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Small rivers contribution to the Quaternary evolution of a Mediterranean littoral system: The western gulf of Lion, France

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Abstract

Along the Mediterranean coasts and the Atlantic French coast, former and actual research programs focused on major river systems, estuaries and deltas, characterized by a last Glacial relative sea level lowstand and incision and a well developed sedimentary incised valley infilling deposited during the following sea level rise and highstand. This paper presents the preliminary results of a program focused on a particular area of the Gulf of Lion coast with a thin sedimentary cover over the substratum and only minor rivers with non-apparent and important sedimentary contribution during the Late Quaternary. The results show that in this area the best Pliocene to Actual sedimentary record is preserved. The paper rests on the analysis of an extensive database of recent high resolution and very high resolution seismic reflection lines and previously published core data. Seismic data show that a major complex of paleovalleys connected with the Orb, Aude and Agly rivers is preserved on the inner shelf and adjacent coastal plain. On the inner shelf, the separated incised valleys merged in a unique broad and shoreparallel incision dipping southward. At the southward extremity, the incision turns eastward and seaward. The basal surface of this incision extends seawards under six to seven Late Quaternary depositional sequences preserved on the mid and outer shelf. The infilling of the complex of paleovalleys is characterized by aggrading deposits attributed to periods of relative sea level rise (transgressive systems tracts), organized into several subunits bounded by internal discontinuities locally deeply incising. The discontinuities are amalgamated surfaces, including successive sequence boundaries (indicative of phases of relative sea level falls) merged with transgressive surfaces (indistinct tidal and wave ravinement surfaces). The subunits are the part of Late Quaternary depositional sequences preserved in estuarine environments. They are the lateral equivalents of landward fluvial terraces and seaward coastal and prodeltaïc deposits on the shelf. Using borehole dataset, the underlying and eroded deposits below the basal unconformity are correlated with Pliocene deposits outcropping landward in the hinterland. The top of the incised valleys complex is capped by the last Glacial lowstand surface of erosion (18 ky B.P.) reworked by the postglacial transgressive surface (TS), dissociated near the shoreline into a tidal and a wave ravinement surfaces. Above the TS, the very high resolution (VHR) seismic data in the lagoons, the tidal channels and cores, reveal in details the stratigraphic architecture of the deposits. At the base, a small wedge constitutes the postglacial transgressive systems tract (TST) locally thinning in the areas distant of the sediment point sources. The TST is capped by a flat surface of wave reworking (maximum flooding surface or mfs) prolongating under the Leucate lagoon and merging offshore at the seafloor. Boreholes and VHR seismic lines trough the coastal barrier and in the lagoon show that the shoreline probably migrated far landward at the end of the transgression. When

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the rate of sea level rise decreased strongly, the shoreline migrated seaward and prograding and aggrading sandy material, with landward muddy lateral equivalent facies, deposited early highstand systems tract (HST) above the MFS. Offshore, fine material deposited as a sigmoidal blanket of mud originating in part from the north-east and Rhône river under oceanic circulation (equivalent to a subaqueous prodelta). Subsequently, the modern beach barrier built up by wave reworking of the early HST. This new study of the western part of the Gulf of Lion inner shelf and littoral illustrates an incised valley complex and thus presents the best preserved example of the sedimentary record of the effects of the relative sea level changes during the Pliocene to Actual period. For the first time, the land to sea transition is preserved and the Late Quaternary depositional sequences are in a great part observed. The last post Glacial deposits present a simplified but very different organisation compared to a record front of the adjacent Rhône river. Consequently a synthesis is now possible.

Keywords: incised valley fill; Late-Quaternary; land/sea correlation; high resolution seismic

1. Introduction

Relative sea level changes, among others factors, control the deposition and architecture of onshore coastal plain and adjacent shelf deposits respectively organized into terraces and marine depositional sequences. In the Gulf of Lion margin as everywhere, marine and continental systems have been initially studied separately (Boyer et al., 2003a,b; Duvail and Le Strat, 2002; Lobo-Sanchez, 2000; Posamentier et al., 1992; Rabineau et al., 1998; Tesson et al., 1990, 1993, 2000; Tesson, 1996). Correlation between continental and marine systems have been achieved for Upper Miocene and Pliocene deposits (Duvail and Le Strat, 2002; Lofi et al., 2003) from industrial and Ecors (French CNRS national program studying the mantel/crust structure) seismic data. However regarding the high frequency glacio–eustatic cycles of the Upper Quaternary, the connections between marine and continental studies in the present day coastal zone are not yet established because of: 1 — the difficulty to use seismic devices in shallow waters (presence of multiples, critical choices between resolution and penetration); 2 — the sedimentary cover above Pliocene substrate is thin and the occurrence of numerous amalgamated surfaces reduces the thickness of the sedimentary units below the seismic resolution; and 3 — outcropping pebbly deposits induce an acoustic diffraction.

In this study, we tentatively correlate marine and continental Quaternary deposits along an incised valley complex that has deeply carved the Pliocene substrate. The infilling deposits of these incised valleys are assumed to have been better preserved than the deposits between the incised valleys. In the marine area, we implemented various high resolution (HR) and very high resolution (VHR) seismic tools which are well suited for studies in shallow water environments (Labaune et al., 2003d). Onland, studies were carried out in collaboration with the “Bureau de la Recherche Géologique et Minière” (BRGM) which provided cores data from the national subsurface data bank (BDSS).

The Rhône postglacial deposits of the delta plain and prodelta rest directly on a thick level of coarse alluvial deposits which probably represent the remnants of the Quaternary transgressive–regressive cycles. Thus we concentrated our study on the Languedoc–Roussillon coastal system (Fig. 1) and the incised valleys (Hérault, Orb, Aude and Agly) and their landward extension buried under coastal plains. Preliminary results (Tesson et al., 2003) show evidences of a broad incised valley complex due to the merging of these rivers in the offshore area (Fig. 2) and presenting two branches: 1 — a “north” branch, oriented from north to south and shore parallel from Cap d’Agde to Cap Leucate; 2 — a “south” branch, shore transverse from west to east, and overlain by the Leucate lagoon and coastal plain. Direct relationships between the depositional sequences on the continental platform and the coastal plain deposit architecture are well exposed. In this paper we shall focus on the part linked to the Agly river.

2. Regional setting

2.1. Morphology

The coastline between the Rhône delta to the east and the Pyrenean mountains to the west is crescent

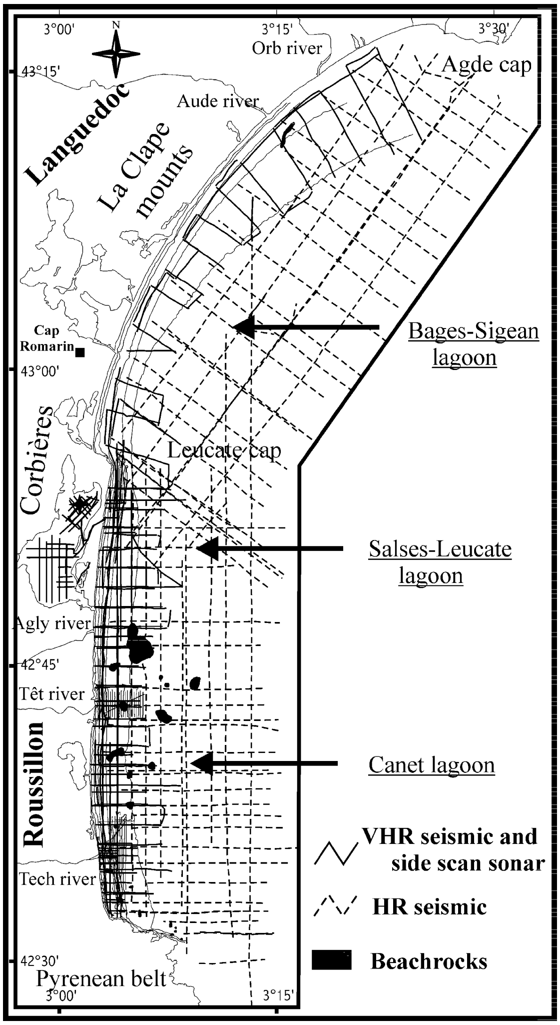

Fig. 1. Map of the Western part of the Gulf of Lion, south of France (Northwestern Mediterranean Sea) showing the study area and the acoustic survey tracklines (extract from the ARGO database). VHR seismic = very high resolution seismic; HR seismic = high resolution seismic.

shaped. It presents extensive beach barriers isolating backbarrier lagoons or "étangs" (from North to South: Bages–Sigean, Salses–Leucate and Canet "étangs"). The beach barrier continuity is interrupted by rocky caps (Agde, Leucate) and fluvial mouthes (Hérault, Orb, Aude, Agly, Tech, Têt). In the southern part of the study area, the Roussillon coastal plain develops between the Pyrenean mountains to the south and the Mesozoic limestone of the "Corbières" to the north. To the north of Cap Leucate, Mesozoic and Cenozoic limestones prolongate near the shoreline (Massif de la Clape) delimiting several minor coastal plains.

2.2. Geology

The construction of the Rhône passive margin was initiated in Upper Oligocene to Lower Miocene times during a phase of rifting, followed by an oceanic spreading (Gorini, 1993; Guennoc et al., 2000). From the Lower/Mid Miocene, the interaction between the post-rift subsidence and the high sedimentary supply from the Rhône hinterland led to the accumulation of a thick wedge of clastic sediments which seals the rift structure.

The constructional process of the shelf was interrupted at the end of Miocene (Messinian) when the Mediterranean Basin was isolated from the Atlantic ocean. Sea level dropped drastically and the margin was deeply eroded by valley incision. Subsequently, at the beginning of the Lower Pliocene, the margin was flooded and the valleys became rias.

Later during the Pliocene, the rias were filled by the progradation of Gilbert type deltas (Clauzon et al., 1987; Lofi et al., 2003), presently outcropping in the upstream part of the Roussillon coastal plain (Fig. 3a). These deposits prolongate under the actual shelf where they have been identified (Lofi et al., 2003; Duvail and Le Strat, 2002). They were incised during Quaternary eustatic changes and present an irregular upper boundary under the Roussillon coastal plain (Fig. 3b), seaward dipping under Quaternary deposits of the shelf. The last synthesis of BRGM core databank (Duvail et al. 2001) describes two east–west oriented major incisions (50 m b.p.s.l.) under the Canet and Salses–Leucate lagoons. Under the Canet lagoon, the incision is bounded seaward by a Pliocene topographic high (5 m b.p.s.l.) (Martin et al., 1981). Under the Salses Leucate lagoon, the precise location and depth of the Pliocene upper boundary is now reinterpreted by our both teams. In the coastal plain out of the lagoons, the Pliocene upper boundary is sub-outcropping. Due to this erosion, the Upper Pliocene would be missing.

The continental Quaternary deposits in the river valleys are preserved and form imbricated terraces due to the interaction of base level drops during the Late-Quaternary sea level cycles and tectonic (uplift). The

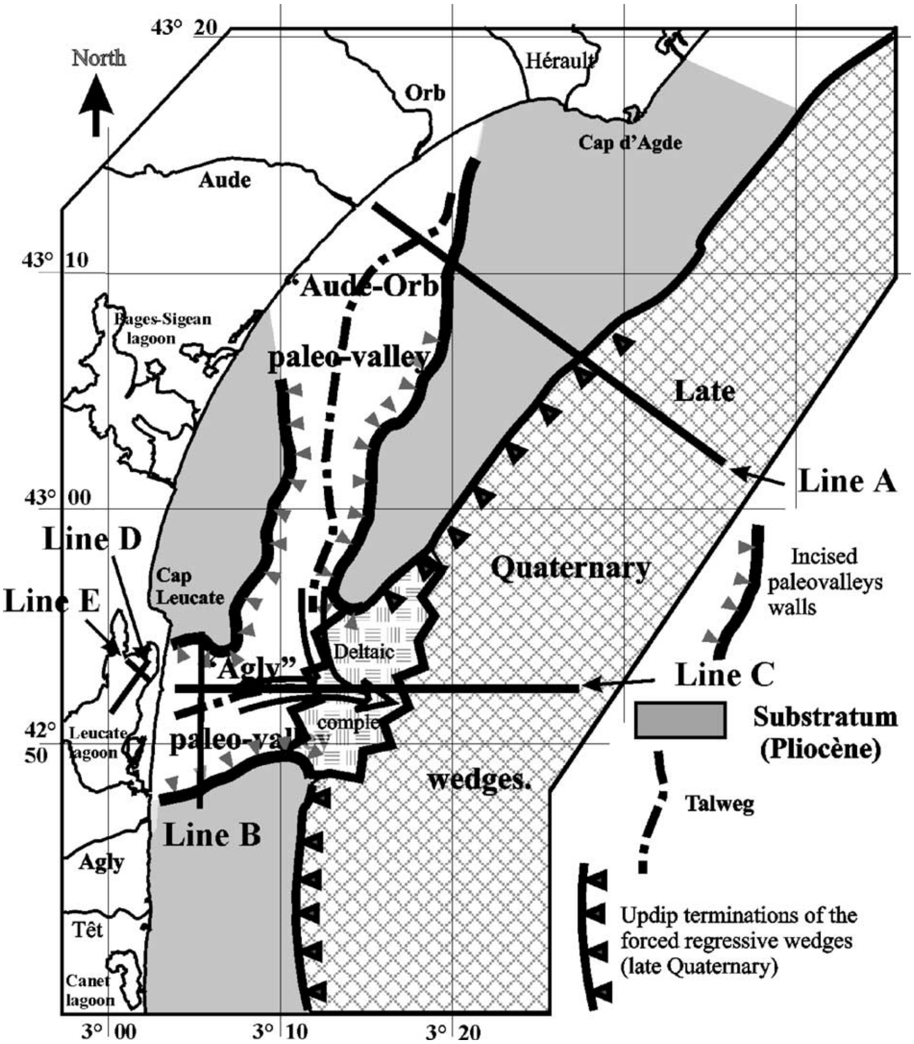

Fig. 2. The Languedoc–Roussillon paleovalley complex incised in the Pliocene of the Gulf of Lion. There is no direct relationship between the incised valley complex and the present Hérault river in the north. Location of the seismic examples used in Figs. 4–8 is indicated.

different terrace surfaces merge in the coastal plain, near the modern littoral (Duvail et al., 2001). Mixed continental/marine deposits are described in the two incisions under the Canet and Salses–Leucate lagoons. Their precise facies and age dating are discussed below.

Under the Canet lagoon, the deposits filling the Pliocene incision consist of marine sands dated of 4–5 ky BP age, overlain by marine clays and beach barrier sands of less than 2 ky BP old. The top of the sandy deposits is located at 10-m b.p.s.l. (Martin et al., 1981). In the northern part of the Leucate lagoon, a short core shows a lower level of red sands (from 13.80 to 2.80 m) dated 8.2 ky BP but this value was considered as not valuable (Martin, 1978). At the base of the 0.60 m uppermost lagoonal clays, a shelly layer has been dated to be 2.1 ky BP. At the North of Cap Leucate (Cap Romarin area, location Fig. 1), drilling data across the coastal plain show (Fig. 4) a sandy prograding unit with a base at about 20 m b.p.s.l., developed between a cliff of Cenozoic rocks and the present shoreline 1 km eastward. It deposited since 4–6 ky BP (Aloisi et al., 1978).

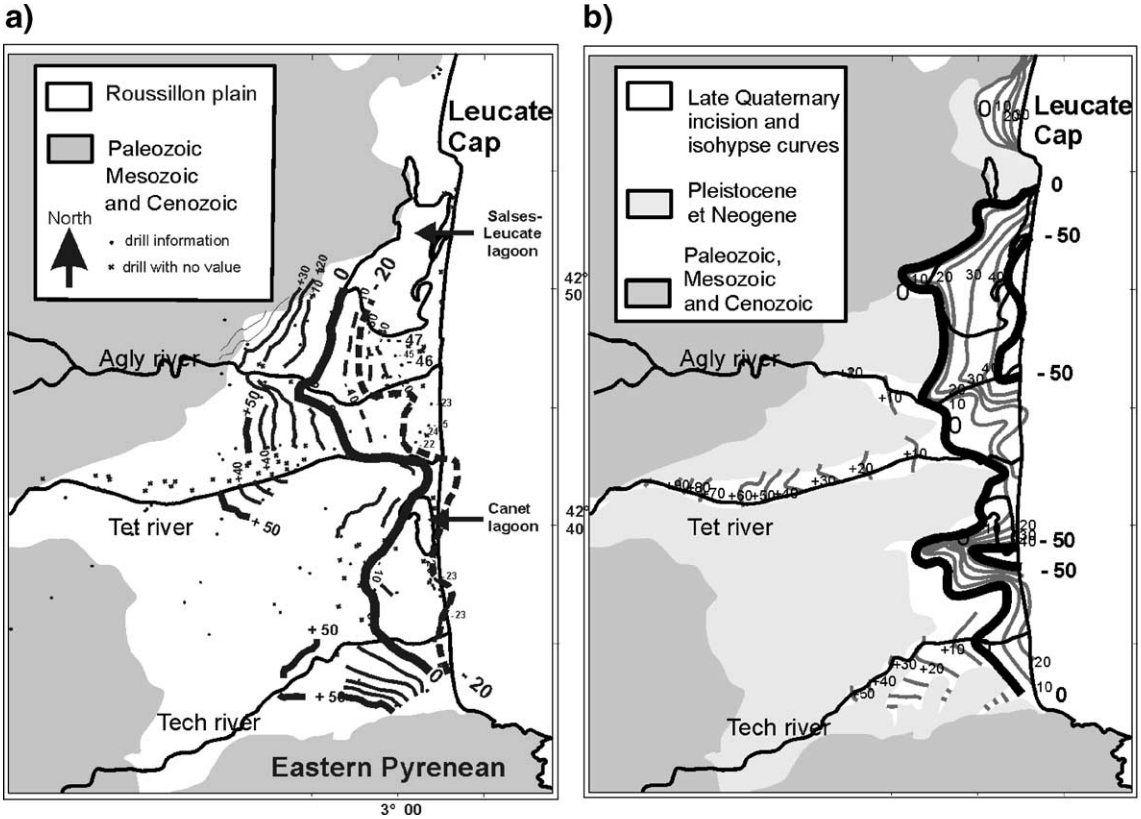

Fig. 3. The Pliocene upper boundary map (a) shows that the Pliocene is mainly seaward dipping north of the Têt river and under the Salses–Leucate lagoon. Map (b) shows the two main Quaternary incisions at the top of the Pliocene deposits, under the Salses–Leucate and Canet lagoons. Near the shoreline, the Pliocene deposits are globally at 50 and 20 m, respectively below sea level surface in these two areas. The best preservation of Quaternary deposits in the nearshore domain is expected in the Salses–Leucate area as confirmed by offshore seismic data. Modified from Duvail et al., 2001.

2.3. Quaternary stratigraphy of the mid/outer shelf

The deposits are organized into depositional sequences assumed to be of Late Quaternary age. The boundary between Early and Late Quaternary is not well known. The sequences are stacked in an aggrading pattern and form a major sedimentary complex wedge (Fig. 5) referred to as "Pleistocene wedge". This wedge is thickening seaward (Tesson et al., 1990, 1993). Its shape has been explained by a synsedimentary differential subsidence (Tesson and Allen, 1995). It pinches landward at the middle shelf (Fig. 2) onto a substrate showing seaward dipping and/or folded reflectors with high amplitude. The upper boundary of the wedge is an erosional and polygenic surface located at the sea floor or overlain by postglacial deposits. Due to the seaward dipping architecture, the more recent sequences are located at the outer shelf, the older sequences are observed at the inner-shelf where they may outcrop. The upper polygenic surface developed during the last relative sea-level fall and lowstand (18 ky BP) and was reworked during the postglacial sea level rise and transgression. In the nearshore area northward of this study area, the postglacial deposits (Gensous and Tesson, 2003) form a sedimentary body comprising the retrograding part of the transgressive systems tract or TST (sometimes unobserved or reduced) bounded by the maximum flooding surface (mfs) and overlain by the prograding deposits of the highstand systems tract (HST). In the study area, the landward boundary of the Pleistocene wedge is located at about 20 km seaward of the

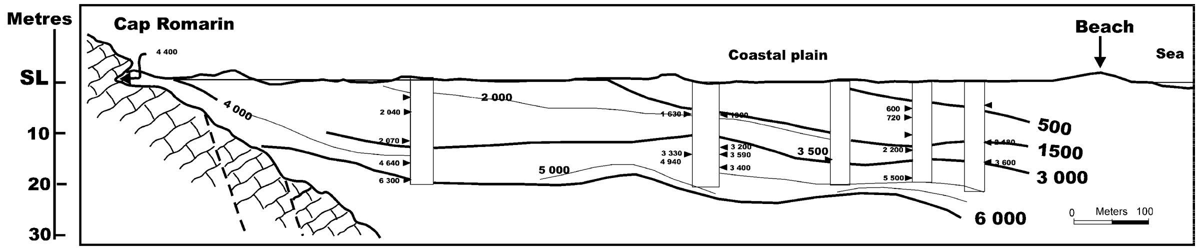

Fig. 4. The Romarin coastal plain initiation of progradation, north of Cap Leucate (location Fig. 1), is dated from about 6000 yr. BP. It represents the last post Glacial highstand systems tract (HST) with a thickness up to 20 m b.p.s.l. No direct fluvial input is known in this area. From Aloisi et al., 1978.

shoreline between Cap d'Agde and Cap Leucate and comes closer the shoreline south of Cap Leucate. The precise architecture of the last postglacial deposits is a part of the research program exposed in this paper. The Quaternary depositional sequences are not well dated on the shelf.

The more recent shelf perched lowstand wedge (Posamentier et al., 1992; Tesson et al., 2000) outcropping at the outer shelf is dated 40 ky cal. BP. It was deposited during the Wurmian sea level lowering phase (Gensous et al., 1993). For the previous lowstand wedges, data are not available however the hypothesis of control of deposition by 4th and/or 5th order glacio–eustatic cycles is proposed (Tesson et al., 1993) and is supported by modelling studies (Rabineau, 2001).

3. Data and methods

3.1. Seismic data

HR and VHR seismic data used in this study are retrieved from the ARGO database (West area, Fig. 1). Seismic devices used were: the Minisparker SIG 50 Joules, the Uniboom EGG 300 joules, and the 2.5 and 3.5 Edo Western mud penetrator. New data since 2001 were acquired using a special IKB Seistec boomer in

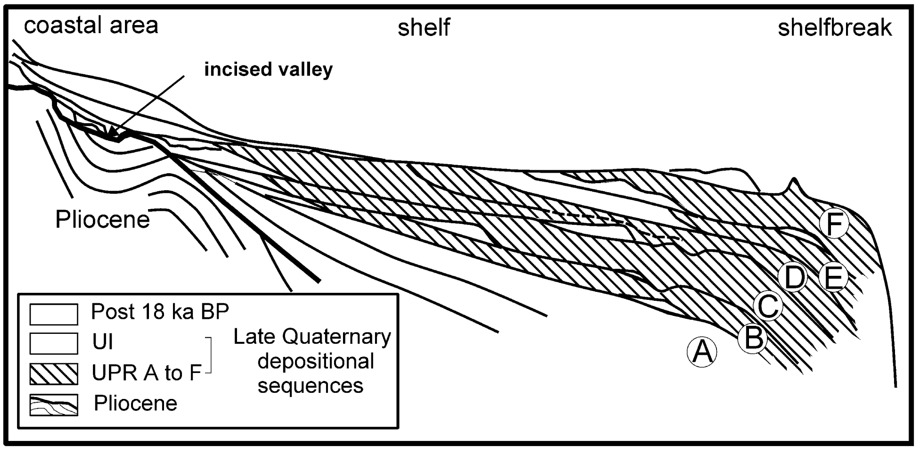

Fig. 5. Simplified sketch of the shelf stratigraphic architecture of the Plio-Quaternary deposits of the Gulf of Lion (modified from Tesson et al., 2000). Each Quaternary depositional sequence consists of a couplet of UPR/UI units. The couplets are considered to represent the Late Quaternary deposits organised in an overall sedimentary wedge, thinning landward. Between the Pliocene and the Late Quaternary wedge, deposits should represent the Early to Mid Quaternary. The schematic representation in the coastal area is based on the present study. UPR = forced regressive wedge or "Unité Progradante Régionale" made of low energy deposits and developed on the whole continental shelf. UPR is considered as a "shelf-perched lowstand" (Posamentier et al., 1988). The mappable UPR are labelled from A to F. UI = "unité intercalée" made dominantly of high energy deposits (sandy paleocoastline on the outer shelf) and irregularly preserved. UI are considered mainly as transgressive deposits, excepted on the outer shelf where they should be in part maximum lowstand deposits.

the near offshore band (Liper cruise, *N/O Téthys II*, 2001) and the submarine beach and lagoon (Litto cruises, 2001–2003). The IKB Seistec boomer (Simpkin and Davis, 1993) has the source and receiver devices included in the same catamaran (offset is reduced to 0.5 m). The technical capacities of the new boomer led to highly increase the seismic resolution and were particularly suitable for studies in very shallow water environment (Labaune et al., in press).

Until 1994, data were recorded in an analogical mode while after 1994 in a digital and georeferenced mode using the Delph 2 system of Triton Elics (Girault and Mathevon, 1990). Time to depth conversion is based on acoustic velocity of 1500 m/s in water and 1875 m/s in sediment which are standard value used in similar previous studies of the Gulf of Lion and Gulf of Mexico (Suter et al., 1987). On seismic line figures, time is expressed in milliseconds two way travel time (ms T.W.T.) The offset between the source and the streamer (very sensitive in shallow depths) has been corrected when needed.

Positioning was acquired with a metrical precision with an onboard GPS and DGPS associated to a navigation system. The metadata concerning the properties of seismic devices and navigation may be consulted on the European database "PANGEA" where they are combined with the Institut Français de Recherche en Mer (Ifremer) metadata base and on the website of the BDSI (http: http://www.univ-perp.fr/see/rch/bpc/present.htm).

Seismic data analysis were made using the principles of seismic stratigraphy analysis (Mitchum et al., 1977) with some adaptations to HR and VHR seismic.

3.2. Core data

Previous core data consist of 2 cores in the southern and northern parts of the Salses–Leucate lagoon (Martin, 1978), 8 cores in the Canet lagoon (Martin et al., 1981) and more than 275 long cores in the emerged coastal plain, referenced into the BRGM databank or BDSS (http://infoterre.brgm.fr). Here we use only a part of these core data.

The S1 core, in the northern Salses–Leucate lagoon (Fig. 6), is 13.80 m long. The top of the core is at about 2.80 m below sea-level. It comprises from base to top: marine sand with very few shells, with increasing pebble content towards the top (13.80 to 2.80 m, thickness 11 m); pebble/gravel level with sand (2.80 to 1.40 m, thickness 1.4 m); pebble and gravel in a muddy sand (1.40 to 0.50 m, thickness 0.9 m); mud with high shell content decreasing upwards (thickness 0.5 m). The levels 0.6/0.8 and 1.4/2.8 m are dated respectively at 2100 and 8200 yr B.P. The last value is considered as doubtful. HR and VHR seismic lines have been acquired just near the core location (Fig. 1).

The S2 core of the BRGM data bank, on the Salses–Leucate beach-barrier (Fig. 6), is 26 m long. The top of the core is at about 1.0 m above sea-level. It comprises from base to top: coarsening up silty sand (28.3 to 22.9 m, thickness 5.4 m); level of pebble in a sandy matrix (22.9 to 21.1 m, thickness 1.8 m); fine sand (21.1 to 18.8 m, thickness 2.3 m); pebble/gravel level (18.8 to 15.2 m, thickness 3.6 m); coarse sand (15.2 to 13 m, thickness 2.2 m); fine sand coarsening up to coarse sand (13 to 5.5 m, thickness 7.5 m); pebble/gravel level (5.5 to 4.3 m, thickness 1.2 m); sandstone (4.3 to 3.5 m, thickness 0.8 m); pebbly coarse sand (3.5 m to surface, thickness 3.5 m). No age calibration is available in the core data bank.

The C1, C2 and C3 cores, in the Canet lagoon (Fig. 7) are 19.8, 15 and 15 m long, respectively (Martin et al., 1981). From base to top, C1 core comprises Pliocene compact clay or marly clay (19 to 8.7 m) and coarsening up sand until surface. C2 core comprises Pliocene compact clay or marly clay (15 to 7.8 m), medium sand (7.8 to 0.5 m, thickness 7.3 m) and clay (0.5 m to surface). C3 core comprises sand fining up to clay (15 to 7 m), clay coarsening up to medium sand (7 to 0.5 m, thickness 6.5 m) and clay (0.5 m to surface). There is no Pliocene at the base of core C3.

The topographic maps of the Pliocene upper boundary and the Quaternary surface of incision in the Roussillon plain have been constructed (Duvail et al., 2001), using the BRGM BDSS data bank. The Pliocene upper boundary maps (Fig. 3) shows that, in the coastal area, the 0 and -20 m curves are located near the coast in the southern part and shifted landward in the north (Salses–Leucate area). The overlying Quaternary deposits have a reduced potential of preservation in the south. The Late Quaternary surface of incision is not clearly dated or correlated with the relative sea level changes. Nevertheless the depth of the incision is locally important and confirms that the places where a part of the Quaternary deposits should

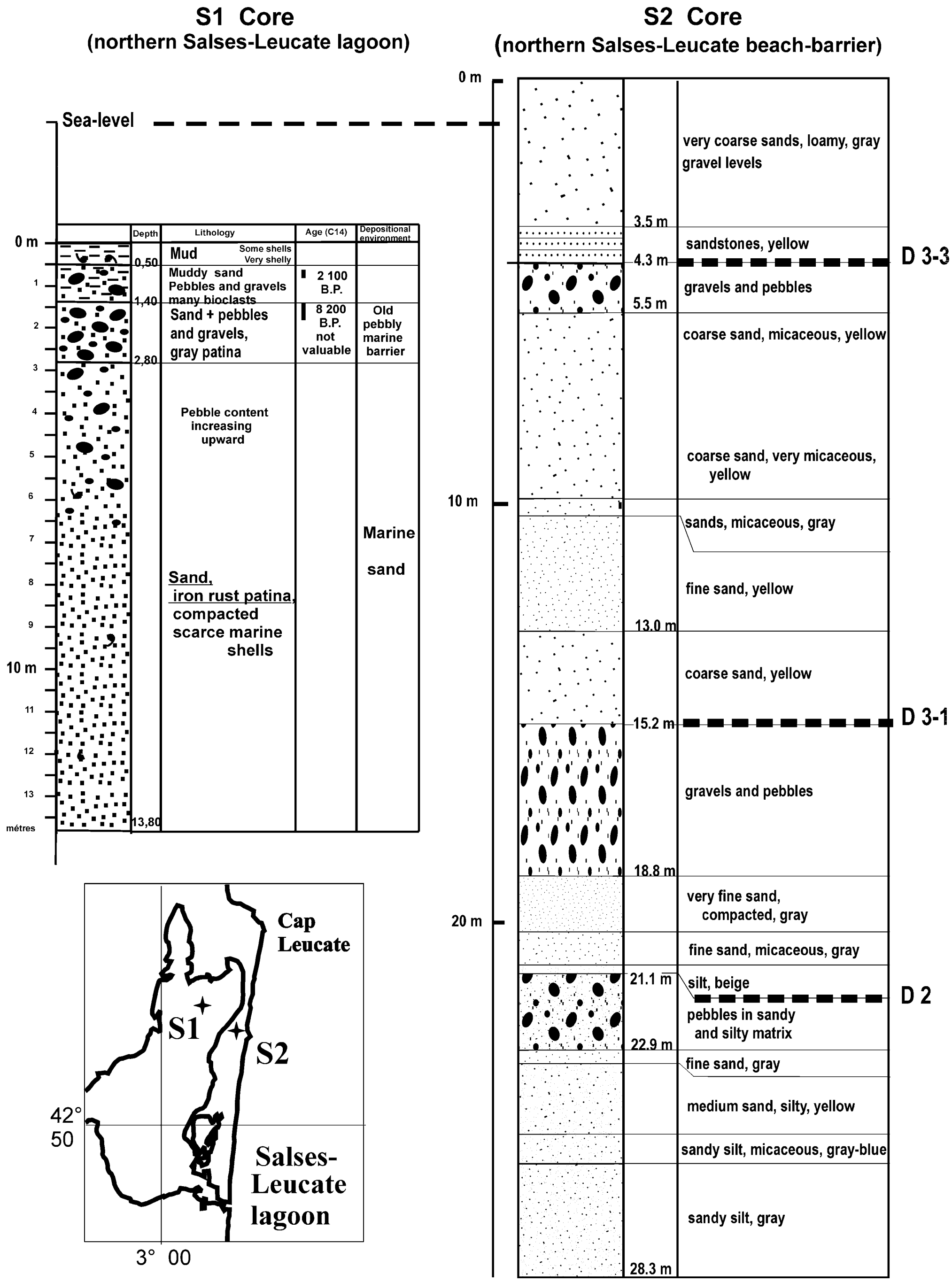

Fig. 6. The S1 core in the Salses–Leucate lagoon is located just at the boundary of the rocky and Tertiary Cap Leucate. The age dating of the upper pebbles and gravels (8200 yr. BP) have been considered as not valuable (Martin, 1978). Above, there are marine sands. The S2 core description (Labaune et al., in press) is from the BRGM databank. This core is adjacent to our seismic lines (Fig. 2) and the tops of the three pebbly levels are strong acoustic reflectors that correlate with our seismic discontinuities (D2, D3-1 and D3-3) on Figs. 10b, 11 and 12.

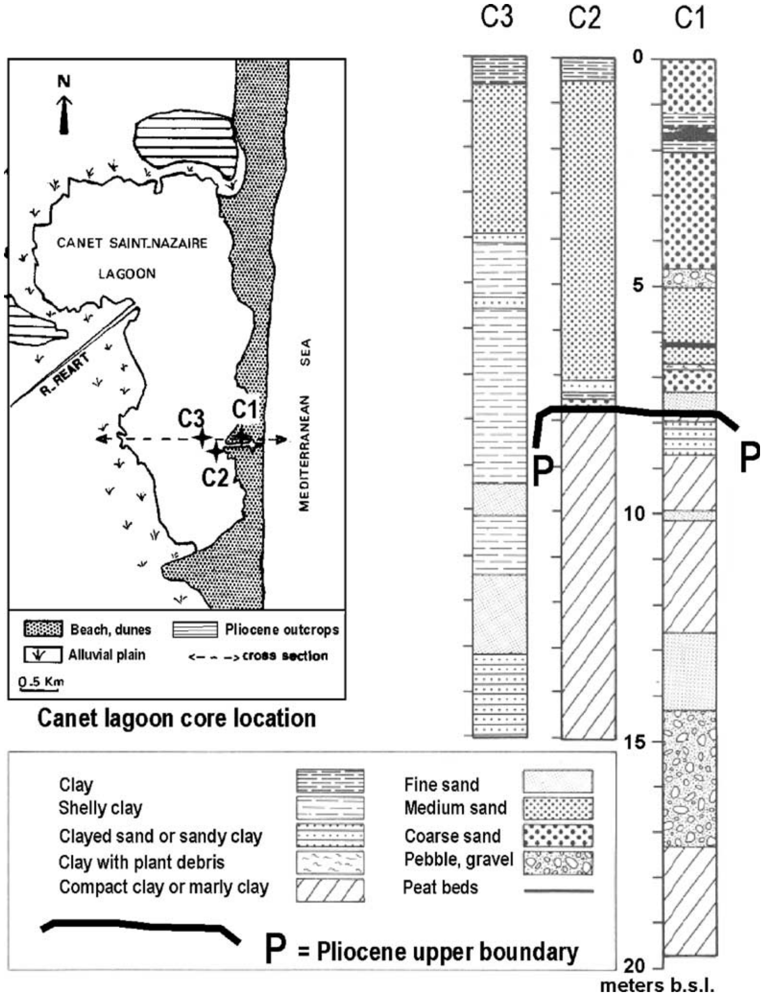

Fig. 7. South of the Tête river, around the Canet lagoon, the Pliocene deposits are outcropping or sub-outcropping as shown by the C1 and C2 cores. The Pliocene topography is very irregular (C3 core does not reach the Pliocene) has previously indicated by the maps of Fig. 3.

have been preserved are two valley axis located below the Salses–Leucate and the Canet lagoons.

4. Seismic analysis

We present a simplified analysis because the reduction scale does not allow to preserve all the original information. Description is essentially based on four HR seismic lines acquired with the minisparker (Fig. 2) and crossing the two main branches of the incised valley complex. Lines A and B are transverse sections. Lines C and D are longitudinal sections superimposed to the talweg and respectively located on the inner shelf and Leucate lagoon. A VHR line (Boomer IKB Seistec) is also presented to show the detailed stratigraphic organization of the upper sedimentary bodies of the coastal and lagoonal Leucate complex (line E).

4.1. Transverse lines

Line A (Fig. 8), oriented SE/NW, crosses the "north" branch of the incised valleys system (Aude–Orb paleovalley). It shows a basal seismic unit (Ub) with high amplitude, low frequencies and continuous reflectors dipping seaward. They are affected by folding structures with S/SW–N/NE axis. The upper

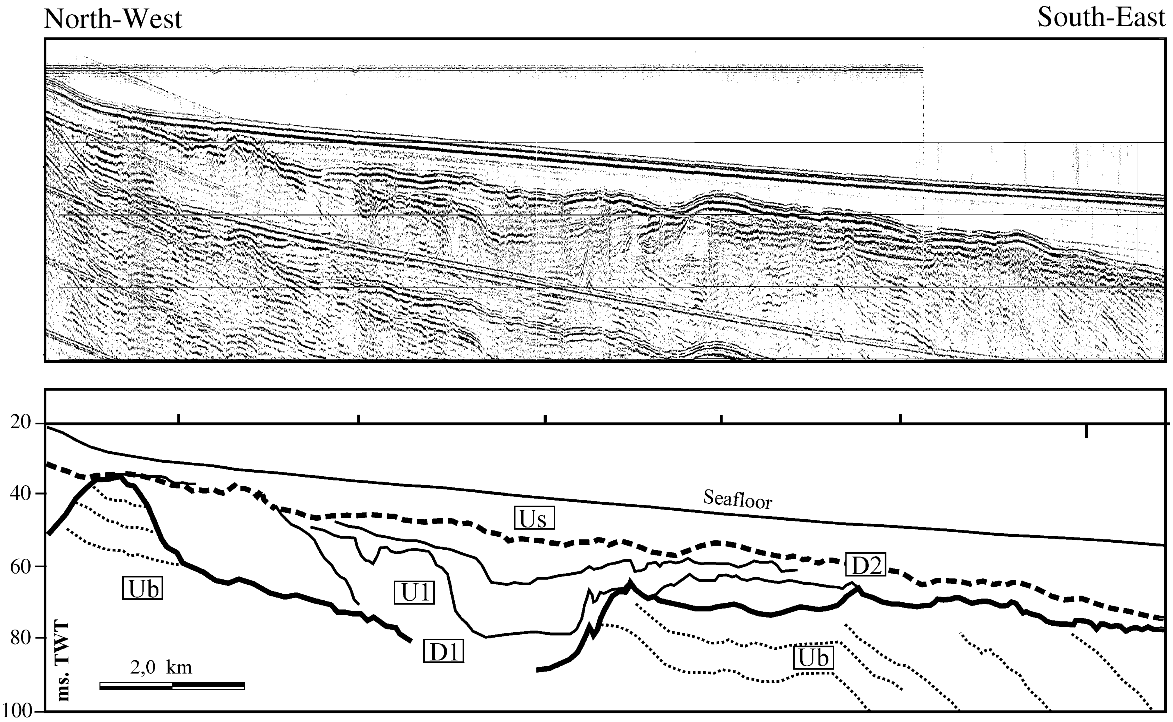

Fig. 8. Transverse line (A) of the "north" branch of the incised valley complex: reprocessed minisparker seismic line and interpreted line-drawing. Location on Fig. 2. Us = upper unit; Ub = basal unit (Pliocene); D1 = basal incision; U1 = incised valley infilling.

boundary (D1) is an erosional discontinuity. It is located at about 35 to 50 ms b.p.s.l. at the shoreline and deepens seaward (75 ms at the east end of line). Near the shoreline, it is truncated at more than 80 ms depth by a trough NS oriented. The filling of the trough is a composite seismic unit (U1) made of sub-units bounded by erosional discontinuities that merge laterally at the edges of the trough. The discontinuities are sub-horizontal with local U-shaped incisions. The sub-units present subhorizontal internal reflectors. The upper boundary of unit U1 is an erosional truncation (D2) that laterally merges with the basal boundary D1. It is marked by truncated terminations of the underlying reflectors. The overlying unit Us appears as relatively transparent but it is probably due to a technical problem.

Line B (Fig. 9), oriented N–S and shoreline parallel, runs across the "south" branch of the incised valleys system (Agly paleovalley). The basal unit Ub is folded in a syncline 12 km wide. The erosional discontinuity D1 at the top of unit Ub is marked by a major incision which axis superimposed to the axis of the syncline. It is located 50 ms b.p.s.l. in the central part and rises laterally until the sea floor. In the northern part, the incision fill (unit U1) is clearly divided into two subunits by an erosional discontinuity. Near the top, several discontinuities, most of them amalgamated, present U-shaped erosional features. At the top of the complex infilling, we observed the D2 discontinuity identified in the previous section but in this section it is underlined clearly by downlap terminations of the overlying Us internal reflectors. The Us seismic facies is characterized by large sigmoidal clinoforms gently dipping to the south. The upper boundary of Us is the seafloor that shows an upward convex (mounded) morphology.

4.2. Longitudinal lines

Line C (Fig. 10a), oriented east–west, follows the axis of the "south" branch of the incised valleys system in the open sea area. The erosional discontinuity D1, at the top of the basal unit Ub is located at 70 ms b.p.s.l. under the shoreline and beach barrier

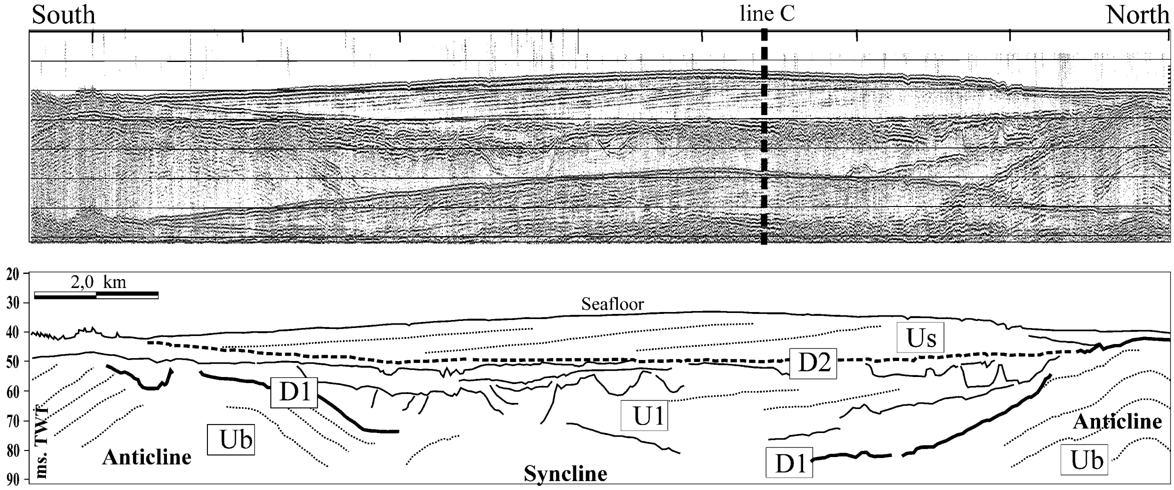

Fig. 9. Transverse line (B) of the "south" branch of the incised valley complex: reprocessed minisparker seismic line and interpreted line-drawing. Location on Fig. 2. TWT ms. = two way travel time in milliseconds.

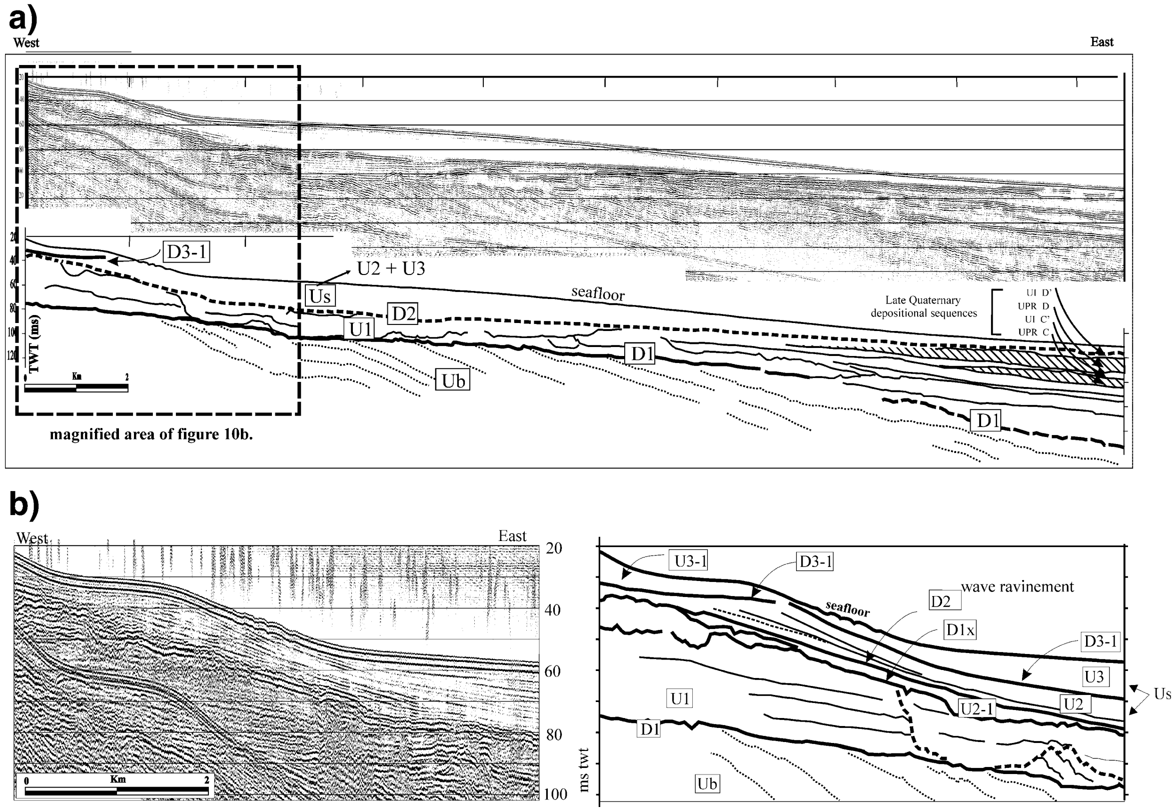

Fig. 10. a) Longitudinal line (C) of the "south" branch of the incised valley complex: reprocessed minisparker seismic section and line-drawing. Location on Fig. 2. The erosional discontinuity at the top of Ub (Pliocene) represents the base of the incised valley complex and extends seaward below the Late Quaternary depositional sequences. b) Magnified nearshore part of the minisparker line presented in Fig. 6a. Minisparker seismic line to the left and line-drawing to the right.

(Labaune et al., 2003b,c, in press). D1 deepens seaward and the overlying unit (U1) thickens. The unit U1 is composed of several encased subunits more or less preserved. They are bounded by discontinuities strongly erosional with escarpments up to 20 ms t.w.t. These subunits present subhorizontal and continuous internal reflectors. Seaward, the discontinuity D1 underlies the Late Quaternary depositional sequences described by Tesson (1996) and Lobo-Sanchez (2000). However direct correlation between the subunits of the U1 unit and the seaward depositional sequences are not precisely ensured. At the top of U1, the D2 discontinuity is a composite surface rising at 25 ms b.p.s.l. under the shoreline. It is overlain by unit Us.

The detailed analysis of the landward section of the Line C (Fig. 10b) allows to follow the uppermost discontinuity (D1x) through the unit U1. It is an erosional and irregular discontinuity. The overlying sedimentary filling is capped by D2 which can locally merge with D1x. Above, the unit Us is subdivided by an erosional discontinuity (D3-1) which appears continuous and subhorizontal nearshore and beneath the beach. Below D3-1, the unit (U2) shows strong clinoform toplaps. Seaward, U2 converges and the reflectors become "paraconcordant". Unit U2 pinches landward. Above D3-1, in the nearshore area, a locally prograding unit (U3-1) thickens landward. It is considered as the basal part of the present coastal wedge (Labaune et al., 2003b,c). Above D3-1 and seaward of the coastal wedge, a lenticular unit (U3) is identified (Fig.10a and b). South of Cap Leucate, it is not connected with U3-1, but at the north it prolongates this unit up to the Cap d'Agde. In the southern area a direct relation may exist near Saint Cyprien area.

Line D (Fig. 11) prolongates line C under the northern part of the Leucate lagoon, in the axis of the incised valley. Three discontinuities are identified and correlated with those of line C. The basal discontinuity is located at 70–80 ms t.w.t. below the beach barrier at the Port-Leucate entrance and at 70–60 ms t.w.t. under the lagoon. It is the discontinuity D1. Above D1, the underlying unit is semi-

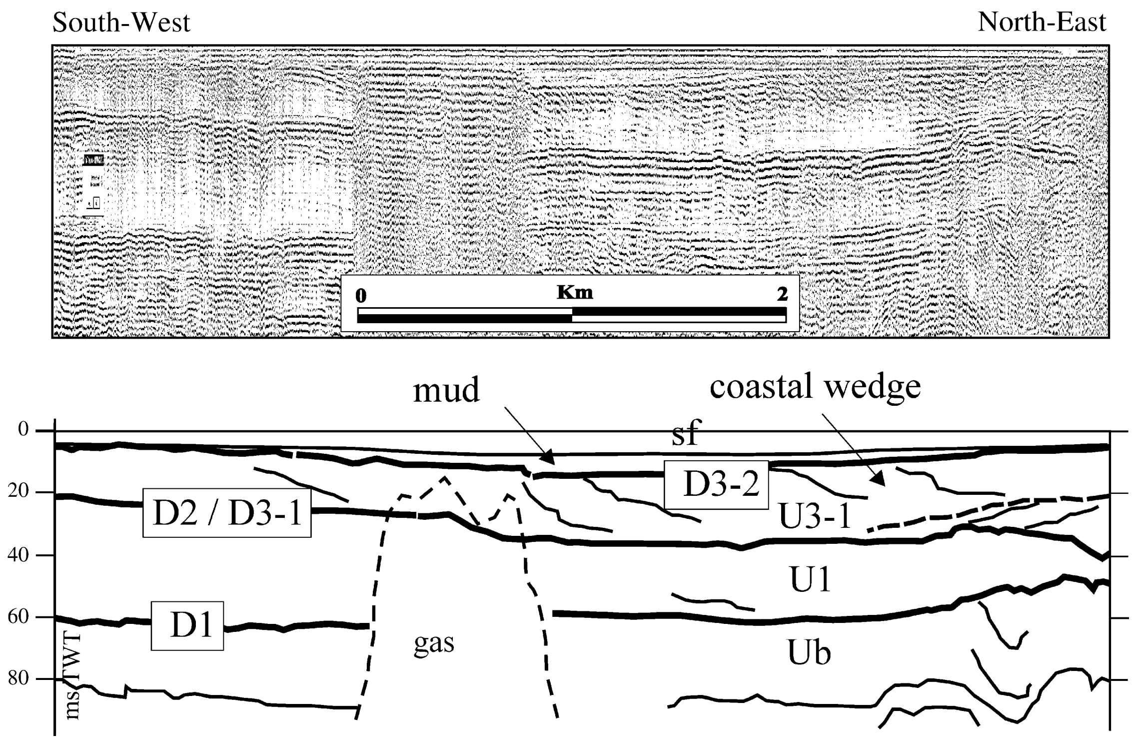

Fig. 11. Longitudinal line of the "south" branch of the incised valley complex under the Salses–Leucate lagoon: reprocessed minisparker seismic line and interpreted line-drawing. Location on Fig. 2. sf = seafloor.

transparent with eastward dipping clinoforms at the top. It is thinning northward, near the Cap Leucate. It is considered as equivalent of unit U1 and its subunits which are not well marked under the lagoon, perhaps due to lower seismic resolution. Its upper boundary is a discontinuity located at 25 ms t.w.t. near the beach barrier and sometimes 30 ms t.w.t. in the mid-lagoon. It would represent the lateral equivalent of the more or less amalgamated discontinuities D2 and D3-1. The upper part of the overlying unit (U3-1) shows oblique–tangential to sigmoidal reflectors. They are seaward dipping and organized in a progradational/aggradational pattern. The lower part shows subhorizontal reflectors. These two distinct seismic facies may characterize two distinct subunits or may be interpreted as upper (topset and foreset) and lower (bottomset) part of a single unit. In the southern part of the lagoon, the unit comprises seaward prograding to aggrading subunits in place of the single reflectors of the northern part. This unit U3-1 is equivalent of the coastal wedge previously documented by line C. Its upper boundary (D3-2) is located at 15 ms t.w.t. in the mid lagoon and rises toward the beach barrier where it merges with the lagoon bottom. A thin sedimentary cover of lagoonal mud can reach 10–15 ms t.w.t. of maximum thickness in its central part.

Line E (Fig. 12), perpendicular to the beach barrier, gives a detailed insight of the upper lagoonal deposits organization. At the base, the equivalent unit of the coastal wedge exhibits a prograding and aggrading pattern under the discontinuity D3-2. This discontinuity rises toward the beach barrier (5 ms t.w.t. at the shoreline) and evolves into an erosional truncature. Between D3-2 and the lagoon bottom, a wedge

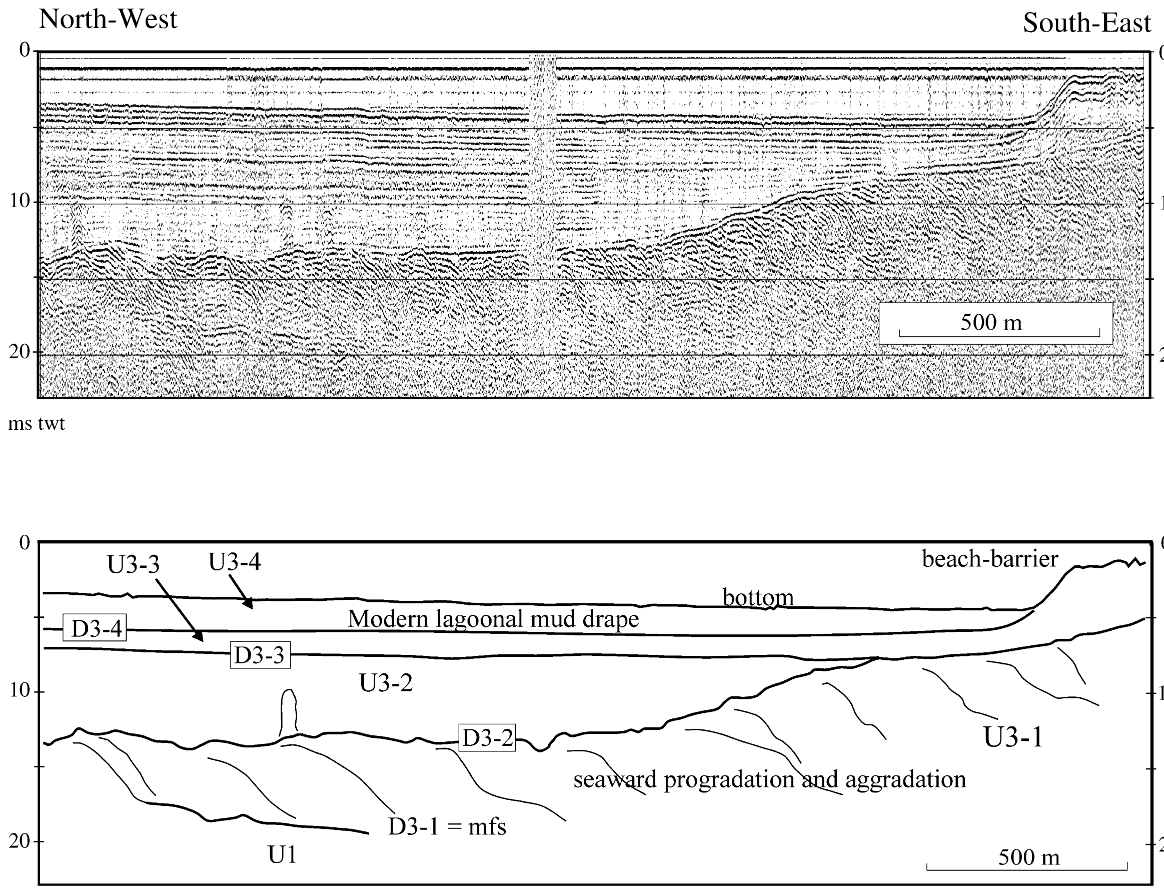

Fig. 12. Lagoonal reprocessed seismic line and line-drawing obtained with VHR IKB-Seistec boomer showing the detailed architecture of the littoral prism. VHR = very high resolution; mfs = maximum flooding surface.

shaped unit with high frequency internal reflectors has a maximum thickness of 10 ms t.w.t. The reflectors are subhorizontal, concordant and onlap onto D3-2. Two internal paraconcordant surfaces (D3-3 and D3-4) evolve toward the beach barrier to discontinuities. They bound a wedge shaped body with diffracting facies representing the beach barrier. At the barrier, D3-3 merges with D3-2 and D3-4 rises until the surface. The three units bounded by D3-2, D3-3, D3-4 and the lagoon bottom are labeled U3-2, U3-3 and U3-4.

5. Interpretation

In a first part, seismic, sedimentologic and chronologic data will be combined to assume an interpretation about the evolution of environmental parameters (such as water depth, oceanic regime and forces, fluvial input, landward and/or seaward shoreline migration) which can induce key surfaces and seismic units characteristics. In a second part, a stratigraphic model will be proposed.

5.1. Depositional environments and base level changes

The basal unit Ub spreads from the Pyrenean apron until the Cap d'Agde with similar characteristics. Synthetic studies of BRGM, onland, indicate a Pliocene age, probably Lower/Middle Pliocene (Duvail and Le Strat, 2002). The deformations cannot be imputed to compression, unknown during Pliocene, but probably result from local variations of the differential subsidence. The Pliocene substrate is made up of blues silty clays and/or yellow marls.

Erosional discontinuity D1 is the lower boundary of the incised complex infilling which has been excavated by the base level lowering during the Late Quaternary cyclic sea level changes (Van Wagoner et al., 1990; Weimer, 1984). This discontinuity rises upstream in the incised valleys. It appears that, at least in marine area, it preferentially incises the synclinal axis of Pliocene substrate. The incision occurred after to the folding episode. Under the Leucate lagoon, the talweg of the incision diverts southward. Therefore, it seems that the Agly paleovalley was located more northward and that the present day course, which is located at the southern edge of the incised system, is very recent. This was observed by Martin (1978) for recent periods, but it appears as a more general trend.

The infilling unit U1 is developed inside the incised valley complex and its extension under the coastal plain. It is interpreted as an infilling with successive stages of aggrading deposition in protected environment and underwent erosion during sea level lowering episodes. The infilling shows laterally accretional structures with high energy diverging reflectors which remind spit sand bars (Chaumillon et al., 2002). This suggests an estuarine environment and the lateral marine and fluvial equivalents. We propose that the complex infilling was deposited into a trough acting as a conduit for continental sediment yield (estuarine system) under control of Upper Quaternary relative sea level changes. Each aggrading subunit would be deposited at the end of a lowering sea level phase followed by a flooding episode due to a base level rise. It comprises a lower part with fluvial lowstand deposits overlain by transgressive deposits. Each internal discontinuity is a composite surface including the upper boundary of the aggrading transgressive infilling and the channel incision of the following phase of the base level lowering (sequence boundary). Under the Leucate lagoon, the "south" branch of the incised valley complex seems to be essentially filled with a single seismic unit without well marked reflectors. The interpretation of this unit as Agly fluvial terrace is consistent with the lithologic descriptions (sands and pebbles levels of the BDSS cores by Duvail and Le Strat, 2002; green sands by Martin, 1978).

The uppermost surface of incision in the infilling deposits (D1x) is considered as a lowstand surface which should correspond with the last relative sea level fall. The infilling is resumed by the ravinement surface D2 (transgressive surface). Beyond the banks of the main incision, D2 merges with the upper boundary of the Pliocene. This would explain the low thickness of Quaternary deposits on the inner shelf outside of the incised valleys areas. Moreover, this surface merges with the sea floor at middle shelf. It is interpreted as a polygenic surface generated during the last sea level lowstand from 50 to 18 ky BP and reworked during the postglacial transgression finished near 5 ky BP.

The unit U2, wedge shaped and prograding/aggrading, is the remnant of a transgressive sedimentary body. It accumulated at the boundary of the inner-shelf during a phase of decreasing rate of sea level rise and/or increasing rate of sediment yield in the context of the last postglacial transgression. The proximal part with high energy facies evolves seaward to fine grained deposits.

The surface D3-1 is an erosional surface of truncature reworking the top of U2 in the nearshore area (Fig. 10b) and evolving laterally to a seaward dipping and conform surface. Under the beach barrier and the lagoon, D3-1 is also a basal surface of seaward progradation. After U2 deposited, the following sea level rise and wave reworking of U2 upper part developed a ravinement surface and simultaneously a lag deposit of coarse material and a healing phase of fine material (Posamentier and Allen, 1993). The fine material of the healing phase should have been redistributed seaward and downward, above the lateral conform equivalent of D3-1. The healing phase constitutes the base of the sigmoidal unit U3. D3-1 properties under the lagoon led to consider that it represents the last Holocene flooding surface (mfs).

The unit U3-1, seaward prograding and aggrading over D3-1 in the nearshore area (Fig. 8), probably developed during the last part of the Holocene sea-level rise. The shoreline migrated progressively until its recent location. The core S1 (Fig. 6) in the north of the Leucate lagoon shows (Martin, 1978) yellow marine sands equivalent to U3-1, with a top located at 3 m b.p.s.l. In the upper part, an age dating of 8.2 ky BP has not been confirmed by Martin (1978). Under the recent coastal wedge and submarine beach, these sands present a semi-transparent seismic facies with few thin downlaps. This facies is contrasting with the true sigmoidal facies observed under the lagoon. The first facies is assumed to correspond to homogeneous sands with their muddy distal termination; the second facies is assumed to correspond to sands strata intercalated with coarse or muddy layers, often observed in semi-enclosed environments. The unit U3-1 probably formed in an open bay environment previously located in the northern part of the Leucate lagoon. In the southern part of the lagoon, a more enclosed environment probably existed but progradation remained (Labaune et al., 2003a,b,c).

Well developed channels are not observed through U3-1 and it may indicate that the Agly river had previously migrated towards the south to its recent location. Backward and behind the seaward prograding beach barrier thin sediments would be deposited. The base of the muddy deposits between D3-2 and D3-3 (Fig. 12) represents those sediments (unit U3-2). Despite a different seismic facies and the discontinuity observed, the prograding sands and mud would be synchronous. Doubts remain about the source of the sediment supply. The eastward/north-eastward progradation leads to exclude a supply due to a southward longshore drift. Moreover, the important volume of deposits excludes a direct supply by the small rivers located in the north/northwest of the Leucate lagoon. Progradation may be attributed to accretion due to the reworking of the old Agly terraces.

Above U3-1 (south-east limit, Fig. 12) the recent beach barrier developed during the stable highstand sea-level period (Fig. 13). It results from the reworking of the top of U3-1. This reworking surface would be correlated seaward with the discontinuity observed under the nearshore (Certain et al., 2004; Labaune et al., 2003b) and under the lagoon with its extension D3-3. This recent beach barrier would essentially consist of sandy deposits and levels of gravels provided by wave granulometric sorting. Toward the lagoon, its lateral extension (U3-3) may consist of tidal inlets sediment reworked by strong waves

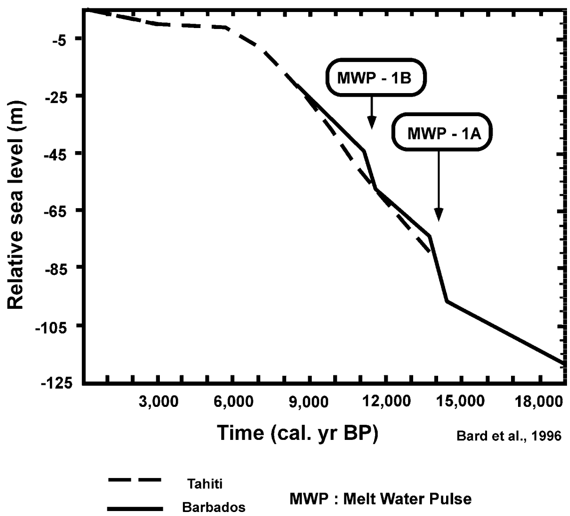

Fig. 13. Eustatic curve showing the alternate periods of increase and decrease rates of sea level rise. MWP are melt water pulses. From Bard et al., 1996. Sea level stabilized at about 6000 yr. BP and most of the coastal and deltaic plains deposits started to prograde.

induced by north-westward wind and/or of washover fan deposits. Above D3-4, the recent mud (U3-4) is deposited in an enclosed environment, the present Leucate lagoon. Some laminated sandy deposits would be locally intercalated.

Beyond of the seaward extension of U3-1 (Fig. 10b), unit U3 would be composed of thin deposits at the base, the healing phase concordant above D3-1. Those deposits, labelled U2b, were formed during the last sea-level rise. In the exposed line, the unit U3 is not clearly connected with U3-1. Nevertheless, it prolongates U3-1 northward of Cap Leucate. It probably developed during the last highstand period and would be an equivalent to U3-1 (thin deposits). It would be also correlated to unit U601 (Labaune et al., 2005, Fig. 3) clearly identified northward of Cap d'Agde.

5.2. Sequence stratigraphy interpretation (Fig. 14)

In sequence stratigraphic terms, the basal discontinuity D1 is a sequence boundary (SB) of 4th order, related to the oldest base level lowering which has been recorded. Due to the possibility of reworking during successive base level falls, its age is not precisely known. In the incised complex infilling, the internal discontinuities may represent younger sequence boundaries, generated during the periods of falling relative sea level which have punctuated the Upper Quaternary.

The subunits bounded by these sequence boundaries represent the remnants of depositional sequences in the complex. Because of aggrading seismic facies, they are interpreted as deposited in protected, semi-enclosed areas during a period of RSL rise. Thus the preserved part of the sequences is attributed to the TST. The number of preserved sequences is a main goal for the future which implies to fully correlate the seismic units along the incised valley complex (a new cruise has been carried out in July 2004).

The upper boundary of the incised complex infilling is wave ravinement surface which marks the final step of the eustatic sea-level rise in the nearshore area. The prograding wedge U2 would be a sedimentary body of the late TST. The healing phase (U2b), reworked top deposits of U2, is also interpreted as a part of the TST. The U2 wedge and the U2b healing phase are not observed within the whole studied area. The upper erosional surface, D3-1 is a ravinement surface and also a flooding surface.

The deposits of the highstand systems tract (HST) overlay the flooding surface and its seaward lateral conform equivalent. The flooding surface is interpreted as the maximum flooding surface (mfs). The lower prograding part of the HST and its lateral conform equivalents (lower lagoonal mud deposits and basal part of U3, above the healing phase) represent the early HST (decreasing rate of sea level rise until the stillstand). The recent beach barrier overlies a wave ravinement surface and its lateral conform equivalent through lagoonal mud. Our data do not show clear internal reflectors of the beach barrier. Hypothesis of a seaward accretion by reworking of previous deposits should be assumed. In this case, the surface is also a downlap surface.

To date, the age of this surface is not precisely defined and it cannot be correlated with an allocyclic event. The beach barrier and its lateral conform equivalent (upper lagoonal mud and upper part of U3) may be interpreted as late HST.

6. Discussion

The Plio–Quaternary record in the littoral area, from onshore core data, has been considered as reduced to a landward uplifting Pliocene boundary covered with Holocene prograding marine mud and continental sand deposited under stable highstand sea level conditions (Duvail and Le Strat, 2002). Two major incisions of the Upper Pliocene boundary were identified, with one located under the Leucate lagoon. In fact, the Pliocene boundary in the Leucate area is probably deeper than expected, and our geometric model (Fig. 14) shows that between this boundary and the uppermost prograding unit considered as the early modern HST, there is a preservation of sedimentary units attributed to several Quaternary relative sea level cycles and depositional sequences. The north to south irregular topography of the Upper Pliocene boundary is responsible for the more or less preserved record of the Quaternary transgressive–regressive cycles.

The location and drawing of the incised valley complex associated with the Aude, Orb and Agly

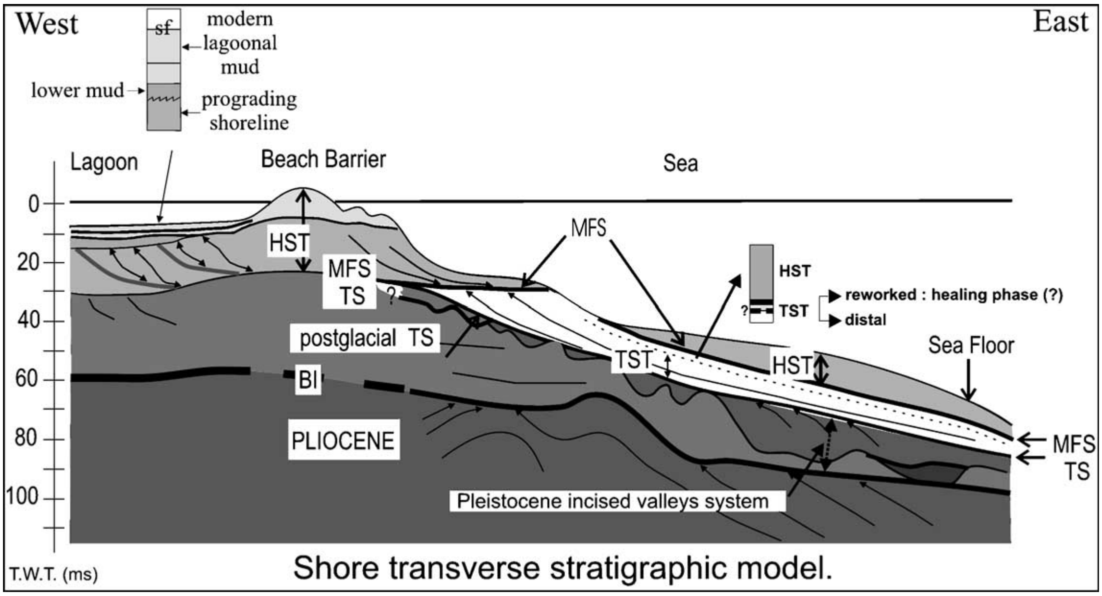

Fig. 14. Shore transverse stratigraphic model according to data of the Languedoc–Roussillon littoral and its buried incised valley complex. BI = basal incision; TS = transgressive surface; mfs = maximum flooding surface; sf = seafloor; TST = transgressive systems tract; HST = highstand systems tract.

rivers seems to have been induced in part by structural control of the underlying Pliocene strata, perhaps associated with lithologic parameters (Pliocene is mainly marly). The west–east oriented Leucate incised valley is superimposed with a syncline axis of the Pliocene substratum. The north–south oriented branch under the inner shelf is also superimposed with 2nd order deformations of the seaward dipping Pliocene strata and protected behind a kind of Pliocene high. The drawing of the incised valley complex shows that during sea level drops, the northern Languedoc–Roussillon rivers shifted southwards with alongshore course and merged. Thus, the drainage morphology was strongly modified and the rivers contribution to shelfal sediment supply evolved from linear to point source. During successive sea level drops of the Late Quaternary, the Gulf of Lion shelf was sediment supplied from only two drainage basins: the Rhône drainage basin in the north and the Languedoc–Roussillon single basin in the east. Consequently, the small Roussillon rivers had no meaningful effect on the strata development on the shelf. A similar change of the drainage system geometry has been described in the west of the Gulf of Mexico (Suter, 1994; Thomas and Anderson, 1991) where the Nueces river became a tributary of the Rio Grande on the shelf.

Preservation of several transgressive system tracts and sequence depositional units in the incised valley complex is not common. They are generally drowned and filled by sediment during the last sea level rise and subsequent highstand (Ashley and Sheridan, 1994; Dalrymple et al., 1992; Zaitlin et al., 1994). On the French Atlantic coast, the incised valley infilling comprises mostly the lowstand fluvial coarse material overlying the sequence boundary, the transgressive estuarine and marine sands with several key surfaces (tidal and wave ravinement surfaces) and the highstand prograding muds over the mfs. The sequence boundary has been incised during the Wurm sea level drop and the incised valley fill (IVF) thickness is rapidly decreasing seaward so that the direct relationship with the stacked depositional sequences on the inner and mid shelf is not clear (Allen and Posamentier, 1993, 1994; Chaumillon et al., 2000; Lericolais et al., 2001; Weber et al., 2003). On the Mediterranean coast, the Rhône river delta shows a similar stratigraphic pattern with a thick pebble and gravel basal level above Pliocene strata, a postglacial TST and a modern HST (Boyer et al., 2003a,b; Gensous et al., 2003; Oomkens, 1967). The pebble level is thick (several 10th of metres) and prevents from accurate drilling operation. Thus it remains possible that this level should be made of several relict and imbricated lowstand units of coarse material. Offshore of the delta, the architecture and the direct link with the Quaternary depositional sequences is not observable because of seismic pulse diffraction and attenuation, due to coarse material and occurrence of gas in the upper deposits. On the mid-outer shelf, there are deposits related to transgressive–regressive cycles (Tesson, 1996) on the western flank of the Rhône incised valley. It may be assumed that the Rhône incised valley fill would have recorded the Late Quaternary sea level drops. The record of these drops is preserved and observed more seaward than in the case of the Languedoc–Roussillon incised valley complex. Similar record is well documented for the Gulf of Mexico (Suter, 1986; Thomas and Anderson, 1994) or Virginia inner shelf (Foyle and Oertel, 1997) where several phases of deep incision have been mapped and the sedimentary infilling is mainly composed of stacked transgressive systems tracts. In our study area, the successive incisions reach great depths.

The tectonic control on the preservation potential of deposits relative to successive sea level drops, in our study area, may exist at the Late Quaternary scale. The fluvial terraces in the hinterland are well preserved and organized in a pattern indicative of a landward uplift (Duvail and Le Strat, 2002). In the Languedoc–Roussillon incised valley complex infilling, the level reached by the successive incisions progressively decreases. If we consider that the base level reached more or less similar depths during the successive Late Quaternary maximum sea level lowstands, then it suggests that the littoral area was slowly subsiding. This is in good agreement with the stratal architecture on the mid-outer shelf and the effects of the control exerted by tectonic has been previously presented (Tesson and Allen, 1995). The hinge point should be located more or less landward, depending on local structural trends (Posamentier et al., 1988). Tectonic controlled the Late Quaternary sedimentation by the means of: 1— the previous deformations of the Pliocene substratum which led to uplifted and lowered areas on which the space needed for sedimentation was reduced or increased, and constrained the river talweg location during the phases of lowering and rising base level, 2— the synsedimentary differential subsidence and uplift during the Late Quaternary. This tectonic control has several major consequences on the depositional units in the littoral area by controlling the geometry and lithology of the deposits, with importance for littoral environment engineering, and also it may be indicative of large scale trend of the fluvial behaviour under sea level oscillations. Together with slope gradient, other factors control the fluvial response to eustasy (Blum, 1990). However the preservation potential here is mainly controlled by tectonics. The actual fluvial talweg location should be temporary and may returned to their “historical” location under catastrophic events.

Sedimentation during the last sea level rise, in this inner shelf/littoral area overlying the previous Agly incised valley, is particular because the present day river has shifted to the south. Above the presumed wave ravinement surface D2, the transgressive systems tract is reduced to a small prograding wedge that is usually indicative of a decrease or stillstand of the rate of sea level rise (Darigo and Osborne, 1986). The upper part of the last progradational clinoforms is at 35 ms b.p.s.l. (about 25 m). Considering a removed part of 5 m sediment, the sea level was at about 20 m b.p.s.l. and refers to about -8000 yr BP (Ters, 1986). If we consider that the progradation is due to decreasing rate of the sea level rise, then we have to explain the origin of the ravinement surface capping the wedge. Because this wedge is not common on the Gulf of Lion shelf and the study area is an active river front (Agly), we propose that the progradation is associated to a local increase of the sediment supply. The initial point of progradation is believed to have been somewhere landward from the actual shoreline. It should have been at the Mesozoic boundary (western side of the Leucate lagoon). The ravinement surface developed as the sediment flux decreased and the shoreline migrated landward again.

The prograding highstand systems tract (PL) observed under the Leucate lagoon developed probably before the end of the sea level rise. The documented coastal plain stratigraphy at the base of the Romarin cliff, a short distance north of the Cap Leucate, shows at the base a transgressive systems tract composed of gravelly sands. This first coastal construction is overlain by 15 m of prograding, well sorted and fine to medium sands with shells. The transition from transgressive to highstand systems tracts occurred at the maximum sea level (prior to 4000 yr BP). The prograding unit PL under the Leucate lagoon is slightly different and downward shifted compared to the Romarin sketch. It progressively uplifts towards the beachbarrier so that the beginning of the highstand systems tract progradation probably started before the end of the sea level rise. This different timing of progradation is assumed to be in relation to a more important sediment supply in the Leucate area than in the Romarin area, that is believed to be induced by the Agly river proximity. This coastal progradation of an early highstand systems tract is in agreement with sequence stratigraphy models (Posamentier and Vail, 1988; Posamentier et al., 1988) and confirms a part of previous works around the Gulf of Lion (Aloisi et al., 1978; Martin, 1978).

The highstand systems tract located seaward and downward of the transgressive wedge and considered as an analog of the subaqueous delta as described by Cattaneo et al. (2003) is similar to the model of fine continental material dispersal and sedimentation on the western coast of the Adriatic sea. It has been mapped seaward of the Rhône delta (Labaune et al., 2003a, 2005) and the direct correlations are expected soon. It consists of fine material and we believe that under modern oceanic environmental conditions the coarse material is stored on the coastal area (with fluctuations depending upon seasonal oceanic climate changes), while the fine material supplied by rivers or delivered by wave reworking is dispersed seaward. A major contribution from the Rhône river sediment input using an along-shore drift is probable.

7. Conclusions

The incised valley fill complex on the Languedoc–Roussillon littoral and inner shelf is directly connected with the landward Quaternary fluvial terraces and the depositional sequences on the mid-outer shelf. Several sea-level drops and their associated key-surfaces and sedimentary units have been recorded. It represents the only area of the Gulf of Lion coast to study the land to sea relationship, their evolution during climate and sea level changes and the sedimentary budget.

The Languedoc rivers have greatly modified their courses during the phases of lowering and rising base level and merged at the inner shelf level. They constituted a shore-parallel estuary successively reoccupied during the Late Quaternary, with a seaward connection several 10th kilometers southward. Consequently the sediment supply that contributed to growth of the Gulf of Lion shelf was mainly delivered by two points sources: the Rhône drainage basin and the studied complex. The southwesternmost Roussillon rivers (Têt and Tech) had little influence on shelf and strata development.

The incised valley fill is largely constituted with Pleistocene transgressive deposits that were erroneously considered as part of the last transgressive system tract (Holocene period).

The preservation of Pleistocene transgressive deposits in the incised valley complex has probably a tectonic origin due to landward uplift and seaward subsidence, with an hinge point located landward of the littoral area.

A small prograding wedge that is sub-outcropping at the base of the littoral wedge is considered to represent a particular event (decreasing sea level rise rate/sediment supply) during the last transgression. Ravinement of its upper part contributed to an healing phase of fine material.

Progradation of the recent coastal plain deposits probably started shortly before the last sea level rise stopped. Complex depositional environments developed with some earlier low energy depositional systems back from the prograding shoreline (initial phase of lagoonal or semi enclosed bodies). This prograding phase constitutes a thinning seaward wedge of submarine beach and sandy coastal bars deposits. A more distal sigmoidal and muddy unit develops and thickens northeasterly constituting probably a subaqueous delta partly supplied with Rhône river fines. The actual system of beach barriers developed later when sea level stabilized and rested upon a wave ravinement surface. Remobilized sandy material from flood tidal delta and washover are intercalated within the lagoonal muds.

The Languedoc–Roussillon littoral area presents sedimentological and morphostructural trends which are in part inherited from the Pliocene and Quaternary. Consequently, the modern sedimentary processes are not the only key to understand the three dimensional architecture and lithology and the past and future evolution.

Acknowledgements

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