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Detailed architecture of a compound incised valley system and correlation with forced regressive wedges: Example of Late Quaternary Têt and Agly rivers, western Gulf of Lions, Mediterranean Sea, France

C. Labaune [a,*], M. Tesson [a,b], B. Gensous [a,b], O. Parize [c], P. Imbert [d], V. Delhaye-Prat [e]

[a] GD ARGO, 14, rue de Théza, 66100 Perpignan, France
[b] BDSI-IMAGES, Université Via Domitia, 56 av. P. Alduy, 66860, Perpignan, France
[c] Areva, Paris, France
[d] Total CST, Pau, France
[e] Total, Nigeria

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ABSTRACT

Quaternary incised valley systems are usually characterized by the preservation of a single valley-fill attributed to the last post-glacial period. Moreover, there are very few cases of correlation between incised valley system developed on inner shelf and sedimentary units observed on the mid to outer shelf, mainly forced regressive wedges. The Roussillon shelf, in the western part of the Gulf of Lion, is a particular example of preserved Quaternary compound incised valley system also characterized by a direct correlation with the forced regressive lowstand wedges on the mid-outer shelf. High-resolution seismic data and a borehole, 60 m deep, located on the beach barrier permit an accurate study of the geometry and lithology of the system. Six imbricated and more or less preserved incised valleys and valley-fills are observed up to the inner to mid-shelf. The key surfaces associated to the incised valleys are correlated to the boundaries of the forced regressive wedges. They are assumed to be reworked surfaces. At the borehole location, only few thin layers, less than 1 m thick, of coarse grain and/or floating pebbles, are observed and should correspond to preserved fluvial lowstand deposits reworked under marine influence. The valley fills are mainly composed of estuarine muddy silts. From AMS ^{14}C age dating it is inferred that the uppermost incised valley system is younger than 45 ky cal BP. Based on those observations, the six preserved incised valley systems are assumed to be controlled by the last six 4th order sea-level cycles — 100 ky — of the middle to late Quaternary. The paleo-topography of the underlying Plio-Quaternary deposits controls the compound incised valley system location. The deep topography of the Messinian Erosionnal Surface is a controlling factor at a lower degree. The partial preservation of the successive valley fill is attributed not only to the differential subsidence but also to the lateral migration of each incision and to the hydrodynamic regime.

1. Introduction

Late Quaternary incised valley systems and associated shelf deposits have recorded the effects of rapid and high-amplitude relative sea-level changes, and their sub-surface position allows us to study their architecture at a regional scale. Although it is not demonstrated whether the sea-level cycles typical of the Late Quaternary also occurred in the past, they are considered as useful analogues that provide a key for a better understanding of ancient sedimentary environments, from both an academic and an economic point of view.

Most descriptions of the responses of river systems to allocyclic forcing parameters have focused on tidal-influenced incised valleys, while these studies deal with estuaries filled during highstand periods (Wilkinson and Byrne, 1977; Fletcher et al., 1990). The 3D geomorphological architecture and facies distribution of Holocene infilling were placed for the first time in a sequence stratigraphy framework (from lowstand to highstand) by the pioneering work of Allen (1991) and Allen and Posamentier (1993, 1994). The "ideal" vertical succession comprises backstepping coarse fluvial lowstand deposits, followed by transgressive estuarine muds and sands, marine mouth sands and then offshore muds (Dalrymple et al., 1992; Allen and Posamentier 1994). While recent studies have highlighted the impact of different factors such as tectonic activity (Wilson et al., 2007), wave to tide ratio (Weber et al., 2004) and valley paleo-morphology (Heap and Nichol, 1997), the reference stratigraphic model remains valid despite the relative variability of such systems. The stratigraphic model refer to "simple"

* Corresponding author. Tel.: +33662968034.
E-mail address: caro.labaune@gmail.com (C. Labaune).
URLs: http://www.gdargo.com (C. Labaune), http://www.gdargo.com (M. Tesson), http://www.gdargo.com (B. Gensous).

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valleys (Zaitlin et al., 1994), which were incised during the last Quaternary 4th-order sea-level fall (sea-level cycle orders given by Mitchum and Van Wagoner, 1991 — 100 ky) and filled by a lowstand-transgressive-highstand succession (i.e. a single depositional sequence), and which have been age dated. Nevertheless, these incised/filled systems were unaffected by the subsequent fall in relative sea-level fall. Considering that the previous Late Quaternary cycles of incision/filling have not been preserved, and then we should expect these incised valleys to have zero preservation potential on the geological time scale. On the other hand, "compound" incised valleys more closely resemble preserved examples in ancient sedimentary successions. They are the preserved parts of successive cycles of incision/filling and display several internal sequence boundaries. The Gulf of Mexico shelf exhibits several intensively studied incised valleys in micro-tidal environments. The Trinity–Sabine system is one of the first systems to be considered as compound (Thomas and Anderson, 1989), being incised into the shelf deposits of previous highstands. Similar occurrences of compound incised valley-fills have been described as being preserved along the west Louisiana and Texas coasts (Abdullah et al., 2004). In macrotidal environments, six depositional sequences beneath the Virginia inner shelf have been identified using seismic data (Foyle and Oertel, 1992, 1997). Nevertheless, most of these studies are based on seismic data and the available chronostratigraphy is often based on ^{14}C age dating that is never used to calibrate deposits older than about 10 ky BP. The core calibration of seismic data can change the interpretation, for example, the Mobile Bay incised valley Bay (Kindinger et al., 1994) has been reinterpreted as a compound system by Greene et al. (2007) who used several boreholes.

During the Late Quaternary, rapid and high-amplitude relative sea-level changes occurred on the shelf, with sediments being deposited during the falling stages depending upon local values of controlling factors (i.e. forced regressive deposits of Posamentier et al., 1992). The landward relationship of the forced regressive deposits with the "simple" incised valley is not commonly observed, either because of the lack of well-preserved deposits on the shelves, or because the two components are disconnected. The "compound" incised valleys of the inner shelves of Virginia (Foyle and Oertel, 1997) and Texas (Thomas and Anderson, 1994), as illustrated by strike seismic sections, are encased in previous prograding deltaic deposits. Although a ground-truth calibration is not available on the Virginia shelf, the interplay of fifth- and fourth-order cyclicity on the Texas shelf is clearly expressed and age dated. Nevertheless, there is still a lack of any longitudinal correlation between the discontinuities and units that characterize the incised valleys and the shelf depositional sequences.

In this study, we describe a continuous system including a compound incised estuary/valley and the seaward-associated forced regressive deposits on the Gulf of Lions shelf. The data base is made up from a dense grid of seismic profiles and a recent borehole in the axis of the valley. The variability of 3D architecture, as well as the seismic and sedimentological facies, is interpreted in terms of primary controlling factors such as climate/sea-level changes, along with tectonic activity and sediment supply. Secondary factors, i.e. paleomorphology, physical oceanography and lithology, are also taken into account. The ^{14}C age calibration extends back to 40 ky BP at mid-borehole depth, thus constraining the stratigraphy as well as the relationships with the 4th and 5th order depositional sequences on the shelf.

2. Regional setting

2.1. Physiography

The Roussillon shelf is situated in the southwestern part of the Gulf of Lions (Fig. 1), bounded to the North by outcrops of Mesozoic limestone (Corbières) and to the South by the Eastern Pyrenean metamorphic promontory. The present-day continental shelf is up to 70 km wide, with a shelf edge eroded by several canyon heads. The coast is linear and sandy with some lagoons. The Roussillon coastal plain is flat, with mostly Pleistocene sand and gravel cropping out, and a thin Quaternary cover near the shoreline. The coast is wave-dominated, with low wave regime (significant wave height is often less than 1 m) and a tidal range comprised between 0.3 and 1 m. The rivers (Agly, Têt and Tech, from north to south, Fig. 2b) display a torrential regime. The catchment areas are located in the Pyrenees mountain range and are relatively small. Nevertheless, the large incised valleys in the nearby piedmont indicate an important erosive activity in the past. At present, these rivers have very low water discharge and sediment load. They develop no apparent delta and/or estuary.

2.2. Geological framework

The continental shelf morphology and structure result from a succession of geological events. The Oligo-Miocene phase of rifting (30 Ma to 21 Ma) was followed by ocean-floor spreading in the Burdigalian (21 Ma to 18 Ma) (Lefevbre, 1980; Guennoc et al., 2000). The rifting episode produced an inherited morphology of horsts and grabens (Fig. 2a), which became largely modified during the Messinian salinity crisis. This event led to a sea-level drop of about 1500 m (Hsü et al., 1973; Lofi, 2002), which is marked (see Fig. 2b) by the "Messinian Erosional Surface" or MES (Cita and Ryan, 1978). In the Roussillon area, the MES is characterized (Gorini et al., 2005) by a main fluvial system corresponding to the paleo-Têt river.

Following the rapid early Pliocene flooding, progradation of Gilbert deltas above the MES led to the construction of the present-day margin (Clauzon et al., 1987; Duvail et al., 2002). The late Pliocene is more influenced by glacio-eustatic cycles, associated with a slowing down of sedimentation (Lofi et al., 2003). During this period, although tectonic activity is assumed to decrease, the effect of differential subsidence increases due to sediment and water loading (Bessis and Burrus, 1986).

2.3. Quaternary shelf stratigraphy

On the middle to outer shelf of the western Gulf of Lions, several superimposed sedimentary prograding units (Aloïsi, 1986) form a seaward-thickening wedge. Five to six depositional sequences were later identified on the entire Gulf of Lions shelf, and attributed to the interplay between eustatic variations, sediment input and subsidence/tectonics (Tesson et al, 1990, 1993; Tesson and Allen, 1995). The components of each sequence are essentially low-angle wedge-shaped units deposited successively seaward during the early and late phases of the Late Quaternary sea-level falls. They are considered as forced regressive deposits/wedges or FRW (Posamentier et al., 1992). Irregularly preserved deposits are intercalated between the stacked regressive units. These "intercalated units", or UIs, represent transgressive coastal and lag material deposited in higher energy environments than the FRW. Massive prograding shoreface sand bodies are well preserved near the outer shelf, comprising either distal intercalated units (dIUs) or late FRW emplaced during the maximum relative sea-level lowstands (Tesson, 1996; Tesson et al., 2000; Jouet, 2007). The Late Quaternary relative sea-level cycles controlling the stratigraphic architecture have been assumed to correspond to N and N + 1 order cycles (Posamentier et al., 1992) of 4th to 5th order (from 100 ky to 20/40 ky). According to the numerical stratigraphic modelling of Rabineau (2001), 4th-order cycles are considered as the only controlling factor, but recent oxygen isotopic data obtained from the DLPG drill-hole on the outer shelf (Bassetti et al., 2006) indicate the presence of 4th, 5th and higher order cyclicities. Stratigraphic modelling also suggests that subsidence rates would have been around 250 m/My at the shelf edge (Rabineau, 2001).

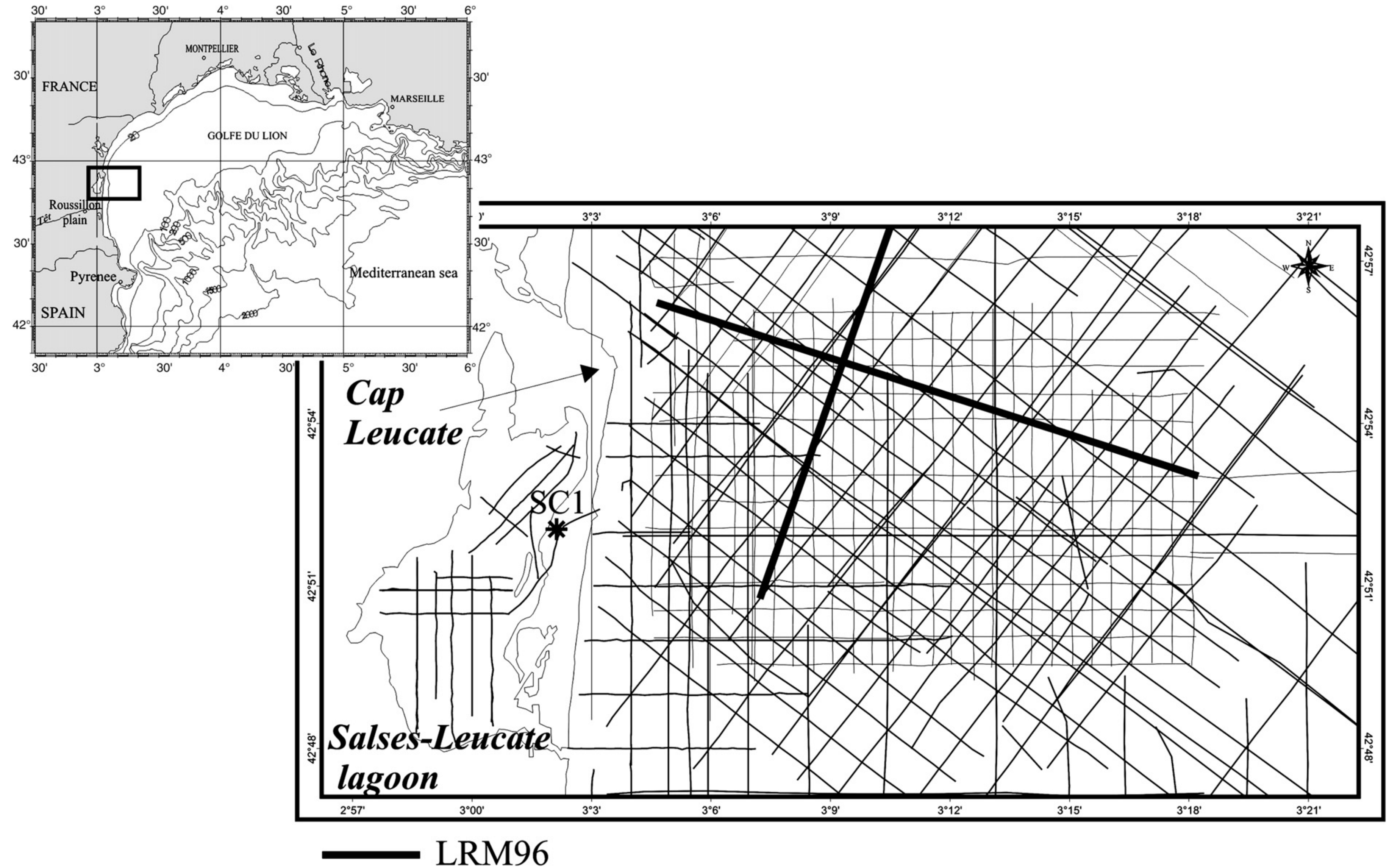


Fig. 1. Study area: the western Gulf of Lions and the high-density seismic grid available for the inner shelf and the adjacent lagoon. The maximum gridding (N to S and E to W orientation) is associated to the targeted acquisition on the incised valley system (2006). The Leucate SC1 borehole was drilled after interpretation of the seismic data.

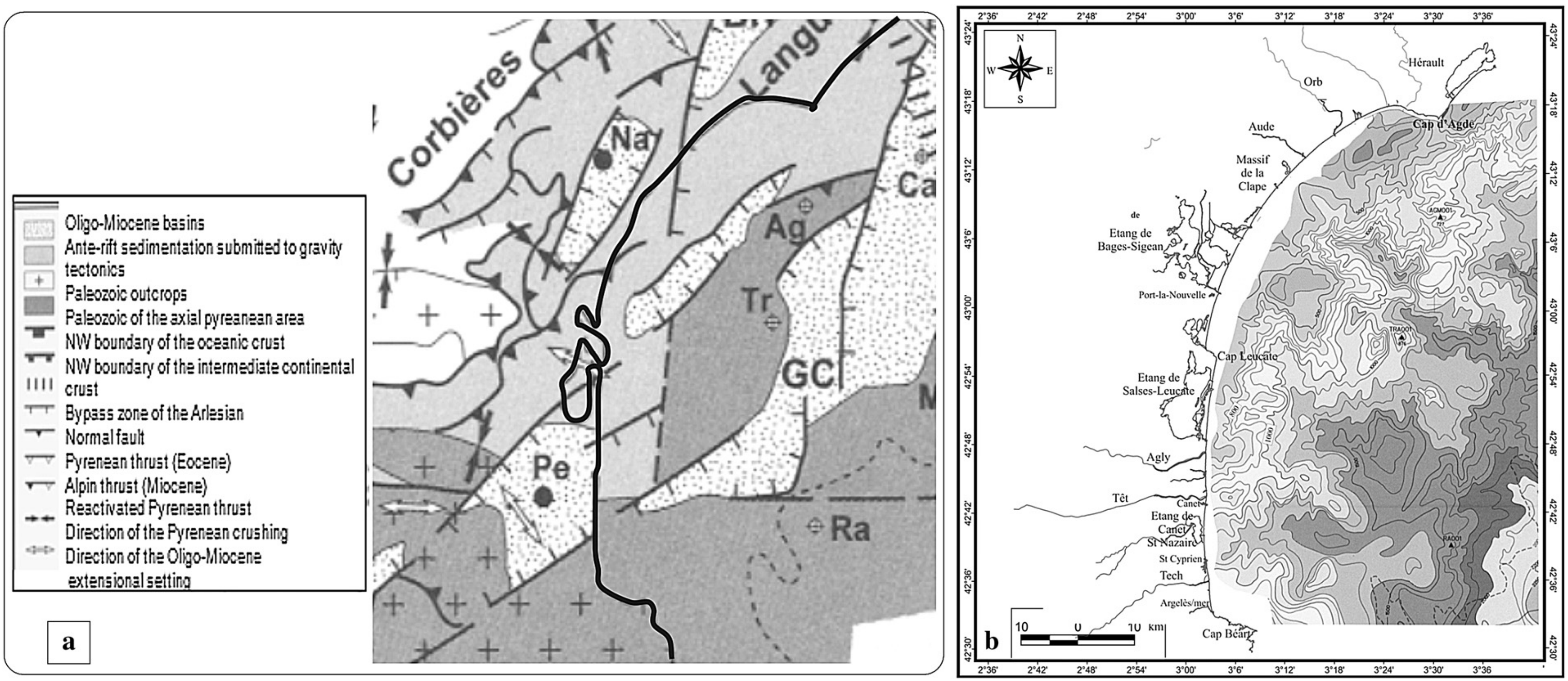


Fig. 2. Geological context. a) Deep structural pattern acquired by the end of the Oligo-Miocene phase of rifting (from Alabouvette et al., 2003); b) Messinian erosional surface (MES, Guennoc et al., 2000).

Landward, the Quaternary wedge pinches out under the inner shelf offshore of the modern Roussillon coastline. The basal surface of the identified late Quaternary FRWs and UIs merges more or less with the last transgressive surface, which is overlain by the coastal prism. The substratum is attributed to the Pliocene, while the early Quaternary seems missing (at about 1.4 My). This pattern is strongly modified in some places where the basal surface becomes a fluvial surface of incision (see Lobo et al., 2004, and paragraph below).

On land, the Quaternary (Pleistocene) deposits of the Roussillon plain are characterized by six imbricated alluvial terraces (Duvail et al., 2001; Alabouvette et al., 2003) associated with 4th and 5th order cycles (100 and 20 ky). The arrangement of these terraces results from continental uplift.

2.4. Previous studies on the late Quaternary incised valleys of the Western Gulf of Lions

As demonstrated by Talling (1998) and Posamentier and Allen (1999), the occurrence of cross-shelf valleys is mainly controlled by the position of the lowstand shoreline below the shelf edge or on the shelf. On the Gulf of Lions shelf, shorelines never extended farther than the outer shelf, so that fluvial incision and valley formation was limited to the highstand coastal prism. The incised valleys buried under the Languedoc and Roussillon inner shelf and coastal plain have been investigated using seismic data and drill logs. The first Digital Elevation Model and the maps of the basal and upper unconformities were published by Labaune (2005) and Tesson et al. (2005). Data from new high-resolution seismic data and one borehole have been acquired in the Roussillon coastal area (2005 and 2006 campaigns). Some preliminary results have been reported (Labaune, 2007, private report). The present study paper gives a detailed description of the stratigraphic architecture as well as a correlation with offshore regressive wedges.

3. Database and terminology

This paper is based on the re-interpretation of previous seismic data improved by a new seismic survey and a borehole (LEUCATE SC1) drilled during the project by GDARGO (www.gdargo.com).

3.1. Seismic data

The main seismic database was acquired in two phases: a regional acquisition between 1995 and 1998, and a targeted acquisition on the incised valley system in 2006 (Fig. 1). A 50-Joule SIG® mini-sparker (average bandpass 30–1500 Hz) was used, with a firing rate of 1 shot s^{-1} and associated with a mono-channel high-resolution streamer. A grid spacing of about 500 m was used for data acquisition in the incised valley system area. Seismic lines were shot in the coastal lagoon and tidal channel, with a vertical resolution varying from 1 to 3 m. DelphSeismic TEI® software was used for the acquisition of georeferenced data.

Data were processed with DelphSeismic software by applying gain correction and bandpass filters (300–1200 Hz). After a pre-interpretation on paper print-outs, the final interpretation was performed using the Sismage software (Total SA proprietary). An offset correction was applied to each individual picking before mapping the seismic horizons. When necessary, time-to-distance conversion was carried out using velocity values estimated from correlation between the SC1 borehole and the seismic line (1650 m s^{-1} for the deposits above the incised valley-fill and 1725 m s^{-1} for the valley-fill).

Seismic data analysis and interpretation are based on the Exxon group concepts developed for low-resolution seismic data at the basin scale (Payton, 1977 — AAPG Memoir no. 26) and adapted in Posamentier and Vail (1988) (Wilgus et al., 1988). The terminology includes the concepts of "forced regressive deposits" (Plint, 1991; Posamentier, 1991, Posamentier et al., 1992; Tesson et al., 2000).

3.2. Leucate SC1 borehole

The SC1 borehole was drilled in February 2006 on the Salses-Leucate lagoon beach barrier (Fig. 1). For technical reasons, it was drilled onshore, but as close as possible to seismic lines acquired in a tidal channel (ca. 300 m away). It was continuously cored, and 44.7 m were recovered out of a total drilled depth of 59.5 m. The recovered section mostly sampled the muddy deposits located below the sandy coastal prism deposits. During drilling, cuttings of consolidated material were removed by water circulating around the rotary bit. When non-consolidated sediments were encountered, cores were obtained using a push-coring device through the drill casing. In this study, we use information published in the preliminary report (Labaune, 2007), improved by a detailed lithological description and the first results of age calibration based on AMS ^{14}C dating (foraminifera and shells). For the ^{14}C age dating, we used the cal. BP scale based on the conversion with the marine curve proposed by Stuiver et al. (2006, Calib^{14}C 5.0.2).

4. Description

4.1. Seismic unconformities, units (incised valley-fill) and facies

Seven (7) regional and erosional unconformities (Fig. 3) can be identified (numbered S100 to S650 from base to top) across the Roussillon coastal plain and inner shelf. The six lower unconformities define valleys thalwegs and are characterized by high-amplitude reflections. The upper surface caps the incised valley system.

Six (6) seismic units, labelled from R100 to R600, are associated with valley-fills.

Five (5) seismic facies are associated with these units as well as the substratum.

The main characteristics of the seismic discontinuities, units and facies are given in Tables 1 and 2.

4.1.1. Seismicunconformities

The lower unconformity S100 is a regional surface. This unconformity is erosional in the present-day inner shelf area and grades seaward into a correlative conformity at the base of a set of forced regressive lowstand wedges. It corresponds to the basal surface of an incised valley system widening seaward. The main axis of the thalweg is oriented W–E. At the coastline, S100, reworked by S200, lies at a depth of up to 70 ms (about 60 m) below sea level, while on flatland in interfluvial areas, it occurs at around 25 ms (20 m). The slope increases seaward in the mid-shelf, where it approaches the pinch-out point of the lowstand wedges.

The unconformity S200 (Fig. 4b) is developed over most of the studied area and reworks the lower unconformity on the inner shelf and part of the coastal area. The S200 incision exhibits a flat-bottomed valley thalweg up to 12 km wide and 26 m deep (30 ms) in the proximal area, with a wide bay configuration in the inner shelf area. This unconformity shows a constant slope in the middle shelf, which corresponds to the area of seaward opening of the wedges.

The unconformities S300, S400 and S500 show similar characteristics, and are not described here separately. They correspond to relict incised valleys showing a main SW/NE axis. Their morphology is characterized by isolated basins (Fig. 4c–e), sometimes difficult to relate to each other. The preserved thalwegs are less than 2 km wide and up to 10–15 ms (9–13 m) deep. The longitudinal profile of the valleys is irregular on the inner shelf and dips regularly seaward. The maximum slope of the thalweg walls is associated with the NW boundaries of the incised valley system located near Cap Leucate, where it reaches 5%.

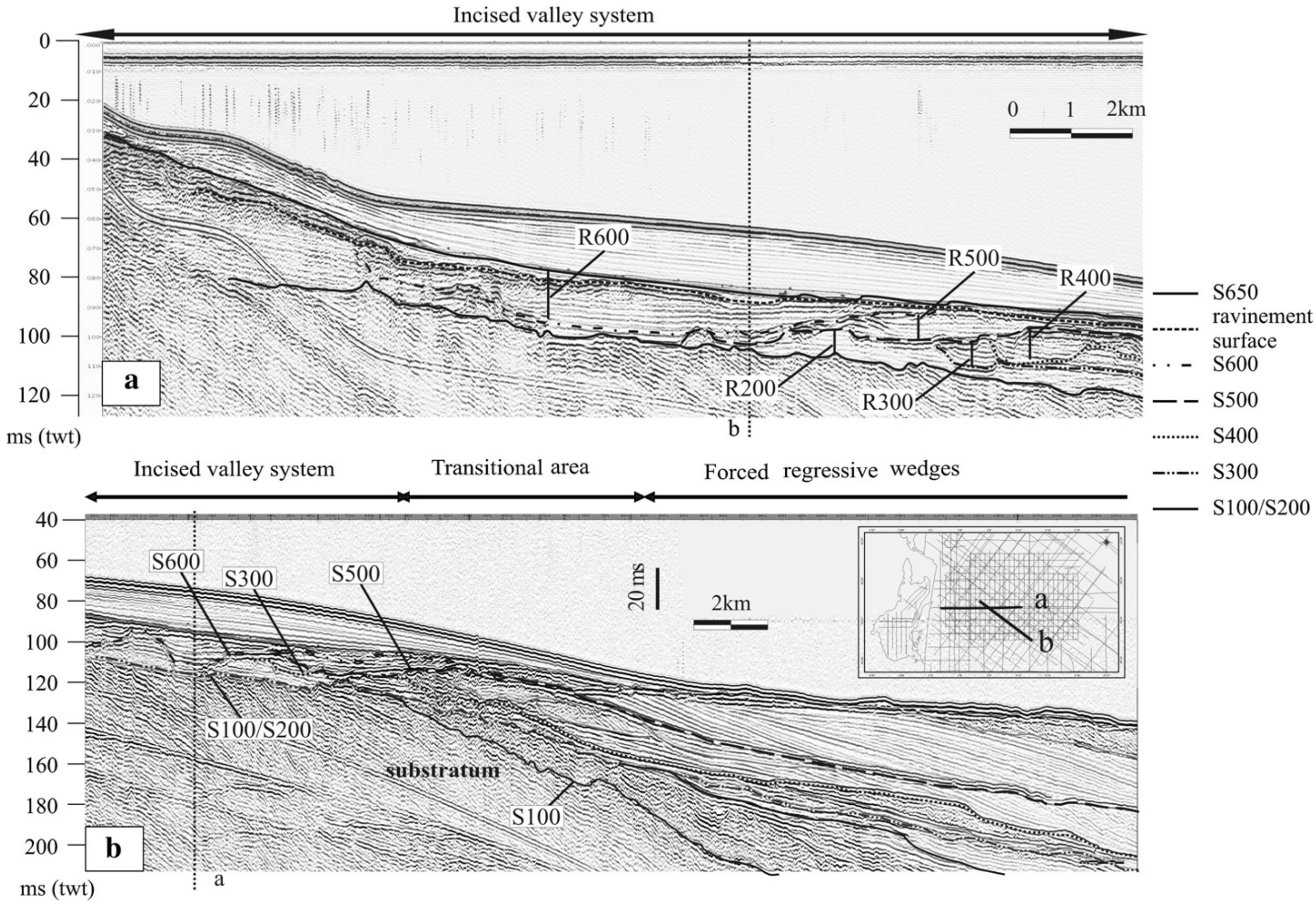


Fig. 3. Dip seismic sections showing: a) the main unconformities within the incised valley system; b) longitudinal correlation from incised valley system to the shelf depositional sequences. S300 is not evidenced in this section.

The unconformity S600 is a regional erosional surface (Fig. 4f). The morphology is very irregular in the inner shelf and shows a relatively constant slope in the coastal and middle shelf areas. Two distinct thalwegs are observed: (i) the major one, oriented W–E, is located in the proximal part. It is up to 4 km wide and 20–25 ms deep (17–22 m), and (ii) the minor one, oriented NW–SE in the distal part of the IVS is less than 2 km wide and up to 10 ms deep.

The upper unconformity S650 is a flat erosional and regional surface (Fig. 4f) at the top of the incision/infilling system. A maximum slope of 0.08% is observed in the coastal zone.

Table 1
Seismic facies and diconstinuities main characteristics.

Discontinuity	Unit	Characteristics	Thickness	Seismic facies
S650		Uppermost ravinment surface		
	R600		23 ms	2 to 5
S600		Reworked SB		
	R500		18 ms	2, 3 and 4
S500		Reworked SB		
	R400		15 ms	2 and 3
S400		Reworked SB		
	R300		20 ms	2 and 3
S300		Reworked SB		
	R200		23 ms	2 and 3
S100		Reworked SB — reworked on the littoral area and inner shelf		
	Substratum			1

The transverse section along the shore of this region shows the vertical and longitudinal relations as well as the variation of the seismic unconformities and their correlative concordant units. The seismic line (Fig. 3b) reveals a good continuity between the incised valley thalwegs and the forced regressive wedge deposits. Each lower boundary of the incised valley (S100 to S600) is correlated with the upper and lower boundary of a single forced regressive wedge.

4.1.2. Seismic units

The acoustic substratum, Ub, located under the basal unconformity, S100, exhibits high-amplitude and relatively continuous seaward dipping reflectors, which are sub-parallel and show toplap terminations. We note undulations with two main axial directions, one at a

Table 2
Summary of the seismic facies.

Seismic facies	Reflectors	Terminations	Amplitude	Comments
1	Oblique-parallel	Toplap	Very high	Affected by gentle folds
2	Sub-horizontal/ parallel	Onlap/truncature	Low to medium	
3	Semi-transparent/ sub-horizontal	Onlap/truncature	Low	
4	Chaotic			
5	Sigmoidal to clinoform	Downlap/truncature	Low to medium	

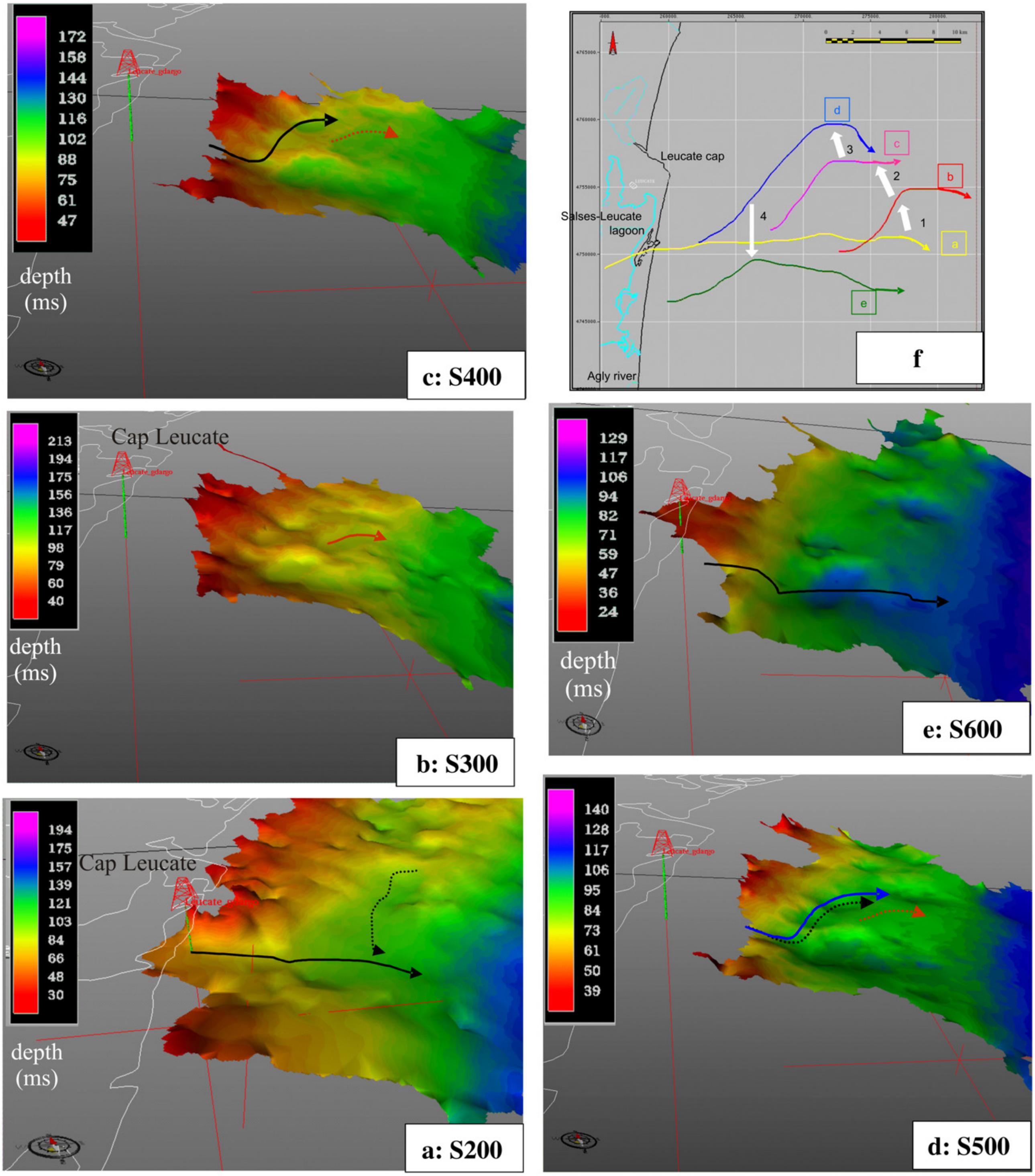


Fig. 4. Isochron maps of unconformities: a) S100 reworked by S200; b) S300; c) S400; d), S500; e) S600; with f) showing the SW/NE trend of each incision and the shift of the thalweg.

large scale striking transverse to the shore, and the other at a smaller scale parallel to the shore.

The unit R100 represents the lowermost preserved valley fill, mainly observed in the proximal part of the system (below the lagoon and beach barrier of the present-day coastline). The mapping of this unit is not possible mainly because of the first sea-floor multiple arrival in shallow water.

Unit R200 is one of the best preserved valley-fills (Figs. 3a and 5a), showing a thickness of about 23 ms (20 m). R200 is arranged in several thick packages which not appear as a continuous thalweg fill mainly because of successive erosion.

Unit R300 is only preserved in the distal part of the incised valley system (Figs. 3a and 5b). It shows an elongated shape, relatively parallel to the coastline. The maximum thickness is about 20 ms (17 m).

Unit R400 is also elongated and relatively parallel to the present-day coastline, but it occurs in a more proximal location (Figs. 3a and 5c). It is the thinnest of the seismic units, with a thickness of less than 15 ms (13 m).

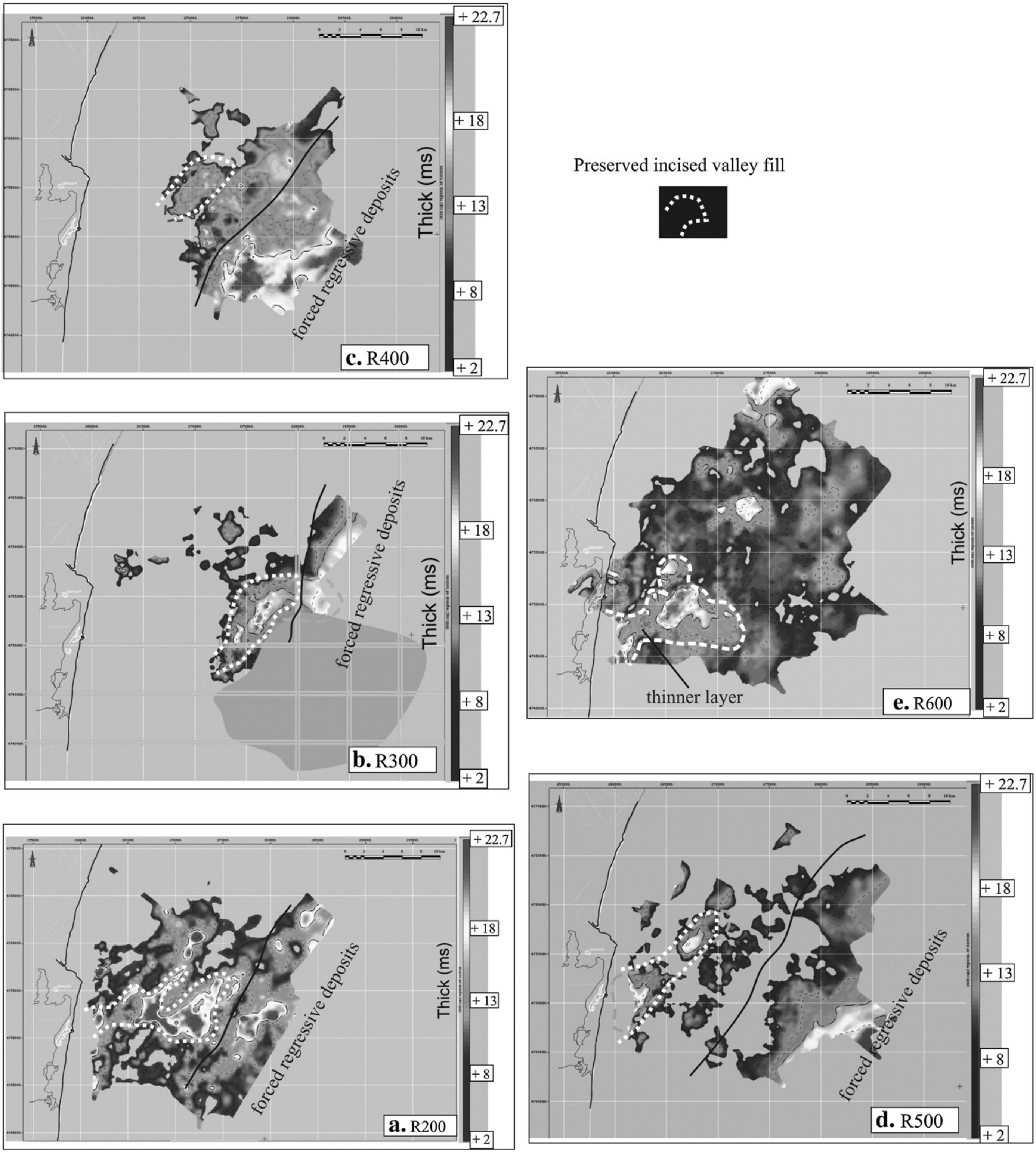


Fig. 5. Isopach maps of valley fills: a) R200; b) R300; c) R400; d) R500; e) R600. The dot lines outline the main preserved valley fill location and the continuous line marks the proximal limit of the forced regressive deposits development.

Unit R500 represents the least well preserved valley fill, being only observed in the proximal part of the incised valley system (Figs. 3a and 5d). The isopach map shows two areas of reduced and disconnected preserved deposits, elongated along a NW–SE trend and up to 18 ms (16 m) in thickness.

Unit R600 (Fig. 3a) corresponds to the uppermost preserved valley fill, extending throughout the incised valley system and displaying a relatively well developed thalweg infilling morphology. Areas of thick deposits in the proximal and middle part of the system are connected by a thin layer (Fig. 5e). The thickness of R500 can attain 23 ms

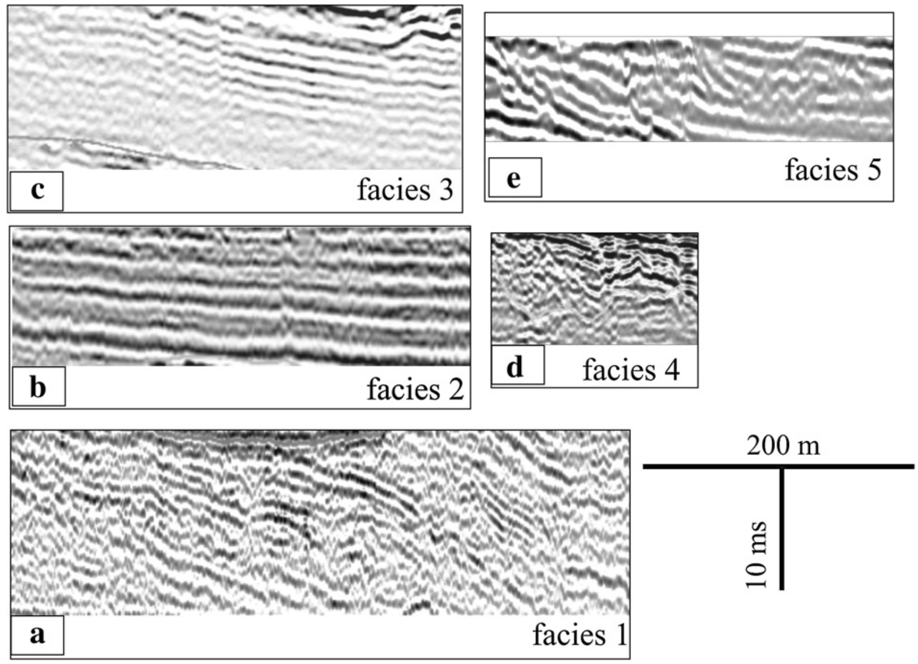


Fig. 6. Seismic sections illustrating the five most common seismic facies characterizing the valley fills. Some or all of these facies are associated together in each valley fill.

(20 m). The thick deposits preserved in the middle of the system have an elongated geometry with a NW–SE trending axis.

4.1.3. Seismic facies

Seismic facies 1 (Fig. 6a) is characterized by very-high-amplitude, oblique-parallel reflectors dipping seaward at an angle of up to 1.5%. It is affected by gentle folds with SSW–NNE and W–E axes (Fig. 7 — line E–W). This facies is typical of the substratum unit Ub.

Seismic facies 2 (Fig. 6b) shows reflectors with low- to medium-amplitude and low-frequency. They are sub-horizontal and parallel, with onlap terminations on the incision walls which give an aggrading pattern. For unit R200, this facies is observed in the upper part of the valley fill. For the other seismic units, facies 2 is more characteristics of the base of the infilling sequence, with reflector amplitude generally decreasing from base to top.

Seismic facies 3 (Fig. 6c) is semi-transparent with sub-horizontal reflectors showing low amplitude and frequency. It is an aggrading seismic facies, observed at the base of R200 and mainly in the middle part of the R300 to R500 valley fill.

Seismic facies 4 (Fig. 6d) is of chaotic type, being mainly associated with the transition area between incised valleys and lowstand wedges. It is sometimes observed in the upper part of units R500 and R600.

Seismic facies 5 (Fig. 6e) is associated with sigmoidal and/or clinoform reflectors that mainly show lateral progradation in the upper part unit R600.

Table 1 gives the main characteristics of each seismic facies.

Within the incised valley fills, seismic facies 2 to 5 can be observed separately or combined in different ways. Both the vertical and longitudinal variation as well as the distribution of these facies can be described in the best preserved valley fill corresponding to R600 (Fig. 8). In addition, these facies enable us to pick out the thalweg axis, linked to the last incision of S600, which displays a meandering morphology.

4.2. Leucate SC1 borehole: lithology

The cored section is divided into five main units defined from their facies (lithology and faunal contents) and vertical evolution; these units are numbered 1 to 5 from the base upwards (Fig. 9). The

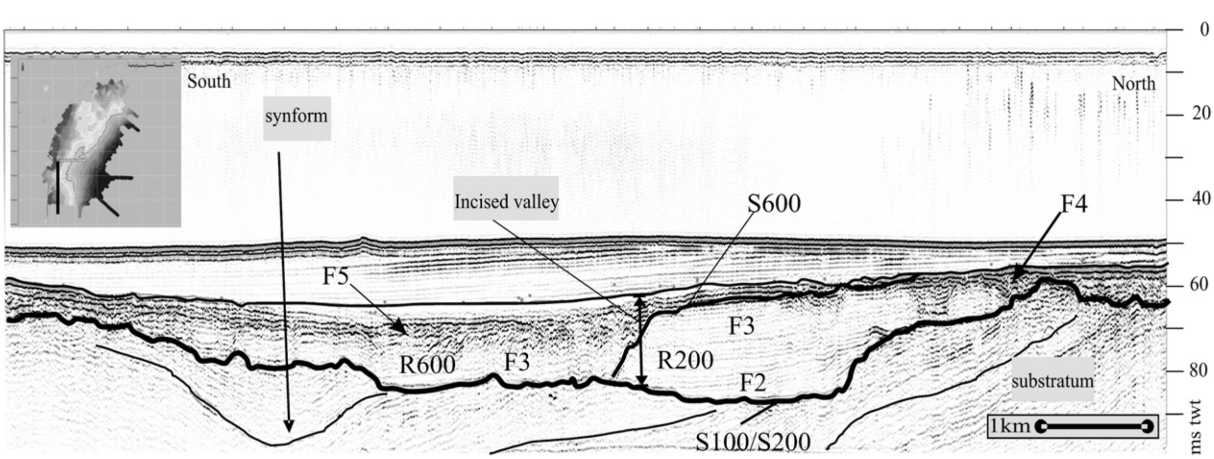


Fig. 7. Location of main valley axis within an antiform of the Pliocene substratum.

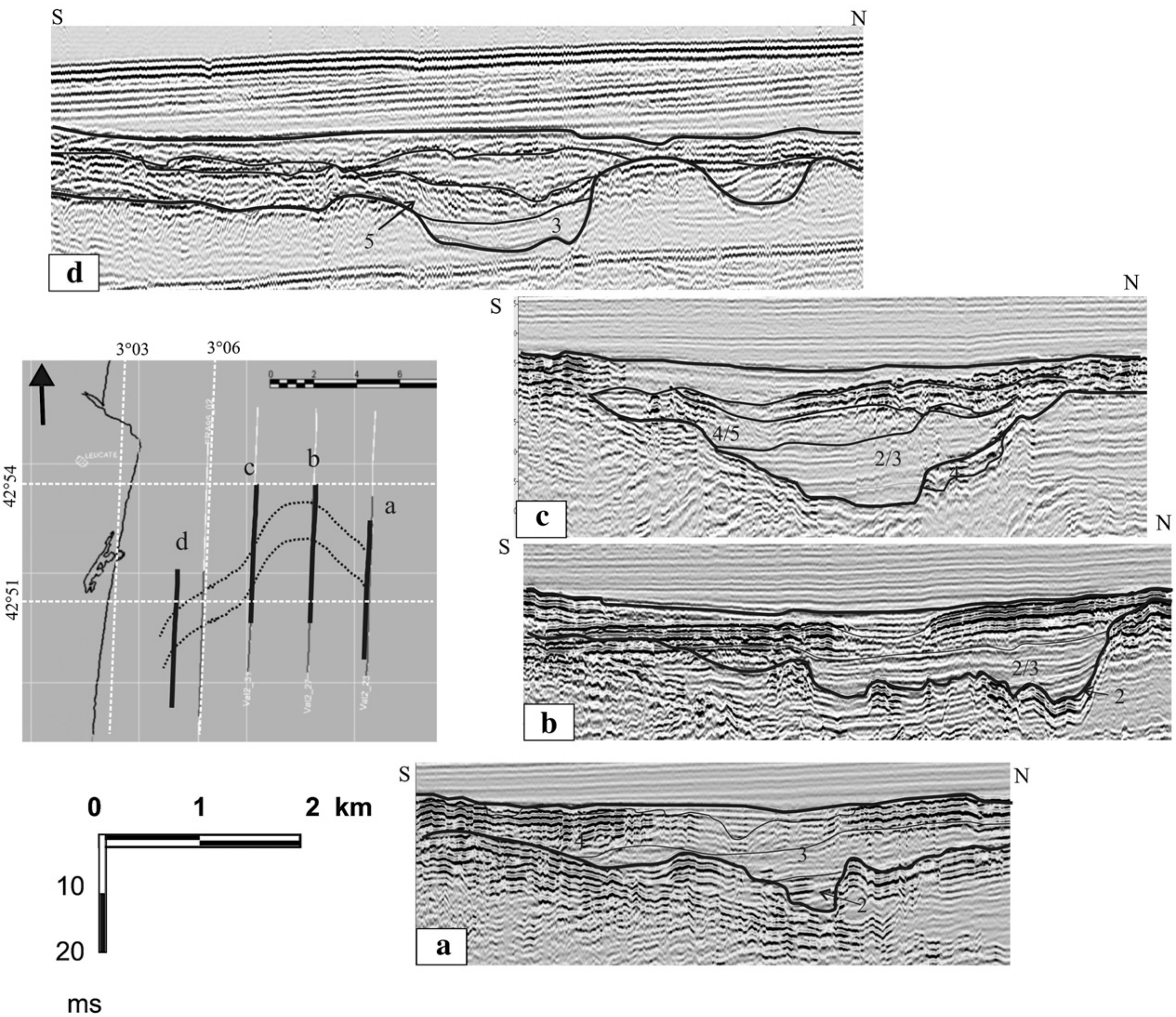


Fig. 8. Example of a paleo-valley thalweg (S600) showing preserved meandering morphology. The seismic lines allow to follow evolution from distal to proximal area (from a to d).

correlation between seismic facies and sedimentary units is based on Mitchum et al. (1977).

Unit 1 (59.5 to 58 m) passes from coarse pebbles in a yellow sandy matrix at the base to green muds with some shell debris at the top. Those coarse pebbles can be associated to the amalgamated discontinuity D100/D200.

Unit 1/Unit 2 contact: A sharp contact is observed between the green muds of unit 1 and the grey muds of unit 2.

Unit 2 (58 to 26.2 m) can be divided into sub-unit 2a at the base and 2b at the top. The sub-unit 2a (58 to 34 m) is dominated by grey muddy silts containing shells and shell debris. Centimetric bioclastic lags are observed (example: mussel-bearing beds at 44 m). At around 45 m, we observe coarser deposits (varying from sands to pebbles) in a muddy matrix, making up layers several cm to m thick. This sub-unit is associated to the seismic facies 3. A metre-thick layer of matrix-supported pebbles without shells characterizes the boundary between sub-units 2a and 2b. The overlying sub-unit 2b is also associated with grey muddy silts containing shells, but more abundant coarse levels are observed (varying from sands to pebbles). The sub-unit can be associated to the seismic facies 2 which shows highest amplitude the seismic facies 3. Bioturbation is observed at the top of this sub-unit. Two layers of matrix-supported pebbles containing shell debris are described, one in sub-unit 2a (40 m) and another in unit 2b (30 m).

Unit 2/Unit 3 contact: The contact appears as erosional and is well marked.

Unit 3 (26.2 to 16.2 m) is mainly composed of fine to coarse grey sands with shell debris and shells. The upper part shows a mica-rich sand layer about 1 m thick. This mica-rich sand deposit contains abundant roots and traces of bioturbation. The unit with several grained-size can be associated to the seismic facies 4 and 5, chaotic and progradational seismic facies respectively.

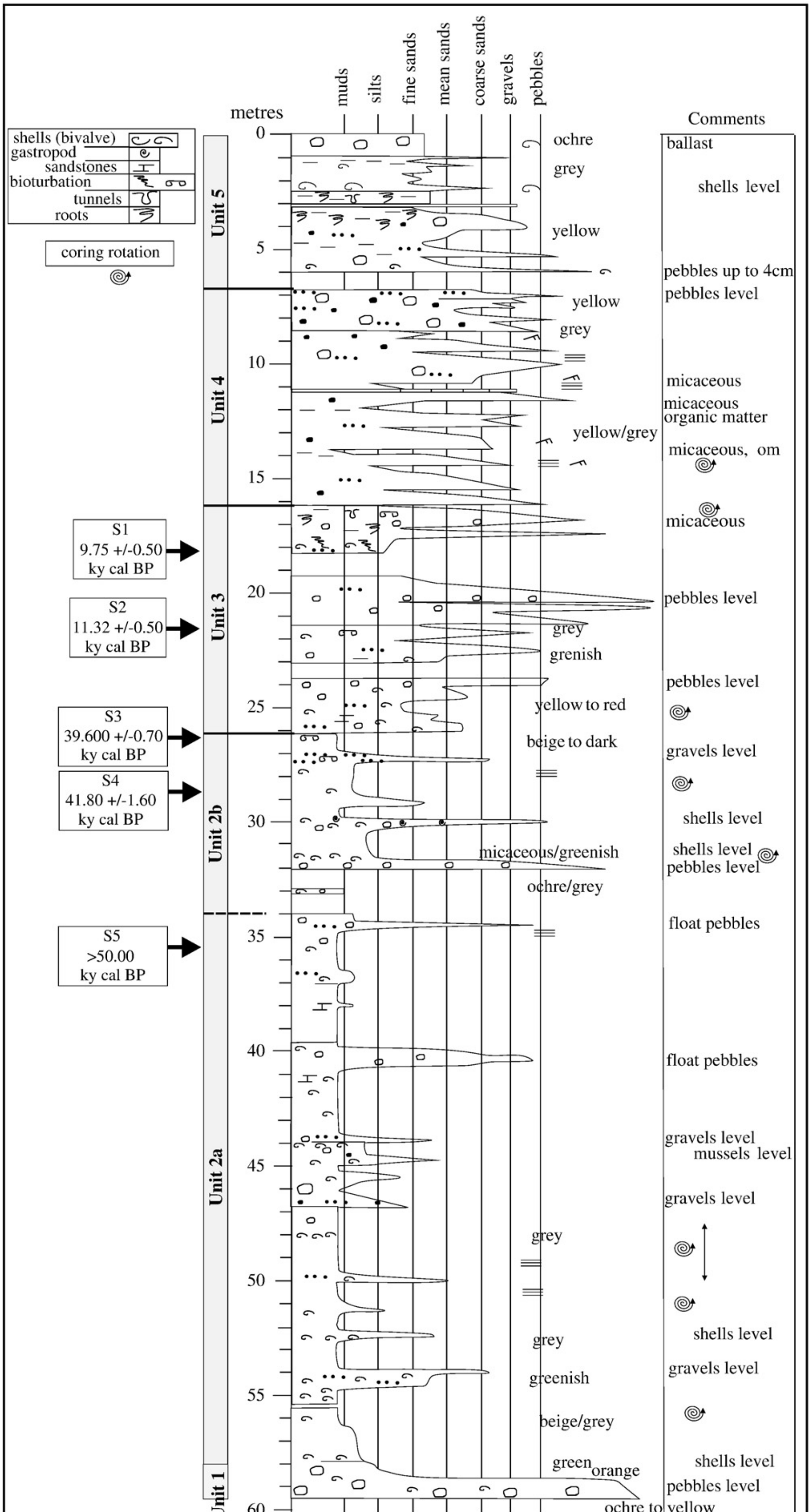
Unit 3/Unit 4 contact: A sharp contact appears between units 3 and 4, but there is no evidence for erosion.

Unit 4 (16.2 to 6.8 m) is composed of a succession of fining-up sequences (from pebbles/gravels to fine sands) dominated by yellow sands. The contact between successive fining-up sequences is generally erosive. Shells are either very scarce or absent.

Unit 5 (6.8 to 0 m) is dominated by grey sand with abundant roots and shells. Gravels and pebbles appear in the lowermost part.

4.3. Leucate SC1 chronology

AMS ^{14}C age dating was performed on five samples from the upper part of the core (0 to 35.4 m). Due to the lack of planktonic foraminifera, we used samples of benthic foraminifera (Miliolidae and Elphidiidae) and sometimes in-place shells. AMS ^{14}C age dating was carried out at the Poznan Radiocarbon Laboratory (Table 3,



muds
silts
fine sands
mean sands
coarse sands
gravels
pebbles
metres
Comments
shells (bivalve)
gastropod
sandstones
bioturbation
tunnels
roots
coring rotation
Unit 5
Unit 4
Unit 3
Unit 2b
Unit 2a
Unit 1
S1 9.75 +/-0.50 ky cal BP
S2 11.32 +/-0.50 ky cal BP
S3 39.600 +/-0.70 ky cal BP
S4 41.80 +/-1.60 ky cal BP
S5 >50.00 ky cal BP
0
5
10
15
20
25
30
35
40
45
50
55
60
ochre
grey
yellow
yellow
grey
yellow/grey
grey
grenish
yellow to red
beige to dark
micaceous/greenish
ochre/grey
grey
grey
greenish
beige/grey
green
orange
ochre to yellow
ballast
shells level
pebbles up to 4cm
pebbles level
micaceous
micaceous
organic matter
micaceous, om
micaceous
pebbles level
pebbles level
gravels level
shells level
shells level
pebbles level
float pebbles
float pebbles
gravels level
mussels level
gravels level
shells level
gravels level
shells level
pebbles level

Fig. 10). Dating was carried out down to a core depth of 35.40 m, where the age of the sediment exceeds the limit of the method.

The age calibration allows us to study the deposition of sediments from 45 ky BP to the present day. This interval of time corresponds to the end of the last sea-level drop, the maximum lowstand, followed by the last sea-level rise and the current highstand.

5. Depositional environments

The acoustic substratum beneath unconformity S100 is correlated with the Pliocene, which is identified in numerous previous drillings in the nearby Roussillon coastal plain (Duvail et al., 2002, 2005). Onland, the Pliocene deposits are linked to the Roussillon coastal plain infilling by prograding Gilbert-type deltas (Clauzon, 1990). The characteristic seismic facies 1 may be attributed to synsedimentary geometry and possibly several prograding deposits seaward of point sources. The shore-parallel deformation could be due to mass gravity features.

5.1. Incised valley-fill interpretation — overall trends

The SC1 borehole can be correlated with the main unconformities observed on the closest seismic lines. Thus, the sedimentary units 1 to 3 appear to be associated with the valley-fill.

The lower sedimentary unit (unit 1) makes up the basal part of the valley-fill, corresponding to a thin layer just above the lower incised valley system boundary. The very coarse pebbles observed at the base of this unit are associated to the main erosional discontinuity D100/D200, are considered as fluvial deposits. Nevertheless, the presence of yellow sands containing shells and shell debris, along with the juxtaposed green muds, suggest a reworking of the fluvial deposits under marine influence.

The sedimentary unit 2 is roughly correlated with the five lower incised valley fills (R100 to R500), in the absence of more accurate correlation. Below the lagoon and coastal area, there is no evidence for seismic unconformities. The seismic units are mainly characterized by seismic facies 2 and 3, medium to low-amplitude sub-horizontal reflectors and semi-transparent facies. Thus, the seismic facies can be associated with muddy-silt deposits with a very low sand/mud ratio at the base (sub-unit 2a) and a higher sand/mud ratio at the top (sub-unit 2b). The muddy silts show onlapping relations with the incision walls and upstream thalwegs, suggesting that the infilling occurred during successive phases of rapid relative sea-level rise. The coarser layers within this unit, the shelly pebble beds, are assumed to represent reworked boundaries between distinct incised valley fills. In a large estuary, the basal pebbles of fluvial origin do usually not contain shells of marine origin. In the case of this study, the estuaries are of small size due to the limited tidal range, so we assume that the borehole is not located directly on the thalweg axis but rather to one side and more elevated. The coarse layers observed are probably older lowstand-related materials, devoid of shells, that were reworked during the transgression when the shoreline was in proximity. The cm-thick sandy beds containing shells could be related to increase marine influence due to storm events.

The low sand/mud ratio of the sedimentary sub-unit 2a is associated with the presence of shell beds, and the shell debris content indicates a marine influence in a low-energy depositional environment. This sub-unit is assumed to correspond to the central part of an estuary environment (Zaitlin et al., 1994), a hypothesis that is supported by the lack of planktonic foraminifera.

The coarser bed between sub-units 2a and 2b, composed of mud-supported pebbles without shells, reflects an increasing fluvial influence. During interglacial phases, particularly associated with warming and sea-level rise, the melting of ice, from the Pyrenean mountains, led to catastrophic outburst floods. Such phenomena could explain the interfingering of continental matrix-supported pebble deposits (related to ice-melting) with the more marine-influenced estuarine muds. The second type of matrix-supported pebble bed contains shell debris. This type of sedimentary association seems to reflect a reworking of incised valley fill and walls.

Above, the sedimentary sub-unit 2b cannot be correlated with a distinct incised valley fill. This coarser sub-unit is associated with shells and bioturbation, suggesting a more marked coastal influence than sub-unit 2a, which reflects its deposition in an estuary-mouth environment. Sub-unit 2b is probably linked to a landward shift of one or more upper incised valley fills.

The sedimentary unit 3 is correlated with the high- to medium-amplitude seismic reflectors of facies 2 and chaotic seismic facies (facies 4) associated with the R600 valley fill. The sedimentary association of muds, pebbles and sands containing shells and bioturbation at the top seems to characterize a coastal environment ranging from low to high energy. This unit is probably associated with the last period of valley fill during the sea-level rise. We assume that unit 3 represents an estuary mouth and/or coastal barrier environment. The presence of proximal depositional environments in the case of the uppermost valley fill suggests a major landward shift of the river mouth compared to the previous incision.

The sedimentary units 4 and 5 are associated with the Holocene coastal prism with its characteristic yellow sands and fining-up trend with reduced faunal contents. The uppermost few metres are probably linked to human activity, corresponding to reworked deposits. The superimposition of several fining-up sedimentary bodies can be attributed to very-high-amplitude cyclicity in coastal prism deposition probably combined with the wash-over deposits observed in littoral areas.

5.2. Interpretation of dating results

The five sedimentary units of the SC1 borehole are considered successively from base to top.

The dating results (Table 1) indicate that sub-unit 2a is older than the limits of the AMS 14C method, with S5 yielding an age exceeding 50 ky cal BP years at 35.4 m core depth. This implies that the main part of the sedimentary unit 2 (associated with the valley fill) is older than 50 ky cal BP (stage MIS3 or older).

The overlying deposits, corresponding to sub-unit 2b, are dated at around 41 ky cal BP at two core depths, 26.30 m (S3) and 28.50 m (S4). The ages of these deposits, correlated with the R600 valley fill, suggest that deposition occurred during the sea-level fall of the last 4th-order eustatic cycle (glacial stage MIS2, Fig. 10).

The sedimentary unit 3 is dated at depths of 18.10 m (S1: 9.75 ky cal BP) and 21.68 m (S2: 11.32 ky cal BP). Moreover, previous age dating is available for this unit (Tesson et al, 2005; Labaune, 2005), indicating that unit 3 corresponds to the last sea-level rise (interglacial stage). The age calibration obtained from S2 suggests a deposition below the maximum sea-level depth assumed by the curve at this stage. Thus, it is probably made up of reworked sediment due to wave ravinement during the post-Glacial transgression.

The two overlying sedimentary units (units 4 and 5) are not dated in this borehole, but previous studies based on vibrocoring data (Labaune, 2005) suggest that deposition occurred during the last highstand period.

Fig. 9. LEUCATE SC1 borehole description (beach barrier of Salses-Leucate lagoon, located in Fig. 1). Lithological description is based on X-ray gammagraphy, 3D scanning and laser granulometry analysis. Age dating is based on calibrated ^{14}C data. The reference datum of the borehole is 2 m above present-day sea level.

6. Stratigraphic architecture

6.1. Development of individual sequence — from incised valley to forced regressive wedge

We adopt the four-fold classification to describe the building of the individual sequence which are associated respectively to the sea-level lowstand (early lowstand system tract), the maximum lowstand (lowstand system tract), the sea-level rise (transgressive system tract) and the highstand (highstand system tract).

6.1.1. Sea-level fall: from highstand to lowstand

The fuvial pebbles observed at the base of the SC1 core (sedimentary unit 1), in a littoral area, are significant to the base-level fall and thus to the sea-level fall. The sea-level fall is the first step of incised valley building.

The initial fall in sea level generates a seaward and downward shift of the upper shoreface (forced regression) and increases the slope in the downstream part of rivers. This produces retrogressive fluvial erosion and incision, linked to the increased sediment flux from rivers, which leads to sediment accumulation seaward of the new shoreline by deltaic progradation and littoral drift. In this way, an initial regressive wedge is formed, overlying a downward shift surface (Posamentier et al., 1992) and the correlative erosional surface in the river. When the initial wedge progradation ceases, the time equivalent surface of its upper surface is represented by a new erosional surface in the river.

The subsequent fall in sea level follows the same pattern, with an additional process corresponding to the sub-aerial erosion of the previously formed emerged wedges. Moreover, in this area of the Gulf of Lions, fluvial erosion does not appear to have extended far across the shelf towards the open sea.

Finally, due to the polygenic nature of the erosional surface in the river, its seaward correlation should be made either with the lower surface of progradation of the forced regressive wedges or with the upper surface (Fig. 11a).

6.1.2. Maximum sea-level lowstand

During falling sea level, the composite forced regressive wedge progrades onto the outer shelf (Fig. 11b). On the inner shelf, the early regressive wedge is more or less well preserved and the highstand deposits are likely to be totally reworked by wave action and aerial erosion. The basal surface of erosion of the river is limited to the inner shelf and coastal plain, associated to the seismic discontinuity D200 to D600, and is covered with a sheet of fluvial deposits. The fluvial deposits are observed at the base of the incised valley system (sedimentary unit 1). The lack of any coarse fluvial material interbedded in the muds of the lower middle section of the SC1 borehole suggests that river sediment load decreases with the progressive fall in sea and base level while the initial coarse material is removed.

6.1.3. Sea-level rise: from lowstand to following highstand

At the beginning of the sea-level rise (Fig. 11c), river flow is little modified on the inner emerged shelf. The landward shift of the shoreline is accompanied with shore-retreat lag deposits and some submarine features (early transgressive systems tract) overlying a transgressive surface and the forced regressive wedge.

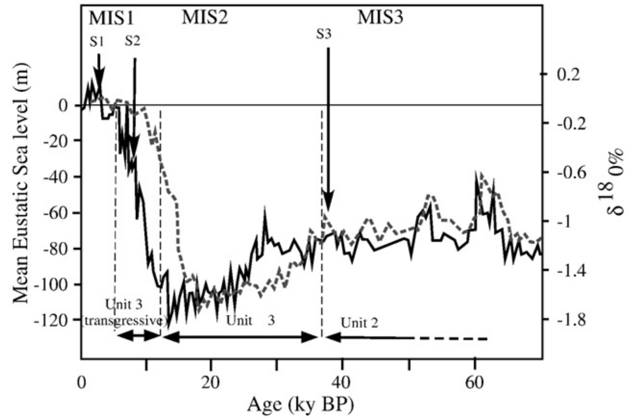


Fig. 10. Correlation of the upper sedimentary units of the SC1 borehole against climate and relative sea-level changes during the late Pleistocene. The sea-level curve is based on oxygen isotope curves are modified from Pillans et al. (1998). The grey dot line is the mean eustatic sea level and the continuous dark line is the δ^{18}O. The age dating from the cores analysis is located on the curve (S1, S2, S3). Based on this correlation, the sedimentary units, units 2 and 3, are associated to different sea-level variations.

As sea level approaches the location of the incised river mouth, the river slope decreases rapidly and the incised valley changes from fluvial-dominated to progressively marine-dominated, either as an estuary or a bay (Fig. 11d). The muddy levels with shells and the mussel levels observed on SC1 clearly indicates brackish water environments i.e. estuary or semi-enclosed bay, due to marine influence. The estuary deposits are probably also associated to the seismic facies 3 with low-amplitude sub-parallel reflectors.At the same time, the mountains of the hinterland provide large amounts of sediment input due to ice-melting during fluvial floods. At the bay mouth, wave reworking of the previous forced regressive wedge re-structures the sands into shoals. The chaotic and progradational seismic facies (4 and 5) and the sandy deposits in the sedimentary unit 3 are associated to the dynamic processes impact.

During the following stages of sea-level rise, the muds accumulate in a low-energy environment and onlap onto the eroded river walls (sequence boundary), suggesting a backstepping infilling, characterized by seismic facies 3. The low amount of sediments suggests that the deposition occurred during a short period. Farther upstream, fluvial influence prevails and coarse material makes up the main component of the sedimentation (Duvail et al., 2002). Under catastrophic events such as floods and/or glacial outbursts, some deposits of floating or mud-supported pebbles extend seaward as far as the central estuary area and are interbedded with the muds as indicated in the SC1 cores.

With rising sea level, the estuary is progressively drowned, and the environment becomes entirely marine-influenced. However, due to the restricted tidal range, a mixed tide/wave ravinement surface is developed.

Reworked sands are introduced by waves and littoral drift, forming a sheet of shelly material with a sharp contact on muds. Locally, river channel fill is imbricated with some pebbly lenses.

6.1.4. Highstand progradation

Equilibrium is established progressively between base-level rise (accommodation space increase) and sediment input (Fig. 11e). Then, the sediment available at the boundary between the inner estuary and fluvial domain starts to prograde. The last well preserved highstand prism is mainly composed of sand interbedded with gravels and pebbles, with sedimentary structures suggesting a fluvial sedimentation near the sea. The occurrence of shelly beds suggests that conditions such as storm events led to the formation of shoreline

Table 3
^{14}C calendar age dating. Depth refers to the top of the drill.

Sample name	Depth	Lab. no.	Code	Age ^{14}C (ky cal BP)
LEUCATE SC1 18.05	18.10	Poz-207117	S1	9.750 +/− 0.50
LEUCATE SC1 21.63	21.63	Poz-207118	S2	11.320 +/− 0.50
LEUCATE SC1 26.30	26.30	Poz-207119	S3	39.600 +/− 0.700
LEUCATE SC1 28.50	28.50	Poz-207120	S4	41.800 +/− 1.600
LEUCATE SC1 35.40	35.40	Poz-207121	S5	> 50.000

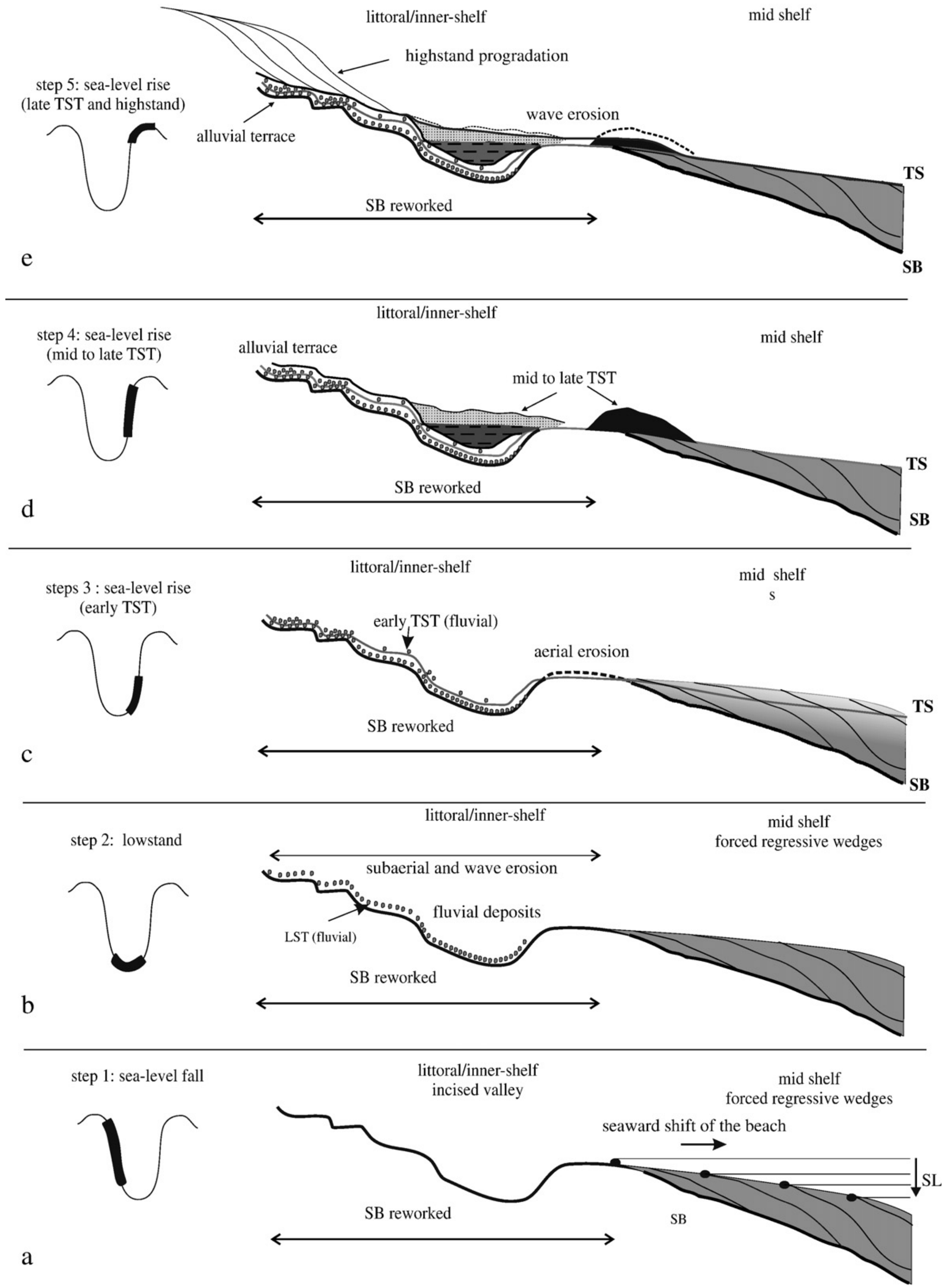


Fig. 11. Stages of building up of a single depositional sequence from alluvial plain to outer shelf. Illustration of incised valley formation, erosion and infilling. (SB: sequence boundary, TS: transgressive surface, WRS: wave ravinement surface, LST: lowstand systems tract, TST: transgressive systems tract, HST: highstand systems tract).

beaches/beach barriers alternating with river channels subject to catastrophic floods. The tidal processes in Mediterranean are too reduced to have a great impact on the sedimentation. The sedimentary unit 4 sandy dominated with scarce or absent shells is characteristic of such littoral environment and corresponds to the progradation of the highstand, those deposits are correlated to the Holocene period.

6.2. Stratigraphic pattern of the succession of incision/fill and correlative forced regressive wedges

The continuity of seismic data acquisition from land (present-day lagoon) to sea (outer shelf), allows us to develop a stratigraphic model

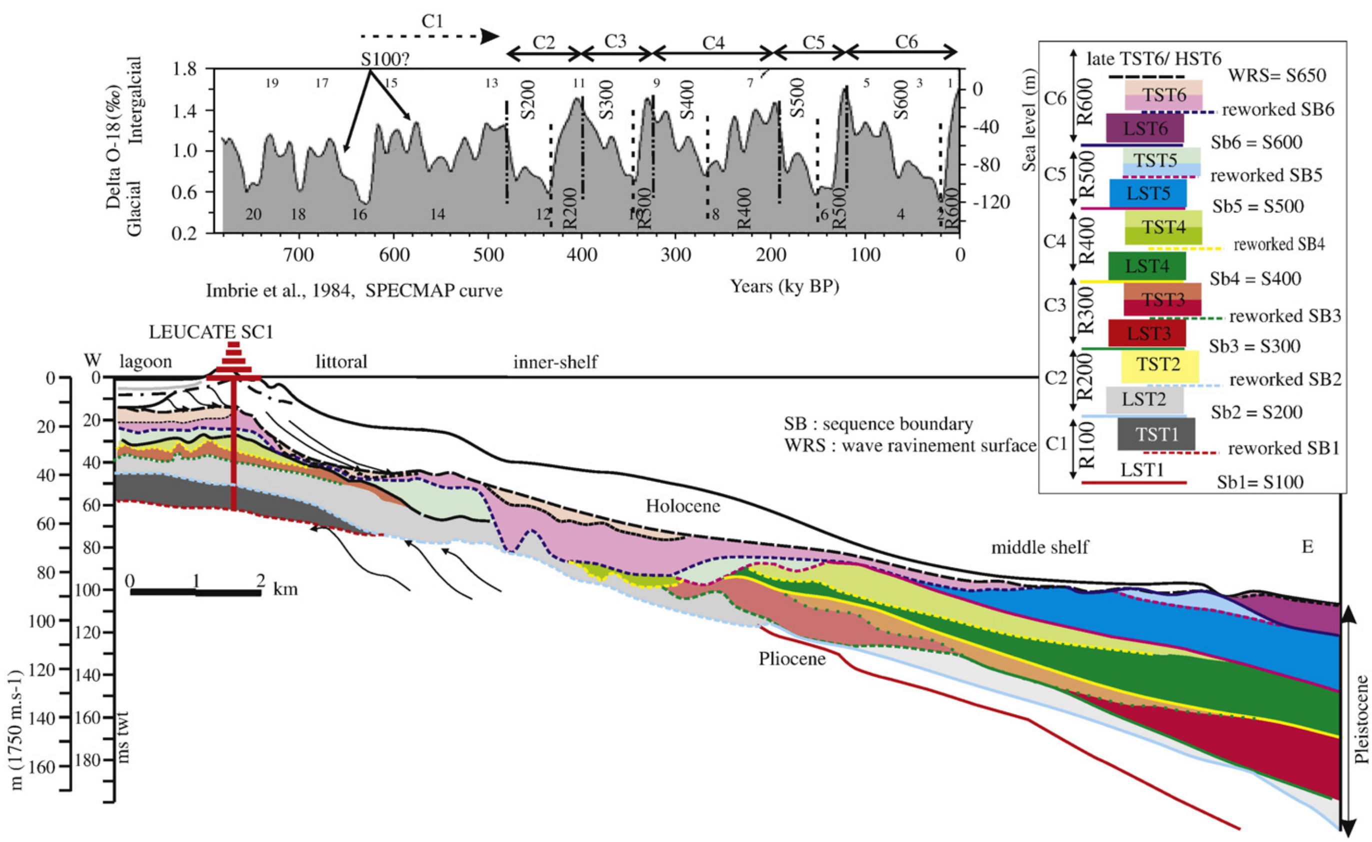


Fig. 12. Stratigraphic model for the Roussillon coastal area and continental shelf, from alluvial plain to middle shelf, comprising five cycles with accumulation of LST and TST deposits.

illustrated in Fig. 12, which shows the unconformities and sedimentary bodies or units interpreted in terms of sequence stratigraphy.

The basal unconformity S100 is observed beneath the coastal area at the top of the Pliocene and extending seaward under the late Quaternary depositional sequences. It forms the lower sequence boundary SB1, which corresponds to the Plio-Quaternary boundary. The wide thalweg morphology of this surface suggests the juxtaposition of several stages of incision probably linked to the low-amplitude sea-level variations of the early Quaternary reworked by the earlier high-amplitude sea-level cycles of the mid Quaternary.

Above the SB1–S100 unconformity, we find six more or less well preserved stacked depositional sequences. Each sequence includes: (i) incised valley fill more or less preserved under the present-day coast and inner shelf and (ii) forced regressive deposits, overlain by patchy deposits associated with a transgressive systems tract, which occurs under the middle to outer part of the present-day shelf (Tesson et al., 1990 and Posamentier et al., 1992).

From the age dating, we assume that each depositional sequence is related to a 4th order sea-level cycle with superposition of 5th order cyclicity. Thus, the six observed depositional sequences are linked to the six last 4th-order sea-level cycles. This hypothesis is backed up by the previous study on the forced regressive wedges.

The succession of sea-level cycles, with erosion during both lowstand and transgressive periods, leads to a partial preservation of the deposits along the shelf. Lowstand wedge deposits are preserved in the middle to outer shelf, and transgressive deposits can be locally observed (Tesson et al., 2000). In the inner shelf, the preserved deposits are associated to the valley fills. In the coastal area and inner shelf, the incised valley fill shows different degrees of preservation depending mainly on the thalweg location and differential subsidence (see next paragraph). The deposits preserved are mainly associated with the mid to late transgressive phases.

7. Discussion

Between the lowermost basal sequence boundary and the upper transgressive surface, the time interval can be as long as 2.0 My. The recorded and preserved section is interrupted by several time gaps, so it is not representative of the regional history. This implies that we should be very careful in interpreting ancient deposits having a very low-resolution chronostratigraphic control compared to Quaternary successions.

The observed Roussillon IVS is mainly the result of base-level variations of the Têt and Agly rivers during the middle to late Quaternary (around 700 ky to present), which are associated with high-amplitude sea-level cycles. From the coastal zone to the inner shelf, the direct superimposition of the system on early Pliocene deposits (Duvail et al., 2005) suggests that a major erosion of the deposits occurred associated with low-amplitude sea-level variations between the early Pliocene and the mid Quaternary. The onshore correlation of the system based on seismic data from the lagoon and coastal area, with the work led on the Roussillon coastal plain (Duvail et al., 2002), allows us to link the valley axes to the Têt piedmont valley. It has been proposed that, during the Quaternary, both rivers had a northward outflow that migrated recently toward the south (Martin, 1978; Labaune, 2005).

7.1. Incised valley system location

A link long has long been established between the location and shape of incised valleys, involving factors such as paleo-topography, structural parameters and rock resistance (Tuttle et al., 1966; Bates and Jackson, 1984). More recently, case studies have been used to discuss some general conclusions about fluvial processes (Schumm and Ethridge, 1994), while other studies have dealt with paleotopographic control (Deibert and Camilleri, 2006) and structural impact (Porebski, 2000; Plint and Wadsworth, 2003).

7.1.1. Paleo-topography

The incised valley system in front of the Roussillon coastal plain seems to be influenced not only by the directly underlying topography but also by older events linked to the Messinian erosion. The main axis of the Roussillon IVS is juxtaposed onto a West to East trending Pliocene synform (Fig. 7). Because of this morphology, the orientation of the Pliocene synform favoured the outflow of rivers from the valley. Moreover, if we interpret the antiforms as prograding accumulations of coarse material on the sedimentary fronts of fluvial tributaries, then the sediments of the interdistributary bays were probably finer grained and exhibited a higher erodability. Although such a correlation is clear in the coastal area, it becomes less evident seaward because the valley does not maintain a well-identified thalweg.

Previous studies of the Gulf of Lions region have provided a digital terrain model (DTM) of the Messinian erosional surface (Lofi et al., 2005). A comparison of the DTM of the MES and the DTM of the basal incision (S100) shows that the two basins are relatively closely juxtaposed (Fig. 13a).

7.1.2. Structural control

The geometry of the Messinian erosional surface (MES) is in large part inherited from the activity of the normal faults which, according to Lofi et al. (2005), led to the Oligo-Miocene horst and graben tectonics (Fig. 2a). The Messinian erosional surface shows very deep basins bounded by topographic highs. This set of faults should have been active also during the Messinian Salinity Crisis.

Petroleum seismic data (LRM97) acquired by Elf highlight this topography and stress its impact on the overlying Pliocene deposits (Fig. 13b). The Pliocene shows a differential compaction of the sedimentary layers, which affects basin morphology extending up to the Quaternary deposits. This differential compaction can account for the soft deformation of the Pliocene (Duvail et al., 2005) and the post-Pliocene accommodation.

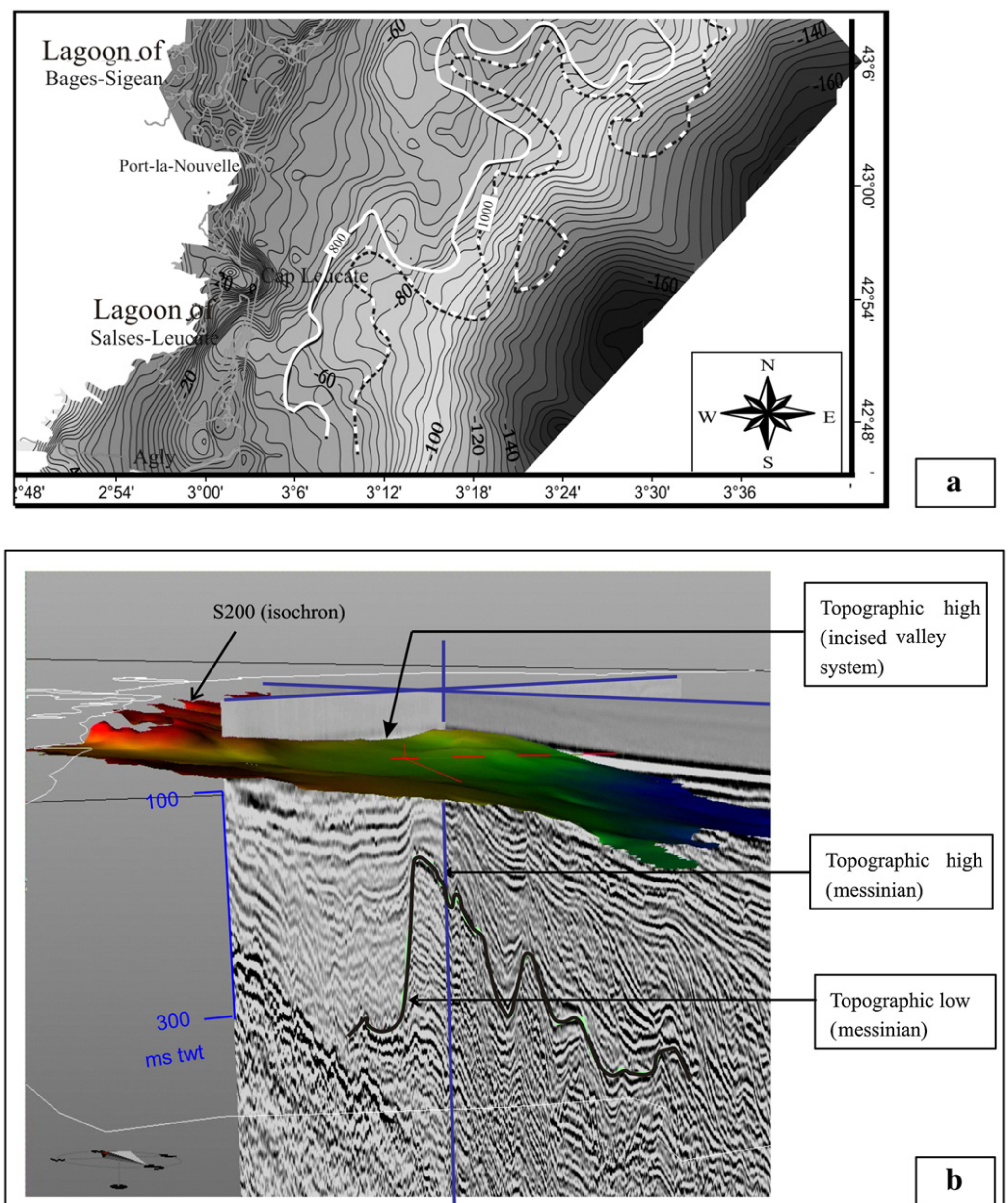


Fig. 13. (a) Extract of conventional seismic lines (96 LRM — 2 cross lines) illustrating the superposition of the main topographic lows and highs between the Messinian surface and the base of the Quaternary incised valley systems and (b) Isochron map of S100/S200 (Pliocene/Quaternary boundary) and superimposed isochron of the Messinian.

The Têt fault, a major normal fault well-identified under the coastal plain (Alabouvette et al., 2003), appears to have controlled the northward extension of the basal incision. This point is subject to discussion because the seaward extension of the fault is not yet identified. Nevertheless, in view of the proposed extension within the littoral zone and the relatively good northward continuity with another identified normal fault, we can assume a structural control (Fig. 2a). Moreover, while Quaternary tectonic activity is recognised on the Têt alluvial plain (Carozza and Delcaillau, 1999), it is not observed on the high-resolution seismic data. Hence, the Quaternary activity of the Roussillon coast and inner shelf is currently poorly known.

7.2. Preservation potential

In most cases, the Quaternary incised valleys on the French coast record the last glacial/interglacial half-cycle (Allen and Posamentier, 1994; Lericolais et al., 2001; Weber et al., 2004) and do not exhibit any physical relationship with the mid-outer shelf lowstand deposits (MIS5 to MIS2). A limited deposition and/or degree of preservation are often linked to macrotidal environments, which enhance the erosion and also to a low subsidence rate. The Roussillon coastal area is a specific study case showing: (i) the preservation of several phases of incision/infilling linked to 4th-order glacio-eustatic cycles, (ii) continuity with the forced regressive lowstand wedges on the shelf. This preservation could be due to several factors: (i) differential subsidence, (ii) lateral migration of the valley thalwegs and (iii) the low-energy hydrodynamic conditions (micro-tidal environment).

7.2.1. Impact of differential subsidence

In the Roussillon region, the good preservation potential is probably linked to the combined effect of the amplitude of sea-level fall and differential subsidence (Tesson et al., 1990 ; Tesson and Allen, 1995). Based on (i) the subsidence rate value of 250 m/My on the outer shelf (Rabineau et al., 1998), (ii) a hinge point located near the present-day coastline (Duvail et al., 2005) and (iii) a continuously increasing 630 rate of subsidence between these two areas, the amount of subsidence can be assessed in different point of the study area.

The incised valley S200 and its valley-fill R200 are associated to the cycle C2, R200 is well preserved all along the study area (Fig. 5). The maximum sea-level lowstand (MIS12) is the maximum observed for the middle to late Quaternary. It is more important than for the two successive maximum lowstand (MIS10 and MIS8, Fig. 14). This observation combined to the differential subsidence rate, from 0 to 32 m up to the next sea-level fall which is less important, can partially explain the well-preservation of R200. Other factors, mentioned in the next sections have to take into account.

The next valley fill R300 is only preserved in the distal part of the inner shelf (Fig. 5). This incised valley is linked to the maximum lowstand of the MIS10 which shows a maximum sea-level lowstand above those associated to the MIS6 and MIS2 (Fig. 14). Thus the partial preservation only in the distal part of the system can be partially linked to the differential subsidence which reaches about 80 m in the area up to the MIS6 period.

The valley-fill R400 is observed only locally as small basins (Fig. 5). The maximum sea-level lowstand originated the incision show the minimum value (Fig. 14). The differential subsidence seems to not be sufficient to compensate the erosion due to the next sea-level fall. It can explain the poor preservation of the valley-fill. The other local factors mentioned in the next section have to be considered for the local preservation.

The valley-fill R500 is also poorly preserved, small basins (Fig. 5). The maximum lowstand which is associated to the MIS6 and induces the incision S500 is equal to the last one associated to MIS2 (Fig. 14). As for the previous system, the differential subsidence seems to be insufficient to allow the preservation of the valley-fill.

Nevertheless, the preservation of R100 both on the coast and in the lagoon area cannot be explained by differential subsidence. The current lack of knowledge on subsidence and tectonic activity during the Quaternary make it difficult to make an accurate interpretation. We could assume the presence of a basin in this area, possibly linked to the Têt fault.

7.2.2. Lateral migration

Lewin and Macklin (2003) evoked lateral migration as a factor controlling the erosion/preservation of older units. The Roussillon is characterized by a sedimentary substratum (Pliocene substratum) which favours the lateral shifting of each 661 successive incision. The maps of the successive incised valleys (Fig. 4f) pick out the lateral migration of the thalwegs between each phase of incision. The dominant trend during the Quaternary is a northward migration. By contrast, the last incision displays a southward migration, which is also the present-day trend (Martin, 1978; Labaune, 2005). Due to the lateral migration, the new incision is not directly superimposed onto the previous one. The continuous migration of the river thalwegs favours the preservation of the pre-existing valley-fill. In other incised valley systems, such as in South Brittany on the French Atlantic coast (Menier et al., 2006), the seaward extension of the Cambrian substratum and its fault system has constrained the river morphology during successive relative sea-level falls in the same fault-controlled incision. Erosional processes prevail in this area, enhanced by the strong tidal range, and only the last transgressive deposits are preserved until the next relative sea-level fall. The oldest deposits are probably restricted to remnant bodies of indeterminate nature and age. The hydrodynamic regime, which induced littoral drift, acts on the lateral migration of the successive incisions.

In the Roussillon region, lateral migrations are confined within a wide thalweg valley in the proximal zone and become unconfined seaward. Structural control affects only the proximal zone and extends as far as the underlying preserved incised valley, thus allowing migrations of the river channel between successive phases of incision/fill.

7.2.3. Hydrodynamic regime

The hydrodynamic regime is another factor that should be considered to explain the preservation of a compound incised valley. The Roussillon coast and inner shelf are currently subject to a low-energy hydrodynamic regime. Such conditions do not offer the high potential for ravinement of valley-fills as observed on the French Atlantic coasts (Allen and Posamentier, 1994; Chaumillon et al., 2008). While the tidal ravinement surface often erodes a large amount of the valley-fill (Foyle and Oertel, 1997; Kitazawa, 2007) in macrotidal environments, it is probably absent in areas of low tidal range. Moreover, when combined with the low-energy hydrodynamic regime, the topographic low generated by the incision enhances the preservation potential.

7.2.4. A special case

The uppermost valley-fill (R600) shows the best preservation, mainly because of the lack of a renewed fall in sea level and incision in recent times. This valley-fill highlights the central role played by variations in relative sea level, and thus base level, in controlling the preservation potential. The good preservation of this valley-fill raises another interesting point; the observation of a continuous thalweg with meandering morphology (Fig. 8). This type of morphology suggests a relatively flat paleo-topography during the formation of the incised valley (Schumm, 1963).

7.3. Specific aspect of the vertical succession of facies in the SC1 borehole

The SC1 borehole is mainly composed of relatively continuous estuarine muddy silts overlying a single fluvial horizon at around 58 m (sedimentary unit 2), which is associated with the incised valley system. Thus, we find no evidence for the well identified erosional surface

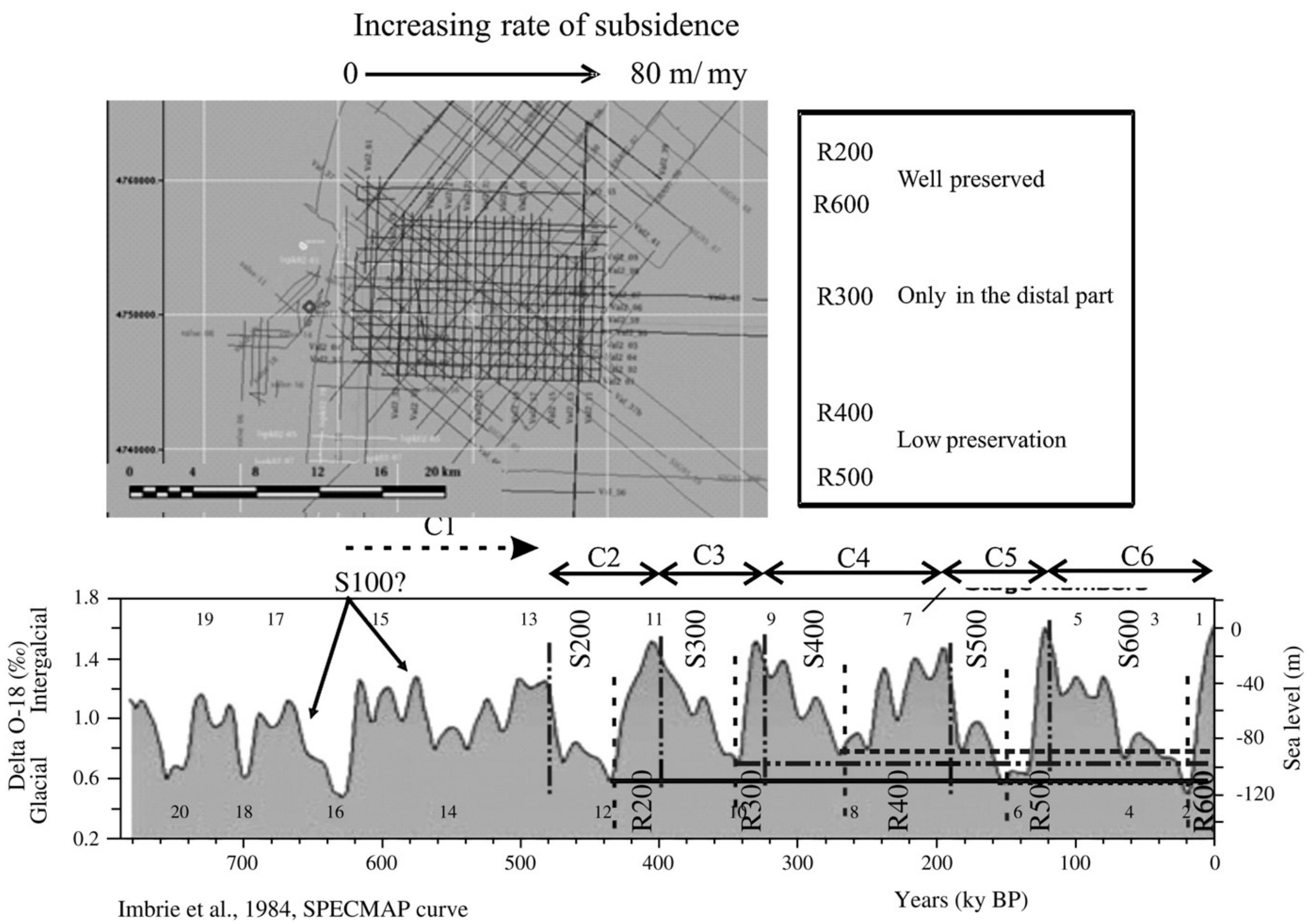


Fig. 14. Estimated sea-level curves with additional differential subsidence effect (rate calculated after Rabineau, 2001) at different locations within the studied area (D: distance to the present coast line). The line corresponding to each valley system is drawn with an origin at the marine isotopic stage assumed to be coeval with incision.

expected between successive phases of incision/fill (Zaitlin et al., 1994). Nevertheless, the occurrence of four thin coarse layers (sands and pebbles) without shells should be considered as indicative of a period of sea-level fall (fluvial incision phase).

8. Summary and conclusions

Recent seismic data calibrated by a 60-m-deep borehole is used to document the late Quaternary history of the incised valleys and fills buried beneath the coastal area and inner shelf of the Roussillon region.

This study provides a rare example of the direct longitudinal correlation of key surfaces and sedimentary units belonging to the lower segment of a compound incised valley system associated with forced regressive deposits offshore.

The incised valley system is composed of a set of six incisions and their fills, which were developed between the Plio-Quaternary boundary and the polygenic wave ravinement surface related to the last glacial transgression.

A chronostratigraphic control is based on AMS ^{14}C age dating of the upper part of the borehole section, showing that the five lower incision/fill sequences are older than 50 ky cal BP, while the uppermost incision is associated with the last 4th-order relative sea-level cycle.

The succession of incisions/valley-fills in the lower part of the section can be correlated with the six last 4th-order (100 ky) RSL cycles. This hypothesis is supported by the seaward correlation of the incision surfaces with the boundaries of the forced regressive lowstand wedges on the shelf, which were previously linked to depositional sequences of the mid to late Quaternary.

The different phases of incision are clearly picked out by seismic data in the lower segment of the compound incised valley. To a limited extent only, these phases appear equivalent to the thin layers of fluvial coarse material in the borehole located farther upstream. The infilling deposits, made up of estuarine muddy silts at the borehole location, are characterized by interfingering layers of matrix-supported pebbles related to ice-melting processes associated with warming periods (interglacials).

During each sea-level fall, the previous transgressive and highstand deposits are incised in the proximal part of the system, while forced regressive wedges are deposited in the distal areas. At the end of the relative sea-level fall, the final erosional surface corresponds to a reworked sequence boundary in the fluvial/estuarine areas and a sub-aerial erosional surface seaward, on top of the forced regressive wedge. During the following sea-level rise, the valley is filled by estuarine to estuary-mouth deposits, while some patchy transgressive deposits remain at the top of the forced regressive wedge.

The location of the system is controlled by the paleo-topography, the compaction of the underlying basin fills and the basement structure. During the time period covering the development of the incised valley system, there is no clear evidence for direct structural control.

The preservation potential depends on the following factors:

- The location of the hinge point representing the balance between eustatic variations and tectonic effects, and the position of the considered segment in the incision system
- The possibility of lateral shifting of the thalweg axis between successive phases (lateral migration)
- The hydrodynamic parameters of the system (fluvial and oceanic).

Finally, the incised valley system of the western Gulf of Lions does not clearly fit with the accepted model of incised valley deposits being made up of sand bodies in mud systems. The example described in this study forms a compound incised estuary/valley associated farther seaward with forced regressive deposits.

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