Geophysics of the Canary Islands

Results of Spain's Exclusive Economic Zone Program

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Table of Contents

Foreword v–vi

J. ACOSTA, E. UCHUPI, A. MUÑOZ, P. HERRANZ, C. PALOMO, M. BALLESTEROS and ZEE Working Group / 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 1–40

J. ACOSTA, E. UCHUPI, A. MUÑOZ, P. HERRANZ, C. PALOMO, M. BALLESTEROS and ZEE Working Group / Salt Diapirs, Salt Brine Seeps, Pockmarks and Surficial Sediment Creep and Slides in the Canary Channel off NW Africa 41–57

J. ACOSTA, E. UCHUPI, D. SMITH, A. MUÑOZ, P. HERRANZ, C. PALOMO, P. LLANES, M. BALLESTEROS and ZEE Working Group / Comparison of volcanic rifts on La Palma and EI Hierro, Canary Islands and the Island of Hawaii 59–90

P. LLANES, A. MUÑOZ, A. MUÑOZ-MARTÍN, J. ACOSTA, P. HERRANZ, A. CARBÓ, C. PALOMO and ZEE Working Group / Morphological and structural analysis in the Anaga offshore massif, Canary Islands: fractures and debris avalanches relationships 91–112

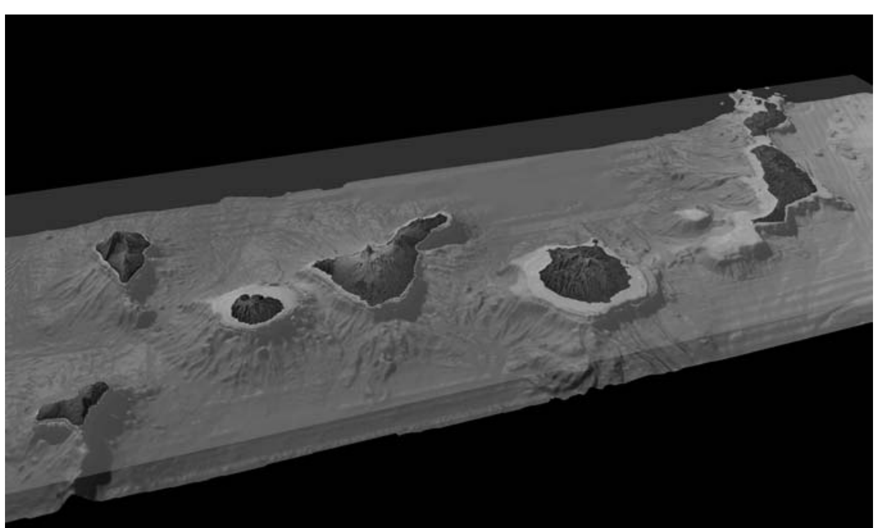
A. CARBÓ, A. MUÑOZ-MARTÍN, P. LLANES, J. ÁLVAREZ and EEZ Working Group / Gravity analysis offshore the Canary Islands from a systematic survey 113–127

M. CATALÁN, J. MARTÍN DAVILA and ZEE Working Group / A magnetic anomaly study offshore the Canary Archipelago 129–148

L.I. GONZALEZ DE VALLEJO, R. CAPOTE, L. CABRERA, J.M. INSUA and J. ACOSTA / Paleoearthquake evidence in Tenerife (Canary Islands) and possible seismotectonic sources 149–160

E. ANCOCHEA and M.J. HUERTAS / Age and composition of the Amanay Seamount, Canary Islands 161–169

Digital Terrain Model of the Canary Islands EEZ. Courtesy of Multibeam Maping Group, Instituto Español de Oceanografia, Madrid, Spain.



Foreword of the Director of the Oceanographic Spanish Institute

The eight papers contained in this special MGR issue reflect partly the successful collaboration between a group of institutions and researchers working on a major research program since 1995: *the Spanish EEZ Program* (Exclusive Economic Zone Program).

The Spanish EEZ program was set up in 1995 after a political mandate of the Spanish government to prepare a full study - comprising hydrography, geology, geophysics and oceanography - of the Spanish EEZ. Leaders of the study were the Instituto Espahol de Oceanografia (IEO) and the Instituto Hidrográfico de la Marina (IHM).

Since its beginning, the program disposed one month per year on the use of the R/V *Hespérides* and other Spanish oceanographic research ships like the R/V *Cornide de Saavedra,* the *Vizconde de Eza* and the *Tofiño*.

Other research groups, universities and private companies also have collaborated in the sea-cruises.

Present special issue shows the first scientific results of the EEZ Program in the Canary Islands area. Moreover, due to its scientific quality, the Program could be considered as an example of cooperation between different institutions, teams and individuals working on the same project.

Finally, the IEO, which supports part of the program, should express its deep gratitude to all captains, crews and technicians of the different oceanographic vessels that participated in the research campaigns. Their work made this issue possible.

Concepción Soto
Directora del IEO

Foreword of the Director of the Hydrographic Marine Institute

Article 132.2 of the Constitutional Law sets the grounds for public property of the natural resources of the Spanish Exclusive Economic Zone (ZEE for its Spanish acronym), implying the sovereign right to explore, exploit, conserve and administer all living and non-living resources coming from the sea-bed and the adjacent waters of the maritime area that goes from the end of the territorial sea to a distance of two hundred sea miles, counting from the base line from where its width is measured.

According to the agreement of the Council of Ministers of April 23rd, 1993, the Ministry of Defence is authorized to use the BIO ‘‘Hespérides’’ to carry-out research campaigns for data gathering during one month per year.

The Hydrographical and Oceanographic Research Plan of the Spanish Exclusive Economic Zone (ZEE) was approved by Ministerial Order 55/1994 of May 30th, amplified by the Ministerial Order 94/1993 of September 21st, in which the FAS Cartographic Plan was approved.

On May 25th of 1994, the framework cooperation agreement between the Ministry of Defence and the Spanish Oceanographic Institute (IEO for its Spanish acronym) concerning Hydrographical and Oceanographic Research on the ZEEE was approved. This Framework Agreement assigns the hydrography of the area to the Marine Hydrographic Institute, using the multi-beam sounding devices installed on the BIO ‘‘Hespérides’’; and the data gathering that leads to a better knowledge of the physical structures of the seabeds to the IEO.

During the years 95, 96 and 97 data gathering has been carried-out on the Balearic Islands and during the years 98, 99 and 2000 on the Canary Islands with campaign heads coming alternatively from IHM and IEO personnel.

The results of the various campaigns were extraordinaire, especially because of the very close collaboration between the participating Institutions, more specific with the IEO, a collaboration of which the results clearly can be seen in this scientific work about the Canary Archipelago and in future joint works that surely will be carried-out

CN. D. Fernando Quirós Cebriá
Director del Instituto Hidrográfico de la Marina

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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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Key words: multibeam mapping, Canary Island, avalanches, geomorphology

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

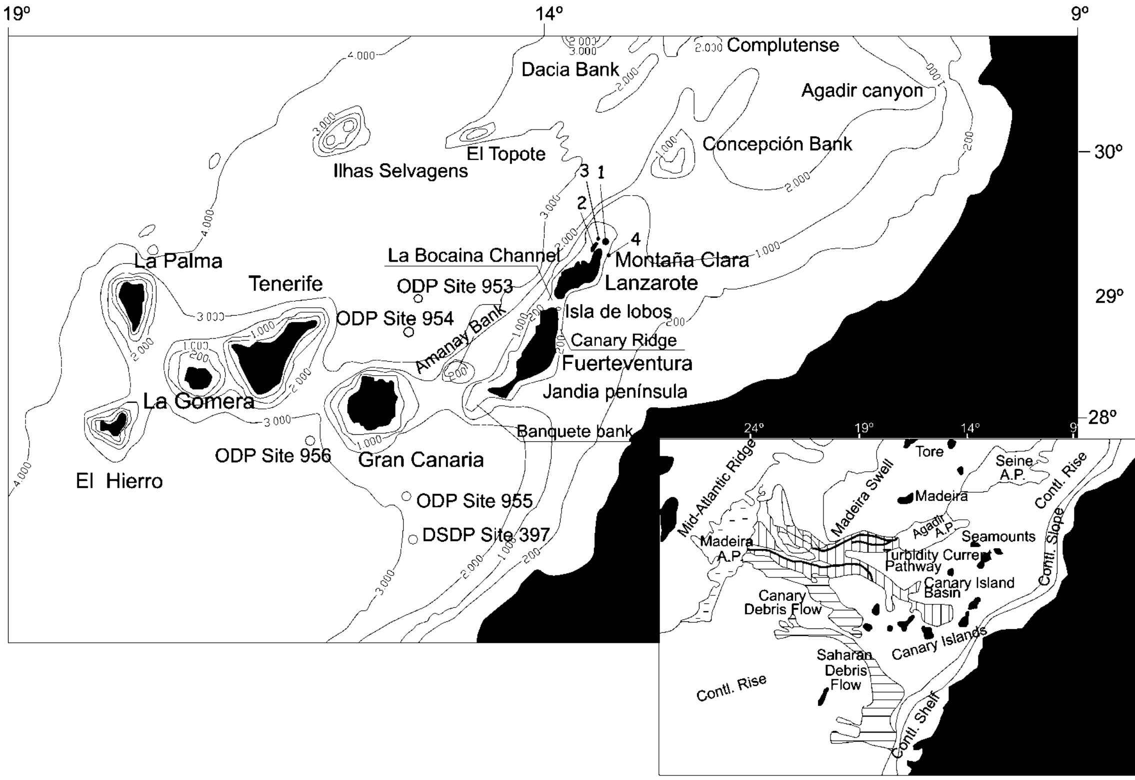

Figure 1. Submarine topography of the Canary Island archipelago region. Bathymetric contours are from GEBCO sheet 5.08 and base map from U.S. Naval Oceanographic Office 51017. Insert map is modified from Wynn et al. (2000). Contour in meters. 1= Alegranza; 2= Graciosa; 3= Roque del Oeste; 4= Roque del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

well as salic 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 deep, flat-topped Conception Bank. This ridge may be

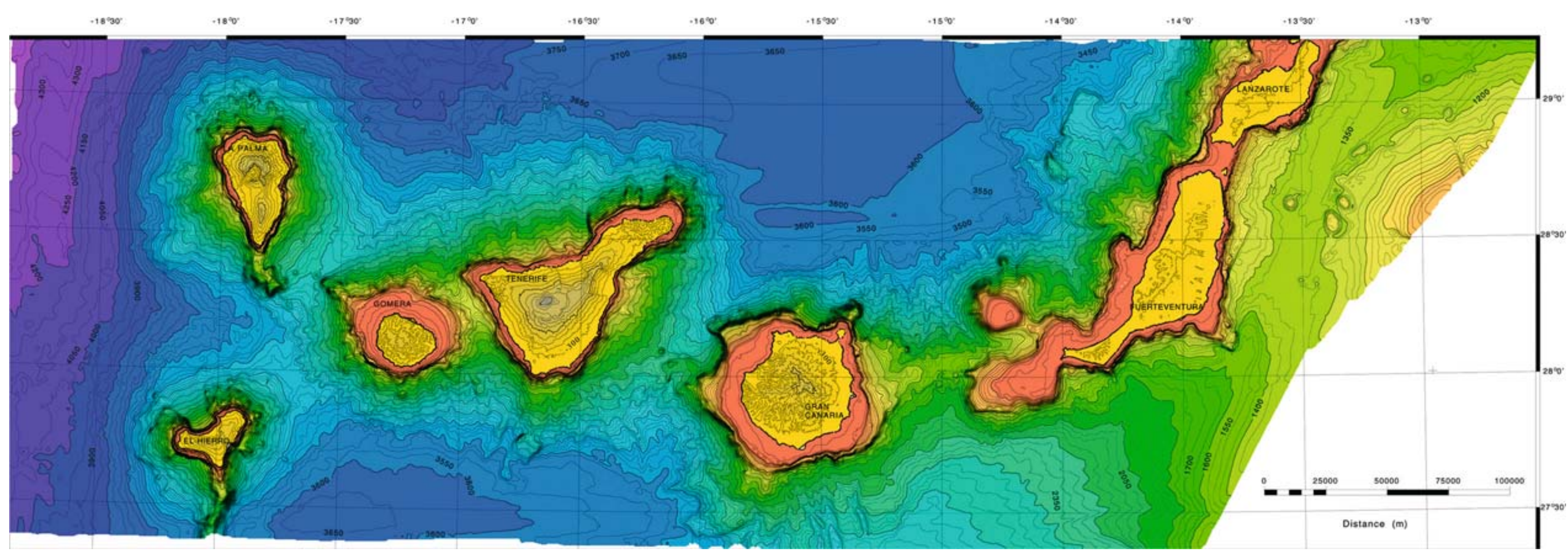

Figure 2. Topographic map of the Canary archipelago region. Offshore contours in meters are based on multi-beam echo sounding data collected during the present investigation and onshore ones also in meters from data provided by Servicio Geográfico del Ejercito, Cartografía Digital, 100 by 100 m grid,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

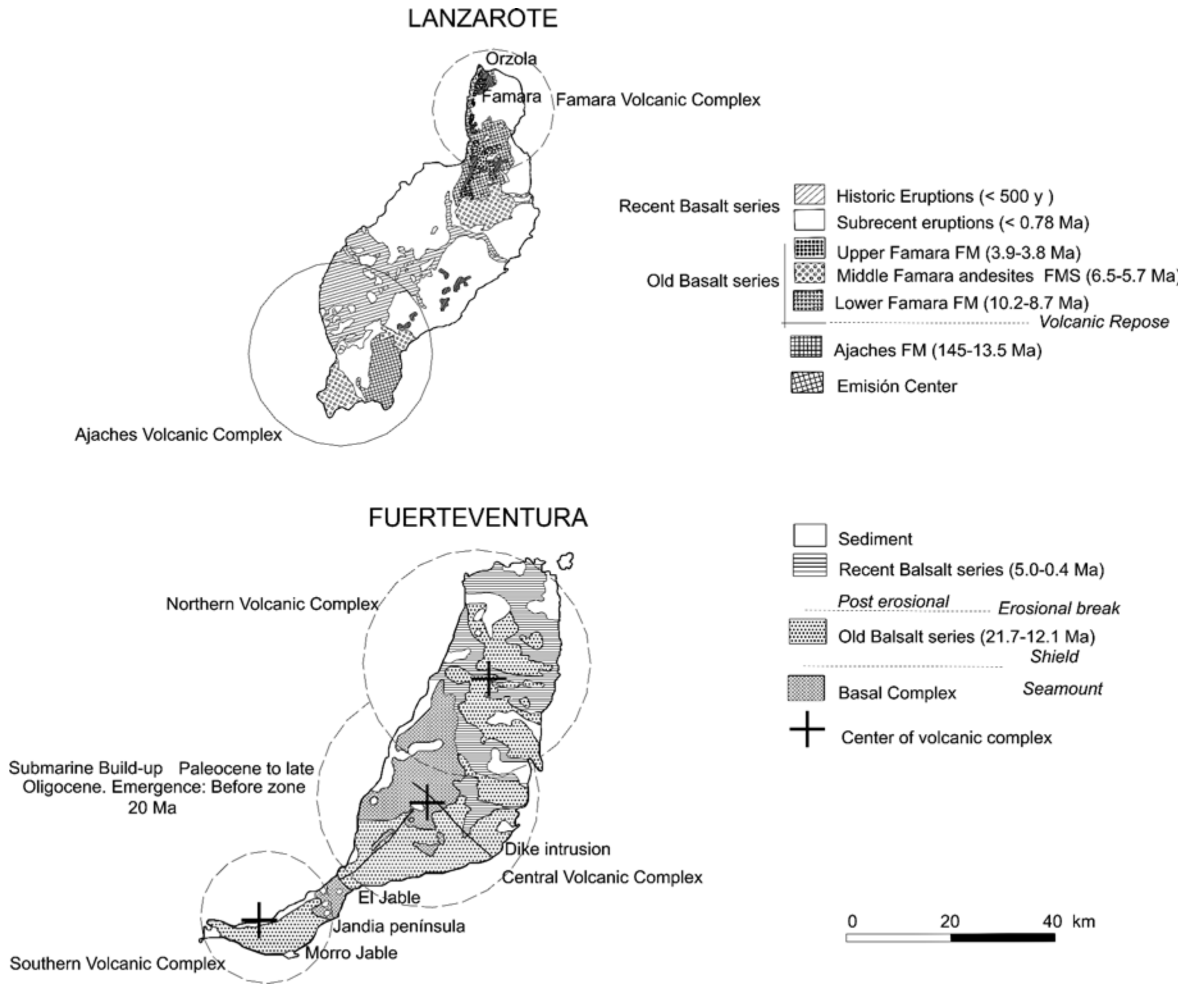

Figure 3. Geologic maps of Lanzarote and Fuerteventura. Compiled from Coello et al. (1992), Carracedo and Rodríguez-Badiola (1993), Ancochea et al. (1996) and Stillman (1999).

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 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.

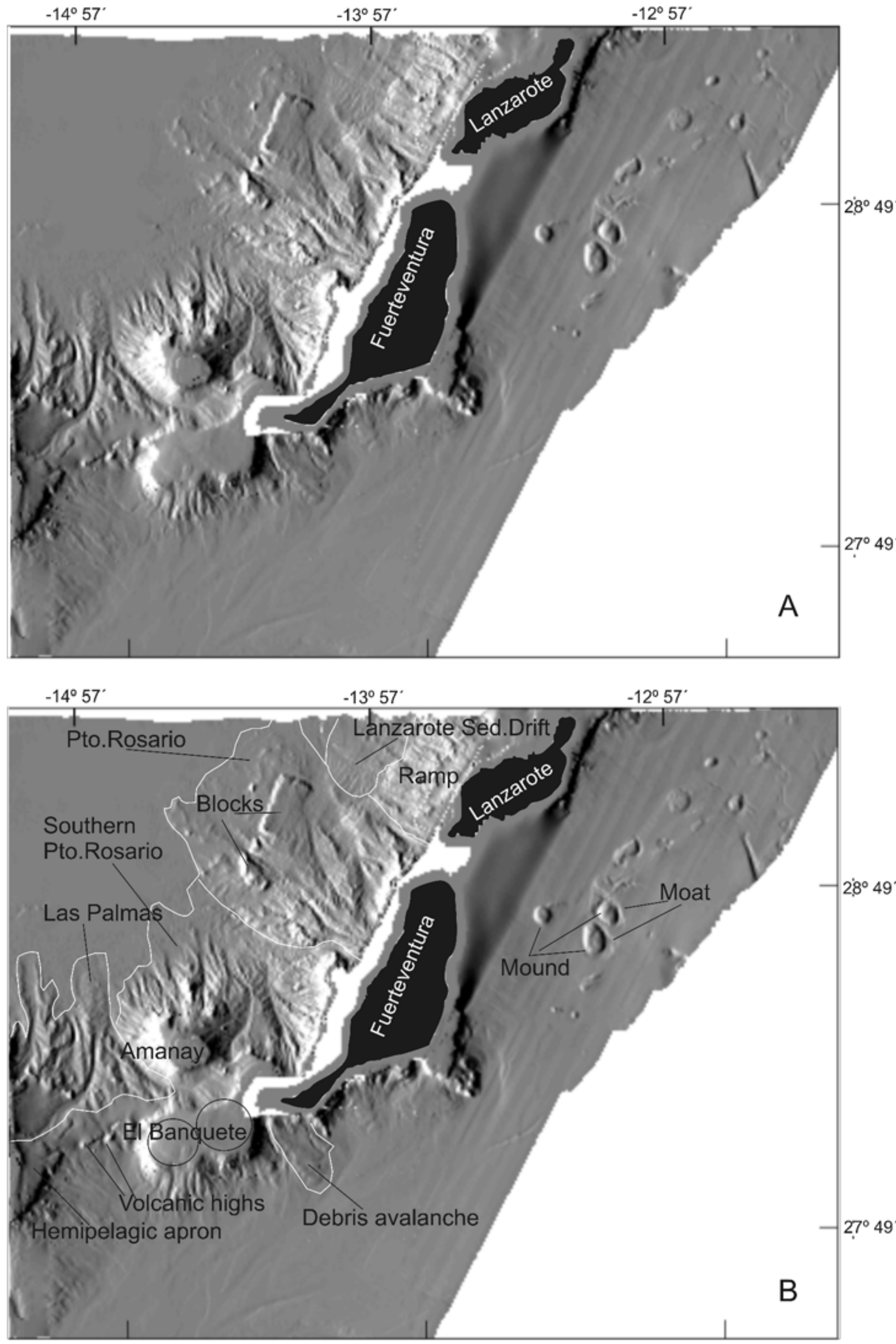

Figure 4. **A**. Shaded relief image of the western margins of Lanzarote and Fuerteventura and side slopes of Banquete and Amanay Banks . Illumination is from northwest. **B**. Shaded relief image of Lanzarote and Fuerteventura margins and Banquete and Amanay Banks showing the distribution of landslide 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).

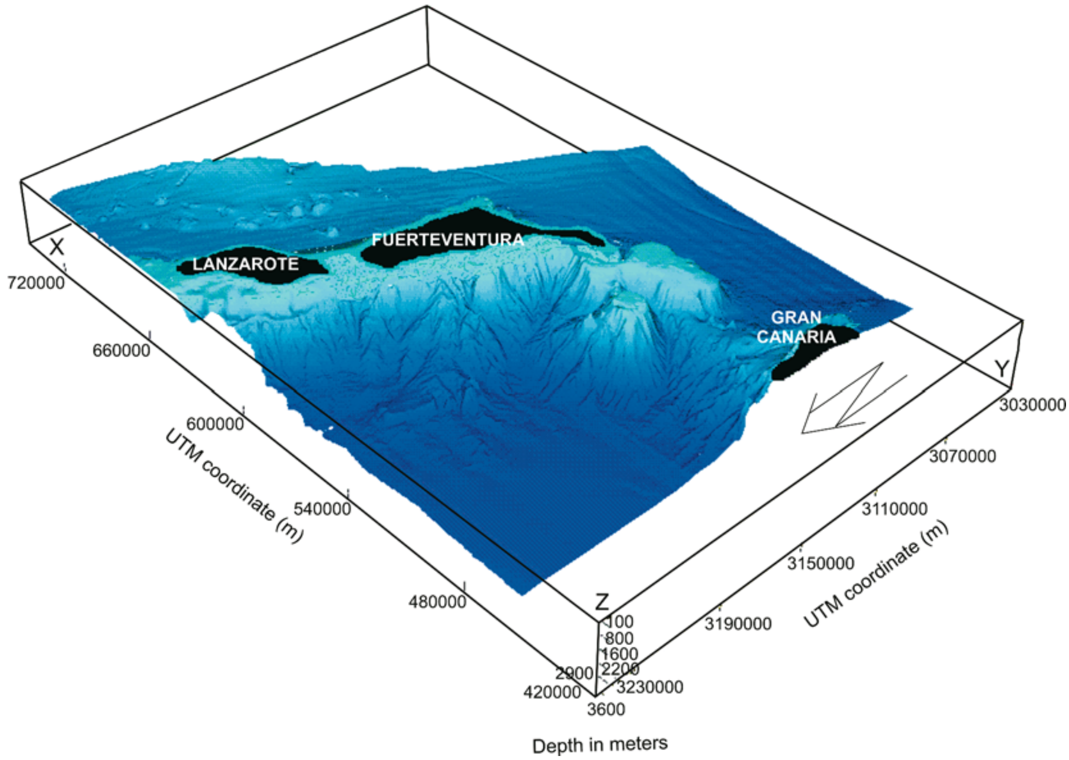

Figure 5. 3D diagram of the western margin of Lanzarote and Fuerteventura looking north. The two flat-topped highs south of Fuerteventura are Banquete (attached to Fuerteventura) and Amanay Banks. The high at the extreme right of the diagram is the tip of Gran Canaria.

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). 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,

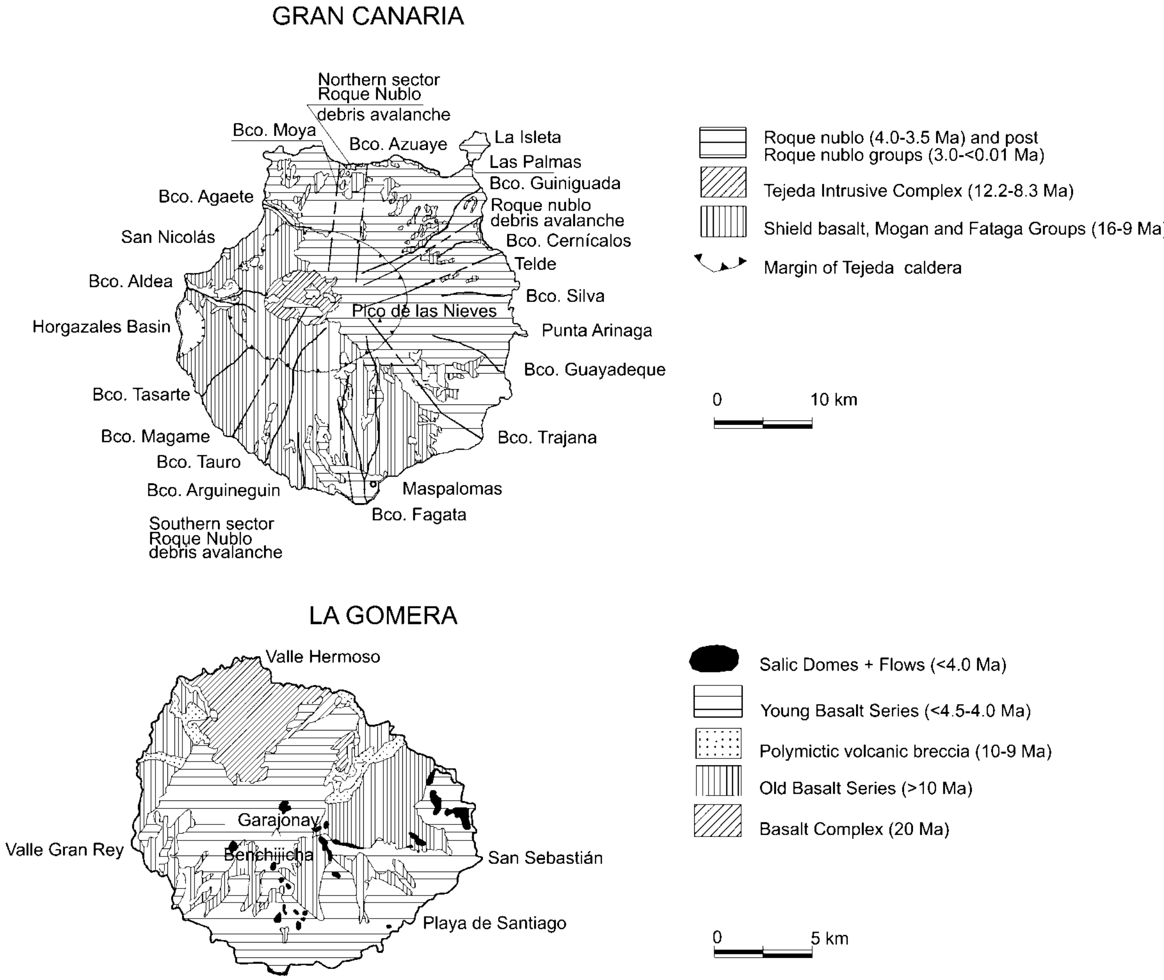

Figure 6. Geologic maps of Gran Canaria and La Gomera. Compiled from Hausen (1965), Cantagrel et al. (1984), Funck and Schmincke (1998), Mehl and Schmincke (1999), Van den Bogaard and Schmincke (1998) and Schmincke and Sumita (1998).

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 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

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