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Quaternary compound incised valleys of the Roussillon coast (SE France): correlation of seismic data with core data

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Key-words. – Incised valley deposits, Quaternary, High resolution seismic, Core data, Gulf of Lion

Abstract. – A detailed study of a Pliocene to Quaternary incised-valley system located under the Roussillon coastal area (Gulf of Lion) is carried out by means of a high-resolution seismic data set (coastal lagoons and adjacent shelf area), drill reports and analysis of a cored drill (Leucate SC1) performed in 2007 on the barrier beach in the North of Leucate lagoon.

The lowermost surface (S100/S200), correlated with a pebbles level on the Leucate core SC1 (R0), erosionnally overlies pliocene deposits. It is incised by a thalweg 15 m depth and deepens progressively from the coastal plain to the outer shelf and dips under the Quaternary forced regressive wedges.

Above this basal surface, the infilling of the incised valley corresponds to the seismic unit U1. The lower part of U1 shows continuous sub-horizontal reflectors and is correlated (Leucate SC1) to marine muds with levels of mud-supported gravels (body B). The upper part of unit U1 comprises seismic erosional reflectors that are almost amalgamated under the barrier beach. It is correlated on the Leucate well to body C comprising coarse levels (gravels and pebbles) alternating with marine muds (lower part) and marine coarse sands (upper part). The upper part of the unit is dated 12900 cal yr B.P. This unit is interpreted as resulting of successive phases of incision and infilling due to base-level changes during Pleistocene glacial and interglacial periods. Coarse levels of sand and gravel corresponding to river stages and sands and muds shelly levels representing marine stages.

The overlying units represent post-glacial late transgressive (S650) and highstand (U660, U661, U662) deposits.

This system is a rare example of well preserved compound incised valleys correlated offshore with Quaternary lowstand wedges.

By comparison, the incised valleys along the Atlantic coast of France are "simple" incised valleys where only the last episode of incision/infilling is observable. The Quaternary "compound" incised valleys cited in the literature represent examples of the fluvial part of incised systems, whereas the Languedoc-Roussillon incised valleys probably correspond to estuary or embayment, successively reoccupied during the various Quaternary eustatic cycles.

Tectonics is the main factor controlling the depositional stratigraphic architecture. The studied area is located at the hinge point between continental uplift and marine subsidence and favoured the preservation of successive phases of erosion/infilling. The geometry of the Pliocene deposits has also an impact on the shape and orientation of the buried paleovalleys.

Le système de vallées incisées composées de la côte du Roussillon (SE de la France) : corrélation des données sismiques et de forages

Mots-clés. – Dépôts de vallées incisées, Quaternaire, Sismique haute résolution, Données de forages, Golfe du Lion.

Résumé. – L'étude détaillée d'un système de vallées incisées quaternaires situé dans le secteur côtier du Roussillon (golfe du Lion), a été menée à partir d'un ensemble de données sismiques haute résolution, de rapports de forages et de l'analyse d'un forage carotté ("Leucate SC1") réalisé en 2007 sur la barrière littorale au nord de l'étang de Leucate.

La surface inférieure (S100/S200), corrélée à un niveau de galets du forage Leucate SC1, surmonte érosionnellement les dépôts pliocènes. Elle est incisée par un talweg de 15 m et s'approfondit graduellement de la plaine côtière vers le large où elle passe sous les prismes de bas niveaux quaternaires. Au-dessus de cette surface, le remplissage de la vallée incisée est représenté par l'unité U1. La partie inférieure de U1 montre des réflecteurs continus sub-horizontaux corrélés dans le forage "Leucate SC1" à des vases marines avec des passées à graviers à texture flottante (Corps B). La partie supérieure de l'unité U1 montre des réflecteurs érosionnels qui s'amalgament sous la barrière littorale actuelle. Cet ensemble inférieur est corrélé sur le forage de Leucate au corps C qui comprend des niveaux grossiers (graviers et galets) alternant avec des vases marines (partie inférieure) et de sables marins grossiers (partie supérieure).

Le sommet du corps C est daté 12 900 cal yr B.P. L'alternance des lithologies suggère un milieu de type estuarien avec les niveaux grossiers de sables et graviers correspondant à des épisodes alluviaux et les niveaux vaseux coquilliers représentant des épisodes marins. Cette unité est interprétée comme résultant des phases successives de creusement et de remblaiement sous l'action des variations du niveau de base durant les périodes glaciaires/interglaciaires.

L'unité située au-dessus représente les dépôts fini-transgressifs (S650) et de haut niveau (S660, S661, S662).

Ce système constitue un des rares exemples de vallées incisées composées bien préservées et corrélées au large avec les prismes de régression forcée quaternaires.

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Par comparaison, les vallées incisées étudiées sur la côte atlantique française sont des vallées incisées simples où seul le dernier épisode de creusement/remplissage a été préservé. Dans la littérature, les études de vallées incisées composées d'âge quaternaire concernent la partie fluviale du système d'incisions alors que dans le cas du Languedoc Roussillon, le secteur étudié/préservé constitue la partie estuarienne qui a été successivement réoccupée de façon cyclique durant le Quaternaire.

La tectonique est un facteur important de contrôle de l'organisation stratigraphique. La zone d'étude où se développent les vallées incisées est située au point charnière entre le domaine continental en soulèvement et le domaine marin en subsidence ce qui a favorisé la préservation des épisodes successifs d'érosion/soulèvement. La géométrie des dépôts pliocènes a également un effet sur la morphologie et l'orientation des paléo-vallées aujourd'hui enfouies.

INTRODUCTION

Incised-valley fills in ancient sedimentary formations have a proven economic interest as potential reservoirs. These features show a complex pattern at a small spatial scale, and studies of recent analogues are needed to enable optimized exploration and development. Since the pioneering work of certain authors [Allen and Truilhe, 1987; Allen and Posamentier, 1993; Dalrymple *et al*., 1992; Wescott, 1993; Wood *et al*., 1993; 1994], detailed studies of modern/recent sedimentary environments [Ashley and Sheridan, 1994; Blum and Aslan, 2006; Chaumillon and Weber, 2006; Kindinger *et al*., 1994; Lericolais *et al*., 2001; Nordfjord *et al*., 2005 and 2006; Osterberg, 2006; Tesson *et al*., 2005; Weber *et al*., 2004; Wellner and Bartek, 2003] have led to a classification in terms of "simple" and "compound" incised valleys [Zaitlin *et al*., 1994]. A few illustrative examples have been given of the more complex and commonly occurring types observed in ancient rocks [Foyle and Oertel, 1997; Thomas and Anderson, 1994].

The extensive seismic database developed in the Gulf of Lions since the 1990s has revealed the existence of a "compound" incised-valley system preserved beneath the Languedoc-Roussillon coastal zone and adjacent inner shelf (southwestern part of the Gulf of Lions) (fig. 1). Detailed data gathering has been recently carried out in this area.

Stratigraphic analyses based on a tight HR seismic grid [Tesson and Labaune, 2003; Tesson *et al*., 2005; Labaune, 2005] have called into question the depositional model for the post-Pliocene formations [Duvail *et al*., 2001]. Such models provide accurate data on a compound-type system of incised valleys located underneath the present deposits of the coastal zone and inner/mid continental shelf, which is connected seaward with Pleistocene wedges made up of forced regression deposits (aggradational offlap) on the shelf [Lobo *et al*., 2004; Tesson *et al*., 1990; Tesson, 1996]. This system is unusually well preserved relative to those elsewhere on French coasts. Moreover, the subsurface database (Banque de Données du Sous-Sol, BDSS) of the French geological survey (Bureau de Recherches Géologiques et Minières, BRGM), essentially made up of drill-log data, allows us to extend the study area landward over the coastal plain [Labaune, 2005]. However, field data are currently ill adapted (inappropriate drill location, rough lithology without sedimentological parameters, lack of chronono-stratigraphy or paleoenvironmental proxies) to test the different hypotheses [Certain *et al*., 2004; Duvail *et al*., 2005]. This paper presents new advances resulting from recent core drilling completed in February 2007 (SC1 Leucate drill hole) on the axis of the southern branch of the incised valley (fig. 2).

GEOLOGICAL SETTING

The margin of the Gulf of Lions is bounded by the Pyrenean and Alpine orogenic belts to the west and east, respectively. Its structure results from a succession of geological events:

1) rifting during the Oligocene-Aquitanian, followed by ocean-floor spreading in the Burdigalian [Gorini, 1993; Guennoc *et al*., 2000];

2) a post-rift episode took place from the early/mid Miocene, characterized by the accumulation of a thick wedge of clastic sediments (900 m on the inner shelf, 1900 m on the outer shelf);

3) an extensional phase during the Late Miocene is linked to the uplift of the eastern Pyrenees;

4) a major fall in sea level occurred at the very end of the Miocene, when the Mediterranean basin was isolated from the Atlantic (Messinian salinity crisis, from 6.3 to 5.2 Ma). The Gulf of Lions margin was deeply eroded by valley incision and a considerable thickness of salt (> 1000 m) was deposited in the basin;

5) a rapid sea level rise and flooding of the margin, when the Mediterranean Sea reconnected with the Atlantic Ocean during the early Pliocene;

6) the accumulation of upper Pliocene and Quaternary deposits (up to 2000 m on the outer shelf) under control of glacio-eustatic effects.

In the study area, located on the western margin of the Gulf of Lions (Roussillon plain), the lower Pliocene is marked by the sedimentary infilling of drowned valleys flooded during the Early Pliocene [Clauzon *et al*., 1987; Lofi *et al*., 2003]. The base of the succession is composed of Gilbert-type delta deposits, overlain by three main superimposed wedges that are seaward dipping beneath the present-day inner shelf [Clauzon *et al*., 1987; Duvail and Le Strat, 2002; Lofi *et al*., 2003].

Pliocene deposits were incised during Quaternary glacio-eustatic sea level fluctuations. Two major, E-W oriented troughs (50 m b.p.s.l.) have been recognized, located under the Canet and Salses-Leucate lagoons, which are filled with marine deposits at the base passing upwards into lagoonal/fluviatile deposits [Duvail *et al*., 2001]. Farther inland, Pleistocene deposits form imbricated terraces owing to the interaction of base-level drops during glacio-eustatic sea-level changes and tectonic effects (uplift). The different terrace surfaces merge near the modern coastline [Duvail *et al*., 2001].

Offshore, the Pleistocene shelf deposits are arranged into superimposed prograding wedges thickening seaward [Tesson *et al*., 1990, 1993; Lobo *et al*., 2004].

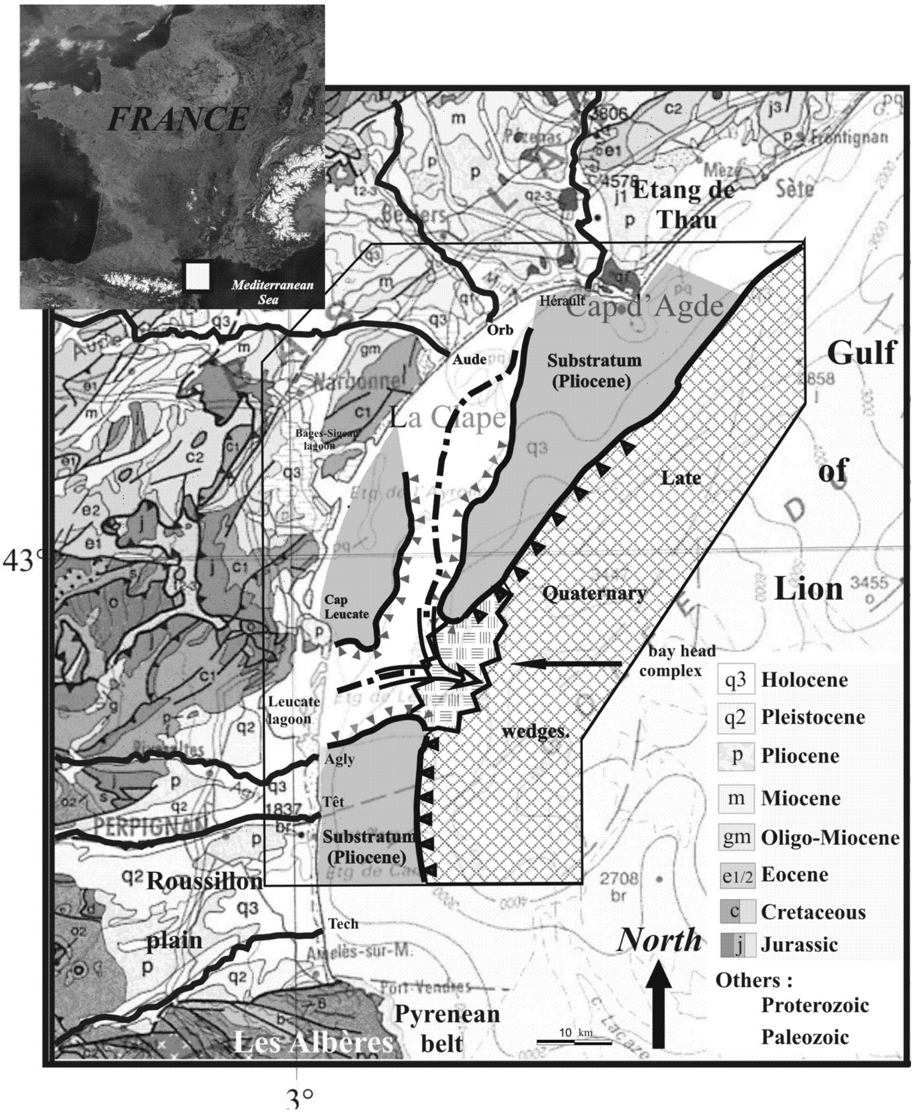

FIG. 1. – Geological setting of the study area.
FIG. 1. – *Cadre géologique de la zone d'étude.*

Margin subsidence began in the Miocene as a consequence of post-rift thermal relaxation enhanced by sediment loading, which accounts for 40 to 50% of the total subsidence [Gorini *et al.*, 1994]. The subsidence rate increased seaward, reaching a maximum value of 250 m/Ma at 70 km from the coast for the last 5.3 Ma [Rabineau *et al.*, 2006]. Subsidence is expressed by the seaward tilting and thickening of the shelf wedges. At the regional scale, the position of the hinge point controlled the landward location and stacking pattern of the prograding wedges on the shelf [Tesson and Allen, 1995].

DATA

Sedimentology: previous data and new Leucate SC1 drill hole

A core drill "Leucate SC1", 60 m length, was performed by FUGRO SA for GDARGO in February 2007 between the tidal channel and the Leucate lagoon, i.e. 200 m from the nearest seismic lines (figs 1 et 2). Cores were stored and analyzed at the Total SA building in Pau (France). Other available data include: (i) lithological logs of 10 m long drill cores, taken from the BDSS of the BRGM [Duvail *et al.*, 2001], (ii) short vibracores data from the GDARGO data bank [Labaune, 2005]; (iii) lithological log of a 15 m long drill core (S1) in the northern part of the Salses-Leucate lagoon [Martin, 1978]; and (iv) one (LE, confidential data) auger record, 55 m long, from holes drilled in 2003 by the BRGM, in the southern part of the lagoon. C^{14} age dating used in this paper are presented in table I.

TABLE I. – ^{14}C calendar age dating. Depth refers to the top of the sea level.
TABL. I. – *Datations ^{14}C citées et/ou utilisées. Profondeur exprimée par rapport au niveau marin.*

Origin	Sampling mode	Location	Depth	Lab. n°	Age 14C (ky cal BP)	Year
GDARGO	Leucate Sc1 cored drill	Figure 1	S1 16.10 m	Poz-207117	9.750 +/- 0.50	2007
GDARGO	Leucate Sc1 cored drill	Figure 1	S2 19.63 m	Poz-207118	11.320 +/- 0.50	2007
GDARGO	Vibrocore Vk02	Figure 1	5.3 m	Poz-8468	4.700 +/- 0.1	2004
BRGM GDARGO	LE Auger drill	Figure 2	18.00 m	Poz-8469	12.970 +/- 0.07	2005
CEFREM (Univ. Perpignan)	*S1 Drill*	*Figure 4a*	*4.20/ 5.60 m*	*?*	*8.200 +-0.15 no calibration information*	*1978*

Data from Cefrem have been considered as no valuable by the author (Martin 1978).

Seismic

The regional seismic database of GDARGO which covers the entire Gulf of Lions shelf has been supplemented by two cruises (CNRS/INSU cruises Valincis 1 and Valincis 2, 2004 and 2006] on the inner/mid shelf in the western part of the area using a Minisparker seismic source (fig. 2). Moreover, in shallow areas with water depths of less than 40 m (including lagoons, rivers and tidal inlets), both high and very high resolution seismic surveys have been carried out from 2001 to 2007 by GDARGO during summer campaigns using a conventional EGG^{TM} boomer and "line in cone" IKB Seistec^{TM} boomer.

All data were acquired in digital and georeferenced mode. Processing included gain attenuation correction and spectral filtering (Delphseismic^{TM} software). Due to the distance between the signal source and the receiver, geometrical distortion increases the measured depth of the seismic reflections. This error increases with decreasing water depth. A simplified correction should be applied using the following formula:

$$h = [(t/2)^2 - (d/2)^2]^{1/2}$$

where h = true depth in time (ms TWT), t = two-way travel time (ms TWT), d = distance from source to receiver, ms TWT = two-way travel time in milliseconds.

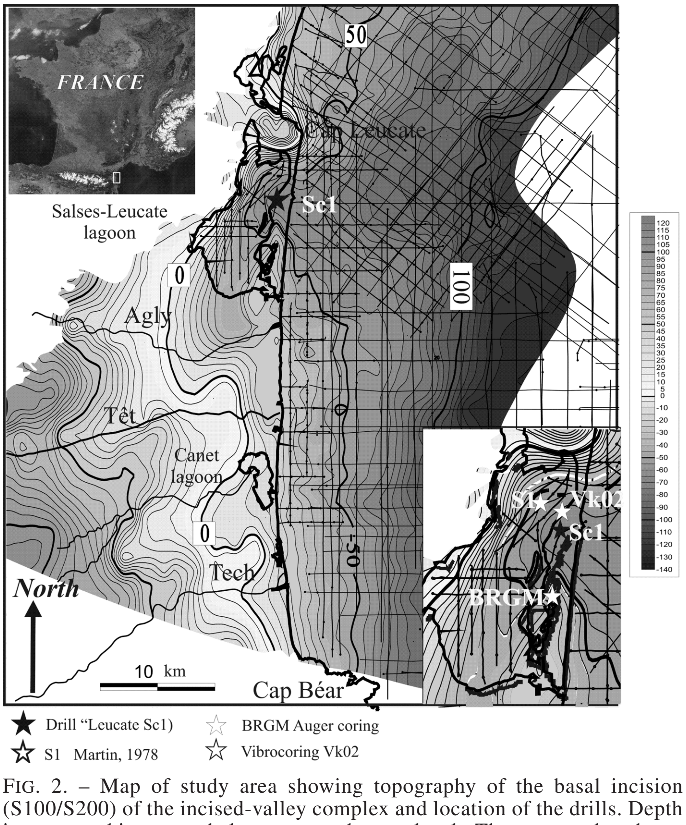

FIG. 2. – Map of study area showing topography of the basal incision (S100/S200) of the incised-valley complex and location of the drills. Depth is expressed in metres below present-day sea level. The present-day shoreline is in red. Based on seismic data offshore (seismic lines are in black) and drillhole data onland. Modified from Labaune *et al.* [2005].

FIG. 2. – *Carte de la zone d'étude montrant la topographie de l'incision située à la base du complexe de vallées incisées (S100/S200) et la position des forages. La profondeur est exprimée en mètres sous le niveau marin. La ligne de rivage actuelle est en rouge. Carte réalisée à partir des données sismiques en mer (les lignes sismiques sont en noir) et des données de forage, à terre. Modifié de Labaune* et al. *[2005].*

RESULTS

Leucate SC1 drill hole: log description (fig. 3)

The total length of the core is 59.89 m, with the top at 2.00 m asl (above sea level), and the base at 57.89 m bsl (below sea level). Four main sedimentary bodies (or units) are superposed at this site. They are labelled from A to D, because, at this stage, there is no established equivalence with seismic units defined in previous studies (see table II).

TABLE II. – Correspondence between terminologies used for the post-Pliocene key surfaces and sedimentary units.

TABLE II. – *Correspondances entre les différentes terminologies utilisées pour les surfaces et unités sédimentaires.*

		past papers		present paper
		Labaune *et al.*, 2005	Tesson *et al.*, 2005	
Us	U3	U3-3/U3-4		U662
		D3-3		S662
		U3-2		U661
		D3-2		S661
		U3-1		U660
		D3-1		S660
		U2-b	U2-2	U650
		D2-2	D2	S650
		U2-a	U2-1	U640
		D2-1	D1x/D2-1	S640
		Ur	U1	U1 (U500, U200)
		D1		S100/S200

At the base, ***body A*** (from 57.80 to 56.50 m bsl) is made of fining-up deposits from gravels and pebbles in a sand matrix to compacted beige muddy sands and green muds.

Body B, from 56.50 to 30.80 m bsl, is made of grey muddy or locally sandy levels with organic matter (black dots) and shells debris. Levels of mud supported gravels are intercalated especially at the upper part. Lithology trend is globally coarsening-up.

Body C, from 30.80 to 19.00 m bsl, is bounded at the top and base by levels of large pebbles. Between these two levels, there are several intervals (up to 20 cm) of coarse beds (pebbles) alternating with muddy levels in the lower part and with sandy levels in the upper part. The lower part is coarsening-up.

Body D, from 19.00 to 00.00 m bsl, is mainly composed of medium to coarse sands with several levels of gravels/pebbles. A thick pebbly level, between 5.00 and 4.00 m bsl, subdivides body D into two parts. The basal sandy unit is coarsening-up and the upper one is fining-up. We have two age dating of 12970 and 9750 cal yr B.P. at the base of body D (depth 19.63 m and 16.10 m respectively).

Except for body A, the vertical succession contains well preserved shells or debris of bivalves and some gastropods. Marine influence appears to be constantly present through

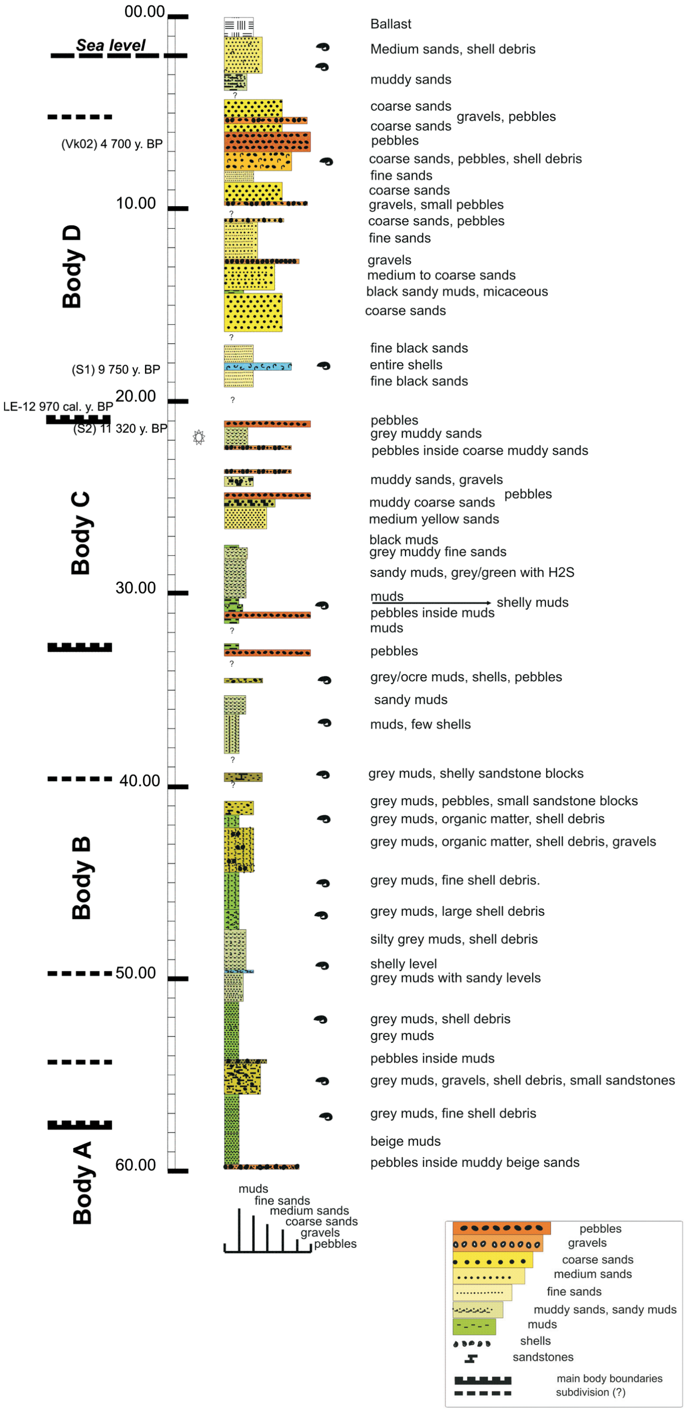

FIG. 3. – Lithological log of "SC1 Leucate" drill hole (location figure 2). Most of the sands and gravels were recovered using a percussion sampling tool. From seismic data, the basal beige and pebbly muds inferred as Pliocene were expected to be drilled at about 55 to 60 m bsl. The top of the drill hole is at 2 m above sea level. Age dating from table I.

FIG. 3. – Log lithologique du forage "Leucate SC1" (position figure 2). Les niveaux sableux et à graviers ont été forés et récupérés en utilisant un outil à percussion. Les vases beiges à galets situées à la base du forage sont attribuées au Pliocène qui, d'après les données sismiques, se situe à une profondeur de 55 à 60 m sous le niveau marin actuel. Le sommet du forage est situé à la cote +2 m. Les datations sont issues de la table I.

the entire column. Only the coarse pebbly beds are unfossiliferous, being possibly indicative of a continental influence (probably fluvial).

Seismic data analysis

The following description is a synthesis of data presented in previous studies [Labaune, 2005; Labaune *et al.*, 2005; Tesson *et al.*, 2005; Labaune, 2007]. The terminology used here is modified from previous papers [Labaune *et al.*, 2005; Tesson *et al.*, 2005] so as to be in agreement with the usage of other teams (Ifremer) working in the Gulf of Lions. Table II presents a comparison of the two terminologies.

The basal unit Ub (figs. 4b, 4c, 5a and 5b) displays continuous reflectors of high amplitude and low frequency, maintaining the same characteristics from the Pyrenean belt to the Cap d'Agde. Reflectors are seaward dipping, with successive low and high dips. Low to medium wavelength undulations follow two main trends (NW/SE and NE/SW). Unit Ub has been correlated with Pliocene deposits [Duvail *et al.*, 2001; Lofi *et al.*, 2003].

The erosional discontinuity S100/S200 truncates the unit Ub. It constitutes the basal surface of the Languedoc-Roussillon incised valley complex (equivalent to D1 in Tesson *et al.* [2005]). The valley axis is at right angles to the shoreline under the inner shelf, and turns southwards under the Salses-Leucate lagoon and the Roussillon coastal plain (fig. 2). In the valley axis, S100/S200 rises steadily up to –75 ms TWT beneath the shoreface zone and is at about 70 ms TWT under the tidal channel and lagoon. It reaches about 30 ms TWT on interfluves below the barrier beach (fig. 2).

Above S100/200, the unit U1 is characterized (figs 4b, 4c and 5a) by successive sets of continuous, sub-horizontal and high- to medium-frequency reflectors separated by erosional surfaces. From the sea towards the shore, most of these discontinuities become shallower and amalgamate. Under the shoreface zone, a main discontinuity is observed (S500) which separates unit U1 into sub-units U200 and U500 (figs 4b and 5a). On the inner shelf, sub units U200 and U500 are locally incised by U600 (fig. 5a).

The unit 640 (figs 4c and 5a) overlies the unit U1. It is a thin unit pinching out landward, bounded by two erosional surfaces: S640 at the base and S650 at the top.

Landward, the erosional discontinuity S650 is superimposed onto underlying discontinuities (subdividing unit U1) that become shallower towards the land. This superimposition is inferred from sinuous and low-frequency reflections showing high amplitudes, very close to each other, which amalgamate with the uppermost and continuous reflector dipping seaward under the Pleistocene forced regression wedges on the shelf.

The overlying U650 unit develops only on the inner shelf. It corresponds to a pinching-out wedge with oblique-tangential reflections that downlap seaward onto the S650 discontinuity (figs 4c and 5a).

The erosional discontinuity S660 (fig. 5a), at the top of the U650 wedge, is sub-horizontal. It merges with S650 under the shoreface zone, the barrier beach and the lagoon.

The unit U660 overlies the amalgamated discontinuities S650/S660. On shelf, it is the uppermost unit. Under the lagoon, U660 exhibits well preserved sigmoidal reflections (fig. 6) that are both aggrading and seaward-prograding towards the ENE.

The discontinuity S661 at the top of the unit U660 rises from about 15 ms in the central northern lagoon to 5 ms

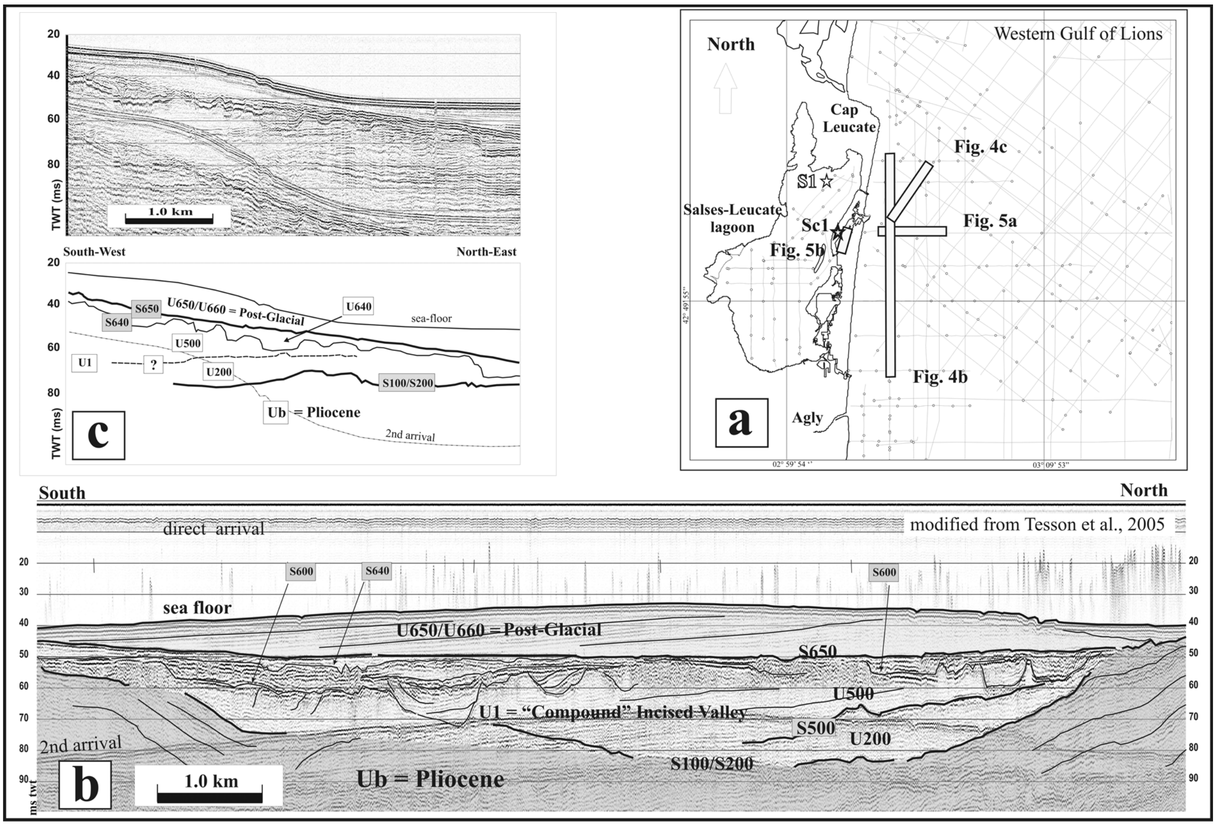

FIG. 4. – (a) Map showing the location of the sections cited in this paper. (b) Shore-parallel seismic section across the incised valley complex. The incised valley is buried and should not be inferred from the sea-floor topography. The valley is incised above an overall syncline affecting the underlying Pliocene. (c) Shore-transverse seismic section and interpreted line drawing along the incised-valley axis. This section documents the few internal discontinuities evident within the U1 unit. Both seismic sections were performed using a Minisparker system. Georeferenced data were acquired and reprocessed with DelphSeismic.

FIG. 4. – (a) *Carte montrant la localisation des sections sismiques citées dans la publication.* (b) *Section sismique parallèle au rivage recoupant le complexe de vallées incisées. La vallée incisée est enfouie et sa présence ne peut-être déduite de la topographie sous-marine actuelle. La vallée est creusée à l'aplomb d'une vaste structure synclinale affectant le pliocène sous-jacent.* (c) *section sismique perpendiculaire au rivage située dans l'axe de la vallée incisée et ligne temps interprétée. Cette section sismique montre les discontinuités internes visibles dans l'unité U1. Les sections sismiques ont été obtenues à l'aide d'un système Minisparker. Les données géoréférencées ont été traitées avec le logiciel DelphSeismic.*

near the barrier beach. This surface is not erosional because the topsets of sigmoidal reflectors of the underlying unit are preserved (fig. 6).

S661 is overlain by three subunits, U661 to U663 that display continuous seismic reflectors with an aggrading pattern. The internal surface S662 is mainly planar and non-erosional. It is a conformable surface, excepted near the beach-barrier (fig. 6).

Correlations of seismic data and Leucate SC1 drill core data are presented on figure 7

In the center, the sedimentological description (log) plotted with a 2.0 m delay relative to sea level, using GPS indications and an estimation of the fresh water level. On both sides of this log, we report the nearest seismic sections located in the lagoon (Minisparker section at the left) and in the tidal channel (Minisparker section and boomer section at the right). The main discontinuities (strong acoustic impedance contrasts) picked on seismic data are correlated with main lithological changes revealed by drilling. The pebble levels do not totally mask the acoustic signal propagation; they nevertheless diffract the signal, while decreasing the energy and shifting the mean frequency of the signal towards low frequencies, which results in a decreased resolution. The upper boundaries of the seismic sections (time = 0 ms = R4) are aligned with 0 m sea level. The sections have been scaled in order to align the basal discontinuity R0 with the upper boundary of the sedimentary body A (Ub).

The HR seismic section located in the tidal channel shows a perfect fit between reflectors labelled R2 and R1 and the pebble layers bounding body C (U600 to U640). They correspond to the sharp contact mud/pebbles or muddy to fine sand/pebbles. The VHR seismic section shows a delay of the direct arrival (R3) due to the distance between signal source and receiver. This artefact decreases downward and the lower R0 reflector fits with the upper boundary of body A.

The HR seismic section located in the lagoon also shows good correlations with core data and emphasizes in particular the highly irregular topography of the R1 and R2 reflectors.

From these data, we obtain a velocity of 1630 $m.s^{-1}$ in the upper sandy deposits and 1750 $m.s^{1}$ in the incised valley infilling. Although the muddy formation remains water saturated, the proposed velocity suggests a compaction of these deposits. For the upper sandy formation, this velocity

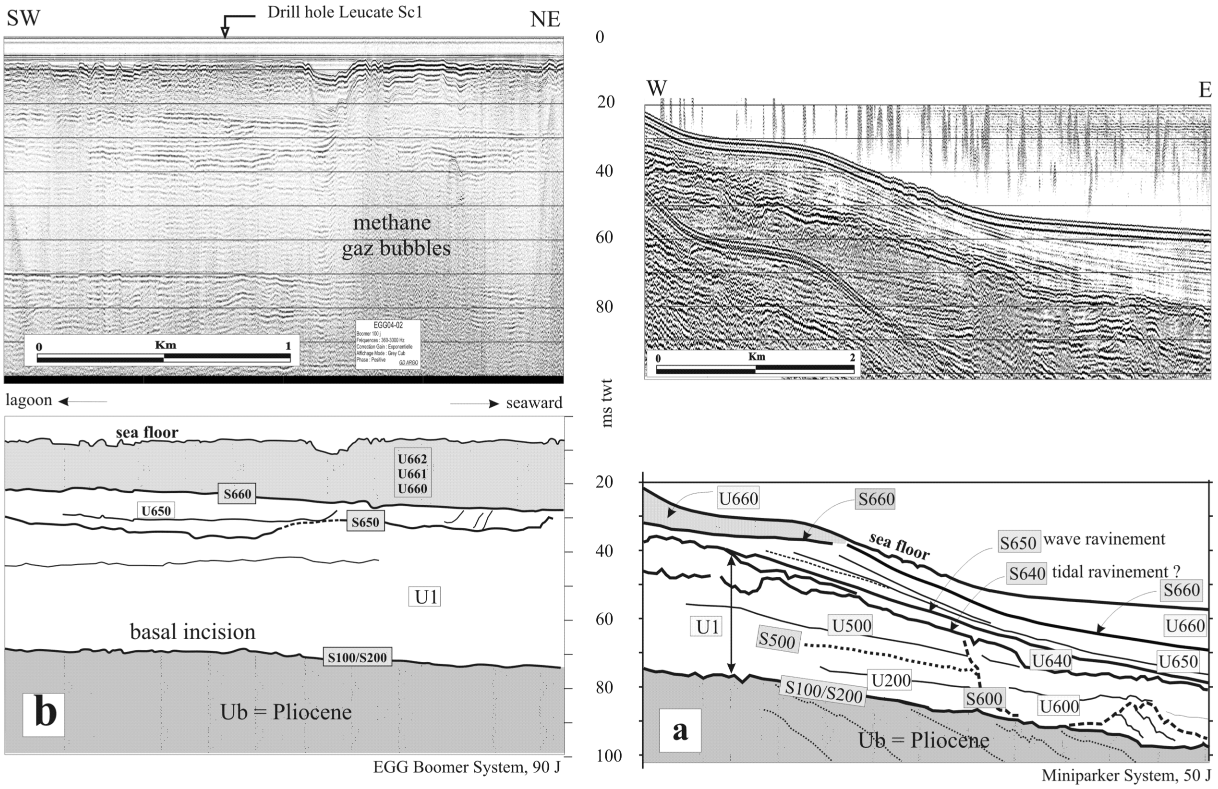

FIG. 5. – Seismic sections with their line-drawing along the axis of the incised valley: (a) offshore [modified from Tesson *et al*., 2005], (b) under the tidal channel, through the barrier beach. See location on figure 4a.
Seismic sections a) and b) were acquired using a conventional boomer system and a 50 joules Minisparker system, respectively (georeferenced data acquired and reprocessed with DelphSeismic).
FIG. 5. – *Sections sismiques situées dans l'axe de la vallée incisée et lignes temps correspondantes :* (a) *sur la plate-forme [modifié de Tesson* et al.*, 2005],* (b) *dans la passe traversant la barrière littorale. Voir position figure 4a.*
Les sections sismiques a *et* b *ont été acquises à l'aide d'un système Boomer conventionnel et d'un Système Minisparker 5 joules (les données, géoréférencées ont été traitées avec le logiciel DelphSeismic).*

represents the usual value for subsurface unconsolidated sediments.

Correlation with BDSS drill holes

In the Roussillon plain, south of Leucate lagoon, Duvail *et al.* [2001] analysed 32 drill logs archived at the BDSS and proposed the following stratigraphic model. The Pliocene substratum (Ub) is truncated and locally incised by an erosional discontinuity (correlated with S100/S200) that may reach 60 m bsl under the coastal plain and that correlate landward with Pleistocene terraces. Above the basal erosional discontinuity, marine muds (correlated with undifferentiated U200 and U500) are erosionally capped at 30 m bsl by a conglomeratic level (correlated with U600 to U640). They are overlain by two units (U650 to U662) composed of continental and then marine sands with a total thickness of up to 25 m. Duvail *et al.* [2005] interpreted the deposits above Pliocene substratum as transgressive deposits passing up, above a marine flooding surface, into a late Holocene unit that prograded since 6000-5000 yr B.P. at constant high sea level. The different facies observed are considered as expressing a lateral variation from proximal to distal environments. The intercalated thick conglomerate (pebbles) are attributed to a special event called "phase of accelerated progradation". The unusual thickness of the Holocene deposits (up to 60 m) is thought to be linked to a local subsidence of the coastal plain.

In 2003, an auger drilling was carried out by the BRGM in the southern edge of the Leucate lagoon. C^{14} dating was performed on benthic foraminifera (insufficient amount of pelagic foraminifera) sampled in a mud/fine sand level intercalated at the upper part of a pebbly unit at a depth of 20 m bsl. This pebbly unit is correlated to the conglomeratic level of Duvail *et al.* [2001] and to the body C on the Leucate SC1 drill (U600/U640). Age dating indicates 12900 cal yr B.P. (corrections were made using software calib4_4_2 from Stuiver *et al*. [1998] in Labaune [2005]). Even assuming that fine sand should be characteristic of water depths of up to 10-15 m, this dating result does not fit with the well calibrated sea level at 12900 cal yr B.P., which is known to be at 60 m bsl. Even with bathymetric and compaction corrections, there is still a great discrepancy. There are two possible explanations: i) either the age is meaningful and these sands were initially deposited farther offshore when sea level was at 60 m bsl, but were then reworked and carried landward when the shoreline migrated; or ii) the age is incorrect (due to contamination, so that the true age is more recent and the error is greater than described), implying that age dating should be interpreted with great caution when sands do not contain pelagic foraminifera.

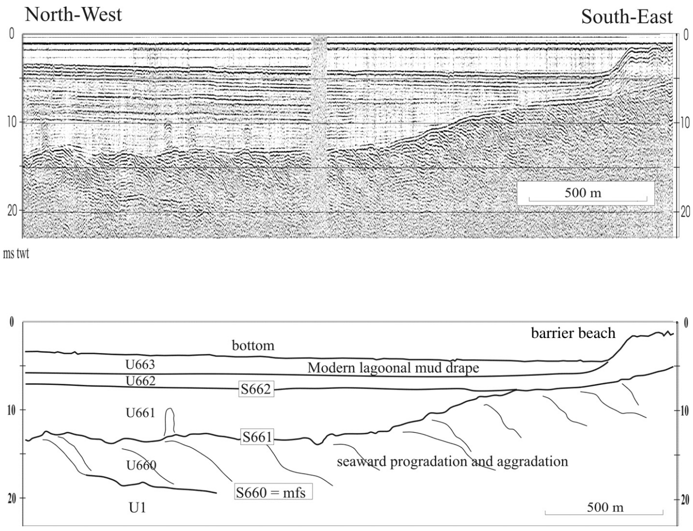

FIG. 6. – Very high resolution (IKB Seistec boomer) seismic line and line drawing showing geometry of deposits located under Leucate Lagoon and adjacent barrier beach.
FIG. 6. – *Ligne sismique très haute résolution (Boomer IKB Seistec) et interprétation correspondante montrant la géométrie des dépôts situés sous la lagune de Leucate et la barrière littorale adjacente.*

Given that the overlying discontinuity represents the post-glacial transgressive surface, the first explanation is considered valid.

A description of a drill hole (S1, fig. 4a) located in the northern part of the Salses-Leucate lagoon is also available [Martin, 1978]. This author reports a marine sandy unit with pebbles and shells extending from 14 to 2.00 m bsl, which is taken here as equivalent to U660. C^{14} dating in the upper part of the unit yields 8200 yr B.P., but the shells are considered as reworked.

INTERPRETATION

The stratigraphic model presented here (see fig. 9) integrates seismic data [Labaune, 2005; Tesson and Labaune, 2003; Tesson *et al.*, 2005] and the sedimentological data of the Sc1 well. There is a good correlation between the main seismic discontinuities picked out on the seismic sections within the incised valley fill and the sedimentary log of the SC1 drill hole. Moreover, the seismic facies also appear as a useful tool for inferring the significance of the main discontinuities (sharp contacts between fines/coarse material) as well as the broad environmental parameters.

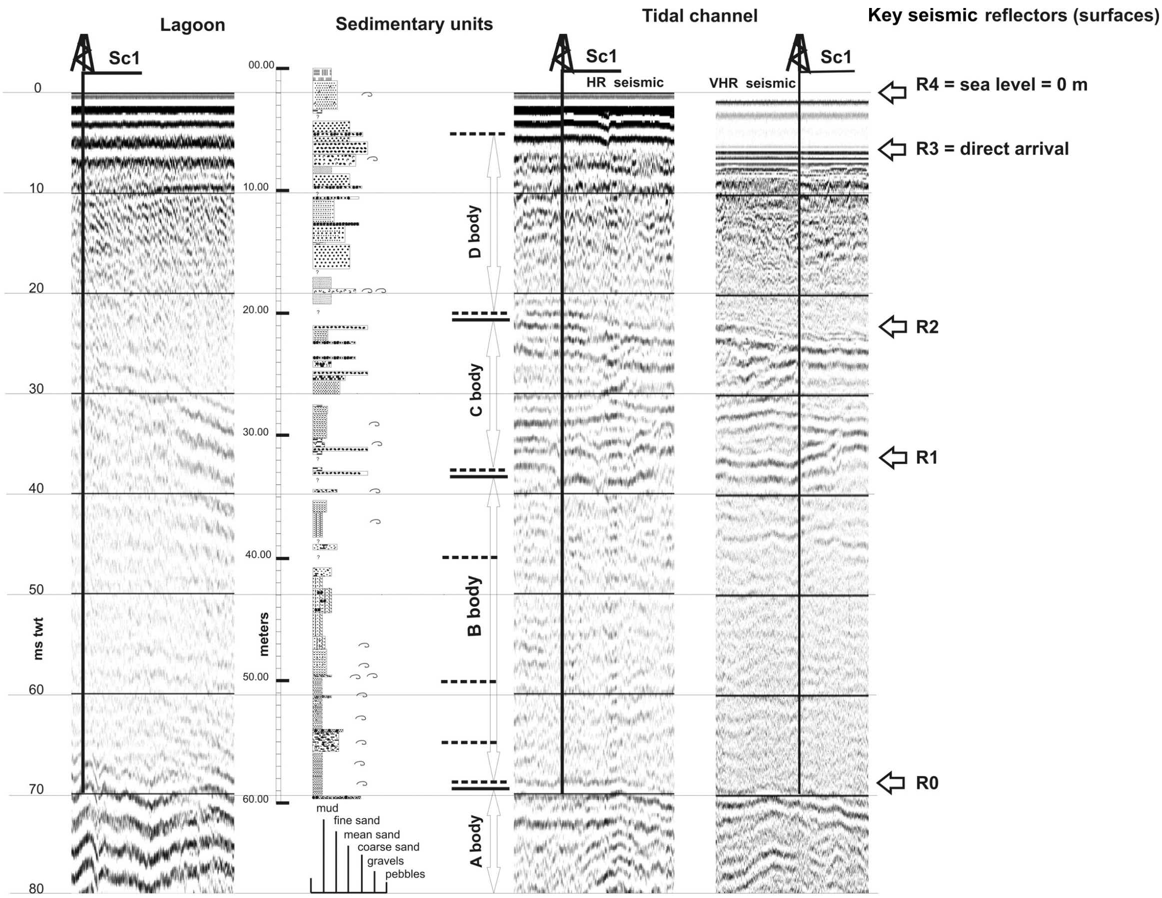

FIG. 7. – Correlation between high-resolution key seismic reflectors and the SC1 Leucate drill hole lithological log. Two different vertical scales are used: metres for the Drilling log and milliseconds two-way travel time for seismic data. See text for additional comments.
FIG. 7. – *Corrélation entre les réflecteurs principaux reconnus sur les données sismiques haute résolution et le log lithologique du forage. Deux échelles verticales sont utilisées : en mètres pour le forage et en millisecondes temps double pour les données sismiques. Voir commentaires dans le texte.*

The lowermost reflector S100/S200 is correlated with the pebbles level R0 and represents the base of the paleo-valley system. Associated compacted beige muds represent Pliocene deposits at the base of the drill. The surface associated to the basal reflector is incised by a thalweg rising progressively from the offshore domain to the present-day coastal plain and lagoon (fig. 2). Under the barrier beach, the thalweg is at about 57 m bsl, while the interfluve is at less than 20 m bsl. Farther seaward (median/outer shelf) the basal surface dips under the Quaternary forced regressive wedges [Tesson *et al.*, 2005].

The basal incision represented by S100/S200 is overlain by unit U1.

The lower part of U1 (U200-U500) shows continuous sub-horizontal reflectors and is correlated on the Leucate SC1 well to a complex of marine muds with levels of mud supported gravels (body B). The upper part of unit U1 (U600-640) comprises seismic erosional surfaces that are almost amalgamated under the barrier beach. They are correlated on the Leucate well to the body C between the R1/R2 interval (from 34 m to 17 m bsl) (fig. 7) comprising coarse levels (gravels and pebbles) alternating with muds in the lower part and coarse sands with marine shells on the upper part. Coarse levels with sand and gravel correspond to river pulses and sands and muds shelly levels represent marine pulses. These alternating levels suggest an estuary

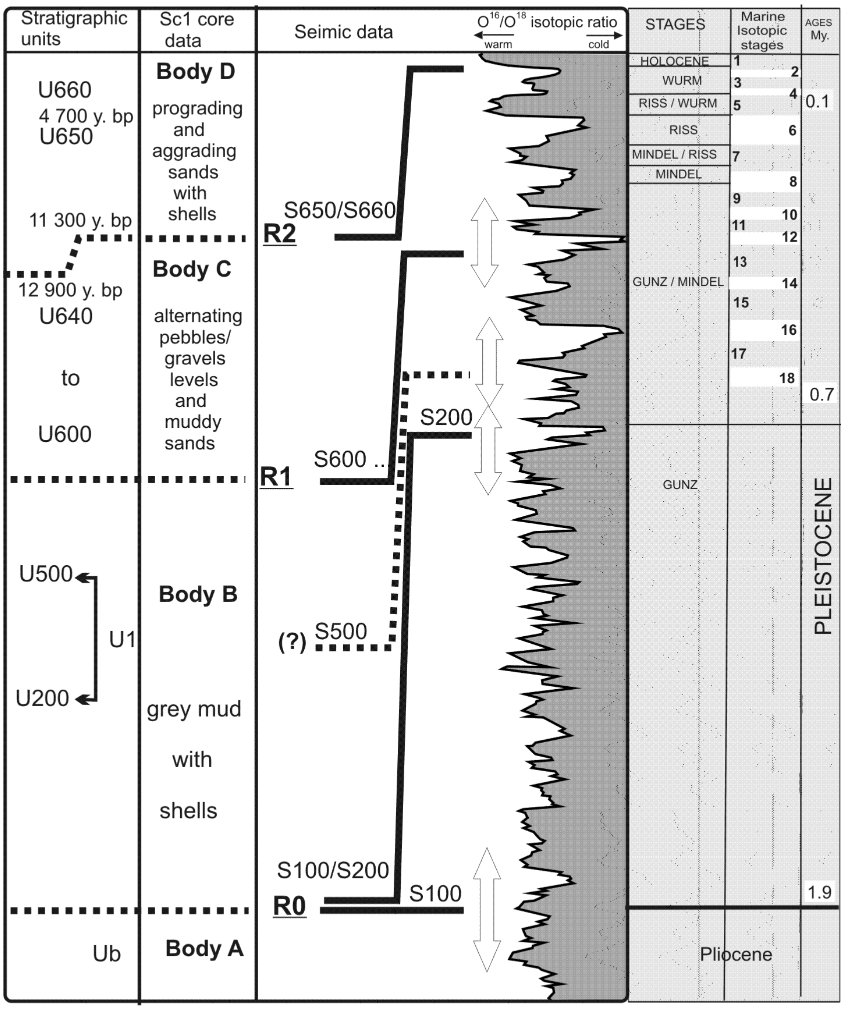

FIG. 8. – The curve of climatic changes during the Quaternary (O^{16}/O^{18} isotops) [Gibbard *et al.*, 2004] shows that only parts of the cycle are recorded in the incised valley complex infilling because this area was subject to drastic erosion during each lowering of sea level. The gravel layers and alternating sandy muds of Body C are assumed to be the preserved part of one or several fourth-order base level fluctuations during the Quaternary. In this sense, the coastal Roussillon system is similar to the "simple" incised valley and/or the "composed" incised-valley models described elsewhere on the Atlantic coast of France. In both cases, the underlying marine muds of body B appear to be associated with warm periods and a high relative position of base level during the Pleistocene. The arrows indicate the degree of uncertainty on the stratigraphic position of the discontinuities.

FIG. 8. – *La courbe des changements climatiques durant le Quaternaire (isotope O^{16}/O^{18}) [Gibbard* et al., *2004] montre que seulement une partie des cycles est enregistrée dans le remplissage des vallées incisées car ce secteur a subi une intense érosion lors de chaque baisse du niveau marin. Dans le corps* C, *les alternances de niveaux à graviers et de vases sableuses ne représentent que la partie préservée de quelques cycles quaternaires d'ordre 4. Dans ce cas, le système côtier du Roussillon est similaire aux vallées incisées simples et/ou aux vallées incisées composées décrites sur ailleurs sur la côte atlantique française. Dans les deux cas, les vases marines inférieures du corps* B *apparaissent associées à des périodes chaudes et un niveau de base relativement haut. Les flèches indiquent le degré d'incertitude quant à la position stratigraphique de certaines discontinuités.*

environment. This unit is interpreted as the preserved deposits of successive phases of incision and infilling due to base level shift – downward and upward – during Quaternary glacial and interglacial periods (fig. 8).

The discontinuity S650 at the upper boundary of seismic unit U1 is well correlated to a coarse level (pebbles reach 3 cm) capping the body C (fig. 3). Age dating from both SC1 drill and the neighbouring BRGM auger drill give 12970 and 11320 yr B.P. (S2 and LE) just at the level or above the body C. Thus the discontinuity S650 should represent the post-Glacial wave ravinement surface that is amalgamated with the transgressive surface in this area (fig. 9).

The sandy prograding wedge labelled U650 is observed exclusively on inner shelf (fig. 5a). It is considered as a late post-Glacial transgressive parasequence.

Under the barrier beach, the erosional discontinuities S650 and S660 amalgamate (fig. 5b) and form the basal progradation surface of the overlying sedimentary unit (U660).

U660 show well formed sigmoidal reflectors making up a prograding/aggrading complex seaward-prograding towards the ENE (fig. 6). Its correlates on Leucate well (fig. 3) with the alternating levels of sands and gravels/pebbles of body D between 16 and 5 m bsl. From the two age dating presented above, we propose that this complex represents a coastal barrier environment that built up during a last step of the post-Glacial sea-level rise and may be continued during the modern highstand (Vk02 at the top: 4700 yr B.P.). In such conditions, we must consider that a maximum flooding surface should exist inside U660, which is expressed offshore on seismic lines but not observed in our beach-barrier data.

Finally, above the S661 discontinuity, the present barrier beach sands and lagoonal muds (U661-U662) developed during highstand sea level (fig. 6).

DISCUSSION

The Leucate SC1 drill hole confirms the depth of incision of the paleovalley (> 50 m) indicated by HR seismic data. The offshore sea floor morphology no longer reflects the width and depth of this buried paleovalley. The Agly and Têt rivers are at the moment reduced to small rivers located farther to the southwest, on a flat coastal plain without any delta. However, the observed incised valleys system associated with those rivers (thalweg reaching 30 m deep and valley reaching more than 5 km wide) and infilling deposits (coarse pebbles levels, mud supported gravels levels) leads us to consider that they would have a different regime and a higher activity during Quaternary cold stages.

Three sets of data provide evidence that the lower part of the infill sequence (U1) was deposited during the Pleistocene: (i) the seaward extension of the basal incision of the paleo-valley system (S100-200) dips below the Late Quaternary forced regressive wedges; (ii) the amalgamated erosional surfaces (S600/S650) prolongate seaward by the erosional surfaces, which separate the Quaternary lowstand forced regressive wedges of the shelf [Tesson *et al*., 2005]; (iii) the boundary between body C and body D is dated 12900/11320 cal yr B.P. indicating that the uppermost erosional surface S650 corresponds to the post-Glacial transgressive wave ravinement surface. Thus, the marine muds, between 57.80 m and 20 m bsl, underlying S650/S660, were deposited prior to the late Glacial maximum (Würm or MIS 2) during Pleistocene relative highstands in sea level (fig. 8). The preserved internal erosional surface (figs 4 and 5) and the gravel/sandy layers intercalated with the Pleistocene muds (fig. 3), should indicate that several Pleistocene glacio-eustatic changes have been recorded.

Consequently, the infilling of the Roussillon plain, which can reach 60 m thick [Duvail *et al*., 2001) is not a unique prograding sedimentary unit, that accumulated since the high sea level stand at 6000-5000 yr B.P. as proposed by Duvail *et al.* [2005]. It integrates Pleistocene deposits (marine muds and conglomeratic level between 60 and 30 m Bsl) and late transgressive and highstand postglacial deposits.

This incised valley complex of the Roussillon area is the analogue of the incised valleys along the Atlantic coast of France. Several papers and oral presentations have documented late Quaternary incised valleys in the Gironde estuary [Allen and Posamentier, 1993; Lericolais *et al*., 2001], Southeast Brittany [Menier *et al*., 2006], “Pertuis Charentais” [Chaumillon and Weber, 2006; Weber *et al*., 2004] and Rhône delta [Boyer *et al*., 2005; Oomkens, 1970]. In these valleys, above the basal incision, lay pebbly deposits, which represent fluvial material deposited during the last maximum lowstand; above, only the upper post-glacial transgressive and highstand deposits are well preserved. They are interpreted as typical “simple” incised valleys [Allen and Truilhe, 1987; Allen and Posamentier, 1993; Dalrymple *et al*., 1992].

However, in some places, the gravel levels overlying the basal incision (inferred from seismic facies, fig. 7) are interpreted as resulting from successive falls in late Quaternary base level. However there are no field data indicating whether they are true Pleistocene relict deposits because the seaward extension of this surface and its relationship within Quaternary depositional sequences is not documented. The Gulf of Lions is the only area where such sequences are well preserved. The Languedoc-Roussillon coast is indeed very different from the other studied areas, with more than 30 m of marine muds at the base of the succession, associated with the S650/S660 erosional surfaces and gravel/pebble layers.

The examples of Quaternary “compound” incised valleys cited in the literature show successive downcutting of highly sinuous valley axes with different trends crossing each other [Foyle and Oertel, 1997; Thomas and Anderson, 1994]. In North Canada, the incised valleys of the Basal Quartz (Alberta and Saskatchewan) also display this type of pattern. However, in all the cited cases, these valleys probably represent examples of the fluvial part of incised systems, whereas the Languedoc-Roussillon incised valleys correspond to some type of estuary or embayment, successively reoccupied during the various Quaternary eustatic cycles. The McMurray Formation (northern Alberta) may represent a sedimentary environment that is comparable to the Roussillon case, with incised valleys leading out to the Cretaceous Boreal Sea in a low-accommodation setting [Ranger and Gingras, 2002].

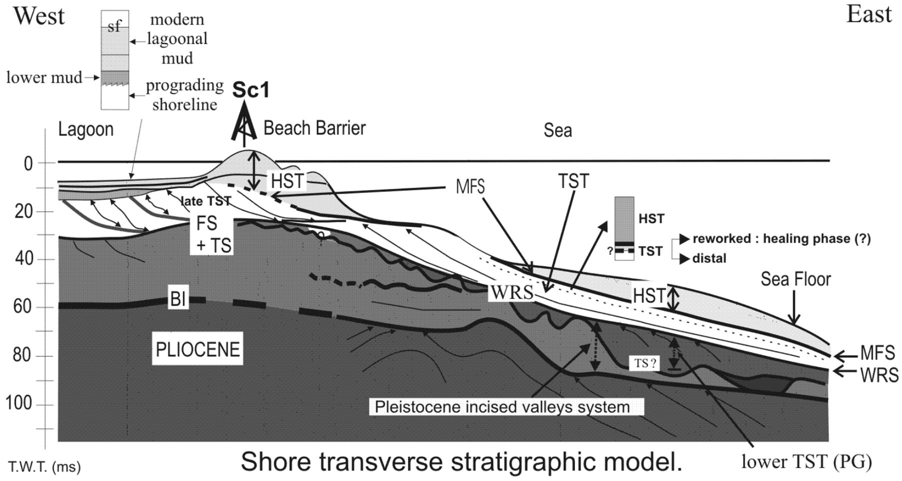

FIG. 9. – Stratigraphic model showing the architecture of the coastal deposits along the axis of an incised-valley complex, under the present inner shelf and adjacent coastal plain. This model is data driven (based on high-resolution seismic survey and drilling data). The post-Glacial transgressive deposits observable offshore, are seen to thin landward. They should be a parasequence. Under lagoon and barrier beach, a second transgressive and prograding parasequence (body D = U660) pinches out seaward over the previous parasequence. The Highstand System Tracts comprises both lagoonal muds and barrier beach sands (body D = top of U660 to U663). The several Pleistocene erosional surfaces observed offshore rise progressively landward and amalgamate with the WRS (Wave Ravinement Surface) and the MFS (Maximum Flooding Surface) in some places. These surfaces correspond to the pebble/gravel layers alternating with sands (Body C = U600/U640) under the barrier beach [after Labaune *et al.*, 2005]. The thick marine muds of the lower part of the SC1 Leucate drill hole (body B = U1 or several sub-units) are bounded by BI (basal incision) and MFS/TS (amalgamated surfaces, see above).
FIG. 9. – *Modèle stratigraphique montrant l'architecture des dépôts côtiers dans l'axe du complexe de vallées incisées, sous la plate-forme interne et la plaine côtière adjacente. Ce modèle est contraint par les données sismiques et de forages. Les dépôts postglaciaires transgressifs observables au large s'amincissent vers la côte et constituent une paraséquence. Une seconde paraséquence transgressive prograde sous la lagune et se biseaute sur la première paraséquence. Elle correspond au corps D et à l'unité U660. Les dépôts de haut niveau marin sont représentés par le remplissage argileux de la lagune et par des sables au niveau de la barrière littorale. Ils comprennent la partie supérieure de l'unité U660 et les unités jusqu'à U663. Les différentes surfaces érosionnelles pléistocènes observées au large s'élèvent progressivement vers la côte et s'amalgament avec la surface de ravinement par les vagues (WRS) et la surface d'inondation maximale (MFS). Ces surfaces correspondent, sous la barrière littorale, aux niveaux à graviers/galets alternant avec des niveaux sableux (corps C = U600/U640) [d'après Labaune* et al., *2005]. Les vases marines épaisses situées à la partie inférieure du forage "Leucate SC1" (Corps B = U1) sont limitées par BI (incision basale) et MFS/TS (surfaces amalgamées).*

Origin of the upper sands and gravel levels (U3-1 or U660)

The uppermost unit U660 shows well-formed sigmoidal reflectors correlated on Leucate SC1 well to alternating levels of sands and gravels/pebbles (body D).

Certain *et al.* [2004] considered this unit (labelled 1N unit) as made up of Pleistocene fluvial deposits that were deeply incised during the last Glacial maximum (Würm or MIS 2, 18000 yr B.P.), with a NW-SE channel under the lagoon. This unit (1N or U660) was originally described by Martin [1978] as a marine sand level with shells, and not as a fluvial deposit. The SC1 drill-hole data also indicate that Unit 1N/U660 is essentially made up of marine facies with shells layers. Moreover, the C^{14} age dating of underlying body C (12970 and 11320 yr B.P.) indicates that this unit is younger than the last Würmian sea-level fall. In the northern part of the lagoon, seismic data (fig. 5) show that the upper boundary (S661), capping the well-preserved sigmoid reflectors of U 660, is not erosional. In the southern part of the lagoon, acoustic turbididty (gas rich muds) precludes any possibility of observation neither the internal architecture nor the lower boundary of the U660/1N unit have been observed.

The sandy deposits of U660 reflect both a marine and continental influence, such as encountered in sheltered environments (coastal bay or semi-enclosed estuary with inner bay head delta). They accumulated during the last part of the post-Glacial sea level rise, when sea level was a few metres below the present day position and they infilled the paleovalley mouth. Deposition would be the result of combined processes of accretion due to littoral drift and orthogonal beach nourishment, occurring in alternation with episodic fluvial floods.

Tectonic vs. eustatic influence

Differential subsidence is a main factor controlling the depositional stratigraphic architecture of the Quaternary shelf deposits [Tesson *et al.*, 1990; Tesson, 1996; Tesson *et al.*, 2000] and continental terraces [Duvail *et al.*, 2001] in the Gulf of Lions. There we must remember that the term "tectonic" is applied in a very broad sense as subsidence should be attributed to deep substratum behaviour (reactivation rifting forms, thermal cooling), sedimentary or water loading, deep salt or mud mass sliding). Since the studied area is probably just seaward of the hinge point between continental uplift and marine subsidence [Duvail *et al.*, 2005; Tesson and Allen, 1995; Tesson *et al.*, 1993], we nevertheless have little idea of the relative importance of these tectonic effects. The preservation of successive erosion/infilling sequences in a late Quaternary context of glacio-eustatic cycles implies that the latest erosional phases did not lead to complete removal of the previous infilling sequence down to the base of the incision. As the successive lowstand levels were far below the depth of the basal incision in the studied area, it implies that erosion was not completely effective. Several mechanisms should be acting separately or associated: one, the river thalweg shape moved from one cycle to an other; second, the flow shear stress was not strong enough to remove the deposits or deposits were too compacted; third, the system was subsiding. In the study area, the Pliocene deposits are seaward dipping and subsidence by compaction is known. The proximity of the hinge point and the observed depth of the basal incision (less than 80 m bsl) led to assume that subsidence effect should have been low (but compaction values are unknown). The erodability of the successive infilling deposits is not a controlling factor because the preserved deposits are mainly muddy. The width of the basal incision is important and the position of the successive incisions should have been different from one cycle to another, and preservation of previous deposits was improved.

Paleomorphology control on incised-valley preservation

The geometry of the Pliocene deposits (seaward dipping and east/west antiforms and synforms) should be considered as tectonic features. The seaward dipping is in part controlled by differential subsidence, but moreover these are prograding deposits linked to several rivers. Consequently, both the seaward dipping and the antiforms and synforms should be only, or in large part, syn-sedimentary features. The paleomorphology must be considered as a dominant controlling factor impacting on the shape and orientation of the buried paleovalleys off the Languedoc-Roussillon coast [Labaune, 2005; Tesson *et al.*, 2005].

CONCLUSIONS

The results of the Leucate SC1 drill hole fully corroborate seismic data showing the existence of a system of buried paleo-valleys extending continuously from the Languedoc-Roussillon coastal plain to the inner shelf.

The lowermost discontinuity, picked out by the uppermost fourth order Quaternary depositional sequence on the shelf, rises landward and reworks the Pliocene deposits. It is a polygenic surface reactivated during the falls and rises in base level associated with the major sea-level changes that characterize the middle-late Quaternary.

Three main sedimentary units encountered in the SC1 drill hole make up the incised-valley infilling, which is described as follows:

1) at the base, thick marine muds with thin gravelly beds probably representing cyclic downward shifts in base level, capped by a set of erosional surfaces, amalgamated and seaward-dipping, which are considered as Quaternary sequence boundaries. These surfaces actually provide the best evidence of the polycyclic nature of the system. The upper erosional surface is the post Glacial wave ravinement surface;

2) above this ravinement surface, several backstepping units characterize the final stages of the Holocene sea-level rise and the end of infilling;

3) the topmost few metres are composed of barrier-beach sands and a part of the lagoonal muds representing the true highstand systems tract.

This example is typical of "compound" incised valleys according to the classical terminology. Such cases are still poorly documented and there is no equivalent of this type of system observed elsewhere in France, where the incised valleys so far described all exhibit a sedimentary facies succession typical of "simple" incised valleys.

The Roussillon paleovalley fill does not correspond to a typical fluvial incised-valley system because a marine influence is apparent throughout the vertical succession. It is essentially a system subject to both marine and fluvial influence, such as observed in estuaries, even if the tidal range was probably of moderate to low amplitude. We can assume that the studied area corresponds to the segments 2 and 1 of the previous model proposed by Zaitlin *et al.* [1994].

Tectonic control is a main factor (uplift onland and differential subsidence seaward) that favoured the preservation of successive phases of erosion/infilling. Nevertheless, the tectonic control of the geometry of the Pliocene deposits has contributed to the shape and orientation of the system of incised valleys on the inner shelf.

Several important problems remain unsolved: why does the last Würmian cycle consist of so much sand and so little mud, and, on the other hand, why are the preserved parts of the older Pleistocene cycles only represented by muds, with only some thin sands/gravels levels. What is the exact timing of incision of the erosional surfaces during base-level fall or during glacial outbursts? What is the timing and nature of the infilling, and what is the precise nature of the heterogeneities within the infilling sequence? Why are the basal muds so underconsolidated; is it because the incision surface behaves globally as an aquifer?

We conclude that this system of incised valleys is probably an exceptional case because it is an example of a "compound valley fill". Moreover, the infilling has a very low sand/mud ratio, which contrasts with the situation normally observed in incised valleys targeted for economic potential.

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