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

Desiré Gàmez Torrent
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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

PhD Thesis
Department of Geotechnical Engineering and Geo-Sciences (ETCG)
Technical University of Catalonia (UPC)
Supervisors:
Dr. J. Antonio Simó Marfà
Dr. Jesús Carrera Ramírez
Tutor:
Daniel Fernández García

UPC
HYDROGEOLOGY GROUP
TECHNICAL UNIVERSITY OF CATALONIA

geomodels
centre mixt d'investigació

Hydrogeochemistry
group

3.4.2.2. Regional Depositional Package III

Regional depositional package III displays a complex facies distribution. At the bottom of the package, III-PAS1 overlies a sharp erosional surface (ES III) and shows a sheet-shape geometry with constant and moderate thickness (less than 10 m) over the outer shelf and upper slope, the thickness decreasing significantly towards the Besòs delta area (fig. 3.11b). Roll-over folds and growth faults are observed at the head of the Morràs canyon. III-PAS1 appears truncated on the outer south shelf. Onshore, thickness map of regional package III shows a dramatic thickness decrease north of Morrot fault (fig. 3.11). III-PAS1 correlates onshore with Fc-Bg sedimentary facies, which displays an increase in thickness in the center of the delta plain (over 20m) and the margins (less than 20 m), interpreted as palaeochannels (fig. 3.10).

Rw facies association above Fc-Bg facies shows an important depocenter up to 30m thick in the southwest delta plain. Rw facies association grades seaward into a complex pattern of seismic units (fig. 3.11). III-LPW1 occurs proximally over the inner and middle shelf above III-PAS1 (fig. 3.11c). III-LPW1 is well developed in the southwestern sector of the study area with a thickness of up to 20m whereas it is poorly preserved in the northeastern sector. Seaward, a set of erosional surfaces bound two SPWs (III-SPW1 and III-SPW2), with III-PAS2 and III-LPW2 intercalated between both SPWs (fig. 3.7 and 3.8). III-SPW1 shows a well-defined shelf-slope profile and is arranged in a seaward-stepping stacking pattern on the middle-outer shelf. III-SPW1 presents a thickness less than 10m over the inner and middle shelf and increases up to 40 m towards the outer shelf-upper slope (fig. 3.11d). III-SPW1 shows a large erosional surface on top (es III). III-LPW2 is located on the inner shelf on top of III-SPW1. III-LPW2 displays an offlapping pattern with a lenticular geometry with a thickness of less than 10m (Fig. 3.7). It is poorly developed in the southwestern part of the study area. The transition between III-SPW1 and III-LPW2 wedges seems to be represented by III-PAS2. III-PAS 2 is thin (less than 10m) and pinches out landward towards the Besòs delta shelf (fig. 3.11e). Distally, III-PAS 2 is overlain by III-SPW2, which displays distal facies. III-SPW2 exhibits a maximum thickness of 70m over the outer shelf to the upper slope (fig. 3.11f), and pinches out landward and towards the Besòs delta.

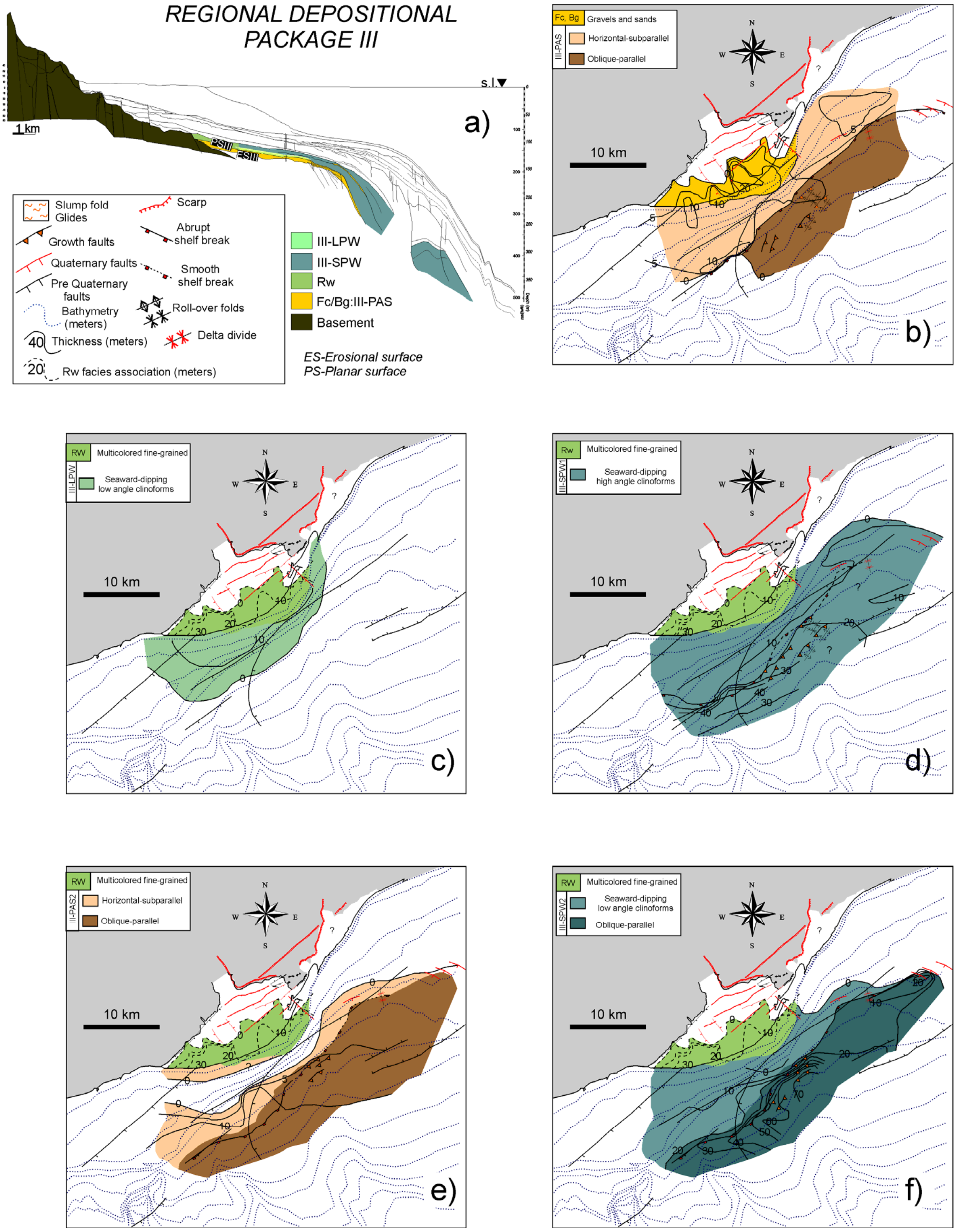

Figure 3.11: Distribution of onshore facies associations (Rw and Fc-Bg, table 3.1) and offshore seismic units (LPW, SPW and PAS, table 3.2) of regional package III in the Llobregat and Besós deltas, in isopach maps and cross section (units interpretation in fig. 3.16). Isopach maps b to f assign the units from bottom to upper. Isopach values are in meters. Bathymetry, gravitational features and tectonic faults are also displayed. Rw facies branches off seawards into five seismic units shown in maps b to e.

Note that the wedge geometry with high to lower angle clinoforms identified in the southwestern inner shelf on the top of III-LPW2 may be correlated with III-SPW2 located on the outer shelf (fig. 3.7). Consequently, these two units are represented in the same thickness map (fig.3.11f). The upper boundary of III-SPW2 shows an irregular topography interpreted as an erosional surface (ES II, figs. 3.7 and 3.8). Regional package III is affected by growth faults, slump folds and glides around the Morràs canyon head.

3.4.2.3. Regional Depositional Package II

The base of regional package II is represented by II-PAS (fig. 3.12b), which shows a confined distribution within a channel on the southwestern outer shelf (fig. 3.7). On the northeastern shelf, the base of regional package II consists of a thick wedge (II-PAS) that laps out landward (figs. 3.8 and 3.9) and shows the maximum thickness on the outer shelf with values up to 20m (fig. 3.12c). Onshore, II-PAS correlates with the Fc-Bg facies association (fig. 3.10). The Fc-Bg facies association is thin or absent along most of margin probably because of fault control. Three depocenters were observed in the margins and the center of the delta plain with a maximum thickness of 20m. One radiocarbon age obtained in Bg facies at 77.3 m.b.s.l. yielded an age older than 42,880 yr cal BP (Airport core, fig. 3.14).

Rw facies above the Fc-Bg facies association show a limited distribution although a large depocenter is located in the southwestern margin, exceeding 20 m in thickness. However, these facies are reduced or absent in parts of the northeastern margin and towards the lower fluvial valley. The Rw sediments were dated by radiocarbon method at 63.18 m.b.s.l. yielding an age older than 44,720yr cal BP, and by the amino acid racemization method at 60.9 m.b.s.l. giving an age of 70,210 ±3621 yr cal BP (Airport core, fig. 3.14). The same facies were dated: a) towards the fluvial valley in the SPZ4 core at 44.11, 43.73 and 41.53 m.b.s.l., yielding the following ages: 232,717±17,664, 203,476±7,730, 162,469± 9,349yr cal BP respectively; b) in the SPZ-16 core at 45.69 m.b.s.l., giving an age of 222,724±21,862yr cal BP; and c) in the SOGIT-15 core at 46.6 m.b.s.l., providing an age of 104,861±4,230yr cal BP.

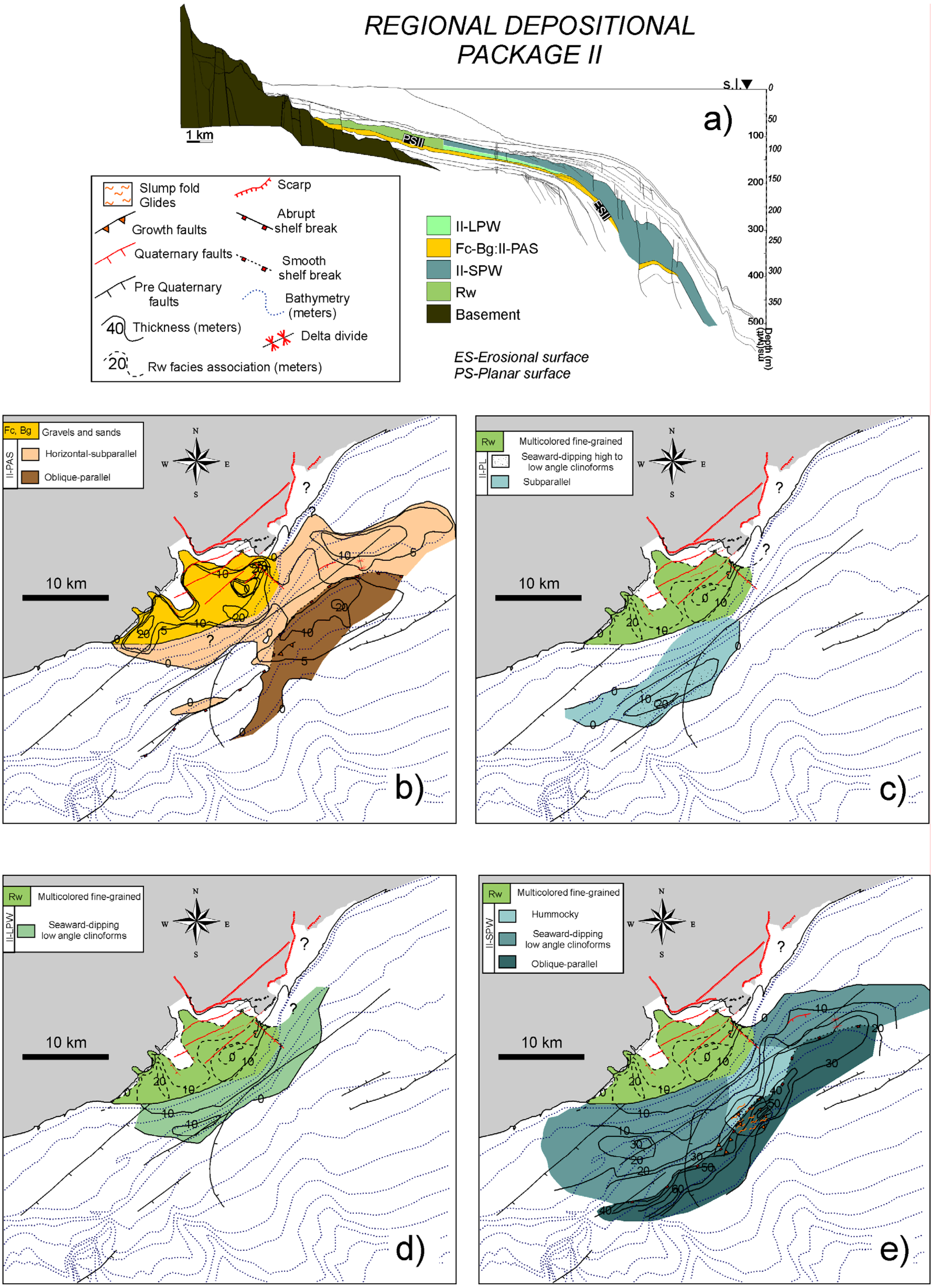

Figure 3.12: Distribution of onshore facies associations (Rw and Fc-Bg, table 3.1) and offshore seismic units (LPW, PL, SPW and PAS, table 3.2) of regional package II in the Llobregat and Besós deltas, in isopach maps and cross section (unit interpretation in fig. 3.16). Isopach maps **b** to **e** assign the units from bottom to top. Isopach values are in meters. Bathymetry, gravitational features and tectonic faults are also displayed. Rw facies branches off seawards into three seismic units shown in maps **c** to **d**.

Rw facies grades seaward into three seismic units. The oldest seismic unit is II-PL (figs. 3.7 and 3.12c), which is only preserved in the southwestern sector. II-PL presents a well-developed lenticular shape, with a maximum depocenter up to 20m thick located on the middle shelf. II-PL lies above ES II and provides evidence of erosional truncation at the top on the inner shelf (fig. 3.7). II-LPW rests above II-PL in the southwestern sector (fig. 3.7) and above II-PAS in the northeastern sector (fig. 3.8). II-LPW is poorly preserved in the northeastern sector and does not present clearly discernible internal reflections. Its lateral extent is reduced to the Llobregat inner shelf, reaching thickness values of 10m (fig. 3.12d). II-SPW lies above II-LPW (figs. 3.7 and 8), displaying two elongated outer shelf depocenters with a maximum thickness of 50-60m (fig. 3.12e). Hummocky internal configuration and growth faults are characteristic of this unit on the northeastern shelf (fig. 3.8). The upper boundary of II-SPW is an irregular erosional truncation over most of the shelf.

Regional package II tends to pinch out towards the Besòs delta area and is affected by instability features such as growth faults, slump folds and glides in the vicinity of the Morràs canyon head. The package is also affected by offset faults (fig. 3.12) which control the alignment of several small depocenters.

3.4.2.4. Regional Depositional Package I

The base of Regional Depositional Package I is composed of I-SAPW (fig. 3.13b), which shows a significant increase in thickness towards the shelf-break, where the maximum thickness exceeds 50m. In contrast, I-SAPW shows less thickness variability and laterally continuous depocenters in an along-shelf direction. This seismic unit pinches out on the northeastern middle shelf and on the southwestern outer shelf. Internal reflections are folded on the northeastern shelf, thus suggesting continuous deformation (fig. 3.9). The upper boundary of I-SAPW provides local evidence of submarine erosion, particularly on the northeastern shelf.

I-PAS is composed of four subunits from bottom to top: I-PAS1, I-PAS2, I-PAS3 and I-PAS4, which rest above I-SAPW (fig. 3.13c). Each subunit is bounded by internal contacts (planar between I-PAS1 and I-PAS2, and erosional between I-PAS2 and I-PAS

3) and are stacked vertically. These subunits correlate with the Bg-Bs facies association and M facies onshore. The lower facies (I-PAS1) in the delta plain (Bg, fig. 3.4) correlate with I-PAS1, which presents a reduced seaward extension. I-PAS2 exhibits a single well-developed progradational body. I-PAS3 presents an irregular surface at the bottom and a relatively lateral continuity. Both I-PAS2 and I-PAS3 seem to correlate with M and Bs facies onshore. Finally, II-PAS4 is located on the middle to outer shelf and upper slope, and could be regarded as the seaward extension of I-LPW. Onshore-offshore thickness map of I-PAS and Fc-Bg-Bs shows an irregular distribution with a maximum depocenter up to 30m thick on the northeastern upper slope. These facies peter out towards the southwestern upper slope (fig. 3.13c) and show an elongated depocenter, oriented in a northwest-southeast direction, along onshore and inner shelf. They are interpreted as a palaeochannel with a thickness up to 20m (figure 3.13c). However, the I-PAS seismic unit shows limited development on the northeastern shelf, where it is interpreted as delta lobes. This facies is interpreted as a channel infill on the southwestern shelf. Marsh sediment (M) radiocarbon dating in the Airport core at 53.56 m.b.s.l. and in the FON core (northeastern margin, fig. 3.14) at 9.2 m.b.s.l indicates ages ranging from 14,565±715yr cal BP (fig. 3.14) to 8,090±110yr cal BP. Beach sand facies (Bs) at 47.81 m.b.s.l were dated at 6,045±125yr cal BP. (Airport core, fig. 3.14) by the radiocarbon method. Ages of 6,095±105 and 5,450±130yr cal BP were obtained in the FOC core at 11.5 m.b.s.l. and in the SIT-16 bis2 core at 8.2 m.b.s.l., respectively (fig. 3.14). I-SAPW and I-PAS exhibit features indicative of instability phenomena such as growth faults, slump folds and glides around the head of the Morràs canyon. These units also fill in a northeastern upper slope depression possibly caused by an extensional collapse.

The most recent unit corresponds to present-day deposits of the Llobregat river. This unit is formed onshore by a typical shallowing-upward and overall coarsening-upward deltaic succession, bottom to top, composed of grey mud and silt facies association (Sw-M), grey silt and shales with interbedded sand (P), yellow to grey sand (Df and Bb) and gravels and red clays (Fc and Fp) (figs. 3.4 and 3.6). Offshore, P facies correlate with I-LPW and more distally with I-PAS4. This recent unit attains a maximum thickness of 60m in the proximity of the river mouth (fig. 3.13d). These deposits developed in the center of the delta plain, decreasing radically in thickness to values between 10 to 20m. Another geomorphological feature is the presence of an undulated sea floor in the area of maximum slope of the most recent LPW in the northeastern sector (Urgeles et al., 2007). Samples from wood fragments, peat, organic sediments and shells in prodelta, marsh, delta front and flood plain facies were collected in cores from the delta plain ("Depuradora" core) and the northeastern margin (FOC core, fig. 3.14). Radiocarbon ages ranged between 6,815±165yr cal BP to 425±105yr cal BP.

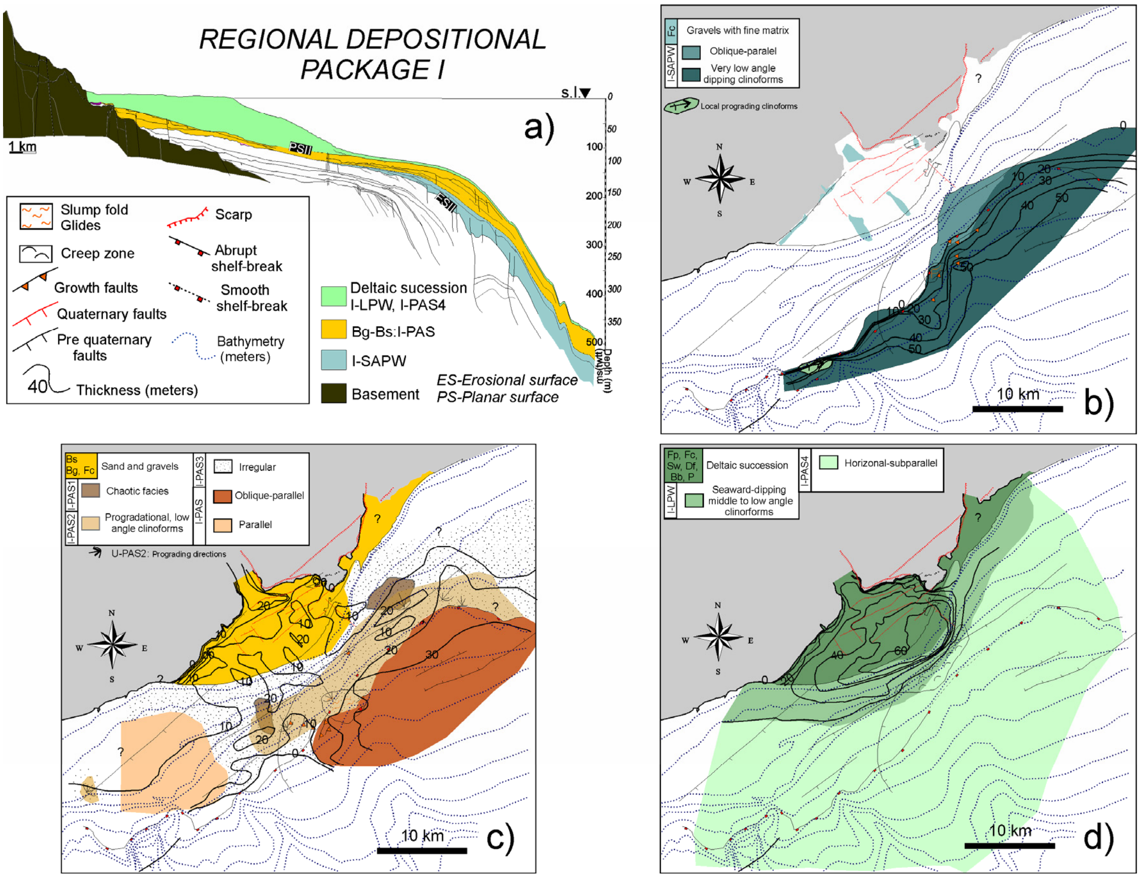

Figure 3.13: Distribution of onshore facies associations (Deltaic succession, Fc and Bg-Bs, table 3.1) and offshore seismic units (SAPW, LPW and PAS, table 3.2) of regional package I in the Llobregat and Besòs deltas, in isopach maps and cross section (unit interpretation in fig. 3.16). Isopach maps **b** to **d** assign the units from bottom to top. Isopach values are in meters. Bathymetry, gravitational features and tectonic faults are also displayed.

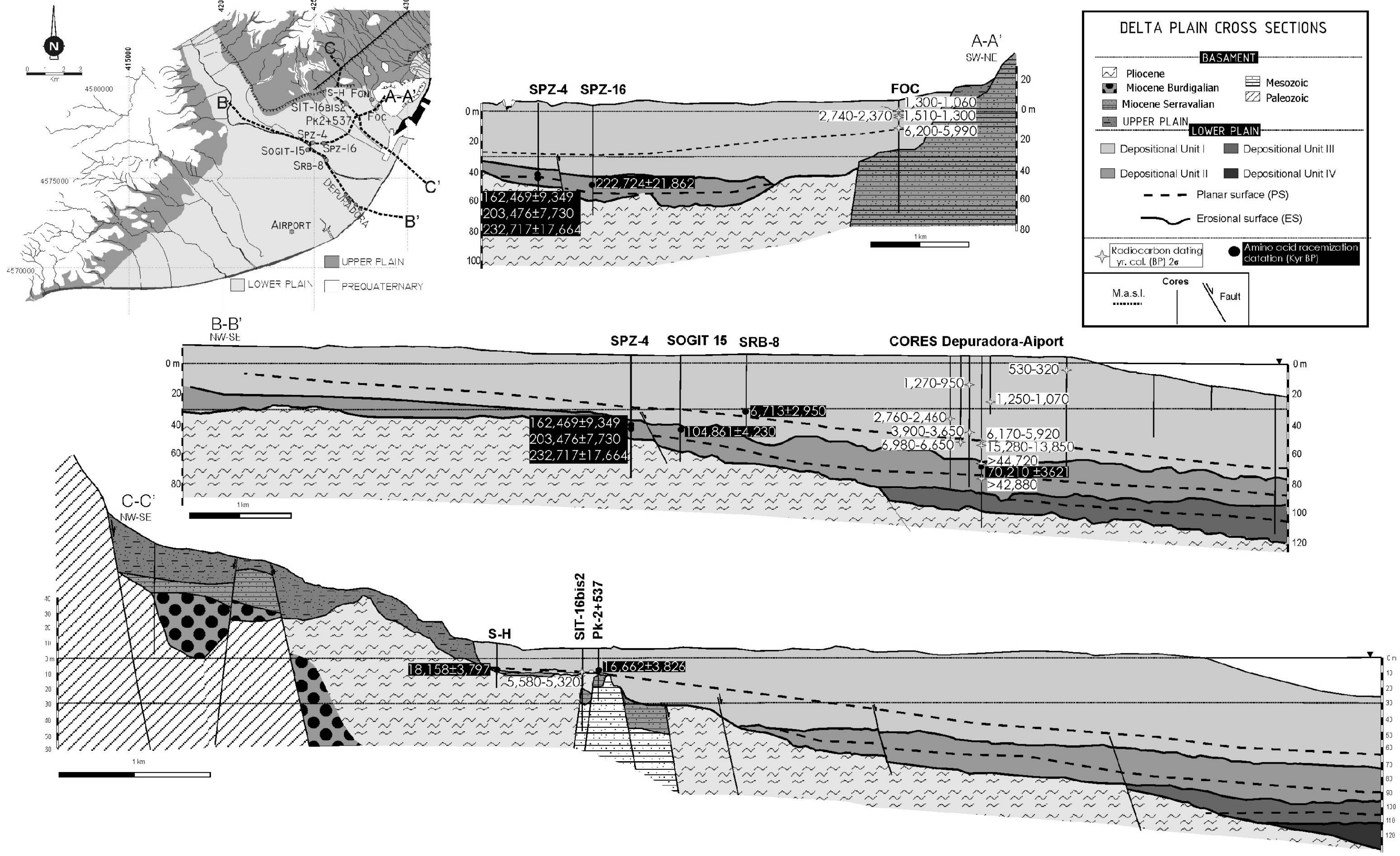

Figure 3.14: Strike (A-A′) and dip cross sections of the depocenter (B-B′) and northeastern margin (C-C′) of regional packages distinguished in the Llobregat delta plain. Amino acid racemization and radiocarbon dating are indicated (fig. 3.4). The upper left map shows the location of the cross sections (dashed lines) as well as of the cores (circles).

3.4.3. Summary

The Llobregat stratigraphic architecture is essentially composed of thick progradational units and thin parallel units (fig. 3.15). The thickness of progradational units increases seaward, thus displaying a typical wedge shape. There are marked changes in thickness and facies over short distances throughout the study area.

The stacking pattern, geometry and seismic facies of depositional packages reveal significant differences between the Llobregat and Besòs deltas. Based on these differences, we distinguished two depositional areas (figs. 3.15 and 3.16): a) the northeastern sector, between the Besòs delta and the Morràs canyon (figs. 3.3, 3.8 and 3.9), and b) the southwestern sector, between the Morràs and Foix canyons (figs. 3.3 and 3.7). The differential sediment loading plays the most important role in this separation. Thus, the southwestern shelf is relatively wide and stable because of fairly uniform sedimentation rates. In contrast, the northeastern shelf is narrow and affected by frequent gravitational syn-sedimentary processes, generating a smooth shelf break and a poor or absent preservation of LPWs and PLs (fig. 3.15).

Four main sectors have been recognized in the study area in according with thickness changes (figs. 3.15 and 3.16): delta plain, inner shelf, middle shelf and outer shelf-upper slope. Moreover, three main areas were identified in the delta plain: the southwestern margin, the center of the delta plain and the northeastern margin. The thickness distribution of depositional packages III, II and I deposits is controlled by basement blocks due to active faults such as the Morrot fault (fig. 3.1). In the center of the delta plain, the thickness reaches 60 m, decreasing towards the southwestern and northeastern margins to values ranging between 15-20m (fig. 3.13). Seaward, acoustic masking prevents the recognition of inner shelf internal configuration (fig. 3.16), making the correlation between offshore cores (fig. 3.4) and the seismic profiles difficult (figure 3.8). Depositional packages IV, III and II reach their maximum thickness seaward, with the largest depocenters located near the outer shelf and upper slope with maximum thicknesses ranging from 40 to 70m. Sediment depocenters are northeast-southwest elongated and laterally continuous, and perpendicular to the direction of progradation.

SPWs and the SAPW thicken seaward towards the shelf margin, but LPWs are thicker over the inner-midle shelf with values between 10 and 20m, with the exception of the youngest LPW, which is thicker near the delta plain-inner shelf transition. PASs are characterized by widespread distributions, but thin (15 m), sheet geometries in the southwestern sector and thick (30 m), wedge geometries in the northwestern sector (fig. 3.15). I-PAS extends from the delta plain to the upper slope, whereas III-PAS and II-PAS show less development in the delta plain and the inner shelf (fig. 3.15).

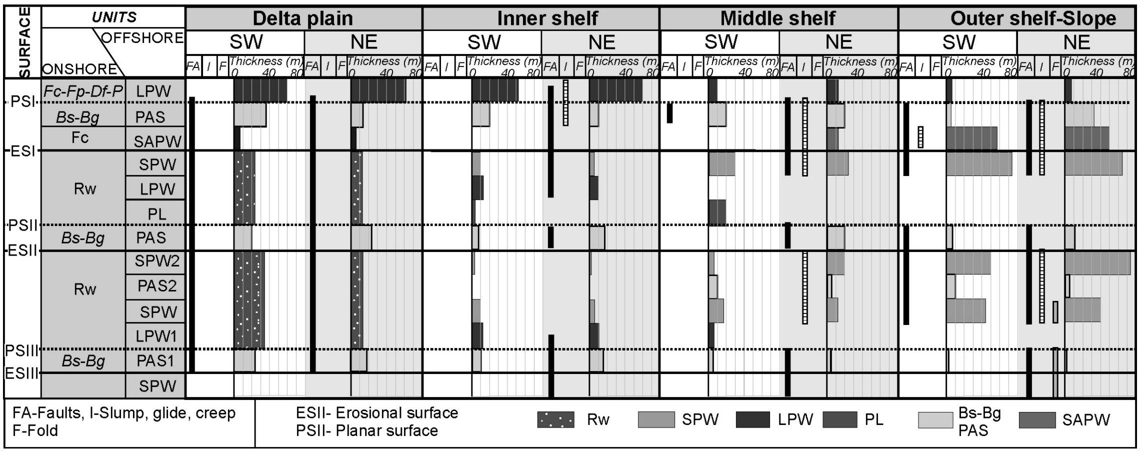

Figure 3.15: Summary of gravitational features and of maximum thicknesses of onshore facies association and offshore seismic units shown in figures 3.11 to 3.13. The position of erosional and planar surfaces is also indicated. The information was organized taking into account across shelf domains (delta plain, inner shelf, middle shelf and outer shelf-upper slope) and along-shelf sectors (northeastern and southwestern sectors).

3.5. Discussion

3.5.1. Sequence stratigraphy of the Llobregat delta

3.5.1.1. Boundaries

We identified four regional depositional packages (IV, III, II and I) interpreted as four depositional sequences (DS IV, III, II and I). These sequences are bounded by prominent, well-defined, and widespread erosional surfaces (ESs III, II and I, fig. 3.15

and Appendixes III and IV). They are interpreted as the lower boundaries of fluvial channels that are truncated seaward by transgressive surfaces eroding the upper boundaries of wedge-shaped regressive units (IV to II-SPWs, fig. 3.10). These erosional surfaces are interpreted as sequence boundaries (SBs III, II and I, figs. 3.16 and 3.17), sharing characteristics similar to those observed on other Mediterranean shelves (Chiocci, 2000; Lobo et al., 2004; Ridente and Trincardi, 2002; Trincardi and Correggiari, 2000). Most studies on deltaic shelves display a well-defined shelf-to-slope break and a sequence boundary located above regional progradational units (Anderson et al., 2004; Browne and Naish, 2003; Kolla et al., 2000; Porebski and Steel, 2003; Roberts and Sydow, 2003). These sequence boundaries can be regarded as polygenetic surfaces generated by shelf erosion during prolonged sea-level falls with fluvial systems eroding earlier delta deposits (see section 3.5.2.1). Subsequently, some of these fluvial deposits were reworked during the transgression (Browne and Naish, 2003; Chiocci et al., 1997; Ridente and Trincardi, 2002). Internal local discontinuities represent minor erosional surfaces (es III, II, fig 3.7, 3.8 and 3.9).

Three planar surfaces (PSI, PSII and PSIII, fig. 3.15) were identified : a) onshore, by making a distinction between gravel-sand facies (Bg, Bs and Fc) and the Rw facies association in depositional sequences III and II (fig. 3.10), and the deltaic succession (P, Df, Fc, Fp, Bb, Sw) in depositional sequence I, and b) offshore, by differentiating between aggradational (PASs) and progradational (SPWs, SAPW, LPWs and PL) seismic units (fig. 3.10). Seismically, these surfaces mark a change from planar and lateral continuity reflections to downlapping reflections and are interpreted as maximum flooding surfaces (mfs, figs. 3.16 and 3.17).

3.5.1.2. High-resolution sequence stratigraphic model

The stratigraphic position and general architecture of the depositional sequences of the Llobregat delta complex provide an example of the type of delta variability generated under different sea-level conditions. In particular, delta shape, orientation with respect to coastline, thickness and variability in geometries and progradation are diagnostic attributes of deltaic genetic mechanisms (Banfield and

Anderson, 2004). Recent studies seek to determine physiographic location (inner, middle, outer shelf) of deltaic bodies as a function of relative sea-level change in continental shelf construction (Porebski and Steel, 2003; Porebski and Steel, 2006). These studies have been carried out in the late Quaternary record of the Gulf of Mexico (Suter and Berryhill, 1985; Suter et al., 1987).

Seismic geometries observed in the Llobregat delta bear a remarkable resemblance to a typical deltaic shelf such as the late Quaternary record of the Gulf of Mexico (Anderson et al., 2004) despite the fact that the Llobregat delta is connected to a smaller basin and was formed in a different geological context. We subdivided the deltaic deposits into three main types as a function of sea level trend: deltaic deposition under falling sea level, rising sea level, and turn-around intervals.

a. - Deltaic deposition under conditions of falling sea level

Two scenarios can be envisaged: a) a sea-level fall below the previous shelf break, resulting in a complete shelf exposure, and b) a sea-level fall above the previous shelf break allowing the deposition of a well-defined sigmoidal profile on the shelf.

Deltaic deposition under falling sea level is represented in the study area by mid-shelf and shelf-margin deltas interpreted as components of the Falling Stage Systems Tract (FSST). These deposits are equivalent to the late HSTs defined in the Gulf of Mexico, where there is no difference between deposits generated during sea-level stabilization and high sediment supply and deposits generated during sea-level fall (Roberts and Sydow, 2003). Therefore, in the Gulf of Mexico, the basal boundary of regional regressive wedges coincides with the maximum flooding surface (Abdulah et al., 2004; Anderson et al., 2004). In our study area, we were able to separate highstand (LPWs, figs. 3.16 and 3.17) from forced regressive deposits (SPWs and PL, figs. 3.16 and 3.17), and therefore the maximum flooding surface only represents the lower boundary of large-scale regressive wedges seaward of shallow-water, highstand deltas. Falling stage deposits have been interpreted within Rw sediments in the Llobregat delta plain discussed in subsection c.1.

a.1 - Deltaic deposition under conditions of sea-level fall resulting in significant shelf erosion and shelf-margin advance

The deposits associated with shelf exposure are equivalent to regional regressive wedges recognized in other Mediterranean shelf settings such as the Gulf of Lions (Tesson et al., 2000) (Field and Trincardi, 1991). Middle-shelf and shelf margin FSST deltas have a number of diagnostic features (Plint and Nummedal, 2000; Porebski and Steel, 2003): a) significant erosion capping the deltas, b) prevalence of oblique reflectors attributed to prodeltaic deposits, and c) general tendency of internal reflections to increase the slope seaward indicative of progradation into deeper water. These characteristics are observed in SPWs. Occasionally, SPWs may show subunits suggesting stepped sea-level fall (for example, III-SPW1 and III-SPW2, see section 3.5.2, fig. 3.17).

a.2. - Deltaic deposition under conditions of moderate sea-level fall

A well-defined break of slope is clearly identified on the southwestern middle shelf (fig. 3.17). This break of slope is generated by II-PL with an internal structure showing distal high-angle reflections characteristic of shoreface deposits downlapping into low-angle parallel-oblique reflections (Porebski and Steel, 2006). This delta was formed during a moderate eustatic fall and a high rate of subsidence. These controls gave rise to a type 2 subaerial unconformity (Vail et al., 1984). The internal architecture of this unit suggests rapid shallowing (Porebski and Steel, 2006). The preservation of a mid-shelf deltaic deposit with a well-defined sigmoid external shape and moderate erosion constitutes a striking stratigraphic feature in this margin given its rarity in most Quaternary deltas. In most examples, the generation of mid-shelf deltas occurred under conditions of overall sea-level fall, resulting in oblique-tangential clinoforms and widespread shelf channeling (Kindinger, 1988; Kolla et al., 2000; Porebski and Steel, 2006).

b. - Deltaic deposition under conditions of sea-level rise

Sheet-like deposits covering most of the shelf are recognized in depositional sequences III, II and I, and are considered to be equivalent to other shelf sheets or drapes characterized by transparent and/or chaotic configurations. They are interpreted as transgressive deposits (Hübscher and Spieß, 2005). Offshore, these transgressive deposits overlie sharp erosional surfaces or sequence boundaries (SBs, figs. 3.10, 3.16 and 3.17) that truncate earlier progradational deltas, and are capped by planar surfaces interpreted as maximum flooding surfaces. Offshore transgressive deposits capped by maximum flooding surfaces are related to onshore beach gravels and sand facies akin to the pattern observed in other deltaic settings (Saito et al., 1989, Amorosi et al., 2004). Transgressive surfaces underlie transgressive deposits formed by the reworking of the tops of fluvio-deltaic sediments owing to the wave-base erosion accompanied by landward migration of the shoreline (Weimer, 1984; Demarest and Kraft, 1987; Nummedal and Swift, 1987; Walker and Wiseman, 1995). Thus, transgressive deposits overlie the sequence boundary seaward, except on the outer shelf of the Depositional sequence I, whose transgressive surface is located above SAPW (figs. 3.8, 3.9 and 3.10). Landward, transgressive deposits are overlain by transgressive or ravinement surfaces.

Transgressive deposits in Depositional sequence I (I-PAS) show a complex pattern with a superposition of chaotic subunits and wedge-shaped to lenticular progradational bodies of moderate thickness interpreted as a transgressive delta as in the case of I-PAS2 (figs. 3.7 and 3.8). Similar transgressive deltas have been reported in the Gulf of Mexico shelf (Abdulah et al., 2004). In general, I-PAS is characterized by high reflectivity in contrast to deltaic bodies formed under conditions of sea-level fall. The I-PAS3 subunit could indicate a dominantly coarse-grained composition correlated with Bs onshore (Saito et al., 1989, Amorosi et al., 2004). The occasional observation of a sheet deposit on top of a transgressive delta would provide evidence of moderate reworking.

c. - Deltaic deposition under turn around intervals

Turn arounds from low-to-high and high-to-low sea levels form two different types of deposits.

c.1. - Deltaic deposition during low sea-level conditions

Like the Gulf of Mexico, the Llobregat margin affords no clear evidence of deltaic deposition during true lowstand conditions or early rising trends in most of the sequences because of enhanced sediment dispersal during sea-level turnarounds or inadequate seismic resolution (Abdulah et al., 2004).

The pattern observed in the Llobregat delta of progressively steeper clinoforms basinwards, particularly seaward of preexisting shelf breaks has been interpreted in other areas as indicative of lowstand deposition (Browne and Naish, 2003). However, the absence of onlap terminations within the Llobregat clinoforms suggests that these deposits are related to progradation into deeper water. From the point of view of sequence stratigraphy, it was concluded that most of the mid-shelf and shelf margin deltas are part of the Falling stage deposits. Lowstand deposits are only observed during the last major low sea-level and not during in earlier sea levels. Similar observations have been made in the Gulf of Cadiz (Hernandez-Molina et al., 2000; Lobo et al., 2005) and the Gulf of Mexico (Abdulah et al., 2004), which suggests a connection with the different pattern of the sea-level during the LGM in contrast to earlier sea-level turnarounds. In particular, the absence of lowstand facies could indicate a relative sea-level fall before a sharp rise (Porebski and Steel, 2003).

The only exception to the aforementioned trend is represented by I-SAPW (depositional sequence I, figs. 3.16 and 3.17), which shows a landward-pinching wedge geometry with oblique-parallel clinoform that onlap upslope and offlap downslope (SB I, figs. 3.16 and 3.17). This aggradational-progradational architecture suggests marine-deltaic deposition (shelf-margin delta) during peak lowstand and the earliest transgression (Kolla et al., 2000; Sydow and Roberts, 1994). These deposits are bounded by the transgressive surface on top and passed landward into the erosional ravinement surface. Low sea-level deposits are interpreted as flood plains and fluvial channels (Fc-Fp facies association) overlying sequence boundaries in the Llobregat delta plain, as reported in other deltaic environments in the Mediterranean (Amorosi et al., 2004) (fig. 3.10).

c.2. - Deltaic deposition during high sea-level conditions

Sea-level variations occur as a continuum with the result that the separation of HSTs from FSSTs is problematic (Ridente and Trincardi, 2002; Trincardi and Correggiari, 2000). A change in geometry from sigmoid to oblique observed in some deltas in the Gulf of Mexico has been attributed to the HST-FSST boundary (Abdulah et al., 2004). In the study area, inner shelf deltaic highstand bodies (LPWs) are separated from subsequent FSSTs (SPWs) by a basal surface of forced regression (fig. 3.10) (Catuneanu, 2002). The clear imaging of these inner shelf deltas may be regarded as a distinctive feature of this margin. HSTs are normally eroded during subsequent sea-level falls and lowstands. They are therefore not preserved (Chiocci, 2000), or have a low generation potential with reduced thickness (Trincardi and Correggiari, 2000). In the Mediterranean Sea, interglacial highstand conditions are recorded by deposition of sigmoid deltas on inner shelves (Aksu et al., 1992). This deltaic pattern differs from other highstand sedimentation frames where low-angle highstand sedimentation covers most of the shelf, making the transition with overlying FSST gradational (Browne and Naish, 2003).

Onshore of the Llobregat delta, it was not possible to differentiate between the HST-FSST deposits in the depositional sequences III and II. It may thus be assumed that the Falling stage deposits peter out towards the delta plain (Fig. 3.16). Onshore, the HST-FSST deposits are interpreted as continental and marine sedimentary after foraminiferal and sedimentological analyses. Paleontological identification revealed resedimentation and fauna reworking (Chapter 2). Falling stage and highstand deposits have been interpreted in facies from the Po delta plain with palaeontological results similar to those of the Llobregat deposits (Amorosi et al 2004).

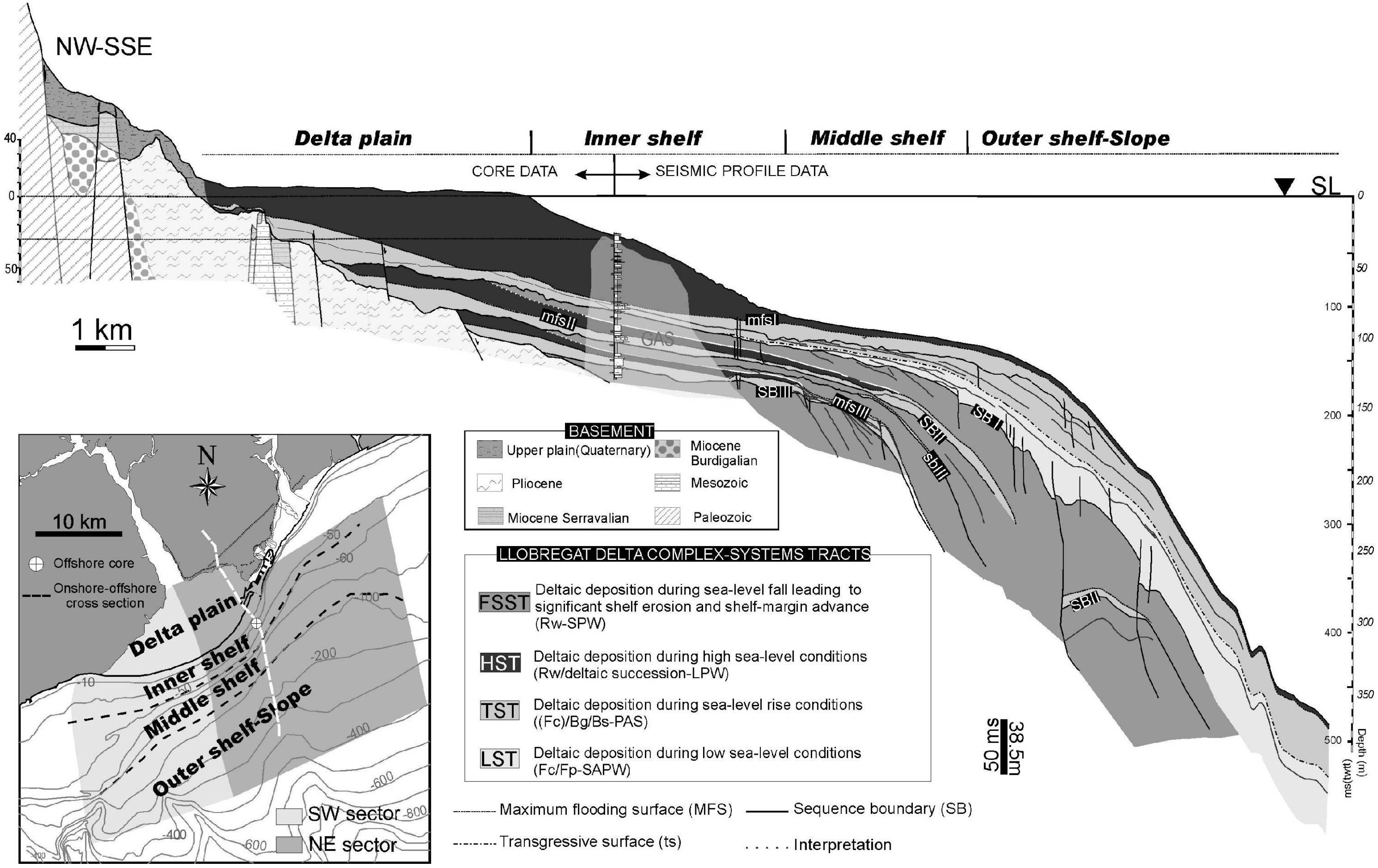

Figure 3.16: Onshore-offshore sequence stratigraphy interpretation according to its associated sea-level trend based on the correlation between onshore cores (fig. 3.6 and 3.14) and seismic profiles (see fig. 3.8) along the northeastern Llobregat delta plain and shelf. Offshore core located on the inner shelf (fig. 3.4) correlates with seismic profile (fig. 3.8).

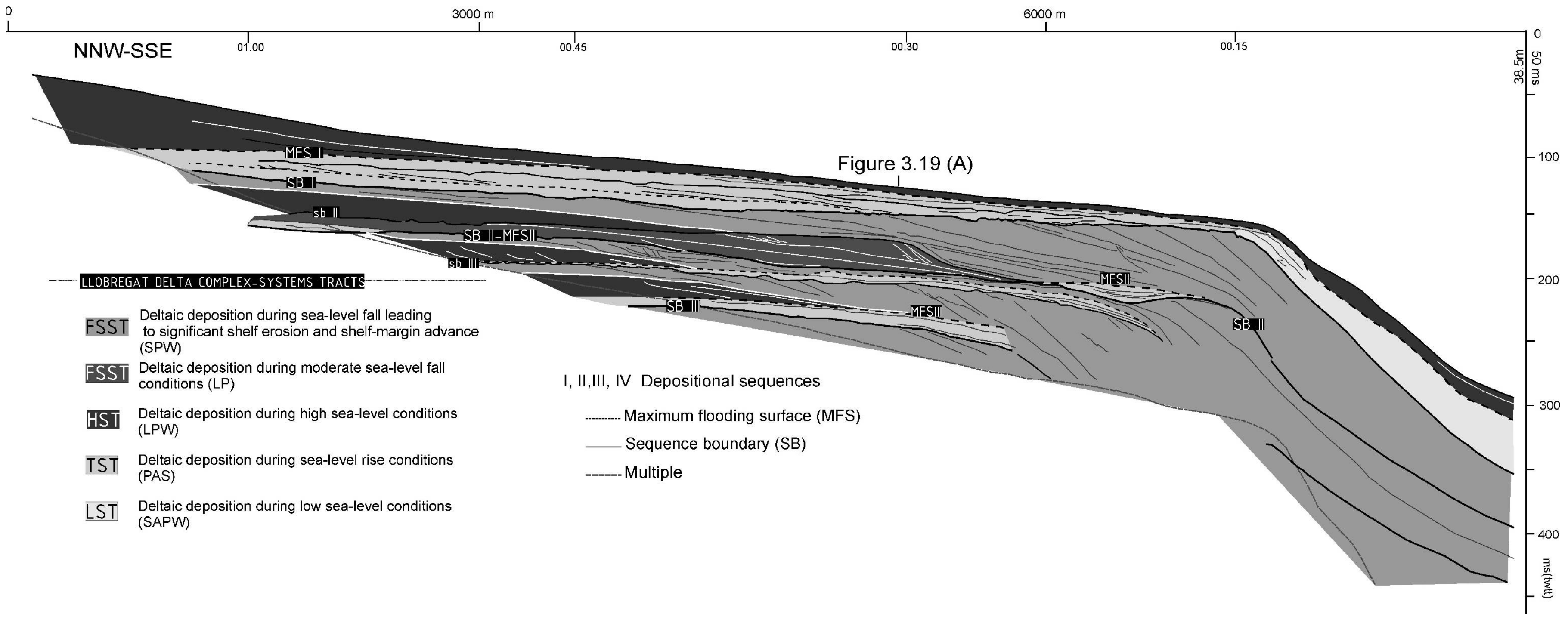

Figure 3.17: Offshore sequence stratigraphy interpretation according to its associated sea-level trend based on seismic profiles (see fig. 3.7) along the southwestern Llobregat shelf.

The only HST unit in the study area without a corresponding FSST component is the modern HST (I-LPW) composed of P, Df, Bb, Fc and Fp facies onshore and correlated with I-LPW and part of I-PAS4 offshore (figs. 3.10, 3.16 and 3.17).

3.5.2. Quaternary factors that control the architecture of the Llobregat delta complex

The potential preservation of the Late Quaternary stratigraphy of the Llobregat delta reveals regional patterns of facies distribution controlled by global eustatic fluctuations as well as by local factors such as shelf physiography and rates of tectonic deformation and sediment supply (Ritchie et al 2004).

3.5.2.1. Global controlling factors: Age supporting 100 kyr sea-level cycles

We identified three well-defined, widespread erosional surfaces that appear to correlate with significant sea-level falls (SBIII, SBII and SBI, figs. 3.16 and 3.17) and shelf-margin migration with frequencies of 100Kyr. The estimated ages are based on the integration of radiocarbon and amino acid racemization dates of depositional sequences II and I and the comparison with depositional architectures reported on other shelves. Asymmetric circa 100kyr long sea-level cycles are considered to be the main control in generating late Quaternary depositional sequences in the Mediterranean Sea (Chiocci, 2000; Chiocci et al., 1997; Rabineau et al., 2005; Trincardi and Correggiari, 2000). In the study area, these high-frequency sequences would be represented by DSs IV, III, II and I (figs. 3.16, 3.17 and 3.18). Similarly, asymmetric 100kyr, glacial cycles are believed to control deltaic architectures on other shelves such as sectors of the New Zealand (Browne and Naish, 2003) and Bengal shelves (Hübscher and Spieß, 2005).

Figure 3.18 shows the proposed chronostratigraphic framework, correlating the facies association and seismic units with the relative sea-level curve. Dating of the multicolored fine-grained facies association (Rw) of depositional sequence II from SPZ-4 and SPZ-16 cores yielded different ages, 104,861±4,230 and 232,717±17,664yr cal BP (figs. 3.14 and 3.18). However, the Rw (DS II) sediments from the depocenter core (in the center of the delta plain) were dated at 70,210 ±3621 cal yr cal BP (figs. 3.14 and 3.18). The examination of the two groups of ages in a diagram depth/time with the sea level curve (fig. 3.18) showed two conflicting age groups for the same stratigraphic unit deposited during MISs 5 and 7. According to the palaeontological analyses, the existence of reworking and resedimentation processes undergone by foraminiferal specimens suggests deposition during the MIS 7 sea-level fall and later resedimentation during MIS 5 (Chapter 2).

Aside from the ages, there is evidence for an additional period of shelf regressive wedge formation (IV-SPW, III-SPW and II-SPW, figs. 3.7 and 3.8), which could also be related to the three major sea-level fall (fig. 3.18). The progradational intervals were confined to the inner-middle shelf with the result that they did not promote shelf lateral accretion. Moreover, the mid-shelf wedge (II-PL) does not show strong evidence of significant top erosion in contrast to large-scale regressive wedges. The upward terminations of this wedge are better defined as toplap terminations (fig. 3.7). These stratigraphic characters would indicate a better correlation with a sea-level fall of less amplitude and extent as in the last glacial cycle. The recognition of this shelf deposit is related to the sequence stratigraphy interpretation of the last glacial cycle comprising circa 125Ky.

The proposed sequence stratigraphy model closely matches the late Quaternary stratigraphy of the Gulf of Mexico, where several high-frequency cycles occur between isotopic stages 5e and 2 known as early/late highstand deposits (Abdulah et al., 2004; Anderson et al., 1996; Anderson et al., 2004; Banfield and Anderson, 2004). In the Lagniappe delta, deltaic lobes that generated during the prolonged sea-level fall between 5 and 2 were regarded as components of the FSST (Kolla et al., 2000). The amount of deltaic lobes formed during early highstand conditions (MISs 5 and 3) is variable possibly due to the different rates of sediment supply. By contrast, a single deltaic deposit was formed during the transition between MIS 3 and 2. These regressive delta lobes are considered to be part of high-frequency (5th order) depositional sequences.

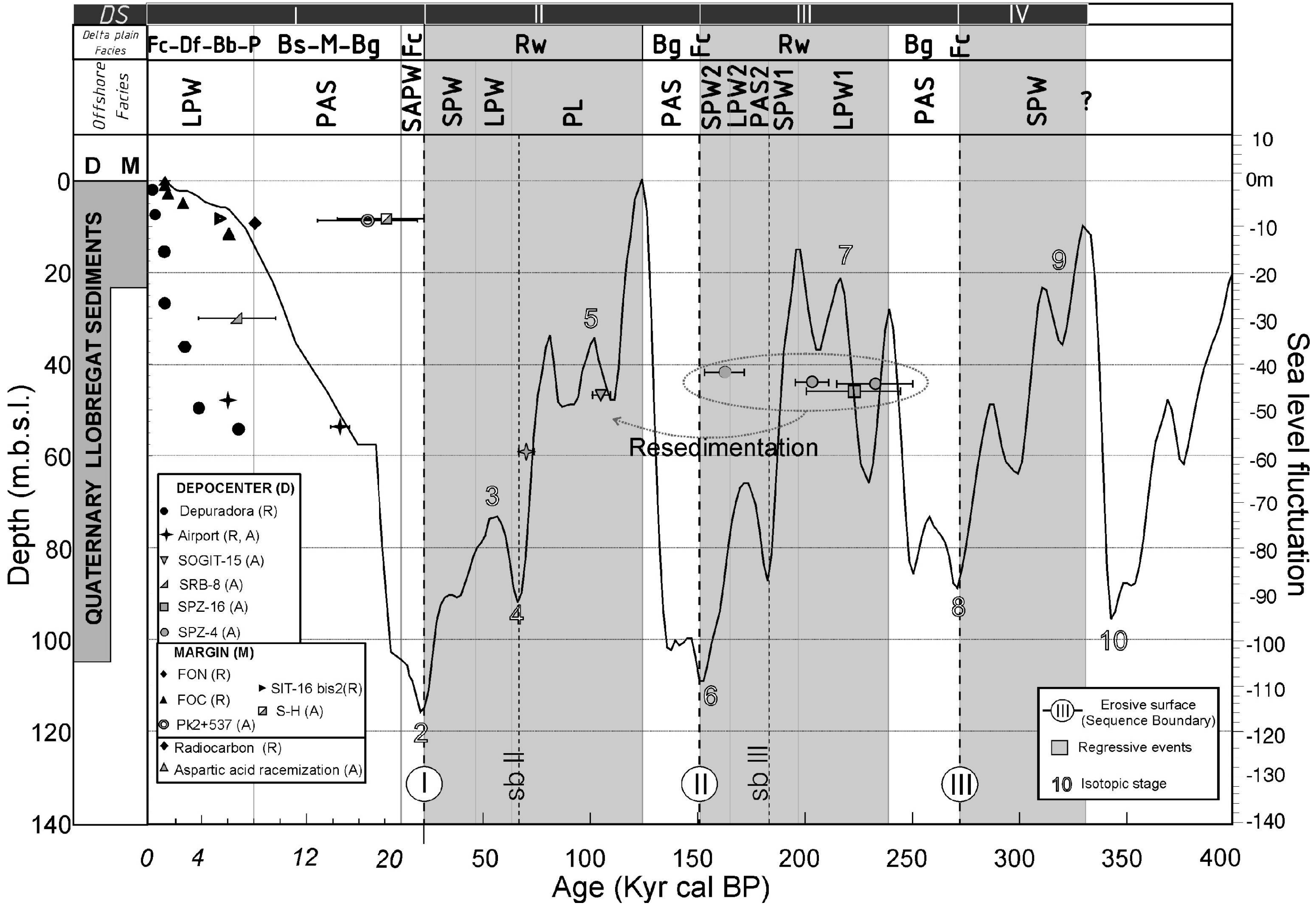

Fig. 3.18: Amino acid racemization and radiocarbon ages versus depth diagram from sampling cores of the Llobregat delta plain. Data are plotted together with sea level curve. We propose a correlation of the depositional sequence and facies units (see table 3.1 and II for unit meaning) defined in the Llobregat delta complex and age data discussed in section 3.5.1. SB applies to the sequence boundary.

Particularly remarkable is the similarity of the late Quaternary stratigraphic architecture observed between the Llobregat deltaic shelf and specific sectors of the Gulf of Mexico shelf, such as the Central and east Texas continental shelf (Abdulah et al., 2004; Eckles et al., 2004).

Therefore, the shelfal late Quaternary record is represented by two progradational deltaic lobes generated during the last glacial cycle; the older lobe is located in a landward position and was generated during MIS 5, and the younger one is located seawards and is related to MISs 3 and 2. The only sequence boundary is related to maximum subaerial exposure during MIS 2 (Abdulah et al., 2004; Anderson et al., 2004; Rodriguez et al., 2000). It may be assumed that the sequence boundary generation only takes place during complete subaerial exposure and that widespread erosion is normally linked to maximum glaciations (in this case, during MIS 2). In contrast, a sequence boundary related to MIS 4 would not be generated at the top of the proximal deposit.

In the light of our observations on the Llobregat shelf, these two main progradational lobes would be comparable to the stratigraphic pattern constituted by II-PL and II-LPW (fig. 3.7). II-PL is considered to be equivalent to early highstand deposits, whereas II-SPW (figs. 3.7 and 3.8) is regarded as equivalent to late highstand deposits recognized in the Gulf of Mexico (Anderson et al., 2004; Wellner et al., 2004). On the basis of these differences, we regard each period of shelf progradation as a single depositional sequence. Therefore, the upper Pleistocene (last 125Ky) record consists of two high-frequency depositional sequences in the Llobregat margin. The marked differences shown by the two types of sequences and sequence boundaries probably reflect the magnitude of shelf exposure. One way to solve this dichotomy would be to consider this seismic unit II-PL as a mid-shelf delta occurring under conditions of overall sea-level fall following sequence stratigraphy terminology. In contrast, the falling stage systems tract, represented by seismic unit II-SPW, is overlain by a regional sequence boundary. The erosional surface on the inner shelf on top of II-PL can be correlated with the MIS 4 lowstand (sb II, figs. 3.17 and 3.18)

There are a number of settings where the upper Pleistocene record is considered to record two high-frequency sequence boundaries, which is the case of the

Llobregat shelf. In several places of the Mediterranean realm the construction of deltaic sequences during the last glacial cycle shows two main build up episodes during MISs 5 and 4, and during MISs 3 and 2 apart from the last depositional sequence during MISs 2 to 1, which is still evolving (Aksu et al., 1987). Another significant example is the Otago shelf, New Zealand (Osterberg, 2006), where an erosional unconformity overlying a deltaic regressive deposit is considered to have developed during the MIS 4 lowstand of sea-level.

Based on the stratigraphic pattern and on the ages in depositional sequence II, a similar pattern is interpreted for depositional sequence III, with a minor sea-level fall marked by sb III and a major erosional surface on top on the sequence (SBII) (figs. 3.16 and 3.17). The sb III surface bounds two sea level fall deposits (III-SPW1 and III-SPW2) separated in time by a unit deposited during sea level rise (III-PAS 2) and highstand (III-LPW 2). Apparently the III-PAS2 seismic unit is located between two major periods of shelf progradation (III-SPW, figs. 3.16 and 3.17) and before III-LPW2. These units may have been deposited during MIS 7 and 6 (fig. 3.18). These minor sequences can be regarded as stadial/interstadial sea-level fluctuations occurring between the major glacial/interglacial cycles, which formed the four depositional sequences (DSs IV to I, fig. 3.18).

The lowest boundary of depositional sequence I in the Llobregat delta is SB I (ES I, figs. 3.16 and 3.17). From bottom to top we observe a transgressive package deposited from 18158±3797 to 6815±165yr cal BP (figs. 3.14 and 3.18). These results are similar to other studies of the western Mediterranean, suggesting a period of accelerated sea-level rise and flooding till 6.9kyr cal BP (Boyer et al., 2005; Checa et al., 1988; Chiocci et al., 1997; Fernandez-Salas et al., 2003; Goy et al., 2003; Lario et al., 2002; Medialdea et al., 1986 and 1989; Somoza et al., 1998; Stanley and Warne, 1994; Vella et al., 2005; Zazo et al., 1996). The I-PAS2 seismic unit is interpreted as a phase of stabilization during the sea level rise, probably built up during the Younger Dryas as reported in some Mediterranean deltas such as the Rhône delta (Labaune et al., 2005b).

The maximum flooding surface (MFS I, figs. 3.16 and 3.17), commonly characterized by condensed sections, was dated in the depocenter of the Llobregat delta as 6815±165 (figs. 3.14 and 3.18). After 6800yr cal BP a deceleration in the rate of sea-level rise favored the progradation of the Llobregat delta. Figure 3.18 illustrates two groups of ages, indicating that the sedimentation rate varies between the margins and the depocenter (Chapter 2). After this period, the autocyclic and allocyclic processes controlled the stacking pattern of the Llobregat Holocene parasequences (Chapter 2). The influence of the superposition of local and regional factors on the stacking patterns account for the Fc-Fp-Df-Bb-P parasequence observed in the Llobregat delta (fig. 3.6, and discussed in Chapter 2).

3.5.2.2. Local controlling factors

The identified depositional sequences not only show contrasting patterns between the northeastern and southwestern shelves but also show significant variability in the dip direction (figs. 3.16 and 3.17). In line with studies in the western Mediterranean continental shelf in Spain, different shelf areas were grouped as a function of the deposit preservation (Ercilla et al., 1994; Ercilla and Alonso, 1996; Farrán and Maldonado, 1990; Lobo et al., 1999). According to these studies, lateral changes in stratal patterns are controlled by local factors such as subsidence induced by sedimentary loading and tectonics, continental shelf physiography and sediment supply changes.

In the Llobregat delta plain, the excellent onshore preservation may be the consequence of the Quaternary growth faults bounding half-graben sub-basins which caused considerable subsidence. A similar depositional mechanism is observed in the Lower Pliocene Crotone basin (Southern Italy), where small-scale cycles are recorded in a shallow-marine setting (Zecchin, 2005). Recent studies confirm the tectonic activity in the Barcelona plain and the Llobregat delta plain (Perea, 2006). Thickness distribution maps suggest a syn-depositional block faulting mechanism of the Morrot normal fault. Thickness maps also help us to identify three areas with moderate or low thickness in the margins and towards the lower river valley. This thickness distribution is related to the existence of structural highs undergoing uplifting controlled by pre-Quaternary faults.

Seaward, shelf physiography seems to play a major role in the formation and preservation of the Llobregat deposits, generating enough accommodation space and limiting the action of wave and storm events. This stacking sedimentary pattern of the deltaic deposits is controlled by 1) the structural control in the continental shelf, which is exerted by northeast-southwest oriented fault systems, where the northeastern and southwestern areas may be controlled by a transfer zone or Fracture Zone (Amblàs et al., 2006; Maillard and Mauffret, 1999), and 2) by fluvial sediment inputs into the Llobregat delta. The onshore prolongation of this transfer zone would be delineated by the Llobregat Fault (fig. 3.1), which crosses the Valles–Penedes rift in the northeast Iberian Peninsula (Anadón et al., 1982). This Fracture Zone is related to the Tertiary narrow depression basement (Barcelona graben, figs. 3.1 and 3.2), which is coincident with the Morràs canyon area (fig. 3.19).

Moreover, geomorphological studies undertaken on the Llobregat and Besòs shelves indicate that an important regional neotectonic reactivation created a set of sea-floor faults which stressed the main northeast-southwest transfer faults (Liquete et al., 2007). This tectonic change altered the observed stacking patterns, both along- and across the shelf (fig. 3.16). The variability of seismic units along the coast is attributed to tectonic effects, which could intensify sediment supply changes. Accordingly, two main morpho-structural sectors can be defined:

a) The Llobregat northeastern shelf, located between the north of the Llobregat river mouth and in front of the Besòs delta plain, shows two distinct domains controlled by the activity of the Barcelona fault (fig. 3.16). The middle shelf to upper slope is characterized by a high sediment thickness and by the occurrence of gravitational features such as growth faults, roll-over folds, glides and slump folds around the Morràs canyon head. These processes may be linked to a high subsidence regime. Extensional listric faults such as the Barcelona fault (figs. 3.2 and 3.19) account for the formation of the Barcelona graben and gives rise to the new accommodation space induced by tectonic movements and sediment loading. High gradients also favored the development of sea-floor instabilities. The influence of the Barcelona fault is particularly evident in the Quaternary deposits (fig 3.19, seismic profile F). In contrast, the inner shelf shows poor preservation with less thickness, which could be ascribed to the Barcelona fault movement. This is due to the moderate uplift of the inner shelf footwall block and to the subsidence of the middle to outer shelf hanging-wall blocks (figs. 3.1 and 3.19).

b) The Llobregat southwestern shelf, located between the south of the Llobregat river mouth and the beginning of the Garraf sea cliff, shows stable deposits with better preservation owing to uniform, high shelf subsidence rates and tectonic stability (fig. 3.16). As a consequence, the low gradients of the middle to outer shelf favored the preservation of small sea-level changes (fig. 3.19).

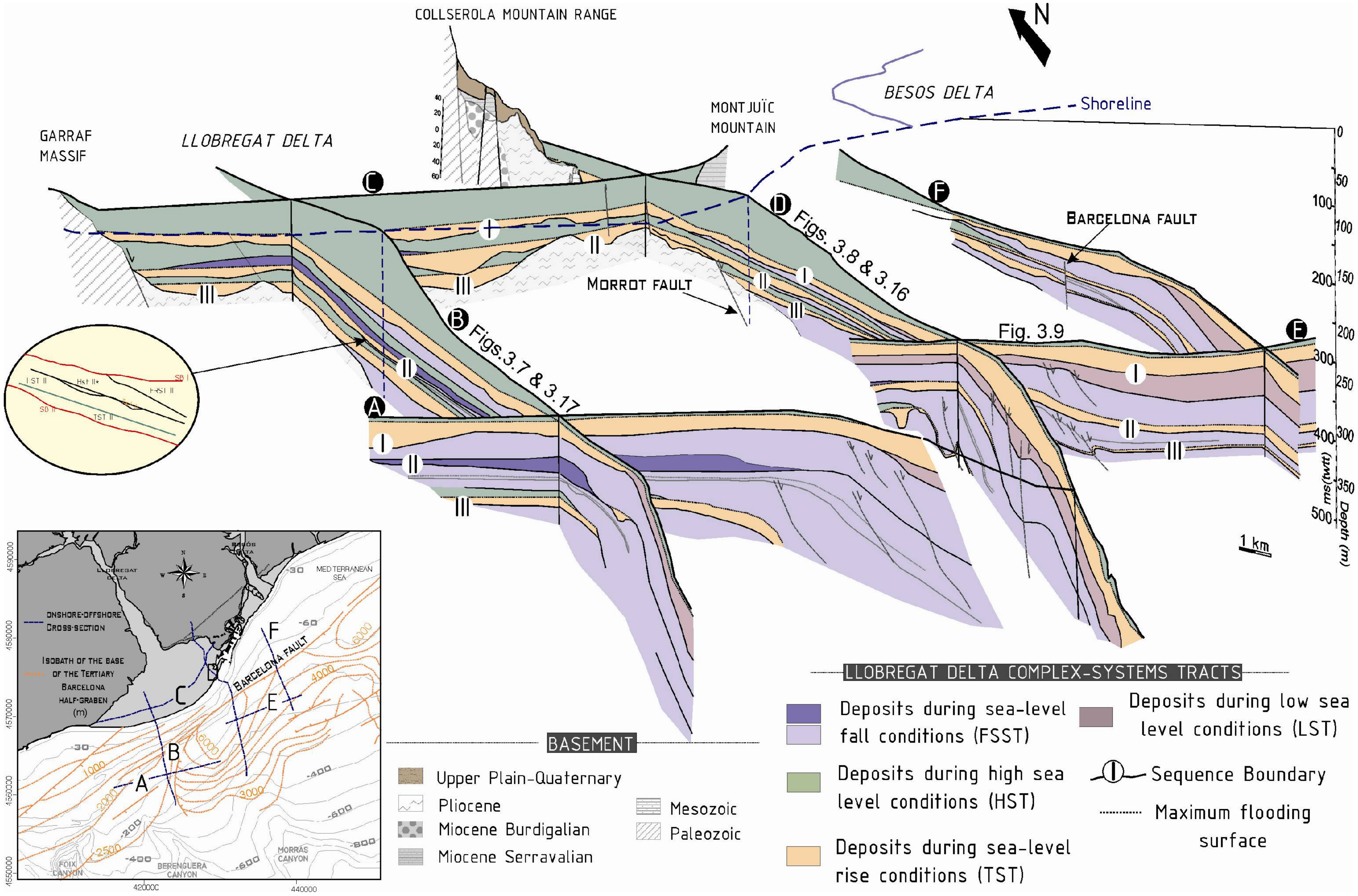

Fig. 3.19: 3D onshore-offshore sequence stratigraphy interpretation diagram of the Llobregat delta. It includes three dip cross sections and three along strike cross sections, based on onshore-offshore cores and offshore seismic profiles. See inset map for cross section location with the isobaths of the base of the Tertiary Barcelona half-graben (mentioned in the text).

3.6. Conclusions

The integration of sediment facies interpretation, dating and seismic stratigraphic analysis of the Llobregat deltaic system reveals a late Quaternary sedimentary record consisting of four depositional sequences (VI, III, II and I) with smaller nested high-frequency sequences. Most sequences comprise the following systems tracts: a) TST, composed of offshore thin sheets (PASs) correlated with Bg-Bs facies association onshore; b) HST, consisting of seaward-thinning shelf wedges (LPWs) correlated with Rw facies onshore; c) RST, constituted by SPWs offshore, correlated with Rw facies association onshore. The upper boundaries of SPWs are extensional regional erosional (ESs) surfaces interpreted as sequence boundaries (SBs). This general pattern shows peculiarities compared with most late Quaternary shelf architectures such as transgressive and highstand intervals that appear to be significantly preserved both onshore and offshore.

The prominent TST-HST-RST repetitive patterns are also highlighted, e.g. LST preservation has only been observed within the most recent depositional sequence, where lowstand deposits is represented by SAPW and correlated onshore with Fc facies. In addition, the regressive interval is represented in depositional sequence II by PL, which exhibits contrasting geometrical patterns in relation to the dominant SPWs.

The geometries provide further insight into the type of delta variability generated under different sea-level trends. During sea-level falls, the dominant sediment record is represented by top eroded mid-shelf and shelf margin deltas attributed to FSSTs. However, the recognition in specific places of a well-developed sigmoid profile with moderate signs of erosion suggests a different mode of formation of shelf deltas during general conditions of sea-level fall. During sea-level rises, the dominant architecture is represented by thin sheets with poor development of deltaic geometries. By contrast, in the last sea-level rise, the combined effect of variable rates of sea-level and sediment supply generated a number of wedge-shaped morphologies in the postglacial transgression deposits. Finally, the record of sea-level stabilization is also present in the preserved deltaic geometries. Seaward-thinning inner-shelf wedges are interpreted as highstand deltas separated from subsequent FSSTs by a basal surface of forced regression. An aggradational to progradational wedge pinching out landward constitutes the most reliable indicator of deltaic deposition under lowstand conditions. This lowstand feature is only evident in the most recent lowstand interval, suggesting the occurrence of a distinct pattern in the earlier lowstands.

The chronology available for the study combined with syn-depositional growth faults and the overall high sediment preservation due to constant subsidence allow us to propose a chronostratigraphic framework for the observed sequences. The most significant and widespread erosions related to progressive shelf break advances are interpreted to have occurred during gradual sea-level falls in the framework of 100 kyr. glacial-interglacial cycles, as reported for other shelves in the Mediterranean. However, most of the regressive deposits show a more complex internal architecture, which suggests the imprint of higher-frequency cycles.

The identification of different seismic units and deformation features along the coast enable us to discern two main morpho-structural sectors: the northeastern sector and the southwestern sector. These sectors are limited by northeast-southwest transfer faults. The sedimentary units distinguished between these sectors were controlled by tectonic fabric superimposed onto the variations in sediment supply. The northeastern shelf shows an across shelf compartmentation owing to the influence of listric faults. The northeastern inner shelf underwent uplifting, whereas subsidence took place on the middle to outer shelf, where high sediment thickness and gravitational processes occurred. The southwestern sector was dominated by high shelf subsidence rates and tectonic stability.