The Cadiz Contourite Channel (Gulf of Cadiz): photographic evidence for active bottom currents and deep tidal influence

El Canal Contornítico de Cádiz (Golfo de Cádiz): evidencias fotográficas de una activa circulación de fondo influenciada por la marea

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Abstract: The Cadiz Channel is the largest and most prominent contourite channel in the middle slope of the Gulf of Cadiz, and is known to siphon off the southern branch of Lower Core of Mediterranean Outflow Water (MOW) as it flows westwards from the Gibraltar Gateway. Bottom photographs and dredge hauls reveal a high-energy channel floor, in places with bare rock, boulders and gravel, and elsewhere covered with sandy contourites. The sandy substrate shows a wide range of current-induced bedforms which orientation indicates flows directed to the S/SW (main channel) and W (spillover channel), which can be related to MOW bottom currents, although with velocities varying between about 0.2 and 0.8 ms^{-1}, even in the same channel location. However, current vane orientation was clearly responding, in part, to tidal effects and periodicity in the Gulf of Cadiz at the time the photographs were taken. Maximum current velocities, therefore, are achieved when spring ebb tides are focussed by the Cadiz Channel at depth and reinforce the normal bottom current due to MOW.

Key words: *Gulf of Cadiz, bottom currents, contourite channel, deepwater tides, seafloor photographs*

Resumen: *El Canal de Cádiz es el canal contornitico más característico del talud del Golfo de Cádiz, actuando como vía de circulación de la rama meridional del núcleo inferior de la MOW. El estudio de numerosas fotografías del fondo y dragas realizadas a lo largo del canal indica unas condiciones de alta energía sobre el fondo, encontrándose afloramientos de rocas, cantos, y gravas, pero donde predominan las contornitas arenosas. Las facies arenosas muestran un amplio rango de formas de fondo que evidencian un flujo hacia el S/SO (canal principal) y O (canal de desagüe) relacionado con la influencia directa de la MOW, cuantificándose variaciones importantes en la velocidad de la corriente (0.2-0.8* ms^{-1}*) incluso para un mismo punto del Canal. Por el contrario, la veleta instalada en la cámara fotográfica indica la existencia de corrientes en direcciones contrarias, que responden al efecto de la marea y su periodicidad en el Golfo de Cádiz. Las máximas velocidades de la corriente se registraron durante las mareas bajas, la cual es canalizada por el Canal de Cádiz y reforzada por el flujo normal de la MOW.*

Palabras clave: *Golfo de Cádiz, corrientes de fondo, canal contornitico, mareas profundas, fotografías submarinas*

INTRODUCTION

The Mediterranean Outflow Water (MOW) forms a strong bottom current in the Gulf of Cadiz (Fig 1). After passing the Straits of Gibraltar, MOW spreads westward, veering north-westward due to the Coriolis force, and progressively descends the slope driven by its excess density, eventually losing contact with the seafloor at 1200-1400 m depth, where it becomes neutrally buoyant. Due to interaction with the bottom topography, MOW subdivides into two principal cores (Upper and Lower MOW). The evolution of the Cadiz margin has been controlled principally by a combination of tectonic activity, climate and sea level change, which have driven both *downslope* and *alongslope* processes. In particular, the strong influence of the MOW on the slope evolution has generated a large complex Contourite Depositional System (CDS) identified in the middle slope (Hernandez-Molina et al 2006). This CDS is composed by five major morphosedimentary sectors: 1) *proximal scour and sand ribbons*; 2) *overflow sedimentary lobes*; 3) *channels and ridges*; 4) *muddy contourite sheets and mounds*; and 5) *submarine canyons*. The *channels and ridges* sector is located in the central area of the middle slope (Fig. 1), lying at a water depth of between 800 and 1600 m. Up to nine contourite channels have been identified in this sector. The *Cadiz Contourite Channel* is the largest and the most important of these (Fig. 2), having a total length of approximately 150 km, a width of 2-12 km (average 6 km), and a maximum depth of incision of ~120m. It is broadly s-shaped in plan view with an orientation that varies from SE-NW to NE-SW.

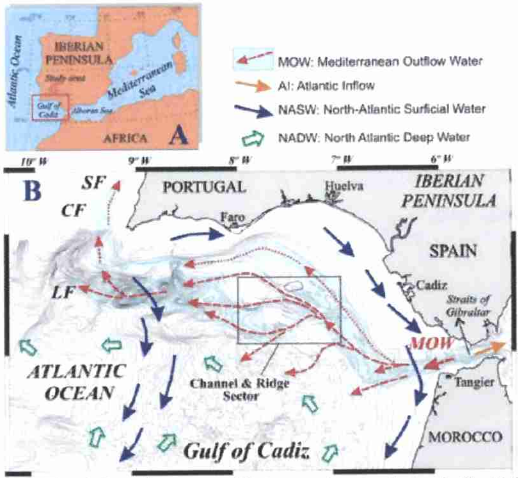

FIGURA 1. Location map and bottom water circulation in the Gulf of Cadiz. Channel and ridge Sector is showed in the middle slope.

Examination of bottom photographs is one of the principal methods by which we can determine the nature of processes operating at the present day in deepwater environments. Despite much intensive research in the Gulf of Cadiz, relatively few papers present some scattered documentation of its seafloor characteristics through photographic evidence (Melieres et al., 1970; Stow et al 2002; Hernandez-Molina et al 2006). In this contribution, therefore, we: (1) present new photographic data from the Cadiz Contourite Channel and adjacent channel segments; (2) consider these data, together with previously published work, in terms of bottom current velocity; and (3) document evidence for the influence of a tidal component operating in the deepwater Cadiz Channel. Present work was carried out by over 3000 submarine photographs, using Ecktacrome (125 ASA) and Kodak Tri-X film, taken with a BENTHOS-372 camera during the ANASTASYA-2001/09 cruise onboard the RV Cornide de Saavedra. Five transects were completed, two from mud volcanoes (L1 & L3) along the Guadalquivir diapiric ridge, and three from the Cadiz Contourite Channel (L2, L4 & L5) (Fig. 2). Transect (L1) crossed the flank of the Cornide mud volcano and part of a contourite spillover channel lying sub-parallel to the main channel. Analysis of the photographs involved systematically recording data on seafloor composition and estimated grain size, sedimentary bedforms, seafloor biota, and current vane orientation. The body of the compass is known to be 7 cm in diameter and the current vane 25cm in length. Where visible, these have been used to calibrate the photographs as well as to obtain directional data.

CADIZ CHANNEL FLOOR BEDFORMS CHARACTERISTICS

A wide range of current-induced bedforms are common in photographs from the medial-distal channel location (L2 & L5), as well as from the spillover channel (L1), indicating their formation at widely differing flow velocities (Fig. 3). The lowest energy bedforms include surface lineation, very small (1-3 cm wavelength) and small (3-4 cm wavelength) *straight-crested ripples*. Moderate energy bedforms are the most commonly observed, ranging from *straight to sinuous-crested ripples* (wavelength 7-8 cm), with distinct *linguoid ripples* (wavelength 7-10 cm) less common. The highest energy bedforms observed are *large sand waves*, with wavelengths of around 3.5- 5 m and trough to crest heights of 0.3-0.9 m. These sand waves are particularly evident in the spillover channel, where they generally show superimposed smaller-scale ripples. Within the main Cadiz Channel, only two sand waves have been partially captured in bottom photographs.

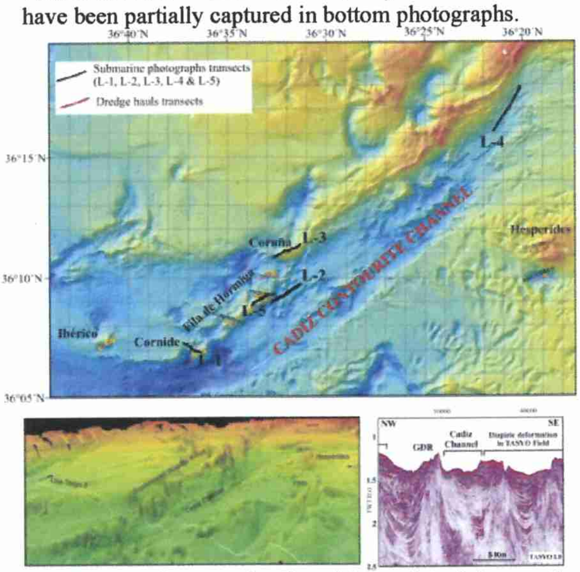

FIGURA 2. Cadiz Contourite Channel image derived from swath bathymetric data, showing location of bottom photograph transects (red), and drag sampling (purple). This map was obtained using the Simrad EM12S-120 system during the TASYO-2000 cruise.

Where the substrate is still coarser grained, *alignment of gravel clasts* is also commonly observed. Finer gravel (and up to small cobble size) occurs in linear *stringers*, from 50 cm to at least 2 m in length. Size sorting in these stringers is extremely poor, and the orientation of elongate clasts is mostly transverse to flow direction (Fig. 3). However, parallel-orientated elongate clasts are also noted in places. Stringers mainly occur approximately perpendicular to ripple crestlines, where these are visible in the same frame. *Obstacle scour* and *tail marks* are visible around the larger boulders, and the tails may extend into gravel stringers. Somewhat irregular, linear *furrows* (~ 5 cm wide) are visible in very few frames from the proximal channel location only (transect L4).

BOTTOM CURRENT AND TIDAL DATA

Regarding to the directional data, bottom current flow direction can be determined from the variety of bedforms and clast alignments described above, and this can be given a specific orientation when the suspended compass is in view in the same frame.

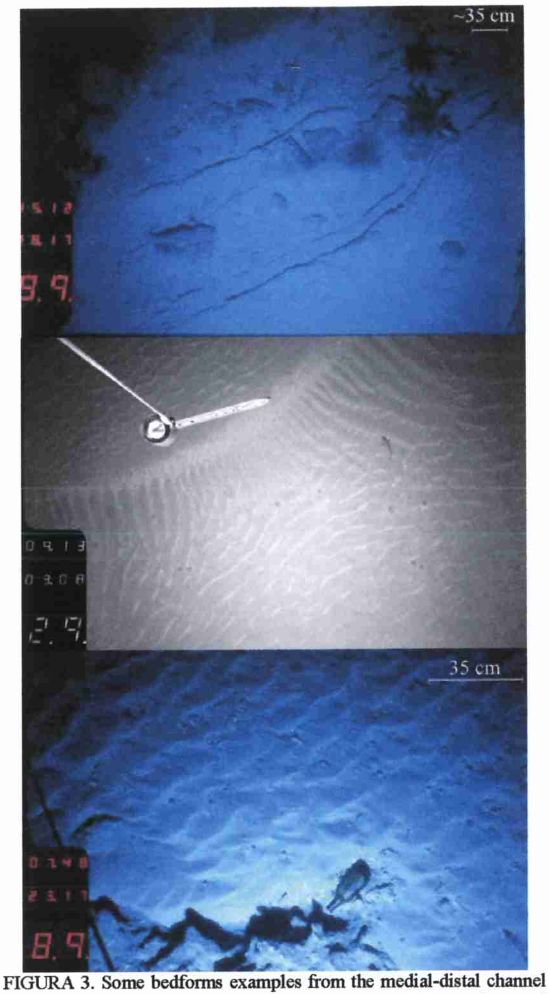

FIGURA 3. Some bedforms examples from the medial-distal channel location: a) linear *furrows* (top); b) *sand waves* with superimposed smaller-scale ripples; and c) linear to sinuous asymmetrical ripples (bottom). Here one notably recent clast (a beer bottle) was observed with a clear transverse to flow orientation.

Data from over 100 measurements made on photographs from Cadiz Channel (L2 & L5) and from over 230 measurements from spillover channel (L1) are show in Fig. 4. For the main Cadiz Channel, there is a dominant preferred flow direction towards the SW quadrant, with some scatter observed from due south to due west. Clearly, this flow direction would have been anticipated on the basis of the SW orientation of the Cadiz Channel and the well documented flow of the Southern Branch of the MOW Lower water mass along this segment of channel. For the spillover channel segment, there is an even tighter spread of measurements around a preferred flow direction due west, with close correspondence between ripple and sand wave orientation. Surface lineations also line up with an east-west trend. Interference ripple patterns are not uncommon in parts of the spillover channel, but much more rarely observed in photographs from the main channel. In each case, these show one principal orientation formed by flow towards the W or SW, and one secondary pattern indicating flow more or less at right angles to this direction or partly reversed.

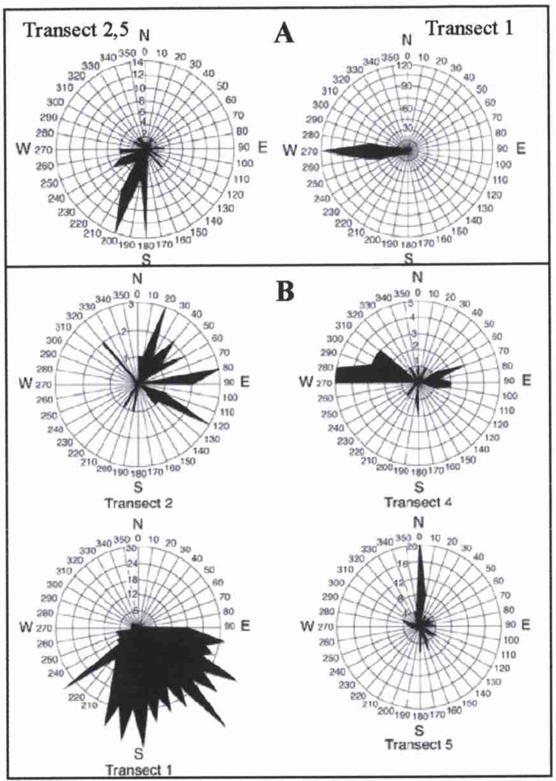

FIGURE 4. A) Bottom current directions as inferred from bedform measurement for Transects L2 and L5 (total of 105 readings); and Transect L1 (total of 234 readings). B) Bottom current directions inferred from current vane orientation.

With such clear directional data for the inferred depositing current, as derived from bedform orientation, the independent measurement of current flow directions, based on current vane orientations, is somewhat surprising Fig. 4. The current directions obtained from 126 different photographs in the main channel (L2, L4 & L5), and over 500 measurements in the spillover channel (L1) are very different and varied. In the main channel, therefore, the indications were of a relatively weak and variable current, although somewhat stronger and more unidirectional during the running of transect 5. For neither transect 2 nor 5 were the flow directions derived from the current vane coincident with flow directions inferred from channel floor bedforms. Nor were they to have been expected from what we know of the generally westward directed MOW currents. The large number of measurements from transect 1 on the flank of Cornide diapir and in the spillover channel show preferred flow directed towards the southeastern quadrant, but with marked scatter from due east to southwest. Here too the indications are for a somewhat weak and variable current with a significantly different flow orientation, both to that derived from bedform observation in the channel and to that expected from previous and extensive MOW measurements.

Because of the apparent discrepancy of current vane orientation with both bottom bedform indications and known MOW flow direction, we consider here the relevant information on tides in the Gulf of Cadiz at the times the photographic transects were run. Data from the Admiralty Tide Tables (2001) for the Port of Cadiz on 16th and 17th September 2001 is shown in Figure 5, together with the duration of photographic transects.

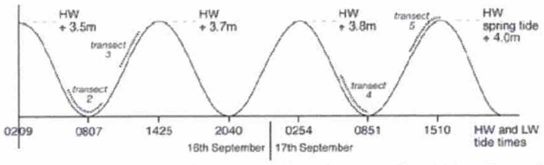

FIGURE 5. Tidal data for 16th and 17th September 2001 (Port of Cadiz). Duration of each photographic transect 2, 3 and 5 is indicated.

DISCUSSION AND CONCLUSIONS

Previous efforts to determine bottom current velocity for various parts of the MOW in the Gulf of Cadiz have been synthesised by Hernandez-Molina et al (2006). Whereas the overall velocity shows a marked decrease from >2 m s^{-1} in the Gibraltar Gateway to around 0.1-0.15 m s^{-1} south of Cape St. Vincent, there is much variation even within the same sector. Estimates for the *channels and ridges* sector, including the Cadiz Channel, are typically in the range 0.2 to 0.8 m s^{-1}. However, we suggest that much of the variation reflects true variability of bottom current velocity. Using the velocity versus bedform matrix for bottom currents, recently proposed by Stow et al (*in press*), we estimate a range of current velocities mainly between 0.2 and 0.8 m s^{-1}. This agrees well with previous data, but also, because the photographs reveal actual current bedforms, it is possible to confirm their formation under low velocity flows (0.2 m s^{-1} for small *straight-crested ripples*), moderate velocities (0.3-0.5 m s^{-1} for *linguoid ripples*), as well as higher velocity episodes (up to at least 0.8 m s^{-1} for *sand waves*). Movement of some of the larger gravel clasts into linear trains would require velocities at the higher end of this spectrum (> 0.8 m s^{-1}), whereas evidence also exists for smooth sediment surfaces, some with lineation marks, indicating velocities <0.15 m s^{-1}. All of these bedforms co-exist within the same relatively small sector of the channel, and in some cases in the same field of view. There is no doubt, therefore, that bottom current velocity within the channel has varied considerably in a short space of time. Furthermore, the current vane data indicates that periodic slack water and reverse flows also occur. The bottom photographs presented herein provide a demonstration of the influence of tides in deep water, especially where there are channels to focus their effects. However, to our knowledge, there have been no previous direct observations reported in the literature of the effects of tides on contourite channel systems. Evidence from the Cadiz Channel and its associated spillover channel clearly shows current vane orientation responding to an up-channel, flood tidal current at a time close to the spring tide maximum, and relatively little current movement in any preferred sense during the slack low tidal period. Furthermore, some photographs show clouds of suspended sediment, presumably due to the bottom photographic assembly hitting the seafloor, moving up-channel with the flood tide. Others show interference ripples in which the weaker secondary ripple set may have been caused by tidal currents. However, there is no doubt that the dominant and strongest current influence, as evidenced by almost all bedforms observed in the photographs, is that of the down-channel directed MOW bottom current. Maximum current velocities, leading to the development of sand waves and gravel stringers, seems likely to be achieved by spring ebb tides reinforcing the normal MOW flow. The more normal current velocities, and generation of the range of ripple types most common on the channel floor, are due to normal MOW flow and normal ebb tidal conditions.

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