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Summary

This thesis offers an extensive perspective of the hydrodynamics and sediment transport of the Gulf of Valencia (GoV) continental margin (NW Mediterranean), focusing on the geomorphological and internal structure description of the bedforms observed over the margin. A comprehensive dataset using a wide range of methodologies was used during the project, spanning from hydrographic and hydrodynamic datasets, instrumented moorings, swath bathymetry, sediment sample and seismic profiles.

The hydrography of the GoV has been characterized evaluating the relation between currents, water masses and turbidity in the area. Surface circulation is marked by a convergence between the southwestward Northern Current carrying old Atlantic waters (oAW) and the northward intrusions of recent Atlantic waters (rAW) imported through the Ibiza Channel. Below this surface circulation, several water masses were identified: Levantine Intermediate Water mass (LIW); the Western Mediterranean Intermediate Water (WIW) and the Western Mediterranean Deep Water (WMDW).

Higher suspended sediment concentrations were observed in the oAW than in the rAW, and an important detachment of particulate matter (nepheloid layer) was observed at the shelf-break depth, extending seawards all across the Ibiza Channel. This indicate a preferential off-shelf sediment export at the southern end of the GoV, where the orientation of the continental margin changes, and where the oAW and rAW merge. On the continental slope, several nepheloid layers detachments were observed between 400 and 600 m, where the LIW interacts with the seafloor, suggesting the possible presence of internal waves causing sediment resuspension and/or maintaining particles in suspension in the mid-slope region. Additionally, circulation patterns and sediment dynamics were studied using measurements from two mooring deployed over the GoV continental slope. Temperature fluctuations of the boundary between the WMDW and the LIW masses were monitored. Several intrusions of WIW were also observed, generally coinciding with changes in current direction. Multiple increases of current magnitude were observed, associated with mesoscale eddies and topographic waves.

A complex relation between the hydrodynamics and sediment transport has been observed over the GoV continental slope, which suggests that other potential sediment resuspension mechanisms not linked with current fluctuations are playing a key role in
the present-day sedimentary dynamics. Resuspension due to bottom trawling is here presented as the most plausible mechanism.

Detailed analysis of recently acquired swath bathymetry, together with high-resolution seismic profiles and bottom sediment samples, revealed the presence of large-scale fine-grained sediment waves over the Gulf of Valencia continental slope. As many other deep-water sediment waves, these features were previously attributed as a result of gravitational slope failure, related to creep-like deformation, and are here reinterpreted as sediment waves fields, extending from 250 m depth to the continental rise, at ~850 m depth. Geometric parameters (wave height, length, asymmetry and steepness) were computed from the high resolution multibeam dataset. Sediment waves length range between 500 and 1000 m, and maximum wave heights of up to 50 m are found on the upper slope, decreasing downslope to minimum values of 2 m along the continental rise. Sediment waves on the lower part of the slope are aggradational whereas they show an upslope migrating pattern from the mid-slope to the upper part of the continental slope. Such observations indicate that regional slope angle is an important factor controlling the development and the shape of these sediment waves. High-resolution sub-bottom seismic profiles show continuous internal reflectors within the sediment waves merging down-section and sediment wave packages decreasing in thickness downslope. These sediment packages are thicker on the crest of each sediment waves and thinner on the downslope flank. \(^{210}\text{Pb}\) analyses conducted on sediment cores collected over the sediment wave fields also indicate higher sediment accumulation rates on the wave crests, indicating that such features are presently growing at 100-yr timescales.

The sediment waves formation processes has been inferred from contemporary hydrodynamics observations, which reveal the presence of near-inertial internal waves interacting with the Gulf of Valencia continental slope. Internal waves' activity is suggested to be the most likely mechanism for the development and/or maintenance of the observed sediment waves fields.

Moreover, single-channel seismic profiles were also analyzed, and showed a second group of sediment waves developing over the outer continental shelf, with wavelengths from 400 to 800 m and heights of 2 to 4 m, also with a clear up-slope migrating pattern. Detailed analysis indicated the presence of several sediment depositional units, some of
them with successive development of sediment waves being truncated by erosive surfaces, which are apparently linked to eustatic sea-level oscillations. Such erosional surfaces can be followed downslope into conformable strata of the sediment waves on the continental slope, where constant bedform growth is observed, without being affected by sea level changes.

Additionally, the multi-channel profiles acquired over the GoV showed that sediment waves over the continental slope region continuously develop on the foreset region of the prograding margin clinoform, and have been preserved in the sedimentary record since the Lower/Pliocene. Several sediment waves units could be differentiated throughout the sedimentary record, evolving concordant with the margin progradation. Thickness maps showed maximum sediment deposition rates on the upper part of the continental slope, coinciding with the largest (in length and height) sediment waves development.

Overall, it has been observed that Plio-Quaternary sediment deposition over the GoV margin is mainly controlled by the slope gradient and the presence of tectonic structures. As internal waves are assumed to be the main formation mechanism of the sediment waves developed over the GoV continental margin, it is here suggested that these oceanographic processes would have been present in this margin almost since the Zanclean reflooding of the Mediterranean Basin, following the Messinian Salinity Crisis event ~ 5.6 Myr ago.
Resum

Aquest tesi ofereix una àmplia perspectiva de la hidrodinàmica i transport de sediment en el marge continental del Golf de València (GoV) (NO Mediterrani), centrant-se en la descripció geomorfològica i de l’estructura interna de les formes de fons observades en aquest marge. Durant aquest projecte s’ha analitzat un extens ventall de dades utilitzant una gran varietat de metodologies, des de dades hidrogràfiques i hidrodinàmiques, anclatges instrumentats fins a batimetria mutifeix, mostres de sediment i perfils sísmiques.

La hidrografia del GoV s’ha caracteritzat avaluant la relació entre corrents, masses d’aigua i la terbolesa de la zona. La circulació superficial ve marcada per la convergència entre la Corrent del Nord que circula cap al sud-sudoest transportant aigües de l’Atlantic antigues (old Atlantic Waters, oAW) i les intusions cap al nord de les aigües atlàntiques recents (recent Atlantic Waters, rAW) a través del Canal de Ibiza. Per sota de la circulació en superfície s’identifiquen diverses masses d’aigua: l’aigua Levantina Intermèdia (LIW); les aigües intermèdies del Mediterrani (WIW); les aigües profundes de l’oest del Mediterrani (WMDW).

En les oAW s’observaren concentracions de sediment en suspensió més altes que en les rAW, així com també un desenganxament de matèria particulada (capes nefeloid), que es va observar a profunditats de vora de plataforma, estenent-se mar endins en el Canal de Ibiza. Això indica que el transport sedimentari entra plataforma i talús té lloc preferentment al sud del GoV, a on hi ha un canvi en la orientació del marge continental, i a on la oAW i la rAW convergeixen. En el talús continental s’observaren varis desenganxaments de capa nefeloid entre 400 i 600 m de profunditat, a on la LIW interacciona amb el fons, suggerint una possible presència d’ones internes que causant resuspensió i/o manteniment de partícules en suspensió a les regions del talús intermedi. Addicionalment, s’han estudiat els patrons de circulació i la dinàmica de sediment utilitzant mesures de dos anclatges fondejats en el talús del GoV. Es van monitoritzar les fluctuacions de temperatura entre la WMDW i la LIW. Es van observar també varies intrusions de la WIW, generalment coincidents amb canvis de direcció de les corrents. Es van observar múltiples augmentes de velocitat, associats a vòrtexs mesoscalars i ones topogràfiques.
S’ha observat una relació complexa entre la hidrodinàmica i el transport de sediment en el talús continental del GoV, cosa que suggereix que altres mecanismes de resuspensió, no relacionats a les fluctuacions de corrent, podrien estar jugant un paper important en la dinàmica sedimentària actual. Es proposa la pesca d’arrossegament com a mecanisme més plausible per a la resuspensió.

Els anàlisis detallats de la batimetria multifeix, juntament a perfils sísmics d’alta resolució i mostres de sediment, mostren la presència d’ones de sediment de gra fi de gran escala en el talús continental del GoV. Tal i com ha succeït en altres casos de ones de sediment en aigües profundes, aquestes formes de fons es van interpretar com a resultat de moviments de massa, relacionats a deformacions per creep, i s’han reinterpretat en aquesta Tesis com a camps d’ones de sediment, estenent-se des de 250 m de profunditat fins a la plana abissal, a ~ 850 m de profunditat. Es van calcular els paràmetres geomètrics (alçada i longitud d’ona, asimetria, inclinació) a partir de la batimetria multifeix. La longitud d’ona varia entre 500 i 1000 m, i s’observa una alçada d’ona màxima de fins a 50 m a la part alta del talús, que disminueix fins a 2 m a la zona de plana abissal. Les ones de sediment a la zona de peu de talús són agradacionals, mentre que mostren un patró de migració talús amunt a les zones intermèdies i talús superior. Aquestes observacions indiquen que l’angle del talús és un factor important que controla el desenvolupament i la morfologia d’aquestes ones de sediment. Els perfils sísmics d’alta resolució mostren reflectors interns continus dins de les ones de sediment que convergeixen, i paquets d’ones de sediment que disminueixen en gruix talús avall. S’observa que aquests paquets de sediment tenen més gruix a les crestes de cada una de les ones de sediment, i que s’aprimen en els flancs talús avall. Els anàlisis de $^{210}$Pb realitzats a les mostres de sediment adquirides en les ones de sediment indiquen també taxes d’acumulació de sediment majors a les crestes, cosa que indica que aquestes formes de fons estan actualment creixent, a una escala de 100 anys.

El procés de formació de les ones de sediment s’ha deduït a partir d’observacions recents de la hidrodinàmica de la zona que mostren la presència d’ones internes quasilinearis interaccionant amb el talús continental del GoV. Es proposa l’activitat d’aquestes ones internes com el mecanisme més viable pel desenvolupament i/o manteniment dels camps de sediment observats.
Addicionalment, s’han analitzat perfils sísmics monocanal, en els que s’observa un segon grup d’ones de sediment que es desenvolupen a la plataforma continental, amb longituds d’ona d’entre 400 i 800 m, amb un patró de migració talús amunt. Els anàlisis detallats indiquen la presència de diverses unitats deposicionals, en algunes de les quals s’observa un desenvolupament continuat d’ones de sediment, les quals es troben truncades per superfícies erosives, aparentment relacionades a oscil·lacions eustàtiques del nivell del mar. Aquestes superfícies erosives es poden seguir des de la plataforma talús avall, a on es troben com a estrats concordants dins de les ones de sediment que creixen de forma continuada al talús, sense estar afectat per les canvis del nivell de mar.

D’altra banda, els perfils sísmics de multicanal adquirits en el GoV mostren que les ones de sediment al talús es desenvolupen sempre a la zona de talús del clinoform del marge progradant, i que s’han preservat el registre sedimentari des del Pliocè inferior/Pleistocè. S’han pogut diferenciar diverses unitats d’ones de sediment dins del registre sedimentari, que evolucionen de manera concordant amb la progradació del marge continental. Els mapes d’isopaques mostren que la sedimentació és màxima a la part alta del talús, coincidint amb les ones de sediment més grans (en longitud i alçada d’ona).

En conjunt, s’ha observat que la sedimentació en el talús continental del GoV durant el Plio-Quaternari està principalment controlada pel pendent del talús i la presència d’estructures tectòniques. D’altra banda, assumint que les ones internes son el mecanisme de formació de les ones de sediment que es desenvolupen sobre el talús continental del GoV, es suggereix que aquest procés oceanogràfic ha estat present en el marge aproximadament des de la inundació de la conca del Mediterrani del Zanclìà, just després de la crisi del Messinià fa ~ 5.6 Ma.
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The research project proposed for this Thesis deals about the study of contemporary sedimentary processes on the Gulf of Valencia (GoV) continental margin (NW Mediterranean Sea). The study of contemporary sedimentary dynamics and sediment fluxes on continental margins has a large multidisciplinary interest. For instance, organic matter attached to particulate matter serves as a food resource for benthic and pelagic species and also affects the oceanic carbon cycle. In addition, most of the contaminants introduced in the marine environment are associated with fine sediment particles. Therefore, such type of studies are an essential task for understanding the biogeochemical cycles of most elements in the oceans and the transport of matter and energy to the marine ecosystem, as well as, for determining the fate and dispersion of many contaminants introduced into the sea by anthropogenic activities. Moreover, studies analyzing seismic data sets were used to identify main factors governing continental slope geometry (Adams et al., 1998; Adams and Schlager, 2000), and multibeam data sets allowed studying the mechanisms that control the geomorphic variability of modern continental margins (Amblas et al., 2006).

In the NW Mediterranean Sea, the Ebro continental margin exhibits one of the largest shelves where several natural processes (e.g., floods, storms, internal waves, etc.) and anthropogenic activities (e.g., trawling) favor the presence of high sediment fluxes. Previous research efforts conducted in this margin stated that the contemporary sediment transport is clearly along-shelf and south-southwestwards, towards the GoV margin, with a negligible cross-margin component. Although the Ebro margin has been intensively investigated under different perspectives of the marine geology, up to date, no previous research has addressed the study of the contemporary mechanisms that contribute to the off-shelf sediment transport processes and control the temporal variability and quality of the exported particles towards the continental slope environments.

Therefore, the initial hypothesis behind the objectives of this project is that such elevated off-shelf transport should be occurring in the southwestern end of the Ebro shelf.
(around the Columbretes Islands), a region that has not been yet investigated from the present day sediment dynamics point of view.

Thus, the main objectives of this Thesis were initially centered in the study of the sediment dynamics over the GoV continental margin. Subsequently, and without changing the initial aim, increased emphasis was placed in the characterization of the GoV continental slope geomorphology, where several characteristic bedforms were observed. Such bedforms, interpreted in this Thesis as sediment waves, have become one of the most important aspects of this thesis in which, in addition to the hydrographical and hydrodynamical descriptions of the study site, there is a detailed geomorphological characterization and determination of the sediment waves internal structure. Furthermore, a mechanism for the formation of the sediment waves is proposed, relating it to the hydrodynamics of the GoV, characterized by the presence of near-inertial internal waves. A geological reconstruction of the continental margin progradation is also performed, in which it can be observed that such sediment waves have been preserved in the sedimentary record since the Early/Lower Pliocene (~ 3.6 Ma). To accomplish all the objectives, annual time series of currents, suspended sediment concentrations and particle fluxes were recorded using several instrumented mooring deployments. During repeated scheduled oceanographic cruises, hydrographic data and sediment samples were collected. In addition, a wide coverage of multibeam bathymetry and high-resolution seismic profiles were acquired during the planned surveys.

**Specific objectives**

- Hydrographic characterization of the GoV area: description of the water masses present on the study site and the sediment transport over the continental margin.
- Characterization of the sediment fluxes: description and analysis of the samples obtained on the sediment traps (vertical fluxes) and measurements acquired with the current meters (advective fluxes).
- Hydrodynamic description of the GoV area: description of the current magnitude and direction over the continental slope, relating it with the water column
temperature fluctuations and variations of suspended sediment concentration. Description of the near-inertial internal waves over the Gulf of Valencia continental slope (in collaboration with Dr. Hans van Haren from the Royal Netherlands Institute for Sea Research (NIOZ)).

- Geomorphological description of the bedforms observed over the GoV margin (using newly acquired multibeam bathymetry, during project COSTEM, in addition to the high-resolution multibeam dataset obtained in collaboration to the Instituto Español de Oceanografía (IEO)).

- Description of the formation mechanism of the sediment waves observed over the GoV continental slope (initially described as gravitational deformation, interpretation that has been changed in this Thesis).

- Description of the internal structure of the observed sediment waves, using several seismic profiles datasets acquired in different resolutions: sub-bottom profiles, obtained from the Instituto Español de Oceanografía (IEO); single-channel seismic lines acquired in collaboration with Dr. Prof. David Van Rooij, from the Renard Centre of Marine Geology (RCMG) of the University of Ghent; and multi-channel profiles, obtained from the Archivo Técnico de Hidrocarburos (ATH).

- Description of the Gulf of Valencia continental margin evolution and progradation.

**Thesis structure**

This Thesis has been structured in ten chapters, starting with a general introduction, providing a general description of the morphology and the sedimentary dynamics on continental slopes and in particular on the GoV continental margin. Chapter 2 introduces the study area focussing on the geological and oceanographic settings, and Chapter 3 describes the methodology used and the techniques followed to conduct the research of the Thesis. In Chapter 4 the hydrographic structure and particulate matter distribution is described, in order to improve the knowledge of the sediment dynamics on the GoV
margin and to understand the relationships between different water masses and suspended sediment distributions, and to identify the main off-shelf sediment pathways. Chapter 5 is centered in the description of the advective and downward particle fluxes over the GoV margin, using current and sediment fluxes annual time series.

In Chapter 6 the hydrodynamics of the GoV continental slope is analyzed and related to the sediment transport, to improve the understanding on the hydrographic structure and the regional circulation. The relation with the sedimentary dynamics over the GoV continental slope is also discussed in this chapter, assessing the role that mesoscale current variability and the near-inertial internal waves might play in the sediment transport on this region. The aims of Chapters 7 and 8 are to present a detailed morphobathymetrical analysis of the observed sediment waves identified over the GoV continental slope and suggest a formation process model for these seafloor morphologies. Chapter 9 focuses on the sediment wave evolution during the Plio-Quaternary sedimentary record, focusing on the GoV outer continental shelf and continental slope. This chapter gives new information for the stratigraphic and architectural characterization of the GoV margin, providing a model for the progradational growth of the sediment waves over the GoV continental slope, and a correlation of the GoV outer continental shelf stratigraphy, related with the eustatic sea level variations. General conclusions and proposed future research lines are exposed in Chapter 10.

Chapters 4, 6, 7 and 8, including the study area description and methodology used, and also the general discussion and conclusions extracted in each one (Chapter 2 and 3, and 10), correspond to peer-reviewed scientific papers published in journals included in the JCR of ISI. In addition Chapter 5 and 9 are in preparations to be also submitted in 2015.
Chapter 1

Introduction
1.1 General sedimentary dynamics on continental margins

The study of contemporary sediment dynamics and sediment fluxes on continental margins has been intensively investigated. However, the mechanisms responsible for the off-shelf sediment transport are still under study due to complexity of the sedimentary dynamics that characterize the shelf-edge and upper slope regions. Continental margins around the world can be classified in two types: passive continental margins, those that ride “passively” within the interior of a lithospheric plate; and active continental margins, those that lie along boundaries between plates and are shaken by the plate movement, formed along convergent or transform plates (Kennett, 1982).

Passive continental margins, where the continental and oceanic crust move in concert, contain a coastal plain a transition zone, which includes the continental shelf, slope and rise, and the abyssal plain (Figure 1.1). The continental shelf is characterized for being a flat surface with a gentle slope (~0.05°) extending from the shoreline to the shelf-break, which is generally located at less than 200 m depth. Its extension and geometry is highly variable depending on the continental margin. The continental slope extends from the shelf-break to water depths ranging between 1 and 3.5 km. Seafloor gradients on the slope are similarly variable, ranging from 1 to 25°, with the overall average being ~4° (Pratson et al., 2007).

Figure 1.1 Schematic sections across a passive continental margin. Vertical exaggeration of x20.
Along the shoreline of the continents the highest density of the population of the world is found, however, many of the sedimentary process responsible for the shaping of the continental margins is poorly understood (Mienert and Weaver, 2003). Ocean management efforts have focused on the need to identify the actual mechanisms that control the sediment transport and the final fate of most particulate matter introduced from the continental to the marine system. Fine particles (settling and suspended) are responsible for much of the flux of matter and energy in the marine environment, playing a key role in the global oceanic biogeochemical cycles and in the marine ecosystems (Asper et al., 1992). Sedimentary processes control the transport of most particulate elements introduced or generated in the oceans, being especially important in continental margins because of the large material inputs from both fluvial and high productivity coastal waters (Walsh, 1991). However, the study of sedimentary dynamics on continental margins is complex because in these areas coexist anthropogenic activities and oceanographic processes that combine their action to influence sediment particles transport and deposition. In general, about 90% of the sediments moved by rivers are carried in the water column as suspended load, part being commonly accumulated on the continental shelf, and part being exported in suspension seawards (Milliman and Meade, 1983; Syvitski et al., 2003). High energetic processes such as tides, surface gravity waves, bottom currents and internal waves contribute to resuspend and remobilize the particles temporarily deposited on the shelf, favoring their transference to the continental slope (Nittruer and Wright, 1994), while topographic structures such as submarine canyons act as preferential sedimentary conduits towards deeper regions (Puig et al., 2003).

Contemporary sediment dynamics and particulate matter distribution of continental margins have been studied in different oceans of the world. The particulate matter distribution in the water column is highly influenced by the hydrographic structure and hydrodynamic processes, as shelf-slope fronts and geostrophic currents (Backer and Hickey, 1986; Durrieu de Madron et al., 1992; Palanques and Biscaye, 1992; Puig and Palanques, 1998). Terrigenous or lithogenic particles, as suspended sediment, do not act like purely conservative tracers of water masses, but their presence in nepheloid layers, defined as layers containing high concentration of particulate matter located at different depths of the water column, can indicate the location and intensity of oceanographic
processes, particularly those involving the resuspension of sediment due to strong bottom currents (McCave, 1986; Gardner and Walsh, 1990).

Additionally, the processes of near bottom sediment dynamics involves feedback mechanisms, with the hydrodynamics, bedforms and sediment transport each one equally interacting and affecting and modifying the other ones. The study of bedforms shape, orientation, morphology and migration provide significant information about sediment dynamics and direction of the sediment transport. Along continental margins, bedforms, formed by gravel, sand or mud, present a wide spatial and temporal scale range. In shallow waters, ripples and megaripples are observed (Wiberg and Harris, 1994; Gallagher, 1998). Shoreface-connected ridges, sorted bedforms, sand banks and sand waves, sand ridges, dunes and ribbons can be found over the continental shelves (Van de Meene and Van Rijn, 2000; Murray and Thieler, 2004; Dyer and Huntley, 1999; Goff et al, 1999). Sediment waves can be observed over prodeltas, outer continental shelf, continental slope, and continental rise (Gallignani, 1982; Trincardi and Normark, 1988; Wynn and Stow; Masson et al., 2004; Van Landeghem et al., 2009). In addition to the sediment waves, sediment drifts and contourites are also observed in deep water environments (Rebesco and Stow; Masson et al., 2002) The characterization of the different type of bedforms is required for understanding and quantifying the influence of seafloor morphology and sediment dynamics on a region, and can be useful for predicting of its natural and anthropogenic changes, and can also be relevant for the sustainable management of the marine environment and resources.

1.2 Sedimentary dynamics and geomorphology on the Gulf of Valencia continental margin (NW Mediterranean)

The sedimentary dynamics in the northwestern Mediterranean continental margin has been continuously studied during the last decades in the framework of many research projects. The earlier studies using moored sediment traps demonstrated that river floods and storms enhanced particle fluxes inside submarine canyons and on the continental slope (e.g., Monaco et al., 1990; Puig and Palanques, 1998). For a long time, these processes were considered the major contemporary mechanisms able to transport sediment from the shelf towards deeper environments. In fact, several studies have
shown that major storms occurring on this margin (Hs > 6 m) are capable of resuspending the fine sediment deposited on continental shelves up to a depth of over 60 m (Puig et al., 2001; Palanques et al., 2002; Ferré et al., 2005). In addition it has been observed that near-inertial internal waves generated after the passage of storms contribute to maintain particles in suspension for long periods of time after the resuspension event (Puig et al., 2001). In some circumstances, the mobility of the sediment during river floods combined with major storms may affect the whole continental shelf (Guillén et al., 2006, Palanques et al., 2008).

The Valencian continental shelf has been widely studied from the sedimentary point of view (Giró and Maldonado, 1983; Maldonado et al., 1983; Young et al., 1983; Díaz del Río et al., 1986; Rey et al., 1999), however up to date, no previous research has addressed the study of the contemporary mechanisms that control the off-shelf sediment transport processes, and the characteristics and fate of the exported particles towards the slope environments. The sedimentary dynamics on the Gulf of Valencia (GoV) continental shelf was initially studied in detail by Young et al. (1983) during the EOPC project (Estudio Oceanográfico de la Plataforma Continental), when three tripods equipped with a current meter and optical transmissometer, measured turbidity at about 50 cm above the bottom, and were deployed off Valencia between depths varying from 10 to 52 m. They observed that periods of high near-bottom water turbidity (increase of suspended material in the water sampled), occurred independently of flow speed events, and were well correlated with high wave energy events.

Later on, during the EBROMS project (EBRO Margin Study), boundary layer measurements were obtained by the benthic tripod GEOPROBE at 60 m on the Ebro continental shelf (Maldonado and Nelson, 1990; Cacchione et al., 1990), and Palanques and Drake (1990) described the main trends of suspended sediment distribution. After this initial observational effort, during the FANS project (Fluxes Across Narrow Shelves), the general pattern and magnitude of sediment fluxes at several locations across the Ebro shelf were analyzed in Palanques et al. (2002). A focused study of the principal mechanisms that contribute to the sediment transport near the bottom and control the variability of the suspended sediment particles within the water column was conducted by Puig et al. (2001), addressing the role of storms and near inertial internal waves over the shelf.
All these previous studies indicated that on the Ebro continental shelf, the mean along-shelf sediment flux towards SSW is dominant over the mean seaward cross-shelf flux, and that maximum near-bottom sediment fluxes are mainly associated with storm events. Further studies of sedimentary dynamics on the Ebro shelf were conducted on the framework of the RESPONSE project (RESPONSE of benthic communities and sediment to different regimens of fishing disturbance in European coastal waters) that studied the effects induced by trawling on benthic organisms and in the remobilisation of surface sediments. During this study, the estimated sediment fluxes also indicated a dominant along-shelf transport towards the SSW and an almost nil cross-shelf transport (Palanques et al., 2005). These prior results suggest that most of the off-shelf transport in the Ebro margin has to occur on its southwestern end, nearby the Columbretes Islands, where the width of the shelf decreases dramatically and the advection of suspended particles can cross the isobaths and reach the continental slope region of the GoV.

In the literature there are no studies of contemporary sedimentary dynamics on the southwestern end of the Ebro continental shelf, but exits indirect evidences that it could be a highly dynamical region with active sediment transport. Large sedimentary features, such as ridges, furrows and sandwaves have been described on this area, and geostrophic currents affecting the region were pointed out to be playing a role in controlling the evolution of such features (Díaz et al., 1990; Muñoz et al., 2005). Muñoz et al. (2005) analyzed the multibeam bathymetry conducted around the Columbretes Islands during the BALCOM project and found numerous bedforms associated to erosion of the seafloor (channels and furrows) and to deposition of sediments (dunes and sediment drifts). These bedforms are apparently active and their directions indicate a direct export of particles from the shelf to the slope, suggesting that a large part of the off-shelf transport in the Ebro margin can be occurring in this region. However, Lo Iacono et al. (2010) concluded that stronger currents than the ones observed in this area are required for the formation of the very large dunes observed over the Columbretes outer shelf. These authors also suggest that the dunes could be produced by very intense near-bottom currents during sporadic energetic hydrodynamic events of the southward-flowing geostrophic current, as it interacts with the rough seafloor of the study area. The subaqueous dunes would be expected to be inactive features with respect to present-day processes (Lo Iacono et al., 2010).
Based on these preliminary results, there is a great interest to investigate, the seafloor morphology southwestwards from the Ebro margin towards the GoV continental margin. This would include the extension of the bathymetric coverage, and the acquisition of an extensive high-resolution seismic database, in addition to the study of the hydrodynamics and sediment dynamics on the continental shelf, extending towards the shelf-break and continental slope. Therefore, the research project presented within this Thesis will help to improve the knowledge of the contemporary sediment dynamics on the GoV margin. In addition new information of the hydrodynamics in this region is provided. Overall, this region presents unique characteristics to advance in the knowledge of the off-shelf transport processes on the southwestern end of the Ebro margin. The Gulf of Valencia is a highly productive region in terms of demersal fisheries and, in this sense it is likely that the sediment dynamics that seem to characterize this region could contribute to maintain such high productivity.
Chapter 2

Study area
2.1 Geological settings

The Gulf of Valencia (GoV) constitutes one of the Tertiary basins of the northwestern Mediterranean, located in the southwestern part of the Valencia Trough (> 1000 m), extending from the southern end of the Ebro shelf (south of the Columbretes Islands) to the promontory of Cap La Nao (Fig. 2.1). Its opening took place during the Early-Middle Miocene (> 20 M.a.) active extensional phase (Díaz del Río et al., 1986). During this period several extensional sub-basins develop, delimited by systems of NE-SW orientated horsts and grabens (Maillard et al., 1992; Maillard and Mauffret, 1999). Shaping of the GoV shelf is mainly dominated by the deep-seated graben system characterized by N-S trending extensional faults, sub-parallel to the actual coastline (Díaz del Río et al., 1986). The GoV continental shelf is characterized by a thick accumulation of sedimentary units and a broad continental shelf. Southwards, the continental shelf show a much reduced sedimentary cover (Stanley, 1977; Mauffret, 1979; Serra et al., 1979; Rey and Díaz del Río, 1983). The southern GoV has subsided at a ratio of ~ 0.45 per 1 ka during the Plio-Quaternary, suggesting a structural control in the depositional behaviour and in the coastal morphology (Rey and Fumanal, 1996).

The extension of the GoV was attenuated during the Burdigalian-Langhian (~ 16 Ma), when the compression in the Betic cordillera started affecting the Balearic Promontory (Geel, 1995). The post-rift stage was followed by deposition of two major prograding megasequences: one pre-Messinian in age, the Castellon Group, records a major overall regressive trend that reflects the major filling of the post-rift subsidence accommodation space (Bartrina et al., 1992; Dañobeitia et al., 1990); and the other, the post-Messinian. The post-rift unit is the Pliocene-Quaternary prograding megasequence, which overlies the Messinian unconformity (Maillard et al., 2006). This unit is known from well-data as the Ebro Group and is largely constituted by Ebro River sediments (Fig. 1). The Messinian unconformity defines the Miocene/Pliocene boundary, and corresponds to the drastic sea level drawdown and subsequent reflooding and re-establishment of open-marine conditions in the Mediterranean. The Messinian Salinity Crisis (MSC; ~ 5.96-5.33 Ma; (Hsü et al., 1973; Krijgsman et al., 1999; García-
Castellanos and Villaseñor, 2011) induced major erosion of the continental margins, while evaporites and anhydrite sequences were deposited in the basin center.

On the GoV margin, the Upper Messinian-Pliocene sequence is characterized from bottom to top by a Lowstand System Tract (LST) just before the reflooding during the Zanclean (~ 5.33 Ma), characterized by Basin floor fan (Bff) facies, Slope fan channel complexes (Sfcc) and a Prograding complex (Pc) facies (Martinez del Olmo, 2011). This Upper Messinian-Pliocene sequence is composed by gypsum turbidites, which are progressively covered by downlapping silts and clays, deposited during the Transgressive System Tract (TST) initiated in Early Pliocene (Martínez del Olmo, 2011). Sedimentation over the continental shelf involves large amounts of sands, whereas the middle and outer shelf are dominated by the silt and clay fractions (Rey et al., 1999). The Upper Pleistocene regression involved a sea level drawdown of up to 110 m. Holocene transgression caused the erosion of the bedforms formed during the previous Pleistocene regression. The new Holocene erosional surface of gravel and coarse sediment determines the recent sedimentation base level (Rey et al., 1999).

The GoV continental shelf is defined as part of a stable passive continental margin, extending southwards from the Ebro shelf (Fig. 2.1). The Ebro shelf is characterized by thick Plio-Quaternary sedimentary units and displays a broad continental shelf of more than 60 km wide and a gentle slope (~ 0.5°) up to the depth of 120 m. However, south of the Columbretes Islands, continental shelf rapidly narrows to a width of 20 km (Fig. 2.1), and the GoV shelf shows a much reduced sedimentary cover, coinciding with a change of the margin orientation, from NE-SW to WNW-ESE (Stanley, 1977; Mauffret, 1979; Serra et al., 1979; Rey and Díaz del Río, 1983). It is observed that the continental slope on the Ebro margin is densely canyoned and, the submarine canyons tend to disappear towards the south, being less incised on the continental slope when entering the GoV, and presenting smoother morphologies (Fig. 2.1). The evolution of these submarine canyons started as a first-order gully system, eroding the continental slope and developing into a shelf-breaching dendritic canyon, which finally evolved into a canyon-channel system extending into the lower continental slope and rise (Micallef et al., 2014). South of the Columbretes Islands (Fig. 2.1), some submarine canyons incise outer shelf sand bodies, which have been interpreted as palaeo-delta deposits, with an
estimated age of ~11,100 yr BP. These sand bodies consist in coarse grained deposits formed in shallow environment during sea-level lowstands and transgressive stages (Lo Iacono et al., 2010). Towards the southwest, the observed canyons have been subsequently infilled by hemipelagic background sedimentation which favoured the margin progradation (Micallef et al., 2014).

The central part of the GoV continental margin, which lacks of major submarine canyon features, presents an amphitheater or cul-de-sac shape, interrupted by two structural highs (Fig. 2.1). Preferential formation of sediment undulations is concentrated in the central part of the GoV slope, while they are not present towards the southern part (Maestro et al., 2005; Díaz del Rio and Fernández Salas, 2005).

![Tectonic map of the eastern Iberian Peninsula and the Valencia and Balearic Margins, indicating the location of the Gulf of Valencia, at the southwestern end of the Valencia Trough.](image)

**Figure 2.1** Tectonic map of the eastern Iberian Peninsula and the Valencia and Balearic Margins, indicating the location of the Gulf of Valencia, at the southwestern end of the Valencia Trough.
2.2 Oceanographic settings

Several studies have shown that shelf-slope fronts and geostrophic currents are the most important factors controlling particulate matter distribution (including all solid particles, lithogenic and biogenic particles) in the water column (e.g. Baker and Hickey, 1986; Palanques and Biscaye, 1992; Durrieu de Madron et al., 1992; Puig and Palanques, 1998). In the northwestern Mediterranean the general surface circulation is cyclonic, and it is dominated by a baroclinic current, carrying old Atlantic Waters (oAW) that flows southwestwards contouring the continental slope from the Gulf of Genoa to the Gulf of Valencia (Font and Miralles, 1978; Salat and Font, 1987, Font et al., 1988). This current, named the Northern Current, is in geostrophic equilibrium with a shelf/slope density front, the Continental Front, due to salinity differences between the slope and shelf waters, with a marked seasonal variability (Béthoux et al., 1982; Font et al., 1988; Castellón et al., 1990). At the entrance of the GoV, a significant part of the flow of the Northern Current proceeds southward, detached from the continental shelf-break where the shelf narrows, directly towards the Ibiza Channel (Salat, 1995; Pinot et al., 1995). The presence of the Balearic Current on the south, towards the NE closes the surface cyclonic circulation in the GoV (Fig.2.2). This current carries recent Atlantic Waters (rAW) from the southwestern Mediterranean through the Balearic passages, mainly the Ibiza Channel, between Cap La Nao and Ibiza (Font et al., 1988; Salat, 1995). The Balearic Current is also in geostrophic equilibrium with a density front, the Balearic Front, caused by the low salinity of the rAW. In coherence with the water exchanges at Gibraltar, this front has a limited vertical extension and is not attached to the bathymetry (Salat, 1995).

The hydrographic structure of the GoV is thus dominated by two current systems, and their associated fronts, subjected to seasonal and mesoscale variability. The circulation over the GoV shelf (simple arrows in Figure 2.2), as it has been described in the Ebro shelf, is highly affected by the wind pattern (Font, 1990; Espino et al., 1998), and local mesoscale events are forced by wind bursts and also by the Ebro River discharges (Wang et al., 1988; Salat et al., 1991; Salat et al., 2002).
Han et al. (1983) studied the circulation on the continental shelf in the GoV, and observed that on the outer shelf, currents are dominated by the flow imposed from offshore in the Catalan Sea, and by wind stress. They also observed that currents on the inner shelf are intensified as the shelf width narrows to the south, from Valencia to near the southern boundary of the GoV, at Cap La Nao (Fig. 2.2).

![Figure 2.2 General circulation in the Catalano-Balearic Sea, focusing on the Gulf of Valencia, characterized by the Northern Current flowing southwards, and the convergence of old Atlantic Waters (oAW) and the intrusions through the Ibiza Channel of recent Atlantic Waters (rAW) flowing northwards (filled arrows). Dashed arrows indicate mesoscale structures, as anticyclonic eddies, based on Pinot et al. (2002) and Ribó et al. (2013). Simple arrows represent the inner shelf circulation on the Gulf of Valencia based on Han et al. (1983).](image)

Over the continental slope, circulation has been described as seasonally dominated by the Northern Current entering as an unstable meandering jet (Font et al., 1988; García et al., 1994; Pinot et al., 1994, 1995 and 2002). The meandering activity is strongest in winter starting in November-December and persisting until May, anticyclonic meanders being the most developed ones, with a characteristic size of typically 20 to 40 km. On several occasions, anticyclonic vortex eddies are found in the interior of the meanders, corresponding to the mature stage of the instability (Pinot et al., 2002). This seasonal modulation of mesoscale activity in the Northern Current was already observed off the
Chapter 2. Study area

Ebro Delta (Font et al., 1995). These mesoscale eddies were described to be presumably produced by the instabilities of the regional circulation, caused by the interactions with the bathymetry (Millot, 1999). As winter forcing relaxes in spring-summer, the Northern Current weakens, and the meandering reduces in parallel with the weakening of the current (Pinot et al., 2002). Eddies produced at the GoV can also cross the Ibiza Channel and strongly perturb the water exchange, forcing the retroflection of northern waters back to the northeast into the Balearic Current below the rAW (Pinot et al., 2002).
Chapter 3

Methodology
3.1 Field data

The techniques used in this Thesis for the study of sedimentary processes related to the morphodynamic evolution of the GoV continental margin consist mainly of continuous and simultaneous measurements (e.g., current speed and direction, temperature, conductivity, turbidity, downward particle fluxes) collected by several underwater oceanographic sensors and sampling devices installed on a network of moored arrays deployed at specific locations of the margin. In addition to the observational data, vertical hydrographical Conductivity-Temperature-Density (CTD) and turbidity profiles were registered, several sediment samples were collected, and wide coverage of multibeam eco-sounding and seismic profiles were acquired.

The observational effort in this research project was conducted during six oceanographic cruises over two years, each one separated 4 months from the next one, which were necessary to collect high-resolution data and to perform maintenance task of the sensors mounted on the moorings (to avoid biofouling in the underwater sensors that corrupted the signals). All oceanographic cruises were performed on board of the R/V García del Cid, which has the right characteristics to perform the required mooring operations and also to carry out most of the tasks planned on this project.

<table>
<thead>
<tr>
<th>Cruise</th>
<th>Dates</th>
<th>Conducted work</th>
</tr>
</thead>
<tbody>
<tr>
<td>COSTEM 1</td>
<td>15\textsuperscript{th}-18\textsuperscript{th} May 2010</td>
<td>Standard moorings deployment. Multibeam bathymetry. CTD transects.</td>
</tr>
<tr>
<td>COSTEM 2</td>
<td>17\textsuperscript{th}-23\textsuperscript{rd} Sept 2010</td>
<td>Maintenance task of the Standard moorings. Multibeam bathymetry. CTD transects. Sediment sampling.</td>
</tr>
<tr>
<td>COSTEM 3</td>
<td>9\textsuperscript{th}-14\textsuperscript{th} Feb 2011</td>
<td>Maintenance task of Standard moorings. Deployment of Thermistor string mooring. Multibeam bathymetry. CTD transects. Sediment sampling.</td>
</tr>
<tr>
<td>COSTEM 4</td>
<td>4\textsuperscript{th}-10\textsuperscript{th} June 2011</td>
<td>Recovery of Standard and Thermistor string moorings. Multibeam bathymetry. CTD transects. Sediment sampling.</td>
</tr>
<tr>
<td>COSTEM 5</td>
<td>1\textsuperscript{st}-5\textsuperscript{th} Oct 2011</td>
<td>Thermistor string mooring deployment. Multibeam bathymetry. Single-channel (Sparker) seismic profiles.</td>
</tr>
<tr>
<td>COSTEM 6</td>
<td>4\textsuperscript{th} March 2012</td>
<td>Recovery Thermistor string mooring.</td>
</tr>
</tbody>
</table>

Table 3.1 Oceanographic cruises performed during the COSTEM project.
In addition, to assess the potential role that resuspension processes caused by bottom trawling activities could have on the study area, the Fishing Monitoring Centre of the Spanish Secretariat of Maritime Fishing (SEGEMAR) provided data from the satellite-based tracking Vessel Monitoring Systems (VMS) of fishing trawlers operating in the GoV. The requested VMS data was from February 2011 to February 2012, which includes two mooring deployment periods (see Chapter 6), and the information was provided encrypted (i.e. without the ship’s identification) and consisted of the vessel’s position, heading and speed measurements, recorded approximately every 2 hours. VMS data was also filtered, and vessels monitored only up to maximum speeds of 5 knots, allowing identification of the positions of the vessels during trawling activities (speeds < 5 kts) and not while steaming from the port to the fishing grounds.

3.2 Moorings

3.2.1 Standard moorings

Three standard moorings were deployed on the continental slope and in the middle or the GoV basin (Fig. 3.1), collecting continuous and simultaneous measurements (e.g., current speed and direction, temperature, conductivity, turbidity, downward particle fluxes) that will be used mainly to evaluate vertical and horizontal sediment fluxes.

<table>
<thead>
<tr>
<th>Mooring</th>
<th>Deployment</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Depth (m)</th>
<th>Dates</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
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<td>39º 38.42’ N</td>
<td>507</td>
<td>18/05/2010</td>
</tr>
<tr>
<td></td>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>0º 30.98’ E</td>
<td>39º 38.43’ N</td>
<td>502</td>
<td>22/09/2010</td>
</tr>
<tr>
<td></td>
<td>3&lt;sup&gt;rd&lt;/sup&gt;</td>
<td>0º 30.90’ E</td>
<td>39º 38.43’ N</td>
<td>504.7</td>
<td>13/02/2011</td>
</tr>
<tr>
<td>B</td>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>0º 16.40’ E</td>
<td>39º 29.88’ N</td>
<td>473</td>
<td>18/05/2010</td>
</tr>
<tr>
<td></td>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>0º 16.14’ E</td>
<td>39º 29.32’ N</td>
<td>475</td>
<td>22/09/2010</td>
</tr>
<tr>
<td></td>
<td>3&lt;sup&gt;rd&lt;/sup&gt;</td>
<td>0º 16.40’ E</td>
<td>39º 29.86’ N</td>
<td>471</td>
<td>13/02/2011</td>
</tr>
<tr>
<td>C</td>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>0º 29.66’ E</td>
<td>39º 24.33’ N</td>
<td>1230</td>
<td>17/05/2010</td>
</tr>
<tr>
<td></td>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>0º 29.07’ E</td>
<td>39º 20.72’ N</td>
<td>1234</td>
<td>22/09/2010</td>
</tr>
<tr>
<td></td>
<td>3&lt;sup&gt;rd&lt;/sup&gt;</td>
<td>0º 29.09’ E</td>
<td>39º 20.52’ N</td>
<td>1234</td>
<td>12/02/2011</td>
</tr>
</tbody>
</table>

Table 3.2 Location, depths and dates of the standard mooring deployments
Chapter 3. Methodology

Figure 3.1 Location of the three standard moorings.

Moorings A and B (short-type) included an Aanderaa Doppler current meter RCM-9 (Fig. 3.2A), located at 5 m above bottom (mab) (Fig. 3.3), coupled with the following sensors:

- Current meter Doppler: Measures the current velocity magnitude and direction with a sampling interval of 30 minutes at the mooring depth.
- Conductivity cell: Measures the seawater salinity using the electrical conductivity with a conductivity range of 0-74 mS.
- Turbidimeter: Measures the suspended particles in the water column in FTU (Formazin Turbidity Units). The turbidity ranges are 0-20 FTU y 0-500 FTU.
- Thermistor: Measures the seawater temperature in degrees Celsius. The temperature range is Low Range: 9.3 – 33.4 ºC.
- Pressure sensor: Measures the water column pressure in MPa.

Moorings C (long-type) was equipped with two Nortek Aquadopp current meters (Fig. 3.2B), located at 5 mab (C_b) and at mid waters, at ~ 500 m water depth (C_i) (Fig. 3.3). These current meters use the Doppler effect to measure current velocity by transmitting a short pulse of sound, including sensors such as pressure, tilt, and compass. Two sensors were coupled:
Chapter 3. Methodology

- **SeaBird**: Measures temperature, salinity (by using the electrical conductivity of the sea water), pressure
- **SeaPoint Turbidimeter**: Measures the turbidity with a range of 0-20 FTU.

**Figure 3.2.** A) Current-meter Aanderaa RCM-9 and B) Nortek Aquadopp current meters including the SeaBird and SeaPoint Turbidimeter sensors

**Figure 3.3** Vertical distribution of instruments in the short and long-type moorings (depths are only illustrative of general mooring design, they are not scaled. Exact depths are indicated in Table 3.2).
Instantaneous suspended sediment fluxes were computed multiplying the instantaneous values of the horizontal current velocity components ($\text{cm s}^{-1}$) and the SSC (mg l$^{-1}$), measured with the current meter in each moorings. In order to obtain the sediment fluxes across- and along- canyon, and across- and along-slope, a clockwise rotation of the coordinate systems of 25º clockwise was performed in mooring A, and an anticlockwise rotation of 45º in mooring B, using the bathymetric map of the study site (Fig. 5.1). No changes in the coordinate system were performed at mooring C site since it was located in the middle of the Gulf of Valencia basin (fig. 3.1), and no bathymetric features were conditioning the currents.

All moorings included sediment traps (Fig. 3.4): one in each of the short-type moorings (A and B), and two in mooring C (long-type): one near the bottom ($C_b$) and one at mid waters ($C_i$).

**Figure 3.4** A) Sediment traps B) Carousel with the 12 sample collectors C) Programmable motor D) Schematic drawing of the sediment trap (modified from Martin, 2005).
Each sediment trap incorporates a carousel with 12 rotary collectors for sampling settling particulate matter (Fig. 3.4B). The upper part of the internal trap collecting hull (Fig. 4.3A) is cylindrical with a height of 190 cm and an inner diameter of 40 cm, the lower part is conical and ends in a collecting cylinder (Fig. 3.4D). The carousel is controlled by a programmable motor (Fig. 3.4C) that allow the pre-setting of variable sampling intervals for each of the 12 sample collectors (Heussner et al 1990). During this project, the sampling collecting interval was set between 10 and 12 days depending on the deployment period. Total sampling period was from May 2010 until June 2011 (see Chapter 5)).

3.2.2 Sediment trap samples treatment

Before the sediment trap deployments, the sample collectors were cleaned and filled with a 5% formalin solution prepared in the laboratory from formaldehyde 40% mixed with 0.2 µm filtered seawater to avoid the degradation of organic matter in the trapped sediment. The solution was buffered (pH = 7.5 – 8) with sodium borate. Sediment samples collected in the sediment traps were processed in the Laboratori de Geoquímica of the Institut de Ciències del Mar (ICM-CSIC).

After the sediment traps recovery, the samples in each collector were completely settled, and the supernatant solution above the samples was clear and could be pumped out and the pH was checked. The living organisms that actively entered in the trap (“swimmers”) were removed from the samples after wet-sieving them through a 1-mm nylon mesh using filtered sea water, and were kept in a 5% formalin solution for further analysis (not included in this Thesis). The sample with filtered sea water was settled again (during one or two days), and examined again in a magnifying glass to remove the organisms smaller than < 1 mm (following the recommendations of Michaels et al (1990). Again, after one or two more days, the sample was settled again, and the sieved material was washed with very cold Mili-Q water and centrifuged three times, in order to extract all the remaining seawater. Each sample was subsequently frozen and dried afterwards by lyophilisation process. Downward particles fluxes were computed using
the total mass weight, extracted from the dry weight of each sample, the trap collecting area, and the sampling interval:

\[
\text{Total Mass flux} = \frac{\text{Sample dry weight} [g]}{(\text{trap collecting area} [m^2] \cdot \text{Sampling interval} [\text{days}])}
\]  

[1.1]

### 3.2.3 Thermistor string moorings

Two thermistor string moorings were deployed on the GoV continental slope in order to study the hydrography structure and regional circulation, and to discuss the relation with the sedimentary dynamics the continental slope.

Both moorings were deployed on structural highs over the continental slope (Fig. 3.5), chosen using the bathymetric map of the study area and in agreement with the local fishermen, to avoid interfering with bottom trawling activities.

![Figure 3.5 Location of the two thermistor moorings](image)

<table>
<thead>
<tr>
<th>Mooring</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Depth (m)</th>
<th>Deployment period</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>0° 06' E</td>
<td>39° 16' N</td>
<td>450</td>
<td>mid-February 2011 – mid-May 2011</td>
</tr>
<tr>
<td>E</td>
<td>0° 20' E</td>
<td>39° 10' N</td>
<td>572</td>
<td>October 2011 – mid-February 2012</td>
</tr>
</tbody>
</table>

Table 3.3 Location, depths and dates of the thermistor string mooring deployments
The two moorings were equipped with a downward-looking 300 kHz four-beam RDI Acoustic Doppler Current Profiler (ADCP), located at 80 m above bottom (mab), covering 40 cells of 2 m size vertically (Fig. 3.6A). They sampled at a rate of once per 10 minutes. Noise was recorded near the seafloor due to direct vertical sidelobe reflection, and therefore these data were not taken into account. The first cell with reliable data was at 8 mab. Both moorings included a thermistor string composed of 110 ‘NIOZ4’ self-contained temperature sensors (Fig. 3.6B), sampling at 1 Hz, with a precision of better than 0.001 °C (van Haren et al., 2009). Unfortunately, during the first mooring deployment (mooring D), these temperature sensors had battery issues, and consequently very limited data was recorded. Data from the high-frequency temperature sensors installed on the second mooring deployment (mooring E) have been previously described in detail in van Haren et al (2013).

Additionally, in between the thermistor sensors, 10 Optical Backscatter Sensors (OBS) were placed along the mooring (Fig. 3.6C), positioned every 5 to 10 m, with the lowest sensor at 5 mab. These OBS measured pressure (resolution < 0.005% full scale), temperature (resolution < 0.003 °C) and turbidity (light source wavelength of 880 nm) with a sampling rate of once per 15 s.

For the purpose of this Thesis, the temperature data from the OBS records collected in both moorings will be analyzed to allow comparisons between both observational sites (see Chapter 6).
Before each mooring deployment and after each mooring recovery, two Conductivity-Temperature-Depth profile casts were performed with a Sea-Bird 911 probe, with the entire thermistor and OBS string coiled and attached to the CTD frame. The raw CTD data was processed through the Sea-Bird data processing software (SBE Data Processing), used for converting, editing, processing and plotting of oceanographic data acquired with Sea-Bird profiling CTDs. Temperature and salinity profiles were used to characterize the hydrographic structure of the study site (see Chapter 6), and to calibrate and correct the measurements of all the temperature sensors mounted on the moorings. After correction, salinity was computed from the conductivity and the recorded temperature was converted into potential temperature ($\theta$).

The OBS also measured turbidity by detecting scattered light from suspended particles in the water, in Formazin Turbidity Units (FTU). The sensor gain was set at 100x for a sensitive of 200 mV/FTU and a range of 0-25 FTU, with an error of 2% up to the maximum concentration. The readings were converted to estimates of suspended sediment concentrations (SSC) following the general equation based on the calibration defined by Guillén et al. (2000):

$$\text{SSC (mg l}^{-1}) = 1.74 \times (\text{FTU} - \text{FTU}_{\text{min}})$$

Values were adapted to the measurements made in the study site, where $\text{FTU}_{\text{min}}$ is the minimum turbidity recorded by the sensor during the two mooring deployment periods. Unfortunately, nearly all OBS were rapidly biofouled and the signal couldn’t be used. Only the lowermost OBS placed at 5 mab provided reliable data with no signs of biofouling through the entire deployment.

Current and sediment flux progressive vector diagrams were computed, and near-bottom instantaneous sediment fluxes and time-integrated cumulative sediment transport were also calculated, using the current measurements from the ADCP at 8 mab and the SSC values at 5 mab. To obtain the along- and across-slope instantaneous sediment fluxes and the along- and across-slope cumulative sediment transport, the coordinate system was rotated to the main isobath orientation of each mooring site, using the bathymetric map of the study area as reference (Fig. 3.5). Current components from the
first mooring (mooring D) were rotated 10° anticlockwise and the positive along-slope direction was 170°. The velocity components from the second mooring (mooring E) were rotated 75° anticlockwise and the positive along-slope direction was 105°.

3.3 Hydrographic data

Historical CTD vertical profiles acquired in June 1995 during the oceanographic cruise MESO’95 (MESOscale processes) were here analyzed in this Thesis (see Chapter 4). During this cruise 190 CTDs were collected along the Catalano Balearic Sea, from which 54 CTD stations were located in the GoV. Spacing between casts along transects was of 10-15 km, and the spacing between transects of 15-20 km (Fig. 3.7). This survey provided hydrographic data on temperature, salinity, fluorescence and light transmission over the GoV region.

CTD data were averaged to 1-m vertical bins. Light transmission measurements were made with a 0.25 m path-length Sea Tech transmissometer (with a wavelength of 660 nm). The transmissometer measures a voltage (V) that is proportional to the light intensity at a distance (L) from the light source (Baker and Lavelle, 1984; Bishop, 1986):

\[ V = V_0 \cdot e^{-\alpha L} \]  \hspace{1cm} [1.3]

where \( V_0 \) is the voltage at \( L=0 \) and \( \alpha \) is the total beam attenuation coefficient.

The total \( \alpha \) has contribution from clear water free of particles (\( \alpha_w \)), suspended matter (\( \alpha_p \)) and dissolved organic matter (\( \alpha_y \)) which is usually assumed to be zero (Jerlov, 1968). Then, the \( \alpha_p \) can be calculated by:

\[ \alpha_p = \left( -\frac{1}{L} \right) \cdot \ln \left( \frac{V}{V_w} \right) \]  \hspace{1cm} [1.4]

where \( V_w \) is the normalization voltage in clear water which can be considered as the maximum voltage measured during the cruise.
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Figure 3.7 Location of the CTD stations performed during the cruise MESO95 used for hydrographic characterization (red dots), and additional CTD stations used to compute the geostrophic field (orange dots).

In order to relate the beam attenuation to suspended sediment concentration (SSC) in mg/l the calibration equation of Guillén et al. (2000) for the Ebro Margin (with $r^2 = 0.84$, calibrated with 127 samples) was applied:

$$SSC = 1.48 \cdot \alpha_p$$  \[1.5\]

where $\alpha_p$ is the beam attenuation coefficient produced by suspended matter

In addition, the field of geostrophic current was calculated from the dynamic height at the CTD stations, with a reference level at 400 m, using also the nearby hydrographic transects towards the northeast to provide a more general view of the GoV circulation (orange dots in Fig. 3.7). These calculations were extended onto the upper slope, where the depth was less than 400 m, by using the continuity equation applied at the deepest level of three-station clusters (Hidaka, 1940). This method could be used to extend the calculated field over the entire shelf, but in this Thesis it was only used for areas deeper than 100 m. Moreover, during the oceanographic cruises COSTEM 1 to COSTEM 4, 14 vertical profiles distributed in two hydrographic transects (Transect 1 and Transect 2) were repeated, also using a CTD Sea-Bird 911 and auxiliary sensors, as a Turbidimeter
Seapoint and a Fluorometer. Data collection was carried out each cruise, during 21 hours, in order to obtain a quasi-synoptic picture of the hydrographic and nepheloid structures (Fig. 3.8). Hydrographical parameters of the water column as salinity (from the conductivity), temperature and depth (from the density) were obtained, and the potential temperature (θ) and potential density (sigma-t) were computed. Turbidity measured was also related to SSC in the water using the calibration equation [1.2]. The measured and calculated hydrographic parameters were represented using the Ocean Data View (ODV) software, which is used for analysis and visualization of oceanographic profiles (Schlitzer, 2010).

![Figure 3.8 Location of the two hydrographic transects (dark red dots indicate each CTD stations) repeated during each COSTEM cruise.](image)

### 3.4 Sediment samples

A representative number of bottom sediment samples distributed along the GoV margin (Fig. 3.8) were collected in order to analyze the grain size and the sedimentation accumulation rate (SAR). A total of 11 sediment cores were collected over the continental slope and central basin (exact location in Table 3.8) using a KC-Denmark Multicorer, which has 6 polycarbonate tubes, each 60 cm long and Ø 10cm (Fig. 3.10).
Figure 3.9 Location of the sediment samples collected during COSTEM-2 (red), COSTEM-3 (green) and COSTEM-4 (blue) oceanographic cruises.

<table>
<thead>
<tr>
<th>Cruise</th>
<th>Sample</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Depth (m)</th>
<th>Length (cm)</th>
<th>Dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>COSTEM-2</td>
<td>MC-A</td>
<td>0º 30.98’ E</td>
<td>39º 38.42’ N</td>
<td>504</td>
<td>44</td>
<td>22/09/2010</td>
</tr>
<tr>
<td></td>
<td>MC-B</td>
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<td>39º 30.09’ N</td>
<td>550.9</td>
<td>22</td>
<td>22/09/2010</td>
</tr>
<tr>
<td></td>
<td>MC-C</td>
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<td>39º 21.3’ N</td>
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<td>28</td>
<td>22/09/2010</td>
</tr>
<tr>
<td>COSTEM-3</td>
<td>MC-1</td>
<td>0º 03.72’ E</td>
<td>39º 18.36’ N</td>
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<td>41</td>
<td>12/02/2011</td>
</tr>
<tr>
<td></td>
<td>MC-2</td>
<td>0º 04.16’ E</td>
<td>39º 18.33’ N</td>
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<td>12/02/2011</td>
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<tr>
<td></td>
<td>MC-3</td>
<td>0º 04.66’ E</td>
<td>39º 18.26’ N</td>
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<td>42</td>
<td>12/02/2011</td>
</tr>
<tr>
<td></td>
<td>MC-4</td>
<td>0º 05.36’ E</td>
<td>39º 18.24’ N</td>
<td>410</td>
<td>46</td>
<td>12/02/2011</td>
</tr>
<tr>
<td>COSTEM-4</td>
<td>MC-1</td>
<td>0º 09.72’ E</td>
<td>39º 09.14’ N</td>
<td>333.2</td>
<td>41</td>
<td>06/06/2011</td>
</tr>
<tr>
<td></td>
<td>MC-2</td>
<td>0º 10.05’ E</td>
<td>39º 09.37’ N</td>
<td>383.3</td>
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<td>06/06/2011</td>
</tr>
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<td></td>
<td>MC-3</td>
<td>0º 10.29’ E</td>
<td>39º 09.57’ N</td>
<td>451.4</td>
<td>39</td>
<td>06/06/2011</td>
</tr>
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<td>MC-4</td>
<td>0º 10.62’ E</td>
<td>39º 09.80’ N</td>
<td>502.4</td>
<td>44</td>
<td>06/06/2011</td>
</tr>
</tbody>
</table>

Table 3.4 Location, depths and dates of the collected sediment samples

During COSTEM-2 cruise three sediment samples, with lengths from 22 to 44 cm, were collected in each one of the standard mooring locations (red dots, Fig. 3.9), to compare the sediment samples with the contemporary annual advective and downward fluxes, and to identify any possible compositional changes over the margin. In addition, during cruises COSTEM-3 and 4, eight sediment cores with lengths from 38 to 46 cm, were collected across the sediment undulations (green and blue, respectively, Fig. 3.9).
3.4.1 Grain size

Grain size over the study area of the GoV continental slope was determined from a dried non-homogenized part (~ 0.3-0.4 g of the total sample) of the 11 sediment sample collected (Fig. 3.9). Immediately after retrieval, the sediment cores, with lengths from 22 to 46 cm, were sub sampled on board in slices of 1 cm thick and were stored in sealed plastic bags at 4 °C for later analysis. Sediment samples were dried in the oven at 40 °C, and a representative aliquot of each slice was used for determination of the grain size. Each sample was treated with 20% H₂O₂ and pyrophosphate in order to eliminate the organic matter, and to avoid particle flocculation. After the treatment of the samples, a Horiba LA950 particle size analyzer (Horiba Ltd., Kyoto, Japan) was used to determine the grain size distribution of the sediment as volume percentage.

3.2.1. $^{210}$Pb analysis

Sediment accumulation rates (SARs) were determined from the eight sediment cores collected across the sediment waves (green and blue dots in Fig. 3.9), during the COSTEM 3 and 4 oceanographic cruises (Table 3.8). After dried, part of the samples was homogenized in an agate mortar for the determination of the concentration of $^{210}$Pb, in order to compute the SARs during approximately the last century. The analyses of
$^{210}$Pb were conducted in 200-300 mg (dry weight) samples following using a method described in (Sanchez-Cabeza et al., 1998). Since $^{210}$Pb cannot be measured directly by alpha spectrometry, and samples were spiked with a known amount of $^{209}$Po as a tracer and acid-digested using a microwave. The concentration of $^{210}$Pb was calculated through the quantification of the activity of its grand-daughter $^{210}$Po (determined from samples by leaching of a sediment aliquot, making the final solution 0.3 M HCL and depositing polonium isotopes onto copper discs), assumed to be in equilibrium, by alpha spectrometry. SARs were estimated by using the CRS (constant rate supply) and CF-CS (constant flux-constant sedimentation) models. Accumulation rates are expressed as mass per unit area per time, which are more consistent for inter-core comparison because they are independent of porosity differences (Nittrouer et al. 1979). The $^{210}$Pb content analysis and the dating are being carried out in the Laboratori de Radioactivitat Ambiental of the Universitat Autònoma de Barcelona (UAB).

3.5 Multibeam echo-sounding

A large part of this Thesis is based on the interpretation of multibeam bathymetric dataset. The swath bathymetry coverage of the Ebro margin and GoV amounts over 18500 km² (Fig. 3.11), and is a composition of different datasets obtained during several surveys. These bathymetric datasets were mainly acquired to map the Spanish Exclusive Economic Zone (ZEE) using a Simrad EM12S multibeam echosounder (12.5 kHz), onboard the BIO Hespérides, during the years 1995 and 1996. The multibeam mosaic was completed and extended with bathymetric data acquired in July 2002 around the Columbretes Islands during the BALCOM cruise, on board R/V Vizconde de Eza, using a Simrad EM300 system (30 kHz), obtained from the collaboration with the Instituto Español de Oceanografía (IEO). Further bathymetric data were acquired from 2008 to 2011, in the frame of the National Projects CASCADES and COSTEM, using the SeaBeam 1050D dual frequency (50 and 180 kHz) multibeam echosounder mounted on the R/V García del Cid (Fig. 3.11). Finally, a much recent high-resolution multibeam data was acquired in April 2011 on board the R/V Vizconde de Eza using the Simrad EM300 multibeam echosounder as part of the CAPESME (Proyecto CArtas de PESca
del MEditerráneo) program, obtained from the collaboration with TRAGSATEC-Secretaria General de Pesca. This dataset has been used in this study for a detailed seafloor morphology description (see Chapter 7).

![Figure 3.11 Areas covered by swath bathymetry building the bathymetric mosaic from the Valencia Trough to the Gulf of Valencia.](image)

All bathymetric datasets were corrected for heading, depth, pitch, heave and roll, and the post-processing was conducted using the HIPS & SIPS system, the mapping and processing software developed by CARIS. The processed multibeam surfaces were exported into ASCII format files and imported into ArcGIS software, in which the Digital Terrain Models (DTM) were created for further analysis. From the created DTM, detailed geo-referenced shaded-relief image are created by considering the illumination source angle and shadows, and shows the intensity of lighting on the studied surface given a light source at a particular location. In this Thesis shaded-relief images have sun-
illumination with an azimuth of 315° and elevation of 45° and three times vertically exaggerated to accentuate the morphologic details on the bedforms. All images are presented using a UTM 31N zone projection in the WGS 1984 geographic coordinate system. In addition, slope gradient maps are also derived from the DTM, by calculating the maximum rate of change from a cell to its neighbors. The slope gradient map is used to indicate the steepness of the terrain (see Chapter 7).

3.5.1 Morphological parameters

Several undulated features have been observed all over the GoV continental margin, being the most notorious ones developed over the continental slope. Two main sediment waves’ fields can be identified, and a morphobathymetric analysis has been performed in order to characterize such features.

More than 1000 equidistant transects orthogonal to the sediment wave crests were drawn using the ArcGIS software (Fig. 3.12A) to determine the morphometric parameters of each undulations in every bathymetric profile.

An automated procedure was used to detect the crests (peaks) and troughs locations of each undulation (Fig 3.12B) along the bathymetric profiles (using Matlab script peakdet.m), after removing the noise with a low-pass data filtering step. The morphological parameters were computed (also using Matlab to automate the calculations) following the notations from Knaapen (2005). Since the study area is located in a steep continental slope, the slope correction has been taking into account in all parameter calculations (Fig. 3.12C).

The wavelength (L), or spacing between two concurrent sediment waves, is determined from trough to trough (Fig. 3.12C), and calculated following the equation:

\[ L = \left( (x_2 - x_1) + (z_2 - z_1) \right)^{1/2} \]  \[1.6\]

The base of the wave is defined by the line connecting the adjacent troughs, and the height (h) is defined vertically from the crest to the baseline, taking into account the slope correction (Fig. 3.12C).
Figure 3.12 A) Location of the orthogonal transects to the sediment waves crests of the northern (green lines, 505 transects) and central (dark red lines, 502 transects) fields over the Gulf of Valencia continental slope. B) Example of a bathymetric profile, indicating what is considered a single sediment wave (green and red asterisk represent the peak and troughs positions). C) Scheme of the sediment wave geometric parameters. L: wavelength; L$_1$: upslope wavelength; L$_2$: downslope wavelength; h: wave height (with slope correction); Z$_c$: depth of the crest, Z$_1$ and Z$_2$: depth of the upslope and downslope troughs, respectively; X$_c$: position of the sediment wave crest along the bathymetric profile; X$_1$ and X$_2$: positions of the upslope and downslope troughs along the bathymetric profile, respectively; α: angle of slope.

If the downslope flank (L$_2$) is defined as the distance between crest and the seaward trough (Fig. 3.12C), then:

$$L_2 = \frac{[L^2 - [(x_c - x_1)^2 + (z_c - z_1)^2] + [(x_2 - x_c)^2 + (z_c - z_2)^2]]}{2L}$$ \hspace{1cm} [1.7]

and subsequently, the wave height (h) can be calculated as:

$$h = \left(\left[(x_2 - x_c)^2 + (z_c - z_2)^2\right] - L_2^2\right)^{1/2}$$ \hspace{1cm} [1.8]
The asymmetry index (AI) is also determined from the shape of the sediment waves. It is defined as the difference of the distance between the trough north of the crest and the distance between the crest and the trough south of the crest divided by the wavelength (Knaapen, 2005):

$$AI = \frac{L_2 - L_1}{L}$$

where $L_1$ is the upslope flank length (distance between upslope trough and crest), and can be calculated as $L_1=L-L_2$.

In contrast to other studies describing sediment undulations, here the terms “stoss side” and “lee side” are not used; instead, upslope and downslope are referred to the regional seaward slope of the GoV continental slope.

Thus, $AI = 0$ (± 0.05) indicates the presence of symmetric bedforms; negative AI values indicate a downslope asymmetry and positive AI values indicate an up-slope asymmetry. The bedform steepness, defined as the sediment undulations height divided by the undulations length (h/L), was also computed in order to determine the location of the steeper bedforms along the continental slope.

### 3.6 Seismic dataset

#### 3.6.1 3.5 kHz parametric sub-bottom profiles (TOPAS)

Two high-resolution seismic profiles across the GoV continental margin were obtained with a TOPAS PS018 parametric echosounder, using a sampling frequency band of 16-20 kHz, on board the R/V Vizconde de Eza by the IEO. The profiles were acquired over the GoV outer continental shelf and slope in a WSW-ENE orientation (70°-250°) along the northern sector of the continental slope, and a SW-NE orientation (40°-220°) along the central sector (Fig 3.13).

The data was given processed (using the TOPAS software) and in SEG-Y format, and the profiles shown here were interpreted in this Thesis using the KingdomSuite software. A constant sound velocity of 1550 m/s has been assumed to transform the sub-bottom depths (given in two way travel time (TWTT) in seconds) in both profiles.
3.6.2 Single-channel (Sparker) seismic reflection profiles

Several single-channel seismic profiles were acquired in October 2011 during the COSTEM-5 oceanographic cruise, in collaboration with the Renard Centre of Marine Geology (RCMG) of the Ghent University. During this seismic survey nine seismic lines were performed, covering approximately 345 line kilometers, distributed in two sets: one set of seven lines perpendicular to the GoV continental slope, and another set of two cross lines, following the bathymetry (Fig. 3.13). These high-resolution single-channel seismic lines where acquired using a SIG Sparker source (120 electrodes). The 600 Joules Sparker source was triggered every 3 seconds while the vessel during Sparker seismic data acquisition was maintained at ~ 3.5 knots.

Single-channel profiles were recorded with a surface streamer using Delph Seismic 2.7.0.0 (Ixsea) acquisition system. Data were pre-filtered using an 80-2000 Hz analogue bandpass filter. The seismic lines were recorded directly in SegY-Motorola format with associated navigation files. The sampling frequency was set to 10 kHz and a record length of 2.8 seconds two way travel time (TWTT) was used. Processing of the data was performed using the seismic processing software RadExPro (Deco Geophysical), while interpretation was performed using the KingdomSuite software (see Chapter 9).

Processing steps of the single-channel lines where: banpass filtering (Ormsby bandpass filter, specifying four frequencies in Hz, which consistently define the 0% and 100% points of signal gating from the side of lower frequencies and 100% and 0% points of signal gating from the side of higher frequencies); remove water noise (picking seafloor, used as a corrector factor with trace math (trace/scalar) module); burst noise removal (removal of high-amplitude noise bursts from the seismic traces); amplitude correction (spherical divergence correction: applies gain function variable in time to traces, allowing compensation for amplitude loss during spherical divergence of wavefront); trace editing (only applied in some cases (top muting or trace killing), if individual traces with error are still not corrected with the previous processing flows).
3.6.3 Multi-channel (Airgun) seismic reflection profiles

Multi-channel (Airgun) seismic reflection data were acquired along ~ 2800 km (Fig. 3.13) in October 2001 by Fugro Geoteam on the vessel R/V Geo-Baltic, and were obtained from the Spanish Ministry of Industry, Energy and Tourism. The seismic profiles were acquired with using Sodera G guns, with a source depth of 6 (+/- 0.5) m, and the length of the streamer was of 6 km, with a depth of 8 (+/- 1) m. The shotpoint interval was of 23 m with a sampling rate of 2 milliseconds (ms). Multi-channel seismic lines had been processed by Robertson Research International LTD. Major processing steps involved: signature deconvolution (using supplied signature output to minimum phase); amplitude compensation (T-Squared); filtering (anti-alias K filter with trace drop; to 240 Channels @ 25 m); shot noise attenuation (using 1250 m/s dip filter); pre-stack time migration (1500 m/s constant velocity F-K migration); gain recovery (removal...
of gain applied step 4 time-velocity squared spherical correction applied using stacking velocities and 2 dB/s to 5.0 s absorption compensation; datum correction (to mean sea level static: correction for shot and cable at water velocity +9.0 ms); bandpass filter; among others. Multi-channel lines interpretation and map generation were performed in this Thesis using the Kingdom Suite software (see Chapter 9).

3.6.4 Industrial wells

In addition to the seismic profiles, information from three industrial drilling holes was also supplied by the ATH: boreholes 354: Marina del Turia E-1; 328: Denia-1; and 444: Golfo Valencia F-1 (Fig. 3.14).

![Figure 3.14 Location of the industrial wells.](image)

Velocities for the depth conversion were taken from the information given in the reports of the industrial wells. A mean velocity of 1550 m/s for the Upper-Quaternary (Holocene) sediments, used mainly to transform the sub-bottom depths (sub-bottom profiles). A mean velocity of 2290 m/s was used for the Pliocene-Pleistocene units, and a velocity of 3400 m/s was used to determine the Miocene/Pliocene boundary (i.e. Top Messinian Salinity Crisis surface). A velocity of 1524 m/s for the water sound velocity was imposed for the study site.
Chapter 4

Hydrographic structure and particulate matter distribution

4.1 Introduction

In the Gulf of Valencia the hydrographic structure is dominated by the presence of the Northern Current, carrying old Atlantic Waters (oAW) southwestwards, which converges with intrusions of recent Atlantic Waters (rAW) flowing northwards (Fig. 4.1). Several studies analyzing the hydrography of the western Mediterranean Sea, and in particular of the southwestern end of the Balearic Sea, have identified three water masses below the surface layer (150-200 m water depth) (Salat and Cruzado, 1981; Millot, 1987; Millot, 1991; Millot, 1999; Pinot et al., 1999, 2002):

- Western Mediterranean Intermediate Water (WIW; formerly called Winter Intermeditae Water): formed in winter near the continental slope in the northern part of the Catalan Sea and Gulf of Lions (Salat and Font, 1987). Throughout the year the influence of WIW is noted by subsurface temperature minimum in the water column (Font, 1987), of 12.5-13ºC, and a salinity of 38.1-38.3.

- Levantine Intermediate Water (LIW): enters the region from the Strait of Sicily with the characteristics 14ºC and 38.75.

- Western Mediterranean Deep Waters (DWMW; formerly called Deep Western Mediterranean Water): with low temperatures of 12.75-12.9ºC and salinities of 38.4-38.48.

The occurrence of mesoscale eddies in the GoV has been described by several authors (La Violette et al., 1990, García et al., 1994, Pinot et al., 1995, 1999, 2002). Some of the observed anticyclonic eddies have been found trapped near the slope region of the inner GoV, south of the Columbretes Islands, where the narrowing of the shelf is affecting the circulation (Fig. 4.1). In addition, as mentioned in the Introduction of this Thesis, several authors observed that contemporary sediment transport on the Ebro continental margin is mainly along-shelf and towards the SSW, with near negligible cross-margin component (Puig et al., 2001; Palanques et al., 2002; Palanques et al., 2005). However, there are no studies focusing on the sediment dynamics southern from the Ebro shelf, on the GoV margin (see Chapter 1). In this chapter the hydrographic
structure is described and related to the circulation and distribution of the nepheloid layers on the GoV continental margin, improving the understanding of the sediment dynamics over this area.

Figure 4.1 Map of the Gulf of Valencia showing the position of the CTD stations analyzed in this chapter (red dots) and the additional CTD stations used to compute the geostrophic field (orange dots). Transects A-A’, B-B’, C-C’, D-D’, and the stations in which each vertical profile was examined (Fig. 4.3A, B, C and D) are also shown in this map. Inner shelf circulation is indicated with simple arrows based on Han et al (1983). General surface circulation is indicated with filled arrows, and dashed filled arrows indicate mesoscale structures, as anticyclonic eddies, based on Pinot et al. (2002).

4.2 Results and Discussion

4.2.1 Water masses and Suspended Sediment Concentration on the Gulf of Valencia

Hydrographic information of the CTDs from the Meso’95 (see Chapter 3) has been plotted in a $\theta$-S diagram, where the color scale represents the SSC parameter (Fig.
Surface waters in June 1995 were mainly warm (~ 20 – 22.6 °C) and showed relatively low salinity (36.8 – 38) and SSC values (≤ 0.3 mg/l). Below surface waters, the general θ-S diagram shows two main branches that converge, confirming the presence of two AW masses clearly different in salinity: the oAW, more saline and the less saline rAW (Fig. 4.2). The rAW had much lower concentrations of particulate matter than the oAW. There were however some CTD casts with high SSC in the rAW near the bottom at stations located over the Ibiza shelf. Maximum SSC values of 1.88 mg/l (out of scale in Fig.4.2) were observed at the region where the oAW and rAW merged (S = 38 and θ = 14 °C).

By looking at the θ-S profiles from individual CTD casts (dashed line in Fig.4.2), it could be observed that in the convergence region between the two water masses, the oAW flowed below the rAW. From 200 m to 400 m, the WIW was found, characterized by a temperature relative minimum of 12.7 °C and a salinity of 38.1, SSC values recorded in this water mass ranged between 0.3 and 0.88 mg/l (Fig. 4.2).
The LIW was observed between 400 m and 700 m, characterized by both temperature and salinity relative maxima 13.3 °C and 38.5, respectively, and high values of SSC, with concentrations up to 1.21 mg/l. Below 700 m, the water column was occupied by the Western Mediterranean Deep Waters (WMDW) that could be identified by temperature and salinity relative minima 13 °C and 38.4, respectively, and showed minimum SSC values of ≤ 0.28 m/l. Although the clearest waters were found in the WMDW at the deepest part of the water column, it has to be noticed that LIW exhibited higher values of SSC, in the transition between the LIW and the WMDW (Fig. 4.2).

### 4.2.2 Particulate matter distribution

The particulate matter distribution along the GoV margin was analyzed, and some differences were found comparing the northern, central and southern part of the margin. Four SSC and fluorometer vertical profiles, located at similar depths, were compared between them in order to illustrate their distribution over the slope more accurately (Fig. 4.3). In the north of the GoV there were nearly no particulate matter detachments (Fig. 4.3A and B), however, a continuous surface nepheloid layer (SNL) was observed with maximum sediment concentrations of 0.5 mg/l, coinciding with increases in the fluorescence signal, indicating presence of biogenic particles in this layer.

On the central and southern part of the basin, slope intermediate nepheloid layers (INLs) were identified between 400 – 600 m, and a bottom nepheloid layer (BNL) ~100 m thick, was observed from 750 to 850 m (Fig. 4.3C). Over the Ibiza Sill, no BNL was present, but a large INL detachment from the shelf-break off Cap La Nao reached this area and was clearly noticeable (Fig. 4.3D).

Additionally, the SNL also had much higher concentrations (up to 0.8 mg/l) along the Ibiza Channel than in other parts of the slope (Fig. 4.3). It has to be noted that fluorescence signal was high coinciding with the SNL and rapidly decreased to minimum values at the shelf-break INL, indicating that phytoplankton was only present in the SNL layer (Fig. 4.3D). Overall, high turbidity in the CTD profiles corresponded to surface, bottom and intermediate nepheloid layers, observed only at specific locations along the margin.
Figure 4.3 Suspended sediment concentrations (SSC) profiles (solid line) and fluorescence profiles (dashed line) along the GoV continental slope during the MESO95 cruise in June 1995. Several particulate matter detachments can be observed in different locations of the study area (SNL: Surface Nepheloid Layer; Slope INL (Intermediate Nepheloid Layer); Shelf-break INL; BNL: Bottom Nepheloid Layer). The CTD locations are indicated in Figure 4.1.

The relationship between these nepheloid layers and vertical and horizontal distributions of temperature, salinity and fluorescence in the water column is represented along four main hydrographic transects, A, B, C and D (Figs. 4.4 to 4.7).

Transect A crosses the north of the GoV, in NW-SE direction, from south of the Columbretes Islands to Ibiza (Fig.4.1). In this transect, oAW was observed between 100 – 150 m, at the northwestern side, while warmer and fresher rAW was located at the southeastern side (Fig. 4.4). A SNL was present along the whole hydrographic transect, with SSC ≥ 0.3 mg l⁻¹, and a clear coincidence with high fluorescence. Over the northern GoV shelf, a small bottom nepheloid layer (BNL) with SSC ~ 0.5 mg l⁻¹ was observed. At the Ibiza slope, an intermediate nepheloid layer (INL) with a maximum of SSC of 0.4 mg l⁻¹ was developed below the LIW, between 300 – 500 m. The WMDW occupied the deeper part of the region of the GoV region, showing SSC values ≤ 0.25 mg l⁻¹ (Fig. 4.4).
Transect B, also in NW-SE direction, shows the hydrographic distribution at the southern part of the GoV, crossing the margin GoV outer shelf to the middle part of the Ibiza Channel (Fig. 4.1). The oAW was again located at its northwestern side, and rAW, with lower temperatures and salinities, at its southeastern side (Fig. 4.5). A wide SNL, again with high fluorescence, covering the entire transect was observed (Fig. 4.5), and a
thick BNL was present over the GoV shelf which extended off-shelf forming an INL particulate matter detachment at the shelf-break with SSC maximum values of 0.6 mg l\(^{-1}\). At the southeastern side of this transect, over the Ibiza Channel, concentrations of 0.4 mg/l were also observed at the same shelf-break depth range (Fig. 4.5). The LIW here was found between 400 – 600 m, with a salinity core > 38.5 between 500 – 600 m. From 400 – 800 m, a well-developed BNL with SSC values > 0.4 mg l\(^{-1}\) was observed along the transect covering the entire south GoV continental slope.

Transect C, oriented in SW-NE direction, crosses the Valencia Trough from the southern GoV continental shelf to the deepest parts of the basin (Fig. 1). Only oAW was identified in this transect without any presence of rAW intrusions (Fig. 4.6). The SNL also coincided with high fluorescence values. The shelf BNL was less developed than the previous transects, and the shelf-break INL detachment was absent (Fig. 4.6). The LIW was identified from 300 to 600 m, and a slope INL was observed, with SSC values of 0.4 mg l\(^{-1}\), at around 500 m. This INL coincided with the BNL seen in transect B crossing obliquely the southern GoV continental slope. Below the slope INL, clear waters, corresponding to the WMDW, were found in the middle of the basin as in the previous transects.

![Figure 4.6](image-url) Figure 4.6 Cross-margin section along transect C showing the temperature, salinity, fluorescence, and suspended sediment concentration (SSC), during June 1995. (The gap in the data was caused because the CTD cast did not arrive to the bottom). The transect location is indicated in Fig. 4.1.
Transect D follows the Ibiza Channel, from Cap La Nao to the southwestern part of Ibiza (Fig. 4.1). Here (Fig. 4.7), rAW were observed along the entire transect at surface and the oAW was found at subsurface levels (Fig. 4.2). High values of fluorescence and SSC were observed near the surface, and a BNL, with SSC values of 0.6 mg/l, was also developed over the GoV shelf. At shelf-break depths, a large INL detachment was observed extending 50 km offshore, almost covering the whole Ibiza Channel (Fig. 4.7). The LIW here was found between 400 – 600 m and a weak increase of SSC > 0.3 mg/ l was observed at 500 m, where it intersected the seafloor on the Valencia continental slope. Below the LIW no BNLs were observed over the Ibiza Sill (Fig. 4.7).

4.2.3 Geostrophic circulation

CTD data from the GoV and from the nearby hydrographic transects towards the northeast (Fig. 4.1) were also used to calculate geostrophic currents in the study area during the cruise at 100 m, referenced to 400 m (Fig. 4.8). The general current, the Northern Current was flowing from the north along the continental slope. An anticyclonic eddy south of the Columbretes Islands and a cyclonic eddy in the middle of GoV were also observed. The presence of the anticyclonic eddy constrained part of the
main jet to turn westwards, forcing the current to flow towards the Valencia continental shelf (Fig. 4.8).

![Figure 4.8](image_url)

**Figure 4.8** Calculated geostrophic velocity on the study area, at a depth of 100 m, relative to 400 m. Interpreted geostrophic current has been indicated with simple arrows. The 100 m isobaths is indicated in a grey color and the dashed line separates the regions where the oAW and rAW circulate.

No indications of the Northern Current crossing the Ibiza Channel were found during the cruise, although, an eastward flow was observed, corresponding to the retroflection of the Northern Current that contributes to the Balearic Current. Intrusions of rAW from the southern part of Cap La Nao through the Ibiza Channel were also observed (Fig. 4.8). These rAW intrusions mainly formed the Balearic Current, flowing northeastwards along the Ibiza continental slope. As it has been mentioned in the introduction, the circulation along the Ebro continental margin is mainly controlled by the general southwestward circulation of the Catalan Sea. Several authors have described permanent features at the GoV, such as recurrent anticyclonic eddies near the Ibiza Channel area, interacting with the topography and directly affecting the channel water exchange, with seasonal and mesoscale variability (Castellón et al., 1990; Pinot et al., 1995; Pinot and Ganachaud, 1999; Pinot et al., 2002). During the present cruise, on June 1995, an anticyclonic eddy was found south of the Columbretes Islands, probably produced by the current interactions with the seafloor where the shelf becomes narrower. In this region, the sediment transported along the shelf was presumably blocked by this
anticyclonic eddy and the associated current jet directed towards the continental shelf, and thus forced to continue southwards. In addition, a cyclonic eddy was apparent in the middle of the GoV, presumably by the obstruction caused by the retroflection of the Northern Current (Fig. 8). Both eddies were concordant with the previous observations of Pinot et al. (2002). At the southeastern part of the GoV, intrusions of rAW were observed, flowing from south of the promontory Cap La Nao, along the continental shelf and slope.

4.2.4 Water masses and nepheloid layer distribution

The nepheloid layer structure along the GoV was analyzed, and similar suspended sediment distribution was found at the GoV shelf, south from the Columbretes Islands where the shelf width diminishes drastically, and off Valencia where the shelf is narrow, around 20 km. As it has been described above, a continuous SNL was observed along the GoV margin, and only small detachments from the shelf BNL at shelf-break depths were seen on the northern GoV shelf (Fig. 4.3A and B, and Fig. 4.4).

On the central part of the GoV, in addition to the SNL, intermediate suspended sediment detachments generating a slope INL were observed along the margin. INLs frequently occur off the upper slope areas, whereas BNL usually extend from the continental shelf to the deep-sea (McCave, 2001). In the GoV, such INLs were centered at 500 m, coinciding with the base of the LIW, and showing concentrations > 0.4 mg/l (Fig. 4.3C and Fig. 4.6). Towards the southern GoV continental slope, a continuous BNL was observed extending down to 850 m (Fig. 4.3C and Fig. 4.5). Additionally, on the southern GoV shelf, an important shelf-break INL detachment was also detected along the Ibiza Channel, reaching as far as 50 km away from the margin (Fig. 4.3D and Fig. 4.7). It has to be noticed that the SNL maximum at subsurface levels was well developed in the region where the oAW and rAW converged (Figs. 4.2 and 4.7). As it has been shown in Figure 3D, high fluorescence values were only seen within the SNL, and not in the shelf-break INL, which indicated that it contained mainly terrigenous suspended particles. Comparing the GoV nepheloid distribution with the one observed in the Barcelona margin by Puig and Palanques (1998), it can be seen that in both areas the
highest surface particulate matter concentrations are restricted to near the coast and over
the shelf. Also, particulate matter detachments (i.e. INLs) have been observed in both
areas on the shelf-break and over the slope where the LIW interacts with the seafloor, at
around 400 m in the Barcelona margin, and around 500 m in the GoV margin. According
to Puig and Palanques (1998) the slope INL on the Barcelona margin is controlled by the
shelf-slope density front and by the Northern Current, and probably re-fed by the
submarine canyons incised on the margin. However, neither submarine canyons are
present on the GoV nor the Northern Current follows the upper continental slope.
Therefore, the presence of the slope INL in the GoV is mainly related to the LIW
interaction with the seafloor, causing particulate matter detachments, possibly generated
and/or maintained by internal waves at the continental slope. The results presented in this
Chapter suggest that both the slope INL and BNL observed on the central and southern
part of the GoV could be related to the presence of internal waves. However, this data
still do not allow us to discriminate if the possible internal waves cause active
resuspension or if the suspended sediment is retained, concentrated and maintained in
these nepheloid layers by the effect of the internal waves on the GoV after suspended
particles have been advected from the shelf towards the continental slope. The spatial
distribution of near-bottom SSC on the GoV continental margin shows that high
particulate matter concentrations were recorded along the margin, being limited at the
upper continental slope by the density gradient of the Continental front (Fig. 4.9).

**Figure 4.9** Distribution map of near-bottom density (A) and suspended sediment concentration (SSC) (B) during the survey in mid June 1995. The dashed line in (B) indicates the isopycnal of 29.1 kg/m$^3$ which determines the location of the base of the shelf/slope density front.
This density gradient (Fig. 9A), produced by the two water masses LIW and WMDW, retains the sediment particles at the base of the LIW, as shown in the θ-S diagram (Fig. 2). On the Ibiza slope another density front, the Balearic Front, was also observed (Fig. 9A), with a stronger gradient caused by the rAW intrusions contributing to the Balearic Current, but without having large SSC associated to it (Fig. 9B). Two large near-bottom SSC peaks of 0.99 mg/l and 1.17 mg/l were seen in the GoV slope at the base of the Continental front at a density of 29.1 kg/m³ (Fig. 9B). The link between the basis of the Continental density front and the isopycnal was also seen in other areas of the NW Mediterranean, such as on the Barcelona continental margin (Puig and Palanques, 1998). The first SSC peak was observed at the slope off Valencia, at a depth of 647 m, and the second one in the southern part of the GoV, in the region where the slope changes orientation, at 841 m, much deeper but still at the basis of the Continental front (Fig. 9b). Both maxima were associated with the presence of the slope INL and BNL along the GoV slope, at the lower limit of the LIW (Figs. 4.2, 4.5 and 4.6).

4.2.5 Off-shelf sediment transport

As mentioned in the introduction of this Thesis (see Chapter 1), the results from previous studies conducted on the Ebro shelf (Cacchione et al., 1990; Palanques et al., 2002) suggested that most of the off-shelf sediment transport in the Ebro margin could occur somewhere on the GoV margin, where the shelf width decreases dramatically from hundreds of kilometres to tens of kilometres, south of the Columbretes Islands. However, the results here presented showed that the off-shelf sediment transport in the GoV occurs mainly at the southern end, off Cap La Nao promontory, where a large shelf-break INL detachment was observed. In this location, the margin changes the orientation, which could favor the off-shelf transport, but most importantly, it is where the oAW, carried by the Northern Current and rAW intrusions from the south, generally merge. Particulate matter transported by the oAW flowing from the Ebro shelf to the Valencia shelf, when arriving to the Cap La Nao promontory, is forced to flow beneath the rAW (Fig. 4.2) and be detached off-shelf (Fig. 4.7). Moreover, the rAW intrusion through the Ibiza Channel, that generates the Balearic Current, allows the sediment be transported along the shelf
within the oAW layer to extend seaward for a long distance and to create a well-developed shelf-break INL detachment covering the entire Ibiza Channel extension from west to east (Fig. 4.7).

The GoV can be compared with the nearby Gulf of Lions (GoL), also located in the northwestern Mediterranean, because in both areas there are large amounts of sediment supplied by rivers and transported along the continental shelf, which narrows in the vicinity of a promontory, the Cap de Creus promontory in the GoL and the Cap La Nao promontory in the GoV. In the GoL, shelf sediments can be resuspended by storms and/or cascading and exported to the slope. The off-shelf transport, occurs mainly associated with storm-induced downwelling and dense shelf water cascading events (Palanques et al., 2006; Canals et al., 2006; Ulses et al., 2008; Puig et al., 2008; Ribó et al., 2011). The connection between the sediment along the continental shelf and the deep sea occurs through the southwesternmost submarine canyon, the Cap de Creus canyon, which is the final outlet before the constriction of the Cap de Creus promontory (Palanques et al., 2006). In comparison, there are no submarine canyons on the GoV slope, and the southward outlet of the GoV shelf sediment takes place by shelf break INL detachments from Cap La Nao promontory. The off-shelf sediment transport in this area is induced by the narrowing of the shelf, but also by the intrusion of rAW through the Ibiza Channel, which advects the oAW off-shelf. Such a convergence of the two water masses around the Cap La Nao promontory seems to be an important factor in the off-shelf sediment transport in the GoV.
Chapter 5

Advective and downward particulate fluxes
5.2 Introduction

During the last decades, research into particulate matter vertical fluxes has focussed in the study of transport and budget of matter on continental margins (Biscaye et al., 1988; Monaco et al., 1990; Biscaye and Anderson, 1994). Settling particles are responsible for much of the transport of matter and energy from the upper ocean to the sea floor (Asper et al., 1992). This transport is especially important in continental margins due to the large material inputs from both terrestrial and high productivity waters of this zone, which play an important role in the global oceanic biogeochemical cycles (Walsh, 1991). The particulate matter distribution in the water column is highly influenced by the hydrographic structure and hydrodynamic processes. Physical gradients such as the thermocline and shelf-slope density fronts (Palanques and Biscaye, 1992) and main flows like geostrophic currents (Baker and Hickey, 1986; Durrieu de Madron et al., 1990) are some of the common factors controlling particulate matter distributions and its transfer to open sea. Sediment traps have been considered the major oceanographic tool for collecting passively sinking particulate material (“particle flux”) in the ocean (Michaels et al., 1990), and sediment traps studies play and important role for the understanding of particulate matter transport processes and fluxes in the ocean water column on days-to-years time scale (Ittekkot et al, 1996). On the GoV margin it has been observed that sediment is transported along-shelf and mainly exported to the deeper regions through its southern shelf-edge, near the promontory Cap La Nao (see Chapter 4). Still, three standard moorings (see Chapter 3) equipped with current-meters and sediment traps were deployed during three periods, covering one year long, from May 2010 to June 2011, in order to characterize the temporal and spatial variability of particulate matter fluxes. Two moorings (short-type) were located at the upper-slope at ~500 m water depth, one at the head of a submarine canyon (mooring A), south of the Columbretes (Fig. 5.1), and the other one (mooring B) located under a wave buoy that “Puertos del Estado” maintains in the study area (39º 30.96’N 0º 12.28’E). The third mooring (long-type) was placed at the end of the Valencia Trough (mooring C, at ~1230 m depth), at the deepest part of the GoV (Fig. 5.1).
5.2 Results and discussion

5.2.1 Time series 2010-2011

Time series of in situ current speed and direction, in situ temperature ($\theta$) and suspended sediment concentration (SSC) were recorded by current meters included in each mooring. At mooring A, current speeds oscillated between 0 and 20 cm s$^{-1}$ (Fig. 5.2A). Low speed values (mean current $\sim$ 5 cm s$^{-1}$) were registered during the first two study periods, from mid-May 2010 to mid-February 2011. Afterwards, an increase of velocity magnitude was registered, lasting until the end of the third study period, beginning of June 2011.

The current direction on the canyon head was scattered, however a preferential direction towards the SSW (between 180 and 270$^\circ$), following the canyon axis direction. This preferential direction is identified during the three study periods (Fig. 5.2B).
Figure 5.2 Time series of A) in situ current speed (cm s\(^{-1}\)), B) current direction (º), C) in situ temperature, \(\theta\) (ºC) and D) suspended sediment concentration, SSC (mg l\(^{-1}\)) recorded by the current meter on mooring A from 20\(^{th}\) May 2010 to 4\(^{th}\) June 2011.

Figure 5.3 Time series of A) in situ current speed (cm s\(^{-1}\)), B) current direction (º), C) in situ temperature, \(\theta\) (ºC) and D) suspended sediment concentration, SSC (mg l\(^{-1}\)) recorded by the current meter on mooring B from 20\(^{th}\) May 2010 to 4\(^{th}\) June 2011.
Temperature registered at 5 mab on mooring A, showed values ranging between 13 and 13.3°C (Fig. 5.2C). At the beginning of the second study period, on mid-November 2010, there is a slight increase in the temperature, which lasted until the beginning of April 2011, when it decrease again down to ~ 13°C. Records of SSC showed very low values of turbidity during the two first periods, with a base line of 0.16 mg l⁻¹. An increase of SSC was recorded during the third study period, with values of up to 1.6 mg l⁻¹ (Fig. 5.2D).

At mooring B, also located ~500 m water depth, at the upper slope on the central part of the GoV margin (Fig. 5.1), the registered current velocities were much higher than on the canyon head, reaching values of up to 36 cm s⁻¹ (Fig. 5.3A). Current velocity at this site showed oscillations during the entire record, in motions with a periodicity from 5 to 11 days (Fig. 5.3A). The current direction also registered oscillations, following the same frequencies registered in the current velocities, and no preferential direction could be determined (Fig. 5.3B). Temperature ranged between 13 and 13.5°C (Fig. 5.3C), as observed in the submarine canyon head (Fig. 5.2C). During the first study period, from mid-May to mid-September 2010, temperature highly oscillated, coinciding with the variations registered in the current velocity (Fig. 5.3C). From the end of November 2010 and lasting until April 2011 temperature registered a slight increase (Fig. 5.3C), as it was also observed on the canyon head (Fig. 5.2C), but with a delay of almost two weeks. Turbidity records were again very low during the three study periods, with a mean SSC of 0.17 mg l⁻¹ (Fig. 5.3 D).

Mooring C was deployed at the center of the GoV basin, including two Aquadopp current-meters, one at mid-waters (C_i) and another one near the bottom (C_b), at 5 mab (Figs. 5.4 and 5.5). Maximum current speeds were of 18 and 21 cm s⁻¹, at C_i and C_b, respectively, showing concordant oscillations throughout the water column (Figs. 5.4A and 5.5A). Such oscillations had periodicities of ~ 20 days, during the first and half of the second study period. From mid-December 2010 the frequency of current oscillations increased registering motions with periodicities of 5-11 days until the end of the record, on the beginning of June 2011. Current direction showed a main preferential direction towards the SSW, starting to oscillate (with the same periodicities as the current speed) from the end of December 2010-beginning of January 2011 (Figs. 5.4B and 5.5.B).
Chapter 5. Sediment fluxes

Figure 5.4 Time series of A) in situ current speed (cm s\(^{-1}\)), B) current direction (º), C) in situ temperature, \( \theta \) (ºC) and D) suspended sediment concentration, SSC (mg l\(^{-1}\)) recorded by the current meter \( C_i \) on mooring C from 20\(^{th}\) May 2010 to 4\(^{th}\) June 2011.

Figure 5.5 Time series of A) in situ current speed (cm s\(^{-1}\)), B) current direction (º), C) in situ temperature, \( \theta \) (ºC) and D) suspended sediment concentration, SSC (mg l\(^{-1}\)) recorded by the current meter \( C_b \) on mooring C from 20\(^{th}\) May 2010 to 4\(^{th}\) June 2011.
Temperature at C_i ranged from 13 to 13.4°C, showing a slight increase from the beginning of January 2011 (Fig. 5.4C). Conversely, temperature at C_b maintained very constant values of 13.1°C (Fig. 5.5C). Turbidity maintained very low values at both depths, with a baseline of 0.16 mg l\(^{-1}\) (Fig. 5.4 and 5.5D). Increases of SSC were registered at C_i, however poor or nil correlation was observed with the current oscillations at the same depth (Fig. 5.4D).

5.2.2 Sediment samples

Three sediment samples were collected in each mooring site, in order to analyze the sediment composition and to identify any changes in the sediment deposition over the GoV margin in each location.

![Figure 5.6 Grain size diagrams of each of the sediment cores collected in A) mooring A, B) mooring B and C) mooring C locations.](image)

Core-A collected in the submarine canyon head, with a length of 44 cm (Fig. 5.6A), had a clear dominance of clay (up to 80%) a small fraction of silt (~ 15%) and barely no sand (~ 5%). Sediment samples collected at the upper-slope (Fig. 5.6B) and at the center of the GoV basin (Fig. 5.6C), with lengths of 22 and 28 respectively, showed similar sediment composition. These sediment samples showed a major fraction of silt (~ 65%) with a small amount of clay (~ 15%), and a sand portion of ~10% (Fig. 5.6B and 5.6C).
Clear lithological differences are observed between the sediment in the submarine canyon head (Fig. 5.5A) and on the open slope and basin (Fig. 5.5B and 5.5C). Finer sediments are observed in the canyon head, where also the current velocities were lower comparing to the open slope and in the middle of GoV basin, where the sediment fraction is coarser (Fig. 5.5).

5.2.3 Advective particle fluxes

Instantaneous sediment fluxes and cumulative sediment transport were estimated for each one of the mooring sites.

At the head of the submarine canyon (mooring A), sediment fluxes maintain very low values of ~ 10 mg m\(^{-2}\) s\(^{-1}\), during the first two study periods (Fig. 5.7A), which is concordant with the low current velocities and turbidity registered at this site (Fig. 5.5). From the end of the second period, beginning of February 2011 to the end of the record, beginning of June 2011, the sediment flux increased, and reached maximum peak values of ~ 100 mg m\(^{-2}\) s\(^{-1}\) (Fig. 5.7A). The computed cumulative transport showed that the sediment transport was mainly down-canyon, reaching values of ~ 0.02 T m\(^{-2}\), whilst across-canyon was almost negligible in a SSE direction (Fig. 5.7B). Sediment flux on the upper-slope of the central part of the GoV margin (mooring B) highly oscillated ranging in between 5 and 110 mg m\(^{-2}\) s\(^{-1}\) (Fig. 5.8A). Such variations were mainly enhanced by current fluctuations registered during the entire time series, since turbidity maintained constant low values (Fig. 5.3).

Cumulative sediment transport along-slope in a SSW direction was slightly higher than the across slope off-shore, with values of 0.1 and 0.22 T m\(^{-2}\), respectively (Fig. 5.8B). It is worth to notice that the current velocity magnitude was smaller in the submarine canyon head than on the open slope (Figs 5.2 and 5.3). Thus, the computed instantaneous sediment fluxes were also lower at the submarine canyon head (Fig. 5.7A) than on the upper-slope (Fig. 5.8A). In addition, cumulative sediment transport at the submarine canyon head (Fig. 5.7B) was one order of magnitude smaller than on the upper-slope (Fig. 5.8B).
Figure 5.7 Time series of A) instantaneous estimated sediment fluxes (mg m\(^{-2}\) s\(^{-1}\)) and B) cumulative sediment transport (T m\(^{-2}\)) for mooring A.

Figure 5.8 Time series of A) instantaneous estimated sediment fluxes (mg m\(^{-2}\) s\(^{-1}\)) and B) cumulative sediment transport (T m\(^{-2}\)) for mooring B.
The results here presented suggests that the sediment transport was mainly towards the SSW with a minor off-shore component, following the bathymetry over the continental shelf and upper-slope, and not channelized through the submarine canyon south from the Columbretes Islands (Fig. 5.1).

In the middle of the GoV basin, at ~ 500 m depth (Ci) the sediment fluxes were mainly smaller than on mooring A and mooring B sites, registering values between 0.5 and 58 mg m\(^{-2}\) s\(^{-1}\) (Fig. 5.9A). Several increases of sediment flux were registered, at the beginning of the time series, end of May 2010, and at the end of the record, April-May 2011, due to a peak of turbidity (Fig. 5.4D). At the end of the second study period, another sediment flux increase was observed, presumably produced by biofouling of the turbidity sensor (Fig. 5.9A). Such sediment flux increases were not affecting the computed cumulative transport, which was homogenously in a SSE direction, being higher the southern component, reaching 0.1 T m\(^{-2}\), twice the eastern component (Fig. 5.9B). At the same mooring site, near the seafloor (Cb), instantaneous sediment fluxes were higher at the beginning of the record, during the first study period, reaching maximums of 75 mg m\(^{-2}\) s\(^{-1}\) (Fig. 5.10A). At mid-December 2010, sediment flux decreased abruptly, enhanced by a SSC decrease, and from that moment sediment flux maintained very low values, between 0.5 and 5 mg m\(^{-2}\) s\(^{-1}\) (Fig. 5.10A).

The near-bottom cumulative sediment transport on mooring C was towards the south, reaching values of nearly 0.1 T m\(^{-2}\), with a negligible E-W component (Fig. 5.9B). Cumulative transport on the middle of the GoV basin showed variations in the direction in which the sediment was transported, comparing the records at mid-waters (Ci) and near the seafloor (Figs. 5.8B and 5.9B). Sediment near the bottom was transported towards the south (Fig. 5.9), while, at the same point but in the middle of the water column (~500 m water depth approx.) the sediment was transported in a southeastern direction (Fig. 5.8). This might suggest a change on the hydrographic structures probably by the intrusion/presence of different water masses and, thus, the hydrodynamics of the study site during the time series.
Figure 5.9 Time series of A) instantaneous estimated sediment fluxes (mg m$^{-2}$ s$^{-1}$) and B) cumulative sediment transport (T m$^{-2}$) for mooring C$i$.

Figure 5.10 Time series of A) instantaneous estimated sediment fluxes (mg m$^{-2}$ s$^{-1}$) and B) cumulative sediment transport (T m$^{-2}$) for mooring C$b$.
5.2.3 Total mass fluxes

The total mass fluxes of settling particulate matter collected by the sediment traps included in the moorings deployed on the GoV margin showed that the highest vertical fluxes were recorded at the sediment trap deployed in the submarine canyon head (Fig. 5.11A), reaching maximum values of 7199 mg m\(^{-2}\) d\(^{-1}\). Total mass fluxes on the other mooring sites were considerably lower (Fig. 5.11B-5.11D), with particle fluxes ranging from 52 to 2279 mg m\(^{-2}\) d\(^{-1}\). Mean annual values of total mass fluxes (Table 5.1) showed that particulate matter in the middle of the GoV basin is considerably lower than on the upper-slope and in the submarine canyon.

<table>
<thead>
<tr>
<th>Sediment trap</th>
<th>Annual average total mass flux (mg m(^{-2}) d(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1598</td>
</tr>
<tr>
<td>B</td>
<td>1048</td>
</tr>
<tr>
<td>C(_i)</td>
<td>672</td>
</tr>
<tr>
<td>C(_b)</td>
<td>542</td>
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</tbody>
</table>

Table 5.1 Annual average of the total mass fluxes in each of the moorings

During the first study period, mean downward fluxes of 831 mg m\(^{-2}\) d\(^{-1}\) were registered in the sediment trap of mooring A (Fig. 5.11A). These fluxes were much higher than in the sediment traps B, C\(_i\) and C\(_b\), where the mean sediment flux were of 236 mg m\(^{-2}\) d\(^{-1}\), 229 mg m\(^{-2}\) d\(^{-1}\) and 319 mg m\(^{-2}\) d\(^{-1}\), respectively (Figs. 5.11B - D).

At the beginning of the second study period, on mid-October 2010 an abrupt increase in the particulate flux was registered at the moorings A and B, reaching fluxes of 7199 and 1830 mg m\(^{-2}\) d\(^{-1}\), respectively (Figs. 5.11A and B). A slight increase of 430 mg m\(^{-2}\) d\(^{-1}\) was registered in C\(_i\) nearly after two weeks (Fig. 5.11C), and almost no changes were recorded in the trap C\(_b\) (Fig. 5.11D). From that moment the total mass flux increased in each one of the sediment traps located at ~500m depth (Figs. 5.11A – D), indicating there was more suspended sediment available at mid-depths in the GoV margin. On mid-December 2010 another isolated peak of particulate matter was registered mainly on the sediment trap of mooring A, reaching values up to 4205 mg m\(^{-2}\) d\(^{-1}\) (Fig. 5.11A).
Figure 5.11 Time series of total mass fluxes of particulate matter on the Gulf of Valencia continental margin for the locations of the moorings A (A), B (B) and C (C and D) during the three study periods.
Between the 4th and 16th of December 2010, the carousel of sediment trap C\textsubscript{b} got stuck with the tail of a fish that entered into the sediment trap, and the sample tube remained opened during 42 days, receiving the particulate flux corresponding to the last four sample tubes of the second study period (TMF was divided into four).

In February 2011, between the second and the third study periods, a general increase of the sediment flux was recorded in all sediment traps. The higher values were again recorded on sediment trap A (Fig. 5.11A), up to 3685 mg m\textsuperscript{-2} d\textsuperscript{-1}, and sediment traps B, C\textsubscript{i} and C\textsubscript{b} registered values of 506, 1312 and 1700 mg m\textsuperscript{-2} d\textsuperscript{-1}, respectively (Figs. 5.11B-D). Overall, during the third study periods, from mid-February to mid-June 2011, the particulate matter was considerably higher than during the first study period. The results here presented showed that the total mass fluxes were always higher at the sediment trap located in the submarine canyon head (Fig. 5.11A). It is also worth to notice that the sediment fluxes on the continental slope varied similarly to particle fluxes on the middle of the GoV basin, at ~ 500 m and ~1200 m depth, mainly during the first study period (Figs. 5.11B and C), differing considerably with the sediment fluxes registered in the canyon head (Fig. 5.11A). This implies that the sediment dynamics in the submarine canyon were different than on the open upper-slope and in the middle of the basin, which are correlated with differences in the hydrodynamics in these areas.

5.2.4 Temporal variability of particle fluxes

Time series of wave height (Hs) and the wave direction (°) during the three study periods were obtained from the data recorded by the wave buoy that “Puertos del Estado” maintains on the central part of the GoV margin, at 260 m depth (see location in Figure 5.1). During the first study period, mean wave height was of 0.7 m with a mean wave direction from the south-southeast (~ 118°). From the second study period, mean wave heights increased up to ~ 1.5 m, and wave direction registered large oscillations, being the main direction from the east-northeast (in between 90° and 0°) (Fig. 5.12).

From mid-May to mid-October 2010 wave height ranged between 0.1 and 2 m, oscillating with periodicities in between 5-11 days (Fig. 5.12A). Wave direction also oscillated with the same frequency, with a mean direction from the southeast (Fig.
5.12B). In between the 11\textsuperscript{th} and the 14\textsuperscript{th} of October 2010, a northeastern storm reached the GoV, with maximum Hs values of 4.6 m. This storm event coincides with the abrupt sediment flux increases registered in moorings A and B (Figs. 5.11A and 5.11B), and in mooring C with a delay of ~12 days (Figs. 5.11C and 5.11D).

![Figure 5.12 A) Significant wave height (m) and B) wave direction (°) at the wave buoy during the three study periods. Blue bar indicated the storm event in mid-October 2010.](image)

After the storm of mid-October 2010, wave heights recovered values between 1 and 2 m, and continuous oscillations of 5-11 days were again registered, with higher amplitudes (Fig. 5.12A). Wave direction also continued oscillating, but with higher amplitude, from wave from the southeast to waves from the southwest (Fig. 5.12B). At the mid-January 2011, another northeastern storm affected the study site, with two major Hs peaks registered, reaching heights oscillating between 2 and 2.5 m (Fig. 5.12A). This event lasted until the beginning of February 2011, affecting the particle fluxes over the GoV margin, which mainly increased on the in submarine canyon head, south of the Columbretes Islands (Fig. 5.11A).

Afterwards, in March 2011 another two storms affected the study site, registering wave heights in between 3 and 3.5 m (Fig. 5.12A). These storm events recorded at the beginning of 2011 could be also increasing the particulate fluxes; however, the amount of sediment collected over the GoV margin was lower than the sediment flux recorded during and after the storm on mid-October 2010 (Fig. 5.11).
The results presented in this Chapter corroborate what has been shown in Chapter 4 that on the GoV margin the sediment is mainly transported along-shelf and upper-slope in a SSW direction following the bathymetry, with a minor off-shore component. Here it has been observed that in the submarine canyon head south from the Columbretes Islands, where the margin drastically narrows, the cumulative transport is one order of magnitude smaller than on the upper-slope and in the middle of the GoV basin. In addition, finer sediments are also found in the submarine canyon, where the current velocity is lower, and coarser sediments are found on the open slope and in the middle of the basin, where the mean velocities are higher. This suggests that fine sediments are trapped inside the submarine canyon since current speeds are lower, with an isotropic direction, without being affected by the general circulation in the study site. These conditions change during storm events, when vertical sediment fluxes increase over the continental margin and the submarine canyon acts as a preferential conduit for the sediment transference and deposition, between the outer shelf and continental slope.
Chapter 6

Hydrodynamics and sediment transport over the Gulf of Valencia continental slope

Part of the content of this chapter is published in Ribó, et al. (2015). *Hydrodynamics over the Gulf of Valencia continental slope and their role in sediment transport*. Deep-Sea Research, 95, 54-66
6.1 Introduction

The general oceanographic circulation of the northwestern Mediterranean has been widely described in numerous studies (Font, 1987; Millot, 1999; Robinson and Leslie, 2001; Salat et al., 2002; Millot and Taupier-Letage, 2005; López-Jurado et al., 2008), with specific ones devoted to the Balearic Sea (García et al., 1994; Pinot et al., 1994, 1995 and 2002; Salat, 1995; Monserrat et al., 2008).

In Chapter 2 and 4, the circulation in the GoV was described, characterized by water mass mixing between the Northern Current flowing along the continental slope towards the southwest carrying old Atlantic Waters (oAW), and the northward intrusions of recent Atlantic Waters (rAW) through the Ibiza Channel. In addition in Chapter 2, the presence of three water mass types below these surface waters: the WIW, found from 200 to 400 m depth; the LIW between 400 and 700 m depth, and the WMDW below 700 m depth. The LIW is carried in the lower part of the Northern Current, and bifurcates to the north of the Ibiza Channel as do the surface waters (Font, 1987; Pinot and Ganachaud, 1999; Pinot et al., 2002). The WIW is formed seasonally, and its production is related to the formation of cold and dense waters in the northwestern Mediterranean in winter. When the WIW is present in or nearby the Ibiza Channel, it usually deflects downwards the LIW, which normally occupies shallower levels when the WIW is absent (Monserrat et al., 2008). Circulation in the GoV has been described as seasonally dominated by the Northern Current entering as an unstable meandering jet (García et al., 1994; Pinot et al., 1995 and 2002). In Chapter 4 it is described that there is a preferential off-shelf sediment export at the southern end of the GoV, where an important detachment of particulate matter was observed off Cap La Nao extending seawards all across the Ibiza Channel. The presence of several near-bottom and mid-slope nepheloid layers, mainly between 400 and 600 m is also described, and their occurrence has been related to the presence of internal waves on the mid-slope region causing resuspension and/or inhibiting suspended sediment deposition, as it has been described in other areas (Cacchione and Drake, 1986; Puig et al., 2004; Hosegood and van Haren, 2004; Bonnin et al., 2006).
Internal wave motions on the GoV continental slope have been recently monitored and characterized through detailed mooring observations, and consisted on stratified perturbations and convective overturns reaching the bottom (van Haren et al., 2013). Van Haren et al. (2013) observed a ~11-day periodic turbulence, which moved cold WMDW underneath the relatively warmer LIW, simultaneously enlarging the bottom boundary layer as might be induced in a wave motion or a bore. This turbulence appears convective, producing shear-induced Kelvin-Helmholtz overturning instabilities reaching the entire sampled water column (i.e. 60 m) above the bottom. The authors observed that inertial motions superimposed on the large-scale processes provided very large convective turbulence, and described that the varying of turbulence intensity could affect the generation of short internal waves near the local buoyancy frequency. It was suggested that the turbulent processes associated with such near-inertial internal waves might play an important role in the nepheloid layer formation, dispersing and maintaining the suspended particles over the slope.

In this chapter, the current fluctuations and the temperature variations measured at two moorings located over the GoV continental slope are analyzed, and these records are related with variations on near-bottom suspended sediment concentration (SSC). In addition, trawling activity in the study area has been also analyzed since previous studies (e.g. Martín et al. 2014) have evidenced that deep bottom trawling on the NW Mediterranean can replace natural processes as the main driving force of sediment resuspension on continental regions, and generate increases on near-bottom SSC, similar to the ones recorded over the GoV continental slope.

6.2 Results and Discussion

The observational work consisted of time series measurements at two locations over the GoV continental slope using thermistor moorings, being mooring D the first mooring deployed, from mid-February 2011 to mid-May 2011, at 450 m depth; and mooring E the second mooring deployed, from October 2011 to mid-February 2012, at 572 m water depth (Fig 6.1).
Figure 6.1 Bathymetric map of the southern part of the Balearic Sea and Gulf of Valencia, showing the major currents characterizing the regional surface circulation scheme (blue arrows, synthesized from Pinot et al., 2002 and Ribó et al., 2013). Red dots indicate the thermistor mooring locations.

Before each mooring deployment and after each mooring recovery, two CTD profile casts were performed (see Chapter 3). Temperature and salinity profiles were used to characterize the hydrographic structure of the study site (Figure 6.2). The signatures of WIW, LIW and WMDW were recognized by identifying the temperature and salinity values characteristic of each water mass (see Chapter 4), and also the variation of the water masses position over the GoV continental slope was evidenced.

Although the first mooring (mooring D) was located at 450 m depth, and the second (mooring E) at 572 m depth, both measured up to 80 mab (grey band in Fig. 6.2) where the LIW and WMDW water mass interface was located. On the first mooring site, before the deployment, the signature of WIW and LIW detected in the CTD cast was not evident (Fig. 6.2A and 2B solid lines). However, after this first mooring recovery, the WIW, LIW and WMDW signatures were clearer (Fig. 6.2B dashed line), and a decrease
of temperature was recorded below 100 m (Fig. 6.2A and 6.2B). At the second mooring site, no presence of WIW was observed before the deployment, and the temperature profile was very uniform with a slight decrease where the WMDW was located, caused by the weak presence of LIW (Fig. 6.2C and 6.2D solid line). In contrast, after the mooring recovery, strong WIW and LIW signatures were recorded on the vertical profile (Fig. 6.2C dashed line), being clearly identified on the $\theta$-S diagram (Fig. 6.2D dashed line).

Figure 6.2 Potential temperature profiles and T-S diagrams from CTD-data before the mooring deployment (solid line) and after the mooring recovery (dashed line), near the first (A and B) and the second (C and D) mooring locations. LIW: Levantine Intermediate Water; WIW: Western Mediterranean Intermediate Water; WMDW: Western Mediterranean Deep Waters.
6.2.1 Hydrodynamics over the Gulf of Valencia continental slope

6.2.1.1 Winter - Spring 2011

The first mooring D was deployed in the central part of the GoV from mid-February to mid-May 2011. During the first 20 days of the deployment, until the 3rd March 2011, variations of current magnitude (Fig. 6.3A) and direction (Fig. 3B) were dominated by near-inertial motions. The inertial motions, defined by the Coriolis parameter \( f \) which depends on the rotation rate of the Earth \( (\Omega=7.292\times10^{-5}\text{ s}) \) and the latitude \( (\varphi) \), were calculated at the study site \( (\varphi=39^\circ\text{ N}) \) following the equation \( f = 2 \Omega \sin \varphi \), and have a periodicity of 18.8h. They are generated via geostrophic adjustment following the passage of disturbances by fronts, mainly atmospheric ones. After an atmospheric disturbance passage, they propagate downward as inertial waves are the only inertio-gravity waves that can pass through both homogeneous and stratified layers (e.g., van Haren and Millot, 2005).

![Figure 6.3](image)

**Figure 6.3** A) Current magnitude (cm/s), B) current direction (°) from ADCP, and C) potential temperature and D) near-bottom turbidity records from the OBS, from the first mooring LIW: Levantine Intermediate Water; WIW: Western Mediterranean Intermediate Water; WMDW: Western Mediterranean Deep Waters.
During the first 20 days of the mooring deployment, current magnitudes maintained relatively low values <10 cm s⁻¹, with some noticeable near-bottom increases, up to 25 cm s⁻¹ (Fig. 6.3A). During this period, current direction at the upper levels was almost perpendicular to the direction of currents near the seafloor, which was mainly towards the south-southeast (Fig. 6.3B). The LIW water mass occupied the entire sampled water during this first period, showing θ values of ~13.25 °C and displaying several temperature oscillations of 0.05 °C (Fig. 6.3C). Near-bottom turbidity at the beginning of the record presented values of 0.5 mg l⁻¹ (Fig. 6.3D), alternating with sharp peaks of >1 mg l⁻¹ followed by an increase of up to 2.9 mg l⁻¹ starting the 25th of February 2011 and lasting for a week, without a clear relation with changes in the current magnitude and direction and/or temperature oscillations.

On the 3rd of March, an abrupt change of current direction towards the south was recorded (Fig. 6.3B), correlated with several increases of the near-bottom velocity, reaching values up to 35 cm s⁻¹ (the 5th of March) (Fig. 6.3A), and a slight decrease in temperature, mainly at the upper levels (Fig. 6.3C). These conditions lasted for 13 days, until the 16th of March, when a rapid change in current direction towards the north was recorded during three days (Fig. 6.3B). Immediately afterward, on the 19th of March, current direction rapidly changed again towards the south coinciding with an abrupt increase in velocity magnitude throughout the entire sampled water column that only lasted for one day, followed by a colder water intrusion (Fig. 6.3C), and a slight increase of near-bottom SSC (Fig. 6.3D). On the 22nd of March, increases of current velocities >20 cm s⁻¹ were observed at the upper levels only, between 380 and 420 m, and not near the bottom (Fig. 6.3A). Current direction abruptly changed towards the north (Fig. 6.3B), accompanied by a strong cooling of the water temperature, reaching values of <13.1 °C, caused by the intrusion of WIW (Fig. 6.3C). The arrival of this cold water mass was concurrent with minimum values of near-bottom turbidity (Fig. 6.3D). On the 5th of April, temperature progressively started to increase again (Fig. 6.3C), coinciding with a decrease of the current magnitude at shallow levels (Fig. 6.3A), whilst the current direction was maintained northward until the 15th of April (Fig. 6.3B). This temperature increase corresponded to the return of the LIW in the sampled range, which rapidly moved upwards (and presumably seaward) allowing the entrance of WMDW in the
lowermost part of the range, decreasing the near-bottom temperatures below 13.1 °C (Fig. 6.3C). From the 15th of April to the end of the record, measured temperatures corresponded to the interface of the LIW and WMDW water masses, at depths between 400 and 420 m, presenting continuous oscillations between 13.15 and 13.25 °C reaching all the way to the bottom (Fig. 6.3C). Current direction presented several shifts, changing sharply from the north to the south with a periodicity of ~5 days, superimposed over low-frequency oscillations (Fig. 6.3B). In addition, current magnitude was relatively low, between 5 and 10 cm s$^{-1}$ (Fig. 6.3A), and SSC varied between 0.6 and 1.6 mg l$^{-1}$, with an increase at the end of the time series reaching values up to 3 mg l$^{-1}$ (Fig. 6.3D).

6.2.1.2 Winter 2011- 2012

During the 2nd deployment, the current magnitudes maintained relatively low values <10 cm s$^{-1}$, alternating with periods of near-bottom velocity increases occurring with 5 and 20 day periodicity (Fig. 6.4A). Current direction was mainly in an ESE direction (Fig. 6.4B), although reversals in the current direction towards the north were observed repeatedly, coinciding with periods of low current velocities, dominated by near-inertial motions (see van Haren et al. (2013) for details).

**Figure 6.4** As Figure 6.3, but for the second mooring.
Since mooring E was located across the interface between the LIW and the WMDW, temperature registered fluctuations from 13.15 to 13.25 °C (Fig. 6.4C), with intrusions of colder waters near the bottom coincident with periods of increased near-bottom current velocities. However, from the second half of the time series, the temperature progressively increased, reaching maximum values of 13.4 °C (over the color scale in Figure 6.4C), due to the downslope displacement of the LIW water mass, presumably caused by the intrusion of the WIW at upper levels (Fig. 6.2C). This warming trend was only disrupted by the intrusion of some cold water pulses that were recorded near the bottom from the 4th to the 9th of February 2012 (Fig. 6.4C).

The near-bottom turbidity maintained minimum values ~0.5 mg l\(^{-1}\) during the first 20 days, with small isolated peaks of ~1 mg l\(^{-1}\), until a sharp increase up to 5 mg l\(^{-1}\) was registered on the 28th of October 2011 (Fig. 6.4D). This event lasted for several hours.

From the 3rd of November 2011 to the 18th of January 2012, the SSC increased again repeatedly, alternating between periods with values oscillating between 2.5 and 3.5 mg l\(^{-1}\) and others with minimum background values (Fig. 6.4D). Such increases in SSC showed no relation with the current magnitude and direction variations. From the 18th of January 2012 until the end of the record, SSC showed again minimum values of ~0.5 mg l\(^{-1}\). It is to be noted that on the 31st of December 2011 a near-bottom current velocity increase up to 28 cm s\(^{-1}\) was registered (Fig. 6.4A), coincident with an increase of near-bottom turbidity, up to 3 mg l\(^{-1}\). However, a similar event occurred on the 4th of February 2012, reaching up to 21 cm s\(^{-1}\) did not generate any increase of SSC (Fig. 6.4D).

### 6.2.2 Progressive vectors of currents and near-bottom sediment transport

As it has been shown, currents on the GoV continental slope are highly variable and extremely conditioned by the local bathymetry. Progressive vectors of currents measured each 10 m above the seabed, and progressive vectors of near-bottom horizontal particle fluxes were here analyzed to determine the sediment transport dispersal pathways (Fig. 6.5 and Fig. 6.6). Temporal progression of the current vectors at the first mooring site showed strong changes throughout the study period and between different heights (Fig. 6.5A). Starting on the 12th of February 2011 and for the first 20 days, currents at upper
levels (from 30 to 70 mab) were flowing mainly in a northeastern direction (Fig. 6.5A). Conversely, currents close to the bottom (from 10 to 20 mab) were predominantly directed towards the south and several wiggles were observed, corresponding to current oscillations dominated by near-inertial motions (Fig 6.5A). On the 3rd of March a rapid turn in the current direction affected all depths, and currents flowed towards the south-southeast homogeneously through the entire sampled water column until the 22nd of March 2011. During this first period, the progressive near-bottom sediment flux diagram followed the same pattern described by the near-bottom currents, flowing southwards and also being affected by the current direction oscillations (Fig. 6.5B). On the 22nd of March the currents and near-bottom sediment flux were directed towards the northeast, until mid-April, when both turned again towards the south (Fig. 6.5A and 6.5B). From the 15th of April 2011 to the end of the mooring deployment, current direction was in general towards the south-southeast, showing several reversals (Fig. 6.5A) that corresponded to the current direction fluctuations, occurring approximately with a 5 day periodicity (Fig. 6.3B). These changes in the flow direction were more visible on the progressive vector diagram of near-bottom sediment flux (Fig. 6.5B).

Figure 6.5 Progressive vector diagrams computed from A) current measurements at different depths (indicated in meters above bottom) and B) near-bottom sediment fluxes at the first mooring.
At the second mooring site, in comparison, the progressive vectors at different heights, from 10 to 70 mab, indicated that currents were more consistent through the entire water column (Fig. 6.6A). Starting the 4th of October of 2011 and throughout the whole record, currents were mainly flowing towards the southeast, following the regional bathymetry, although turning towards the east with depth. Such a behavior indicates that the currents on this mooring site were affected by a strong offshore veering (Fig. 6.6A), presumably induced by the local topography of the structural high where the mooring was deployed.

During the entire record, several steps were observed in the progressive vectors, coincident with changes in current direction mainly towards the north (Fig. 6.6A). These periods were characterized by weak current velocities <10 cm s\(^{-1}\) with fluctuating current directions at near-inertial frequencies (Figs 6.4A and 6.4B).

Figure 6.6 As Figure 6.5, but for the second mooring.
Progressive vectors of near-bottom sediment flux agreed with the current at 10 mab, also reproducing the same changes in the preferable direction of sediment transport (Fig. 6.6B). At the end of the time series, during the last 20 days, these direction shifts in the current and near-bottom sediment flux progressive vectors were more frequent, continuously turning from the southeast to the north and southeast again. The changes in direction were stronger closer to the seafloor than higher up in the water column (Fig. 6.6A), and therefore, they favored near-bottom across-slope sediment transport, being predominantly in the offshore direction (Fig. 6.6A).

6.2.3 Along- and across-slope near-bottom sediment fluxes

Instantaneous near-bottom suspended sediment fluxes, and cumulative sediment transport along and across the continental slope, were computed to determine their magnitude and dominant direction (Figs. 6.7 and 6.8). During the first mooring deployment instantaneous along-slope near-bottom suspended sediment flux ranged between 0.21 and 0.33 g m$^{-2}$ s$^{-1}$, in a NNW and SSE directions respectively (Fig 6.7A).

Throughout the record, instantaneous sediment fluxes presented oscillations, which seem to be dominated by near-inertial motions since their periodicity is of $\sim$18.8h. Such fluctuations were also observed in the instantaneous across-slope sediment flux records, with values ranging between 0.17 and 0.13 g m$^{-2}$ s$^{-1}$, off-shore and on-shore, respectively (Fig. 6.7B). At the beginning of the mooring D deployment, the cumulative sediment transport across- and along-slope was on-shore and in a SSE direction, respectively. From the 3$^{rd}$ of March 2011 there was an increase of the along-slope sediment flux in a SSE direction (Fig. 6.7A), also reflected on the cumulative sediment transport (Fig. 6.7C). On the 19$^{th}$ of March 2011, an abrupt increase on the sediment flux towards the SSE was observed (Fig. 6.7A), but rapidly turning again northwards, until the 22$^{nd}$ of March, coinciding with the intrusion of the WIW (Fig. 6.3C). From that moment on, the sediment flux was towards the NNW and off-shore (Fig. 6.7A and 6.7B). This trend lasted until the 15$^{th}$ of April 2011, where the along-slope sediment flux slightly turned again towards the SSE, whereas the across-slope component persist off-shore (Fig. 6.7C).
Figure 6.7 A) Instantaneous along-slope suspended sediment flux, B) instantaneous across-slope suspended sediment flux, and C) cumulative sediment transport along-slope (dashed line) and across-slope (solid line) at the first mooring site (see location in Figure 6.1).

Figure 6.8 As Figure 6.7, but for the second mooring.
The net across-slope near-bottom sediment transport reached values of ~0.1 T m\(^{-2}\) off-shore, while the net along-slope sediment transport was four times higher, ~0.4 T m\(^{-2}\) in a SSE direction (Fig. 6.7C). On the southern part of the GoV continental slope, where the second mooring was located (Fig. 6.1), instantaneous along-slope suspended sediment flux continuously oscillated at low frequencies (Fig. 6.8A), occurring with a 5 – 20 day periodicity (Fig. 6.8B). Along-slope instantaneous sediment flux ranged in between 0.16 and 0.61 g m\(^{-2}\) s\(^{-1}\), in a WNW and ESE directions, respectively (Fig. 6.8A).

Across-slope instantaneous sediment flux component was less important, with values ranging between 0.23 g m\(^{-2}\) s\(^{-1}\) off-shore and 0.14 g m\(^{-2}\) s\(^{-1}\) on-shore (Fig. 6.8B). During the entire deployment the near-bottom cumulative sediment transport was predominantly in an ESE direction, mainly following the bathymetry, with an important off-shore component (Fig. 6.8C). The along-slope cumulative transport reached 2.1 T m\(^{-2}\), while the net across-slope component was 0.8 T m\(^{-2}\) (Fig. 6.8C).

6.2.4 Role of the water masses and mesoscale current variability

The northwestern Mediterranean regional circulation and the respective role of the different water masses found over the GoV continental slope have been largely described (Font, 1987; Salat, 1995; Millot, 1999). Specifically, the circulation in the GoV region is characterized by a complex variability caused by large instabilities of the Northern Current and by the development of mesoscale eddies, which appear to be strongly influenced by the intrusion of seasonal Western Mediterranean Intermediate Waters (WIW) during winter (Pinot and Ganachaud, 1999; Pinot et al., 2002 López-Jurado et al., 2008; Monserrat et al., 2008). Pinot et al. (2002) observed that post-winter stratification, which is strongly dependent on the amount and properties of the WIW layer, is the main factor controlling the size of the mesoscale eddies. They also observed that these eddies can be slowly funneled through the Ibiza Channel, causing a complete retroflection of the Northern Current, or they can be trapped inside the GoV for several weeks.

Under this second situation, their presence distorts the Northern Current flow without fully obstructing the water exchange through the channel (Millot, 1999; Pinot et al., 2002; López-Jurado et al., 2008). In this Chapter, the recorded data showed an
intrusion of the WIW in early spring 2011 over the central part of the GoV, at 450 m depth (Fig. 6.3), which deflected the Levantine Intermediate Waters (LIW) downwards, evidenced by an abrupt decrease of the sampled temperature range (Fig. 6.3C). This cold water intrusion was concurrent with an abrupt change of the current direction towards the north (Fig. 6.3B) and an increase of the velocity magnitude at the upper levels of the sampled range (Fig. 6.3A).

These observations support the fact that the presence of the WIW water mass in this region can enhance the development of mesoscale structures, affecting the near-bottom circulation over the continental slope. In particular, this current reversal that lasted for 24 days was presumably related to the formation of a mesoscale (typically anticyclonic) eddy that develops over the central part of the GoV continental slope (see mooring position relative to circulation scheme in Fig. 6.1). These results are also consistent with previous studies conducted over the GoV, which showed that deep channel-size eddies can become trapped for long periods of time north of the Ibiza Channel, particularly during spring (Pinot et al., 2002). In the southern part of the GoV continental slope, although the incursion of the WIW during spring 2012 was not directly observed, it could be inferred by a downslope displacement of the LIW, and by a progressive increase of the temperature in the sampled range (Fig. 6.4C). There, the intrusion of the WIW at the upper levels did not cause any major changes in the current direction, probably because an eddy was not formed that year, or because it remained isolated in the central part of the GoV, without affecting the southern part of the continental slope region where the second mooring was located (see mooring position and circulation scheme in Fig. 6.1).

The presence of the mesoscale variability on this southern region seems to be mainly attributed to the unstable behavior of the Northern Current, which is intensified when entering to the GoV as a meandering jet (Pinot et al., 2002). As has been mentioned, this meandering activity is strongest during winter and can persist until early-spring, and can extend down to the bottom. Such instabilities in the Northern Current could be responsible for the near-bottom fluctuations observed on the southern GoV continental slope, particularly during winter 2011-2012 (Fig. 6.4). Mooring records during winter-spring 2011 did not show clear evidence of these fluctuations (Fig. 6.3),
presumably because the observations were made in the inner part of the GoV continental slope, sheltered from the general current oscillations. However, the current and sediment flux progressive vectors at this mooring site showed several 5-day oscillations at the end of the record, which are likely to correspond to instabilities of the Northern Current (Fig 6.5). Similar low frequency fluctuations have also been described northwards on the northwestern Mediterranean, as in the Ligurian Sea or in the Gulf of Lions, and were identified as topographic waves (Crépon et al., 1982; Sammari et al., 1995; van Haren and Gostiaux, 2011). In the Ligurian Sea, fluctuations of the meandering current were observed parallel to the coastline, with periods of 10 - 20 days, and perpendicular to the coast with periods of 3 - 6 days (Sammari et al., 1995).

Overall, the current fluctuations observed on the GoV continental slope had a periodicity of 5 to 20 days, and were presumably generated by the topographic waves affecting the study area. Variations in the temperature records also followed such current fluctuations near the bottom, providing evidence of the oscillation of the Western Mediterranean Deep Waters (WMDW) and Levantine Intermediate Waters (LIW) water masses interface close to the seafloor.

As could be clearly observed during the second deployment in the southern GoV continental slope, during periods characterized by low (<10 cm s⁻¹) current velocities (Fig. 6.4A) and by changes in current direction at near-inertial frequencies (Fig. 6.4B), warmer temperatures at the base of the LIW occupy the sampled water column. During periods when near-bottom current magnitudes were high and preferentially oriented towards the SSE (Fig. 6.4A), colder temperatures from the WMDW affected the lowermost part of the sampled water column. Under these later conditions, fluctuations in the along-slope instantaneous sediment fluxes were recorded (Fig. 6.8), despite the variations in the SSC-values observed in the records (Fig. 6.4D), due to higher current velocities and the sustained direction along-margin.

This clearly indicates that the sediment transport on the GoV continental slope is mainly controlled by the current fluctuations associated with such topographic waves, even though few, if any, sediment resuspension events could be clearly related with current speed increases.
6.2.5 Suspended particles maintained by internal waves

Detailed observations of the time series showed that overlying the above described current fluctuations associated with the topographic waves, near-inertial motions were recorded, which at the GoV have a periodicity of 18.8 h. The spectra of kinetic energy based on the ADCP data deployed on both moorings are shown in Figure 6.9, in which the main current fluctuation periodicities on the study site were determined.

It can be observed that the two spectra deviate, presenting the maximum differences, approximately in between 0.1 and 6 cycles per day (cpd). This includes the near-inertial and tidal bands (Fig. 6.9). The spectrum at the first mooring (black line) is more elevated in this range, with an additional peak at the diurnal frequency and slightly elevated inertial and semidiurnal tidal peaks (Fig. 6.9). The broad range of elevated variance is attributable to more strongly variable boundary currents, steered by the sloping topography (van Haren and Millot, 2005). Expansions of 4-days record over the first and second mooring deployments are shown in Figures 6.10 and 6.11, respectively. The near-inertial motions can be observed with the repeated along- and across-slope current increases (panels A, B in Figs. 6.10 and 6.11). During both mooring deployments, vertical currents were one order of magnitude smaller than the along- and across-slope currents (Figs. 6.10C and 6.11C). During the second mooring deployment, vertical upward currents were more bottom intensified, associated with eastern and onshore currents, following the near-inertial periodicity, and, for the vertical current, shorter periodicities ‘high-frequency internal waves’ associated with the stratification (Fig. 11C).
Figure 6.10 Four days zoom of the first mooring time series, including detailed observations of A) along-slope, B) across-slope, C) vertical current velocity components D) temperature and E) along- (red line) and across- (black line) slope sediment fluxes. Horizontal red bars indicate (solid) the local inertial period (f ~ 18.8h) and (dashed) the semidiurnal lunar tidal periods (M2 ~ 12.4h).

Figure 6.11 As Figure 6.10, but for the second mooring.
The observed oscillations caused vertical displacements of the isotherms over 30-60 m, throughout the range of the sampled water column (Figs. 10D and 11D) and similar to previous findings elsewhere (e.g. van Haren and Gostiaux, 2011). These near-inertial temperature variations were mainly correlated with along and across-slope current oscillations that modulate the sediment flux direction (Figs 6.10E and 6.11E). Van Haren et al (2013) associated those temperature variations with internal waves that can generate very large convective turbulence episodes, with large (>50 m) overturns, over the GoV continental slope. These turbulent processes might play an important role in formation and maintenance of bottom nepheloid layers, and in the dispersion of suspended particles towards the ocean interior as intermediate nepheloid layers. Following this approach, in Chapter 4 it was attributed that the existence of bottom and intermediate nepheloid layers over the GoV continental slope as being generated by the presence of internal waves at the interface between the Levantine Intermediate Waters (LIW) and the Western Mediterranean Deep Water (WMDW). The sediment particles detached from the slope would then be maintained in suspension by the density gradient existing throughout the water column. Several other studies have related the presence of nepheloid layers with internal waves in many different areas (Cacchione and Drake, 1986; Puig et al., 2001; McPhee-Shaw and Kunze, 2002; Puig et al., 2004; McPhee-Shaw, 2006). It has been also postulated that internal wave turbulence interacting with the bottom of continental slopes can induce sediment resuspension (e.g., Hosegood and van Haren, 2004). However, in the near-bottom turbidity records presented in this Chapter, no resuspension peaks (i.e., sharp increases of SSC) were observed linked to the near-inertial internal waves monitored at the study site. Nevertheless, as it has been previously indicated, they modulate the along- as well as the across-slope sediment flux oscillations, and follow the current direction fluctuations at the same near-inertial time scale (Figs. 6.10E and 6.11E). This indicates that the across-slope sediment transport in the GoV margin is mainly controlled by such near-inertial motions, which, over time, preferentially advect suspended particles off-shore (see Fig. 6.6B). Thus, these results reveal that internal waves interacting with the GoV continental slope play an important role in the maintenance of the suspended sediment that is being advected along- and across-slope, although no sediment resuspension process seems to be associated to them.
6.2.6 Role of bottom trawling

As has been emphasized, the unexpected high SSC peaks observed at both mooring sites could not be related with any of the hydrodynamics processes operating on the GoV continental slope. This suggests that other potential resuspension mechanisms unrelated with current fluctuations might play an important role in causing the observed sharp and short-lived SSC increases that have been observed in this study and that contribute to the present-day sedimentary dynamics.

Surprisingly, unusual high values of near-bottom turbidity of 3-5 mg l\(^{-1}\) were recorded near the bottom during specific periods during both mooring deployments (i.e. 15\(^{th}\) of April 2011 in Fig. 6.3D and from 28\(^{th}\) to 30\(^{th}\) of October 2011 in Fig. 6.4D). Such values appear to be much higher than the SSC values recorded by means of hydrographic profiles conducted within the well-developed bottom nepheloid layers observed on the GoV continental slope, which were ~0.6 mg l\(^{-1}\) (Ribó et al. 2013).

Additionally, at the beginning of the record of the second mooring site (Fig. 6.4D), near-bottom turbidity maintained background values of ~0.5 mg l\(^{-1}\), lasting for almost the first month, that agreed with the SSC obtained during the hydrographic surveys, but suddenly the SSC increased. Several peaks (up to ~3 mg l\(^{-1}\)) were recorded during almost the next two months, in the middle of the monitoring period. Background values were again recorded over one month, until the end of the mooring deployment (Fig. 6.4D). This anomalous progress of the near-bottom turbidity during winter 2011-2012, with no correlation with changes in current direction and/or magnitude, indicate, a possible external factor controlling the SSC increases on the GoV continental slope during certain periods. Also, no correlations were found during the period with anomalous high SSC and the occurrence of major storms in the study area or flood events from the Ebro or other nearby rivers (data not shown). Several studies have demonstrated that resuspension by bottom trawling activities can create turbid clouds of high suspended sediments concentration, which have been observed mainly on continental shelves (Churchill, 1989; Schoellhamer, 1996; Stavrakakis et al., 2000; Palanques et al., 2001 Durrieu de Madron et al., 2005; Ferré et al., 2008).
On the other hand, the occurrence of turbidity increases caused by trawling activities over continental slopes has been less investigated. Recent studies conducted on the northwestern Mediterranean slope have described the resuspension effects of bottom trawling over the seafloor, whose effects can be propagated deeper than the fishing grounds (Puig et al., 2012; Martín et al. 2014). These studies were conducted on a submarine canyon flank, where highly-concentrated bottom and intermediate nepheloid layers were generated after the passage of the trawling fleet. Martín et al. (2014) also suggested that trawling activities, by playing an important role in generating near-bottom SSC increases, can currently be the major mechanism involved in the development and maintenance of high-concentration turbid layers on continental slope regions, down to 1000 m depth. Taking into consideration that the two moorings were located in the middle of currently exploited fishing grounds, and had to be deployed on structural highs to protect the instrumented lines from fishing activities (extending to maximums of 800 m depth), it is very plausible that trawling activity on the GoV continental slope could be the source of the randomly high SSC recorded near the bottom.

To assess the potential role of bottom trawling activities as an active sediment resuspension mechanism, the VMS positions (course and speed) of the trawling vessels operating in the study area were analyzed. VMS data was plotted in two detailed maps nearby the mooring sites, differentiating between periods with high increases of near-bottom suspended sediment concentrations and periods with minimum background turbidity values (Figs. 6.12 and 6.13).

At the beginning and at the end of the first mooring deployment, from mid-February to end of March 2011, and from mid-April to mid-May 2011, respectively, the SSC records showed values continuously oscillating between 0.6 and 1.6 mg l\(^{-1}\), with several increases up to 3 mg l\(^{-1}\) (Fig. 6.3D). Coinciding with these same two periods, numerous bottom trawling vessels could be tracked nearby and even over the first mooring location (Fig.6.12A). On the contrary, when minimum or background turbidity values were recorded, from end of March to early April 2011, only few vessels were positioned nearby the mooring site (Fig. 6.12B).
Figure 6.12 Position, heading and speed VMS data of bottom trawling vessels fishing nearby the first mooring location (black dot), A) during high SSC values from the 18th of February to the 22nd of March 2011, and from the 11th April to the 13th of May 2011, and B) during low/background values from the 24th of March to the 8th of April 2011.

Figure 6.13 Position data of bottom trawling vessels fishing nearby the first mooring location (black dot), A) during high SSC values from the 31st of October 2011 to the 16th of January 2012, and B) during low/background SSC values from the 5th to the 18th of October and from the 19th of January to the 20th of February 2012.

Similar observations were made for the second mooring site (Fig. 6.13), when during almost the entire deployment, from the end of October 2011 to mid-January 2012, a large number of bottom trawling vessels passed close to and over the mooring site (Fig.
This coincided with repeated increases of suspended sediment concentrations, with values oscillating between 2.5 and 3.5 mg l-1 (Fig. 6.4D). When only background turbidity values were recorded, from beginning to mid-October 2011 and from mid-January to the end of February 2012 (Fig. 6.4D), just a few bottom trawling vessels were positioned near the mooring site. In addition, most of the vessels were operating down-current from the mooring site (Fig. 6.13B), and the potential resuspended sediment could not be registered by the moored turbidity sensors since it was mainly advected towards the ESE (Fig. 6.8C). Nonetheless, the ultimate dispersion of the resuspended sediment up into the water column and the development of the observed bottom and intermediate nepheloid layers in the GoV (see Chapter 4) seems to be related to the presence of internal waves at depths where the boundary of the LIW and WMDW interacts with the seafloor, as their associated turbulence presumably contributes to maintaining the resuspended particles in the water column and to advecting them seawards.
Chapter 7

Gulf of Valencia continental slope geomorphology

Part of the content of this chapter is published in Ribó, et al., (2015) *Morphobathymetric analysis of the large fine-grained sediment waves over the Gulf of Valencia continental slope (NW Mediterranean)*, Geomorphology (under review)
7.1 Introduction

Deep-water sediment waves have been studied since the 50’s all over the world in many different marine sedimentary environments, the first examples being described on the eastern US continental rise by Heezen et al. (1959). Deep basin bottom currents were assumed to be the main formation process of these sedimentary features. However, in the early 70’s a scientific debate started when Embley and Langseth (1977) introduced turbidity currents as another possible formation mechanism. Several subsequent studies confirmed/identified the presence of either bottom current sediment waves (Lonsdale and Hollister, 1979) or turbidity current sediment waves in deep waters (Damuth, 1979). The occurrence of such type of currents in specific settings was not always clear, and some authors suggested the breaking of internal waves over the continental shelf and upper slope as a mechanism that could also generated sediment waves (e.g. Southard and Cacchione, 1972; Normark et al., 1980). However, in specific cases, the mechanism responsible to generate sediment waves is not always clear, and multiple and concomitant formation processes have been invoked (e.g., Faugères et al., 2002).

Wynn and Stow (2002) provided a classification and criteria to distinguish between deep-water sediment waves generated by currents flowing across-slope over the seabed (i.e., downslope turbidity currents) and the ones generated by along-slope bottom currents. Such classification, however, did not included examples of sediment waves generated by internal waves. More recently, sediment wave’s symmetry and migration direction started to play an important role on the interpretation of their origin and relative classification (e.g., Knaapen, 2005; Xu et al., 2008), and several studies started to describe the relevance of sediment transport and depositional processes on the sediment wave generation (Cattaneo et al., 2004; Berndt et al., 2006; Levchenko and Roslyakov, 2010; Lesshafft et al., 2010; Cartigny et al., 2011; Reeder et al., 2011; Van Landeghem et al., 2012). In some cases, the sediment waves observed on continental slopes were first misinterpreted as a result of gravitational slides and an intense debate started on whether these bedforms were generated by sediment transport processes or were created as a result of gravitational deformation. Some examples are the case of the “Humboldt slide”
(Gardner et al., 1999; Lee et al., 2002), the sediment waves observed on the Bay of Biscay over the Landes Plateau (Stride et al., 1969; Kenyon et al., 1978; Faugères et al., 2002), or the sediment waves field described along the Namibian continental slope (Keil and Spieß, 2010) on the Cape Basin.

![Bathymetric map of the Catalano-Balearic Sea](image)

**Figure 7.1** Bathymetric map of the Catalano-Balearic Sea, composition of the GEBCO digital database (IOC et al., 2003) and the detailed swath bathymetry mosaic from the Valencia Trough (in rainbow color scale). Arrows indicate the regional surface circulation (rAW: recent Atlantic Waters; oAW: old Atlantic Waters). Red square indicates the location of the area in which this chapter is focused on.

In the Mediterranean Sea, similar sediment undulations were described over the Gulf of Valencia (GoV) continental slope, and were related to creep movements, presumably affected by neotectonic fracture system, which apparently produced mass movements along the continental slope (Díaz del Río et al., 1986; Herranz et al., 1996; Díaz del Río and Fernández Salas, 2005; Maestro et al., 2005). However, the analysis of previous data could have been misinterpreted as it occurred in the cases outlined above. The aims of this Chapter are to present a detailed morphobathymetrical analysis of the observed sediment undulations identified in the GoV continental slope using recently...
acquired swath bathymetry (Fig. 7.1), together with parametric sub-bottom seismic profiles and characterisation of sediment cores.

7.2 Results and discussion

7.2.1 Gulf of Valencia continental slope geomorphology

A detailed multibeam bathymetry from the GoV continental margin has been used to describe and analyze the geomorphological features that develop on it (Fig. 7.2).

Numerous sediment undulations (hereafter attributed to sediment waves (see section 7.2.6) can be distinguished from the GoV DTM, being the best developed ones, in which this study is focused on, those observed over the continental slope (Fig. 7.2). These are concentrated in two main fields separated by structural highs, the northern and central fields, extending from approximately 250 m depth to the continental rise, at 850 m depth. Sediment waves cover a total area of 200 km$^2$ on the northern field and of 250 km$^2$ in the central field. It is worth noting that on the central field, the sediment waves appear to be interrupted by the presence of some incipient submarine canyon heads (Fig. 7.2). A detailed morphological analysis (not shown), indicate that these incised canyon heads are actually being infilled by recent sediment deposited in this area. The sediment waves’ dimensions on these two fields appear to grow upslope, being the bigger ones (in height and length) found on the upper continental slope (Fig. 7.2). Overall, the sediment waves covering the GoV continental slope have rounded crests and narrow troughs and are parallel to sub-parallel to the bathymetric contours following the margin orientation, occasionally bifurcating. At some points, it is not clear if a single wave bifurcates or two crests are converging, diminishing their lateral continuity, which range from some hundreds of meters to tens of kilometers (Fig. 7.2). A southern field of sediment waves over the continental slope was also mapped, where the slope is gentler (Fig. 7.2). Two families of sediment waves are identified in this field: one set of waves oblique to the slope, which seems to overlap on a second set, where the crests are parallel to bathymetric contours. These sediment undulations are interweaved, indicating that both wave groups might have simultaneous formation processes (Fig. 7.2).
Since the sediment waves in this southern field are less developed than on the northern and central fields, this field was not taken into account on the morphobathymetric analysis (Section 7.2.2).

Over the outer continental shelf and on the continental rise several sediment waves with different characteristics are also observed (Fig. 7.2). Although this study is not focused on such undulations, there are noticeable morphological differences (in wave lengths and heights) with the sediment waves developed over the continental slope. Additionally, several pockmarks are observed over the structural highs, and in between the lower part of the northern field and near the northernmost sediment waves on the continental rise (Fig. 7.2). There is a remarkable presence of pockmarks on the
southeastern structural high, showing a circular to oval-shaped plan view geometry, with diameters ranging from 50 to 600 m and reliefs of 1 to 15 m (Fig. 7.2).

The slope gradient on the GoV outer shelf increases from less than 1° to 2-3° towards the continental shelf-break, and from 5° to up to 15° on the upper part of the continental slope (Fig. 7.3). It has to be taken into account that these slope gradient values on the upper slope are affected by the steepness of the upslope flank of each sediment wave, which present slope values of ~ 10-15° (yellowish colours). The GoV continental slope gradient decreases downslope, reaching values of <1° at the lower parts, along the toe of the sediment wave fields (Fig. 7.3). On the continental rise the seafloor gradient ranges from ~ 2° to a flat seafloor in the middle of the GoV basin (Fig. 7.3).

7.2.2 Morphobathymetric analysis of the sediment undulations over the Gulf of Valencia continental slope

Sediment waves over the continental slope are described and characterized with detailed morphobathymetric analyses. An area covering each one of the main sediment wave fields was delimited in order to analyze the geometric parameters without the
interference of the other geomorphological structures over the continental slope, as the structural highs (Fig. 7.4). It should be taken into account that the lack of lateral continuity of the sediment undulations can affect the geometrical parameters calculations, and invalid values will be concentrated on the borders of the limited areas. However, a general morphological characterization of the undulated features over the GoV continental slope is here presented.

Figure 7.4 Spatial distribution of the geometric parameters in the northern and central sediment wave fields over the Gulf of Valencia continental slope. A) Wavelength (m) (L); B) Wave height (h) (m); C) Asymmetry index; D) Steepness (h/L).
The mean sediment wavelength (L) is ~ 900 m along the continental slope (Fig. 7.4A). Even though no direct relationships between wavelength and water depth are observed (i.e. near homogeneous distribution of the sediment wavelengths is observed over the continental slope in both sediment waves fields), the largest wavelengths are located in between ~ 200 and ~ 600 m water depth, with values ranging between 800 and 1800 m (larger values in the Figure 7.4A represented in greenish and bluish colors along the borders of the analyzed area correspond to errors on the calculations near the limits of each area). From mid-slope to the lower part of the slope (from ~ 600 to ~ 800 m water depth), sediment wavelengths range between 200 and 1000 m, with mean values of ~ 600 m (Fig. 7.4A). The sediment wave heights (h) range between <2 m to a maximum of 50.5 m (on the central field), being the highest ones located on the upper and mid-slope, in between ~ 200 and ~ 600 m depth, and clearly decreasing downslope (Fig. 7.4B). On the northern field, the highest sediment waves are concentrated on the upper-slope, between ~ 200 and ~ 450 m water depth, and nearby the structural high (Fig. 7.4B). In both sediment wave fields, from ~ 600 m depth to the lower part of the continental slope wave heights are clearly smaller, passing from values of ~15 m to less than 2 m height, coinciding with a decrease on the lateral continuity of the sediment undulations (Fig 7.4B).

The sediment waves asymmetry index (AI) mainly has negative values, indicating a general downslope asymmetry (Fig. 7.4C). The highest asymmetry is observed on the upper- and lowermost parts of the slope, corresponding to the greatest negative values (bluish to pink colors; grey color corresponds to values below -0.8, which is here considered a threshold of non-valid values). The less asymmetric waves are concentrated in the middle slope, represented by the smallest negative values in greenish colors (considering a threshold of AI ≈ -0.3). On the northern field, the most symmetric bedforms (-0.05 < AI < 0.05, yellowish color) are concentrated nearby the structural high, between ~ 450 and ~ 600 m water depth, whereas on the central field they are found slightly below ~ 650 m water depth (Fig. 7.4C). The mean steepness (h/L) values range from 0.01 to 0.03 and generally decrease downslope (Fig 7.4D). On the northern field the steepest sediment waves are focused nearby the structural high, coinciding with the highest undulations (Fig. 7.4B). On the central field maximum steepness values of
0.04 (out of scale) are also coinciding with the highest waves, located between 500 and ~600 m depth (Fig. 7.4D). The results here presented showed morphobathymetric differences between the sediment waves on the upper- and mid-slope and the ones located at the lower part of the northern and central fields.

7.2.3 Sub-bottom seismic profiles

Two TOPAS seismic profiles are here presented in order to characterize the internal structure of these bedforms (see location in Figure 7.2). On the northern seismic profile (Fig. 7.5) tow different sets of sediment waves can be distinguished. The most notorious ones are those developed over the continental slope region (i.e., the ones analyzed in section 7.2.2), but a second set of sediment waves can be also observed over the outer continental shelf region, also recognizable on the DTM (Fig. 7.2). These outer shelf features are clearly smaller in height and length, than the sediment waves observed over the continental slope, and will not be further considered in this Chapter.

As seen in the DTM (Fig. 7.2) the sediment waves over the upper- and mid-slope region exhibit larger wave heights and wavelengths than the ones located at the lower slope, which are more flattened (Fig. 7.5). These differences in morphology coincide with changes on the regional slope gradient (i.e., from the entire continental margin at large spatial scale), which varies downslope from ~ 3.5º to ~ 1.2º, gently dipping seawards. On the seismic profile located on the central field (see location in Figure 7.2), the sediment waves over the outer continental shelf are not observed on the actual seafloor, but are slightly inferred in the internal structure (Fig. 7.6). Again, sediment waves with large wavelengths and wave heights occupy the upper- and mid-slope, decreasing towards the lower part of the slope. These morphological differences throughout the continental slope are less pronounced than on the northern profile (Fig. 7.5), but also coincide with the regional variations of the slope gradient, which in this central field varies from ~ 5º to ~ 1.8º at the lower parts of the continental slope. In both seismic profiles the seafloor displays a concave shape, with sediment waves over the continental slope from ~ 250 to ~ 850 m water depth, developing on the foreset region, showing a well layered seismic facies (Figs. 7.5 and 7.6).
Figure 7.5 TOPAS seismic profile crossing perpendicularly the sediment waves over the northern field (see location in Figure 7.2). The different parts of the continental margin and the different types of sediment waves identified on the continental slope are indicated.

Figure 7.6 TOPAS seismic profile crossing perpendicularly the sediment waves over the central field (see location in Figure 7.2). The different parts of the continental margin and the different types of sediment waves identified on the continental slope are indicated.

Across the continental slope, two groups of sediment waves are clearly differentiated: along the lower continental slope region, sediment waves are aggradational, while they become up-slope migrating sediment waves towards the upper
part of the continental slope (Figs. 7.5 and 7.6). Through the seismic profiles several sediment wave packages can be differentiated (identified by higher and lower amplitudes, corresponding to clearer and darker shades of grey), decreasing in thickness downslope, and which can be followed through the subsurface (down to the upper 200 m below the seabed, being the maximum TOPAS penetration at this site). The downslope flank of one wave meets the upslope flank of the adjacent one, within a sharp but traceable zone (masked by diffractions). The internal structure is similar from one wave to the next one, being constant throughout the entire bedform fields, and although some inflections appear in the troughs, individual reflectors can be continuously traced across-slope throughout the entire seismic profiles (Figs. 7.5 and 7.6).

### 7.2.4 Sediment composition and accumulation rates

Sediment grain size characteristics and sediment accumulation rates (SAR) over the GoV continental slope were analyzed from eight short sediment cores collected over the uppermost part of the slope across the northern and central field (see location in Figure 7.2). The samples were taken on the crests and on the downslope flanks of two or three adjacent sediment waves (see bathymetric profiles (dashed line) in Figures 7.7 and 7.8).

Bottom sediments on the GoV continental slope are consistently uniform along the sediment waves, with dominant silt (up to ~60 – 70%) and clay (~25%), and a small portion (~5 – 15%) of sand, which in some cores (e.g. core-1) is concentrated on the uppermost 5 – 10 cm (Figures 7.7A and 7.8A). Under steady state conditions of sediment accumulation and bioturbation, the distribution of excess $^{210}$Pb in a core commonly allows differentiating two zones: a surface mixed layer (SML) where bioturbation mixes the sediments producing a layer of uniform concentration of the excess $^{210}$Pb; and a layer of exponential decrease of the excess $^{210}$Pb activity. The apparent accumulation rates can be estimated from the slope of the log-linear fit of the decreasing excess $^{210}$Pb in each core versus the accumulated mass (Nittrouer et al., 1984; Masqué et al., 2002). A SML is identified in some of the sediment cores, occupying the topmost 5 – 10 cm, sometimes coinciding where the main portion of sand is found. A rapid decrease of excess $^{210}$Pb concentrations is then observed below the SML (Fig. 7.7A and 7.8A).
The estimated SARs (see Chapter 3) on the northern field seem to be constant on the sediment wave located on the uppermost part of the continental slope, with accumulation rates of $\sim 8$ mm yr$^{-1}$ on both cores 1 and 2 retrieved at 290 and 340 m in depth, respectively (Fig. 7.7B). Downslope, the adjacent sediment wave presents slightly higher SAR on the crest than on the downslope flank, with values of $\sim 9$ mm yr$^{-1}$ and of $\sim 8$ mm yr$^{-1}$, corresponding to cores 3 (at 360 m depth) and 4 (at 410 m depth), respectively (Fig. 7.7B). On the central sediment wave fields, the estimated SAR at core-5, located on the flank of the uppermost sediment wave, at 333 m depth nearby the shelf-break, was of 7 mm yr$^{-1}$ (Fig. 7.8B). On the adjacent crest of the following wave, at core-6 collected at 383 m depth, the SAR was of 9 mm yr$^{-1}$, whereas on the downslope flank of the same
wave, core-7 at 451 m depth was of 6 mm yr\(^{-1}\). The SAR on the crest of the subsequent wave, core-8 collected at 503 m depth, the measured SAR was of 13 mm yr\(^{-1}\) (Fig. 7.8B).

It has been observed there is a general trend of accumulation rates varying from the crest to the flank within the same sediment wave, being slightly higher over the wave crest (Figs. 7.7A and 7.8A). However, this pattern is not observed in the upper slope of the northern sediment waves field (Fig. 7.7B), where similar accumulation rates are found on the crest (core-1) and on the downslope flank (core-2). It has to be noted that core-2 presents a significant increase of the sand portion (up to 40%) within the uppermost 10 cm, comparing to the shallower core-1 (Fig. 7.7A). These results indicate there might be a punctual change in the sedimentation pattern at the core-2 site, which could be caused by external factors.
7.2.5 *Reported sediment waves on continental slopes*

Sediment waves over continental slopes have been widely observed all over the world, with similar key characteristics, as shown in Table 7.1. As it has been stated previously, on several occasions, sediment waves observed on continental slopes have been first misinterpreted as slump or landslide deformation or creep. One of the most better-known cases is the “Humboldt slide”, on the northern California slope (Lee et al., 2002). Gardner et al. (1999) first interpreted the observed undulations as a result of a landslide deposit, however, Lee et al. (2002) showed that it was a field of upslope migrating sediment waves after highlighting the absence of headwall scarp or the continuity of internal reflectors across the crest and trough of each wave, among other arguments. The authors attributed the formation process to turbidity currents (i.e., fluid muds) generated on the Eel River shelf and flowing through a series of upper-slope incised gullies draining into the amphitheatre that contains the sediment-wave field (Lee et al., 2002). Another example is the sediment wave field observed on the Landes Plateau, Bay of Biscay, first interpreted as compressional ridges resulting from deformation associated with a slump (Stride et al., 1969; Kenyon et al., 1978). However, detailed analysis of the sediment waves internal geometry indicated that depositional and gravitational processes might have played a major role in the formation of these bedforms (Faugères et al., 2002). In a similar line, on the Namibian continental slope, sedimentary undulations were first interpreted as a series of parallel troughs formed by downslope sliding of sediments in a highly fluidized state (Bremner, 1981). However, Keil and Spieß (2010) showed that the described undulations were in fact an elongated and confined sediment waves field. Sediment undulations were also observed on the western Gulf of Taranto, in the Calabrian margin (not included in Table 7.1), being developed over the continental slope between 400 and 600 m depth (Rebesco et al., 2009). However, such undulations were not interpreted as “true” sediment waves, and the combination of sediment deformation (creeping) and sediment deposition by downslope density (hyperpycnal) flows was suggested as the formation mechanism. There are many more cases of sediment waves found over continental slope regions in
many occasions being developed in enclosed or semi-enclosed parts of the margin. Such regions are sometimes bounded by islands and/or submarine crests or ridges or found in parts of the margin where the continental shelf drastically narrows, and generally display an amphitheater or cul-de-sac shape (Table 7.1). Some other examples are the sediment waves over the western continental slope of the Caspian Sea, which narrows westwards of the Derbend Basin (Levchenko and Roslyakov, 2010); the sediment waves on the Cilician Basin, northeastern Mediterranean Sea (Ediger et al., 2002); the sediment waves observed on the Great Australian Bight (Anderskouv et al., 2010); the sediment waves on the south Adriatic margin (Verdicchio and Trincardi, 2006; Verdicchio et al., 2007); or the large subaqueous dunes observed over the South of China Sea slope (Reeder et al., 2011), bounded by Taiwan to the north and the Luzon Ridge on the east side (Table 7.1).

As described in the previous sections, over the continental slope of the GoV, two major sediment waves’ fields have been identified in this Chapter (Fig. 7.2), which share some of the characteristics of sediment waves reported on continental slopes elsewhere. These sediment undulations were initially related to creep-like deformation and/or sediment instabilities flowing downslope along decollement surfaces oriented sub-parallel to the actual coastline (Díaz del Río et al., 1986). Such initial interpretations were made by analysing only few seismic lines of limited vertical resolution, but even subsequent morphological studies including these features continued describing them as a result of sliding and/or creeping (Herranz et al., 1996; Acosta et al., 2002; Díaz del Río and Fernández-Salas, 2005). However, the newly acquired bathymetric, seismic profiling data and the examination of the sediment samples discarding out the gravity deformation or creep as the formation mechanism for the observed bedforms.
<table>
<thead>
<tr>
<th>Sediment waves field</th>
<th>Geographic location</th>
<th>Continental margin characteristics</th>
<th>water depth range (m)</th>
<th>Wave length range (m)</th>
<th>Wave height range (m)</th>
<th>total coverage (km²)</th>
<th>Sediment wave field characteristics</th>
<th>Formation process</th>
<th>Imagery</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td>&quot;Humboldt slide&quot;</td>
<td>northern California (United States)</td>
<td>Amphitheater shaped margin with a gullied and overconsolidated upper part</td>
<td>500 - 700</td>
<td>400 - 1000</td>
<td>4 - 10</td>
<td>200</td>
<td>Large-scale migratory sediment waves. Surface with an overall concave-upward shape.</td>
<td>Turbidity currents flowing through a series of deep gullies.</td>
<td>Hi-tech sub-bottom image. Shaded relief bathymetry</td>
<td>Lee et al. (2002)</td>
</tr>
<tr>
<td>Landes Plateau</td>
<td>Bay of Biscay, North Atlantic</td>
<td>Narrow gulf shaped margin with continental shelf narrowing from 140 km to 50 km, extending only 12 km only in some places</td>
<td>400 - 1000</td>
<td>800 - 1600</td>
<td>20 - 70</td>
<td>1300</td>
<td>Field located on the uppermost part of the continental slope. Elongated field N-S along the slope: 40-50 km long and 5-15 km wide. Mean slope 2°-3° westward and 0-40° northward</td>
<td>Multi-processes. Depositional processes (turbidity currents), contouritic processes, hemipelagic and/or very low-energy turbidite or contouritic sedimentation, syndepositional gravity deformations</td>
<td>Multibeam and ITSAS seismic reflection profiles</td>
<td>Faugeres et al. (2002)</td>
</tr>
<tr>
<td>Durban Basin</td>
<td>Caspian Sea</td>
<td>Basin stretching from NW to SE, with continental margin narrowing from 125-130 km to 15-20 km southwards</td>
<td>100 - 800</td>
<td>300 - 1600</td>
<td>5 - 40</td>
<td>-</td>
<td>Sediment waves are not elongated features but rather ellipsoidal-shaped with axis ratio 1:3</td>
<td>Bottom currents and/or turbidity currents or by both processes</td>
<td>High-resolution seismic/acoustic single-channel (sparker) profiling system. Very-high-resolution narrow-beam parametric echosounder</td>
<td>Levchenko and Roshyakov (2010)</td>
</tr>
<tr>
<td>Cilician Basin</td>
<td>Northeastern Mediterranean</td>
<td>Margin with the continental shelf narrowing from approx. 40 km to 15 km</td>
<td>250 - 360</td>
<td>700 - 1800</td>
<td>20 - 40</td>
<td>110</td>
<td>Field located on the upper slope on the eastern side of an interflue between two submarine canyon heads, where a sedimentary wedge is present.</td>
<td>Bottom-current-controlled, gravity flow-controlled or combination of processes</td>
<td>Standard EG&amp;G sparker seismic profiles</td>
<td>Edgar et al. (2002)</td>
</tr>
<tr>
<td>South China Sea</td>
<td>South China</td>
<td>Semi-enclosed, marginal sea, bounded by Taiwan, Philippines, Bonin and southeast Asia.</td>
<td>250 - 600</td>
<td>&lt;280 - 350</td>
<td>3 - 16</td>
<td>-</td>
<td>Closely spaced dunes, which size and structure changes across the field (downslope) coinciding with changes on the slope gradient.</td>
<td>Shoaling deep-water Internal Solitary Waves</td>
<td>Acoustic echosounder systems. Sub-bottom chirp profiler</td>
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</tr>
<tr>
<td>Novarinsky canyon head</td>
<td>Bering Sea</td>
<td>Outer continental margin of the Bering Sea, with very flat continental margin and steep continental slope incised by submarine canyons</td>
<td>225 - 460</td>
<td>600 - 650</td>
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<td>1400</td>
<td>Well-developed sand waves in the head of Navarinsky Canyon</td>
<td>Internal-wave-generated currents propagating shoreward.</td>
<td>High-resolution seismic-reflection profiles</td>
<td>Karl et al. (1986)</td>
</tr>
<tr>
<td>Great Australian Bight</td>
<td>Southern Australian</td>
<td>More than 1000 km long and up to 260 km wide embayment continental margin</td>
<td>200 - 450</td>
<td>340 - 1150</td>
<td>4,4 - 39,7</td>
<td>680</td>
<td>Sediment waves are highly elongate low ridges oriented parallel to regional bathymetric contours. Are typically accreted by a combination migration and aggradation.</td>
<td>Downslope density driven flow</td>
<td>Multibeam seafloor bathymetry. High-resolution reflection seismic profiles</td>
<td>Anderskov et al. (2010)</td>
</tr>
</tbody>
</table>

**Table 7.1.** Examples of sediment wave fields over continental slope regions elsewhere
7.2.6 Sediment waves over the Gulf of Valencia continental slopes

The results presented in this Chapter indicate that the sediment waves over the GoV continental slope are fine-grained sediment waves, and can be classified as mud waves (Figs. 7.7 and 7.8). Morphobathymetric analysis showed that the sediment wavelengths mainly (~ 75%) range between 400 and 1000 m in both, the northern and central fields (Fig. 7.9A). Wave heights values distribution is also similar in both sediment waves fields, with most of the sediment waves (~ 44%) with heights between 5 and 10 m (Fig. 7.9B), being the maximum heights (i.e., 50.5 m) observed on the upper-slope (Fig. 7.9B).

**Figure 7.9** Comparative histograms of the sediment A) wavelength (m) (L), indicating the coverage of 75% and B) wave height (h) (m), on the northern and central fields. Geometric parameters, C) wave length and D) wave height versus depth, comparing the northern and central sediment wave fields.

In contrast to the sediment wavelength which does not show any correlation with the water depth (Fig. 7.9C), sediment wave heights decrease with increasing water depths (Fig. 7.9D). The steepness (h/L), which is mainly dependent of the wave heights,
also decreases with increasing water depths (Fig. 7.4D). This implies that sediment waves located on the lower part of the continental slope have more flattened shape than the ones on the upper slope, as it is also confirmed by the seismic data (Figs. 7.5 and 7.6). The two TOPAS seismic profiles display a concave-up shape, differentiating several sediment waves packages, with a neat lateral continuity below the seabed, and decreasing in thickness downslope (Figs. 7.5 and 7.6). Inside these sediment wave packages, seismic-reflection character is similar from one wave to the next one, and internal reflectors can be traced across the crests and troughs of each sediment wave along both seismic profiles (Figs. 7.5 and 7.6). The change of the morphology of the sediment waves, from aggradational sediment waves on the lower part of the slope becoming up-slope migrating sediment waves on the mid and upper part of the slope, coincide with a change in the regional slope gradient across the margin, indicating that the regional slope angle is an important factor controlling the development and the shape of these sediment waves.

No headwall scarps at the upper continental slope have been observed in the swath-bathymetry maps, and there is also a lack of compressional features at the toe of the sediment wave field, which are usually observed in slide deposits (Lee et al., 2002). The seismic records show that the plane separating the adjacent sediment waves has no consistent trend with depth, while if gravity deformation was the formation mechanism, a progressive reduction of the angle of climb would be observed throughout the sediment wave field (as listric faults in rotational slumps). In addition, it has been observed in both seismic profiles that the dipping of the strata is approximately constant within each undulation (Figs. 7.5 and 7.6), which denotes no synchronous deformation (Lee et al., 2002; Faugères, et al., 2002). Moreover, individual sediment waves present thicker sediment packages on the upslope flanks and crests than on along downslope flanks, suggesting differential deposition that could induce the growth of the sediment waves (Figs 7.5 and 7.6). This coincides with the slightly higher sediment accumulation rates (SARs) observed on the crests of given sediment waves when compared with the adjacent flanks, derived from the \(^{210}\text{Pb}\) analysis (Figs. 7.7 and 7.8). The differential SARs between sediment wave crests and downslope flanks, apparently indicate that the sediment waves over the mid-slope are still growing in present conditions (i.e., at 100-yr
timescale). Nevertheless, on the northern field, the sediment wave located on the upper part of slope show similar SARs over the crest and on the downslope flank (Fig. 7.7B). This might be associated with an increase of coarser sediments over the crest (up to 40% of sand portion), which could behave differently under the same hydrodynamic forcing conditions. Alternatively, such increase of coarser sediment in the first 10 cm of this specific core could be associated with a winnowing effect caused by the bottom trawling activity in the area, as it has been observed elsewhere (Martín et al., 2014). The evidence of trawling-induced resuspension has been demonstrated in Chapter 6, and could lead to apparently similar recent SARs determined on the crests and on the downslope flanks of the uppermost sediment waves of the northern field (Fig. 7.7B).
Chapter 8

Sediment waves
formation processes

Part of the content of this chapter is published in Ribó, et al., (2015) *Morphobathymetric analysis of the large fine-grained sediment waves over the Gulf of Valencia continental slope (NW Mediterranean)*, Geomorphology (under review).
8.1 Introduction

Sediment waves have been observed throughout the world’s deep ocean, and they are mainly formed in fine-grained sediment (clays and silts) and occur regularly over large areas. Notwithstanding the location or morphological characteristics of the observed sediment wave fields over continental slope regions (see Table 7.1 in Chapter 7), three main processes have been mainly used to explain their formation: a) Turbidity-current processes, commonly formed by unconfined or confined flows within submarine canyons and/or channels or gullies; b) Bottom-current processes, induced by along-slope currents and/or downslope density driven flows (i.e. dense water cascading); c) Multi-process formation (e.g. gravity deformation process controlling the sediment deposition process). In Chapter 7 it has been observed that sediment waves developed over the GoV continental slope are very unlikely to be formed by turbidity or bottom currents, as, for instance, there are no evidences of existence of turbidity channels or fan like depositional features at the lower part of the slope. The incipient submarine canyons incised on the shelf-break and upper slope (see Fig. 7.2 in Chapter 7), which could have been a preferential conduit for turbidity currents during sea level lowstands, are continuously being infilled by the suspended sediment transported and deposited over the GoV continental slope (i.e. sediment waves are developed where the canyon axis would be located). The development of such incipient canyons can be explained by the presence of a paleo-river reaching the shelf-break, which in this case would be an extension of the Júcar River (see Fig. 7.1 in Chapter 7). This river is the closest one to these features with the potential to trigger gravity flows by intense sediment supply and depositional overstepping, which would incise on the shelf-break and upper slope, as the evolution of the incised submarine canyons on the Ebro margin described by Micallef et al (2014). Unconfined turbidity current flows are also doubtful, because of the absence of an alternative major sediment source nearby the GoV margin, as the Ebro River is located 150 km towards the North (Fig. 7.1). Additionally, this area is not affected by local dense shelf water formation which could ultimately cascade as a downslope density driven flow over the GoV continental slope (Pinot et al., 1994; 2002), and therefore, this
process is also unlikely to contribute to the sediment wave’s development. Some studies have also taken into consideration internal waves as a formation mechanism of sediment wave fields over continental slope regions. Karl et al. (1986) inferred that internal waves were the most probable formation mechanism for the sediment waves observed in the Bering Sea, although the authors had no field data to support that statement. Faugères et al. (2002) also considered internal waves as one of the processes that could contribute to the development of the Landes Plateau sediment waves, as oceanographic measurements revealed the presence of enhanced internal wave activity in the Bay of Biscay (Cavanié and Hyacinthe, 1976). Recent field observations of shoaling trans-basin internal solitary waves (ISWs) disturbing the benthic layer and dissipating extremely large amounts of energy were obtained on the South of China Sea slope by Reeder et al. (2011). These authors conclude that sediment redistribution generated by shoaling ISWs was the most likely formation process of the large subaqueous dunes located on the upper continental slope, presenting unique observations of sediment waves formed by internal waves (Reeder et al., 2011). Field observations over different continental shelves and/or submarine canyons on the Mediterranean Sea allowed relating the internal wave activity to the generation and maintenance of nepheloid layers (Puig et al., 2004; McPhee-Shaw, 2006) and also to the resuspension and sediment transport over shallower undulated areas (Puig et al., 2007; Urgeles et al., 2011). Recent studies analyzing the hydrodynamics of the GoV continental slope lead to the determination of the presence of strong near-inertial internal wave activity (van Haren et al., 2013; Ribó et al., 2014), which have been suggested to be the most likely mechanism for the maintenance of bottom and intermediate nepheloid layers and for the across-slope dispersion of suspended sediments (see Chapter 6).

8.2 Results and discussion

8.2.1. Formation process: internal waves

Experimental studies analysing the interaction of internal waves over continental slopes have been published since the 70’s (e.g. Southard and Cacchione, 1972;
Cacchione and Wunsch, 1974; Thorpe and Haines, 1987). Cacchione and Drake (1986) included both observational and theoretical data to evaluate the reflection of internal waves on the continental slopes as a function of the slope gradient. Several works analyzed the energy dissipated and the disturbance of the benthic boundary layer induced by internal waves, through numerical simulations (Bogucki and Redekopp, 1999; Wang et al., 2001), and field observations (Nash et al., 2004; McPhee-Shaw et al., 2004). Cacchione et al. (2002) related the internal waves reflection conditions over continental slopes (e.g. off northern California and off New Jersey) with the threshold shear stress required for the deposition or erosion of the bottom sediment.

Further works using laboratory models studied the possible mixing mechanism near a sloping topography enhanced by internal waves (Dauxois et al., 2004; Zhang et al., 2008), and newly published studies based on numerical simulations examined the resuspension, dispersal and transport processes of mud-like sediments controlled by shoaling internal waves on slopes (Bourgault et al., 2014).

The above-mentioned studies evidenced that the internal waves interacting with sloping bottom cause up-slope energy propagation, generating shear instability. It has also been observed that internal waves normally incident onto the slope divide into three reflection conditions, depending on the ratio between the bottom slope ($\gamma$) and the internal wave energy propagation relative to the horizontal direction ($c$), also termed energy propagation angle relative to the horizontal, which is defined as:

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

where $\sigma$ is the internal-wave frequency, $f$ is the local Coriolis (inertial) frequency, and $N$ is the Brunt-Väisälä (buoyancy) frequency, which is dependant of the density of the sea water and increases with depth. When $\gamma/c < 1$ the reflection conditions are transmissive, when $\gamma/c > 1$ the reflection conditions are reflective, and critical conditions are found when $\gamma/c \approx 1$. Under these critical conditions, the internal wave energy becomes trapped along the slope and the wave itself develops a bore-like form that propagates up the slope surface (Pratson et al., 2007).
Cacchione and Drake (1986) described that the enhanced turbulent stresses under transmissive or subcritical conditions ($\gamma/c < 1$), generated by upslope amplification of the bottom velocities, could cause resuspension of bottom sediment and generate near-bottom high turbid zones. More recent laboratory experiments also showed that in subcritical conditions the disturbance generated by the incident internal wave breaking against the slope, can “fold-up” the isopycnals and wave overturns may develop around the front (buoyancy becomes unstable). These overturns can migrate up-slope and the folded isopycnals collapse into turbulence that mixes the density field within the breaking region (Dauxois et al., 2004). Furthermore, laboratory experiments conducted by Zhang et al. (2008), analyzing the boundary flows observed on continental slope on critical conditions ($\gamma/c \approx 1$), showed strong shear perpendicular to the slope, leading to density inversion and formation of Kelvin-Helmholtz billows, which can break and cause mixing.

Indeed, moored thermistors measurements over the GoV continental slope showed very large overturns (50 m in height) triggering convective turbulence (van Haren et al., 2013, their Figure 6). These observations were conducted on the mid-slope region (at ~570 m water depth), and the observed overturns are equivalent to the Kelvin-Helmholtz billows observed on the laboratory experiments performed under critical conditions (Zhang et al. 2008, their Figure 4).

### 8.2.2 Sediment waves formation process on the Gulf of Valencia continental slope

Calculations of $\gamma/c$ ratio were made for the GoV continental slope in order to attest the presence of different reflection conditions over the continental slope. The angle of the internal wave energy propagation ($c$), was calculated using the exponential fit of the buoyancy frequency ($N$) computed at 10-m intervals from the Conductivity-Temperature-Depth (CTD) profiles (Fig. 8.1), collected along hydrographic transects crossing the GoV continental margin in May and September 2010 (Transect 1 in Fig. 3.9 in Chapter 3). The vertical distribution of $N$ through the water column decrease progressively with depth, which makes $c$ increase with depth (Fig. 8.1).
At the study site, the inertial motions, defined by the Coriolis parameter ($f$) have a periodicity of 18.8 h, corresponding to a frequency of 1.26 cycles per day (cpd), while contemporary hydrodynamic data of the GoV continental slope determined that the presence of near-inertial internal waves with a frequency of 1.31 cpd (van Haren et al., 2013). Regional bottom slope gradients ($\gamma$) were computed from over more than 1000 bathymetric profiles orthogonal to the sediment wave fields (See Figure 3.12A and 3.12B in Chapter 3). Since there is a clear change in the sediment waves morphology coinciding with variations of the downslope gradient over the GoV continental slope (Figures 7.5 and 7.6 in Chapter 7), $\gamma$ was computed for three fixed depth intervals that appears to define three regions that fulfill different reflection conditions for near-inertial internal waves.

On the lower part of the continental slope (from ~ 780 m up to ~ 600 m water depth), transmissive or subcritical conditions ($\gamma/c < 1$) are found, coinciding with the presence of the aggradational sediment waves (Fig. 8.2). Critical conditions ($\gamma/c \approx 1$), represented by the greenish colours in Figure 8.2, are observed on the GoV mid-slope region, extending from ~ 600 m up to ~ 450 m in depth, and coinciding with up-slope
migrating sediment waves. Finally, on the upper part of the slope, between ~ 200 and ~ 450 m, reflective conditions are found where the up-slope migrating sediment waves disappear (Fig. 8.2).

The results presented in this Chapter suggest that the variation of slope gradient determines the shape of the sediment waves observed over the GoV continental slope, also coinciding with the regions were the reflection conditions change. Therefore, despite other generation mechanism might be also possible; the interaction of internal waves over the GoV continental slope seems to be the most likely formation process for sediment transport and subsequent generation of the observed fine-grained sediment waves. This mechanism could be extended to similar sediment undulations developed in other continental slope regions, especially in those areas presenting regional morphologies that could focus the internal wave activity towards specific sectors of the margin.
Figure 8.2 A) Map of the internal wave reflection conditions ($\gamma/c$) for depths greater than 200 m. Bluish colours indicate reflective conditions ($\gamma/c > 1$), greenish colours correspond to critical conditions ($\gamma/c \approx 1$) and yellowish colours indicate transmissive conditions ($\gamma/c < 1$). Dashed lines indicate the isobaths in which the three regions are differentiated: depth ranges of 200 - 450 m, 450-600 m and 600 - ~750 m. Solid line indicates the location of the seismic profile (B) used to illustrate the proposed sediment waves formation process model in the GoV continental slope.
Chapter 9

Spatio-temporal sediment waves evolution

Part of the content of this chapter will be published in Ribó et al., (2015) Spatio-temporal sediment waves evolution: Plio-Quaternary sedimentary record of the Gulf of Valencia margin (NW Mediterranean). Marine Geology (Special Issue)
Chapter 9. Sediment waves evolution

9.1 Introduction

During the last decades, extensive efforts have been made to study the Pliocene-Quaternary deposits in the Mediterranean basin, focussing on determining the sea-level evolution directly linked to the development of sedimentary facies and shelf-edge sand bodies (Bassetti et al., 2006, 2008; Rabineau et al., 2006; Liquete et al., 2008; Gámez et al., 2009; Sierro et al., 2009). The stratigraphic record of most Mediterranean margins is strongly marked by the occurrences of the Messinian Salinity Crisis (MSC), that led to a large sea-level fall (Hsü et al., 1973), causing extreme erosion and incision on the margins with development of a pronounced unconformity (Messinian erosional surface) and large canyon systems. This erosive surface is overlain by a thick Pliocene-Quaternary progradational prism which re-established the typical shelf-slope morphologies (Lofi et al., 2003; García et al., 2011).

On the Catalan margin, the Quaternary stratigraphic architecture is represented by several progradational sequences separated by major discontinuities. The continental shelf is characterized by thin Quaternary deposits at the coast, increasing abruptly their thickness towards the shelf-edge (García et al., 2011; Lastras et al., 2011). The progradational growth pattern of the margin has been related to the fourth-order (100-120 kyr) asymmetric glacio-eustatic cycles that have been prevailed during the Late Quaternary (Medialdea et al., 1989, 1986; Checa et al., 1988; Alonso et al., 1990; Farrán and Maldonado, 1990; Díaz and Ercilla, 1993; Ercilla et al., 1994; Liquete et al., 2008; Gámez et al., 2009).

The main Quaternary depocenter in the Catalan margin occurs on the Ebro shelf, where several progradational and aggradational seismic units develop in the inner and middle to outer shelf (Soler et al., 1983; Medialdea et al., 1986; Alonso et al., 1990). Several studies centered on the Catalan and Valencian margins, have described the stratigraphy and margin structure, extending from Early Miocene to Quaternary (Mauffret et al., 1992; Maillard et al., 1992, 2006; Maillard and Mauffret, 1999, 2013; Martínez del Olmo, 2011). However, only few studies focussed on the Gulf of Valencia (GoV), located in the southwestern end of the Valencia Trough, and were mainly
centered on the study of the tectonics and sedimentation over the continental shelf (Díaz del Río et al., 1986; Maldonado et al., 1983; Rey and Fumanal, 1996). The sedimentary cover over the GoV margin corresponds to a thick series of Plio-Quaternary deposits, becoming progressively thinner southwards in the direction of the Betic system (Rey and Díaz del Río, 1983). The structure of the GoV continental shelf is primarily determined by the deposition of this Plio-Quaternary sequence, which is the result of a series of epeirogenic flexure movements (Díaz del Río et al., 1986). Over the GoV inner shelf the most recent sedimentary cover is characterized by the occurrence of several barrier-lagoon systems, whose formation has been related to Late Quaternary stillstand periods, and their preservations implies very high subsidence rates (Albarracín et al., 2012; Alcántara-Carrió et al., 2012).

The morphology of the GoV margin is strongly influenced by the deposition of post-Miocene sequences. In the central part of the outer shelf and extending onto the continental slope, a series of undulations were observed, aligned sub-parallel to the isobaths and becoming more complex as the slope steepens (Rey and Díaz del Río, 1983; Díaz del Río et al., 1986). These undulations where first interpreted as mass movements of material towards the continental slope along decollement surfaces subparallel to the seafloor (Díaz del Río et al., 1986), and afterwards, related to creep movement over the continental slope (Acosta et al., 2002; Díaz del Río and Fernández-Salas, 2005; Maestro et al., 2005). A recent study analyzing the newly acquired multibeam bathymetry, high resolution seismic profiles and sediment cores have determined that such undulations are muddy sediment waves (Ribó et al., 2015 submitted in Geomorphology). Two main sediment wave fields (northern and central fields) have been identified over the GoV continental slope region, from 250 m depth to the continental rise, at ~ 850 m depth. The sediment wavelengths range between 500 and 1000 m, with the largest ones observed on the uppermost part of the slope, and maximum wave heights of up to 50 m, also on the upper-slope, decreasing downslope to just 2 m high in the continental rise. The analysis of the sediment wave’s internal structure showed continuous internal reflectors, with waves merging down-section and several sediment wave packages were differentiated, decreasing in thickness downslope. It was also observed that sediment waves on the lower part of the slope are aggradational, and become up-slope migrating sediment
waves on the upper part of the slope. These clear changes in the sediment wave’s morphology coincide with variations of the downslope gradient over the continental slope.

The proposed formation mechanism for the sediment waves observed over the continental slope was related with the presence of strong near-inertial internal wave activity, determined with contemporary hydrodynamic data of the study area (van Haren et al., 2013). This oceanographic process is described as the main process for sediment transport and deposition over the GoV continental slope, and hence for the formation of the sediment waves. Differences in the sediment waves morphology coinciding with changes in the slope gradient were related with the variation of the internal wave’s propagation angle relative to the horizontal when interacting with sloping bottom, which cause up-slope energy propagation, generating shear instability (Dauxois et al., 2004; Zhang et al., 2008; Bourgault et al., 2014). Depending on the ratio between the bottom slope and the internal wave energy propagation angle relative to the horizontal, internal waves normally incident onto the slope divide into three reflection conditions (Southard and Cacchione, 1972; Cacchione and Wunsch, 1974). Over the GoV continental slope the three different reflection conditions were found over the lower, middle and upper part of the slope, where aggradational, up-slope migrating and absence of sediment waves are observed. It was then conclude that the regional slope gradient ultimately determines the shape and evolution of the sediment waves over the GoV continental slope (see Chapters 7 and 8).

In addition to the sediment waves developed over the continental slope, smaller (in length and height) sediment waves are displayed over the outer continental shelf (Chapter 7). The present Chapter focuses on the analysis such sediment waves over the continental shelf, their formation processes and their link with the sediment waves over the continental slope. Additionally, with the analysis of the Plio-Quaternary sedimentary record, using multi- and single-channel seismic lines acquired over the GoV margin (Fig. 9.1), this Chapter aims to trace the origin of the sediment waves back in time, determine their influence on the architectural pattern of the sedimentary prograding wedge in the GoV continental margin, and understand the variations and intensity of the mechanisms that shape those sediment waves in time and through the eustatic sea level variations.
9.2 Results and discussion

9.2.1. Sediment waves over the Gulf of Valencia continental margin

High-resolution single-channel seismic lines, extending from the GoV outer shelf to the lower part of the continental slope (Fig. 9.1), showed a concave-up profile on which sediment waves develop from the outer shelf down to the continental slope and continental rise (Fig. 9.2). It is observed that over the continental slope the largest...
sediments waves are located on the upper slope, gradually decreasing in amplitude and wavelength downslope and seawards.

In the seismic profile crossing the northern field (Fig. 9.2A), sediment waves seem to be sharper than on the central field (Fig. 9.2B), in which the sediment waves have more rounded crests. On the lower part of the continental slope sediment waves are aggradational (they develop vertically) and become up-slope migrating sediment waves on the upper part of the slope (Fig. 9.2). The rate of up-slope migration of individual sediment waves within the upper slope seems to increase in time, which translates into a shelf-bending sediment wave axis. Internal structure is similar from one wave to the next one, and individual reflectors can be continuously followed downslope, through one wave to the adjacent one (Fig. 9.2). Several sediment wave packages decreasing in thickness downslope are differentiated through the seismic profile (identified with amplitude variation). However, such packages are not always coinciding with the depositional units differentiated over the outer shelf, which are followed downslope (delimited by dark green lines Fig. 3). It is also apparent that onset of sediment waves build-up well beyond the limit of penetration of the Sparker signal. They become gentler downsection (lower wave-amplitude), but do not completely disappear (Fig. 9.2). Thus, the bottom boundary of the sediment waves cannot be delimited within the single-channel seismic profiles

In these single-channel profiles it is observed that up-slope migrating sediment waves develop over the outer continental shelf (Fig. 9.2). These sediment waves are smaller (in wavelength and height) than those developed on the continental slope. Several sediment depositional units are differentiated over the outer continental shelf (dark green lines, Fig. 9.2), which show uninterrupted development of the sediment waves on the continental slope, sometimes truncated by erosive surfaces (dark blue lines, Fig. 9.2). Such erosive surfaces can be followed from the outer shelf downslope on the continental slope into conformable strata within the sediment waves (Fig. 9.2A and 9.2B). The sediment depositional units are established on the basis of amplitude variations along the section and the limits are set at particularly bright reflectors.
Figure 9.2 Single-channel lines crossing the A) northern and B) central sediment waves fields (see location in the inset), showing the two sets of sediment waves, over outer continental shelf and over the continental slope. Dark blue lines indicate the erosional surfaces and dark green lines delimit the different sediment depositional units.
Chapter 9. Sediment waves evolution

9.2.2 Outer continental shelf sediment waves record

Over the outer continental shelf, the youngest sediment unit, identified as U1a, has its boundary top on the present seafloor, and is displayed above an erosive surface, the first sequence boundary, SB1 (Figs. 9.3A and 9.3B). This unit is very thin and on the northern field is composed by two subunits (Fig. 9.3A): on the bottom, a subunit characterized by parallel reflectors on the inner shelf down-lapping the SB1; and on the top, a subunit characterized by sediment waves (also observed on the bathymetry, Fig. 9.1B), which are typically 400 to 800 m in wavelength and 2 to 4 m in height. This subunit pinches out on the inner shelf and ends near the shelf-edge where the reflectors toplap below the seafloor (Fig. 9.3A). On the central field, unit U1a is characterized by parallel reflectors, and no sediment waves are developed on the present seafloor (Fig. 9.3B).

Beneath unit U1a a second unit, unit U1b, is identified, decreasing in thickness landward, showing the presence of sediment waves, which are truncated by the erosive surface SB1 (Figs. 9.3A and 9.3B). On the northern field sediment waves within U1b extend until the shelf-edge (Fig. 9.3A), while on the central field, sediment waves, which are larger in length, disappear on the middle-outer shelf (Fig. 9.3B).

The bottom boundary of unit U1b is unit U1c, a very thin (2-4 m thick) depositional unit, with weak amplitude reflectors, which seems to maintain constant thickness over the continental shelf. Sediment waves also developed within this unit U1c, being limited to the inner shelf on the central field (Fig. 9.3B) and extending to the shelf-edge on the northern filed (Fig. 9.3A).

Below U1c, unit U1d also show sediment wave development, limited to the mid-shelf on the northern field (Fig. 9.3A), and on the inner shelf almost disappearing over the central field (Fig. 9.3B). It can be observed that this unit U1d increases in thickness landwards, and sub-parallel reflectors mark the bottom boundary, just above the next unit, unit U1e (Fig. 9.3A and 9.3B).
Figure 9.3 Detail of the Gulf of Valencia outer continental shelf on the A) northern and B) central sediment wave fields (see locations in Figure 3). Several sediment depositional units (U1a, b, c, d, e, f, g) are differentiated (dark green lines delimit such units), some of them developing stages of sediment, truncated by erosional surfaces (dark blue lines) determining several sequence boundaries (SB). White line represents the multiple of the single-channel seismic profile.
Unit U1e presents an aggrading-prograding configuration (Fig. 9.3B) with oblique-parallel reflectors, which on the inner shelf tolap with the bottom of unit U1d (Fig. 9.3A). On the northern field sediments seem to be deformed developing some undulations near the shelf-edge (Fig. 9.3A). On the central field reflectors on the base of unit U1e are onlapping the second sequence boundary, SB2 (Fig. 9.3B).

The erosive surface SB2 truncates the sediment waves developed in the unit below, unit U1f. On the northern field, sediment waves are almost inexistent, and only some undulations are observed on the shelf-edge (Fig. 9.3A). On the contrary, large sediment waves are observed on the central field (Fig. 9.3B). Unit U1f increase in thickness seawards and is bounded by the next sequence boundary, SB3, truncating the sediment waves developed in the unit below, U1g (Figs. 9.3A and 9.3B). Such sediment waves in unit U1g are similar than the ones observed within unit U1b, being also smaller (in length and height) on the northern field (Fig. 4A) than on the central field (Fig. 9.3B).

Below unit U1g, an additional depositional unit could be differentiated on the central field (dashed green line in Fig. 9.3B), which is bounded by another erosive surface, SB4 (dashed dark blue line). This erosive surface truncates the sediment waves developed on the unit below (Fig. 9.3B). However, on the northern field (Fig. 9.3A) these additional depositional units (not named) and the sequence boundary are masked by the multiple (white line in Fig. 9.3A), and cannot be correlated over the margin.

Overall, it is observed that the depositional architecture of the GoV continental shelf is composed by three major erosional unconformities (labeled as SB1-SB3 from top to bottom), which limit four main groups of seismic units: U1g; U1f; units U1e – U1b; and the uppermost U1a. All these seismic units present different stratigraphic patterns, varying in thickness, configuration, lateral continuity and external form along the study area.

9.2.3 Sedimentary record of the sediment waves over the continental slope

A broad overview of the architecture of sediment waves developed on the continental slope is given by the multi-channel seismic profiles acquired over the GoV margin (Fig. 9.1A). Such profiles show a prograding foreset region on the upper.
continental slope and an aggradational bottom set region on the lower part of the slope (Fig. 9.4). Over the seismic line crossing the northern sediment wave field it is observed that Plio-Quaternary sedimentation and progradation are structurally influenced by the Valencia Fault (red line in Fig. 9.4A). This fault offsets the basement, the Top MSC Surface and a large portion of the Plio-Quaternary sequence. The Lower Pliocene and Pleistocene sediments display growth structures on the seaward-side of the fault, evidence of significant fault activity during this period (Fig. 9.4A).

Additional constrains to Plio-Quaternary sedimentation include salt-diapirism, which originate on Triassic salts, mainly affecting the lower part of the continental slope on the central sediment wave field (Fig. 9.4B), and hence It is difficult to determine the shelf-edge trajectory in the lower portion of the Plio-Quaternary section because it largely coincides with the location of the Valencia Fault (Fig. 9.4A), and hence to determine the exact location of the rollover point or shelf-edge trajectory in the GoV Late Quaternary continental margin. However, there is a general ascending and seaward migration of this rollover point in the Late Quaternary GoV continental margin (Fig. 9.4), which is consistent with a general trend of margin regression with rising relative sea level.

Stratigraphic information from the industrial wells over the continental shelf and slope of the central part of the GoV margin, indicate that the base of the Plio-Quaternary section (i.e., the Miocene/Pliocene unconformity) is located ~ 1000 m below seafloor (mbsf) (wells 444 (Golfo de Valencia F-1), and well 354 (Marina del Turia E-1), see location in Figure 9.1). On the southern part of the GoV continental shelf, this limit is however found at ~ 1800 m (well 328 (Denia-1), see location in Figure 9.1) and the Miocene deposits are located directly upon the evaporitic Keuper. The wells display relatively homogeneous lithology of fine-grained sediments throughout the entire Plio-Quaternary section (Fig. 9.4A). The sedimentary facies include mainly slightly calcareous grey clays, with abundant shells, with thin sandstone and microcrystalline limestone-clayey-dolomitic beds (Fig. 9.4A). Over the continental slope, clay and limestone are the predominant lithology, despite a significant proportion of siltstones is observed just above the Miocene-Pliocene unconformity. This latter surface is characterized by the presence of anhydrite.
Figure 9.4 Multi-channel lines crossing the A) northern and B) central sediment waves fields (see location in the inset), extending from the outer shelf to the Gulf of Valencia continental rise. Red line indicates the position of the Valencia Fault, which offsets the basement and the Top MSC Surface (green line). Color lines indicate the limits of several sediment waves units (U1, U2, U3, and U4) differentiated through the sediment record. Black square indicate the roll-over points of the prograding margin. Stratigraphic column extracted from well 444 Golfo de Valencia F-1 (see location in Figure 9.2).
Multi-channel seismic reflection lines show that the slope sediment waves are consistently developed on the foreset region of the prograding margin clinoform, throughout the Plio-Quaternary as soon as normal marine conditions resumed after the MSC (Fig. 9.4). Sediment wave were formed, maintained and continuously developed concomitant with the margin progradation (Fig. 9.4) until present day, as it is observed in the multibeam dataset (Fig. 9.1B).

Several megasequential units could be identified from the present sea floor to above the Top MSC Surface (U1 to U4), based on geometric relationships between strata and considering sediment wave morphological variations, with regard to wavelength and wave height (Fig. 9.4). Tectonic deformation of such units is observed in the northern field caused by the presence of the Valencia Fault (Fig. 9.4A). It is worth to notice that through time (described here from younger to older units), the sediment wave fields distribution pattern is not always the same. The youngest unit U1 presents the best developed sediment waves, extending throughout the entire foreset of the prograding margin clinoform, bounded to the top by the present seafloor (Figs. 9.4A and 9.4B). Below, in unit U2 the sediment waves on the upper and mid-slope are larger (in length and height) than on the lower part of the continental slope (Fig. 9.4A and 9.4B), and on the central field, the area covered by the sediment waves split in two (Fig. 9.4B). They are developed on the upper and mid-slope and on the lowermost part of the slope, showing in between an area without sediment waves, where parallel-even reflectors are present (Fig. 9.4B). On units U3 and U4 sediments develop again over the entire foreset region. On the northern field, unit U3 is thinner than on the central field, and the area covered by the sediment waves is more extensive since it is less deformed by the Valencia Fault (Fig. 9.4A). On the central field, the area covered by the sediment waves on unit U4 is slightly more extensive than unit U3 (Fig. 9.4B). The base of unit U4 is marked by the start of sediment wave’s development over the GoV margin (Figs. 9.4A and 9.4B). Below unit U4 a depositional unit is observed, with a thickness ranging between 300 and 350 m decreasing seawards, and high amplitude parallel reflectors which indicate homogeneous and continuous infill on the margin. This homogeneous depositional unit is above a lower sequence of chaotic seismic facies, in contact with the erosive surface over the irregular Messinian basement.
9.2.4 Sediment waves distribution vs margin paleomorphology

It is observed in the multi-channel lines that the area occupied by the sediment waves in each unit progressively occupies further seaward locations. The extension of such sediment waves over the margin was delimited, and it is shown that the number of sediment wave’s fields has not remained constant through time (Fig. 9.4). In addition, the horizons delimiting each of the sediment waves units over the GoV continental margin were mapped using the dense grid of multi-channel seismic lines (Fig. 9.5).

In units U4 and U3 sediment waves developed in three separated areas along the continental margin, the most extended one located on the central part, and the smallest one located on the northern part of the margin (Figs. 9.5A and 9.5B). The separation of such areas was mainly caused by the presence of the Triassic salt intrusions, which caused the deformation of the Messinian unconformity, conditioning the sediment deposition (Fig. 9.4B). The two northernmost areas in unit U4 and U3 (Fig. 9.5A and 9.5B) are merged in one in unit U2 (Fig. 9.5C). The salt diapir continues acting as a barrier between the two areas where sediment waves are developed, even sediment waves on the northernmost area seems to overlap the structural high (Fig. 9.5C). It is worth to notice the presence of a third small area, separated from the southern area, were sediment waves are also developed (Fig. 9.5C). This separated area it might be attributed to the deformation of the sediment deposition over continental slope due to another salt intrusion. On the topmost unit U1 the areas covered by the sediment waves are more extensive than in the units below, being more widespread through the lower part of the continental slope, and showing a clearer separation between the northern and the central areas of sediment waves (Fig. 9.5D). In addition, a small area is newly developed towards the southern part of the margin (Fig. 9.5D). Finally, on the present seafloor, sediment waves are developed in three sediment wave fields, limited by the presence of the two main structural highs, generated by the salt intrusions evolution (Fig. 9.5E). The best developed areas are the ones on the northern and central parts of the continental margin, corresponding to the present-day northern and central sediment waves field observed in the bathymetry (Fig. 9.1B).
Figure 9.5 Evolution of the sediment wave units identified in the multichannel lines through the sediment record. The different maps represent the location of the area covered by A) Unit 4 (U4), B) Unit 3 (U3), C) Unit 2 (U2), D) Unit 1 (U1) and E) the sediment waves over the present seafloor. F) Progradation of the sediment waves units from U4 (A) to the present location of the sediment waves (E).
Overall, a sediment waves progradation over the continental margin is clearly observed (Fig. 9.5F), being controlled by the changes on the continental margin morphology and by the tectonics affecting the area (Figs. 9.4 and 9.5). These observations are consistent with the general prograding GoV continental margin (Fig. 9.6), which is marked by the shelf-edge trajectory determined on the multi-channel profiles (Fig. 9.4). On the depth map of the Top MSC surface, the Valencia Fault and La Nao High are indicated, and a depocenter is observed on the central part of the margin, reaching depths of ~ 2700 m (Fig. 9.6A). The southern part of the margin is the most developed one due to the presence of La Nao High and progradation of the margin after the MSC is centered in this sector (Figs. 9.6B). As the progradation continues, the central and northern parts of the GoV margin rapidly progress, showing the major changes on the margin configuration (Figs. 9.6C to 9.6E). It is observed that the presence of salt intrusions greatly conditioned the shape of the margin (Fig. 9.6E), and that the southern part presents a wider continental shelf since the progradation was greater in this part. Thus, the final GoV margin configuration shows a cul-de-sac or amphitheater shape (Fig. 9.6F).

9.2.5 Sediment waves spatial distribution vs sediment paleo-dispersal patterns

Isochron maps of the Plio-Quaternary sedimentary record over the GoV continental margin show that the greater sediment deposition after the MSC occurred on the southern part of the margin (Fig. 9.7A), where the prograding clinoform started to develop, nearby the La Nao High (Fig. 9.6A). On the northern part of the margin, sedimentation was limited and deformed by the Valencia Fault (Fig. 9.7A). Sediment waves started to develop in unit U4 on the foreset region of the clinoform, distributed in three main sediment wave units (dashed lines over imposed in Fig. 9.7B). The southernmost one is the most extensive, and is located on the central part of the margin, coinciding with the maximum sediment accumulation (Fig. 9.7B). With the same trend, sediment waves in units U3 and U2 developed where the sediment deposition was maximum, primarily over the central part of the continental slope (Fig. 9.7C and 9.7D).
Figure 9.6 Scheme of the Plio-Quaternary Gulf of Valencia margin progradation. A) Depth of the Top MSC Surface. Main structural features are displayed (Valencia Fault, La Nao High, extension of Betic Thrust); B) Depth of the seafloor when sediment waves started to develop, base of unit U4; C) at the base of unit U3; D) at the base of unit U2; E) at the base of unit U1 and F) Depth of the present seafloor. Depths conversions were performed using the information of the industrial wells. Dashed lines indicate the location of the shelf-break. The contours and shelf-break limits are superimposed (dashed line) in each depth map in order to illustrate the margin progradation.
Figure 9.7 Isopach maps of the identified units with thickness in meters (depth conversion was performed using the information of the industrial wells). Maps represent the top-to-bottom successions (differentiating the units by the base of each unit): A) from the Top MSC Surface to U4, B) from U4 to U3, C) from U3 to U2, D) from U2 to U1 and E) from U1 to present seafloor. The area covered by the sediment waves in each unit is overimposed to the maps (dashed lines). F) Thickness map from the Messinian to the present seafloor (notice that different color scale is used to represent this total thickness map).
Large amount of sediment is deposited over the GoV margin, from unit U1 to the present-day seafloor, predominantly over the upper part of the continental slope (Fig. 9.7E). This maximum thickness of sediment accumulation coincides with the development of the largest (in amplitude and wavelength) sediment waves, also located on the upper-slope (Fig. 9.2 and Fig. 9.4).

Overall, maximum sediment deposition during the Plio-Quaternary focuses on the central part of the GoV continental margin (Fig. 9.7F). The areas where sediment accumulation is minimum coincide with the location of the structural highs (salt diapirs). Additionally, high sediment accumulation coincides in the areas over the continental slope where sediment waves are developed. This trend helps explaining the preferential location of the sediment waves fields observed in the present seafloor, and their evolution throughout the sediment record.

9.2.6 The Gulf of Valencia continental margin: a Plio-Quaternary record of sediment waves development

The Messinian Crisis finished ~5.33 Ma, when the Atlantic waters found a way through the present Gibraltar Strait and refilled the Mediterranean (Hsü et al., 1973; Krijsman et al., 1999), the Zanclean or post-Messinian flood event, interpreted as a catastrophic water flow lasting a few years (Blanc, 2002; Garcia-Castellanos et al., 2009). On the Catalan and Valencian margins, the basal Pliocene sediments (Ebro Clays) and the geometries within the seismic Pliocene-Quaternary prograding megasequence, also show that the Messinian/Pliocene boundary corresponds to a drastic reflooding and re-establishment of the open-marine conditions following the MSC (Maillard et al. 2006). Accordingly, the water column became stratified again and hydrologic and hydrodynamic conditions on the Mediterranean Sea were also restored.

In this Chapter it is shown that sediment waves on the GoV margin started to develop on the foreset region of the prograding clinoform nearly after the MSC, on the Early/Lower Pliocene, when the margin started to develop a clinoform geometry, with a well differentiated topset (corresponding to the outer continental shelf), foreset (continental slope) and bottomset (continental rise) parts (Fig. 9.4B). It has also been
observed that several sediment waves units were differentiated, and their distribution over the continental margin evolved in agreement with the margin progradation (Fig. 9.5 and 9.6). Thickness of the Plio-Quaternary sedimentation is determined by the sediment progradation and aggradation into the GoV margin, which as a general trend, increases in the central and southeastern part of the continental margin (Fig. 9.7). Maximum thickness coincides with where the northern and central sediment wave fields are located and the maximum sediment accumulation is concentrated on the upper- and mid-slope (Fig. 9.7), coinciding where the largest (in height and length) up-slope migrating sediment waves are developed (Fig. 9.2).

In the present Chapter it is also shown that during the GoV margin progradation, the margin configuration was modified by the presence of tectonic structures, as the Valencia Fault and the salt diapirs, and the shape of the continental slope varied throughout the sedimentary record (Fig. 9.4). However, it has been observed that sediment waves have been always developed on the foreset region of the prograding margin clinoform, since the Early/Lower Pliocene to present (Fig. 9.4). In addition, clear differences in the present-day sediment wave’s morphology have been observed coinciding with variations in the downslope gradient over the continental slope (Chapter 7). The results here presented indicated that Plio-Quaternary sediment deposition on the GoV continental margin was controlled by the slope gradient and the presence of tectonic structures, and that there is a direct correlation between the inclination of the continental slope and the initiation of the sediment waves formation.

Taking into account that internal wave’s activity has been described as the main mechanism for the present-day sediment waves formation over the GoV continental slope (Chapter 8). In addition, it has been observed that a minimum slope gradient is needed when internal waves interact with the bottom enhancing the sediment transport and deposition and generation of sediment waves (Chapter 8). Thus, it can be assumed that over the GoV margin internal wave activity would have been present almost since the Zanclean reflooding of the Mediterranean Basin, following the Messinian desiccation event, when sediment waves started to develop. Sediment waves have been preserved in the sedimentary record until present day (Fig. 9.4), and thus, it can be
presumed that the GoV continental slope have continuously received the impact of the energy of internal waves since the Early/Lower Pliocene.

**9.2.7 Effect of eustatic sea-level variations in sediment wave development**

Plio-Quaternary sequences have been widely analyzed over the NW Mediterranean in order to study the sea-level oscillations (Hernandez-Molina et al., 1994; Hernandez-Molina et al., 2000; Ribenau et al., 2006; Bassetti et al., 2008; Gámez et al., 2009; Liquete et al., 2008; Urgeles et al., 2010). It has been observed that sea-level oscillations directly shape the sequence architecture on continental shelves (Lobo and Ridente, 2014), which can substantially vary depending on sediment supply, tectonics, eustatic cycle duration, amplitude and rates of sea-level variations (Chiocci, 1994; Zecchin et al., 2010). Over the GoV continental shelf, single-channel seismic lines showed several sediment depositional units (Fig. 9.3), included in the megasequential unit U1 (Fig 9.4). Some of these units display successive sediment waves development interrupted by erosive unconformities (Fig. 9.3), which determine sequence boundaries (SB).

The Plio-Quaternary deposits on the GoV could not be directly dated, however the erosional surfaces observed over the continental shelf truncating the sediment waves could be linked to eustatic sea level oscillations (Fig. 9.8). An interpretation of the depositional cycles and stratigraphic architecture of the GoV continental shelf is here proposed (Fig. 9.8).

The two major erosional surfaces, sequence boundaries SB1 and SB3 could be correlated with the two major glacial periods, corresponding to MIS-2 and-6, including in between a sea-level lowstand corresponding to MIS 4 (Figs. 9.8B). The stage MIS-2 corresponds to the Last Glacial Maximum (LGM) in which the sea-level lowstand ranged between -150 m and -118 m below the actual sea level (Chappell and Shackleton, 1986; Bard et al., 1990). However, these estimations can differ from one region to another, as for example, sea level at the Gulf of Lions during MIS-2 was estimated at -102 ± 6 m (Rabineau et al., 2006).
Surface SB1 cut the topmost group, which includes the depositional units from U1b to U1e, and surface SB2 and SB3 truncate depositional U1f and unit U1g, respectively (Fig. 9.8A). The identified sediment depositional units are interpreted to correspond to progradational sequences occurring during the intra MIS 2-4 and MIS 4-6 stages (Fig 9.8B). From the LGM (MIS-2) to the Last Interglacial (MIS 5.5) several sea-level highstands, matching to a 20 ka periodicity, were identified (MIS 5.1 and 5.3) alternating to sea-level minima (intra MIS 3, 4, 5.2 and 5.4). This last highstand (MIS 5.5) was estimated to be few meters higher than the present sea-level (Lambeck et al., 2002).
Maximum sea level decreased in 15-40 m depth interval during MIS 5 and in 50-75 m depth interval during MIS 3 (Bloom et al., 1974; Chappell and Veeh, 1978; Chappell et al., 1996; Cutler et al., 2003; Fairbanks and Matthews, 1978; Linsley, 1996; Shackleton, 1987; Siddall et al., 2003). Stage MIS-6, which would be marked by the erosive surface SB, corresponds to the penultimate glaciation period (Fig. 9.8).

It has been shown that the presence of different depositional units over the continental shelf is apparently related to the relative sea-level oscillations. Thus, the presence and absence of sediment waves developed within such depositional units would be conditioned by the thickness of the water column covering the continental shelf, and therefore, the internal wave’s dynamics affecting the sediment transport and deposition over the GoV continental shelf. In addition, the used single-channel seismic profiles showed over the continental slope a constant sediment waves growth in the different sediment depositional units between two successive erosional unconformities (Fig. 9.2). Apparently, it can be stated that during sea-level fall sedimentation was homogenous, represented by parallel reflectors and during sea-level rises sediment waves would develop. In general, these results showed that the sea level variations affecting the continental shelf have not affected the sediment waves development over the continental slope.
Chapter 10

Conclusions and future research lines
Conclusions

The main objective of the research presented in this Thesis was to provide new information to improve the knowledge of sedimentary processes operating in the outer continental shelf and continental slope on the Gulf of Valencia (GoV) continental margin. To this end a wide range of methodologies have been used, spanning from hydrographic and hydrodynamic data, sediment sampling, and multibeam and seismic datasets. The most relevant findings of this research are summarized below, following the main goals proposed for this project.

- **Hydrographic characterization of the GoV area**: The GoV is characterized by the convergence of old Atlantic Waters (oAW) flowing southwards and recent Atlantic Waters (rAW) intrusions flowing northwards throughout the Ibiza Channel. Below, several different water masses have been observed: a pool of Western Intermediate Waters (WIW), formed during wintertime, characterized by relative temperature minima; the Levantine Intermediate Waters (LIW), centered on ~ 400 m water depth, characterized by relative temperature and salinity maxima; and the near-homogeneous Western Mediterranean Deep Waters (WMDW) filling the deeper parts of the basin. Results showed that the oAW transport higher suspended sediment concentration (SSC) values than the rAW in the GoV, since the oAW circulates all along the NW Mediterranean continental margin receiving the sediment discharged from the major rivers (i.e. Rhône River in the Gulf of Lions and the Ebro River in the Ebro margin). Particulate matter distribution indicates that sediment transport on the GoV continental shelf is mostly along-shelf and is mainly exported to the slope through its southern shelf-edge, where the margin changes the orientation due to the Cap La Nao promontory, being transferred in shelf-break intermediate nepheloid layers (INL) along the Ibiza Channel. The sediment is detached off-shelf enhanced by the convergence of water masses that forced the oAW to flow beneath the rAW, which drives the sediment transported within the oAW to extend as far as 50 km away from the margin. Water parcels with high SSC observed on the central and southern parts of the GoV continental slope, which are distributed in INL and bottom
nepheloid layers (BNL), seems to be related with the presence of internal waves, focussed where the LIW interacts with the seafloor.

- **Characterization of the sediment fluxes:** Time series of current magnitude and direction, in-situ temperature and SSC, on three mooring deployed from spring 2010 to summer 2011, have shown clear differences of the sediment fluxes over the GoV margin. On the northern part of the GoV, in the submarine canyon head located south from the Columbretes Islands, very low currents and SSC were registered. On the contrary, very high currents were observed on the upper part of the continental slope and on the middle part of the GoV basin, suspended sediment and current magnitude were also low, especially near the bottom. Cumulative sediment transport was towards the south, in the center of the GoV and southwestwards on the upper-slope, following the bathymetry, with a minor off-shore component. Through the submarine canyon, sediment was mainly transported down canyon, but it was one order of magnitude lower than on the continental slope and in the middle of the GoV basin. This difference is mainly enhanced by the current, which are very low and showing isotropic directions within the submarine canyon, suggesting that is not affected by the general circulation, which favours the fine sediment to remain trapped, while on the open slope coarser sediments are observed. These observations imply that the sediment is mainly transported along the shelf and upper-slope, but is not channelized through the submarine canyons. On the contrary, during storm events affecting the Catalan and Valencian margins, maximum vertical particle fluxes were recorded in the submarine canyon head, almost doubling the mean fluxes registered on the open slope and on the middle of the basin. Under this conditions, submarine canyons act as a main conduit for sediment transport and deposition, between the continental shelf and the continental slope.

- **Hydrodynamic description of the GoV area:** Description of the hydrographic structure together with the hydrodynamics over the GoV continental slope, improved the understanding on the regional circulation near the bottom and their role in sediment transport, during spring 2011 and 2012. Intrusions of the WIW water mass were observed largely affecting the near-bottom slope hydrodynamics. In the central part of
the GoV continental slope, the WIW intrusion was associated with a change of the current direction that appeared to be related to the development of a trapped mesoscale anticyclonic eddy. In the southern part of the GoV slope, the intrusion of WIW did not cause major changes on the current direction, but enhanced the unstable behavior of the Northern Current entering into the GoV. Such instabilities were recorded as low-frequency near-bottom current fluctuations, which had a periodicity of 5-20 days, and were attributed to topographic waves. In general, currents at the southern part of the GoV margin were mainly south-southeastwards along the slope (following the bathymetry of the structural high, where the mooring was deployed), with alternating periods of low current velocities (< 10 cm s\(^{-1}\)) dominated by near-inertial changes in the current direction, preferentially directed towards the north and offshore. Temperature fluctuations at near-inertial frequencies were also recorded during these low velocity periods, and were associated to the presence of internal waves. Near-bottom turbidity records show a lack of correlation between increases in SSC and intensification of the current velocity, changes in current direction and oscillations in temperature. Along-slope sediment transport mainly followed the bathymetry, and was intensified by the current increases driven by the topographic waves. The across-slope dispersion of the suspended sediment is mainly related to the presence of the observed near-inertial internal waves interacting with the seafloor, whose turbulence appears to contribute to the maintenance of the bottom and intermediate nepheloid layers observed over the GoV continental slope. The sharp and short-lived SSC peaks observed in the records suggest the presence over the GoV of other potential sediment resuspension mechanisms unrelated with current fluctuations. Trawling-induced sediment resuspension is the most plausible mechanism, which seems to play an important role in the present-day GoV sedimentary dynamics.

- **Geomorphological description of the bedforms observed over the GoV margin:** Results of the morphobathymetric analysis indicate that the undulated features observed over the GoV continental slope, first interpreted as creep-like deformation, are fine-grained sediment waves. Recently acquired swath bathymetry, seismic profiles and sediment samples during this Thesis, allowed determining the
geometrical parameters, interpreting the uppermost internal structure and computing the sediment accumulation rates of the observed sediment waves. Such sediment waves cover an area of 450 km$^2$ over the continental slope, extending from ~ 250 m to ~ 850 m water depth, with wavelengths ranging between 500 and 1000 and wave heights from 2 to 50 m, decreasing downslope. These sediment waves have rounded crests and narrow troughs, and the highest ones are observed over the upper- and mid-slope regions, with larger wave heights and wavelengths than the ones located at the lower slope, which are more flattened. High-resolution seismic profiles showed concave shape seafloor, with aggradational sediment waves along the lower continental slope region, becoming up-slope migrating sediment waves towards the upper part of the continental slope. Continuous internal reflectors could be followed downslope, and the presence several sediment wave packages were observed decreasing in thickness downslope. In addition, slightly higher sediment accumulation rates are found on the crest than on the downslope flanks, indicating that sediment waves are presently growing at 100-yr timescales

- **Description of the formation mechanism of the sediment waves observed over the GoV continental slope:** Contemporary hydrodynamic data collected on the GoV continental slope allowed determining the presence of strong near-inertial internal wave activity. The angle of propagation for the internal waves energy over the GoV continental slope reveal that transmissive conditions are found on the lower part of the slope where aggradational sediment waves are observed; critical reflection conditions are reached over the mid-slope where up-slope migrating sediment waves develop, while the upper-slope has reflective conditions and coincide with the region where sediment waves disappear. It can be suggested, therefore, that the interaction of internal waves over the continental slope seems to be the most likely formation process for the sediment transport and deposition causing the subsequent generation of the observed fine-grained sediment waves over the GoV continental slope, where the regional slope gradient ultimately determines their shape and evolution

- **Description of the internal structure of the observed sediment waves:** Analysis of single- and multi-channel seismic profiles acquired on the Gulf of Valencia margin
provided new information for the stratigraphic and architectural characterization of the sediment waves observed over the outer continental shelf and over the continental slope. The results presented showed that Sediment waves develop over the outer continental shelf in several depositional units, some of them truncated by erosive surfaces, apparently linked to eustatic sea level oscillations. Over the continental slope, apparent constant bedforms growth is observed in the different units between two successive erosional unconformities, suggesting that sea level variations have not affected the sediment wave development. Sediment waves over the GoV continental slope are continuously developed on the foreset region of the prograding margin clinoform through the sedimentary record since they were first started to develop, in Early/Lower Pliocene.

- **Description of the Gulf of Valencia continental margin evolution and progradation**: It has been observed that Plio-Quaternary sediment deposition, and consequently, the sediment wave’s development over the GoV continental slope, was controlled by the slope gradient and the presence of tectonic structures. Internal waves activity is assumed to be the main sediment waves formation mechanism, thus this oceanographic process might have been present in this margin almost since the Zanclean reflooding of the Mediterranean Basin (~ 5.3 Ma), when open-marine conditions were re-established. Internal solitary waves propagating up-slope are presumably the generation process of the up-slope migrating sediment waves over the outer continental shelf.
This thesis has provided great insights into the hydrodynamics, sediment dynamics on the Gulf of Valencia continental margin, in addition to the geomorphologic and internal structure description of the sediment waves observed over the outer continental shelf and slope. However it would be recommendable to deepen certain aspects proposed here as future research lines:

a. *Seasonality of the hydrographic structure:* In Chapter 4 the hydrographic structure on the GoV basin was described and related to the particulate matter distribution. Since the results presented were from a dataset of CTD profiles acquired during a cruise in June 1995, only summer characteristics could be studied. The repetition of the same grid of CTDs during a complete year would help to improve the knowledge of the seasonality in the hydrographic structure composition and the variability of the presence of nepheloid layers over the continental slope.

b. *Composition of sediment trap samples:* Advective and downward sediment fluxes over the GoV margin were determined in Chapter 5. However, the major constituents of the particulate matter, as lithogenics, carbonates, organic carbon, opal, and heavy metals were not determined in this thesis. This would give information of the main compositional trends of the suspended sediment over the upper-slope and central part of the basin, and the composition of the sediment transported through the submarine canyons on the northern part of the GoV. These datasets in addition to the $^{210}$Pb activity on the collected sediment cores would allow determining the sources of the sediment and thus, identifying more accurately the sediment transport paths and sediment accumulation rates over this continental margin.

c. *Bottom trawling on the GoV continental margin:* The role of the bottom trawling has been described in Chapter 6, focussing on the period from February 2011 to February 2012. Sediment resuspension peaks were related to the bottom trawling activity near the mooring deployments, however, no further analysis were conducted. It would be
interesting to determine the impact of the bottom trawling in sediment distribution and accumulation over the entire GoV margin and to evaluate any possible variation of the seafloor morphology over the continental shelf.

d. **Sediment wave’s migration:** Geomorphology of the GoV continental slope is described in Chapter 7 together with a detailed morphobatymetric analysis of the sediment waves observed. Analysis of the $^{210}$Pb activity from sediment samples collected over the sediment waves have determined that these features are presently growing at 100-yr timescales. Moreover, the comparison between several multibeam bathymetric datasets over the sediment waves fields, would show any changes in morphologies and position, and will give information of the sediment waves migration over the continental slope.

e. **Sediment transport modelling:** Sediment dynamics over the GoV continental margin have been determined using time series from moorings deployed at fixed sampling points. Such observations have been correlated from one site to another to describe the hydrodynamics and sediment transport over the margin. Internal waves activity was observed over the GoV continental slope and were determined to be the main mechanism for sediment transport and deposition, and hence for the sediment waves formation. Next step would be to use numerical simulations to examine idealized situations for sediment transport and deposition by internal waves interacting with the slope and to model the sediment waves development.

f. **Determine the chronological sequence of the Plio-Quaternary sediments on the GoV margin:** In Chapter 9 an interpretation of the variation of the relative sea level affecting the sediment deposition and sediment wave development over the outer continental shelf. In addition it has been shown that sediment waves over the continental slope have been preserved since Early/Lower Pliocene. However, absolute ages within the Plio-Quaternary sequence are not determined, and thus the exact moment when the sediment waves started to develop cannot be defined. Collecting new sediment cores to study the geochronology of the GoV margin after
the Messinian Salinity Crisis will provide new information on the geological history of the NW Mediterranean basin.

g. Geotechnical characterization of the GoV continental slope: Sediment cores over the GoV continental slope could be collected to measure engineering properties as bulk density, water content, porosity, permeability, plasticity, state of consolidation, and shear strength. Evaluating such properties will allow prediction of bearing capacity of the floor under an applied load, its resistance to penetration as well as later settlement under loading over a prolonged period. In addition, geotechnical characterization will give great knowledge to investigate trigger mechanisms and sediment failure processes and it might be useful to demonstrate the presence of hydrate.
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