Volcanic mega-landslides in Tenerife (Canary Islands, Spain)

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ABSTRACT: In the last two decades it has been demonstrated the occurrence of large landslides in volcanic buildings, as well as the influence of these processes in the evolution of volcanic islands. More than 20 paleo-landslides have been described in the Canary Islands. Güímar and La Orotava valleys, in Tenerife island, originated by megalandslides some hundreds of thousands years ago, are two exceptional examples because of their geomorphological features and the identification of the subaquatic landslided deposits in the ocean floor and in the interior of the underground galleries excavated in the island. In spite of their importance and the acceptance of the occurrence of these instability processes by the scientific community, only few investigations have been carried out to analyse and to explain these processes under the geomechanical point of view. The authors are developing a research project, supported by the Geological Survey of Spain and the Commission for Science and Technology of Spain, being the main objective to explain why and how these megalandslides took place, which were the mechanisms, the influencing and triggering factors and their role. Detailed studies on characterization of volcanic rock materials involved in the landslides, geological evolution, morphological reconstruction, geophysical data interpretation, laboratory tests, age determinations, etc. have been or are currently being carried out in order to prepare the geological, hydrogeological and geomechanical models for the analysis and evaluation of the influence of the different factors affecting the stability and mechanical behaviour, to verify the current hypothesis on La Orotava and Güímar large valleys generation and to explain the mechanisms of the megalandslides in volcanic buildings slopes.

1 INTRODUCTION

The origin of the large valleys of La Orotava and Güímar, in Tenerife island, has been historically one of the main unknown aspects of the canarian geology. Nowadays, the widely accepted theory is that they were originated by large landslides. Next are listed the main arguments which initially supported this theory:

1 The similar morphological features with other avalanche calderas (Navarro & Coello 1989).
2 The existence of landslide deposits, locally known as *mortal*on, which can be observed in the adits (galleries) excavated in the island (Bravo 1962, Coello 1973).
3 The identification of large deposits of mobilised and chaotic landslided materials on the see floor (Watts & Masson 1995).

More than 20 megalandslides have been described in the islands of the Canary Archipelago (Ablay & Hürliman 2000, Acosta et al. 2005, Krastel et al. 2001, Masson et al. 2002, Urgeles et al., 1998, Watts & Masson 2001). The resulting deposits, or landslided masses, on the ocean floor, cover areas of thousands of square kilometres (350-2600 km^2) and volumes of hundreds of cubic kilometres (80-650 km^3).

However, in spite of their importance and the acceptance of the occurrence of these instability processes by the scientific community, only few investigations have been carried out until now to analyse and to explain these processes under the geomechanical point of view.

The authors are carrying out a research project, supported by the Geological Survey of Spain and the Commission for Science and Technology of Spain (IGME-CICYT 2005-2007), being the main objective to explain why and how these megalandslides took place, which were the mechanisms, the influencing and triggering factors.

In this paper, mainly focussed on Güímar y La Orotava landslides, some of the main topics of this research project are presented, related to geological and volcanological features, influencing factors and stability mechanisms analysis.

2 LOCATION OF THE STUDY SITE

The Canary Archipelago is formed by seven main islands between 3000 and 4000 m high above the sea floor until the sea level. It is located 100 km to the west of the northwest african coast. During the growth of the islands, several constructive-destructive processes have been responsible for the actual geology and morphology. The volcanic activity cycles have been different and independent in each of the islands; the ancient formation outcrop, Oligocene, known as *basal complex*, is located in Fuerteventura island; the more recent first emerged volcanism is in El Hierro island (Inf. Pleistocene).

Tenerife is the largest (2058 km^2) and highest island of the Archipelago (mount El Teide, 3718 m). The ancient materials (*Old Edifices*) form the *Roque del Conde* (11.6-6.4 Ma), *Anaga* (8.05-3.2 Ma) and *Teno* (7.4-4.5 Ma) rock masses. The *Cañadas Edifice* (<3.5-0.15 Ma) and *Dorsal Edifice* (>1 Ma) were formed after. The last volcanic building, now active, is the *Teide-Pico Viejo* c*omplex* (0.15 Ma-now), (Fig. 1) (Ancochea et al., 1999).

Güímar y La Orotava valleys are located in the *Dorsal Edifice*. The chronological limits of the landslides which formed these two valleys have been established between 0.69 and 0.54 Ma, for La Orotava, and >0.84 Ma for Güímar landslide (Cantagrel et al. 1999).

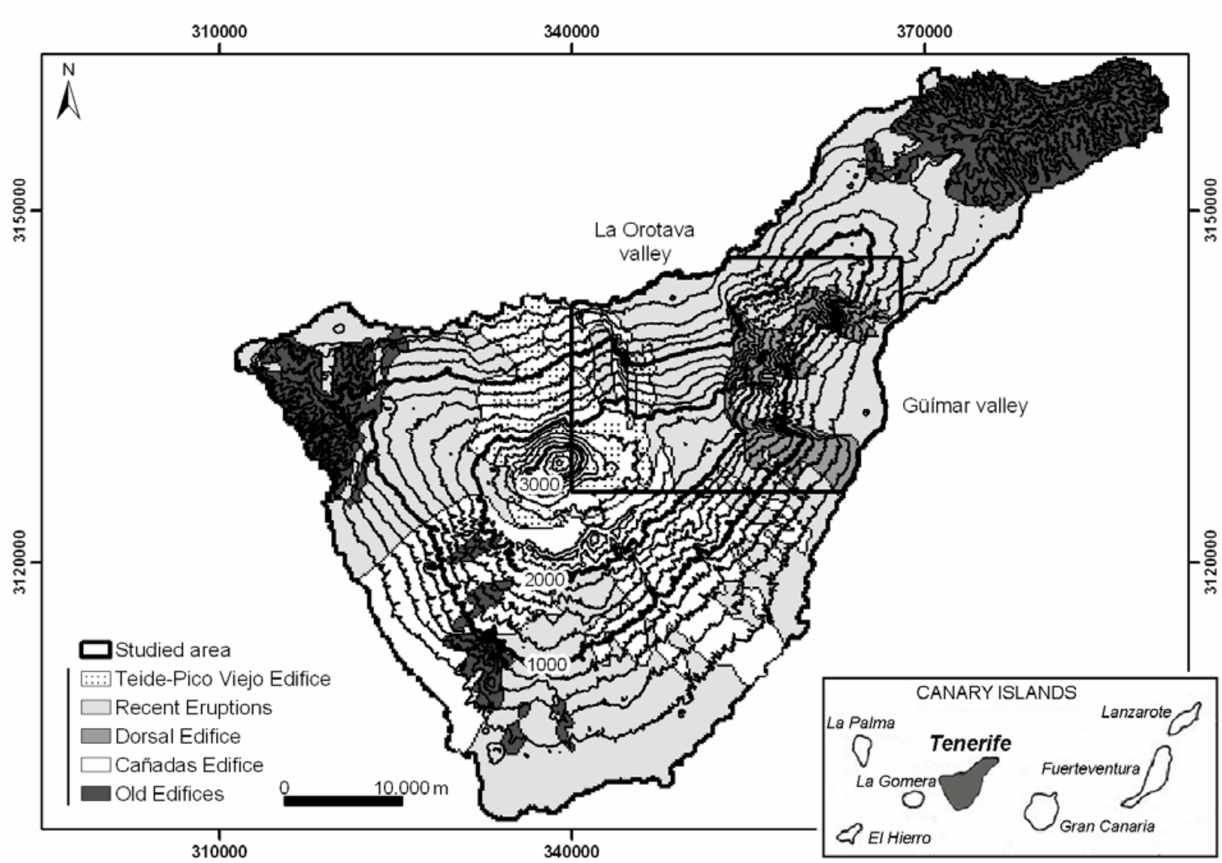

Figure 1. Simplified geological map of Tenerife Island (modified from Ancochea et al. 2004). Location of the study area.

3 OBJECTIVES

The main objective of this research is to explain why and how the Güímar y La Orotava megalandslides took place, which were the mechanisms, the influencing and triggering factors and the role they played.

For this, different aspects must be considered:

- The characteristics of the processes (morphology, geometry, depth, magnitude, velocity, extent, temporal evolution).
- Geological and geomechanical characterization of the volcanic materials affected by the landslides.
- Chronological relationships and geological evolution of the study site.
- The analysis of the landslided deposits (composition, mineralogy, strength, etc).
- The study of the conditioning and triggering fac-

tors, their characteristics and degree of influence.
- The definition of geological, hydrogeological and geomechanical representative models.
- The analysis of the processes and influencing factors (morphological, strength and deformability properties, water and magmatic pressures, dynamic loads, etc.).
- Stability analysis of the volcanic buildings.

4 METHODOLOGY

The methodology followed in the study includes:
- Bibliographic collection and analysis of the available information.
- Field work (outcrops and adits (galleries) excavated in the island).
- Analysis and processing of the data: GIS.
- Laboratory tests (identification, classification, strength).
- Mineralogical analysis (thin section, X-ray diffraction).
- Chronological determinations (Ar/Ar).
- Geomechanical modelling.
- Numerical analysis.

5 DESCRIPTION OF GÜÍMAR AND LA OROTAVA SITES

Güímar y La Orotava valleys are 9-12 km wide; they present opposite vergence, ESE and NNW respectively. The heads of the valleys are located in the *Cordillera Dorsal*, main rift zone in the island with NE direction and maximum heights between 1700 and 2200 m (Fig. 2).

The morphological characteristics of the valleys are singular, outstanding the symmetry and the important height of the lateral scarps (~500 m) (Fig. 5), formed by pre-landslide volcanic materials (Inf. Pleistocene), with slopes more than 35º. The depressions formed by the large landslides were filled by volcanic materials post-landslide (Med. and Sup. Pleistocene) with smooth slopes (<15º) (Fig. 2).

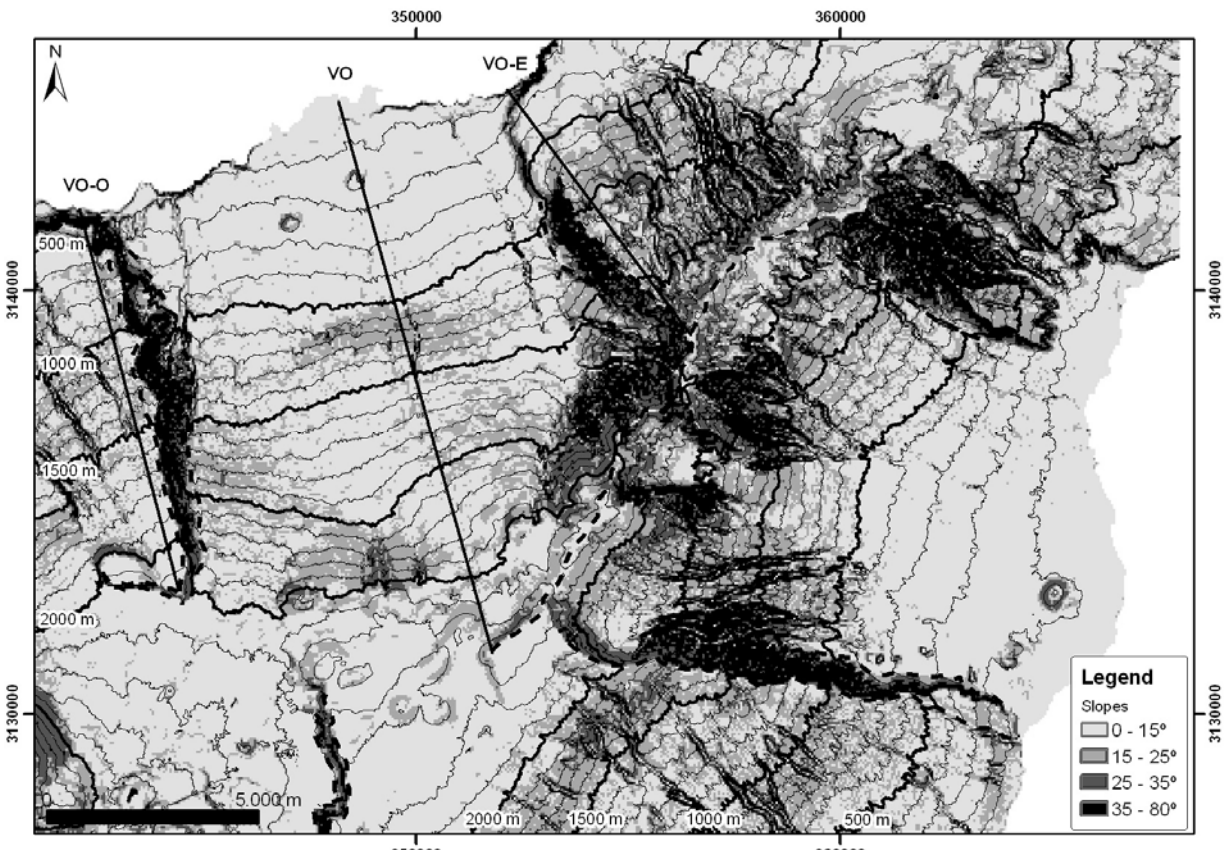

Figure 2. Slope map of Güímar (looking south-east) and La Orotava (looking north) valleys, Tenerife island. Digital terrain model.

From the analysis of bathymetric data (IEO), and the digital models of the ocean floor, submarine channels can be identified corresponding to the landslides, 6 km wide and more than 10 km long, limited by lateral scarps with 8 a 15º slopes. In the submerged area in front of Güímar valley, a large landslide deposit fan can be identified with typical hummocky morphology. The submerged landslided deposits corresponding to La Orotava cover an extent of 2200 km^2, and a length of 75 km from the coast; the extent of the submarine deposits corresponding to Güímar landslide reaches 2600 km^2, and 85 km from the coast (Acosta et al. 2005).

6 CHARACTERIZATION OF THE VOLCANIC MATERIALS INVOLVED IN THE LANDSLIDE PROCESSES

The materials involved in the landslide processes have been observed and characterized in superficial outcrops and in the interior of underground excavations (galleries) all around the island to get fresh water (Fig. 3). Next are listed the main characteristics.

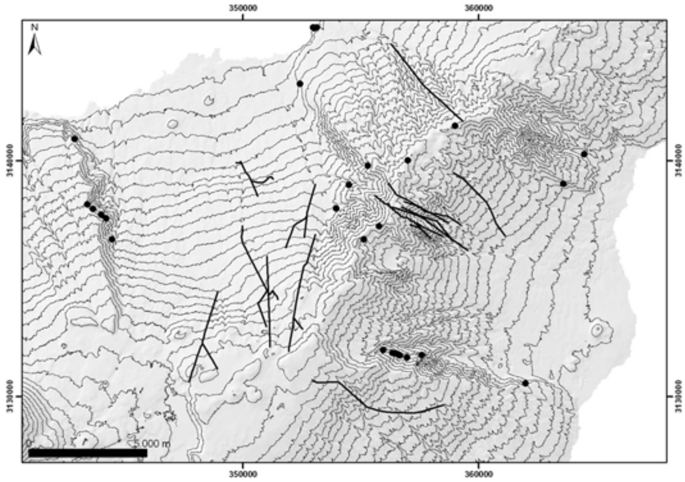

Figure 3. Location of the main outcrops and galleries for the characterization and data collection of the materials involved in the landslide processes.

6.1 *Outcrops*

The materials which were affected by the landslides can be observed in the outcrops of the lateral and head scarps and inside the galleries (once the filling materials and the *mortalón* have been passed), what has allowed the characterization of the rock masses forming the landslided slopes of the volcanic edifice.

In the lateral scarps metric successions of basaltic lavas are predominant (except in the west scarp of La Orotava landslide, where differentiated rocks are abundant). In the head the pyroclastic materials and dykes are predominant. The dykes affect to an area several km wide which corresponds to the structural axis of the volcanic building or rift zone.

Applying the RMR classification to these different rock masses it has been obtained a value between 47 y 82 (class II-III).

6.2 *Inside the galleries*

Inside the galleries excavated in the volcanic rocks it is possible to observe the pre-landslide materials, once the filling volcanic materials, and the landslided deposit known as *mortalón*, have been surpassed.

Between the materials pre and post-slide are some important differences. The former are heavily affected by dyke intrusion and open joints, both subvertical, in the zone coinciding with the structural axis; besides the jointing the hydrothermal alteration also is characteristic of this zone. It can be observed the importance of the influence of the water level in the properties of the materials.

7 THE LANDSLIDE'S DEPOSITS

The landslide deposit (the so called *mortalón*) can be observed inside the galleries. The material is formed by a sand-clayey matrix and mixed rock blocks (sized cm^3-m^3) with different mineralogical composition (Fig. 4).

Figure. 4. The so called *mortalón* inside the galleries excavated in the island.

All the data dealing with the landslide deposits collected inside the galleries (not only geological or mechanical characteristics but also the geographical coordinates where they appear) have been include in a data base and GIS, in order to prepare the corresponding digital terrain models. The depth of the post-landslide filling materials overlying the landslide's deposit has been estimated between 100 a 600 m (Fig. 5).

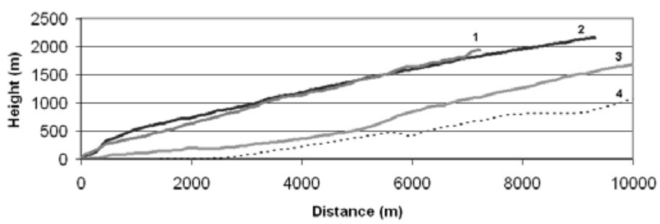

Figure. 5. Comparative profiles of La Orotava valley: (1) east scarp, VO-E; (2) west scarp, VO-W; (3) bottom of the valley, VO; y (4) top of the *morlatón* deposit, VO. The profiles are represented in Figure 2.

8 MODELS

The main influencing factors affecting the landslide processes are: morphology and slopes, lithology, geological structure, stratigraphy, hydrogeological behaviour of the materials, geomechanical properties, state of stress, weathering degree and alteration. All of them must be considered in the models prepared to develop the analysis of the stability and behaviour of the volcanic slopes.

Next are included some general aspects of the different models, which have been prepared at 1:50.000 scale.

8.1 *Geometrical model and paleo-topographycal reconstruction*

The geometrical model previous to the occurrence of the landslides has been prepared from the paleo-topographycal reconstruction and the analysis of the representative profiles of the valleys, lateral scarps and pre-landslide volcanic building.

Also, the geometry of the submerged slopes has been deduced from the analysis of the bathymetric profiles of non-slided submerged slopes of the island.

The paleo-geographycal reconstruction has been carried out from the analysis of the non-slided slopes of the volcanic building, and considering the volcanic-geological history of the area. The reconstructed volcanic building reaches 3500 m maximum and 12,5 to 20,5º slopes.

The submarine profile (representing the submerged non-slided slopes) is –2500 m depth and it is formed by different slope ranges of 19º, 7º and 3º, decreasing with the distance to the coast line.

8.2 *Hydrogeological model*

It has been prepared from the data collected by the Consejo Insular de Aguas de Tenerife (CIATFE).

The water level representing the situation before the landslides occurrence has been situated at 600 to 700 m from the surface, except in the areas near the coast line. It must be pointed out the elevation of the water level in the central area (structural axis) due to the influence of the open joints and dykes.

8.3 *Geological model*

The geological model has been prepared from the field observations and data collection (outcrops and galleries).

The submerged part of the model has been defined from bibliographical data and the study and analysis of the evolution and growth of the volcanic islands and the materials produced during the submarine stages.

In the emerged building next materials have been differentiated:

Forming the slopes:

- Lava flows predominant, above the water level.
- Lava flows predominant, under the water level.

Forming the structural axis:

- Pyroclastic materials predominant and lava flows.

On the other hand, in the submerged building it has been differentiated hyaloclastites, gravitational deposits and pillow lavas.

With respect to the dyke intrusion, three areas have been distinguished depending on the number (intensity) of dykes intruding the materials in 100 m length (measured inside the galleries):

- A: very heavy dyke intrusion, more than 10 dykes per 100 m (structural axis).
- B: heavy dyke intrusion, between 5 and 10 dykes per 100 m (upper part of the structural axis and deep parts of the slopes).
- C: less heavy dyke intrusion, less than 5 dykes per 100 m (medium-high parts of the slopes).

The materials of the geological model and the water level have been represented in Figure 6.

8.4 *Geomechanical model*

For the geomechanical model, physical and geomechanical representative properties are assigned to each of the different materials defined in the geological model, based on the field observations and geomechanical classifications of the rock masses, empirical criteria and bibliographical compilation and statistical analysis. The results obtained from these study on the geomechanical properties of volcanic rocks and rock masses has been published in the frame of this research project by González de Vallejo et al., 2006.

9 TRIGGERING FACTORS

The factors influencing the occurrence of these large landslides can be classified into non volcanic and volcanic. The main of the volcanic factors are: volcanic seismicity, explosive eruptions, dyke intrusion, hydrothermal processes, caldera collapses, tectonic movements associated to volcanic processes, etc. Each of these factors must be considered in the modelling and analysis of the landslide processes, and parametric studies must be developed in order to assign the degree of influence of the different factors on the stability of the volcano’s slopes.

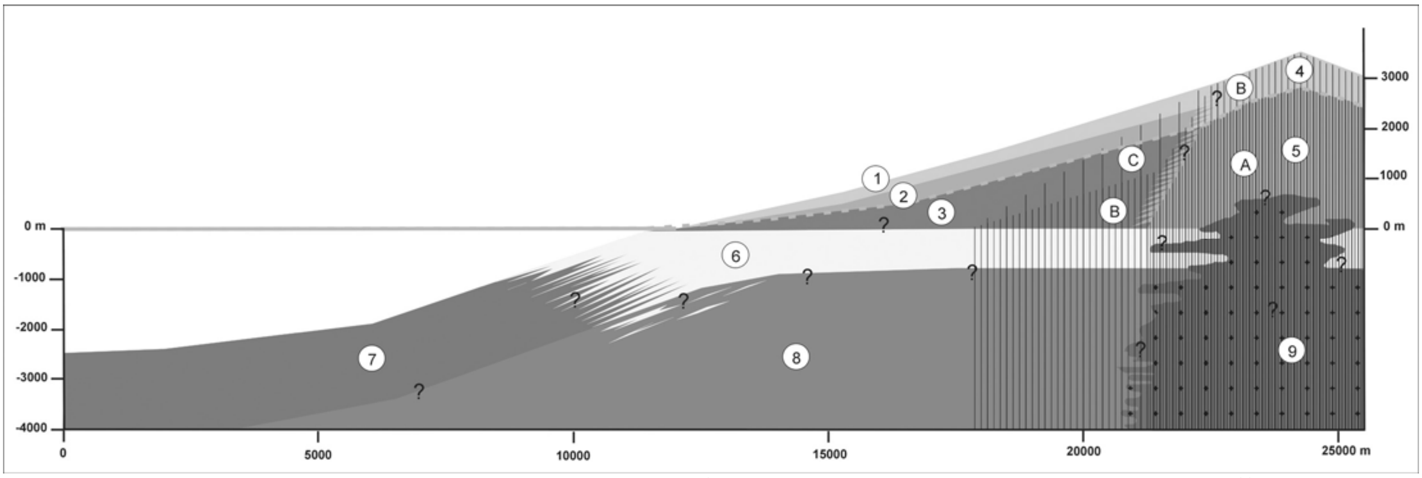

Figure 6. Geometrical, geological and hydrogeological models of the volcanic building. Numbers represent the different materials; letters represent the dyke intensity. 1, 2, 3, emerged materials forming the slopes: lava flows predominant; 4, 5, emerged materials forming the structural axis: pyroclastic materials predominant; 6, 7, 8, submerged materials: hyaloclastites, gravitational deposits and pillow lavas; 9, plutonic complex. A, B, C, areas with different dyke intrusion intensity. Dashed line: water level (? - uncertainties)

10 CONCLUSIONS

The Güímar y La Orotava valleys (Tenerife island), formed by mega-landslides, are two exceptional cases due to their outstanding morphological features and the presence of the landslided materials on the sea floor and in the interior of the galleries excavated in the island.

The U-shaped depressions formed by the landslides, now filled with post- landslide volcanic materials, are limited by high lateral and head scarps showing the pre-landslides rock masses. On the sea floor, the valleys are reflected with submarine channels and deposit fans with a typical hummocky morphology. The landslide's deposit which can be observed in the galleries is several hundred meters below the surface. It is composed of a sand-clayey matrix with heterogeneous rock blocks (size and composition).

From the field observations, data collection, analysis and desk work, the geological, geometrical and hydrogeological models have been defined, needed for the stability and mechanical analysis of the landslide processes.

The geometrical model is based on the paleogeographical reconstruction of the volcanic building, and the analysis of representative bathymetric and topographic sections of the island's slopes.

For the hydrogeological model, the water level is located at several hundreds of meters below the surface (less near the coast), with a significant elevation in the structural axis (central part of the building), because of the presence of dykes and open fractures.

In the geological model the different materials forming the emerged and submarine parts of the volcanic building have been described. Basaltic lava flows predominate in the emerged slopes, and pyroclastic materials predominate in the central axis of the building. The presence of water and hydrothermal processes affects to the properties of the materials. Also the dyke's intrusion intensity has been considered in the geological model. The submerged part of the building is mainly formed by pillow-lavas, hyaloclastites and gravitational deposits.

In the geomechanical model, representative physical and mechanical properties are assigned to the different materials.

The application of numerical analysis will allow the modelling and the study of the landslide processes, as well as the study of the different factors influencing the behaviour and stability of the volcanic rock masses forming the slopes, and will allow to explain the mechanisms and causes of the mega-landslides in Tenerife.

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