VOLCANO COLLAPSE-GENERATED MEGATSUNAMIS: FACT OR FICTION?

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The tsunamigenic potential of flank collapse at ocean-island volcanoes continues to drive fierce debate, and no more so than in relation to the Cumbre Vieja volcano on La Palma (Canary Islands) (e.g. Ward & Day 2001; Mader, 2001; Gisler et al. 2006; Masson et al. 2006; McGuire, 2006). Here, we discuss the case for flank collapses at ocean island volcanoes, such as the Cumbre Vieja, as megatsunami sources. Two broadly equivalent definitions of a megatsunami are (i) a tsunami in excess of 100 m in height at source and which remains destructive at oceanic distances (McGuire, 2006) and (ii) a tsunami larger than can be produced directly by an earthquake of terrestrial (i.e. non-impact) origin.

As the collapse of an ocean-island volcano has never been observed, our current knowledge of the mechanism comes from direct observations of smaller-scale volcano flank collapses, geological and structural analysis of ancient ocean-island collapse features and associated deposits, and theoretical modelling. Key to integrating these lines of evidence is the understanding that observations of historical, smaller-volume collapses at strato-volcanoes (e.g. Ritter Island, PNG, 1888; Bezymianny, Russia, 1956; Mount St. Helens, USA, 1980), provide important pointers to the kinematics and mechanics of larger-volume ocean island collapses and the resulting landslides, and hence their tsunamigenic potential. Total collapse volume at island arc and terrestrial volcanoes on the one hand, and ocean-island volcanoes on the other, differ by three orders of magnitude; but many similarities are recognised. These include the block and matrix nature of resulting deposit facies, block geometry and size range relative to collapse volume, the ranges of slope angles on which deposits occur, and inter-relationships between volume and the drop-height/run-out ratio. Taken together, such similarities support the notion that, to a significant degree, small volume flank collapses at terrestrial and island arc volcanoes can be regarded as reasonable analogues for large-scale ocean-island flank failure.

Many factors contribute to the tsunamigenic potential of flank collapse at ocean-island volcanoes. While some — such as collapse-headwall geometry — are well constrained, others are not. With reference to the Cumbre Vieja, but also future island volcano collapses in general, we regard the following as the key questions pertinent to tsunamigenic potential:

- What will be the volume and geometry of the collapse?
- Will the collapse occur as one or more events?
- What will be the peak slide velocity of the collapsing mass?
- Will the resulting tsunami disperse rapidly, or will it propagate efficiently, thereby presenting a threat to life and property at transoceanic distances?

Collapse volume and thickness

Ward & Day (2001) estimate the potential volume of a future Cumbre Vieja collapse to be up to 500 km^3, assuming failure at 2 - 3 km beneath the summit ridge. This is challenged by Masson et al. (2006), who use pre-collapse reconstructions of volcanoes on the neighbouring islands of Tenerife and El Hierro to argue that the maximum thickness of a future collapse is likely to be around half this. Their reconstructions assume, however, that the headwalls of not normally the case, as evidenced by reconstructions of pre-collapse edifices on Fogo (Cape Verde Islands) and, among the Canary Islands, on Fuerteventura, Tenerife and the Cumbre Nueva on La Palma itself: in all of these, the collapse scar geometries support the model geometry proposed by Ward & Day (2001). Similarly, recent strato-volcano collapses, such as 1980 Mount St Helens and 1888 Ritter Island, also cut deeply into the opposing flanks and reduced the heights of the volcanoes by several hundred meters.

Single versus multiple collapse events

Several lines of evidence suggest that flank collapses at volcanoes involve the deep-seated failure of one or a few large blocks, which break up during subsequent movement. First is direct observation, as seen best at Mount St. Helens in 1980 (Voight, 1981): note that although geometries of volcano flank collapse at different types of volcano (such as island arc strato-volcanoes and oceanic island shield volcanoes) differ in detail, they are more similar to one another than to the generally much thinner landslides that occur in non — volcanic settings, so we consider that comparison between different types of volcano is valid where flank collapses are concerned. Second is the enormous volume of some individual blocks in debris — avalanche type submarine landslides. Third is that *every* island volcano collapse and large volcanic landslide for which we have written observations (Table 1) — around a dozen in all - also produced significant tsunamis. Each of these tsunamis consisted of the single, continuous series of waves expected from a single catastrophic failure (albeit sometimes involving failure growth upslope or downslope over a period of minutes, and followed by small rock-falls from the unstable face of the newly-created collapse scar).

In contrast, work offshore from the Canary Islands (Masson et al., 2006) has led these authors to the alternative view that flank collapse at ocean-island volcanoes might occur over a period of hours to days as a series of small landslides, each with reduced tsunamigenic potential compared to a single, catastrophic event. Maps of landslide deposits around the Canary lobes deposited from successive small landslides, and show that the landslide deposits have the long run-outs relative to their volumes that are typical of the largest landslides. Instead, Masson and colleagues construct their thesis by linking stacked turbidite sub-units *c.* 300 km north of the Canary Islands to past flank collapses of El Hierro and Tenerife; a similar turbidite architecture was identified by Garcia (1996) in only one out of several turbidites cored off Hawaii. Each sub-unit is interpreted by these authors as being representative of a single landslide within a multi-stage flank collapse, on the assumption that one turbidite sub-unit = one landslide. A number of mechanisms exist, however, by which a single landslide may generate multiple turbidity currents, or multiple pulses within a single current, at different stages in its movement history:

1). The formation of distinct sediment-laden vortices above the landslide, generated as the fragmented landslide moves rapidly across the sea floor (Gisler et al. 2006), may result in series of high energy turbidity currents similar to those interpreted by Yokose & Lipman (2004) as depositing high-energy, syn-collapse, turbidites linked to the Alika-2 landslide (Hawaii).

2). As the landslide moves onto the sediment — covered seafloor at the foot of the volcanic edifice, it may erode this sediment or trigger a series of failures in the sediment sequence, to generate a series of sediment intraclast — rich debris flows that then further transform into multiple turbidity currents.

3). As the distal part of the landslide crosses subtle topography on the nearly — flat ocean floor and is diluted by seawater entrainment, it may separate into multiple lobes that source a series of turbidity currents that start near-simultaneously, but which follow different paths, with different lengths and velocities, finally converging on a distant sedimentary basin where turbidite beds are deposited in succession as discrete units.

4). Further stratification in the final deposit may be produced by the spontaneous development of pulsing within individual turbidite currents during

The one turbidite = one landslide assumption that underlies the Masson et al. (2006) argument is therefore questionable, and so we argue that the piecemeal collapse model that it is used to support is also in doubt.

Slide velocity of the collapsing mass

Another key control on tsunamigenic potential is the slide velocity of the collapsing mass. Empirical evidence indicates that high transport velocities are the norm for volcano lateral collapses. The May 1980 failure of Mount St. Helens north flank provides the only direct estimate of flank collapse velocity (Voight, 1981), which exceeded 80 m s^{-1} on a slide plane of *c.* 10° (comparable with slide-plane slopes on the submarine flanks of the Canary Island volcanoes). Ward & Day (2003) use tsunami data to show that velocities during the 1888 Ritter Island collapse reached *c.* 45 m s^{-1}, following an initial drop of the centre of mass of 700 m, and that velocities as high as 80 m s^{-1} may have been achieved. We suggest that the inferred Ritter Island velocities provide a conservative lower value for ocean island landslide velocities, with the corollary that these larger volume landslides are predicted to have greater velocities and constitute even more efficient tsunami sources (e.g., Satake et al. 2002). With a drop height exceeding 4,000 m, the 100 ms^{-1} velocity used by Ward & Day (2001) in their model of a future Cumbre Vieja collapse may, if anything, be conservative. Even at this speed, only 10 — 15 percent of the gravitational energy lost in the landslide transfers to the tsunami waves.

Tsunami decay rates during propagation

Close to source, modelling by both Ward & Day (2001) and Gisler et al. (2006), predict very large initial waves (respectively 900m and 1500m) for Cumbre Vieja collapse volumes *c.* 500 km^3, which are likely to lead to massive destruction within the archipelago. In relation to the far field, however, debate has centred on the ability of such tsunamis to retain the eastern seaboard of North America. Mader (2001) and Gisler et al. (2006) argue that rapid frequency dispersion of the relatively short —period, landslide — generated tsunami waves will produce a decrease in wave height with the square of distance travelled. This, however, is at odds with direct evidence of the 1741 Oshima Oshima (Japan) and 1888 Ritter Island collapse — generated tsunamis, that were damaging at distances of several hundred to over 1000 km from source, despite having short dominant wave periods (~ 3 minutes in the case of the 1888 Ritter Island tsunami). These data, and data for nuclear explosion —generated tsunami waves (Van Dorn, 1961), point to a maximum amplitude decrease with distance r from source as $\sim 1/r^{(5/6)}$. Since dominant tsunami wave period is likely to increase linearly with the source landslide dimensions, it is probable that the amplitude decay rate with distance from source for oceanic island landslides will be even slower, and so the future Cumbre Vieja collapse — generated tsunami will be destructive at transoceanic distances.

We conclude that although uncertainties still exist regarding the timing of a future flank collapse of the Cumbre Vieja volcano, the various lines of evidence presented here provide strong indications that when such collapses do occur at La Palma and other oceanic islands in the geologically near future, the resultant tsunamis will have the potential to remain highly destructive at oceanic distances.

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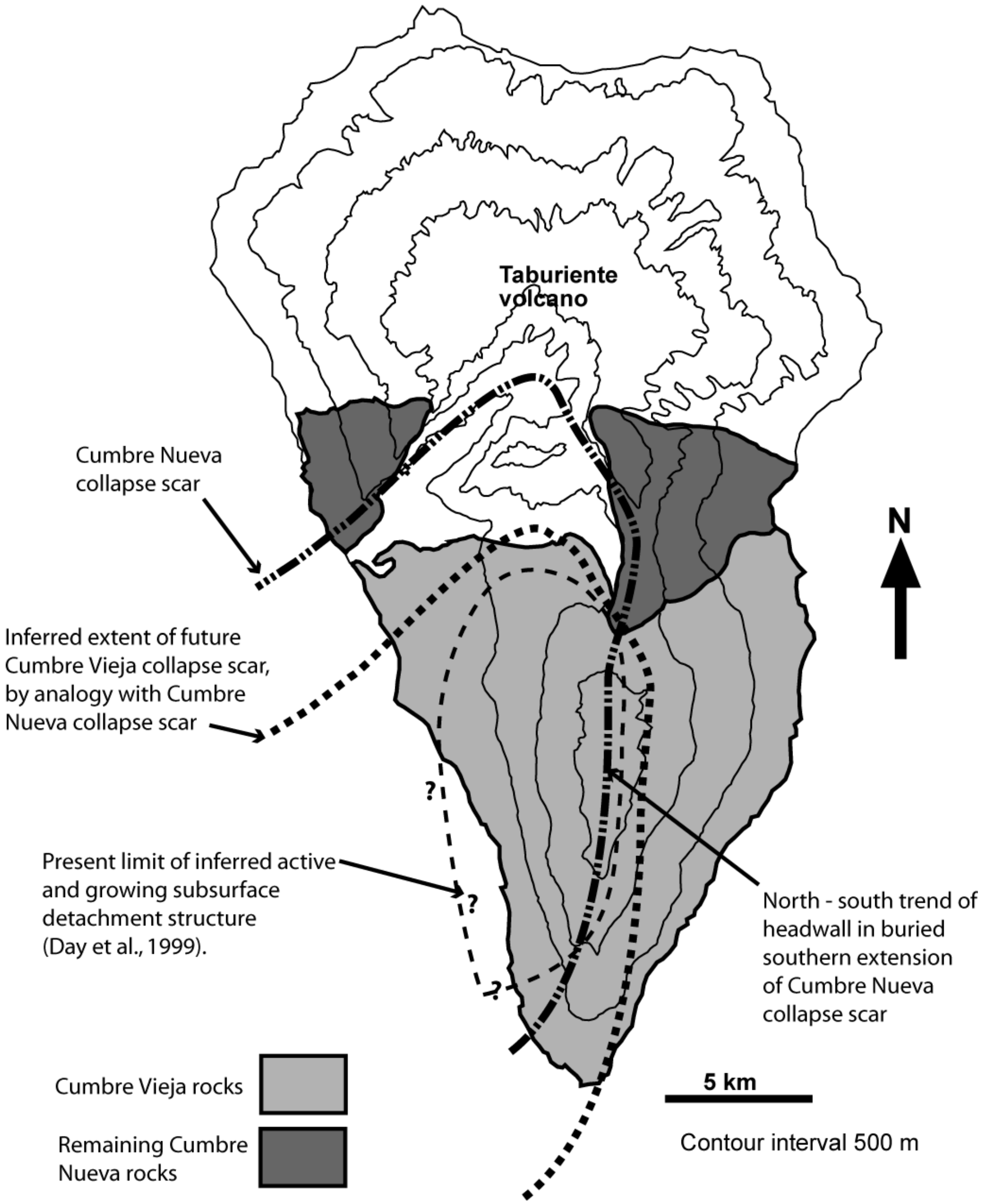
FIGURE AND TABLE CAPTIONS

Figure 1. Map view of a model geometry of a future lateral collapse of the Cumbre Vieja volcano (La Palma), based upon the location of an inferred developing detachment structure under the western flank of the volcano and the geometry of the previous Cumbre Nueva collapse structure (Day et al., 1999): note that collapse structures in the Canary Islands have relatively uniform geometry, in contrast to the wide range of collapse geometries observed in the Hawaiian Islands. A simplified version of this collapse geometry was used in the tsunami source model of Ward & Day (2001).

Table 1. Historical sector collapses and large landslides at island and coastal volcanoes. A distinction exists between volcano collapses with volumes typically > 1 km^3 and maximum thicknesses > 500 m, and large landslides with volumes < 0.1 km^3 and thicknesses < 100 m. Note that all ocean — entering volcano sector collapses for which written historical records exist have produced tsunamis.

FIGURE 1


Taburiente volcano
Cumbre Nueva collapse scar
Inferred extent of future Cumbre Vieja collapse scar, by analogy with Cumbre Nueva collapse scar
Present limit of inferred active and growing subsurface detachment structure (Day et al., 1999).
North - south trend of headwall in buried southern extension of Cumbre Nueva collapse scar
N
?
?
?
5 km
Contour interval 500 m
Cumbre Vieja rocks
Remaining Cumbre Nueva rocks