ISLAND SHELF AND SLOPE GEOMORPHOLOGY OF LA PALMA ISLAND (SOUTHERN SECTOR)

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Island shelf and slope geomorphology of La Palma island (southern sector).

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TABLE OF CONTENTS

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Abstract

The studies of submarine geomorphology have had an important boom with the development of multibeam bathymetric echosounders and the construction of digital terrain models from these data. Geographic Information Systems are very useful techniques in these studies due to using different spatial analysis tools on bathymetry data allows recognize different morphological elements and units. In the present work, the geomorphology of the insular shelf and the slope of the southern sector of La Palma island is explained. In the study area several structures are recognized, such as volcanic cones, flat-topped cones, lava flows, different types of sediment deposits, scarps, landslide scars, valleys and the insular shelf itself, among others. The study of the morphology of these elements have allowed to establish relationships with the processes that have taken place for their formation and their evolution observing, for example, that the scars are related to processes of mass movement by action of gravity, being this a erosive process, while volcanic cones are the result of magmatic activity. These types of relationships are established for all the morphological elements characterized. In addition, there are two regions with lava flows, which could have come from eruptions that have taken place on land and have spread to the sea.

Resumen

Los estudios de geomorfología submarina han tenido un importante auge con el desarrollo de las ecosondas batimétricas multihaz y la construcción, a partir de estos datos, de modelos digitales de terreno. Los Sistemas de Información Geográfica son herramientas muy útiles en el estudio de la geomorfología submarina ya que mediante el uso de las diferentes técnicas de análisis espacial que proporcionan estos programas aplicados sobre los datos de batimetría podemos reconocer diferentes elementos y unidades morfológicas. En el presente trabajo se explica la geomorfología de la plataforma insular y del talud del sector sur de la isla de La Palma. En el área de estudio se reconocen diversas estructuras tales como conos volcánicos, conos volcánicos erosionados o de techo plano, flujos de lava, diferentes tipos de depósitos de sedimento, escarpes, cicatrices de deslizamiento, valles y la propia plataforma insular, entre otros. El estudio de la morfología de estos elementos ha permitido establecer relaciones con los procesos que han tenido lugar para su formación y su evolución observándose, por ejemplo, que las cicatrices están relacionadas con procesos de movimiento de masas por acción de la gravedad, siendo esto un proceso erosivo, mientras que los conos volcánicos son resultado de la actividad magmática. Este tipo de relaciones se establecen para todos los elementos morfológicos caracterizados. Además, se observan dos regiones con flujos de lava, que podrían proceder de erupciones que han tenido lugar en tierra y se han propagado hacia el mar.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. Introduction

The geomorphology is the study of the Earth's surface landforms, and the analyse of the genetic processes that shaped them in the past and their behaviour in the present. There are different submarine environments (for example shelf or slope), characterized by several morphological features, differentiated by its geometry, positive or negative relief and surface gradient, between other morphological parameters, that could be generated by different geological processes, between them the main are tectonics, volcanism and sedimentary dynamics, both erosive and depositional features related to processes as bottom currents, waves and mass transport.

The main aim of the present work is the geomorphological study of the submarine environments corresponding to the insular shelf and slope of a volcanic island, the south sector of the volcanic island of La Palma at the Canarian archipelago (Fig. 1). This study requires the identification of the geomorphological elements and units present in these submarine environments and their relationship with the dominant geological processes in the area.

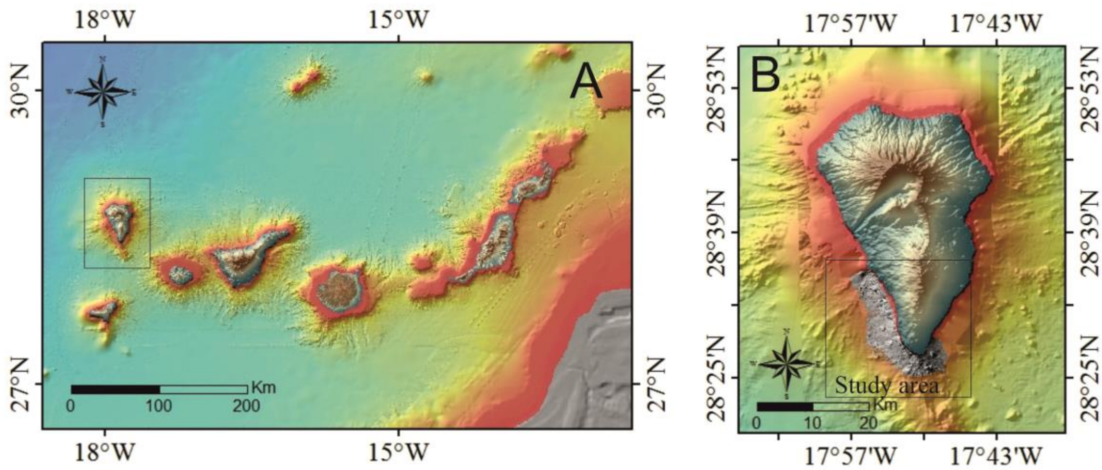

Fig. 1. A) The Canary archipelago with La Palma marked. B) Map of La Palma with the study area.

La Palma Island is located in the Canary archipelago. The morphological evolution of volcanic hotspot islands is in relation to the mechanisms that act in them and how they vary, the balance between constructive and destructive processes (Ramalho et al., 2013). Characterize the morphological features in the study area allows us to know the different types of processes have taken placed and, by this way, understand the possible evolution and development of the island (Schmincke, 2004; Quartau et al., 2014). To perform the mapping of the geomorphological units we have worked with multibeam bathymetric data and information derived from them, and we have carried out it in two different ways, qualitative or handmade and automatic. Therefore, another objective of the study is to make a comparison between both types of cartography and establish their differences or complementarity.

1.1 Geographical and geological setting

The Canary Islands is an archipelago located on the African plate, forming part of the Macaronesia region, east-central Atlantic Ocean. The Canary archipelago is built on oceanic lithosphere of Jurassic age and its formation and evolution are controversial. Several theories have been proposed to explain their genesis, but the main argument accepted is an asthenospheric plume (Carracedo et al., 1998; 2002). The progressive counterclockwise rotation of the African plate to the NE over the hotspot area is the reason why there are different large volcanic buildings forming islands and their chronological evolution decreasing in age towards the southwest (Holik et al., 1991; Carracedo et al., 1998, 2002; Schminke & Sumita, 2010). In addition, due to these age differences, the islands are in different stages of development (Carracedo et al., 1998, 2001, 2002).

The islands geomorphology depends on their stage of evolution, for example the oldest islands are characterized by erosive reliefs and by great developed insular shelves while the youngest islands are in the shield stage of evolution, which is characterized by underdeveloped islands shelves, fast volcanic growing, formation of great landslides and steep relief (Carracedo et al., 1998, 2001, 2002). The stage of evolution of La Palma is the shield stage. The main features present on the island are steep slopes, vertical cliffs, depressions and wide ravines. The Caldera de Taburiente, for example, is one of the major depression on the island, which was formed by lateral collapses (Carracedo et al., 2001; Carracedo & Troll 2016). The ravines or gullies are significant due to the high erosion rate of the island.

The magmas are predominantly basanites (Klügel et al., 1999; Carracedo et al., 2001), although in more than one eruption evolved magmas (phonolites) were involved (Hernández-Pacheco et al., 1983), as cryptodomes that were pushed, as plugs, almost solid, to the surface (Jedey eruption, 1585) or in small quantities as pyroclastic material, founded as cores in basaltic ballistic ejecta (Araña & Ibarrola, 1973).

La Palma Island is the most volcanically active island of the Canary Islands in historical times (Carracedo et al., 2001). The recent volcanic activity on the island is concentrated in the south, an area known as Cumbre Vieja volcano (Guillou et al., 1998; Carracedo et al., 1999; Klügel et al., 2000; Klügel, 2001; Guillou et al., 2001; Galipp et al., 2006). Cumbre Vieja area is characterized by fissural type volcanism and the activity is concentrated along the longer axis of the edifice (N-S), generating a rift zones (Annexe A). The most common eruptive products are lava flows, cinder cones and lapilli fields corresponding to strombolians or phreato-strombolians eruptions, interacting with sea or subsurface water reservoirs. A characteristic for the volcanic eruptions in Cumbre Vieja area, and the rest of the Canary Islands, is to build up a cone where most of the gas and pyroclastic material is ejected during a predominantly explosive phase. Later, in a lower topographic level, a new fissure will give the lava flows that will go downhill generating lava deltas and extensive coastal platforms (Klügel et al., 1999; Carracedo et al., 2001).

The last eruptive events of La Palma are from the 20th century, 1949 and 1971. The location of the 1949 event was the summit and the western flank of the island and lasted 38 days (Carracedo et al., 2001; Carracedo & Troll, 2016). The event took place at three different eruption points open in different phases along a 2 km line (Klügel et al., 1999). The lowest point, Llano del Blanco, discharged large volumes of very fluid lavas that formed a coastal platform (Carracedo et al., 2001). The eruption of 1971 was in the Teneguia Volcano, situated at the south end of the island. The event began as an eruptive fissure, which later made a group of cinder cones. It duration was 25 days long and also created a coastal platform, over another already formed in that place in a previous volcanic event (Afonso et al., 1974; Carracedo et al., 2001).

During the 1949 eruption, a superficial fracture system was developed along the crest of the volcano, between two of the eruption centres. It has been interpreted as the first surface rupture along a developing zone of deformation that could lead to a giant collapse of the west part of the island (Day et al. 1999; Ward & Day, 2001; Løvholt et al. 2008). Recently, Gonzalez et. al (2010) using RADAR images from ERS1/2 and Envisat satellites, determined the geometry and slip for a near-horizontal dislocation beneath the western flank of Cumbre Vieja, and suggested a sub-horizontal fault system at 2-3 km depth and an annual creep rate of 12 mm.

The study area is on the southern submarine area of La Palma island, which is one of the most occidentals of the archipelago, the fifth in extension and the second in height.

The basal perimeter is 120km in diameter and the depth around is approximately 4000 m. The study area is, concretely, the insular shelf and slope of the south and southwest sectors of the island, located between [28º-24´ – 28º36´] N latitude and [17º57´ – 17º47´] W longitude (see fig. 1). The bathymetric data shows significant features around it, in relation to the different constructional and destructive processes that could have occurred (Masson et al., 2002).The study area corresponds to the sector of the island where the most recent volcanic eruptions of the last century have occurred.

2. Submarine geomorphology of volcanic islands: State of the Art

The oceanic volcanic islands are highly dynamic systems, which are influenced by genetic and evolutive processes. The morphological evolution of hotspot island systems have certain similarities between them, however, it can differ from the local geodynamic and geology (Menard, 1986; Schmincke, 2004; Ramalho 2011; Carracedo & Troll, 2016).

Nowadays there is not enough information about the development and evolution of island shelves. Island shelves are developed from coastal platforms as a result of wave erosion and sea level changes, include glacial-interglacial cycles, and their amplitude and depth are also controlled by these mechanism (Menard, 1983, 1986; Llanes et al., 2009; Quartau et al., 2010; Ramalho et al., 2013; Romagnoli, 2013). The width of the shelf is influenced by enlarging and fill processes (Menard, 1983, 1986). The shelves in which enlargement processes predominate, such as the erosion of the waves, have a greater shelf width, while those that dominate the filling processes, volcanic events for example, are narrower (Quartau et al., 2010, 2012, 2014, 2015). In addition, there is a relation between the shelf wide and the shelf age when the wave erosion is dominant (Menard, 1983; Llanes et al., 2009; Quartau et al., 2010; Romagnoli, 2013).

The morphology of the Faial Island shelf, Azores, was studied by Quartau et. al (2012) and these authors conclude that the wave erosion is the main modelling process and, therefore, responsible for its width. Generally, the wider Azores shelves are dominated by wave erosion and have abraded surfaces (Casalbore et al., 2015). Nevertheless, the shelf of Faial and Pico islands (Azores) show that exist an important role of volcanic progradation. When an insular shelf has been formed before the last glacial maximum and currently the progradation is dominant, it is called rejuvenated shelf (Quartau et al., 2015).

The break in the edge of the insular shelf is where the slope begins. The island slope is characterized by an increasing angle of inclination and by developing gullies and canyons networks that work as the transference channels of sediments (Porter-Smith et al., 2012). Submarine gullies are small valleys often found within or next to canyons and may represent an incipient stage of development (Micallef et al., 2017).

Beyond the steep part of the slope, many different morphological units can be found and the distribution and shape of those units give important information about the formation processes and the interaction between them, related to active volcanic or tectonic processes, or to sedimentary processes partially controlled by the different gradient of slope. In this sense, linear eruptive centres, singled or complex volcanic cones, flat-topped cones, irregular and longitudinal scarps, landslide scars and landslide deposits can be found, among other structures, in the low slope.

- Linear eruptive centres are elongated structures along the tectonic trend (Casalbore et al., 2015).
- Volcanic cones are positive features presents in the study area forming by volcanic activity.
- Flat-topped cones mean eroded volcanic cones.
- Scarps are geomorphological elements defined as the break in the relief and act displacing seafloor.
- Landslide scars are structures caused by landslides that are defined as the breaking surface they leave with steep slopes and in the direction of collapse.

Differences in size and shape between the same type of structures reveal distinct types of formation and, in addition, there is a change in the sort of volcanic edifice with the depth (Casalbore et al., 2015).

3. Data and methods

3.1 Datasets used

3.1.1 General data

The European Marine Observation and Data Network, EMODnet, is a European network that includes several organisations working together to observe, acquire and process data. The information is public and of free access as data products or data layers. The general bathymetric data in this work was obtained from the database EMODnet Bathymetry where the “Instituto Español de Oceanografía” (IEO) has the coordinator function in Spain. In addition, data from the ZEE project (economic exclusive zone) are also used as support by means of a cooperation agreement between the "Instituto Hidrográfico de la Marina" and the IEO.

3.1.2 Southern La Palma data

The data analysed in this work were obtained in two oceanographic cruises, VULCANA 1015 and VULCANA 0318, aboard the B/O Ángeles Alvariño by a team constituted by researchers of the Oceanographic Centres of Canarias, Cadiz and Malaga, in 2015 and 2018 respectively. The data were acquired by multibeam echosounder of high resolution (EM710) and the data process was done with CARISHIPS & SIPS software. Data studied have a 10x10 m resolution grid and the depth ranges from -17 m to -1948 m.

3.2 Use of Geographic Information Systems in Geomorphology

Geographic Information Systems (GIS) applications in the marine environment are suitable for all areas of oceanography. Cartography tools are very important because they can show the spatial distribution of a data set. The visualization of the temporal distribution of them provides knowledge of the nature of the data set that can reveal characteristics of special interest (Valavanis, 2002).The geomorphology of the study area was interpreted by GIS analysis. Multibeam data, after been corrected, were analysed by ArcGis Desktop 10.6.1 software using morphometric functions. The objective of these functions was the differentiation and characterization of the different morphologic elements. The multibeam data were extracted from the digital terrain model (DTM) which is a lifting surface that represents the bare earth referenced to a common vertical datum.

3.2.1 Application of morphographic techniques on bathymetric data

The qualitative or handmade geomorphological study and cartography were supported mainly by the Spatial Analysis Tools of ArcGis and the derivation of several maps from DTM database as follow (Fig. 2):

- Slope gradient is the first derivate of the DTM and identifies the steepness from each cell. It is calculated in degrees (Fig. 2A).
- Curvature functions. The curvature is the second derivate of the DTM and is the change in the slope. There are two optional output types, the profile curvature and the plan curvature. The profile curvature means the direction of the slope

(Fig. 2B) while the plan curvature is the curvature perpendicular to the slope direction.

- Aspect indicates the downslope direction for each cell to its neighbours, that is, the orientation (Fig. 2C).
- Contour creates lines that connect locations of equal value of elevation (Fig. 2D).
- Hydrology functions are used to know the drainage systems. The hydrology function used is the Flow Accumulation (Fig. 2E); which indicates where channels are.

The Analysis tools explained help us to identify geomorphological structures. Slope is useful to observe the landslides and scarps, the curvature functions also help in the observation of scarps, aspect is good to observe the different orientations of the sides of the canyons and the hydrology functions in submarine environments show the areas of zero accumulation, which are the ridges.

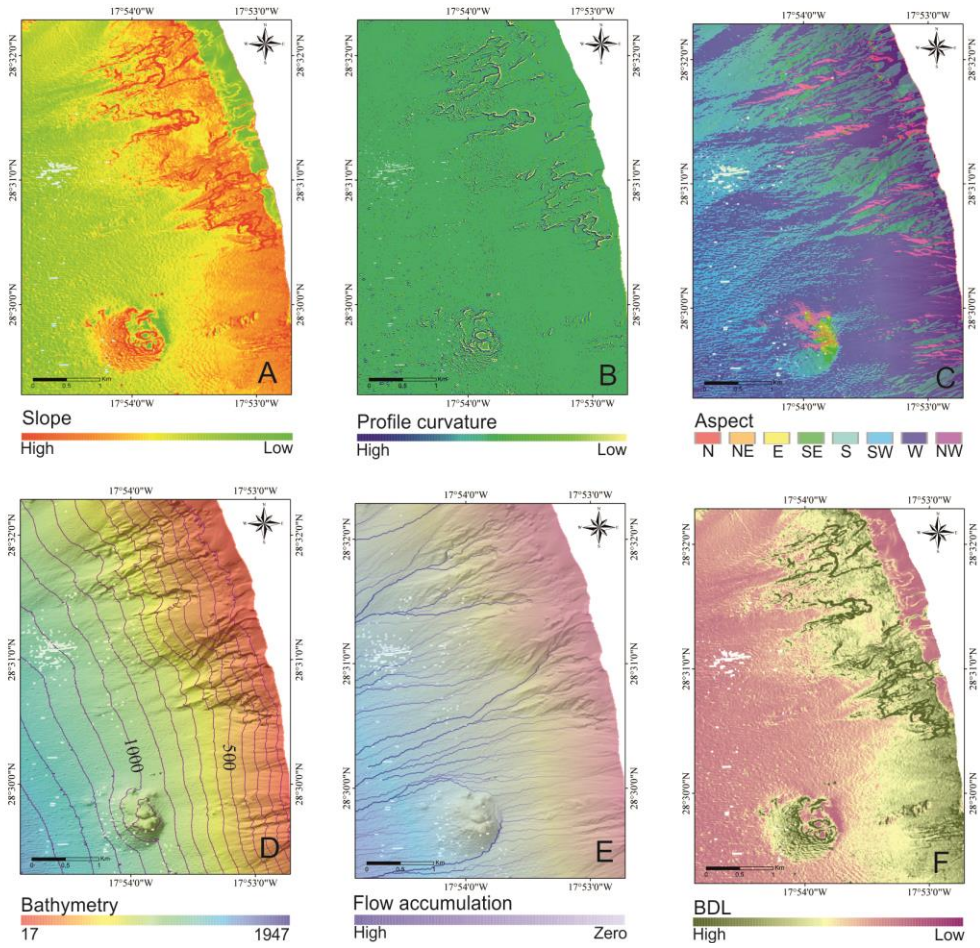

Fig. 2 Comparison of analysis methods applied; A) Slope; B) Profile Curvature; C) Aspect; D) Bathymetry (countours every 100 m); E) Flow accumulation and F) Boundary Delimitation Layer (BDL).

We use the combination of the slope and the curvature of the profile to make a delimitation of the boundaries of the building (Fig. 2F), with the aim of correctly define the size of each one. Grosse et. al (2012) define this equation as:

$$\text{Boundary Delimitation Layer (BDL)} = \text{Profile curvature}_{norm} * f + \text{Slope}_{norm} * (1-f)$$

Where f is a factor from 0 to 1 and

$$\text{Profile curvature}_{norm} = (\text{Profile curvature}_{n} - \text{Profile curvature}_{min}) / \text{Profile curvature}_{range}$$

$$\text{Slope}_{norm} = (\text{Slope}_{n} - \text{Slope}_{min})^2 / (\text{Slope}_{range})^2$$

3.2.2. Realization of morphometric techniques on bathymetric data

Morphometric parameters were determined for the distinct geomorphological units and elements. The variables measured by ArcGIS Analysis Tools were the Perimeter (P), Area (A) and Length (L), which were calculated directly; Height (H), which was measured as the difference between north and south; Slope (S), which as it can see before is the first derivate from the DTM; and Azimuth (Az), that indicates the orientation of the element. The combination of used variables offers valuable information about the size and shape of the geomorphological units and help to establish the genetic processes.

3.3 Qualitative or Handmade mapping

GIS analysis through morphometric functions gives us enough information about the morphologic elements present in the study area. Classical cartography is obtained when these characteristics are identified, that is, the qualitative cartography shows a relation of the different structures that have been found from the layers worked in ArcGIS.

3.4 Automatic mapping

Through applications make to GIS another series of functions, normally unavailable inside the normal software, can be done. This work uses the Benthic Terrain Modeler (BTM) application (https://coast.noaa.gov/digitalcoast/tools/btm.html).

The BTM program allows analysing the benthic terrain with the aim to make a classification about the features in the seabed, and to that there are processes series that must be done. These processes are the Bathymetric Position Index (BPI), the Classify Benthic Terrain, build a zone dictionary and calculate the slope. In addition, Terrain Ruggedness are also calculated with BTM to the study area.

BPI is a derivate of the bathymetry and is used to define specific characteristics, basically this index allows to differentiate changes in the slope about the relation between concavity and convexity of the terrain. BPI has two functions, broad-scale BPI (used to define larger regions) and fine-scale BPI (used to define smaller features), and both of them are employed in this file. The standardize BPI are also needed.

Classify Benthic Terrain creates a classification of the structures using the BPI, bathymetry, slope and standard deviations. In addition, this tool needs a dictionary to translate de data into regions. The dictionary is specific for each region in the ocean, and it was necessary to make one to our present study area. First, a general survey was made and the regions that wanted to be obtained were established, also using the results of the qualitative mapping. When the regions were determined, it was played with both types of BPI (standardized), slopes and depths, to generated the regionals limits (Annexe B). The result is a layer with the main morphological terrain units and its correlation with benthic data will allow the habitat benthic mapping.

Terrain Ruggedness calculates the rugosity, it means, the terrain heterogeneity and it is related directly to the slope (Wallbridge 2018). This tool is useful to identify areas with high biodiversity. Low values of rugosity mean low slopes.

4. Results

4.1 Elements and geomorphological units in a classical cartography

Different structures can be found in the study area, identified in this work as elements or geomorphological units (Fig. 3).

Within each section, the elements are numbered from the north of the study area to the south. The classification is done only by the bathymetric data; there are not sediment cores, samples or seismic data.

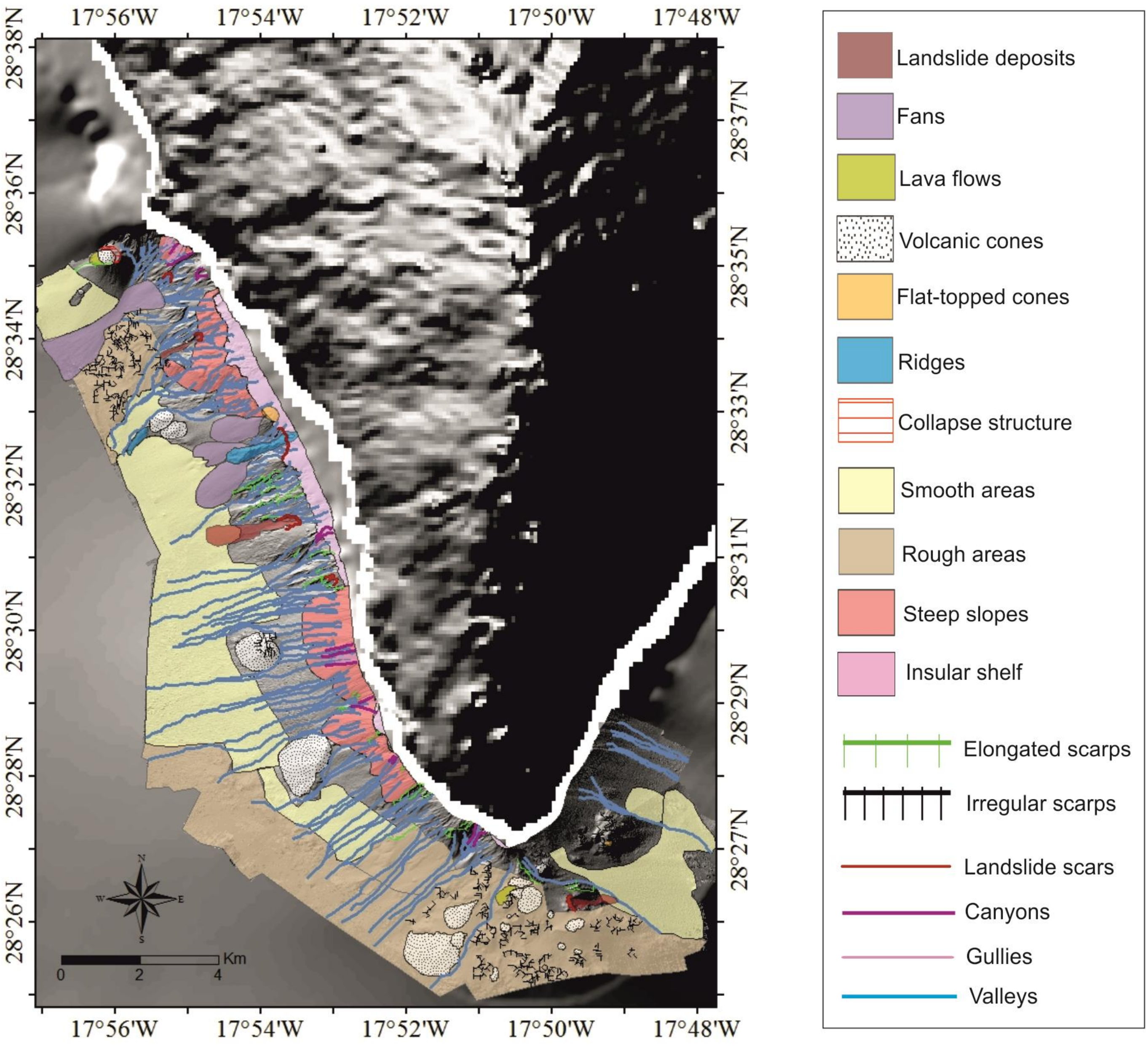

Figure 3. Qualitative or Handmade geomorphological mapping.

Landslide scars

Structures caused by landslides. There are 7 in the study area and all of them are located on the insular slope. Sometimes, these elements have sediment depositional bodies related (Fig. 4A). These types of scars have very varied lengths and reliefs, and steep slopes (Table I). They are found in the steep area within the insular slope, mainly in the west flank but also there is one in the southern spur.

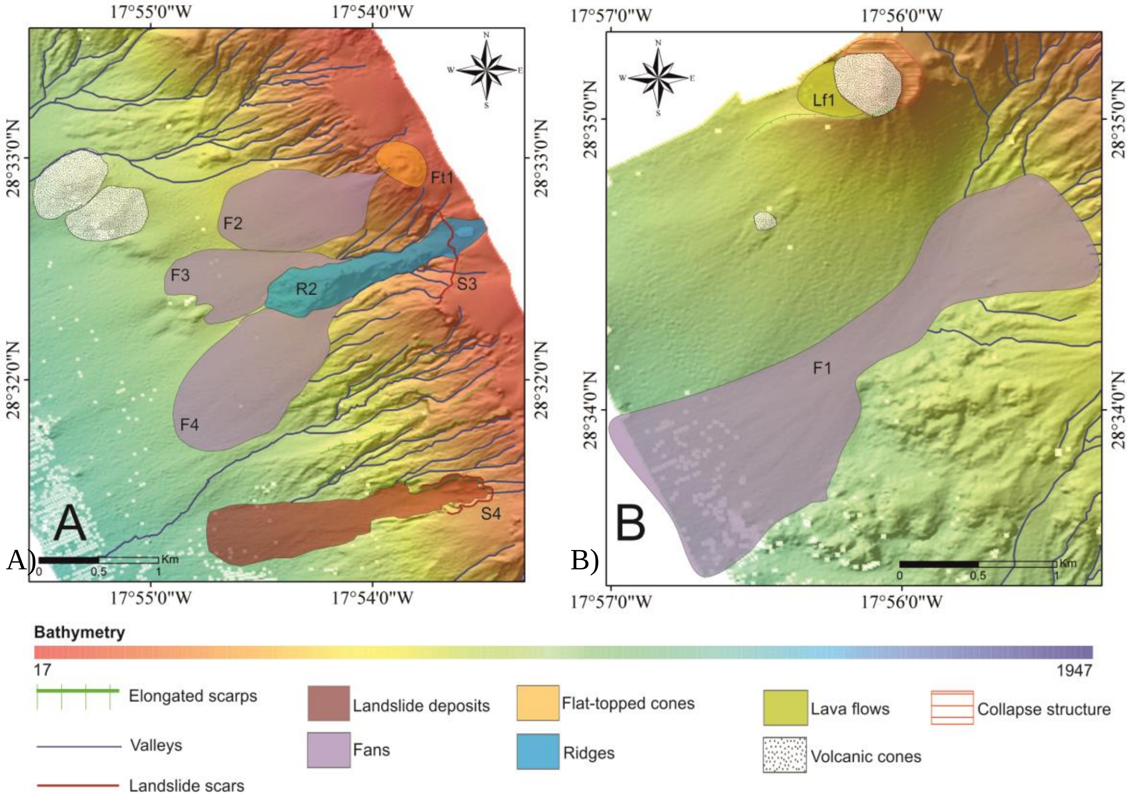

Figure 4. Examples of geomorphological elements presents in the study area. A) Landslide scar S4 with its sedimentary deposit, L2, which represents the major structure inside the landslide scars in terms of length. Ridge 2 and fans associated. Flat-topped cone, FT1, located in the insular shelf and the deposit generated. Valleys are also visible. B) North of the study area where a huge fan, F1, a volcanic cone with three other structures in relation (lava flow deposit, collapse structure and scarp) and a single volcanic cone can be seen. Valleys are visible.

The third one, S3, has other structures grow in him, for this reason is not possible calculate the real slope and the real height of the element.

Table I. Morphometric parameters of landslide scars and their association or not with deposits.

	Length (m)	Slope (º)	Relief (m)	Associated deposit
S1	535.53	55	36	✗
S2	455.36	53	52	✓
S3	860.05	-	-	✗
S4	1151.85	65	58	✓
S5	421.79	51	32	✗
S6	399.83	61	68	✗
S7	646.71	67	122	✓

Scarps

Scarps are defined as the break in steep slopes. In the study area there are many of them with different shapes but all located on the insular slope. In the present work their shape, having then elongated scarps and others more irregulars that are associated with terraced areas (Fig. 5), differentiates them.

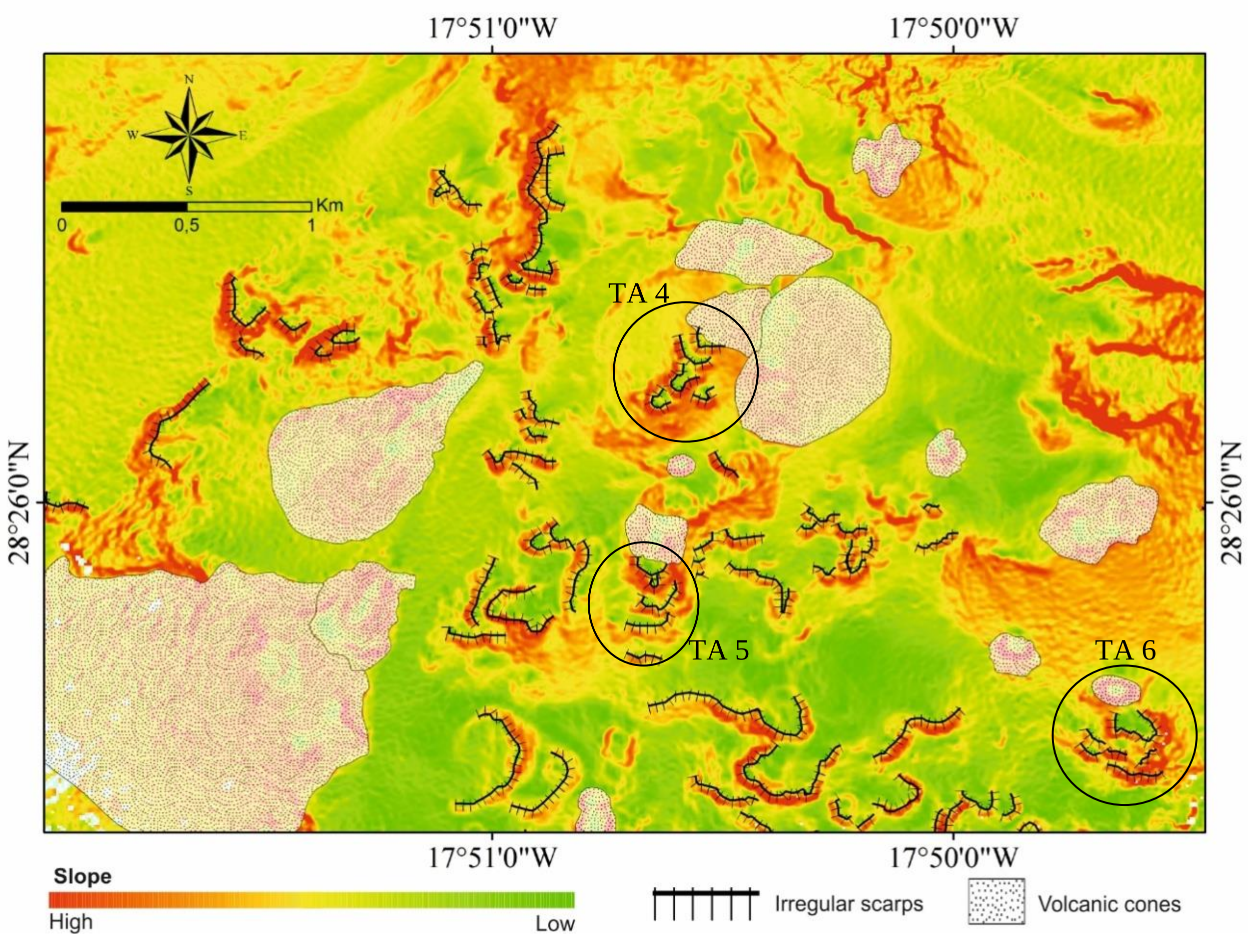

Figure 5. Irregular scarps present in the south of the study area. The irregular scarps are in relation with terrace areas, identified in the image as green areas next to the scarps. The terrace areas can be related also with volcanic cones (groups 4, 5 and 6), it can be seen in the figure too.

- Elongated scarps: these kinds of scarps are in the steepest area inside the insular slope. In the work, only those that have been considered major due to their great slope have been marked. In the study area there are 41 elongated scarps.
- Irregular scarps: they can be found in the lower part of the insular slope and mainly in two differentiated zones, one of them in the north and the other in the south of the study area. There are 214 scarps of this type and have not a specific shape and they constitute a distinct group because they are associated with terraces areas.

The morphometric parameters (Fig. 6) were obtained for all of the scarps but they are diverse, for this reason and with the objective to study if there is or not a trend, the results were treated in XY scatter plots (Fig. 6A, 6B and 6C).

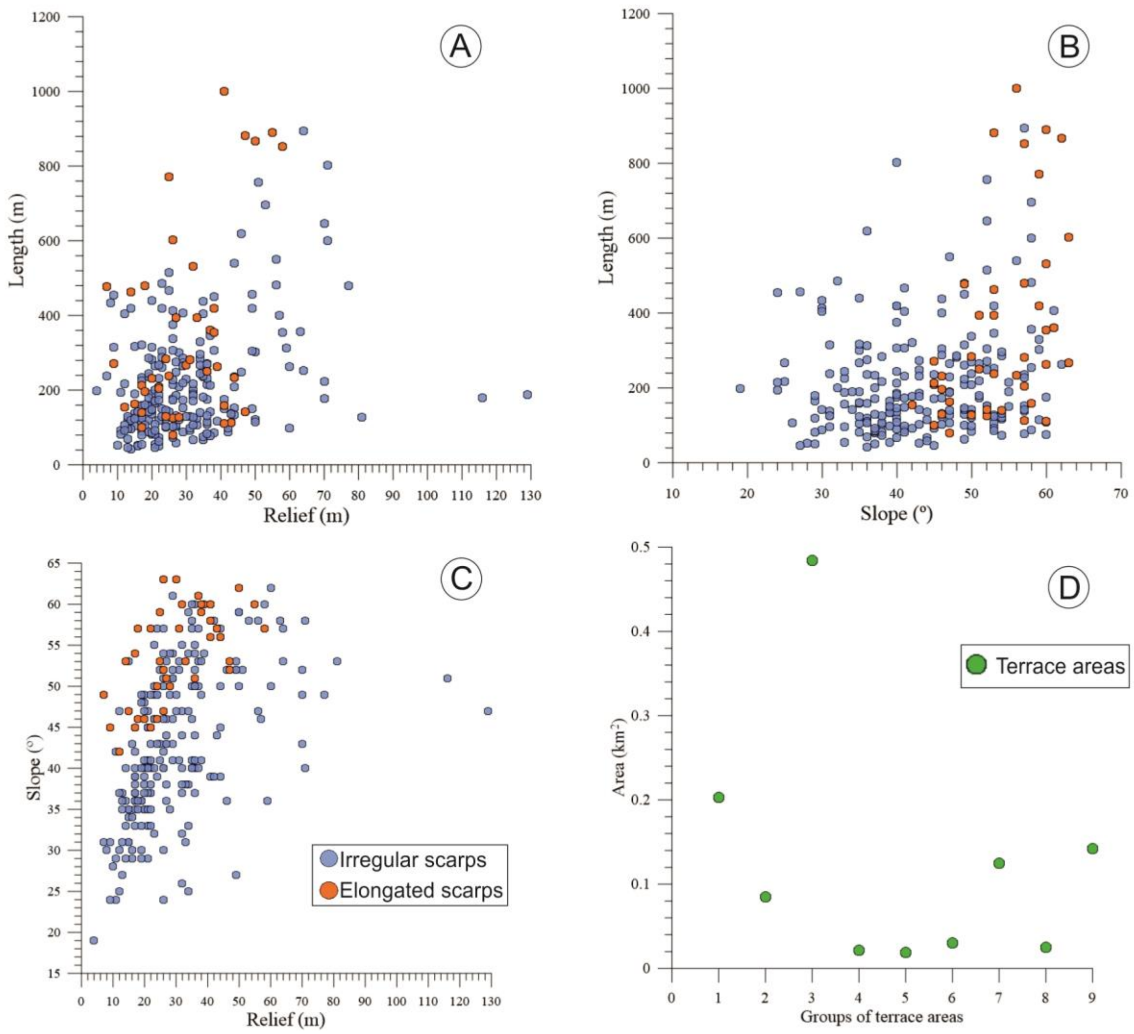

Figure 6. XY scatter plots of the variables for all the scarps present and the areas of the terrace regions. A) Relief (X) vs. Length (Y); B) Slope (X) vs. Length (Y); C) Relief (X) vs. Slope (Y); D) Groups of terrace areas (X) vs. Area (Y).

The length vs. relief distribution is similar to both types of scarps and shows a correlation between these variables, when the length increases also does the relief (Fig. 6A). The majority of the scarps are shorter than 520 m and the reliefs are lower than 50 m. The figure 6B shows the correlation between length and slope and it is easy observe that both types of scarps have also a similar distribution, where the elongated scarps tend to have higher slopes (>40º). However, there is not a relationship between the two variables observed. The lengths are lower than 320 m in the most cases. In the other hand, there is a correlation in the slope vs. relief distribution, the graphic C show than when reliefs grow also the slopes do (Fig. 6C). This correlation is for both types of scarps.

Terrace areas

Associated to irregular scarps there are regions with low slope, almost flat, defined as terrace areas. They are divided in 9 different groups, from the north of the study area to the south, differenced when they are in regions of lava flows or around a specific volcanic building. The values of the areas of each group are shown in Fig. 6D. Some of these units can be observed in Fig. 5 as green areas next to the scarps.

Groups 4, 5 and 6 are related to a volcanic cone (TA4, TA5 and TA6 in Fig. 5). The others scarps presents in the Fig. 5 are the group 3, lava flow region. The largest areas of terraces are those related to lava flows (Fig. 6D).

Ridges

Ridges are defined as elongated elevations of the seabed that constitute independent geomorphological units, which have their own characteristics. In the study area there are two main ones located in the insular slope (Fig. 4A).

The first one is apparently alone, no association with a cone or a volcanic structure has been observed and it has a delayed continuation. The second, (R2 in Fig. 4A), is the largest (Table II) and is located on the steep part of the insular slope. In addition, it has two associated deposits (F3 and F4 of the Fig. 4A) to this ridge.

Table II. Ridges morphometric parameters.

	Perimeter (m)	**Area (m^2)**	**Slope (º)**	**Relief (m)**
R1	1776.15	114250.48	42	33
R2	4004.17	447132.07	67	124

Depositional bodies

In the study area there are different volcano-sedimentary deposits, all of them in the insular slope (Table III). Dependent of the type of process that gives rise to the deposit, different characteristics are formed, therefore, by studying these characteristics, the conditions that have been given for their formation can be induced. In this work the types deposits (Fig. 4A and 4B) are differentiated in those which are associated to landslides scars; lava flows in relation with volcanic edifices; and fans, particularly a huge one in the north of the study area, F1 (Fig. 4B). The classification is done only by the bathymetric data, in this way, there are not enough evidences to determinate the sedimentary or geological medium of the fans.

Table III. Morphometric parameters of the different types of deposits.

		Perimeter (km)	Area (km^2)
Landslides deposits	**L1**	2.32	0.10
	L2	4.98	0.67
	L3	2.50	0.19
Fans	**F1**	8.02	1.90
	F2	3.31	0.62
	F3	3.54	0.42
	F4	4.12	0.89
Lava flows	**LF1**	1.14	0.06
	LF2	1.54	0.11

Textural patterns

Within the study area, we wanted to differentiate three zones in relation to their morphological texture, these are areas with steep slopes, rough areas and smooth areas (Fig. 7). The first one belongs to large areas in which the slope was a common feature observed in the layer. The rough areas are related to regions with mediums slopes and where the surface is rugged. The smooth ones are zones with slopes lower than 25º, without great slope changes, homogeneous and continuous bathymetric pattern.

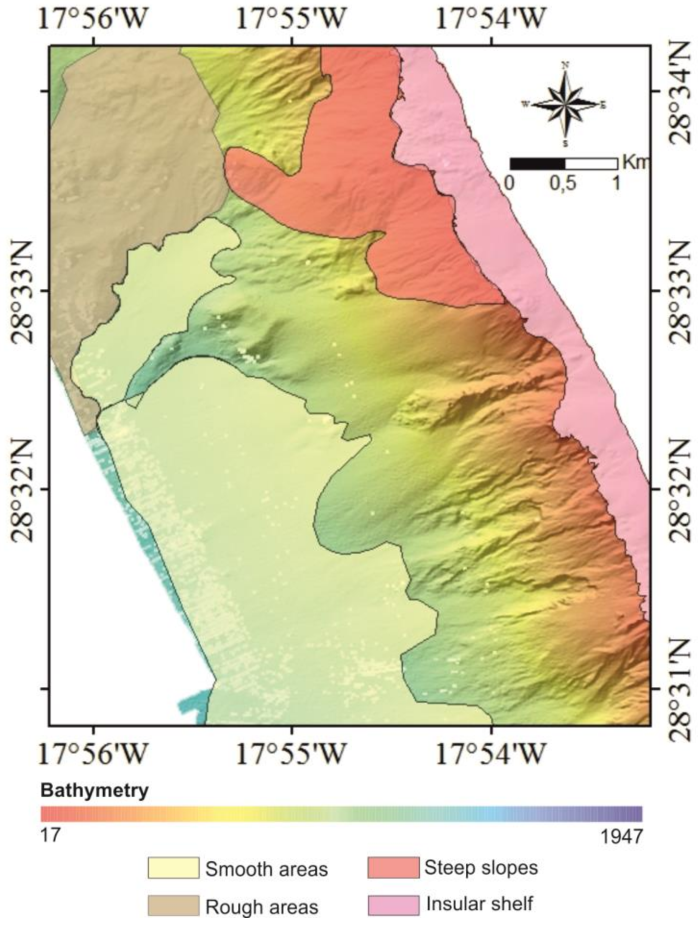

Figure 7. Examples of morphological texture patterns present in the study area and the main part of the continental shelf (pink). The yellow ones are smooth zones, brown are the rough areas and the red are areas with steep slopes.

Canyons and gullies

Canyons are great channels for sedimentary transport, while gullies are a primitive stage of development of the canyons. Both geomorphologic elements are present in the steep part of the insular slope. The study area has a high number of these structures and sometimes their differentiation is not easy. In this way, in the present work we have marked all of the valleys observed but only a few ridges of the canyons and gullies, the main ones. The morphometric parameters for the main canyons are explained in Table IV. The parameters are intervals due to they refer to the two slopes of the canyon.

Table IV. Morphometric parameters of submarine canyons.

	Slope (º)	Relief (m)		Slope (º)	Relief (m)
C1	18 – 35	20.02-91.05	**C5**	25 – 37	25.97-41.86
C2	24 – 31	22.48-48.80	**C6**	23 – 35	78.06-88.23
C3	21 – 33	9.67-10.45	**C7**	27 – 37	13.39-24.77
C4	26 – 37	19.86-30.49	**C8**	15 – 28	14.67-24.38

Valleys

In the case of valleys, unlike with canyons, all those that have been observed that were born from the top of the island slope have been marked, leaving those that are born in the lower part without marking because they are not related to canyons (Fig. 4A y 4B). The valleys are left unmarked when they reach a deposit. To explain better this feature, statistics have been done to study the orientation of the valleys and observe their trends (Fig. 8). The orientation is between 45º - 90º mainly, it means, the valleys come from ENE-WSW to E-W.

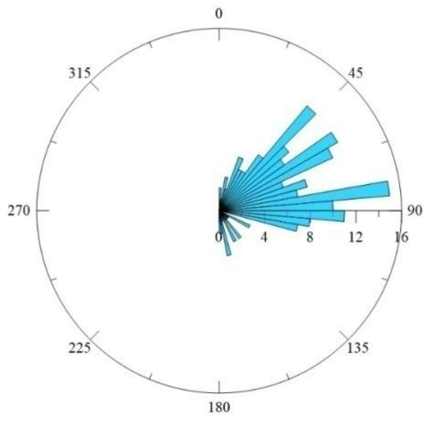

Figure 8. Rose diagram which represents the orientations of the valleys.

Collapse structure

A collapse structure has been identified at the north of the study area, associated to a volcanic cone (Fig. 4B), with a sub-circular shape and 820.85 m length.

Volcanic Cones

Volcanic cones are common in the study area where 23 have been identified. With the aim to make easier the explanation and the understanding of these volcanic structures a series of differentiations have been made. First, they have been classificated in those which are eroded (flat- topped cones) and those which are not, resulting 2 of the first type and 21of the second one. Then, the morphology (circular, elongated and irregular) of the volcanic cones without erosion allows to differentiate them, being those of circular morphology the most abundant. The different types of volcanic cones can be seen in the figures 4A and 4B, and 5. The values of the principal morphometric variables (area, height and slope) of all these volcanic cones are showed in the figure 9.

The area vs. relief distribution is similar to all types of volcanic cones and shows a correlation between both variables, when the area is higher, the relief also is higher (Fig. 9A). The majority of volcanic cones have areas lower than 0.30 km^2 with reliefs lower than 150 m. The greater volcanic cone is an irregular one with also the most relief and a slope of 35º approximately. The variables slope and relief have not a correlation cause when the relief grows the slope does not grow necessary (Fig 9B).

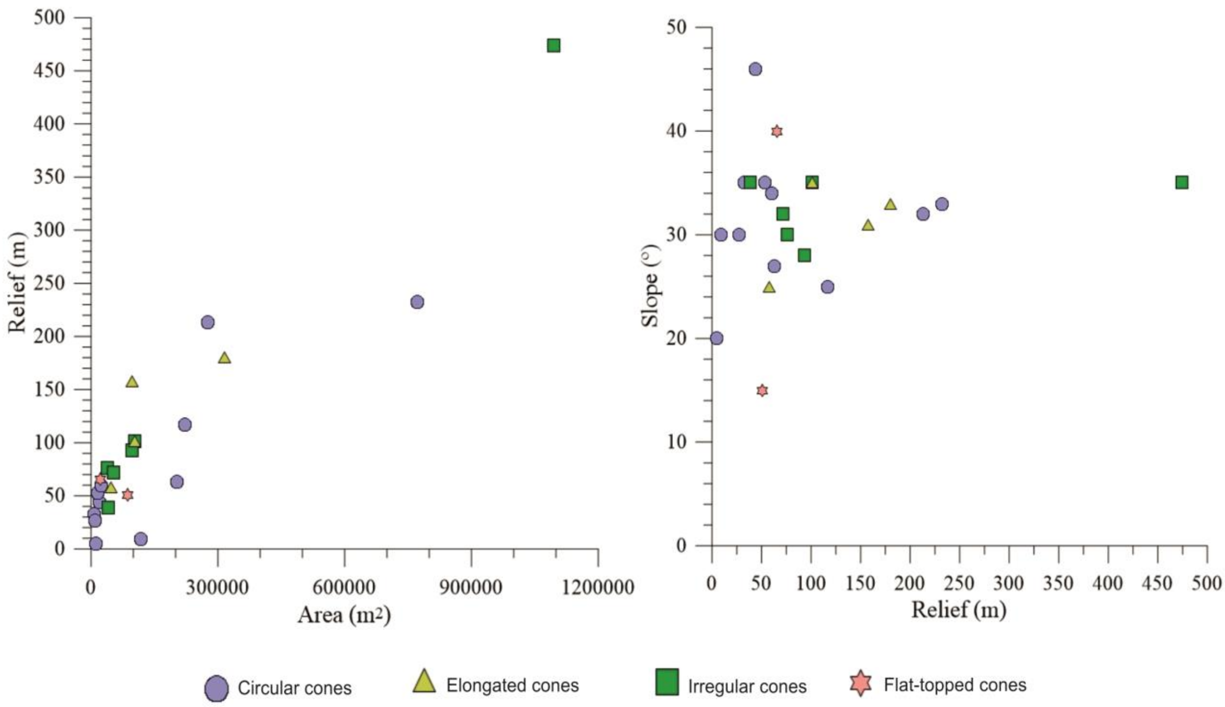

Figure 9. XY scatter plots of the variables for all the volcanic cones presents in the study area. A) Area (X) vs. Relief (Y); B)Relief (X) vs. Slope (Y).

The most non-eroded cones have circular shapes. The flat-topped cones have a similar relief but really different slopes, and both have circular shapes. Irregular cones have all of them similar slopes.

Insular shelf

The insular shelf is underdeveloped in the study area (Fig. 7), as befits to a young volcanic island in its first evolutive stage (shield stage) of growing. However, it can be identified inside the insular shelf some geomorphological elements such as a landslide scar, a simple volcanic cone, a flat-topped cone and terraces. In addition, when the slopes were studied, a non-normal pattern was observed cause there are steep areas. The slopes range is between 5º and 10º, with an average of about 7º. However, we find some areas where the slopes reach up to 31º, these zones correspond to a ridges area, which could be associated with the discharge of lavas flows. The area of the insular shelf is 3054909.09 m^2.

Moreover, the width of the shelf and the depth of the break were calculated, changing both parameters along this domain and being between 231.39 m – 1059.76 m long for the first parameter and between 26 m – 183 m depth for the break of the edge.

4.2 Morphological classes in an automatic cartography

Broad and fine scales BPI (bathymetric position index) were made to the dataset, these tools allow to define differences of concavity-convexity at two scales after that standardize has been done to facilitate BTM classification. With the broad BPI, a zone classification is obtained, where the positive values show regions that are higher than the surrounding area, ridges, while the negative values show regions that are lower than the surrounding area, depressions. With the fine BPI a better classification of features is obtained. Afterwards, with the combination of the both BPI, slope values and the bathymetry, a benthic terrain classification has been done by a dictionary previously created (Annexe C). Through that we obtained the cartography.

The zones identified in the study area are deep depressions, depressions, low slope areas, smooth areas, gullies, shelf, crests, scarps zones, high slopes and summit areas, (Fig. 10).

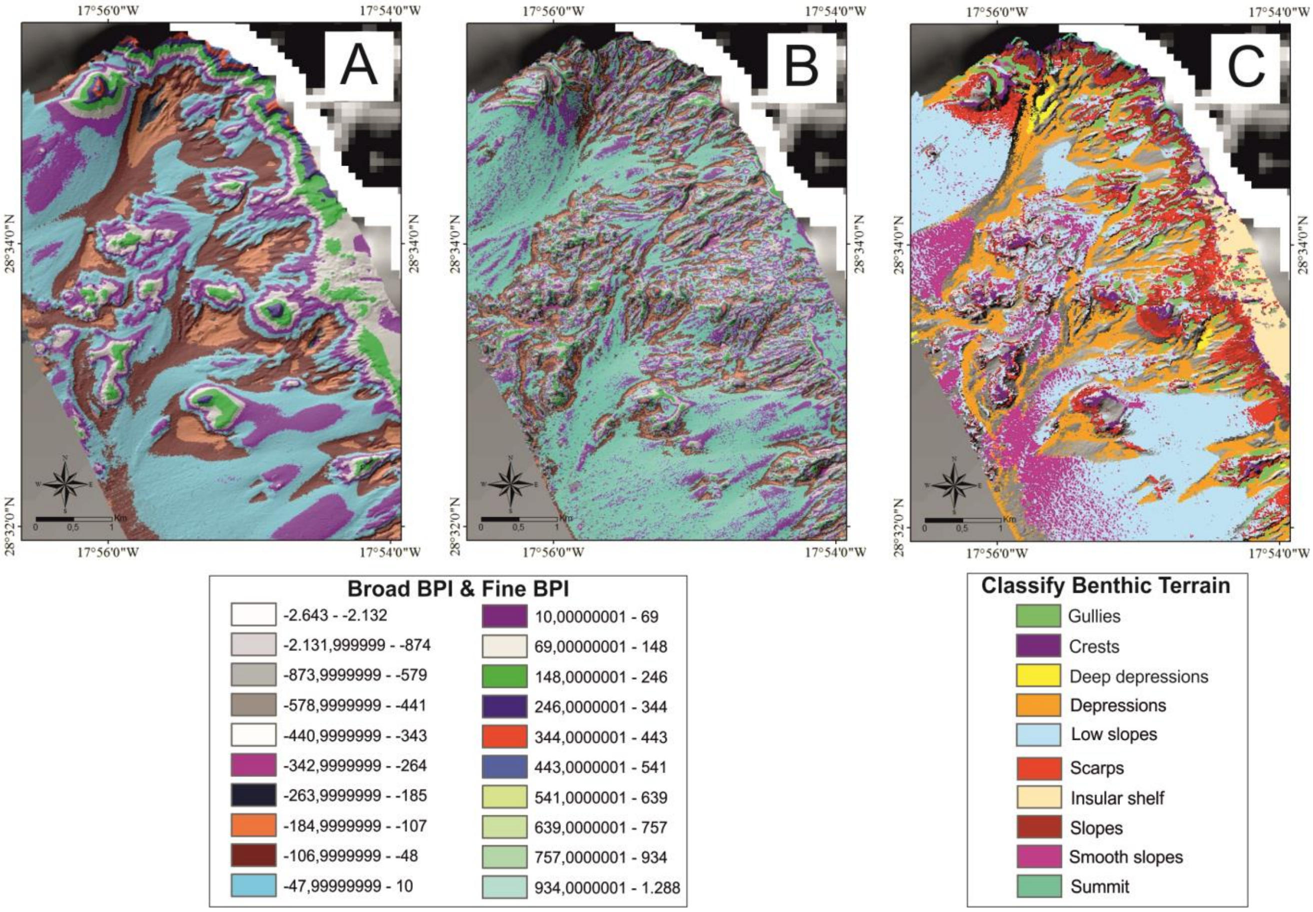

Figure 10. Automatic mapping. A) Broad BPI; B) Fine BPI; C) Classify Benthic Terrain. Classify Benthic Terrain is the result, in the present study, of the combination of the two previous layers (BPIs), with the depth and the slope.

- Deep depressions: areas where the relief are lower than in the surrounding regions, really low points with the most negative values.
- Depressions: low areas with negative values, but softer then deep depressions.
- Low slopes: quiet areas but with slopes between 10º-25º, located in the lower insular slope.
- Smooth areas: areas almost flat, with slopes < 10º and located also in the lower part of the insular slope.
- Gullies: areas with negative values, similars to depressions, but defined by only fine features. Limited up to 700 m depth, lower part of the insular slope.
- Shelf: flat areas, slope < 20º, but in the shallow part, up to -183 m depth. Good defined by broad features.
- Crests: regions of high reliefs where two slopes meet, high positive bathymetric values.

- Scarp zones: areas with slopes between 19º and 78º, defined by broad and fine features in width ranges.
- High slopes: areas with high slopes, from 30º to 78º, defined also by broad and fine features in narrow ranges.
- Summit areas: areas with the most positive position values in relation with their surrounding areas.

5. Discussion

5.1 Geological processes related to genetics and evolution of the structures.

The result obtained in the present work allows us to describe the geomorphological units, their distribution and the relation to different processes. Next, the processes that have led to the geomorphology of the study area are discussed.

Mass-transport processes

Processes that imply the mass movement of materials by the gravity action. There are many reasons behind this kind of processes, such as oversteepening, seismic loading or the incohesive nature of sediments (Quartau et al., 2012). The mass wasting processes which are erosive and cause several features like landslide scars and their related mass transport deposit, as well as canyons and gullies.

Landslide scars are common instabilities features and they can be considered as a type of scarps. The lobes related to landslide scars are surfaces located downslope of them because of mass-transport and depositional processes (Sanchez-Guillamon et al., 2018). In the study area not all landslide scars have depositional lobes. When landslides scars have not deposits is because there is other process or element related to them. As example, the landslide scars S3 (Fig. 4A), has a ridge that grow in it, and that is the reason to has not mass-transport deposit.

Gullies and canyons are usual entities in the insular slope, which act as transport sediment channels. These structures are associated with the shelf and upper slopes erosion, an increase in the slope promotes the evolution of these channels by the action of gravity currents (Porter-Smith et al., 2012). In the study area there are several canyons and gullies in the west and southwest flank, but not in the east. Nevertheless, it was difficult to differentiate them because there were a high number of scarps on the insular slope too. Canyons that have a link whit the insular shelf could have fluvial connections or development of erosive guillies onshore, it means, an onshore channel which continues offshore (Llanes et al., 2009) probably in low sea level events.

Tectonics

Scarps could be a consequence of the tectonic processes, and their specific name would be fault scarps. A large number of scarps were observed in the study area with two main shapes, elongated and irregulars. In the present work there are unavailable seismic data and the link between these elements and tectonics cannot be done. Elongated scarps were in the steep part of the insular slope, perpendiculars to bathymetry, and it could be related to tectonics, to slope gradient or event to volcanic processes. In addition, there is elongated scarp within a volcanic cone, maybe as a result of the erosion of the cone. Irregular ones are in the lower part of the slope related with terrace areas, forming the steeps fronts of them and they are related to depositional processes. However, scarps may be a great proxy of stress field (Casalbore et al., 2015). Tectonics can control geomorphology, gullies development and influence erosion, such as triggering mass-wasting events (Ramalho et al., 2013), resulting in sub-circular scarps interpreted as landslides scars.

Volcanic processes

Volcanic processes are all related with volcanic eruptions. In the volcanic island's environment these processes could be the most important and there are several elements connected whit them.

A type of collapse structure has been identified in the summit of a volcanic cone (Fig. 4B). Collapse structures can occur at the same time as the volcanic activity or later and there are several processes that could be behind them. The great variability of the processes that can generate these structures and the lack of other types of data, seismic data for example, makes it not possible to establish the formation and/or evolution of the collapse structure in the study area.

Lava flows are a mantle of lava that descends along the slope. Within the qualitative/handmade mapping there are two lava flows interpreted as depositional elements, the reason to classified these elements as deposits are due to these flows are continuous, as a unique body and proceed form possible effusive centre. However, in the study area there are two zones with well-preserved lava flows where found smooth areas surrounding or not a volcanic cone forming terraces, which are interrupted by scarps. This geomorphology is due to the mantle of lava went on flowing getting cold successive. Lava flows could be signs of volcanic progradation of subaerial lavas offshore (Quartau et al., 2014). That hypothesis could be possible in the study area because Holocene lava flows are located near to the zones of the last eruptive on-shore events on La Palma (Annexe A). On the other hand, in the insular shelf there is a ridges area related to lava flows too, which could be an evidence of the youth of the shelf (Quartau et al., 2014, 2015).

Volcanic cones are the foremost morphologies related to volcanic processes. These structures can be distinct shapes, seen in the results, and they also can be related to other elements and processes. Differences in formation and evolution give differences in the shapes; elongated cones are developed from tectonic lineations forming fissure eruptions while circular cones come from point sources (Casalbore et al., 2015). Volcanic cones which have smooth regions at the north have been influenced by erosion (Quartau et al., 2014), in this work it is easy to observe in the most of them. There is a volcanic cone with a scarp (Fig. 4B), which forms a crest, consequence of erosive process, as mass transport or tectonics. Flat-topped cones in the study area have not the same origin. The erosion is the cause behind the flat-topped located on the insular shelf, due to their shallow depth while the flat-topped in the lower part of the insular slope, south of the study area, is result of the interaction between crustal thickness and hydrostatic pressures (Casalbore et al., 2015).

Ridges are elevated volcanic features formed by chains of volcanic cones. There are two in the study area. The morphology of the first one suggests apparently that it is affected by erosion or mass wasting processes. The tendency of the second (R2 in Fig. 4A) can be observed easily, it begins in the insular shelf probably by the primary cone after a mass wasting event, which forms a landslide where the ridge is emplaced.

Depositional processes

Depositional processes are those which are related to sedimentary or volcanic deposits. In the handmade mapping there are three main elements emerged to these processes, and other element in relation, smooth areas.

The geomorphological elements in direct relation with depositional processes are the landslide deposits, lava flows deposits and fans. The landslide deposits are previously explained as depositional lobes result of mass wasting and depositional processes. Lava flows are deposits consequence of volcanic activity placed by the action of gravity slope downwards. Fans are surfaces down other elements like smooth ridges or flat-topped cones (Fig. 4A and 4B), though it could not establish specific depositional environments due to there are not samples or seismic data, probably related to turbiditic or volcaniclastic flows.

Smooth areas constitute regions that could be influenced by similar depositional processes as fans resulting from other geomorphological elements. These regions could be aprons, it means areas in the base of the insular slope where coalescent processes inside of them are not possible to distinguish only one singular fan deposit.

Erosion and progradation in the insular shelf

In the study area the insular shelf is divided into three sections, being two of them really undeveloped. The main part, located on the south west of the island, changes their values of the width and the depth of the edge along itself. However, the insular shelf is narrow and shallow. It is possible to observe several elements related to enlarge and fill processes. Related to enlarge processes there is a flat-topped cone, which is an evidence of the shelf erosion. In another hand, a ridges area and a simple volcanic cone are evidences of volcanic events (fill processes). Ridges area is related to lava flows, probably representing the progradation of subaerial lava flows into the sea (Quartau et al., 2014; Casalbore et al., 2015). Moreover, the shelf has a lot of surrounding gullies.

The competition between enlarging and filling processes, with the dominance of the last ones, is a characteristic of young shelves. The width and depth of the shelf and the presence of gullies on the edge, and their predominance instead of embayments, constitute others evidence of the youth of the La Palma insular shelf. (Quartau et al., 2014). The presence of lava flows in the shelf support the hypothesis that the insular shelf in the study area is young (Quartau et al., 2014, 2015).

5.2 . Morphological classes in an automatic mapping.

Benthic Terrain Modeler lies in automatic classification done in this work to obtain cartography of the study area. Ten zones are assigned in this work, based on bathymetric and slope features mainly. BTM provides us useful tools to work on geomorphology as long as a good idea and knowledge of the area. Nevertheless, it cannot be named as automatic mapping because in the processes there are some important steps that you must do handmade.

BTM has some disadvantages such as trial-and-error is needed to define the zones in the dictionary classification and also is needed when we do the BPI, to define values for the inner and outer radius. In addition, with the BTM is not possible to obtain specific features based in specific processes. For example when the summits were defined in this work the aim was the tops of the volcanic cones and ridges but the result gave us also summits in some parts of the insular slope, regions without relation apparently. Another example is whit the crests, the parameters limitation into the dictionary do not permit us a good definition.

The comparison between both types of cartography allows us to understand better the semi-automatic one (Fig. 11).

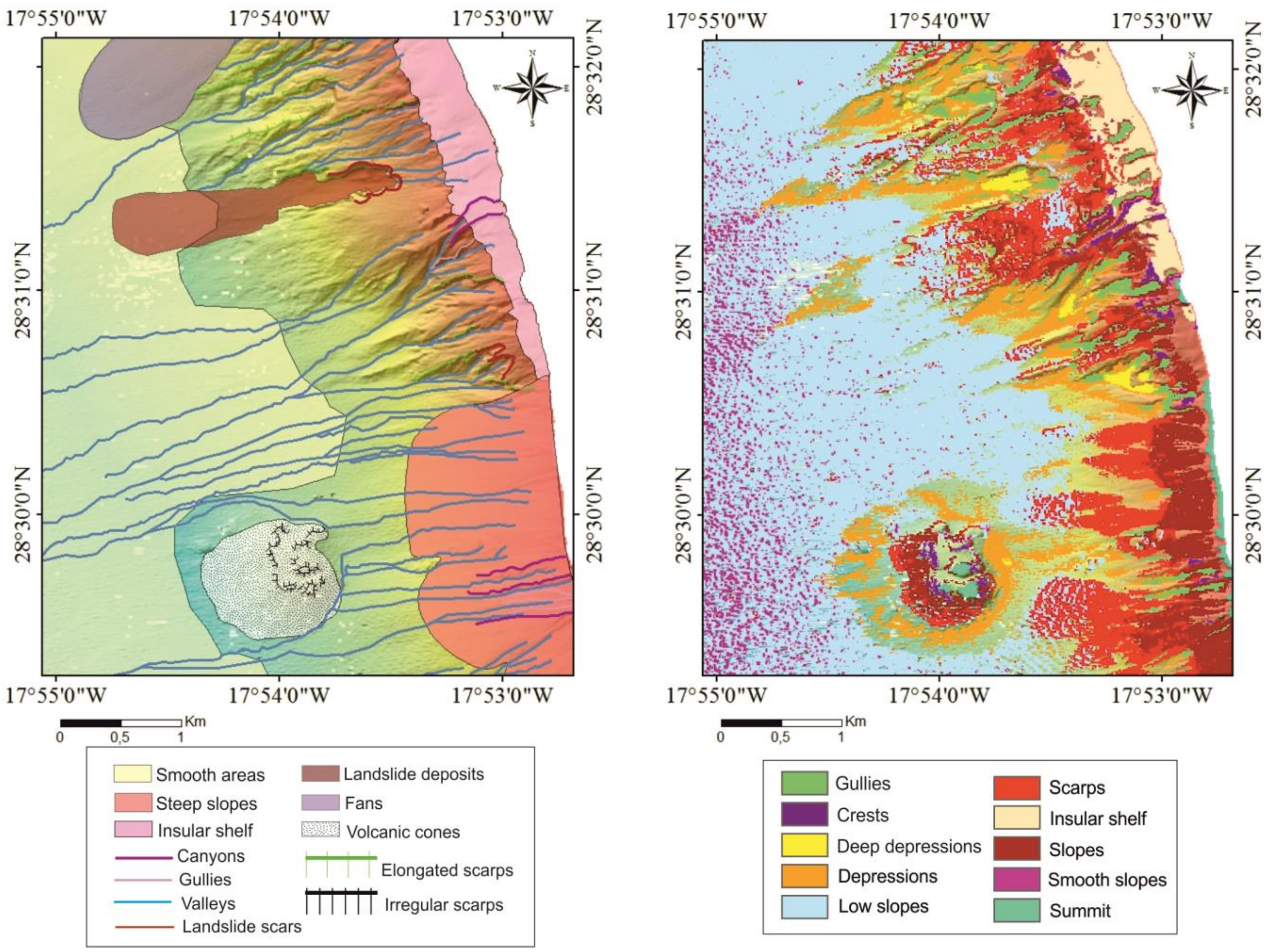

Figure 11. Comparison between the two types of cartography made. A) Qualitative or Handame mapping. B) Automatic mapping.

The mainly part of the insular shelf had been obtained good with the BTM. Gullies in semi-automatic mapping are related to valleys in handmade mapping. Smooth and low slopes defined with the BTM correspond to smooth areas (or aprons), being better determinate in the semi-automatic due to all zones with the same features are marked.

The terrace areas explained in relation with the irregular scarps when the handmade mapping was done can be well seen with the BTM, showed like smooth and low slopes.

Depressions and deep depressions are only indicated in the semi-automatic mapping, however, inside these zones distinct structures cannot be defined (such as channels or trenches).

Deposits cannot be obtained through semi-automatic cartography, because the parameters with BTM works do not allow to establish distinctions between areas of deposits and smooth zones, for example.

6. Conclusions

The principals conclusions to this work are:

1. High-resolution bathymetric data had allowed us to extract information to define the geomorphological elements and units in the study area. The geomorphological study is a good tool to understand and establish the genetic and evolutive processes.
2. The insular shelf of La Palma Island is young due to it is narrow, the shallow depth and the occurrence of gullies and lava flows.
3. In the study area there are many signs of volcanic activity, such as ridges, volcanic cones and lava flows, being this process one of the most important in the submarine geomorphology of the island.
4. The processes acting in modeling the seabed do not give isolated, there are continuous interactions between all of them and the result of this is the different geomorphological elements and units.
5. The canyons and lava flows located on the insular shelf show that maybe there is continuity between onshore and offshore processes.
6. The semi-automatic mapping cannot do alone in geomorphological studies because it is not explicative about the specific morphologies; it defines big regions but not concrete elements. This type of mapping is always a complement of the classical cartography.
7. When the classify terrains is done the semi-automatic mapping is useful to extract benthic maps, and use them in another kind of studies such as marine habitats definition.

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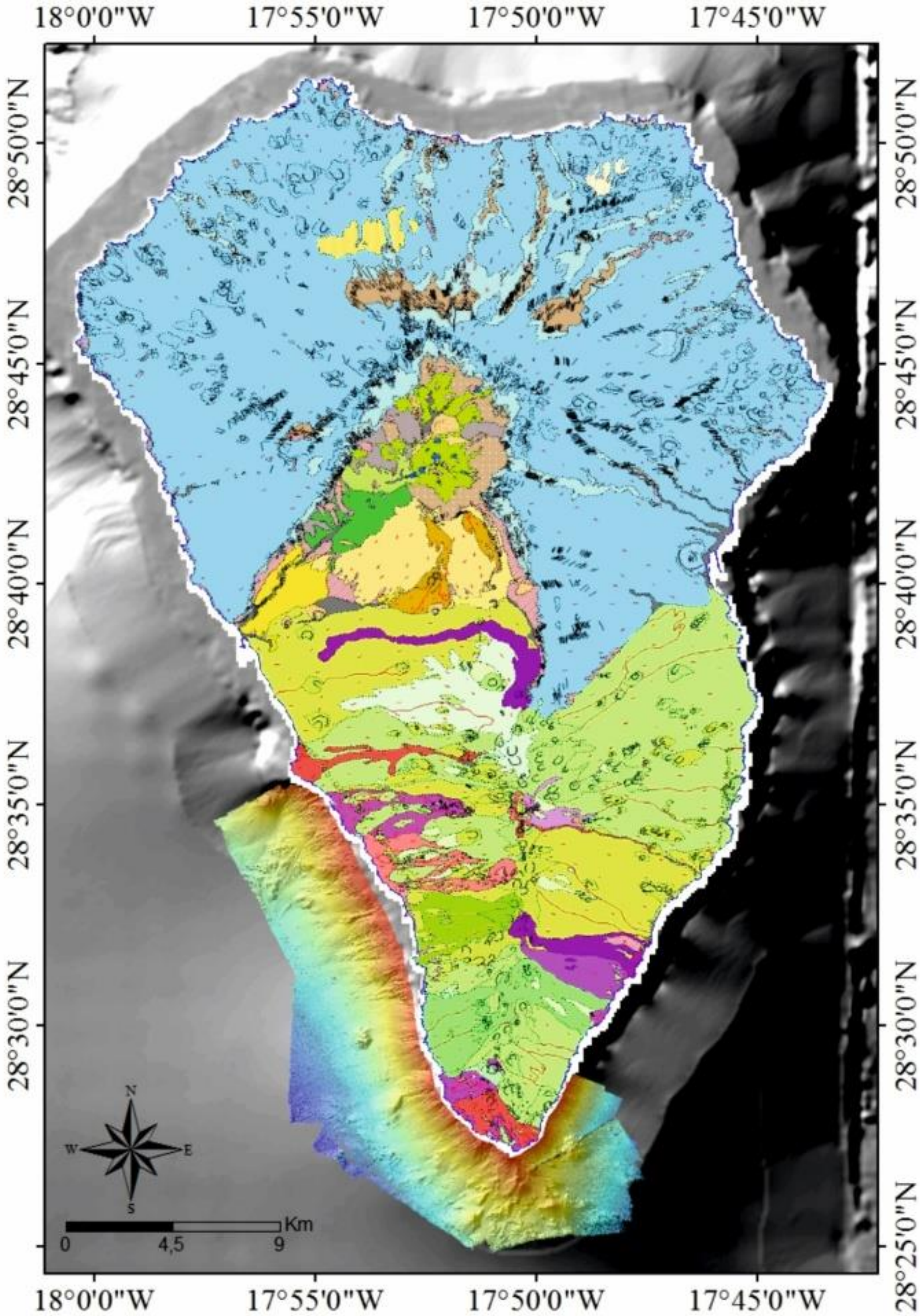
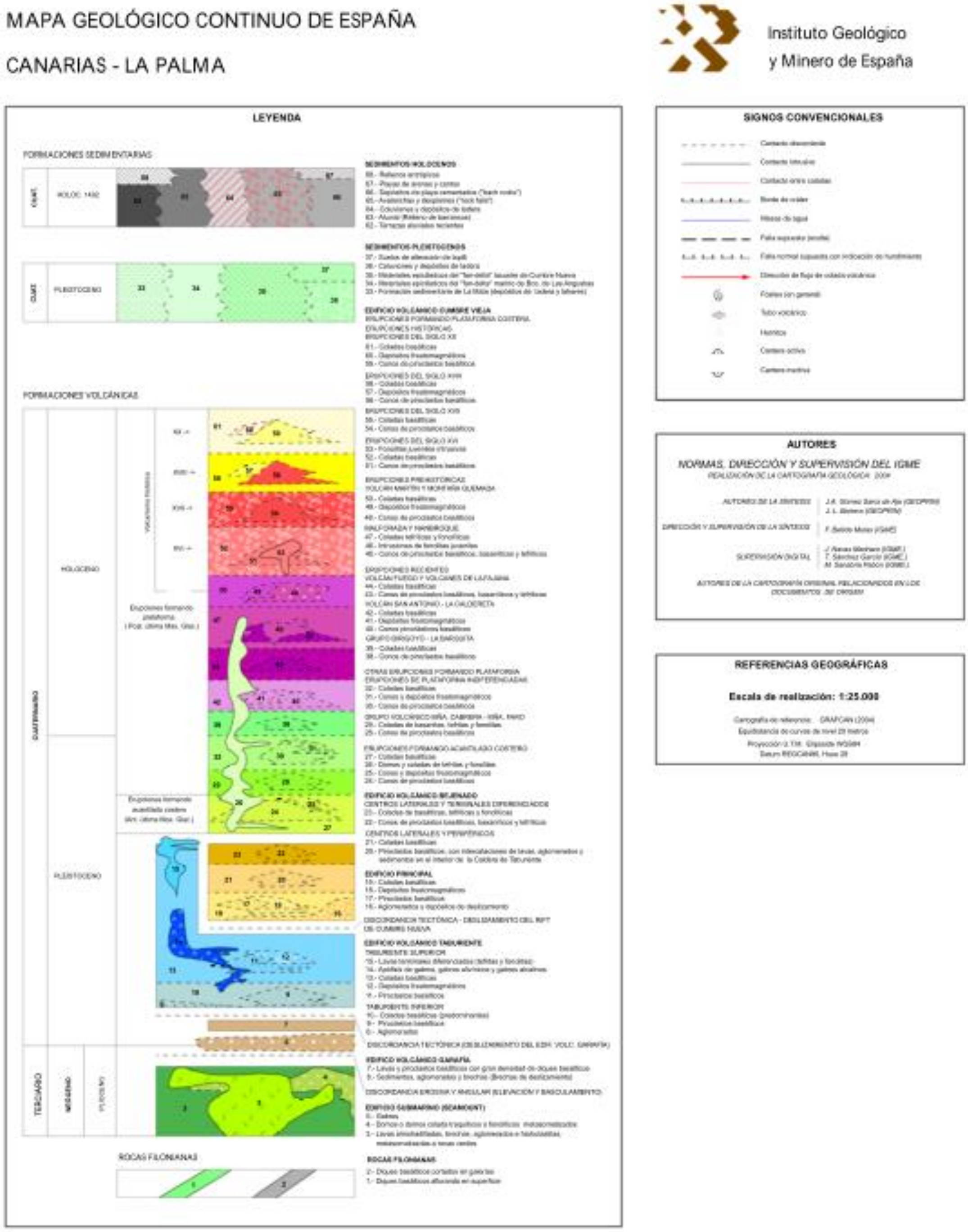
8. Annexes

Annexe A. Geological map and geological legend of La Palma island (modified after Carracedo et al., 2001).




MAPA GEOLÓGICO CONTINUO DE ESPAÑA
CANARIAS - LA PALMA
Instituto Geológico y Minero de España
LEYENDA
SIGNOS CONVENCIONALES
AUTORES
REFERENCIAS GEOGRÁFICAS
Escala de realización: 1:25.000

Annexe B. Dictionary used to extract zones in BTM.

Zones	Broad_lower	Broad_upper	Fine_lower	Fine_upper	Slope_lower	Slope_Upper	Depth_Lower	Depth_Upper
Slopes	10	541	-183	69	30	78		
Deep depressions	-2643	-185	-2643	-48				
Depressions	-185	-48	-185	-10				
Low slopes	-47	148	-47	246	10	25		-183
Smooth slopes	-47	148	-47	148	0	10		-183
Crest	148	344	148	344				
Scarps	-20	148	-12	148	19	78		
Summits	344	1288	344	1288				
Shelf	10	300	-48	246		20	-183	
Gullies			-2643	-70			-700	

Annexe C. Zones in classify benthic terrain. The legend is the same that in figure 10.