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## Güímar and La Orotava mega-landslides (Tenerife) and tsunamis deposits in Canary Islands

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### Abstract

More than 20 mega-landslides have been described in the Canary Islands affecting the flanks of the volcanic edifices. Güímar and La Orotava landslides, in Tenerife, are two exceptional cases due to their huge dimensions and outstanding geomorphological features. The estimated volume of these landslides exceed tens of cubic km. Tsunami deposits have been also identified in some of the islands of the archipelago probably associated to the large landslides of the islands flanks.

An investigation has been carried out to explain the causes of these large instability processes and their failure mechanisms. One of the main aspects investigated was the geomechanical characteristics of the volcanic rock masses, specially the hyaloclastite rocks forming the substratum underlying the emerged volcanic building. The low strength and high deformability properties of these rocks have played a fundamental role on the stability of the island flanks. The results have shown the gravitational origin of these instability processes as the main failure mechanism. Volcanic eruptions or large earthquakes could be contributing factors to the instability, but according with the data obtained in Guimar and La Orotava cases they are not necessary as triggering factors.

As a result of the field work carried out in the frame of the project, three large tsunami deposits have been identified in the islands of Lanzarote, Tenerife and Gran Canaria attributed to mega-landslides, possibly related to Guimar and La Orotava. A summary of their main features is described.

**Keywords:** volcanic landslides, tsunami deposits, Canary Islands, Tenerife.

### Introduction

The landslides affecting the flanks of volcanic islands are some of the largest in the world. Güímar and La Orotava valleys, in Tenerife, were formed by gigantic landslides some hundreds thousand years ago (1 and 0.6 Ma respectively). The main arguments that support this are listed below:

- The existence of landslide deposits observed inside the galleries excavated in the island.
- The identification of large volumes of landslide deposits (debris avalanches) on the ocean floor facing the valleys (Masson *et al.*, 2002; Acosta *et al.* (2003).
- The similarity of morphological features with other oceanic islands in the world also affected by large flank failures.

The presence of large masses of rocks and debris avalanche deposits lying on the sea bed surrounding the island of Tenerife has been the main evidence of these large landslides. According to Acosta *et al.* (2003) La Orotava submarine debris avalanche deposits cover an area of 2,200 km<sup>2</sup> reaching as far as 75 km from the coast, and the submarine deposits from Güímar landslide occupy an area of 2,600 km<sup>2</sup> reaching a distance of 85 km from the coast. The volume of these debris avalanches in the ocean floor has been estimated around 120 km<sup>3</sup> in the case of Güímar landslide and less than 500 km<sup>3</sup> in La Orotava (Masson *et al.*, 2002). In contrast the volume of these landslides deduced from the valleys sizes is much lower, and they are in the range of 30-60 km<sup>3</sup>.

### Morphological features of Güímar and La Orotava valleys

Güímar and La Orotava valleys are trough-shaped depressions 10-12 km wide inclined towards the sea. They

present opposite orientations, ESE and NNW respectively. Their heads, partially overlapping, are located in the *Cordillera Dorsal*, a mountain chain that forms the main rift zone in the island with NE direction and maximum heights reaching between 1,700 and 2,200 m (Fig. 1).

The morphological characteristics of the valleys are singular, outstanding the symmetry and the important height of the lateral scarps (more than 500 m in some areas; Fig. 2), cut in pre-landslide volcanic materials with slope angles higher than 35°. The depressions formed by the landslides were filled with post-landslide volcanic materials, mainly lava flows coming from new volcanoes in the upper part of the valleys, with slope angles lower than 15° today.



Figure 2 View of La Orotava valley, 12 km wide, bordered by 500 m high lateral scarps. In the background El Teide volcano (3,718 m).

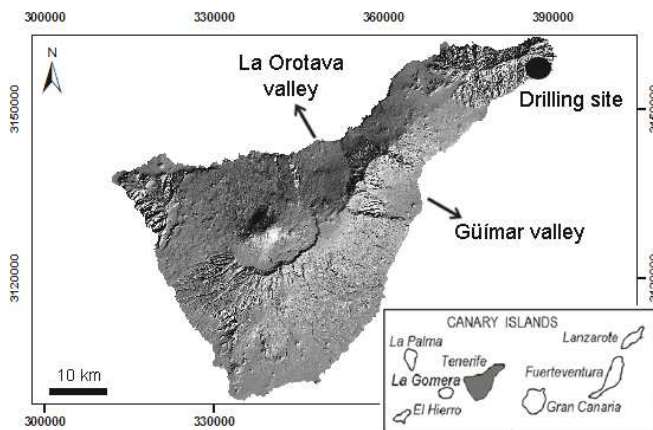


Figure 1 Location of Güimar and La Orotava valleys and drilling site location, Tenerife (Canary Islands).

The estimated volume of the landslide rocks from the volcanic flanks, calculated roughly from the depressions created by the rockslides, is in the order of 70-100 km<sup>3</sup> each.

In the submarine extension of the valleys, characteristic landslide forms have been mapped, highlighting large fan deposits with hummocky morphology.

Also in the subaerial part of the flank deposits attributed to landslides, now buried hundreds of meters deep at the bottom of the valleys are preserved; they can be seen inside the galleries excavated in the island, and consist of a sandy clay matrix with blocks of various sizes and varying composition.

The age of Güimar rockslide has been estimated approximately 1 Ma (Ferrer *et al.*, 2008). The age of La Orotava rockslide has been estimated between 0.54 to 0.69 Ma (Cantagrel *et al.*, 1999).

### Geological and geomechanical conditions of the pre-landslide volcanic edifice

The materials involved in the instability processes are those which form the flanks of the volcanic edifice today in the areas not affected by landslides. They outcrop in the head and lateral scarps left by the landslides and in deep gullies carved by erosion in the pre-landslide materials. They can also be observed in the galleries excavated through the flanks of the volcanic edifice.

### Geological and geomechanical model

One of the main aims of this investigation has been the “reconstruction” of the pre-landslide edifice, as well as to assign representative geomechanical properties to the different types of materials that form it. Thus, the simplified geological, geomorphological and geomechanical representative models of the pre-landslide edifice have been proposed.

The geometrical model previous to the occurrence of Güimar and La Orotava rockslides has been assessed considering paleo-morphological data obtained from the slopes and lateral scarps of the volcanic edifice not affected by landsliding processes. The morphological features of the submarine slopes have been obtained from bathymetric data analysis.

It has been assumed that the ground water conditions for the pre-failure edifice could be similar to those encountered before intensive ground water exploitation of the island aquifers had taken place. A water table at 600-700 m below surface was estimated according with ground water records. In the central part of the edifice due to the presence of a large number of dykes the ground water levels should be higher.

Geological and geotechnical data were recorded from field survey and from the extensive network of small diameter tunnels (galleries), with a total length over of 4,000 km, excavated in the subaerial island flanks for

ground water supply purposes. Geotechnical properties of the volcanic materials of the emerged edifice have been also obtained from engineering geological surveys (González de Vallejo *et al.*, 2008; Seisdedos, 2008).

With respect to the geological and geomechanical data of the submarine edifice, only morphological and tectonic data are available from oceanographic surveys. In the eastern corner of the island site investigations have been carried out where submarine rocks outcrops (Fig. 1). Three boreholes have been drilled in hyaloclastites reaching one of them at 200 m depth.

Hyaloclastites and basaltic lavas have been the rock materials drilled in the three boreholes, although hyaloclastite has been the predominant lithology. In situ tests (pressuremeters) and laboratory tests have been carried out on the samples from the boreholes for the physical and mechanical characterization of the submarine materials.

The simplified geological model for the pre-failure edifice is shown in Fig. 3. The materials were grouped in those corresponding to the emerged edifice (above sea level) and the submarine edifice (below sea level). The lithological units or groups distinguished as representative for geomechanical purposes in the simplified geological model of the flanks of the island of

Tenerife are described below.

### Emerged edifice materials

On the emerged edifice the materials which form the island flanks have been distinguished from those that form the structural axis, which is the main growth area of the island. This zone is characterised by a dense network of dikes, associated with intense fracturing and alteration. There is a significant presence of pyroclasts and lava flows with scoria layers and dikes. The flanks are formed by rocks from the eruptive centres of the structural axis, mainly lava flows with scoria layers whose degree of alteration and compaction increase with depth. In the inner part of the flanks, close to the structural axis, dike intrusion is more intense. Depending on the number of dikes and the intrusion density observed in the galleries the following zones have been identified: very intense intrusion density, with more than 10 dikes per 100 m of gallery length; intense, 4-10 dikes per 100 m; low intensity, less than 4 dikes per 100 m. Some strength rock properties and alteration characteristics of the rock masses have been influenced by the hydrological processes therefore the water table depth has been considered to assess different grades of alteration.

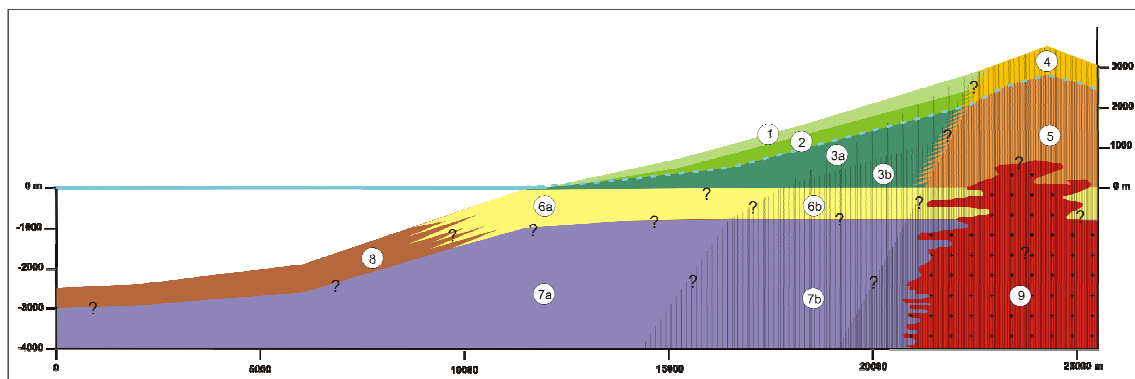


Figure 3 Geological model representative of the pre-landslide volcanic edifice of Güímar and La Orotava landslides (dashed blue line: water level; question marks: uncertainties).

The lithological units, or lithological groups, that form the island flanks and the structural axis of the pre-rockslide edifice are shown in Fig. 3 and their main characteristics are:

- Unit 1: Recent lava flows with scoria layers, with a low degree of alteration, layers of loose scoria and cavities.
- Unit 2: Slightly altered lava flows with scoria layers; lower presence of cavities than Unit 1.
- Unit 3: Altered lava flows and highly compacted pyroclastic layers with intense dike intrusion. Depending on the dike intrusion density two sub-units have been differentiated (3a and 3b).
- Unit 4: Pyroclasts and lava flows with scoria, and

intense dike intrusion; low degree of alteration, high grade of compaction and intense dike intrusion.

- Unit 5: Pyroclasts and altered lava flows, with very intense dike intrusion. These materials are highly compacted and fractured.

### Submarine edifice materials

The materials which form the submerged part of the volcanic edifice represent the submarine growth phases of the island. Most of the information regarding the properties of these materials has been obtained from literature and from boreholes drilled in Tenerife island (see Fig. 1). Some of these lithological units have been subdivided depending on the dike intrusion density in

the same way as in the emerged edifice. Their main characteristics are described below (see Fig. 3):

- Unit 6: Hyaloclastite rocks including the materials from subaerial flows which flow into the sea forming ‘deltas’, as well as from submarine eruptions. The thickness of this unit has been estimated as 800 m according to literature (Staudigel and Schmincke, 1984; García and Davis, 2001; De Paolo, 2001).

- Unit 7: Pillow-lavas from submarine eruptions representing the main phase of submarine growth of the island.

- Unit 8: Gravitational deposits from gravitational slides on the submarine island flanks. These instability submarine processes occur throughout the growth of the island and produce deposits of slid materials or submarine debris avalanches.

- Unit 9: Dikes and plutonic complex. It is mainly formed by a dense dike swarm representing the feeder vents of the different island growth phases, with plutonic rocks and, to a lesser extent, submarine volcanic rocks.

### Properties of the hyaloclastites

In the eastern part of the island of Tenerife three boreholes have been drilled in hyaloclastites one of them reaching 200 m depth (Fig. 1). Hyaloclastites are composed of clastic particles of irregular shape and sizes ranging from 0.5 to 3 cm, forming a green, grey or brown coloured breccia (Fig. 4). This material is poorly consolidated and weakly cemented. Voids and vacuoles are occasionally present with sizes from 0.5 to 3 cm. Secondary minerals are observed inside them. Fracture zones and slickenside surfaces have been identified.



Figure 4 Hyaloclastite rock specimens.

Pressuremeter tests inside the boreholes and laboratory tests have been carried out. The deformational properties of the hyaloclastite rock mass were obtained from 16 pressuremeter tests carried out at different depths in one of the boreholes. The values for pressuremeter moduli ranged from 50 MPa to 3,200 MPa, with mean representative values of 560 MPa.

Table 1 shows the mean values for some physical and mechanical properties of the hyaloclastite rocks obtained from different laboratory tests on the specimens from the boreholes.

Table 1. Hyaloclastites properties from laboratory tests.

Property	Mean values
Unit weigh	2.3 – 2.9 g/cc
Uniaxial strength	16 MPa
Tensile strength	1.5 – 1.8
Young modulus	4,300 MPa
Poisson coefficient	0.27 – 0.31
Strength parameters c, $\phi$	3-5 MPa, 43-50°

### Stability conditions of the pre-failure edifice

Stability analysis has been carried out in the pre-failure edifices of Güimar and La Orotava applying limit equilibrium and stress-strain methods. A first analysis has been developed using rock mass parameters obtained from the application of Hoek-Brown failure criterion (Table 2).

Fig. 5 shows the results of the analysis showing a deformational pattern affecting the whole edifice. In this case the factor of safety is  $SF > 1.3$ .

A second stability analysis has been carried out in order to obtain the “failure” values for the hyaloclastites (back-analysis). Fig. 6 shows the results obtained. In this case, the strain distribution shows larger deformations affecting the hyaloclastites and defining a complex failure surface. In this analysis values of 0.1 MPa for cohesion and 16° for angle of friction are needed to reach limit equilibrium.

Table 2. Geomechanical properties obtained for the units of the pre-failure edifice using H-B criterion.

Unit	c (MPa)	$\phi$ (°)	E (MPa)
1	0.9	51	6,750
2	1.7	47	8,920
3a	2.3	34	4,200
3b	3.1	25	2,780
4	0.9	33	2,300
5	2.8	22	2,050
6a	1.5	30	1,010
6b	2.5	35	1,170
7a	8.0	36	12,020
7b	11.4	34	13,180
8	1.0	20	1,000
9	13.2	33	10,230

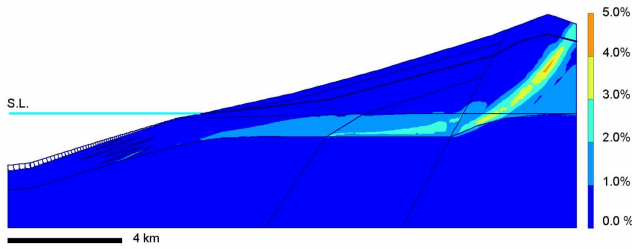


Figure 5. Deformational model from the stability analysis using properties in Table 2. Horizontal scale = vertical scale.

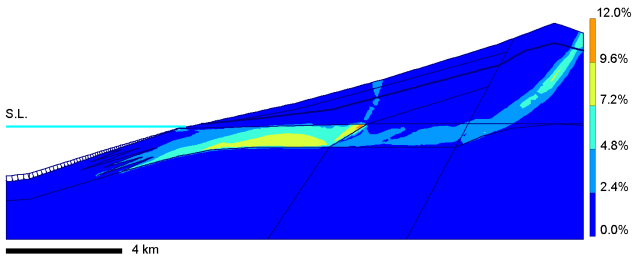


Figure 6. Deformational model for the initiation of failure (SF=1.0) and values for the hyaloclastite rocks:  $c = 0.1$  MPa and  $\phi = 19^\circ$ . Horizontal scale = vertical scale.

Although these results are still preliminary they present significant potential failure surfaces that are in accordance with the geomorphological and geological features observed in Güímar and La Orotava valleys, as well as with the geomechanical properties of the materials involved.

The importance of the hyaloclastites rocks has been also pointed out on the stability of the Hawaiian volcano flanks (Schiffman *et al.*, 2006).

### Tsunami deposits

Large tsunami deposits have been identified in Teno (Tenerife), Piedra Alta (Lanzarote) and Agaete (Gran Canaria). The last one has been described by Pérez Torrado *et al.* (2002) and Madeira *et al.* (2011), and it represents at least 3 different tsunami events. Paleontological and paleoclimatic investigations indicate an age between 1.8 to 2.0 ma (Meco *et al.*, 2008). Teno tsunami deposits, in Tenerife, are probably associated to the flank collapse of the Cañadas Edifice, ca 150-180 ka. Piedra Alta tsunami deposits, located in Lanzarote island, contain many specimens of marine fauna and an age ca 330 ka has been attributed based on paleoclimatic and paleontological criteria (Meco *et al.*, 2008).

The characteristics of all these deposits indicate a high energy source and a high speed mechanism. Although the tsunami sources are still being investigated, a relation with the large landslides occurred in the Canary Islands during the Pleistocene, with giant rock avalanches entering into the sea is probable.



Figure 7. Tsunami deposits in the northwest coast of Tenerife (area shown 2 m height).

The possible run-up of the largest waves of these tsunamis exceeds 50 m height at the Agaete and Teno sites, and at least 25 m height at the Piedra Alta site, as deduced from the location of the deposits today.



Figure 8. Tsunami deposits in the southwest coast of Lanzarote (area shown 2.5 m height).

### Conclusions

The highly deformable hyaloclastite rocks can play a primary factor in the destabilization process of the flanks of Tenerife. The preliminary results obtained have shown the geometry of the potential failure surfaces of Güímar and La Orotava rockslides. These results are in accordance with the geomechanical properties of the rocks, the surface and submarine geomorphological data and the mechanisms of the geological processes involved. The results suggest that the large instability processes common of the volcanic islands flanks depend on the

high deformability properties of hyaloclastites, as well as the morphological conditions of the emerged volcanic edifice, mainly the height and the slope angle of its flanks, so that they are mainly caused by gravitational disequilibrium. Other influencing or triggering factors such as dyke intrusion pressures and volcanic seismicity activity should be also considered as contributing factors. The tsunami deposits identified in three islands suggest a very rapid rock mass movement of rocks and debris entering into the sea with a high energy impact. Tsunami waves have reached over 50 m height and propagated to neighboring islands at distances of many km away from the tsunami sources.

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## References

- Acosta, J., Uchupi, E., Muñoz, A., Herranz, P., Palomo, C., Ballesteros, M. (2003). Geologic evolution of the Canarian Islands of Lanzarote, Fuerteventura, Gran Canaria and La Gomera and comparison of landslides at these island with those at Tenerife, La Palma and El Hierro. *Mar. Geophys. Res.* 24: 1-40.
- Cantagrel, J.M., Arnaud, N.O., Ancochea, E., Fuster, J.M. and Huertas, M.J. (1999). Repeated debris avalanches on Tenerife and genesis of Las Cañadas caldera wall (Canary Islands). *Geology*, vol. 27, no. 8, p. 739-742.
- DePaolo, D.J. (2001). Deep drillig into a hawaiian volcano. *EOS* 82 (13): 149, 154-155.
- Ferrer, M., González de Vallejo, L.I., Seisdedos, J., García, J.C., Coello Bravo, J.J., Casillas, R., Martín, C., Hernández, L.E. (2008). Large rockslides hazards in Tenerife island. Geological analysis and geomechanical modeling of instability mechanisms, IGME-CICYT CGL2004-00899 project, internal report (unpublished).
- Ferrer, M., Seisdedos, J. and González de Vallejo, L.I. (2010). The role of hyaloclastite rocks in the stability of the volcanic island flank of Tenerife. In: Olalla *et al.* (Editors), *Volcanic Rock Mechanics*, Taylor and Francis Group, London, UK, pp: 167-170.
- García, M.O. and Davis, M.G. (2001). Submarine growth and internal structure of ocean island volcanoes based on submarine observations of Mauna Loa volcano, Hawaii. *Geology* 29 (2): 163-166.
- González de Vallejo L.I., Hijazo, T. and Ferrer, M. (2008). Engineering geological properties of the volcanic rocks and soils of the Canary Island. *Soils and Rocks* 31: 3-13.
- Madeira, J., Ferrer, M., Gonzalez de Vallejo, L.I., Andrade, C., Freitas, M.C., Lomoschitz, A. and Hoffman, D. (2011). Agaete revisited: new data on the Gran Canaria tsunamiites. *Geophysical Research Abstracts*. Vol. 13, EGU2011-2292-2, EGU General Assembly 2011.
- Masson, D.G., Watts, A.B., Gee, M.J.R., Urgeles, R., Mitchell, N.C., Le Bas, T.P. and Canals, M. (2002). Slope failures on the flanks of the western Canary Islands. *Earth Sci. Rev.* 57, 1-35.
- Meco, J. and col. (2008). Historia geológica del clima en Canarias. <http://hdl.handle.net/10553/700>
- Pérez Torrado, F., Paris, R., Cabrera, M.C., Carracedo, J.C., Schneider, J.L., Wassmer, P., Guillou, H. y Gimeno, D. (2002). Depósitos de tsunami en el valle de Agaete, Gran Canaria (Islas Canarias). *Geogaceta* 32, 75-78.
- Seisdedos, J. (2008). Large paleo-rockslides of Güímar and La Orotava (Tenerife): Geological analysis, instability mechanisms and geomechanical modelling. PhD Thesis (UCM). Madrid. E-prints Complutense.
- Schiffman, P., Watters, R.J., Thompson, N. and Walton, A.W. (2006). Hyaloclastites and the slope stability of Hawaiian volcanoes: Insights from the Hawaiian Scientific Drilling Project's 3-km drill core. *Journal Volcanology and Geothermal Researches* 151: 217-228.
- Staudigel, H. and Schmincke, H.U. (1984). The pliocene seamount series of La Palma, Canary Islands. *J. Geophys. Res.* 89 (B13): 11195-11215.