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A review of undulated sediment features on Mediterranean prodeltas: distinguishing sediment transport structures from sediment deformation

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Abstract :

Most Mediterranean prodeltas show undulated sediment features on the foresets of their Holocene wedges. These features have been described all along the Mediterranean for the last 30 years and interpreted as either soft sediment deformation and incipient landsliding, and more recently, as sediment transport structures. We perform a review and detailed analysis of these undulated sediment features using ultrahigh-resolution seismic and bathymetric data as well as geotechnical information and hydrodynamic time series and hydrographic transects. In this study we show that the characteristics of the sediment undulations (configuration of the reflections down section and between adjacent undulations and overall morphologic characteristics) are incompatible with a genesis by sediment deformation alone and do not show evidence of sediment deformation in most cases. Various processes in the benthic boundary layer can be invoked to explain the variety of features observed in the numerous areas displaying sediment undulations.

Keywords

Undulated sediments, prodeltas, slope failure, sediment waves, hyperpycnal flows, internal waves

Introduction

The last two decades have provided profuse evidence of undulated sediment features on Mediterranean prodeltas (Galignani, 1982; Mougenot et al., 1983; Aksu and Piper, 1988; Checa et al., 1988; Trincardi and Normark, 1988; Romagnoli and Gabbianelli, 1990; Agate and Lucido, 1995; Ercilla et al., 1995; Chiocci et al., 1996; Correggiari et al., 2001; Lykousis et al., 2001; Marsset et al., 2004; Cattaneo et al., 2004; Fernandez-Salas et al., 2007; Urgeles et al., 2007; Lykousis et al., 2008; Agate et al., 2009; Rebesco et al., 2009; Bárcenas et al., 2009)). Early studies on these features proposed interpretations involving sediment deformation and slope failure phenomena (Galignani, 1982; Mougenot et al., 1983; Aksu and Piper, 1988; Checa et al., 1988; Romagnoli and Gabbianelli, 1990; Agate and Lucido, 1995; Ercilla et al., 1995; Chiocci et al., 1996; Correggiari et al., 2001; Lykousis et al., 2001; Fig. 1). Such evidences came from seismic reflection profiles where sediment undulations appeared to be separated by shear planes.

With popularization of very high resolution chirp-sonar profiling and mapping systems based on multibeam technology, seafloor surface geometries compatible with submarine slope deformation alone were questioned (Cattaneo et al., 2004; Urgeles et al., 2007; Fernandez-Salas et al., 2007; Bárcenas et al., 2009). An intense debate started on whether these features were in fact created by sediment transport processes on the bottom boundary layer (i.e. we were imaging sediment waves), or by deformation. Mixed theories (i.e. initial sediment deformation and growth by differential sediment accumulation patterns) were also proposed (Cattaneo et al., 2004). The resolution of the geophysical data used to investigate those features appeared not high enough or not comparable to the outcrop scale analogs, where soft sediment deformation structures can be readily identified on paleo-prodeltas (Bhattacharya and Davies, 2001), to be able to assign a genetic mechanism to these structures. The debate was not restricted to the Mediterranean Sea, a few specific case studies in shallow water settings (Bornhold and Prior, 1990; Mosher and Thompson, 2002; Boe et al., 2004; Hill et al., 2008) and deep-water settings (Field and Barber, 1993; Gardner et al., 1999; Lee et al., 2002) of various areas of the world ocean also attracted quite vivid debate (e.g. the Humboldt slide off northern California; Normark et al., 1979; Normark, 1980; Gardner et al., 1999). Significant efforts have been carried out to understand undulated sediment features in deep-water settings, which has been shown that a variety of process are also able to shape undulated sediment features in these environments (Wynn and Stow, 2002), though deep-water undulations are at least one order of magnitude larger (Nakajima and Satoh, 2001).

In the case of Mediterranean prodeltas, with one of the most heavily populated coastlines of the world, the identification of the sediment undulations as depositional or deformation features has important implications for offshore and coastal management (Trincardi et al., 2004; Urgeles et al., 2007). This triggered a multidisciplinary investigation that included collection of oceanographic and geotechnical data. Efforts were put to model and monitor active sediment transport on the seafloor (Puig et al., 2007; Sultan et al., 2008). The aim of this paper is to provide new data and the latest view on the origin of these undulated seafloor features in the prodeltas of the Mediterranean Sea, where this type of structures share many characteristics that are not found in deeper water settings.

Mediterranean setting

The Mediterranean region is seismically active, and is currently undergoing rather rapid deformation (Vannucci et al., 2004; Jiménez-Munt et al., 2006). In a very simplified way, the Mediterranean region records, from west to east, a passage from a simple deformation at the oceanic plate boundaries of the Atlantic, characterized by narrow seismic belts, to a broad belt of seismicity and deformation that characterizes the continental collision setting (McKenzie, 1972; England and Jackson, 1989). Seismicity is widespread in the Mediterranean region, although it is not restricted to narrow seismogenic boundaries, but is generally rather diffuse. The eastern Mediterranean and the Aegean Sea in particular, are the most active seismic regions.

The system of extensional Mediterranean basins have been formed during the latest phases of subduction of several segments of the Tethys oceanic lithosphere and the extensional orogenic collapse caused either by delamination of thickened continental lithosphere (Platt and Vissers, 1989; Docherty and Banda, 1995; Vissers et al., 1995; Seber et al., 1996; Platt et al., 1998; Calvert et al., 2000), rollback of oceanic plates

(Lonergan and White, 1997), or a combination of both processes (Faccenna et al., 2004). Subduction is also responsible for the formation of contractional belts like the Apennines or the Betics. Typically those belts have also undergone extensional processes, which in a number of cases are currently active, as is the case in the Betics (Balanyá et al., 1997; Johnson et al., 1997; Martínez-Martínez y Azañón, 1997) and in the Apennines (Collettini, 2004, 2005). The coastal morphology of the Mediterranean Sea is a direct result of the tectonic setting and it is characterized by coastal mountain ranges with high mountain peaks in the catchment basins of the rivers and areas of tectonic uplift.

Mediterranean climate and sediment delivery to Mediterranean prodeltas

The Mediterranean climate shows a marked seasonal regime modified locally by complex geographic factors. During the long summer season the subtropical circulation causes warmth and dryness, while in winter the temperate circulation brings milder and wetter air masses from the north-east. The Mediterranean Sea has a role of heat reservoir and source of moisture for surrounding land areas. The Mediterranean climate is also characterized by the presence of regional energetic mesoscale features and cyclogenesis areas (Lionello et al., 2006).

Most of the Mediterranean drainage network is made of medium-to-small fluvial systems, with only 9 rivers longer than 450 km (Nile, Ebro, Rhone, Chelif, Po, Moulouya, Ceyhan, Evros and Medjerda; Fig. 1). The Mediterranean river systems show relatively high temperature, small size, high seasonal variability, high population density, and high slope due to the short distance between the mountain ranges and the coast (Liquete et al., in prep.). In general, rivers from the northern Mediterranean region are orographically more abrupt, climatically colder and wetter, and hydrologically more active. The largest runoff (>1000 $mm \cdot yr^{-1}$) is found in a few Greek and Albanese rivers associated with the greatest precipitation falls over the Albanian and Croatian basins. Italy concentrates the watersheds with more erodable and less vegetated land. The most arid conditions are typically found in North African, Sicilian and Spanish Levantine river basins.

The current freshwater surface discharge to the Mediterranean Sea is estimated in 400-450$km^3 \cdot yr^{-1}$, about one half of what it was at the beginning of the 20th century (UNEP, 2003; Ludwig et al., 2009). It is suggested that the overall sediment flux to the Mediterranean Sea is 730×10^6 $t \cdot yr^{-1}$ (UNEP, 2003).

Available measurements from 88 Mediterranean watersheds (Milliman and Syvitski, 1992; Probst and Amiotte-Suchet, 1992; UNEP, 2003; RIKZ et al., 2004; EEA, 2006; FAO, 2007; Syvitski and Milliman, 2007; Liquete et al., 2009) allowed estimating their average suspended sediment yield in 352 $t{\cdot}km^{-2}{\cdot}yr^{-1}$, which is approximately twice the 150-200 $t{\cdot}km^{-2}{\cdot}yr^{-1}$ world average (Milliman and Syvitski, 1992). The relatively low water discharge of these systems (see for instance FAO, 2007) related to their moderate-to-high sediment flux suggests that the Mediterranean watersheds are particularly competent as sediment suppliers to the sea. The lowest sediment discharge values are found in the NW Mediterranean region, notably in France and Spain (UNEP, 2003; EEA, 2006; Liquete et al., 2009), although the fluvial sediment load is known to be highly variable in the area.

Mediterranean wave and tidal regime

The Mediterranean Sea has a relatively mild climate on the average, but substantial storms are possible, usually in winter. The maximum measured significant wave height reaches 10 m, but model estimates for some non-documented storms suggest much larger values (Cavalieri et al., 2005). The winter mean significant wave height in the Mediterranean ranges from ~0.8 to ~2 m. The area with the largest winter mean significant wave height is the Gulf of Lions, in the Western Mediterranean Sea (Cavalieri et al., 2005). Wave dynamics in the Mediterranean Sea is mostly influenced by the regional orographic conformation and fetch (Lionelli and Sanna, 2005).

Tidal currents in the Mediterranean Sea are important only close to major passages (e.g. the Strait of Gibraltar, the Channel of Sicily), in some minor ones (e.g. the Strait of Messina) as well as in all coastal pond outlets where they can reach a few m s^{-1} (Millot and Taupier-Letage, 2005b). Over most of the Mediterranean, however, tidal currents can be neglected since they have a velocity of a few mm s^{-1} only (Albérola et al., 1995). Also tidal amplitude rarely exceeds 0.5 m except in the Gulf of Gabes off the coast of Tunisia (tide range of nearly two meters) and areas where amplification occurs due to summing of the coastal setup and seiches, as in the northern Adriatic (Tsimplis et al., 1995).

Oceanography of shallow Mediterranean waters

The semi-enclosed Mediterranean Sea is characterized by evaporation exceeding precipitation and river runoff (Le Vourch et al., 1992; Millot and Taupier-Letage, 2005a). The tendency for a difference in level between the sea and the Atlantic Ocean leads the surface Atlantic Water to flow into the Mediterranean Sea (Millot and Taupier-Letage, 2005b). The incoming Atlantic Water is continuously modified due to interactions with the atmosphere and mixing with older Atlantic Water remaining at the surface and with the waters underneath (Fig. 1).

In winter, cold and dry air masses entrained by relatively brief episodes of strong northerly winds induce marked evaporation and direct cooling of modified Atlantic Water, resulting in a dramatic increase in its density which makes it sink. Sinking and deep-water formation occurs in a series of specific zones where deep dense water convection takes place, generally located in the northern parts of the basins (Fig. 1). Due to the Coriolis Effect all waters that are forced to circulate at basin scale (at all depths) tend to follow, in the counterclockwise sense, the isobaths corresponding to their density level (Millot and Taupier-Letage, 2005b). Several evidences show that current circulation could be associated with bedforms at several deep-water sites of the Mediterranean, including the Sicily Channel, the Southern Adriatic Margin and the Corsica Basin (Verdicchio and Trincardi, 2009).

On the continental shelves of the northern Mediterranean basins (i.e. Gulf of Lions, northern Adriatic and northern Aegean), waters are markedly cooled during wintertime because the reduced depth does not represent a large reservoir of heat. Despite the gain in buoyancy caused by freshwater inputs due to river runoff, dense waters are also generated on the northern Mediterranen shelves. Such dense waters travel along the shelf and cascade to greater depths, mainly through submarine canyons, until reaching their density equilibrium level (Durrieu de Madron et al., 2005). These waters are rapidly lost due to mixing induced by the relatively intense circulation along the slope (Le Vourch et al., 1992).

Sea level history in the Mediterranean Sea

The Quaternary is characterized by cyclic climate and related sea-level changes (Shackleton, 1987) that strongly impacted the sedimentary architecture of continental margins. These events have also strongly influenced sediment distribution and architecture of sedimentary bodies in continental shelves of the Mediterranean Sea (e.g. Jouet et al., 2006; Berne et al., 2007; Cattaneo et al., 2007; Liquete et al., 2007). The Quaternary climate changes also had a profound effect on adjacent river watersheds, which resulted in a sedimentary flux 3 to 3.5 times greater than the present one, during the maximum of glaciation (Bossuet et al., 1996).

During the last glacial-interglacial cycle, the Mediterranean Sea has been connected to the global ocean and therefore has followed the same trends in sea-level changes (Berné et al., 2007). Isotopically-derived sea-level curves for the last 120 kyr (e.g. Shackleton, 2000, Waelbroeck et al., 2002) display a general fall until the LGM, punctuated by high-frequency changes. The last sea-level lowstand is generally set around 110 and 120 m below present sea-level, but estimates going from 90 to 150 m have also been proposed (Shackleton, 1977, Fairbanks, 1989, Bard et al., 1990, Lambeck and Bard, 2000 and Clark and Mix, 2002). The position of relative sea-level during the maximum lowstand is at least 115 m in the Mediterranean Sea (Jouet et al., 2006).

On Mediterranean continental shelves, sediment supply decreased abruptly at 15 kyr BP, because of the rapid landward shift of fluvial outlets during the deglacial sea-level rise (e.g. Jouet et al., 2006). Sea-level rise for the Post Younger Dryas period in the Mediterranean show a constant global sea-level rise with values between 1 and 1.5 cm/yr (Lambeck and Bard, 2000; Berné et al., 2007). Archaeological observations along the Mediterranean coast indicate that sea level remained below its present level until about 3 ka BP (Lambeck et al., 2004). High frequency sea-level fluctuations during the last 4 ky were relatively minor, fluctuating by less than 1 m (Lambeck and Bard, 2000; Sivan et al., 2001). Hernández-Molina et al. (1994) also show that during Late Pleistocene-Holocene times, climate-induced relative changes in sea level were faster than fault movements or local subsidence, at least on the Iberian Mediterranean coast.

Methods

The evidences discussed in this manuscript are mainly based on a set of previously published data. Published data were obtained using a variety of tools with differing resolution, penetrations, spatial and temporal coverage. They include shallow water multibeam echosounder (Cattaneo et al., 2004; 2006; Urgeles et al., 2007; Fernández-Salas et al., 2007; Rebesco et al., 2009), seismic reflection profiles (Aksu and Piper, 1988; Checa et al., 1988; Mougenot et al., 1983; Trincardi and Normark, 1988; Díaz and Ercilla, 1993; Ercilla et al., 1995; Chiocci et al., 1996; Cattaneo et al., 2004; 2006; Urgeles et al., 2007; Fernández-Salas et al., 2007; Lykousis et al., 2008; Rebesco et al., 2009; Agtate et al., 2009), high resolution 3D seismic data (Marsset et al., 2004), hydrodynamic time series and hydrographic transects across undulated seafloor features

(Puig et al., 2007), sediment samples for geotechnical tests (Sultan et al., 2004; 2008), CPT insitu measurements (Sultan et al., 2004; 2008) and river water and sediment discharge obtained from several regional and global databases (Liquete et al., in prep.). For the details on these data sets the reader is referred to the original sources were these data were published.

Unpublished data presented in this paper, shedding additional light into the processes at the origin of these undulations, include ultra-high resolution chirp profiles from the Adriatic, Algerian and Llobregat areas. The systems used in these areas are respectively the CHIRP sonar of the R/V Urania, the 2.5-5.5 kHz hull-mounted source of the R/V L'Atalante operated with the 'CHEOPS' acquisition software, and a Simrad TOPAS PS-040 5 kHz parametric echosounder,. We also show bathymetric data from the central Adriatic obtained with an EM300 Simrad multibeam echosounder operated from the vessel Odin Finder (see details in Cattaneo et al., 2004), and Simrad EM3000 data off the eastern Iberian prodeltas. The sediment core data off Bourmedes was acquired from the R/V L'Atalante through a Kullenberg piston core.

These high-resolution data are a key to identify the origin of the sediment undulations, as they provide details that were unadverted in previous lower resolution surveys.

Morphology

Most sediment undulations in Mediterranean prodeltas develop in water depths ranging between 20 and 100 m, mainly beyond the clinoform rollover point, on the steepest part of Holocene prodeltas. They are found on slopes between 0.2º and 3º (average 2º) and affect areas of different size (3.7 km^2 in the Ebro prodelta, 25 km^2 in the Llobregat prodelta, 25.7km^2 on the Guadalfeo, 100 km^2 in the Tiber prodelta and about 800 km^2 on the central Adriatic shelf). They commonly present a relatively elongated shape controlled by the two isobaths mentioned above (Fig. 2A). In cross-section the area where the undulations develop is commonly concave upward. Where multibeam data is available the undulation crests are more or less parallel to the bathymetric contours and have slightly sinuous to rectilinear shape in planform view (Cattaneo et al, 2004; Fernandez-Salas et al., 2007; Urgeles et al., 2007; Fig. 2, 3). Exceptions to this occur in the Ebro and Fluvià-Muga prodeltas where the sediment undulations have crests respectively perpendicular and oblique to the bathymetric contours and develop within shallower or deeper depth ranges (8-15 m and 60-100 m respectively; Table 1 and Fig. 2C). The undulations often show an intricate pattern of bifurcating and truncated ridges and can be traced for distances ranging between a few tens of meters to 2 km, but most commonly range in between 200 to 400 m.

The amplitude and wavelength (see also Cattaneo et al., 2004) of the sediment undulations is variable. From crest to trough the undulations range from as high as 5 m to a few cm (Table 1; Fig. 4). They also range from about 300 m wavelength to about 20 m in sediment undulations that develop in relatively shallow waters and those that extend from shallow to deeper waters in the prodelta foresets. However, undulations that develop only in the deeper parts of the prodelta show larger wavelengths that may reach up to 1 km (Fig. 4). Generally no trend is observed in wave amplitude or wave length with water depth and increasing distance from shore. This is specially the case for the deeper prodeltaic undulations. However, where undulations develop over extensive areas and are better developed, such as in the Adriatic (Cattaneo et al., 2004) and in the Llobregat prodelta (Urgeles et al., 2007), the undulations tend to show a decrease both in wavelength and amplitude with water depth, especially for those situated above 40 mwd. The shallower undulations show relatively short upslope limbs and long downslope limbs (near 0 asymmetry values) while in deeper waters the undulations are more symmetric. In the Adriatic Sea these undulations are associated in some cases with small-scale mud reliefs in water depths of 70 to 110 m, with preferred crest orientations that are perpendicular to regional contours (Marsset et al., 2004). The association of these two features is continuous along some kilometers to tens of kilometers in three sectors of the central Adriatic shelf, but it is not ubiquitous (Fig. 5).

The undulations that develop on the prodeltas of the Mediterranean Sea generally have L/H ratios in the range of 50-400 (Fig. 4). The wavelength is on the tenths to hundreds of meters scale. This contrasts with deep-water sediment waves that have wavelengths in the km scale (Wynn and Stow, 2002). Similarly sediment undulations on prodelta wedges of the Mediterranean Sea are only a few meters high, while deep-water sediment waves worldwide are tens of meters high (Wynn and Stow, 2002). Within the sediment undulations that develop on the continental shelves of the Mediterranean, those that are attached to the inner shelf have generally shorter wavelengths, than those that occur on the mid-shelf (e.g. Fluvià-Muga; Fig. 2c and Table 1).

Seismostratigraphic analysis

On the new and published seismic reflection profiles, the sediment undulations of Mediterranean prodeltas hold the following common characteristics: 1) They are rooted at the Maximum Flooding Surface (MFS) or a secondary flooding surface and develop on the Late-Holocene High-stand Systems Tract (HST) mud wedge (Figs. 3, 6 and 7); 2) the shallowest parts of these undulated prodeltas appear largely void of reflectors or these appear with a very low amplitude and more chaotic character (see Trincardi and Normark, 1988; Correggiari et al., 2001; Cattaneo et al., 2004; Urgeles et al., 2007; Lykousis et al., 2009). This facies is distinctive of shallow gas enriched sediment layers, which mask the underlying reflectors (Sultan et al., 2008); 3) in most cases, sediment undulations develop downslope from the gas front, and only at a few locations the uppermost undulations are on top of the gassy zone (e.g. the Ebro prodelta); 4) the sediment undulations are mostly characterized by a uniform wavy stratified pattern of strong to faint prograding seismic reflectors on the prodelta front, in which both wavelength and amplitude of the undulations generally decrease with increasing stratigraphic depth (Figs. 6, 7 and 8).. Where this seismic character is present (most prodelta settings except the prodeltas of Andalusia) the sediments are probably quite homogeneous and fine grained (see Table 1). Borehole samples confirm that the sediment composition of the undulations is quite homogeneous (Cattaneo et al., 2003). Where piston cores are available, the dominant lithology is muddy, as in the case of the the Algerian shelf (Fig. 8) and central Adriatic (Cattaneo et al., 2004; Sultan et al., 2008, Fig. 9). The prodeltaic Holocene mud wedges that are affected by the undulations have thicknesses that do not exceed 50 ms TWTT and extend offshore for a few kilometers (generally <10 km).

The analysis of high resolution seismic reflection profiles shows that undulations at the seafloor may correspond to more than one undulation below seafloor and the opposite way-round: various undulations on the seafloor may correspond to one single undulation below seafloor (Figs. 6-8). Also areas that do not presently show undulations at the seafloor, may show evidences of seafloor undulations down section, with the undulations being truncated at the seafloor (Fig. 6 and 8). This pattern occurs in the shallowest water depths. At other locations where the seafloor is devoid of undulations but sediment undulations are present on the stratigraphic record, the undulations are masked by more recent sedimentation concealing the undulations (Fig. 8). These two examples of undulation suppression indicate that, within late Holocene prodeltas, differential deposition or erosion may smoothen out pre-existing seafloor undulations.

The crest and trough angle of climb of most sediment undulations are not homogeneous down section (Fig. 6 and 8). Variations are also not consistent, i.e. the angle may increase or decrease or change in trend down section, i.e. displaying alternations between convex and concave shapes (Fig. 6).

The largest sediment undulation fields in the Adriatic and Llobregat prodeltas are predominantly muddy (respective average clay, silt and sand contents of 65%, 35% and 5% in the Adriatic and 15%, 46% and 39% in the Llobregat). In relatively energetic environments like the "Ramblas" in southern Andalusia, (Bárcenas et al., 2009) the sediment undulations may be formed by coarser material, being sand the predominant grain size fraction (Table 1).

Geotechnical investigations

Samples for deep geotechnical investigation have only been obtained in the Adriatic Sea where a major European effort (project PROMESS-1) aimed to understand the genesis of these undulations through drilling (Sultan et al., 2008). Shallow geotechnical data exists also for other areas such as the Tiber pordelta (Tommasi et al., 1998). The drilling in the Adriatic Sea was targeted to penetrate through one of the potential shear planes in between two sets of undulation packages and through the MFS. This area is particularly active in terms of earthquakes and there was a concern that seismic ground motions where at the origin of the observed seafloor undulations. Undrained shear strength data measured with a hand operated torvane shortly after the cores were acquired, an automated laboratory shear vane and laboratory fall cone showed quite consistent results, indicating that a sharp increase in shear strength of about 12 kPa occurred when moving from the upper to the lower undulation (Fig. 9). Cyclic triaxial tests indicated that silty and sandy sediments such as those occurring near the MFS (Fig. 9) were the most sensitive to earthquake loading. Pre-consolidation pressures measured with an incremental loading oedometer indicated normal to slightly underconsolidated sediments in the upper undulation and a higher degree of underconsolidation within the undulation directly below the plane separating the two undulations (Fig. 9). However, it was found that neither sediment accumulation rates nor earthquake ground motions could explain the excess pore pressure resulting from this consolidation state (Sultan et al., 2004; 2008). It was suggested that overpressure could result from gas generation (Sultan et al., 2008). The facts above were not incompatible with an origin by sediment deformation. To the contrary, such a situation would be favorable to deformation by earthquake shaking. Therefore, an analysis of the slope stability under cyclic ground motions due to earthquakes was undertaken having into account historical earthquake records and in situ ground shaking measurements performed with Ocean Bottom Seismometers (Sultan et al., 2008). Assessment of the sediment liquefaction potential was made using Cyclic1D, a nonlinear finite element program for execution of one-dimensional site amplification and liquefaction (Elgamal et al., 2002). The simulation showed that, for characteristic earthquakes in that area, liquefaction of the level above which the undulations detach and deformation of the overlying sediment, could only occur when that level was only 5 mbsf or shallower. It was shown that further burial and increase in confining lithostatic pressure actually prevents sediment liquefaction (Sultan et al., 2008).

Sediment transport processes

The sedimentary dynamics in the Mediterranean continental shelves has been continuously studied during the last decades in the framework of many research projects. However, few studies have been conducted in prodeltaic areas affected by undulated seafloor features using bottom boundary layer instrumentation (e.g. Cacchione et al., 1990; Jiménez et al., 1999; Puig et al. 2001; Palanques et al., 2002; Fain et al., 2007); and to our knowledge, only one of them (Puig et al., 2007) was addressed to establish relationships between active sediment dynamics and the formation/maintenance of the undulated seafloor features. This study was conducted in the western Adriatic, off Pescara (Fig. 10), in a region characterized to have large portions of the late Holocene prograding mud wedge affected by seafloor undulations.

The proposed observational approach consisted in measuring sediment transport process across an undulated clinoform by means of deployments of two boundary-layer tripods in 12 and 20 m water depth and a mooring in 50 m water depth, right in the middle of the undulations. This mooring line was equipped with two RCM-9 current meters placed at 2 meters above the seafloor (masf) and at 20 m water depth, in intermediate waters 30 masf. Thermistors were also mounted on the mooring line at numerous heights above the seabed between the two current meters. Observations took place from late October 02 to early May 03 in two consecutive three-month deployments and hydrographic sections were conducted at the time of instruments deployment, maintenance and retrieval (see Puig et al., 2007 for details).

The across-shelf distributions of temperature, salinity and suspended sediment concentration (SSC) in the study area during November 2002 are shown in Fig. 10. Temperature and salinity hydrographic transects clearly reflected the presence of coastal waters influenced by the discharges from the Po and Apennine rivers, which occupied the entire topset region and were characterized by having lower salinities and colder temperatures than the offshore waters. Water temperature distribution in November 2002 also reflected the typical late-summer situation for Mediterranean surface waters, showing a wide and well-developed thermocline with the maximum gradient between 40 and 80 m water depth, coinciding with the region affected by the undulated seafloor (Fig. 10). SSC distribution indicated the presence of a surface nepheloid layer, being constrained by coastal colder and less saline waters, and the development of a bottom nepheloid layer that detaches where the thermocline intersected with the seabed (Fig. 10A).

Sediment transport processes were analyzed at the topset and foreset region of the undulated clinoform and the role of wave-current interaction and internal waves on sediment resuspension were investigated. Several sediment-resuspension events were recorded at the tripod site, mainly related to Bora and Sirocco storms, during which current and wave shear stresses reached similar values. After the passage of a storm, activity of near-inertial internal waves (~17 h) was also recorded by the moored current meters and temperature sensors (Fig. 10B).

During periods characterized by strong near-inertial fluctuations, increases of the water SSC clearly coincided with the offshore direction of the cross-shelf velocity component and with strong temperature and salinity fluctuations showing excursions through the water column of tens of meters (Fig. 10B). During the sediment transport events associated to the passage of internal waves, current directions are aligned normal to the crests of the seafloor undulations, exporting suspended sediment in an oscillatory way from the topset to the bottomset region of the clinoform.

Discussion: Origin of the sediment undulations: sediment deformation or bedforms formed by bottom boundary layer processes

The characteristics of individual sediment undulations and that of the sediment undulation field sometime provide inconclusive evidence of the process at the origin of such morphology. For instance, most sediment undulation fields like the Llobregat or central Adriatic have a shape elongated along the direction of the prevailing bottom currents (parallel to the bathymetric contours), which suggest a relationship to boundary layer transport processes. However sediment transport processes also control diversion of river plumes and therefore the location of depocenters, which most likely corresponds to the location of excess pore pressure and gas generation and therefore the most likely location for gravity deformation. In the following sections we review the morphological, seismic, geotechnical and boundary layer processes that, when examined together, allow determining the process at the origin of these features.

Assessing the origin of the undulations by sediment creep

Influence of gravity-induced sediment instabilities is preferentially invoked in many studies, such as in the Gulf of Castellamare (Agate et al., 2009), the Tiber (Bellotti et al., 1994; Chiocci et al., 1996), Sarno (Sacchi et al., 2005), Fluvià-Muga prodeltas (Díaz and Ercilla, 1993; Ercilla et al., 1995) and early studies of the Adriatic prodeltaic wedge (Correggiari et al., 2001) and the Llobregat prodelta (Checa et al., 1988).

In favor of the deformation origin of these structures is that there seems to be a clear spatial relationship between the location of the gas front in the prodeltas and the onset of sediment undulations on most prodelta slopes (Trincardi and Normark, 1988; Urgeles et al., 2008; Cattaneo et al., 2004; Fernández-Salas et al., 2008; Lykousis et al., 2009; Fig. 3, 5 and 6). Gas in shallow water environments is known to affect slope stability in undrained unloading conditions (Vanoudheusden et al., 2004). The lack of a major headwall suggests that in all these areas failure would be at a very incipient stage, if this is the process that actually prevails in these undulated sediment fields.

If it is assumed that the sediment undulations are formed by slow gravitational deformation, the lack of compressional features at the toe of the prodelta wedge, as observed in most cases, implies a low angle detachment level. Mud-diapir-like structures have been identified at certain locations of the toe of the Adriatic prodelta wedge (Correggiari et al., 2001), and it could be argued that they result from sediment compression at the toe of the mud-wedge. This genetic association with undulations (as expression of compression at the toe of supposed extension domains represented by the undulations) was proposed by Correggiari et al. (2001) at a time where multibeam bathymetry was not available. However, mud reliefs could also result from fluid expulsion and successive differential deposition guided by the dominant countour-parallel bottom current. In addition to this, there is the fact that such mud reliefs are not found in several other areas of the Adriatic prodeltaic wedge and nowhere else in the fields of undulations of the Mediterranean Sea there are similar features reported (Fig. 5).

The lack of hyperbolaes on the synform part of the folds would also imply that there is no rupture of the reflectors and therefore that deformation is ductile rather than brittle. It is also peculiar that no anthitetic shear planes develop in any of the sediment undulation wave fields, while this is a common characteristic of prodeltaic environments were growth faults are present (Bhattacaria and Davis, 2001). Indeed, because within each undulation the dipping of strata is relatively constant as depicted on available seismic reflection data (Ercilla et al., 1995; Chiocci et al., 1996: Correggiari et al., 2001; Cattaneo et al., 2004; Urgeles et al., 2007; Lykousis et al., 2009; Figs. 3, 6, 7 and 8), this implies that there is no synchronous deformation while deposition that could induce growth features (i.e. if the undulations result from sediment deformation there must be one single phase of deformation). In other words, as the deformation is not gradual, creep is not a valid genetic mechanism to explain the sediment undulations.

Assessing the origin of the undulations by (partial) slope failure

The statements above do not preclude a genesis by sediment deformation, since a genesis due to a punctual event such as an earthquake or major storm is also possible. This event needs to be relatively recent as the undulations affect the whole or the upper Holocene mud wedge in most instances (Figs 3, 6, 7 and 8). Comparing the seismic stratigraphy between adjacent undulations and attempting to trace the reflectors across the supposed shear planes that separate undulations shows that on the upper part of the undulations the displacement is larger than on the lower part (Fig. 6), which is kinematically not possible. Also the fact that the plane separating the different undulations (or angle of climb using sediment bedform terminology) shows no consistent trend with depth, i.e. normally there should be a progressive reduction in angle, appears mechanically incompatible with gravity deformation (Fig. 6). Also the intricate pattern of branching and truncated undulations is common to almost all fields where swath mapping is available (Cattaneo et al., 2003; Urgeles et al., 2007; Fernández Salas et al., 2007; Bárcenas et al., 2009; Figs. 2-3), and this pattern is difficult to explain by gravitational downslope movement, while it is relatively common in sediment transport structures (Mazumder, 2003).

An additional exercise to rule out the genesis of the undulations by sediment deformation is to assume that the difference in elevation from trough to crest on the landward side of the undulations corresponds to the vertical component of the deformation. That elevation may reach values of ~0.5 m. From seismic data it can be seen that the slope angle of the plane that separates the different undulations (supposed shear plane) is up to 20º, while the angle of the supposed detachment level at the base of the undulations is less than 1º. Supposing that failure occurs along these two planes in a circular fashion, than the 0.5 m in vertical displacement must translate ~1.5 m horizontal displacement. Because there are various undulations in each sediment undulation field (Ercilla et al., 1995; Chiocci et al., 1996: Correggiari et al., 2001; Cattaneo et al., 2004; Urgeles et al., 2007; Lykousis et al., 2009; Figs. 3, 6-8), this implies that the total horizontal displacement may amount to more than 10 m. Such a large displacement is unlikely to take place without brittle deformation. Thus, the fact that reflectors are not broken is inconsistent with an origin of the undulations by one single phase of sediment gravitational deformation.

Finally, Sultan et al. (2008) showed that, at least in the Adriatic case, formation of the undulations by deformation is only possible at a very early stage in the sedimentation of the Holocene mud wedge and that latter undulation evolution or preservation is not related to sediment deformation. Cattaneo et al. (2004) proposed a hybrid genetic mechanism by which the sediment undulations were initiated by seafloor liquefaction, which generated a roughness facilitating the latter growth of the undulations by processes in the bottom boundary layer. As explained earlier, however, most of the undulations root at the MFS (some root at a secondary flooding surface), and such an interpretation would imply that sediment liquefaction occurred shortly after that event took place. Therefore, it is difficult to explain the onset of the many undulation fields in the Mediterranean Sea by generalized liquefaction events at the times when the sealevel attained a relatively high position and spanning passive and active margins. This does not prevent that for some sediment undulation fields some amount of deformation might be involved in the genesis of a seafloor roughness that nucleated the generation of the sediment undulations. Yet, considering the variety of tectonic environments, it is unlikely that the all sediment undulations fields were initiated thanks to sediment deformation induced roughness. Therefore, despite this roughness might be an important factor in the initial development of the sediment undulations, the actual mechanism that generates this roughness, if present at all, does not need to be sediment deformation.

Explaining the sediment undulations by processes in the bottom boundary layer

All evidence above suggests that the sediment undulations are better explained by bottom boundary layer processes instead of sediment deformation. Amongst the processes acting on Mediterranean prodeltas there are a few of them that could be at the origin of the sediment undulations. We summarize here the various processes that could be at the origin of the sediment undulations and attempt to assign a genetic mechanism to the variety of features observed in the various prodeltaic sediment wave fields (Table 2).

Waves and tides

The Mediterranean Sea is a microtidal sea with limited wave period. Only major storms could cause sediment resuspension and transport in water depths below 35 m (see Puig et al., 2001; Palanques et al., 2002), where most sediment undulations on the prodeltas of the Mediterranean Sea begin to occur (Table 1). Sea waves can only account for the sediment undulations that occur on the shallowest areas of the prodeltas, such as in the Ebro prodelta (Fig. 2B; Table 2). The shallow undulated seafloor features in the Ebro prodelta, located south from the river mouth (Cape Tortosa), seem to be related with enhanced alongshore currents during large wind storms, when near bottom currents in nearby locations can reach 63 cm/s (Palanques et al., 2002).
The effect of waves could barely reach the deepest limit of most sediment undulations fields in the Meditterranean Sea, which is at ~100 m depth such as those of the Tiber, Fluvià-Muga (Díaz and Ercilla, 1993; Ercilla et al., 1995), Ter (Díaz and Ercilla, 1993; Ercilla et al., 1995), Llobregat (Urgeles et al., 2007), Gualdalfeo (Fernández-Salas et al., 2007; Bárcenas et al., 2009) and also to those that terminate is shallower waters such as that of the Adriatic (Correggiari et al., 2001; Cattaneo et al., 2004) and many Andalusian prodeltas (Fernández-Salas et al., 2007; Bárcenas et al., 2009). For example a storm with a return period of 50 years in the Llobregat prodelta area has a significant height and a significant period of 5.1 m and ~10 s respectively (Bolaños et al., 2001), which would be able to produce water motion at depths down to 86 m. For a 10 year return period storm the significant height and periods are respectively 4.3 m and 9.5 s (Bolaños et al., 2001), which would be able to produce water motion at depths down to 70 m. The storms significant height and period necessary to produce sediment resuspension and mobilization at these water depths is however much higher. It should be noted also that in many areas the sediment undulations are aligned oblique to the

direction of wave propagation during major storms, while most bedforms are generally aligned parallel or perpendicular to the predominant currents (Mazumder, 2003).

Hyperpycnal flows

Estimates of solid discharge and sediment concentration in the Mediterranean area can be obtained from rating coefficients (Syvitski et al., 2000). Based on these rating coefficients, historical document sources and paleoflood events determined from slackwater paleoflood deposits, the recorded peak water discharges may induce sediment concentrations high enough to allow the formation of sediment hyperpycnal flows off the Llobregat River (Thorndycraft et al., 2005), off the Po River and a few Apennine rivers (Milliman and Syvitski, 1992; Syvitski and Kettner, 2007) and also off some of the rivers and ramblas of Mediterranean Andalusia (Liquete et al., 2005; Benito et al., 2008). In fact, the Mediterranean rivers of Andalusia are the prototype river that is able to produce hyperpycnal plumes: typically drain small mountainous watershed with easily-erodible sediments, and have low to moderate annual discharge (Imran and Syvitski, 2000).

In some prodelta environments there are a number of features that would point to an origin by hyperpycnal flows. For instance, in the Verde and Seco prodeltas the undulations appear to occur on the flank of a prodelta channel which would suggest a relation to hyperpycnal flows spilling over that channel. Also the aspect ratio (L/H) appears to decrease away from the axis of influence of the fluvial inputs (Bárcenas et al., 2009). In the Po River prodeltaic wedge the area displaying undulated sediments occurs where flood deposits have recently accumulated (Wheatcroft et al., 2006) suggesting also a relationship to hyperpycnal flows.

In the Andalusian prodeltas a relationship between the aspect ratio (L/H) of the sediment undulations and the discharge characteristics (torrential vs. more fluvial) and slope of the nearby river was also found (Fernández-Salas, 2007; Bárcenas et al., 2009), suggesting that the undulations that have the larger aspect ratio could be induced by hyperpycnal flows (Table 2; Fig. 3). Andalusian river courses that were artificially diverted with respect to the original river path showed two sediment undulation fields: one facing the old river mouth and another facing the newer one. On these occasions, it was found that the undulations close to the recent sediment source have higher L/H ratios (Bárcenas et al., 2009).

Recent dam construction, paving and stepping of the river course as well as growth of urban areas in many of the Mediterranean watersheds prevents most sediment to reach the prodelta slope nowadays, and this could be at the origin of the difference in sediment undulation characteristics in prodeltas with an old and a recent sediment source. The facts reported here suggest that hyperpycnal flows could be at the origin of the sediment undulations, at least for the undulations displaying the lower L/H ratios (Table 2; Fig. 3). In many other instances, due to river regulation and climatic forcing, water and sediment discharge have decreased to a point (Ludwig et al., 2009) that prevents hyperpycnal flows to form, at least often enough so that the shallower sediment undulations are able to cope with the competing effect of sea waves (Fig. 6). Therefore maintenance of the undulations by this mechanism on many Mediterranean prodeltas appears not plausible (Puig et al., 2007). This is specially the case for areas where these undulations are relatively widespread laterally, such as in the Adriatic Holocene mud wedge, because river plumes that could give rise to hyperpycnal flows tend to deposit at a relatively short distance from the river mouth (Wheatcroft and Borgeld, 2000; Wheatcroft et al., 2006).

Hyperpycnal flows commonly/rarely go supercritical (Froude number > 1). The observed undulations in areas where hyperpycnal flows are likely could therefore correspond to cyclic steps. Cyclic steps are sediment waves generated by supercritical or near supercritical turbidity currents (Kostic and Parker 2006; 2007), and often occur associated to channel-levee systems, either within the channel or overbank deposits (Fildani et al., 2006). Cyclic steps have been characterized as long-wave antidunes that are locked in sequence by hydraulic jumps. Its upstream and downstream end are characterized by a short zone over which the flow makes a rapid conversion from shallow, swift supercritical flow (Fr > 1) to deep, tranquil sub-critical flow (Fr < 1). This locking by hydraulic jumps allows for orderly updip migration. Different flow regimes result in different wavelength of the steps (Fildani et al., 2006).Cyclic steps can be net-erosional and/or net depositional, covering a large spectrum of flow conditions (Fildani et al., 2006; Heino and Davies, 2009). It must be noted however that much smaller wavelength, at least one order of magnitude (20-300 m vs. 1-6 km), is observed in sediment undulations of Mediterranean prodeltas (Table 1)nwhen compared to the ones occurring in deep-water settings (Nakajima and Satoh, 2001, Fildani et al., 2006). A few prototype examples of cyclic steps have however been been mapped and observed to migrate upslope on extremely active shallow prodelta environments (e.g. Hughes-Clarke et al., 2009).

Internal waves

Evidence of erosion in the shallowest undulations is present at least on the Llobregat prodelta in relatively shallow waters up to, at least, 30 mbsl (Fig. 6), which suggests that storms have an influence on recent reshaping of the sediment undulation field. However, storms with a recurrence period of 5 years still have a significant wave height and period that is able to produce water motion up to 63 mbsl, and therefore it seems necessary to invoke an additional mechanism for maintaining the sediment undulations on the observed depth ranges (30-90 mbsl). Recent work by Puig et al. (2007) in the Adriatic Sea has shown that internal waves can play a role in resuspending and transporting sediment in prodeltaic undulated areas (Fig. 10). Near-inertial internal waves induced by local wind pulses tend to propagate across the water column through isopycnals and concentrate their energy at the shelf regions where the seasonal thermocline intersects with the seabed, which turns out to be the depth range characterized by having an undulated seafloor (Puig et al., 2007). This is shown in the near-bottom time-series of Fig. 10, which show a remarkable energy peak around 17.7 h, mainly in the turbidity and across-shelf velocity spectrum, suggesting that fluctuations induced by near-inertial internal wave activity dominate in the record. Also it is clear in Fig. 10 that near-inertial internal wave activity also contributes to the across-shelf sediment transport in the undulated clinoform region, as turbidity increases associated with this mechanism clearly coincided with periods when the currents were directed offshore and water temperature and salinity decreased. Currents induced by near-inertial internal waves were predominantly directed offshore, while the onshore direction was very weak (Fig. 10). It must be pointed out also that the long crests of the Adriatic undulations, which can be followed for many tens of kilometers in the along-strike direction, parallel to the bathymetric contours (Correggiari et al., 2001; Cattaneo et al., 2004) can only be generated by a process that is continuous and equally intense over a similar distance, as it could occur with internal-waves.

Strong near-inertial current fluctuations induced by internal waves have been also observed in other prodeltaic areas of the Mediterranean Sea such as the Ebro prodelta (Puig et al., 2001) and the Llobregat prodelta (Demestre et al., 2004) and they are ubiquitous in the Mediterranean Sea (e.g. Millot and Crépon, 1981; Font et al., 1990; Leder, 2002). In the Central Adriatic, where dedicated experiments were carried out, and also in other prodelta environments (see Table 2) the spatial distribution of seafloor undulations, the decrease of their wavelength and dimensions in the onshore direction and their long, linear crests, suggest that internal waves play a major role in their formation and/or maintenance (see Puig et al., 2007 for a comprehensive discussion).

Bottom currents

In a few cases, the undulations occur in relatively deeper water, are not parallel to the bathymetric contours and have a much larger wavelength (i.e. Fluvià-Muga prodeltas; Table 2; Fig. 2C). On these settings the sediment undulations cannot result neither from hyperpycnal flows nor internal waves and are likely the result from strong bottom currents. In the case of the deeper part of the Fluvià-Muga prodeltas, the origin of such currents appears to be related with the advection of dense shelf waters originated in the Gulf of Lions during storm events, since modeling results reproduce enhanced near bottom currents with high suspended sediment loads over this undulated seafloor region (Ulses et al., 2008, their Fig. 5).

Strong shelf currents may also be induced by large wind storms (Bassetti et al., 2006) and/or the general geostrophic circulation (Monaco et al., 1990). For example the "Liguro–Provençal–Catalan Current", one of the main components of the general circulation in the western Mediterranean, is characterized by speeds ranging from 50 cm s^{-1} near the surface (Monaco et al., 1990). According to Millot (1990), the core of the Northern Current follows the continental slope most of the time, but the trajectory can be temporally altered during northwesterly wind, when the superficial waters tend to penetrate onto the continental shelf forming a current front that can reach 30 cm s^{-1} after the wind decay (Millot and Wald, 1980).

Conclusions

a) Sediment undulations are widely present in the Holocene mud wedge of prodeltas in the Mediterranean Sea. Sediment undulations are rooted on a flooding surface, develop within the highstand systems tract and occur in most instances beyond the clinoform rollover point.

b) They affect areas of various sizes and, in most instances, have sinuous to rectilinear crests parallel to the bathymetric contours. Wavelength rarely exceeds 400 m and amplitude 5 m.

c) The geometric characteristics of the plane separating adjacent undulations, the configuration of the reflections down section and between adjacent undulations, the lack of hyperbolae in seismic reflection profiles and the overall morphologic characteristics preclude an origin of the sediment undulations by gravitational instability, either gradual or rapid.

d) In the Adriatic shelf, sediment deformation has been invoked to explain the initial roughness on which sediment undulations developed as sediment transport structures. In many other areas there is no evidence for such a deformation. Therefore, it is not clear the role of an initial roughness in allowing later development of the sediment undulations. An initial phase of sediment deformation is not a pre-requisite for development of sediment undulations on prodeltaic wedges.

e) Different processes on the benthic boundary layer might be at the origin of sediment undulations on Mediterranean prodeltas. The most likely mechanisms for the genesis of the sediment undulations are sediment resuspension by internal waves and hyperpycnal flows. Evidence suggests that sediment undulations generated by these two processes probably differ in L/H ratio, with undulations generated by hyperpycnal flows showing lower values. Additional mechanisms that may induce formation of sediment undulations in Mediterranea prodelta settings include waves and derived longshore currents in the shallowest undulation fields, or strong bottom currents in the deepest water sediment undulation fields.

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Table 1: Morphology and characteristics of major sediment undulation fields in prodeltaic areas of the Mediterranean Sea. ‖=parallel, ╗=perpendicular, /=oblique, ↓=decrease, ↑=increase; mwd= meters water depth. Units of length are meters (except otherwise expressed)

	Adra	Central Adriatic	Albuñol	Algerian shelf	Ebro	Fluvià-Muga	Guadalfeo	Gualchos	Gulf of Corinth and Kyparissiakos Gulf	Llobregat	Seco	Verde	Ter	Tiber
Min. water depth	18	30	9	55	7	60	10	13	25	35	3	9	60	45
Max. water depth	60	70	71	110	15	100	108	56	50	90	65	65	100	100
Wavelength min-max (mean)	21-244 (76)	53-477 (212)	23-163 (61)		145-320 (222)	~1000	19-252 (80)	19-140 (53)	80-150	37-235 (105)	25-74 (46)	38-103 (73)		~100
Wavelength trend		↓ (> 40 mwd)								↓				↑
Amplitude min-max (mean)	0.04-2.34 (0.45)	0.17-3.76 (0.92)	0.02-4.22 (0.53)		0.2-2 (1.1)	0.5-4	0.07-5 (0.85)	0.02-2.21 (0.32)		0.03-1.3 (0.55)	0.06-2.19 (0.70)	0.13-1.28 (1.05)		7 (max)
Amplitude trend		↓ (> 40 mwd)								↓				↓
Sediment type	Gravelly sand	mud	mud	mud	Sand	mud	Silty sand	Silty sand		Sandy mud	Silty sand	Silty sand	mud	mud
Affected thickness		<35				4-25			10-15	<30			5-37	30
L/H ratio	~300 (169)	100-400 (230)	296 (115)		100-500 (202)		129 (84)	~300 (166)		100-400 (191)	148 (66)	183 (70)		
Crest length					480-1300	~100 - 1000				300-2000				
Crest pattern		≈			≈					≈				
Crest trend (with respect to bathymetric contours)	‖	‖	‖		╗	/	‖	‖		‖	‖	‖	‖	‖
Area (km^2)	6,2	~800	5,5		3,7	20.04	25.7	3,3		25	1,4	2		100
Slope	3.1	0.2-1º	4.5		1º	0.60	2.48	3.7	0.5-2	0.3-3º (2º)	4	5	0.75	0.7-1.2
Assymetry	~1.7	>1 (> 40 mwd) ~1 (< 40 mwd)	1.6		0.9		1.58	~1.2	>1	>1 (> XX mwd) ~1 (< XX mwd)	0.94	1.05		>1
Sedimentation rates (mm/yr)		10			0.6-3.7				3-5	0.7-34				5.6-28.8

Table 2: Distinctive characteristics of the sediment undulation fields with respect to assigned genetic mechanism.

Mechanism at the origin of the sediment undulations	Shape of sediment wave field	Elongation of crests relative to bathymetric contours	Mean L / mean H	Water depth range	Other features	Examples
Internal waves	Elongated parallel to shoreline	Parallel	190-230	30-90		Central Adriatic, Llobregat, Ter
Hyperpycnal flows	Elongated perpendicular to shoreline to circular	Parallel	60-170	3-110	Channels	Guadalfeo, Seco, Verde, Gulachos, Albuñol, Adra, Po
Bottom currents	Elongated parallel to shoreline	Oblique to perpendicular	~450	60-100		Fluvià-Muga
Longshore currents	Circular to parallel to shoreline	Subparallel to perpendicular	~200	3-15		Ebro

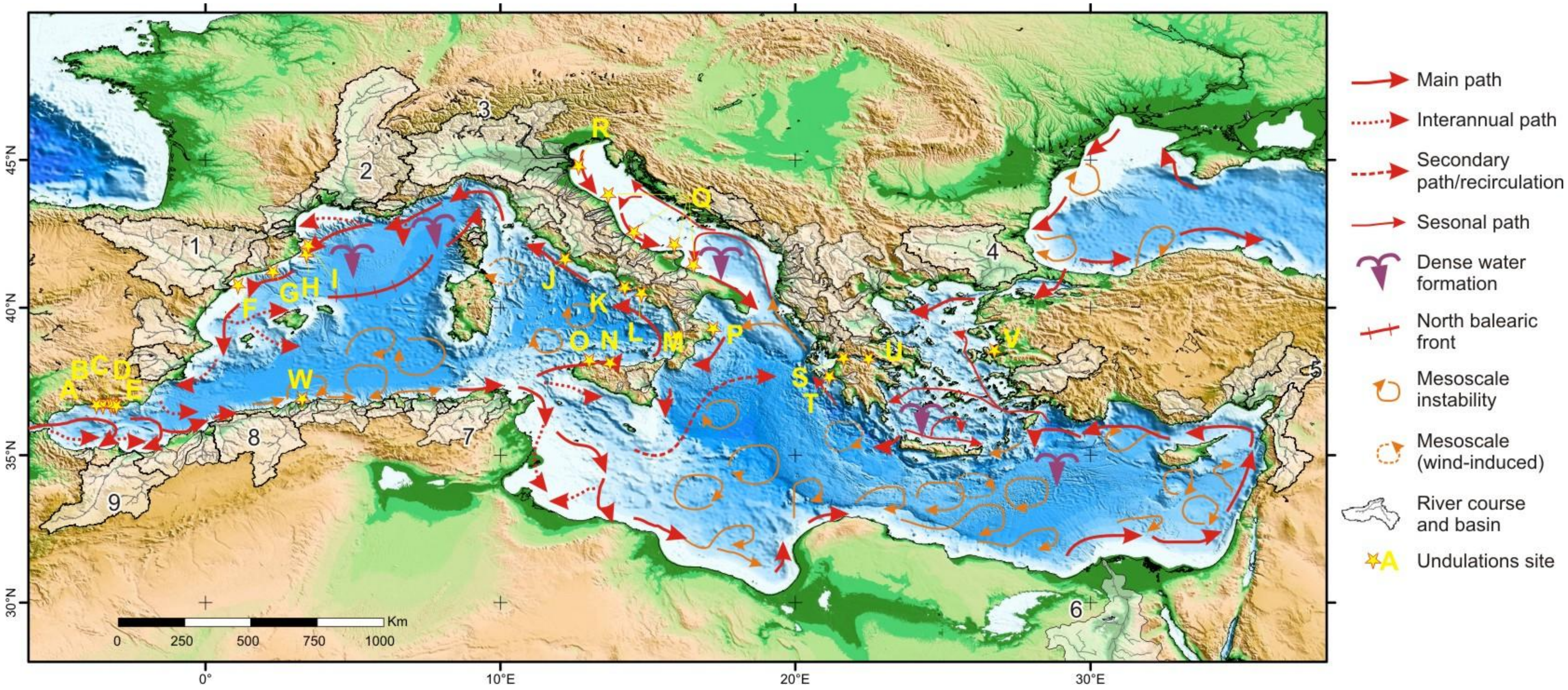

Fig. 1: Distribution of undulated sediment features on prodeltas of the Mediterranean Sea (yellow stars) in the frame of surface oceanographic circulation patterns (Millot and Taupier-Letage, 2005b) and major river basins (Liquete et al., in prep.). Major Mediterranean rivers include the Ebro (1), Rhone (2), Po (3), Evros (4), Ceyhan (5), Nile (6), Medjerda (7), Chelif (8) and Moulouya (9). A, Verde and Seco, B, Guadalfeo, C, Gualchos, D, Albuñol, E, Adra prodeltas (Fernández-Salas et al., 2007; Bárcenas et al., 2009); F, Ebro prodelta (Urgeles et al., this work); G, Llobregat prodelta (Checa et al., 1988; Urgeles et al., 2007); H, Ter prodelta (Díaz and Ercilla, 1993; Ercilla et al., 1995); I, Fuvià-Muga prodelta (Díaz and Ercilla, 1993; Ercilla et al., 1995); J, Tiber prodelta (Trincardi and Normark, 1988; Chiocci et al., 1996); K, Sarno prodelta (Sacchi et al., 2005); L, Bonea prodelta (Budillon et al., 2005); M, Calabrian shelf (Gallignani et al., 1982); N, northern Sicilian shelf (Agate and Lucido, 1995); O, Gulf of Castellammare (Agate et al., 2009); P, Corigliano basin (Romagnoli and Gabbianelli, 1990; Rebesco et al., 2009); Q, Adriatic shelf (Correggiari et al., 2001; Cattaneo et al., 2004; Marsset et al., 2004; Berndt et al., 2006; Cattaneo et al., 2007; Puig et al., 2007; Sultan et al., 2008); R, Po prodelta (Correggiari et al., 2001); S, northern Kyparissiakos Gulf (Lykousis et al., 2009); T, Patraikos Gulf (Lykousis et al., 1991; Lykousis et al., 2009); U, western Gulf of Corinth (Lykousis et al., 2009); V, Gediz prodelta (Aksu and Piper, 1983); W, Algerian littoral prism (Sultan, unpublished).

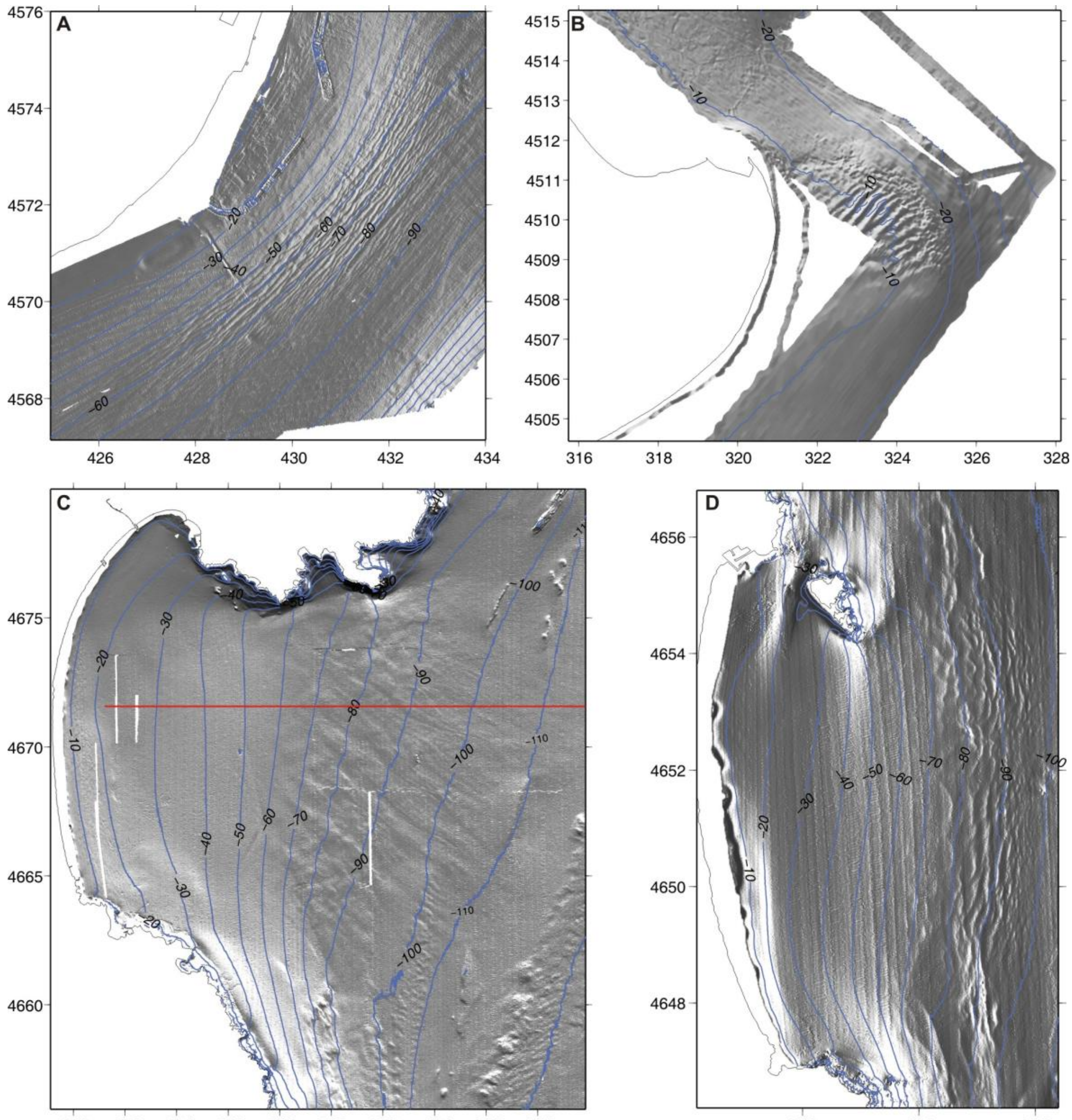

Fig. 2: Shaded relief multibeam maps displaying different types of undulated sediment features on prodelta settings. Contours are plotted at 10 m intervals. A) Llobregat prodelta, B) Ebro prodelta; C) Fuvià-Muga and D) Ter prodelta. Maps are displayed in UTM coordinates for zone 31 (labels in the vertical and horizontal axis display km). Red line in C) shows approximate location of Fig. 3B in Ercilla et al., (1995).

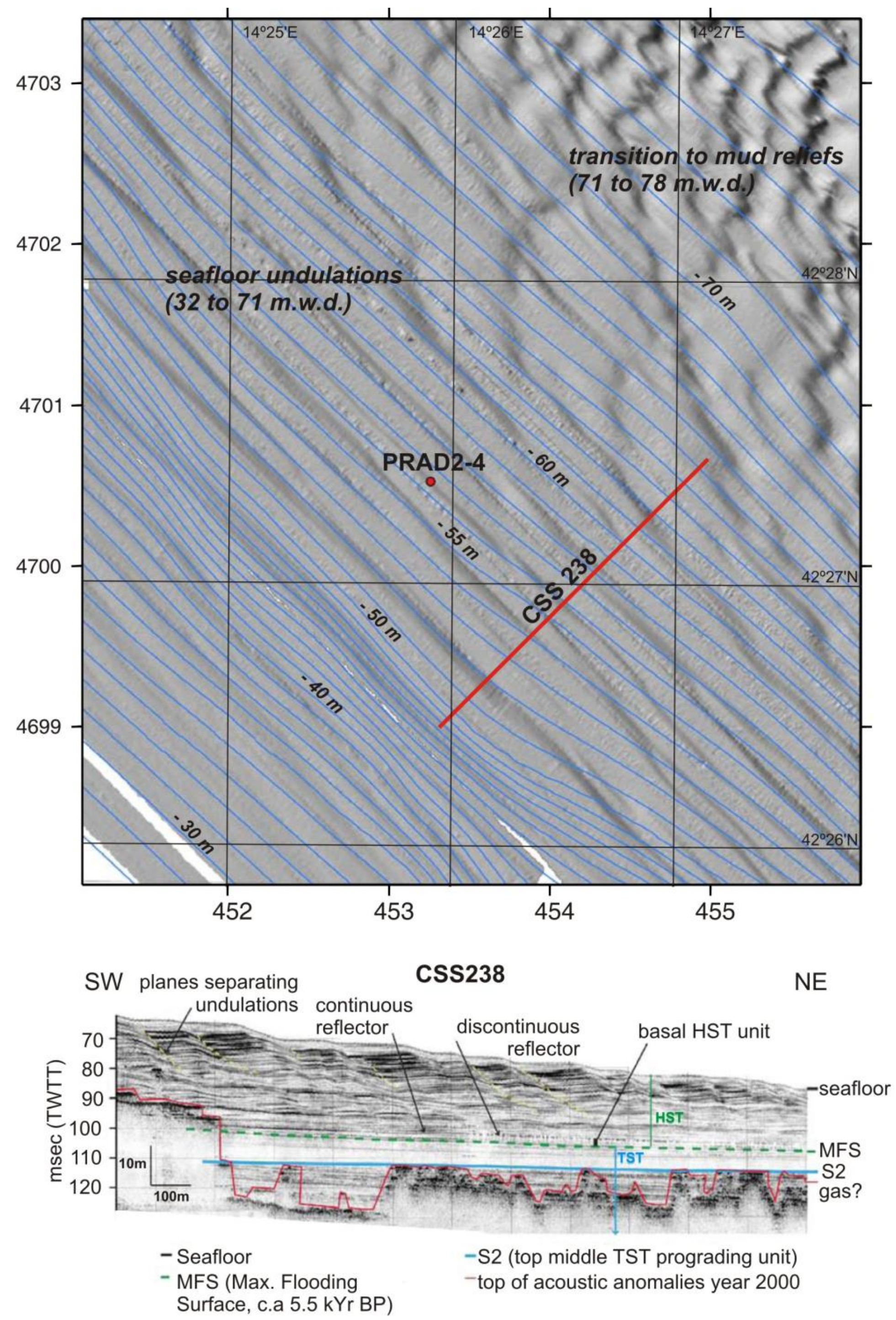

Fig. 3: Shaded relief multibeam map on the central Adriatic shelf showing seafloor undulations with linear crests aligned in a NW-SE direction, parallel to the coastline, between ca. 32 and 71 m of water depth, and a transitional zone to seafloor mud reliefs. Map is displayed in UTM coordinates for zone 33 (labels in the vertical and horizontal axis display km).. See details in Cattaneo et al., 2004, Fig. 7). The red dot marks the location of geotechnical borehole PRAD2-4 (see Sultan et al., 2008 for detail). Red line shows location of chirp profile below. See Figs. 1 and 5 for location

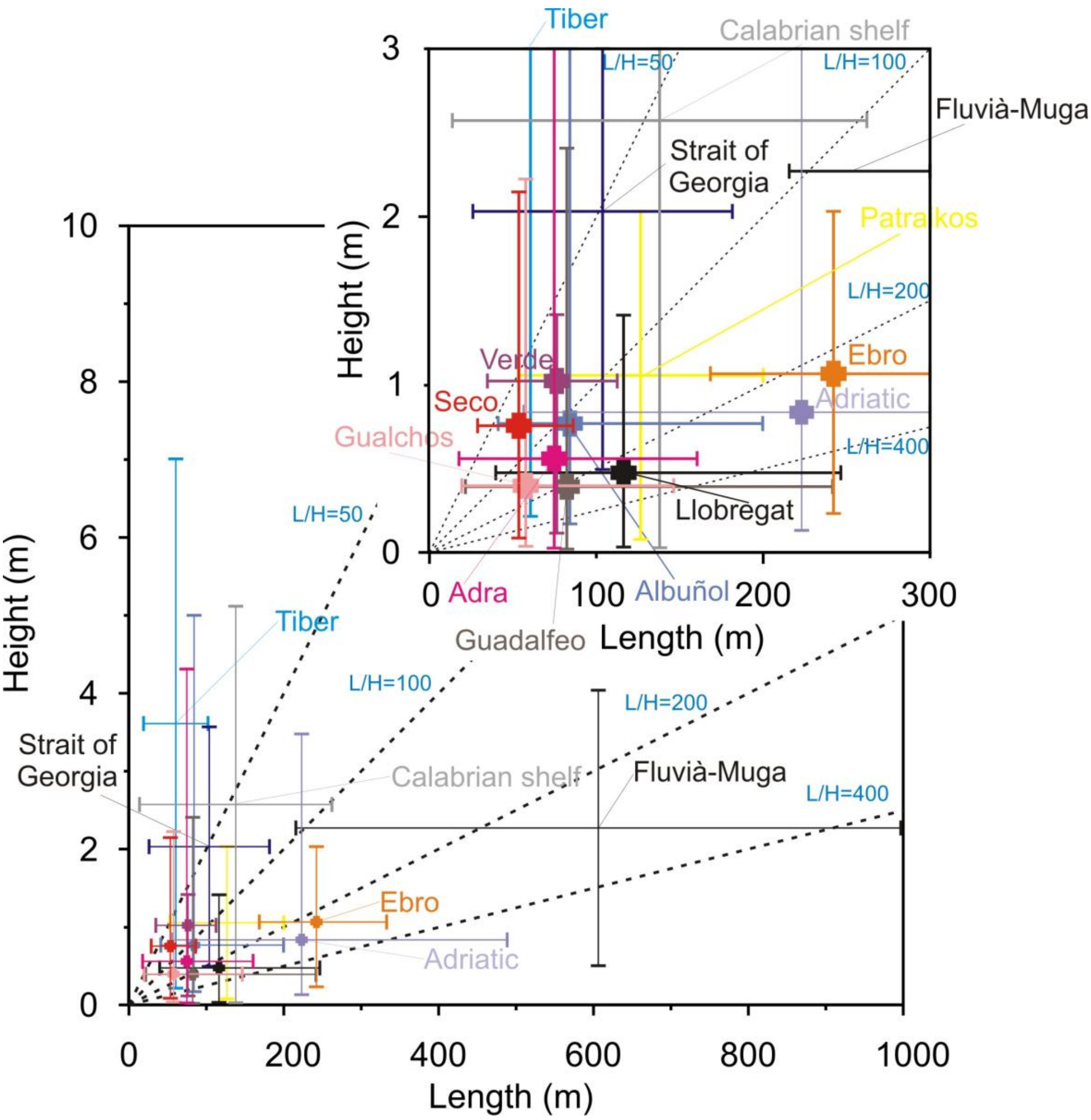

Fig. 4: Main morphological features of undulations on Mediterranean prodeltas

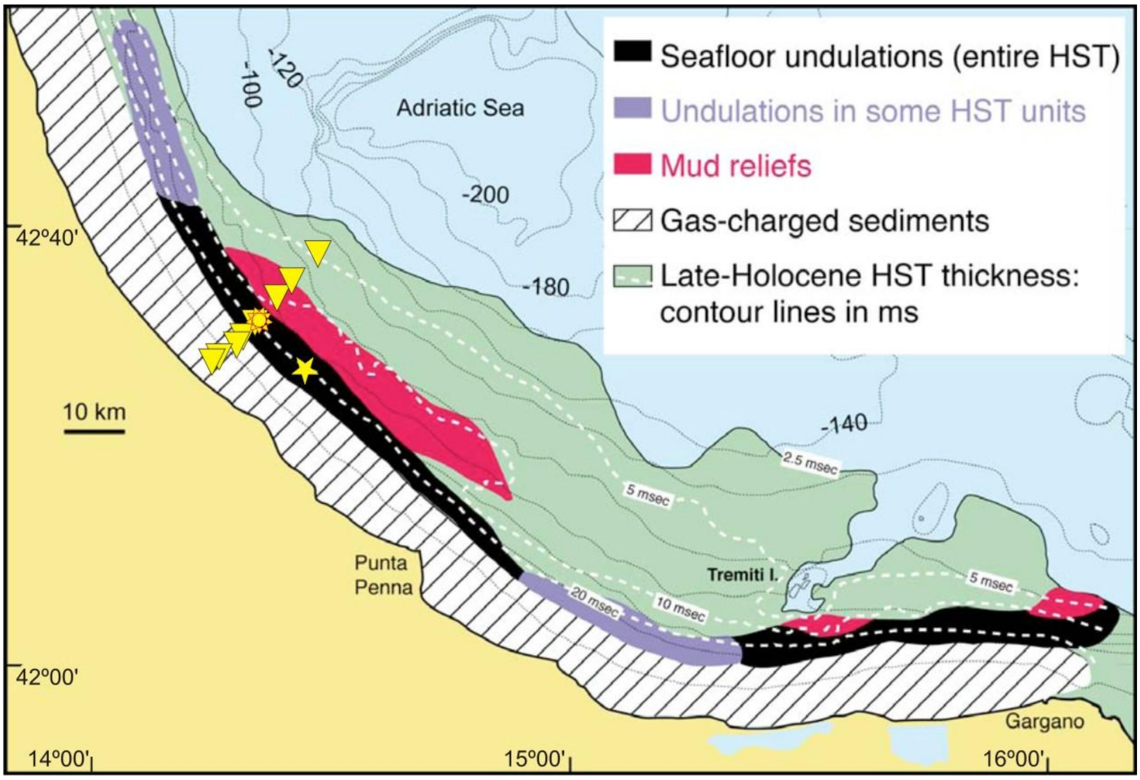

Fig. 5: Areal distribution of the sediment undulations and seafloor mud reliefs on the central Adtiatic shelf. Note that the association between these two features occurs only in part of the area with undulations. Modified from Correggiari et al. (2001). Yellow star shows location of borehole PRAD2-4. Yellow triangles show CTD stations. Complex yellow star with red outline shows location of instrumented mooring.

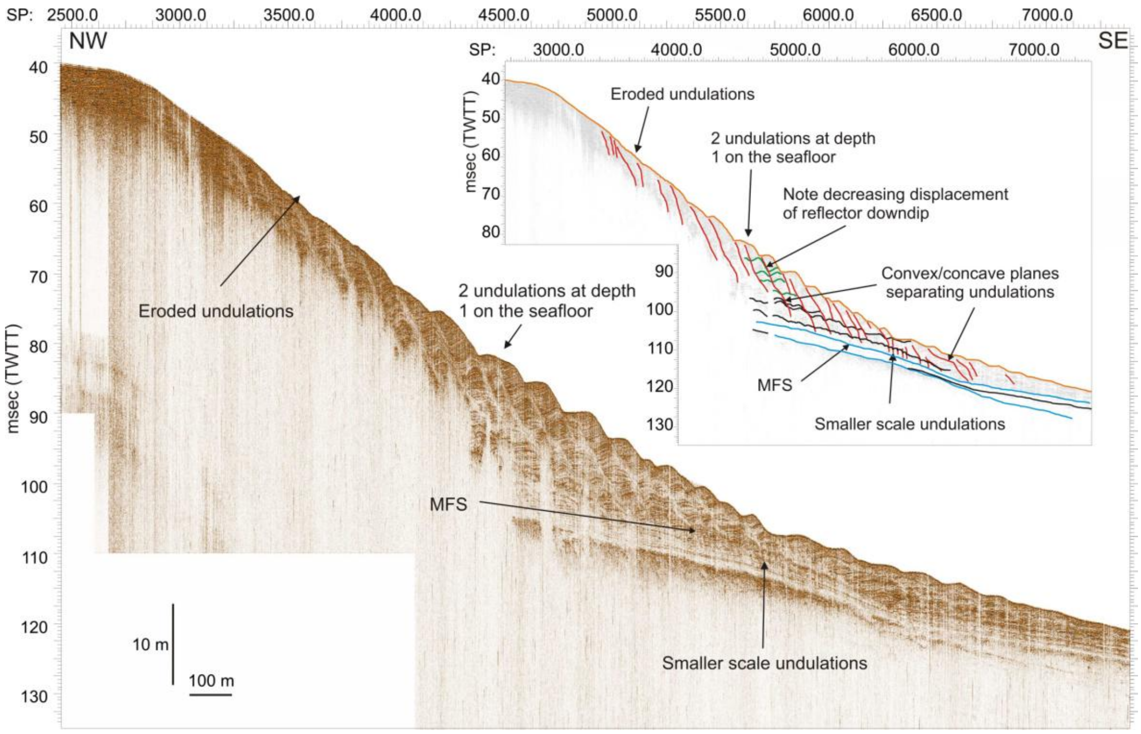

Fig. 6: Seismic section showing overall aspect of sediment undulations and internal structure on the Llobregat prodelta foresets. For location see Fig. 8 (and also Fig. 1). Inset shows line drawing with the main elements of the sediment undulations that allow identification as sediment transport structures rather than sediment deformation.

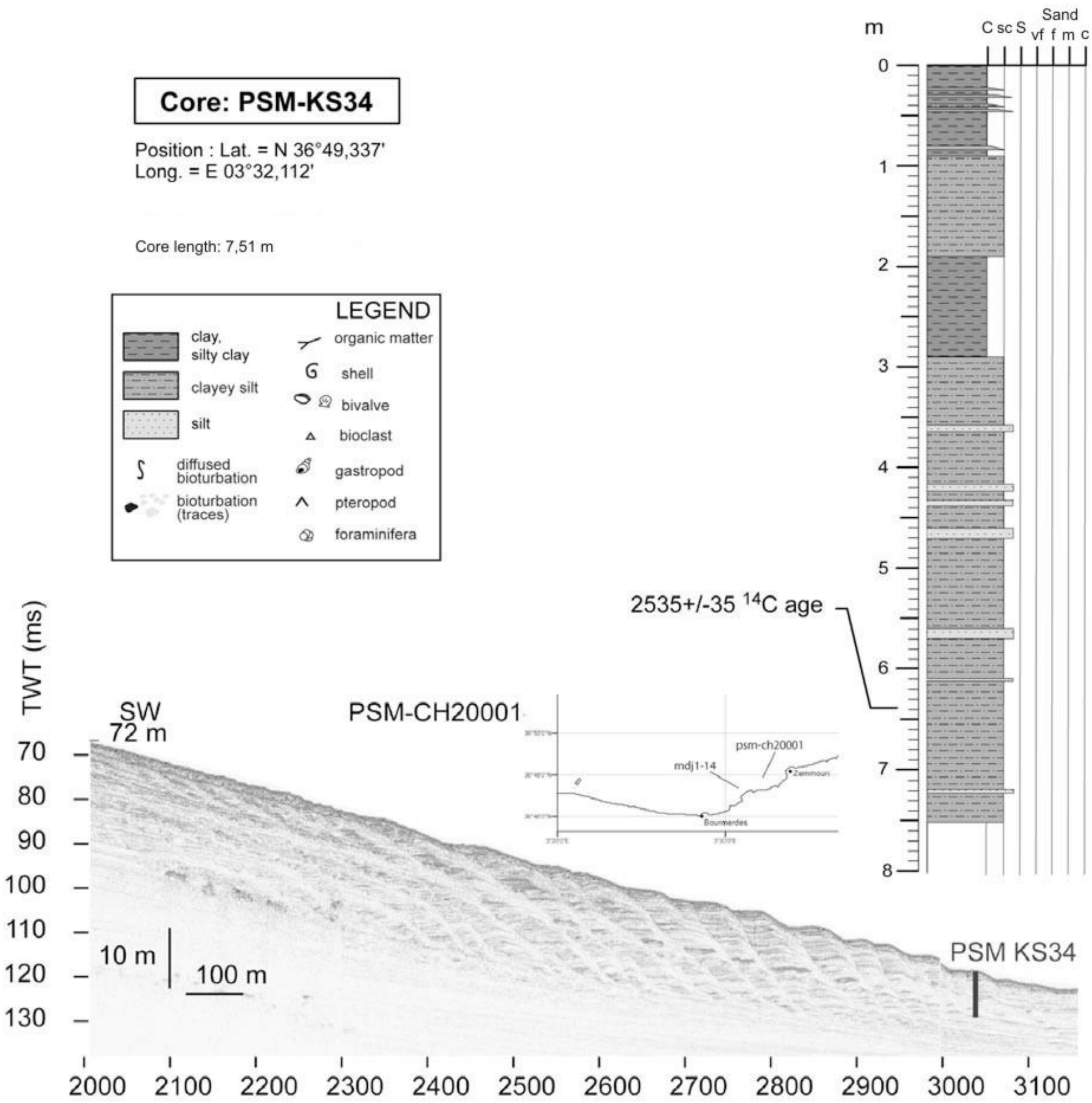

Fig. 7: CHIRP-sonar prodile on the central Algerian shelf showing sediment undulations with a decreasing amplitude and wavelength with increasing depth. The sediment core PSM-KS34, at 95 m w.d. recovered a relatively homogeneous succession of silty clay. Mixed planktic foraminifera extracted by wet sieving at 6.45 m below the seafloor gave a non calibrated age of 2535+/-35 kyr BP, confirming that the undulations belong to a highstand mud wedge deposited in the late Holocene. See also Fig. 1 for location.

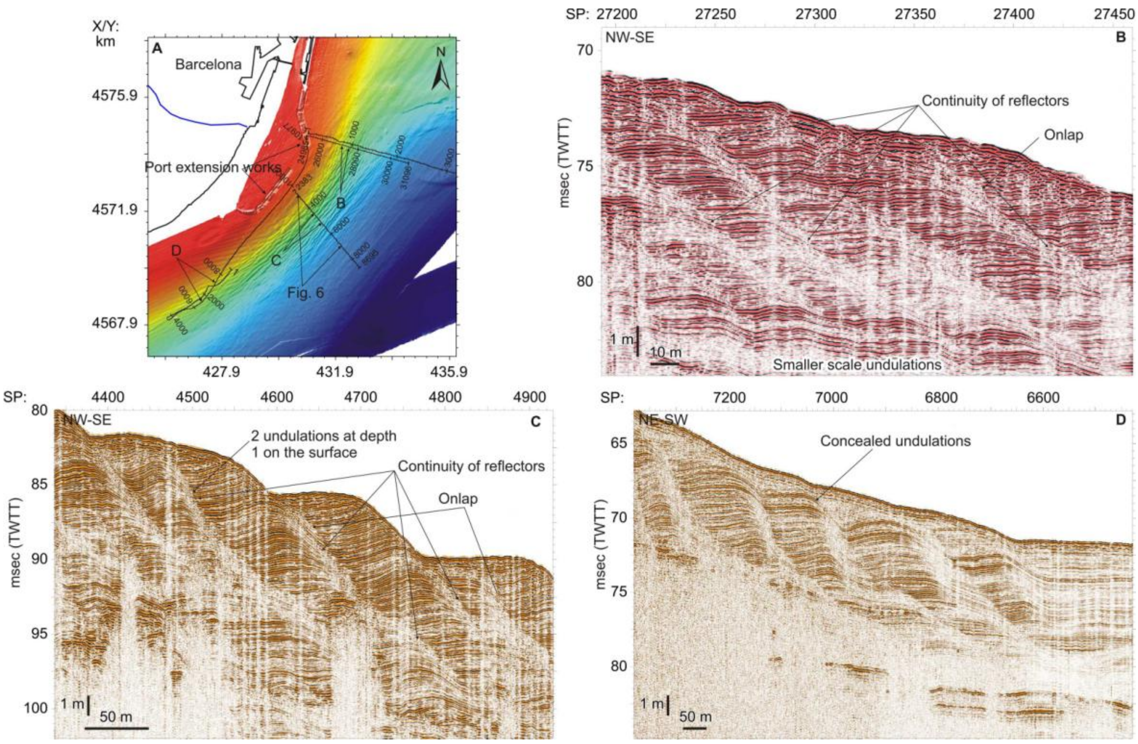

Fig. 8: Details of the undulations on the Llobregat prodelta from 5kHz subbottom profiler data.

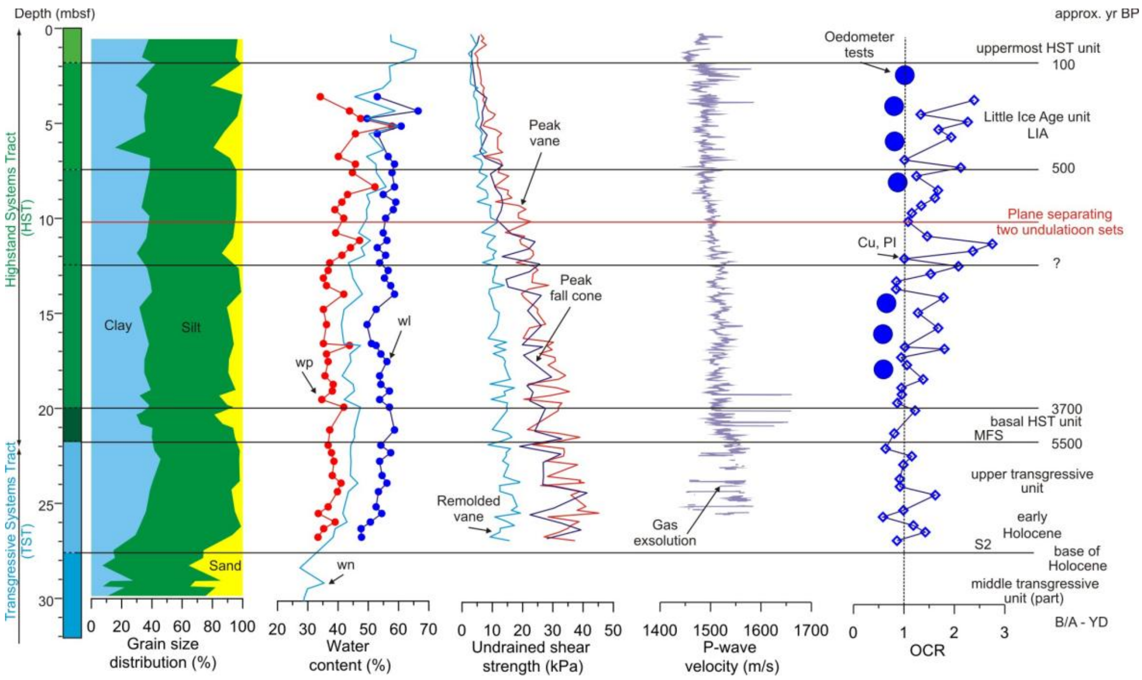

Fig. 9: Summary of chrono-stratigraphic and geotechnical characteristics of undulations from the Adriatic Sea (wp: plastic limit; wl: liquid limit; wn: natural water content; Cu, PI: consolidation state derived from undrained shear strength and plasticity index using Skempton's (1954) relationship (C_u/σ'_p=0.0037PI+0.11); OCR: OverConsolidation Ratio). See Fig. 5 for location of Geotechnical borehole.

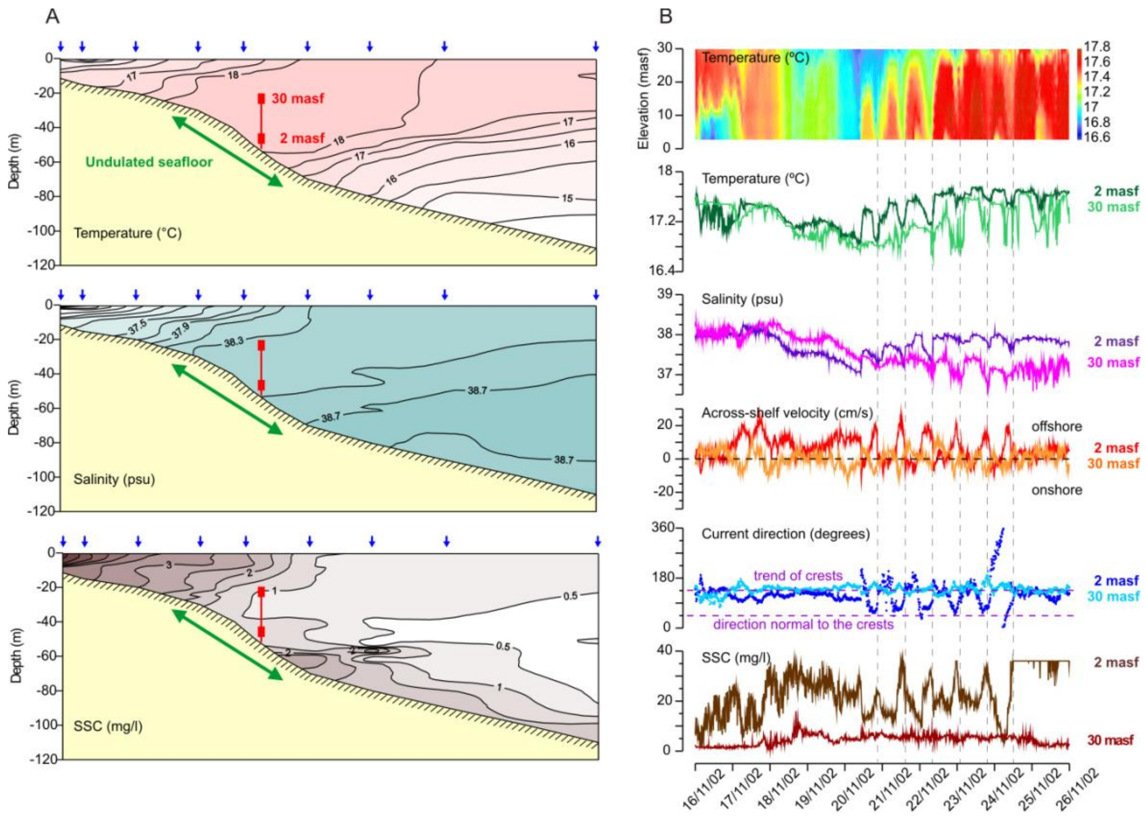

Fig. 10: A. Across-shelf hydrographic sections off Pescara showing the vertical distribution of temperature, salinity and SSC recorded on November 2002. Note the presence of a surface nepheloid layer, being constrained by coastal colder and less saline waters, and the development of a bottom nepheloid layer that detaches where the thermocline intersects with the seabed. The location of the instrumented mooring and the region affected by an undulated seafloor are also shown. B. Detail of the instrumented mooring time series during a period characterized by a strong near-inertial signal after the passage of a Sirocco storm. Temperature from 20 to 50 m water depth varied with the same periodicity (~17 h) as the fluctuations of the near-bottom turbidity and velocity components, indicating a strong displacement of the thermocline and the presence of active sediment transport by near-inertial internal waves. Increases of the SSC clearly coincide with the offshore direction of the cross-shelf velocity component, with current orientations normal to the crests of the seafloor undulations. See Fig. 5 for location of CTD stations and instrumented mooring.