parameters controlling the energy dissipated into the tsunami wave. We must emphasize that the purpose of this paper is not to give exact theoretical solutions for actual case studies of seismic and slumping events, but rather to provide orders of magnitude of the

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amount of energy which can be disseminated into the tsunami wave by the various sources.

2. The Dislocation Source

The generation of a tsunami by a dislocation source deforming the bottom of the ocean can be schematized by the model shown on Figure 1. In its simplest form, we consider a sudden uplift of a section of ocean floor of area S, moved vertically an amount δh. If this deformation is instantaneous, it results in the development of an identical hump on the ocean surface (Fig. 1a). The increase in the potential energy of the ocean is computed readily by displacing a volume of water $S \cdot \delta h$ from the bottom to the surface of the ocean:

$$\Delta W_1 = \rho_w g S \delta h H, \tag{1}$$

where ρ_w is the density of water, H the depth of the ocean column, and g the acceleration of gravity. This also represents the work of the pressure forces $S \rho_w g H$ displacing the ocean bottom a distance δh. Because the ocean is a non-viscous fluid, the hump is unstable and will flow back to the ocean surface, whose steady-state level will be unchanged on account of the very large lateral dimension of the ocean basin as compared to S (Fig. 1c). The center of mass of the displaced water, initially at height $\delta h/2$ above the ocean floor (solid dot on Fig. 1b) is transferred to the ocean surface at height H, so that the eventual change in potential energy is only

$$\Delta W_2 = \rho_w g S \delta h (H - \delta h/2). \tag{2}$$

The difference between (1) and (2) is the energy available to the gravitational oscillation induced by the collapse of the hump, which is the tsunami wave:

$$E_T = \Delta W_1 - \Delta W_2 = \frac{1}{2} \rho_w g S (\delta h)^2. \tag{3}$$

This very simple model is applicable because, in all practical cases, the source duration (i.e., the time over which the deformation of the ocean floor takes place) is short as compared to the time it takes for the tsunami wave to settle and eliminate the hump. The former is on the order of the dimension of the source, L, divided by the rupture velocity of the seismic source, v; the latter on the order of L/c, where c is the phase velocity of the tsunami. When the deformation takes place rapidly ($v \gg c$), hydraulic equilibrium is not reached at all times during the upwards motion of the ocean floor, the deformation is not reversible, more work is done than the eventual increase of potential energy in the new steady state, and the difference is funneled into the tsunami wave. Should the uplift take place very slowly ($v \ll c$), then equilibrium would be reached at all times during the deformation, which means that the hump on the surface would disappear faster

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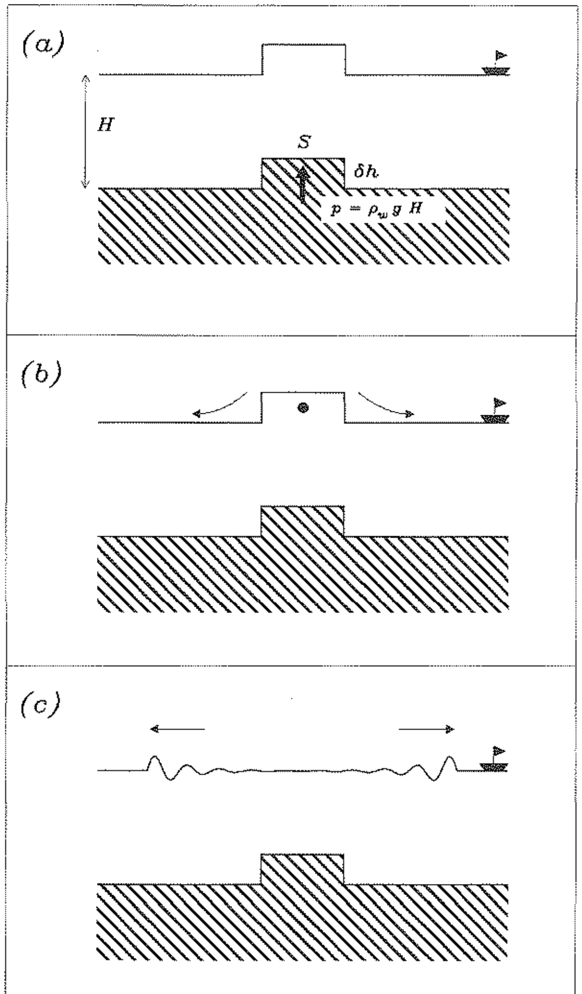

Figure 1
Excitation of a tsunami by a seismic dislocation. In this very simple model, a fraction of the ocean floor is suddenly uplifted, resulting in an immediate and identical hump on the ocean surface (*a*). Because the ocean is fluid, the hump is unstable and flows sideways (*b*), with the center of mass of the displaced material (solid dot) falling down by an amount $\delta h/2$. The resulting change in potential energy makes up the energy of the tsunami wave, which propagates away from the now defunct hump (*c*).

than it is being created; as a result, the pressure forces on the bottom would continuously adjust to the new height of the water column, the process would be thermodynamically reversible, and the work done to deform the ocean floor would be the exact difference in potential energies; there would be no energy available to the tsunami wave. In practice, for seismic sources, the rupture velocity v is on the order of 3 km/s, whereas the tsunami velocity $c = \sqrt{gH}$ is typically less than 250 m/s, even for the deepest ocean basins. Thus the regime is the irreversible one, and the model in Figure 1 is warranted.

When the size of the parent earthquake is increased, seismic scaling laws (e.g., GELLER, 1976) predict that δh scales as L, S as L^2, and the seismic moment M_0 as L^3. As a result, the energy E_T is expected to scale as M_0 raised to the power 4/3. This extremely important result, first obtained by AIDA (1977) and discussed by KAJIURA (1981), means that the energy sent into the tsunami wave by an earthquake source grows faster than the seismic moment, and hence than the total elastic energy released at the source, $E_e = \mathbf{M}_0 : \boldsymbol{\varepsilon}$, given by the scalar product of the moment tensor $\mathbf{M}_0$ into the strain release tensor $\boldsymbol{\varepsilon}$, the latter expected to have a constant amplitude (in practice 10^{-4}), characteristic of the material properties of the rock. In other words, the fraction E_T/E_e of the total elastic energy release made available to the tsunami wave grows with the seismic moment like $M_0^{1/3}$. Note further that the energy E_T is, as expected, independent of the sign of δh, and hence of the polarity of the deformation of the ocean floor (i.e., reverse *vs.* normal faulting).

The proportionality between E_T and $M_0^{4/3}$ can be further modeled by considering a tsunami wave as a superposition of the normal modes of a specific branch of spheroidal free oscillations of the Earth along the formalism introduced by WARD (1980) and discussed by OKAL (1982, 1988, 1991). In this framework, discussed in detail in a companion paper (OKAL, 2003b), we use a conventional eigenfunction of the tsunami wave to relate the energy contained in a tsunami mode, E_l^m, to its amplitude at the surface, Y. We then use normal mode theory to express the amplitude Y excited by a seismic source of moment M_0 located immediately below the water-solid interface, with the result averaged over all possible focal mechanism geometries. The energy of the tsunami is obtained by summing up the individual modes, the summation over l being equivalent to integration over the angular frequency ω. High-frequency contributions are altered to reflect a corner frequency in the source spectrum, expected to behave like $M_0^{-1/3}$, while at the same time seismic scaling laws are used to account for the necessary extension of the width of the fault at depth (which affects the excitation of the tsunami mode) when the size of the earthquake, and hence M_0, grows. The final result is that the energy of the tsunami can be written

$$E_T = 0.22 \frac{\rho_w g}{\mu^{4/3}} \cdot \varepsilon_{\max}^{2/3} \cdot M_0^{4/3}, \tag{4}$$

where μ is the elastic rigidity of the solid Earth, and $\varepsilon_{\max}$ the characteristic strain release during the rupture. For $\mu = 7 \times 10^{11}$ dyn/cm^2, characteristic of the upper mantle, and $\varepsilon_{\max} = 10^{-4}$, this yields

$$E_T = 7 \times 10^{-17} M_0^{4/3} \tag{5}$$

where E_T is in ergs and M_0 in dyn-cm (OKAL, 2003b). Equation (4) is formally equivalent to the formula proposed by KAJIURA (1981), although the constants in (4) and (5) are greater than he proposes.

Equation (5) allows the computation of orders of magnitude of the energy of tsunamis generated by major earthquakes. For example, in the case of the 1964 Alaskan earthquake ($M_0 = 7.5 \times 10^{29}$ dyn-cm) (KANAMORI, 1970), it yields $E_T = 5 \times 10^{23}$ ergs. For the largest event ever recorded, the 1960 Chilean earthquake ($M_0 = 2 \times 10^{30}$ dyn-cm), the energy would reach $E_T = 2 \times 10^{24}$ ergs, which remains 1/100 of the total elastic energy released during the event. Incidentally, the Chilean earthquake also features the longest documented single episode of seismic rupture, with $L = 800$ km. Assuming that this number could be tripled to obtain a maximum conceivable size of subduction zone earthquake (although no such coherent fault system is, to our knowledge, documented on Earth), we would reach $L = 2500$ km, corresponding to $M_0 = 3 \times 10^{32}$ dyn-cm and $E_T/E_e = 4\%$; in this respect, the finite radius of the Earth, which scales the size of the tectonic plates, and hence to a large extent the maximum dimensions of earthquake sources, prevents the energy of the tsunami from catching up with the total available elastic energy.

3. *The Slump Source*

The case of an underwater slump can be modeled in extremely simplified fashion by considering (Fig. 2) that it consists of translating a mass of solid material along the sea floor, and hence, of combining a negative source of the type studied in Section 2 at the heel of the slump with a positive one at its toe. The slump source thus appears as dipolar in nature, with the total energy of the tsunami being the sum of the two contributions of each element of the dipole.

However, in this particular case, we can no longer assume that the displacement of the ocean floor takes place instantaneously as compared to the evolution of the tsunami wave. This is because, in the case of a gravitational slump, the velocity acquired by the slumping mass is controlled by the gravity field g. In practice, the maximum velocity reached during a slumping event on an inclined plane is given by $v = \sqrt{2gz}$, where z is the maximum vertical extent traveled by the slumping material. Then, v must be compared to the phase velocity c, their ratio being $\sqrt{2z/H}$. This number can never be large, since the slump has to be contained in the water column; in practice, a slump sliding 500 m in a 1500-m deep ocean would correspond to $v/c = 0.8$.

For such values of z and H, the regime would be neither fully irreversible (as in the case of the seismic dislocation), nor fully reversible (in which case the slump would be so slow as to generate no tsunami). Thus, our estimate of the energy radiated into the tsunami must be corrected by modeling quantitatively the

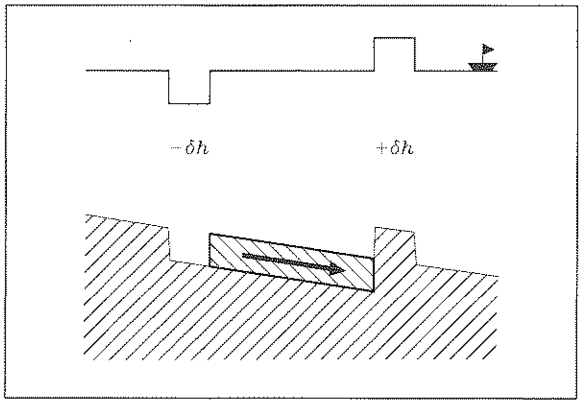

Figure 2
Generation of a tsunami wave by an underwater slide. In this highly simplified conceptual model, the moving slide or slump creates a bulge, and hence a positive hump on the surface, at its toe, while leaving a mass deficiency, and hence a trough at the surface, at its heel. As a result, the initial condition of the ocean surface takes a dipolar character.

development of the tsunami wave during the slumping. For this purpose, we use the schematic model of a block sliding on the bottom of an ocean of constant depth H, at a velocity v, starting from a standstill at $t = 0$ (Fig. 3a), and stopping abruptly at $t = T$. We assume that the block has the shape of a gaussian, so that the deformation can be given by:

$$\varepsilon(x,t) = A \exp[-k(x - vt)^2] \quad (0 \leq t \leq T). \tag{6}$$

The deformation of the surface of the ocean, $\eta(x,t)$, then satisfies

$$\frac{\partial^2 \eta}{\partial t^2} - c^2 \frac{\partial^2 \eta}{\partial x^2} = \frac{\partial^2 \varepsilon}{\partial t^2}. \tag{7}$$

The solution is obtained by combining ($\eta = \eta_1 + \eta_2$) the case (Fig. 3b) of a block moving indefinitely for all positive times ($t \geq 0$),

$$\eta_1(x,t) = AH(t)\left[\frac{v^2}{v^2 - c^2}\exp[-k(x - vt)^2] + \frac{v^2}{2c}\left(\frac{\exp[-k(x+ct)^2]}{c+v} + \frac{\exp[-k(x-ct)^2]}{c-v}\right)\right], \tag{8}$$

(where $H(t)$ is the Heaviside function), with that of a block of negative amplitude, $-A$, starting its motion at the time $t = T$ and at abscissa $x = L = v \cdot T$,

$$\eta_2(x,t) = -AH(\tau)\left[\frac{v^2}{v^2 - c^2}\exp[-k(\xi - v\tau)^2] + \frac{v^2}{2c}\left(\frac{\exp[-k(\xi+c\tau)^2]}{c+v} + \frac{\exp[-k(\xi-c\tau)^2]}{c-v}\right)\right], \tag{9}$$

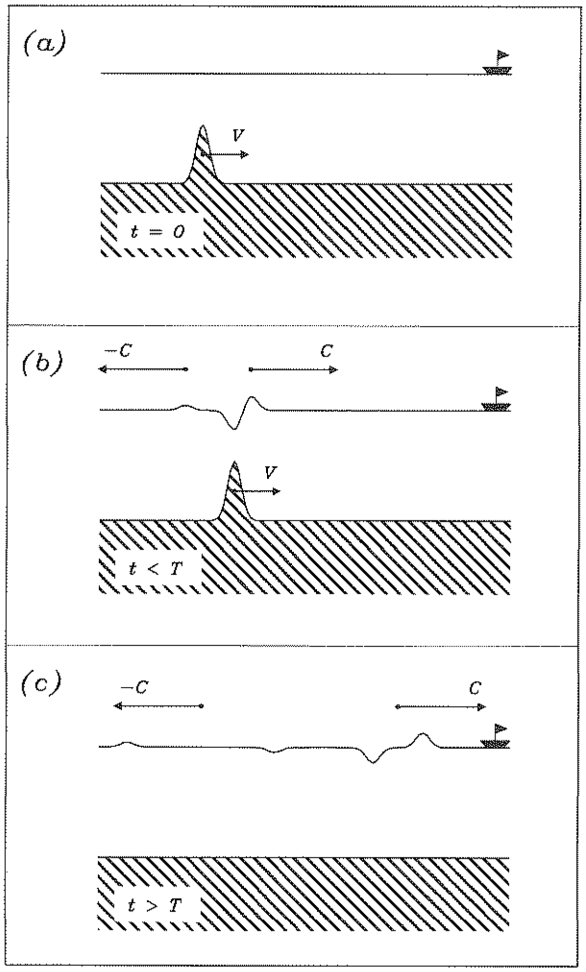

Figure 3
Tsunami wave generated by a bulge moving on the ocean floor at velocity V, illustrated in the subsonic case ($V < C$). The motion starts at $t = 0$ (*a*) and stops at $t = T$. For $t < T$, (*b*) represents the solution (8), in which the tsunami wave develops ahead of the deformation, while a smaller wave propagates in the opposite direction. After the motion has stopped (*c*), a stopping phase is added to the solution (10). The tsunami wave propagating outwards has the structure of a dipole, as does the wave propagating backwards, albeit with a reduced amplitude of the displacement, and an enhanced arm of the dipole. Note that the amplitude of the wave is scaled to the ocean deformation, but not to the thickness of the oceanic layer.

where $\xi = x - L$ and $\tau = t - T$. For $t \geq T$, the combined solution is then

$$\eta(x,t) = \frac{Av^2}{2c}\left[\frac{\exp[-k(x+ct)^2] - \exp[-k(\xi+c\tau)^2]}{c+v} + \frac{\exp[-k(x-ct)^2] - \exp[-k(\xi-c\tau)^2]}{c-v}\right]. \tag{10}$$

The first term in (10) represents the tsunami wave propagating to the left, i.e., upslope of the slump, while the second term propagates downslope.

This simple model suggests an order of magnitude of the effect of the finite duration of the slumping on the scaling of the energy available to the tsunami. With respect to the case of the fast, irreversible deformation generated by a seismic dislocation, the waves propagating upslope and downslope can thus be regarded as emanating from dipolar sources, the amplitude of the "charges" being modulated by

$$\alpha_{\mathrm{up}} = \frac{v^2}{2c\,(c+v)}; \quad \alpha_{\mathrm{down}} = \frac{v^2}{2c\,(c-v)} \tag{11}$$

or, on the average, $\alpha = v^2/2c^2$. Similar results were obtained by TINTI and BORTOLUCCI (2000).

In trying to apply this result quantitatively to the case of the PNG slump, we take appropriate values $H = 1500$ m ($c = 120$ m/s), an average thickness of the slide $h = 500$ m, and a total vertical drop during the slumping $z = 500$ m. These values are taken from the shipboard observations of TAPPIN *et al.* (1999) and SWEET and SILVER (2003).

We note, however, that, under the effect of buoyancy, the slumping sedimentary material of density ρ_s will be accelerated only by an effective gravity $\gamma = g(\rho_s - \rho_w)/\rho_s$, so that the maximum velocity reached during the slumping will be only $\sqrt{2\gamma z}$ or $v_{\max} = 70$ m/s, given $\rho_s/\rho_w \approx 2$. A more typical value of v during the slumping may be $v = 0.5\,v_{\max}$ or 35 m/s, leading to $v/c \approx 0.3$. The coefficient α is then about 0.04, leading to a dipole (hump-and-trough) of amplitude 20 m upon termination of the slumping.

This value is in very good agreement with that modeled by SYNOLAKIS *et al.* (2002), who obtained initial peak and trough values of 14 and 16 m respectively. If we further take $L = 5$ km, and a width of 4 km, the surface of the slump (20 km^2) then leads to a total energy $E_T \approx 8 \times 10^{20}$ ergs.

We emphasize once again that this value should not be considered more than an order of magnitude of the energy available to the tsunami, as generated by a crude model of the PNG slump. It is remarkable that it is only 40 times less than that computed above for the 1964 Alaskan earthquake, the second largest event ever recorded; conversely, and in the framework of Equation (5), the PNG energy would be equivalent to that of an earthquake of moment $M_0 = 4.5 \times 10^{28}$ dyn-cm, comparable to such large earthquakes as the 1922 Chilean ($M_0 = 4.2 \times 10^{28}$ dyn-cm), or the 1923 event in Kamchatka ($M_0 = 5.5 \times 10^{28}$ dyn-cm) (OKAL, 1992), both of which created substantial transpacific tsunamis. Why then did the PNG slump raise only negligible tsunamis at teleseismic distances? This question will be examined in the next section.

4. *Far-Field Behavior of Tsunamis Generated by Earthquakes and Slumps*

We recall very briefly in this section the principal results obtained by OKAL (1990), to which the reader is referred for full details. The far-field amplitude of tsunamis generated by either source can be most efficiently studied in the formalism of normal modes. The difference in far-field properties stems from the combination of two factors: the different mechanical nature of the source, and a fundamental difference in its time function.

4.1. Mechanical Nature

It has been now been known for about 45 years that earthquake dislocations can be described by a system of forces known as a double-couple (VVEDENSKAYA, 1956). On the other hand, landslides or slumps can be modeled as single forces, representing the reaction, on the solid Earth, of the acceleration of the sliding mass (KANAMORI *et al.*, 1984). Coefficients for the excitation of a normal mode of the Earth by either a single force or a double-couple can be readily derived theoretically (GILBERT, 1970). In the case of single forces, their expression was given by EISSLER and KANAMORI (1987), and their relation to the double-couple coefficients was discussed by OKAL (1990). In very simple terms, the excitation coefficient of a normal mode whose displacement eigenfunction is $\mathbf{u}$ by a single force $\mathbf{F}$ is proportional to the scalar product $\mathbf{F}\cdot\mathbf{u}$, while its excitation by a double-couple $\mathbf{M_0}$ is proportional to $\mathbf{M_0} : \boldsymbol{\varepsilon}$, where $\boldsymbol{\varepsilon}$ is the eigenstrain of the mode, and thus the ratio of the excitability of a given normal mode by a single force and a double-couple is proportional to its equivalent wavelength $\Lambda = 2\pi a/(l + 1/2) = 2\pi c/\omega$, where a is the radius of the Earth and l the mode's orbital number:

$$X_{SF/DC} = b\,\frac{F}{M_0}\Lambda, \tag{12}$$

where b is a coefficient varying from 1.25 in the case of Love waves, to 2.65 for Rayleigh waves and 6 for tsunamis. The physical meaning of Equation (12) is that a single force, being the spatial integral of a double-couple, should excite a given mode (or wave) more efficiently at lower (spatial or temporal) frequencies, and hence would be expected to be a better tsunami generator than a double-couple, as compared for example to their respective excitation of Rayleigh waves. However, this preliminary interpretation assumes comparable source time functions, and thus grossly overlooks the fundamentally different time histories of earthquakes and landslides.

4.2. Source Time Function

In the case of an earthquake dislocation, the time history of the seismic moment release, $M_0(t)$, coincides with that of the seismic displacement on the fault, $\Delta u(t)$. At long enough periods, it behaves fundamentally like a Heaviside function $H(t)$. By contrast, the time history of a single force $F(t)$ representative of a landslide must satisfy a condition of zero impulse, necessary to keep the closed Earth system globally unaccelerated. An appropriate source time function for $F(t)$ would be the full period of a sinusoid, expressing the acceleration of the slumping material, followed by its deceleration and eventual stop (HASEGAWA and KANAMORI, 1987). The source time function of the single force thus appears fundamentally as the second derivative of that of the double-couple, which will bring an additional factor of order ω^2 to the ratio (12). As a result, the ratio will behave like ω, rather than $1/\omega$, at low frequencies.

In conclusion, a landslide modeled as a single force with a realistic source time function will be a deficient generator of low-frequency energy in the far-field, and in particular of tsunamis, when compared with a dislocation modeled by the familiar step-function double-couple.

5. *Conclusion*

By using very simple models of dislocations and slumps on the ocean floor, as well as theoretical results from normal mode theory, we obtain two fundamental results.

First, the energy of the tsunami generated by an underwater slump of the dimensions of the PNG event is on the same order as that expected from a seismic dislocation of moment 4×10^{28} dyn-cm. That this is at all possible while the slump clearly involves a smaller volume of material illustrates the dependence of E_T on $(\delta h)^2$: the slump moves less material, but it moves it vertically 100 times as much as the comparable earthquake. Because the PNG slump was, at 4 km^3, of relatively modest size, these results confirm that large slumps, involving hundreds if not thousands of km^3, are potentially catastrophic tsunami generators, on a scale dwarfing the 1998 PNG disaster, itself the deadliest tsunami worldwide in 65 years.

Second, the slumping source is fundamentally of a dipolar nature, as compared to the monopolar seismic dislocation. This dipolar nature is evident from local modeling, but can be reconstructed in the formalism of sources represented by combinations of forces, once proper attention is given to the behavior of the relevant source time functions. As a result, i.e., at distances greater than a few times the arm of dipole, the tsunami radiated by a slumping event is expected to decay faster in the far-field than that of a dislocation source. This will occur as soon as the epicentral distance is one order of magnitude greater than the arm of the dipole, itself controlled by the total dimension L of the slump. In addition, this deficiency will be emphasized at low frequencies, and hence will be stronger than for regular seismic waves.

The combination of these two results—tsunami energy comparable to that of a major earthquake, but deficiency in the far-field—clearly requires a concentration of exceptionally large tsunami amplitudes in the near-field. This is exactly why the slumping model is required to account for the observed characteristics of the PNG event, namely exceptionally high runup on the local coast, and minimal if at all detectable amplitudes at transpacific distances.

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