Sequence Stratigraphy as a tool for water resources management in alluvial coastal aquifers: application to the Llobregat delta (Barcelona, Spain)

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CHAPTER 3: Onshore-offshore correlation of the deltaic system, development of deltaic geometries under different sea-level trends, and growth fault influences

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Chapter 3

Onshore-offshore correlation of the deltaic system, development of deltaic geometries under different sea-level trends, and growth fault influences

Quaternary deltas contain valuable information on the influence of changes in sea-level, sediment supply and tectonic activity given their role in modern clastic continental margins. An improved understanding of Quaternary deltas yields fresh insights into ancient delta deposits when the sea level is poorly constrained and dating is difficult. A critical observation of Quaternary deltas depends on the definition of stratal geometries and bounding surfaces in dip and strike sections. This allows us to construct 3-dimensional geometries and their controlling mechanisms.

The correlation between deltaic architectures and well known glacio-eustatic cycles enables us to determine predictive parameters. This allows us to establish a more robust classification of deltaic geometries in response to changing sea levels, which is a big improvement on more classic approaches based on products generated by depositional processes (Porebski and Steel, 2003; Porebski and Steel, 2006). The comparison of stratigraphic geometries under similar glacio-eustatic conditions provides clues about controls in shelf sedimentation processes (Anderson et al., 2004), with subsequent generation of end-member models (Bart and Anderson, 2004; McKeown et al., 2004). The determination of sea-level change frequencies responsible for shelf margin architecture and sequence generation is one of the main issues in Quaternary delta literature (Rabineau et al., 2005). Delta dating is essential when addressing this issue. In most Mediterranean cases, 100kyr glacial–interglacial cycles generated patterns of progradation–retrogradation due to sea-level fluctuations, resulting in the process of depositional sequence formation and continental shelf build-up (Chiocci et al., 1997; Chiocci, 2000; Trincardi and Correggiari, 2000; Rabineau et al., 2005). Relatively high sediment supplies and tectonic processes may also have favored the potential preservation of glacio-eustatic cycles with periodicities lower than 100 Ky. Except for some studies (Aksu et al., 1987; Aksu et al., 1992; Chiocci, 2000; Tesson et al., 1990), in most Mediterranean settings, shelf areas have not been directly influenced by changes in river supply with the result that shelf growth has been preferentially attributed to a process of coastal-to-marine progradation rather than to successive deltaic accumulation.

Other studies have focused on the preservation of deposits along strike and dip sections controlled by different sea-level stages, synsedimentary tectonics and variations in sediment supply. In particular, delta plain Pleistocene deposits are generally poorly represented or even absent. Some authors relate this to Quaternary delta plain uplifting both in passive (Ercilla et al., 1994; Labaune et al., 2005a; Tesson et al., 2005) and in active margins (Ricci Lucchi et al., 2006). Therefore, most coastal plain Pleistocene studies are carried out in exposed terraces due to tectonic activity or sea-level fall (Cantalamessa and Di Celma, 2004; Massari et al., 1999; Zazo et al., 2003). In contrast to the general trend, the Llobregat delta plain provides an important Pleistocene sediment record.

As a result of the poor preservation of coastal plain deposits, most studies focus on the marine realm, because of the good preservation of Quaternary stratal patterns. The sedimentary architecture of many Mediterranean continental shelves provides a record of the influence of high-frequency glacio-eustatic fluctuations on depositional geometries and environments. Nevertheless, the late Quaternary Mediterranean shelf record is characterized by high-frequency depositional sequences mainly composed of large-scale regressive wedges with poor preservation of transgressive to highstand intervals (Amorosi and Milli, 2001; Chiocci, 2000; Ercilla and Alonso, 1996; Ercilla et al., 1994; Ridente and Trincardi, 2005). The development and preservation of transgressive to highstand deposits are reported only in a few studies given the existence of one or more of the following factors: increased sediment influx, varying rates of eustatic rise and tectonic influences (Diaz and Maldonado, 1990; Lobo et al., 1999; Lobo et al., 2002; Rabineau et al., 1998; Tesson et al., 2000). In addition, most approaches to Quaternary deltaic sedimentation focus either on offshore or on the adjacent deltaic plain, but few studies correlate and integrate the entire system (Roberts and Sydow, 2003). The Llobregat delta is a good example of the integration of onshore-offshore data in conjunction with a high preservation of transgressive to highstand intervals.

In this chapter, we describe and interpret the architecture of the Llobregat Quaternary delta located in the Catalan margin in the northwestern part of the Mediterranean Sea. The study area comprises a narrow shelf which shows neotectonic activity. The objectives of this work are as follows: a) to analyze deltaic stratal geometries; b) to correlate and date the different deltaic bodies observed in the coastal plain and offshore; c) to discuss the role of global and local controlling factors, such as high-frequency glacio-eustatic cycles and neotectonic influence; and d) to draw comparisons with other deltas in the Mediterranean Sea and the Gulf of Mexico.

3.1. Onshore-offshore geological and oceanographic settings

The study area is located along the Catalan Coastal Range, eastern Iberian Margin, and represents a Neogene rifted margin associated with the opening of the Valencia Trough. The structure of the Coastal Range is dominated by longitudinal, near-vertical basament faults that trend from NE-SW to ENE-WSW. A large number of normal faults result from the negative inversion of Paleogene thrusts or strike-slip faults, and the deep extensional detachment correspond to the reactivated sole thrust of the Paleogene contractional system (Gaspar-Escribano et al., 2004; Guimera, 1984). The inversion began during the late Oligocene, and the rifting activity decreased during the Burdigalian. Thermal subsidence characterized middle and late Neogene times.

There are two Neogen half-grabens in the central part of the Catalan Coastal range: the onshore Vallés-Pendés half-graben and the offshore Barcelona half-graben (Roca, 1994; Roca and Guimerà, 1992) (figs. 3.1 and 3.2). These grabens are separated by the Garraf and Collserola-Montnegre horsts. The Barcelona plain and Llobregat delta are depressions controlled by faults and filled with Pliocene and Quaternary deposits located between the area linking the Garraf and Collserola-Montnegre horst and the Barcelona half-graben (fig. 3.2). This zone is complex and contains several minor tectonic units bounded by the northeast- southwest oriented Tibidabo, Barcelona and Morrot faults (fig. 3.1).

Offshore, the Barcelona half-graben is up 60km long and 16km wide. It is in the north-west bounded by a SE-dipping extensional listric fault (Barcelona fault, fig. 3.1) with a displacement of up to 6 km (Bartrina et al., 1992). In the Barcelona half-graben, the pre-Cenozoic rocks are tilted towards the southeast forming a synclinal parallel to the fault. In the structural high, the pre-Cainozoic rocks define an anticline of 15-30km, which is bounded by normal faults (fig. 3.2) that dip mainly northwestwards (Bartrina et al., 1992).

The study focuses on the Quaternary sediments deposited in the Llobregat delta plain and the Barcelona shelf (northeast of Spain, fig. 3.1). The present Llobregat river flows north-south from the Pre-Pyrenean Cordillera to the Mediterranean Sea, reaching the coast south of Barcelona (Spain). It is 156.6km long with a mean slope of 0.012º, and a drainage area of 5045km^2. The Llobregat river has a typical Mediterranean regime, influenced by seasonal and sporadic rainfalls giving rise to powerful stream floods during the Quaternary. The largest palaeoflood dated provides an estimated minimum discharge of 4680m^3/s in AD 1516–1642, 50km north of the Llobregat delta mouth (Thorndycraft et al., 2005).

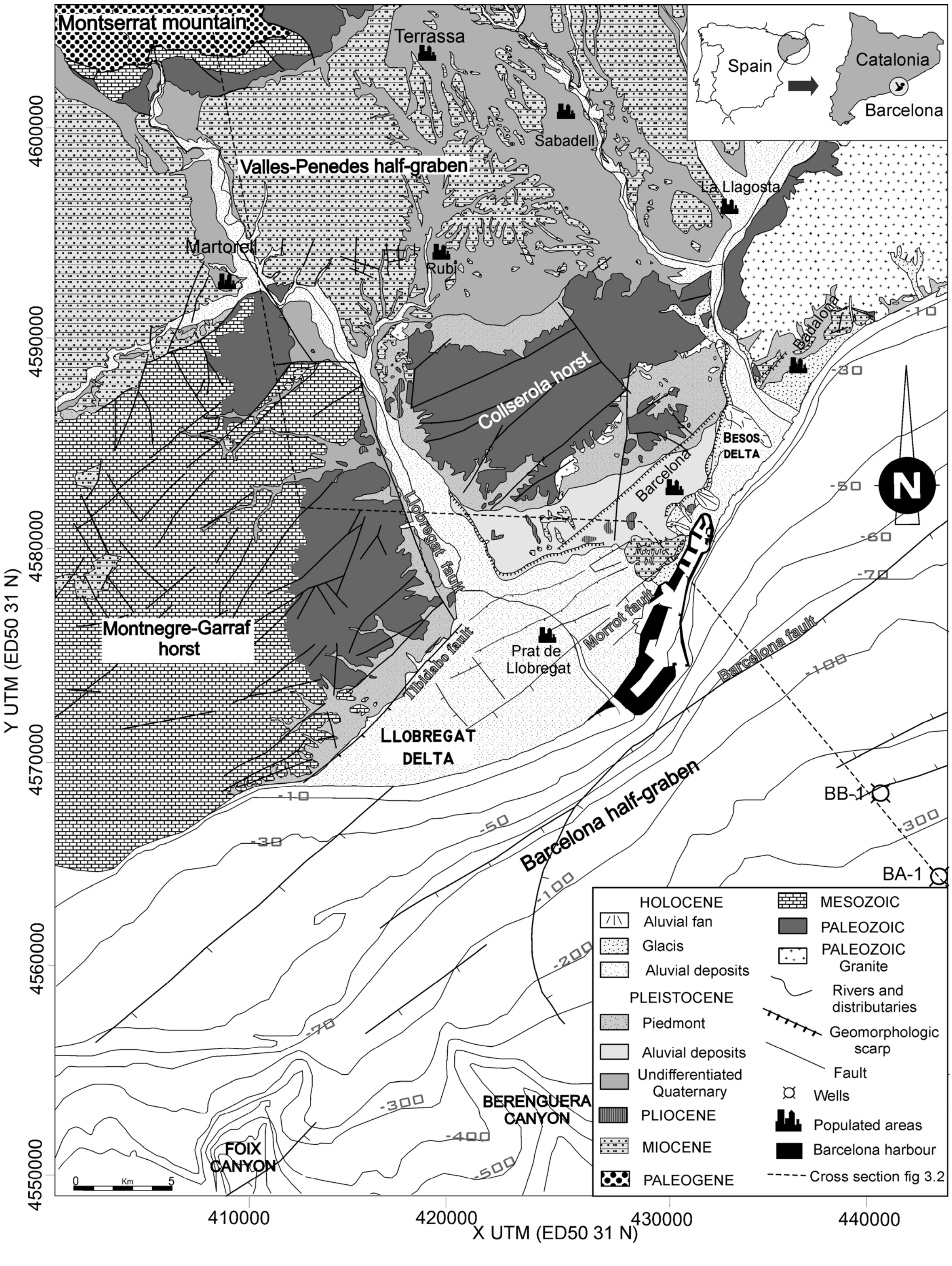

Figure 3.1: Onshore-offshore geographical and geological setting of the Llobregat and Besòs deltas (northeast Spain, northwestern Mediterranean Sea). After Medialdea et al. (1986 and 1989), ICC (2005) and Perea (2006).

Geomorphologically, the Barcelona area is made up of two units, the Upper and Lower Plain, separated by a geomorphological scarp (fig. 3.1). The Upper plain is interpreted as alluvial fan-fluvial facies (Cassasas and Riba, 1992; Ventayol et al., 2002) (table 3.1). This unit rests unconformably on top of Paleozoic to Pliocene deposits and presents an irregular thickness (with a maximum of 20m) owing to neotectonic influence (Perea, 2006). The Lower plain consists of the Llobregat and Besòs delta plains (fig. 3.1). The Llobregat delta plain covers an area of 97km², has a shoreline of about 23km and is bounded by the Llobregat (northeast- southwest) and Tibidabo faults (northwest- southeast). The Llobregat delta is relatively large compared with its basinal area; however, the shoreline is short.

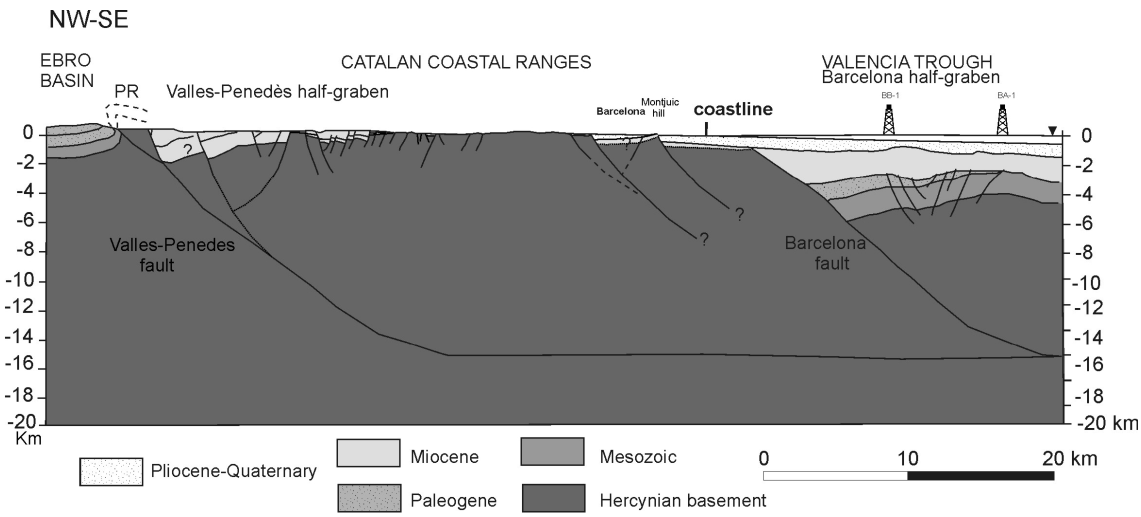

Figure 3.2: Cross-sectional structural sketch of the Catalan Coastal Ranges showing the tectonic structure of central plain and shelf off Barcelona. See figure 3.1 for location. From Parcerisa (2002).

The Barcelona shelf is located in a siliciclastic passive margin basin. The shelf is very narrow, about 6-20km wide. The slope ranges between 0.7° and 0.3° on the shelf and attains 21° on the shelf-break off. The depth of the shelf-break varies from 90-95m in the north to 75-85m in the south. The oceanographic regime of the Western Mediterranean Sea is characterized by low-energy waves (give average height) and weak tidal ranges of a few centimeters with strong southward current (30cm/s) on the outer shelf (Chiocci et al., 1997).

The Foix and Besòs submarine canyon systems are located on the outer shelf-slope on the south and north of the Llobregat river mouth, respectively. These canyons are deeply incised into the continental shelf. The Morràs and Berenguera submarine canyons, which are wider and smoother, are located in front the Llobregat delta, (Amblàs et al., 2006). Numerous shoreline-parallel faults and shoreline-perpendicular deep incised canyons cut the continental slope (Medialdea et al., 1986; Medialdea et al., 1989). Apparently the canyons are disconnected from fluvial sources such as those incised into the Barcelona continental slope, suggesting an important tectonic control between the Morràs-Besòs and Foix-Berenguera canyons (Amblàs et al., 2006; Canals et al., 2004, fig. 3.3).

3.2. Methods

3.2.1. Core data and stratigraphic correlation

Three hundred and ninety three cores of the Llobregat delta plain were compiled from available geotechnical and hydrogeological reports and recent campaigns (Appendixes I and III). Most of the deepest cores were collected for hydrogeological purposes (MOP, 1966; PHPO, 1985); more recently, geotechnical work has provided new geological information extracted from sedimentary facies and palaeontological analysis and dating. A total of 107 cores were described in detail for this study including 29 offshore cores. The density and distribution of the cores sites are not homogenous as 70% of them are concentrated in the northeastern margin (fig.3.3).

3.2.2. Chronostratigraphy

Amino acid racemization, radiocarbon dating and detailed foraminiferal analyses were carried out on 11 cores (Chapter 2 and Appendixes I and II). Dating Llobregat samples provided 17 ages from Holocene sediments and two from Pleistocene by radiocarbon method at Beta Analytic Inc., Florida (USA). Eight samples from Holocene and Pleistocene sediments were analyzed by amino acid racemization at the Biomolecular Stratigraphy Laboratory of Madrid (“Universidad Politécnica de Madrid”, Spain). Results are shown in figure 3.4.

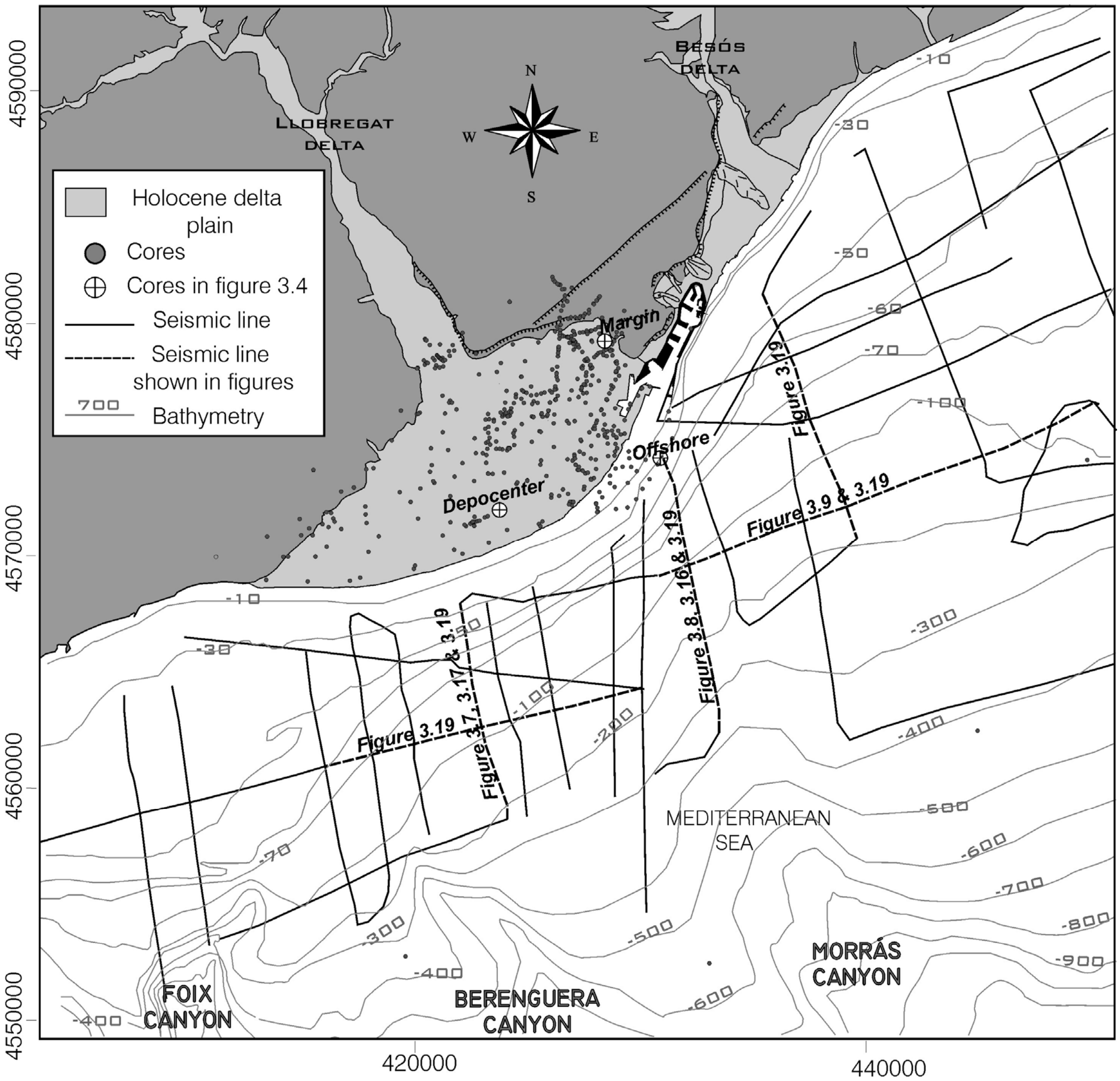

Figure 3.3: Location of cores and offshore high-resolution seismic profiles used in this study. Crossed white circles refer to the cores shown in figure 3.4. Dashed lines identify the seismic profiles in figures 3.7-3.9, 3.16-3.17 and 3.19 (more details in Appendix IV). Bathymetric contours are given in meters. The names of the canyon systems mentioned in the text are also included.

3.2.3. High resolution seismic profiles

The seismic data used in this study were collected under the framework of the program designed to map the Spanish Continental Shelf (FOMAR Project) undertaken by the Spanish Geological Survey (Medialdea et al., 1986 and 1989). The seismic data were obtained in 1982 and 1985 in four oceanographic surveys onboard the B/O Cornide de Saavedra (CO-82-2) and the B/O Garcia del Cid (GC-85-2, GC-85-5 and GC-

85-6). The total available data (Appendixes I and IV) provide a rectangular mesh of profiles along and across the continental shelf in front of the Llobregat and Besòs deltas (fig. 3.3). High-resolution seismic profiles were recorded by employing SPARKER (4.500 joule) and Uniboom (GEOPULSE) seismic sources. Positioning was achieved by using a Syledis system provided by the Oilfield Hydrographical Projects of Spain in CO-82-2 survey, a radio positioning Maxiran system (Hidronav, S.A.) in GC-85-5 survey and a Loran C and radar system in GC-85-2 and GC-85-6 cruises.

In this study, we imposed a uniform 1550m/s for the velocity of sound in water to convert the seismic profile to calculate the thickness of quaternary sediments offshore.

3.3. Quaternary Stratigraphy

3.3.1. Previous scheme of the onshore-offshore Llobregat delta

Earlier studies on the Llobregat delta depositional system date from the XIX century (Almera, 1891; Llopis, 1942; Llopis, 1942; Llopis, 1946; Solé-Sabarís, 1963; Solé-Sabaris et al., 1957). The main hydrogeological units of the delta plain were first described by the "Comissaria d'Aigües del Pirineu Oriental" (MOP, 1966). Marques, (1984) devised the previous geological model for the stratigraphy of the Llobregat delta plain. The geological model discriminated between two detritical complexes in the present-day deltaic plain: a Pleistocene Lower Detritical Complex and a Holocene Upper Deltaic Complex. Holocene inner and onshore facies were later studied by Manzano, (1986). The first reports of offshore stratigraphy were produced during the eighties from the analysis of marine seismic reflection profiles (Medialdea et al., 1986; Medialdea et al., 1989). These studies recognized three offshore Pleistocene units deposited during the three most recent late Quaternary glacial-interglacial cycles. The youngest onshore Holocene unit was deposited in the post-glacial transgression (Checa et al. 1988). Recent studies have focused on the characterization of Holocene architecture based on geotechnical records in a small section of the Llobregat delta plain (Lafuerza et al., 2005), and on the evaluation of the influence of anthropogenic impacts using geomorphology on the continental shelf (Liquete et al., 2007). In line with this approach, a number of modern and relict sedimentary features have been recognized in relation to the seascape development of the Barcelona shelf (Amblàs et al., 2006), such as sediment undulations on the Llobregat River prodelta (Urgeles et al., 2007) or submarine landslides in the proximity of Foix Canyon (Lastras et al., 2007).

3.3.2. Description and Interpretation of Sedimentary Facies Association in the Llobregat delta plain

Ten sedimentary facies grouped into six facies associations were interpreted in accordance with their dominant grain size and secondary sedimentary features such as fauna content, sedimentary structures, etc. These facies associations are described below (table 3.1, fig. 3.4).

3.3.2.1. Gravel and red clay facies association (Fc-Fp)

Fc facies consist of massive, fining-upward, very poorly sorted gravels with well to poorly rounded pebbles embedded in a fine-grained matrix with wood fragments and sharp erosional bases. Pebbles are heterometric and composed of different lithologies (Fc, table 3.1, fig. 3.5). Red silts and clays with millimetric-scale sand laminae occur within *Fc* facies or at the very top. Roots, soil micro-nodules and continental fauna are also common. This sediment facies is designed as Fp (figs. 3.4 and 3.5).

Fc facies are interpreted as fluvial channel and ephemeral fluvial deposits. Fp facies are laterally extensive and may fill abandoned palaeochannels. Fp facies are considered to be flood plain deposits. Four stratigraphic Fp/Fc intervals were recognized from the stratigraphic correlation between cores: a Holocene fluvial system and a minimum of three Pleistocene palaeochannels (fig. 3.6). Morphologically, the oldest palaeochannel is not preserved in the northeastern delta margin and is more spatially confined. Fine matrix percentage increases downsection. The youngest Pleistocene complex has lateral continuity and covers the entire delta plain.

3.3.2.2. Multicolored fine-grained facies association (Rw)

Rw facies comprise, in order of abundance, red and yellow clays and marls, white, yellow, black or light grey silts with mottled oxidation with marine and continental fauna, pebbly sandstones (table 3.1, fig. 3.5) and well sorted fine to coarse yellow, partially cemented sandstone with fauna and phyllosilicate minerals, (table 3.1, fig. 3.5).

Fauna content suggests a high degree of reworking of older foraminifers (Miocene, Pliocene and Quaternary) and ostracods as well as a mixture of marine and non-marine fauna (Chapter 2). Rw facies vary vertically and horizontally with internal erosions and complex facies relationships. They are interpreted as a mixture of littoral facies (beach, lagoon and washover) and continental facies (distal alluvial fan and floodplain) (Chapter 2). These facies associations occur between the three Pleistocene palaeochannel complexes and are laterally continuous throughout the delta plain except in the places where palaeochannels amalgamate (figs. 3.4 and 3.6).

3.3.2.3. Clean sand-gravels (Bs-Bg)

Bg facies consist of well rounded to sub-angular polymictic and heterometric gravels with clasts ranging from granule to cobble with lithofagous-bored pebbles and diverse micro- and macrofauna such as large oyster sp., shell fragments, gastropods and scaphopods (Bg, table 3.1, fig. 3.5). Foraminifera and ostracod in Bg facies indicate mixing of marine and brackish water and fauna reworking. Bg facies have no matrix or cement in the youngest Pleistocene units but both increase downsection. Bg facies grade seaward into interbedded sandstone and gravel (fig. 3.4).

Bg facies are interpreted as beach deposits with mixed marine and terrestrial fauna indicating reworking of alluvial deposits by marine processes. Bg facies cap the three Pleistocene palaeochannels (Fc). In some places Fc and Bg facies cannot be discerned because of the low matrix preservation in geotechnical cores.

On top the youngest Fc-Bg palochannel system, discontinuous well-sorted sands with abundant fauna and bioclasts (Bs) are observed. Bs facies are interpreted as sandy beach deposits. Their discontinuous plan view suggests that they are landward-stranded beaches (figs. 3.4, 3.5 and 3.6).

3.3.2.4. Grey silt and shales with interbedded sand (P)

This facies association consists primarily of bioturbated and massive grey shales and silty clays with sparse shell fragments interbedded with thin, silty sand to fine sands (fig. 3.5). Coarsening-upward cycles were recognized in cores (fig. 3.4). This interval is about 55m thick and pinches out in all directions (fig 3.6, see section 3.4).

P facies are interpreted as prodeltaic sediments deposited below the storm wave base. Sand layers are attributed to storm currents, whereas clays are ascribed to the fall out of suspended fine sediments. Coarsening-up parasequences are interpreted as progradation pulses of the delta system.

3.3.2.5. Yellow to grey sand facies association (Df-Bb)

Yellow to grey sand facies interfinger with the prodelta facies association in a landward direction (fig. 3.6). These facies consist of coarsening-upward, well-sorted sands grading upward into sub-rounded pebbly sands (Df facies, fig. 3.5C) with fragmented molluscs, small pebbles and phyllosilicate minerals. These facies are interpreted as distal to proximal deltaic front (Df in figs. 3.4 and 3.5). To the north-east, these facies consist of coarse to middle sands with abundant mica and sparse shell fragments, with an elongate geometry (Bb facies, fig. 3.6), and are interpreted as beach barrier.

3.3.2.6. Grey mud and silt (M-Sw)

This facies association consists of dark muds and silty clays rich in organic matter with brackish to fresh-water gastropods and shells (M). Black muds with brown plant debris and continental gastropods (Sw) are also described. These facies are up to 3m in thickness and up to 7km² in length (figs. 3.4 and 3.5). M and Sw facies are interpreted as marsh to lagoonal deposits with a variable organic matter content indicated by color differences. Some Sw facies contain gas. Marsh facies are associated with beach facies, which are best preserved in the younger palaeochannel complex, whereas Sw facies primarily occur in the northeastern delta plain margin (fig. 3.4).

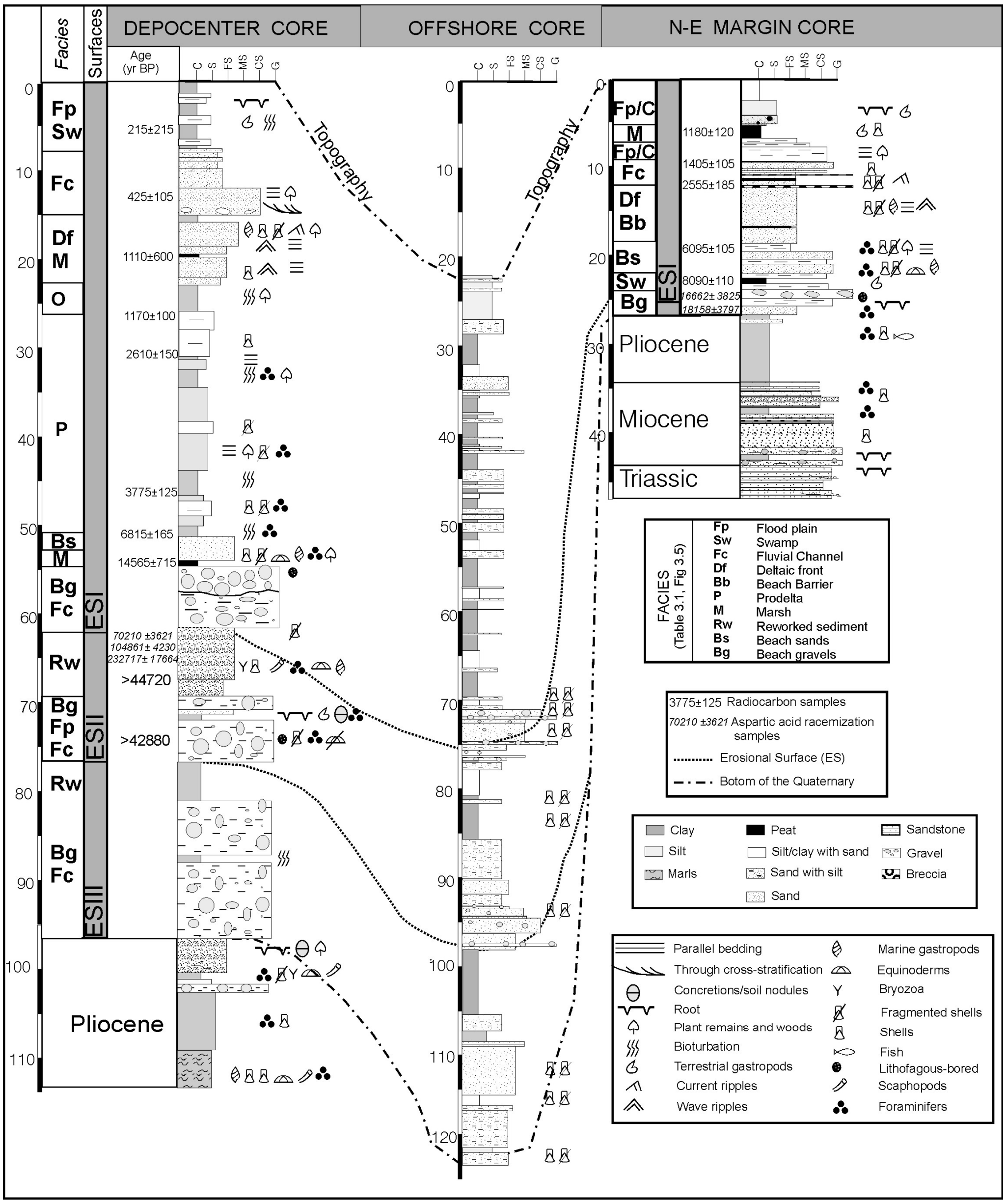

Figure 3.4: Stratigraphic columns and vertical facies distribution (table 3.1) representative of the depocenter and margin of the onshore domain, and of the offshore domain (see location in figure 3.3). A schematic correlation of the main erosional surfaces (ESs) discussed in the text is indicated. The approximate position of the amino acid racemization and the radiocarbon ages are also included (for a precise location of the cores used for dating see fig. 3.14).

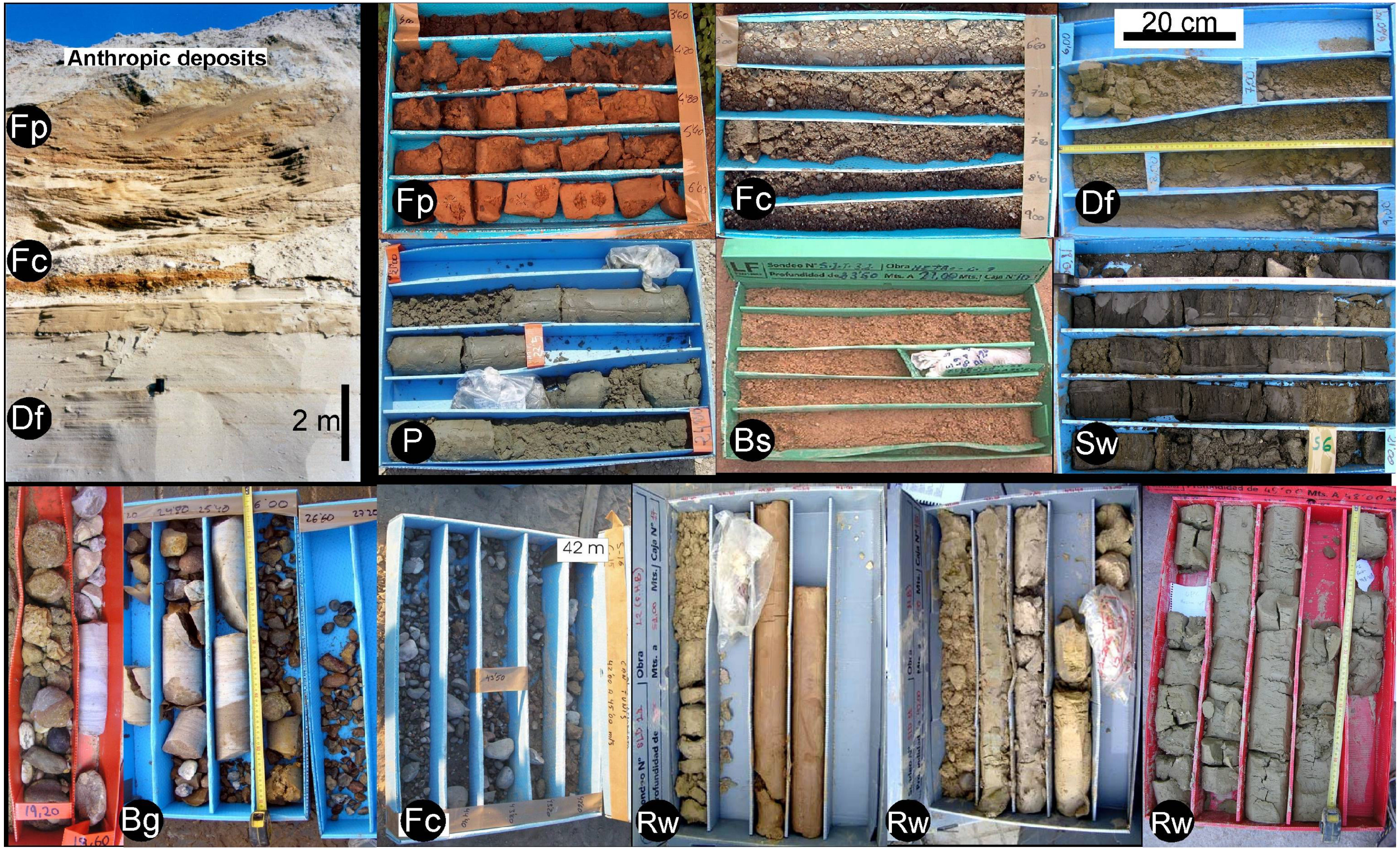

Figure 3.5: Representative pictures of the facies described in cores and Holocene outcrops in the Llobregat delta plain. Nomenclature used: Fp (Flood plain); Fc (Fluvial channel); Df (Delta front); P (Prodelta); Bs (Beach sand); Sw (Swamp); Bg (Beach gravel); and Rw (Multicolored fine-grained facies association, reworked sediments) (see table 3.1 and figure 3.4). The maximum dimension of the core boxes is 60 cm.

Table 3.1: Classification of the facies associations together with their main attributes based on core descriptions and palaeontological analysis. The correspondence with regional packages is also included (see distribution on fig. 3.6).

Unit	Facies association	CODE (Fig. 3.4, 3.5)	Textures	Sedimentary structures and fauna	Geometries and boundaries (fig 3.6)	Interpretation	Regional package
LOWER PLAIN	*Gravels and red clays*	Fc	Gravels with sandy matrix and fining upwards with wood fragments, lenses organic matter. At the bottom they have clay balls. The pebbles are well rounded to poorly rounded, heterometric and composed of different lithologies.	Cross-stratification to ripples (outcrop picture in Fig 3.5)	Concave-up shape. Top:flat, Bottom:erosional	Fluvial channel and torrent	I, II, III
		Fp	Red silt composed of millimetric-scale of sand laminae	Massive. Root marks, bioturbation and continental fauna (gastropoda)	Large extension and lateral continuity. Occasionally filling concave-up shape	Flood plain	
	Multicolored fine grained	Rw	Different facies: a) White and red clays with pebbles, b) Clay, marls and silt typically white, yellow or light grey, c) Well sorted yellow fine to coarse sands, dispersed centimetric pebbles	From a) root marks and bioturbation, some continental gastropod, to b) shells, ostracoda and foraminifera reworked and resedimented. Phyllosilicate minerals	Large extension and lateral continuity	Littoral to continental facies	II, III
	Clean sand-gravels	Bg	Gravels well-rounded to angular pebbles and polymictic and heterometric clast from granule to cobble, sand matrix. Some layers are cemented	Reworked-resedimented fauna and pebbles with lithofagous-bored pebbles	Sheet-like shape to concave-up shape. Top:flat, Bottom:erosional	Beach	I, II, III
		Bs	Yellow well-sorted sand	Rich fauna and bioclasts	Discontinuous lens shape. Bottom:unconformably over previous deposits		I
	Grey silt and shales with interbedded sand	P	Grey and black shales and silt, variability interbedded with fine to very fine sand. Cycles coarsening-up sequences are observed	Laminated to massive structure. Bioturbation and sparse shell fragments	Wedge shape pinching out in all directions	Prodelta	
	Yellow to grey sand	Bb	Coarse to medium yellow sand. Well sorted with sub-rounded pebbles	Rich micaceous mineral and sparse fragmented shells	Elongate. Locating in eastern margin	Beach barrier	
		Df	Yellow and grey fine to coarse well sorted sand (coarsening up-wards), some pebbles.	Frequently shell fragmented and shell well preserved. Micaceous mineral	Dipping clinoform shapes and flat bases	Delta front	
	Grey mud and silt	Sw	Grey to black clay and silty clays, black color indicating high content of organic matter	Brackish to fresh-water gastropods and bivalves	Elongated lens-shaped	Swamp	
		M	Black mud. Concentration of fibrous organics	Fresh and brackish associations, dominated by poorly diversified of fauna.	Thin patchy shape	Marsh	
UPPER PLAIN			Interbedded deposits of breccias, red siltstone, grey and yellow claystone, poorly-sorted gravels with angular and sub-angular pebbles, fine-grained and well sorted sandstones, and moderately to well developed thin paleosoil horizons	Caliches	Sheet-like shape. Bottom: unconformable above Paleozoic to Pliocene	Alluvial deposits	

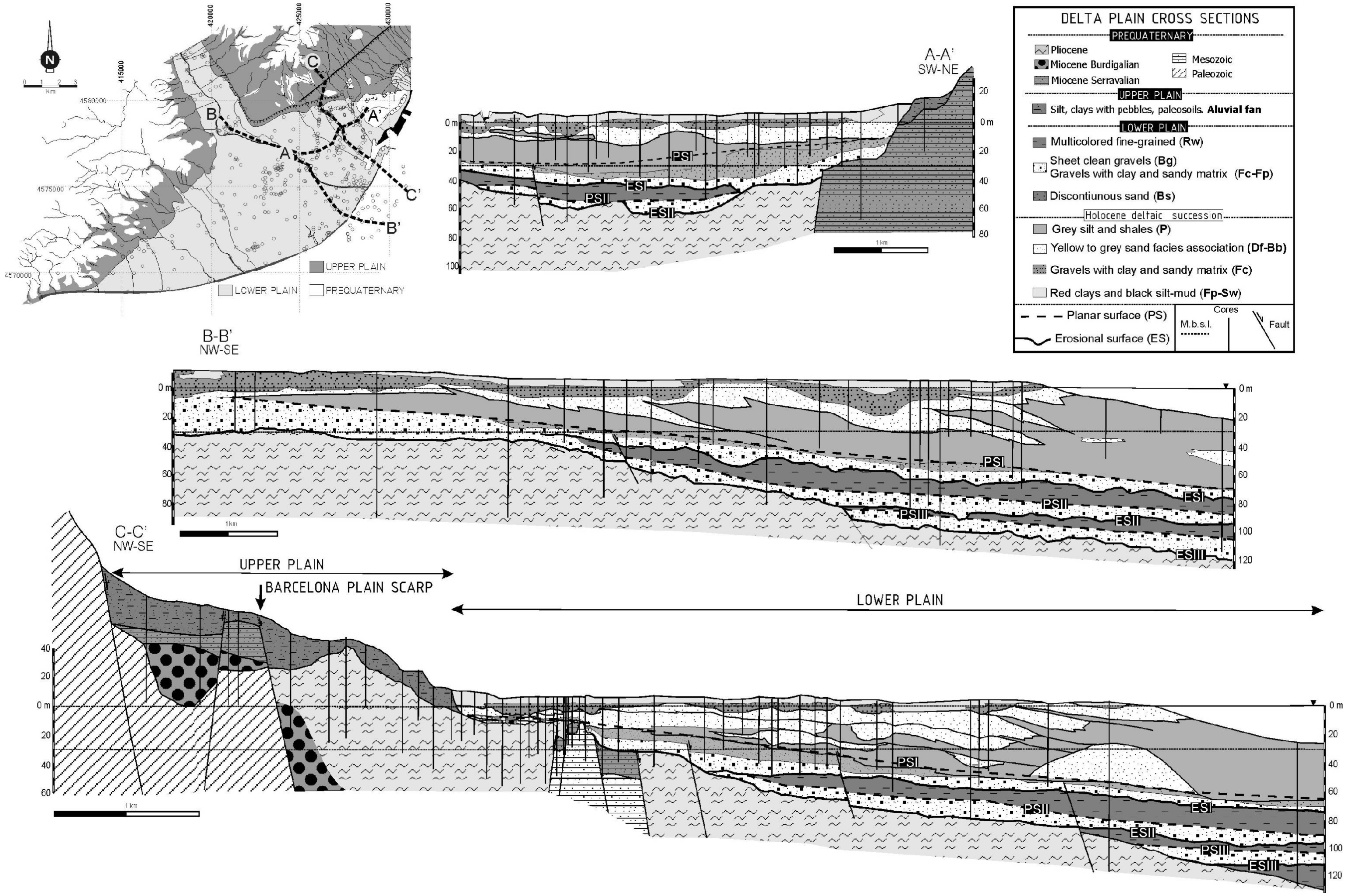

Figure 3.6: Strike (A-A´) and dip cross sections of the depocenter (B-B′) and the northeastern margin (C-C′) of the Llobregat delta plain deposits from core observations (more details in Appendix III). Three regional erosional surfaces (ESs) and planar surfaces (PSs) were identified. The sedimentary record above ESs and below PSs is composed of fluvial channel facies (Fc) and beach gravel facies (Bg) together with beach sand facies (Bs). The sedimentary record above PSs and below ESs is composed of multicolored fine grained facies (Rw), and of a complete deltaic succession in the most modern sediments. The map in the upper left corner shows the location of the sections (dashed bold lines) and cores position (empty circles).

3.3.3. Description of Llobregat Shelf Seismic Units

The analysis of high-resolution seismic profiles enables us distinguish from bottom to top: an aggradational to progradational upper slope wedge (SAPW), widespread sub-parallel sheets (PASs), proximal landward-thickening progradational wedges (LPWs), a progradational mid-shelf wedge (PL), and seaward-thickening progradational wedges with widespread upper erosion (SPWs). This pattern is shown in table 3.2 and figures 3.7, 3.8 and 3.9. Identified seismic units are described in detail below.

3.3.3.1. Aggradational to progradational upper slope wedge (SAPW)

This type of seismic unit is only recognized in the youngest part of the stratigraphic record, on the shelf break and upper slope in the southwest sector and on the middle to outer shelf and slope in the northeastern sector (figs. 3.7, 3.8 and 3.9). It shows a divergent configuration with inclined internal reflections showing onlap terminations with respect to the lower boundary, which exhibits an erosional character on the middle to outer shelf. The top boundary is a planar surface whose internal reflections show concordance.

3.3.3.2. Seaward-thickening progradational wedges with widespread upper erosion (SPWs)

These seismic units are characterized by seaward thickness increases with maximum depocenters located on the shelf break and upper slope. The dominant seismic configuration is high to mid-angle oblique-parallel although hummocky patterns were also observed on the northeastern shelf. SPWs are characterized by bottom downlap and well-defined top erosional surfaces with frequent channel incisions. We recognized three SPWs throughout the shelf (figs. 3.7, 3.8 and 3.9).

3.3.3.3. Widespread sub-parallel sheets (PAS)

Sheet-shaped geometries (PASs) occur on top of SAPW and SPWs. Internally they show subparallel reflections, but towards the top they may show chaotic, low-angle oblique-parallel configurations (figs. 3.7, 3.8 and 3.9). The lower boundary shows erosional base and onlapping terminations landward. The tops of PASs are flat surfaces with concordant terminations. We recognized four PASs in the study area (figs. 3.7, 3.8 and 3.9).

3.3.3.4. Progradational mid-shelf wedge (PL)

This type of seismic unit was a lenticular shape with the thickest part on the inner to middle shelf. At least, two seismic subunits are shown. The oldest subunit displays a low-angle, parallel-oblique configuration with downlap and toplap terminations. The youngest subunit shows a well-defined wedge shape with a high-angle parallel-oblique configuration. This unit has only been preserved on the southwestern shelf (fig. 3.7).

3.3.3.5. Proximal seaward-thinning wedges (LPWs)

Seaward-thinning wedges occur over the inner-middle shelf overlying PASs and/or PL. LPWs show seaward-dipping middle to low-angle clinoforms and moderate development, except the most recent LPW, which develops a significant proximal depocenter. Downlap and toplap terminations are common. Four LPWs were observed on the southwestern shelf (fig. 3.7), whereas only three LPWs were detected on the northeastern shelf (figs. 3.8 and 3.9).

Table 3.2: Types of offshore seismic units and their main seismic attributes. Nomenclature: S (Seawards); L (Landwards); P (Progradational); PA (Parallel); A (Aggradiational); W (Wedge); S (Sheet, in PAS seismic units); L (Lenticular, in PL seismic units). The correspondence with regional packages is also included (see seismic profiles in figs. 3.7, 3.8 and 3.9).

Seismic facies	CODE (Fig. 3.7, 3.8, 3.9)	Internal structure	Geometrical shape	Type of termination: Bottom boundary	Type of termination: Top boundary	Shelf position	Location	Interpretation	Regional package
Widespread sub-parallel sheet	**PAS**	Parallel, chaotic and low angle seaward dipping clinoforms to oblique-parallel	Sheet tend to amalgamate and form bodies of similar thickness throughout	Downlap to onlap	Concordant	Inner shelf to slope	Throughout shelf area	Coastal deposits dominated by coarse sediments	I, II, III
Proximal Landward-thickening progradational	**LPW**	Seaward middle to low angle dipping clinoforms	Seaward wedge-ending	Downlap	Toplap	Inner to middle shelf		Beach deposits evolving seaward to shelf muds	
Progradational mid-shelf wedge	**PL**	Parallel-oblique clinoforms at the base and high angle dipping clinoforms at	Lenticular -Sigmoidal				South-western area	Beach deposits	II
Seaward-thickening progradational wedges with widespread upper erosion	**SPW**	Seaward high to middle angle dipping clinoforms to oblique-parallel facies	Landward wedge-ending	Downlap	Erosional truncation	Inner shelf to slope	Throughout shelf area	Lower shoreface to prodeltaic deposits	II, III, IV
Aggradational-to-progradational upper slope wedges	**SAPW**	Seaward high to low angle dipping clinoforms to oblique-parallel facies		Offlap to onlap	Concordant	Middle shelf to slope			I

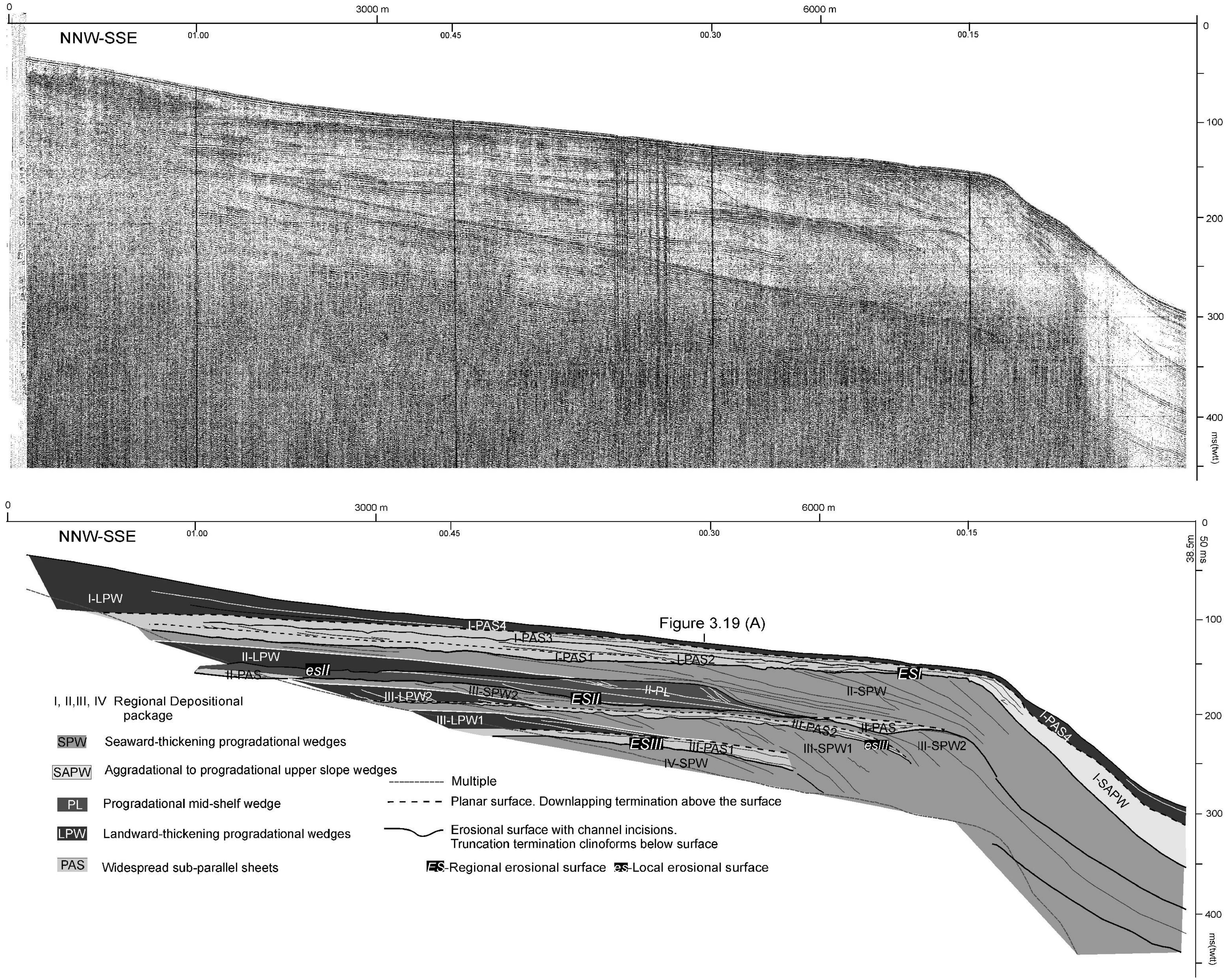

Figure 3.7: Uninterpreted (top) and interpreted (bottom) dip seismic profile of the Llobregat delta southwestern shelf. Three regional erosional (ESs) and planar surfaces (PSs) and two local erosional surfaces (ess) are recognized. ESs limit four regional packages (I, II, III and IV) composed pf SAPW, PAS, LPW, PL and SPW seismic units (table 3.2) that show specific external shape and internal configuration. The location of the seismic profile is shown in fig. 3.3.

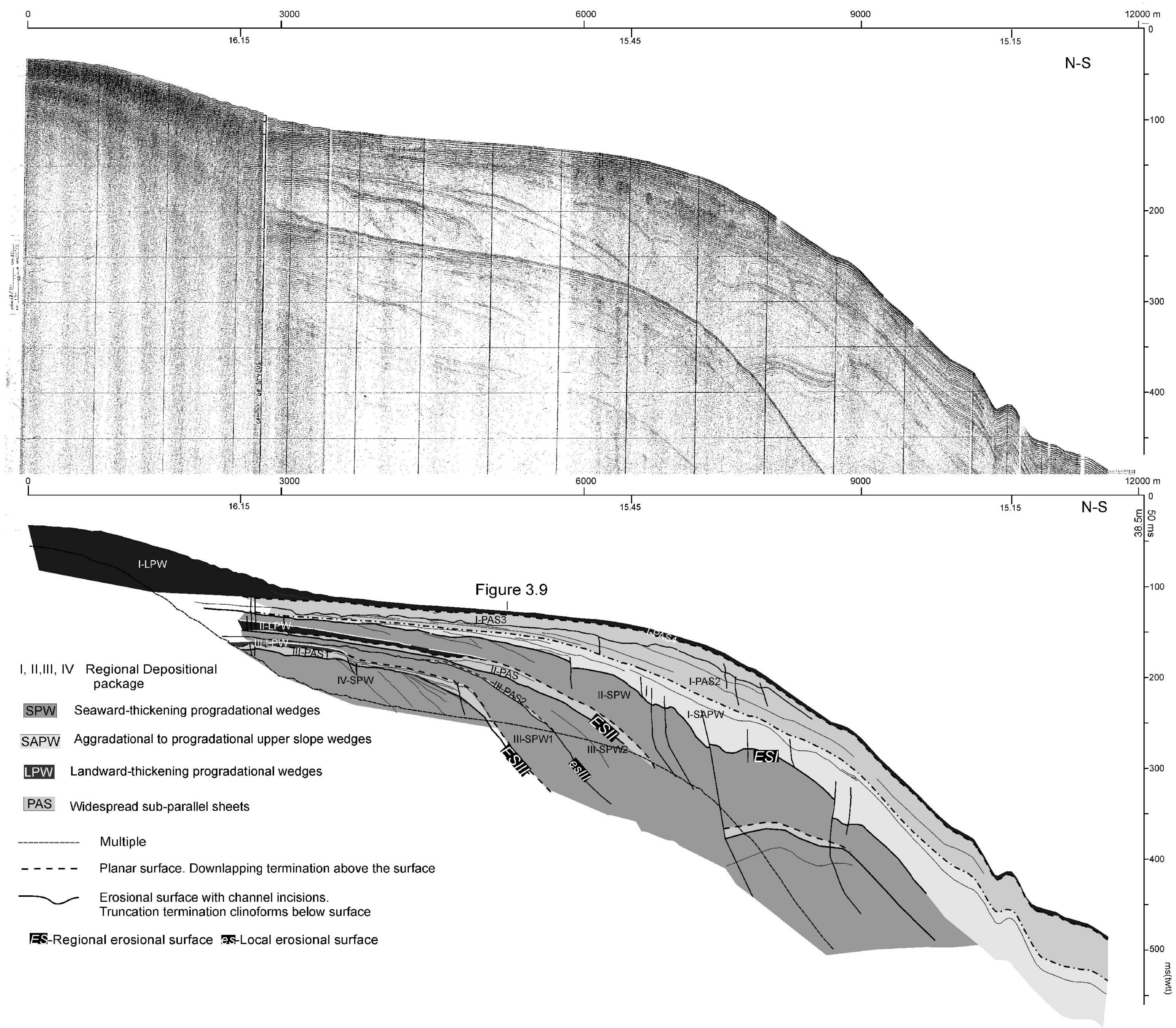

Figure 3.8: Uninterpreted (top) and interpreted (bottom) dip seismic profile of the Llobregat northeastern shelf. Three regional erosional (ESs) and planar surfaces (PSs) and one local erosional surface (ess) are recognized. ESs limit four regional packages (I, II, III and IV) composed of SAPW, PAS, LPW and SPW seismic units (table 3.2) that show specific external shape and internal configuration. The location of the seismic profile is shown in fig. 3.3.

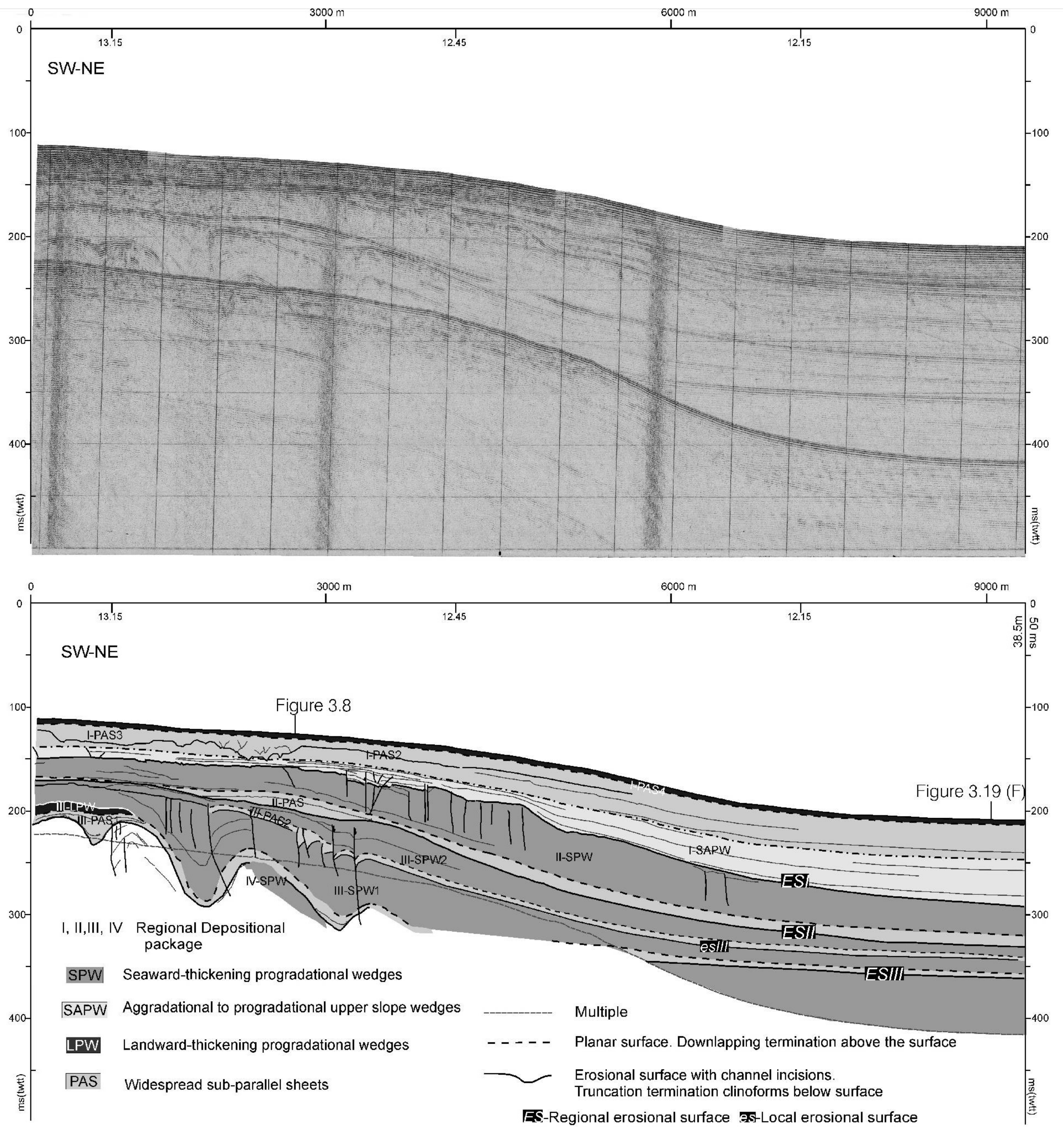

Figure 3.9: Uninterpreted (top) and interpreted (bottom) strike seismic profile of the Llobregat northeastern shelf. Three regional erosional (ESs) and planar surfaces (PSs) and one local erosional surface (ess) are recognized. ESs limit four regional packages (I, II, III and IV) composed of SAPW, PAS, LPW and SPW seismic units (table 3.2) that show specific external shape and internal configuration. The location of the seismic profile is shown in fig. 3.3.

3.4. Onshore-offshore correlation

3.4.1. Quaternary Overview

The integration of coastal plain and offshore sediment cores with offshore high-resolution seismic records provides an overall framework for the quaternary stratigraphic architecture of the continental margin. The onshore-offshore correlation is based on the identification of fluvial valleys onshore (fig. 3.6) and erosional truncations offshore (figs. 3.7, 3.8 and 3.9), and on planar surfaces over the entire study area. Three regional erosional surfaces (ESs III, II and I, figs. 3.6, 3.7, 3.8 and 3.9) and three planar surfaces (PSs, figs. 3.6, 3.7, 3.8 and 3.9) were identified in the study area as well as minor discontinuities or local erosional surfaces (ess, figs. 3.7, 3.8 and 3.9). ESs limit four regional depositonal packages (named from bottom to top IV, III, II and I). These surfaces (ESs and PSs) are key to relating the onshore sedimentary facies with the offshore shelf seismic units. The bottom of each regional depositional package above an ES and below a PS consists of fluvial channels (Fc), beach gravel (Bg) and beach sand (Bs) sediment facies onshore that grade offshore into widespread PASs (fig. 3.10). Multicolored fine-grained (Rw) facies occur onshore in the upper part of depositional packages III and II above PSs and below the consecutive ESs, grading offshore into LPWs and SPWs. Above the last PS in depositional package I lies a deltaic succession grading offshore into LPWs (fig. 3.10). In addition, PL is only preserved in depositional package II in the northwestern part of the study area, whereas SAPW only occurs in depositional package I.

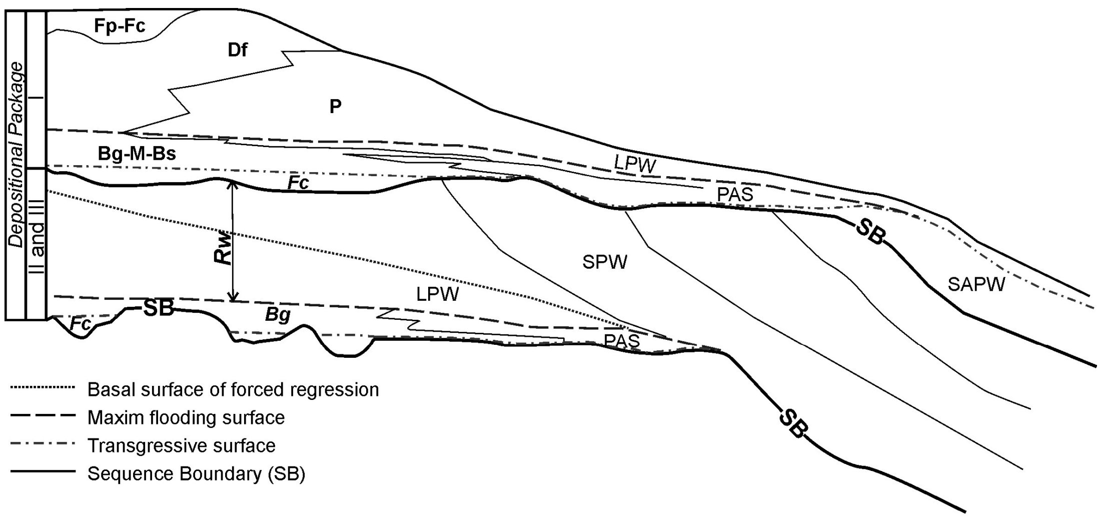

Figure 3.10: Simplistic conceptual model scheme of the regional depositional package I, and the pattern scheme of depositional packages II and III showing the correlation between onshore facies association and offshore seismic units. Onshore facies association nomenclature; Fp: Flood plain; Fc: Fluvial channel; Df: Delta front; P: prodelta; Bg: beach gravel; Bs: beach sand; M: Marsh; Rw; Reworked sediments. Offshore seismic unit nomenclature; LPW: Proximal landward-thickening progradational wedge; PAS: Widespread sub-parallel sheet; SPW: Seaward-thickening progradational wedge with widespread upper erosion; SAPW: Aggradational to progradational upper slope wedge. Dashed lines interpreted by sequence stratigraphy are discussed in section 3.5.

3.4.2. Thickness maps of onshore-offshore facies units and ages

We created isopach maps that show the thickness and facies distribution within each regional depositional package on the basis of the regional correlation of ESs (figs. 3.11, 3.12 and 3.13). From bottom to top, we recognize four regional depositional packages.

3.4.2.1. Regional Depositional Package IV

Regional depositional package IV is only observed offshore. We only recognize IV-SPW (figs. 3.7, 3.8 and 3.9) because the lower boundary is obscured by the multiple. This consists of several wedge-shaped progradational subunits arranged in a forestepping stacking pattern. This unit is present along the shelf, showing roll-over folds and growth faults around the Morràs canyon head (fig. 3.9).