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Role of internal waves in the generation of nepheloid layers on the northwestern Alboran slope: Implications for continental margin shaping

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[1] The role of internal waves in the sediment dynamics of the northwestern Alboran continental slope was investigated in a selected area around the Guadiaro submarine canyon. Nepheloid layer distribution was identified using closely spaced CTD/transmissometer profiles collected during two hydrographic surveys. A well-defined pattern of suspended sediment distribution consisting of surface, intermediate, and near-bottom nepheloid layers was found. Intermediate and bottom nepheloid layers were always observed within the canyon and on the adjacent continental slope, spanning mainly from 200 to 500 m depth. In addition, a current meter with a turbidimeter was deployed in the lower section of the Guadiaro Canyon at 600 m depth, 25 meters above the seafloor. Time series analysis indicated that the currents, temperature, and turbidity within the canyon fluctuate mainly at semidiurnal tidal frequencies, suggesting the presence of semidiurnal internal tides affecting the near-bottom suspended sediment concentration along the canyon axis. High-resolution bathymetry from the study area was used to evaluate the internal wave reflection conditions at semidiurnal tidal frequency for the entire continental slope region. Critical slope conditions were reached on the upper continental slope and along the canyon axis, coinciding with the region in which nepheloid layers were observed. This region also coincides with a zone of erosion on the upper continental slope of the study area previously identified by *Hernández-Molina* [1993]. These results indicate that the generation of intermediate and bottom nepheloid layers, as well as the erosion and shaping of the northwestern Alborán continental slope, may result from the interaction of internal waves and the seafloor morphology.

INDEX TERMS: 3022 Marine Geology and Geophysics: Marine sediments—processes and transport; 3045 Marine Geology and Geophysics: Seafloor morphology and bottom photography; 4544 Oceanography: Physical: Internal and inertial waves; 4558 Oceanography: Physical: Sediment transport; *KEYWORDS:* internal waves, nepheloid layers, continental slope

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1. Introduction

[2] Nepheloid layers are present on the continental margins of the oceans worldwide, and these turbid layers carrying high concentrations of suspended particles are considered very important to the transport of matter and energy [*Eisma*, 1993]. Several studies of particulate matter dispersal on continental margins have noted bottom and intermediate nepheloid layers on the shelf and upper continental slope [e.g., *Pak et al.*, 1980; *Dickson and McCave*, 1986; *Puig and Palanques*, 1998; *Walsh and Nittrouer*, 1999; *Durrieu de Madron et al.*, 1999] and within submarine canyons [e.g., *Drake and Gorsline*, 1973; *Gardner*, 1989a; *Durrieu de Madron*, 1994].

[3] There are various causes for the formation of nepheloid layers in the different oceans of the world [*McCave*, 1986], although, on continental margins, internal waves have been postulated as one of the major mechanisms contributing to their formation and maintenance. *Cacchione and Southard* [1974] suggested that bottom shear stresses generated by internal waves could be large enough to resuspend sediment over continental shelf and slope regions, as bottom intensified flows associated with internal waves can occur where the slope of the topography is similar to that of the internal wave characteristics. Under these conditions, known as critical reflection, the internal wave energy is concentrated in a near-bottom band and boundary layer instabilities are generated, leading to the development of vortices or mixing cells that may explain the generation and maintenance of bottom nepheloid zones observed over certain continental shelves and slopes [*Cacchione and Drake*, 1986].

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[4] While the potential of internal waves in resuspending sediment or maintaining particles in suspension has been demonstrated or implied in many studies [e.g., *Hotchkiss and Wunsch*, 1982; *Gardner*, 1989b; *Palanques and Biscaye*, 1992; *Bogucki et al.*, 1997, *DeSilva et al.*, 1997; *Puig et al.*, 2001; *McPhee-Shaw and Kunze*, 2002], it is difficult to observe these phenomena directly and to evaluate their contribution to the sediment dynamics. To progress in the understanding of this mechanism, numerical models have begun to be used to improve assessment of sediment resuspension and transport by internal waves [e.g., *Ribbe and Holloway*, 2001].

[5] Recently, *Cacchione et al.* [2002] demonstrated that bottom shear velocities caused by semidiurnal internal tides on the northern California continental slope were high enough to inhibit deposition of fine-grained sediment, and that erosion of bottom sediment might also occur. In a more general view, these authors stated that this situation could be reached on many continental slopes and that the angles of energy propagation of semidiurnal internal tides may determine over time the average gradient of continental slopes in ocean basins (~2 to 4 degrees), which are an order of magnitude lower than the internal angle of repose of marine mud. Following these hypotheses, this paper analyzes the role of internal waves in the generation of intermediate and bottom nepheloid layers within and around the Guadiaro submarine canyon, and provides evidence that this mechanism could have also contributed to the shaping of the northwestern Alboran continental slope.

2. Regional Background

[6] The Guadiaro submarine canyon is located in the northwestern Alboran Sea, close to the Strait of Gibraltar (Figure 1). The circulation and water masses of this region are coupled to the exchange through the Strait of Gibraltar caused by the excess of evaporation over precipitation and river runoff in the Mediterranean. This deficit produces a thermohaline circulation that can be summarized as Atlantic water ($S < 37$) flowing at the surface of the strait into the Alboran Sea, and saltier and denser Mediterranean water ($S > 38$) flowing at depth toward the Atlantic [*Perkins et al.*, 1990].

[7] The oceanographic characteristics of the study area are influenced by the Atlantic Jet (AJ) that enters the Alboran Sea through the Strait of Gibraltar. The AJ maintains a density front in the northwestern Alboran Sea, separating new Atlantic Water (AW) to the south from waters of Mediterranean origin to the north [*García Lafuente et al.*, 1998; *Viúdez et al.*, 1998]. For practical purposes the limit between these two waters has been established by many authors as the $S = 37.5$ isohaline. This density front extends from the surface to nearly 150 m, reaching greater depths (~200 m) in the center of the western Alboran basin. Between 200 and 600 m depth, the water column is occupied by Levantine Intermediate Water (LIW), which can be clearly distinguished by temperature and salinity maxima, and below it, the basin is filled with Western Mediterranean Deep Water (WMDW), which is characterized by a decrease in potential temperature and salinity with depth [*Gascard and Richez*, 1985; *Parrila et al.*, 1986].

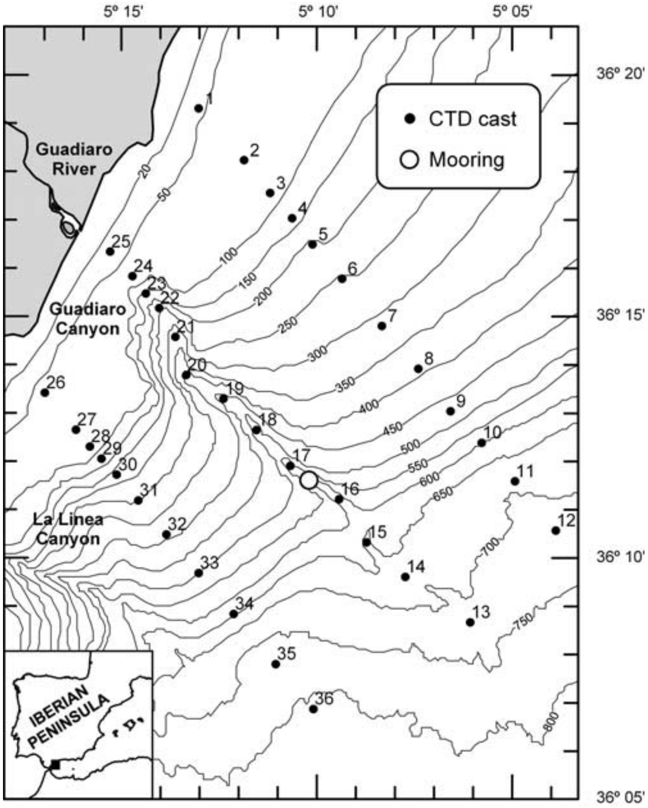


Figure 1. Bathymetric map of the Guadiaro submarine canyon showing the distribution of the three hydrographic transects of CTD/transmissometer profiles (solid circles) conducted in May and October 1998, and the location of the moored current meter (open circle) deployed within the canyon at 600 m depth, 25 m above the seafloor.

[8] Currents in the study area are dominated by a strong semidiurnal tidal component (M2) oriented along the coast (16.1 cm/s and 9.9 cm/s for the major and minor axis), while the inertial currents are very small [*Alvarez Fanjul et al.*, 2000]. Tidal activity in the Alboran Sea is restricted to the westernmost area, forced mainly by the Atlantic tide through the Strait of Gibraltar, with the free tide being negligible. The tidal currents in the Strait of Gibraltar are basically barotropic, but the interaction with the topography distorts the pattern, causing a relatively large baroclinic or internal tide [*García Lafuente and Cano Lucaya*, 1994].

[9] The behavior of the barotropic and baroclinic tide on the northwestern Alboran continental margin was previously studied on the shelf and upper continental slope [*García Lafuente and Cano Lucaya*, 1994] and inside the Guadiaro [*Vargas-Yáñez*, 1998] and La Linea [*García Lafuente et al.*, 1999] submarine canyons. These studies indicated that tidal currents outside submarine canyons and above canyon rims are influenced by barotropic and baroclinic tides of comparable intensity. The barotropic tide is oriented in the along-margin direction, whereas the baroclinic tide, which is out of phase, is predominantly oriented in the cross-margin direction. Inside canyons, currents are phase-locked with the baroclinic tide observed above canyon rims, and tidal ellipses are oriented along the canyon axis. Near-bottom tidal currents reach maximum values of ~30 cm/s at 390-m

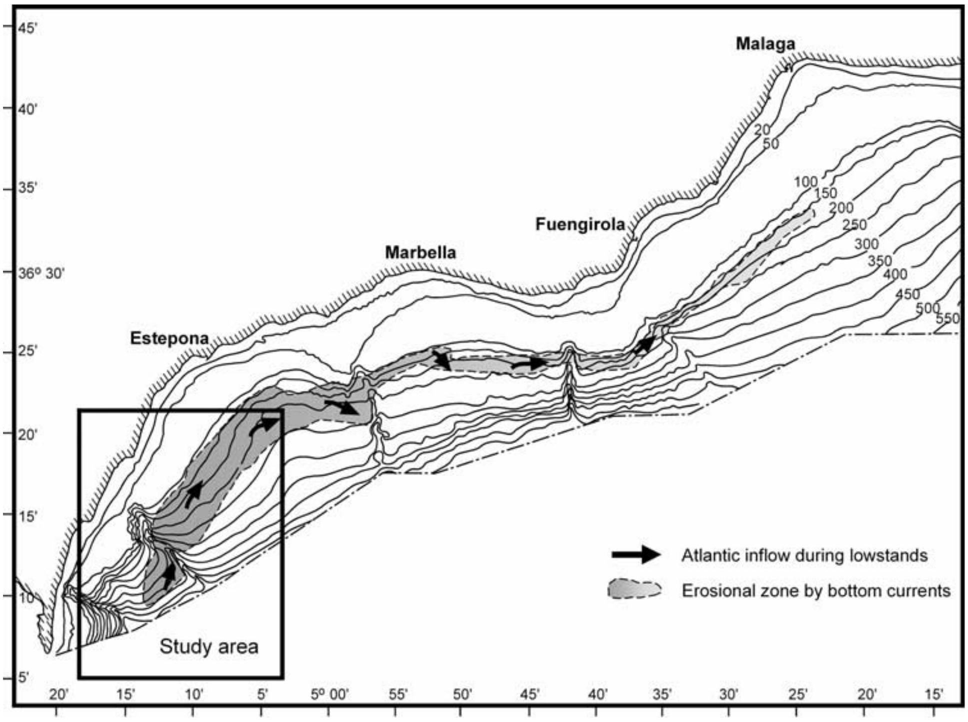


Figure 2. Map of the erosional zone that extends along the northwestern Alboran continental slope [after *Hernandez-Molina*, 1993].

water depth inside the Guadiaro Canyon [*Vargas-Yáñez*, 1998], and of ~60 cm/s and ~40 cm/s at 190- and 390-m water depth, respectively, inside La Linea Canyon [*García Lafuente et al.*, 1999].

[10] The morphology of the study area is characterized by the presence of the Guadiaro submarine canyon (Figure 1). This canyon has developed a turbidite system fed by sediment supplies from the Guadiaro River, which began its deposition in the early Quaternary [*Ercilla et al.*, 1992; *Pérez-Belzuz*, 1999; *Alonso and Ercilla*, 2003]. Toward the west, La Linea Canyon also incises the slope, developing a smaller depositional system.

[11] The continental shelf in the study area is quite narrow (~4 km), and the shelf-break is located at around 90-m water depth, being shallower (~70 m) around the head of the Guadiaro Canyon. The continental slope is also narrow (~10 km), and the base-of-slope starts at 600-m water depth. The Guadiaro Canyon has an average relief (i.e., from the canyon axis to its rims) of ~100 m and is up to ~1 km wide, displaying a relatively straight pathway. At the base-of-slope the canyon evolves to a 7-km-long leveed channel that extends down to 750-m water depth, where a turbidite lobe deposit develops. The axial gradient along the Guadiaro Canyon decreases from 7° at the canyon head to 2° at the canyon mouth, reaching 0.8° at the distal part of the Guadiaro Channel [*Alonso and Ercilla*, 2003].

[12] The adjacent continental slope (at both sides of the canyon) is characterized by an erosional region that extends along the upper slope and becomes narrower and shallower toward the east [*Hernandez-Molina*, 1993]. This erosion zone was identified using the spatial distribution of textural and grain size analysis of surface sediment and the echo-character of seismic profiles, and was attributed to the winnowing of fine particles by bottom currents, associated with the inflow of Atlantic waters during lowstands of sea level (Figure 2).

3. Methods

3.1. Hydrography

[13] Two oceanographic cruises were conducted on the northwestern Alborán continental margin in May and October 1998 on board the García del Cid oceanographic vessel, both during spring tide. On each of these cruises, 36 vertical profiles divided into three hydrographic transects were collected using a CTD Neil Brown Mark III coupled with a Sea Tech 25-cm path length transmissometer. One transect was performed along the Guadiaro Canyon axis and the other two on the adjacent northern and southern open continental slope (Figure 1). The cruises were carried out within 4 days in order to obtain a quasi-synoptic picture of the hydrographic and nepheloid structures.

[14] Water samples were taken in selected casts near the bottom, at the surface, and in intermediate waters by means of 5-L Niskin bottles mounted on a General Oceanics CTD rosette sampler. Samples were filtered through 47-mm-diameter and 0.45-μm-pore preweighed Nucleopore polycarbonate filters to determine their suspended sediment concentration (SSC). The transmissometer values were converted to beam attenuation coefficient (BAC) and were correlated by means of least squares linear regression with SSC obtained from filtered water samples for transmissometer data calibration ($R^2 = 0.97$, n = 113). The CTD profiles were averaged every meter, and cross-margin contour transects were created. The same stations and transects were performed for both cruises in order to identify the

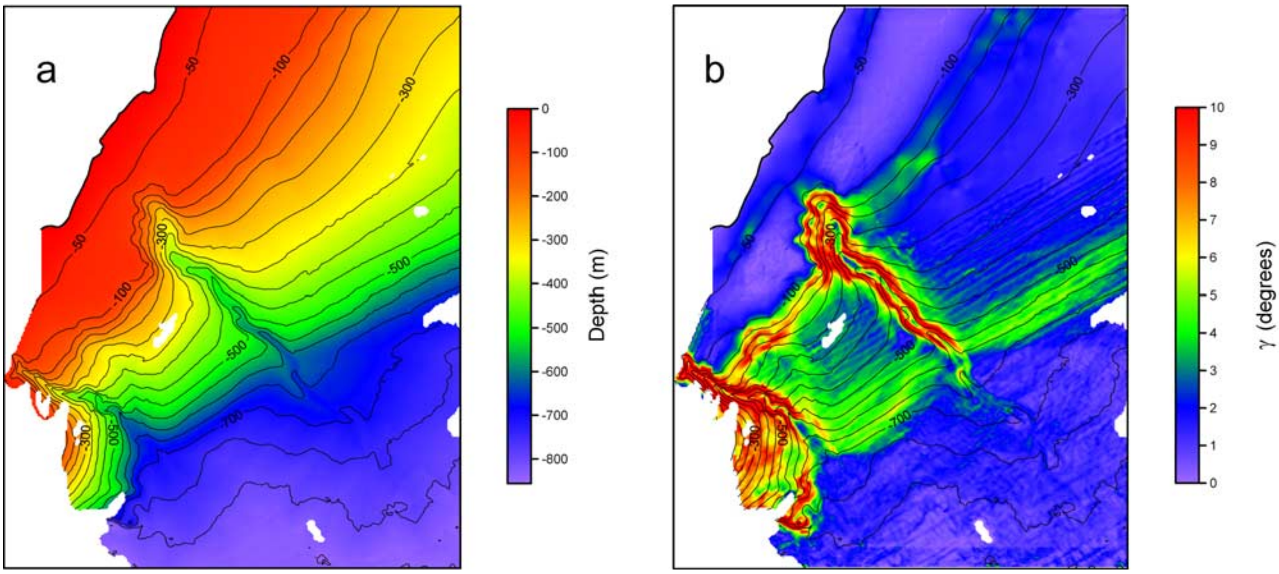


Figure 3. Maps of the (a) high-resolution bathymetry and (b) associated slope gradients (γ) of the study area. The alignments parallel to the isobaths correspond to artifacts caused by the superposition of the swath bathymetry tracks.

main hydrographic features and the temporal and spatial particulate matter variability.

3.2. Hydrodynamics

[15] An Aanderaa RCM9 current meter coupled with turbidity, temperature, conductivity, and pressure sensors was deployed in the lower section of the Guadiaro Canyon at 600 m depth, 25 m above the seafloor (Figure 1). This deployment was carried out between the two hydrographic cruises, and the current meter recorded good data from 17 May to 13 September 1998, when biofouling started disturbing the turbidity signal. Data from 7 to 10 July 1998 were not recorded correctly, and were therefore removed from the time series. The current meter sampling frequency for this study was set at 30 min.

[16] The Aanderaa RCM9 current meter uses a Doppler current sensor with four piezoceramic acoustic transducers placed 90° apart, which transmits 600 acoustic pulses of 2 MHz distributed over the entire measuring interval. The temperature sensor uses a thermistor with an accuracy of ±0.05°C, and the conductivity sensor uses an inductive cell made of two toroids with an accuracy of ±2% of selected range (0–74 mS/cm). The turbidimeter coupled to the RCM9 current meter is an optical backscatter sensor that uses infrared light (880 nm wavelength) and has an angle of measured diffused radiation of 30°. This sensor is calibrated with Formazine Turbidity units (FTU) and has a 0.1% resolution and a 2% accuracy of full scale (0–20 FTU). FTU can be easily converted into SSC using a simple regression equation, and this relationship was calculated for the study area using gravimetric measurements [see *Guillén et al.* [2000] for further details) and used to calibrate the turbidity record.

3.3. Riverine and Oceanographic Conditions

[17] The Guadiaro River water discharge during the study period was facilitated by the "Confederación Hidrográfica del Sur" and measured daily at the gauging station from San Pablo de Buceite, located ~25 km upstream of the river mouth. Wave conditions were provided by "Puertos del Estado" and recorded hourly by a hydrographical buoy located in 585-m water depth (36°13.8′N 5°1.8′W) about 16 km east of the Guadiaro Canyon.

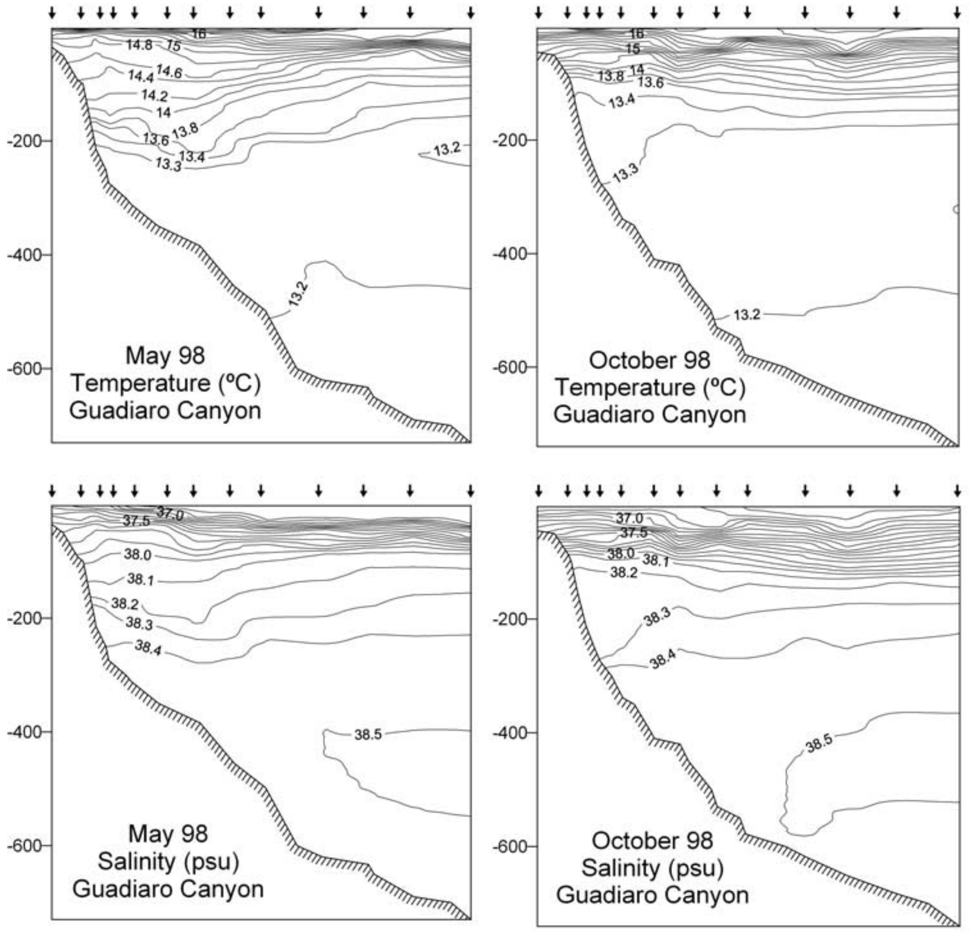
3.4. Seabed Morphology

[18] A bathymetric survey using a Simrad EM-12 S120 multibeam echosounder installed on board the R/V *Hesperides* was conducted in the western Alboran Sea in 1992 as part of the Alba-92 cruise (see *Alonso and Ercilla* [2003] for further details). This multibeam echo sounder uses a frequency of 12 kHz, has an aperture angle of 120°, and provides 81 values of bathymetry across the ship track, covering a sector of the seafloor approximately 3 times the water depth. These data were recorded and processed with a wrong sound velocity correction for surface waters, which slightly distorted the outermost soundings and caused artifacts in the areas where the swath bathymetry tracks overlie.

[19] Data from the Alba-92 survey included a bathymetric mosaic from the lower continental slope of the Guadiaro Canyon region that has been used in this study. Additionally, a high-resolution bathymetry of the Guadiaro continental shelf and upper continental slope was obtained from the "Instituto Hidrogáfico de la Marina" [*Hernández-Molina*, 1993]. Both bathymetric data sets were merged in a 100 × 100 m grid, and detailed maps of bathymetry and slope gradients of the study area were created (Figure 3).

4. Results

[20] The salinity and temperature distribution across the hydrographic transects allow identification of the main water masses of the study area. A surface layer corresponding to waters of Atlantic origin occupies the upper 150–200 m; LIW is found between 200 and 600 m, with the high-salinity core located between 400 and 600 m


May 98
Temperature (ºC)
Guadiaro Canyon

October 98
Temperature (ºC)
Guadiaro Canyon

May 98
Salinity (psu)
Guadiaro Canyon

October 98
Salinity (psu)
Guadiaro Canyon

Figure 4. Salinity and temperature distribution during May and October 1998 obtained from the hydrographic transect along the Guadiario submarine canyon axis. Arrows indicate the position of the CTD/transmissometer profiles.

and slightly separated from the seabed, and below it WMDW fills the deeper parts of the study area (Figure 4).

[21] Suspended particles in the water column are distributed in nepheloid layers in surface, intermediate, and near-bottom waters, showing a similar nepheloid distribution and similar concentrations in both surveys (Figure 5). The surface nepheloid layer is usually more developed near the coast and shows a seaward continuity associated with waters of Atlantic origin. Near the bottom, a well-developed nepheloid layer, which is usually >100 m thick and has maximum concentrations of ~0.6 mg/L, extends from the shelf and upper slope down to the deep-slope region (500–600 m). This nepheloid layer is not restricted to regions of density gradients between different water masses and tends to develop mainly at water depths occupied by LIW (Figures 4 and 5). The upper slope region also exhibits several intermediate nepheloid layer detachments, mainly concentrated at the shelf-break and around 300 m depth. These detachments are more developed along the Guadiaro submarine canyon, although suspended sediment concentration (SSC) inside and outside the canyon is similar. In deep waters (i.e., below 600-m water depth) the suspended sediment profiles lacked any significant nepheloid structure, showing a near-bottom SSC lower than 0.1 mg/L.

[22] Time series of surface wave conditions recorded by the hydrographic buoy, along with water temperature, current components, and SSC recorded in the Guadiaro submarine canyon at 600 m depth, 25 m above the seafloor, are illustrated in Figure 6. The Guadiaro River discharge during the study period (not shown) was quite constant and below 10 m^3/s, corresponding with the dry season (the flood period usually occurs during wintertime). Several weak storms occurred during the study period, which showed a periodicity of approximately 6 days related to either dominantly easterly or westerly winds and associated with the passage of atmospheric pressure cells. Significant wave heights during storms were usually below 1 m, and occasionally reached 1.5 m (Figure 6a), while significant wave periods (not shown) were ~6 s.

[23] Near-bottom temperature at the mooring site during the study period ranged from 13.02° to 13.23°C and oscillated at semidiurnal tidal frequencies, with fluctuations of approximately 0.1°C that were clearly noticeable despite being at the limit of the measurement error of the temperature sensor. Longer temperature oscillations were also observed in the record, with a periodicity of ~28 days, probably corresponding to spring and neap tidal cycles (Figure 6b).

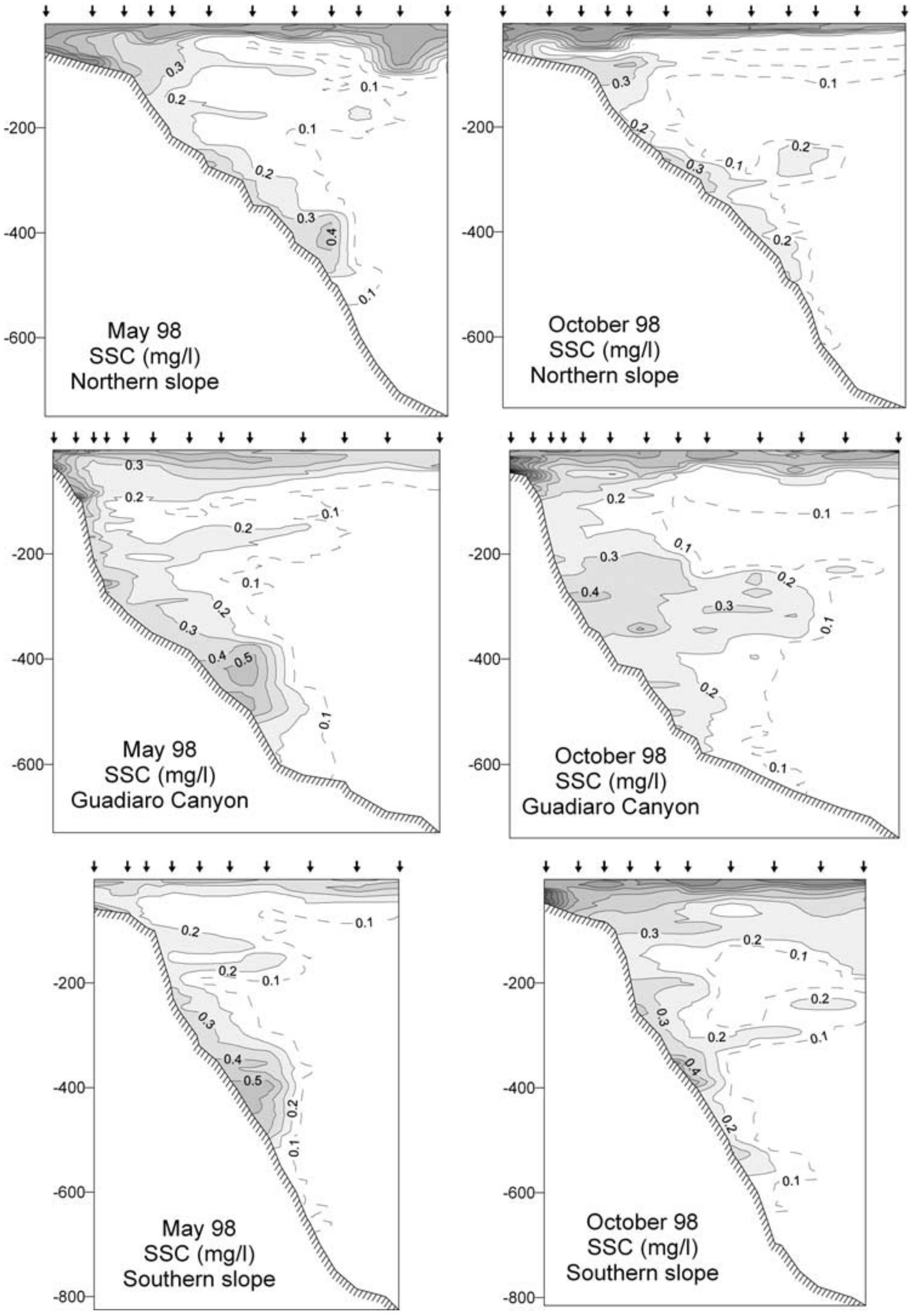


Figure 5. Suspended sediment concentration (SSC) distribution along the Guadiaro submarine canyon and adjacent continental slope during the hydrographic surveys conducted in May and October 1998. Note the detachments of intermediate nepheloid layers in the upper slope region and the development of a bottom nepheloid layer extending mainly from 200 to 500 m depth. Arrows indicate the position of the CTD/transmissometer profiles.

[24] Currents also fluctuated at semidiurnal tidal frequencies, although variations in their intensity were not clearly affected by spring-neap tidal cycles and were not related to temperature oscillations (Figures 6c and 6d). Current velocities at 25 mab sporadically reached peaks of 28 cm/s, although during regular tidal cycles maximum velocities were ~20 cm/s. Currents were not preferentially oriented along the canyon axis, probably due to the small relief of the canyon walls at the mooring site (70 m). The average cross- and along-canyon components of the current velocity were 1.04 cm/s directed toward the northeast and 0.56 cm/s directed up-canyon, respectively, representing an almost null net water displacement.

[25] Periodic fluctuation of near-bottom SSC within the canyon also occurred at semidiurnal tidal frequencies and oscillated between baseline values of 0.28 mg/L and max-

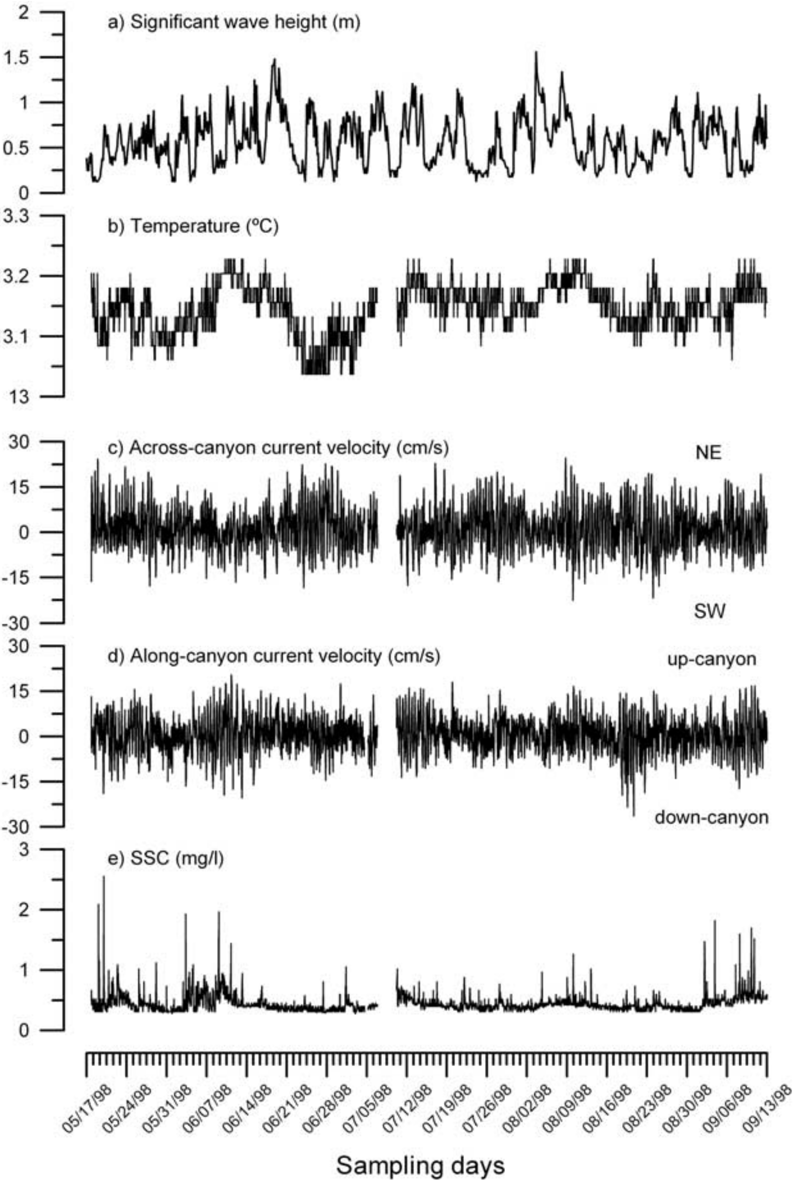


Figure 6. Time series of surface wave conditions along with water temperature, current components, and water turbidity recorded in the Guadiaro submarine canyon at 600 m depth, 25 m above the seafloor.

imum values of ~1 mg/L, although sporadically SSC reached peaks higher than 2 mg/L (Figure 6e). Increases in both baseline and peak values of SSC were not associated with storm events or periods of intense along-canyon current velocities. During most of the record, SSC fluctuations were very close to the baseline values without showing a general trend, but when SSC was higher, peaks of SSC coincided with increases in temperature and with down-canyon current velocities (Figure 7a), although sharp peaks of SSC (>1 mg/L) occurred occasionally when the currents suddenly changed from down-canyon to up-canyon direction (Figure 7b).

5. Discussion

[26] The results of this study reveal that in summertime near-bottom SSC at 600 m depth within the Guadiaro Canyon is not directly affected by the occurrence of storms that could cause sediment resuspension on the shelf and favor transport of suspended particles down-canyon. Rather, when near-bottom SSC increases, it fluctuates at semidiurnal tidal frequencies together with along-canyon current oscillations and large (~0.1°C) changes in temperature. Although the cause of these SSC fluctuations could be difficult to determine from the data of a single moored instrument, such a clear relationship suggests the presence of semidiurnal internal tides affecting the near-bottom SSC along the canyon axis.

[27] An integrated study conducted by *Gardner* [1989a, 1989b] in Baltimore Canyon using moored current meters and transmissometers revealed that sediment from the canyon floor was resuspended regularly when energy of internal tides was focused along the canyon axis. Analysis of time series was used to describe a mechanism consisting of a bore of cold water with a turbulent head moving up-canyon that resuspended sediments, resulting in a sharp

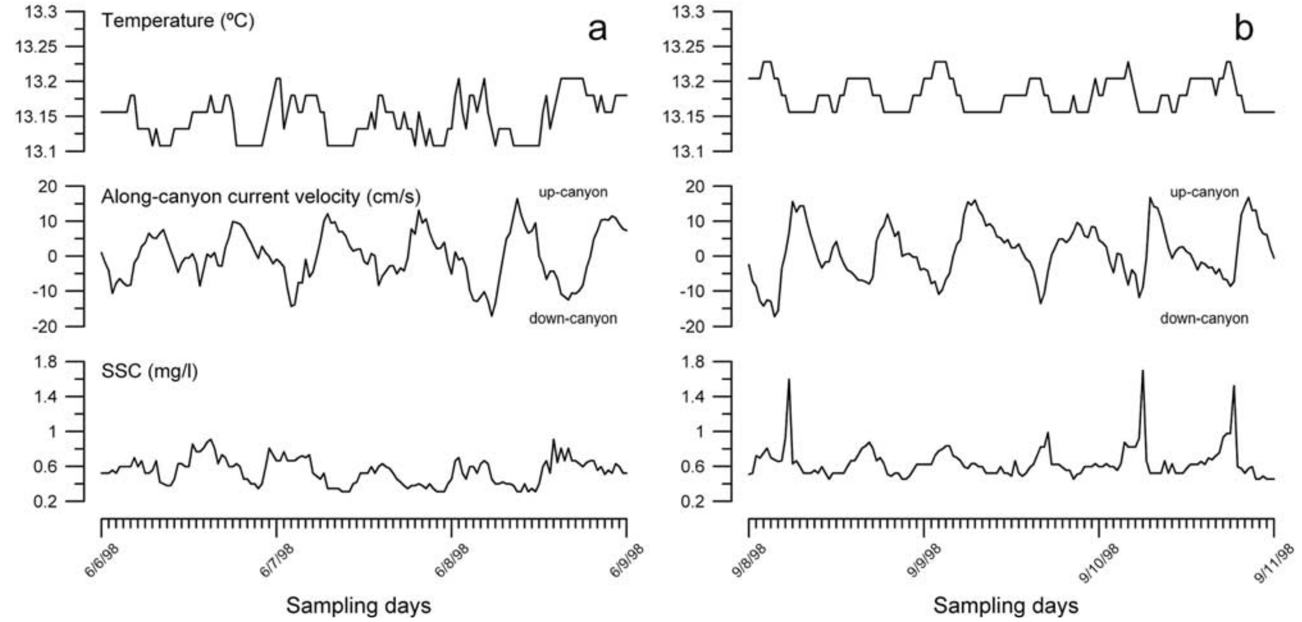


Figure 7. Detail of the temporal evolution of temperature, along-canyon current component, and SSC showing (a) the increases in SSC associated with intensifications of the down-canyon current component and increases in temperature and (b) the sharp peaks of SSC associated with sudden changes from down-canyon to up-canyon current direction.

peak of SSC at the beginning of the event, and as the current reversed and moved down-canyon, a smaller and more continuous increase in SSC was also observed, which corresponded to particles resuspended during the up-canyon surge and potentially to further sediment erosion of the down-canyon flow. This resuspension mechanism allowed Gardner to explain the formation of bottom and intermediate nepheloid layers found in the Baltimore Canyon between 200 and 800 m depth.

[28] The data presented in this study suggest the occurrence of a similar process in Guadiaro Canyon, which could explain the development of the bottom and intermediate

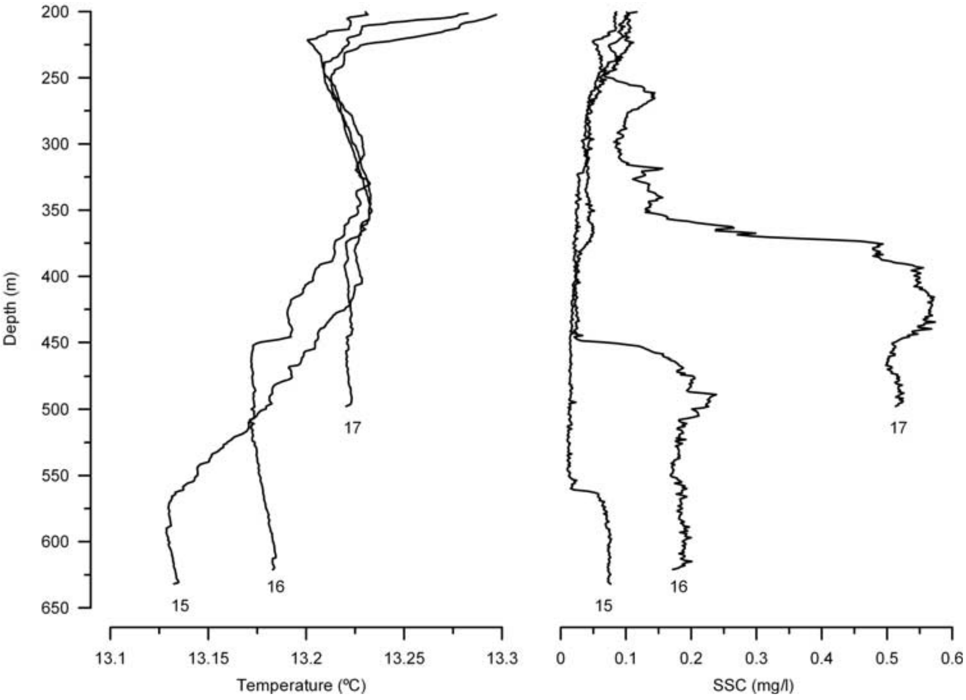


Figure 8. Detail of the vertical profiles of temperature and SSC (from 200 m down to the bottom) from the CTD stations up- and down-canyon of the mooring location. The cast number of each profile corresponds to the numeration used in Figure 1.

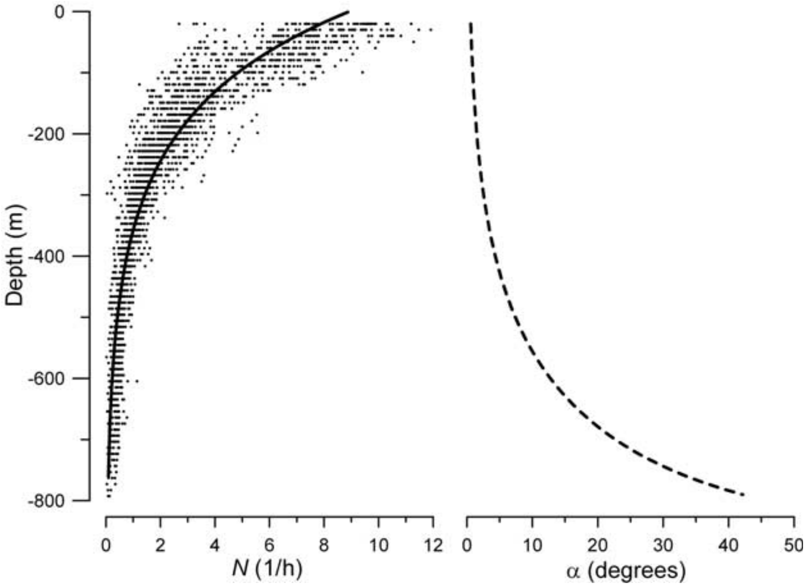


Figure 9. Brunt-Väisälä frequency (N) computed at 10-m intervals from the CTD profiles collected during the May and October 1998 hydrographic surveys. The solid line represents the exponential fit ($R^2 = 0.86$) of all values. The dashed line represents α calculated for the semidiurnal internal tide as a function of the water depth.

nepheloid layers found between 200 and 600 m depth. Unfortunately, the mooring was placed too deep and the sampling interval was too long (30 min) to clearly depict the internal wave resuspension mechanism. However, the sporadic sharp peaks in SSC occurring when current shifted up-canyon might well correspond to internal wave resuspension events, while the SSC fluctuations associated with increases in temperature and with down-canyon current velocities could correspond to the advection of suspended particles previously resuspended by internal waves in shallower regions (Figure 7). The stronger tidal currents measured at shallower locations in Guadiaro Canyon [*Vargas-Yáñez*, 1998] also suggest focusing of internal tide energy along the canyon axis.

[29] The occurrence of such a process is supported by temperature and transmissometer profiles collected within the Guadiaro Canyon during the May cruise, which indicate the presence of a well-developed bottom mixing layer around the mooring location. This layer was 70, 170, and 125 m thick at stations 15, 16, and 17, respectively, and scaled in thickness with the bottom nepheloid layer (Figure 8). The development of this thick mixing layer can be explained by the presence of internal waves within the canyon, which can generate high levels of shear and turbulence and maintain particles in suspension up to 170 m above the seafloor. During the October cruise the bottom mixing region and associated nepheloid layer within the canyon was less developed, although several intermediate nepheloid layer detachments were observed at various depths.

[30] Nepheloid layers in the study area are not restricted to the canyon axis region. The development of a well-defined bottom nepheloid layer on the adjacent open slope from 200 to 500 m depth and the detachments of intermediate nepheloid layers at ~300 m depth suggest that the effect of internal tides on the generation and maintenance of enhanced near-bottom SSC can affect the entire continental slope. Intermediate nepheloid layer detachments were also observed around the shelf break, although they were presumably related to the advection of sediment particles resuspended on the shelf by waves and currents.

[31] As stated in section 1, laboratory and numerical studies indicate that over a sloping topography, bottom intensified flows associated with internal waves may occur when the slope of the seabed is similar to that of the internal wave group velocity vector, and that these intensified flows may well be the dominant process contributing to the enhancement of bottom shear stresses on continental slopes, and therefore, may be important in determining sediment resuspension and transport.

[32] To test whether the bottom nepheloid layer observed on the continental slope of the study area could be generated by internal wave activity, the angle of the internal wave group velocity vector relative to horizontal (α) can be calculated as

$$\alpha = \arctan\left[\left(\frac{\sigma^2 - f^2}{N^2 - \sigma^2}\right)^{1/2}\right],$$

where σ is the internal wave frequency (M2 for this study), f the local inertial frequency, and N the Brunt-Väisälä or buoyancy frequency. In regions where α is greater than the slope of the seabed, internal tidal energy is transmitted landward as it bounces between the seafloor and the base of the mixed layer (transmissive conditions); in regions where α is lower, the energy is reflected back toward the deep ocean (reflective conditions); and in regions where α is equal to the slope of the seabed, critical reflection is reached and resuspension or inhibition of sedimentation caused by internal waves can be expected.

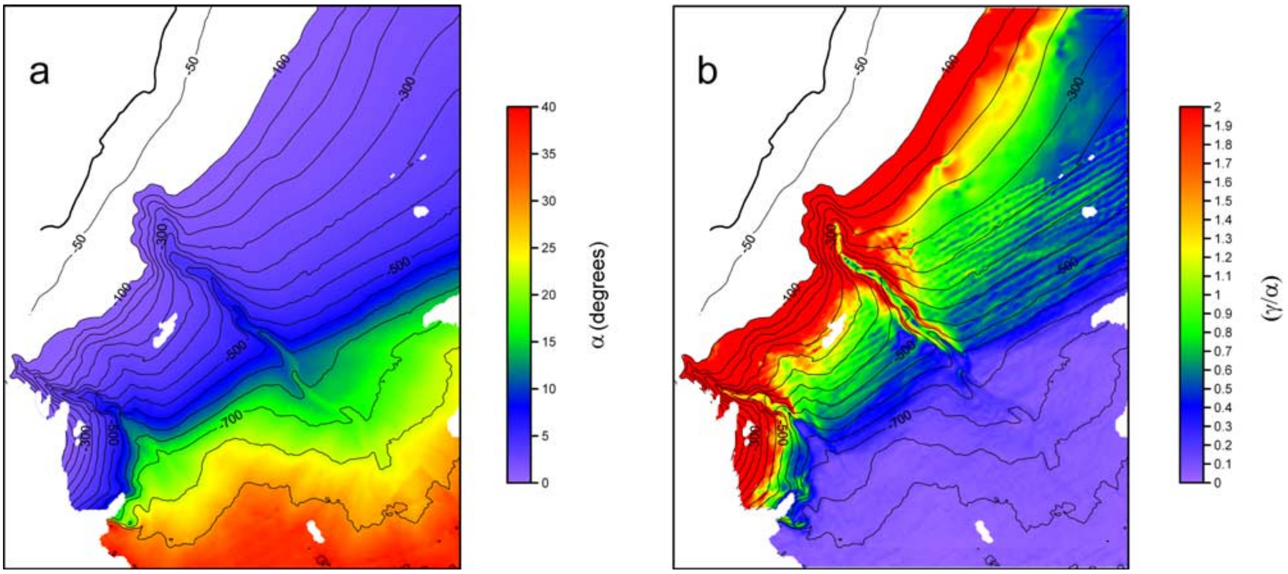


Figure 10. Maps of the (a) angle of the group velocity propagation for the semidiurnal (M2) internal tide relative to horizontal (α) as a function of the water depth and (b) reflection conditions (γ/α) for depths greater than 100 m. Warm colors indicate reflective regions (γ/α > 1), cold colors correspond to transmissive regions (γ/α < 1), and green and yellow colors (γ/α ∼ 1) indicate regions that exhibit critical conditions for semidiurnal internal tide frequencies. The alignments parallel to the isobaths correspond to artifacts caused by the superposition of the swath bathymetry tracks.

[33] Therefore, α was calculated using the exponential fit ($R^2 = 0.86$) of N computed at 10-m intervals from all the CTD profiles collected during the May and October 1998 hydrographic surveys (Figure 9). The vertical distribution of N through the water column makes α increase progressively with depth, showing values lower than 5° at water depths corresponding to the shelf and upper continental slope region. Using the relationship of α versus depth and the bathymetric grid from Figure 3a, a map of the internal tide characteristics can be generated for the study area (Figure 10a). The combination of this grid with the one from the slope of the seabed (Figure 3b) can be used to identify the regions in which the two angles are similar (Figure 10b). Therefore, critical conditions for semidiurnal internal tide (γ/α ∼ 1) extend from 200 to 500 m depth, whereas regions shallower than 200 m exhibit reflective conditions (γ/α > 1) and the base of the slope and the basin have transmissive conditions (γ/α < 1). The Guadiaro canyon axis also exhibits critical conditions, extending down to the canyon mouth region, close to where the mooring was located. Interestingly, regions that have critical conditions for semidiurnal internal tide reflection coincide with the distribution range of the intermediate and bottom nepheloid layers observed in the hydrographic surveys. This concordance indicates that the generation of intermediate and bottom nepheloid layers within the Guadiaro Canyon and the adjacent continental slope may result from the interaction of internal waves and the seafloor morphology.

[34] The critical slope region also coincides with the erosional zone identified by *Hernández-Molina* [1993], which was originally attributed to the winnowing of fine particles by bottom currents associated with the inflow of Atlantic waters during lowstands of sea level (Figure 2). The fact that the observed nepheloid structures are located approximately in the same region indicates that at present particle resuspension can occur on the upper continental slope and suggests that this erosional (i.e., nondepositional) zone can be generated by a contemporary sediment transport mechanism, such as internal waves, rather than by the Atlantic Jet during past ice ages. This hypothesis is reinforced by the concordance between the spatial distribution of the erosional zone, which becomes shallower and less evident toward the east, and the distribution of the intensity of the baroclinic tide, which also becomes less distinctive toward the east until the tidal component in the currents is almost negligible at the Malaga Bight [*García Lafuente and Cano Lucaya*, 1994].

[35] Therefore the results obtained in this study support the hypothesis of *Cacchione et al.* [2002], which suggests that the angles of energy propagation of semidiurnal internal tides, among other factors, may determine the average gradient of continental slopes in ocean basins by preventing deposition of fine-grained sediment. In the northwestern Alboran margin this hypothesis has been found to be true.

6. Conclusions

[36] The results of this study indicate that internal tides in the northwestern Alboran Sea may be responsible for the generation and maintenance of nepheloid layers within and around the Guadiaro Canyon. The angle of energy propagation for the semidiurnal internal tide reaches critical conditions on the upper continental slope (from 200 to 500 m depth) and along the axis of the Guadiaro Canyon, where a well-developed bottom nepheloid layer and intermediate nepheloid layer detachments are found. This critical region also coincides with a zone of erosion on the upper continental slope of the study area, suggesting that internal

tides could also control resuspension and/or prevent sedimentation in this part of the margin and hence determine the shape of the northwestern Alboran continental slope.

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