Sedimentary processes on the Iberian continental margin viewed by long-range side-can sonar Part 1: Gulf of Cadiz

Sonographs
Sediment waves
Eastern boundary current
Mediterranean outflow
Submarine canyons

Image acoustique
Rides sédimentaires
Courant géostrophique
Écoulement de l'eau méditerranéenne
Canyons sous-marins

J.V. Gardner[a], R.B. Kidd
Institute of Oceanographic Sciences, Wormley, Godalming, Surrey GU8 5UB, UK.
[a] Permanent address: US Geological Survey, Menlo Park, California 94025, USA.

Received 19/11/82, in revised form 7/3/83, accepted 24/3/83.

ABSTRACT

A long-range side-scan sonar (Gloria) survey of the central and western Gulf of Cadiz reveals fields of sediment waves in water depths ranging from less than 2 000 to over 4 000 m. The sediment waves in water depths less than 2 000 m have an average amplitude of 23 m and an average wavelength of 1 892 m. These bedforms appear to be directly related to Mediterranean outflow. Sediment waves in water depths greater than 2 000 m are different in size from those shallower than 2 000 m; they have average wave heights of 8 m and average wavelengths of 1 121 m. These bedforms are probably not related to Mediterranean outflow, but rather are the result of a proposed eastern boundary current that appears to flow along the Northwest African margin, into the Gulf of Cadiz, and along the Western Iberian margin.
Submarine canyon systems show the development of gulleys and dendritic-like drainage systems in the upper portions of the canyons. The floors of the canyons appear to have large blocks of material scattered along axis. The lower regions of the canyons merge onto the Seine and Horseshoe abyssal plains with no apparent development of fans, distributary channels, levees, etc.

Oceanol. Acta, 1983, **6**, 3, 245-254.

RÉSUMÉ

Processus sédimentaires dans la marge continentale ibérique observés par sonar latéral à longue portée. 1re partie : le Golfe de Cadix

Une reconnaissance effectuée dans le Golfe de Cadix à l'aide d'un sonar latéral à longue portée (Gloria), révèle l'existence de rides sédimentaires de 1 000 à plus de 4 000 m de fond. Au-dessus de 2 000 m, leur amplitude moyenne est de 23 m et leur longueur moyenne de 1 892 m. Ces structures sont dues à l'écoulement dans l'Atlantique des eaux d'origine méditerranéenne. Au-dessous de 2 000 m, les rides sont moins étendues, avec une amplitude moyenne de 8 m et une longueur de 1 121 m. Ces figures sédimentaires profondes sont alors plutôt la conséquence du passage d'un courant géostrophique aux limites orientales de l'Atlantique. Dirigé vers le Nord, ce courant longe la marge au nord-ouest de l'Afrique, pénètre dans le Golfe de Cadix, puis remonte le long de la péninsule ibérique.
A la tête des canyons sous-marins, les images acoustiques mettent en évidence de nombreux affluents organisés en réseau de drainage dentritique. L'axe des canyons semble obstrué par de grands blocs effondrés. Dans leur cours inférieur qui rejoint les plaines abyssales de la Seine et du Fer-à-Cheval, on ne remarque aucun éventail profond accompagné de chenaux ou de levées.

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INTRODUCTION

Continental margins, especially the continental slope, are typically thought of as areas of major down-slope sediment movement. This province necessarily is the zone through which sediment must pass as it works its way to the continental rise and abyssal plains. One consequence of this view is the impression that continental slopes are replete with all scales of slumps, slides and general mass movement features. Much of the work on the slope for the past 30 years has concentrated on these often spectacular features (Heezen, Ewing, 1952; Heezen, Drake, 1964; Embley, 1976; Embley, Jacobi, 1977; Malahoff *et al.*, 1980, to name just a few). These studies have typically relied on narrow-beam echo sounding, high- and low-resolution seismic-profiling surveys and more recently surveys by mid- to short-range side-scan sonar (Belderson, Kenyon, 1976; Kenyon *et al.*, 1978; Ryan, 1982; McGregor *et al.*, 1982; Twichell, Roberts, 1982). Most of these techniques provide narrow corridors of data often separated by tens of kilometres between adjacent profiles.

Gloria Mark II is a dual side-scan sonar system that provides almost the equivalent of a continuous regional sonic photograph of up to 60-km maximum swath of the sea-floor perpendicular to the ship's track. A zone about 5 km to either side of the ship's track is typically not insonified. This system transmits a linear FM sweep with a bandwidth of 100 Hz and an operating frequency of 6.5 kHz (Somers *et al.*, 1978). Because of electronics limitations, the nominal separation of targets down range is 45 m (at the 60 km total-range setting) and the nominal resolution parallel to the ship's track is 40 sec. × ship's speed in m/sec. (200 m at 10 kts).

In 1978 Discovery Cruise 90 of the Institute of Oceanographic Sciences collected over 4 000 km of analogue Gloria-II data, seismic-reflection and 10-kHz data along the continental margin of the Iberian peninsula (Fig. 1). The survey was run at speeds of 7 to 9 knots and controlled by satellite navigation. The sonograph images shown in this report are the original slant-range sonographs anamorphically corrected for variations along track (Rusby, Somers, 1977). Preliminary studies of these data have been reported by Roberts and Kidd (1982), and Kidd and Roberts (1982).

The present study interprets in detail the data covering the entire western Iberian margin and the western and central Gulf of Cadiz in terms of the major sedimentary features. Because the area is quite large and the coverage is dense, the Iberian margin has been subdivided into three segments: central and western Gulf of Cadiz; southwestern Iberian margin; and northwestern Iberian margin. This report deals only with the Gulf of Cadiz segment (box labelled 1 in Fig. 1). The two remaining segments are at present in preparation for publication in this journal.

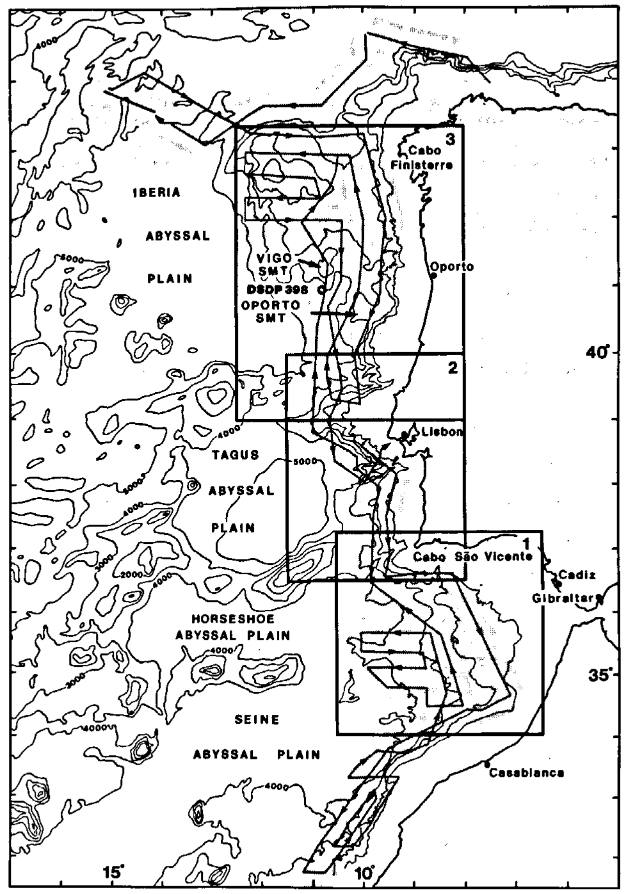

Figure 1

Location map showing Discovery 90 Gloria sonographs coverage of the Gulf of Cadiz and southern Iberian margin (stippled). The 4,000-m water depth contour is as drawn by Laughton et al. *(1975). The area within box 1 is the central and western Gulf of Cadiz, the subject of this paper. The southwestern Iberian margin (box 2) and also the northwestern Iberian margin, will be the subjects of subsequent papers in this journal.*

METHODS USED IN INTERPRETATION

The methodology used in this study was to first annotate a transparent Gloria-II track chart with detailed observations from the airgun and 10-kHz profiles. Annotations included the position and facing directions of all changes in slope, occurrences of sedimentary bedforms, echo-sounding types, and any feature suspected of being directly related to underlying structure (diapirs, fault blocks, etc.). Next, the Gloria-II mosaics were interpreted on this same transparent overlay. The last step involved overlaying the interpretations on a bathymetric chart to look for relationships between the Gloria-II features and the bathymetry.

The Gloria-II sonographs commonly show extremely low-relief lineations that undoubtedly are bedforms. Although some of these features can be traced for over 5 km, they are so subtle that, although discernible on the original sonographs, we were unable to illustrate them adequately in this paper. We feel that these bedforms are either low amplitude sediment waves or erosional furrows, because they trend in a consistent direction and are often sub-parallel to the larger-scale bedforms described later. This observation illustrates that low-relief bedforms are quite common on this section of the sea-floor and that Gloria-II is capable of resolving quite subtle features.

The 10-kHz profiles taken at the time of the Gloria-II survey show features that cannot be matched one-for-one with features seen on the sonographs. This is primarily due to the approximately 5-km zone on either side of the ship's track that typically is not insonified. But in addition, this lack of resolution by Gloria-II is, in part, a function of the geometry of the features. The height resolution of Gloria-II is a function of frequency (6.5 kHz) and is theoretically somewhat less than 20 cm. We believe that the horizontal dimensions, linearity or lack thereof, the facing slope angles of the features, their orientation relative to the ship's track, and their distance away from the track all play a deciding role in whether or not a feature will backscatter enough energy to be resolved on Gloria-II analog sonographs. For instance, all channels found on the 10-kHz records were resolved on Gloria-II sonographs. It is probable that many of the bedforms not resolved on Gloria-II sonographs are sinuous in shape and short crested. Facing slope angles of bedforms were calculated from the 10-kHz record and it appears that features with facing slope angles $>6^{\circ}$ are easily resolved and those $< 6^{\circ}$ are not. These calculations were made on bedforms in water depths of about 2 500 m. It should be emphasised that in all areas where the 10-kHz profiles show bedforms, the Gloria-II sonographs show bedforms; it is the number of individual bedforms that differs.

The olistostrome in the Gulf of Cadiz, proposed by Roberts (1970), does present the problem of separating features on the sonographs that would be expected to result from a large, tectonically implaced mass from those features related to currents and gravity-induced sediment movements. We have concentrated on identifying features related to sedimentary processes and have attempted, using the above methods, not to confuse these with structurally related features. However, the successful identification of some features remains unequivocal.

REGIONAL FRAMEWORK OF THE GULF OF CADIZ

The general bathymetry of the Gulf of Cadiz (Fig. 2) has been discussed by Heezen and Johnson (1969) and Roberts (1970). The Gulf of Cadiz is an eastward-projecting *cul-de-sac* in an otherwise north-south continental margin. The continental slope within the Gulf of Cadiz has quite gentle gradients in the central region (about 0.01 along 36°N) and only steepens to about 0.05° along the southern Iberian and northern Moroccan sectors. The transition from slope to rise is subtle; gradients of the continental rise vary from 0.014° along 36°N to 0.005° along the southern Iberian margin.

Studies based on seismic-reflection profiling have suggested that the northern and eastern Gulf of Cadiz were tectonically deformed into long, curvilinear ridges and valleys (Roberts, Stride, 1968). Roberts (1970) proposed that a large olistostrome was emplaced in the Gulf of Cadiz in the Late Miocene. This proposed olistostrome could account for the abnormally gentle gradients and the rather disrupted mesoscale bathymetry. The Gulf of Cadiz is also at present a seismically active area (Udias, 1967).

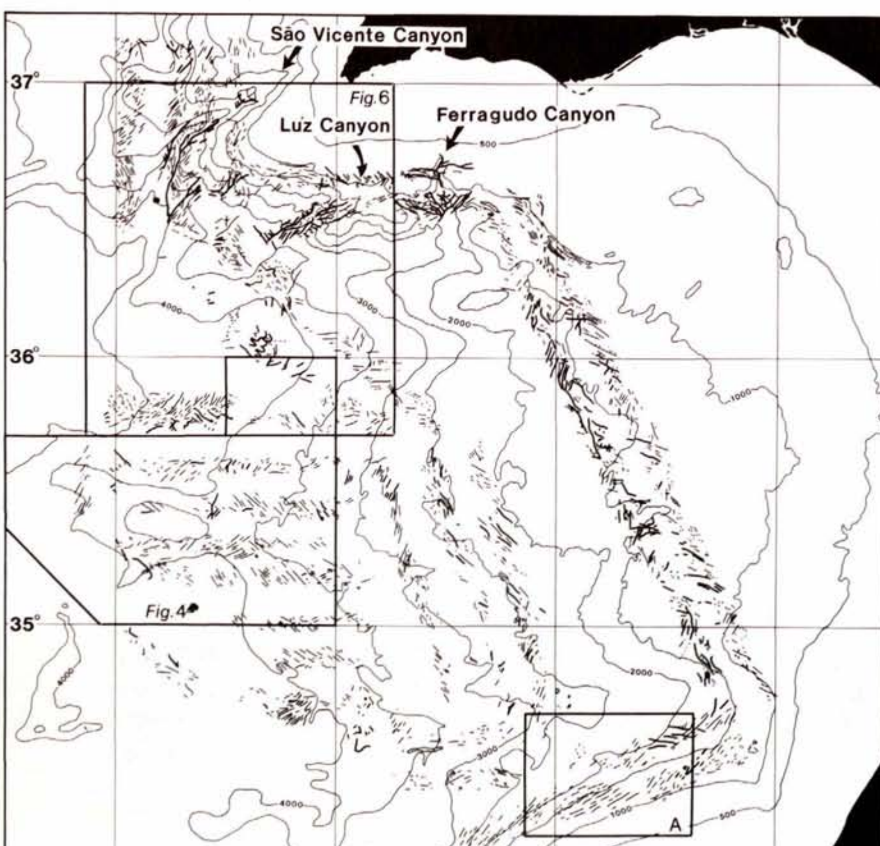

Figure 2 *a*

◄ *General bathymetry and traces of features identified on Gloria-II sonographs. The bathymetry is plotted at a 500-m contour interval and is generalised from Laughton* et al. (1975). *The heavier lines indicate negative-relief features such as channels identified on the sonographs. The lighter lines indicate features interpreted as sediment waves. The areas shown in Figures* 4 *and* 6 *are indicated by boxes.*

Figure 2 *b*

Sonograph mosaic of the Gulf of Cadiz. See *Figure* 2 *a for an interpretation of the sonographs.*

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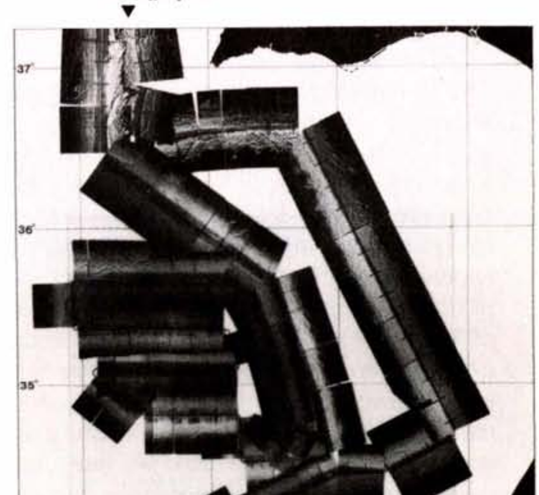


Heezen and Johnson (1969) studied the relationship between microtopography and the flow of the Mediterranean undercurrent in the northern Gulf of Cadiz. Melières *et al.* (1970) correlated features from bottom-photographs with the Mediterranean undercurrent in the northern Gulf of Cadiz. Both studies found a high correlation between the core of Mediterranean undercurrent, identified by the 35.5% isohaline, and current-swept features such as rock, sand and gravel surfaces, large bedforms, scour, etc. Hydrographic studies have suggested that the path of the Mediterranean undercurrent in the northern Gulf of Cadiz may be influenced by bathymetry, especially submarine valleys (Madelain, 1970). However, Zenk (1975 *a*) and Ambar and Howe (1979 *a*; 1979 *b*) have suggested the Mediterranean water is differentiated into two distinct cores near the Strait of Gibraltar and that bottom topography imparts only a secondary influence on the outflow water.

Kenyon and Belderson (1973) advanced the earlier geological studies of the central Gulf of Cadiz by using Gloria-I medium-range (7 and 19-km swath) and shorter range (1-km swath) side-scan sonar surveys. Their survey is located at about 36°N and ranges from 6°30'W to 8°W (north and east of the area reported on here). Their study refined the distribution and types of bedform features (sand ribbons, sand waves, large mudwaves, depositional ridges, channels, etc.) that directly underlie the Mediterranean undercurrent. A systematic progression of features was related to the decreasing flow regime of the Mediterranean undercurrent.

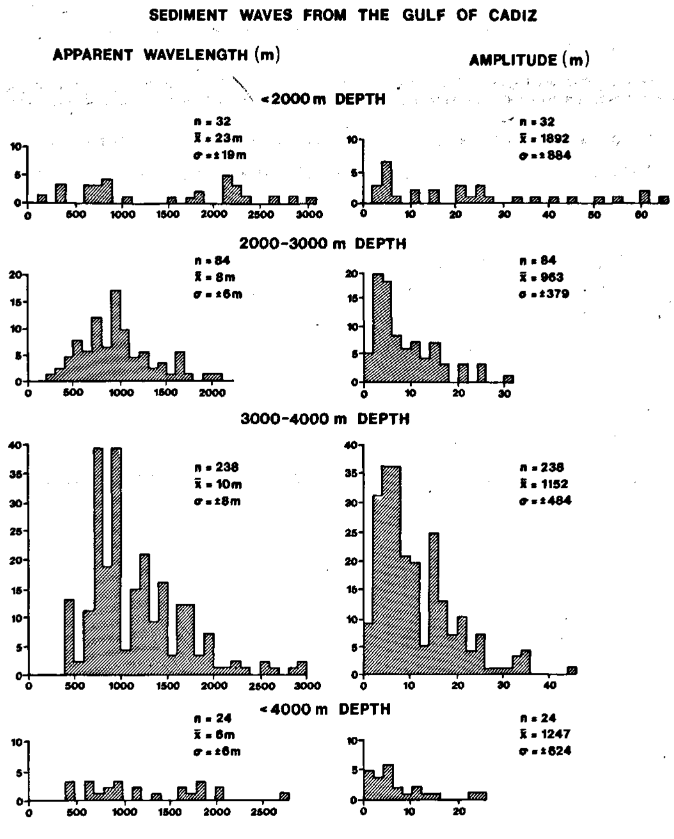


Figure 3

Histograms of sediment wave geometries measured on 10 kHz records. The sediment waves are subdivided by water depth into 1,000 m depth intervals.

DISTRIBUTION OF MAJOR FEATURES

Major sedimentary features identified on Gloria-II sonographs in the Gulf of Cadiz, in order of importance, are: 1) sediment waves and other bedforms; 2) submarine canyon systems; and 3) channels. All available seismic-reflection records crossing the Gulf of Cadiz were scanned so that outcrops of acoustic basement would not be misinterpreted as sedimentary features.

Bedforms

The terminology to describe different bedforms from the deep sea can, at first, be misleading. Terms such as mudwaves and sandwaves are often used, but these terms imply that the sediment facies is known. Lonsdale and Spiess (1977) defined mudwaves and sandwaves not by facies but rather by their dimensions; mudwaves have wavelengths of several kilometres and amplitudes of tens of metres, whereas sandwaves have wavelengths of 10 to 100 m. All of the bedforms described here fall into the above category of mudwave because of their size as measured on the 10 kHz profiles. However, we use the term sediment wave because it is a purely descriptive term and because we have few descriptions of surface sediment that can be usefully related to bedforms seen on the sonographs.

The entire central and western Gulf of Cadiz is covered with scattered fields of sediment waves. They appear on the sonographs as groups of linear, *en échelon* positive features, typically about 2-km long (Fig. 2 *a*).

We compiled measurements of wave height and apparent wavelength of all sediment waves found on the 10-kHz profiles (Fig. 3). Wavelengths are apparent because the ship's track crossed bedforms at various angles and individual crests of bedforms commonly do not correlate between the 10 kHz profile and the Gloria-II sonograph. The sediment waves fall into two classes that each occur in separate bathymetric provinces. Relatively high-amplitude (mean = 23 m) long wavelength (mean = 1 892 m) sediment waves occur between 1 000 and 2 000 m water depth (Fig. 3). They trend parallel to sub-parallel to bathymetric contours and are both symmetrical and asymmetrical in cross-section. The compilation by Lonsdale and Spiess (1977) suggests mudwaves are aligned roughly parallel to the relatively fast currents that formed them. Accepting this interpretation, the sediment waves between 1 000 and 2 000 m depth appear to be responses to relatively strong currents within this depth zone.

The region between 2 000 and 4 500 m water depth has sediment waves of rather uniform dimensions (Fig. 3). These bedforms have mean amplitudes of about 8 m and mean wavelengths of about 1 121 m. The crests of these sediment waves trend sub-parallel to the bathymetric contours and appear to be oriented around

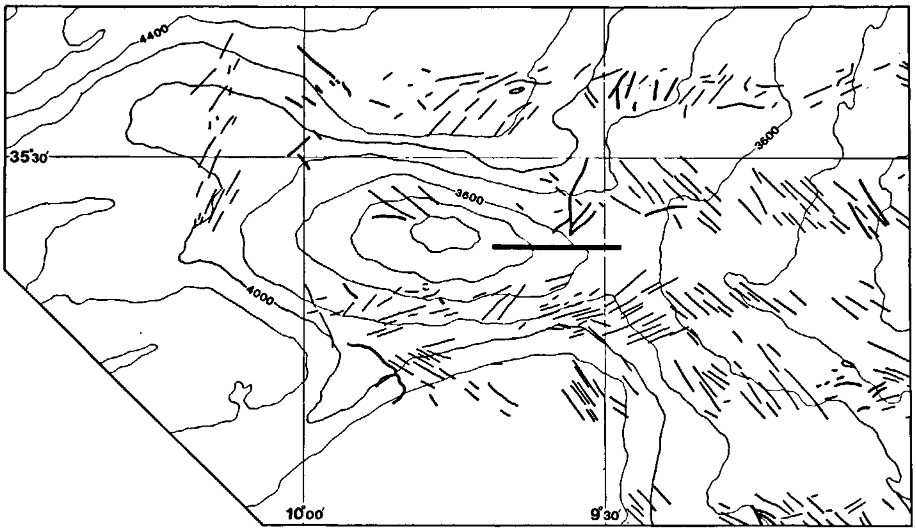


Figure 4
Line tracing of the sediment waves in the western Gulf of Cadiz seen on the sonograph mosaic. See Figure 2 for location. Note the "steering" of the sediment waves around the 1,000-m high bathymetric feature. Contour interval is 200 m. Heavy line is the track of the 10 kHz record shown in Figure 5.

large bathymetric highs, such as shown in Figure 4. The sediment waves in these depths found on a slope are asymmetrical in cross-section on 10-kHz profiles (Fig. 5) but they are nearly symmetrical where found on flat sea-floor. The smaller dimensions of these bedforms suggests that flow in this deeper region may have been different than the flow above 2 000 m. Alternately, these sediment waves may be relict features that have been considerably re-worked and partially destroyed.

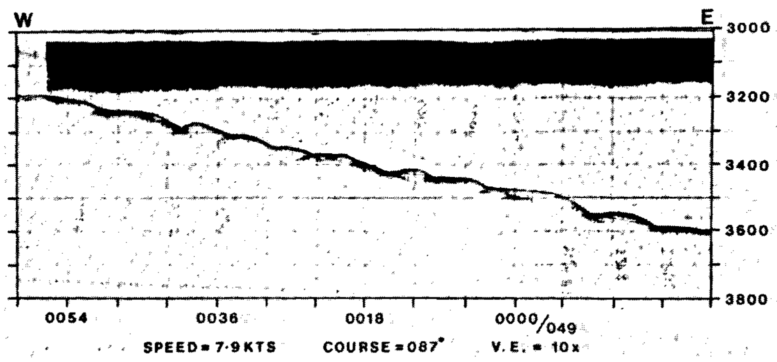


Figure 5
10-kHz echo-sounder profile over the 1,000-m high bathymetric feature showing the sediment waves that ornament its surface. Figure 4 shows the ship's track.

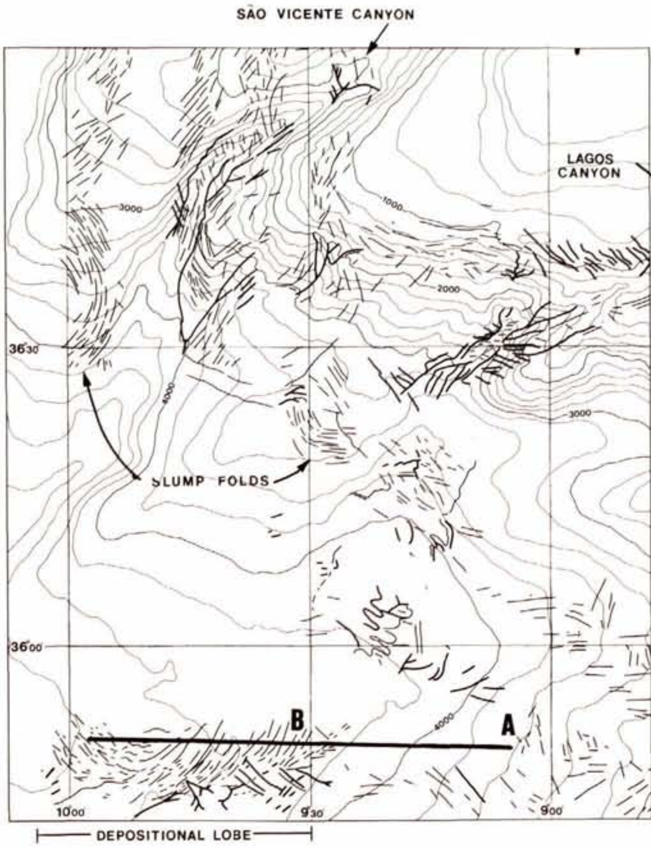
Submarine canyon systems

Three large submarine canyon systems were surveyed by Gloria-II in this segment of the Iberian margin (Fig. 2). Saõ Vicente Canyon heads at Cabo Saõ Vicente on the inner shelf, incises the shelf, slope and rise, and leads directly onto Horseshoe abyssal plain at about 4 800 m depth. The second canyon, informally called Lagos Canyon here (following Vanney, Mougenot, 1981) heads on the upper slope southeast of Cabo Saõ Vicente at about 1 000 m depth and, like Saõ Vicente Canyon, incises the slope and rise and leads directly onto Horseshoe abyssal plain. The third canyon, informally called Portimao Canyon here (again after Vanney, Mougenot, 1981) is located just east of Lagos Canyon and appears from the available bathymetry to head on the upper slope and incise only the slope. The bathymetry suggests that Portimao Canyon joins Lagos Canyon at about 3 500 m depth.

Portimao Canyon has the least Gloria-II coverage of the three canyon systems; only the upper reaches of the canyon were surveyed. It appears on Gloria-II records as a narrow, steep-walled main canyon axis with numerous tributary side-canyons joining the axis along its course (Fig. 2). The tributary side-canyons also have their own tributary side-canyons (second- and third-order tributaries) joining into them. A zone about 30 km wide is covered by a dendritic-like drainage system feeding into the main axis that suggests headward erosion (Fig. 2). Many of the second- and third-order tributaries head on the continental slope, not the shelf. This pattern is similar to that described from side-scan sonar from the northern margin of the Bay of Biscay (Belderson, Kenyon, 1976; Kenyon *et al.*, 1978) and from the US continental margin (McGregor *et al.*, 1982; Ryan, 1982; Twichell, Roberts, 1982).

Lagos Canyon is almost completely covered by Gloria-II sonographs (Fig. 6*a* and 6*b*). The head of Lagos Canyon is at about 1 800 m water depth. A system of gulleys occurs on the northwestern wall of the upper canyon. These gulleys feed directly into the upper reaches of the main canyon axis. The canyon proper is 2.5 to 3 km wide as it crosses the continental slope. Second-order tributaries join the main canyon axis all along its length from the head to about 3 500 m water depth (Fig. 6).

Features up to 1 km long, resolved on the floor of the upper section of Lagos Canyon, appear to be blocks, possibly similar to the large slide blocks described by McGregor and Bennett (1979). These features are aligned roughly perpendicular to the canyon axis and they may actually be large masses of coherent material that have spalled off the upper canyon walls but have not been transported too far down axis. The mid-canyon area has features of similar dimensions to those in the upper canyon, but here they appear to be aligned roughly parallel to the axis, as if following flow lines. Farther down-axis these features are not present but the channel fill shows high backscattering (Fig. 6*b*) that suggests either considerable bottom roughness or a



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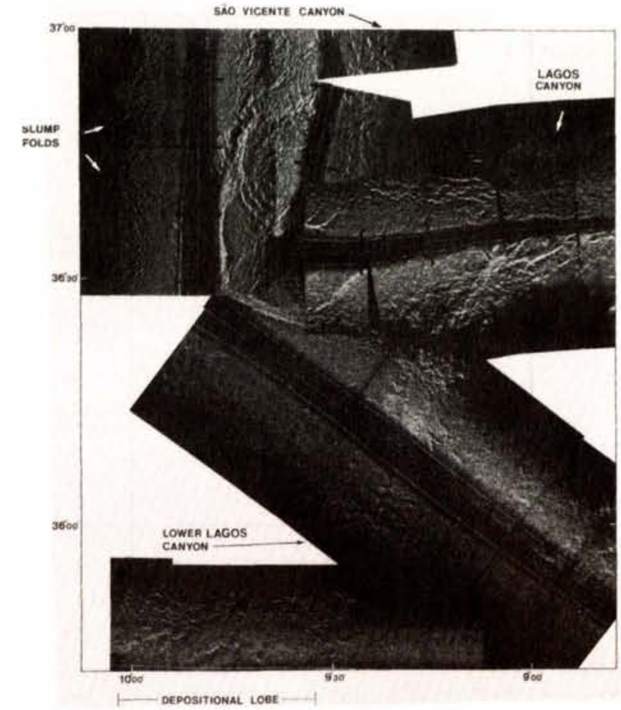

b

Figure 6

Line drawing (6 a) and sonograph mosaic (6 b) of the features associated with Lagos and Saõ Vicente canyons. See Figure 2 for location. Heavy line is the track of Discovery 126 3.5-kHz profile shown in Figure 7.

coarse sediment facies, or a combination of both. This zone may be one of sheet flows or grain flow that have by-passed the slower moving large blocks.

Lagos Canyon abruptly changes its form at 3 500 m water depth from an incised canyon to a feature of very low relief, very high reflectivity, and very irregular outline. The 10-kHz echosounder profiles show a change in acoustic character over this feature. As the zone is approached, the profile shows a relatively flat, featureless surface with a strong surface echo and faint, continuous sub-bottom reflections. The bottom changes within the feature to a small-scale hummocky surface that produces a diffuse surface echo of small-scale hyperbolae tangent to the sea-floor and no sub-bottom reflections. The sonographs show a very marked increase in reflectivity, suggesting an increase in bottom roughness, that outlines this zone. The acoustic characteristics strongly suggest that this zone is composed of debris flow deposits. The probable debris flow deposits vary from about 8.5 to 14.5 km wide, are about 40 km long, and have completely filled the lower portion of Lagos Canyon. The lower half of the Lagos Canyon system has what appears to be meandering channels parallel to the regional slope that abruptly appear and disappear (Fig. 6). These may be former tributary channels that have been partially blocked off and filled by debris flow deposits. The path of Lagos Canyon makes a right-angle bend from a trend of 70 to 180° just at the beginning of the debris flow.

The only portion of the Lagos Canyon system not covered by Gloria-II sonographs is the transition between 4 200 and 4 400 m water depths from the probable debris flow deposits to a very low-relief depositional lobe. This lack of coverage makes the relationship of the depositional lobe to the canyon system equivocal. The depositional lobe is either the distal part of the Lagos Canyon system or an interfluve slump feature, similar to those described by Kenyon *et al.* (1978). The depositional lobe appears roughly semicircular with concentric features having a maximum diameter of about 30 km (Fig. 6).

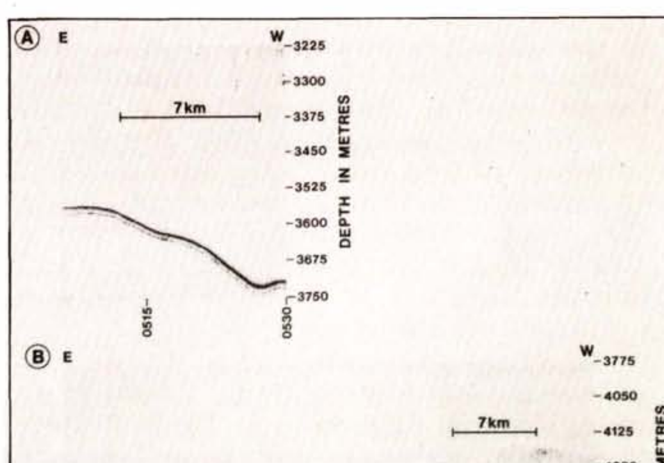

Figure 7

Discovery 126 3.5-kHz profile across the depositional lobe. (A) is outside and (B) is within the depositional lobe. See Figure 6 a for location of the track.

A 3.5-kHz profile across the northernmost part of the sonograph (Fig. 7) shows an abrupt change from parallel continuous, strong surface and sub-surface reflectors outside the depositional lobe to a hummocky, diffuse surface echo with no sub-bottoms over the depositional lobe. The lack of sub-bottom layering within the lobe discounts its interpretation as a submarine fan lobe. A series of meandering tributary channels on the southeastern margin of the lobe appears to have been partially buried by the depositional lobe (Fig. 6 *a*). The depositional lobe grades into the flat, featureless expanses of Horseshoe abyssal plain without any surface expressions of channels, levees, distributary features, etc.

The third canyon in this segment of the Iberian margin is Saõ Vicente Canyon (Fig. 6). This canyon heads at the shelf break, incises both the slope and rise, and feeds directly onto Horseshoe abyssal plain. The Gloria-II coverage includes only the slope and upper rise portion of the canyon. The trend of Saõ Vicente Canyon is toward the south-southwest, transverse to the regional bathymetry. The main axis of the canyon is about 3 km wide and about 45 km long. The canyon walls show a series of linear and curved features in water depths between about 2 000 and 3 000 m that may be slump folds or sediment failures. Like Lagos Canyon, Saõ Vicente Canyon has a broad floor with well-developed features that may be large detached masses. These features trend roughly perpendicular to the main axis in the continental slope section of the canyon axis, but trend parallel to the axis in the upper rise section. These features appear to be a succession of large blocks, similar to those described in Lagos Canyon.

The Gloria-II sonographs also show an increase in reflectivity (Fig. 6 *b*) on the floor of Saõ Vicente Canyon that indicates the presence of either a coarse sediment facies or bottom roughness or both. Concentric features similar to the ones described at the terminus of Lagos Canyon, occur just west of the canyon axis in 3 000-to 4 200-m water depth (Fig. 6). The pattern adjacent to Saõ Vicente Canyon appears to reflect a series of interfluve slumps and possible slump folds generated by sediment creeping down into the lower reaches of Saõ Vicente Canyon.

Our sonograph coverage does not show the presence of submarine fans and fan systems along the northern Gulf of Cadiz such as those shown by Vanney and Mougenot (1981). We believe that sediment transported to the outer shelf and slope is first intercepted by the strong flow of Mediterranean outflow. Sediment not entrained in the Mediterranean outflow is re-worked by the eastern boundary current and eventually transported northward. Consequently, even though fairly sizeable rivers such as the Guadiana and Guadalquivir rivers flow into the Gulf of Cadiz, the sediment they contribute is re-worked along slope by geostrophic flows and not down slope by gravity-induced processes.

Channel-like features

Numerous channel-like features, distinguished by negative relief, appear on the Gloria-II sonographs from the Gulf of Cadiz but they are not so continuous that they can be connected into a true channel system (Fig. 2). In general, these channels do not have *levées*, are less than 100 m deep, are cut traverse to the regional bathymetry and appear to meander. Channels are most common on the upper slope (< 1 500 m deep), common to rare on the lower slope (1 500 to 2 500 m deep), and rare to absent on the rise (> 2 500 m deep). Many of the channel-like patterns interpreted from the bathymetry of Heezen and Johnson (1969), Hydrographic Department (1969), and Laughton *et al.* (1975) are not apparent on the Gloria-II sonographs. The lack of Gloria-II definition of these bathymetric interpretations may be a result of either their small relief, or very low angles of the walls, or of inaccurate bathymetry. Many of the channels seen on the sonographs on the upper slope have second- and third-order tributaries but none of them appear to have distributary systems. The most surprising yet consistent characteristic of the channels is their short length and lack of interconnections. The channels are rarely more than 15 km long and many are only 3 to 4 km long. Some may be related to surface morphology on an olistostrome, as postulated for the region by Roberts (1970).

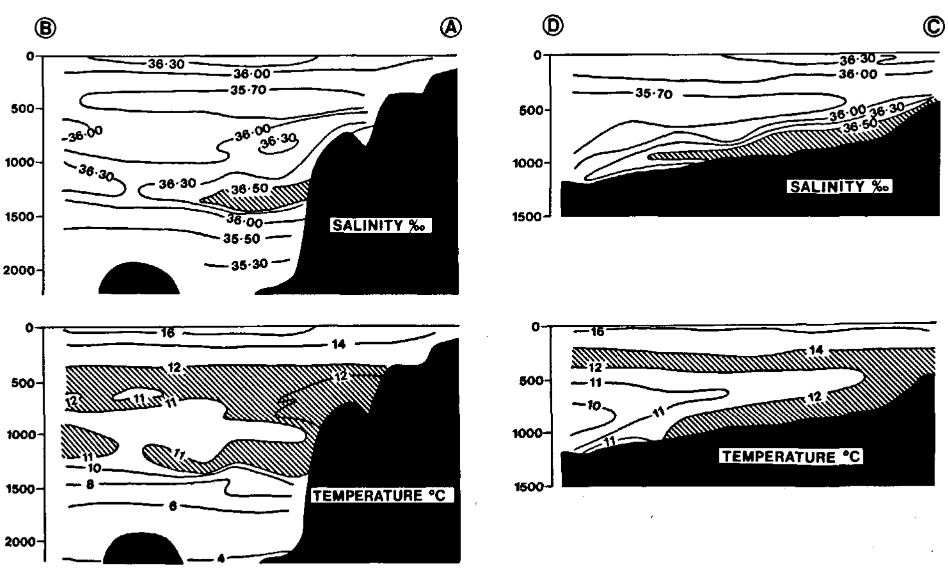

Figure 8

Two profiles of temperature and salinity showing the tongue of Mediterranean outflow water as it leaves contact with the sea-floor (modified from Madelain, 1970). Note the progressive deepening of the influence of Mediterranean outflow water from east to west. See Figure 9 for locations of A-B and C-D.

DISCUSSION

The Mediterranean outflow has been investigated in some detail (Heezen, Johnson, 1969; Madelain, 1970; Melières *et al.*, 1970; Kenyon, Belderson, 1973; Zenk, 1975*b*; Ambar, Howe, 1979*a*; 1979*b* and references therein). The Mediterranean outflow water leaves contact with the sea floor at 1 000 m in the eastern region and at 1 400 m in the western region (Fig. 8). The relatively large-amplitude sediment waves in the northern Gulf of Cadiz that occur between 1 000 and 2 000 m depth are probably related to warm, salty, sediment-laden Mediterranean outflow (Kenyon, Belderson, 1973; Thorpe, 1972) possibly coupled with effects of internal waves. Kenyon and Belderson (1973) mention maximum current speeds of Mediterranean outflow of 250 cm/sec. and Ambar and Howe (1979*b*) calculate speeds of 181 cm/sec. The sediment facies from 1 000 to 2 000 m depth of the continental slope has been described as silty lutite with variable amounts of foraminifers and sandy interbeds (Heezen, Johnson, 1969; Diester-Haass, 1973). Current speeds somewhat less than 100 cm/sec. are required to erode (and hence form depositional bedforms) in cohesive clay, and non-cohesive silt and sand would require even slower speeds (Southard *et al.*, 1971; Lonsdale, Southard, 1974; Young, Southard, 1978). Consequently, we believe the sediment waves found on the Gloria-II survey between 1 000 and 2 000 m depth are a direct result of the shear produced on the surface sediments by Mediterranean outflow.

It is possible that sediment waves found between 1 000 and 2 000 m deep are relict features, but, if so, they must have been produced during former periods of eustatic high sea-level rather than low stands. A drop of sea-level during global glacial conditions of only 130 m (Bloom, 1971) would reduce the cross-sectional area of the Gibraltar sill, at present about 200 m deep (Curray, 1969) by 65 to 90%, depending on the geometry used for the sill area. This reduction in cross-sectional area suggests that if any outflow did occur during global low sea levels, then the flux was probably greatly reduced over today's. Thunell (1979) has suggested from paleotemperature estimates that the eastern Mediterranean, the region where Mediterranean deep water is produced, has had sea-surface temperatures comparable to today's for much of the last 5 million years. These estimates of sea-surface temperatures suggests that the salinity of the eastern Mediterranean for the late Neogene was often similar to today's.

Indeed, conditions similar to today's probably have a much longer history. Deep-sea drilling into pre-Messinian sequences of both the western and eastern Mediterranean has shown that the pattern of water mass exchange with the Atlantic Ocean through a restricted portal in the west was established in the Lower Miocene (Hsü *et al.*, 1978). Connection was lost with the Indian Ocean during the Burdigalian. It follows that the formation of Mediterranean outflow water may have been a common phenomena during periods of high eustatic sea levels throughout much of the late Neogene.

If pelagic sediment requires higher flow regimes to form sediment waves than occur here today, then possibly the sediment waves could have initially formed during bursts of Mediterranean outflow as pulses of dense water spilled into the Gulf of Cadiz just after eustatic transgressions. Another possibility is that Mediterranean water was more saline (denser) in the past and hence penetrated deeper with greater speeds than occurs today.

However, the smaller amplitude sediment waves found between 2 000 and 4 000 m depth probably were not produced by Mediterranean outflow water. The orientation of the sediment waves around bathymetric contours implies a geostrophic flow and the existence of a deep eastern boundary current. The proposed flow must be northward because a southward flow would be deflected towards the west by the Coriolis force and hence not follow the general bathymetry of the Gulf of Cadiz.

The sediment waves occur considerably below the present depth of Mediterranean outflow water, which is restricted to the top of upper Deep Water at depths less than 2 000 m (Newmann, Pierson, 1966; Senk, 1975; Ambar, Howe, 1979*b*). The sediment waves found between 2 000 and 4 000 m occur within the deep water mass. Cross-sections of temperature and salinity at 36°N show that the deep water-mass structure of the Gulf of Cadiz is similar to that of the deep eastern North Atlantic basin (Fuglister, 1960). Defant (1961) suggests that a slow (< 3 cm/sec.), northward-flowing, geostrophic, deep water-mass may circulate through the Gulf of Cadiz. Meincke *et al.* (1975) and Swallow *et al.* (1977) report northward flowing water with speeds less than 3 cm/sec.west of Portugal from depths over 2 000 m. Lonsdale (1978) reported short-term current-meter data from the Moroccan rise (~4 300 m deep) and the Saharan rise (~3 950 m) off Northwest Africa. At both localities, maximum recorded current speeds of 9 and 19 cm/sec. respectively were recorded above fields of bedforms and the current directions were all toward the Northeast.

We believe that the bedforms found deeper than 2 000 m are a result of a northward flowing deep eastern boundary current. Currents with speeds of about 3 cm/sec. may not be capable of forming bedforms of non-cohesive sediment and are even less likely to be able to form bedforms in cohesive material (Lonsdale, Southard, 1974). The few bottom samples reported from 2 000 to 4 000 m depth in the Gulf of Cadiz are all categorised by Heezen and Johnson (1969) as "normal pelagic" and "pelagic ooze"; a sediment that should act in a relatively cohesive manner. However, sediment waves do occur, suggesting the sediment facies is relatively non-cohesive, or perhaps the current strength is greater, or both, or possibly the sediment waves are relict from a time when this flow was much stronger.

The regional bathymetry of the Gulf of Cadiz forms a *cul-de-sac* to the proposed northward-flowing boundary current. The orientations of the sediment waves, sub-parallel to the contours, show the path taken by the deep eastern boundary undercurrent. Figure 9 shows our interpretation of this flow through the Gulf of Cadiz.

SUMMARY

Mapped bedforms interpreted from Gloria-II sonographs and 10-kHz echo-sounder profiles from the central and western Gulf of Cadiz reveal two distinct classes of sediment waves that occur in distinct bathymetric provinces. Sediment waves in water depths less than 2 000 m have average amplitudes of 23 m and average wavelengths of 1 982 m. These sediment waves appear to be direct responses to the strong flow of Mediterranean outflow. The sediment waves may either be presently forming or be relict. However, if they are relict, they must have formed during periods of eustatic high sea level because of the constraints imposed by the sill depth of the Strait of Gibraltar on outflow.

Sediment waves from depths greater than 2 000 m have average amplitudes of 8 m and average wavelengths of 1 121 m. These bedforms are not related to Mediterranean outflow but are responses to an eastern boundary current that flows along the continental margins of the eastern North Atlantic. The flow may have been episodic or continuous and may have been stronger in the past than it is today. The flow (or current) was competent to form large-scale sediment waves of a surface sediment that we presume to be of a relatively cohesive pelagic facies. This implies current speeds of the order of > 10 cm/sec. Current-meter stations west of Portugal show a persistent northward flow, but with speeds less than 3 cm/sec.

Three submarine canyons were surveyed with Gloria-II. The upper canyon regions of Lagos and Saõ Vicente Canyons appear to have a disoriented fill of large blocks of debris. Their mid-canyon channels show a more ordered arrangement of large blocks, possibly along flow lines, and the lower canyon region appears to be filled with sediment that has by-passed the blocks. The portion of Lagos Canyon across the lower continental rise has either been filled by an interfluve slump or by a depositional lobe of channel fill. Nowhere did we observe distributary channel systems or even submarine fan systems along the continental rise/abyssal plain boundary.

The second segment of this Iberian margin study, the Southwestern Iberian margin, will discuss in detail the importance of submarine canyons to the sedimentary processes of this margin.

Acknowledgements

The officers and scientists aboard RRS Discovery during Cruise 90, in particular the Gloria technical support team, are acknowledged for their major contribution to the findings reported here through collection of the data. This was a constituent cruise of the Department of Energy-sponsored Continental Margin Programme.

Peter M. Hunter and Amanda M. Bates at IOS are thanked for their considerable help in producing charts, mosaics and other illustrations that formed the basis of this phase of the Gloria interpretation. Constructive reviews by R.H. Belderson, D.G. Roberts, S.A. Thorpe and N.H. Kenyon were greatly appreciated as were those by two anonymous reviewers. All added significantly to the interpretations presented here.

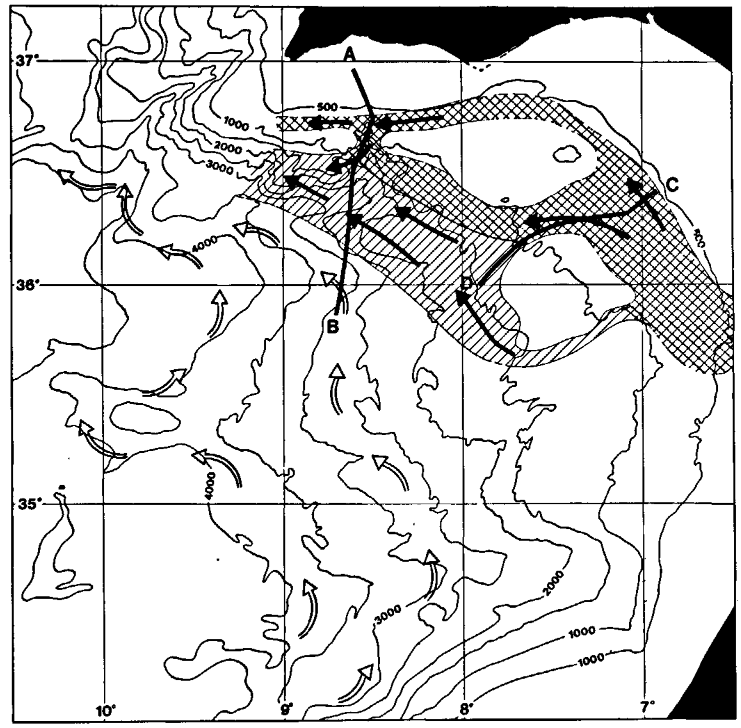

Figure 9
A highly generalised depiction of the flow of Mediterranean outflow water (black arrows), salinity 36.5 ‰ (shaded), and of the proposed deep eastern boundary current (open arrows). The heavier patterned area of Mediterranean outflow water represents the zone where the water mass is in contact with the sea-floor. The lighter pattern represents the region where this water is not in contact with the sea-floor. Lines A-B and C-D are the tracks for the temperature and salinity profiles in Figure 8.

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