Marine Geophysical Researches (2005) 26:109–122
DOI 10.1007/s11001-005-3711-z

Integration of high and very high-resolution seismic reflection profiles to study Upper Quaternary deposits of a coastal area in the western Gulf of Lions, SW France

Caroline Labaune*, Michel Tesson and Bernard Gensous
Laboratoire de Biophysique et Dynamique des Systèmes Intégrés, BDSI Perpignan University, 52 Avenue Paul Alduy, 66860 Perpignan cedex, France
**Corresponding Author (Phone: +33-4-6866-2112; E-mail: labaune@univ-perp.fr)*

Received 30 January 2004; accepted 5 June 2005

Key words: borehole, coastal plain, Gulf of Lions, lagoon, late Quaternary deposits, near-shore, seismic stratigraphy

Abstract

High resolution (HR – sparker) and very high resolution (VHR – boomer) seismic reflection data acquired in shallow water environments of the Roussillon coastal area are integrated to provide an accurate image of the stratigraphic architecture of the Quaternary deposits. The complementary use of the two systems is shown to be of benefit for studies of shallow water environments.The HR sparker data improved the landward part of a general model of Quaternary stratigraphy previously established offshore. They document an incised valley complex interpreted as the record of successive late Quaternary relative sea-level cycles. The complex is capped by a polygenetic erosional surface developed during the last glacial period (> 18 ky) and variably reworked by wave ravinement during the subsequent post-glacial transgression. The overlying transgressive systems tract is partly preserved and presents a varying configuration along the Roussillon coastal plain.The VHR boomer data provide information on the architecture of the uppermost deposits, both in the near-shore area and in the lagoon. These deposits overlie a maximum flooding surface at the top of the transgressive systems tract and constitute a highstand systems tract composed of two different architectural elements. In the near-shore area, a sandy coastal wedge is subdivided into a lower unit and an upper unit in equilibrium with present day dynamics. In the Salses-Leucate lagoon area, the sedimentary architecture is highly complex due to the closure of a former embayment and the formation of the present beach barrier.

Introduction

Most studies of near-shore areas have focused on the hydrodynamic regime and its impact on recent sedimentation (Nielsen et al., 2001; Stépanian and Levoy, 2003). Integration over longer timescales has usually been applied either to deposits onshore in the coastal plain or offshore across the continental shelf. In particular, many studies have addressed the late Quaternary architecture of continental shelves (Suter et al., 1987; Hernandez-Molina et al., 1994; Tesson et al., 2000; Ridente and Trincardi, 2002). However, few studies have really dealt with the architecture of deposits across the coastal zone, i.e. the transition between the continental and marine domains spanning the coastal plain to the inner continental shelf. One of the first was proposed by Penland et al. (1988) in the Mississippi delta area and focused essentially on the post-glacial transgressive deposits and the development of coastal barriers. Thomas and Anderson (1994) carried out a study of a late Quaternary incised valley system on the Texas continental shelf and proposed a correlation with coastal plain deposits. Locker et al. (2003) carried out seismic studies on the post-glacial Florida inner shelf and near-shore area. In most areas, however, there remains a gap concerning the geological evolution of the near-shore area due to a lack of direct correlation between data from the onshore and marine domains.

The Roussillon coastal plain (western part of Gulf of Lions, France), its shoreface and the adjacent continental shelf have been the subjects of a number of sedimentological studies, none of which have integrated the transition from the coastal plain to the continental shelf. Several studies, based on borehole data or geomorphology, have dealt with the Quaternary fluvial terraces on the coastal plain (Carozza and Delcaillau, 1999; Duvail et al., 2001). The post-glacial infill of the Salses-Leucate and the Canet-St Nazaire lagoons were studied without real correlation to the marine area (Martin, 1978; Martin et al., 1981; Certain et al., 2004). Durand (1999) focused on the shore face area in order to determine the recent evolution of the beaches attributed to present hydrodynamic conditions. A preliminary study of the onshore to inner shelf transition was presented by Monaco (1971), but was limited by a lack of near-shore data.

In order to fill the coastal data gap, several seismic acquisition cruises have been undertaken since 2000 along the Roussillon coast, both in shallow marine areas and in lagoons. The high and very high resolution (HR and VHR) seismic reflection data that were acquired supplement a HR seismic database previously acquired across the Gulf of Lions continental shelf (Tesson et al., 2000; Gensous and Tesson, 2003). In this paper, an integration of the HR and VHR seismic data types is presented and used to discuss the evolution of the Roussillon coastal area during the Quaternary. The marine and lagoonal seismic profiles are correlated with a borehole previously acquired on the beach barrier, allowing us to relate the key seismic surfaces and facies to lithology and so improve the architectural model.

Regional setting

The Gulf of Lions is a passive margin that has developed since the Messinian salinity crisis (Hsü et al., 1973) under the influence of sea-level variations. In addition, during the Plio–Quaternary (Bessis and Burrus, 1986; Clauzon et al., 1987) differential landward uplift and seaward subsidence have led to a sedimentary architecture of deposits characterised onshore by an imbricated system of fluvial terraces (Duvail and Le Strat, 2002) and on the shelf by stacked marine depositional sequences (Lofi et al., 2003).

The onshore area of Languedoc–Roussillon is characterised overall by a Pliocene substratum overlain by a system of imbricate Quaternary fluvial terraces that record a history of uplift movements (Duvail and Le Strat, 2002). The terraces have also been influenced by late Quaternary glacio-eustatic cycles and associated changes in base level.

On the Roussillon coastal plain, lithological analysis of boreholes (Duvail et al., 2001) has contributed to a general stratigraphic model of the Plio–Quaternary deposits that is still in development. Pliocene strata underlie much of the Roussillon plain. Lower Pliocene deposits outcrop as Gilbert deltas (Clauzon, 1990) in the upstream parts of the plain as seaward-dipping marine muds

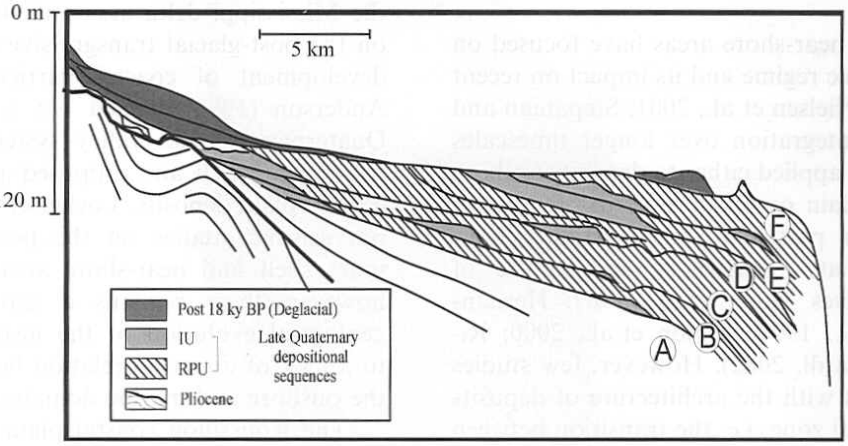

Figure 1. Architectural model of Plio–Quaternary deposits in the western part of the Gulf of Lions (Languedoc-Roussillon continental shelf, modified from Tesson and Gensous, 1998). IU: Intercalated Unit; RPU: Regional Prograding Unit.

overlain by marine sands and capped by continental muddy-sands. The upper boundary of the Pliocene corresponds to a major unconformity at the base of Pleistocene alluvial terraces. The Holocene is represented by a prograding system comprising a succession of basal marine muds, marine sands and complex continental deposits (fluvial sands, conglomerates and/or lagoon muds).

On the shelf, the late Quaternary deposits comprise stacked marine depositional sequences, the upper of which are mainly related to the fourth-order glacio-eustatic cycles of sea level that punctuated the late Quaternary (Aloisi, 1986; Tesson et al., 1990; Tesson et al., 1993; Rabineau et al., 1998; Lobo et al., 2004). The sequences pinch out landward at about 80 m below sea level (Figure 1) except in the north of the Gulf where they seem to extend below the recent lobes of the Rhone delta. Each sequence comprises a wedge-shaped prograding unit, or RPU, of regional extent and locally an intercalated unit or IU (Figure 1). The RPUs are interpreted as lowstand wedges associated with relative sea-level fall and the following lowstand period. They provide an example of forced regressive deposits (Tesson et al., 1990; Posamentier et al., 1992). The IU represents near-shore sand bodies that accumulated either during the period of maximum relative sea level lowstand and/or during stillstands that occurred during the following period of rise (Tesson et al., 2000).

Throughout the study area, the Pleistocene deposits are capped by a polygenetic erosional surface that developed during the last relative sea level fall and the subsequent post-glacial relative sea level rise (Figure 1). The post-glacial deposits are concentrated along the outer and inner shelf as retrograding units of the transgressive systems tract. A regressive highstand systems tract developed on the inner shelf but is poorly known because previous studies generally do not extend to less than 20–25 m water depth (Monaco, 1971; Aloisi et al., 1975; Gensous and Tesson, 2003; Lobo et al., 2004). Onshore, the post-glacial deposits are mainly represented by alluvial plain deposits (Duvail et al., 2001).

The present Roussillon shoreline is sandy and interrupted from north to south by three rivers (Agly, Têt and Tech). Moreover two lagoons (Salses-Leucate and Canet-St Nazaire) are isolated behind a beach barrier subjected to microtidal and wave dynamics. Median grain size increases from 0.6 to 1.8 mm from north to south (Durand, 1999). Seaward, the sand to mud boundary lies near 30 m b.s.l. (Figure 2). Some beachrocks or sandstones, considered as relict Quaternary deposits, outcrop at up to 50 m b.s.l. (Monaco et al., 1972). In the lagoons, the uppermost deposits are muds (Martin, 1978; Martin et al., 1981) that should represent the transgressive and highstand deposits of the late post-glacial period (Certain et al., 2004).

Data and methods

Two types of seismic reflection profiles, HR and VHR, were acquired, in some cases along the same lines. Seismic units identified in the lagoon were correlated to those in the near-shore area using a borehole previously acquired on the beach barrier.

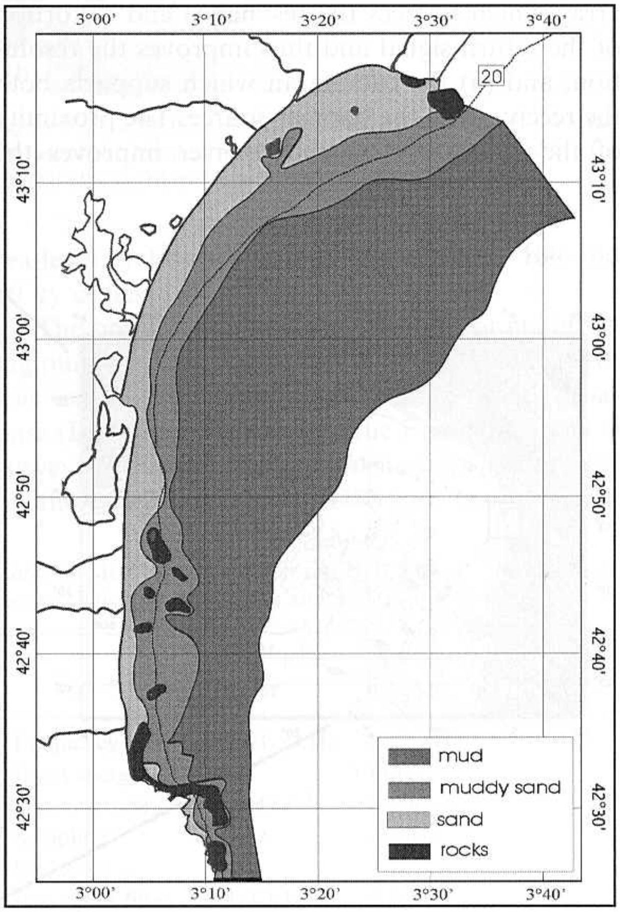

Figure 2. Simplified surficial sediment facies distribution across the study area (modified after Aloisi, 1986 and Gensous et al., 1993). Bathymetric contour shown is 20 m below sea level.

The seismic acquisition was carried out using two different platforms: seaward of 15 m b.s.l., a conventional 25 m research vessel (N/O Tethys II of CNRS-INSU) was used, whereas in shallower water and in the lagoon, a 5 m boat was used. About 200 km of HR seismic profiles and 1000 km of VHR profiles were acquired (Figure 3), both in the Salses-Leucate lagoon and in shallow marine environments. All seismic data were acquired digitally, using the Delphseismic 2.1 software, and geo-referenced using a differential global positioning system (DGPS).

The HR seismic data were acquired with a SIG™ mini-sparker composed of a multi-electrode sparker array and a single channel streamer with five hydrophones (Figure 4). The VHR seismic data were acquired with a novel type of boomer, the IKB Seistec™ boomer (Figure 5), developed for marine and lacustrine environments in 1987 (Simpkin and Davis, 1993). The innovations of the boomer are (i) the line-in-cone receiver array which reduces the resonance and distortion of the return signal and thus improves the resolution; and (ii) the catamaran which supports both the receiver and the boomer source. The proximity of the source and of the receiver improves the definition of close targets. A filter removes frequencies below 1000 Hz directly at the top of the line-in-cone receiver.

Since the study focused both on the overall Quaternary stratigraphy and on the detailed post-glacial evolution, it was necessary to operate seismic systems that combined both penetration and resolution. This would normally imply acoustic pulses that are characterised by a broad bandwidth since higher frequencies are quickly attenuated during travel time but give HR, whereas lower frequencies give lower resolution but better penetration. The integration of the mini-sparker, HR system with relatively good penetration (up to 80 m), and the boomer, VHR system with good resolution (about 0.25 m) was found to be a good alternative. The technical and acquisition characteristics of each system are listed in Table 1.

For interpretation, the seismic profiles were converted from two-way time to depth in meters using 1700 m s^{-1} sound velocity in the sediments and 1500 m s^{-1} in the water column. The interpretation was based on the seismic stratigraphic concepts and methods first outlined in AAPG Memoir 26 (Mitchum et al., 1977). These concepts were improved by Posamentier et al. (1988) and

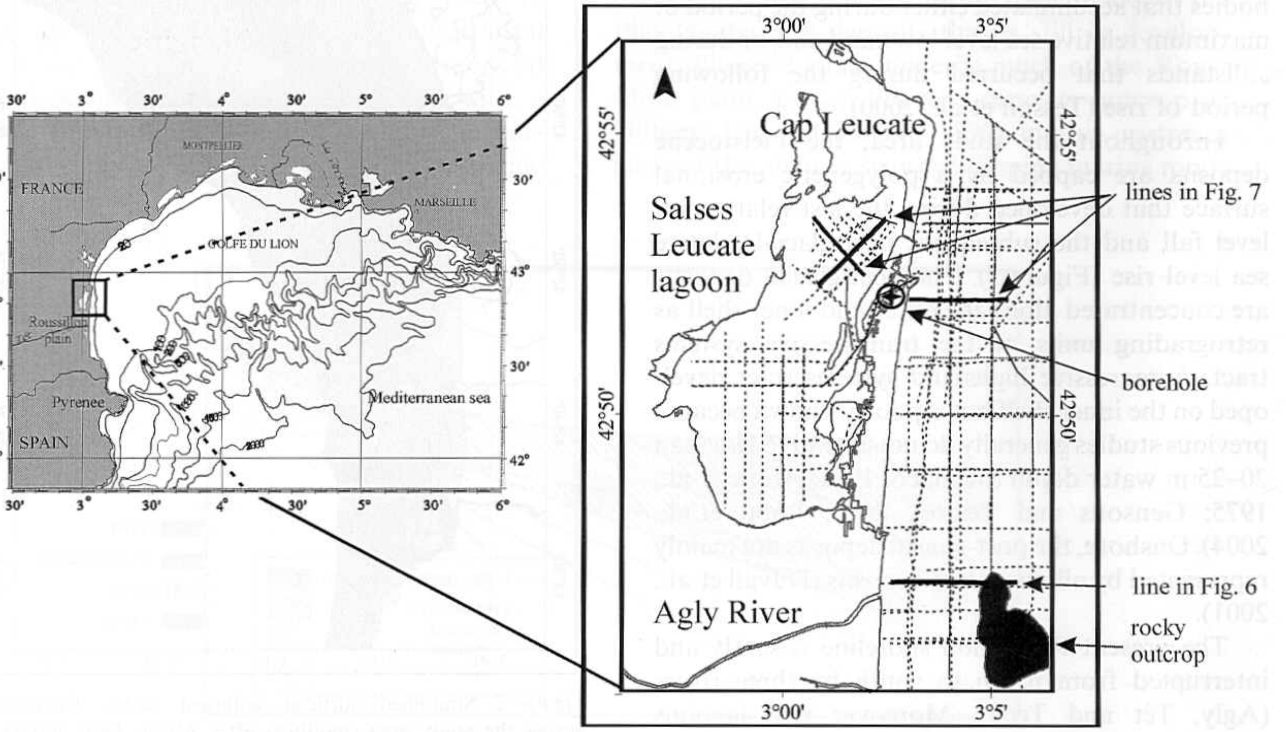

Figure 3. Map showing the locations of seismic profiles acquired in the study area. Highlighted lines correspond to seismic profiles shown in Figures 6 and 7.

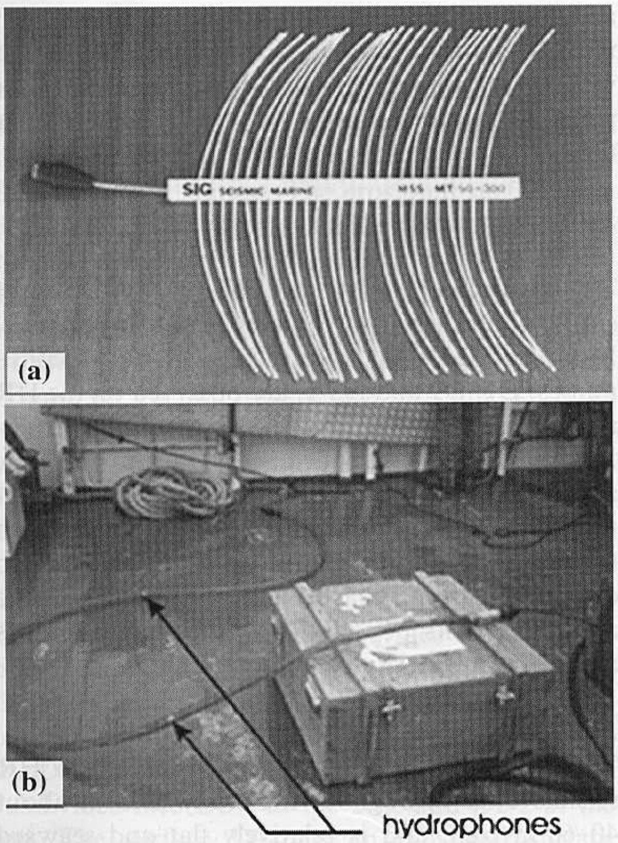

Figure 4. The SIG^{TM} mini-sparker components: (a) the multi-electrode sparker array; (b) the single-channel streamer composed of five hydrophones at 1 m spacing.

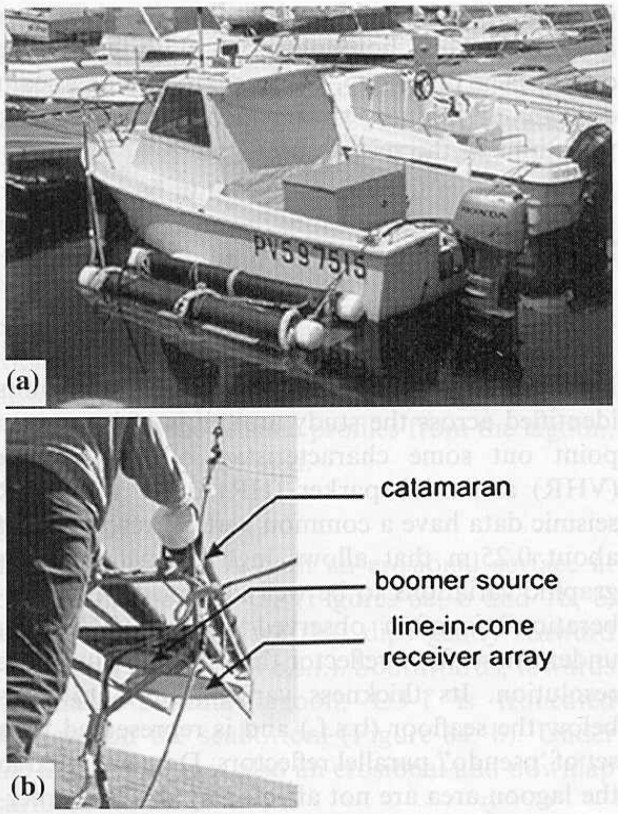

Figure 5. The IKB-Seistec^{TM} boomer equipment: (a) the catamaran of the boomer on the side of the 5 m boat used for the coastal study; (b) main components of the boomer.

Posamentier and Vail (1988) and key terminology defined by Van Wagoner et al. (1988). The sequence stratigraphy concepts are based on the identification of regional discontinuities bounding stratigraphic units interpreted as sequences and/or their internal components (systems tracts). The genesis of the sequences and systems tracts is attributed to relative sea-level changes, and specific increments of the cycles and local variations are due to 2nd order controlling factors such as the sediment load. The identification of physical discontinuities and acoustic facies by seismic systems is essential to define the sequences and the systems tracts when boreholes are not available This model was initially developed using conventional seismic exploration data and borehole calibration and further applied to HR and VHR seismic data. The key unconformities observed on the seismic profiles are interpreted as regressive and transgressive surfaces and maximum flooding surfaces that are related to relative sea-level cycles of 4th and 5th order, i.e. 100 and 20 ky cycles.

The borehole previously acquired for engineering purposes on the beach barrier in the mid-1970s was available from the national subsurface database (BDSS) of the BRGM (the French geological survey). Generally, little information is available on the boreholes of the BDSS and in this study,

Table 1. SIG^{TM} mini-sparker and IKB Seistec^{TM} boomer systems; acquisition parameters and data characteristics.

	SIG^{TM} mini-sparker	IKB Seistec^{TM} boomer
Frequency band	0.05–1.5 kHz	1–12 kHz
Input energy	50 J	140 J
Shooting rate	2 shots s^{-1}	2 shots s^{-1}
Sampling frequency	6 kHz	24 kHz
Band pass filter	0.4–1.1 kHz	1–3 kHz
Resolution	1–2 m	0.25 m
Penetration	Up to 80 m in study area	Up to 20 m in sands and muddy sands

only the lithological log based on cuttings was available. This borehole log indicates strong contrasts in lithology, assumed to be significant enough to induce strong acoustic impedance variations in the seismic profiles.

Results

Seismic characteristics

Before describing the seismic surfaces and units identified across the study area, it is of interest to point out some characteristics of the boomer (VHR) and mini-sparker (HR) data. The VHR seismic data have a common vertical resolution of about 0.25 m that allows high frequency stratigraphic variations to be well identified. A "reverberation" is often observed on the VHR data under the seafloor reflector that locally reduces the resolution. Its thickness varies from 4 to 2 ms below the seafloor (b.s.f.) and is represented by a set of 'pseudo" parallel reflectors. Data acquired in the lagoon area are not affected by this "reverberation".

The HR data are generally affected by acoustic ringing caused by the bubble oscillation of the sparker source. However, the data show a different acoustic response in the lagoon and near-shore areas where the data quality is improved with reduced acoustic ringing (from 4 to 2 ms) and a weak first multiple arrival. This allows a better penetration, up to 70 m, that permits the deeper targets to be investigated.

Seismic stratigraphy

The main characteristics of the observed seismic surfaces and units are summarized in Table 2. From base to top, three main regional discontinuities, D1, D2 and D3-1, are observed on the HR and VHR seismic profiles (Figures 6 and 7). Locally, D2 is subdivided into D2-1 at the base and D2-2 at the top. Above D3-1, several discontinuities of local extent are observed especially in the lagoon (D3-2, D3-3 and D3-4). D3-3 seems to extend across the beach barrier in the shore face area. The units bounded by these discontinuities are labelled Ub, Ur, U2 and U3.

Surface D1

The basal discontinuity D1 is observed on HR seismic data throughout the study area at about 40–60 m b.s.l. and is relatively flat and seaward dipping. It truncates a basal unit, Ub, characterized by oblique reflectors of high amplitude and low frequency. The unit Ub exhibits well-developed folded structures.

Table 2. Properties of the observed seismic discontinuities and units.

Discontinuities	Units	Properties of discontinuities	Type of discontinuities	Area of location
	U3-4			
D3-4		Para-concordant surface	Facies boundary	Lagoon
	U3-3			
D3-3		Erosional surface (marine area) Para-concordant (lagoon)	Wave reworking surface (marine)	Lagoon and near-shore
	U3-2			
D3-2		Seaward rising with topset below and onlap above	Facies boundary	Lagoon
	U3-1			
D3-1		**Erosional and linear surface** **Toplap below, downlap above**	**Ravinement surface and maximum flooding surface**	**Lagoon and marine**
	U2-b			
D2-2		Onlaps above	Wave ravinement	Lagoon and marine
	U2-a			
D2-1		**Toplap/onlap terminations**	**Transgressive surface**	**Lagoon and marine**
	Ur			
D1		**Subaerial erosional surface** **Toplaps below**	**Unconformity: sequence boundary**	**Lagoon and marine**

The discontinuity D2 mentioned in the text is subdivided into D2-1 and D2-2. The main discontinuities are highlighted in bold.

Unit Ur

Above D1, the HR seismic data show a set of erosional surfaces bounding seismic units globally labelled Ur (Figures 6 and 7b). The maximum thickness of the unit is about 20 m in front of the Salses-Leucate lagoon. The erosional surfaces are imbricated and comprise sub-horizontal parts and channel incisions from 1 m to about 10 m depth. The infill of major channels is characterized by aggrading sub-horizontal reflectors, whereas in smaller channels the seismic facies is rather chaotic (Figure 6b, d). Southward, the erosional surfaces tend to merge. Under the lagoon, only one sub-horizontal surface is observed between D1 and D2. The extension of unit Ur under the lagoon is not clearly observed on the seismic data (Figure 7c).

Surface D2

Ur is capped by an erosional surface D2 that is an unconformity. D2 is relatively flat in the south of the study area (Figure 6) and dips gently seaward in front of the Salses-Leucate lagoon (Figure 7b, d). D2 is a polygenetic surface, either merged or subdivided into D2-1 at the base and D2-2 at the top. The surface D2-1 is an erosional surface incised by small channels (Figure 7b), observed especially on the VHR seismic data. The surface D2-2 is identified in the shore face zone in the southern part of the study area (Figure 6a) and beyond 20 m b.s.l. in front of the Salses-Leucate area (Figure 7b) and is an erosional surface that onlaps in distal areas and downlaps in proximal areas. In the lagoon, the penetration of VHR seismic profiles is not adequate to clearly identify D2 and the surface that is observed on the HR seismic data is too deep to represent D2. It is more likely that D2 is merged with the surface D3-1 above.

Unit U2

The unit U2 is developed between D2 and D3-1 (Figures 6a and 7b, d) in the area in front of the Salses-Leucate lagoon, at about 20 m b.s.l. It has a maximum thickness of 10 m and is subdivided into U2-1 at the base and U2-2 at the top. Unit U2-1 is relatively thin (maximum thickness 3–4 m) and contains small channels and chaotic facies (Figure 7b). Unit U2-2 is composed of truncated oblique clinoforms dipping seaward with upper terminations either as coastal onlap or toplap. On the HR seismic lines, the clinoforms are characterized by low amplitude and low frequency. In the area located south of Salses-Leucate lagoon, U2 (Figure 6a, b) is also subdivided into U2-1 and U2-2 but with different properties and seismic facies. The unit U2-1 is only observed in the area below 20 m b.s.l., where its seismic facies evolves from chaotic to oblique reflectors. The unit U2-2 is present in the shoreface area and below 30–35 m b.s.l. where it is composed of oblique tangential reflectors with toplap and downlap terminations, whereas in distal areas, it is a thin unit with sub-horizontal reflectors. On the seismic profiles from the lagoon, U2 is not clearly defined.

Surface D3-1

The surface D3-1 is both an erosional surface at the top of the unit U2 (Figures 6a, b and 7b, c) and a downlap surface that dips gently seaward (between 15 and 30 m b.s.l.). Southwards, towards the Salses-Leucate lagoon, D3-1 is truncated seaward on the seabottom (Figure 6a, b). Under the lagoon, D3-1 is also an erosional and downlap surface.

Unit U3

Overlying D3-1, unit U3 is wedge-shaped and pinches out seaward at about 30 m b.s.l. in the south of the area. In the northern part of the area, in front of the Salses-Leucate lagoon, it evolves seaward into a thin layer (3 m b.s.f.) detected only on the VHR seismic profiles. In the shoreface area, the U3 wedge is subdivided into unit U3-1 at the base and unit U3-3 at the top, separated by the seismic surface D3-3. U3-1 is composed of prograding clinoforms and its thickness reaches 15 m. Above, U3-3 corresponds to the near-shore sand ridges that constitutes the modern upper shoreface. The seismic facies of U3-3 is obscured by the first multiple arrival and the boomer reverberation due to the very shallow water (Figure 6b). In the Salses-Leucate lagoon, unit U3 is more complex and comprises four units (Figure 6a). The basal unit U3-1 is composed of a set of seaward prograding and aggrading sedimentary bodies characterised by sigmoidal clinoforms. It is the most developed unit with a maximum thickness of about 10 m. Above U3-1, three units with similar characteristics are stacked (U3-2, U3-3 and U3-3 from base to top). They are characterised by aggrading

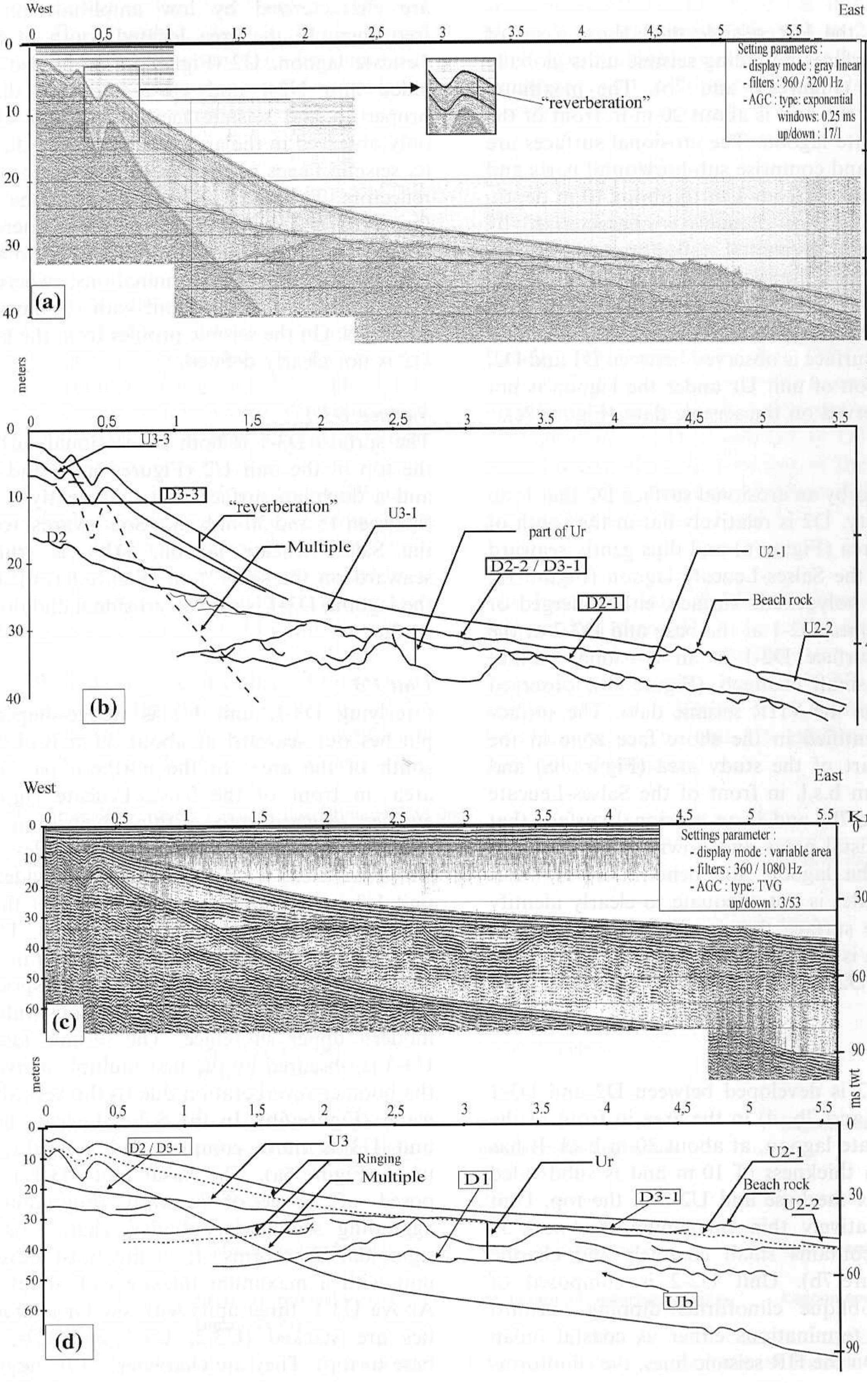
West
East
Km
meters
ms twt
Setting parameters :
- display mode : gray linear
- filters : 960 / 3200 Hz
- AGC : type: exponential
windows: 0.25 ms
up/down : 17/1
"reverberation"
(a)
U3-3
D3-3
"reverberation"
U3-1
Multiple
D2
part of Ur
D2-2 / D3-1
U2-1
D2-1
Beach rock
U2-2
(b)
Settings parameter :
- display mode : variable area
- filters : 360 / 1080 Hz
- AGC : type: TVG
up/down : 3/53
(c)
D2 / D3-1
U3
Ringing
Multiple
Ur
D1
D3-1
U2-1
Beach rock
U2-2
Ub
(d)

Figure 6. Seismic profiles showing the architecture of deposits in the southern part of the study area. Lines (a) and (b) represent the boomer profile and its line-interpretation. Lines (c) and (d) represent the mini-sparker profile and its line-interpretation. The main characteristics of the single channel seismic recording can be seen including the 'ringing' or the 'reverberation' and the first multiple arrival. Line (b) shows two discontinuities, D2 and D3-1, which merge in the near-shore area. They delimit two units U2 and U3. In line (d), a new basal discontinuity (D1) forms the lower boundary of unit Ur.

sub-horizontal reflectors. The subdivision of U3-2, U3-3 and U3-4 is mainly based on seismic facies, amplitude and frequency variations. They are bounded by D3-2 at the base, an onlap surface, and the para-concordant surfaces D3-3 and D3-4 and the bottom floor at the top. U3-2 is restricted to the central part of the lagoon and shows aggrading sub-horizontal reflectors onlapping toward the beach barrier. The two upper units, U3-3 and U3-4 do not exceed 2–3 m in thickness. Unit U3-3 extends through the beach barrier, whereas Unit U3-4 is restricted to the lagoonal area.

Correlation to borehole lithologies

The borehole (Figure 7e) was located on the beach barrier between the lagoon and the shelf (see Figure 3) with the top at about 1 m a.s.l. The total borehole penetration was 27 m. The lithological log shows prevailing sandy deposits interrupted by three thick levels of gravels and pebbles (from 1 to 4 m thick) at about 4 m, 16 m and 21 m b.s.l., respectively. Above the uppermost pebble level, the sands are coarsening upwards. Between 4 and 16 m b.s.l., two trends are observed, fining upwards at the base and then coarsening upwards. The lower two units, below the second and the lowermost pebble level, both coarsen upwards. Macrofaunal data are not referred to in the borehole log description, so the depositional environment could not be deduced. The sharp contacts between pebbles and overlying sands constitute major levels of acoustic impedance contrast and are correlated with major reflectors in the seismic profiles. The upper boundaries of the first level and second level of pebbles are correlated to D3-3 and D3-1 respectively. In the shoreface off the lagoon, D2 and D3-1 are amalgamated but it may be assumed that a subdivision occurred under the beach barrier and thus the pebble level at 21 m b.s.l may correlate to D2.

Discussion

Surficial sediment effect on seismic records

Considering information on the surficial sediment distribution from north to south along the shoreface area (Durand, 1999), and from the shoreline to the inner shelf (Aloisi, 1986), the "reverberation" seems to vary in correspondence with surficial sediment texture. The "reverberation" is amplified where the seafloor sediments are coarse-grained, whereas in the lagoon, where surficial sediment is of fine muds, the "reverberation" is not observed. The "reverberation" intensity would seem to be proportional to the grain size of the surficial sediment, it could therefore be interpreted as a resonance phenomenon linked to the character of the surficial sediment immediately beneath the water bottom.

On the HR seismic data, the thin surficial muddy layer, which gives a reduced impedance contrast between the water column and the sea-bottom, also reduced the first multiple arrival and the ringing due to the bubble pulse oscillation. These effects improve the data quality in the lagoon, increasing both the penetration and the resolution.

Stratigraphic interpretation in relation to sea level variation

The stratigraphic architecture is presented in Figure 8. The basal unconformity D1 is correlated landward to the upper boundary of the lower Pliocene (Duvail and Le Strat, 2002). Thus the unit underlying Ub also includes the lower Pliocene deposits that are the substratum of the Quaternary deposits. D1 is interpreted as a sequence boundary which probably marked the end of the last Pliocene 3rd order sea-level cycle (cycle 3.8, Haq et al., 1987).

The imbricated erosional surfaces and units (Ur) observed above D1 represent an Incised

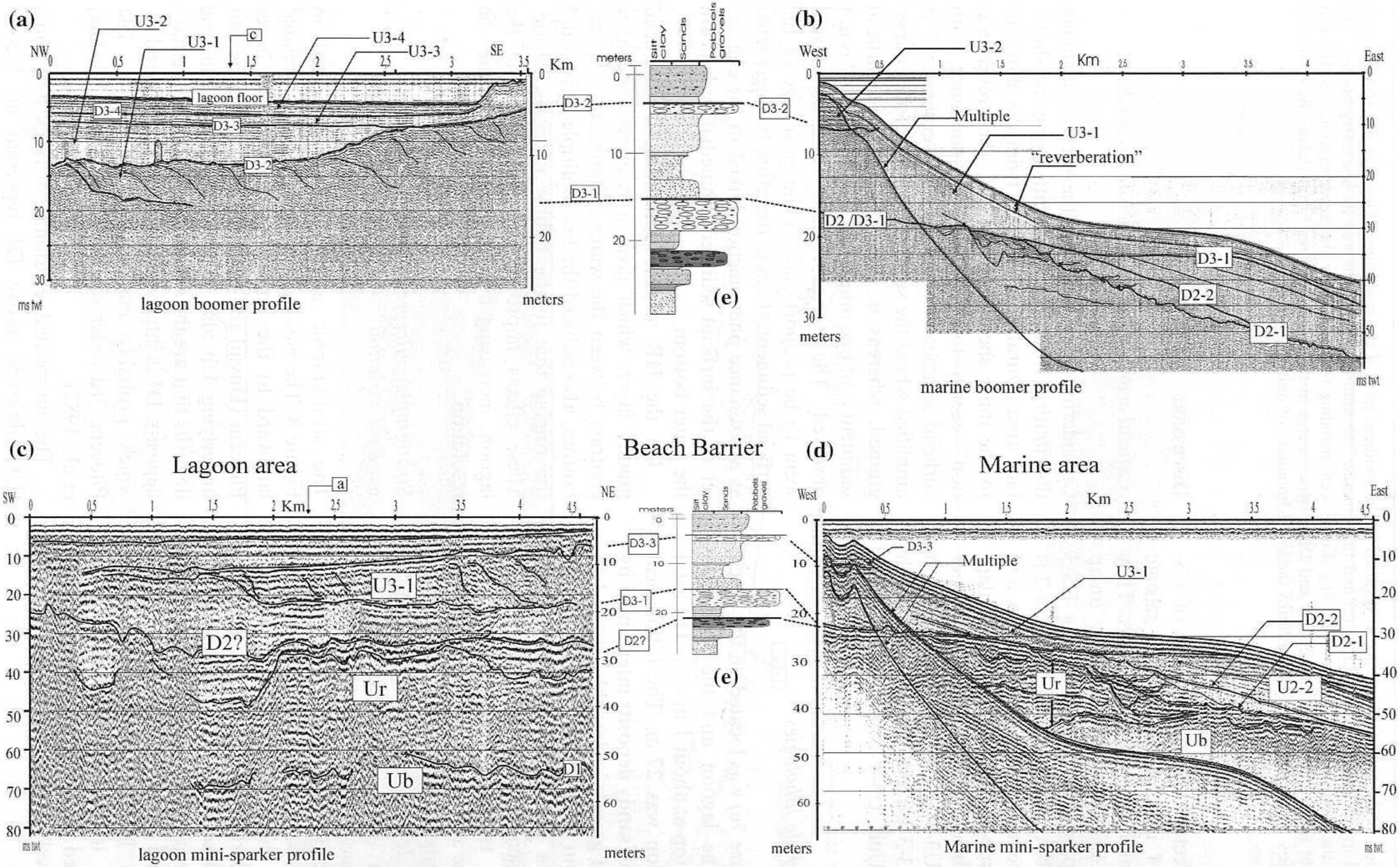

Figure 7. Seismic profiles showing the architecture of deposits in the lagoon area (a, c) and in the near-shore area (b, d) off the lagoon. The correlation is based on lithologic information from a borehole (e), located on the beach barrier. In the lagoon, line (a) shows three upper discontinuities D3-2, D3-3 and D3-4, not identified in front of the Agly River. D3-3 is correlated via the borehole (e) to the marine environment (b). In the marine environment, the discontinuity D2 is divided seaward into D2-1 and D2-2 (b, d).

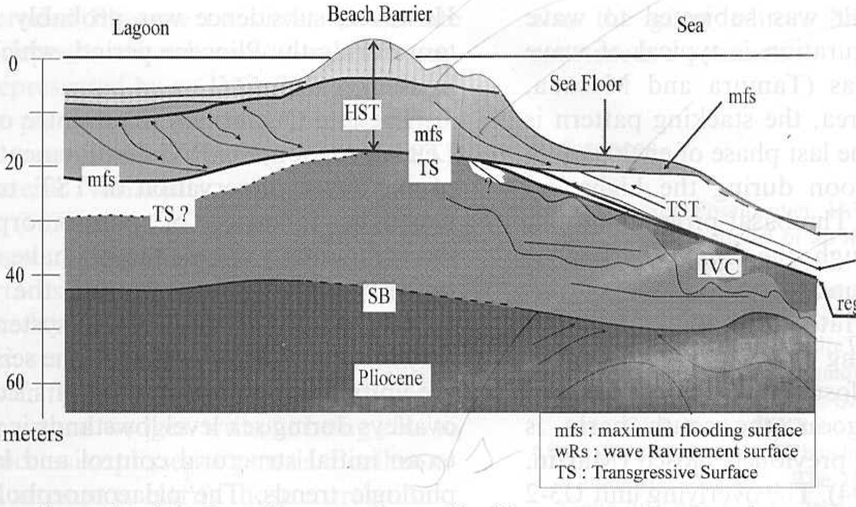

Figure 8. Stratigraphic model of the Roussillon coastal area. The Pliocene upper boundary is a sequence boundary (SB). The overlying Quaternary deposits are poorly developed except in the area of the incised valley complex (IVC). The IVC infill is truncated by a polygenetic erosional surface correlated to the regression and transgression of the last (fourth-order) sea-level cycle. The overlying transgressive systems tract (TST) and the highstand systems tract (HST) are separated by a maximum flooding surface (mfs).

Valley Complex (IVC) and its infill, the latter not clearly resolved. Each erosional surface is a sequence boundary, correlative to the successive falling sea-levels of the late Quaternary glacio-eustatic cycles of 4th order. The IVC may be laterally correlative to onshore fluvial terraces (Duvail and Le Strat, 2002) and lowstand wedges observed on the continental shelf (Lobo Sánchez, 2000). Work by Thomas and Anderson (1994) on the Texas continental shelf led to a similar interpretation, whereas the infilling of the incised valley system of the Gironde (France) seems to record only the last glacio-eustatic hemi-cycle (Allen and Posamentier, 1993). This difference is probably due to dynamic conditions, in which a dominantly macro-tidal environment with large estuary development is not favourable to the preservation of deposits. A detailed study of the IVC is ongoing and the first results are the subject of a paper in preparation by the authors.

The sedimentary hiatus between the Pliocene and Quaternary deposits is likely related to the absence of important glacio-eustatic variations prior to the major late Quaternary glacio-eustatic variations (of about 120 m amplitude, Lambeck et al., 2002).

The IVC is capped by the polygenetic erosional surface D2, which we attribute to the last (4th-order) sea-level cycle. D2-1 is also a sequence boundary, interpreted as a lowstand surface attributed to the late glacial maximum and probably merged with the post-glacial transgressive surface (TS). The overlying erosional surface D2-2 is assumed to be a wave ravinement surface (wRs) due to post-glacial shoreline transgression. Unit U2 overlies the TS and represents a transgressive systems tract (TST). It is composed of units U2-1 and U2-2, which are variably preserved along the study area. As with the late Quaternary IVC infill, this TST is mainly developed off the Salses-Leucate lagoon, suggesting that this area has remained a persistent depocentre during shoreline retreat. The upper boundary of the TST is the surface D3-1 which is interpreted as the maximum flooding surface (mfs). In the north of the study area, ^{14}C dating of shell layers indicates the mfs at about 20 m b.s.l. (Aloisi et al., 1978) which corresponds to the depth of D3-1 and confirms our interpretation.

The uppermost unit U3, composed of several sub-units of regional to local extent, represents a HST and exhibits different stratigraphic patterns on the seaward and the lagoonal sides of the beach barrier. Seaward, a sandy coastal wedge is subdivided into two units: U3-1 and U3-3 (from base to top), considered to have been deposited during the early and the late highstand periods, respectively. No accurate age dating is available, but a transition between early and late highstand deposits is consistent with the facies analysis and the inferred dynamic conditions. The lower unit seems to not be affected by present day reworking, whereas the upper unit was subjected to wave reworking. This configuration is typical of wave dominated coastal areas (Tamura and Masuda, 2004). In the lagoon area, the stacking pattern is more complex due to the last phase of enclosure of the Salses-Leucate lagoon during the highstand period (Martin, 1978). The basal prograding unit U3-1, correlated through the beach barrier, is associated with the construction of the barrier during the decreasing rates of sea-level rise that occurred at the beginning of the highstand period. It induced the final enclosure of the north basin of the Salses-Leucate lagoon, the south basin is presumed to have been previously closed (Martin, 1978; Certain et al., 2004). The overlying unit U3-2 is inferred to comprise the landward muddy sediments deposited synchronously with the build-up of the beach barrier. In such a case, these units are lateral facies variations rather than units having chronostratigraphic significance. The two upper units U3-3 and U3-4 correspond to the late highstand period and were deposited under low dynamic conditions. They are typical lagoonal deposits.

Other controlling factors

Fourth-order glacio-eustatic cycles of sea level are inferred to have been the first-order control on the stratigraphic architecture of the late Quaternary deposits. This is a relatively general statement for a passive continental margin. Superimposed six-order glacio-eustatic cycles can be recognised throughout the TST deposits, as will be detailed in forthcoming studies.

Over the timescale of the late Quaternary, the effects of subsidence can normally be neglected on passive margins. Nevertheless, the influence of differential subsidence is evident both on the continental shelf and across the Roussillon coastal plain. Seaward, net subsidence has controlled the stacking of prismatic units on the outer shelf (Tesson and Allen, 1995; Lofi et al., 2003). On the inner shelf, the preservation of deposits of several successive sea-level lowstands implies some amount of subsidence. Onshore, the Roussillon plain has been affected by Quaternary uplift movements (Carroza and Delcaillau, 1999; Duvail and Le Strat, 2002). The hinge line between landward uplift and seaward subsidence is assumed to lie just landward of the present coastline. However, subsidence was probably more important during the Pliocene period, which is recorded by thicker deposits.

The late Quaternary depocentre off the Salses-Leucate lagoon, the IVC development and the area of maximum preservation of TST, together highlight the influence of palaeomorphology and sediment supply. These factors have no real effect on the primary properties of the stratigraphic model, i.e. the key surfaces and systems tracts, but they affected the thickness and the seismic facies of the units. The similar location of successive palaeovalleys during sea level lowstands is probably due to an initial structural control and later geomorphologic trends. The palaeomorphology seem to have guided drainage flow during base level falls. The occurrence of a thick TST depocentre off the Salses-Leucate area is probably due to a higher sediment supply from the Têt and Agly Rivers. Some Roman writers, in the period BC, spoke of an important river associated with the Têt River near the Salses-Leucate lagoon; the Têt River has probably moved southward in recent time. The lateral variability observed in the coastal area, and particularly in the recent post-glacial deposits of the Salses-Leucate lagoon, of thickness and stacking pattern variations, is attributed to local evolution mainly controlled by hydrodynamic factors, alternating river mouths and sedimentary spit formation.

Conclusions

This study represents one of the first attempts to integrate HR and VHR seismic reflection data across a coastal area, from the coastal plain to the inner shelf, in order to develop an architectural model of late Quaternary deposits. The use of the two acoustic systems, combining the penetration of HR seismic and the resolution of VHR seismic, proved very useful in a complex area such as a coastal zone. Nevertheless, areas of sandy seafloor remained more difficult to study than muddy areas, because of the degradation of seismic data quality due to decreased penetration and the phenomena of reverberation and ringing.

The observations made in this study have allowed a model of the sedimentary architecture of the late Quaternary coastal deposits to be presented from the coastal plain to the inner shelf.

continental shelves: model for very high resolution sequence stratigraphy, *Mar. Geol.* **120**, 129–174.

Hsü, K.J., Cita, M.B. and Ryan, W.B.F., 1973, The origin of the Mediterranean evaporites, in Ryan, W.B.F. and Hsü, K.J. (Eds.), Initial Reports of the Deep Sea Drilling Project 13, US Government Printing Office, Washington DC, pp. 1203–1231.

Lambeck, K., Esat, T.M. and Potter, E.K., 2002, Links between climate and sea levels for the past three million years, *Nature* **419**, 199–206.

Lobo, F.J., Tesson, M. and Gensous, B., 2004, Stratral architectures of late Quaternary regressive-transgressive cycles in the Roussillon Shelf (SW Gulf of Lions, France), *Mar. Petrol. Geol.* **21**(9), 1181–1203.

Lobo Sánchez, F.J., 2000. Estratigrafia de alta resolución y cambios del nivel del mar durante el cuaternario del margen continental del golfo de Cádiz (S de Espana) y del Roussillon (S de Francia) : estudio comparativo. PhD thesis, Cádiz, Facultad de Ciencias del Mar, Spain.

Locker, S.D., Hine, A.C. and Brooks, G.R., 2003, Regional stratigraphic framework linking continental shelf and coastal sedimentary deposits of west-central Florida, *Mar. Geol.* **200**, 351–378.

Lofi, J., Rabineau, M., Gorini, C., Berne, S., Clauzon, G., De Clarens, P., Tadeu Dos Reis, A., Moutain, G.S., Ryan, W.B.F., Steckler, M. and Fouchet, C., 2003, Plio-Quaternary prograding clinoform wedges of the western Gulf of Lion continental margin (NW Mediterranean) after the Messinian Salinity Crisis, *Mar. Geol.* **198**, 289–317.

Martin, R., 1978, Evolution Holocène et actuelle des conditions de sédimentation dans le milieu lagunaire de Salses-Leucate. PhD thesis, Perpignan University, France.

Martin, R., Gadel, F. and Barusseau, J.P., 1981, Holocene evolution of the Canet-St Nazaire lagoon (Golfe du Lion, France) as determined from a study of sediment properties, *Sedimentology* **28**, 823–836.

Mitchum, J.R., Vail, P.R. and Sangree, J.B., 1977, Seismic stratigraphy and global changes of sea level, part 6: Stratigraphic interpretation of seismic reflection patterns in depositional sequences, in Payton, C.E. (Ed.), *Seismic Stratigraphy – Applications to Hydrocarbon Exploration*, pp. 117–133. Mem. Am. Assoc. Petrol. Geol. vol. 26.

Monaco, A., 1971, Contribution à l'étude géologique et sédimentologique de plateau continental du Roussillon (Golfe du Lions). PhD Thesis, Université des Sciences et Techniques du Languedoc, France.

Monaco, A., Thommeret, J. and Thommeret, Y., 1972, L'âge des dépôts quaternaires sur le plateau continental du Roussillon (Golfe du Lion), *C. R. Acad. Sci. Paris – série D* **274**, 2280–2283.

Nielsen, P., Robert, S., Moller-Christiansen, B. and Oliva, P., 2001, Infiltration effects on sediment mobility under waves, *Coastal Eng.* **42**(2), 105–114.

Penland, S., Boyd, R. and Suter, J.R., 1988, Transgressive depositional systems of the Mississippi delta plain: a model for barrier shoreline and shelf sand development, *J. Sediment. Petrol.* **58**, 932–949.

Posamentier, H., Jervey, M. and Vail, P., 1988, Eustatic control on clastic deposition I – Conceptual framework, in Wilgus, C., Kendall, C., Posamentier, H., Ross, C. and Van Wagoner J. (Eds.), *Sea-level Changes: An Integrated Approach*, pp. 109–124, SEPM Spec. Publ vol. 42.

Posamentier, H. and Vail, P., 1988, Eustatic controls on clastic deposition II sequence and systems tract models, in Wilgus, C., Kendall, C., Posamentier, H., Ross, C. and Van Wagoner J. (Eds.), *Sea-level Changes: An Integrated Approach*, pp. 125–154, SEPM Spec. Publ vol. 42.

Posamentier, H., Allen, G., James, D.P. and Tesson, M., 1992, Forced regressions in a sequence stratigraphic framework: Concepts, examples, and exploration significance, *AAPG Bull.* **76**, 1687–1709.

Rabineau, M., Berne, S., Ledrezen, E., Lericolais, G., Marsset, T. and Rotunno, M., 1998, 3D architecture of lowstand and transgressive Quaternary sand bodies on the outer shelf of the Gulf of Lion, France, *Mar. Petrol. Geol.* **15**, 439–452.

Ridente, D. and Trincardi, F., 2002, Eustatic and tectonic control on deposition and lateral variability of Quaternary regressive sequences in the Adriatic basin (Italy), *Mar. Geol.* **184**(3–4), 273–293.

Simpkin, P.G. and Davis, A., 1993, For seismic profiling in very shallow water, a novel receiver, *Sea Technol.* **34**, 21–28.

Stépanian, A. and Levoy, F., 2003, Morphodynamical evolution sequences of intertidal bars on a macrotidal beach: case study of Omaha beach (Normandy, France), *Oceanol. Acta* **26**(2), 167–177.

Suter, J.R., Berryhill, Jr. H.L. and Penland, S., 1987, Late Quaternary sea-level fluctuations and depositional sequences, southwest Louisiana continental shelf, in Nummedal, D., Pilkey, O.H. and Howard, J.D. (Eds.), *Sea-level Fluctuation And Coastal Evolution*, pp. 199–219, SEPM Spec. Publ vol. 41.

Tamura, T. and Masuda, F., 2004, Inner shelf to shoreface depositional sequence in the Sendai coastal prism, Pacific coast of northeastern Japan: spatial and temporal growth patterns in relation to Holocene relative sea-level change, *J. Asian Earth Sci.* **23**(4), 567–576.

Tesson, M., Gensous, B., Allen, G. and Ravenne, C., 1990, Late Quaternary deltaïc lowstand wedges on the Rhône continental shelf, France, *Mar. Geol.* **91**, 325–332.

Tesson, M., Allen, G.P. and Ravenne, C., 1993, Late Pleistocene shelf-perched lowstand wedges on the Rhone continental shelf, in Posamentier, H.W., Summerhayes, C.P., Haq, B.U. and Allen, G.P. (Eds.), *Sequence Stratigraphy and Facies Associations: International Association of Sedimentologists*, pp. 183–196. Special Publication vol. 18.

Tesson, M. and Allen, G., 1995, Contrôle tectonique et eustatique haute-fréquence de l'architecture et de la stratigraphie de dépôts de plate-forme péricatonique. Exemple du Golfe du Lion (Méditerranée, France) et des dépôts quaternaires, *C. R. Acad. Sci. Paris- série IIa* **320**, 39–46.

Tesson, M., Posamentier, H. and Gensous, B., 2000, Stratigraphic organization of the Late Pleistocene deposits of the western part of the Golfe du Lion Shelf (Languedoc shelf), Western Mediterranean Sea, using high resolution seismic and core data, *AAPG Bull.* **84**, 119–150.

Thomas, M.A. and Anderson, J.B., 1994, Sea-level controls on the facies architecture of the Trinity/Sabine incised-valley system, Texas continental shelf, 1994, in Dalrymple, R.W., Boyd, R. and Zaitlin, B. (Eds.), *Incised-Valley Systems: Origin and Sedimentary Sequences*, pp. 63–82, SEPM Spec. Publ. vol. 1.

Van wagoner, J.C., Posamentir, H.W., Mitchum, Jr. R.M., Vail, P.R., Sarg, J.F., Loutit, T.S. and Hardenbol, J., 1988, An overview of the fundamentals of sequence stratigraphy and key definitions, in Wilgus, C., Kendall, C., Posamentier, H., Ross, C. and Van Wagoner, J. (Eds.), *Sea-level Changes: An Integrated Approach*, pp. 39–46, SEPM Spec. Publ vol. 42.