Salt Diapirs, Salt Brine Seeps, Pockmarks and Surficial Sediment Creep and Slides in the Canary Channel off NW Africa

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Abstract

Circular to elliptical mounds in the Canary Channel with reliefs of 75 to 375 m and diameters of 4 to 8 km partially surrounded by moats with reliefs of 25 to 75 m, were formed by piercement of the seafloor by Mesozoic evaporites. Several long gullies, < 1 km wide, with abrupt terminations and pockmarks associated with these mounds were probably eroded by dense brine and hydrocarbon seeps. The salt brines that eroded the gullies were formed where salt diapirs intersect the seafloor, or in the subsurface by circulating ground water heated by igneous activity along the Canary Ridge. If the brines originated in the subsurface they reached the seafloor along faults. Displacement of the surficial sediments by sliding and creep is probably the result of the expulsion of hydrocarbons and/or vertical motion of the Mesozoic evaporites. Microtopographic features along or near the east flank of the Canary Ridge are the creation of uplift of the ridge, hydrothermal activity, mass wasting processes and turbidity currents.

Introduction

Cold seeps in the marine environment have been reported in historical times as far back as 10 A.D. when the people of Aradus, an island city 4 km offshore Syria, obtained fresh water from a submarine spring located between the islet and the mainland during sieges (Emery and Uchupi, 1984). It was not until the mapping of pockmarks on the Scotian Shelf by King and MacLean (1970), however, did we came to appreciate the importance of fluid discharge in the marine environment. There is no doubt that the expulsion of fresh water, salt brines, or gas and oil plays a significant role in recycling processes and in sculpturing the morphology of continental margins.

In active margins the diffused discharge of pore fluids from a tectonically dewatered and degassed accretionary wedge has led to the construction of mud volcanoes and diatremes (formed by rapid flow of pore fluids through a sediment mass which becomes fluidized and entrained into the discharged fluids) (Brown, 1990). In addition, such dewatering has caused precipitation of authigenic carbonates in the form of thin crusts, slabs, irregular edifices and chimneys with reliefs of 1 to 2 m, the grown of mats of chemoautotrophic oxidizing bacteria, and colonies of benthic invertebrates that obtain their nutrients from the oxidizing bacteria (Cadet et al., 1987; Le Pichon et al., 1987; Ohta and Labuier, 1987; Pautot et al., 1987; Kennicut et al., 1989; Henry et al., 1990; Kulm and Suess 1990; Lewis and Cochrane, 1990; Wang et al., 1995; von Rad et al., 1996). Along active transform plate margins, such as the Eurasian/African boundary in the Gulf of Cádiz, mud and fluid eruptions have led to the construction of mud volcanoes and carbonate pipes, chimneys and mounds (Maldonado et al., 1999; Somoza et al., 2002).

Seeps in passive margins have been reported in environments ranging from lakes, intertidal/shallow tidal areas, bays, fjords, marginal seas, gulfs, continental shelves and continental slopes, submarine canyons and deep-sea fans (Hovland and Judd, 1988; Uchupi et al., 1996; Stakes et al., 1999). They are particularly abundant in offshore evaporite, or hydrocarbon regions where salt brines, crude oil, fluid mud and gases are common seep products (Roberts et al., 1990). Examples of such regions include the Gulf of Mexico, the Gulf of Cadiz, the Kattegat Strait between Denmark and Sweden, the southern Skagerrak between Norway and Denmark, the North Sea, the northern Norwegian shelf, and the Persian Gulf (Behrens, 1988; Kennicutt and Brooks, 1990; MacDonald et al., 1990; Sassen et al., 1991; Hovland, 1992; Aharon, 1994; Roberts and Aharon, 1994; Baraza and Ercilla, 1996; Uchupi et al., 1996; Aharon et al., 1997). In most of these regions the deep-seated hydrocarbons are linked to salt-induced faults that provide the conduits for the migration and seepage onto the seafloor.

The most common seep related-features in continental margins are pockmarks, although mud volcanoes and mud diapirs formed by the upwelling of gaseous muds are also quite common; e.g. Nigeria; (Graue, 2000), in the Gulf of Mexico (Neurauter and Bryant, 1990) and Gulf of Cadiz (Maldonado et al., 1999; Somoza et al., 2002). Associated with some of the pockmarks are black-sulphide rich sediments, mats of sulphur oxidizing bacteria and invertebrates, which obtain their nutrition from species with symbiotic sulphur-oxidizing bacteria and symbiotic methane-oxidizing bacteria (Dando and Hovland, 1992; Dando et al., 1991). Degradation of hydrocarbons seeps has also resulted in authigenic carbonate build-ups (Roberts et al., 1989). This combination of authigenic carbonate formation and biological accumulation can lead to the formation of mounds (von Bitter et al., 1990; Dando et al., 1991; Hovland et al., 1994; Beauchamp and Savard, 1992) or pseudobioherms, i.e. bioherm-like features not rising above the seafloor and lacking reef builders (Gaillard et al., 1992).

According to von Rad et al. (1996) pockmarks in the Makran accretionary wedge, offshore Pakistan, were formed by focused fault-controlled expulsion of fluids. At or near some plate boundaries of transform/compression type, such as those in the Mediterranean and New Zealand, some of the pockmarks are related to volcanism and may have been formed by the expulsion of hydrothermal gases and water (Pickrill, 1993; Acosta et al. 2001). Other pockmarks are due to biogenic gas formed by the decay of organic matter. Such organic-rich sediments are abundant within the Pliocene-Quaternary sediments of the Mediterranean (Cramp and O'Sullivan, 1999; Thomson et al., 1999; Coleman and Ballard, 2001).

Where salt domes pierce the seafloor brine pools may form, such as the pool seen within a fractured carbonate cap in the Gulf of Mexico (Bright et al., 1980). In another part of the Gulf, flowing brine has been trapped on the axis of a circular basin formed by the coalescing of several salt domes. The brine in the basin (Orca Basin) merges from flows into small gullies cut on the flanks of the salt domes (Shokes et al., 1977). Brines may also fill some pockmarks by lateral seepage through the pockmark walls (MacDonald et al., 1990; MacDonald, 1992). Brine seepages along the base of the Florida Escarpment in the Gulf of Mexico have also led to the establishment of methane-oxidizing bacteria that serve as a food source for a densely packed population of invertebrates via symbiosis (Paull et al., 1984). Paull and Neumann (1987) further inferred that the acid generated by the oxidation of the sulfide in the brines might undercut the scarp causing its collapse and retreat.

In this study we describe gullies associated with salt diapirs from the Canary Channel, which are inferred to be formed by brine seepages. This is the first report of such occurrences off the African margin. They were discovered in the course of an investigation of the Canary Island archipelago.

Material and methods

Three data sets were used in this study. One set consists of single channel seismic reflection profiles recorded during the International Decade of Ocean Exploration investigation of the west African margin. The profiles included in this report were collected aboard the R/V Atlantis II in 1973. These profiles were recorded using a 300 in^3 air gun fired every 10 or 12 seconds and two 30 m hydrophone arrays, whose signals were summed, amplified and recorded in a dry-paper printer; ship's position was obtained via satellite at two hour intervals. Uchupi et al. (1976) published line interpretations of these profiles in a manuscript regarding the morpho-tectonic setting of the northwest African and south Iberian continental margins.

The second data set corresponds to the bathymetry of the Canary Channel based on swath data recorded by the Instituto Español de Oceanografía and the Instituto Hidrográfico de la Marina between 1998 and 2002. The data were collected during an investigation of the Canary archipelago aboard the R/V Hesperides and R/V Vizconde de Eza. The multi-beam sounding systems used separately or in combination included Simrad EM 1000, EM 1002 and EM 300, in conjunction with GPSD and inertial navigation systems, were used to survey shallow waters and an EM12S in deep waters. A DTM and contour software (Cfloor from Roxar) and a Geographic Information System (IberGIS from ICI) was used to create a bathymetric map of the Canary Channel and the shaded relief and 3D block diagrams of the surveyed area.

The third data set was obtained during a cruise aboard R/V Vizconde de Eza in October 2002. During this cruise three of the mounds in the Canary Channel were sampled and photographed. Sampling was by means of a biological dredge and photography with a Benthos model 372 submarine camera capable of operating to depths of 11000 m. The photos were acquired with the vessel drifting over the mounds at a speed of 0.5–1.0 knots using a Dynamic Positioning System. The photographs were taken every 10 seconds along five paths with the camera 'flying' 6 m above the sea floor. More than 3000 photographs were recorded during the cruise with each covering an area of about 21 m^2. The morphology and structure of the mounds during the R/V Vizconde de Eza cruise was defined with the aid of a SIMRAD EM-300 multibeam echosounder, a Topas 018 high resolution seismic profiler and a marine Geomag SMM with 0.01 nT precision magnetometer. The ship's position during the survey was determined with a D-GPS integrated with a inertial navigation system Seapath 200.

Morpho-tectonic setting of the Canary Channel

Stratigraphic setting

Making up the flanks of the Canary Channel, offshore northwest Africa, are the African passive margin on the east and the Canary Ridge on the west (Figure 1). Construction of the passive margin is due to syn-rift deposition prior to 190 Ma (Late Triassic-Early Jurassic) and post-rift sedimentation since sea-floor spreading began about 190–185 Ma latest Early Jurassic (Toarcian-Present; Hinz et al., 1982; Emery and Uchupi, 1984; Steiner et al., 1998). The syn-rift sequence roughly consists of continental clastic rocks, volcanic rocks, evaporites and carbonates. The post-rift or drift strata are made up of Mesozoic platform and distal carbonates, regressive clastics, transgressive carbonates and euxinic and clastic sediments, Paleogene manganese oxide and phosphatic and siliceous deposits and Neogene clastic sequences. Drift deposition was influenced by events such as the massive gravitational sliding off the Suess Trough in the Late Cretaceous, possibly due to uplift of the western High Atlas and motion along the South Atlas Fault (Price, 1980). Volcanic construction of the Canary Ridge in the Early Cretaceous-Cenozoic, establishment of polar circulation and the trade winds in the Paleogene, Cenozoic Pyrenean-Alpine orogenies and glacially induced transgressions and regressions during the Cenozoic and Quaternary also contributed to the formation of the west African margin.

Construction of the Canary Ridge along the west side of the Canary Channel apparently took place along the continental/oceanic crustal boundary (Coello et al., 1992; Ancochea et al., 1996; Steiner et al., 1998; Martínez del Olmo and Buitrago Borrás, 2002). Price (1980) also proposed that volcanism along the ridge may have take place along a sinistral shear fault, the curved seaward continuation of the South Atlas Fault. This fault merges southwestward with the east-west trending fracture zone along the trend of Gran Canaria, Tenerife, La Gomera and El Hierro islands. Others have ascribed a hot-spot origin for the volcanism in the Canary Islands (Holik et al.,1991; Hoernle and Schmincke, 1993; Carracedo et al., 1998; Dañobeitia and Canales, 2000). With construction of the north trending Canary Ridge, the African continental rise was split in two and sediment input to the distal part of the African continental rise became drastically reduced.

Results

Neogene acoustic stratigraphy

The acoustic stratigraphy displayed by the seismic reflection profiles acquired in the Canary Channel aboard the R/V Atlantis II is probably limited to the Neogene. The presence of diapirs along some of the profiles do indicate, however, that the Upper Triassic/Lower Jurassic evaporites in the coastal basins extend offshore. The wide line spacing, the lack of tie

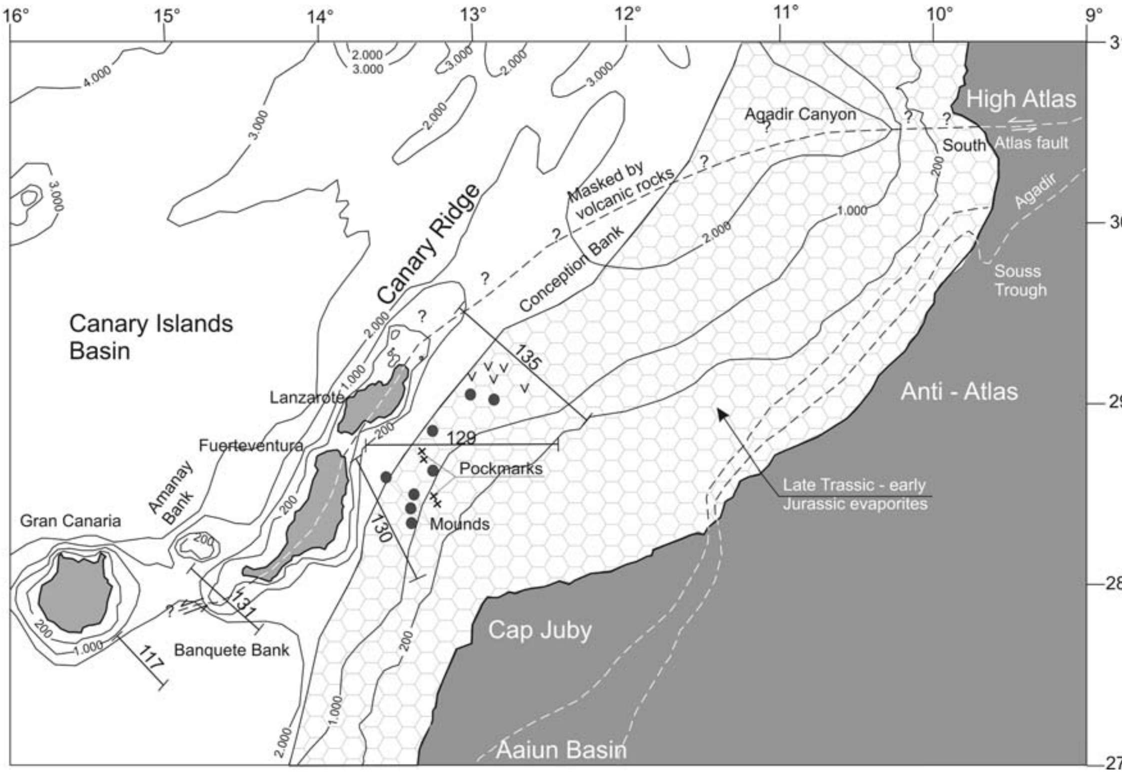


Figure 1. Morpho-tectonic map of the Canary Channel showing location of the seismic reflection profiles shown in Figures 2 and 3. Compiled from Uchupi et al. (1976) and Hinz et al. (1982). Hexagonal pattern = Extent of Mesozoic evaporites. Water depths in meters.

lines and the presence of a massive diapiric field makes it difficult to define the Neogene acoustic stratigraphy of the Canary Channel as a unit. In the absence of stratigraphic data is impossible to assign ages to the units imaged by the seismic profiles. Each of these lines displays an acoustic facies suggesting that sediment input from the Canary Ridge was important during the Neogene and that input from the African margin and the Canary Ridge varies along the strike of the channel. This variation coupled with salt diapirism, bottom current and vertical oscillations of the Canary Ridge has led to a complex geometric facies pattern in the Canary Channel.

Line 117 (Figure 2) extends southeastward from the flank of Gran Canaria to a water depth in excess of 2000 m. It is only along this line that stratigraphic data from Ocean Drilling Program (ODP) Site 955 makes it possible to determine the lithology and ages of the seismic units imaged by the seismic reflection profiles described in this report. ODP Shipboard Scientific Party (1995) identified five units, A–E, at ODP Site 955 at a depth of 2865 m (3.8 seconds) on the volcanic apron surrounding Gran Canaria. The upper sequence made up of units A–C consists of Pleistocene to late Pliocene nanno ooze interbedded with clayey silt and sand and early Pliocene to late Miocene nannofossil ooze. The lower sequence made up of units D to E consists of middle to upper Miocene nannofossil ooze interbedded with quartz silt and sand at the top and a mixture of nannofossil ooze, volcaniclastics and siliciclastics at the base. The volcaniclastic detritus is correlative with the Miocene Fataga and Mogan Group volcanism in Gran Canaria. The upper sequence thickens basinward and displays lateral changes in seismic facies and the lower sequence thins basinward. Acoustic basement at the base of unit E is the top of the lower volcanic sands correlative with the Mogan Formation of Gran Canaria. These two sequences could be correlative with units 1–3 imaged by the profiles in the Canary Channel. The absence of a tie line and location of ODP Site 955, on the Gran Canaria volcanic apron 109 km southwest of Fuerteventura and 125 km west of the African margin (Shipboard Scientific Party, 1995), make such

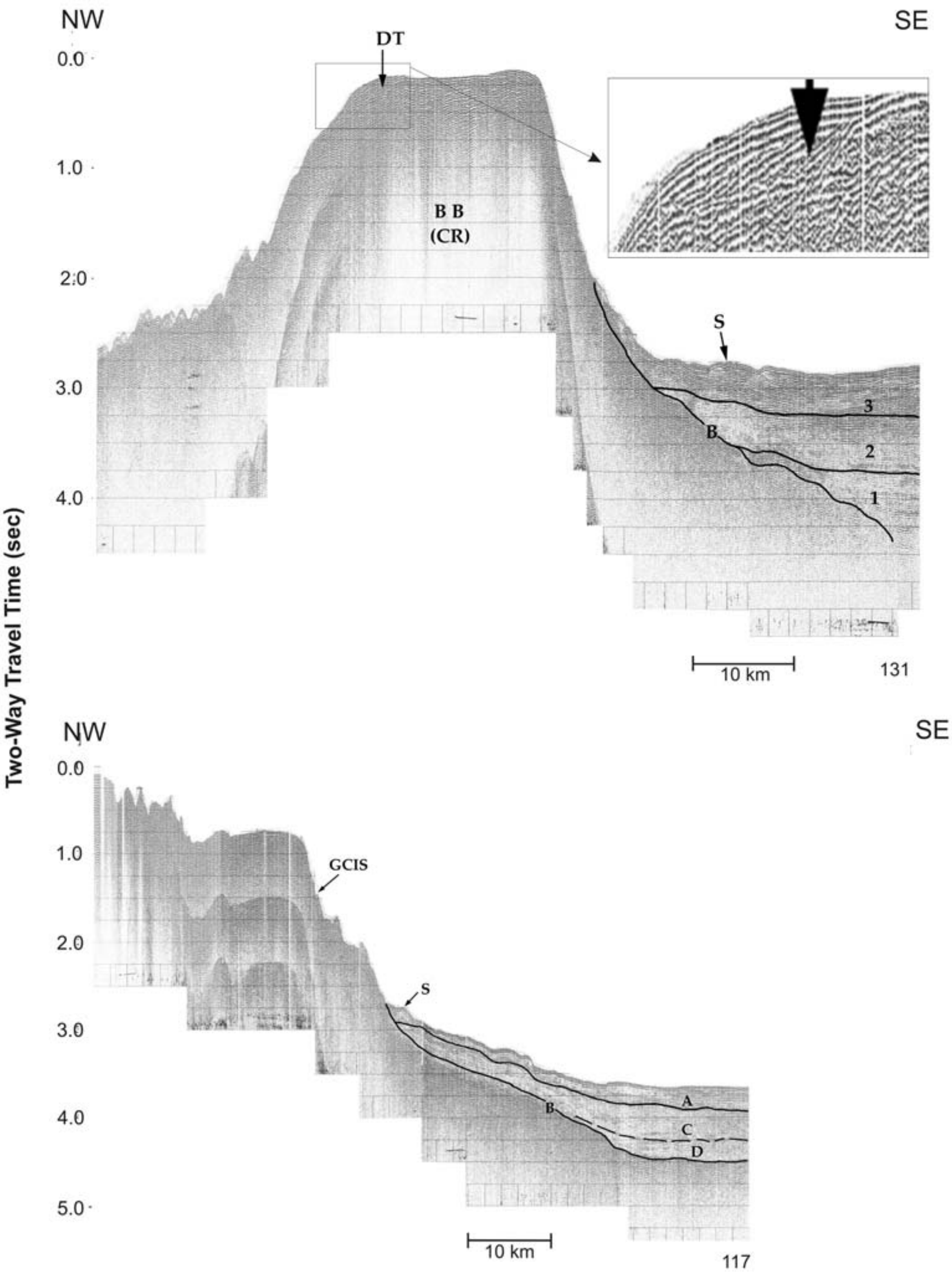


Figure 2. Seismic reflection profiles 131 and 117. See Figure 1 for location of profiles. B = Basement; BB = Banquete Bank; CR = Canary Ridge; DT = Delta; GCIS = Gran Canaria Insular Slope; S = Slump or Sediment waves. Units A, C and D along profile 117 are from Shipboard Scientific Party (1995).

correlation tenuous at best. Thus we use a distinct stratigraphic nomenclature for the lines in the Canary Channel and Line 117.

Its possible that the Neogene stratigraphic sequence in the lines in the Canary Channel is more compatible with that at Deep Sea Drilling Project (DSDP) Site 397 drilled on the continental rise at a depth of 2914 m (Arthur et al., 1979). This site is located over 100 km southwest of the Canary Channel. If so, then Neogene deposition in the channel was influenced by massive erosion by a geostrophic bottom currents and slumping during the late Eocene to late Oligocene and by early-late Miocene hemipelagic deposition in an upwelling environment. Subaerial volcanism during the middle Miocene in Fuerteventura and Lanzarote was another event that influenced deposition in the channel. This event is represented at DSDP Site 397 by volcaniclastic debris flows and rhyolitic ash layers. Late Neogene deposition at the site is characterized by high carbonate productivity under upwelling conditions and minor input of terrigenous influx. At other sections of the margin, however, the terrigenous input was high. A seismic reflection profile linking DSDP Sites 369 on the slope and 397 on the continental rise has been described by Hinz (1979). This profile clearly images the massive erosion that the slope off northwest Africa underwent from late Eocene to late Oligocene.

The Neogene sequence along this profile on the upper rise (Hinz's acoustic sequence CB1b) is well stratified. Its lower boundary, the erosional surface carved by geostrophic bottom current erosion in late Eocene to late Oligocene, is not marked by a strong reflector. The Cenozoic sequence (Hinz's acoustic sequence CB1a) on the lower slope consists of a prograding unit downlaping on a lower unit and is not continuous with CB1b on the rise. Apparently part of this unit was eroded before the deposition of sequence CB1b. No such geometry is displayed by the Neogene acoustic succession in the Canary Channel and none of the profiles in the channel display the massive erosion displayed by this profile. Thus, the correlation of the Canary Channel acoustic succession with that of DSDP Sites 397 and 369 also is not feasible. These sites are too far from the channel, too deep and the influence of the Canary Ridge on the depositional history of DSDP Site 395 was of secondary importance. This ridge, not only contributed detritus to the channel, but also acted as a dam to continental detritus preventing its dispersion to the deep-sea.

The presence of oceanic crust south of Gran Canaria (Emery and Uchupi, 1984) suggests that line 117, southwest of the Canary Channel, is located over oceanic crust and explains the lack of piercement structures along the line (Figure 2). Of the seismic units described by ODP Shipboard Scientific Party (1995) in the vicinity of ODP Site 955, line 117 on the Gran Canaria insular slope only displays Units A, C and D. ODP Shipboard Scientific Party (1995) interpreted an undulating reflector on top of Unit A as possible mud waves. Unit C is irregularly stratified upslope and is characterized by at least one lens-like sediment build-up on the distal end of the profile. Unit D also displays undulating reflectors. The acoustic basement, the top of Gran Canaria's clastic flank facies, can be traced the length of the profile. Data from ODP Site 955 suggests that Units A and C along 117 correlate with Quaternary and lower Pliocene-upper Miocene nannofossil ooze mixed with foraminifers. Unit D is constituted of upper to middle Miocene nannofossil clay toward the top and Miocene volcaniclastic sediments toward the bottom.

Line 131 at the southwest end of the Canary Channel is either on oceanic crust or continental crust. If the line is over continental crust the lack of diapirs along this line could be due to masking by volcanic rocks. Line 131 cuts obliquely across El Banquete Bank located at the southwest end of the Canary Ridge. The bank has a flat-top beneath which there is evidence of stratification with the superficial sediments along the northwest edge of the bank displaying a geometry suggestive of shelf progradation (DT, Figure 2). The three sediment units (1–3) along this line rest on the east flank of the Canary Ridge with the upper one (Unit 3) displaying an acoustic character typical of mass movement or bottom current activity (S, Figure 2). Southeastward the bedding within this unit is suggestive of the merging of two sources, one from the ridge and another one from the African margin.

Line 130 (Figure 3), cutting obliquely across the embayment separating Fuerteventura and Lanzarote, ends just east of the axis of the Canary Channel. Whereas along Lines 135 and 129 the flank of the Canary Ridge (probably the top of the islands clastic flank facies) plunges rapidly eastward, the ridge's east flank along line 130 descends more gradually and can be traced to, at least, the axis of the Canary Channel. The absence of diapirs along this line most probably results from acoustic energy not being able to penetrate the volcanic apron off Fuerteventura. Line 130

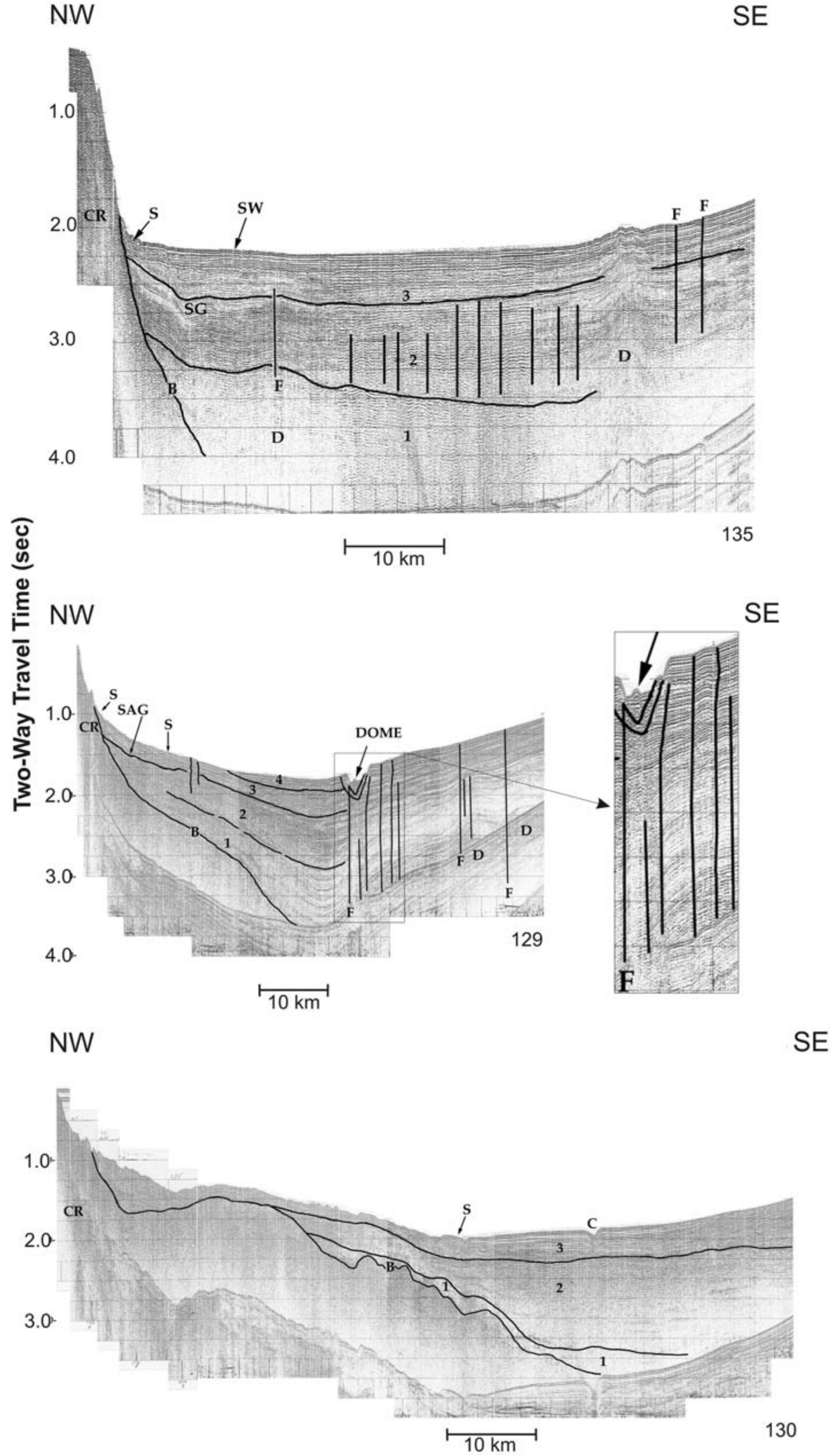


Figure 3. Seismic reflection profiles 135, 129 and 130 across the Canary Channel. See Figure 1 for locations of profiles. B = Acoustic Basement; C = Channel; CR = Canary Ridge; D = Diapir; F = Fault; S = Slump; SG = Sag; SW = Sediment Waves. Sag may be due to uplift of Canary Ridge. Diapirs along profiles 135 and 129 were formed by the plastic flow of Mesozoic evaporites.

also displays three units with a reversed in the dip of strata in Unit 2 suggests that either part of the sequence was derived from the Canary Ridge or is due to the uplift of the ridge after its deposition. Unit 3 is cut by a low relief channel (C, Figure 3) near the axis of the Canary Channel at a water depth of 750 m. West of this channel the surface of the unit is rough, with irregularities that may reflect mass movement or bottom current activity. This unit also reverses its dip west of the axis of the Canary Channel suggesting that part of the unit may have been derived from the Canary Ridge.

Two diapirs and a 3.5 km wide and 225 m deep low disrupt the stratigraphic succession along line 129 (Figure 3). The fault network disrupting the strata has led us to infer that the low is a graben that structurally controls the erosional channel. A 300 m wide and 400 m high mound in the center of the channel rests on a horizon displaying sag beneath the mound and the acoustic character below this horizon is chaotic. Strata beneath this chaotic sequence and immediately east of the low, in the vicinity of two diapirs (D, Figure 2), are diffused, a texture possibly resulting from the formation of the piercement structures and fault network seen in the profile. West of the low the dip of Units 1–3 changes abruptly from west to east. We infer that this change in inclination is due to subsidence of the Canary Channel. It is this subsidence that also may be responsible for the faulting along Line 129. No such subsidence is displayed by the Canary Channel to the north (Line 135) nor to the south (Line 130) suggesting that this subsidence is not a regional phenomena. Possibly the subsidence and associated faulting may be due to salt withdrawal that led to the formation of the salt massif on the eastern end of Line 129.

On Line 135, extending from the flat-topped northern end of the Canary Ridge to the African margin (Figures 1 and 3), the acoustic basement of the Canary Ridge is covered by a stratified unit (1) whose eastward dip indicates that it was either derived from the ridge or is due to uplift of the ridge. Units 2 and 3 dip westward indicating that they were derived from the African margin. Unit 2 near the ridge displays a sag (SG, Figure 3) west of which the strata's dip changes to the east. Although the reversal in dip could indicate a change in sediment source from east to west (Canary Ridge), we infer that this change in dip results from the tectonic uplift of the Canary Ridge. Such deformation is not surprising as Martínez del Olmo and Buitrago Borrás (2002) have inferred from the stratigraphy of a well in Lanzarote that the Canary Ridge has experienced an uplift of 3500 to 2000 m in the Cenozoic. The surficial sediments of Unit 3 at the base of the Canary Ridge display features that appear to be the result of slumping (S, Figure 2). Further down slope the seafloor is undulating (SW, Figure 3), a morphology that we infer to be due to bottom currents. Immediately below this undulating seafloor, the subsurface strata display a slight up-doming that also is reflected in the seafloor. This slight upwarp imaged throughout the width of the profile is due to vertical flow of the Mesozoic evaporites at the base of the sediment apron (D, Figure 2). The eastern end of the profile shows a prominent piercement structure with seafloor expression.

Swath Bathymetry

The swath bathymetric data provides additional constraints on the geologic setting of the Canary Channel (Figures 4–6). The topographic map shows a broad swell (S, Figure 4) with a minimum water depth of 475 m, centered near 28° 30′ N and 13° 0′ W. This high plunges to the northwest in the direction of the axis of the Canary Channel. Cutting the northwest flank of the swell is a northwest-trending narrow trough whose relief ranges from 25 m at its northwest end to 250 m at its southeast end. The low is asymmetrical in cross section with its steeper side on its southwest side. This is the graben imaged by Line 129 (Figure 3). Two channels dominate the axis of the Canary Channel, one drains northeast and the other southwest. The channels are separated by a high with a relief of > 275 m extending from 28° 18′ N to 28° 38′ N. The northern Canary Channel is slightly convex westward as it flows around the base of the continental slope. This valley can be traced for a distance of 87 km to a water depth of 1550 m at the northern limit of the swath survey. The southern Canary Channel is slightly convex eastward as it flows around a southeast trending buttress attached to Fuerteventura (Figure 4). This channel has a topographic expression for a distance of 40 km where it debouches into the southwest trending trough south of El Banquete Bank at a water depth of 1650 m. The buttress attached to Fuerteventura is made up of two topographic features, a shallow platform less than 200 m deep at its northwest end and a series of circular highs suggestive of volcanic construction at its southeast end (Figure 4). Ancochea et al. (1996) interpreted the buttress as a submarine prolongation of the sheeted

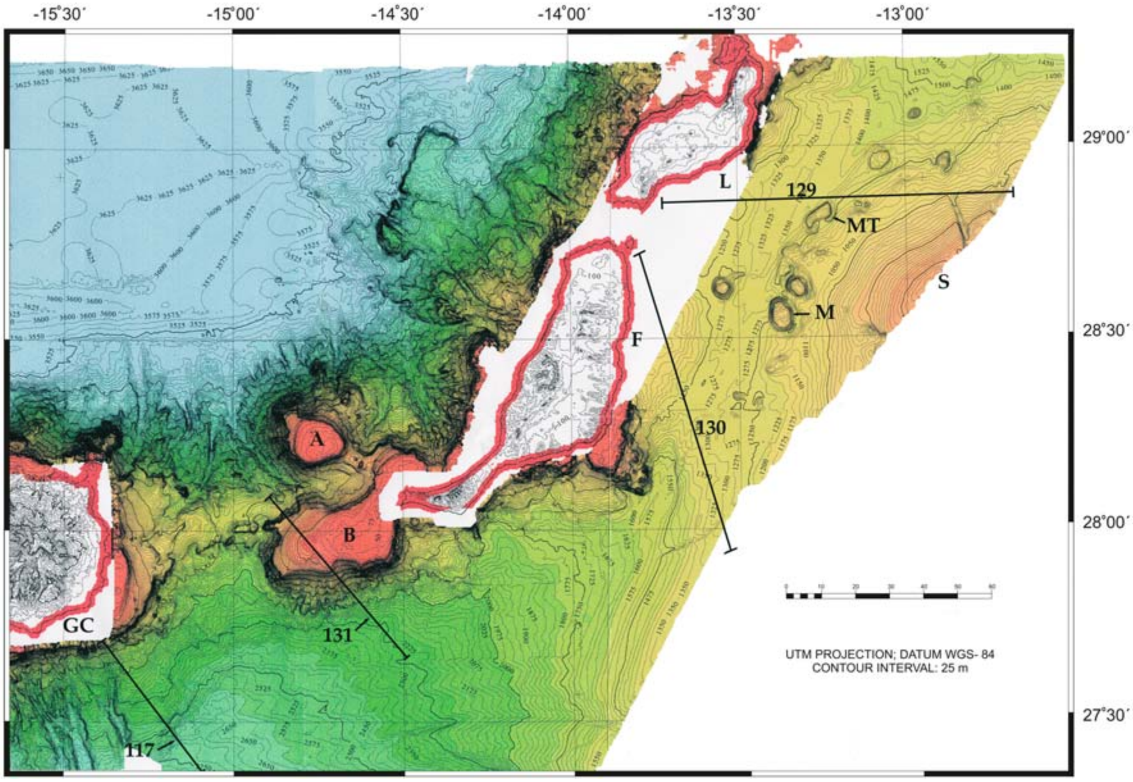


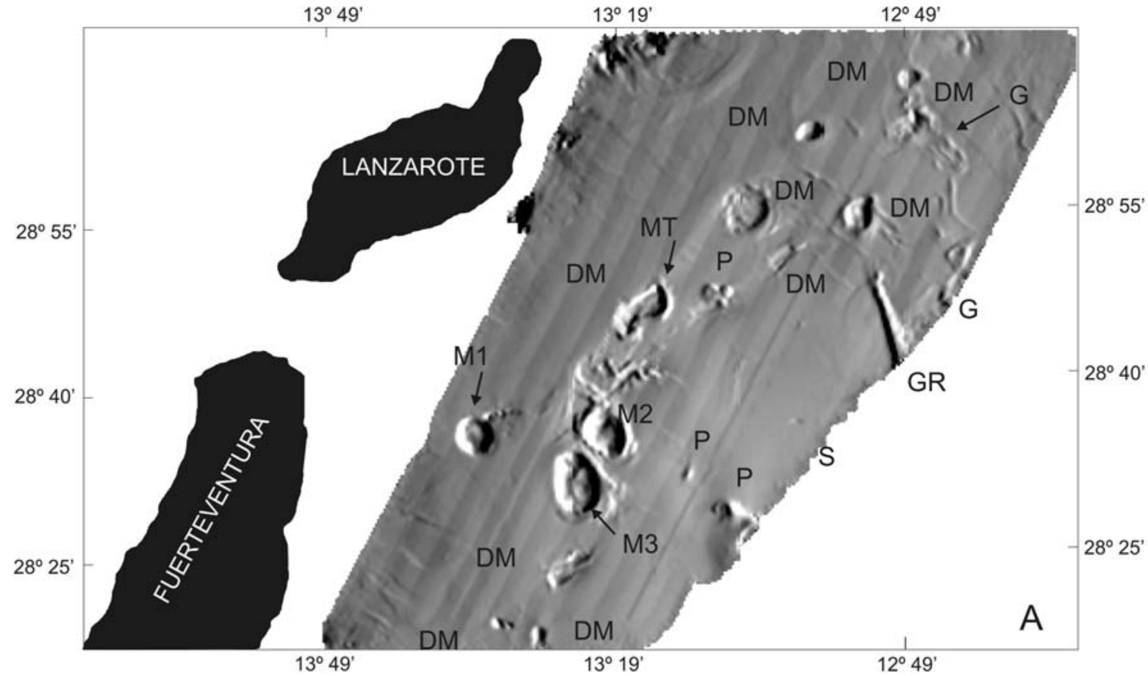
Figure 4. Swath bathymetric map of the Canary Channel showing locations of seismic reflection profile 129, 130, 131 and 117. A = Amanay Bank; B = Banquete Bank; F = Fuerteventura; GC = Gran Canaria; L = Lanzarote; M = Mound; MT = Moat; S = Swell.

dike swam intruded into the Central Volcanic Complex in Fuerteventura.

Along the base of the continental slope, centered near 28° 40′ N and 13° 19′ W, is a northeast trending chain of circular to elliptical mounds. Those at the southern end of the chain have reliefs of about 100 m and diameters between 2 and 10 km. These are features that we have named mounds M2 and M3, and were surveyed aboard R/V Vizconde de Eza (Figures 7 and 8). Those in the center of the chain display reliefs of 100 to 375 m and diameters between 6 and 10 km and those at the northern end of the chain have heights between 75 and 100 m and diameters of 4 to 8 km. The mounds in the center of the chain are surrounded by moats depressed between 25 and 75 m with respect to the surrounding seafloor. West of the center of the chain, near the flank of the Canary Ridge, is another mound (Mound M1, Figure 7). This high lacks a moat, appears to have a crater on its crest, has a relief of 275 m and a diameter of 6 km (Figures 4, 6 and 7). This is the third high that was surveyed aboard R/V Vizconde de Eza.

The mounds and surrounding moats are clearly imaged on the relief map (Figure 5A). A 3D diagram (Figure 6) constructed from the swath data not only images the morphology of the mounds and their surrounding moats, but also a series of small pockmarks, the crater on the apex on Mound 1 located near the base of the Canary Ridge and a system of gullies. The largest of these gullies originates at the base of continental slope from where it meanders down slope dying out northward among two of the smaller mounds (Figure 5A). Other gullies appear to form along the side of one of the mounds with their heads truncated by the moat surrounding the dome.

The shaded relief image (Figure 5A) shows that the Fuerteventura slope where the trend of the insular slope changes from northeast-southwest to east-west, is scalloped, a feature indicative of mass wasting. At the base of this slope segment are apron-shaped sediment accumulations resembling a landslide. At the southwest tip of Fuerteventura is a ramp-like feature that may represent a slump (Figure 5B). Along the west side of this slump is a gully whose head is



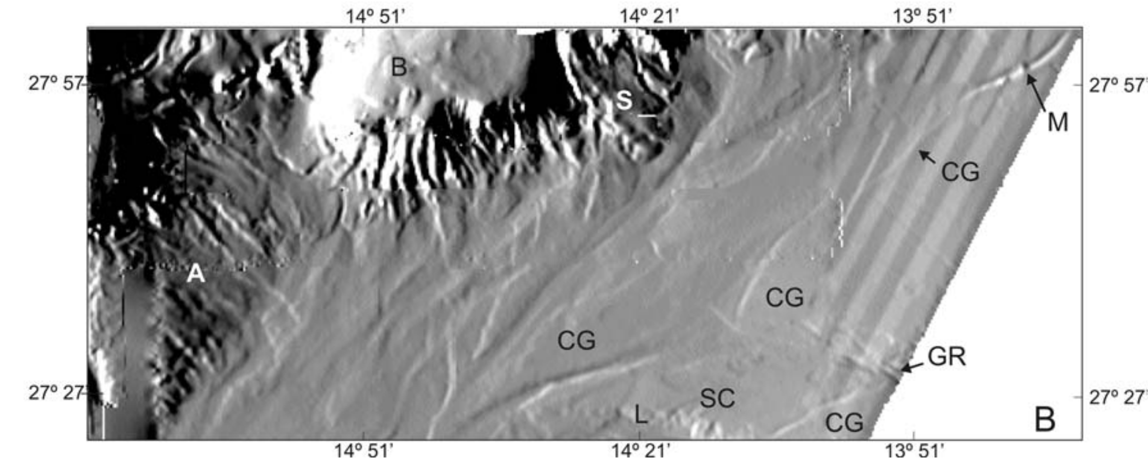


Figure 5. A. Shaded relief diagram of the of the Canary Channel imaging the salt diapir mounds (DM), Volcanic Mound? (M1), Moat (MT), Gullies (G), Graben (GR), Pockmarks (P) and Swell (S) on the seafloor of the channel. B. Shaded relief diagram of the southern approach to the Canary Channel showing the turbidity current generated channel system and mass wasting features. GR = Grooves; L = Landslide; SC = Scar. Note curved groove (CG) on right side with two small mounds (M).

embayed and that terminates abruptly seaward; the gully may represent the pathway of a debris flow with the flow located at its mouth. The southern side of El Banquete Bank is indented by two small embayments that may represent the detachment planes of landslides. West of El Banquete Bank (B, Figure 5B) is an apron (A, Figure 5B) whose surface is cut by gullies that can be traced to the distal end of the apron. Beyond this apron is a braided system of gullies that originate on the southern slope of El Banquete Bank and the southwest tip of Fuerteventura.

The most unusual features in the Canary Channel are the channels located east of the braided system described above. One of these channels or grooves is convex southeastward at its northern end and northwestward at its southern end. Two small highs occur along its axis. Farther south there is another channel that is convex northward. To the east of this channel

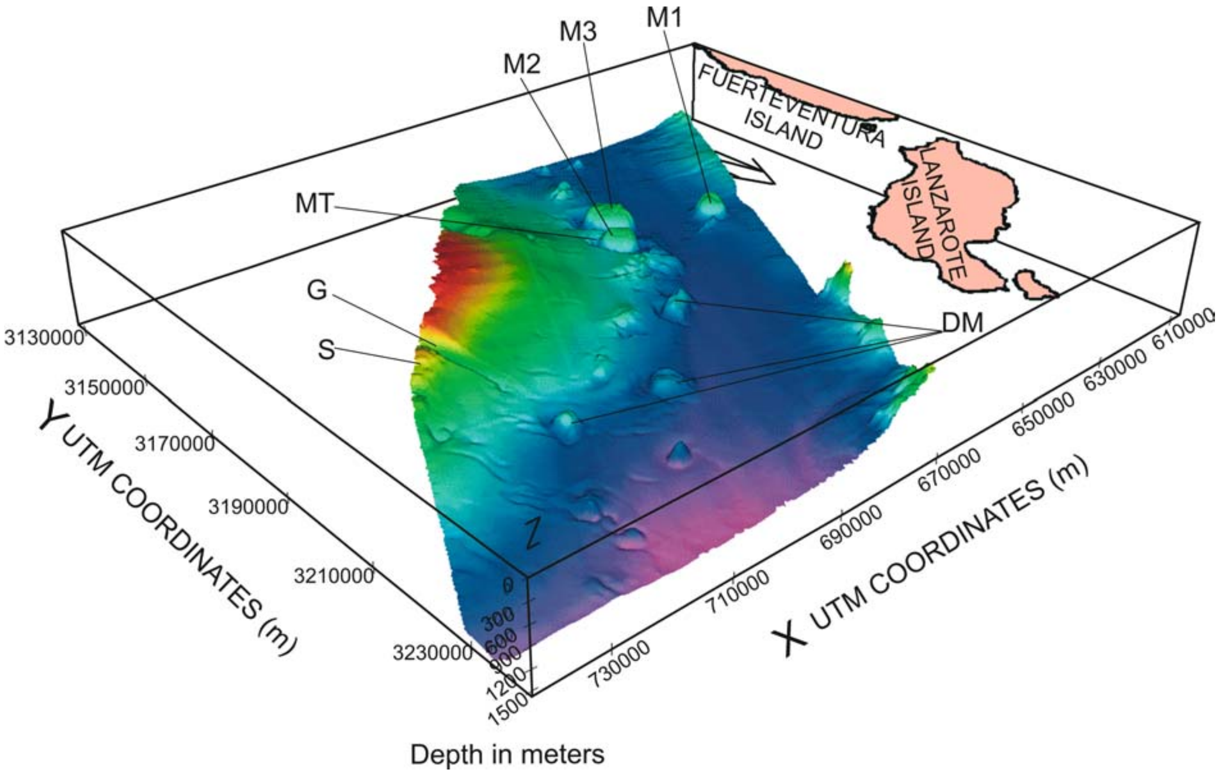


Figure 6. 3D diagram of the mounds in the Canary Channel. DM = Diapiric Mounds (cold seep); MT = Moat; G = Graben; S = Swell; M1 = Volcanic Mound (hot seep). Note that diapiric mounds are located along the base of continental slope.

or groove are two subparallel grooves that divert at their western end. To their south is another curved groove convex northward that terminates on an irregular south-facing low relief scar. None of these channels or grooves displays morphology typical of a turbidity current regime.

Discussion

The seismic reflection Profiles 135 and 129 and those recorded by Hinz et al. (1982) demonstrate that the Canary Channel is underlained by Mesozoic evaporites whose plastic flow has led to the formation of diapirs and piercement structures. These evaporites were deposited in a basin along the northwest African continental margin from Senegal at 10° N to the southern Iberian peninsula at 37° N (Uchupi et al., 1976). Within the Canary Channel the evaporite province extends westward from the northwest African margin to the vicinity of the Canary Ridge terminating southwestward at about the same latitude than the most southern tip of Fuerteventura. However, since evaporites may be masked by Miocene volcanic rocks it is possible that the evaporite province extends farther south and west. Of the lines described in this report, only on Line 135, at the northern end of the Canary Channel, do the diapirs have seafloor expression. Another seafloor feature that may be the result of diapirism is the broad swell on the east side of the Canary Channel centered about 28° 40′ N. Only its western side lies within the area surveyed by swath bathymetry. As defined by the 1000 m contour the feature is about 90 km long in a northeast direction and 20 km wide in a northwest direction. Seismic reflection Profile 129 across the northeast edge of the swell suggests that there are at least two diapirs beneath the swell. The rest of Line 129, extending eastward beyond the shelf's edge (not included in this report), reveals several diapirs beneath the upper continental slope and continental shelf (Uchupi et al., 1976); thus the swell may be a salt massif.

One of the features imaged by the swath bathymetric map, as well as the relief and 3D diagrams in the Canary Channel are pockmarks formed by the expulsion of fluids. Their occurrence within a salt diapiric field suggests that the fluids are of thermogenic origin.

Another feature imaged by the swath data are low relief circular to elliptical mounds (Figures 4–8). One of the mounds is within a graben and is associated with faults that propagate to the seafloor. Two other small mounds are located within a convex shaped groove. The others are located along the base of the salt massif. Except for the mounds in the convex groove that have reliefs of less than 10 m and diameters of tens of meters, mounds have heights of 75 to 375 m, diameters of 4 to 10 km and are partially surrounded by moats with reliefs of 25 to 75 m. As there is evidence of bottom current activity in the region (Jacobi and Hayes, 1992; this study) it is possible that the moats surrounding the mounds are due to current scour (Figure 8). However, their reliefs suggest that they may be structural in origin.

None of the seismic reflection profiles described in this study crosses these features, thus, it is not possible to determine their relationship to the salt diapirs imaged in the seismic reflection profiles. The high immediately east of the Canary Ridge (Mound M1, Figures 5A and 7) does not have a moat and displays a crater on its crest, a feature not observed on the other highs (Figures 6 and 8). It is also located on top of toe thrusts and overhangs along the east flank of the Canary Ridge described by Martínez del Olmo and Buitrago Borrás (2002). We infer from its proximity to the Canary Ridge and its location over the overhangs that this mound is probably the consequence of the expulsion of volcanogenic gas, hot venting (Figure 7). Such a conclusion is also supported by geomagnetic studies (Catalán et al., this issue) that show that Mound 1 has a 300 nT absolute magnetic maxima (peak to peak) showing a characteristic induced dipolar aspect. In contrast Mounds 2 and 3 display a small amplitude short wavelength maxima (smaller than 20 nT).

Analytical signal studies (magnetic source boundaries without remnant magnetism) further support our contention that Mound 1 is of volcanic origin and Mounds 2 and 3 are not. The other highs, located within the diapiric field along the base of the salt massif centered at 28° 45′ N and 13° 19′ W may be the result of salt diapirs. Possibly hydrocarbon and oil seeps (cold venting) along the crest of the salt diapirs may be responsible for much of the relief of the mounds. In the Gulf of Mexico such seeps along faults on the crests and flanks of salt diapirs has led to the creation of small depressions, mud vents or carbonate mounds (Roberts et al., 1989, 1990). In addition to carbonate build-ups the topographic highs in the Gulf of Mexico formed by diapiric activity are also capped by carbonate-rich, lithified sediments and yellowish to orange nodules of thermogenic gas hydrate associated with lithified carbonate rubble and crude oil. Dredge samples recovered from Mound 3 are of similar composition consisting of carbonate pavement and manganese oxide coated yellowish nodules.

The gullies or rills (Figures 5 and 6) associated with the mounds and pockmarks north of 27° 30′ N tend to begin and end abruptly. The largest of these gullies originates in the swell centered near 28° 30′ N and meanders down its side terminating in the vicinity of two other mounds. The other gullies occur in the vicinity of the mound and appear to originate from the sides of the mounds. The morphology of these gullies is suggestive of erosion by a dense flow, possibly salt brine. As noted by MacDonald (1992) such brines are produced where the salt comes in contact with seawater along fault planes. According to MacDonald (1992) these brines typically have salinities that exceed 200 ppt and density that is at least 125% that of salt water. This density difference tends to preserve the salt brines as a distinct fluid on the sea floor, a fluid that can flow down-slope eroding gullies on the surficial sediments. Another possible mechanism for brine formation in the Canary Channel region may have been igneous activity on the Canary Ridge. That the ridge could have served as a thermal source is not unrealistic as Lanzarote has been active between 1730 and 1736 when extrusives covered much of the southwest side of the island. (Carracedo and Rodríguez Badiola, 1993) and hot springs are present in the Montaña del Fuego, Lanzarote (Calami and Ceron, 1970). If interstitial waters warmed by the heat produced by this volcanicity propagated eastward and deep into the sediments in the Canary Channel it may have led to the dissolution of the Mesozoic salt and formation of brines. Once formed the brines would have migrated upward along faults created by salt diapirism.

Other channels in the region tend to differ from those that we ascribe to erosion by brine seeps.The channels south of 27° 57′ N and west of 14° 51′ W display characteristics typical of turbidity currents. Those channels south of 27° 57′ W and east of 14° 51′ W display an unusual morphology. They tend to be sharply curved with two small mounds located along the axis of one of the lows. Their morphology demonstrates that they are not the creation of brine seeps or turbidity currents. The grooves are associated with a scalloped scarp south of 27° 27′ S that may represent the failure plane or head of scar of a landslide involving the uppermost sediments (Figure 5B). Possibly the

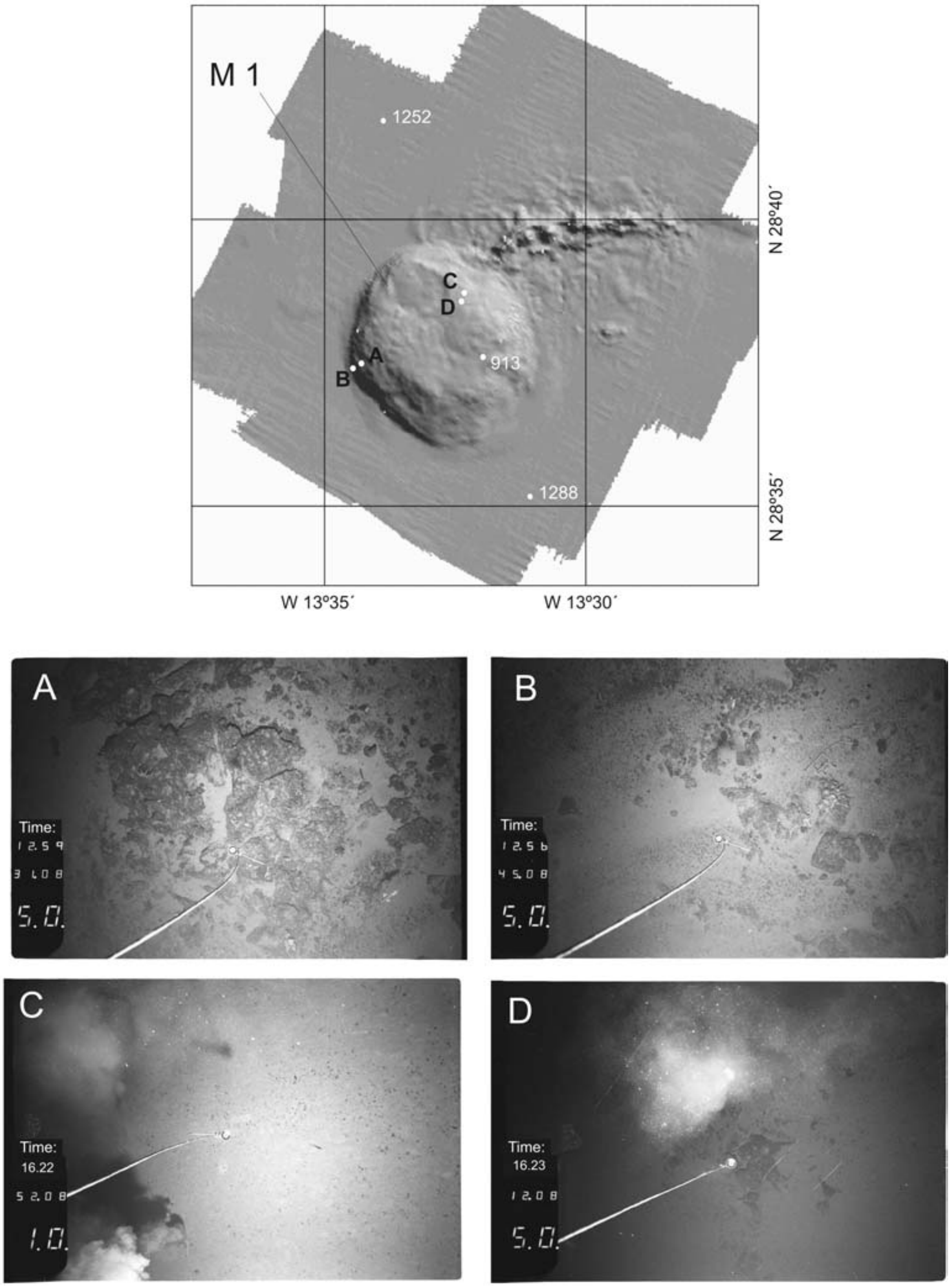


Figure 7. Upper Panel: Shaded relief diagram of Mound 1. A–D = Positions of bottom photographs; White numbers = water depth in meters. Lower Panel: A–B: Flank of Mound 1 showing outcrops surrounded by sediments. The outcrops may represent carbonate pavement or lava. The twigs in B may be deep-water coral. C–D = White smoker on crest of Mound 1. Area covered by each photographs is approximately 5 × 4 meters.

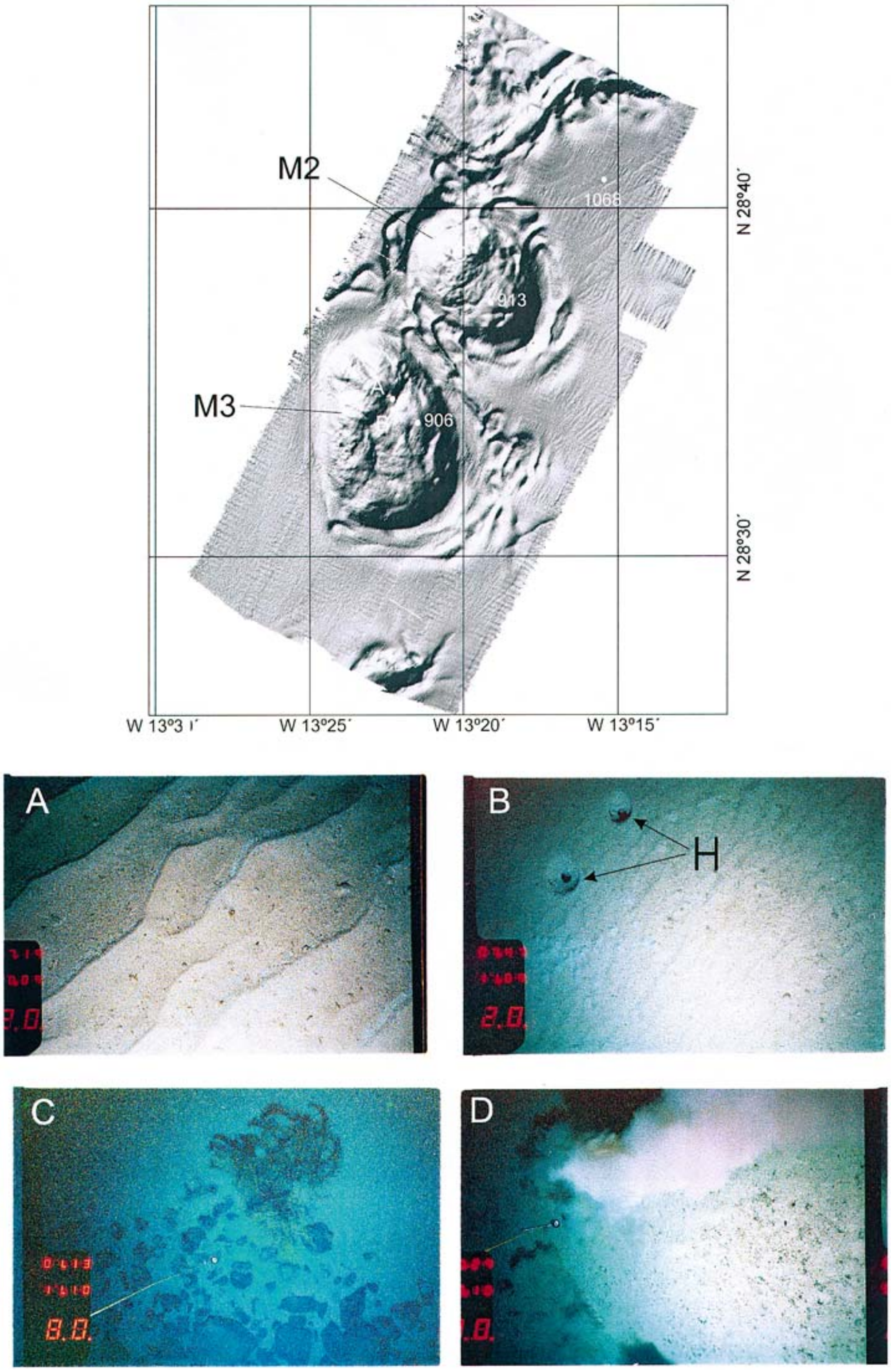


Figure 8. Upper Panel: Shaded relief diagram of Mounds 2 and 3. A–D = Positions of bottom photographs. White numbers = water depth in meters. Lower Panel: A–B: Photographs on crest of Mound 3, showing sediment waves. H: Holes created by bioturbation or fluid seepage. C: Photograph on crest of Mound 2 showing crinoids (dark), deep-water corals (branches below the crinoid) and rock out crops that may represent carbonate pavement. D: Photograph in crest of Mound 2. ‘Sediment cloud’ in photo was generated by the impact of compass on seafloor. Area covered by each photograph is approximately 5 × 4 m.

curved grooves north of the landslide scar may represent cracks on the surficial sediment section that is being displaced downslope by creep. A possible scenario for their evolution may involve sediment creep down slope creating the grooves until part of the sediment becomes detached to form the slide scar south of 27° 27′ S. The presence of two small mounds within one curved groove (Figure 5B) suggests that fluid expulsion has played a role in sediment instability. In the ultimate instance, these gravitational micro-structures also may have been triggered by fluid expulsion and vertical motion of the Mesozoic evaporites.

Conclusion

Features found during a swath bathymetric survey of the Canary Channel include a mound near the east flank of the Canary Ridge, landslide scars and landslide deposits along the base of the Canary Ridge, a line of mounds aligned in a northeast direction along the axis of the channel, gullies associated with mounds that have abrupt terminations, pockmarks and curved grooves. The features along or near the east flank of the Canary Ridge are probably the creation of tectonism and turbidity current activity. The mound, a smoker, was formed by hydrothermal activity. The features in the Canary Channel have a different origin. The mounds in the channel have diameters of 4 to 10 km, reliefs of 75 to 375 m and are partially surrounded by moats. They occur within a Mesozoic evaporitic basin. One of the mounds is a smoker. We infer that the mounds may represent the crests of salt diapirs capped by carbonate pavement, mud vents, and yellowish to orange nodules of thermogenic gas hydrate associated with lithified carbonate rubble and crude oil. These seeps may have provided nutrients to bacteria that in turn served as a food chain for carbonate-secreting organisms. We further speculate that the gullies found in the vicinity of the mounds were eroded by dense salt brines created where salt in the diapirs are in contact with sea water at the seafloor or were formed in the subsurface by water heated by igneous activity along the Canary Ridge. From there the brines migrated upward along the fault system that served as conduits for the hydrocarbons. The pockmarks associated with the diapirs are probably the result of expulsion of thermogenic fluids and the curved grooves may reflect sediment displacement by creep of the surficial sediments and gravitational sliding triggered by salt and hydrocarbon seeps.

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