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ORIGINAL PAPER

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The channel between Gran Canaria and Tenerife: constructive processes and destructive events during the evolution of volcanic islands

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Abstract Seismic, sidescan sonar, bathymetric multibeam and ODP (Ocean Drilling Program) data obtained in the submarine channel between the volcanic islands of Gran Canaria and Tenerife allow to identify constructive features and destructive events during the evolution of both islands. The most prominent constructive features are the submarine island flanks being the acoustic basement of the seismic images. The build-up of Tenerife started following the submarine stage of Gran Canaria because the submarine island flank of Tenerife onlaps the steeper flank of Gran Canaria. The overlying sediments in the channel between Gran Canaria and Tenerife are chaotic, consisting of slumps, debris flow deposits, syn-ignimbrite turbidites, ash layers, and other volcaniclastic rocks generated by eruptions, erosion, and flank collapse of the volcanoes. Volcanic cones on the submarine island flanks reflect ongoing submarine volcanic activity. The construction of the islands is interrupted by large destructive events, especially by flank collapses resulting in giant landslides. Several Miocene flank collapses (e.g., the formation of the Horgazales basin) were identified by combining seismic and drilling data whereas young giant landslides (e.g., the Güimar debris avalanche) are documented by sidescan, bathymetric and drilling data. Sediments are also transported through numerous submarine canyons from the islands into the volcaniclastic apron. Seismic profiles across the channel do not show a major offset of reflectors. The existence of a repeatedly postulated major NE–SW-trending fault zone between Gran Canaria and Tenerife is thus in doubt. The sporadic earthquake activity in this area may be related to the regional stress field or the submarine volcanic activity in this area. Seismic reflectors cannot be correlated through the channel between the sedimentary basins north and south of Gran Canaria because the channel acts as sediment barrier. The sedimentary basins to the north and south evolved differently following the submarine growth of Gran Canaria and Tenerife in the Miocene.

Keywords Canary Islands · Landslides · Ocean islands · Submarine volcanism · Volcanic evolution

Introduction

Major oceanic islands appear as large volcanic structures when only viewed above sea level. When stripped of the water column, they emerge as colossal mountains whose height dwarfs high peaks on land and whose basal diameter approaches that of some mountain chains. Intraplate volcanic oceanic islands are generally believed to be generated above rising mantle plumes (Morgan 1972; Wilson 1973). They grow by magmatic/volcanic activity, but destructive events such as giant landslides are closely linked to the construction of volcanic islands (e.g., Moore et al. 1989; Krastel et al. 2001b; Masson et al. 2002). Major oceanic archipelagos, such as the Canary Islands and the Hawaiian Islands, typically form island chains defining the trace of a mantle plume relative to the moving plate. Major islands are separated by channels, which can vary in depth and width. The structure and the deposits in such channels greatly aid in elucidating the evolution of the adjacent islands. For example, what determines the width of these channels, in other words, the distance between the islands? What are the origins of the channels? Are they structural features characterized by underlying basement lineaments and/or younger faults, or are they the result of a shift of channelized magma ascent between the islands as first order foci of magma rise? Is there a clear onlap of a younger island flank on top of an older one, which would help to understand the temporal evolution of an island chain?

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How are the constructive volcanic processes and destructive events (landslides) and periods of intense erosion reflected in the sediments and morphology of the channel area? How do the volume, age, and structural arrangement of young volcanoes, located in the channel region, compare with that of the islands? What role do channels play as pathways for sediments supplied from the subaerial and submarine island flanks, proceeding to adjacent broader sediment basins and as gateways for ocean currents? We will provide partial answers to some of these questions, based on detailed seismic and morphological analyses supplemented by data from drilling the volcanic aprons of Gran Canaria and Tenerife, Canary Islands.

Previous accounts (Geisslinger et al. 1996; Teide Group 1997; Funck and Schmincke 1998; Romero Ruiz et al. 2000; Krastel et al. 2001a) concentrate on specific aspects of the above questions and/or consider only briefly the interaction of the islands. In this manuscript, we analyze and combine different aspects of the channel's structure in the light of the evolution of both islands. We will discuss our new data on the channel between Gran Canaria and Tenerife and summarize present knowledge.

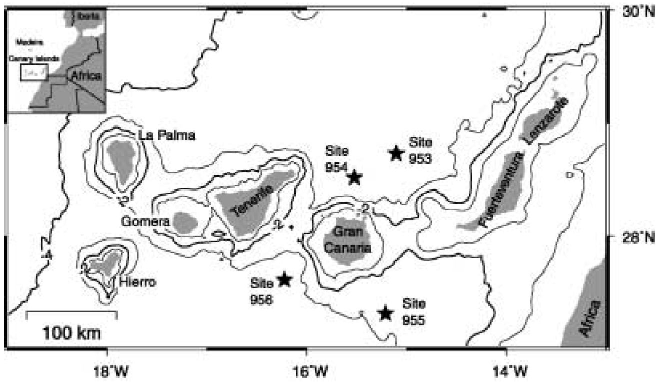

Fig. 1 Overview map of the Canary Islands. Contour interval is 1 km. The sites of ODP-Leg 157 (Schmincke et al. 1995) are marked by *stars*

Geological setting

The Canary Archipelago located off the West African continental margin (Fig. 1) is one of the major oceanic island groups in the world, Gran Canaria and Tenerife being the two central islands. The age and duration of the submarine growth phases of both islands are unknown. The subaerial volcanic/magmatic history of Gran Canaria started about 15 Ma and was divided into three main phases (McDougall and Schmincke 1976; Schmincke 1976, 1982, 1998; Hoernle and Schmincke 1993a, 1993b; van den Bogaard and Schmincke 1998). The subaerial Miocene phase started with rapid formation of tholeiitic to weakly alkalic shield basalts. The basaltic shield phase was followed by emplacement of composite ignimbrite P1 at 13.95 Ma on top of the basaltic shield marking the beginning of a 0.6-million-year-long sub-phase of trachytic to rhyolitic volcanism (Mogán Group). The large Tejada caldera (ca. 20 km diameter) in the center of Gran Canaria began to collapse synchronously with this major ignimbrite. The Mogán Group is overlain by trachyphonolitic ignimbrites and lava flows (Fataga Group, 13.4–8.5 Ma). This subphase was accompanied and followed by intrusive syenites and a large cone sheet swarm making up the central caldera complex (Schirnick et al. 1999).

A volcanic hiatus occurred from 8.5 to 5 Ma and was followed by the second main volcanic/magmatic phase, the Pliocene Roque Nublo phase with peak activity at 4 Ma. The third major volcanic/magmatic phase in the late Pliocene and Quaternary – predominately nephelinites and basanites – is restricted to the northern part of the island. The island can be considered volcanically active, as testified by numerous prehistoric basanite scoria cones, maars, and lava flows. Two young eruptions on Gran Canaria have been dated at ca. 3,000 years B.P.

The oldest volcanic series of Tenerife are three shield basalt complexes differing in age and composition. They are exposed in three not visibly connected areas (Fig. 2). Age determinations of the Roque del Conde massif in the south are scattered between 12.0 and 6.4 Ma. The activity in the Teno massif in the northwest took place between 6.7 and 4.5 Ma whereas the Anaga massif in the northeast grew between 6.5 and 3.6 Ma (Ancochea et al. 1990).

The large Cañadas volcano in the center of Tenerife was built on top of the three Miocene shield complexes. This central volcano is linked to the northeast with the Anaga peninsula by a chain of basaltic emission centers, the Cordillera Dorsal (Fig. 2), with peak activity around 0.8 Ma. The valley of Güimar and shortly afterwards that of Orotava were formed by large landslides less than 0.8 Ma ago, and probably before 0.6 Ma ago. The Cañadas caldera may have had several collapse phases and the present so-called caldera was formed by a landslide less than 0.2 Ma ago. Thereafter it was partly filled by the huge Teide volcano (3,718 m), which has been active until present. Two young basaltic emissions 2 km north of the caldera occurred in 1909 (Ancochea et al. 1990, 1999; Thirlwall et al. 2000).

Previous studies

The submarine flanks of Gran Canaria and Tenerife were surveyed during several geological and geophysical research cruises. Studies around Gran Canaria and Tenerife include refraction seismic transects across both islands (Watts 1994; Watts et al. 1997; Ye et al. 1999; Canales et al. 2000; Krastel and Schmincke 2002), high resolution seismic studies of the volcaniclastic apron (Funck et al. 1996; Geisslinger et al. 1996; Teide Group 1997; Funck and Lykke-Andersen 1998b; Funck and Schmincke 1998), morphological work around both islands (Watts

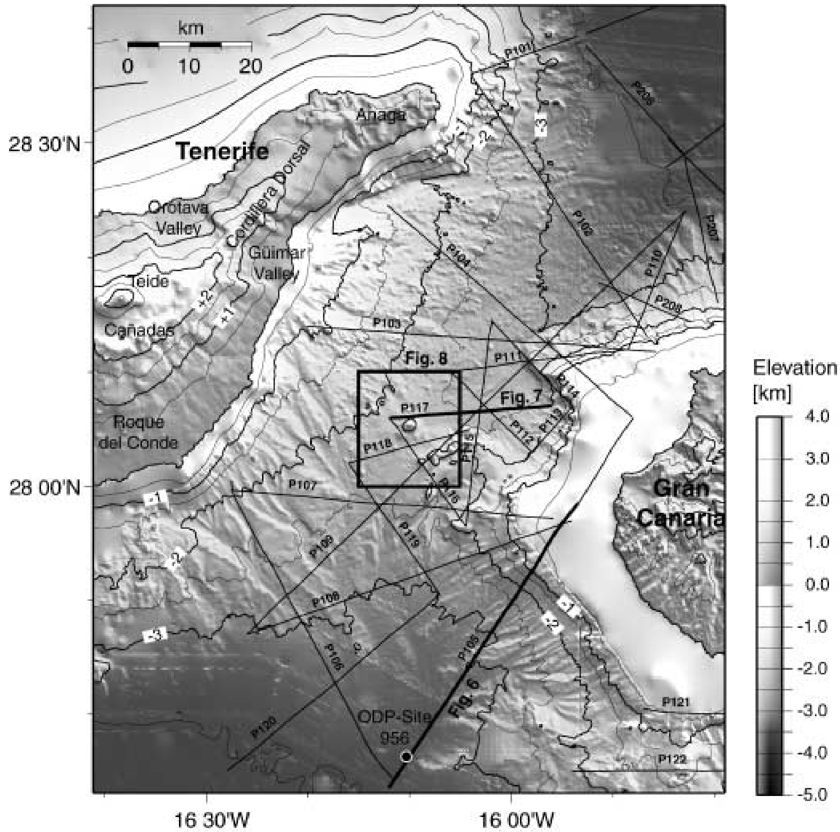

Fig. 2 Bathymetric map of the channel and locations of seismic reflection profiles. Smooth areas are not covered by the bathymetric multibeam data. Some linear features (e.g., E–W lines in the southwest) are also caused by incomplete data coverage. Contour interval is 0.5 km (*bold lines* 1-km isolines). The plot is shaded by artificial illumination from the north-northeast. Also marked is ODP-Site 956

and Masson 1995, 1998, 2001; Funck et al. 1996; Teide Group 1997; Funck and Schmincke 1998; Romero Ruiz et al. 2000; Krastel et al. 2001a, 2001b; Masson et al. 2002), and detailed analysis of ODP holes (Schmincke and Sumita 1998).

Major NE–SW-trending faults between Gran Canaria and Tenerife have been postulated repeatedly (e.g., Dash and Bosshard 1969; Mezcua et al. 1992; Romero Ruiz et al. 2000). These faults were generally believed to be directly related to similarly striking Miocene faults formed in the Atlas Mountains, but the geophysical evidence for faults is not very compelling. Romero Ruiz et al. (2000) re-emphasized the importance of this postulated fault zone also in the context of the purported dominance of northwest–southeast and northeast–southwest alignments in the Canary Islands. Romero Ruiz et al. (2000) place major emphasis on the alignments of submarine morphological highs, interpreted by them as volcanic cones, along these directions. They also argue that the submarine parts of the shields of both Anaga and Teno grew substantially following the growth of the subaerial shields. Significant volumes of evolved rocks are unknown from either Anaga or Teno, and restriction of shield activity to the submarine part, therefore, is not compelling, unlike Gran Canaria where Schmincke and Sumita (1998) reasoned that major low density magma reservoirs largely prevented basaltic magmas reaching the surface in the Miocene.

Data collection

The main methods used in this study are reflection seismic profiling, ODP drilling, and mapping of the seafloor by means of sidescan sonars, bathymetric multibeam systems, and sediment echosounders. Data were collected during METEOR-cruises M24 (Schmincke and Rihm 1994) and M43 (Schmincke and Graf 2000), Charles Darwin-cruise CD109 (Rihm et al. 1997), and ODP-Leg 157 (Schmincke et al. 1995).

Twenty-one reflection seismic profiles were recorded in the channel between Gran Canaria and Tenerife (Fig. 2). A sleevegun cluster of four guns with a volume of 0.65 l each served as seismic source. Bubble-oscillations were effectively suppressed by the narrow gun clustering of 0.5 m. The seismic energy was recorded by means of a 24-channel streamer with a group spacing of 6.25 m, resulting in a total active length of 143.75 m. The firing rate – chosen depending on the water depth – was 5, 7.5 and 10 s corresponding to a nominal shotpoint distance of 12.5, 18.75, and 25 m, respectively. The data were stacked and time-migrated. Prior to migration the data were resampled from 1 to 2 ms since the frequency spectra showed that the seismic energy lies between 20 and 240 Hz. Because of the rough morphology in the channel between Gran Canaria and Tenerife side echoes are occasionally visible, which cannot be treated properly with the applied 2-D migration algorithm.

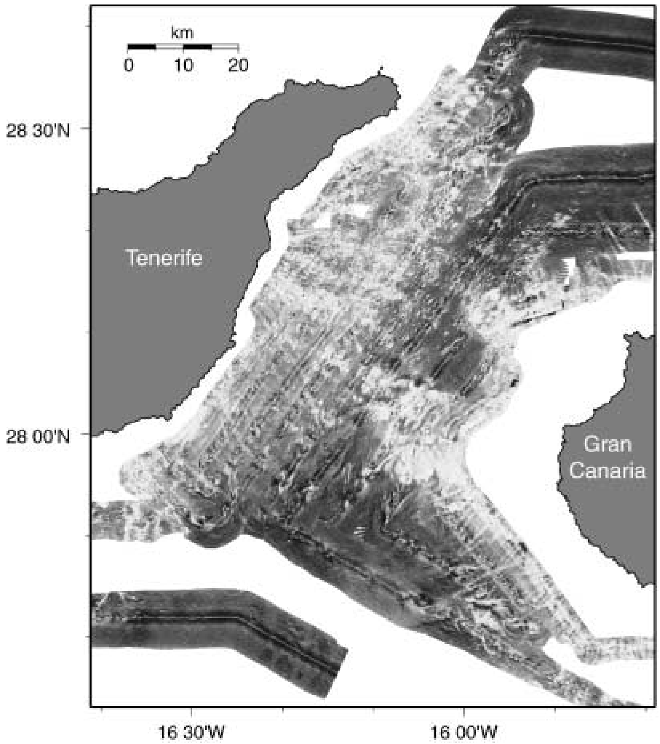

Fig. 3 EM12 backscatter data in the channel between Gran Canaria and Tenerife. *Dark tones* are areas of low backscatter. Note the subdivision of the channel into a northern part characterized by a *speckled high backscatter pattern* and a southern part, where this pattern is missing. The strong linear features mainly in a SW–NE direction are artifacts (ship tracks) inherent to the EM12 system

Bathymetric data were recorded using a Simrad EM12 and a Hydrosweep multibeam echosounder. The Hydrosweep system uses 69 beams with a swath angle of 90° giving a coverage of two times the water depth. The angular coverage of 81 beams of the EM12 system is 120° giving a swath width of up to 3.5 times the water depth. The accuracy of both systems is generally 0.25% of the water depth but up to 1% in areas with steep slopes. Accurate navigation data were collected with Differential GPS receivers. The bathymetric data were merged with topographic data from the island. Mercator projected grids with a grid cell dimension of 78 m at 30°N were calculated from the merged data (Fig. 2). Gebco data were used for areas without bathymetric coverage (especially northwest of Tenerife). Incomplete coverage of bathymetric data close to the coast and in the northern- and southernmost areas of the channel results in some artifacts (Fig. 2). The data are displayed using the Generic Mapping Tools (GMT) software (Wessel and Smith 1998). The Simrad EM12 system also recorded 32 backscatter values from each single beam, which were used to construct backscatter images (Fig. 3), similar to sidescan sonar images.

Four ODP-sites were drilled in the volcaniclastic apron around Gran Canaria during ODP-Leg 157 (Fig. 1, Schmincke et al. 1995). Site 956 is located ca. 45 km southwest of Gran Canaria and 60 km southeast of Tenerife (Fig. 2). The sediments drilled at site 956 (704 m penetration) range in age from middle Miocene to Holocene.

Results

Morphology of the channel between Gran Canary and Tenerife

The morphology of the channel between Gran Canaria and Tenerife is highly variable. Several features reflecting both active constructive processes and sudden destructive events can be identified. The minimum width of the channel is ~60 km, the minimum depth ~2,200 m (Fig. 2). The submarine flanks of Gran Canaria and Tenerife contrast strongly in their morphology (Funck and Schmincke 1998; Krastel et al. 2001a). Several bathymetric profiles across the channel are shown in Fig. 4. Most of these profiles are biased close to the coast because almost no bathymetric data were collected in water depth shallower than 800 m. The shallow water features are best illustrated in the bathymetric profile 1 of Fig. 4 as these bathymetric data were collected along a seismic line reaching close to the coast.

Gran Canaria is surrounded by an up to 10-km-wide and ~100-m-deep shelf. The shelf-break occurs at ~125 m water depth. From there on the slope gradient is 4–5° up to a water depth of ~600–900 m, where in most cases a second sharp break occurs and the slope gradient steepens to as much as 25°. Such a second break is not evident in profile 2 of Fig. 4. This profile runs through a large submarine reentrant, which can be clearly identified on the bathymetric map (Figs. 2 and 4). This reentrant is interpreted as an old landslide scar and the collapse of the submarine flank probably destroyed the original morphology. The slopes flatten again at a water depth of 2,000–3,000 m. The transition to the gently sloping basins north and south of Gran Canaria is continuous. A sharp break occurs in the central part of the channel where the seafloor starts to rise towards Tenerife (Figs. 2 and 4). This sharp break is absent in the northern and southern part of the channel. Because of the greater distances to the coasts, submarine slopes of both islands are generally less steep and a smooth transition occurs instead.

No broad shelf was found off the southeast coast of Tenerife (Figs. 2 and 4). The submarine flank of Tenerife drops with gradients of up to 20° to water depths between 1,000 and 2,000 m. The slopes gradually flatten with increasing water depth.

The contrasting morphologies of the submarine flanks of Tenerife and Gran Canaria basically reflect the difference in age and geological evolution of both islands. Volcanic activity on Tenerife began about 12 Ma ago and continues vigorously to the present. Major hiatuses may not have occurred at least during the past ca. 6 million years (Ancochea et al. 1990). Hence, no broad shelf was

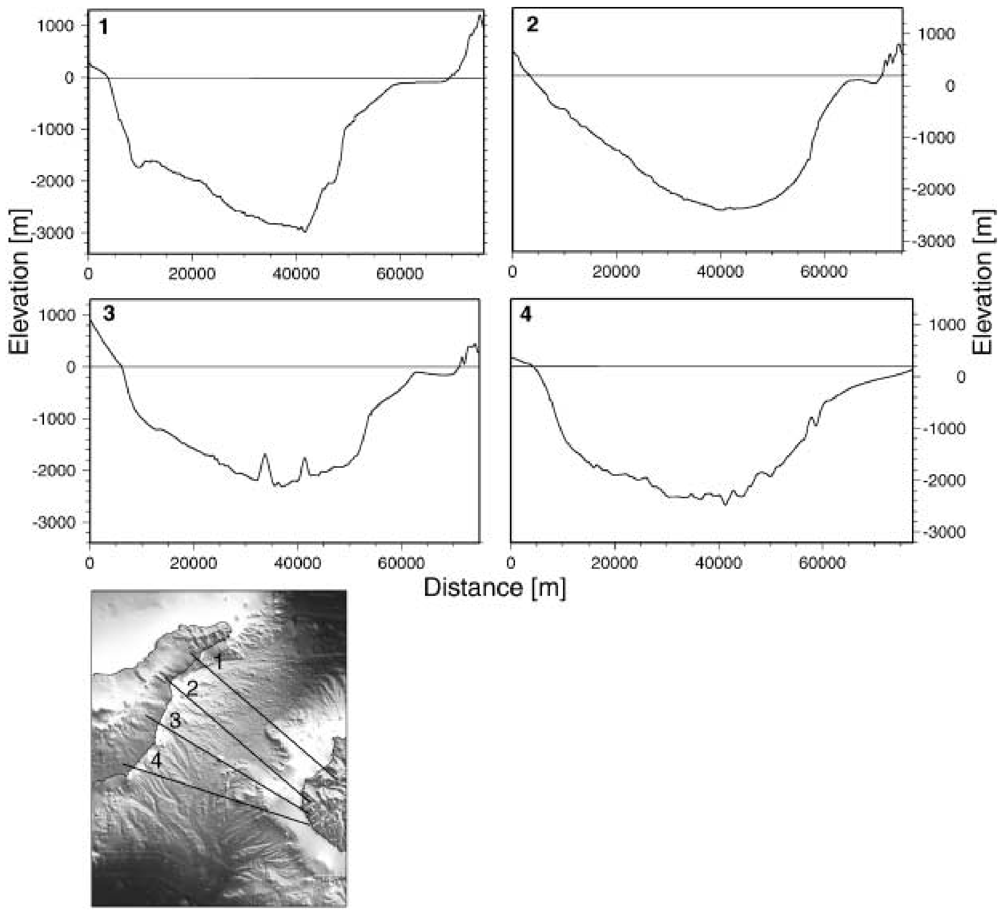

Fig. 4 Bathymetric profiles across the channel between Gran Canaria and Tenerife showing the different morphology of the submarine island flanks. Most of these profiles are biased closed to the coast as almost no bathymetric data were collected in water depth shallower than 800 m

able to form and no major breaks are present in the submarine morphology. Gran Canaria is also an active volcanic island, but the Holocene eruptions were not very voluminous and restricted to the north (Schmincke 1998). The broad shelf off the west coast of Gran Canaria indicates a long period of marine abrasion and the conservation of the slope breaks indicates that no major volumes of lava entered the sea or were erupted under water off the west coast of Gran Canaria in the Pliocene or Quaternary. However, we want to point out that the shelf break is not that well preserved all around the island. The slope break in the south of Gran Canaria, for example, is much less well preserved probably because of Pliocene Rouqe Nublo avalanche deposits, which entered the sea (Funck and Schmincke 1998).

The submarine flank of Tenerife in the channel shows a significant subdivision into a northern part characterized by a speckled high backscatter pattern on the EM12 backscatter map and a southern part where this backscatter pattern is missing. Several downslope-trending bands of a higher backscatter value than average are characteristic for this part (Fig. 3).

The backscatter pattern in the northern part of the channel represents a large number (>200) of individual hummocks of different sizes covering an area of ~1,600 km^2. Single hummocks can be recognized up to 70 km off the coast of Tenerife. The hummocks are also evident on the detailed bathymetric map (Fig. 2), which is available for most parts of this area. Most blocks are found at water depths between 1,500 and 3,500 m. They have a diameters of up to 1 km and rise 50–150 m above the surrounding seafloor. Only a few isolated blocks were identified at water depths >3,500 m and distances >50 km off the coast. Smaller blocks (<50 m diameter) probably exist beyond the margin, but were not detected because of the limited resolution of the systems. We interpret the morphology of the northern part of the channel as representing a major debris avalanche deposit (Fig. 5). Debris avalanches are fast long-runout mass movements in which fragmentation has reduced the landslide mass to individual blocks during sudden, catastrophic failures; they commonly start at a well-defined amphitheater at their head and the deposits are represented by a hummocky terrain in the lower part (Moore et al. 1989). However, it can not be ruled out that some of the larger hummocks are actually volcanic cones (see below).

The southern submarine island flank of Tenerife in the channel between Gran Canaria and Tenerife does not show evidence for giant landslides, but numerous submarine canyons can be identified on the bathymetric map (Fig. 2) and the EM12 backscatter map (Fig. 3). These canyons can be traced from close to the coast to water depth >3,000 m (Fig. 5). They are up to 3 km

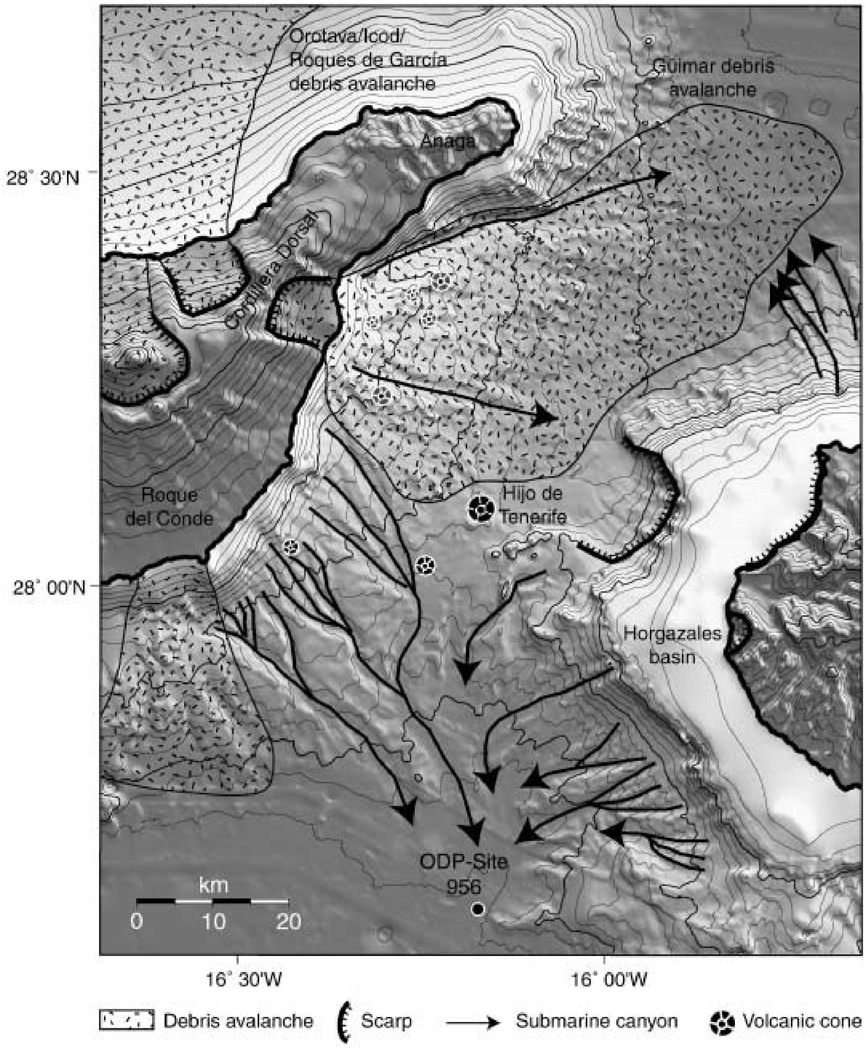

Fig. 5 Interpretation map of the channel. Numerous landslides and submarine canyons, which are major pathways for sediment transport from the islands to the basins, can be identified in the channel. Contour interval is 200 m (*bold lines* 1-km isolines). Features not covered by our data are taken from Watts and Masson (1995, 1998, 2001)

wide and up to 200 m deep. Similar canyons are also evident on the submarine flanks of Gran Canaria. GLORIA sonographs (Krastel et al. 20001a) and the EM12 backscatter data indicate that large amounts of sediments are transported through these canyons into the volcaniclastic apron. At least the canyons on the submarine flanks of Gran Canaria mainly occur in areas where abundant canyons were found on the island itself though it is not possible to trace the canyons from the island to the submarine flank because of missing bathymetric data coverage close to the coast. Nevertheless, we interpret most of the submarine canyons as continuation of subaerial canyons transporting sediments from the islands far into the sedimentary basins (Krastel et al. 2001a).

Only few detailed data are available south of the Tenerife (west of 16°25′W, Figs. 2 and 3). The EM12 backscatter map shows a relatively high amount of backscatter with a partly speckled pattern. This pattern indicates the occurrence of another debris avalanche (Fig. 5), an interpretation supported by GLORIA side-scan data in this area (Krastel et al. 2001b).

Seismic structure of the apron

The term apron is used following the definition of Schmincke and Sumita (1998) and includes the submarine volcanic edifice and the volcaniclastic sediments in the basins adjacent to the islands. Schmincke and Sumita (1998) define three main facies. The flank facies, the slope facies, and the basin facies. The flank facies is seismically opaque or chaotic and is characterized by discontinuous reflectors and rough topography. It consists of hyaloclastic lapillistones and breccias as well as basaltic debris flows as much as hundreds of meters thick, the latter representing the emergent stage of the oceanic island. The flank facies contains only minor non-volcanic sediments. Close to the island (up to ~50 km off the coast), the flank facies is overlain by the slope facies, characterized by slumps, discontinuously bedded units, debris flows, and erosional canyons. The slope facies grades laterally into the basin facies, characterized by more continuous reflectors or groups of reflectors indicating an interbedding of pelagic and volcaniclastic sediments. The volcaniclastic sediments include

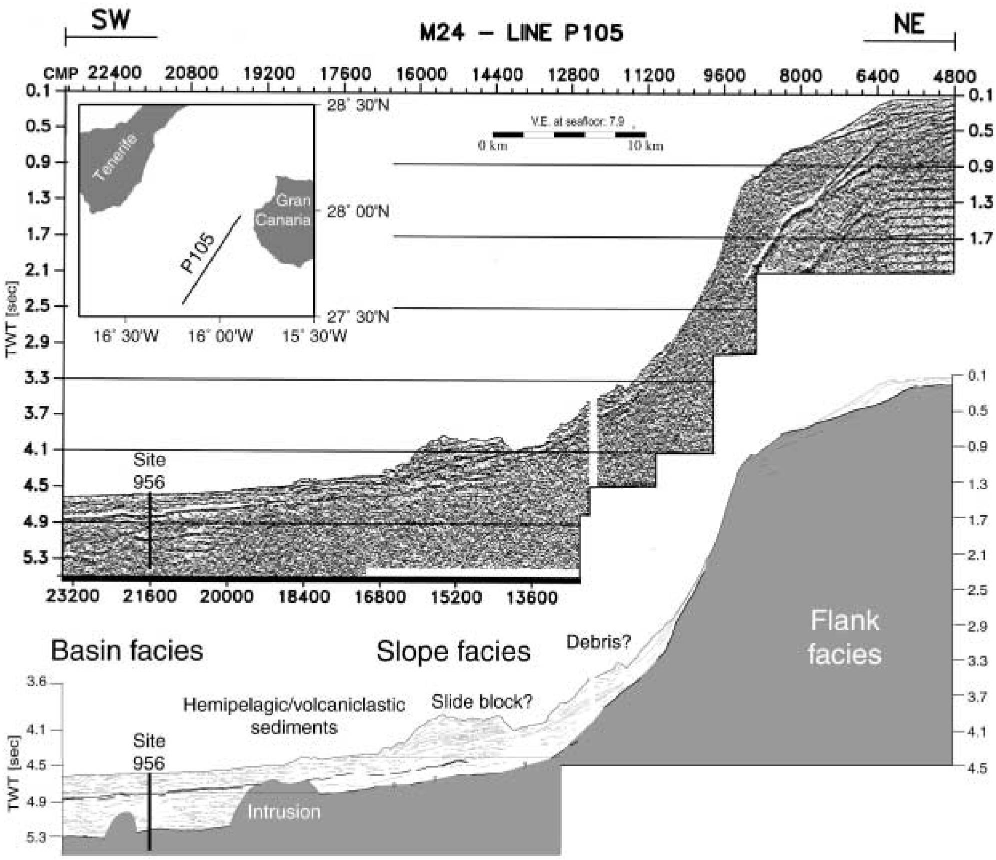

Fig. 6 Part of seismic line P105 with line drawing. The different facies of the volcaniclastic apron can be identified on this profile. The location of the part of the profile shown here is marked in bold on Fig. 2

fallout ash layers, debris flows, distal ignimbrites, turbidites, and other volcaniclastic rocks generated by eruptions, erosion, and flank collapse of the volcanoes.

The different facies are clearly visible on seismic profile P105 southwest of Gran Canaria (Fig. 6). The reflector interpreted to represent the island flank is the acoustic basement of the seismic data indicating the occurrence of massive basaltic breccia, lavas, or hyaloclastites, which cannot be penetrated by the seismic signal. In the channel between Gran Canaria and Tenerife, both island flanks can be identified on the seismic data (Fig. 7). The flank of Tenerife onlaps the flank of Gran Canaria, indicating that the submarine island flank of Tenerife is younger than the submarine portions of Gran Canaria. It is only possible, however, to trace the island flank of Gran Canaria beneath the flank of Tenerife for a very short stretch because the seismic energy did generally not penetrate the island flank of Tenerife. The island flank of Tenerife represents the acoustic basement and masks the deeper flank of Gran Canaria. The slope angles on seismic line P117 (Fig. 7) are biased because this profile crosses the slope in an oblique angle. In the central part of the channel, the submarine island flank of Gran Canaria is much steeper than the onlapping flank of Tenerife (Fig. 4).

Both slope and the basin facies can be identified on profile P105 above the flank facies (Fig. 6). The slope facies is characterized by discontinuous reflectors and many indications of slumps and slides. Most reflectors onlap the island flank. The reflectivity is high because of a large amount of volcaniclastic material, showing a high impedance contrast compared with the hemi-pelagic background sedimentation. With increasing distance from the island's coast, the continuity of the reflectors increases and the slope facies grades laterally into the basin facies. Abundant volcaniclastic sediments were identified in ODP-Site 956 (Schmincke et al. 1995) at the southwestern end of profile P105 (Fig. 6). This marks only the beginning of the basin facies. Volcanic turbidites probably sourced in the Canary Islands are found up to a distance of 1,000 km in the Madeira Abyssal Plain (Weaver et al. 1998).

No basin facies is visible in the channel between Gran Canaria and Tenerife (Fig. 7). The sediments above the island flanks show a pattern typical for the slope facies. The sedimentary section consists of deposits from both islands being the result of an interaction of subaerial and submarine constructive phases and destructive events. The prominent cone at the western end of seismic line P117 (Fig. 7) is a young submarine volcano on the submarine island flank of Tenerife provisionally named "Hijo de Tenerife" (Schmincke and Rihm 1994). The seismic line does not cross the top of this volcanic cone (Fig. 2). This volcanic cone (discussed below) is an example for the ongoing volcanic activity in the channel between Gran Canaria and Tenerife.

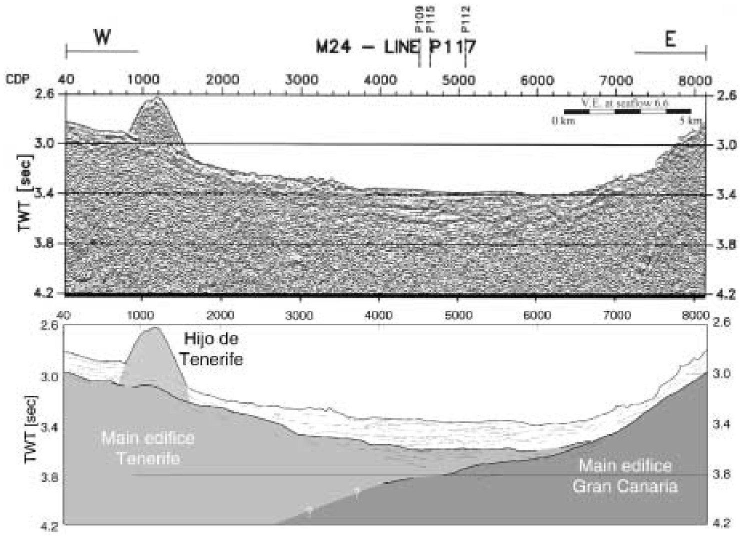

Fig. 7 Seismic line P117 with line drawing. The younger volcanic flank of Tenerife onlaps the older and steeper flank of Gran Canaria. No indications for a major fault are visible on this profile. Hijo de Tenerife, a young volcanic cone, is an example for the ongoing volcanic activity in the channel between Gran Canaria and Tenerife. The location of the profile is marked in bold on Fig. 2

Discussion

The submarine island flanks: criteria to distinguish their ages

The temporal succession of the submarine and subaerial island flanks of the Canary Islands have been interpreted differently. Age data for Gran Canaria show that the oldest rocks on Gran Canaria are about 15–16 Ma (van den Bogaard and Schmincke 1998). Age data for Tenerife are more contradictory. Ancochea et al. (1990) gave ages of 6.5–3.6 Ma for the Anaga shield in the NE and 6.7–4.5 Ma for the Teno shield in the NW. Most age data of the Roque del Conde shield in the south scatter between 8.5–6.4 Ma. One age of 11.6 Ma was given for one sample in the Roque del Conde shield, but this age was doubted by the authors themselves as this sample was taken from a dike cutting lava flows roughly 6–7 Ma old. Because a dike cannot be older than the lavas it cuts it appeared to be logical to assume that the age of 11.6 Ma was erroneous. Funck et al. (1996) showed that the submarine island flank of Tenerife is younger than the submarine island flank of Gran Canaria based on an onlap of the flank of Tenerife on the flank of Gran Canaria visible in reflection seismic data. Geisslinger et al. (1996), however, interpreted their seismic data as indicating their reflector C being Miocene in age (16 Ma), but consisting of apron material of both islands. Hence they propose synchronous volcanic activity at an early stage of the construction of both islands. They explain the fact that the surface rocks of Tenerife are much younger than that of Gran Canaria by cessation of volcanic activity on Tenerife by the end of the construction of the submarine shield apron while volcanic activity on Gran Canaria continued. More recent $^{40}Ar/^{39}Ar$ dating by Thirlwall et al. (2000) and van den Bogaard (unpublished data), have confirmed the older age (11 Ma) of the Roque del Conde Massif. Thirlwall et al. (2000) showed that the three old shields of Tenerife have different mantle sources.

Taking into account these new age data we reanalyzed the seismic data originally studied by Funck et al. (1996). All seismic profiles collected during Meteor-cruise M24 between both islands show an onlap of the gently dipping submarine flank of Tenerife on the steeper flank of Gran Canaria (Fig. 7). The submarine island flank of Gran Canaria cannot be traced far beneath the flank of Tenerife because the seismic signal did not penetrate any of the basaltic island flanks. Nevertheless, the extension of the different flanks helps to better understand the evolution. The island flank of Tenerife can be traced relatively close to Gran Canaria and terminates against the steep flank of Gran Canaria. This distribution clearly shows that the growth of Tenerife to the east was limited by the already existing flank of Gran Canaria. A similar pattern shows the island flank of Gran Canaria between Gran Canaria and Fuerteventura where a ponding of volcaniclastics against the older submarine flank of Fuerteventura is observed (Funck et al. 1996). We can only speculate about the shape of the submarine island flank of Gran Canaria beneath the flank of Tenerife, but at least the morphology of the flank in the channel up to the point where it is covered by the flank of Tenerife looks similar to the pattern observed on seismic profile P105 to the south of Gran Canaria (Fig. 6). The evolution of the submarine island flank of this profile was not influenced by any other island or seamount and, therefore, the submarine flank of Gran Canaria to the west was probably also deposited without any influence of Tenerife. Assuming that the submarine construction of Gran Canaria started at about 16 Ma as indicated by drilling (Schmincke et al. 1995), the unhindered deposition of the submarine flank of Gran Canaria shows that the submarine and subaerial construction of the different Tenerife shields had not started at this time. We do not see evidence for an early submarine volcanic stage on Tenerife.

The seismic data in the channel only allow determination of the relative ages of the submarine island flanks, i.e., the submarine flank of Tenerife being younger than the flank of Gran Canaria, but nothing can be said about the time gap between the deposition of both flanks. The time gap between the deposition of the older flank of Gran Canaria and the younger flank of Tenerife should be larger in the north than in the south because the Anaga massif in the north of Tenerife is younger than the Roque del Conde massif in the south (Ancochea et al. 1990) whereas no major differences in age exists for the deposition of the submarine flank of Gran Canaria (Schmincke 1998). We do not see, however, any significant difference between the northern and the southern part of the channel. The main reason for this is the chaotic sediment pattern in the channel, which does not allow to trace reflectors through the channel. Thus, it is not possible to correlate the sedimentary section in the south of the channel above the Roque del Conde shield with those in the north above the Anaga shield. Nevertheless, some of the oldest sediments visible on the island flank in the south must be masked in the north because of the younger age of the Anaga shield.

Morphological highs: young volcanic cones or exotic blocks?

An interesting feature are the numerous blocks of variable size on the flanks of both islands. Such prominent blocks, sometimes collectively called seamounts, around volcanic archipelagos were once all interpreted to be constructive features of volcanic activity, in short, submarine volcanoes. This interpretation, first questioned by Moore (1964) for one area south of the Big Island of Hawaii, experienced a massive reinterpretation following regional mapping by GLORIA around the Hawaiian Archipelago in the late 1980s (Lipman et al. 1988; Moore et al. 1989). Large block-fields were interpreted as the deposits of giant debris avalanches. The very detailed recent studies of the submarine flanks of many of the Canary Islands led to similar conclusions (Watts and Masson 1995, 1998, 2001; Masson 1996; Teide Group 1997; Urgeles et al. 1997; Funck and Schmincke 1998; Gee et al. 2001; Krastel et al. 2001b; Masson et al. 2002).

Though a large block-field is suggestive of a debris avalanche deposit, we cannot exclude that some or all of the blocks are volcanic cones. Unfortunately no clear criteria for the distinction between exotic blocks and cones are available (Fig. 8). A large block-field was discovered in the northern part of the channel between Gran Canaria and Tenerife (Figs. 2, 3, and 5). We interpret this block-field as representing basically the deposits of a debris avalanche. Geological studies of Güimar Valley landward of the submarine deposits showed that the valley was formed by a flank collapse younger than 0.83 Ma, the most recent age obtained for lava flows in the scarp (Ancochea et al. 1990). Güimar valley is interpreted as the source area for the deposits (Fig. 5). In addition, debris flow deposits interpreted to be the distal equivalent of the debris avalanche are thought to have been detected

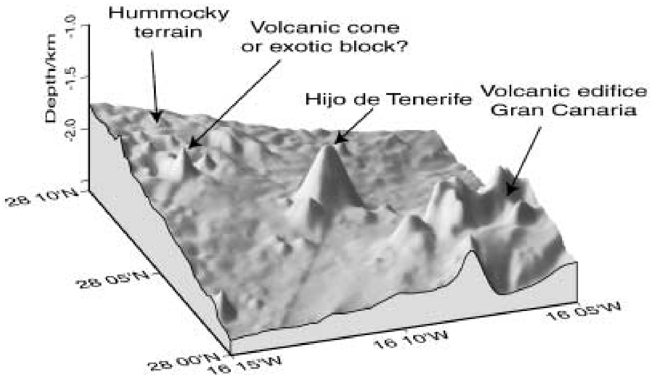

Fig. 8 Perspective view of Hijo de Tenerife, a young, possibly active volcanic cone. The block/cone in the northwestern part of this figure demonstrates the difficulty to distinguish between exotic blocks and volcanic cones. View is from SSW, vertical exaggeration is 5. See Fig. 2 for location

in ODP drill holes 954 and 953 (Fig. 1), the latter 156 km off the coast of Tenerife (Sumita et al. 2000). In summary, the northern part of the channel has been clearly affected by a debris avalanche, called Güimar debris avalanche. Generally, large block-fields on the submarine flanks of the Canary Islands were only found offshore of subaerial island flanks showing clear indications for flank collapses (Krastel et al. 2001b). Hence, such block-fields are definite evidence for the deposits of a giant landslide.

Though areas of debris avalanche deposits can be identified by the hummocky terrain it does not answer the question of which blocks are transported by the debris avalanche and which morphological highs are volcanic cones. The most prominent cone in the channel between Gran Canaria and Tenerife is located at 28°05′N, 16°10′W (Figs. 5, 7, and 8). This seamount was discovered and provisionally named “Hijo de Tenerife” during Meteor-cruise M24 in 1993 (Schmincke and Rihm 1994). The height of this feature is ~600 m, the diameter ~3.5 km (Fig. 2). The dimensions of this feature are so large that we interpret it as volcanic cone, an interpretation supported by dredging during Meteor-cruise M43. Several dredges contained entirely bomb-shaped bread-crusted volcanic clasts up to 20 cm in diameter. These very fresh rocks are of intermediate composition, but contain both entire and fragmented peridotite xenoliths as well as slightly metamorphosed sandstones of possibly Mesozoic age. The volcano is speculated to be still active (Schmincke and Graf 2000). A second cone, located at 28°13.5′N, 16°18.1′W (basal dimensions of 2.5×1.7 km, height of 300 m, Figs. 2 and 5), was also sampled during Meteor-cruise M43 and was identified as submarine scoria/lapilli cone rather than a landslide block (Schmincke and Graf 2000). This cone is located in the Güimar debris avalanche area, but in an area with only some isolated blocks of relatively large dimensions. Large isolated blocks may be indicative for volcanic cones though no samples are available for other blocks. We interpret these large isolated blocks as volcanic cones, though we cannot provide final proof for this interpretation (Fig. 5). Nevertheless, we think that the majority of the hummocks (>80% being a rough estimate based on an analysis of their shapes) are exotic blocks transported by a debris avalanche. Such a large number of small and large hummocks on the lower slopes are not found elsewhere in the channel between Gran Canaria and Tenerife, and the dimensions of the blocks fit well with those reported from other debris avalanche deposits at the submarine flanks of the Canary Islands (Krastel et al. 2001b; Masson et al. 2002).

Romero Ruiz et al. (2000) estimated that at least 16 highs in the channel between Gran Canaria and Tenerife are of volcanic origin based on a detailed analysis of geomorphological parameters. We plan to do a dedicated cruise for detailed bathymetric analyses and dredging to allow a more rigorous identification of the origin of morphological highs in what appear to be clear debris avalanche fans. However, we want to point out that volcanic cones can be transported in a debris avalanche and may appear as rooted volcanoes. Moreover, landslide scars are commonly also the site of subsequent volcanic activity. Scars commonly became completely buried under new volcanic products and the appearance of young volcanic cones in thick submarine debris flow/avalanche deposits may highlight some structural lineaments utilized by subsequent volcanic activity, which is more frequent in such zones of structural weakness than in nearby flank areas.

Is the channel a zone of major dynamic activity?

Many authors have emphasized the structural interpretation of the channel orientation as a major fault zone, following the original hypotheses of Dash and Bosshard (1969). Mezcua et al. (1992) analyzed a magnitude 5.2 earthquake followed by a large number of aftershocks and conclude that a horizontal compressional stress regime in NW–SE direction is present in the channel region, which is compatible with the tectonics in the northwestern part of the African continent. Seismic line P117 (Fig. 7) crosses the postulated fault east of “Hijo de Tenerife”. No major offset can be identified on this or any other line. This result is consistent with the analysis of Funck et al. (1996): hence the existence of a fault zone is questionable.

We think that the sporadic earthquake activity in this area is not related to a major fault, but maybe related to the regional stress field or the submarine volcanic activity in this area, e.g., of Hijo de Tenerife (see above). The observed earthquake activity (Mezcua et al. 1992; Romero Ruiz et al. 2000) occurs predominately in the area of Güimar debris avalanche, an area with abundant blocks, some of them being volcanic cones. Romero Ruiz et al. (2000) stated that the seamounts they interpreted as volcanic cones follow the main volcano-tectonic trends (NW–SE and NE–SW) of the Canary Archipelago. They correlate the NE–SW line with the fault described above. However, we want to point out that almost all of these cones are scattered in the area modified by the Güimar debris avalanche. We interpret these cones as the result of post-failure volcanism not related to the postulated fault zone.

How many debris avalanche deposits can be recognized in the channel area and what other destructive processes occur?

The different data sets in the channel between Gran Canaria and Tenerife used in this study allow an estimation of the importance of large-scale slides during the evolution of both islands and the general importance of landsliding during the evolution of volcanic islands. The morphological data (sidescan sonar and bathymetry) provide information about young slides whereas the seismic data in combination with ODP drilling and land studies allow buried older slides to be identified.

One of the most prominent deviations from the general circular shape of Gran Canaria is a 19-km-wide reentrant at the northwest coast extending 4.5 km inland (Fig. 5). Funck and Schmincke (1998) interpret this reentrant as the remnants of an amphitheater-shaped scarp of the type typically associated with a landslide. The estimated age of this landslide is ~14 Ma. Funck and Schmincke (1998) identified a second Miocene landslide off Horgazales basin (Fig. 5), a major refilled scarp in the Miocene shield volcano of Gran Canaria (Schmincke 1968). A >80-m-thick debris flow was found at the base of the 700-m-deep ODP-Site 956 45 km southwest of Gran Canaria. This debris flow was interpreted to have been derived form Horgazales basin as it is overlain by two thinner basaltic debris flows that corresponds compositionally to the more evolved basalts of the Horgazales Formation filling the major collapse scarp (Schmincke and Segschneider 1998). Another scarp was identified in the submarine flank of Gran Canaria (Fig. 5), but no landslide deposits were detected as they are probably buried by the younger island flank of Tenerife. These slides developed at the end of the shield building phase, the main constructive phase during the evolution of an ocean island. No Miocene landslides on Tenerife were identified based on our data. Watts and Masson (1995, 1998, 2001) found clear indications for landslides with an age >>0.5 Ma north of Tenerife, but the exact age is unknown. The high accumulation rates of volcanic turbidites in the Madeira Abyssal Plain since 7 Ma, however, indicate major mass-wasting events during growth of Tenerife in the Miocene (Weaver et al. 1998).

Moore at al. (1989) showed that most landslides around the Hawaiian Islands occur late in the period of active shield growth when the volcanoes are close to their maximum size and are young and unstable and when seismic activity is high. The same is valid for the Canary Islands, but in contrast to the Hawaiian Islands post-shield volcanic activity is much stronger and the individual islands are volcanically active for a much longer time span. This long-lasting and intense post-shield activity is accompanied by giant landsliding. Güimar debris avalanche (Fig. 5) occurred during the formation of the Cordillera Dorsal, a chain of basaltic emission centers linking the central Cañadas volcano with the Anaga peninsula in the northeast. The peak activity was around 0.8 Ma, which is also the estimated time for the collapse resulting in the deposition of Güimar debris avalanche. More landslides occurred during the other major volcanic phases on both islands, e.g., the Roque Nublo debris avalanche on Gran Canaria during the Pliocene volcanic phase on Gran Canaria (García Cacho et al. 1994; Funck and Schmincke 1998; Mehl and Schmincke 1999), and several debris avalanches on Tenerife, which affected the Cañadas volcano and the Cordillera Dorsal (Ancochea et al. 1990; Watts and Masson 1995, 1998, 2001). The long-lasting volcanic constructive history of individual islands is balanced by a correspondingly long history of destruction (Krastel et al. 2001b).

Destruction of the islands does not only occur during large destructive events, but is a continuous process caused by normal erosional processes. The importance of erosion by rainfall is well documented on Gran Canaria. The northern and eastern part shows vigorous erosion because of the northeast trade winds and the associated rainfall whereas the southern part is characterized by a much dryer climate resulting in single deep canyons, but a generally smaller amount of erosion. The canyons play a key role for the transport of the eroded material into the sedimentary basins (Fig. 5). Most of the subaerial canyons have submarine continuations. Large amounts of sediments transported through the canyons were identified on the submarine island flanks by means of GLORIA sonographs (Krastel et al. 2001a) and the EM12 backscatter data. Some of the major canyon systems on Gran Canaria have persisted for at least 14 million years (Schmincke 1968, 1976) and sediment transport seems to be concentrated in these canyons. The submarine canyons being aligned with the subaerial canyons are probably the result of the concentrated sediment transport. Downslope-eroding mass flows originate on land, enter the sea, and continue below sea level for several tens of kilometers. The mass flows erode proto-canyons on the submarine island flanks, which become deepened by further erosion and failures of the canyon-walls and/or floor (Krastel et al. 2001a). Other processes might be responsible for the formation of the swell and valley morphology off southeastern Tenerife as well (Fig. 5). The Teide Group (1997) showed that parts of the swell and valley morphology on the southeastern flanks of Tenerife were created by two overlapping debris flows with the topographic lows being aligned along the axes of the lower flow, but we consider submarine erosion as the main process for the formation of the submarine canyons.

How do the sediments in the basins north and south of the channel differ from each other?

The presence of channel areas, morphologically higher than the basins north and south of the central Canary Islands, together with the general age progression from east to west, were the reason for developing a drilling strategy north and south of Gran Canaria to get a better picture of the contrasting evolution of the sedimentary basins (ODP Leg 157; Schmincke et al. 1995). This assumption was clearly supported by the results of drilling, which showed that the basins started to develop when the island chain migrated westward, thereby subdividing larger sedimentation areas into two sub-basins, north and south of the growing chain.

The seismic data north and south of Gran Canaria show some similarities, but also major differences. Some reflectors can be clearly identified in both basins, e.g., the strong reflector about 300 ms TWT below the seafloor on the southwestern end of seismic profile P105 (Fig. 6). Drilling the apron showed that this reflector consists largely of basaltic lapillistones deposited in the Pliocene during a major phase of volcanic activity on Gran Canaria. Correlation of other reflectors, however, is difficult because it is impossible to trace reflectors through the channel. The reflectivity is generally higher in the northern basin. Funck and Lykke-Andersen (1998a) showed that most reflectors in the northern basin are the result of volcaniclastic material derived from the islands showing a large impedance contrast to the hemipelagic background sedimentation. The lower reflectivity in the southern basin indicates a lower amount of volcaniclastic material in this basin, an interpretation supported by drilling (Schmincke et al. 1995). The old islands of Fuerteventura and Lanzarote (15–20 Ma) northeast of Gran Canaria protect the northern basin from input of terrigenous sediments whereas large amounts of terrigenous material were identified in ODP-holes south of the Canary Islands (Schmincke et al. 1995). The slightly greater depth of ~3.600 m in the northern basins compared to ~3.400 m south of Gran Canaria is probably the result of the higher input of terrigenous sediments derived from Africa into the southern basin. Though a few reflectors can be clearly correlated in the southern and northern basin, the basins developed differently following the build-up of the islands in the Miocene. The channels between the islands are ~1,000 m shallower than the basins and act as major barrier for sediment transport between the north and the south.

Conclusions

The detailed analysis of seismic and bathymetric data in the channel between Gran Canaria and Tenerife allow conclusions to be drawn on the evolution of the channel, which is influenced by geological processes on the adjacent islands.

1. The chaotic seismic pattern in the channel is the result of the interaction of subaerial and submarine constructive phases and destructive events.
2. The main constructive phase is the build-up of the island flanks. The submarine island flank of Tenerife is younger than the submarine flank of Gran Canaria.

3. The very fresh rocks of Hijo de Tenerife indicates ongoing volcanism in the channel area.
4. Large block-fields were found on the submarine island flanks. It is difficult to distinguish exotic blocks from volcanic cones, but we consider most of the blocks (>80%) to be exotic blocks transported by a landslide. Volcanic cones in the areas affected by landsliding are probably the result of a changing stress field following the flank collapse.
5. We did not find evidence for a major fault in the channel area between Gran Canaria and Tenerife.
6. Giant landsliding is the most prominent process for sediment transport from the islands into the apron. Landslides occur during the entire volcanic evolution of the individual islands of the Canary Archipelago. Large amounts of sediments are also transported through the numerous submarine canyons form the islands into the basins.
7. The channels between the islands are a major barrier for sediments resulting in a different evolution of the basins north and south of the Canary Archipelago.

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