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Sea floor morphology of the Ebro Shelf in the region of the Columbretes Islands, Western Mediterranean

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Abstract

Widespread volcanism off eastern Spain in the western Mediterranean is associated with Cenozoic crustal attenuation and sinistral motion along the Trans-Moroccan–Western Mediterranean–European mega shear, extending from northern Morocco to the North Sea via the Alboran Basin, eastern Iberia, the Valencian and Lyons basins, France and Germany. The Quaternary Columbretes Islands volcanic field is the most prominent example of this volcanism associated with this mega shear. The islands are located in the Ebro continental shelf on top of a structural horst probably made of Paleozoic metamorphic rocks. Surrounding the emerged islands are volcanic structures and associated flows partially mantled by a sediment drift whose morphology is controlled by the southwestward flowing Catalan Current. This association is rather unique and appears to have never been described from a continental shelf in the Mediterranean Sea or outside the sea. The morphology of both kinds of structures, obtained by means of swath bathymetry data and very-high resolution seismic profiles, is presented in this study. They provide striking images of this previously unstudied part of the western Mediterranean seafloor. These images suggest that the volcanic structures are intruded into the surficial Holocene sediments indicating that volcanism in the Columbretes has extended into Holocene.

Keywords: Submarine geomorphology; Multibeam bathymetry; Volcanic field; Western Mediterranean

1. Introduction

The eastern Iberian margin in the western Mediterranean is made up of the Ebro continental shelf and slope, the Valencia Trough and the Balearic Promontory (Fig. 1). These features are the consequence of the following tectonic events: Late Cretaceous to present convergence of Africa and Eurasia that led to the creation of thrust and fold belts in the Balearic Promontory and simultaneous extension in the Valencia Trough. Such a tectonic regime, extension in the

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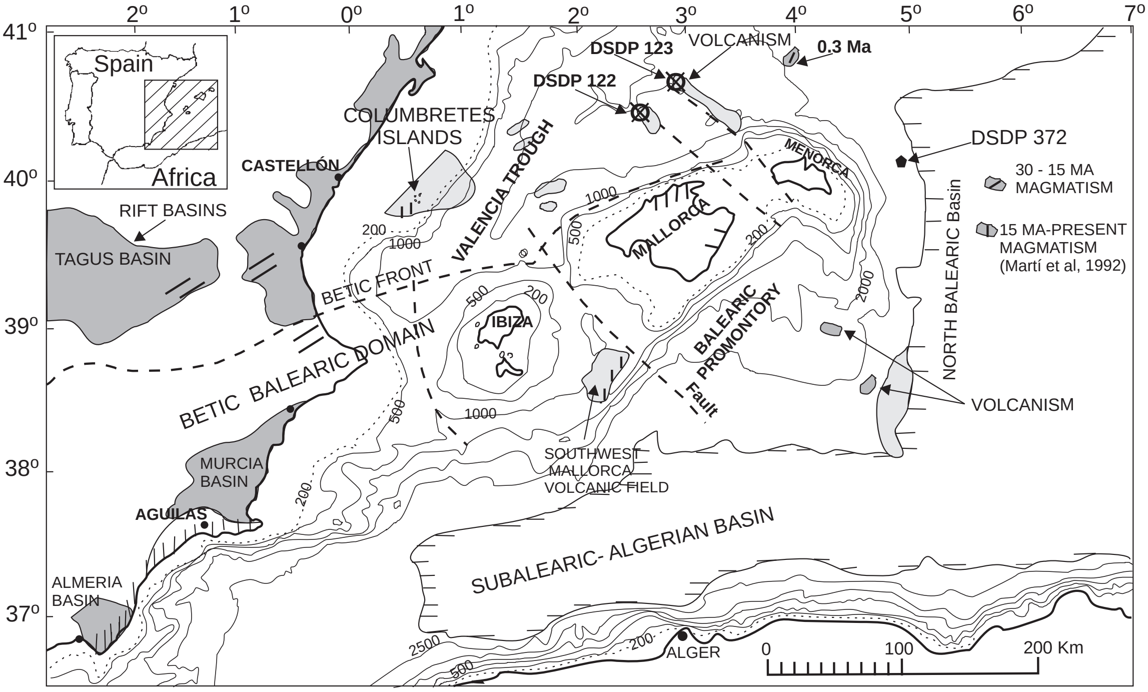


Fig. 1. Morphology of the margin off eastern Spain (western Mediterranean) showing the distribution of the Neogene volcanic centres. Compiled from Martí et al. (1992), Maillard et al. (1992) and Acosta et al. (2001). According to Martí et al. (1992) the locations of the main centres of this volcanic event are related to the regional structure with a 24 to 18.6 Ma old volcanic cycle being represented by calc-alkaline rocks along the thrusts of the Betic–Balearic domain and the offshore areas of the Catalan–Valencian domain. Examples of this cycle are represented by small outcrops in Mallorca, at DSDP sites 122 and 123 in the Valencia Trough and in several exploratory wells off Valencia (Maillard et al., 1992; Martí et al., 1992). A second 10 Ma to Holocene alkaline volcanic cycle is associated with a northeast trending Trans-Moroccan–Western Mediterranean–European sinistral mega fault (López-Ruiz et al., 2002). The most recent magmatic activity associated with this shear occur in the Columbretes Islands and near Barcelona.

northwest and mostly compression in the southeast is supported by the magnetically smooth Balearic Promontory and the very intense magnetic anomalies in the Valencia Trough (Galdeano and Rossignol, 1977). The extension in the Valencia Trough behind the thrust front in the Balearic Promontory has been ascribed to several tectonic processes. They include: (1) the migration of different tectonic blocks and clockwise rotation of the Balearic Promontory (Vegas, 1992); (2) subduction rollback; (3) crustal collapse produced by delamination of lithospheric mantle and (4) mantle upwelling and intrusion of an asthenospheric plume (Doblas and Oyarzun, 1990; Maillard and Mauffret, 1993; Longergan and White, 1997).

The degree of crustal attenuation determined from a comparison of observed and modeled tectonic subsidence in the Valencia Trough region suggests that extension in the trough is not due solely to Late Cretaceous–Cenozoic tectonic events. As a result of this observation Roca and Desegaulx (1992) and Roca and Guimerá (1992) proposed that part of the rifting in the Valencia Trough took place during Late Triassic–middle Cretaceous prior to the convergence of the African and Eurasian plates. They suggested that this extension prior to the convergence is due to the divergence of the African and Eurasian plates in Late Triassic–middle Cretaceous.

Surface heat flow values in the southwestern Valencia Trough also indicate that its tectonic history is much more complex than crustal attenuation behind a zone of Late Cretaceous–Holocene convergence. These values are indicative of three Mesozoic rift events, a Paleogene compressional phase accompanied by erosion of 5 km of Late Jurassic and Cretaceous sediments and Neogene rifting (Fernández et al., 1995).

The Neogene rifting in the western Mediterranean is not a single basin wide event, but took place in several discrete episodes. They include opening of the Gulf of Lion, Ligurian Sea and Algerian basin, counterclockwise rotation of the Sardinian–Corsican block and opening of the North Balearic Basin in Oligocene–early/middle Miocene. The second rifting episode took place in late Oligocene–early Miocene and involved the opening of the Valencia Trough and clockwise rotation and extension of the Balearic Promontory. With this second rifting event the Western Mediterranean acquired its present configuration.

Associated with these rifting episodes are a series of volcanic events. Those in the Valencia Trough (Fig. 1) are made up of two volcanic cycles (Martí et al., 1992). The first one, which took place during early to middle Miocene, is a calc-alkaline event; the second one, from middle Miocene to Holocene, is of alkaline nature. Both types of volcanism may exist at the same site with the younger lavas possibly resulting from the reactivation of the older volcanic centres (Mauffret, 1977). López-Ruiz et al. (2002) ascribe the calc-alkaline middle to late Miocene volcanic event to the extension associated with the clockwise rotation of the Balearic Promontory and opening of the Valencia Trough. This extension supposedly triggered upwelling of sublithospheric material, melting of the lithospheric mantle and extrusion along normal faults associated with the horst and graben structures. They suggested that the Miocene–Holocene alkali event was due to sinistral motion along the northeast trending Trans-Moroccan–Western Mediterranean–European mega shear extending from northern Morocco to the North Sea.

2. Data set

The data described in this report were obtained by the Instituto Español de Oceanografía during the Bal-Com cruise in July 2002 on board R/V Vizconde de Eza. Swath bathymetry data were collected with a Simrad EM-300 system along a series of overlapping tracks for a 100% seafloor coverage (Fig. 2). Very-high resolution seismic reflection profiles were recorded with a TOPAS PS018 sub-bottom profiler using FM-pulses. Positioning during the cruise was

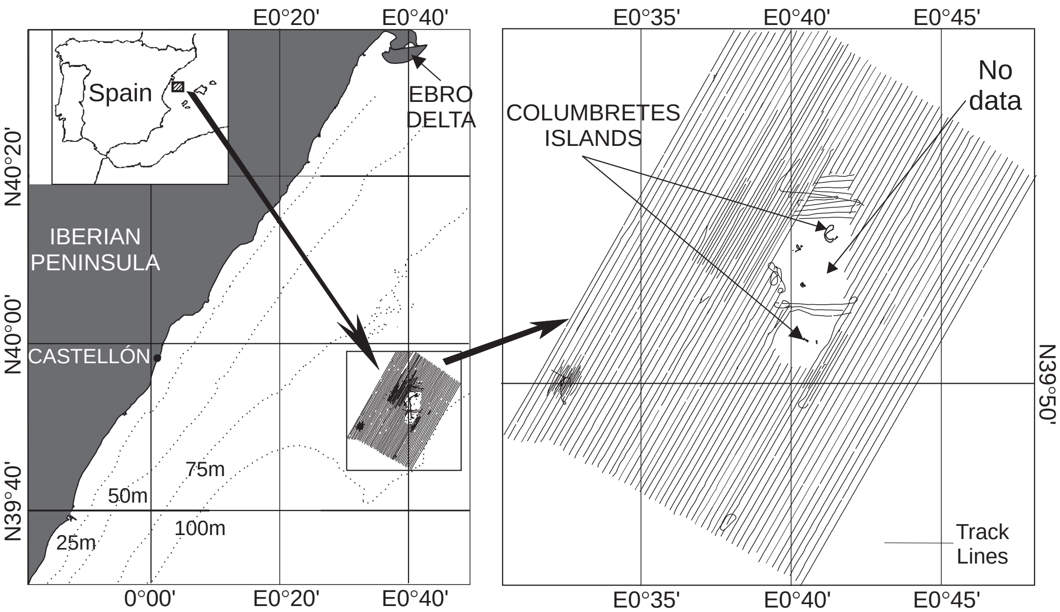


Fig. 2. Left panel: geographic location of the studied area. Right panel: multibeam and HR seismic profiles (Topas PS018). Geophysical track lines carried out: 1144.2 km of multibeam and HR seismic lines.

controlled using a D-GPS integrated with a inertial-aided Seapath 200 system for an accuracy of 0.7 m RMS.

3. The Columbretes Volcanic Field

3.1. Subaerial segment

The Columbretes volcanic field offshore Castellón is located on the outer Ebro continental shelf covering an area of 90 km × 40 km at 80–90 m water depth (Maillard and Mauffret, 1993). Well data (Lanaja, 1987) show that volcanic activity in the area was continuous from early to middle Miocene. Seismic reflection profiles from the region image features that are indicative of this volcanism. They include an opaque facies, strong reflection horizons within the sedimentary strata and chaotic reflectors that may be ash layers, (Maillard et al., 1992; Maillard and Mauffret, 1993). These facies extend well into the Valencia Trough.

Along the eastern edge of the Columbretes Volcanic Field are the Columbretes Islands, the only subaerial part of this field (Fig. 1). These islands are one of the scarce sites of Quaternary volcanic activity in eastern Spain (Hernández-Pacheco and Asensio Amor, 1966; Cañada-Guerrero, 1971; Instituto Geológico y Minero de España, 1972; Aparicio et al., 1994; Aparicio and García, 1995; López-Ruiz et al., 2002). Other sites of Quaternary volcanism in eastern Spain occur in the Northeast Volcanic Province (Ampurdán, Selva and Garrotxa) near Barcelona (López-Ruiz et al., 2002) and at Cofrentes southwest of Valencia (Ancochea and Huertas, 2002). The orientation of the archipelago, made of small groups of islands (Fig. 3), suggests that they may be aligned along north to northeast trending fractures. The Columbrete Grande Group is in the form of a broken-ring consisting of one large island and three small ones, Columbrete Grande has a relief of 67 m, El Mascart a relief of >30 m, La Señorete a relief of >20 m and Mancolibre a relief of 34 m. To the southwest of this group is the Islote de Ferrera Group made up of Ferrera with a relief of 43 m, and Ferreruela, Malaespina, Veldés, Escull de Ferrera and Laja Navarrete with reliefs of about 20 m. Farther south are the Islote de Lobo Group consisting of El Lobo, Piedra Joaquín, Horadada and Méndez Núñez and the El Bergantín Group of El Bergantín, Peñón Cerquero, Churruca and Baleato. All the larger islands consist mainly of pyroclastics but the smaller groups consist of massive phonolite. All the islands display extensive evidence of marine erosion.

The only groups of islands that have been investigated in any detail are the Columbrete Grande Group at the northern end of the archipelago and Islotes de Ferrera Group. The ring-shape of the Columbrete Grande suggests that the group is a former volcanic cone that has been eroded by marine processes. Aparicio et al. (1991) inferred that the cone forming the Columbrete Grande was constructed during four volcanic episodes from 1.0 to 0.3 million years ago. Hernández-Pacheco and Asensio Amor (1966) proposed that prior to erosion this structure had a relief of 300–325 m above the 85 m deep seafloor. The Columbrete Grande group is composed of alkaline basanites (Aparicio et al., 1994). Aparicio et al. (1994) also stated that the smaller islets south of the Columbrete Grande Group are composed of massive salic flows of phonolites and tephretic phonolites. Their ages are yet to be determined, but their morphology suggest that they are of the same age as the flows in Columbrete Grande Island.

3.2. Submarine morphology

The Columbretes Islands are located along the crest of a north–south trending tear-drop shaped swell at the outer shelf off Castellón trending obliquely to the northeastward-trending shelf edge (Fig. 3). The high, whose base is at 80 m water depth, has a relief of 60 m. It is about 12 km long and 4 km wide and is partially mantled by pre-Neogene sedimentary rocks.

The presence of staurolite, andalucite and sillimanite in the sediments blanketing the high led Cañada-Guerrero (1971) to propose that its core consists of Paleozoic metamorphic rocks. Small enclaves of sedimentary rocks, gabbros and nephelinic syenites in the salic rocks in the small islets of the Columbretes verify such interpretation (Aparicio et al., 1994). This high may be part of the northeast trending left-lateral Trans-Moroccan–Western Mediterranean–European (TMWME) mega fault zone. This shear supposedly was the creation of north–south compression as a result of an increase in the rate of convergence of

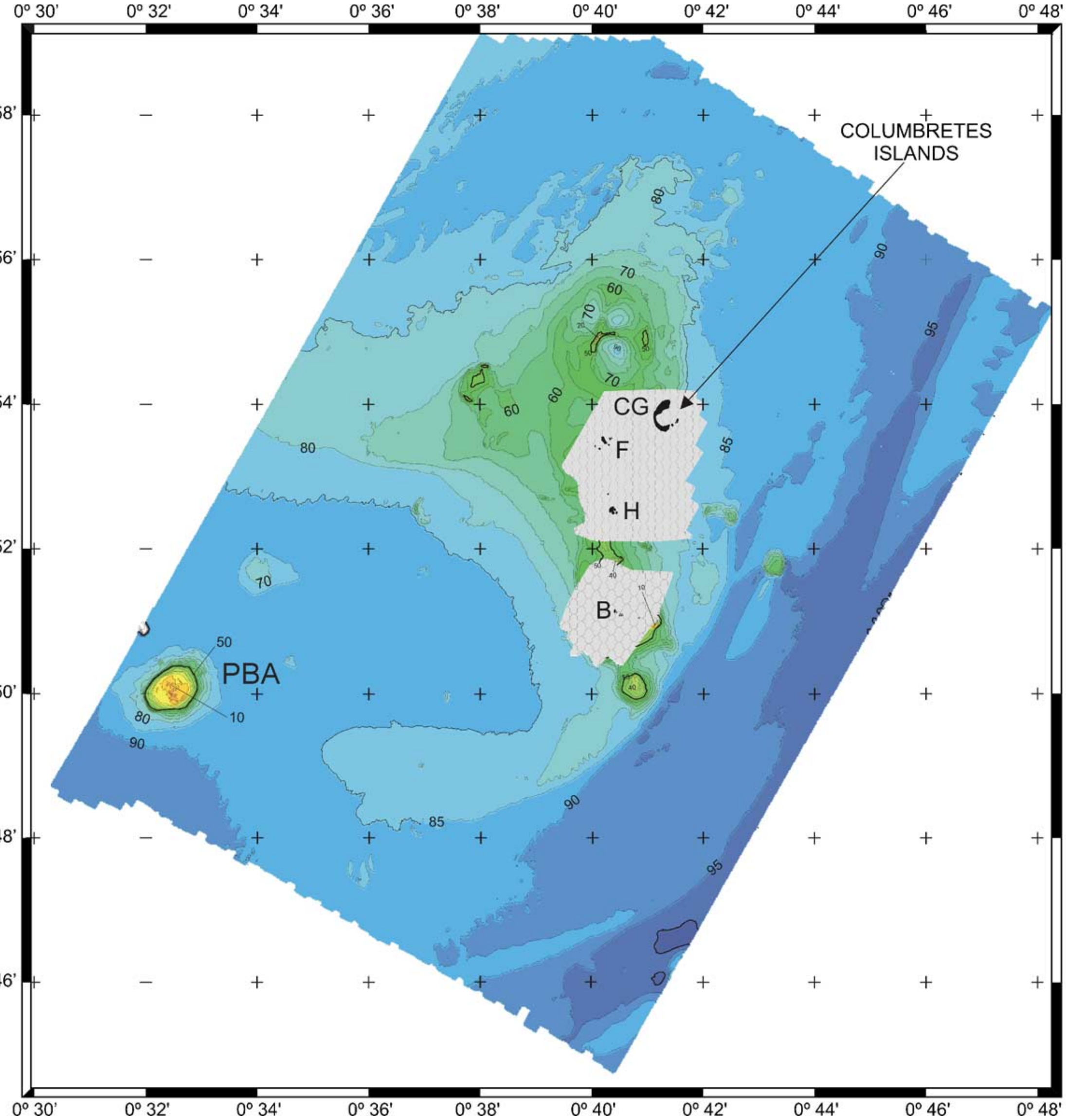


Fig. 3. Multibeam bathymetry map of the Columbretes archipelago region. Contour interval is 5 m. This small archipelago extends from 39° 50.87′N to 39° 54.12′N and from 4° 21.25′E to 4° 22.33′E. CG=Columbrete Grande; F=La Ferrera; H=Horadada and B=El Bergantin; PBA=Placer de la Barra Alta.

the Africa–Eurasian plates. This led to the formation of the TMWME shear bounding a west directed escaping western Mediterranean European block (López-Ruiz et al., 2002). Volcanism in the Columbretes, part of the Gulf of Valencia Volcanic Province, appears to be the consequence of sinistral transtensional displacement of the TMWME (López-Ruiz et al., 2002).

The Columbretes volcanism is concentrated along the edge of the high associated with TMWME. At the southern end of the high there are circular structure tens of meters across. Similar highs also are found to the east and southeast including the Placer de la Barra Alta (PBA) southwest of the high (Figs. 3 and 9). Shaded-relief maps, built from swath bathymetry data recorded during the present investigation, demonstrate that these features associated with this high are volcanic in origin (Figs. 4 and 6–9).

West of north of the Columbretes archipelago is a hill with a diameter of 4 km (Figs. 5 and 6, labelled DFP). Along its eastern side is a 15 m high north-trending scarp and on it are 3 craters (α, β, and γ) with diameters of about 1 km that are partly infilled by recent sediments (Fig. 6). The southern depression (γ) is circular in shape and consists of two craters superimposed one upon another with the younger one having a relief of 34 m (Fig. 6, DFP). Its morphology demonstrate that the high is a volcanic edifice.

To the north of this volcanic structure are 5 to 10 m high, irregular outlined northeast-oriented apron. We infer that this apron represents pyroclastic deposits or lava flows. East of the DFP are smaller highs and off its southwest side is an irregular outlined high and a crescent shaped high (BC). We interpret the smaller highs (pimple like highs east of DFP) as volcanic pinnacles and the irregular outlined high as a volcanic flow that appear to have originated from a semi-

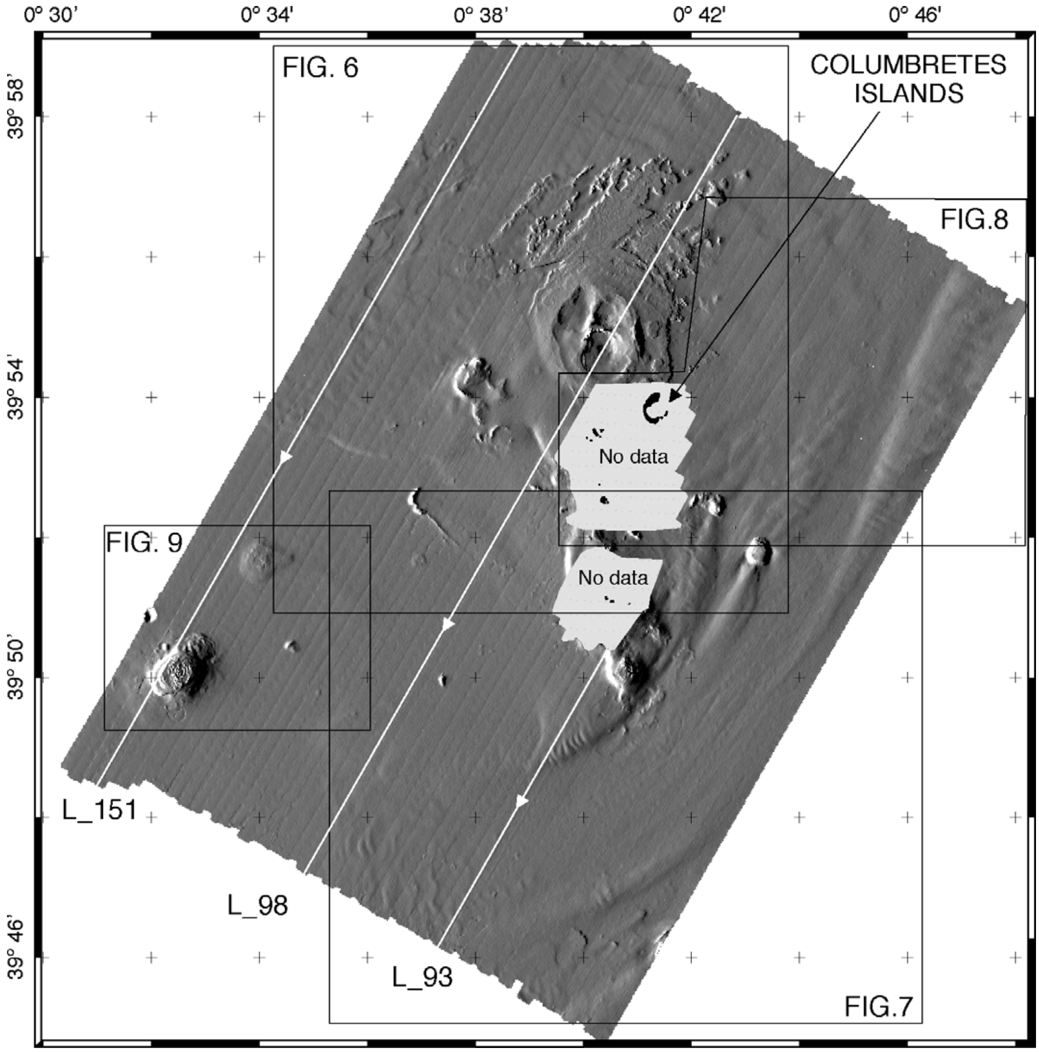


Fig. 4. Shaded relief map of the Columbretes archipelago region showing the locations of shaded relief diagrams in Figs. 6–9 and seismic reflection profiles in Figs. 10–12. This shaded relief map and those in Figs. 6–9 were compiled from multibeam bathymetric data. Artificial illumination is from NW.

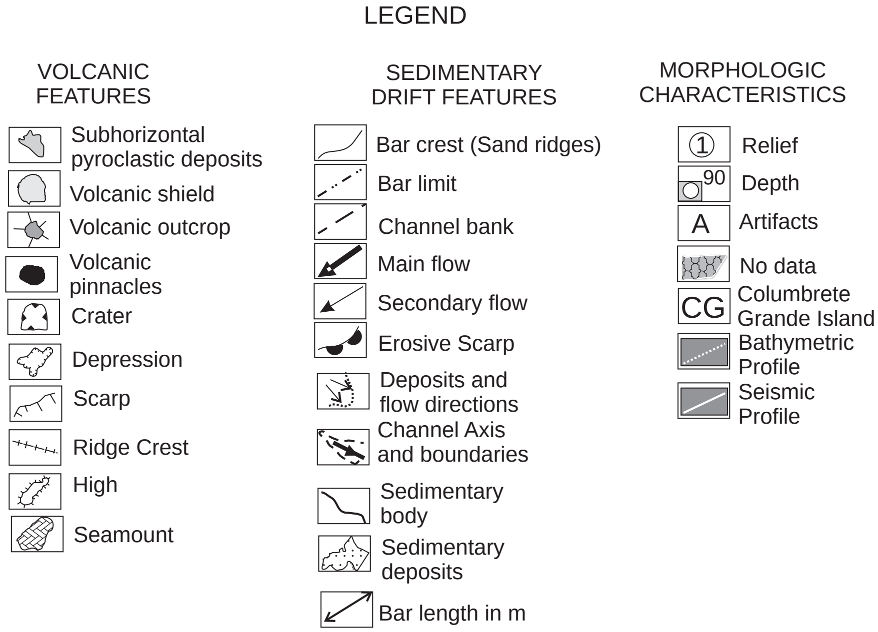


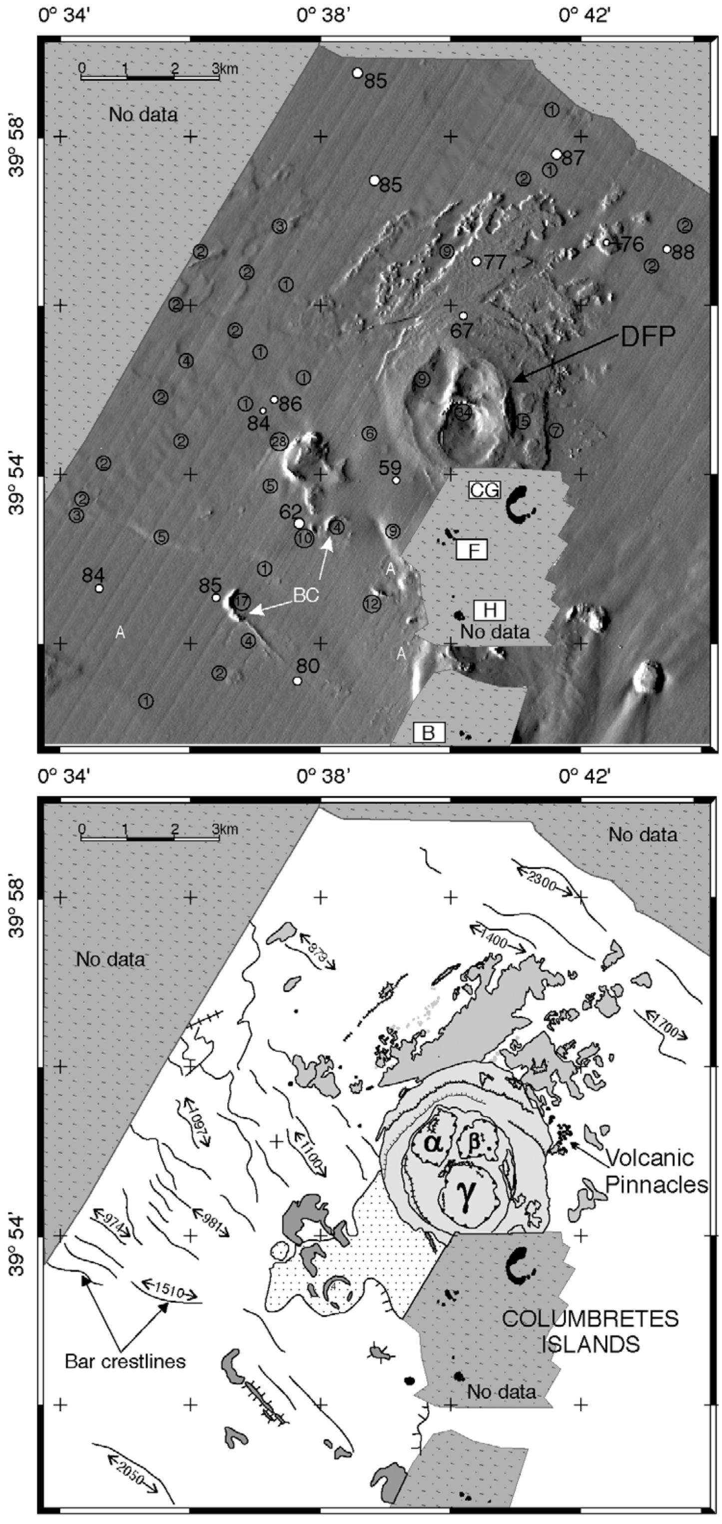
Fig. 5. Legend for Figs. 6–9 and 13.

circular scarp that may be a remnant of a volcanic cone (Fig. 6, BC). Southeast of this feature (BC) is a northwest trending narrow high that may represent a fracture.

The features displayed in Fig. 6, that we infer to be of igneous origin, are partially buried by sediments displaying northeast–southwest furrows, ridges, swells on the southwest side of the volcanic features and areas where the sediment surface lacks relief. We propose that these sedimentary structures are characteristic of current controlled deposition. The northeast–southwest trending furrows are of erosional origin, the ridges we interpret as sandbars, the swells on the southwest side of topographic highs as "sediment tails" formed on the lee of topographic obstructions and the smooth areas with pronounced side slopes on the lee of a volcanic high as sediment plains (Fig. 7).

Shaded-relief maps of the region of the southern and northeastern ends of the Columbretes archipelago is imaged in Figs. 7 and 8 respectively. In the two areas the seafloor is dominated by swells and erosional furrows that we infer to be current created forms. The erosional furrows and a sediment ridge south of the Columbretes, whose crest is marked by sedimentary waves, are oriented parallel to the south–southwest flowing currents and the smaller sediment waves are aligned at right angles to the currents (Fig. 8). Northwest of this sedimentary ridge there is a sediment plain (Fig. 7).

We infer that the current-controlled sediment structures surrounding the Columbretes Islands are formed by a southwestward flowing current locally known as the Liguro–Provençal–Catalan Current or Northern Current. The density contrast producing this current is controlled by a salinity gradient, that originates by a shelf-slope front separating the low-density coastal water from the high-density open-sea water (Alvarez et al., 1994; Font et al., 1995; García-Ladona et al., 1996; Puig et al., 2000; Salat et al., 2002). Fresh water from continental river discharges reinforces this density front, feeding it with plumes of cool water that can be traced in satellite thermographs (La Violette et al., 1990). Changes from erosion to deposition are related to seafloor roughness created by the volcanic terrain. Where the current is decelerated by the volcanic edifices, deposition occurs, sediment waves are produced by localized small topographic steps and erosion is due to enhanced bottom flow (Flood, 1988; Flood and Giosan, 2002).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CG
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A
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0° 34'
0° 38'
0° 42'
39° 58'
39° 54'
0 1 2 3km
No data
No data
2300
1400
873
1700
1097
1100
974
981
1510
2050
α
β
γ
Volcanic
Pinnacles
COLUMBRETES
ISLANDS
Bar crestlines
No data

Seafloor morphology southwest of the Columbretes is displayed in Fig. 9. Among the interesting features imaged by this figure is a nearly buried high associated with aprons at the northern end of the illustration. Along the west side of Fig. 9 (MP) there is a circular depression whose sides do not display any noticeable slope. At the southwest part of the image is the Placer de la Barra Alta (PBA) displaying ring-like structures along its crest and two highs attached to it. Along the southwest side of PBA there is a scarp with a relief of 36 m and extending southwestward from this scarp there is a narrow fracture (Fig. 9, F). We speculate that aprons associated with the nearly buried high on Fig. 9 are volcanic flows and the large depression along the west of the figure was formed by fluid discharge, a mega-pockmark (MP, Fig. 9), similar to those described in Belfast Bay, Maine (Kelley et al., 1994). The concentric ring-structures displayed by PBA resemble the multiple superimposed radial flows in the mud volcanoes in the Gulf of Cadiz (Murton and Biggs, 2003). Thus, in the absence of seafloor photographs and samples, it is possible, but highly improbable, that PBA located some distance from the high along which the Columbretes Volcanic Province is located could be of sedimentary origin.

3.3. Seismic profiles

High-resolution, narrow beam TOPAS seismic profiles (Figs. 10–12) show the sub-seafloor complexity of the Columbretes region. Based on acoustic signature we have divided the acoustic sequence displayed by the profiles into four sequences. In the absence of stratigraphic data we have assigned the following ages to the units: I Holocene and II–IV Plio-Quaternary. The configuration of Unit I is controlled by bottom currents. Unit II is well stratified and Unit III is somewhat acoustically transparent. The lower unit, IV, has an irregular surface, its internal stratification is poorly developed and its base, acoustic basement, is broadly undulating. At the base of these strata along Line 151 (Fig. 11) are semi-transparent to transparent acoustic spots that we infer to represent Bright Spots created by the presence of gas.

On the basis of their morphology the igneous structures intruded into units I–IV have been classified into pinnacles which probably represent dykes (V), clusters consisting of several highs (VI), plugs (VII) whose sediment cover is deformed and VIII sub-horizontal lava flows that appeared to have originated from VI (Fig. 13). Emplacement of the volcanic structures has resulted in pronounced deformation of the adjacent strata (Figs. 10 and 11). Along Line 98 (Fig. 10) emplacement of one of these plugs has even resulted in the deformation of the seafloor indicating that magmatic activity is taking place today. The seismic profiles also image bright spots and acoustic wipeouts that were caused by hydrothermal gases in the sediment. As this wipeout involves the Holocene sediments (Fig. 12) it indicates that this gas expulsion is taking place now or in the recent past. Seismic profiles also demonstrate that the sediment structures on the sea floor are of depositional (sediment buildups; near centre, Fig. 11, left and right side, Fig. 12) and erosional origin (cut subsurface reflectors; Fig. 10, left and right sides; left sides, Figs. 11 and 12; on either of PBA, Fig. 11).

3.4. Age of the submarine volcanic structures

Although we do not have any data regarding the age of the submarine volcanic features some inferences can be made regarding their age from their state of preservation, their depth and their acoustic signature. The 1.0–0.3 Ma old volcanic edifices rising above sea level have undergone extensive marine erosion, so much so that the original volcanic structures are no longer recognizable on most of the archipelago. Only in the Columbrete Grande Group can we identify the remains of the volcanic edifice. That the features have undergone so much marine erosion is not surprising as mapping on Columbrete Grande indicate that the islands consist of partially cemented

Fig. 6. Shaded relief map of the region north of the Columbretes archipelago (upper panel) with morphological interpretation of the area (lower panel). Craters (α, β, and γ) of the large volcanic edifice (DFP) north of Columbretes form a dog's "paw print" structure. Diameters of the craters are 1292, 984 and 1439 m respectively, with maximum depths of the crater floors being 74, 78, and 81 m. The gentle flanks of DFP continues northeastwards to a extensive sub-horizontal pyroclastic or lava flow covering an area of 7.29 km^2. Further NE and NW this pyroclastic carpet is broken into isolated pieces of different sizes. CG=Columbrete Grande, F=La Ferrera, H=Horadada and B=El Bergantin. See Fig. 4 for location of the map and Fig. 5 for legend.

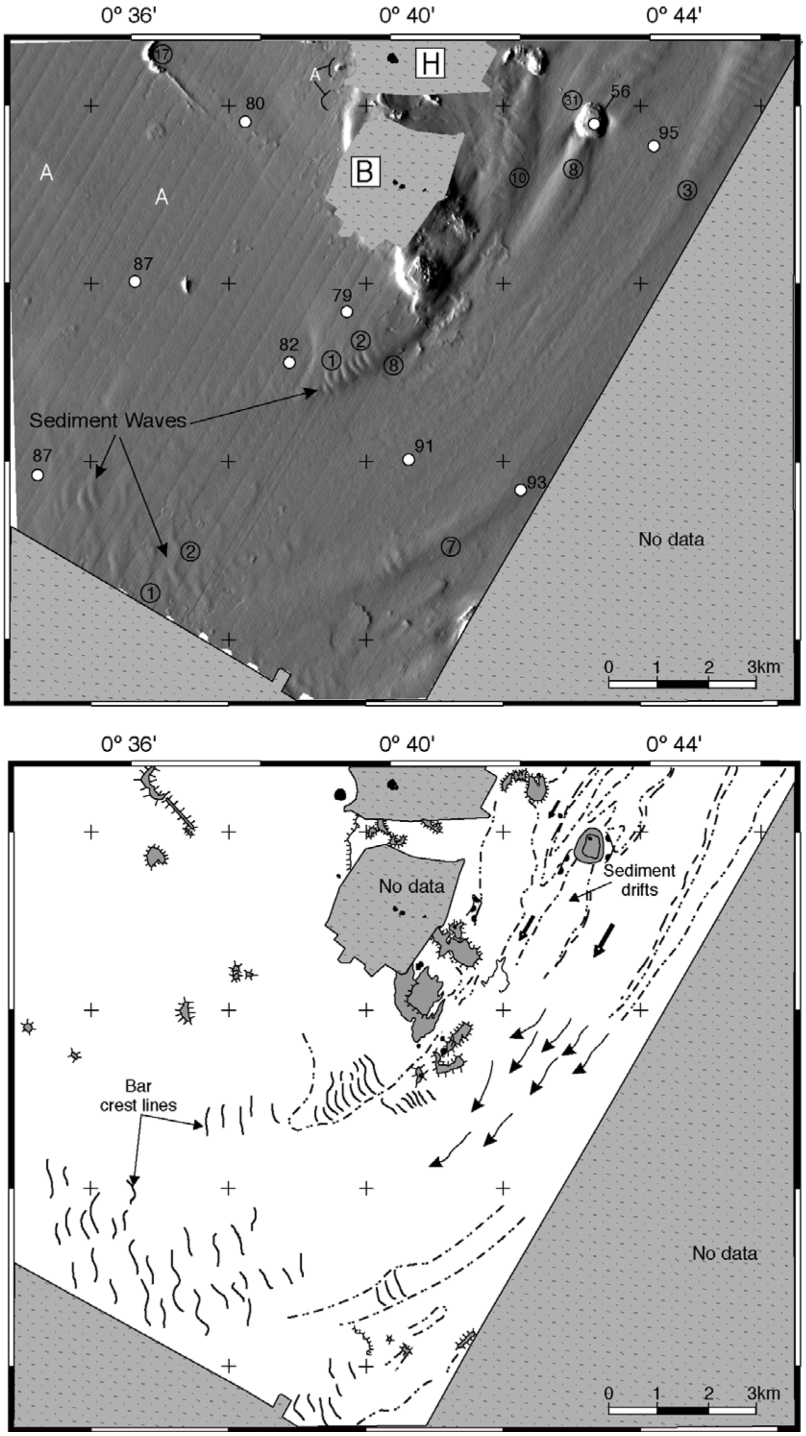

Fig. 7. Shaded relief map of the region east of the Columbretes archipelago (upper panel) with morphological interpretation of the region (lower panel). Circled numbers are relief of features in meters and white paint numbers representing water depth in meters. See Fig. 4 for location of diagram and Fig. 5 for legend.

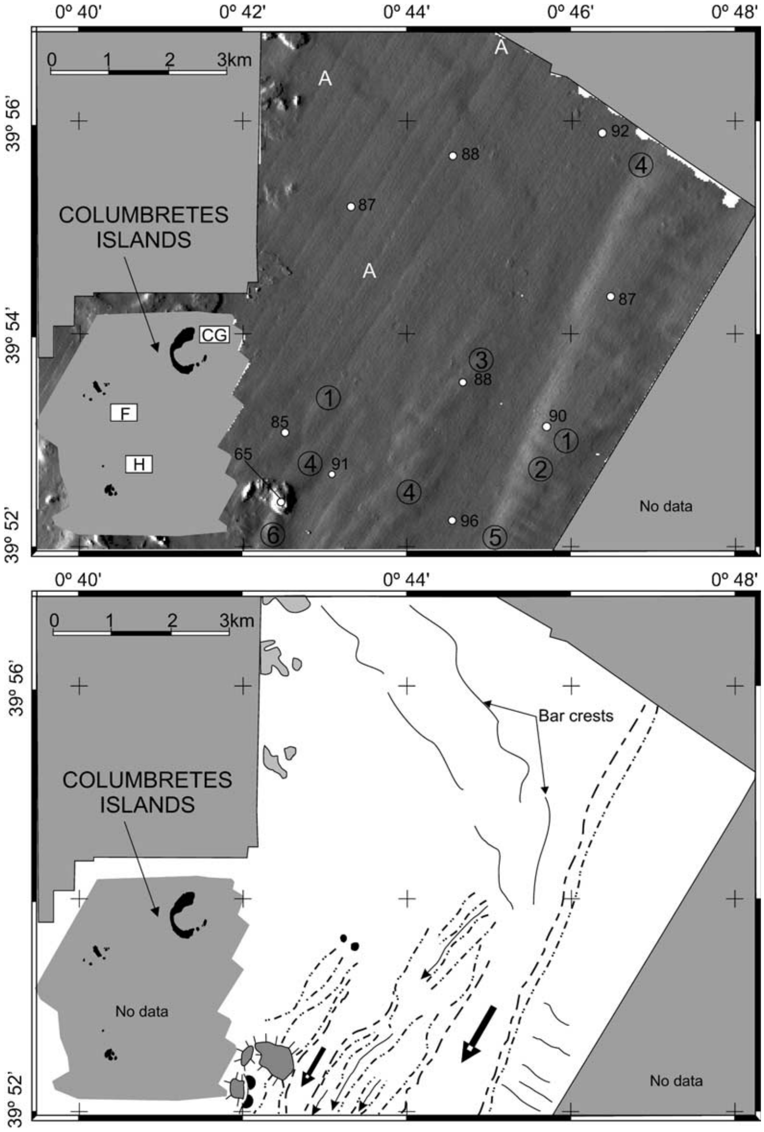

Fig. 8. Shaded relief map of the region southeast of the Columbretes archipelago (upper panel) with morphological interpretation of region (lower panel). Note the sediment tails on the lee of the volcanic edifices and the sedimentary ridge south of El Bergantin (B) along whose crest are sediment waves. The trend of the ridge is parallel to the southwest North Current and the sediment waves at right angles. H=Horadada. See Figs. 4 and 5 for location of diagram and legend.

trachytic pyroclastics ranging in texture from fine sand to gravel and basaltic lapilli (Hernández-Pacheco and Asensio Amor, 1966). Included in the stratigraphic section are volcanic, sedimentary and metamorphic clasts and volcanic bombs as large as 75 cm. According to Aparicio and García (1995) the islets toward the south consist of massive phonolites containing numerous volcanic bombs. Volcanic buildup in Columbrete Grande appears to have been discontinuous as the 36 m thick sequence is disrupted by four disconformities. Capping the sequence are several meters of loess that Hernández-Pacheco and Asensio Amor (1966) speculated were derived from the northeast in the vicinity of the Alps. In spite of all the erosion, none of the islands

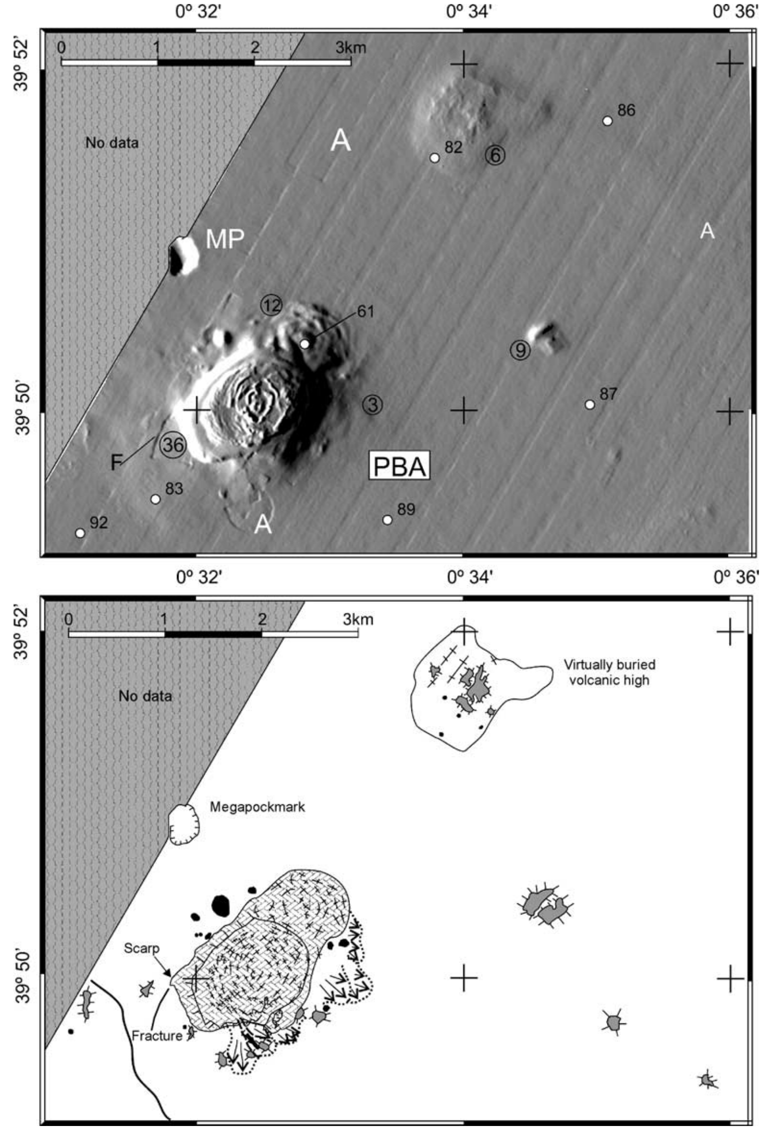

Fig. 9. Shaded relief map of the region southwest of the Columbretes archipelago (upper panel) with morphological interpretation of the region (lower panel). PBA=Placer de la Barra Alta. PBA dimensions are: diameter of the base 2065 m, diameter of top 1700 m, and a minimum water depth over the top of 10 m. Note concentric structures on the crest of the structure. A=Processing artifact; MP=Mega pockmark; F=Narrow fracture. See Figs. 4 and 5 for location and legend.

display features that would have been formed by erosion (wave cut terraces) or features constructed from material derived from erosion of the volcanic edifices (beaches, bars, barrier islands).

In contrast, the submarine volcanic structures in water depths of less than 80/70 m (Fig. 3) appear pristine and their peripheries do not display any evidence of erosion. If such erosional features were present, the multibeam system with resolution of several decimeters would have been able to detect them. One could argue that the absence of such erosion in the submarine features is because they were never at depths shallow enough have undergone wave/surface current erosion.

However, these features are at a depth that was subaerially exposed during the Quaternary glacially

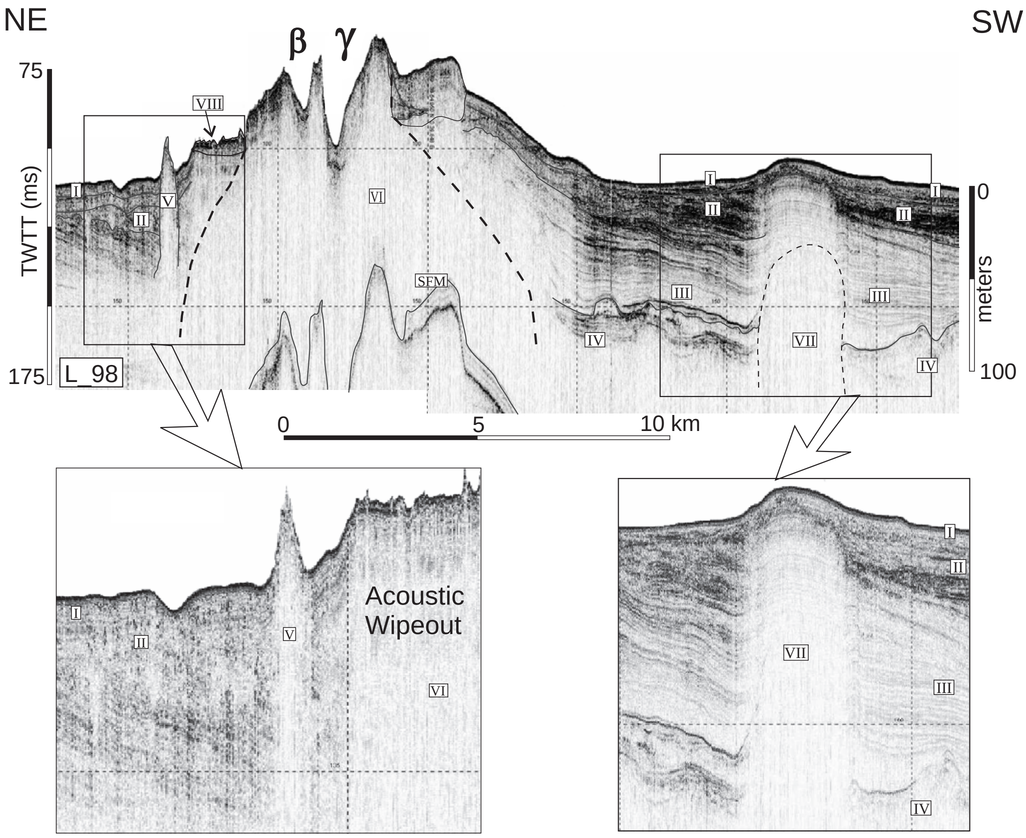

Fig. 10. Very-high resolution seismic reflection profile Topas L-98 from the Columbretes archipelago region. Craters belonging to DFP volcanic structure. SFM: sea floor multiple. We have tentatively assigned the following ages to the acoustic units: I. Holocene whose configuration appears to be controlled by bottom currents; II–IV. Plio-Quaternary. On the basis of their morphology, the volcanic structures have been classified into Pinnacles which probably represent dykes (V), clusters consisting of several highs (VI), plugs (VII) whose sediment cover is deformed and VIII sub-horizontal lava flows that appeared to have originated from VI. TWTT was converted to meters using a 1700 ms^{-1} sediment velocity. The lower panels are blown ups of segments of the upper panel. Note that emplacement of the plug on the right side of profile has affected the seafloor. See Fig. 4 for location of profile.

induced regressions/transgressions. According to Lambeck and Bard (2000) sea level during the Last Glacial Maximum 22,000 years ago in the Columbretes Islands region was at an elevation of −115 m. As the ice retreated northward sea level transgressed across the shelf and by 4,000 years ago it had risen to an elevation of −4 m. If the submarine volcanic edifices are as old as the 1.0–0.3 Ma old features rising above sea level they must have gone some erosion during this transgression, yet they show little evidence of erosion. Possibly this reflects a rapid rise in sea level, so rapid that the features were little affected by the transgression. Pulses of rapid sea level rise separated by periods when sea level rose much slower is documented by the sea level curve of Lambeck and Bard (2000). According to this curve sea level rose at rates of 7.2 m/1000 years from 22,000 to 18,600 years ago, 5.8 m/1000 years from 18,600 to 15,500 years ago, 9.6 m/1000 years from 15,000 to 13,000 years ago, 6.6 m/1000 years from 13,000 to 10,000 years ago and 11.7m/1000 years 10,000 to 4,000 years ago when sea level reached an elevation of −4 m. However, these changes in the rate of sea level rise appear to be too small for the submarine features to have escaped erosion. The other possibility for the pristine state of the submarine features is that the structures formed after sea level reached an elevation of −60 m 13,000

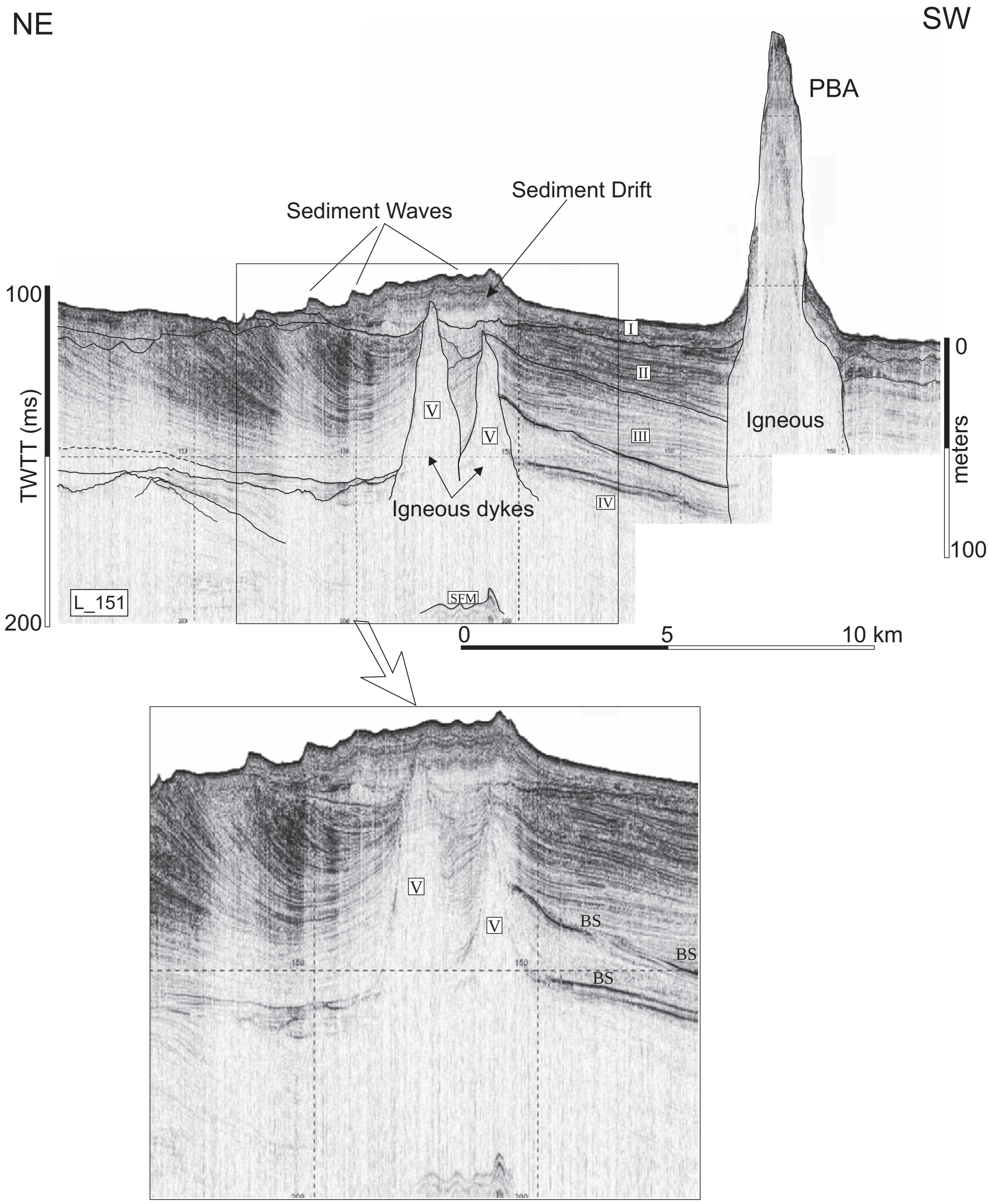

Fig. 11. Very-high resolution seismic reflection Topas profile L-151 from the Columbretes archipelago. BS: bright spot; PBA: Placer de la Barra Alta. Concentric ring-structures on top of this high resemble the multiple superimposed radial flows in mud volcanoes in the Gulf of Cadiz. Note that the creation of Sediment Drift seems to be related to the outcrop of two volcanic pinnacles following a lee-wave model. See Fig. 4 for location of profile and Fig. 10 for description of the acoustic units.

years ago as they are deeper than this level. That the features may be recent also is supported by updoming of the seafloor by an igneous plug (Fig. 10), the pimples on the seafloor east of DFP (Fig. 6) that may represent dykes and deformation of the Holocene sediment drift by dyke intrusion (Fig. 11). If volcanic activity in the Columbretes Islands region is that young, then, possibly the magmatic activity and

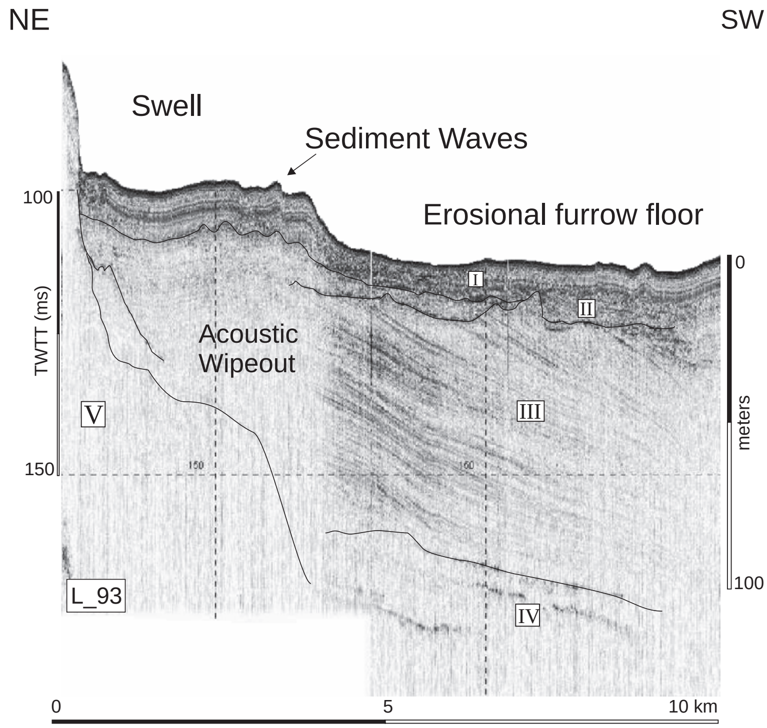

Fig. 12. Very-high resolution seismic reflection Topas profile L-93 from the southeast Columbretes archipelago region showing acoustic wipeout. See Fig. 4 for location of profile and Fig. 10 for description of the units.

associated seismicity may have been responsible for the large catastrophic sediment failure east of the islands described by Lastras et al. (2002).

4. Geologic significance

The volcanic cover of the shelf off Castellón, Spain, makes this segment shelf rather unique in the Mediterranean. No such structures are found on the rest of the shelf off eastern Spain, nor on the shelves off southern France, northern Africa, the islands of Corsica, Sardinia and Sicily, eastern Italy and along the east side of the Adriatic Sea. On the western Italian shelf only one such structure occurs off Naples (Inusha Seamount; Vanney and Gennesseaux, 1985); the rest of the structures are on the continental slope and in the adjacent Tyrrhenian Basin. Similarly off Greece the volcanic structures are found on the continental slope. Even on the Balearic Promontory the volcanic edifices occur off the insular shelves (Acosta et al., 2001).

In contrast, off Castellón the outer Ebro continental shelf is covered by 90×40 km volcanic field at 80/70 m water depth. A small segment of this field rises above sea level to form the Columbrete Island Grande Group and the smaller islets south of the group. These islands and associated submarine volcanic field are one of the rare examples of Quaternary volcanism in the Mediterranean. Whereas the volcanic edifices above sea level display evidence of marine erosion, many of those below sea level appear to be pristine only being partially or completely covered with sediment. It is this observation that has led us to infer that the features may be Holocene and much younger that the subaerial volcanic edifices. The other feature that makes this volcanic field unique is the Recent sediment drift associated with the submarine volcanic features. Such association does not appear to have been described previously from any continental shelf in the Mediterranean or elsewhere in the world. The sediment ridges, swells, waves and erosional furrows in the drift are being constructed by the southwesterly flowing Liguro–Provençal–Catalan Current or North-

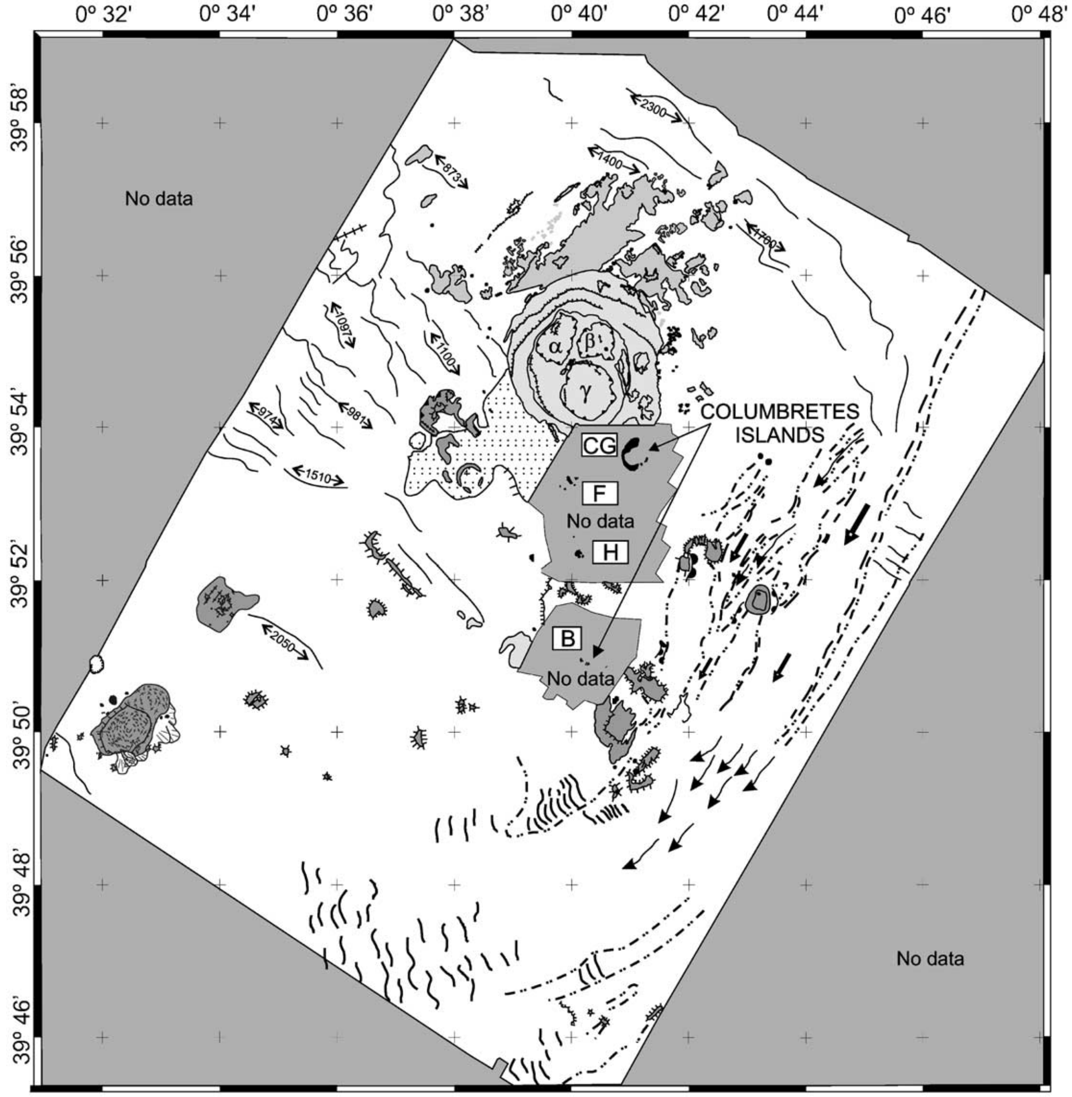

Fig. 13. Morphological interpretation of Columbretes area. See Fig. 5 for legend.

ern Current out of the shelf's sediment cover. The volcanic edifices of the Columbretes volcanic field are acting as obstacles to the southwesterly flowing Northern Current and influencing the construction of the sediment drift.

5. Conclusion

The Columbretes volcanic field off Castellón, Spain, is dominated by a 60 m high, 12 km long and 4 km wide north–south trending swell at the outer shelf at a depth of 80 m. This swell may have a core of Palaeozoic rocks and represents a horst associated with a sinistral northeast trending left-lateral Trans-Moroccan–Western Mediterranean–European (TMWME) mega fault zone extending from western Morocco to northern western Europe. The Columbretes archipelago located along the crest of the high consists of several 1.0–0.3 Ma old volcanic edifices. The submarine structures may be much younger being about 13,000 years old. The submerged structures of range from pinnacles to plugs, to volcanic edifices and lava flows some of which pierced and updomed the seafloor. Some of these features are partially or completely buried by a sediment drift controlled by the southwest flowing Catalan Current.

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