Cumbre Vieja Volcano -- Potential collapse and tsunami at La Palma, Canary Islands

Steven N. Ward

Institute of Geophysics and Planetary Physics, University of California, Santa Cruz California, USA

Simon Day

Benfield Greig Hazard Research Centre, Department of Geological Sciences, University College, London, UK

Abstract. Geological evidence suggests that during a future eruption, Cumbre Vieja Volcano on the Island of La Palma may experience a catastrophic failure of its west flank, dropping 150 to 500 km^3 of rock into the sea. Using a geologically reasonable estimate of landslide motion, we model tsunami waves produced by such a collapse. Waves generated by the run-out of a 500 km^3 (150 km^3) slide block at 100 m/s could transit the entire Atlantic Basin and arrive on the coasts of the Americas with 10-25 m (3-8 m) height.

1. Lateral collapse of island volcanoes -- A tsunami wave source

Lateral collapses of oceanic island volcanoes rank amongst the most spectacular natural events on Earth. Although no such lateral collapse punctuates the historical past, residual debris found on the seafloor evidence their abundance in recent geological time. *Moore* (1964) first identified the remains of lateral collapses off the flanks of Hawaii. Since then, dozens have been recognized adjacent to island volcanoes in nearly every ocean (*Moore et al*. 1994; *Keating* and *McGuire,* 2000). These observations constrain not only the geography and frequency of lateral collapses, but also their magnitude (up to 5000 km^3 of material), extent (to 300 km length) and ferocity (underwater speeds to 140 m/s).

Tsunami list among the many hazards associated with lateral collapses. Admittedly, direct geological evidence of tsunami in identifiable deposits (*Moore* and *Moore*, 1984) or coastal erosion features (*Young* and *Bryant*, 1992) are controversial. Still, history has documented large and damaging tsunami from far smaller lateral collapses of stratovolcanoes in island arc environments (*Johnson*, 1987; *Satake* and *Kato*, 2001). Prudence dictates that the lack of abundant wave-caused signatures associated with collapses of oceanic island volcanoes be viewed as more a function of scanty preservation than evidence that these events do not produce tsunami.

Hazard from collapse tsunami may be particularly important in the Atlantic Ocean because of both the number of active oceanic islands there and the recent proposals (*Day et al.*, 1999a, 1999b) that at least two of these volcanoes show signs of incipient instability. It seems timely then, for this paper to investigate the consequences of tsunami waves induced by a collapse of one of these unstable volcanoes -- Cumbre Vieja on the island of La Palma, Canary Islands (Figure 1).

2. Geological evidence for a future collapse of the Cumbre Vieja

During most if not all of the past 125ka, Cumbre Vieja has been the most active volcano in the Canary Islands (*Carracedo et al.,* 1999). Subaerial Cumbre Vieja forms the southern third of the island of La Palma (Figure 2), rising 2 km above sea level with average slopes of 15° to 20°. The early Holocene has seen major changes in Cumbre Vieja. *Day et al.* (1999a) observe that, over the last several thousand years, the distribution and orientation of vents and feeder dykes within the mountain have shifted from a triple rift system (typical of most oceanic island volcanoes) to one consisting of a single N-S rift with westward extending vent arrays. They argue that these structural re-organizations are in response to evolving stress patterns associated with the growth of a detachment fault under the volcano's west flank. Coincident with the most recent eruption of the Cumbre Vieja in 1949 (*Bonelli Rubio,* 1950), the steeply inclined headwall section of this detachment surfaced as a west-dipping normal fault along the crest of the volcano (see Figure 2). The scarp extended 4 km with a maximum offset of 4 m. The appearance of surface rupture is ominous because: (1) initial subsurface development of a detachment fault, (2) its later propagation to the surface, and (3) ultimate slide block failure, typically sequences landslide development (*Martel* and *Muller*, 2000). Detailed examination of the 1949 rupture and geodetic measurements in the period 1994-1998 (*Moss et al.,* 1999) indicate that the fault has been inactive since 1949. Inactivity is not unexpected however, because the triggering of flank instability on steep volcanoes generally requires additional destabilizing influences such as dyke emplacement or pressurization of trapped groundwater (*Elsworth* and *Voight,* 1995). These events often accompany a volcano's eruptive phases.

This line of reasoning leads us to believe that a future eruption near the summit of the Cumbre Vieja will likely trigger a flank failure. To estimate the surface extent, subsurface geometry and total volume of such a failure we turn to geological evidence and comparisons with existing lateral collapse scars. Because the breadth of the Holocene structural changes in Cumbre Vieja appears to have affected the entire subaerial edifice, *Day et al.* (1999a) conclude that the developing detachment now underlies most if not all of the western flank of

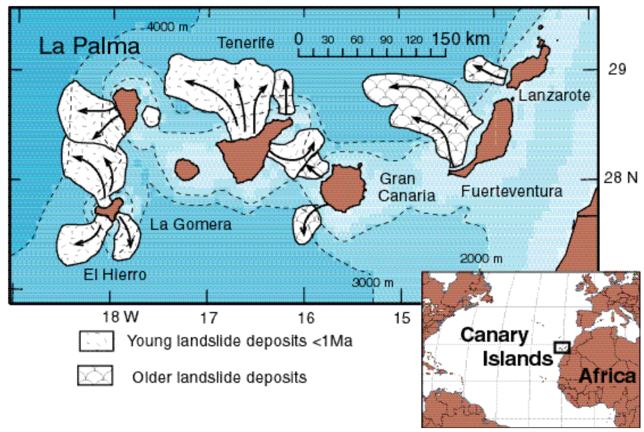


Figure 1. *Inset.* Canary Island chain off the western coast of Africa. *Above.* Location of La Palma Island, home to Cumbre Vieja volcano. As evidenced by the abundant landslide deposits strewn about their bases, the Canary Island volcanoes have experienced at least a dozen major collapses in the past several million years.

the volcano. The unstable block above the detachment extends to the north and south at least 15 km, however its length may be greater as these edges lack surface expression. The 1949 fault break skirts the crest of the volcano about 8 km inland and it marks the eastern boundary of the presently unstable zone. Because lateral collapses typically cut across the crest of volcanoes and into their reverse slopes (e.g. Mount St. Helens, *Voight et al.*, 1983), we place the head of the future La Palma collapse 2 to 3 km east of the 1949 rupture (Figure 2). The western boundary of the unstable block lies hidden underwater. Bathymetric and imaging sonar surveys of older collapses at La Palma and elsewhere (*Watts* and *Masson*, 1995; *Urgeles et. al*., 1999) suggest that the toe of the block surfaces in 1 to 3 km water depth -- about 5 to 10 km offshore.

The best geological evidence that we have paints a Cumbre Vieja collapse sending down a slide block 15-20 km wide and 15-25 km long. The thickness of the slide block is not easily fixed. Mapping the depth to the detachment surface by locating earthquakes that occur on it has not been possible. No records exist of seismic activity associated with the 1949 eruption, or the subsequent 1971 eruption at the island's southern tip. No other tectonic earthquakes of consequence have struck under La Palma in the last three decades either. Nevertheless, characteristics of past collapses point to a listric detachment 2 to 3 km below the summit of the volcano. Toward the west, the surface dips seawards at a shallow angle to intersect the offshore toe. Toward the east, the detachment steepens sharply to intersect the surface within a few km of the mountain's crest. In consideration of everything, we believe that a future flank failure of Cumbre Vieja volcano will dislodge a broadly wedge-shaped slide block as cartooned at the bottom of Figure 2. The volume and mean thickness of rock participating in a flank failure depends upon the detailed shape of the basal surface, but they should fall in the range of 150 to 500 km^3 and 1 to 2 km respectively. The inferred geometry and volume of the expected failure coincide closely with features of the previous La Palma collapse (~566 ka), remains of which are still visible to the north on Cumbre Nueva (*Day et al.*, 1999a).

3. Landslide Tsunami Model - Generalities

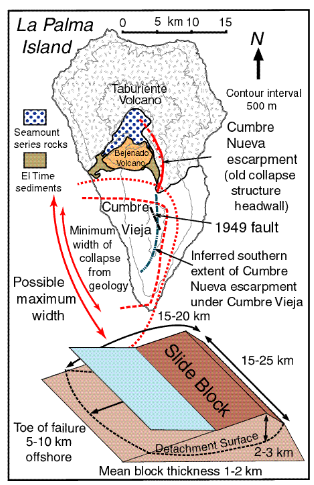
The section above provides a feeling for the size and shape of the block that may slide into the sea during a lateral collapse of Cumbre Vieja. What magnitude of tsunami might this collapse induce? One straightforward means to address this question employs classical, linear wave theory. Consider a uniform ocean of depth h. Under this theory, a general vertical bottom disturbance (i.e. the landslide) $u_z^{bot}(\mathbf{r},t)$ starting at t=0 stimulates surface tsunami waveforms (vertical component) at observation point $\mathbf{r}$ of (*Ward*, 2001)

$$u_z^{surf}(\mathbf{r},t) = \int_0^\infty \frac{d\omega\, k(\omega)}{2\pi u(\omega)\cosh(k(\omega)h)} \int_{A(t)} d\mathbf{r}_0\, J_0(k(\omega)|\mathbf{r}-\mathbf{r}_0|) \times \int_0^t dt_0\, \dot{u}_z^{bot}(\mathbf{r}_0,t_0)\cos[\omega(t-t_0)] \qquad (1)$$

In (1), k is wavenumber, ω is frequency $\omega=\{gk(\omega)\tanh[k(\omega)h]\}^{1/2}$, $d\mathbf{r}_0=dx_0dy_0$, superscript $\cdot=\partial/\partial t$ and $J_0(x)$ is the cylindrical Bessel function of order zero. The second integral covers area *A*(t) that includes all points $\mathbf{r}_0$ where $\dot{u}_z^{bot}(\mathbf{r}_0,t_0)\neq 0$ for $t_0<t$. Any number of strategies can be used to evaluate (1) given a kinematic prescription of the landslide $u_z^{bot}(\mathbf{r},t)$. Mostly, the strategies reduce to finding an efficient means to compute the three integrals and to adapting the equation to non-uniform depth oceans. One approach shingles the source with many, small simple slides. These are then added up in a number and combination needed to represent adequately the spatial and temporal history of the entire landslide. A simple slide element is rectangular, with length L and width W. On these elements, a landslide of constant thickness T and step function time dependence, starts along one width of the rectangle at $\mathbf{r}_s=\mathbf{0}$ and $t_s=0$, and runs down its length at slide velocity v_r. If $\mathbf{r}$ is not too close to the slide, and $t>L/v_r$, then (1) becomes in a non-uniform depth ocean,

$$u_z^{surf}(\mathbf{r},t) \approx \frac{TLW}{2\pi}\int_0^\infty d\omega\, \frac{k_0(\omega)J_0(\omega T(\omega,\mathbf{r},\mathbf{r}_0))\cos[\omega t+X(\omega,\theta)]}{u_0(\omega)\cosh[(k_0(\omega)h(\mathbf{r}_0)]} \times \frac{\sin X(\omega,\theta)}{X(\omega,\theta)}\frac{\sin Y(\omega,\theta)}{Y(\omega,\theta)}G(\mathbf{r},\mathbf{r}_0)S_L(\omega,\mathbf{r},\mathbf{r}_0) \qquad (2)$$

where $X(\omega,\theta)=L(k_0(\omega)\cos\theta-\omega/v_r)/2$; $Y(\omega,\theta)=W(k_0(\omega)\sin\theta)/2$, and θ is angle between the slide direction and the observation point. The $k_0(\omega)$ and $u_0(\omega)$ are the wavenumber and group velocity now specific to frequency ω in water of depth $h(\mathbf{r}_0)$ at the source. The new terms $T(\omega,\mathbf{r},\mathbf{r}_0)$, $G(\mathbf{r},\mathbf{r}_0)$ and $S_L(\omega,\mathbf{r},\mathbf{r}_0)$ in (2) account for changes in travel time, and wave height due to geometrical spreading and shoaling in oceans of variable depth. Their functional form can be found in *Ward* (2001). The advantage to the "simple slide" approach (2) versus the general expression (1) is that the integrals over $\mathbf{r}_0$ and t_0 can be done analytically The downside is that a large number of simple slide elements might be needed.



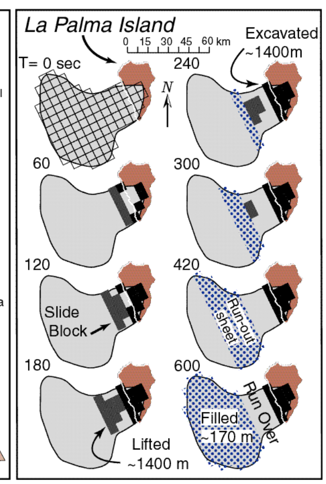


Figure 2. Map of La Palma Island showing the major geological deposits together with the visible and inferred headscarps of the potential slide block pictured at the bottom.

Figure 3. Time/space history of the La Palma landslide simulation. The upper left panel shows the "shingling" of the collapse scar (light gray sack) with many simple slides. The black, dark gray/dotted, and light gray regions map areas excavated, covered, and unchanged, versus time during the slide. The mass movement took 10 minutes to complete and reached 60 km out to sea.

4. La Palma Landslide Model - Specifics

To model the potential tsunami generated from a collapse of Cumbre Vieja, let's consider a worst case (in terms of slide volume) -- a 500 km^3 block, 25 km long, 15 km wide, and 1400 m thick that breaks away and spills westward into the deep ocean. Judging from the shape of the previous La Palma slide and past collapses of similar volume elsewhere in the Canaries, we suppose that material in the 375 km^2 excavation will cascade down the steep offshore slope for about 60 km

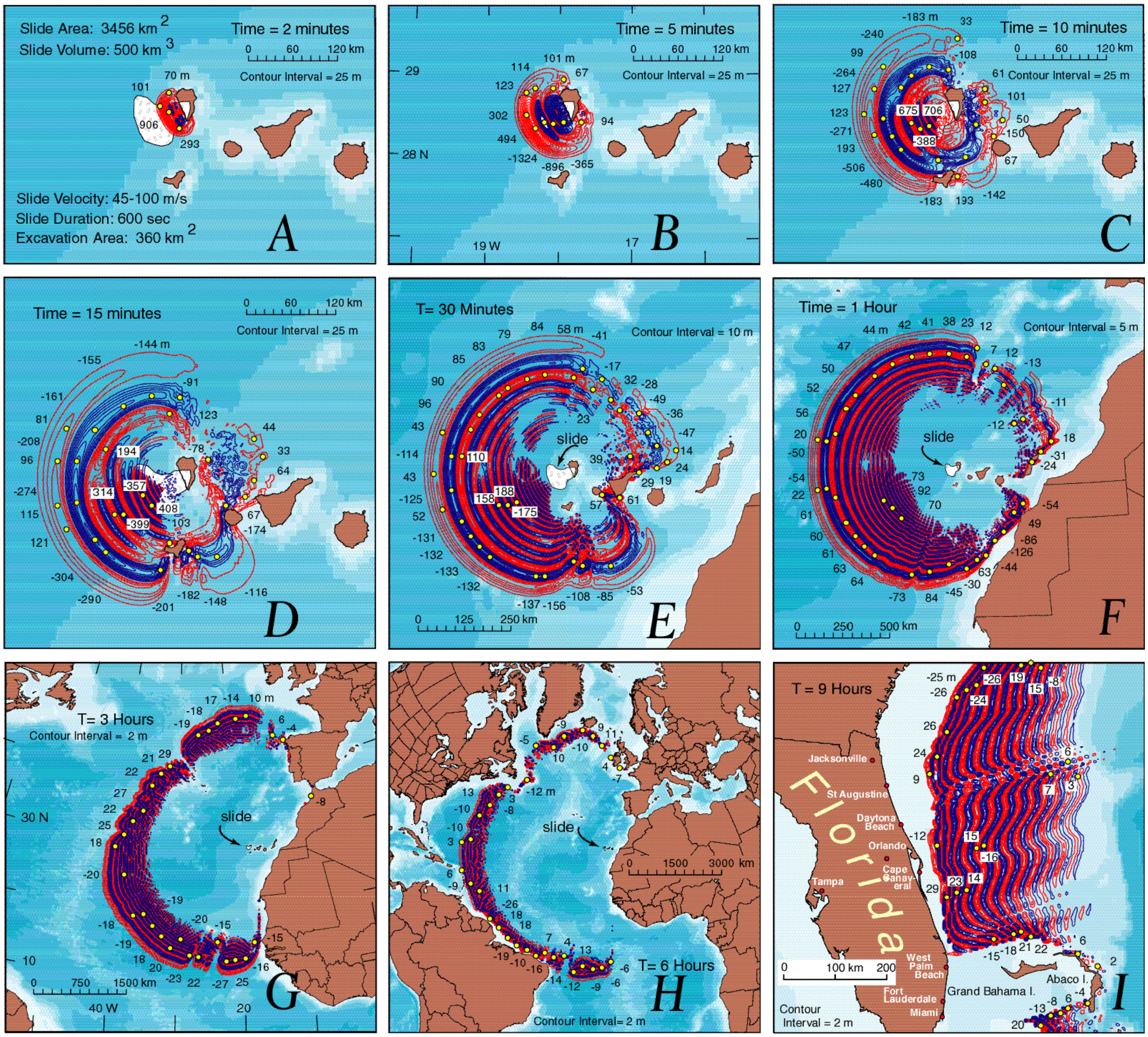


Figure 4. Evolution of the La Palma landslide tsunami from 2 minutes (a, upper left) to 9 hours (i, lower right). Red and blue contours cover elevated and depressed regions of the ocean respectively and the yellow dots and numbers sample the wave height, positive or negative, in meters. Note the strong influence of dispersion in spreading out an original impulse into a long series of waves of decreasing wavelength. See also that the peak amplitudes generally do not coincide with the first wave. Even after crossing the Atlantic, a lateral collapse of Cumbre Vieja volcano could impose a great sequence of waves of 10-25 m height on the shores of the Americas.

until it reaches the flat ocean floor at 4000 m depth. To run these distances, slides likely raft on a highly pressurized layer of mud or fault gouge breccia (*Day*, 1996; *Van Wyk de Vries et al.,* 2001) that reduces basal friction and permits rapid acceleration. We further imagine that the slide block travels as a unit for 15 km out to the slope break before it begins to tear apart. The run-out sheet formed from the disintegrating block will then thin, expand laterally, and eventually cover a jug-shaped region about 3,500 km^2.

To compute the tsunami, we cover the postulated collapse scar with 96 simple slides, 6 km square (*upper left*, Figure 3). These elements fire off (some more than once) as the front or back of the slide passes. Each firing of a simple slide calls for evaluation of expression (2). The total tsunami field is then summed for fixed times and many positions **r**. The sequence pictured in Figure 3 mimics the progression of a break-away, hat-shaped block initially sliding intact down slope, and then disintegrating into a flow covering 2,826 km^2 to 177 m depth. We chose the latter value so that the volume deposited equals the volume excavated. Although many kinematic histories can be proposed, we envision an accelerating block that quickly reaches a peak velocity of 100 m/s before it disintegrates into a run-out. Tsunami generation is most efficient when landslide velocity approaches the local water wave speed $\sqrt{gh}$ (*Ward*, 2001). Because the ocean depth at the La Palma slide generally exceeds 2000 m, a 100 m/s slide velocity substantially lags the tsunami speed, even near the shore. Proportionally larger or smaller waves could be generated by selecting a higher or lower peak slide velocity (see Section 6). Note finally that because the slide block originates mostly above sea level, none of the excavation (*black color*, Figure 3) was permitted to be tsunami-producing.

5. La Palma Tsunami

Figure 4 contours tsunami height relative to sea level from our La Palma landslide model. Within 2 minutes of the initial failure (Figure 4a), a water dome has built atop the sliding block to 900 m height -- only somewhat less than the thickness of the block. Within 5 minutes (Figure 4b), the fast-traveling initial wave crest has outrun the now disintegrating landslide front. The leading wave height has dropped to 500 m after 50 km of travel. Large negative waves now appear behind the leading crest. These are due partly to rebound of the initial dome and partly due to the passing of the back of the slide block that drops the water column (dark gray squares to light gray squares in Figure 3). At 10 minutes (Figure 4c), the slide has run its course. The tsunami disturbance has grown to 250 km in diameter and several hundred-meter high waves have rolled up the shores of the three westernmost islands of the Canary chain. Note the relatively non-directional character of the wave pattern and that already, the leading positive wave (200 m) is no longer the largest. Several negative and positive ones 2-3 times larger trail behind. From 15 to 60 minutes (Figure 4d-f), waves sweep eastward through the rest of the Canary Islands and 50-100 m waves make first landfall on the African mainland. Upon nearing the West Saharan shore, the tsunami waves slow, and crush together (Figure 4f). In contrast, toward the west, a great train of dispersed waves 500 km across, develops as the tsunami moves into the Atlantic basin. Peak wave heights (60 m) there show up in the second crest. From 3 to 6 hours (Figure 4g,h), the tsunami expands across the Atlantic retaining palpable amplitude in an arc subtending more than 180 degrees. Toward the northeast, Spain and England experience 5 to 7 m waves. La Palma Island itself blocked most of the radiation in this direction. Vanguards of the tsunami (10 m) first brush North America near Newfoundland. Simultaneously, larger (15-20 m) waves arrive at the north shore of South America. At 9 hours (Figure 4i), Florida faces the tsunami, now parading in a dozen cycles or more. In 50 m of water offshore Cape Canaveral, even after being weakened by geometrical spreading and frequency dispersion, tsunami from lateral collapses of the volume, dimension, and speed of that expected at La Palma could retain 20-25 m height. Shoaling waves do not continue to grow much in water shallower than their height, so 20-25 m probably reflects the terminal height of the waves expected on Florida's beaches.

6. Conclusions

Geological evidence suggests that during a future eruption, Cumbre Vieja Volcano on the Island of La Palma may experience a catastrophic flank collapse. For a 500 km^3 slide block running westward 60 km down the offshore slope at 100 m/s, our computer models predict that tsunami waves 10 to 25 m high will be felt at transoceanic distances spanning azimuths that target most of the Atlantic basin. Simulations of other collapse scenarios indicate that for slides that do not run too close to the tsunami wave speed, peak tsunami amplitude follows roughly in proportion to landslide volume times peak landslide velocity. (The proportionality is location-dependent, and it holds more strictly for volume and less strictly for peak velocity.) Thus, more modest assumptions on the size and peak speed of the slide make for smaller waves. For instance, a 250 km^3 block running westward 60 km at 50 m/s generates tsunami with about 1/4 to 3/8 the amplitude of those presented above.

In the past million years, dozens of lateral collapse landslides of a size comparable to the one considered here have been shed from volcanic islands in the Atlantic. If our models are correct, tsunami from these incidents should have washed several times over most coasts that have good exposure to the sea. A test of these predictions lies in whether tsunami deposits associated with specific collapses can be identified, dated, and widely correlated. Ironically, because of the more favorable preservation conditions underwater, evidence of collapse tsunami may be more widespread on the continental shelf than on land. Still, the low-lying, tectonically stable, non-glaciated margins of west Africa, the southeast United States and northeast Brazil, together with the Bahamas carbonate platform, should be particularly suitable sites for geologists to search for footprints of these occasional visitors.

References

Bonelli Rubio, J.M., 1950. *Contribucion al estudio de la erupcion del Nambroque o San Juan*. Madrid Inst. Geografico y Catastral, 25 pp.

Carracedo, J.C., S.J. Day, H. Guillou and P. Gravestock, 1999. The later stages of the volcanic and structural evolution of La Palma, Canary Islands. *Geol. Soc. Am. Bull. 111,* 755-768.

Day, S.J., 1996. Hydrothermal pore fluid pressure and the stability of porous, permeable volcanoes. In: *Volcano instability on the Earth and terrestrial planets* (eds. W. McGuire, J. Neuberg & A. Jones), Geol. Soc. Lond. Spec. Publ. 110, 77-93.

Day, S.J., J.C. Carracedo, H. Guillou and P. Gravestock, 1999a. Recent structural evolution of the Cumbre Vieja volcano, La Palma, Canary Islands. *J. Volcan. Geotherm. Res. 94,* 135-167.

Day, S.J., S.I.N. Heleno da Silva and J.F.B.D Fonseca, 1999b. A past giant lateral collapse and present day flank instability of Fogo, Cape Verde Islands. *J. Volcan. Geotherm. Res. 94,* 191-218.

Elsworth, D. and B. Voight, 1995. Dike intrusion as a trigger for large earthquakes and the failure of volcano flanks. *J. Geophys. Res. 100,* 6005-6024.

Johnson, W., 1987. Large-scale volcanic cone collapse: the 1888 slope failure of Ritter volcano. *Bull. Volcan. 49,* 669-679.

Keating, B.H. and W.J. McGuire, 2000. Island edifice failures and associated tsunami hazards. *P. Appl. Geophys. 157*, 899-955.

Muller, J.R. and S.J. Martel, 2000. Numerical models of translational landslide rupture surface growth. *P. Appl. Geophys. 157,* 1009-1038.

Moore, J.G., 1964. Giant submarine landslides on the Hawaiian ridge. *U. S. Geol. Survey Prof. Paper 501-D*, 95-98.

Moore, J.G. and G.W. Moore, 1984. Deposit from a giant wave on the island of Lanai, Hawaii. *Science 226*, 1312-1315.

Moore, J.G., W.R. Normark and R.T. Holcomb, 1994. Giant Hawaiian Landslides. *Ann. Rev. Earth Planet. Sci*. 22, 119-144.

Moss, J.L., W.J. McGuire and D. Page, 1999. Ground deformation monitoring of a potential landslide at La Palma, Canary Islands. *J. Volcan. Geotherm. Res. 94*, 251-265.

Satake, K. and Y. Kato, 2001. The 1741 Oshima-Oshima eruption: extent and volume of submarine debris avalanche. *Geophys. Res. Lett. 28*, 427-430.

Urgeles R., D.G. Masson, M. Canals, A.B. Watts and T. Le Bas. 1999. Recurrent large-scale land sliding on the west flank of La Palma, Canary Islands. *J. Geophys. Res. 104,* 25,331-25,348.

Van Wyk de Vries, B., S. Self, P. W. Francis and L. Keszthelyi, 2001. A gravitational spreading origin for the Socompa debris avalanche. *J. Volcan. Geotherm. Res. 105*, 225-247.

Voight, B., R. J. Janda, H. Glicken and P. M. Douglass 1983. Nature and mechanics of the Mount St. Helens rockslide-avalanche of 18 May 1980. *Geotechnique 33,* 243-273.

Ward, S.N., 2001. Landslide Tsunami, *J. Geophys. Res. 106*, 11,201-11,215.

Watts, A.B. and D.G. Masson, 1995. A giant landslide on the north flank of Tenerife, Canary Islands. *J. Geophys. Res. 100,* 24487-24498.

Young, R.W. and E.A. Bryant, 1992. Catastrophic wave erosion on the southeastern coast of Australia: impact of the Lanai tsunami c.105 ka? *Geology 20*, 199-202.

S. N. Ward, IGPP, University of California, Santa Cruz, CA 95064 USA (*ward@uplift .ucsc.edu*).

S. Day, Benfield Greig Hazard Research Centre, Department of Geological Science, University College, London, United Kingdom

(Received March 2, 2001; revised May 11, accepted June 27, 2001.)

Paper number 2001GL000000.
0148-0227/01/2001GL000000$09.00