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Geologic evolution of the Canarian Islands of Lanzarote, Fuerteventura, Gran Canaria and La Gomera and comparison of landslides at these islands with those at Tenerife, La Palma and El Hierro

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Abstract

In this paper we discuss the results of a swath bathymetric investigation of the Canary archipelago offshore area. These new data indicate that volcanism is pervasive throughout the seafloor in the region, much more that would be suggested by the islands. We have mapped tens of volcanic edifices between Fuerteventura and Gran Canaria and offshore Tenerife, La Gomera, El Hierro and La Palma. Volcanic flows are present between Tenerife and La Gomera and salic necks dominate the eastern insular slope of La Gomera. This bathymetry also supports land geologic studies that indicate that the oceanic archipelago has acquired its present morphology in part by mass wasting, a consequence of the collapse of the volcanic edifices. In the younger islands, Tenerife, La Palma and El Hierro, the Quaternary (1.2 to 0.15 Ma) debris avalanches are readily recognizable and can be traced offshore for distances measured in tens of km. Off the older islands, Lanzarote, Fuerteventura, Gran Canaria and La Gomera (<20 to 3.5 Ma), the avalanches have been obscured by subsequent turbidity current deposition and erosion as well as hemipelagic processes. The failure offshore western Lanzarote is in the form of a ramp at the base of the insular slope bound on the seaward side by a scarp. Its size and the lack of evidence of rotation along its landwards side precludes the possibility that it is a slump. It probably represents a slide whose outer scarp is caused by break-up of the slide. Mounds on the ramp's surface may represent post-displacement volcanic structures or exotic blocks transported to their present locations by the slide. The failures offshore Fuerteventura are so large that, although they occurred in the Miocene-Pliocene, exotic blocks displaced from upslope are still recognizable in the insular margin morphology. The Canary Island insular margin appears to be a creation of Miocene-Pliocene mass wasting and more recent turbidity current deposition and erosion, and hemilepagic deposition. Failures offshore La Gomera are due to debris flows and/or turbidity currents. These events have obscured earlier mass wasting events.

Introduction

In this study we use multi-beam data acquired in the Canary Islands by the Instituto Español de Oceanografia to determine the role that landslides have played in the construction of the islands present morphology. In the course of our investigation we discovered that volcanic edifices are quite extensive, much more that expected from the extent of volcanism in the islands. Volcanic structures were imaged by multibeam recordings between Fuerteventura and Gran Canaria and offshore Tenerife, La Gomera, El Hierro and La Palma. Probable volcanic flows also were imaged between Tenerife and La Gomera as well as salic

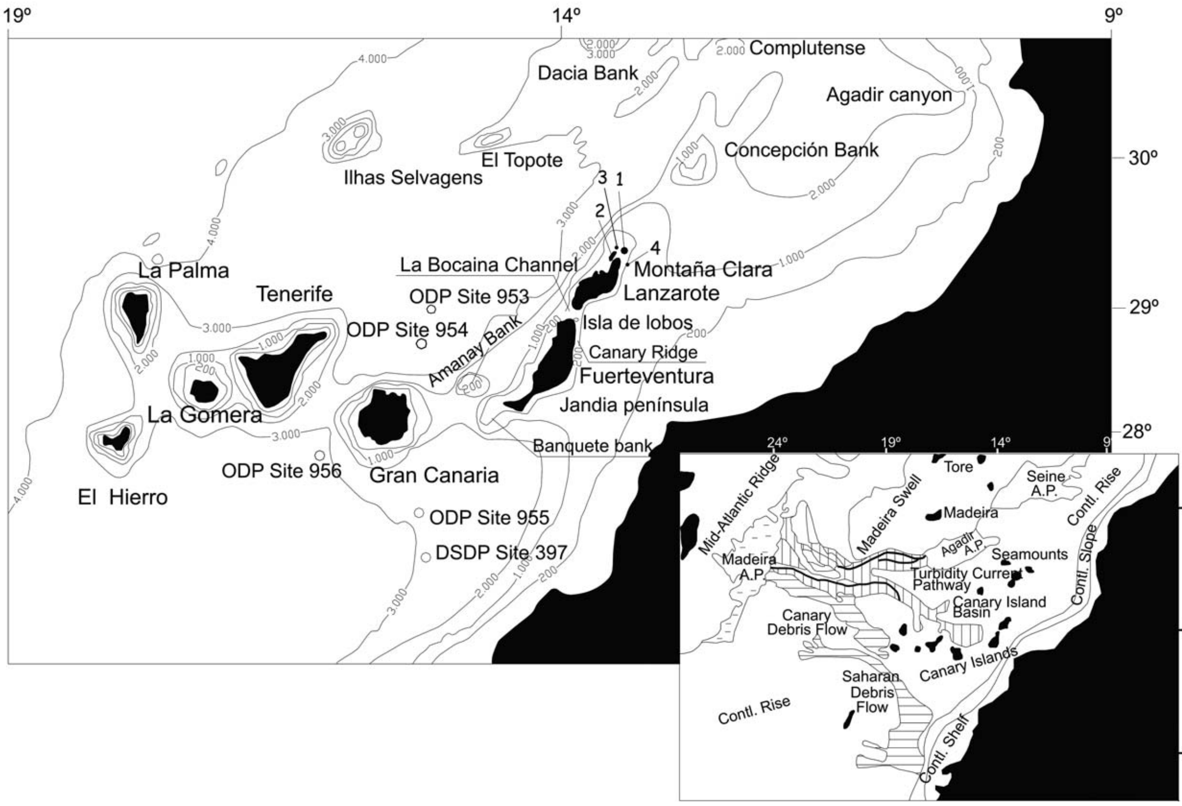

Figure 1. Submarine topography of the Canary Island archipelago region. Bathymetric contours are from GEBCO sheet 5.08 and base map from U.S. Naval Oceanographic Office 51017. Insert map is modified from Wynn et al. (2000). Contour in meters. 1= Alegranza; 2= Graciosa; 3= Roque del Oeste; 4= Roque del Este.

necks on the eastern insular slope of La Gomera. The most spectacular of these features are the mega-avalanches, particularly those off Tenerife, El Hierro and La Palma. As other studies have demonstrated, landslides are amongst the most significant processes in the creation of the morphology of mature oceanic volcanic islands. They have been reported from the Hawaiian Islands (Moore et al., 1989, 1994), Reunion Island (Labazuy, 1996) and the Canary Islands (Watts and Masson, 1995; Urgeles et al., 1997, 1999; Carracedo et al., 1999a, 1999b). Moore et al. (1989, 1994) recognized at least 68 such flows off Hawaii, some of which are 200 km long, incorporate as much as 5000 km^3 of volcanic material and cover an area of 100,000 km^2. Mass wasting facies off Hawaii take two forms: (1) slow moving slumps, up to 110 km wide and up to 10 km thick, characterized by transverse blocky ridges and steep toes that are up to 230 km long, and (2) 0.05–2 km thick, fast moving debris avalanches (Moore et al., 1989). To date eleven giant slides also have been mapped in the Canary Islands affecting the subaerial and submarine slopes of the islands of La Palma, El Hierro, Tenerife, Fuerteventura and Gran Canaria (Navarro and Coello, 1989; Holcomb and Searle, 1991; Carracedo, 1994, 1996; Masson and Watts, 1995; Watts and Masson, 1995; Masson, 1996; Masson et al., 1997; Guillou et al., 1998; Urgeles et al., 1998, 1999; Teide Group, 1997; Stillman, 1999). Masson et al. (2002) have summarized the results of these investigations.

Regional setting

The Canary archipelago is located on the continental rise off Cape Juby, northwest Africa (Figure 1). Fuerteventura and Lanzarote at the eastern end of the chain are 100 km from the African coast, and El Hierro and La Palma at its western end are 500 km from the coast. Lanzarote and Fuerteventura are along the crest of the northeast trending Canary Ridge, on the upper continental rise at a water depth of about 2000 m. Its northeast terminus is defined by the less than 200 m

Figure 2. Topographic map of the Canary archipelago region. Offshore contours in meters are based on multi-beam echo sounding data collected during the present investigation and onshore ones also in meters from data provided by Servicio Geográfico del Ejercito, Cartografía Digital, 100 by 100 m grid, Madrid.

deep, flat-topped Conception Bank. This ridge may be aligned along the contact between attenuated continental crust on the east and oceanic crust on the west (Emery and Uchupi, 1984). The rest of the archipelago, Gran Canaria, Tenerife, La Gomera, La Palma and El Hierro, at water depths of 3000 to 4000 m, are on oceanic crust of Jurassic age (Uchupi et al., 1976). Gran Canaria, Tenerife and La Gomera trend east-west parallel to the oceanic fracture zone trends in the region with Tenerife's long axis being oblique to this trend. La Palma and El Hierro, at the western end of the island chain, are offset to the north and south of this trend (Figure 1).

A subsurface oceanic basement high appears to link La Palma to Ilhas Selvagens (Figure 1) (Uchupi et al., 1976). From the Ilhas to the northeast end of the Canary Ridge are two northeast trending ridges, subparallel to the Canary Ridge, along whose crests are seamounts (Dañobeitia and Collette, 1989). One of these volcanic structures, Dacia Seamount, is flat-topped. Sediments in the lows between the ridges grade south into the Canary Island Basin west of the Canary Ridge and north into the Agadir Canyon with the drainage divide located near 30°30′ N (Figure 1). The seafloor of the Canary Islands Basin ranges from 3000 m on its eastern side to 4000 m along its western side. Here a slight shallowing of the basin floor to less

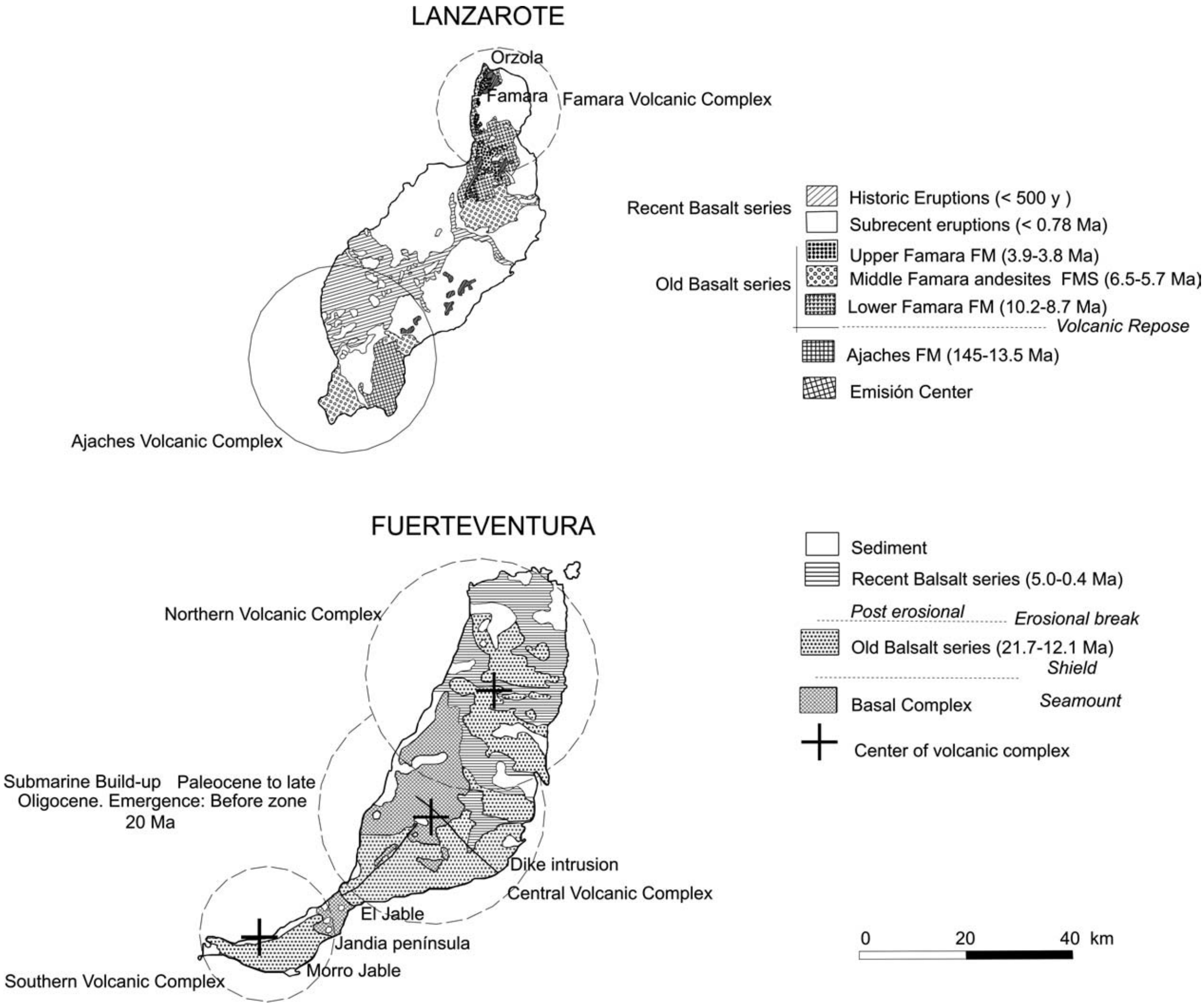

Figure 3. Geologic maps of Lanzarote and Fuerteventura. Compiled from Coello et al. (1992), Carracedo and Rodríguez-Badiola (1993), Ancochea et al. (1996) and Stillman (1999).

than 4000 m reflects the subsurface high linking La Palma and Ilhas Selvagens. A gap in the high near 17°30′ W, 29°30′ N serves as passageway for turbidity currents into the Madeira Abyssal Plain to the west (insert, Figure 1). Gaps between the Canary Islands along the southern side of the basin serve as passageways for the southerly flowing North Atlantic Deep Water (NADW) at a depth of 2000-3800 m and northerly flowing Antarctic Bottom Water (AABW) below 3800 m.

Volcanism in the Canary Islands region has occurred at various times since the Late Cretaceous, the oldest represented on Fuerteventura, to the present in the western, La Palma and El Hierro (Le Bas et al., 1986). Based on their eruptive histories Carracedo (1994) divided the islands into three groups, those that have had eruptions in historic times (<500 years; Tenerife, La Palma; Lanzarote and probably El Hierro), those with a history of Quaternary volcanism (Fuerteventura and Gran Canaria) and those lacking evidence of Quaternary volcanism (La Gomera). Individual islands appear to have gone through four geomorphic phases: a seamount phase, a shield-building submarine and subaerial phase characterized by rapid growth and massive slope failures, a period of quiescence and deep erosion (erosional gap), and post-erosional stage of volcanic activity. In some islands the last phase also is characterized by renewed mass wasting. Lanzarote, Fuerteventura and Gran Canaria are in the post-erosional phase, Gomera in the repose stage (gap stage) and Tenerife, La Palma and El Hierro are in the shield stage of development (Carracedo, 1999).

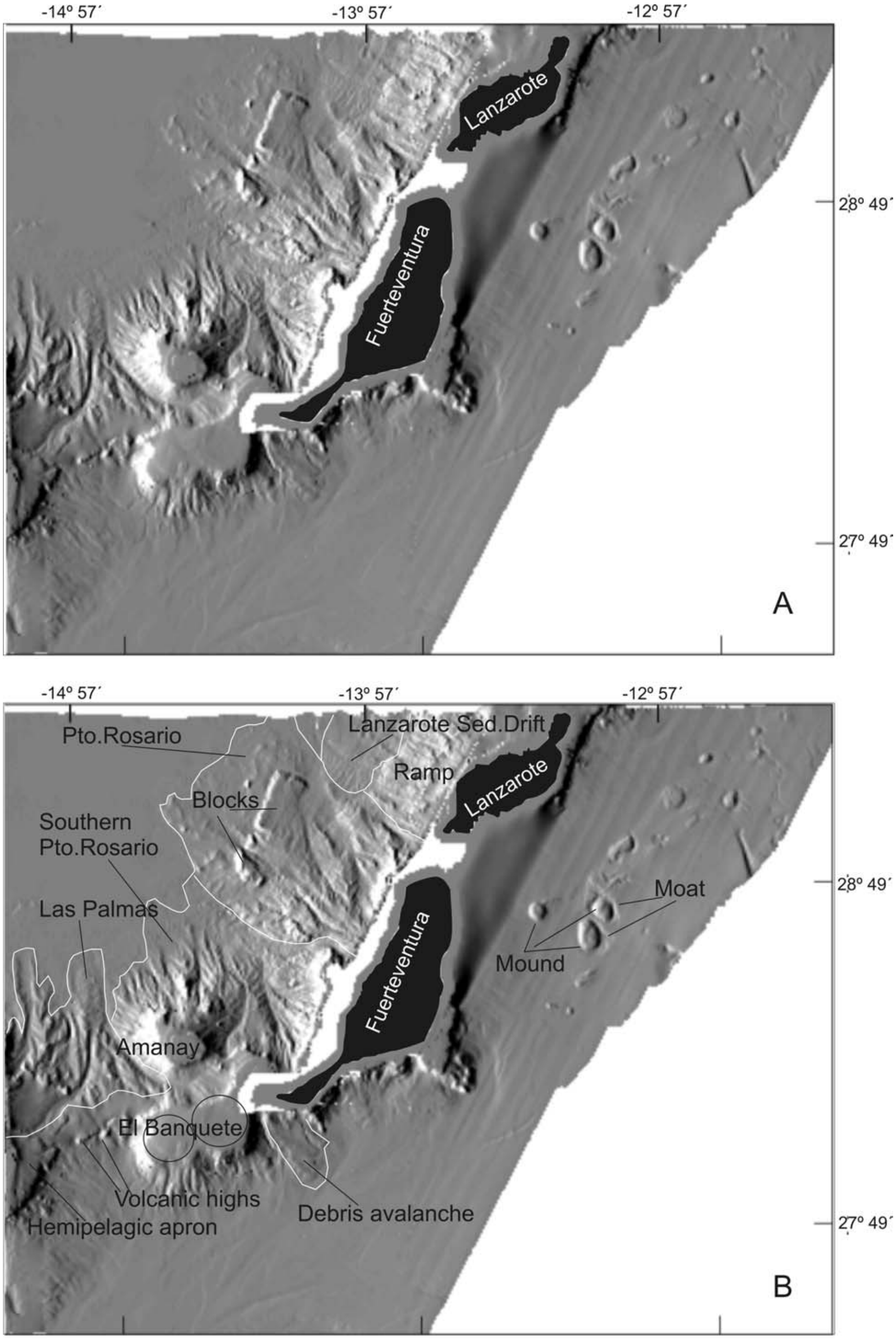

Figure 4. **A**. Shaded relief image of the western margins of Lanzarote and Fuerteventura and side slopes of Banquete and Amanay Banks . Illumination is from northwest. **B**. Shaded relief image of Lanzarote and Fuerteventura margins and Banquete and Amanay Banks showing the distribution of landslide areas west and south of Fuerteventura (Puerto Rosario, Southern Puerto Rosario and Las Palmas debris avalanches) and east of Gran Canaria. We infer that the highs along the northwest edge of the Puerto Rosario avalanche are exotic blocks. No such features appear to be present off Lanzarote where the margin consists of westerly dipping platform cut by northwest aligned channels and ridges some of which are capped by circular highs. This terrain probably is the creation of slumping and subrecent and historical lava lava flows. The seafloor beyond the platform is dominated by northeast trending highs and lows. We infer that this morphology is the creation of southerly flowing North Atlantic Deep water (NADW) and named the region the Lanzarote Sediment Drift. The mounds and moats east of Lanzarote and Fuerteventura are described and discussed in Acosta et al. (this issue).

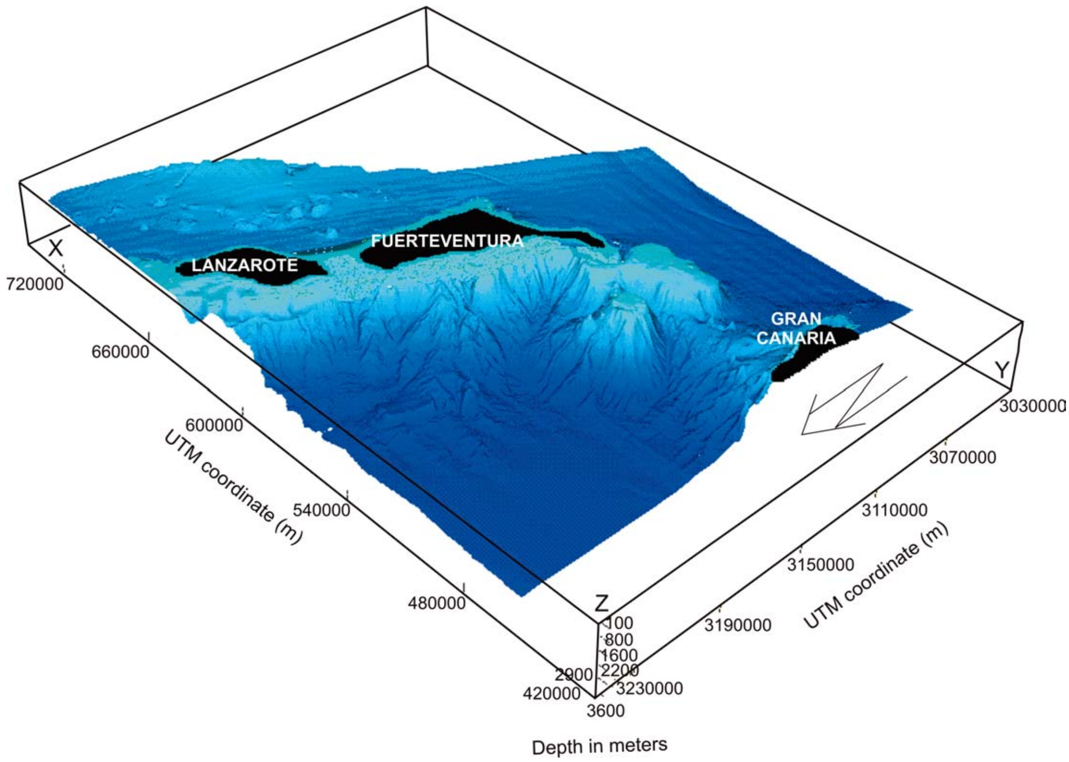

Figure 5. 3D diagram of the western margin of Lanzarote and Fuerteventura looking north. The two flat-topped highs south of Fuerteventura are Banquete (attached to Fuerteventura) and Amanay Banks. The high at the extreme right of the diagram is the tip of Gran Canaria.

The tectonic setting of the Canary Islands consists of rift-type clusters of aligned eruptive vents (single or triple) and caldera-type depressions (Carracedo, 1994). Where the wide arcuate landslide depressions are related to triple rift geometry, they tend to be located at the junction between the two most active rifts with the third one acting as buttress for the landslide. It is the development of these triple rifts and the concentration of dikes leading to the destabilization of the flanks through magma overpressure and mechanical and thermal overpressure of pore fluids that lead to gravitationally unstable volcanic flanks (Carracedo, 1994, 1996; Elsworth and Day, 1999).

Methods

In 1995 the Instituto Español de Oceanografía and the Instituto Hidrográfico de la Marina began an investigation of the Spanish Exclusive Economic Zone. During this investigation the bathymetry of the region was mapped using a multibeam system during which 100 per cent coverage was obtained. At the same time high-resolution parametric seismic reflection profiles, as well as gravity and magnetic, were also recorded in the surveyed areas (Muñoz et al., 1998). This paper describes the results of the multibeam bathymetric investigation of the Canary archipelago from 27°10′ N to 29°15′ N and from 13°30′ W to 19°15′ W.

The survey of the archipelago during four cruises from 1998 to 2001, aboard the R/V Hespérides and R/V Vizconde de Eza, was carried out using a variety of multibeam sounding systems that were used separately or in combination. Simrad EM1000, EM 1002 and EM 300, in conjunction with GPSD and inertial navigation systems, were used to survey shallow waters and EM12S in deep waters. Acoustic backscatter data were displayed in real time by means of sidescan sonar trace. A Microsystems SV-Plus Velocimeter was employed to correct depths for variation of sound velocity in the water column. The multibeam data were logged and post-processed in a Unix environment. Simrad Mermaid-Merlin software was used at sea for logging and real time quality assessment of the acquired data using color swaths bathymetric plots. As data collection per day in excess of 300 Mbytes is not uncommon, data validation is a major problem

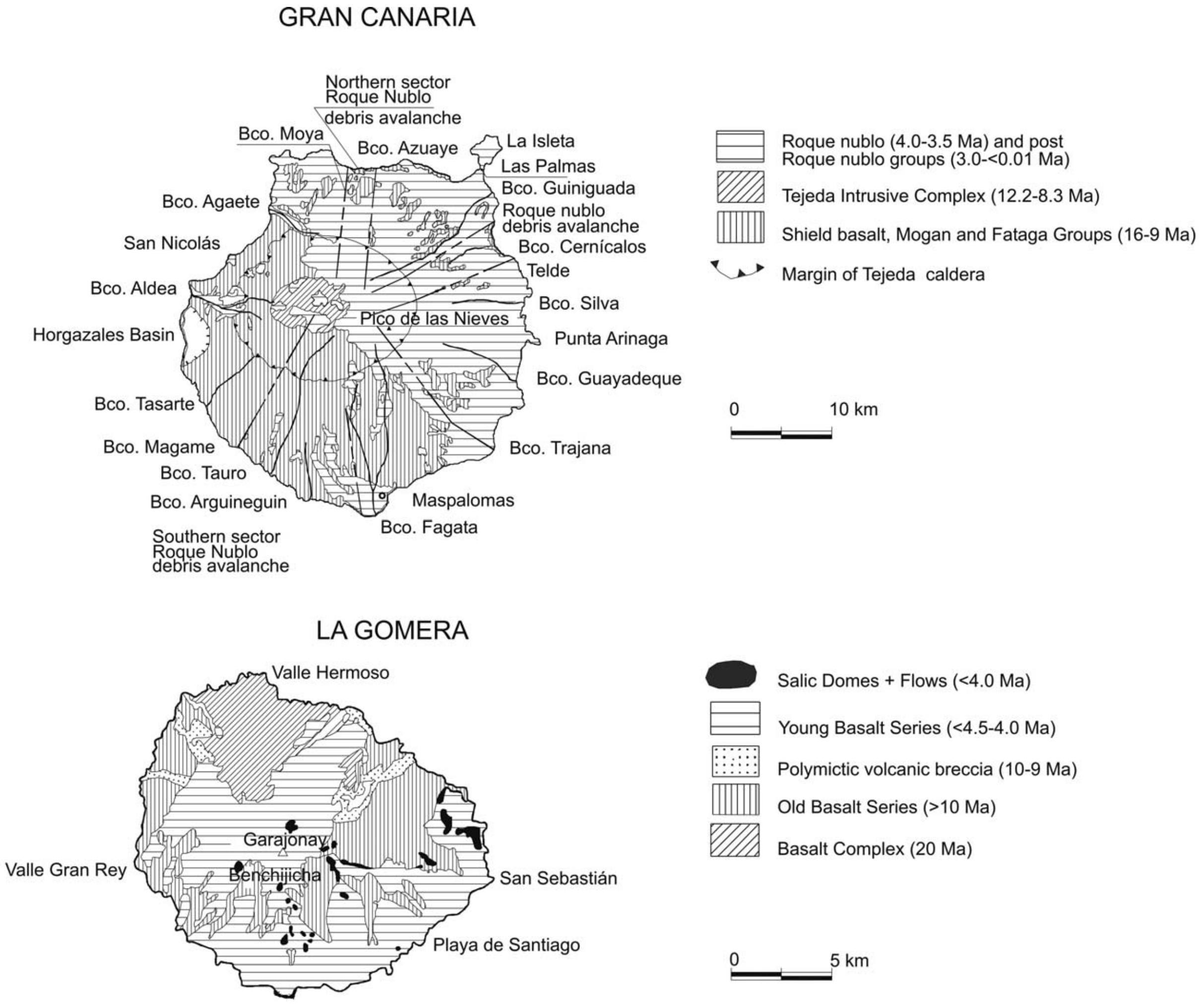

Figure 6. Geologic maps of Gran Canaria and La Gomera. Compiled from Hausen (1965), Cantagrel et al. (1984), Funck and Schmincke (1998), Mehl and Schmincke (1999), Van den Bogaard and Schmincke (1998) and Schmincke and Sumita (1998).

with multibeam systems. A Neptune package was used in post-cruise processes of the data. This post-cruise processing included the application of cleaning and editing tools for attitude, navigation and bathymetric data. The use of statistical analyses was of considerable help in detecting spurious data. The use of Geographic Information Systems (Cfloor from Roxar and IberGIS from ICI) allowed us to create, not only bathymetric maps, but also digital terrain models and 3D block diagrams of the surveyed area. In addition to computer mapping, the application of GIS also allowed complex spatial analyses of data. Thus, for the first time, the availability of such swath bathymetric and terrain maps of the whole Canary archipelago allows us to appreciate the extent of catastrophic slope failures. In the present study we describe for the first time the landslides that contributed to the present morphology of the seafloor surrounding the older islands of Lanzarote, Fuerteventura, Gran Canaria and La Gomera. We also incluce a brief discussion on the landslides of the younger islands, Tenerife, La Palma and El Hierro.

Recognition of gravity driven facies

Mass wasting is important in the geologic evolution of oceanic islands edifices during the shield-building phase. As described by Normark et al. (1993) landslides produced by the collapse of volcanic edifices take various forms ranging from slumps, debris avalanches to debris flows. Slump movement is an elastic-plastic flow involving rigid blocks that are internally undeformed and are displaced along curved slip surfaces. If not modified by concurrent or subsequent volcanism, slumps tend to have well-defined amphitheaters at their proximal ends that broadly correspond to the detachment surfaces of the slumps. The displaced material is generally found on the volcano flanks, reflecting the limited seaward transport of the displaced strata. The surface of the slump structures may be characterized by transverse ridges and scarps and on their seaward ends by scarps onlapping the undisturbed seafloor. These structures are rare in the Canary Islands and to date have only been described in El Hierro (Masson et al., 2002) and off the eastern side of Gran Canaria (Funck and Schmincke, 1998). Data from the present investigation suggest that such a structure may be present along the western margin of Lanzarote.

Debris avalanches cutting the flanks of volcanic edifices are elastic flows made up of internally rigid blocks that roll, slide and glide along shear planes. The avalanches are longer and thinner than slumps, with their inner side being marked by embayments. In Hawaii avalanches display a middle and distal train of hummocky debris (Normark et al., 1993) and scattered over their surfaces are blocks tens of km in horizontal dimension on their proximal ends to $<$1 km on their distal end. Jacobs (1995) proposed that avalanches might be the end result of slumping and suggested that as slumps travel across uneven slopes they break down and accelerate into avalanches. Why some terrains fail by slumping, while others having the same structure and petrology fail by formation of debris avalanches is yet to be resolved.

Debris flows are plastic flows that are characterized by shear throughout the flow. Such a flow may develop when a debris avalanche breaks apart. As defined by Masson et al. (2002) such flows only affect the sedimentary cover of the submarine island slopes, whereas debris avalanches and slumps cut into the extrusive and intrusive rocks of the island. Such a debris flow in the Canary Islands is the Canary Debris Flow off El Hierro that supposedly was triggered by the El Golfo Debris Avalanche. Both debris avalanches and debris flows in turn can evolve into turbidity currents, a viscous fluidal flow (Varnes, 1958).

Turbidity currents triggered by debris avalanches and debris flows are recorded in the Madeira Abyssal Plain. Volcanic turbidites on this plain go back 17 Ma with their occurrence increasing markedly at 7 Ma, a time when the volcanic edifice in Tenerife was growing (Weaver et al., 1998). According to Masson et al. (2002) turbidites during the last 7 my reached the Madeira Abyssal Plain every 100 ky. Thus Masson et al. postulated that if each turbidite event documents a debris avalanche in the Canary Island archipelago, then the 80 volcaniclastic turbidites at Ocean Drilling Program ODP Site 951 in the Madeira Abyssal Plain since 7 Ma is a minimum record of the volcanic collapses in the Canaries during that time.

In the present investigation we use data provided by the multi-beam bathymetric map and relief and 3D diagrams to identify the facies described above. Even though avalanche scars and valleys have been modified by later lava flows, sedimentation and by subaerial and submarine erosion, scars created by mass wasting can still be recognized in Gran Canaria and exotic blocks on the Fuerteventura insular margin. Slope segments not affected by such avalanches tend to terminate abruptly down slope, are more irregular and much steeper than scarps created as a result of an avalanche; they have gradients as high as 30°. In contrast, those slope segments affected by avalanches tend to be smoother than the original rough volcanic slope and have gradients ranging from 10° on mid slope to 5° on the lower slope/upper rise (Gee et al., 2001a; Masson et al., 2002). Slope segments created by avalanches also can be distinguished from those created by turbidity currents by their concave upward profile, their low relief and their linear flat-bottomed channels. In contrast, slopes created by turbidity currents are convex upward and are characterized by a high relief trunk tributary/distributary system (Masson et al., 2002). V-shaped channels in a slope created by an avalanche are restricted to the uppermost insular slope and merge down slope into a single flat-bottomed low, a channel that lacks distributaries and maintains its character to its distal end. These valleys also display features that have not been observed in the V-shaped turbidity current canyons, such as arcuate steps and longitudinal parallel ridges undulating down channel disrupting the valley floors. Such ridges, described from known volcanic avalanches, are either the creation of compression or scour. If compressional, they were created by velocity differences in adjacent flows such as in the ridges in the Mount St. Helens Avalanche, offshore British Columbia and offshore Norway (Voight et al., 1981; Prior et al., 1982; Bugge et al., 1988). The distal ends of avalanches consist of lobes onlapping each other and the undisturbed deep-sea sediments beyond the catastrophic flow. The surface of these lobes tends to be disrupted by linear hummocks and lows that

Voight et al. (1981) have interpreted as grabens and horsts formed as a result of lateral spread within the apron.

The most unique feature displayed by 3D diagrams created from the multibeam surveys is the rough surfaces of the avalanches. Side-looking sonar and seismic reflection recordings demonstrate that some of these features represent post-avalanche volcanic cones and others represent exotic blocks scattered over the surface (Moore and Clague, 2002). The dimensions of the exotic blocks (hundreds of meters long and tens of meters thick) are clear evidence that they could only have been transported by a massive flow, not by turbidity currents. The lack of coherent deformation structures (e.g. transverse fault zones and scarps) in the avalanche deposits is another argument against slow and episodic slumping. Furthermore, the distances of the exotic blocks from probable sources also demonstrate that they could not have been transported to their present site by slumping.

Various processes may account for the present location of the blocks. They may have glided along the surface of the avalanche to their present sites with the excess pore water pressure in the avalanche acting as a lubricant. Possibly they were carried to their present location within the flow or along its surface where they were supported by a matrix of fine sediment (Bugge et al., 1988; Lee et al., 1993). As the blocks retained their identity during their transport it indicates that the blocks were more resistant to the internal shear of the flow than the other material making up the avalanche. Teide Group (1997) noted that some of the blocks had enough momentum to outrun the main part of the flow. Offshore Tenerife these blocks also controlled the locations of the post-avalanche turbidity current fans beyond the exotic blocks.

Ages assigned to the various debris avalanche deposits mapped in the Canary archipelago are generally (but not always) based on the ages of the collapse structures onshore from which the debris avalanche deposits appear to originate; alternative approaches include inferences from the thicknesses of later sediment cover as imaged by backscatter measurements, and indirect upslope correlations from major turbidite units in adjacent basins (Masson, 1996; Masson et al., 2002). However, as documented by the bathymetry map compiled by the present swath data, the onshore and offshore structures are not continuous, but are separated by a several hundred meter high scarp on the upper insular slope. Also differences in backscatter measurements between adjacent flows may not reflect different ages, but the presence of a volcanic cover or differences in rate of deposition.

Collapse of the Canarian Volcanoes

Islands in posterosional stage

Lanzarote-Fuerteventura: Inshore

Lanzarote and Fuerteventura, at the eastern end of the Canary Island archipelago, are separated by the less than 50 m deep La Bocaina Channel (Figure 1). They form a contiguous high, the Canary Ridge, with its northern end being defined by Conception Bank at 30–31°N. Ancochea et al. (1996) proposed that the Canary Ridge was constructed by a row of volcanoes aligned subparallel to the African coast, volcanic edifices that were built during several submarine and subaerial phases. The ridge and the islands along its crest appear to be the result of three igneous episodes and one erosional cycle. The earliest volcanic episode, the seamount phase, is represented by the Basal Complex along the west side of Fuerteventura (Figure 3). In Lanzarote this complex may be buried in the center of the island at depths of 900–2700 m below sea level (Coello et al.,1992). The tabular lavas and pyroclastic rocks resting unconformably or comformably on the Basal Complex represents the shield phase. This volcanic phase was followed by an erosional cycle that in turn was followed by another volcanic cycle represented by lava flows and volcanic cones oblique to the long axes of the islands.

Two Miocene volcanic edifices, Famara and Los Ajaches, constructed during the shield phase have been mapped over the Basal Complex in the northeastern and southwestern parts of Lanzarote (Figure 3). Famara, with an elevation of over 600 m, was built during late Miocene-Pliocene eruptive cycles 10.2-8.7, 6.5-5.7 and 4.9-3.9 Ma (Carracedo and Rodríguez Badiola, 1993; Coello et al., 1992; Ibarrola et al., 1988; Hausen, 1959). Los Ajaches edifice, with a maximum elevation of 560 m, was build up in the Miocene between 16 and 12 Ma (Ibarrola et al., 1988; Coello et al., 1992). The western part of this volcano is covered by younger flows (Abdel-Monen et al., 1971; Coello et al., 1992; Carracedo and Rodríguez Badiola, 1993). Ancochea et al. (1996) inferred that Famara was originally 1.0–1.3 km high and Los Ajaches 1.1–1.4 km high. The post erosional volcanic phase in Lanzarote that followed a 2 my long erosional phase following the construction of Famara

(Miocene-Pliocene) and Los Ajaches (Miocene) consists of scattered volcanoes and associated lava fields of late Pliocene-Holocene age trending northeast and east-northeast (Coello et al., 1992). Some of these flows were extruded as recently as the 18th century. Raised marine terraces and beaches and Tertiary marine and lacustrine limestone at elevations of 55-60, 20 and 10 m document uplift of Lanzarote since the Pliocene (Hausen, 1959; Coello et al., 1992; Stillman, 1999). 12 Quaternary marine terraces from 0 to 70 m above sea level support such uplift (Zazo et al., 2002). The terraces document an uplift of 1.7 cm/1000 years for Lanzarote and Fuerteventura for the last million years. Present elevation of the last interglacial deposits further suggest that during the last 300,000 years Lanzarote has experienced subsidence of about 0.7 cm/1000 years whereas Fuerteventura has been stable during that time. Limestone and conglomeratic layers composed of rounded pebbles of colored limestone also occur in Graciosa and limestone ejecta in Roque del Este. Sediments similar to these, unsorted coral breccia-conglomerates, also have been described from Molakai and Lanai, Hawaiian Islands. Moore and Moore (1984, 1988), Moore et al. (1994) and Moore (2000) proposed that these sediments, occurring <60 m above sea level and nearly 2 km inland from the present shoreline in Molokai, were deposited by a giant tsunami wave triggered by one of the submarine slides mapped on the lower slopes of the Hawaiian Islands. However, the association of the deposits in Lanzarote and Fuerteventura with marine terraces and their occurrence at elevations of less than 10 m above sea level in Graciosa and Roque del Este suggest that such an origin is unlikely for these deposits. Some workers have even rejected a tsunami origin for the deposits in the Hawaiian Islands and have interpreted the elevation of these sediments in Molakai as a result of uplift due to lithospheric flexure rather than deposition by a giant tsunami wave (Grigg and Jones, 1997).

Fuerteventura can be divided into three topographic provinces parallel to the island's long axis (Figure 2). Along the west side is the Western Domed Area, in the center a Central Depression and on the east side the Eastern Rise. The Western Domed Area is an elongate oval area, with an elevation of 200 to 300 m, in which the seamount Basal Complex is exposed (Figure 3). Stillman (1999) inferred that the uplift, which occurred as a result of either isostatic rebound or thermal uplift, is recent. Prior to the uplift of the Western Domed Area the Central Depression extended westward to the coast. The Central Depression, with an elevation of 100 m to 200 m, probably first formed as much as 18 Ma (Stillman, 1999) and is now covered by a succession of recent sediment and Pliocene and Pleistocene volcanic rocks. The Eastern Rise dips eastward with a 20° gradient and is cut by 'barrancos' separated by sharp-crested divides (Cuchillos) draining radially away from the center of the island toward the west (Ancochea et al., 1996). This terrain is a remnant of the shield phase.

Volcanism in Fuerteventura was initiated sometime after the Cenomanian (Late Cretaceous) and before or during the Paleocene (Stillman, 1999). Submarine volcanic activity occurred, perhaps only episodically, between the Paleocene and the late Oligocene with initial emergence of parts of the island taking place before 20 Ma (Figure 3). Fragments of plutonic rocks indicate part of the island was undergoing erosion at that time (Robertson and Stillman, 1979). During the shield stage volcanic phase three volcanic structures were built in the northern (Northern Volcanic Complex, 14-12 Ma), central (Central Volcanic Complex, 20-18 Ma and from 17.5-13 Ma) and southern (Southern Volcanic Complex, 16-14 Ma) parts of the islands (Figure 3). Amanay Bank and El Banquete (Figures 1 and 2) offshore the southern end of Fuerteventura may correspond to other volcanic edifices. The summits of the northern central and southern volcanic complexes may have reached heights of 2300–3000 m, 2600–3300 m and 1600–2100 m above sea level (Stillman, 1999). The Southern Volcanic Complex at the southern tip of Fuerteventura in the Jandía peninsula is separated from the Central Volcanic Complex by El Jable, a narrow low covered by eolian sands and calcrete (Figures 1 and 3). Like the Central Volcanic Complex this volcano also was centered offshore of the present shoreline (Ancochea et al., 1996). The volcano remnant of the Southern Volcanic Complex consists of a northward facing convex scarp, La Pared, cut by radial 'arroyos' draining westward and separated by narrow divides (Cuchillos). North of La Pared is an arcuate low marked by prominent valley formed by the convergence of the gullies cut on La Pared. At least half or more of the South Volcanic Complex slid seaward in the Miocene producing the 3 to 7 km wide, 45 km long north-northwest trending low east of Amanay Bank. As in Lanzarote the shield phase in Fuerteventura was followed a major phase of erosion during which the Basal Complex was exposed and relief was decreased to around 200 m in less than 2 m.y. (Stillman, 1999). After the erosional phase

Miocene basalts and Pliocene to Pleistocene volcanic rocks covered a small area of the Basal Complex and the Central Depression.

Stillman (1999) proposed that denudation of Lanzarote and Fuerteventura during the erosional cycle was by massive landslides, multiple slips that transported the volcanic structures northwestward into the sea. Stillman calculated that during this cycle as much as 3000 km^3 was removed from Fuerteventura in less than 2 m.y. The 17.6 to 16.5 Ma debris deposit cored at Deep Sea Drilling Project (DSDP) Site 397 (Figure 1) are evidence of such destruction in Fuerteventura or Banquete Bank southwest of the island. The flow has an average thickness of 20 to 30 m, forms a 5 to 25 km wide narrow tongue trending southwesterly along the base of the African continental slope, has an area of 2000 km^2 and a volume of 50 km^3 (Arthur et al., 1979). As the debris flows are mainly hyaloclastics with abundant palagonitized sideromelane shards they probably reflect a submarine shield-building stage of Fuerteventura or the bank (Schmincke and Von Rad, 1979). The microgabbro fragments in the flow suggest that part of Fuerteventura, or the bank, was already above sea level.

Lanzarote-Fuerteventura: Offshore

Our present discussion is limited to the west side of the Canary Ridge. In another paper (Acosta et al., this issue) we discuss the nature and origin of the morphology of sea floor of the Canary Channel east of the ridge. The characteristic topographic features of the western insular margins of Lanzarote and Fuerteventura are ambiguous. The presence of features that may be exotic blocks, however, has led us to infer that mass wasting has played a major role in the shaping of the margin. We argue that, the margin has been created by mass wasting, turbidity current activity and hemipelagic deposition.

Evidence of debris avalanches due to the collapse of the volcanic edifices is not apparent on the offshore swath bathymetry west of Lanzarote. The multibeam relief diagram of this slope does not display the morphologic characteristics of debris avalanches, such as coastal embayment and scars created by avalanches (Figure 4). Instead it indicates that the margin is dominated by a seaward-dipping platform bound by scarps on the landward and seaward sides. Seaward of the ramp is a northeast-oriented sediment wave, the Lanzarote Sediment Drift, that we infer to have been sculptured by the southerly flowing North Atlantic Deep Water (NADW) at a depth of 2000–3800 m. The ramp's surface is cut by narrow gullies or rills and above it rise 100 m high circular mounds (Figures 2, 4 and 5). These mounds are aligned at right angles to the slope's contours with the gullies between them terminating abruptly up slope. We infer that the highs are volcanic cones and the gullies were probably eroded out of a thin sediment cover. That the cones are volcanic structures is plausible as Lanzarote experienced extensive volcanism in the 18th century (1730-36). Contemporary accounts cited offshore explosions and discoloring of the water, and finding of unknown species of deep-sea fish killed and brought to the surface (Carracedo and Rodíguez Badiola, 1993), (Figure 3). The origin of the ramp is yet to be resolved. It could be a massive slump, but as no rotation appears to have taken place along the inner scarp it precludes such a possibility. The ramp probably represents an avalanche that broke apart during its displacement.

Like the Lanzarote the margin offshore Fuerteventura also lacks features characteristic of a mass wasting terrain. It too lacks coastal embayments and slopes scars produced by avalanches. However, the land geology with its history of catastrophic collapses of mass wasting indicates that landslides played a major role in the sculpturing the island's margin. A spur-like feature south of 28°30′ N divides the northwest insular margin of Fuerteventura in two (Figures 2, 4 and 5). This feature was inferred by Ancochea et al. (1996) to represent an erosional remnant of the Central Volcanic Complex whose center was located offshore of the present shoreline. The insular slope/rise northeast of the spur is characterized by northwest-trending lobes separated by V-shaped to box-shaped valleys. Along the crest of one of the lobes is a meandering valley with short distributaries. This lobe and valley morphology terminates rather abruptly at a depth of 3000 m. Along this seaward edge are a 22 × 11 km rectangular flat-topped high, a 4 × 4 km high and an 11 × 6 km elliptical shaped high (Figure 4). Short box-shaped valleys separate these highs from one another. We infer that these highs represent very large exotic blocks carried to their present sites by the debris avalanches that originated during the collapse of the Northern and Central Volcanic Complexes. We have named this unit, with an area of 3500 km^2, the Puerto Rosario Debris Avalanche (Figure 4; Table 1). Such an interpretation of the highs may not be unrealistic because a seismic reflection profile recorded by Uchupi et al. (1976) shows that basement immediately west of Banquete Bank is 1.5 seconds (1500 m; assuming a sediment velocity of 2 km/sec) below the seafloor. However, in the

Table 1. **Statistics of Landslides**

Dimensions of El Julan Debris Avalanche and Canary and Saharan debris flows are from Masson et al. (2002); thickness of units used to calculate volumes are from Masson et al. (2002) and Teide Group (1997); ages are from Cantagrel et al. (1999), Carracedo et al. (1999a), Urgeles et al. (1997; 1999), Masson et al. (2002) and extrapolation from onshore geology. Areas of units inshore and offshore were calculated by tracing their outlines; cutting and weighting them, and converting their weights into areas by dividing them by the weight of a known area. DA=Debris Avalanche; DF=Debris Flow; S=Slump.

Name	Type	Length (km)	Max. Width (km)	Area (km^2)	Volume (km^3)	Age
Lanzarote	S?	>40	>30	>800		18-16 Ma
Fuerteventura						
Puerto R.	DA?	70	50	3500		>17.5 Ma
S Puerto R.D.C	DA?	35	45	1200		>17.5 Ma
Gran Canaria						
Las Palmas	DA	45	25	1100		9 Ma; 4.0-3.5 Ma
Galdar	DA	30	10	300		4.0-3.5 Ma
Agaete	DA	30	7	200		12?/14? Ma
NW	S	50	7	400		15 Ma
SW	DA	30	10	250		4.0-3.5 Ma
R. Nublo	DA	12	11	150		4.03.5Ma
La Gomera						
I	DF?	15	10	80		4.0? Ma
II	DF?	10	15	80		4.0? Ma
III	DF?	45	15	340		4.0? Ma
IV	DF?	45	8	160		4.0? Ma
V	DF?	40	16	300		4.0? Ma
VI	DF?	20	5	40		4.0? Ma
VII	DF?	24	7	50		4.0? Ma
VIII	DF?	32	25	300		4.0? Ma
Tenerife						
Teno	DA	35	15	400		6 Ma
R. Garcia	DA	95	30	2200		0.6-0.7? Ma
Icod	DA	95	18	1500		<0.15 Ma
Tigaiga	DA	30	10	200		>2.3 Ma
Orotova	DA	75	40	2200		0.69/0.54 Ma
Anaga	DA	33	15	500		
Güimar	DA	85	45	2600		<0.84 Ma
A	DA	22	4	80		
B	DA	17	5	80		
C	DA	7	5	30		
La Palma						
PV	DA	50	35	1600	520	1.0-0.8 Ma
CN	DA	43	30	700	80	<536->125 Ka
W-PN	DA	>40	15	>300		
E-PN	DA	40	11	400		
SC	DA	50	35	1700		>1.0 Ma
El Hierro						
Golfo	DA	60	50	1700	170	9/15-10/17;17-9 Ka
PN	DA	35	25	1300		
LPI	S	30	15	1300		545-261/176 Ka
LPII	DA	45	340	350	<50	545-261/176 Ka
Julan	Da	48		1800	130	500-300;130 Ka
Debris Flows						
Canary	DF			40,000	400	13–17 Ka
Saharan	DF			48,000		60 Ka

absence of seismic reflection profiles directly over the features themselves the possibility that they represent peaks in oceanic basement cannot be dismissed.

The insular slope/rise south of the spur at 28°30′ N consists of sediment lobes cut by a complex of valleys. Although the terrain has the appearance of being formed by turbidity current processes, we propose that this process only contributed to the modification of a pre-existing terrain. We infer that debris avalanches triggered by the collapse of the Central and South Volcanic Complexes contributed to the original construction of this terrain. At least half or more of the South Volcanic Complex slid seaward in the Miocene (Ancochea et al., 1996) producing part of the 3 to 7 km wide, 45 km long north-northwest trending low east of the Amanay and northeast of Banquete Bank (Figures 4 and 5). Banquete Bank, southwest of Fuerteventura, is a flat-topped high with a minimum depth of 60 m that is attached to the island. It appears to consist of two circular highs whose geometry is suggestive of volcanic construction. If so then the geometry of the South Volcanic Complex differs from that described by Ancochea et al. (1996). It may have consisted of three overlapping volcanoes, rather than a single edifice (Figures 2, 4 and 5).

The west and southwest sides of the Banquete Bank are scalloped suggestive of mass wasting. Northwest of the bank is an apron cut by gullies draining into a valley between El Banquete and Amanay Banks. Northeast of Banquete Bank is a triangular shaped smoothed top sediment lobe whose northern tip is cut by low relief gullies radiating outward. Its southern tip, next to the bank, terminates on a northeast-trending scarp whose surface is gullied. The feature may define a detachment surface suggesting that the triangular sediment body is a debris avalanche or slump. East of this slump is an amphitheater-like indentation on the Fuerteventura insular slope whose surface is characterized by small gullies and intervening ridges. This feature also may document a mass wasting episode.

Immediately north of Banquete Bank is Amanay Bank that Ancochea et al. (1996) interpreted as a submarine volcano. The apron on the southwest side of the bank is narrow and terminates against a valley that originates in the low between Banquete and Amanay Banks. On the bank's west side is a sedimentary apron cut by gullies that fan out down slope. The bank's northeast side is dominated by two box-shaped valleys whose distal ends are bordered by levee-like ridges. Southeast of this valley system is a small circular high that is either an exotic block or a volcanic cone and a grid system of narrow highs and lows. These highs and lows are flanked on their east side by a valley that separates them from a sediment lobe off the northern tip of Banquete Bank (Figure 4). Overall the morphology of Banquete and Amanay Banks appears to be the creation of mass wasting followed by a more recent cycle of turbidity current deposition. We have named this multiple event deposit feature, covering an area of 1200 km^2, the South Rosario Debris Avalanche Deposit Complex (Table 1). If this morphology does reflect mass wasting it was created by the collapse of the South Volcanic Complex in Fuerteventura and the volcanic edifices in Banquete and Amanay Banks.

Gran Canaria: Inshore

Gran Canaria, a nearly circular island with a diameter of 45 km and an area of 1532 km^2, is separated from the southwest end of the Canary Ridge by a 50 km wide north-south trending low (Figures 1 and 2). The highest point in the island, Pico de Las Nieves, has an elevation of 1949 m (Figure 6). The peak is located in the center of the island from which a radial system of canyons, known locally as barrancos, extends to the coast (Funck and Schmincke, 1998). Several valley-embayments dissect the island coastal region. The largest of these, Caldera de Tejada, extends from the western edge of the island to nearly its center (Hausen, 1962). Another large embayment, Caldera de Tirajana occurs on the southeastern sector of Gran Canaria. Young volcanic cones occur over the northern half of the island down to the coast forming a promontory, La Isleta (Figure 6). Many of the lava streams from these structures have partly filled the barrancos, subduing the topography. The island's coast is generally smooth being disrupted by a few promontories such as La Isleta in the northeast, Punta de Arinaga in the east and Maspalomas, a broad headland, in the south.

The major subaerial magmatic episodes, which build the island, took place in the Miocene between 16 and 9 Ma (Figure 6) (Funck and Schmincke, 1998; Schmincke and Sumita, 1998). Volcanic activity was absent from 9 to 5 Ma, and the island, which had an elevation of about 2000 m, was deeply eroded and debris flow fans were deposited over the eroded Miocene igneous rocks. Above these sediments are 5 Ma nephelinites and basanites and the Roque Nublo Group, a post-erosional feature, emplaced between 4.0 and 3.5 Ma. A stratocone, possibly as high as 3000 m, was constructed above the eastern rim of the Miocene caldera during the Roque Nublo cycle (Funck and Schmincke, 1998; Mehl and Schmincke, 1999). A possible brief gap in volcanism was followed by another period of volcanism 3.2 to 1.8 Ma. Quaternary volcanism has been restricted to the northern half of the island. Such activity may have constructed the volcanic edifice off La Isleta, whose radial lobes may represent submarine volcanic flows (Funck and Schmincke, 1998), and the circular highs in the divide between Gran Canaria and Fuerteventura. The occurrence of 3000 year BP basanite scoria cones and lavas flows indicates that Gran Canaria continues to be volcanically active.

Landslides and debris avalanches took place at the end of the Miocene basaltic shield phase 13.3-9.0 Ma and during the Pliocene Roque Nublo phase 4.0 to 3.5 Ma (Funck and Schmincke, 1998; Mehl and Schmincke, 1999). The Roque Nublo Debris Avalanche resulting from the collapse of the Pliocene Roque Nubo stratocone that crops out along the south, northeast and northwest present coast of Gran Canaria, a distribution that demonstrate that the flow must have entered the sea. Included within and on top of the avalanche are at least seven megablocks with diameters of >100 m, blocks 0.25 to 100 m in diameter, and blocks up to 100 m in diameter that were highly brecciated during the transport. The largest of the megablocks blocks (Roque Nublo Plateau) is 1200 m long, 800 m wide and about 300 m thick (Mehl and Schmincke, 1999).

Gran Canaria: Offshore

Like the insular margin offshore Lanzarote and Fuerteventura, the margin of Gran Canaria may be mainly the creation of turbidity currents and hemipelagic deposition. However, segments of the margin appear to reflect mass wasting, particularly in the divide between Gran Canaria and Fuerteventura and offshore the north and west sides of the island. The region where the Gran Canaria edifice overlaps the Fuerteventura structure is one of the most complex topographic regions in the Canary Island archipelago. It is here that Amanay and Banquete Banks offshore Fuerteventura are found. Funck and Lykke-Andersen, (1998) and Funck and Schmincke (1998) inferred that the a 200-m-deep and 3-km-long erosional channel was formed in the region by bottom currents, but the new swath data demonstrate that the topography is more complex (Figures 7 and 8). Linking Banquete Bank and a northeast-trending swell offshore Gran Canaria are two small highs separated by south and north draining channels. Along the southeast side of the swell and highs are numerous circular highs whose topography is suggestive of volcanism (Figures 4 and 7). Southeast of the swell is a sediment apron whose surface is cut by low relief gullies. This apron, flanked on the east by Banquete Bank and on the west by a deep-sea fan offshore the south coast of Gran Canaria, was formed from sediments washing over the divide between Fuerteventura and Gran Canaria (Figure 7). The contact between Banquete Bank and the overlying apron to the north is sharp with the apron gullies curving along the edge of the bank. The contact between the apron and the deep-sea fan to the west is one of overlap with the apron prograding over the fan.

Two curved north-draining valleys originating on the east side of Gran Canaria dominate the sea floor between Amanay Bank and Gran Canaria. The northern end of the valley divide is irregular and shallower, whereas its southern end is deeper and smoother. The rough topography of the northern end of the divide appears to be due to mass wasting and the smooth topography of the southern end of the divide is the result of either recent slumping or sediment being trapped behind the higher northern end of the divide. If due to sedimentation, then the deposits were dammed behind the detachment surface of debris avalanche. At the northern end of the seaward extension of Barranco Silva (Figure 6), is a rough surfaced debris flow or avalanche. Roughness is due to northeast and northwest-trending grooves segmenting the flow. A western valley, the seaward extensions of Barranco Guiniguada, displays low relief grooves aligned parallel to its axis. They represent scour marks and the ridges flanking the distal end of this valley represent levees. Seaward of this valley is a sediment lobe that represents either a debris flow, on avalanche or a turbidite fan. We infer that much of this topography is due to a combination of mass wasting and subsequent turbidity current activity and have named the feature the Las Palmas Debris Avalanche (Figure 7; Table 1). The avalanche has an area of 1100 km^2 and is probably the consequence of three events, a Miocene (9 Ma) event that led to the construction of the bulk of the unit, the Pliocene Roque Nublo collapse at 3.5 Ma that led to the avalanches associated with the seaward extensions of barrancos Silva and Guiniguada, and post-Pliocene erosion and deposition by turbidity currents.

Between La Isleta and Galdar, at the northeast tip of Gran Canaria, is a wide valley, the seaward extension of Barranco Azuaye (Figures 6, 7 and 8). At its mouth is a rough surface sediment lobe that can

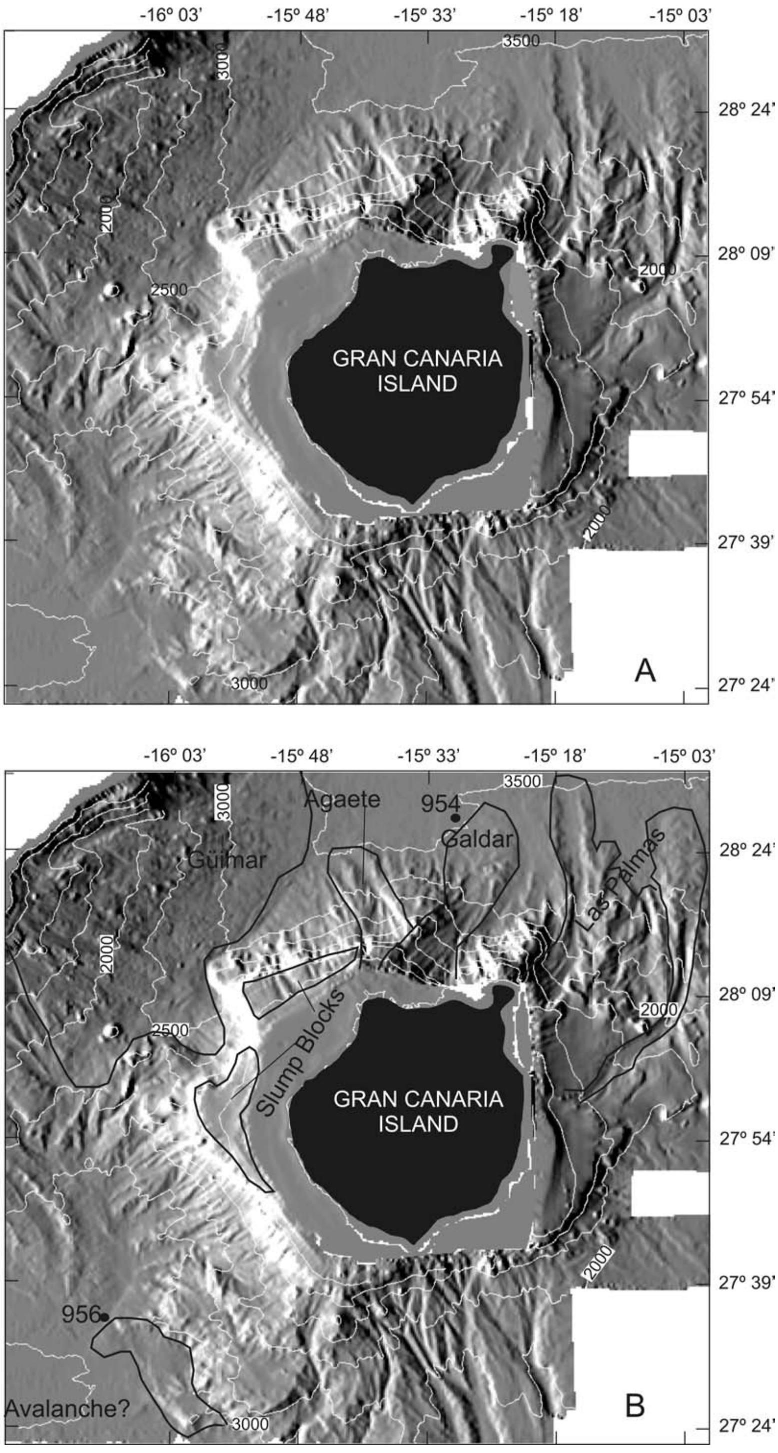

Figure 7. **A**. Shaded relief image of Gran Canaria margin. Illumination is from northwest. **B**. Shaded relief image of Gran Canaria displaying the extent of possible mass movements off Gran Canaria and eastern Tenerife.

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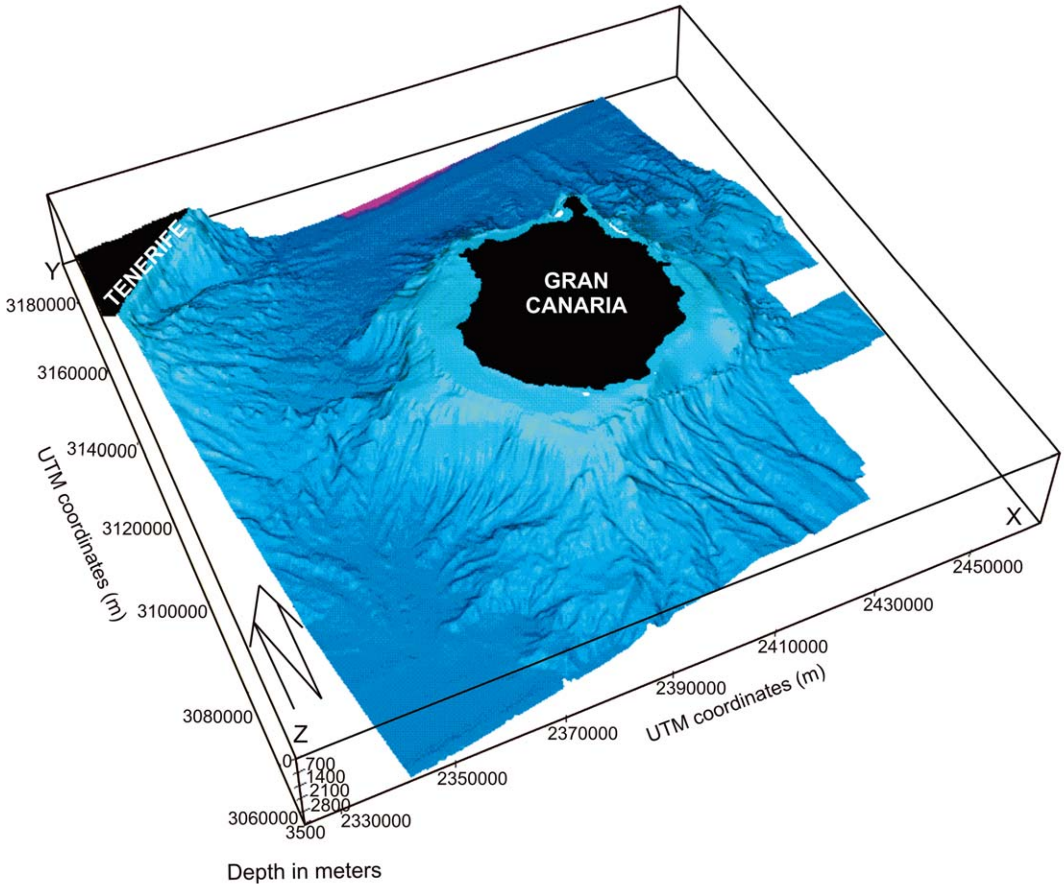

Figure 8. 3D image of Gran Canaria margin and tip of the Tenerife margin looking north. Note high linking Gran Canaria and Tenerife. It consists of basement highs and sediment ridges created by the southern flowing North Atlantic Deep Water. This high forced the Güimar Debris Avalanche off Tenerife northeast. The fan off southern Gran Canaria is separated from the apron off western Gran Canaria by a triangular shaped high, which we infer was created by intrusive/extrusive igneous activity along a rift zone. The two terraces on the upper slope separated by an embayment may be due to slumping. High on east side links Gran Canaria with Banquete Bank off Fuerteventura.

be traced to a water depth of 3400 m. This valley may have been formed by an avalanche, debris flow or turbidity current with the low grooves paralleling its axis, representing scour marks. The lobe at the mouth of the low represents sediments deposited by the avalanche or debris flow or turbidity currents. We have named the event that eroded this scar the Galdar Debris Avalanche (Table 1).

A debris avalanche origin for this valley is supported by the lithology at ODP Sites 953 and 954. (Figures 1 and 7; Shipboard Scientific Party, 1995a, b). The Miocene sediment section at ODP Site 953, the more distal site, consists volcanic debris flow and turbidites, nannofossil sediment, volcaniclastic material and distal submarine ash flows correlative with the Fataga and Mogan phases of volcanism. Also included in the section is late Miocene to early Pliocene nannofossil ooze correlative with the hiatus in volcanic activity and early to late Pliocene volcaniclastics and nannofossil ooze correlative with the Roque Nublo phase. The section at ODP Site 954, the more proximal site, consists of 15-14 Ma breccia composed of basaltic clasts with minor green hyaloclastic tuffs, lapillistone, calcareous sediment and clay and late Pliocene lapillistone with volcanic clasts (Shipboard Scientific Party, 1995b).

Funck and Lykke-Andersen (1998) inferred that the breccia unit with an area of >60 km^2 was a debris deposit emplaced >14 Ma and transported 70 km from its source. In contrast Schmincke and Segschneider (1998) suggested that the breccia unit is a consequence of the collapse of part of the shield volcano at the end of its shield-building phase. The swath bathymetry is not conclusive in regards to the origin of the breccia

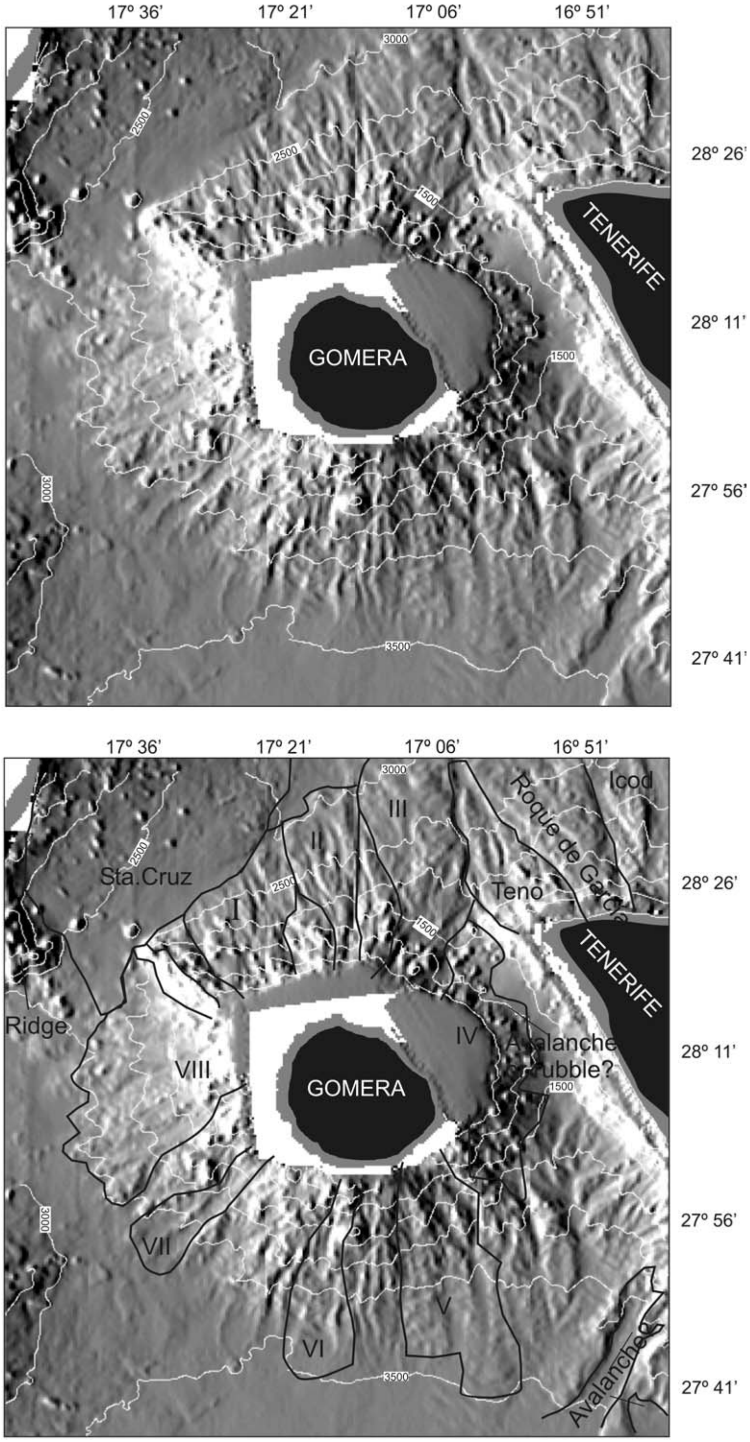

Figure 9. **A**. Shaded relief image of La Gomera margin. **B**. Shaded relief image of La Gomera region displaying possible debris flows on the margin. Note that those on the northern slope merge down slope.

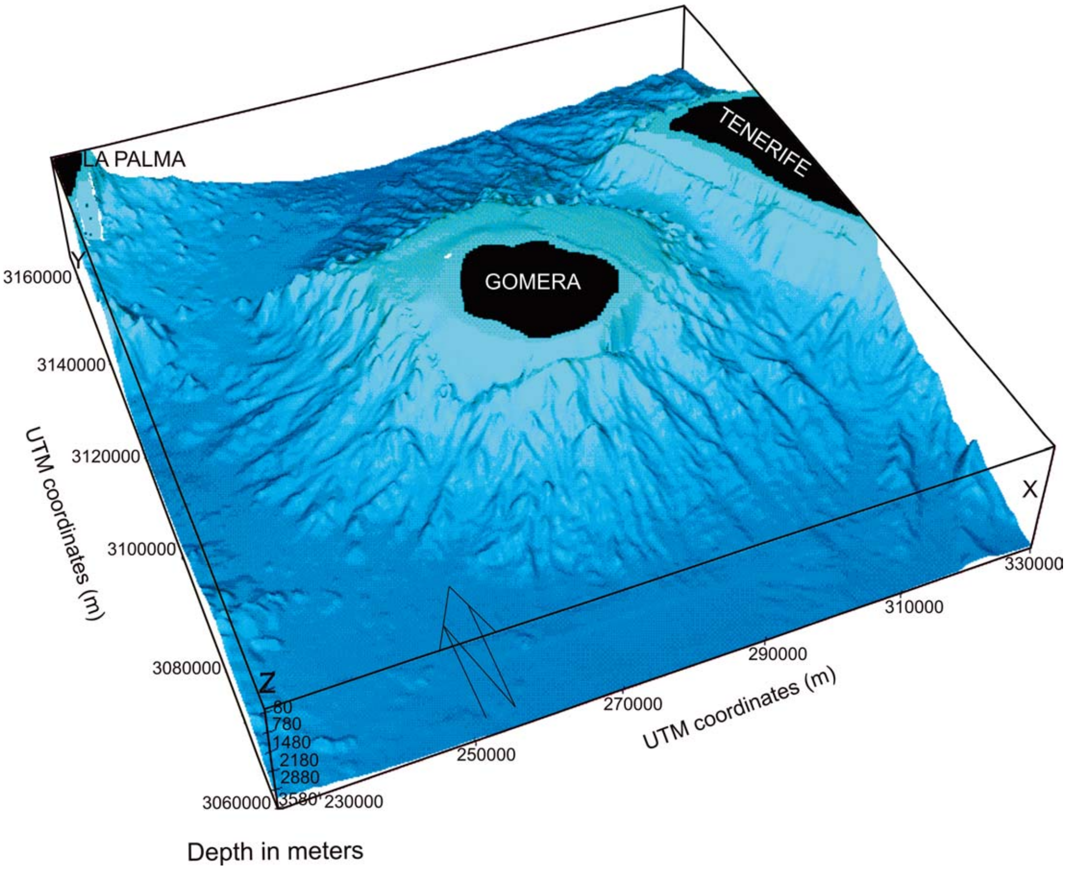

Figure 10. 3D image of La Gomera (G) margin looking north. We infer that the chutes on the right and left may represent scars eroded by debris flows. Another debris unit may be represented by the low on the southeastern slope of the island.

unit, but the location of the breccia at the mouth of valley appears to support Funck and Lykke-Andersen (1998) speculation that the breccia is a debris flow that originated 70 km away. We suggest that the valley was formed or exhumed during the Roque Nublo phase 4.0-3.5 Ma. We further propose that the path of the Miocene avalanche responsible for the deposition of the breccia lay farther west, probably the low offshore Galdar. We infer that the valley was created by a flow that we named the Agaete Debris Avalanche (Figure 7; Table 1). It was this Miocene flow that deposited the lobe offshore Galdar, a lobe that was cut during the Roque Nublo event leading to the formation of the Galdar Scar.

The northwest coast of Gran Canaria, between Galdar and San Nicolas, is dominated by a broad 19 km wide and 4.5 km deep coastal re-entrant. Its landward side is characterized by a >1000 m high cliff displaying a gradient of 45°. Funck and Schmincke (1998) proposed that this feature is the head of a landslide comparable to those found in El Hierro. They suggested that the collapse is related to the formation of the Tejada Caldera during the Miocene about 15 Ma. Offshore the feature is characterized by protrusion on the insular shelf at the north and a re-entrant at the south. A seismic reflection profile recorded by Funck and Schmincke (1998) shows that two wedge-shaped sedimentary units, pinching out at a depth of 1000 m, mantle the protrusion. The top of the wedge forms the insular slope and its outer surface the upper insular slope. The 180 m thick upper unit consists of volcaniclastics and biogenic sediments emplaced after the collapse of the coastal low. The over 200 m thick lower unit may represent debris flows emplaced during the collapse of the low with the shelf protrusion representing a massive slump block. The displacement of the slump supposedly formed the shelf's re-entrant south of the protrusion. The seafloor seaward of the protrusion ranges from mounds to northeast-trending furrows on the surficial sediments blanketing the Tenerife volcanic edifice. The mound topography may be related to sediment recently displaced from up the Tenerife insular slope. The furrows are probably of erosional origin and were created by southerly flowing NADW (Teide Group, 1997).

West of Barranco Aldea (Figures 6 and 8) is a northeast-southwest trending irregular surfaced ridge linking the Gran Canaria and Tenerife margins. Seismic reflection profiles recorded by Teide Group (1997) indicate that the high consists of oceanic basement highs and sediment waves formed by the south-flowing NADW. The protrusion of Gran Canaria shelf's edge south of San Nicolás is the seaward edge of a scar in the Miocene shield volcano (Figure 6). The low defined by this scar, the Horgazales Basin of Schmincke (1968), is filled on land with late shield basalts of the Mogan Group. If so this suggests that the scar is >14.1 Ma, Funck and Schmincke (1998) suggested that the offshore extension of this low is filled with volcanic debris comparable to those onshore. They interpreted a 650 m thick lower sediment unit imaged by seismic reflection profiles as possibly representing this volcanic debris flow. Schmincke and Segschneider (1998) speculated that this debris flow was created by the collapse of the subaerial and submarine flank of Gran Canaria to form Horgazales Basin. Funck and Schmincke (1998) further speculated that the hummocky topography seaward of Horgazales Basin represents slump blocks formed during the creation of the low. An 80 m thick Miocene debris flows cored at ODP Site 956 support such a collapse model (Shipboard Scientific Party 1995c).

The Gran Canaria southwest slope is characterized by a V-shaped northeast-trending valley system, draining into a northwest-trending trough at a depth of 3000 m. A narrow ridge, possibly generated by volcanism along a rift, dominates the margin off the southwest tip of Gran Canaria. At the end of this ridge is a smooth northwest-trending platform partially fronting a sediment apron (Figure 7). The northeast side of this platform is gullied and its southwest side is scalloped suggesting that the high has experienced mass wasting. Whether the high is a volcanic construction or represents an exotic block displaced from Gran Canaria cannot be determined from our data set. That it may represent an exotic block is not unrealistic as mass wasting deposits have been documented at ODP Site 956 just west of the high (Figures 1 and 8). The early Pliocene to late Miocene nannofossil ooze at this site is characterized by slump structures and slump debris that were emplaced during the collapse of the shield volcano that led to the formation of Horgazales Basin >14.1 Ma (Shipboard Scientific Party, 1995d).

The Plio-Quaternary section at Site ODP 956 consists of nannofossil ooze interbedded with coarse debris rich in pumice whose source is Tenerife. Schmincke and Segschneider (1998) speculated that the 75 to 100 m thick sandstone interbedded with turbidites of mixed volcaniclastics and biogenic sediments above the debris flow is a tsunami deposit. They pointed out that its composition indicates that the sandstone was derived from a mafic/ultramafic source and proposed that it was derived from La Gomera. They also point out that Gran Canaria itself could have been the source of this sediment if Jurassic oceanic crustal material was transported to the island surface by phreatic explosions.

On the southern Gran Canaria margin is a fan cut by a system of branching canyons (Figures 7 and 8). This fan, centered on Barranco de Arguineguin, was probably constructed from material discharged offshore by the radial canyons between Barranco de Mogan and Barranco de Fagata (Funck and Schmincke, 1998). Mehl and Schmincke (1999) inferred that the Pliocene Roque Nublo debris avalanche traveled more than 50 km beyond the present south coast and that a major part of the avalanche debris was deposited as a debris flow on the apex of the fan. From seismic reflection data Funck and Schmincke (1998) proposed that the lobe had an approximate volume of 20 km^3. They also proposed that canyon cutting in the fan took place during the Roque Nublo phase 4.5-3.5 Ma, an erosive phase that was aided by the wet climate that prevailed at that time. If the sediment lobe along the crest of the fan is the seaward extension of the Pliocene Roque Nublo and canyon cutting took place at 4.5-3.5 Ma, then the fan beneath the debris lobe must have been constructed during the Miocene. If so then a significant volume of debris produced by the collapse of the Miocene shield volcano at 9 Ma was transported southward to construct the fan offshore the southern coast of Gran Canaria.

Island in Repose Stage (Gap Stage)

La Gomera: Inshore

La Gomera is semi-circular in outline with an east-west diameter of 24 km, a north-south length of 20 km and an area of 378 km^2 (Figures 1 and 2). The center of the island is occupied by an undulating upland with a maximum elevation of 1375 m at Alto de Garajonay

(Figure 6). Barrancos radiate in all directions from the upland to the coast and steep and rocky cliffs, particularly in the north and south, surround the island (Hausen, 1965). Hausen (1971) inferred that the barrancos are the products of two cycles of erosion with some of the older features being cut off by precipices in the vicinity of the coast and others being deepened by younger narrow canyons when reaching the coast. With the exception of a small indentation on the west coast, La Gomera lacks the amphitheaters and buttresses characteristic of the other islands suggesting that La Gomera either has not experienced massive catastrophic failures of its volcanic edifices or these features have been erased by erosion. This denudation has not yet been followed by post-erosional volcanic activity as the island is devoid of younger volcanoes with its morphology, giving an impression of old age.

Hausen (1971) proposed that faulting has uplifted the island 900 m at the north and tilted it to the south. It is this uplift that supposedly was responsible for the creation of mountain blocks on the north and west coasts and the initiation of the younger erosional cycle that rejuvenated the older forms. Evidence for post-tectonic erosion includes the deep barrancos radiating from the island's center, the landslides in the barrancos and along the coast, the truncation of flat-lying basalts by the steep sea cliffs at the north and west coasts and the presence of a phonolitic neck at the water's edge at the northwest coast. Hausen (1971) proposed that this neck was emplaced at the time when the coast lay far to the north.

As noted by Abdel-Monem et al. (1971) the geology of La Gomera is quite simple. At the base is a basal complex comparable to the complex in Fuerteventura and La Palma (Bravo, 1964a, b; Hausen, 1965, 1971; Cendrero, 1967; Cantagrel et al., 1984). Resting unconformably on basement are the older tilted basalts (Basaltos Antiguos of Bravo, 1964a) exposed on the northeast coast. Resting unconformably on the basement and the older tilted basalts is the shield phase of volcanism consisting of basalt lavas, tuffs and agglomerates. Pliocene salic lava sheets, sills, dikes and laccoliths, represent the concluding phase of this volcanic episode.

Cantagrel et al. (1984) inferred the following history for La Gomera: 1. The age of the basement complex is not well constrained, an age of 20 Ma reported by Abdel-Monem et al. (1971) may be conservative; 2. The age of the unconformity truncating the basement complex also is unknown; 3. The Older Basalts are older than 10 Ma (Cantagrel et al., 1984); 4. Polymictic breccias above these basalts are 10 to 9 Ma and the upper old basalts 9 to 6 Ma (Cantagrel et al., 1984); 5. The hiatus truncating these deposits is 6 to 5 Ma; 6. The radial dikes were intruded at 5 Ma; 7. The Younger Basalts were extruded 4.5 to 4.0 Ma with local igneous activity taking place 2.8 Ma. Prior to the extrusion of the younger basalts the island subsided southward at 8 to 5 Ma, accounting for the greater thickness of the basalt in that direction. In time the whole island was covered by basalts. This basaltic extrusion was not continuous, but was disrupted by periods of erosion and barranco formation that were later filled by younger lavas. The volcanic phase was terminated with the emplacement of salic lavas of phonolitic composition in the form of flows, cones, dikes, sills and laccoliths. The salic volcanic phase was followed by a long period of erosion during the Pliocene-Quaternary. How extensive this erosion was is attested by the Roques. These columnar structures, that rise hundreds of meters above their surroundings, were formed by erosion of the cone leaving the conduit fill of salic lavas as erosional remnants.

La Gomera: Offshore

Much of the morphology of the insular margin of La Gomera has the appearance of a terrain created by turbidity current processes (segment II) modified to some degree by hemipelagic sedimentation. Not all the morphology, however, appears to be the creation of these two processes. For example, segment III, has the appearance of a debris flow, but again it could be interpreted as a fan. Whatever mass wasting events took place that led to the creation of the present morphology of La Gomera they are no longer recognizable offshore. What few features on the slope that can be attributed to gravitational processes originated on the insular slope and may have been triggered by turbidity currents. For example, the slope on the east side of La Gomera, segment IV, is rough and may consist of exotic blocks and represent an avalanche deposit (Figures 9 and 10). However, in the absence of sampling or bottom photographs the possibility that the highs may represent salic necks (comparable to the Roques on land) or volcanic cones or even simply valley divides cannot be eliminated. On La Gomera's northwest sector, segment I, the margin is in part in the form of a northwest-trending ridge over 100 m high which may represent a rift, with a chain of volcanic cones along its crest. The slope/rise on the island's south side consists of wide flat-bottomed valleys (segments V-VII) entrained in lobes having the appearance of deep-sea

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Figure 11. **A**. Shaded relief map of the Canary archipelago. **B**. Relief map showing the distribution of landslides on the flanks and tops of the Canary Islands. LRM= Low Relief Mounds.

turbidite systems. Segment VIII on the southwest side of the island also displays the same morphology. All in all the morphology of La Gomera, both inshore and offshore differs from the other islands. Nowhere does the morphology display features diagnostic of mass wasting.

Younger Islands

Tenerife, La Palma and El Hierro

Whereas in the older islands landslides triggered by collapse of volcanic edifices are obscured by subsequent events, those in the younger islands, Tenerife, La Palma and El Hierro, are readily recognizable and can be traced tens of kilometers offshore. On land such catastrophic episodes are documented by breached calderas, impressive coastal embayments and massive breccia flows. It is for these reasons that all investigations of mass wasting to date have been concentrated in these islands. Although our survey has provided us with an extensive data base on these events (Figures 2, 11 and 12), our description of them is brief. The reader is referred to a recent summary by Masson et al. (2002) for a discussion of the younger islands. We should mention, however, that our survey revealed avalanches north of La Palma and Hierro that were not known before and that the Santa Cruz Debris Avalanche east of La Palma is more extensive than proposed by Masson et al. (2002). Our survey also demonstrates that although the offshore landslides are aligned with the failures on land, they are not topographically continuous, but are separated by a several hundred meter high scarp on the insular slope.

Tenerife: Inshore

The pyramid-shaped Tenerife, with the double peak stratovolcano, Pico Viejo (3100 m) and Teide (3710 m), with the Cañadas Caldera at its apex, began to form subaerially 11.6 Ma (Miocene) (Ancochea et al., 1990). Resting on the older volcanic units, the Anaga, Teno and Roque del Conde massifs, are the Cordillera Dorsal and Las Cañadas volcanic edifice built between 3.5 and <0.15 Ma. The island acquired part of its present morphology as a result of volcanic collapses that took place along north draining valleys (>2.3 Ma Tigaiga Debris Avalanche; the Roques de García Debris Avalanche 0.7?-0.6 Ma; the Cordillera Dorsal and Cañadas III failure <0.84 Ma to <0.15 Ma; Orotova 0.69-0.54? Ma and Icod de los Vinos <0.15 Ma) north of the Cordillera Dorsal and a south draining valley (Güimar Valley <0.84 Ma) south of the cordillera (Cantagrel et al., 1999). The many small individual basaltic volcanoes scattered throughout the islands and the Teide-PicoViejo which erupted in historical times have added to Tenerife's morphology (Ancochea et al., 1990).

Tenerife: Offshore

On top of the offshore extension of the Anaga Massif is a valley/ridge system that can be traced to a depth of 3000 m. They define the pathways of the flows making up the Anaga Debris Avalanche lows (Masson et al., 2002). Seaward of the Teno Massif is another debris avalanche, represented on land by a breccia overlain by 6.7 to 6.3 Ma and 5.6 to 5.0 Ma volcanic rocks. Cantagrel et al. (1999) dated this avalanche as being approximately 6 Ma. East of the Teno Avalanche is another unit that Masson et al. (2002) correlated with the Roques de García Debris Avalanche on land. Seaward of the Tigaiga Massif is a triangular shaped rough surfaced high that extends to a water depth of 1200 m (Figure 11). Topographically this insular slope spur appears to be an expression of the Tigaiga Avalanche on land, but such a supposition needs to be verified by sampling. The high could simply be part of the flank of the volcanic edifice that survived the avalanches.

Between the Anaga and Teno Massifs offshore the northwest coast are two avalanche deposits that can be traced for tens of kilometers offshore, the Icod and Orotova Avalanches (Figure 11). Associated with them are small highs that Watts and Masson (1995) and Teide Group (1997) interpreted as exotic blocks transported by the avalanches. Not all the highs within the flows are of this origin. At least one high at the head of Orovota flow, however, displays a circular morphology more suggestive of volcanic construction (Teide Group, 1997). The Orotova/Icod failures supposedly triggered a turbidity current, which deposited a volcaniclastic layer in the Madeira Abyssal Plain west of the Canary Islands (Figure 1) (Rothwell et al., 1998) and Agadir Basin north of the Canary Islands (Figure 1) (Masson et al., 2002). Teide Group (1997) noted that, although the offshore slope failures are aligned with the Orotova and Icod Valleys, no topographic continuity exists between them; a north-facing 100–600 m high scarps separates them.

The southwest margin of Tenerife is rectilinear and has the appearance of a fault scarp whose movement has truncated the Teno and the Cañadas volcanic series (Figures 11 and 12). At its steepest the scarp, whose

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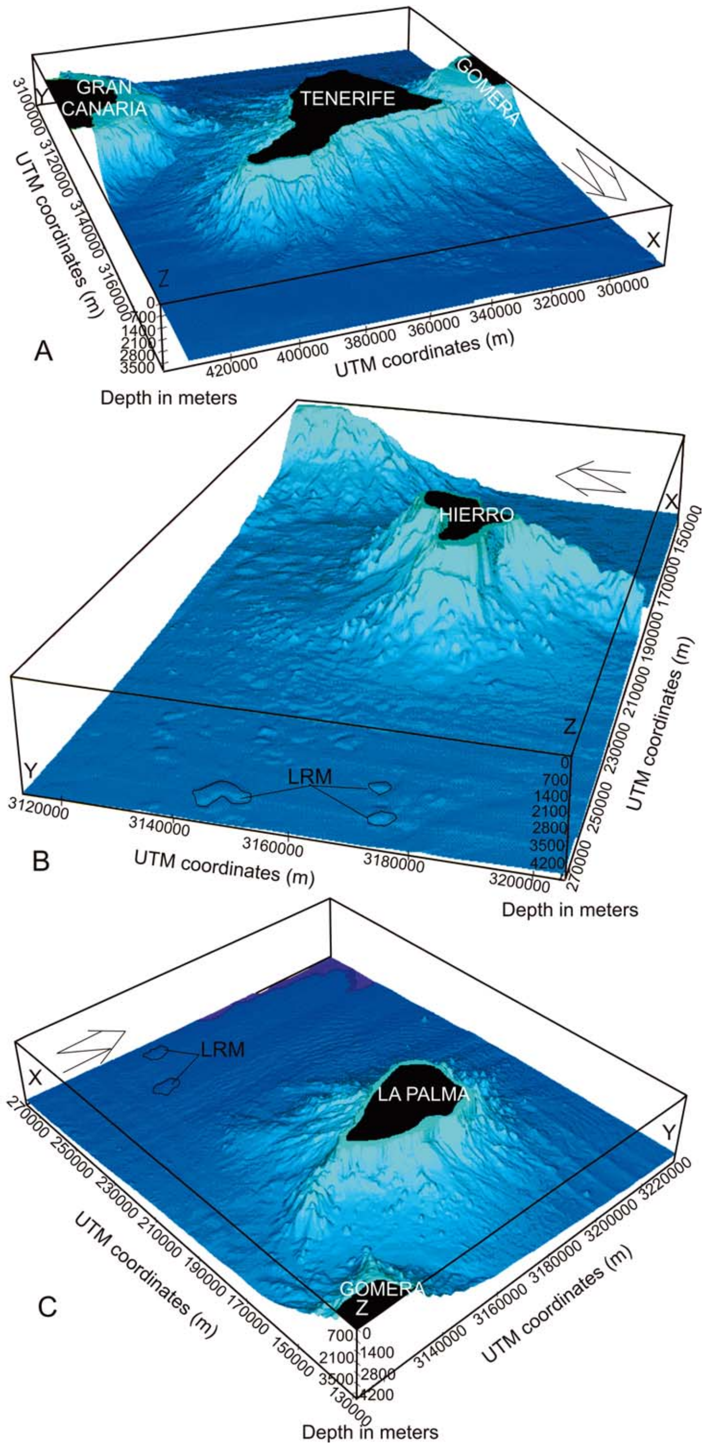

Figure 12. 3D images of the Younger Canary Islands: A) Tenerife, B) La Palma and C) El Hierro. The smooth low relief slope segments represent avalanche scars. Note the sediment drift off the distal ends of the avalanches offshore La Palma and El Hierro. We infer that these sediment waves were formed by currents of AABW. LRM= Low Relief Mounds

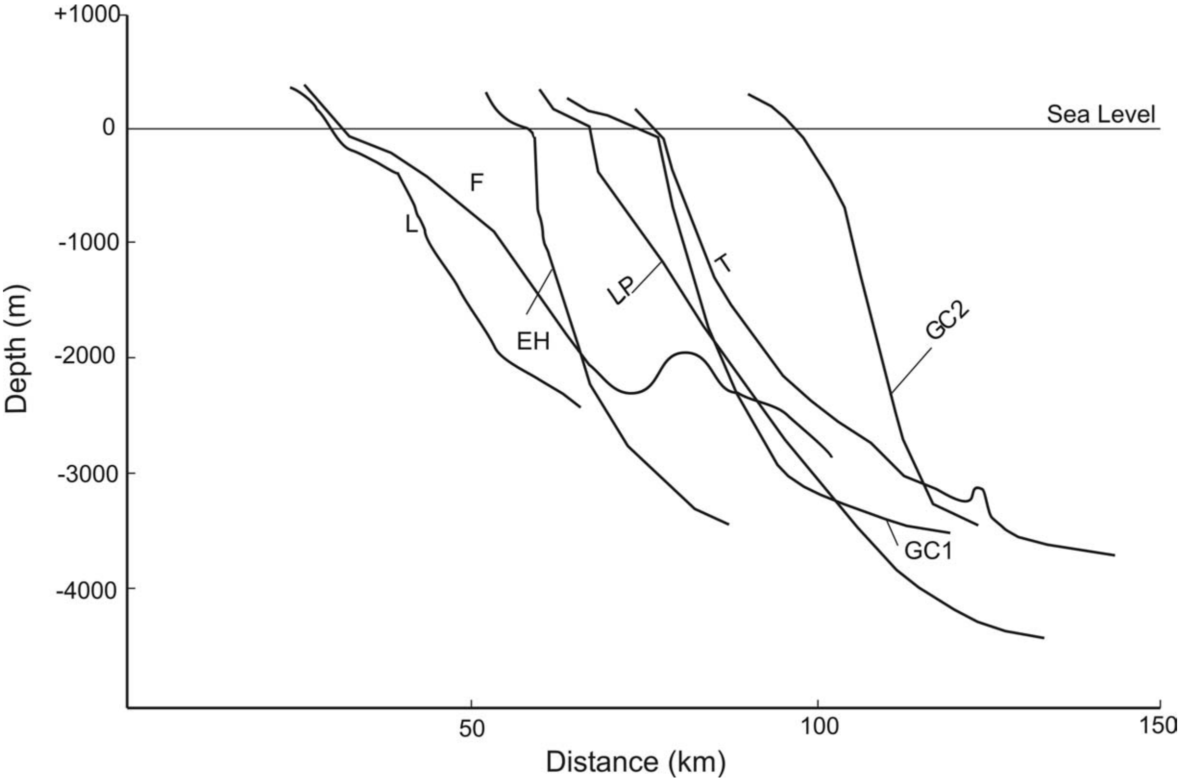

Figure 13. Depth profiles of the Canary Islands compiled from Figure 2. Note that whereas the younger islands margins display concave upwards profiles characteristic of mass wasting, Fuerteventura's and La Gomera's margins are convex upwards characteristic of a turbidity current regime. The Gran Canaria margin is both concave and convex upwards suggestive of mass wasting and turbidity currents. The platform outline of the Lanzarote margin is suggestive of slumping. EH= El Hierro; F= Fuerteventura; GC= Gran Canaria; L= Lanzarote; LP= La Palma; T= Tenerife.

base is at depths of 1500 to 1125 m, descends at a rate of 330 m per km. The scarp is divided in two by a transverse spur oriented at right angles to the coast (Figure 9). At the base of the scarp, southeast of this transverse structure, is a rise whose channels drain southwestward terminating against the rise south of La Gomera. Most of this terrain appears to be the creation turbidity current processes (Figure 9). The apron is missing northwest of the transverse high and the insular slope is bordered by a smoothed floored low. Apparently deposition on this low was primarily by pelagic processes, with little or no slope degradation from either Tenerife or La Gomera. Alternatively the lack of relief is due to lava flows.

Morphologically Tenerife's southeast insular margin, buttressed by Gran Canaria, can be divided into two provinces (Figure 12). From the Bandas del Sur to the Anaga Massif the Tenerife coast displays two embayments separated by a buttress at the mouth of Güimar Valley. The buttress is due to lava flows extruded by several volcanoes at the mouth of the valley. The embayments are the result of a catastrophic failure extending southeastward to the rise northwest of Gran Canaria where it fills a re-entrant on the Gran Canaria margin with the distal end being deflected southeastward by Gran Canaria (Masson et al., 2002). Scattered over the surface of this failure, the Güimar Debris Avalanche, are numerous highly reflective small objects, which we infer to be exotic blocks. A ridge extending from Gran Canaria to Tenerife near 28°05′ N also prevented the avalanche from flowing southwestward (Figures 11 and 12). Like the debris avalanches offshore Orotova and Icod Valleys on the northwest coast, this debris flow is separated from the unit in Güimar Valley by a 700 m high scarp that is slightly convex to the east. This slope is cut by V-shaped canyons at the mouths of which are fans resting on debris avalanche. Except for one V-shaped canyon on its northeast side due to post-failure local erosion by turbidity currents (Krastel et al., 2001), the offshore avalanche surface is smooth. Two volcanic highs within the debris avalanche deposit, indicative

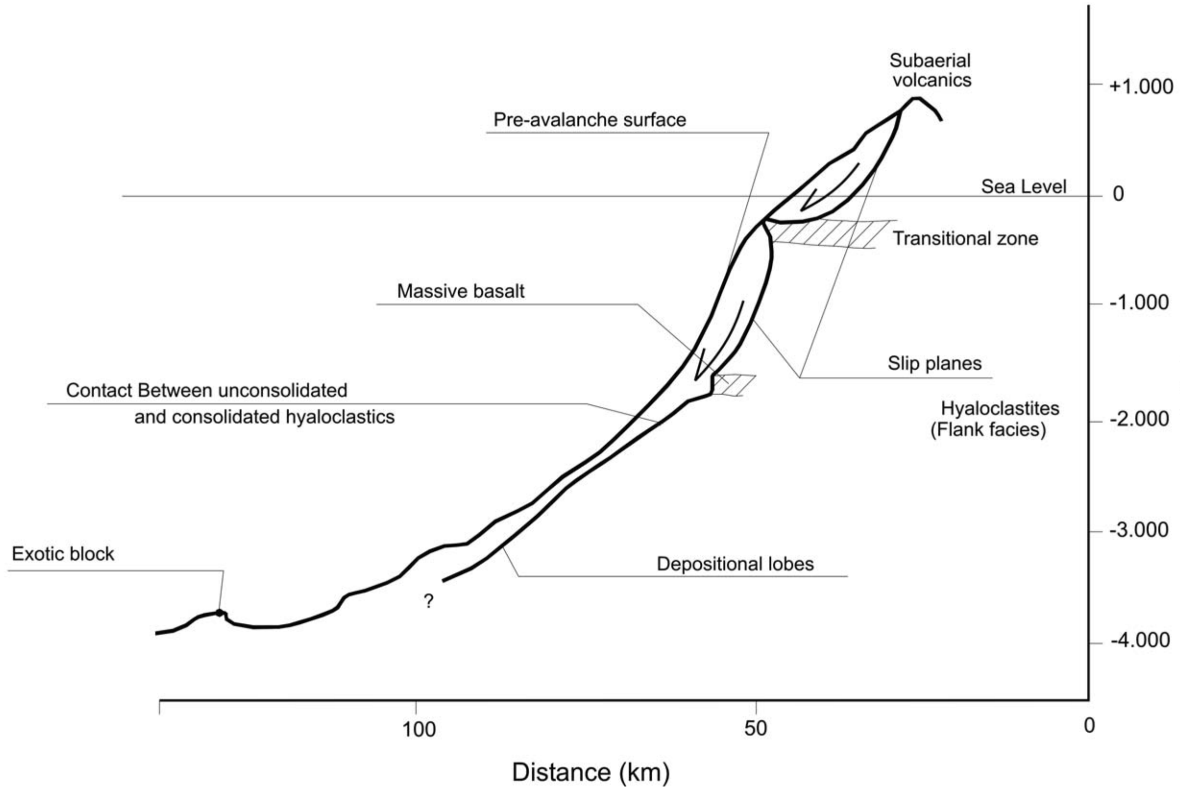

Figure 14. Schematic cross-section of the slip surfaces of the inshore and offshore debris avalanches. The inner scarp represents the detachment surface of the inshore avalanche with the base of the avalanche being along the top of the transitional zone between the subaerial and submarine lava flows. The slip surface of the offshore deposit is along the outer surface of the transitional zone. This model is modified from Jacobs (1995) using data from DePaolo et al. (2001).

of post failure volcanic construction, may be correlative with the latest Pleistocene-Holocene volcanoes in the Güimar Valley. At the distal end of the debris avalanche deposit, next to Gran Canaria, is an erosional trough that Teide Group (1997) inferred to be cut by the southwest flowing NADW.

At the southwest corner of Tenerife is the Bandas del Sur Fan, a thick pyroclastic apron that correlates with the upper group felsic formations exposed in the Las Cañadas Caldera (Ucanca Formation 1.59-1.18 Ma; Guajara Formation 0.85-0.57 Ma; Diego Hernández Formation 0.53-0.18 Ma; Martí et al., 1994). It is composed of pumice, ignimbrites, basaltic scoria cones, lavas and mudflows (lahars) with steep-sided erosional remnants of the older basaltic series rising above its general surface. Offshore the Bandas is a northwest-trending fan that can be traced to a depth of more than 3000 m (Figures 11 and 12). Its surface is cut by a system of canyons that is slightly convex toward the east. The fan is bordered on its west side by a sediment-covered ridge that may have been constructed by igneous activity along a rift. Toward the northeast the fan terminates against an oceanic basement high offshore Gran Canaria that, preliminary results suggest may represent a rift related to the volcanic construction of Gran Canaria. Further south the fan is separated from an apron offshore Gran Canaria by a northwest trending low.

La Palma: Inshore

Pear-shaped La Palma is the second youngest island of the Canary Island archipelago. Its surface is cut by many barrancos, the largest of which is the westward draining Barranco de las Angustias that originates in the Caldera de Taburiente (type caldera) whose vertical walls are up to 800 m high (Hausen, 1969) and whose floor has a maximum elevation of 1500 m (Ancochea et al., 1994). Extending southward from the rim of the Caldera de Taburiente to Punta de Fuencaliente at the southern tip of La Palma is a narrow ridge, Cumbre Vieja, whose crest is over 1300 m above sea level. Along the crest and slopes of Cumbre

Vieja, at Punta Fuencaliente, and on the outer slopes at the northern end of the island are many young cinder cones. Lava flows originating from the cones along the crest of the Cumbre Vieja extend along the east and west coasts of La Palma filling many of the barrancos in the slopes. The island's coasts are generally steep and rocky with noticeable re-entrants along the north, east and west coasts.

The earliest volcanic collapse in La Palma took place at 1.2 Ma as a result of which a south-southwest trending paleocaldera was formed at the site of the Taburiente Caldera. This relief was subsequently subdued by the construction of the southern ridge (Cumbre Nueva high) by three overlapping edifices to form the northern shield of La Palma (Carracedo et al., 2001). This structure in turn was destroyed about 0.4 Ma to form the 'Cumbre Nueva collapse scar' and the 'Caldera Taburiente'. Ancochea et al. (1994) inferred that large landslides formed both the Cumbre Nueva collapse scar and the Caldera de Taburiente 700-710 Ka, whereas Carracedo et al. (1999b) and Carracedo et al. (2001) inferred that only the Cumbre Nueva collapse scar was formed by a collapse 560 Ka. Carracedo et al. (1999b) suggested that the Caldera de Taburiente is erosional in origin and formed by a drainage system trapped between the growing Bejenado Volcano and the 558 Ka Cumbre Nueva collapse scar. More recently Carracedo et al. (2001) inferred that the geology of the caldera is due to gravitational collapse, the emplacement of the Bejenado Volcano inside the collapse structure and the incision of the Barranco de las Angustias along the western boundary of the collapse to form the Caldera de Taburiente. The Cumbre Vieja Volcano at the southern end of Cumbre Vieja Ridge began to form on the flank of the Taburiente-Cumbre Nueva Caldera about 123 Ka, a volcanism that has continued until the present (Guillou et al., 1998; Carracedo et al., 2001).

La Palma: Offshore

Like Urgeles et al. (1999) we infer that the aprons on the east and west insular margins of La Palma are the creations of mass wasting (Figures 11 and 12). They recognized two avalanche deposits on the west side of the island consisting of three lobes. They inferred that the central lobe is Cumbre Nueva and the lobe north this lobe as Playa de Veta (Urgeles et al., 1999). From its sediment cover they suggested that the southern lobe is older than the Cumbre Nueva Debris Avalanche and correlated it with the Playa de la Veta Debris Avalanche north of Cumbre Nueva. According to Urgeles et al. the onshore headwall of the Cumbre Nueva Debris Avalanche is defined by the Caldera de Taburiente and Cumbre Nueva Ridge and is 558 Ka. They correlated the Playa de la Veta Debris Avalanche Deposit with the collapse of Garafía Volcano, beneath south-southwest trending beneath Caldera de Taburiente dates from 1.2 Ma (Figure 11). According to Carracedo et al. (2001) this volcano developed steep walls closely centered over the seamount forming the foundation of La Palma. This volcano was at least 2000 m high with a diamater of 25 km and covered much of the northern end of La Palma. On land the Playa de la Veta flow may be represented by a several hundred meter thick breccia atop the seamount series in the east and southeast of the Caldera de Taburiente (Carracedo et al., 2001). We question the age assigned to the southern lobe by Urgeles et al. (1999). Instead we propose that this is part of the Cumbre Nueva Debris Avalanche. We ascribe differences in sediment cover between the northern and southern sides of the Cumbre Nueva Debris Avalanche, not to different ages, but to differences in rates of deposition, a difference documented by the thick sediment apron on the west flank of the Cumbre Vieja Ridge. Thus the avalanches off the west consist of two lobes, the Playa de la Veta to the north overlapped to the south by the Cumbre Nueva Avalanche. How far south the Playa de la Veta Avalanche extends beneath the Cumbre Nueva cannot be determined from our data.

Several small debris of limited extent were imaged by the new multi-channel data on the north insular slope (Figure 11). A third large debris avalanche off the east coast was identified by Masson et al. (2002) and named the Santa Cruz Debris Avalanche deposit. They inferred it to be older than 1 Ma and that the plane of separation of the avalanche might be located in the embayment in Santa Cruz. According to Carracedo et al. (2001), however, there is no geological evidence onshore for this slide. Data collected during the present survey indicate that the deposit is much more extensive than inferred by Masson et al. (2002). In plan view the Santa Cruz Debris Avalanche deposit displays a fan shape with its apex located in the vicinity of Santa Cruz. From its morphology the Santa Cruz Debris Avalanche appears to consist of three units, a northern one entrained by northeast-trending lows and ridges with an extensive coverage of exotic blocks, a central one also cut by similar lows bordered by ridges but with sparce coverage of exotic blocks on its surface, and a southern one lacking the lows and ridges, but having a noticeable coverage of highs that are circular suggesting that they represent volcanic cones (Figure 11). The contact between the northern and central units is gradational, with the flows being distinguished from one another by block concentration, whereas the boundary between the central and southern flow is sharp, being defined by a chain of blocks. Along the southern side of the Santa Cruz Debris Avalanche is a line of three volcanic cones extending from the offshore ridge south of La Palma (Figures 11 and 12). Along the southwest border of the Santa Cruz Debris Avalanche is a submarine ridge on strike with the Cumbre Vieja Ridge on land. This ridge plunges offshore to a depth of 3000 m, is convex in plan view and curves toward the east in the direction of the northwest trending fracture zone off La Gomera.

As there is no obvious geological evidence onshore for this slide (Carracedo et al., 2001), we suggest that its path to a potential source was buried by subsequent volcanic activity. Consequently we infer that the Santa Cruz Debris Avalanche was the creation of either the collapse of the southeast flank of the Garafía Volcano or the east flank of the Cumbre Nueva Rift. If the failure is due to the collapse of the Garafía Volcano then the Santa Cruz Debris Avalanche is 1.2 Ma and if due to the collapse of the Cumbre Nueva Ridge then the avalanche is 560 Ka. If the flow originated as a result of the collapse of the Garafía Volcano, then it probably was continuous with the Playa de Veta west of La Palma and was cut in two by the construction of Cumbre Nueva and Cumbre Vieja Ridges. If due to the collapse of the Cumbre Nueva Ridge then it may have been continuous with the Cumbre Nueva Flow Avalanche west of La Palma and was cut in two with the construction of the Cumbre Vieja Ridge.

On the distal ends of the western and eastern avalanche deposits and the rough terrain off the northern end of La Palma, at a water depth of 3600 to 4500 m, is a sediment drift. Northwest-trending channels originating on the northwest insular slope of La Palma segment the field. South of the drift are the El Golfo Debris Avalanche and the Canary Island Debris Flow (Figure 11). According to Masson et al. (1992) the Canary Debris flow is younger than the sediment drift, implying that the sediment drift is older than 15 Ka. The sediment drift is absent in the gap between the avalanche deposits offshore southern La Palma and northern El Hierro. Wynn et al. (2000) inferred that this is the result of a predominance of mass wasting processes in the region.

The crests of the sediment waves in the sediment drift are parallel or subparallel to the insular slope, with their crests being sinuous and bifurcate. According to Wynn et al. (2000) the sediment waves are asymmetrical with a steeper slope facing down slope, become smaller down slope, have average wave heights of 21 m and wavelengths of 1.2 km. Core samples indicate that the sediment waves were formed from volcaniclastic turbidites interbedded with pelagic/hemipelagic layers, and apparently have migrated upslope through time.

Two origins have been proposed with regard to the sediment drift. As the features lie within the northeast flowing Antarctic Bottom Water (AABW) Jacobi and Hayes (1992) and Masson et al. (1992) proposed that the sediment waves were or are formed and maintained by this current. Wynn et al. (2000) rejected such an origin on the basis of the following observations: (1) AABW flow in the region is weak and bottom photographs display no evidence of significant bottom current activity; (2) waves formed in this manner should be oriented at an angle to the current and will migrate up current and to the right of flow direction; those in the La Palma field, however, are aligned approximately parallel to the current and display an upslope migration; (3) the waves are located within a zone of mixing of northeast flowing AABW and southwest flowing NADW, a zone of 'no motion'; and (4) the waves display no change in direction and orientation across the zone of mixing. Although rejecting such an origin they did point out that features may be relict and may have formed during glacial periods when the AABW current was stronger.

Wynn et al. (2000) favored formation of waves by down slope turbidity currents. They point out that such an origin is supported by the following: (1) the waves are at right angles to such flow; (2) the waves display evidence of migration up slope (up current); (3) the waves decrease in size down slope, reflecting a reduction in the velocity of the turbidity currents with a decrease in slope gradient, and (4) the features occur in an area of numerous fine grained volcaniclastic turbidites. They proposed that the features were formed at the distal ends of the avalanches where the turbidity currents escape the confines of channels and are able to spread laterally as sheet flows.

We question the validity of a turbidity current origin for the sediment waves off La Palma and El Hierro for the following reasons. Where the waves are the creation of turbidity currents, they tend to be found in areas where turbidity currents are of low-speed and have low sediment concentration, such as the backside of levees (Normark et al., 1980). They can also be found within the channels themselves where currents may die out. This is not the setting of the waves seen offshore La Palma. Channels cutting the waves indicate that the region is not one of weak turbidity currents. The wave field also is too extensive to be diagnostic of low-density, low-velocity turbidity currents. Wave orientation and migration patterns also cannot be used to support a turbidity current origin. As summarized by Normark et al. (1980) such waves can be oriented not only transverse, but also parallel to the currents and they can migrate up current, possibly down current and may even be stationary relative to the current. Another observation that makes us question a turbidity current origin for the waves is their relation to the volcanic peaks northeast of La Palma. The waves tend to be warped along the edges of the volcano, a geometry that is not supportive of a turbidity current. Such currents would erode on the up-current side of the high and deposit on the down-current side of the volcanic features. Such a geometry is not present. It is for these reasons that we support the concept that the waves are relict and was formed at the time when AABW flow was stronger than now.

El Hierro: Inshore

In plan view El Hierro has an irregular outline, being essentially three lobes whose intersection forms a tableland in its center. This trilobate morphology is typical of three-armed rifts (Carracedo, 1994). The tableland with a few erosional barrancos displays the greatest concentration of cinder cones in the archipelago (Hausen, 1973; Fuster et al., 1993). In contrast to La Palma that has had seven eruptions in the last 500 years, only one of these cones has been active in historical time (Hernández Pacheco, 1982; Carracedo et al., 2001). The island's periphery consists of steep cliffs indented by three embayments, Las Playas, El Julan and El Golfo. The semicircular El Golfo, opened to the northwest, has an arc of 25 km with its steep side descending abruptly about 1100 m to a 5 km wide platform filling the embayment. The inner side of this platform has an elevation of about 300 m and its irregular outer side is at sea level. Las Playas has an arc of 9 km, is opened to the southeast and is bordered by 900 m high cliffs and El Julan has an arc of 8 km, is opened to the southwest and bordered by 600 m high cliffs. These cliff bound embayments have been ascribed to the collapse of volcanic edifices (Ridley, 1971; Hausen, 1973; Bravo, 1982; Holcomb and Searle, 1991; Fuster et al., 1993; Guillou et al., 1996; Carracedo, 1994, 1996).

The main bulk of El Hierro was built during the Tiñor and El Golfo volcanic phases. According to Carracedo et al. (2001) the volcanic edifices in El Hierro, like those in La Gomera and Gran Canaria, overlap concentrically. In contrast those of Fuerteventura-Lanzarote and La Palma are aligned in prominent directions. We think, however, that the edifices in La Palma overlap more than those in Lanzarote and Fuerteventura. The Tiñor Volcano at the eastern part of the island was built between about 1.12 and 0.882 Ma and El Golfo from about 550 to 130 Ka (Guillou et al., 1996). A break in volcanic activity between these two volcanic edifices coincides with the regional rapid growth of Cumbre Nueva volcanic activity in La Palma (Carracedo et al., 2001). El Hierro acquired much of its morphology as a consequence of volcanic collapses. The westerly-directed Tiñor collapse took place about 882 Ka during which more than half of the northwest flank of the edifice was removed (Carracedo et al., 1999a, 2001). This displacement was followed by the construction of the El Golfo Volcano between 545 and 130 Ka that filled the depression formed by the collapse of El Tiñor Volcano (Carracedo et al., 2001). The failure of the El Golfo structure formed the El Golfo Embayment (Carracedo et al., 1999a). Correlation of the El Golfo Debris Avalanche with the Canary Debris Flow offshore and a turbidite in the Madeira Abyssal Plain (turbidite b of Weaver et al., 1992) led Masson (1996) and Urgeles et al. (1998) to suggest that the El Golfo collapse took place between 9 and 15 Ka or 10 and 17 Ka. Geologic observations along galleries excavated for ground water exploration led Carracedo et al. (1999a) to infer that the collapse took place earlier, about 130 Ka, that a marine terrace was eroded in El Golfo 130 to 25 Ka and that lavas 20 to 15 Ka covered the terrace. It was the collapse of the seaward edge of this lava cover and the submarine slope beyond 17 to 9 Ka that supposedly produced the offshore avalanche debris, the Canary Debris Flow and the turbidite sequence b at its distal end, not the collapse of the volcanic edifice.

El Hierro: Offshore

The El Hierro insular margin is divided into three compartments by a system of ridges trending northeast, northwest, west and southwest (Figures 11 and 12). The NE, W and SW (South Ridge) ridges, continuations of those found onshore, extend as much as 20 km offshore and can be traced to a water depth of about 3200 m. The NE and W ridges are lobate and have the appearance of volcanic aprons, whereas the SW high displays a ridge morphology. This high, the Southern Ridge, is 38 km long, 2000 m high, is 20 km wide on its proximal end, 10 km wide at its distal end and curves gently southwestward (Gee et al., 2001a). One minor and three major avalanches are present within and between these ridges (Figure 11). The minor one occurs within the northwest rift whose head is at the upper end of the insular slope (Figure 11). Two major landslides, Las Playas I and II, occur off Las Playas Embayment (Gee et al., 2001a; Masson et al., 2002). Within these avalanches are less than 200 m high and 2 to 4 km wide pinnacles that Gee et al. (2001b) inferred to represent dikes. At the head of this collapse is a narrow, steep-sided embayment parallel to the southern end of the San Andrés Fault System. Day et al. (1997) inferred this fault system to be the head of an aborted landslide whose displacement took place between 545 and 261-176 Ka and gave rise to Las Playas I and II Avalanches. Carracedo et al. (1997) inferred that the slumping was due to one major movement along the fault, a movement that took place 250 to 150 Ka.

Carracedo et al. (1997) proposed that the landslide off El Julan Embayment took place prior to 158 $\pm$ 4 Ka and Masson (1996) suggested that the failure took place about 500 to 300 Ka. Carracedo et al. (1999a) inferred that the avalanche probably took place when the El Golfo Volcano was well-developed, before 130 Ka. More recently Carracedo et al. (2001) stated that that lavas belonging to rift volcanism in the water galleries in the El Julan Collapse Embayment constraints the minimum age of the collapse to 150 Ka.

Sidescan sonar recordings described by Masson et al. (2002) and swath bathymetry obtained during the present study display a 124 km^2 wave field within an 8 km long and 2 km wide channel in the El Julan debris (Figure 11). The waves have lengths of 0.4 to 1.2 km and heights of 6 m and are aligned parallel to the contours. These features are part of the El Hierro Sediment Drift. Sidescan sonar recordings also indicate that the surface of the El Julan slide is cut by a series of sediment draped steps of fault origin with a few exotic blocks (Masson et al., 2002). Displacement along the steps may have been triggered by the erosion of the toe of the avalanche deposit by the Saharan Debris Flow (Masson et al., 2002). This flow originated in the African margin about 60 Ka and flowed westward along 24° N (Insert, Figure 1). According to Gee et al. (1999) 40 km^3 of the El Julan Debris Avalanche deposit was eroded and incorporated into the Saharan Debris Flow.

Offshore El Golfo Embayment is the El Golfo Debris Avalanche deposit whose landward termination is a 400 high scarp on the upper insular slope (Masson, 1996). Like other landslides in the region, sidescan sonar images of the surface of the El Golfo Avalanche show typical exotic blocks up to 1.2 km wide and as much as 200 m high. These blocks are particularly abundant at a depth of 3500 m with a few blocks extending to a depth of nearly 4000 m. As previously described correlation of the debris avalanche with the Canary Debris Flow and the flow with turbidite b in the Madeira Abyssal Plain (Weaver and Rothwell, 1987; Weaver et al., 1992; Masson, 1996) implies that the avalanche must be 15 Ka and that the collapse of the El Golfo volcanic edifice that created the avalanche must have occurred at 15 Ka. Onshore geology, however, suggests that the collapse of the El Golfo volcanic edifice took place 130 to 100 Ka. This variance in age led Carracedo et al. (1997) to propose that the failure in El Golfo Embayment occurred in two phases, the collapse of the El Golfo volcanic edifice 130 to 100 Ka and the collapse of the volcanic platform filling the embayment and the submarine slope beyond the platform 17 to 9 Ka. It was the collapse of the platform, not the volcanic edifice that produced the Canary Debris Flow. More recently Carracedo et al. (2001) inferred that the geology of the marine abrasion platform beneath the lavas filling the El Golfo Embayment is incompatible with features associated with a single event collapse. From the geologic data they suggested that the subaerial embayment might have formed after the extrusion of lavas over the cliff sequence at 134 Ka. They also point out that the magnetic studies of Szérémeta et al. (1999) of the El Golfo and Rift sequences at the El Golfo escarpment suggests that the section has experienced continuous clockwise rotation.

The El Golfo Avalanche grades westward into the Canary Debris Flow. Immediately west of El Golfo Debris Avalanche the Canary Debris Flow is characterized by an opaque facies partially overlapped by the avalanche. At the distal west end of the debris flow is a transparent facies onlapping the stratified pelagic/hemipelagic sediments of the Madeira Abyssal Plain. The debris flow is lobate in form, is 60 to 100 km wide and flowed 600 km westward from the El Hierro Rise (Urgeles et al., 1997; Masson et al., 1997). The flow is a mixture of clasts and matrix with the clasts ranging in size from cm up to 300 m. The larger sediment clasts were derived locally rather than upslope indicating that the debris was capable of eroding the seabed in the middle part of its course.

Unusual features imaged by the relief diagrams constructed from the swath bathymetry off El Hierro are low relief mounds surrounded by moats (Figures 11 and 12). They have reliefs of 25 to 50 m and are 10 to 2 km long and l to 5 km wide. A few are circular and others are kidney shaped. These features occur within the El Hierro Sediment Drift, within the Canary Island and Saharan Debris Flows and between the flows. They also appear to be present west of the West La Palma Sediment Drift (Figure 11). They tend to occur at water depths of 4000 m. Within the debris flows they could represent blocks eroded locally by the currents. Outside the flows they could represent exotic blocks that outran the main part of the debris avalanches that originated in the insular slopes. Such origins do not explain the moats around them. That they surround the highs also suggests that they are not due to erosion by northeasterly-flowing AABW. If they were formed in this manner the lows would to be eroded only up current of the mounds with their down-current sides being sites of deposition. Morphologically they resemble the mounds described by Hovland et al. (1994) offshore western and northwest Australia, that were created by seepage of hydrocarbons along faults that first eroded the seafloor to form the moats with local nutrient enrichment of the overlying waters and enhancement of carbonate accretion in the moats. If they occurred in this manner then the gas must of be hydrothermal origin. In the absence of any information, besides that of their surficial shape, any attempt to determine their origin is premature.

Discussion

Sedimentary processes in the Canary Island Basin during the Neogene were influenced by the stages of volcanic development of the islands. Offshore deposition around those islands in the shield phase, Tenerife, La Palma and El Hierro, is dominated by debris avalanches that extend tens of km offshore to a water depth of 3000-4000 m (Figure 11). Construction of post-avalanche volcanic cones, salic necks and extrusion of lava flows offshore, reworking by bottom currents, turbidity current processes and hemipelagic deposition has modified the surface morphology of these deposits. The margins of those islands in the erosive cycle, Lanzarote, Fuerteventura, Gran Canaria and La Gomera reflect mainly turbidity current activity and hemipelagic processes and secondarily avalanche deposition and volcanic activity. Those in the shield phase, Tenerife, El Hierro and La Palma are dominated by mass wasting processes and widespread volcanic activity.

That turbidity currents were a major contributor to the construction of the insular margins of Fuerteventura and La Gomera is indicated by their depth profiles. Whereas the younger islands display concave upwards profiles these islands display profiles that are convex upward (Figure 13). Both islands, including Lanzarote, lack calderas, coastal embayments and scars produced by avalanches cascading down the slope. However all three islands have undergone massive erosion and uplift that may have erased these features. In addition geologic data have shown that Fuerteventura's volcanic edifices were eroded by mass wasting. As the centers of two of these cones were located off the present west coast, construction of the island's western margin must have been primarily by mass wasting processes. In contrast to the other islands the Gran Canaria margin displays profiles that are both convex and concave upwards indicating that mass wasting and turbidity currents have played roles in the formation of its margin. The profile of Lanzarote's margin is in the form of a ramp, suggesting that mass wasting played a role in creating its morphology (Figure 13). La Gomera is unusual in that the island has been so eroded that it does not display any evidence of mass wasting, such as collapse scars or coastal embayments. Landslides on this island are young and are limited to the 'barrancos', the base of the seacliffs and the insular slope.

Mass wasting

Massive failures in the younger Canaries are related to rift geometry with some of the volcanism occurring along or fanning out from rifts. Other volcanic structures trend at an angle to the rifts, or occur along troughs created by avalanches, or at the junction of two islands, such as Fuerteventura and Gran Canaria, where volcanic trends change abruptly. Associated with some of the rift volcanic edifices are what appear to be lava fronts and topographic features resembling lava falls and lobes spreading out over the sea floor adjacent to the rifts. Massive failures in the Canary Islands occur at the junction between the two most active rifts, with the third one acting as buttress for the landslide. It is these triple rifts, the concentration of dikes leading to the destabilization of the flanks through magma overpressure, mechanical and thermal overpressure of pore fluids, oversteepening due to rapid volcanic deposition, and seismic activity that leads to formation of gravitational unstable volcanic flanks (Carracedo, 1994, 1996; Elsworth and Day, 1999; Masson et al., 2002). Masson et al. (2002) proposed that failures tend to be concentrated on that flank of the rift having the greatest gravitational potential for lateral movement due to its steeper gradient.

Seismicity and sea level fluctuations affecting the stress regime in a volcanic island also may contribute to slope instability. McGuire et al. (1997) proposed glacially induced sea level regressions, which reduce the water volume on the flanks of the islands by about 100 m, to decrease radial compressive stresses by as much as 1 Ma. Such a reduction would tend to enhance extrusion on the volcanic edifice. Such lowering in sea level also reduces shear-stress on the volcanic flanks that in turn would tend to enhance slope instability. This model, however, is too simplistic. As documented by Guillou et al. (1998) volcanism along the Cumbre Vieja in La Palma was pronounced during the glacially induced regressions and transgressions 125 to 80 Ka. Volcanism was sporadic from 80 to 20 Ka when sea level reached its lowest level and Cumbre Vieja Volcano underwent massive erosion forming seacliffs as high as 700 m. There was intense rift volcanism during the subsequent rise in sea level from 15 Ka to the present. Masson et al. (2002) also suggested that climatic changes, affecting rainfall and groundwater levels within the volcanic edifices, also contribute to its failure. Preferential deposition and accumulation of weak layers within a previous failure would tend to encourage failures in the same area.

Most workers have proposed that the onshore and offshore avalanches in the Canary Islands are continuous. Mapping of the offshore deposits is based mainly on swath methodology that has a minimum depth of 200 m. Thus these marine data do not provide information on the critical link between the onshore and offshore avalanches. Although the swath bathymetric map compiled during the present investigation (Figure 2) is limited to depths greater than 200 m it does show that the onshore and offshore avalanches are not continuous, but are separated by a several hundred meter high scarp on the upper insular slope. Such a scarp also was reported off El Hierro by Masson (1996) and off Piton de Gran Brulé, Reunion Island by Lénat et al. (1990). It is the existence of this topographic divide between the onshore and offshore deposits that led Teide Group (1997) to infer that failures off Orotova, Icod and Güimar Valleys in Tenerife may have taken place in two stages. The failure on land created an avalanche or slump that extended some distance offshore. It was the failure of the distal end of the onshore structure along the scarp of the upper slope that Teide Group (1997) proposed to have created the offshore avalanche. They further inferred that the area of rough topography at the base of the scarp offshore Tenerife represented a matrix-rich, poorly sorted, chaotic-rich debris avalanche that originated on the 100–600 m slope. Teide Group (1997) further suggested that blocks on the lower slope represent earlier failures of the front and that these blocks obstructed the more recent flows. Carracedo et al. (1999a) suggested such a model for the offshore segment offshore El Golfo Embayment in El Hierro.

Failure of the upper slope avalanche may be the consequence of tectonic uplift, seismic activity or sediment loading on the slope. The intertidal fossils found by Bravo (1952) 8 m above sea level on the seacliff northwest of Tenerife may support such recent tectonic uplift. Other evidence for uplift comes from the gravity field of the island. Bosshard and MacFarlane (1970) inferred that a large positive gravity anomaly in the region indicates that a magma body may be beneath the Las Cañadas Caldera and that basement in Tenerife has been uplifted 1 km above its surroundings. The time interval between these two events is yet to be determined, although in the chronology described by Carracedo et al. (1999a) for El Hierro indicates that they occurred about 100 ky apart. We, however, do not infer that the offshore deposits are not due to uplift or faulting on the upper slope. The intertidal fossils found 8 m above sea level in Tenerife reflect, not tectonic uplift, but glacially induced changes in sea level during the Pleistocene. Funck and Schmincke (1998) and Carracedo (1999) have demonstrated that, except for Lanzarote and Fuerteventura, the Canary Islands have remained relative stable with respect to sea level for some time.

Masson et al. (2002) rejected the model that suggests that the offshore avalanches, at least in Tenerife, were the result of the collapse of the wall of the crater. According to them such a model is not supported by the volume assessment of the offshore avalanche, or by offshore mapping evidence. However, offshore volume measurements are too uncertain as to be more than educated guesses. The avalanche deposits are acoustically opaque, so that low energy single channel reflection profiles used in most investigations only provide information on their surface configuration. Changes in the landslide scars by post-avalanche erosion and volcanism, show that the scars may have served as chutes for more than one avalanche. Some of the avalanche detritus may come to rest within the collapse structures or within the chute itself, and that material along the path transversed by the avalanches is probably incorporated into the avalanche, making use of volume estimates to determine the extent of insular degradation above sea level unrealistic. It is, however, a relative estimate of the degree of degradation of the volcanic edifice above and below sea level. Although our estimates of the volumes of the avalanches, except for Las Playas II, in Table 1 are comparable with those reported by Masson et al. (2002) we still tend to put little reliance on them. It's even possible that the features we identified as debris flows off La Gomera may be turbidite systems that originated on the uppermost insular slope. That little reliance can be placed on the offshore avalanche volumes is shown by a comparison of the offshore and inshore data in Orotava Valley. As a result of the numerous galleries that have been dug for ground water in the valley (Coello, 1973), the geologic parameters in the valley are reasonably constrained. The valley has an area of 100 km^2 and is filled with 50 km^3 of avalanche debris, 35 km^3 of post avalanche volcanic rock and has a space volume from the top of the volcanic rocks to its rim of the valley of 30 km^3. Thus the valley could only have provided a volume of about 70 km^3 of avalanche debris offshore yet Masson et al. (2002) and the Teide Group (1997) reported that the volume of the offshore Orotova Debris Avalanche was about 400 and about 500 km^3 (minus the volume in Orotova Valley) respectively. Apparently the path traversed by the avalanche provided most of its volume.

Not only is the volume of the offshore avalanche not an index of the extent of erosion above sea level, but also the detritus contributed by the volcanic collapse above sea level may not be as voluminous as postulated. Were the calderas (in the topographic sense of the word) formed by mass wasting, or are they due to magma collapse as it has been proposed for the Caldera de las Cañadas (Martí et al., 1997) or fluvial erosion as proposed by Carracedo et al. (1999a, b), or a combination of collapse and fluvial erosion as inferred by Carracedo et al. (2001) for the Caldera de Taburiente in La Palma. Masson et al. (2002) stated that geologic mapping on land and the huge volume of the debris avalanche offshore Tenerife do not support a magma chamber collapse as a major factor in the formation of the Caldera de las Cañadas. However, if the offshore avalanche contains a large volume of sediments derived from the insular slope, then collapse of the north wall may have been sufficient to account for the amount of offshore deposit derived from above sea level. In contrast to Masson et al. (2002), Martí et al. (1994) believe that surface geologic data on land does support a magma chamber collapse origin for Las Cañadas Caldera. Martí et al. (1997), Martí and Gudmundsson (2000) and Soriano et al. (2002) inferred that the Las Cañadas Caldera is the creation, not of one, but of three vertical collapses from 1.6 Ma to 179 Ka, that triggered the Orotova, Güimar and Icod Valleys by lateral collapses. Data from the galleries excavated for groundwater (Coello, 1973) and wells drilled in the caldera (Martí et al., 1997), however, are too limited to verify or reject the validity of the existence of a north wall.

Present model

We propose instead that the distinct difference in volume between the inshore and the offshore debris avalanches is a reflection of the manner that failures take place along the flanks of volcanoes. We infer that failures in the Canary Islands took the form described by Jacobs (1995) for the Nuuanu Debris Avalanche in Oahu, Hawaii. Here failure was in two synchronous or near synchronous avalanches with the slip-surface on the onshore delineated by the steep cliffs parallel to the coast, the Nuuanu Pali, and the offshore one by a steep scarp on the upper slope. We farther propose that the location of the surface separating these two slip surfaces was controlled by the geology of the flank of the volcanoes. The stratigraphic succession on the slope of the Hawaiian Volcano was documented by a 3098 m boring on the flank of Mauna Kea, Hawaii (DePaolo et al., 2001). It is true that the Canary Islands differ from the Hawaiian chain. They differ in magma production, eruptive frequency and the Canary Islands have not subsided significantly during their construction. Differences in the rate of subsidence probably are related to differences in the age of the oceanic crust on which they rest, Jurassic for the Canaries and Cretaceous for Hawaii. However, the Canaries do display similar features with the Hawaii chain in having a two-stage subaerial evolution (shield stage volcanism separated from the post-erosional volcanism by an erosional gap), as well as common structural features such as rift zones, and multiple gravitational collapses (Carracedo, 1999). Thus the stratigraphic section revealed at the drill site at Mauna Kea may be applicable to the slopes of the Canary Islands volcanoes.

From this stratigraphic section we infer that the scarp on the upper slope in the Canary Islands archipelago defines the transition from subaerial lavas above to the clastic facies below, a transition marked by volcaniclastic rocks, glassy lavas and massive basalt layers. It is this contact that defines the surface separating the slip-planes of the subaerial and submarine avalanches (Figure 14). We further speculate that these two avalanches were probably near or synchronous with the subaerial failure occurring first followed soon after by the submarine one. As in Jacobs (1995) description of Nuuanu Debris Avalanche, the avalanches offshore the Canary Islands were the creation of these two events. As the subaerial debris avalanche entered the sea it eroded small V-shaped canyons out of the harder units along the transition between the subaerial and submarine series on the upper slope and triggered the offshore avalanche, possibly by sediment loading, and became mixed with it. The slip surface of the offshore unit was within the units on the transition and the décollement along which the offshore avalanche was displaced down slope is the contact between the unconsolidated and consolidated hyaloclastics. It was the mass wasting of the slope facies that created the flat-bottomed channels and irregular crested divides. The ridges in the valleys are due to scour compression between different flows. Secondary debris flows may be responsible for the discontinuous bedded insular units described by Schmincke and Sumita (1998). The hummocks and lows at the end of the debris flows represent grabens and horsts constructed by the lateral spreading of the distal ends of the avalanches. We further speculate that some of the exotic blocks found on the surface of the avalanche may have originated on the transitional zone on the slope rather than inshore and that the steps noted in some of the offshore avalanches may represent either local exposure of massive basalt beds that are intrusives, large lithic clasts or subaerial flows that may continued offshore. All in all the morphology of the offshore avalanche appears to be the result of several events of varying intensity. These distinct flows may reflect displacement along bedding planes of the different volcanic flows dipping away from the center of the volcanic edifice. As the failure continued mass wasting may have gradually changed to debris flows that in turn led to the formation of turbidity currents. It is these currents that were responsible for the fans seaward of the avalanches offshore Tenerife. According to the Teide Group (1997) the sediments in these fans are made up of at least six turbidite sequences, further verification that catastrophic failure of the slope was not a single event, but by repetitive landslides. However, in the absence of detailed seismic reflection coverage of the upper insular slope coupled with extensive bottom sampling the above scenario has to be considered to be in the realm of speculation. Possibly the origin of the scarp on the upper slope may have a simpler explanation. It may simply represent differences in the thickness of the avalanche deposits or a plane of separation between the head and toe of the avalanche. If it is a plane of separation it would imply that as the avalanche traveled down slope it broke apart into two or more segments with the upper one being perched on the flank of the subaerial segment of the volcanic edifice.

Another factor that controlled the physical aspects of inshore/offshore composite avalanches is the location of the volcano whose collapse contributed to the avalanche. For example the 3500 m high Pliocene Roque Nublo cone was built in the center of Gran Canaria. The Roque Nublo breccia, formed by one or more subaerial volcanic debris avalanches created by the collapse of the cone, had to travel 10 to 20 km via barrancos to reach the coast. In contrast the centers of the Central and Southern Volcanic complexes in Fuerteventura were located on the present coast and the avalanches could be deposited directly offshore. Similarly the distances from the volcanic edifices in La Palma and El Hierro to the offshore depocenter were also short as reflected by the pronounced coastal embayments in these islands. Distances from source to depocenter were somewhat greater in Tenerife and Lanzarote. In the islands where the source was near the depocenter the avalanche must have been quite coarse and contained an over overabundance of exotic blocks. As the flow was probably quite dense its travel distance offshore was short even though its momentum was much greater than the flows described below. As the distance increased, the avalanche became finer, and the exotic block content diminished. However, the finer avalanche would be able to travel a longer distance than those produced by a source located near the depocenter. As the transport distance increased the avalanche may evolve into a debris flow or a turbidity current.

An additional factor that controls the dimensions of a debris avalanche is the texture of its deposits with runout distances increasing as the amount of fine-grained sediment content increases (Iberson, 1997). This increase in distance with decreasing grain size is because fines tend to sustain high pore pressure that reduces frictional resistance. This suggests that the flows offshore La Gomera are short because they are coarse, the flows offshore La Palma and El Hierro have a lobate form because they are somewhat finer-grained, and the avalanche offshore Tenerife are linear because they are even finer grained (Masson et al., 2002). Such assumptions, however, are in need of testing. The surface features of these offshore flows are well known, but their internal structure and texture is unknown. To date the only flows mapped in detail are those on land, such as the Pliocene Roque Nublo Debris Avalanche in Gran Canaria (Mehl and Schmincke, 1999). Other flows on land that have been mapped to some degree are the avalanches in Tenerife (Bravo, 1952; Coello, 1973).

Conclusion

Volcanism in the Canary Islands appears to be rift related with mass wasting being represented by two landslides, one above sea level and the other on the submarine insular slope. The surface separating these two landslides is either the detachment surface along which the landslide broke in two or represents the transition between the subaerial volcanic rock and the slope hyaloclastic rocks. Drilling in Hawaii indicates that alternating massive basalts, subaerial flows that continued beyond the shoreline, marks this transition with the flank hyaloclastic rocks. Catastrophic failures are readily recognizable in Tenerife, La Palma and El Hierro, islands in the shield-phase of development (Figure 1). The failures are generally interpreted as avalanches; the only debris flow identified is the Canary Debris Flow off El Hierro. However, it is possible that the landslides are not solely the creation of avalanches, but are constructed by both debris avalanche and debris flow processes. Such an interpretation is not unrealistic, as these sediments were deposited during repetitive failures. Slumps have been recognized along the flanks of Lanzarote, El Hierro and Gran Canaria. It is possible that some of the features identified as avalanches on land may represent slumps that turned into avalanches on their distal ends as they broke apart as they moved across the volcano's uneven surface. The debris avalanches of the young islands in the shield-phase, Tenerife, La Palma and El Hierro, have runout distances that range from 12 to 95 km, cover 30 to 3500 km^2 of sea floor, and have volumes <50 to 800 km^3. Differences between flows off the islands are related to their texture, with the finer ones with a greater water content traveling farther. At their proximal ends, in depths shallower than 3000 m, the avalanches are in the form of flat-bottomed steep sided chutes, where erosion and down-slope transport predominate. At the heads some of the chutes are low relief ridges aligned parallel to its axis. These highs may be due either to scour or to compression created by velocity differences between adjacent flows. The distal ends of some of the chutes are characterized by a series of convex down-slope steps that may be the creation of a series of overlapping flows, or represent local exposures of massive basalt levels. At their distal ends the flows are in the form of overlapping lobes. The surfaces of the lobes are disrupted by hummocks and lows that may represent grabens/horsts resulting from their lateral displacement. Scattered over the surfaces of the lobes are exotic blocks that glided to their present sites from inland and/or the insular slope by being supported by the excess pore water pressure of the avalanche, or supported by a matrix of fine grained sediment in the avalanche. Most of the blocks retain their integrity, indicating that they were resistant to the internal shear of the flow. Some of these blocks had enough momentum to outrun the main part of the flow.

Defining the processes that sculptured the margins of the islands in the erosional phase (Lanzarote, Fuerteventura, Gran Canaria and La Gomera) from their morphology is not as clear-cut as the islands in the shield-volcano phase. If it was not for the presence of highs that resemble exotic blocks and box-shaped canyons, the margins could be interpreted as the construction of turbidity currents and hemipelagic deposition. The margin of La Gomera, for example, has the appearance of being mainly the creation of turbidity current deposition and erosion, with volcanic edifices aligned along a rift offshore the northwest corner of the island adding to the margins configuration. The western margin of Lanzarote consists of a westerly dipping platform cut by low relief channels whose divides are made of numerous small highs and bound on the landward and seaward sides by scarps. No other island displays this type of morphology. This morphology could be the consequence of a massive slump with the highs representing small volcanic cones emplaced after slumping, or a volcanic apron. We interpret the morphology of the western margin of Fuerteventura, the side slopes of Banquete and Amanay Banks, as well as the divide between Gran Canaria, as the creation of mass wasting. The terrain has been modified by post-landslide turbidity current deposition and erosion and hemipelagic deposition. That features created by mass wasting in the Miocene (Miocene) and <4 Ma (Pliocene) are still recognizable off Gran Canaria is a reflection of the intensity and magnitude of these processes. It is not surprising that such events can also be recognized in Fuerteventura. This island experienced deep erosion at the end of the shield building phase by catastrophic failures <12 Ma that reduced its relief by nearly 3000 m in 2 Ma.

In addition to being modified by turbidity currents and hemipelagic sediments, the landslides have been modified by bottom current activity. Southerly flowing NADW has created a sediment drift out of the sediments off Lanzarote and sediments waves and furrows out of the deposits in the divide between Gran Canaria and Tenerife. North flowing Antartic Deep Water (AADW) has created a sediment drift out of the landslides offshore El Hierro and La Palma. Whereas the features molded by NADW are recent, those formed by ADDW may be relict and were formed in the Pleistocene when the water mass was characterized by stronger currents.

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