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Compound incised-valley characterization by high-resolution seismics in a wave-dominated setting: Example of the Aude and Orb rivers, Languedoc inner shelf, Gulf of Lion, France

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ABSTRACT

A branch of a time-calibrated late Quaternary compound incised valley complex is investigated using high- and very-high-resolution seismic data. The incised valley system is confined on the inner shelf, and entrenched parallel to the shore in unconsolidated Pliocene deposits. The infilling of the incised valley system comprises three sigmoidal bodies dipping progressively downstream representing depositional sequences. The lowermost sequences are less well preserved at their downstream extremity and the whole system is both aggrading and prograding. Older Pleistocene/Late Quaternary sequences could be preserved under the coastal plain. Individual sequences are closely similar to the classic model of a microtidal incised valley fill. Nevertheless, the central estuary/bay basin muds are seen to interfinger locally with high-energy deposits that represent potential reservoirs. The properties (prograding and aggrading architecture and occurrence of high energy deposits) and preservation of these compound incised valley fill deposits are attributed to general (glacio-eustatic cycles) and local (atmospheric and oceanic regime and proximity of the hinge line) conditions. Data acquisition strategy is a determining factor to interpret such systems.

1. Introduction

Upper Quaternary incised valley systems are key targets for both economic and academic objectives: they are analogs of hydrocarbon and water reservoirs, representing a key aspect of sequence stratigraphy concepts inasmuch as their sedimentary fill commonly contains a detailed record of glacial periods (relative sea level lowstands), interglacial periods (relative sea level highstands) and glacial to interglacial transitions (sea level rises). To facilitate the study of these sedimentary fills, their subsurface characteristics are used since they are generally easily accessible *via* high-resolution marine seismic surveys and long cores in modern estuaries and deltas.

Following early work on the Upper Quaternary Gironde estuary fill (Allen et al., 1970; Allen and Truilhe, 1987; Allen and Posamentier, 1992), most studied estuaries have been found to comprise "simple" incised valleys (Zaitlin et al., 1994). According to the examples documented by various authors (*e.g.*, Ashley and Sheridan, 1994; Kindinger, 1988; Kindinger et al., 1994; Nichol et al., 1994; Lericolais et al., 2001; Gutierrez et al., 2003; Weber et al., 2004; Nordfjord et al., 2006; Green, 2009), the evolution of incised valleys involves an initial phase of river entrenchment and erosion, followed by infilling related to the late Pleistocene relative sea level fall and rise (RSLF and RSLR) events. The basal incision forms a sequence boundary and is overlain by lowstand fluvial sediments. During the ensuing RSLR, the sedimentary sequence represents a retrogradational depositional environment. Sedimentary facies systematically step landward and upward, evolving from continental to marine-influenced. In all the studied late Quaternary "simple" incised valleys, this evolution ends when RSL highstand conditions are re-established. Consequently, in such a model, we fail to address the issue of preservation potential following a succession of sea-level rises and falls. As a result, these "simple" systems can lead to overly-simplistic models.

The Upper Quaternary is characterized by a succession of several RSL fluctuations (cycles) of high amplitude and high frequency (100 to 20 kyr) driven by climate change (associated with glacial and interglacial periods) and tectonic uplift/subsidence. Documented examples of ancient incised valleys (Rahmani, 1988; Leckie et al., 1994; Martino, 2004) are commonly characterized by a longer duration and thus likely record a polycyclic history, with multiple generations of fluvial erosion and filling events. Such multi-cycle incised valley fills are referred to as "compound". In contrast with the widely-preserved "simple" incised valleys, few Upper Quaternary "compound" examples have been studied. Examples of "compound" incised valleys are described from the Mississippi shelf (Suter and Berryhill, 1985), the Virginia inner

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shelf (Foyle and Oertel, 1992), and, more recently, in Tai O Bay (Bahr et al., 2005), the Lagniappe delta (Roberts et al., 2004), Mobile Bay and Mississippi Sound (Greene et al., 2007) and the Llobregat delta (Gámez et al., 2009). In general, the scarcity of studies of near-modern polycyclic incised valleys is due to the fact that they are relatively deeply buried, so they have not been identified on seismic data and high-cost long cores are not available. Consequently, some of these incised valley fills have been incorporated incorrectly into a "simple" model of transgressive successions. Several recent reinterpretations of previous studies (see Bartek et al., 2004; Greene et al., 2007; Estournes et al., 2012) point out this problem of identification. However, even in these cited studies, ground-truth control remains absent.

The present study concerns the northern branch of an incised valley complex (IVLR) connected with the drainage basins of four rivers (from south to north, the Têt, Agly, Aude and Orb) flowing into the western Gulf of Lion on the Mediterranean coast (Languedoc-Roussillon, France) (Figs. 1 and 2). Previous studies (Labaune, 2007; Labaune et al., 2010; Tesson et al., 2010, 2011) focused on the southern branch of this complex (incised valley of the Têt and Agly rivers, "IVTA" system). The analysis of a closely-spaced grid of high-resolution seismic lines, calibrated with a 60-m-long core (providing data on facies sequences, nanoplankton and pollen) showed that the "IVTA" infilling records several successive upper Quaternary glacio-eustatic cycles from as early as MIS 15 to the present day (covering a period of about 600 kyr). The IVTA system is an example of a time-calibrated "compound" incised valley or estuary system as observed in low subsidence areas.

The present study focuses on the incised valley of the Aude and Orb rivers ("IVAO" system), whose morphology differs from the more southerly IVTA system as it extends over a sector roughly parallel to the shoreline (Fig. 2). Northward, the system connects inland with two river catchment areas. The IVAO system deepens toward the south-west and feeds the offshore domain, either directly *via* a channel to the east or as a tributary of the southern system (IVTA). An additional (localized and closely-spaced) grid of very-high- resolution seismic lines was acquired in order to: i) obtain a detailed quasi-3D model of the main fluvial and transgressive surfaces of erosion, ii) characterize the preserved depositional facies in both longitudinal and transverse sections within each identified incision/infilling system, and iii) determine the main controlling factors and processes leading to the imbricated incision/infilling system, focusing on a possible distinction

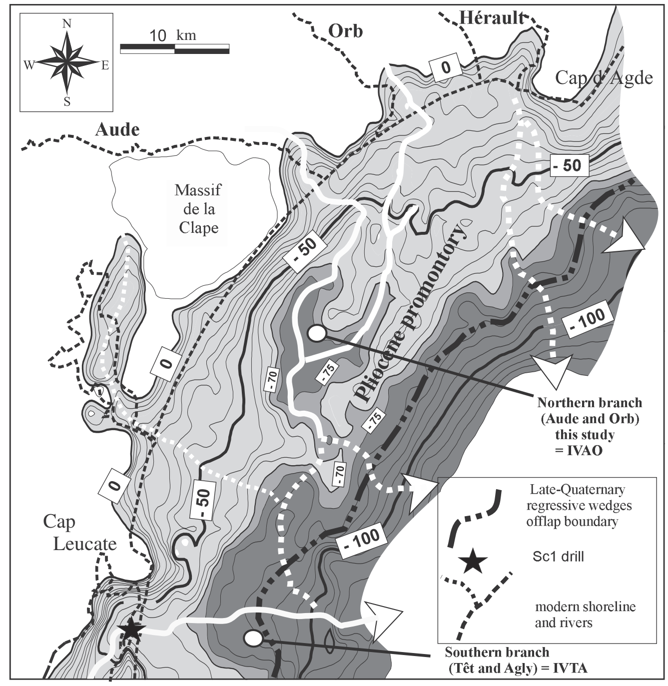

Fig. 2. Regional paleotopographic map of the lower erosional surface at the top of the upper Pliocene under the inner shelf. Topography in meters below sea level. The white lines represent the thalwegs of the basal incision (S40 in this study), but the actual successive river paths are different. Seaward of northern branch (IVAO system), the preserved Pliocene succession forms a shore-parallel promontory. (Modified after Tesson et al., 2005a, 2005b).

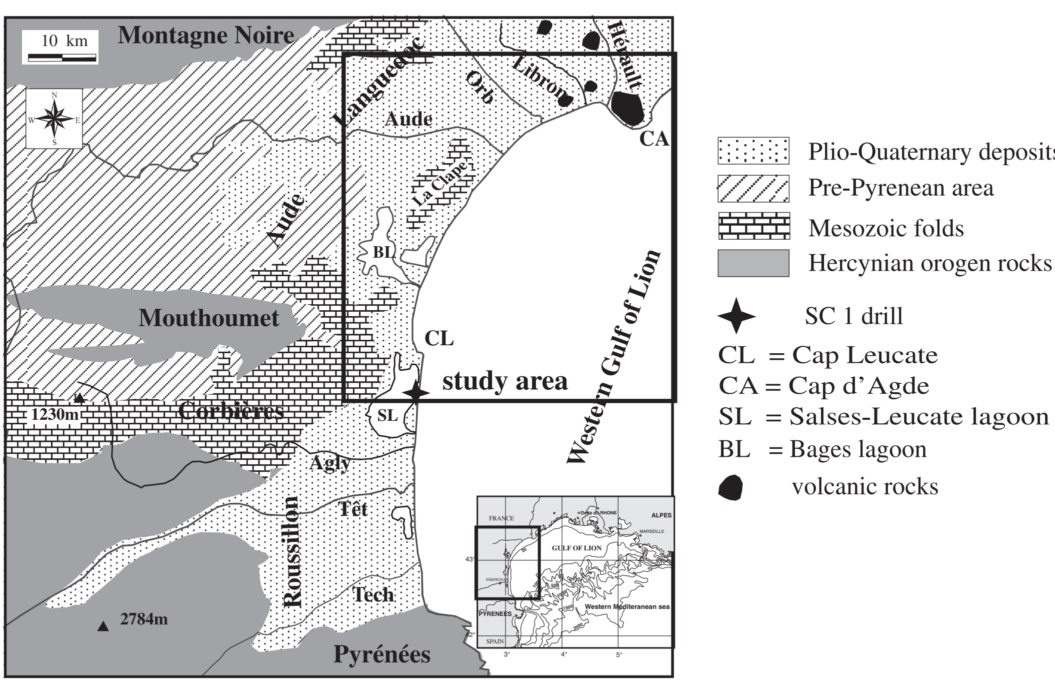

Fig. 1. Geological map of the onshore sector adjoining the study area. The small inset shows the location of the Gulf of Lions. Highlighted box shows the study area.

between allocyclic or autocyclic origin. We first propose a description of the stratigraphic discontinuities and main seismic facies, followed by an interpretation in terms of depositional environments.

We then present a depositional model for the northern system (IVAO, this study) and compare it with the results from the southern system (IVTA) of the Languedoc–Roussillon incised valley complex (IVLR).

2. Regional setting

2.1. Physiography

The study area coastline is sand-rich and arcuate in form, extending from Cap Leucate in the south to Cap d'Agde in the north (Figs. 1, 2) and trending southwest–northeast. The coastal area is characterized by a broad coastal plain on either side of the centrally located Cretaceous cliffs at La Clape, where only a narrow sandy beach is locally observed. When a coastal plain is present, it is associated with a beach barrier and several back-barrier lagoons. Four rivers are observed in the northern sector, including, from north to south, the Herault, Libron, Orb and Aude. A possible ancestral Aude River flowed south of the Massif de la Clape (Fig. 2, dashed and white line). The inner shelf sea floor is relatively featureless, with the exception of some minor highs made up of cemented sand and pebble beachrocks just south of the Aude River mouth. Outcrops of Cretaceous and volcanic rocks are observed in front of the Massif de la Clape and south of the Cap d'Agde, respectively.

The river mouths comprise minor estuaries (Pauc, 2005) with minimal landward extension (less than 1 km upstream). The river drainage basins extend into the nearby Montagne Noire to the north (Herault, Libron and Orb rivers) and the Corbières mounts to the west (Aude and Agly rivers). During catastrophic floods, because of the proximity of the mountainous drainage basins, the coastal plains are drowned and the sediment load is fully evacuated to the sea. Debris flows may occur along with the development of short-lived muddy and silty prodeltas.

The oceanic climate is characterized by a microtidal and medium wave-energy regime, associated with a Mediterranean fluvial regime. Waves come from two prevailing directions: 1) from the east/southeast, oriented transverse to the shore, and 2) from the northeast, generated by strong continental northerly/north-westerly winds. The resulting longshore drift is complex, with sedimentary cells in which sands are transported along-shore either from the north or from the south (Certain, 2002; Ferrer, 2010). In the IVTA (Têt and Agly rivers) south of Cap Leucate, the longshore drift is from south to north, while in the IVAO (this study area), it is dominantly from north to south.

2.2. Plio-Quaternary evolution

Following the Messinian salinity crisis in the Mediterranean Basin and the reflooding of the deeply incised margin and coastal basins, the erosion of proximal mountains during the Pliocene supplied abundant clastic sediment load to rivers. These rivers built Gilbert-type deltas which prograded far offshore, thus infilling the basins as well as the accommodation space associated with the subsiding shelf (Lofi et al., 2003; Guennoc et al., 2000).

Later, during the Quaternary, only thin continental deposits accumulated in the coastal basins, which were uplifted by low-amplitude vertical tectonic movements, as attested by terrace systems (Duvail et al., 2001). Farther seaward, differential subsidence maintained accommodation and several depositional sequences accumulated on the shelf during the Pliocene (Tesson et al., 1990, 1993; Posamentier et al., 1992; Rabineau et al., 1998).

The transition between the uplifting coastal plain and subsiding shelf (hinge line) is located at a variable distance offshore (Tesson and Allen, 1995). To the south, seaward of the Roussillon plain, it is located several kilometers offshore (Lobo-Sanchez et al., 2004; Tesson et al., 2000). To the north, between Cap Leucate and Cap'Agde (this study area), the hinge line is located even farther seaward, approximately 30 km offshore; the Pliocene succession forms a submerged shallow-water plateau in the inner shelf area. Consequently, on the Roussillon inner shelf, the river incised directly seaward during the lowstand (Glacials) periods and its valley progressively deepened (Tesson et al., 2011). To the North, in an area where the Pliocene plateau is broad and relatively flat, the rivers were less active in downcutting during the successive falls in base level. In this way, the rivers formed a complex set of imbricated coastal bay/estuary systems (Tesson et al., 2005a,2005b) that were constrained to extend parallel to the coast by atmospheric and oceanic influences and the induced littoral drift.

These incised valleys (IVAO system in the study area) are topped by the Post Late Glacial Maximum (PLGM) wave ravinement surface (WRS) and buried under the thick late transgressive and highstand deposits (Labaune, 2005; Labaune et al., 2005, 2008). In this paper, the WRS is labeled S10 in the forthcoming text and pictures.

3. Materials and methods

3.1. Seismic data

3.1.1. Tools

Two HR (high resolution) acoustic systems were employed, a 50-Joule minisparker and a boomer (Labaune et al., 2005). The minisparker comprised a streamer composed of 5 hydrophones with each at an interval of 1 m. The signal was filtered between frequencies ranging from 300 to 1200 Hz, resulting in a vertical resolution of 3–4 m and a penetration of up to 200 m in soft sediment. Each shot (two shots per second) was georeferenced using a differential GPS (Global Positioning System) with 3–5 m accuracy; source and streamer were deployed about 15 m and 50 m off the stern of the vessel, respectively. The boomer plate and streamer were located side by side at 5 m off the stern of the vessel. The boomer seismic signal has a frequency range of about 800 to 3000 Hz. Resolution is 1 m or better and penetration varies from several meters up to 100 m (depending upon numerous factors, such as pulse energy, occurrence of gas and pebbles, sand content and layering). The boomer data provides the best compromise between tools allowing either penetration or good resolution (which are inversely proportional). The boomer is useful for distinguishing tightly-spaced unconformities and characterizing seismic facies. Moreover, the system functions in fresh as well as in salt water (useful in lagoons and river mouths). This system is very sensitive to noise and needs fair-weather conditions. Shore-transverse lines were acquired from the beach (0.5 m water depth) up to 13 km offshore (about 35 m water depth) using a small vessel (6 m long) of the GDARGO (Groupe pour le Développement d'Activités de Recherche en Géologie et Océanographie).

3.1.2. Seismic grids

The location maps of the minisparker and boomer lines are presented separately (Fig. 3A and B). The average spacing between dip- and strike-oriented seismic profiles is 500 m and ranges up to 20 m in some areas for boomer data. The high-density and more recent boomer grid was acquired between 2005 and 2010 (four cruises).

3.1.3. Data processing

Data processing includes frequency filtering and attenuation correction using true signal processing software (Delph seismic). For the minisparker system, the exact location and offset (distance between source and streamer) are corrected. No correction is applied to the boomer system data. The x, y, and z parameters of the seismic horizons are either used directly and mapped in the UTM 31 projection system, or exported and converted to geographic (WGS84 ellipsoid) data for mapping in the Mercator projection system. Time to depth conversion is based on a water velocity of 1500 m/s and a sediment velocity of 1650 m/s estimated from the SC1 long core obtained several kilometers

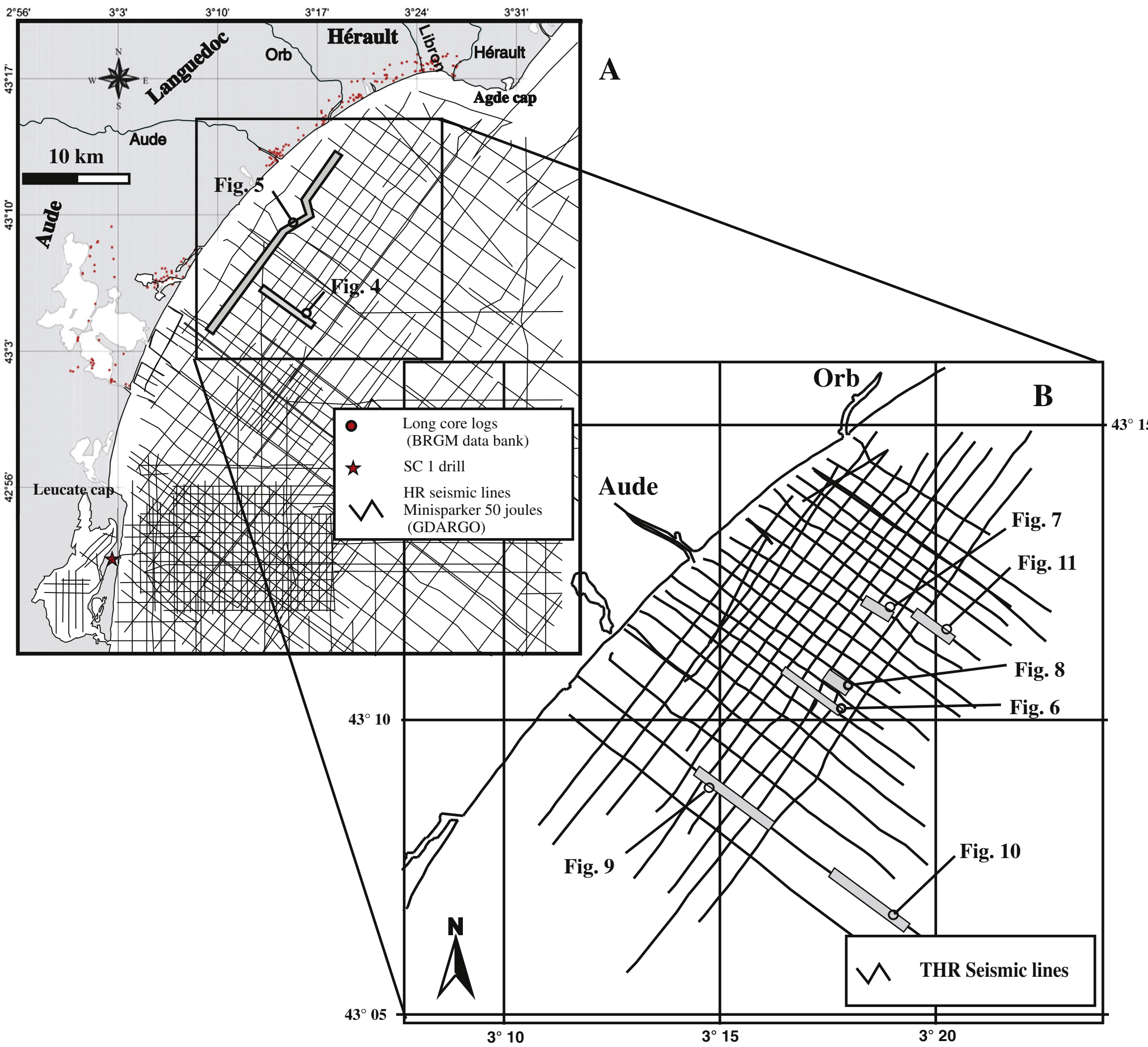

Fig. 3. Location maps of the study area showing the data sets used: Fig. 3A) high-resolution and medium-spaced seismic lines (minisparker) and long cores onland; Fig. 3B) very-high resolution and closely-spaced seismic lines (boomer) indicated in the box shown in Fig. 3A. Seismic data from the GDARGO team. The long core logs (red dots) are stored in the French BRGM data bank. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

to the south (Labaune, 2007). Due to frequent hamping of seismic signal by gas and cemented coarse deposits, only the map of the basal unconformity of the incised valley is presented in this paper (Fig. 2).

3.1.4. Seismic stratigraphy

In this study, a classic seismic interpretation methodology (Mitchum et al., 1977; Sangree and Widmier, 1977) based on reflection terminations and continuity is employed to identify unconformities and seismic units. We used also this methodology for seismic facies interpretation applied to high-resolution seismic data in a way consistent with the approach adopted in previous studies and other settings (Belknap and Kraft, 1977, 1985; Colantoni et al., 1981; Stefanon, 1985; Foyle and Oertel, 1992; Ashley and Sheridan, 1994; Bartek et al., 2004). We reinforced the seismic facies interpretation using results from studies integrating ground truth data derived from oil industry drilling results similarly to Novak and Krarup Pedersen, 2000; Roberts et al., 2004; Bahr et al., 2005; Nordfjord et al., 2006; Greene et al., 2007. Finally we used our own correlations between high-resolution seismic data and cores obtained during our previous studies all over the Gulf of Lion shelf (Gensous and Tesson, 2003; Labaune et al., 2005; Labaune, 2005) and the French Atlantic coast (Chaumillon et al., 2002; Weber et al., 2004) to constrain the seismic facies interpretation. The stratigraphic terminology used for this incised valley study is that outlined in Allen and Truilhe (1987) and Allen and Posamentier (1993,1994).

3.2. Drill core data bank

The described data bank refers to drill cores located in the study area.

Two sources of core data are used: the SC1 long core of GDARGO, and a free-access set of core logs collected and stored by the BRGM (Bureau de Recherche Géologique et Minière, France).

The SC1 long core (approximately 63 m long) was acquired during the summer of 2006 in the axis of the southern branch (IVTA) of the incised valley complex (Fig. 1, SC1 drill hole) under the modern coastal sandy beach. We implemented the drill hole 100 m to the north of two seismic lines acquired from a tidal channel of the Leucate lagoon. The multiproxy analysis results and the core facies correlation with seismic data have been published in detail by Labaune et al. (2010) and Tesson et al. (2011).

The BRGM stored logs contain data from 135 on-land boreholes (red dots on Fig. 3a). They are located on the coastal plain between the Agde and Leucate caps. Several boreholes are very close to the shoreline and to the landward terminations of our boomer seismic lines. The log interpretation was realized in our laboratory.

The SC1 multiproxy analyses evidenced that, in this area, several late-Quaternary 4th order climate cycles and associated base level cycles are recorded within the inner-shelf buried incised valley fills (Fig. 4). As the two northern and southern branches are very close and converging seaward, we assume, in this study, that they were connected during some late-Quaternary periods and that the two branches were probably submitted to the same climate and base level cycles and thus belong to the compound incised valley model. Moreover, as the SC1 drill hole is close to seismic lines, we correlated several seismic and sedimentary facies. These correlations are also used to help the seismic facies interpretation in the study area (IVAO).

In this study, the onland BRGM core logs were used to identify the incised valley extension under the coastal plain. Based on their interpretation (Lortal, 2005), we correlated the onland erosional contact between the Pliocene and the overlying Quaternary with the offshore basal unconformity of the IVTA observed on the landward extremities of the boomer seismic lines transverse to the shore. The extracted x, y, and z data were used to elaborate the basal unconformity or incision map (S40 on Fig. 2).

4. Stratigraphic results

4.1. Main seismic unconformities and units

Four unconformities and five seismic units have been identified in the study area (Table 1). The seismic units are preserved only as channel infills, and very few or none of these deposits exist outside channels in the northern part of the system. Because of successive phases of reworking, these seismic units are not present everywhere.

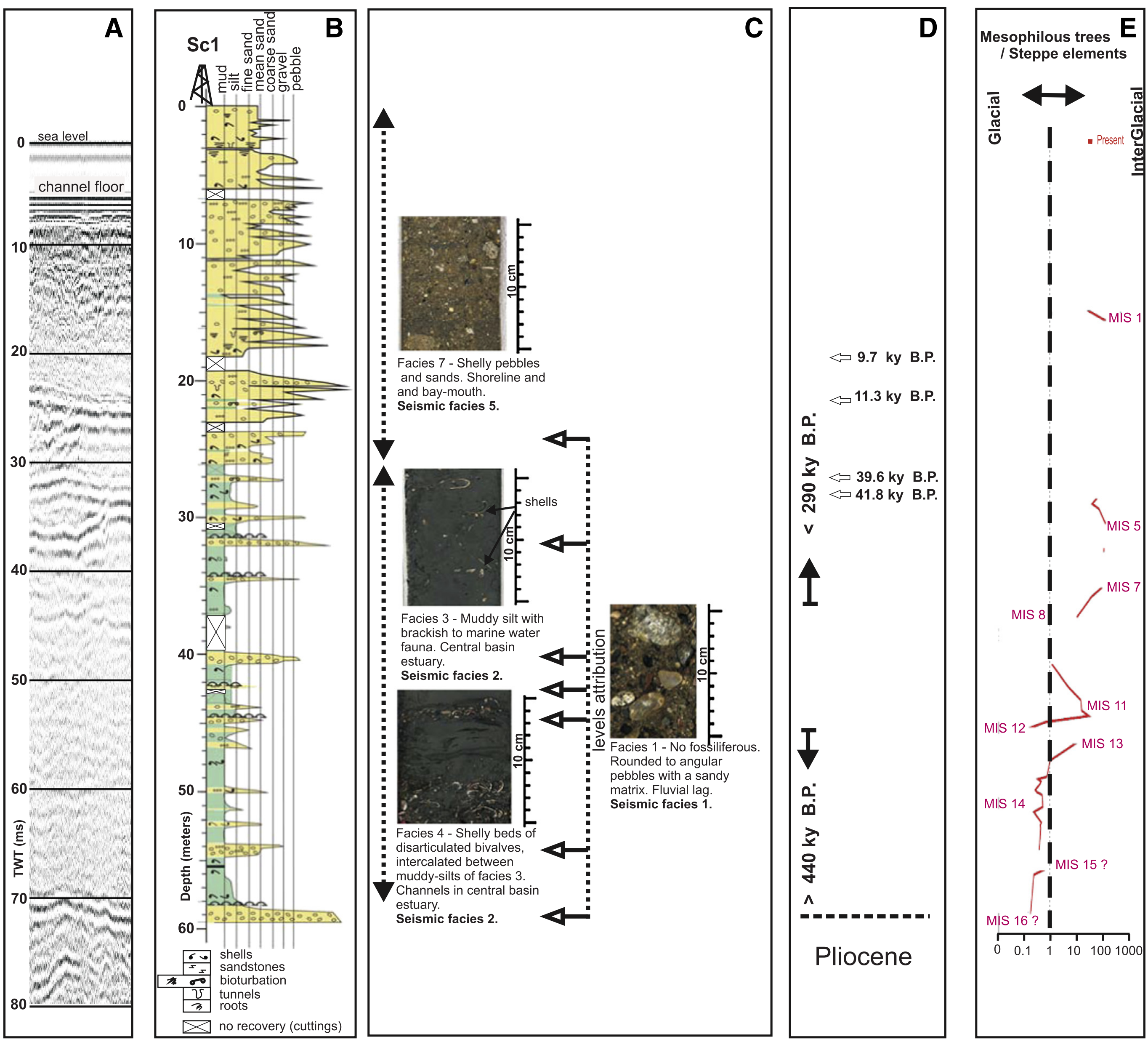

Fig. 4. Seismic facies, sedimentary facies and time calibration of the Têt/Agly incised-valley system (southern branch, IVTA) of the Languedoc–Roussillon incised-valley complex (IVLR) based on the SC1 long core and adjacent channel high-resolution seismic line data. Seismic section and SC 1 drill are about 100 m apart. Time scale is in milliseconds and depth is in meters. A is the seismic section; B is the lithologic log; C the main sedimentary facies; D the chronomarks based on calcareous coccoliths; E presents the pollen stratigraphic attribution to the upper-Quaternary glacial and interglacial events.
Modified from Tesson et al., 2011 (Figs. 6, 7 and 8).

Table 1
Unconformities, seismic units and seismic facies units observed and pointed on the seismic lines in the study area. Seismic facies units are described farther in the text and Table 2 and they are cited without chronostratigraphic meaning inside each seismic unit.

Unconformities	Seismic units	Seismic facies units
Seafloor		
	U10	SF 3 SF 8
S10		
	U20	SF 7 SF 5 SF 3 SF 2 SF 1
S20		
	U30	SF 7 SF 6 SF 1
S30		
	U40	SF 7 SF 6 SF 2 SF 1
S40		
	UP	SF P

Figs. 4–6 show key lines illustrating the unconformities and seismic units.

4.1.1. Seismic unit P

The top of this unit is the inner shelf substrate (Fig. 5) into which the western Gulf of Lions paleo-valleys are entrenched (Fig. 2). Between the Cap d'Agde (CA) and Cap Leucate (CE), Unit P makes up a wide plateau extending up to 20 km offshore, with reflectors gently dipping seaward which abruptly deepen and then disappear beneath the Quaternary cover. Northward and southward of the two capes, the Pliocene plateau is narrow. Because of further incision by river entrenchment, the seaward-preserved Pliocene succession forms a promontory anchored to the Cap d'Agde.

4.1.2. Unconformity S40

The top of Unit P is truncated by a major unconformity (S40) (Fig. 4) representing the basal erosional surface of the incised valley system (Fig. 2) (Tesson et al., 2005a,2005b). It shallows upstream progressively (Fig. 6). Downstream, S40 deepens abruptly (Fig. 6 central part of the longitudinal section) and progressively appears as a polygenetic surface resulting from the merging of other unconformities (S30 on Fig. 6). To the north, near the modern Aude and Orb river mouths, S40 is irregular and characterized by high relief and narrow channel-like features (Fig.7 and 8). In the southern part of the study area, S40 exhibits only minor irregularities (Fig. 5) and forms a broad shore-parallel incision (maximum depth is about 75–80 m bpsl). S40 is commonly masked here by the presence of gas and a seafloor multiple (Fig. 6). Finally, to the south, the S40 incision (Fig. 2) is either connected with the southern branch (IVTA) of the main IVLR complex (Labaune, 2007; Lortal, 2005) or turns seaward, incised moderately into the Pliocene promontory.

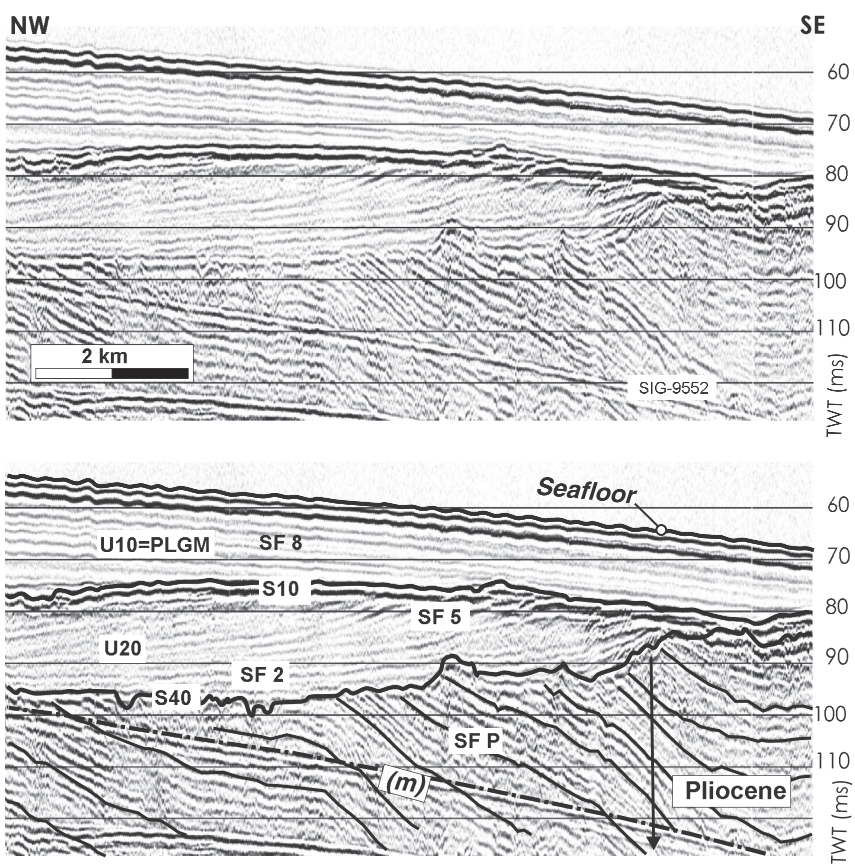

Fig. 5. Uninterpreted and interpreted coast-transverse seismic section showing seaward-dipping and truncated reflectors (seismic facies SFP) of the substratum (unit P) and the lowermost unconformity (S40) of the incised valley system. Unit P represents prograding Pliocene deposits identified onland in drill cores (red dots on Fig. 3). To the south-east of the incision, the prograding soft sediments of the Pliocene form a shore-parallel high plateau. The incised system is preserved behind this high plateau. (m) represents the first multiple. The location of this section is shown in Figs. 3a and 13. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

4.1.3. Seismic unit U40

This unit is observed only in the northern part of the system (Fig. 6), where it overlies the unconformity S40. On seismic lines both transverse and parallel to the incision axis, the internal reflectors onlap S40 (Fig. 7). The top of the unit is deeply incised by the channel-like features of later unconformities. Farther southward, the degree of reworking of U40 increases (Fig. 7, S30 deep incision) and the seismic unit completely disappears. The southward-limited extent of U40 is attributed to post-depositional channel erosion (Fig. 7, S30).

4.1.4. Unconformity S30

S30 deeply incises U40 (Fig. 7) and makes up the base of several channels in the northern area. S30 abruptly deepens to the south, where it totally removes the underlying U40 and merges with the basal unconformity S40 (Fig. 6).

4.1.5. Seismic unit U30

In the northern part of the system, and similarly to U40, this unit is thick only in the channel incisions between the unconformities at the base of the system (S30 or polygenic S40/S30) and S20. It thickens southward, and extends beyond the unit U40 (Fig. 6), becoming finally truncated by the overlying and dipping unit S20.

4.1.6. Unconformity S20

To the north, S20 appears either as a channel incision truncating S30 and S40 (Fig. 8) or as a flat and regular concordant surface (Figs. 7 and 9). S30 and S20 incisions are difficult to separate in this sector due to the complex geometry and local acoustic problems (gas and cemented coarse-grained deposits). Farther southward, and similarly to the previous unconformities, S20 deepens abruptly, truncating the underlying units, and merges with the polygenic basal unconformity S40/S30.

4.1.7. Seismic unit U20

This unit overlying unconformity S20 is the uppermost unit of the incised valley fill system, and is the only unit continuously preserved from north to south. The maximum thickness (up to 15 ms TWT) is observed in the north along the axis of the valley incisions (Fig. 8), and in the broad depression incised by the polygenic and basal unconformity S40 in the south (Figs. 5 and 6). Nevertheless, the thickness of U20 remains significant (up to 10 ms TWT) over interfluves (Figs. 7 and 9).

4.1.8. Unconformity S10

This surface is relatively flat and slightly erosional, and caps the incised valley system (Figs. 6, 7, 8 and 9). From north-east to south-west, S10 caps progressively younger seismic units (U-40, U-30 and then U-20, Fig. 6). In shore-transverse sections, S10 dips progressively seaward. Near the shore, S10 is observed at less than 30 m depth and truncates some channel-like erosional features filled with low-amplitude reflectors. Deep incisions suggesting fluvial valleys are not observed, implying that S10 is different from the other unconformities.

4.1.9. Seismic unit U10

On the shore-transverse sections, deposits lying above S10 and below the sea-floor are homogenous (constant seismic facies, see below) and present over the entire study area (Figs. 5–12). U10 is several tens of ms TWT thick but thins both landward and seaward.

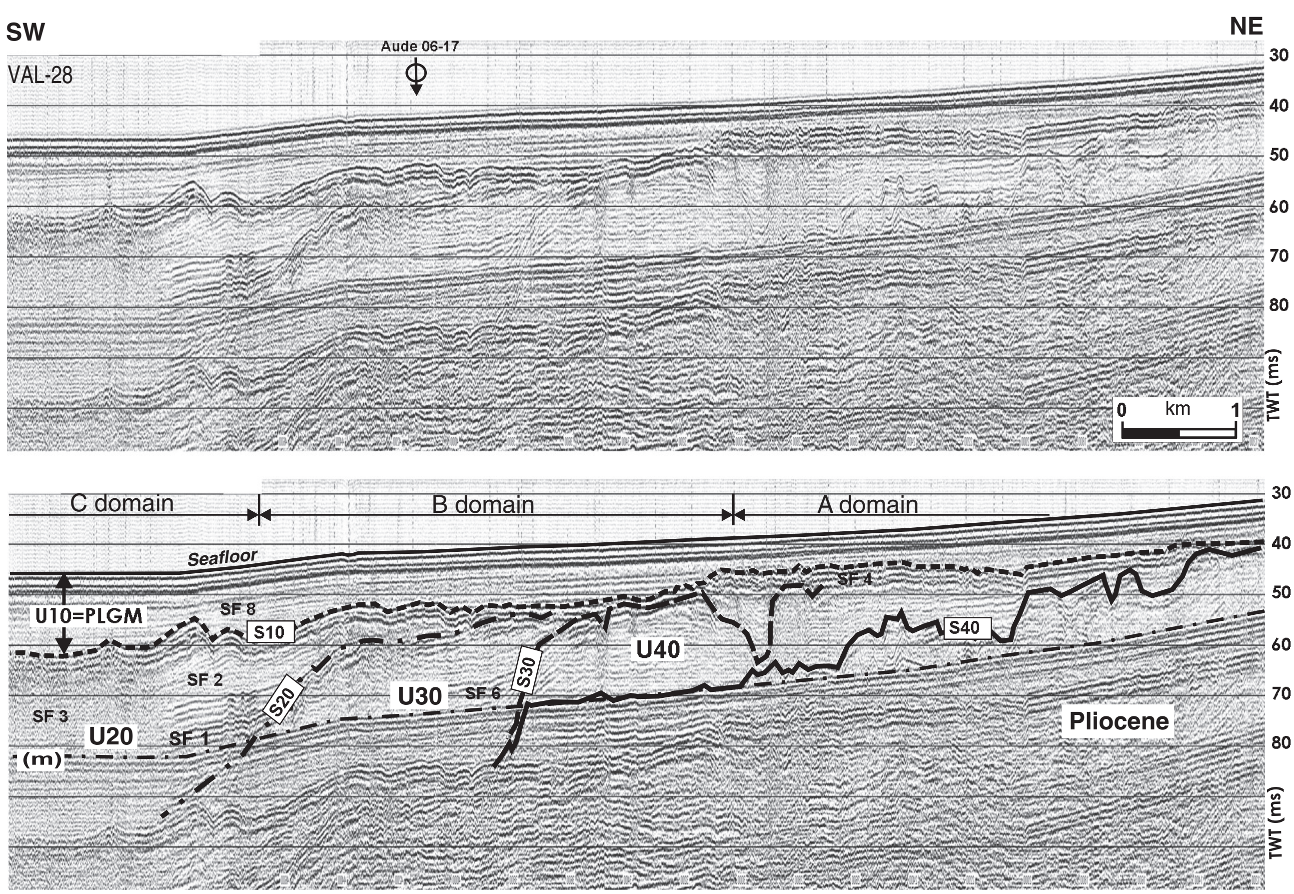

Fig. 6. Uninterpreted and interpreted coast-parallel sparker seismic line. In the downstream direction, from north-east to south-west, erosional surfaces (unconformities S40 to S20, see Table 1) are successively abruptly dipping. They merge progressively, so S40 evolves to form a polygenic erosional surface. On this section, the lower part of U30 and U20 is clearly characterized by high-amplitude low-frequency reflectors (SF1, see Table 2). The A, B and C domains are described further in the text. (m) represents the first multiple. The location of this section is shown in Figs. 3a and 13.

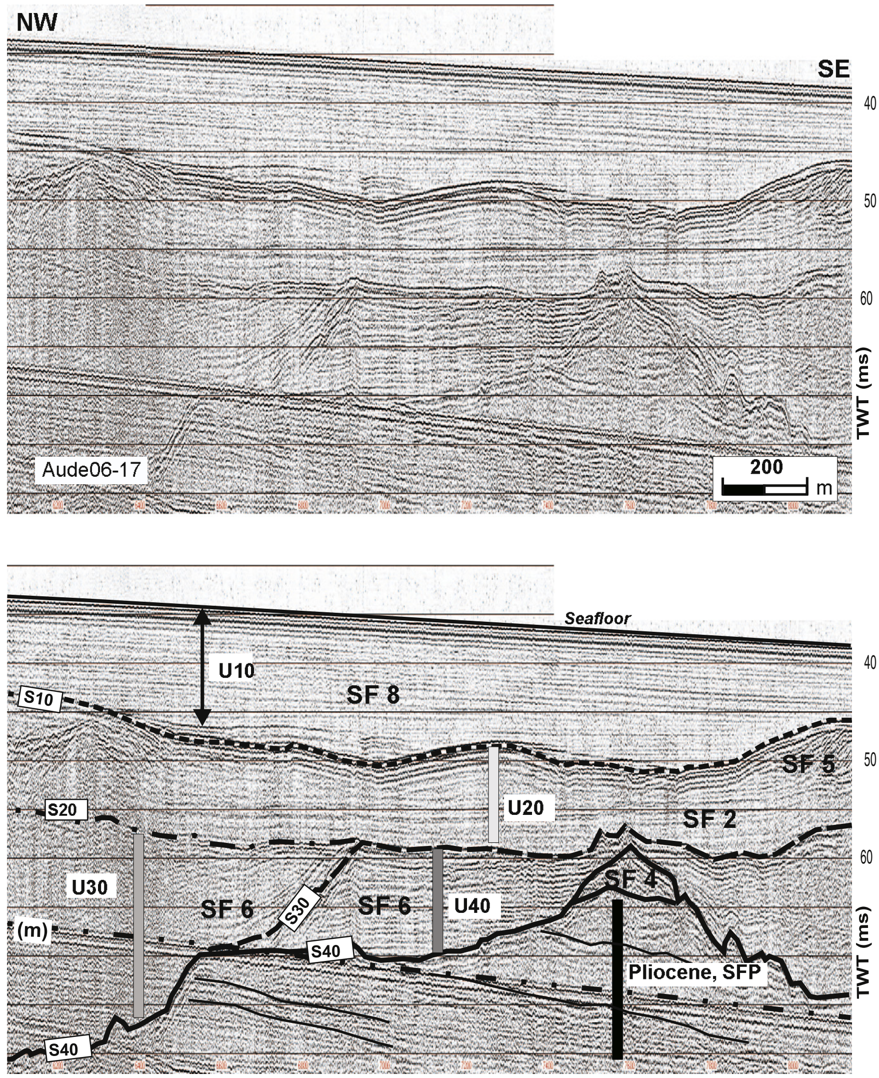

Fig. 7. Uninterpreted and interpreted boomer seismic section transverse to the coast and the incised valley/estuary complex, illustrating: a) the relationship of unconformities and particularly the reworking of the oldest by the youngest (S30/S40), as previously shown on Fig. 6 (B domain), b) the SF6 aggrading facies with lateral onlaps of the incised valley fill (U40), and c) the SF5 sigmoidal, prograding and high-angle reflections at the top of U20. (m) is the first multiple. The location of this section is shown in Figs. 3b and 13.

4.2. Description of seismic facies units

We identify eight (SFI–SF8) seismic facies within the channel-infill seismic units and one seismic facies (SF1) specific to the Pliocene (Table 2). Not all the seismic facies are present within each seismic unit, and their spatial distribution within the seismic units varies from one unit to another.

4.2.1. Seismic facies P (SFP)

This facies is restricted to the lowermost seismic unit P, into which valleys were incised during the Quaternary. The internal reflections, generally seaward dipping (Fig. 5), are discontinuous and characterized by low frequencies and high amplitudes. In both dip and strike seismic sections, this unit is characterized by local up- or down-convex structures.

4.2.2. Seismic facies 1 (SF1)

SF1 is observed at the base of most of the deep incisions in the upstream area. It displays two configurations: i) high-amplitude and low-frequency, sub-horizontal or gently concave-up reflections (Fig. 8), and ii) chaotic reflections of high amplitude (Fig. 12).

4.2.3. Seismic facies 2 (SF2)

This facies is characterized by high-frequency parallel and continuous reflections onlapping the flanks of channels. The reflections may be either sub-horizontal (Fig. 7, U20) or concave-upward (Figs. 10 and 11, U20). On the down-system part of shore-parallel seismic sections, reflections may be gently seaward-dipping toward the lower reaches (Fig. 6) and represent the most developed facies within the U20 unit.

4.2.4. Seismic facies 3 (SF3)

This facies is characterized by a sharp and irregular upper bounding surface, with hyperbolic reflections that mask the underlying reflections. In the southern part of the system, the SF2 seismic facies of U20 is locally replaced by SF3 facies (Fig. 6); it may appear farther north in some channel infillings.

4.2.5. Seismic facies 4 (SF4)

SF4 is a high relief and semi-transparent diffracting facies locally lying above the main unconformities. It may or not totally mask the underlying units. The thickness of SF4 may reach several meters (Fig. 7, top of Pliocene; Fig. 12, top of U20). This facies is particularly well developed in the upstream area, where it hampers penetration of the seismic signal.

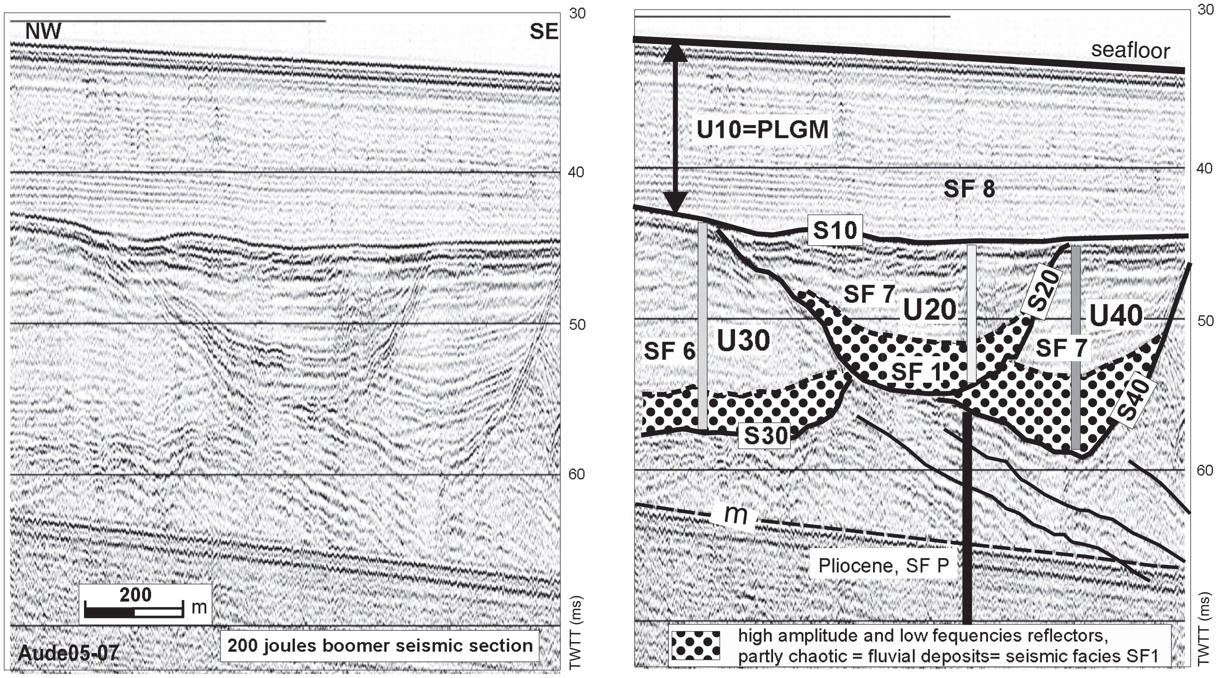

Fig. 8. Uninterpreted and interpreted high-resolution boomer section showing imbricated incisions in the northern area and common facies of the infilling deposits. The high-amplitude low-frequency and/or chaotic seismic facies SF1 at the base of the seismic units is typical of coarse fluvial deposits underlying sequence boundaries in incised valleys. The dashed upper bounding surface of this facies may represent a transgressive surface. The overlying facies SF7 (U20 fill of narrow valley) is characterized by low-amplitude, sub-horizontal as well as a few up-concave reflections onlapping the flanks of the paleovalleys. (m) represents the first multiple. The location of this section is shown in Figs. 3b and 13.

4.2.6. Seismic facies 5 (SF5)

This seismic facies displays sigmoidal and oblique–tangential reflections with steeply dipping clinoforms. The bottomset terminations may appear either as a sharp contact or can extend subhorizontally to merge with SF2 reflectors. SF5 may form: i) divergent assemblages (Fig. 10); and ii) sedimentary wedges prograding landward and southwest-ward, which are located at the entrance of lows (lateral channels) at the top of the Pliocene promontory (Fig. 11). This facies is particularly well developed at the top of seismic unit U20 in the D domain (Fig. 13). In the southern part of the study area, other sedimentary bodies with SF5 facies are stacked on the flanks of the broad incision at the contact with the Pliocene promontory. However, correlation with the different incised valley-fill units remains difficult. SF5 is also identified at the southern entrance/mouth of the IVAO system.

4.2.7. Seismic facies 6 (SF6)

This facies displays two types of reflector configurations observed on seismic sections transverse to the channel axis.

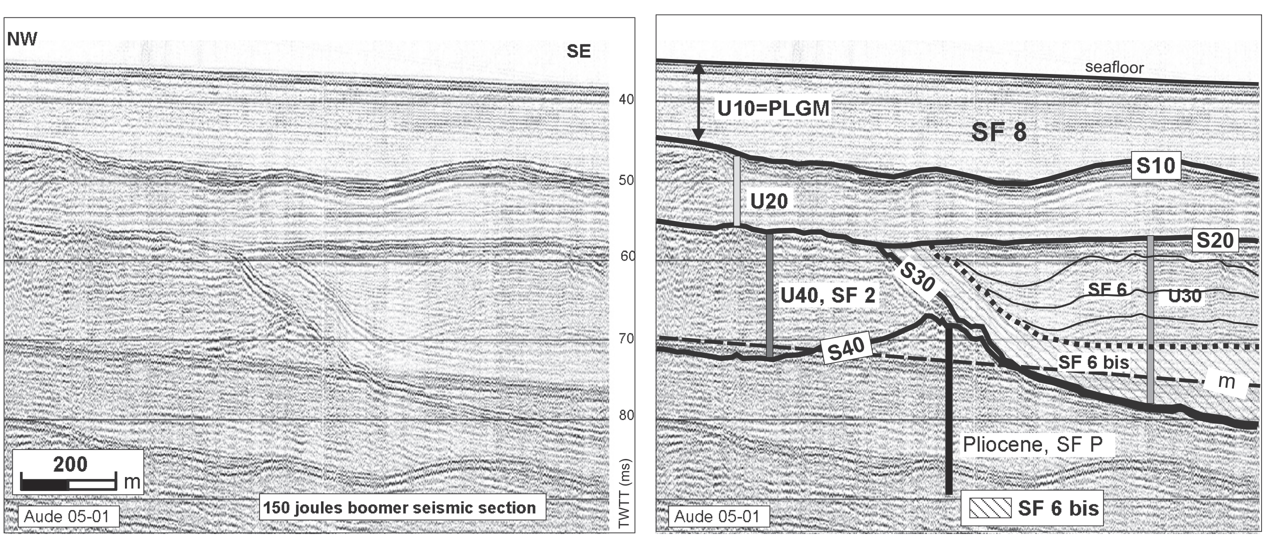

Fig. 9. Uninterpreted and interpreted high-resolution boomer section showing the particular depositional facies which characterize the U30 infilling of a paleo-valley in the northern part of the study area. The west side of U30 shows parallel reflectors molded over the valley flank and downward-correlated with the continuous, high-amplitude and low-frequency reflectors of the valley bottom (SF6 bis). The channel infilling overlying SF6 bis is composed of up-convex, aggrading and offlapping high-frequency reflectors (SF6). (m) represents the first multiple. The location of this section is shown in Figs. 3b and 13.

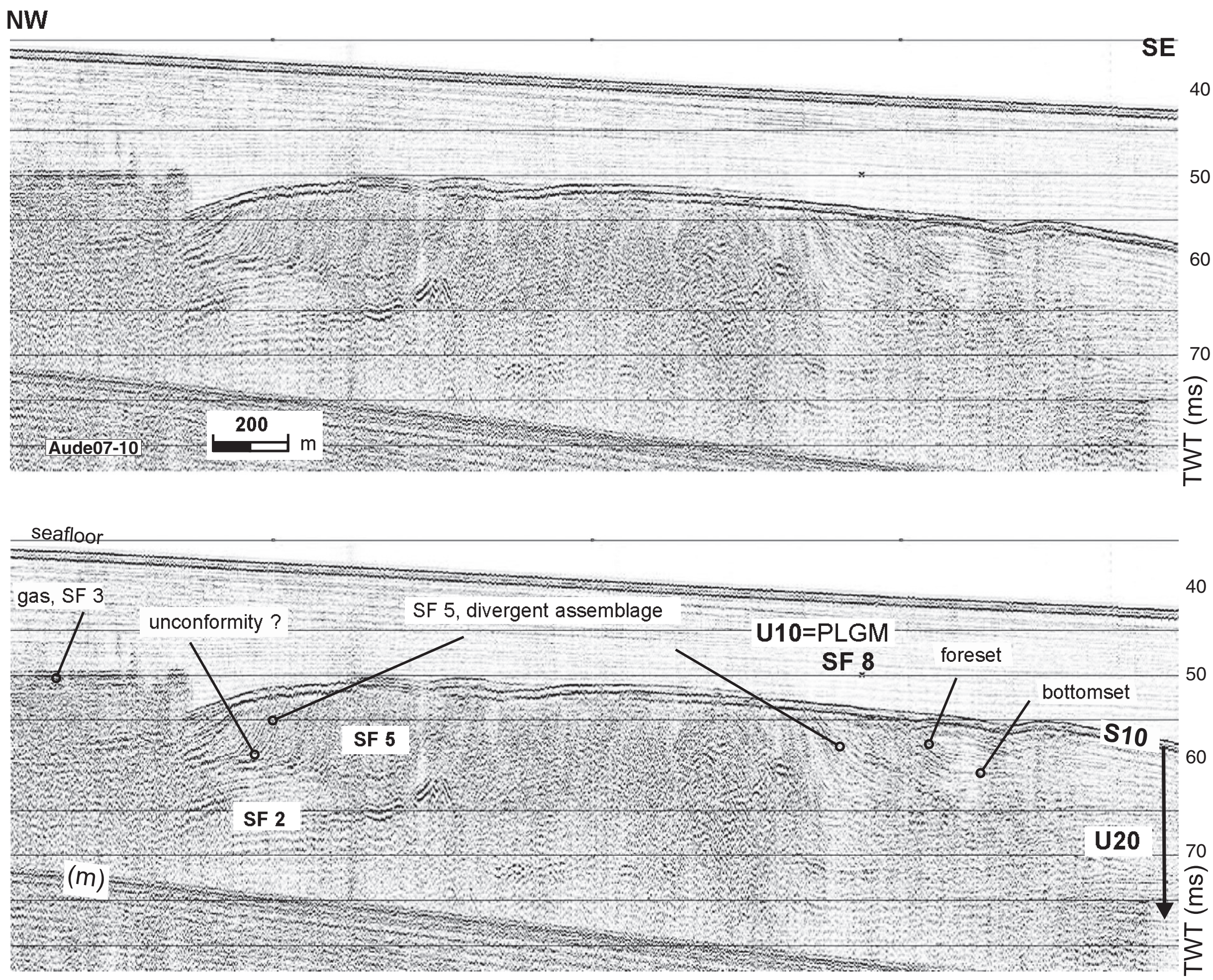

Fig. 10. Uninterpreted and interpreted high resolution boomer section showing lateral sigmoidal, prograding and high-angle dipping reflections (SF5). The reflectors form two divergent sets, suggesting that the section is transverse to a high-energy prograding sandy or muddy sand feature (bay-head delta, longitudinal bar, lateral flood delta or washover fan). To the NW, the prograding reflections are apparently downlapping onto an unconformity at the top of SF2, but not to the SE where the bottomsets seem tangential. (m) represents the first multiple. The location of this section is shown in Figs. 3b and 13.

The first configuration is characterized by up-convex and laterally onlapping reflections, as well as a good penetration of the boomer seismic signal (Fig. 9, U30).

The second configuration (SF6 bis) exhibits high continuity and frequency, with parallel reflections molded over the western flank of the channels. These reflectors extend downward in the channel axis (dashed zone on Fig. 9, U30).

4.2.8. Seismic facies 7 (SF7)

This facies displays two types of reflector configurations observed on seismic sections transverse to the channels axis: i) low angle sigmoidal reflections associated with prograding and aggrading sedimentary bodies anchored alternatively to one side or the other (Fig. 12), and ii) low frequency, up-concave and onlapping onto the channel margins (Fig. 8, U20 and U40, underlying SF1).

4.2.9. Seismic facies 8 (SF8)

This facies characterizes the seismic unit U10 (Figs. 5, 7 to 12) and displays continuous and parallel reflections of low energy and high frequency that are gently seaward dipping. SF4 reflections are both downlapping and onlapping with respect to the low-relief features of the unconformity S10 which caps the incised valleys system.

5. Interpretation and discussion

5.1. Stratigraphic significance of the seismic facies units

In the following, we interpret the observed seismic facies (SFP and SFI to SF8) that are more or less associated within each individual seismic unit (Unit P-U10). For this purpose, we use established and widely used criteria for the calibration of seismic facies with core data in terms of lithology and depositional environments.

5.1.1. Seismic facies P (SFP): Pliocene substrate

This facies is well observed on seismic lines and is present over the entire Gulf of Lions inner shelf and under the coastal plain (lagoons and channels). Owing to previous studies based on numerous coastal plain cores (Duvail et al., 2001), we have established (Labaune, 2005; Tesson et al., 2005a,2005b; Lortal, 2005) that the SFP facies corresponds to unconsolidated Pliocene prograding deltaic deposits.

5.1.2. Seismic facies 1 (SF1): fluvial deposits

In the southern branch (IVTA system) of the complex described here (Incised Valleys of the Languedoc Roussillon, IVLR), the lithology log of the SC1 long core (Fig. 1) shows several levels of non-fossiliferous sandy and oxidized gravels encased within fluvio-estuarine silty/muds. These levels represent fluvial lag deposits attributable to successive glacial periods with base-level falls that can be correlated directly

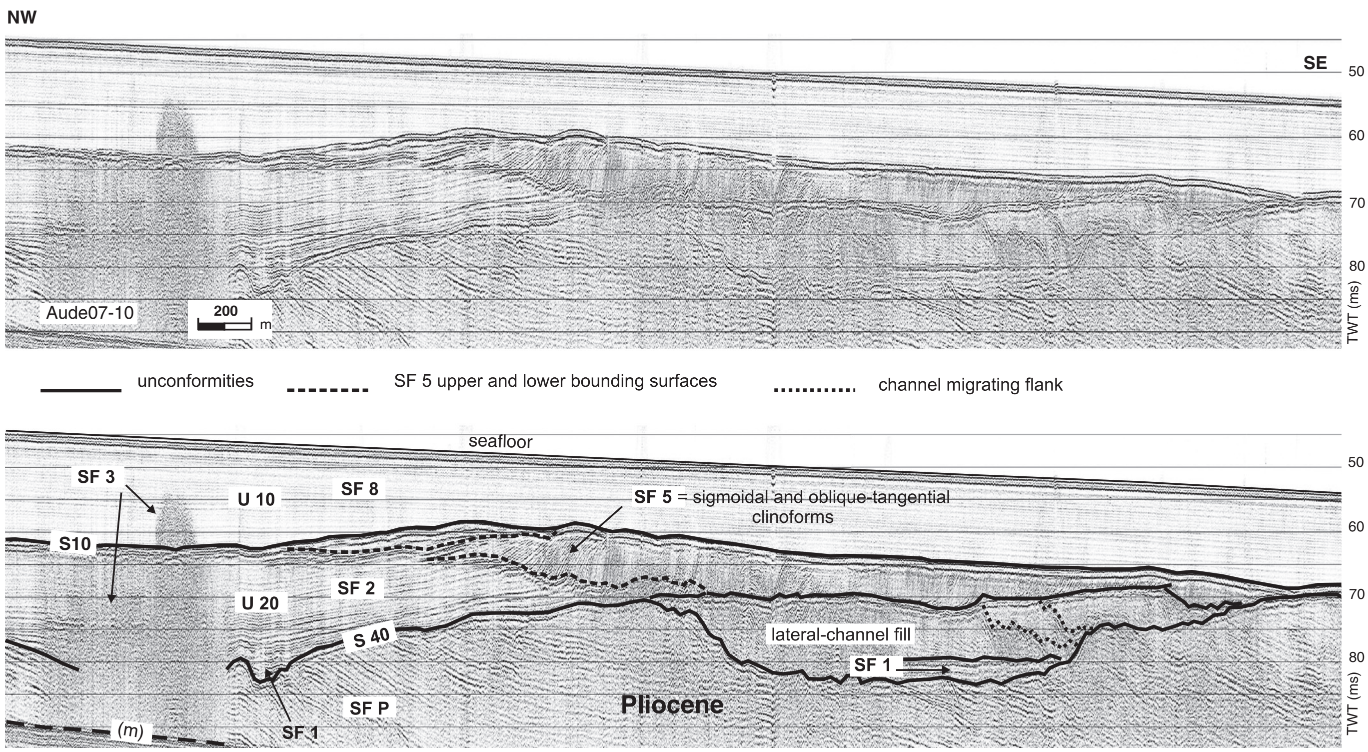

Fig. 11. Uninterpreted and interpreted high resolution boomer section showing lateral sigmoidal, prograding and high-angle dipping reflections (SF5). This section is transverse to the eastern flank of the incised valley complex (Fig. 3b) in the downstream area (C domain of Fig. 6). The Pliocene promontory is incised by a transverse channel infilled by migrating deposits. Above a top-truncated channel infilling, high-energy deposits characterized by SF5 prograde eastward toward the incised valley axis. Laterally, high-energy SF5 evolves toward low-energy SF2 locally exhibiting gas seepage (SF3). In plan view, SF5 is connected with the SF5 unit shown on Fig. 10 and displays a multi-lobate shape interpreted as internal channel mouth shoals. When a channel is not present, SF5 could be interpreted as a wash-over fan. These occurrences of SF5 are essentially observed at the top of U20. (m) represents the first multiple. The location of this section is shown in Figs. 3b and 13.

with the high-amplitude and low-frequency reflections of SF1 (Labaune et al., 2010). Elsewhere, in other incised valley systems, "chaotic to semi-parallel reflectors" (Greene et al., 2007), "high-amplitude chaotic" (Nordfjord et al., 2006), or "chaotic to sub-parallel, high amplitude reflections" (Bahr et al., 2005) have been similarly attributed to fluvial lag.

5.1.3. Seismic facies 2 (SF2): central basin/bay fill

This facies has been observed and described as "sub-horizontal, continuous reflections" (Foyle and Oertel, 1997), "low amplitude, weakly layered" (Nordfjord et al., 2006), and "low-amplitude, parallel reflections, stratified, onlapping" (Bahr et al., 2005), considered to be typical of low-energy environment deposits such as muddy estuary basin fill. Similarly, we have observed and calibrated this type of facies in the Marennes–Oleron basin (Chaumillon et al., 2002), but not in the Gironde estuary (Tesson et al., 2005a,2005b). Nevertheless, Greene et al. (2007) described "semi-parallel inclined reflections (inclined both toward the valley flanks and down the valley axis….or acoustically transparent facies" very similar to the reflection configurations observed in the study area. However, these authors (*op. cit.*) calibrated this facies using a core (MS-04-1) and attributed it to bay-head delta deposits.

We consider that, in view of the good penetration of the seismic signal and the sagging, SF2 most probably represents muddy central basin deposits in the study area.

5.1.4. Seismic facies 3 (SF3): diffracting facies (gas)

The masking effect of SF3 is referred to as "acoustic blanking" (Duarte et al., 2007) and is characteristic of biogenic gas accumulation encountered into either deep or shallow water environments (Edgerton and Leenhardt, 1966; Stefanon, 1985). In shallow waters, gas occurrence is common in fine and organic-rich muds accumulated in low-energy environments with high biogenic production such as protected embayments, estuary central basins and offshore prodelta systems (Aloisi and Monaco, 1980; Gensous and Tesson, 2003; Garcia-Garcia et al., 2004; Tessier et al., 2010; Labaune et al., 2005).

5.1.5. Seismic facies 4 (SF4): cemented coarse-grained deposits

This facies characterizes outcropping relief that is common over the Gulf of Lion inner shelf sea floor. Samples collected by diving (Labaune et al., 2005) are composed of cemented sand and gravels with rounded or semi-angular clasts. SF8 is interpreted as representing cemented coarse-grained deposits. The deepest SF4 features cannot be interpreted due to gas because their lower boundary, observed on Figs. 7 and 12, is not affected by a pull-down effect.

5.1.6. Seismic facies 5 (SF5): sandy estuary mouth or lateral channel shoals

Foyle and Oertel (1997) interpreted "large or small parallel or sigmoidal reflectors" (similar to SF5) as estuary mouth shoal or tidal inlet deposits. In the present study, sedimentary deposits characterized by SF5 occur at the entrance of lows (channels) at the top of the Pliocene promontory (Figs. 10 and 11) as well as near the southern estuary mouth. These deposits are typical of channel entrance shoals (flood tidal delta) or washover fans resulting from the wave reworking and longshore drift transport of the Pliocene promontory formations.

5.1.7. Seismic facies 6 (SF6): downstream fluvial infilling

The first configuration, with up-convex and laterally onlapping reflections (Fig. 9), suggests longitudinal bars in estuaries. The good penetration of the boomer seismic signal suggests that these bodies are mostly composed of silt/mud. The lack of wavy structures at the top, suggesting dunes and ripples as observed in tidal bars, supports the hypothesis of weak tidal control. This configuration could be attributed to the lower part of the fluvial environment at the entrance of an

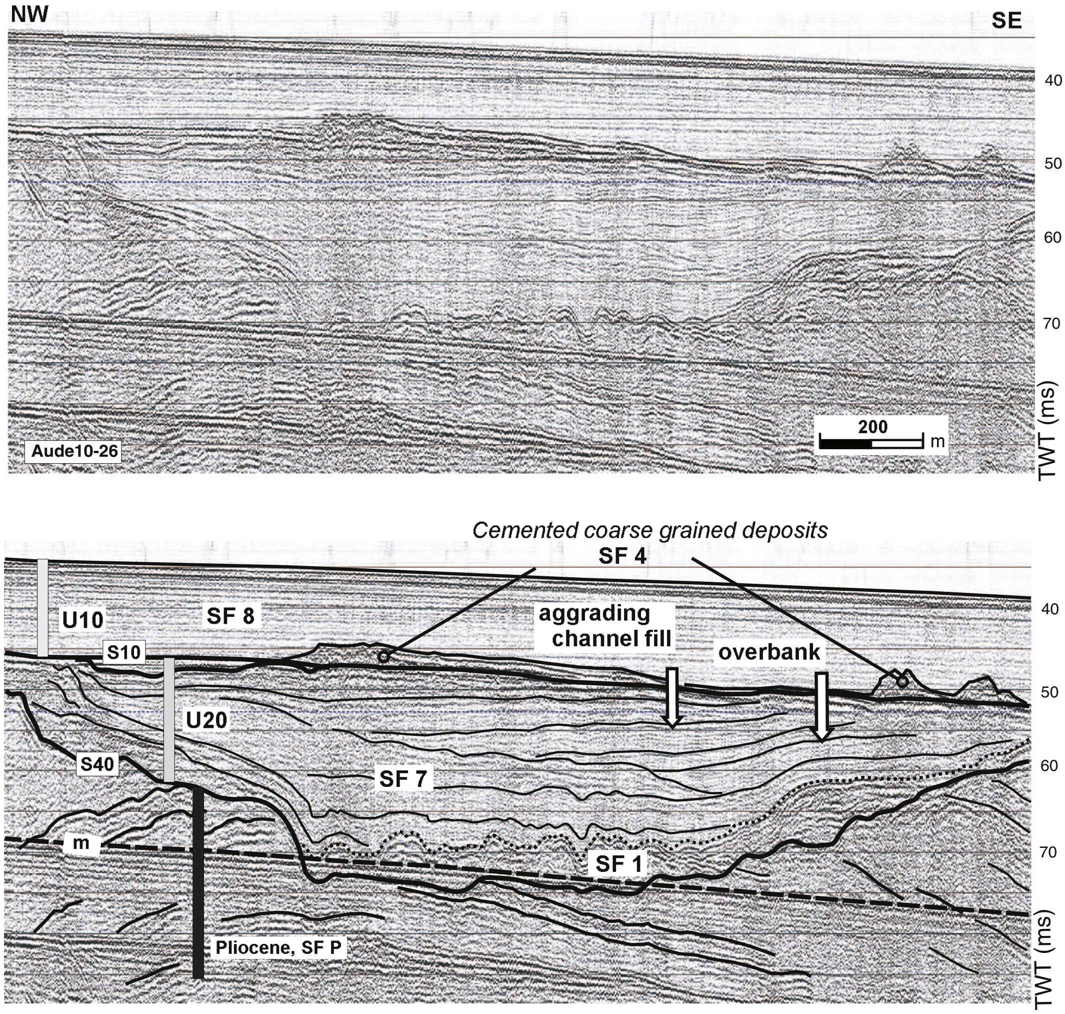

Fig. 12. Uninterpreted and interpreted high-resolution boomer seismic section across a paleovalley of the A domain. The infill (U20) consists of two main facies (SF1 and SF7). The chaotic facies SF1 overlies the base of the channel and the incised Pliocene substratum. SF7 is subdivided into two sets of lateral migrating and some aggrading reflections anchored respectively onto the western and eastern flanks of the channel incision. Overlying the ravinement surface (WRS or S10) at the top of the infilling, irregular highs with chaotic reflections (SF4) are made up of cemented coarse-grained deposits which diffract the seismic signal and the underlying structures become more or less observable. (m) represents the first multiple. The location of this section is shown in Fig. 3b.

Table 2
Summary of the seismic facies and internal reflection characteristics as observed in the study area. The interpretation in terms of depositional environments and systems tract is detailed in the text.

Label	Internal reflections	Interpretation	Figure	Systems tract
SF P	- High amplitude, low frequency, discontinuous, seaward dipping	Gilbert delta progradation	Figs. 4 to 8, 10, and 11	Pliocene HST
SF1	- High amplitude, low frequency, sub-horizontal to up-concave - High amplitude and chaotic	Fluvial lag	Figs. 7, 10, and 11	LST
SF2	- Low amplitude, high frequency, parallel, continuous, sub-horizontal to up-concave, aggrading and onlapping	Low energy deposits of protected environments, bay or central estuary basin	Figs. 4, 5, 6, 8, 9, and 10	TST
SF3	- Hyperbolic, diffracting, no structure masking effect	Gas accumulation or seepage	Figs. 5, 9, and 10	TST
SF4	- Diffracting, no structure, semi-transparent. high relief upper bounding surface	Cemented coarse grained deposits	Figs. 6 and 11	TST/HST
SF5	- High-energy, high dipping angle Sigmoidal to oblique-tangential. Diverging and landward prograding assemblages	Lateral channel entrance shoals and/or wash-over fans May be bay-head deltas	Figs. 4, 6, 9, and 10	TST
SF6	- Up-convex and laterally onlapping. - High continuity, high frequency, parallel, molded on channel flanks or horizontal	Downstream fluvial system, near estuary entrance. Longitudinal bars and flank marsh deposits	Figs. 6, 7, and 8	TST
SF7	- Sigmoidal, low angle, transverse to channels - Low frequency, up-concave, onlapping channel flanks	Upstream fluvial system. Channel fill transverse migration, point bars	Figs. 7 and 11	TST
SF8	- Low-energy, high frequency, continuous, parallel. Downlap and onlap the underlying erosional surface relief	Offshore muddy silts deposits	Figs. 4 to 11	PLGM TST and HST

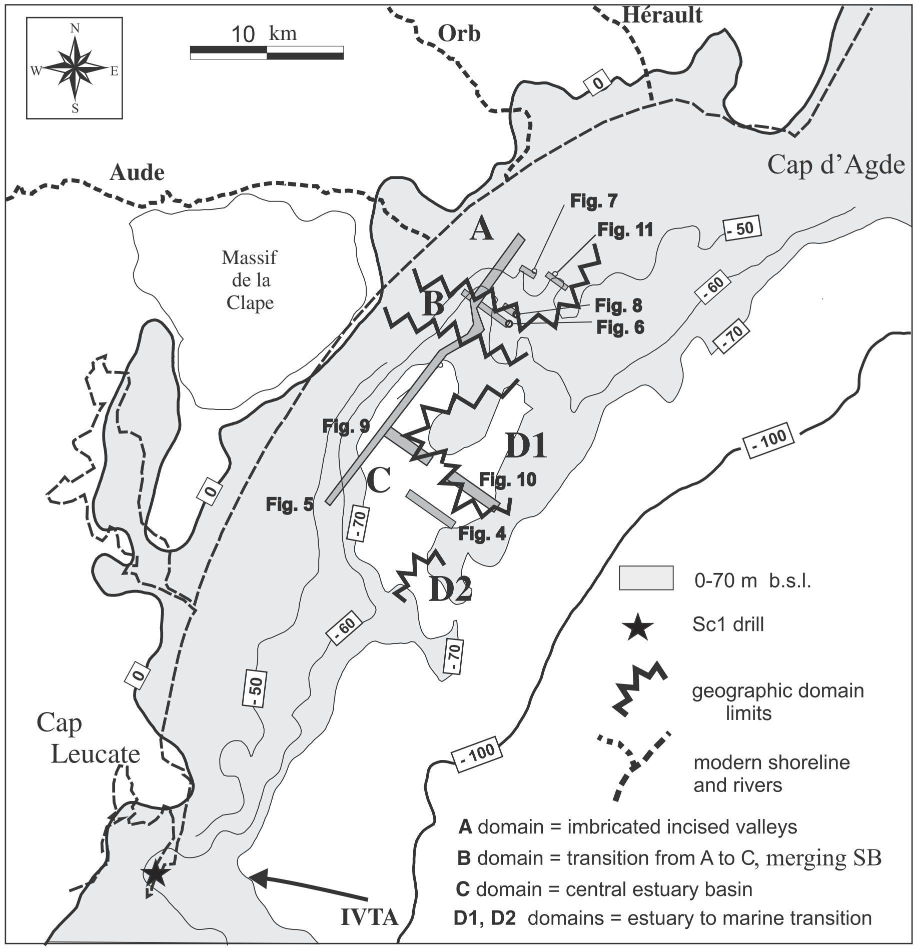

Fig. 13. Morphosedimentary domains superimposed onto the basal S40 incised surface (in meters bpsl) and the illustrated seismic sections: A) areas of imbricated paleo-valleys; B) transition between domains A and C; C) central basin with muddy facies (SF2), gas occurrences (SF3) and lacking seismic units U40 and U30; and D) areas of prograding sandy bodies (Pliocene low shoals and/or wash-over fans D1, estuary/bay mouth shoals D2).

estuary/bay. The second configuration, with reflections molded over a channel flank (dashed area on Fig. 9), has been described (Nordfjord et al., 2006) on the New Jersey shelf, where it is interpreted as "estuarine flank deposits" composed of salt-marsh and tidal-flat sediments. Similar features and architectures are observed in the Bahia Blanca estuary (Ginsberg and Aliotta 2011), being considered as progradational deposits typical of point bars in tidal channels. As tidal influence is reduced in the study area, this facies could also be attributed to the downstream part of the fluvial environment.

5.1.8. Seismic facies 7 (SF7): upstream fluvial infilling

The first configuration displays low-angle prograding and aggrading reflections transverse to the channel that are anchored alternatively onto one flank or the other. This seismic facies may be interpreted either as laterally migrating bay-head delta deposits (Greene et al., 2007) or fluvial channel fills which are assumed to represent upstream fluvial deposits.

The second configuration shows low frequency, upward-concave and onlapping reflectors on the channel flanks (Fig. 8, U20 and U40, underlying SF1). This type of configuration has never been described elsewhere and is difficult to interpret. The low-frequency and high-energy reflectors may be due to gross stratification and coarse material. Considering that this facies is observed in the upstream part of the system, near the river mouths, we suggest attributing them to the upstream part of the fluvial environment.

5.1.9. Seismic facies 8 (SF8): Post Late Glacial Maximum (PLGM)

This facies characterizes the seismic unit U10. We sampled SF8 by gravity coring, and the results of sedimentary analysis and age dating show the presence of silty mud with organic content which was supplied by the Aude and Orb rivers and deposited during the PLGM late transgressive sea-level highstand (Labaune, 2005).

5.2. Morphological and facies zonation in the incised valley complex

Based on the shapes of the unconformities (S40, S30 and S20), the extent of the seismic units in plan view (U40, U30 and U20) and the facies distribution within the seismic units, we can identify four domains labeled from A to D (Figs. 13 and 14).

The A domain is located in the northern part of the IVAO system just in front of the Aude and Orb river mouths (Figs. 6, 8 and 12). It is characterized by several imbricated channel incisions (S40, S30 and S20) and associated infilling deposits U40, U30 and U20 (Fig. 14a). The channel paths are irregular because of recurrent phases of reworking and are thus difficult to map.

The B domain is located downstream of the A domain and is characterized by the marked south/south-westward dip of S40, S30 and S20 (Fig. 6, longitudinal section; Fig. 7, transverse section). Consequently, the seismic units U40, U30 and U20 successively almost disappear southward. This domain is of limited extent.

The C domain is located the farthest downstream, covering a major part of the system. It corresponds to an area where the S30 and S20 unconformities merge with the oldest unconformity (S40). In this way, a unique broad depression (estuary basin or bay) is developed instead of several imbricated incised valleys. This depression is incised at a maximum depth of 75 m below the present sea level (bpsl) into the Pliocene plateau. The basal unconformity (S40) shows some narrow and shallow channels. The southward connection of the depression with the mid-outer shelf (estuary/bay mouth) is not clearly evident (Figs. 2 and 13). The infilling deposits of the depression are reduced to U20, which is itself overlain by the PLGM (U10) capping the IVAO system. The infilling (U20) is confined to the Pliocene plateau without any seaward physical link with the well-identified Upper Quaternary depositional sequences on the shelf (Tesson et al., 2000; Lobo-Sanchez et al., 2004).

The D domain comprises two sedimentary bodies, disconnected and attached either to lateral channels incised into the eastern Pliocene flank of the C domain depression, or to the southern estuary/bay mouth (Fig. 13, D1 and D2 respectively). In the D1 area, SF5 reflections prograde toward the depression axis and evolve laterally toward the SF2 reflections of U20 (Fig. 11). Thus, the prograding sandy lobes or shoals of D1 and the muddy silts of D2 are coeval. Nevertheless, the D1 area is the expression of sedimentary processes transverse to the normal longitudinal succession of depositional environments from upstream to downstream in the incised valley.

The spatial distribution of seismic facies inside the infilling deposits depends on the areal extent of each seismic unit and the considered domain (Figs. 13 and 14b). In the A and B domains, the deposits filling U40, U30 and U20 are typical of upstream fluvial environments in the northern part (SF1 and SF7) and downstream fluvial/near estuary entrance environment in the southern part (SF6). In microtidal depositional environments, the transition from estuarine to fluvial facies is rapid and, depending on the seismic unit, a given infilling deposit may exhibit more fluvial or more estuarine characteristics than another (Fig. 8, facies SF6 for U30 and SF7 for U40 and U20). In the B domain, the unconformities S40, S30 and S20 deeply incise the seismic units

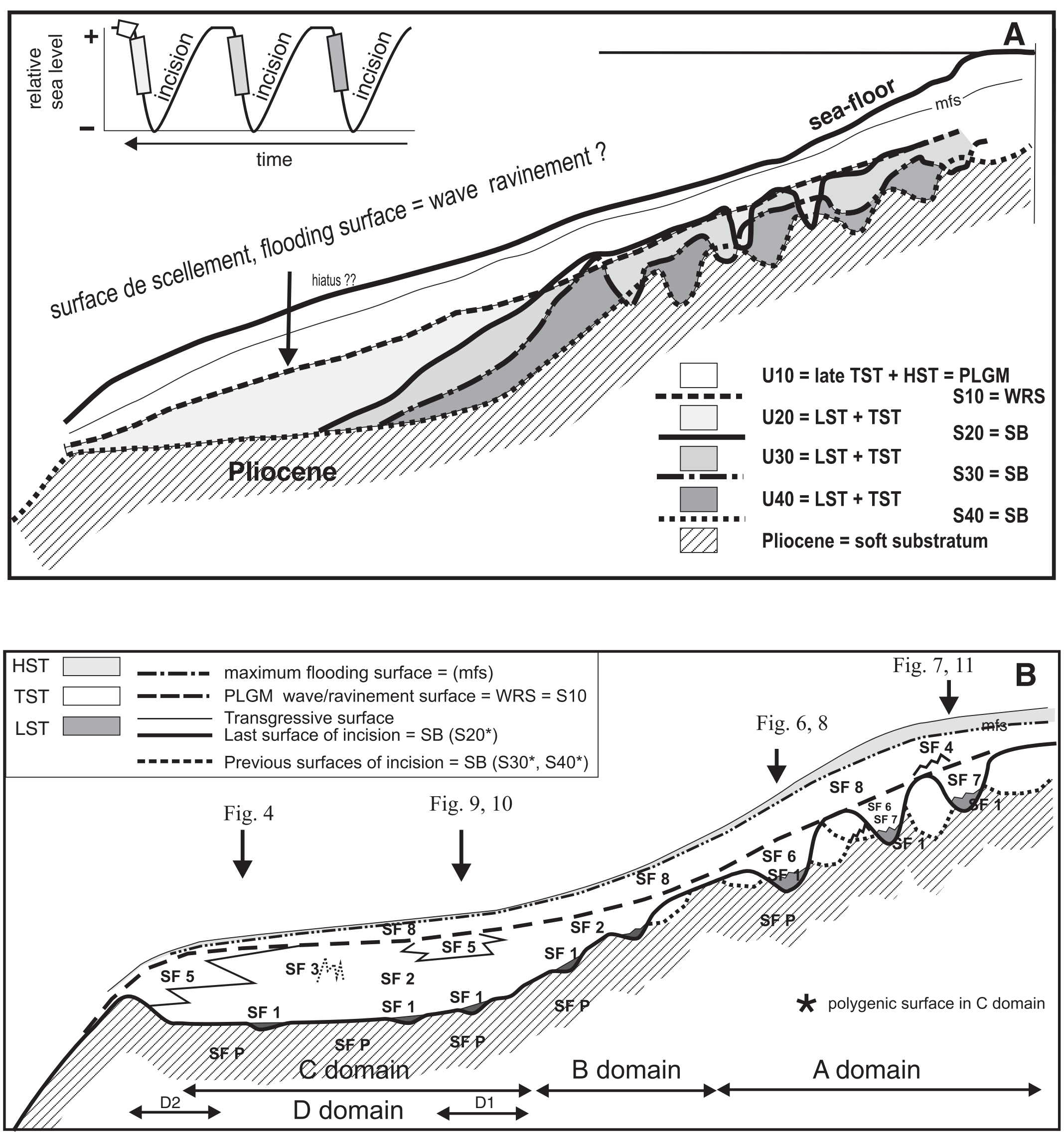

Fig. 14. Schematic interpretation of the imbricated surfaces of erosion and filling deposits along the longitudinal axis of the system. The landward domain on the right is of fluvial nature and strongly incised. The erosional surfaces rework each other. More seaward and downward, on the left, the erosional surfaces dip abruptly and merge. The preserved parts of the depositional sequences (U40 to U20) are generally aggrading and prograding (Fig. 6, SW half of the seismic section), deposits are muddy and no channel incision is observed. Fig. 14a is a simplified stratigraphic framework describing the unconformities and seismic units. See text for discussion. LST: lowstand systems tract; HST: highstand systems tract; SB: sequence boundary; WRS: wave ravinement surface; mfs: maximum flooding surface. The relative sea-level curve has no chronostratigraphic significance and hiatuses may occur. Note that the mfs and the separated TST and HST units within U10 are not documented here (see references). Fig. 14b shows the localization of different facies along the longitudinal axis and the respective illustrations.

(Pliocene, U40 and U30), which are almost entirely removed away, while the unconformities successively merge downward. In domain C, over the basal Pliocene unit, only U20 is well preserved, corresponding to typical downstream deposits of the central estuary basin/bay (SF2, mud and SF3, gas). Underlying SF2, the fluvial lag SF1 (well preserved upstream at the base of each incision) is surprisingly scarce and thin. Two processes may be suggested: strong erosion (attested by the removal of S40, S30 and S20) or a reduced bedload transport of coarse material in the C domain (in contrast to the A domain). At the top of U20 in the C domain, the occurrence of irregularly distributed SF5 facies, especially in the D domain, reflects the lateral intrusion of marine-influenced and coarse deposits into the central estuary/bay basin (coeval SF5 and SF2).

5.3. Three-dimensional architecture and origin (simple step-wise falling stage of incision and filling vs. multiple cycles of sea-level fall and rise)

Various geometric/genetic models have been proposed illustrating upper Quaternary incised-valley deposits in coastal plain and shelf settings: i) a simple erosional phase during the last sea/base level fall (Würm) and retrogradational infilling during the ensuing post-Glacial rise, such as for the Gironde (Lericolais et al., 2001), Charente (Weber et al., 2004) and other incised valleys on the Biscay shelf (Chaumillon et al., 2010); ii) channel avulsion or lateral migration during highstand conditions (Anderson et al., 1996; Martino, 2004); iii) incision/deposition during a simple falling stage with multiple channel belts under lowstand conditions, such as for the Colorado River in Texas (Blum, 1994; Blum and Price, 1998); and iv) several phases of fluvial entrenchment (base level falls) and infilling (following base level rises) linked to the upper Quaternary glacio-eustatic cycles, such as for the Virginia inner shelf (Foyle and Oertel, 1992) and Tai O Bay (Bahr et al., 2005). Although the interpretations are based on seismic data, a sedimentological calibration is not always available and the chronostratigraphy remains uncertain.

Seismic units in the study area broadly display a progradational and step by step downlapping pattern (Fig. 14a). This does not support the hypothesis of a simple relative base level rise, which would have initiated a transgressive retrogradational infilling of the incised valley. Moreover, the increasing depth of incision (Fig. 2) from upstream (25 m bpsl at the modern shoreline) to downstream (about 75 m bpsl) is not indicative of channel avulsion or lateral migration during a period of stable and highstand base level. The sedimentary architecture is rather in favor of incision and filling during successive stages of falling sea level generating several erosional unconformities from S40 to S20.

These cycles are common during the Late Quaternary (see Regional setting), consisting of well constrained 4th- and 5th-order climatic cycles of 100 to 20 kyr duration associated with asymmetric and complex sea-level changes that are less well known in detail. Nevertheless, during these cycles, sea level oscillated from the present-day level (highstand) to 70 to 120 m bpsl (lowstand). We have established (Labaune et al., 2010; Tesson et al., 2011) that up to six 4th-order cycles are recorded within the incised valley infilling of the southern system (IVTA). Due to the proximity with the present study area, we assume that these cycles similarly control the sedimentation and erosion cycles observed in the IVAO system.

The IVAO is a typical "compound" incised valley system and, as shown in Fig. 14a and b, each erosional surface (unconformity) exhibiting deep and narrow incised valleys in the A domain (S40, S30 and S20) is a sequence boundary (SB), and each seismic unit (U40, U30 and U20) is a depositional sequence in the sense of Posamentier and Vail (1988) adapted to incised valleys (Allen and Posamentier, 1991, 1992, 1993). The uppermost unconformity described here (S10) is erosional but does not incise deep and narrow valleys. S10 corresponds to the PLGM transgressive surface due to wave ravinement in the tideless Mediterranean Sea (wave ravinement surface or WRS). If we consider that U10 lies above S10 and is not an infilling deposit, the seismic facies identified in each depositional sequence (U40, U30 and U20) of the IVTA system represent the LST (Fluvial lag) and TST. Due to intense erosional processes punctuating the development of the IVTA, the depositional sequences U30 and U20 exhibit only part of the typical architecture of an incised valley fill. However, the uppermost and more recent U20 represents the entire systems tract if we integrate the sequences belonging to U10: the late transgressive deposits are found at the base of the systems tract overlying the WRS (S10), while the modern highstand deposits at the top are observed prograding over a maximum flooding surface (mfs).

5.4. Intra-sequence deposits and facies succession in space and time

We describe the evolution of a theoretical incised valley during an individual fourth order cycle of rsl change. Because of the important reworking of the older sequences, we essentially make use of the well preserved uppermost unit U20 and overlying unit U10 (Fig. 14b).

5.4.1. Step 1: early falling period

A period of global climate cooling leads to a lowering sea/base level and induces a forced regression (Posamentier et al., 1992). Due to the sequestration of water in mountain glaciers, river discharge decreases, but there is an increase in hydraulic gradient and sediment transport capacity. In the northern part of the study area (A domain), the Orb and Aude rivers entrench and incise narrow channels within the Pliocene substrate and/or overlying deposits. The fluvial erosional surface and its correlative aerial weathering surface on the interfluves forms a sequence boundary (SB). Coarse deposits occupy the river beds and make up part of the fluvial lag (SF1). As sea level fall continues, the two rivers converge southward and the coalescent channel occupies a broad and elongated basin (C domain).

5.4.2. Step 2/ maximum lowstand

The sea level is about 120–140 m bpsl and the shoreline is located at the shelf edge. The incised valley system is perched onto the Pliocene plateau at a maximum depth of 70–75 m bpsl, while the sequence boundary reaches its maximum areal extent. The exposed shelf is broad (more than 30 km) and shows low gradients. 1–2 m-deep fluvial incisions are observed/preserved on the shelf, but these incisions are up to 10 m deep at the shelf edge. The transition between the coastal incised valley system and the mid/outer shelf corresponds to a 20 m amplitude ramp (Fig. 2), but the real extension of the incised valley toward the shelf is hypothetical. The incised and perched system comprises, from north to south, an upstream A domain where a narrow and deep river channel incises previous fluvial and alluvial deposits, a downstream B domain where the deep fluvial erosion reaches the Pliocene basement and, finally, a broad and relatively flat basin (C domain) directly overlying the eroded Pliocene. River discharge from the upper drainage basin (ice-covered mountains) is reduced and sedimentary input is supplied by weathering of the Pliocene coastal plain deposits.

5.4.3. Step 3: early transgressive period

The global climate trend reverses and warming starts. The shoreline migrates landward onto the mid to outer shelf, but sea-level rise is not yet sufficient to modify the upstream part of the river slope on the sur-elevated Pliocene plateau. Sub-aerial erosional processes still prevail and we assume that the river channel entrenchment (domain A) and basin reworking (domain C) reaches a maximum because of the increase of river discharge from ice melting in the mountains. The final entrenchment of rivers (channels of domain A) takes place at this time, along with the development of a strong erosional surface of transition in domain B and the erosion of Pliocene basement in the C domain.

5.4.4. Step 4: mid-transgressive period (Fig. 15)

When sea level is about 75 m bpsl, the southern part of the C domain starts flooding and becomes an estuary farther downstream. Sandy shoals prograde inside the estuary from the southward mouth (D2), and fine deposits (SF2) start accumulating in the central estuary basin of the C domain. Northward, in the A domain, coarse material (fluvial lag SF1) is continuously being supplied by rivers. In agreement with other authors (Foyle and Oertel, 1997), we consider that the fluvial lag does not belong solely to the LST but may be attributed, entirely or in part, to the lower TST.

As flooding progresses in the C domain, the deposits in the downstream fluvial (SF6) and central estuary basin (SF2) aggrade and retreat toward the northern parts of the B and A domains (Fig. 15A and B), overlying fluvial lag (SF1) deposits. Oceanic waves generated by strong northerly and easterly winds penetrate *via* lateral channels into the shallow-water estuary basin (C domain). In front of these channels, sand bodies prograde and create shoals (SF5 in D1, Figs. 10 and 11) and fine-grained deposits which contribute to the infilling of the central basin (SF2). The sandy facies of SF5 and muddy facies of SF2 represent lateral facies variations involving an evolution from the bottomset of the sigmoidal reflections to the sub-horizontal and high-frequency reflections of SF2. However, the contact is locally sharp (Figs. 10 and 11) suggesting reworking by wave action on the eastern side of the estuary. The reworking surface could be analogous to an “internal unconformity” or “bay ravinement surface” (Foyle and Oertel, 1997).

5.4.5. Step 5: late transgressive-highstand sea level period

When sea level reaches 60 m bpsl or less, the domains B and C are entirely flooded as well as the Pliocene promontory (A domain). During the final stage of shoreline migration, the estuary basin muddy infilling continues to aggrade and waves penetrate and truncates the top of the previous deposits (wave ravinement surface, or WRS, such as S10). The estuary basin becomes fully marine and fine material accumulates (late transgressive deposits) over the wave ravinement surface.

In the northern domain A, before flooding, the narrow incised channels continue to fill with a complex association of fluvial deposits (SF6 and SF7) fining upward showing local features such as lateral accretion or point bars overlying a basal fluvial coarse lag (SF1).

When sea level reaches the highstand position, the entire system is covered by marine waters and late transgressive deposits (TST) corresponding to the lower part of U10 (SF8) accumulate above the WRS (S10) all over the shelf. Coastal progradation may occur depending on river discharge (water flow and sediment load) and oceanic regime. This corresponds with the present-day situation, where highstand fine

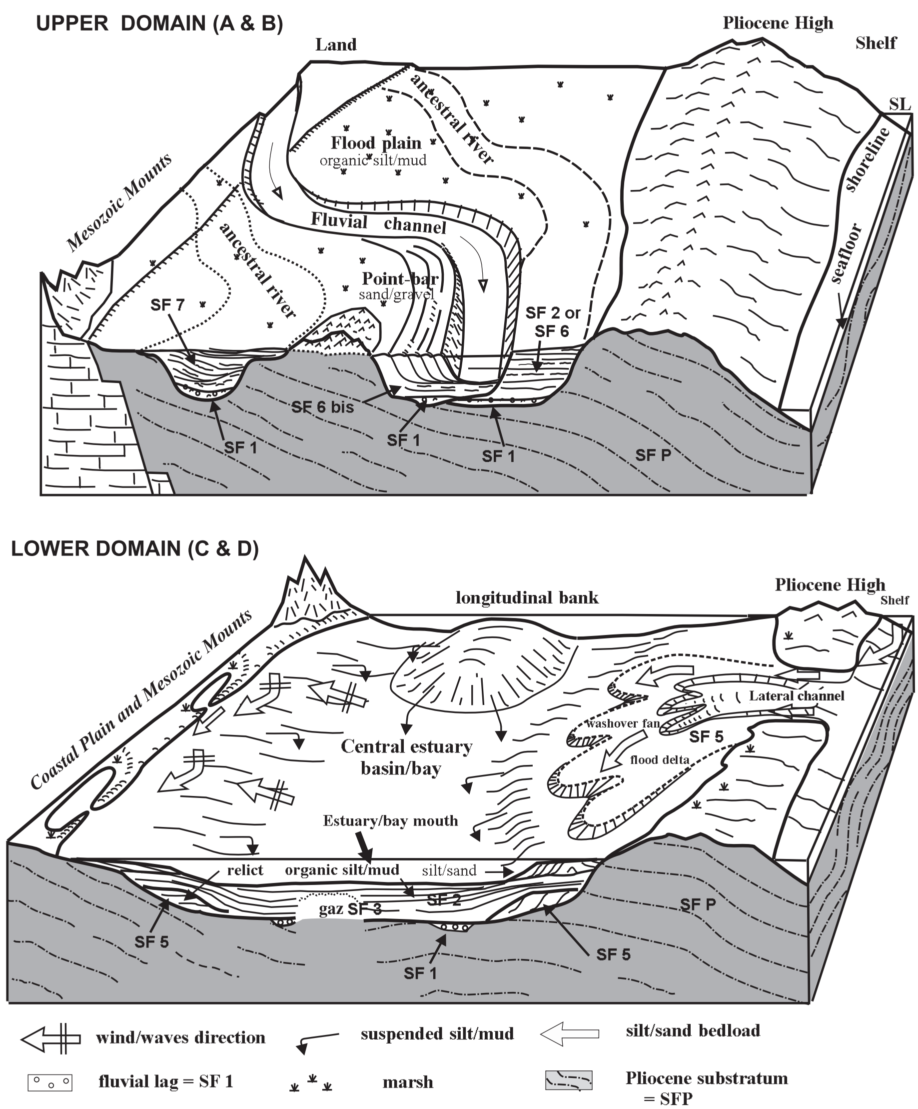

Fig. 15. Schematic 3D illustration of the sedimentary filling of the incised valley (upper domain A and B) and estuary/bay system (lower domain C and D) during a late relative sea-level rise, when the central estuary basin is progressively flooded. The ancestral rivers and relict deposits are linked to previous relative sea-level cycles. Based on the seismic sections in this study and the whole seismic data base.

deposits of the highstand systems tract (HST) overlay the late transgressive marine muds initially deposited above the wave ravinement surface.

5.4.6. Step 6: falling sea-level and early transgressive stage

A new cycle begins, as described in steps 1 to 5.

The new base level fall removes the upper part of the depositional sequence, either by river entrenchment or weathering of the interfluves, thus generating a new sequence boundary at the top of the previous incised valley infilling. The river incisions may follow different paths compared with those developed in step 1 or step 2. This explains the preservation of earlier deposits as remnants in the upstream B and A domains.

Nevertheless, as stated above, the maximum erosion by river entrenchment probably occurs also during the early transgressive period (step 3) when river load is increased by ice melting in the mountains around the drainage basin and when the basin area is slowly flooded and reworked by wave action. Thus, the lower and upper sequence boundaries are polygenic surfaces developed over a very long time span and not only during the falling stage. Moreover, depending on the domain in question (A, B or C representing the upper, middle or lower reaches of the system, respectively), the erosional processes are not the same and the effects are not similar. The sedimentary column preserved as remnants in the northern domain A is different from the almost completely reworked column in domain C which lacks any evidence of the upper and middle parts of the sequence. Consequently, a transgressive surface (TS) should be placed either somewhere within or at the top of the fluvial lag.

5.5. "Simple IVF" vs. "Compound IVF" facies partitioning

In the "simple IVF" model due to Allen and Posamentier (1991) and Zaitlin et al. (1994), the early lowstand fluvial and erosional surface (sequence boundary) and associated deposits (LST) are overlain by a vertical succession of sediments deposited during a phase of sea-level rise (TST) ending with a highstand period (HST) of sedimentation. Following lowstand fluvial deposition, the vertical trend of facies from distal to proximal (Fig. 16a) is retrogradational and transgressive (A, B and C units), and then becomes prograding and regressive.

In the "compound IVF" model adopted here (Fig. 16b), the basal sequence boundary and lowstand deposits are overlain by a set of prograding sedimentary units (A, B, and C) bounded by fluvial erosional surfaces that are high-frequency depositional sequences and sequence boundaries, respectively, associated with several base-level cycles of fall and rise. These sequence boundaries merge downward and distally.

In the distal part of the complex (downstream), the vertical succession of facies from base to top is similar regardless of whether the system is "simple" or "compound": it consists of coarse fluvial deposits overlain by central estuary basin mud and offshore/river mouth sand. Upstream in more proximal settings, the two vertical successions differ depending upon the model. In the "simple IVF" model, the vertical succession remains the same as in the downstream part (the central basin muds thicken progressively and finally grade into the fluvial section). In the "compound IVF" model, the central basin muds progressively interfinger landward with rising and separating sequence boundaries, each being immediately overlain by coarse fluvial material. In their most proximal settings, "compound IVF" successions are again similar to "simple IVF" successions in that they consist solely of amalgamated fluvial deposits.

It is noteworthy that the preservation potential of the intra-valley depositional sequences in "compound IVFs" depends upon the rate and depth of fluvial erosion associated with each phase of entrenchment (*i.e.*, relative base-level fall) as well as the upstream *vs.* downstream location of the observation area.

The model of an incised valley fill sequence influenced by a microtidal range and wave-dominated regime is well illustrated by the uppermost incised valley sequence developed in the Aude/Orb system. Nevertheless, the model needs to be slightly modified because, in the study area, sandy shoals are not only related with deposits formed by the retreating estuary mouth, but also with lateral channels located far upstream on the seaward-side of the central estuary basin.

5.6. Factors controlling development and preservation of IVF systems

At the regional scale, the interplay between eustatic variations and tectonics leads to relative changes in sea/base level. In general, as eustatic variations stem from a global mechanism that affects all areas synchronously, any differences observed from place to place would be linked to variations in tectonic activity and sediment supply. However, in detail, we also have to consider numerous additional parameters (including the coastal-zone gradient, the lowstand shoreline position relative to the shelf-edge, the amplitude and duration of base-level fall, water flow fluctuations and coastal area structures) (Posamentier and Allen, 1999; Schumm, 1993; Zaitlin et al., 1994; Blum and Tornqvist, 2000; Posamentier, 2001). In the following, we discuss the parameters that likely controlled the development and preservation of the IVAO system.

5.6.1. Tectonic control

The Gulf of Lions is a passive margin characterized by seaward increasing subsidence rate and onland uplift. Variations occur in the landward *vs.* seaward position of the hinge line (*i.e.*, where subsidence is equal to uplift). Consequently, the upper-Quaternary depositional sequences in the eastern and western Gulf of Lions show different stacking patterns (Tesson and Allen, 1995; Tesson et al., 2000). Nevertheless, at the small scale of the study area, the hinge line does not vary and remains near its position for the IVAO system. This may be explained by the onland proximity of the stable Mesozoic and Cenozoic mounts (La Clape, Fig. 2), as well as the far seaward position of the offlap regressive wedges on the shelf.

On the inner shelf, where the subsidence rate is high enough, the sequence boundaries and river incisions are preserved as observed relatively well around the Gulf of Mexico (Greene et al., 2007; Roberts et al., 2004) and the Louisiana shelf (Foyle and Oertel, 1992). But, more often, the subsidence decreases and reverses at the hinge line, leading to a thinning and pinching out of the marine depositional sequences. Thus, the sequence boundaries merge and the fluvial incisions become more or less imbricated. This is the case on the French Atlantic coast where subsidence is reduced or totally absent and the incised valleys are considered as "simple" following the Gironde model (Allen and Posamentier, 1991, 1994; Lericolais et al., 2001; Weber et al., 2004; Chaumillon et al., 2008). On the contrary, various patterns are encountered around the Mediterranean. The Llobregat Delta, south of the Ebro River in Spain, records several phases of incision/filling (compound IVF model) due to a local high rate of subsidence at the coast (Gámez et al., 2009). The IVTA (incised valley of Tet and Agly) which is the southern branch of the IVLR complex studied here, also corresponds to a "compound IVF" model (Tesson et al., 2011) even though it is located near or landward of the hinge line. In the case of the studied area (IVAO or incised valley of Aude and Orb), the seaward position of the hinge line and the pinching out of stacked regressive wedges, demonstrate that subsidence is not the only controlling factor explaining preservation in these "compound" IVF models.

5.6.2. Morphostructural and lithological control

In many cases, the location and orientation of stream flow are structurally controlled (faults and folds) and rivers are re-incised along the same path during successive falling stages, with the result that the final incised valleys appear "simple". This situation arises on the French Atlantic coast with the incised valleys of Brittany (Proust et al. 2010), Charente (Weber et al., 2004) and Gironde (Allen and Posamentier, 1991).

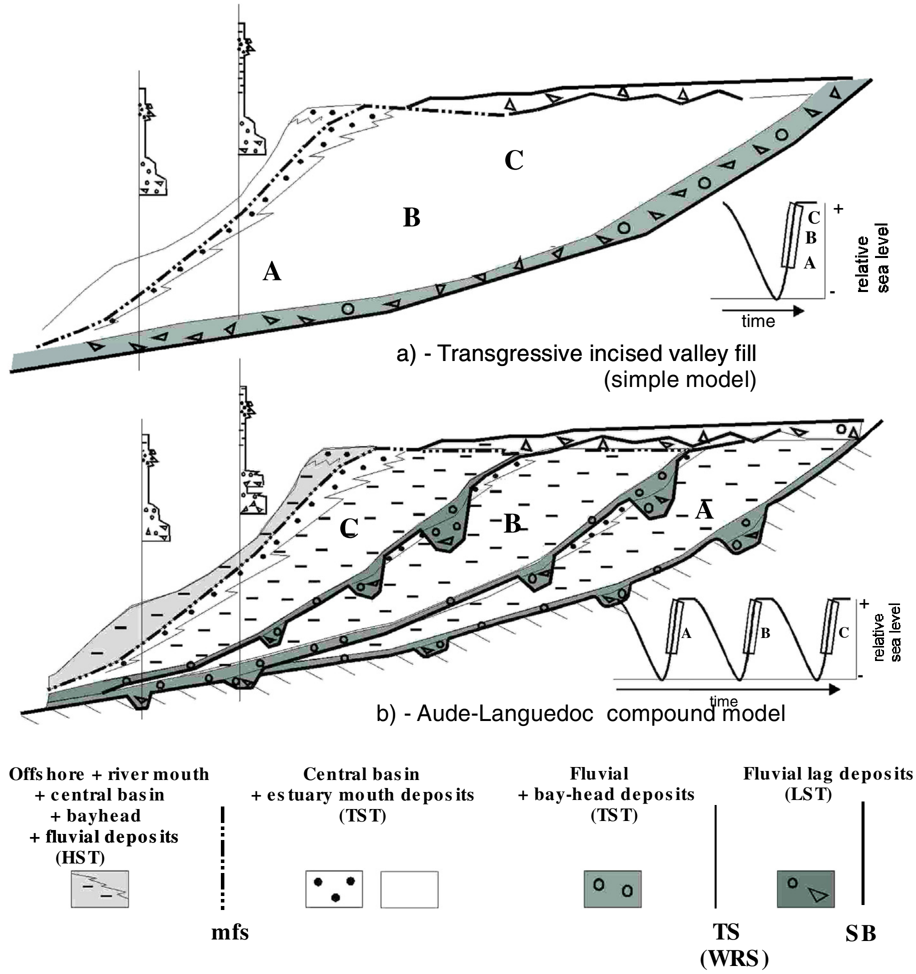

Fig. 16. Simplified patterns of two similar sedimentary prisms showing the main stratigraphic differences between: Fig. 16a a simple retrogradational incised valley fill and; Fig. 16b the example of a compound valley fill described in the study area. In the "simple IVF" model from Allen and Posamentier (1992) and Zaitlin et al. (1994), the early lowstand fluvial and erosional surface (sequence boundary) and deposits are overlain by a vertical succession of sediments deposited during a single phase of base-level rise ending with a highstand period. From distal to more landward areas, the vertical succession of facies remains similar. The whole succession is retrogradational and transgressive (units A, B and C), and then becomes prograding. In the "compound IVF" model of this study, the early sequence boundary and lowstand deposits are overlain by a prograding set of sedimentary units (A, B, and C) bounded by fluvial erosional surfaces which are depositional and sequence boundaries associated with several base-level cycles of fall and rise. The internal sequence boundaries merge downward and seaward. From distal to more landward areas, the vertical succession of facies is initially similar to the "simple IVF" model, but the basal fluvial and coarse deposits shallow progressively upward and are sandwiched between central basin retrogressive muds. Note that the preservation potential of the internal depositional sequences depends on the rate of fluvial erosion (*i.e.*, relative base-level fall) and the location of the observation area.

On the western Gulf of Lions, the IVTA (Têt-Agly) system (Labaune et al., 2010; Tesson et al., 2011) is bounded on the landward side by the uplifted Corbières limestone mounts. These authors (*op. cit.*) suggest that the northward shift of the stream flow during the successive upper-Quaternary base-level falls was induced partly by a northward tilting of the plain. The shifting of stream flow ceased when the river reached the Corbieres cliff (fault boundary). In this case, there were no re-incisions at the same place, probably because the morphostructural control was only partly effective.

In the studied area (IVAO), the Mesozoic La Clape mounts probably controlled the Aude river path onland, but stable geological formations offshore deepen abruptly due to a complex system of faults. Overlying the Miocene deep deposits, there are several hundreds of meters of Pliocene composed of gravels, sands and mud layers. There are no faults and folds affecting the Pliocene, which could have directly controlled the behavior of the IVAO system. Nevertheless, some other features of the Pliocene plateau were able to exert a control: i) morphology (shallow depth, broad and relatively flat plateau); and ii) lithology (seaward-dipping layers of alternately more or less indurated sediments).

The shallow water depth of the basal incision means that, even after several phases of sea-level fall, rivers were not able to incise deeply into the plateau. We consider that, due to the shallow depth of the plateau, the hydraulic gradient of the river bed remained weak and the erosive capacity was insufficient. Consequently, during different cycles, rivers may have followed the strike of the less consolidated strata in the Pliocene, which corresponds to the shore-parallel direction.

5.6.3. Coastal hydrodynamic regime

The local coastal regime is controlled by tides and waves induced by atmospheric circulation at the regional scale. A microtidal regime probably prevailed during the Late Quaternary since the shape of the Mediterranean basin was not very different from the present day. The atmospheric circulation and the effects of propagating waves probably varied along the shoreline (littoral drift pattern forming a complex system of transport cells described by Certain, 2002). Nevertheless, the E–W orientation of the Pyrenean range is the main factor controlling the paths of the high and low pressure systems that generate the wind and waves. The intensity probably varied, but the main paths were perhaps not so much affected. Looking at the arcuate shape of the shoreline between Cap Leucate and Cap d'Agde (Fig. 2), it is clear that the cumulative effects of coastal sedimentary dynamics led to a shore-parallel distribution of the river load (Ferrer, 2010). Thus, the constant southward shift of the Aude and Orb river flows during successive cycles of RSL changes appears to be controlled by a southward-oriented longshore drift, even though this is partly hypothetical.

5.7. Regional variability

On the Languedoc–Roussillon inner shelf and adjacent coastal plain, the two branches (IVAO and IVTA systems) of the Languedoc–Roussillon incised valley complex (IVLR) are converging and spatially very close to each other. Nevertheless they show the following differences.

5.7.1. River course shape

The successive incisions in the IVTA under the coastal plain have migrated northward and the lower reaches are oblique to the shore (Fig. 2). Nevertheless, under the inner shelf, the river incisions have shifted progressively to the north from one cycle to the next, shifting completely to the south at the present day. The IVAO incisions are generally transverse to the shore under the coastal plain, but become abruptly more or less shore-parallel under the inner shelf, finally merging with the IVTA southern branch (white continuous line) or turning toward the open sea (dotted white line).

5.7.2. IVF stratigraphic architecture

The IVTA system incises Pliocene deposits and comprises six (6) imbricated depositional sequences bounded by fluvial erosional surfaces that strongly rework each other (Labaune, 2007; Labaune et al., 2010). On the inner/middle shelf, fluvial deposits interfinger with the updip terminations of the Late-Quaternary regressive wedges, and a continuity is observed from the fluvial to the estuary/bay and marine domains. In the IVAO system, only three (this study, see descriptions in text) erosional surfaces and infilling depositional sequences are confined to the Pliocene plateau and just in front or near the modern river mouths (A domain). No direct relation is preserved downstream with the Late Quaternary regressive wedges stacked on the shelf.

5.7.3. Factors controlling regional variability

The IVTA river course pattern, with its lateral shifting, has been attributed to the combined effects of tectonic activity (northward tilting of the basement of the coastal plain limited by a normal fault to the North) and oceanic regime (preferential direction of longshore drift).

In the case of the IVAO system, the shore-parallel river courses appear to be controlled by the Pliocene morphostructure (shallow depth of offshore plateau) and the lithology (dip direction of more or less indurated layers). We also suggest that the oceanic regime induced a preferential direction of littoral drift that interacted with the other factors.

The IVTA architecture exhibits a continuity from the coastal plain to the inner/mid shelf which has been attributed to several factors: high levels of river discharge and sedimentary load, and increased erodability of Pliocene deposits possibly due to fracturing by faults associated with the tilting of the coastal plain. It has also been suggested that the progressive shifting of the river courses preserved the earlier depositional sequences from an excessive downstream erosion and allowed the preservation of six sequences on the inner shelf. The stratigraphic architecture of the IVAO system (preservation of incisions only in a limited area close to the modern river mouths, confinement of the IVAO onto a shallow-water plateau, and lack of continuity toward the shelf) is attributed to the difficulty for rivers to entrench the plateau, due either to river flow parameters, plateau lithology, or a lack of tectonic control on the plateau. The reduced number of depositional sequences may be due to the fact that they form a retrogradational trend from the younger to the older sequences, and additional sequences may be present under the modern coastal plain but have not been identified in the long core logs (poor quality of the data).

6. Conclusions

The northern branch/system (IVAO) of the Languedoc–Roussillon incised valley complex (IVLR) comprises, from base to top, two Pleistocene depositional sequences (U40 and U30) and a PLGM sequence (U20) that are confined along-shore at the top of a shallow depth Pliocen plateau.

The sequence boundaries are characterized by fluvial incisions just front and near the modern river mouths but dip abruptly downstream and successively erode previous sequence deposits forming a polygenic basal sequence boundary.

The three infilling depositional sequences, imbricated but preserved upstream and progressively fully eroded downstream, present an overall aggrading and prograding trend. Only the youngest PLGM sequence is preserved in the whole area

Due to the decreasing preservation of the depositional sequences from upstream to downstream, the seven depositional facies that characterize the infilling of an incised valley infilling are irregularly distributed. Upstream the three sequences comprise a basal fluvial lag SF1 (lowstand and early transgressive period) and an overlying fluvial infilling (mid to late transgressive period), comprising downstream and upstream fluvial facies (SF6 and SF7 respectively). Downstream, when the Pleistocene sequences still exist, each one comprises the basal fluvial lag SF1 and an overlying transgressive central estuary/bay basin muddy facies (SF2) associated with coeval high-energy facies SF5 (sandy shoals) prograding toward the central basin and gas facies (SF3) probably more recent. At the downstream extremity of the incised-valley system, only the PLGM sequence is preserved and the transgressive central estuary/bay basin mud (SF2) and high energy facies (SF5) lie above SF1.

The classic wave-dominated model of incised valley fill sequence globally applies to the individual sequence deposits, nevertheless the central basin muds (SF2) are coeval with unusual marine sandy packages (SF5) introduced far upstream from lateral tidal channels.

The whole IVAO system corresponds to a compound incised valley model with an overall aggrading and prograding pattern of sequence boundaries and depositional sequences. The interpretation can be in terms of a “simple” or “compound” model (this study), which could have consequences for exploration and prospection.

The differences between the northern branch (IVAO, this study) and the southern branch (IVTA, previous studies) of the Languedoc–Roussillon compound incised-valley complex (IVLR) are attributed to the distance of the hingeline from the shoreline as well as the associated width of the Pliocene plateau, the possibility of fracturing and erodability of the underlying Pliocene layers and the atmospheric/oceanic regime.

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