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Sediment undulations on the Llobregat prodelta: Signs of early slope instability or sedimentary bedforms?

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Abstract. A field of sediment undulations has been mapped by means of high resolution multibeam bathymetry and seismic reflection profiles in the Llobregat River prodelta, off the city of Barcelona, Catalonia, Spain. Similar features had previously been recognized in other prodelta environments and interpreted either as downslope sediment deformation or sedimentary structures induced by bottom currents or hyperpycnal flows. Since the study area is undergoing significant offshore development, proper interpretation of such sediment undulations is needed for a correct risk assessment. The occurrence of the sediment undulations is restricted to the prodelta front on slope gradients between 3 and 0.2º. The undulations have developed at the edge and atop an area of gas bearing sediments within the Late-Holocene high-stand mud wedge. An evaluation is made of the characteristics of the sediment undulations in order to determine the most likely process for the origin of these structures. Amongst these characteristics are the continuity of the reflections and lack of diffractions in between different undulations, their size distribution (large to small) both from shallow to deep and with depth in section, the asymmetry (decreasing from proximal to distal), the crest to trough vertical distance on the landward side of the undulations (up to 0.5 m), and the lack of features that could indicate a progressive movement such as growth structures and drag folds. These characteristics indicate that the sediment undulations on the Llobregat River prodelta do not result from sediment deformation, but rather from the interaction of bottom currents generated by hyperpycnal flows from the Llobregat River with regional sea water circulation. Their identification as sediment waves implies that such features do not pose a major hazard for further offshore development.

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1. Introduction

Undulated sediment features are commonly observed on the seafloor deep below the wave base [see *Correggiari et al.*, 2001; *Lee et al.*, 2002; *Mosher and Thomson*, 2002; *Cattaneo et al.*, 2004]. Some authors argue that those features are sediment waves induced by bottom currents and/or hyperpycnal flows [e.g., *Trincardi and Normark*, 1988; *Bornhold and Prior*, 1990; *Lee et al.*, 2002], others identify those areas as sediment deformation structures, creep and/or early signs of slope instability [e.g., *Lee et al.*, 1981; *Field and Barber*, 1993; *Baraza and Ercilla*, 1996; *Chiocci et al.*, 1996; *Gardner et al.*, 1999; *Correggiari et al.*, 2001], while some works also attribute these structures to result from the combination of both processes [*Faugères et al.*, 2002; *Cattaneo et al.*, 2004]. This debate has been especially intense in areas such as the "Humboldt Slide" offshore California [*Gardner et al.*, 1999; *Lee et al.*, 2002] and the Adriatic shelf off Eastern Italy [*Correggiari et al.*, 2001; *Lee et al.*, 2002; *Cattaneo et al.*, 2004] illustrating how little is known about the origin and evolution of these undulated sediment features since none of the proposed mechanisms can be easily confirmed or refuted. Noteworthy is that in continental shelf settings these features occur in areas off river outlets, such as prodeltas characterized by high sedimentation rates and gas-charged sediments e.g. the Tiber River prodelta off Rome, Italy [*Trincardi and Normark*, 1988; *Chiocci et al.*, 1996], the Noeick River prodelta [*Bornhold and Prior*, 1990], the Gulf of Cadiz

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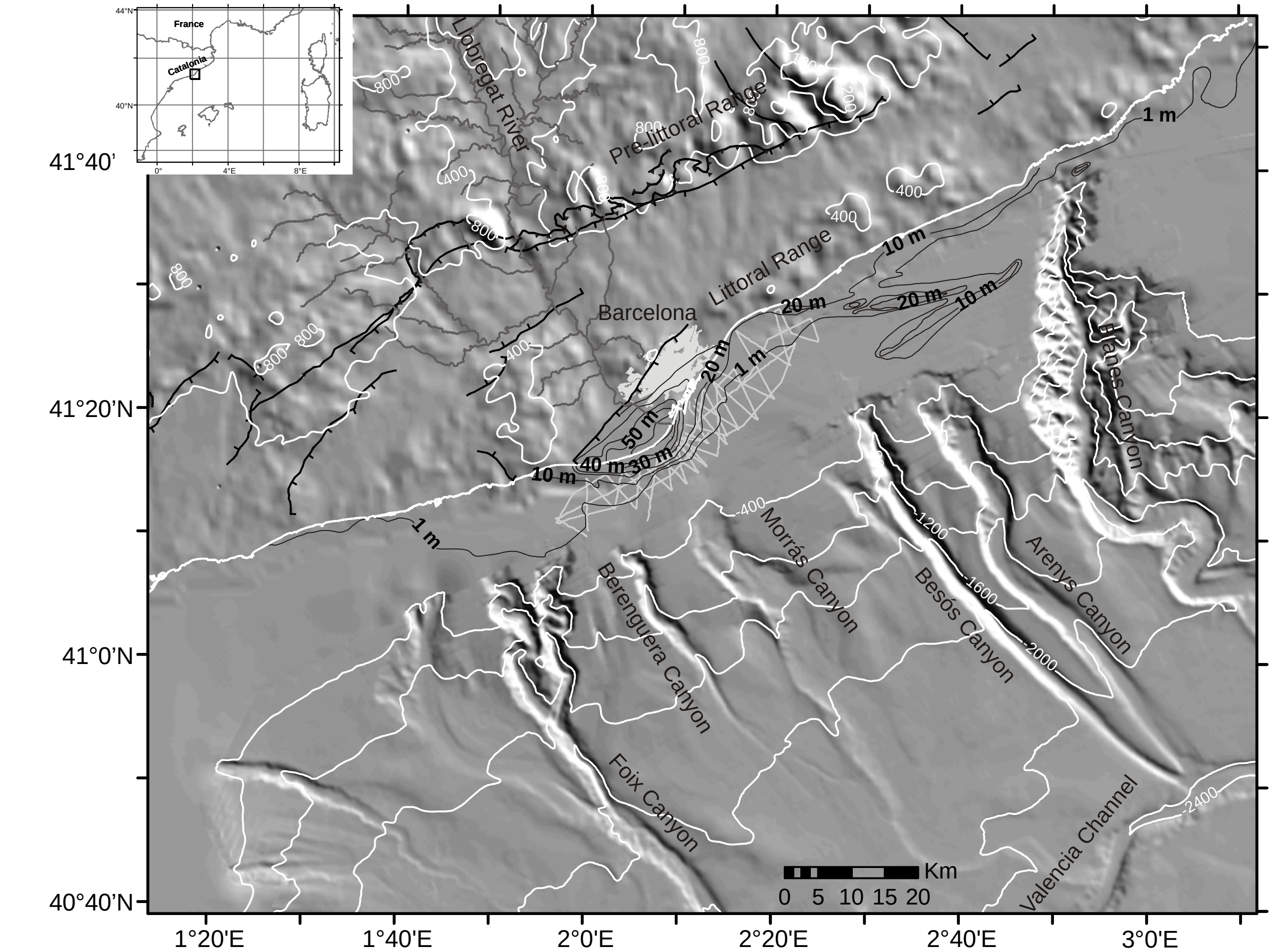

Figure 1. Shaded relief image and contours from topography and swath bathymetry around the Llobregat delta and prodelta. Major geological structures onland, Barcelona urban area (grey shaded area), sediment thickness of prodeltaic systems, and network of seismic reflection profiles used in this study (grey lines) are shown.

[*Baraza and Ercilla*, 1996; *Lee and Baraza*, 1999], off the Eel River [*Gardner et al*., 1999; *Lee et al*., 2002] as well as off the Po River and other Apennine streams in the Adriatic Sea [*Correggiari et al*., 2001; *Cattaneo et al*., 2004]. In many areas of the Western Mediterranean Sea they have been described to be rooted immediately above the last Maximum Flooding Surface (MFS) [*Díaz and Ercilla*, 1993; *Ercilla et al*., 1995; *Chiocci et al*., 1996; *Correggiari et al*., 2001; *Cattaneo et al*., 2004].

A recent survey showed that a similar set of features occurs off the Llobregat River delta, Barcelona, Spain. The sediment undulations at this location are also accompanied by free gas in the sediment and high-sedimentation rates [*Sánchez-Cabeza et al*., 1999]. In particular, this area is currently under strong nearby human influence in a range of offshore structures, most notably the extension of the port of Barcelona. Therefore a correct interpretation of such features is necessary for a proper risk evaluation. Ongoing deformation or creep has the potential to evolve into a submarine landslide, which would notably affect these structures. If, on the other hand, the sediment undulations result from depositional or current induced sediment transport processes the damage to offshore structures is likely to be more limited (and to take the form of sporadic operations to dredge sediment to prevent port obstruction). Therefore, identification in one sense or another may mark the bounding line between safe offshore development or not.

Modern satellite interferometric techniques combining the SAR sensors of the ERS-1 and ERS-2 satellites and the more advanced SAR (ASAR) of the ENVISAT satellite, have demonstrated that the urbanized onshore delta area close to the actual Llobregat River mouth is undergoing a rapid subsidence in excess of 1 mm/yr [*Duro et al*., 2003]. This area is immediately inshore the sediment undulations, and arises additional concerns on whether the displacement recorded by the satellites responds just to subsidence phenomena (compaction by natural loading or anthropogenic water extraction) or to slow creeping of the delta sediments.

2. Geological framework

The Llobregat delta and prodelta are located South of the city of Barcelona (Figure 1).

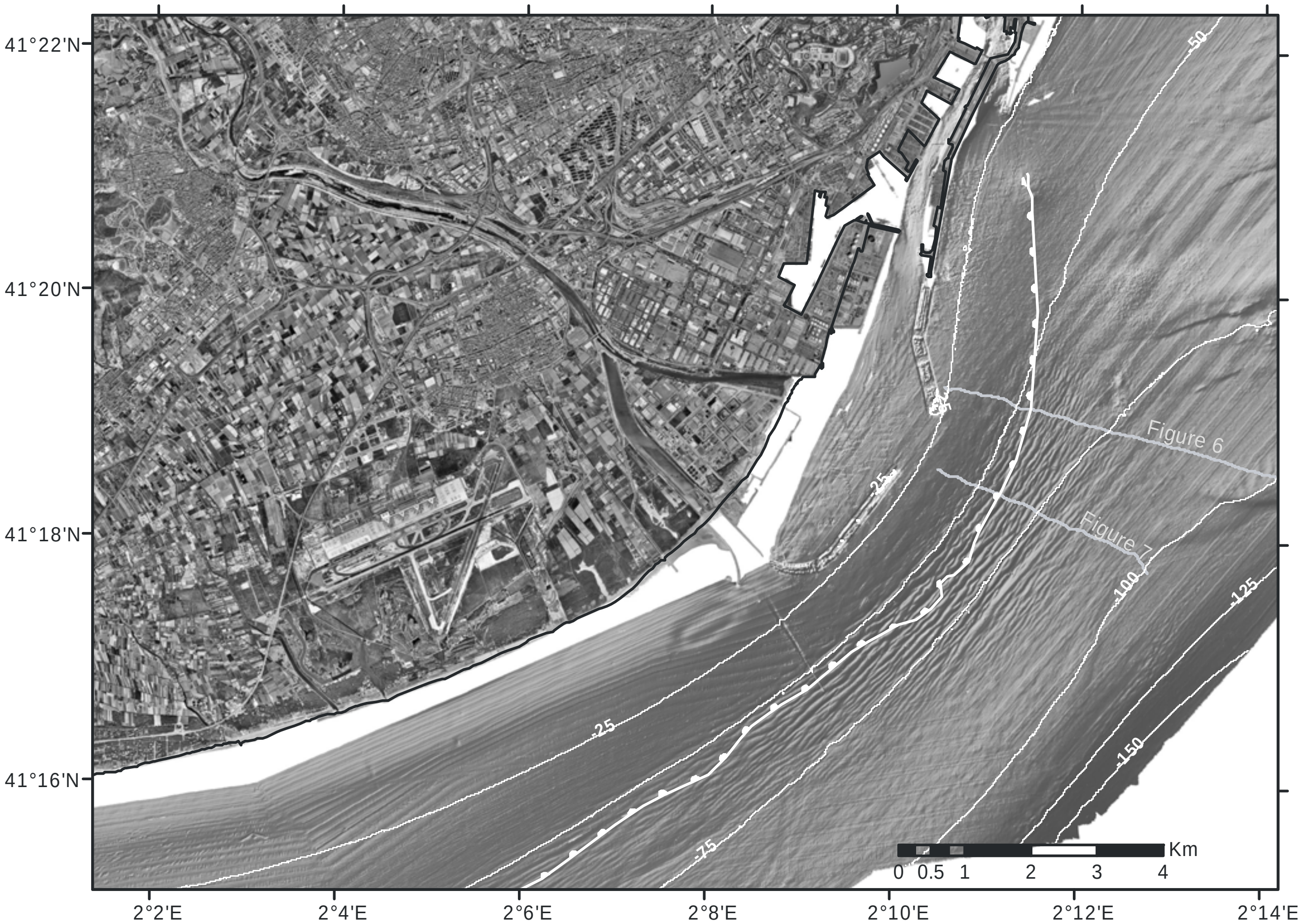

Figure 2. Shaded relief of the Llobregat River prodeltaic area with ortophoto map (Courtesy of the Institut Cartogràfic de Catalunya, 2005) of the subaereal delta. Note diversion of the Llobregat River 2.5 km south of its former mouth to accommodate the enlargement of the Port of Barcelona . The dredging operations and port construction works are denoted by the two arms in between the present river mouth and port in the shaded relief. Note also the field of sediment undulations that develops in front of the future port. Contours are plotted for reference every 25 m. The location of Figures 6 and 7 and the gas front (bold white line with hemicircles) as mapped from the seismic reflection profiles is also shown. For further reference see Figure 3.

They are part of the geological domain of the Barcelona half-graben which is bounded to the NW by the Garraf–Montnegre horst, part of the Catalan Littoral Range (Figure 1). These two regions are separated by a major ENE–WSW-oriented normal fault: the Barcelona fault (Figure 1) [*Roca et al*., 1999]. Major tectonic activity of this and associated faults ceased in the late Burdigalian [*Roca et al*., 1999]. The historical records of seismicity show that the Catalan Coastal Ranges, divided into Littoral and Prelittoral and separated by the SW-NE oriented Valles-Penedes grabben, have had no catastrophic earthquake events. Only two earthquakes causing moderate damage are catalogued [*Fontserè and Iglésies*, 1971]. Paleoseismicity studies show evidence of Quaternary seismic activity with estimated $M_L = 6.5$ [*Massana*, 1996].

The Llobregat River drains an area of 5045 km^2 while the submerged prodelta represents an extension of about 165 km^2. The Llobregat River receives waters from the Eastern Pyrenees and flows through plutonic, metamorphic and sedimentary terrains before discharging about 527 hm^3 yr^{-1} (16.7 m^{3}s^{-1}) of water at the river mouth. The present-day river discharge is regulated by three dams that were built in its upper course, the oldest one dating back to 1957 AD. These dams regulate about 16.7 % of the total basin area. As of 2004 AD the mouth of Llobregat River has been diverted 2.5 km further South in order to extend the port of Barcelona (Figure 2).

The thickness of Holocene deposits in the Llobregat delta ranges from 20 m close to the delta apex, 8 km landward from the present coastline, to about 60 m at the present coastline (Figure 1) [*Marquès*, 1975; *Manzano*, 1986]. Two radiocarbon dates from prodelta silts at 58.5 m and 37.5 m below the present delta plain surface obtained from a borehole having its top at 3.5 m above sea level yielded 10900± 140 yr BP and 2300± 1200 yr BP, which represent mean sedimentation rates between 5.3 and 5.4 mm yr^{-1}, and 10.7 and 34 mm yr^{-1}, respectively [*Marquès*, 1975; *Manzano*, 1986]. The MFS in Spanish Mediterranean waters has been dated to 6900 yrs B.P. [*Lario et al*., 1995; *Somoza et al*., 1998].

The delta has little tidal influence as the Mediterranean Sea is a microtidal sea with tidal oscillations in the range of a few centimeters. The mean wave climate in the study area is of low energy with a wave significant height of 0.74 m, a wave period of 4 s and major storms produced by NE winds [*Barrera*, 2004]. Storms with a recurrence period of 100 years have a significant wave height of 5.9 m and a wave period of 9.5 s [*Barrera*, 2004]. The maximum depth at which sea waves are estimated to produce sediment transport is 20-25 m [*Hernández-Molina et al*., 2000].

Sánchez-Cabeza et al. [1999] show that present sedimentation rates near the river mouth are relatively low, in the order of 0.7 mm/yr, and increase on the prodelta front to about 1.5-1.7 mm/yr. It appears that most of the material is transferred southwestwards along the continental shelf, following the path of the prevailing currents, from the prodelta to the Foix Canyon area where it is deposited at about the mid-slope [*Puig and Palanques*, 1998].

The grain size of the superficial sediment in the Llobregat River prodelta has a high temporal variability [*Puig et al*., 1999]. It may range from well sorted, coarse sediments (sands) to fine sediments (mud). The modern prodelta forms a 'mud belt', which extends NE–SW along the inner and mid-shelf. The prodeltaic deposits are separated from the coastline by coarser sediments and overlay relict bioclastic muddy sands that outcrop on the outer continental shelf. The grain size distribution illustrates the strong influence of marine currents on the Llobregat prodelta deposits, with the fine sediment inputs of the Llobregat River being deflected from the mouth southwestwards [*Puig et al*., 1999].

The sea water circulation along the Catalan shelf is dominated by the Liguro-Provençal Current (LPC), which flows southwestward along the shelf break, separating the shelf waters from the offshore ones [*Arnau et al*., 2004]. On the Barcelona continental margin, the LPC reaches depths of nearly 250 m, with highest velocities around 30 cm s^{-1} [*Castellón et al*., 1990], although in winter they can reach maximum velocities of 40 cm s^{-1} [*Castellón et al*., 1991].

The main seawater circulation is sometimes modified by, relatively small gyres. These are generated by local winds and reinforced by the topographic effect of the continental shelf (anticyclonic gyres) or submarine canyons (cyclonic gyres). Though the largest gyres have been observed during the months of maximum water stratification (usually in the summer months), they occur throughout the year. Off the Catalan coast, mesoscale gyres generated in the Gulf of Lions propagate southwards at a speed of about 5 cm s^{-1}. The mean time interval for the passage of two consecutive mesoscale gyres is about 20 days [*Arnau et al*., 2004]. When mesoscale structures are in transit in the study area, they may induce a nearshore flow toward the east-northeast and redirect hypopycnal and/or hyperpycnal river plumes and coastal waters toward the shelf edge and continental slope.

3. Methods

This study is based on 515 km^2 of multibeam data and 337 km of seismic reflection profiles acquired on board the 12 m yacht "Arraix". The multibeam data were obtained using Simrad's 300 kHz EM3000 dual multibeam echosounder, which was mounted external at the bow of the yatch. The EM3000 dual provides 254 beams (1.5º x 1.5º beam width, 0.9º beam spacing) of depth information from a swath width up to 10 times the water depth or 200 m (maximum horizontal range due to attenuation of sound energy) in up to 150 m water depth with a maximum ping rate of 40 Hz. Raw data was processed using the SwathEd Tools. Bathymetric data processing included editing of navigation, automatic filtering and manual beam editing and refraction correction. The final DTMs were produced at 2 m resolution.

High-resolution single channel seismic profiles were collected in a triangular pattern more or less perpendicular to the shore and connected with two along shore transects. The average spacing between lines is about 2 km. Two seismic lines were collected with a 200J SEISTEC boomer system using a sampling frequency of 1GHz. This resulted in a horizontal resolution of about 3 m and a vertical resolution of 0.5 m. Most of the profiling data were collected, however, with a 300J SIG sparker system, using a sampling frequency of 6 kHz and a shooting interval of 750ms. The sparker profiles are characterized by a horizontal resolution of 9 m and a vertical resolution of about 2 m. The sparker profiles have been processed with a band pass filter (200-220HZ and 1200-1220HZ) and a centered Automatic Gain Control. Processing of the higher resolution boomer profiles included, band pass filtering (500 and 3000 Hz), swell filtering, spiking deconvolution and centered Automatic Gain Control.

For multibeam data acquisition, accurate navigation and real time pitch, heave and roll corrections were ensured by means of the Seatex Seapath 200 two, fixed basline GPS carrier-phase receivers and integrated Kalman filters and its MRU5 inertial motion sensor. Differential GPS corrections were obtained from coastal radio beacons through a Trimble AgGPS132 GPS receiver. Navigation during seismic data acquisition also relied on the Seapath 200 and AgGPS132 devices, but additional layback and offset of source and streamer corrections were carried out. Data was acquired at about 8 kn for multibeam transects and about 4 kn for seismic lines.

4. Results

4.1. Surface morphology of the undulations

The prodelta system of the Llobregat River has an overall convex outwards shape, in prolongation of the subaerial delta. The multibeam data show that close to the shoreline the seabed is rather smooth, except for the few places where anthropogenic modification is clear, i.e. ongoing extension of the port of Barcelona, an outfall from a wastewater treatment plant South of the study area and a few rough, mound-shaped areas that appear to be dumping sites (Figures 2 and 3). Remarkable features in the Eastern part of the seafloor map are the sharp well delimited linear features, creating depth steps (Figures 2 and 3). These relict relieves have been interpreted as migrating ancient shorelines, responding to rising sea level after the Later Glacial Maximum [*Díaz and Maldonado*, 1990]. At about 6 km

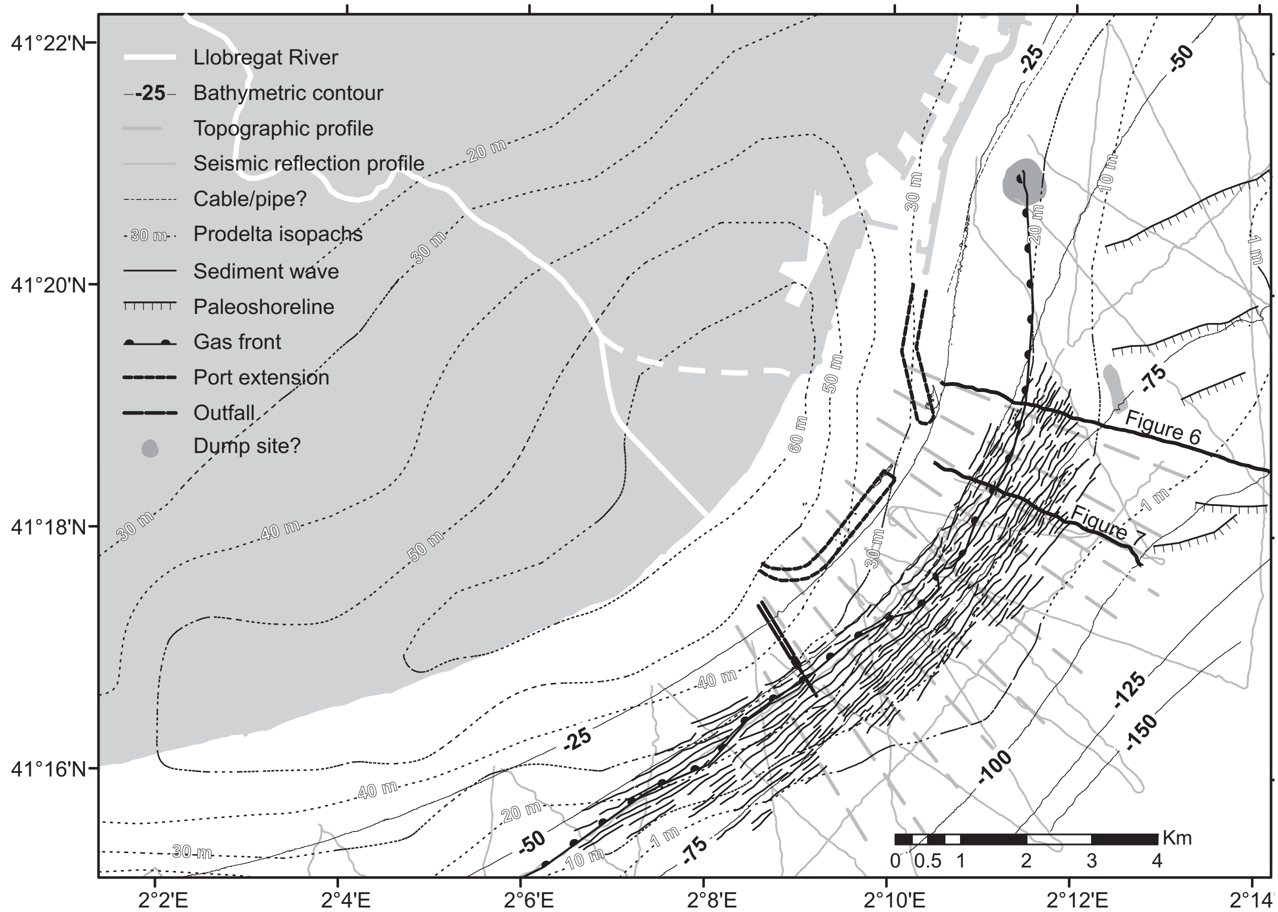

Figure 3. Map showing major features recognizable in Figure 2. Also plotted are the prodelta isopachs, the network of seismic profiles used in this study and the bathymetric profiles that were used to extract statistical information depicted in Figures 4 and 5.

offshore the seabed slope plunges into the steep walls of the Morràs Canyon. Off the Llobregat River outlet the prodelta has its maximum extension with the base of the prodelta almost reaching the head of the Morràs Canyon.

The most outstanding feature on the prodelta is a series of sediment undulations that develop between 35 and 90 m water depth, on the steepest part (average slope of 2º) of the prodelta (Figure 2). They are present in an elongated area along the delta front on slopes that have a minimum and maximum angle of 0.3º and 3º, respectively, and overall is concave upward. The area occupied by these sediment undulations is about 25 km^2, about 2.2 km wide and 12 km long. In plan view these undulations appear as a series of slightly sinuous ridges and swales with an intricate pattern of bifurcating and truncated ridges. Most undulations can be traced for 300 to 400 m along isobaths but they can be as long as 2 km.

The amplitude and wavelength of the sediment undulations is variable. From crest to trough the undulations range from as high as 1.3 m to to a few cm. They also range from about 200 m wavelength on the shallower parts to about 40 m on the deepest parts of the prodelta.

The morphology of the undulations in the Llobregat prodelta can also be described using parameters that have been used in other fields of sediment undulations [see also *Nakajima and Satoh*, 2001; *Cattaneo et al*., 2004]. The parameters were measured along 10 profiles, perpendicular to the regional bathymetric contours, extracted from the swath bathymetric data (Figure 3). Measurements of key geometric parameters included wavelength (L), wave height (H), wave-form index (H/L), asymmetry index (length of upslope limb / length of downslope limb) and downslope-limb slope angle (Figures 4 and 5).

The sediment undulations on the Llobregat River prodelta are relatively small compared to deep-water sediment undulations, but also compared to other prodeltaic settings (Figure 4). Most of the undulations on the Llobregat prodelta show H/L ratios between the ratio lines of 100 and 400 (Figure 4B), in close similarity with other fields of sediment undulations in prodeltaic systems [e.g. *Cattaneo et al*., 2004]. Across the prodeltaic slope (and water depth) the geometric parameters of the sediment undulations show relatively rough trends (Figure 5). The wavelength (L) appears to decrease with water depth, but no clear trend is observed in wave height (H). Asymmetry shows a more clear evolution from shallow to deeper waters and distance from first wave. The shallower undulations show relatively short uslope limbs and long downslope limbs (near 0 asymmetry values) while in deeper waters the undulations are more symmetric. The upslope limb of the undulations may face landward or seaward, while the downslope limb always faces seaward. The angle of this downslope limb shows little variation with water depth, but deeper undula-

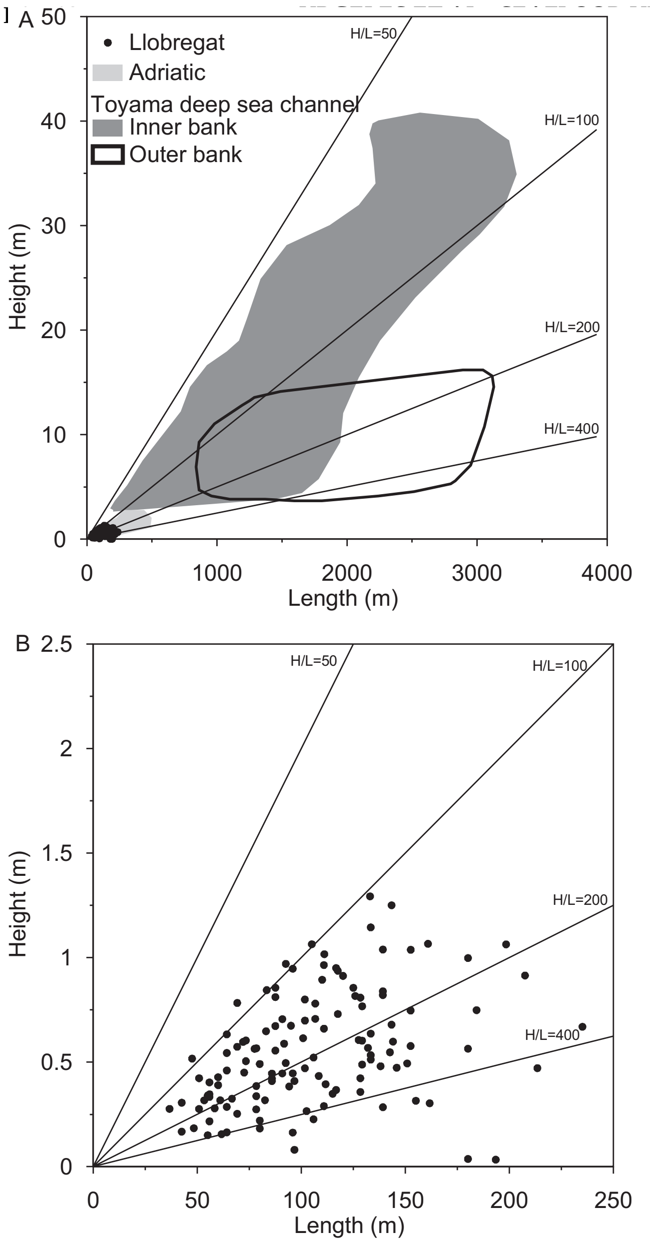

Figure 4. A. Diagram of wave height (H) vs. wavelength (L) of published deep-water sediment waves [from *Nakajima and Satoh*, 2001], the Adriatic sediment undulations [*Cattaneo et al*., 2004] and the Llobregat prodelta (for lines on which measurements were carried our see Figure 3). The Adriatic and Llobregat data are restricted to a small area close to the origin of the diagram. B. Diagram close-up showing the Llobregat data.

tions appear to have slightly steeper downslope limb angles.

4.2. Subsurface structure and facies

The seismic stratigraphy shows that the Holocene Llobregat prodelta can be divided in four main units (Figures 6 and 7) based on the angular relationship amongst reflectors and seismic facies. The shallower part of the study area (up to 30 m depth) shows a zone that is largely void of reflectors or these appear with a very low amplitude and more chaotic character. This facies is distinctive of shallow gas enriched sediment layers, which mask the underlying reflectors. Noteworthy is the fact that sediment undulations develop downslope from the gas front, and only at a few locations the uppermost undulations are on top of the gassy zone (Figures 6 and 7). However, some gas might also be present within the sediments affected by the undulations up to 70 m depth as inferred from local polarity inversions and bright spots of some reflectors.

The top of the section is marked by an acquisition artifact creating a ghost reflector or doublet of the seafloor, which interferes with the real reflectors. The depth of the ghost is variable with the depth variation of the streamer depending on the sea -state and the sailing direction of the yacht. The seafloor marks the upper level of unit A bounded by relatively high-amplitude reflectors while internally displaying weak gently dipping reflectors. Unit A pinches out offshore forming a wedge with a maximum thickness of 30 msec TWTT at 3 km offshore and only 3 msec TWTT at 4.5 km (Figures 6 and 7). The base of the unit is a downlap surface. Its seismic character suggests that sediments are homogeneous and fine grained. By analogy to other detailed seismic studies in the Mediterranean Sea [*Trincardi and Correggiari*, 2000; *Correggiari et al.*, 2001], unit A most probably represents the Late-Holocene High-stand Systems Tract (HST) mud wedge. The extent of the gas free sediments within this unit is more or less coincident with the occurrence of the undulating features, although there is a certain overlap (Figures 2 and 7). Variations in amplitude of the lower discontinuity are related to local enrichment of sediments with gas. The second unit (B) is relatively thin (no more than 10 msec) and shows high-amplitude laterally continuous reflectors. It is bounded to the top by a prominent reflector interpreted as the MFS and shows an onlap relationship with the unit C below (Figures 6 and 7). Unit B is interpreted to be part of a Trangressive Systems Tract in the prodelta system. The top of unit C is marked by an erosional truncation or a toplap configuration with respect to the above unit B. As with unit A, it shows weak seaward gently dipping reflectors and pinches out offshore forming a wedge. Unit C is also interpreted as a HST. The base of the unit is also a downlap surface below which there is unit D, which is analogous in character to unit C (Figure 6).

The lowermost part of the sequence appears faulted with individual faults having a slip of no more than 5 msec TWTT. The reflectors of unit A compared with those of unit C, together with the upward termination of the normal faults, indicate that the undulations in unit A have no relation to the faulting below (Figure 6). Figure 6 also shows an area of chaotic reflectors in unit C (the following High-stand Systems Tract) that broadly coincides with the area displaying the sediment undulations. The sediment body that displays such seismic facies appears to originate from a series of truncated reflectors and can be clearly identified as a scar and debris flow deposited at the foot of the scar (Figure 6).

The sediment undulations develop exclusively within unit A and are characterized by a uniform wavy stratified pattern of strong to faint prograding seismic reflectors (up to 20 msec TWTT thick) on the prodelta front. They appear to root at the top reflector of unit B, which has been identified as the MFS in this area. The reflectors within this geo-

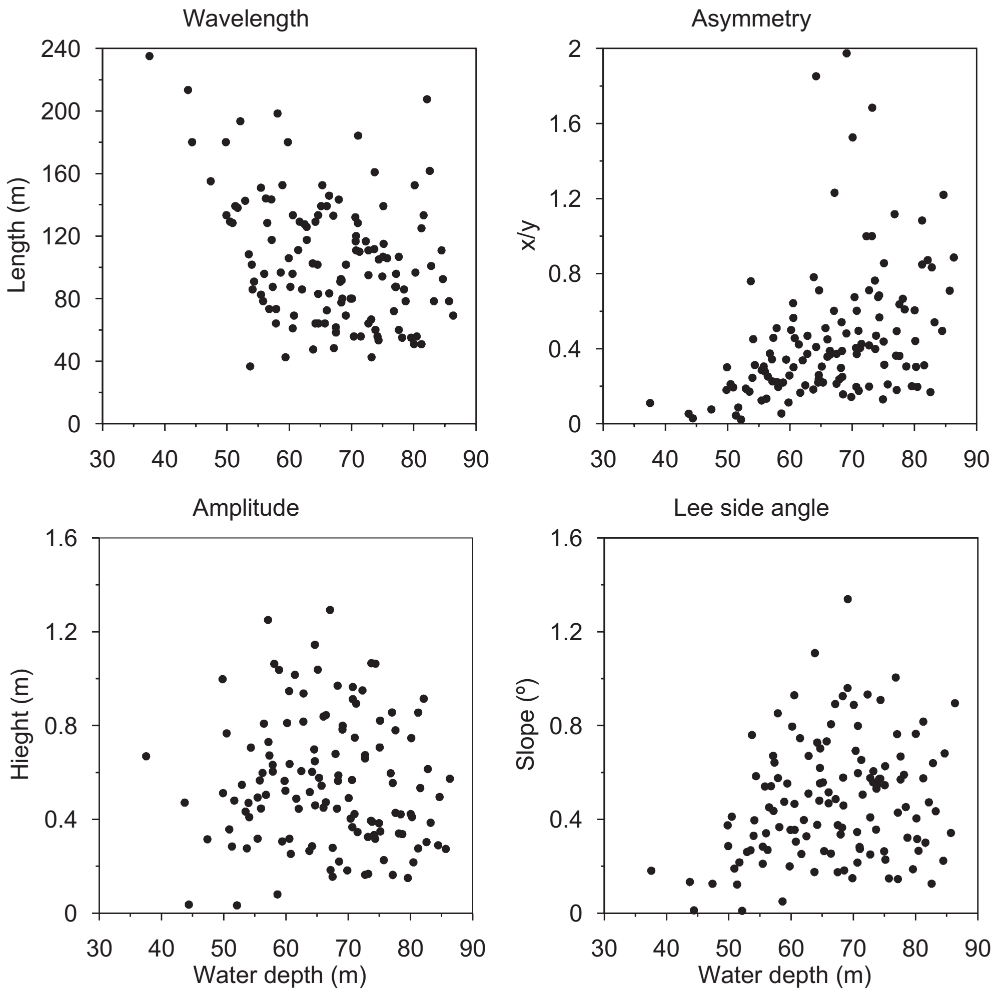

Figure 5. Plot of wavelength, asymmetry, amplitude and undulation lee side angle vs. water depth as measured along the bathymetric profiles shown in Figure 3 (perpendicular to the bathymetric contours).

graphic area are characterized by undulating topography comprising a succession of broad crests and narrow troughs. The seismic reflectors, though, can be traced through out the whole set of undulations along the prodelta front. As observed from the multibeam data, in cross section, the undulations display larger wavelength in the upper part than in the lower part of the slope. In the same way both wavelength and amplitude tend to decrease with increasing stratigraphic depth (Figure 7). The reflectors in the basal part of unit A are not exactly parallel to the upper continuous higher amplitude reflectors, and several terminations occur. It is also noteworthy that within the extent of an undulation on the seabed, several smaller scale (< 200m in wavelength) undulations exist in the basal part.

5. Interpretation and discussion

It is clear from the wave and tide regime (see introductory section) that those two processes are unable to create sediment transport in water depths between 35 and 90 m where the sediment undulations on the Llobregat River prodelta occur. In other prodeltaic areas the world over, three principal hypotheses have been given for the genesis of similar sediment undulations. The first one postulates a formation induced by bottom currents [*Trincardi and Normark*, 1988; *Mosher and Thomson*, 2002], the second one suggests an origin from hyperpycnal flows/turbidity currents [*Bornhold and Prior*, 1990] and the third one relates these features to downslope sediment deformation or creep [e.g., *Díaz and Ercilla*, 1993; *Ercilla et al*., 1995; *Chiocci et al*., 1996; *Correggiari et al*., 2001]. A complex origin with interaction of bottom currents and downslope sediment deformation has also been suggested in some particular cases [see *Faugères et al*., 2002; *Cattaneo et al*., 2004]. In this section we will discuss the different arguments that may allow us identifying the genetic mechanism of the sediment undulations on the Llobregat prodelta.

5.1. Sediment deformation vs. sedimentary structures

The first thing to remark is that the sediment undulations only occur in a restricted area of the prodelta slope. The field of sediment undulations is elongated southwestwards

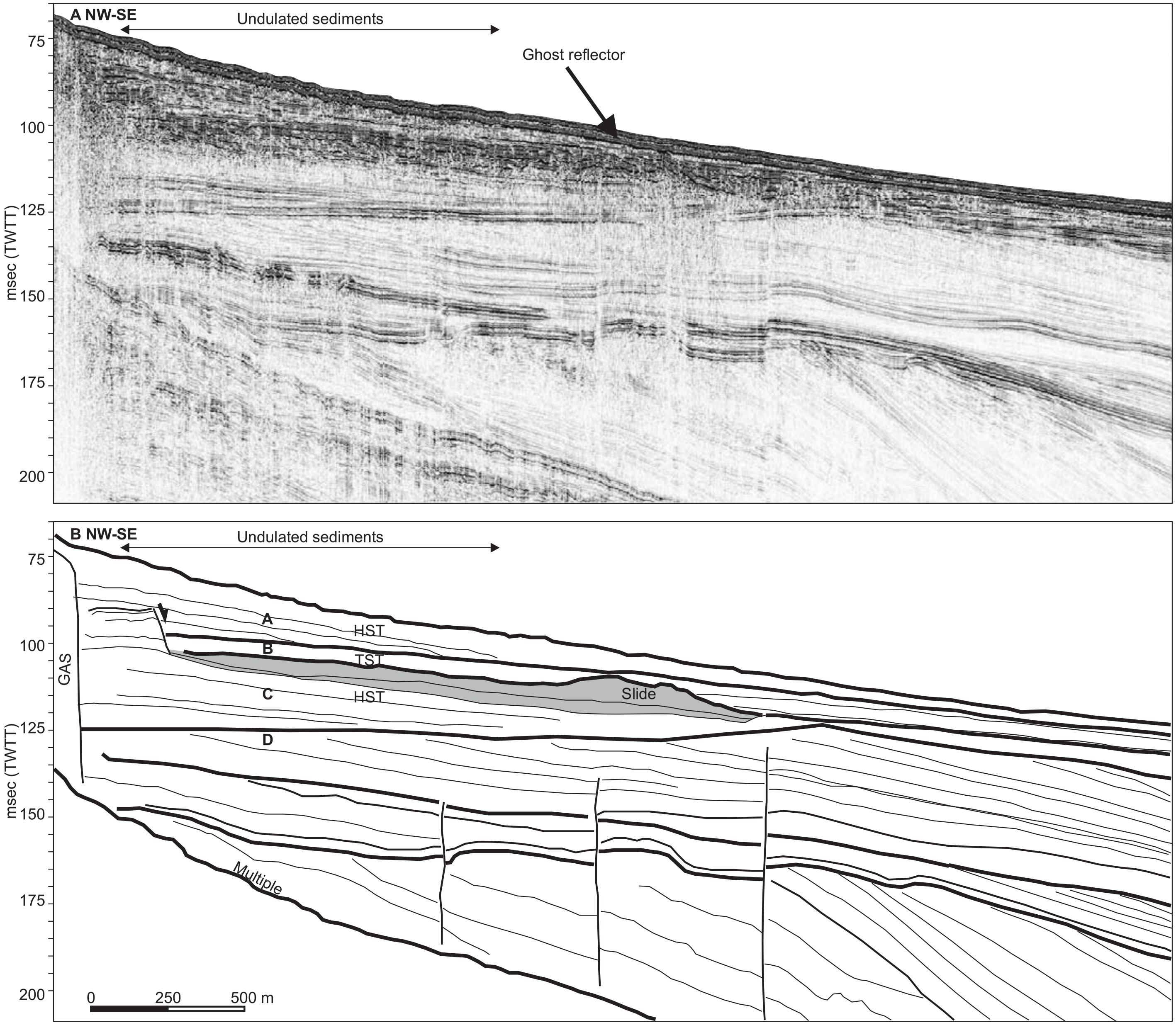

Figure 6. Sparker seismic reflection profile (A) and linedrawing (B) showing location of the sediment undulations in respect to the overall stratigraphy of the Llobregat River prodelta.

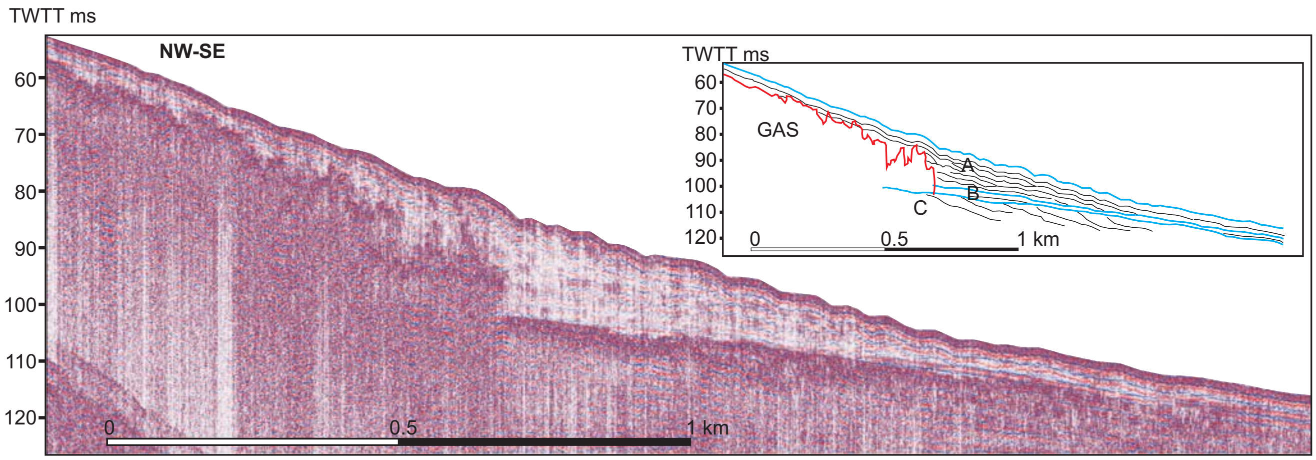

Figure 7. High resolution boomer profile showing the stratigraphy of the Late Holocene mud wedge and internal geometry of the field of sediment undulations.

from the Llobregat River outlet, which most probably results from the prevailing oceanic circulation, but this does not preclude its formation by means of one mechanism or the other. Geostrophic water circulation controls diversion of river plumes (hyperpycnal or not) and also location of the depocenter (and therefore excess pore pressure development due to high sedimentation rate, gas generation and the area of most likely deformation). There is also no visible headscarp in the study area as is commonly the case in submarine sediment slides, but this is to be expected if failure is at an early stage, it is developing or only incipient failure occurred.

There seems to be a clear spatial relationship between the gassy sediments and the location on the Holocene mud wedge of the sediment undulations (Figures 6 and 7), the later developing in front of the gas bearing sediments. Sediments containing gas are known to reduce the sediment shearing resistance and recent studies have shown that shallow gassy submarine sediments are especially hazardous when unloaded (tidal cycles, erosion, natural slope instabilities, excavation) [*Vanoudheusden et al*., 2004].

It is also evident from the seismic reflection data that at least a relatively small slide with complete failure and generation of a small debris flow deposit has occurred in the past in the same area and sequential stage (Unit C – the following HST) than that displaying the sediment undulations (Figure 6). These observations reinforce or would point out an explanation of those features as the result of sediment deformation or creep. Assuming that the observed undulations correspond to sediment deformation, it must be noted that the event that generated them is still active (in the case of slow deformation) or is very recent (in the case of rapid deformation in response to a specific event) because it affected the present-day seafloor (Figure 2) without evidences of draping or smoothing of the undulations due to subsequent sediment deposition (Figure 7).

Detailed analysis of the sediment undulations shows that the larger ones occur on the upslope part of the prodelta (Figure 5). This would imply a larger amount of deformation there and, as a consequence, that sliding progressed downslope, while most slides show a retrogressive behavior [*Canals et al*., 2004].

On the seismic reflection profiles the character of individual reflectors is quite continuous and no diffractions are visible on the sinform part of the folds, which could indicate rupture of the reflectors. It is also noteworthy the lack of compressional features at the toe of the prodelta front. Absence of such features would imply a low angle detachment level as proposed by *Lee et al*. [2002] for the Humboldt slide, but such a level is not evident on the seismic reflection data (Figure 7). Shear deformation along the planes separating the undulations would imply the formation of drag folds, which are absent too. Another striking characteristic of the sediment undulations off the Llobregat River mouth is the absence of growth features (Figure 7), indeed if the surfaces separating blocks would represent the shear planes then the slip along those surfaces is constant, which would actually imply a single phase of movement (no synchronous deposition while deformation) and therefore deformation is not progressive as is typically the case with creep. The later would imply an increasing slip with depth. Growth faults in prodelta settings are also typically characterized by antithetic faults [e.g., *Bhattacharya and Davies*, 2001], but they can not be recognized in the study area too. Under the supposition of rapid deformation in response to a specific event (earthquake, very large storm…), the trough to crest vertical distance on the landward side of the undulations (not wave height, H, see *Cattaneo et al*., 2004) could be seen as the minimum vertical displacement associated with the deformation. This distance amounts up to 0.5 m for some undulations. The cumulative displacement along a transect (see Figure 3) would be of a minimum of 1.6 m. From the undulation geometry (Figures 2 and 7), the horizontal displacement is more difficult to quantify but it is probably of the same order of magnitude or larger assuming rotational or log-spiral movement for each failed slice [see also *Casson et al*., 2005]. Such a displacement is rather high for coherent slices of sediment to slump in a single event, especially considering that horizontal displacements of a few cm are reported to be able to create full sediment failure [see *Wilson and Keefer*, 1983; *Mankelow and Murphy*, 1998; *Miles et al*., 2000]. The high sedimentation rates reported in the literature [*Marquès*, 1975; *Manzano*, 1986] point out that for such a deformation the sediment is likely to behave contractively, probably inducing large runout and development of a flow [*Iverson et al*., 2000] as observed for an older landslide in Figure 6.

It is also curious that within different undulations the dipping of strata is similar (Figure 7) [see also *Lee et al*., 2002]. This regularity is better explained by sediment waves formed by bottom currents than creep. The later would typically show different degrees of deformation. It is also difficult to find the intricate pattern of branching and truncated undulations (Figures 2 and 3) in known subaereal and submarine failures, while it is quite common in current driven sediment structures such as ripples and aeolian sand dunes [e.g. *Mazumder*, 2003]. *Wynn and Stow* [2002], also point out that in planform view most sediment waves appear as linear features with varying degrees of sinuosity and/or bifurcation while creep/slump folds are arcuate, and do not show bifurcation [e.g. *Kenyon et al*., 1978].

5.2. Bottom currents vs. hyperpycnal flows

From the previous section it appears unlikely that the sediment undulations on the Llobregat prodelta result from sediment deformation. There are also a number of characteristics that help identifying whether the sediment undulations/waves resulted from bottom/geostrophic currents or whether they could result from hyperpycnal flows derived from the Llobregat River. For this we will draw analogies with the more studied deep-water bottom current and turbidity current sediment waves. Deep-water turbidity current sediment waves will be used as analogous of those formed by hyperpycnal flows. Indeed hyperpycnal river flows are one of the ways in which turbidity currents can be generated [*Mulder and Syvitski*, 1995]. Nevertheless, it must be noted that deep-water sediment waves are several orders of magnitude larger, and that sediment accumulation rates are as much as three orders of magnitude higher in prodeltaic settings [*Cattaneo et al*., 2004], but the processes that act to create the different types of waves are equivalent.

Studies of deep-water sediment waves have found that bottom current waves have no consistent change in wave dimensions up- or downslope [e.g. *Cunningham and Barker*, 1996]. *Wynn and Stow* [2002] have also shown that wavelength and height typically decrease downslope in turbidity current – sediment wave fields , as observed in the Llobregat prodelta. *Normark et al*. [1980] concluded that this is due to slowing of turbidity currents as they progress towards flatter areas.

Studies of deep-water sediment waves have also shown that fine-grained bottom current waves develop with wave crests aligned at a certain angle (typically 10-50º) to the regional contours, while the crests of turbidity current waves on slopes are normally slope-parallel [*Wynn and Stow*, 2002], as is the case in the study area.

In close similarity with the Llobregat prodelta, the stratigraphic interval over which turbidity current wave fields occur often shows a progressive downslope decrease in thickness [e.g. *Ercilla et al*., 2002]. *Wynn and Stow* [2002] suggest that this indicates that the wave sequence is sourced from upslope, not alongslope as is normally the case for bottom current waves. These arguments indicate that the most probable mechanism that could form the undulations on the Llobregat prodelta is hyperpycnal flows originating from the Llobregat River. However, the overall shape of the field of sediment undulations, elongated SW from the pre-2004 river mouth, suggests a control by bottom currents on diversion of hyperpycnal flows.

5.3. Are hyperpycnal flows likely to take place on the Llobregat River prodelta?

Historical document sources show that the Llobregat has had 171 flood events at the river mouth in the period between 1315 and 2000 AD [*Llasat et al*., 2005]. Of these events, 81 were classified as extraordinary (bank overflow without significant damage) and 21 as catastrophic (bank overflow with significant damage) [*Llasat et al*., 2005]. A summary of the major floods in the Llobregat River during the 20th century is provided by *Thorndycraft et al*. [2005]. They show that the Llobregat River has had 9 major floods during the 20th century which reached peak water discharges between 1100 and 3080 m^3/s. Nevertheless, water discharge of paleoflood events estimated from slackwater paleoflood deposits indicate that peak water discharges may exceed 4600 m^3/s [*Thorndycraft et al*., 2005]. Unfortunately there are no records of solid discharge for the Llobregat River.

Estimates of solid discharge and sediment concentration for the Llobregat River based on rating coefficients can be made from regression equations proposed by *Syvitski et al*. [2000]. Those estimates vary largely depending on the choice of regression equation and associated input parameters. For instance for the flood event of 1971, which had a peak discharge of 3080 m^3/s, the derived sediment concentrations range between 17 and 68.3 kg/m^3. The sediment concentration in fresh water that is needed to overcome the density of seawater, and produce an hyperpycnal flow in temperate seas such as the Mediterranean Sea is 42.74 kg/m^3 (density of seawater taken as 1.02661×10^{-3} kg/m^3 [see *Mulder and Syvitski*, 1995]). The water discharge that is needed for the Llobregat River to produce hyperpycnal flows is thus between 1905 and 7907 m^3/s. The flood discharges for the Llobregat River fall within this range [*Thorndycraft et al*., 2005] and thus it appears that the river can produce hyperpycnal flows during flood events. The higher discharge estimates from paleoflood deposits would rather support such a possibility. Recent work also shows that hyperpycnal flows may form with sediment concentrations as little as 1 kg/m^3 [*Parsons et al*., 2001], and under these circumstances the Llobregat River would easily produce hyperpycnal flows. However, damming of the river, channel paving and stepping of the river course might have presently reduced the likelihood of hyperpycnal flows on the Llobregat prodelta.

6. Conclusions

Very high-resolution multibeam bathymetric data and seismic reflection profiles demonstrate that the prodelta front of the Llobregat River is dominated by a 25 km^2 field of sediment undulations which develops between 35 and 90 m water depth, on slopes between 3 and 0.3º. Detailed morphologic and seismostrtigraphic analysis of the sediment undulations allows identifying such structures as sediment waves (in opposition to sediment deformation) most likely generated from hyperpycnal plumes derived from the Llobregat River. Nevertheless the overall shape of the field of sediment undulations suggests a certain control by bottom currents. Data from historical and pre-historical flood records indicates that hyperpycnal flows are likely to take place in the Llobregat River during major floods. The data would therefore suggest that such a feature presents no major threat for offshore development and enlargement of the port of Barcelona. However, final conclusion and decision should be subject to the acquisition of more detailed geophysical profiling, sediment samples for geotechnical analyses and probably in situ testing. Special attention should be given to dredging operations in proximal prodelta areas where gassy sediments are ubiquitous. Resemblance (in terms of time framework, stratigraphic setting, and location with respect to river outlets) of the undulations found in the Llobregat prodelta and other undulations in prodeltaic settings of the Mediterranean suggests a common genetic origin. However, some particularities to these other occurrences may indicate that additional genetic processes need to be considered in these areas.

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