

Stratal architectures of late Quaternary regressive–transgressive cycles in the Roussillon Shelf (SW Gulf of Lions, France)

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Abstract

A seismic and sequence stratigraphy scheme of the southwestern area of the Gulf of Lions Shelf (NW Mediterranean Basin) is presented, through the analysis of high-resolution seismic profiles obtained with a Minisparker system and calibrated with published seismic and core data of the adjacent Languedoc area. The observed stratigraphic architecture records the repetition of four regressive–transgressive cycles, which constitute high-frequency depositional sequences (DSs).

Regressive intervals dominate the generation of shelf sedimentary architecture. Within regressive intervals, the identification of progressively shallower clinofolds, from proximal to distal in a downdip direction, constitutes a strong indicator of the occurrence of forced regressions. This stratigraphic pattern documents the preservation of potential sand-prone reservoirs encased within widespread regressive wedges and directly connected with organic matter rich muds, as distally there is no sharp basal contact between the two.

The unusual preservation of pre-Last Glacial Maximum transgressive deposits is attributed to the combined influence of previous shelf topography and dominant wave regime. The most significant transgressions were recorded by shallow-water deposits in distal, middle and proximal locations. Distal and proximal deposits develop over relatively steep surfaces, which caused slower transgressions and favoured the generation of wave-dominated coastal deposits. In contrast, middle deposits show moderate development over a smooth shelf profile as a consequence of rapid shoreline translation.

The analysis of spatial changes of regressive–transgressive cycles provided important information about the nature of shelf processes and about the relative significance of regressive versus transgressive intervals within each individual DS, whose development was led by recent, high-frequency sea-level cycles. Dominance of 120 ka cycles would imply that transgressive deposits represent a partial record of glacial–interglacial transgressions. Dominance of 20 ka cycles is not favoured by the fact that the preservation of Quaternary deposits is apparently limited on the shelf.

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1. Introduction

The sedimentary architecture of Quaternary siliciclastic shelves is strongly dominated by major-scale regressive wedges (e.g. Chiocci, 2000; Chiocci, Ercilla, & Torres,

1997; Hernández-Molina, Somoza, & Lobo, 2000a; Kolla, Biondi, Long, & Fillon, 2000; Trincardi & Correggiari, 2000). These studies based their interpretations on the supposition that deposition of regressive wedges was associated with forced regressions, as they were generated during long-lived late Quaternary falling sea levels, in contrast to short-lived highstand intervals (Chiocci 2000; Hernández-Molina et al. 2000a; Kolla et al. 2000; Trincardi & Correggiari 2000). However, conclusive stratigraphic evidence of the occurrence of forced regressions is generally lacking, as internal downward shift surfaces (Tesson,

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Posamentier, & Gensous, 2000) or successive offlap breaks (Trincardi & Correggiari, 2000), considered as reliable indicators of forced regressions, may not be present in many locations. Besides, internal surfaces may be the result of delta lobe switching and not necessarily linked to a forced regression process (Kolla et al., 2000).

In contrast to regressive wedges, transgressive (TSTs) and highstand system tracts (HSTs) formed prior to the Last Glacial Maximum (LGM) are poorly developed or even absent in many shelves (Ercilla & Alonso, 1996; Hernández-Molina et al., 2000a; Okamura & Blum, 1993; Trincardi & Correggiari, 2000). In general, pre-LGM TSTs are largely restricted to drowned river channels (Anderson, Abdulah, Sarzalejo, Siringan, & Thomas, 1996; Carey, Sheridan, & Ashley, 1998; Kolla et al., 2000; Hiscott, 2001), or deposited under the form of thin sediment veneers, originated from reworking of coastal sediments (Aksu, Ulug, Piper, Konuk, & Turgut, 1992; Barnes, 1995). Isolated deposits away from incised valleys have been rarely documented (Carey et al., 1998; Sheridan, Ahsley, Miller, Waldner, Hall, & Uptegrove, 2000; Suter, Berryhill, & Penland, 1987). Consequently, high-frequency depositional sequences (DSs) are formed almost exclusively by regressive wedges.

The Gulf of Lions Shelf (NW Mediterranean Sea) represents one of the few areas where regressive–transgressive cycles have apparently been preserved. There, the Quaternary sedimentary succession is represented by a middle-outer shelf sedimentary wedge constituted by two types of deposits (Gensous & Tesson, 1996; Tesson, 1996;

Tesson, Gensous, Allen, & Ravenne, 1990; Tesson et al., 2000):

- Regional prograding units (RPU) are laterally extensive, low-angle prograding wedges. RPUs formed during relative sea-level falls through forced regressions (Posamentier, Allen, James, & Tesson, 1992).
- Intercalated units (IUs) are located between RPUs and are constituted of several patchy, high-angle prograding shelf deposits. IUs were interpreted as the sedimentary record of transgressive intervals. The Gulf of Lions is one of the few areas where transgressive deposits seem to be significantly preserved.

Because of the good preservation of regressive–transgressive cycles, the Gulf of Lions Shelf is an area where the spatial arrangement of shelf stratal packages can be studied with great detail. We have focussed on the shelf off the Roussillon coast, located in the SW part of the Gulf of Lions (Fig. 1). The objectives of this study are to:

- Identify stratigraphic patterns that could be considered reliable indicators of forced regressions and may serve as models for sand-prone reservoirs.
- Discuss alternative interpretations and controlling factors to explain the genesis and unusual preservation of IUs.
- Document the spatial changes of shelf stratigraphic packages and relate them with high-frequency glacio-eustatic cycles.

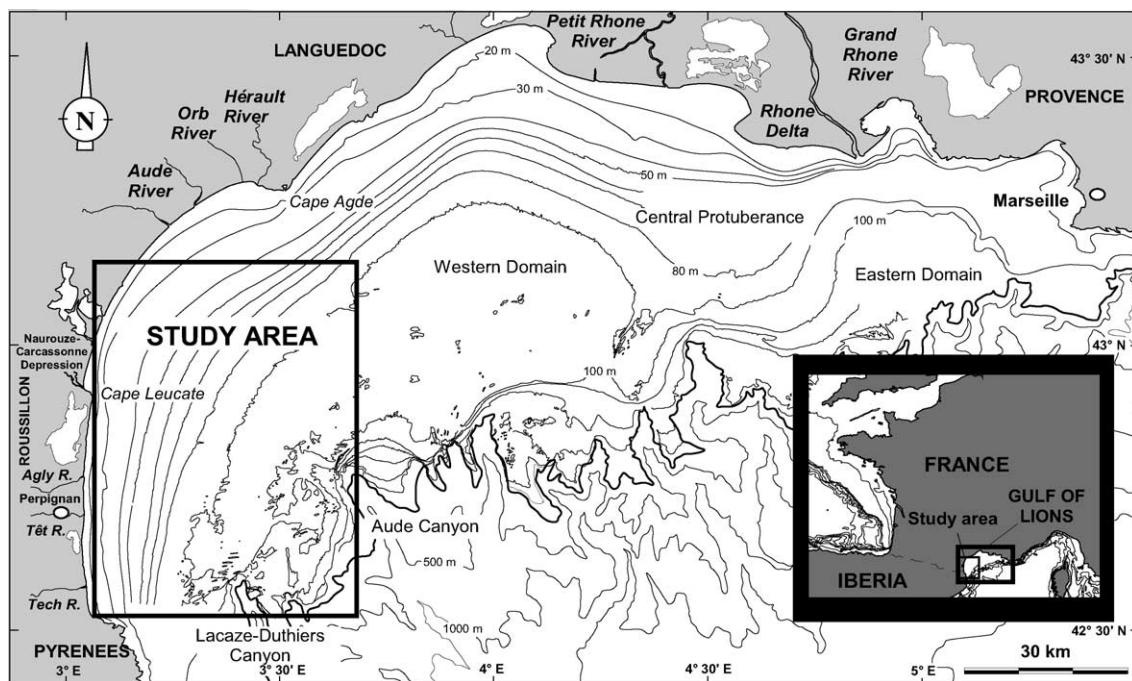


Fig. 1. Geographical setting and general bathymetric chart of the Gulf of Lions, with indication of the study area off the Roussillon. The Western and Eastern Domains are separated by a Central Protuberance. In the study area, the Lacaze-Duthiers and the Aude Canyons incise the outer shelf. Bathymetric contours are given in meters below mean sea-level. Modified from Tesson (1996).

2. The Roussillon Shelf

2.1. Geographic and geologic location

The Gulf of Lions is located at the NW termination of the Mediterranean Sea Western Basin between coordinates 3° and 5°E, and 42°30' and 43°30'N, adjacent to the French regions of Provence, Languedoc and Roussillon from NE to SW. The Gulf of Lions is a passive margin located between two more tectonically active regions, the Provençal and Pyrenean margins (Aloisi, 1986). The study area is the southwestern sector of the Gulf of Lions shelf, adjacent to the Roussillon coast (Fig. 1).

2.2. Sediment source areas and primary fluvial systems

The Naurouze–Carcassonne depression is a E–W small basin located between the Pyrenees and the Central Massif, which supplies sediment to the following streams: Agly, Tech, Têt and Aude from the Pyrenees–Corbières zone, and Orb and Hérault from the Central Massif (Fig. 1). Regional climate is of Mediterranean type with moderate rainfall ranging between 250 and 600 mm. Summer climate is dry, due to the influence of the Azores Anticyclone. In contrast, winter climate is humid, due to the westward displacement of Atlantic meteorological depressions. As a consequence, the river supply regime is torrential and markedly irregular (Lacombe & Tchernia, 1972).

2.3. Oceanographic conditions

The littoral and continental shelf of the Gulf of Lions are dominated by a moderate to low wave climate. Waves from the E and SE are dominant, characterised by maximum heights of 5 m and periods of about 8 s (Ascensio, Bordreuil, Frasse, Orioux, & Roux, 1977). They generate a complex pattern of littoral drift whose associated sedimentary transport is generally limited to the upper part of the shoreface (water depths <7 m). However, bottom currents with speeds ranging between 30 and 100 cm/s at 20 m of water depth can be generated during severe storm conditions (Millot, 1981). Tidal currents are too low to be measured on the shelf (Millot, 1979). The general circulation is dominated by the Liguro-Provençal current, whose surficial waters may flow southwestwards over the shelf with velocities ranging between 5 and 10 cm/s (Millot, 1990; Millot & Wald, 1981).

2.4. Physiographic and morphologic features

The shelf off the Roussillon coast shows a southward width decrease from 40 to 15 km (Got, Aloisi, & Monaco, 1972; Got, Guille, Monaco, & Soyer, 1968; Monaco, 1973). As well as in other sectors of the Gulf of Lions Shelf, it is possible to distinguish three domains: inner, middle and outer (Berné, Carré, Loubrieu, Mazé, & Normand, 2002;

Tesson, Gensous, Naudin, Chaignon, & Bresoli, 1998). The inner domain extends up to 90 m water depth, with gradients ranging between 0.5 and 1.7° and characterised by parallel and regularly spaced isobaths. The middle domain extends between 90 and 110–120 m water depth, with gradients ranging between 0.06 and 0.3° and characterised by a rugged morphology. The outer domain extends between 110 and 120 m water depth and the shelf break, characterised again by a smooth morphology (Fig. 1).

The main surficial morphological elements include prodeltaic deposits on the inner shelf (Aloisi, 1986), and coastal depositional systems over the outer shelf, which bound middle shelf depressions, previously interpreted as lagoon systems (Tesson & Gensous, 1998). The shelf break is located at variable depths between 100 and 200 m, due to the occurrence of two major submarine canyons, the Lacaze-Duthiers and the Aude Canyons (Monaco, 1973).

2.5. Tectonic setting and fault systems

The margin basement is deformed by NE–SW oriented horst and graben systems of Oligocene–Miocene age (Arthaud, Ogier, & Séguret, 1980–1981; Cravatte, Dufaure, Prim, & Rouaix, 1974; Rehault, Boillot, & Mauffret, 1985). Half-graben basins are bounded by NW–SE oriented transfer zones (Gorini, 1993), of which the Catalonian transfer zone represents the SW boundary of the Gulf of Lions margin (Gorini; Guennoc, Debeglia, Gorini, Le Marrec, & Mauffret, 1994; Lefèbvre, 1980). The main structure of the shelf off the Roussillon coast is a NE–SW oriented mid-shelf graben referred to as the Central Graben (Fig. 2A), which is marked by a basement deepening from 1 s two-way travel-time in the coastal domain to 3–4 s two-way travel time in the middle shelf (Lefèbvre, 1980; Gorini, 1993). The Central Graben is bounded seaward by the Mistral Horst (Fig. 2A) (Lefèbvre, 1980). Neogene structures were reactivated during the Quaternary, as NE–SW directed faults parallel to the orientation of Pyrenees structures affected the surficial sedimentary cover to the south of the Roussillon Shelf (Fig. 2B) (Got & Monaco, 1969; Monaco, 1973).

3. Methodology

This study is based on the analysis of about 2528 km of high-resolution seismic profiles collected on the Roussillon Shelf during seven oceanographic surveys between 1994 and 1997. Spacing between nearby lines usually ranges between 1 and 2 km (Fig. 3). The seismic source was a Minisarker 50 Joules SIG, with an emission frequency of 100–1500 Hz and an average vertical resolution of 1.5 m. The information was digitally recorded with a Delph 2 system. The positioning system was GPS or differential GPS.

A seismic stratigraphy analysis was conducted focusing on the uppermost shelf sedimentary succession off the Roussillon coast. Seismic units were designed from older (B)

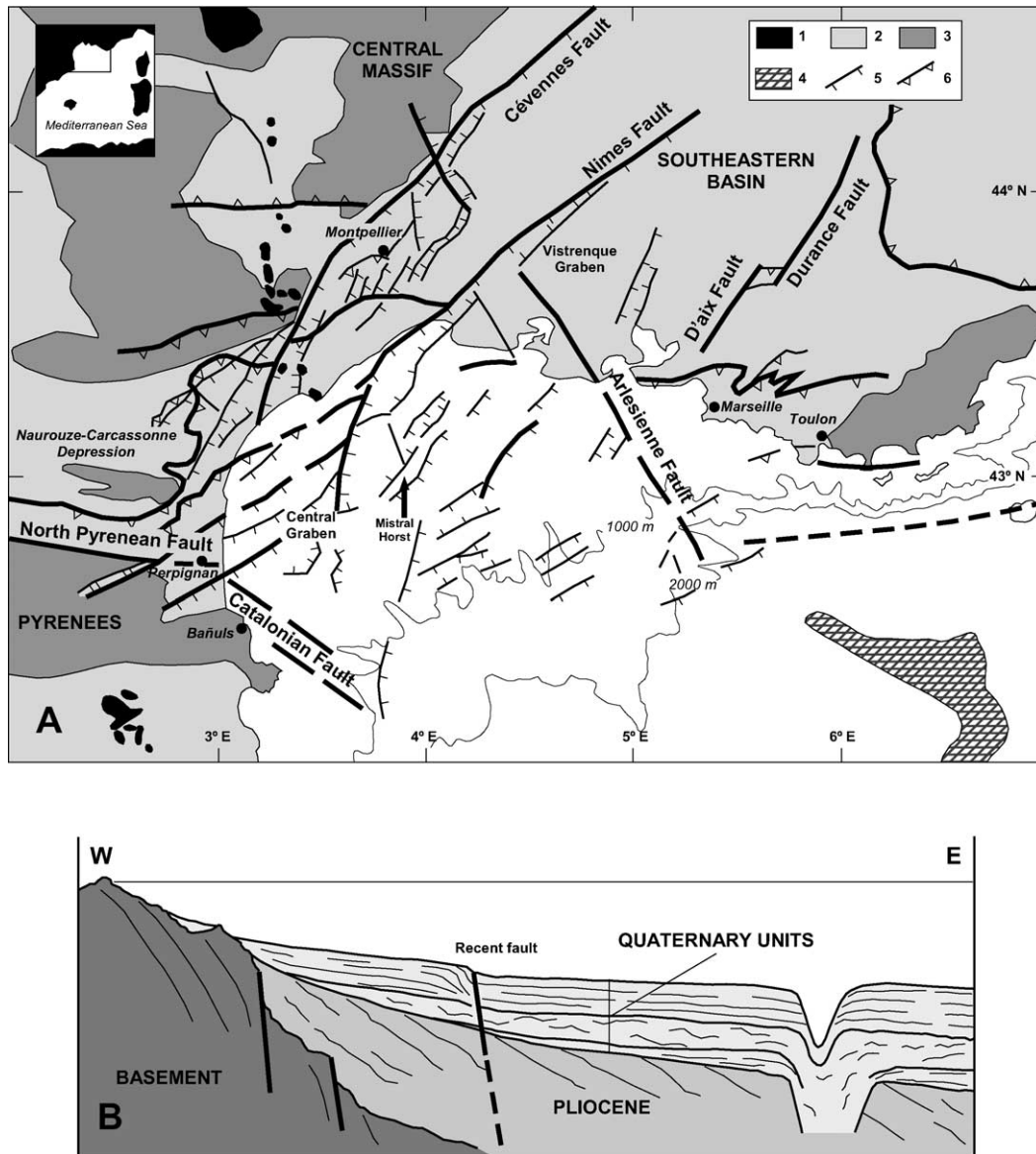


Fig. 2. Tectonic setting of the Gulf of Lions margin: (A) Mapping of main tectonic features in the Gulf of Lions margin. Legend: (1) vulcanism (Pleistocene); (2) post-hercynian sediments; (3) hercynian basement; (4) salt domes; (5) normal faults; (6) inverse faults. Taken from Guennoc et al. (1994). (B) Synthetic interpretative profile off the Pyrenees, showing recent faulting that affects to Quaternary deposits. Simplified from Got and Monaco (1969).

to younger (G) following the nomenclature of Tesson (1996) and Tesson et al. (2000), previously defined for the Rhône and Languedoc Shelves. The sea-floor multiple and the erosive character of the upper and lower boundaries prevented from recognising and mapping seismic unit A at regional scale, and for that reason it was not considered in the study.

A picture of the distribution patterns of shelf seismic units was achieved through the elaboration of isopach maps. For each seismic unit, two-way travel time values of the upper and lower boundaries were measured at specific locations. In the places where the boundaries showed a smooth character, those values were picked at regular distances. The spacing between measurement points was reduced where the boundaries showed irregular patterns.

In such cases, we chose inflection points of upper and lower boundaries as measurement points. The resulting values were interpolated on a grid and contoured by using the Surfer software.

4. Stratigraphic architecture of the shelf succession off the Roussillon coast

The identified seismic units were initially classified into RPU and IU, following the nomenclature established in the Rhône and Languedoc Shelves (see references above). This classification into two main types of seismic units implies a genetic interpretation, as RPU and IU were related with periods of regression and transgression,

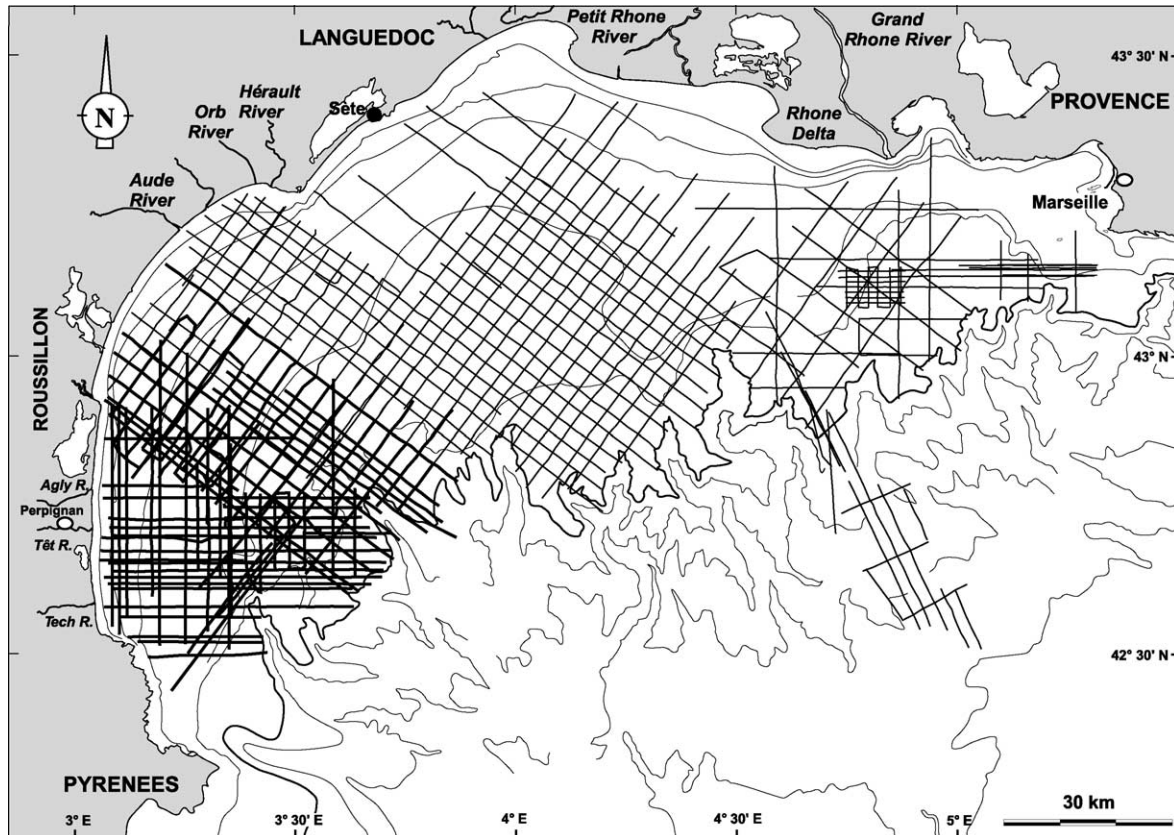


Fig. 3. Location of high-resolution seismic data base collected in the Gulf of Lions shelf. The seismic profiles used for the present study in the Roussillon area are in bold. Data were acquired using a Minisparker (50 J) system during the period 1989–1996 under the Starho Program, and were computer-georeferenced using a Delf system.

respectively. However, some of the units identified in the shelf off the Roussillon coast showed distinct distribution patterns, external geometry and seismic facies, which were not recognised previously and did not fit into the two-fold general scheme. Consequently, the genetic interpretation is different as well. Thus, two additional types of seismic units were defined: mid-shelf prograding units (MPUs) and a regional aggrading unit (RAU). The stratigraphic architecture of the Roussillon Shelf and the classification of seismic units into different types (RPU, IU, MPU and RAU) are shown in Fig. 4.

4.1. Regional prograding units (RPUs): B, C, D, E and F

The upper boundaries of RPUs are erosive, angular unconformities. Frequent 1–2 km wide depressions and erosive channels occur on top of RPUs B and C (Fig. 5A). Maximum channel depth may range between 20 and 30 ms. In contrast, the upper boundary of RPU D does not show a marked irregular topography, and concordant relations are observed distally. An irregular topography also characterises the upper boundary of RPUs E and especially F (Fig. 5B and C), where small-scale, NNE–SSW oriented channels with depths lower than 15 ms are identified. The lower

boundaries of RPUs are generally downlap surfaces (Fig. 5A).

Distribution patterns of RPUs show two distinct trends. RPUs B, C and D show widespread distribution over the middle-outer shelf, as they develop over tenths of kilometers in cross-shelf sections and are continuous in along-shelf sections. On the inner domain, they are identified locally, as in the case of seismic unit C. They can increase the thickness over the upper slope, although in general thickness decreases significantly towards the shelf break (Fig. 6). The most significant depocenters of RPUs are elongated, oriented NNE–SSW to NE–SW and laterally continuous. Maximum thickness ranges between 20 and 30 ms, although in places thickness may be as high as 35 ms (Fig. 6). In contrast, RPUs E and F are distributed over the outer shelf and upper slope, showing significant basinward thickness increase. Thickness is generally lower than 20 ms on the outer shelf, but it increases to values ranging between 40 and 90 ms on the upper slope (Fig. 6).

A distinctive stratigraphic characteristic of RPUs is the dominance of low-angle prograding configurations, generally directed seaward but a southward progradation was also detected. Parallel-oblique facies ($0.3\text{--}0.6^\circ$) prevail on the shelf, but oblique-tangential facies ($0.3\text{--}0.7^\circ$) can also be widespread (Fig. 5A and B). Distal reflectors show higher

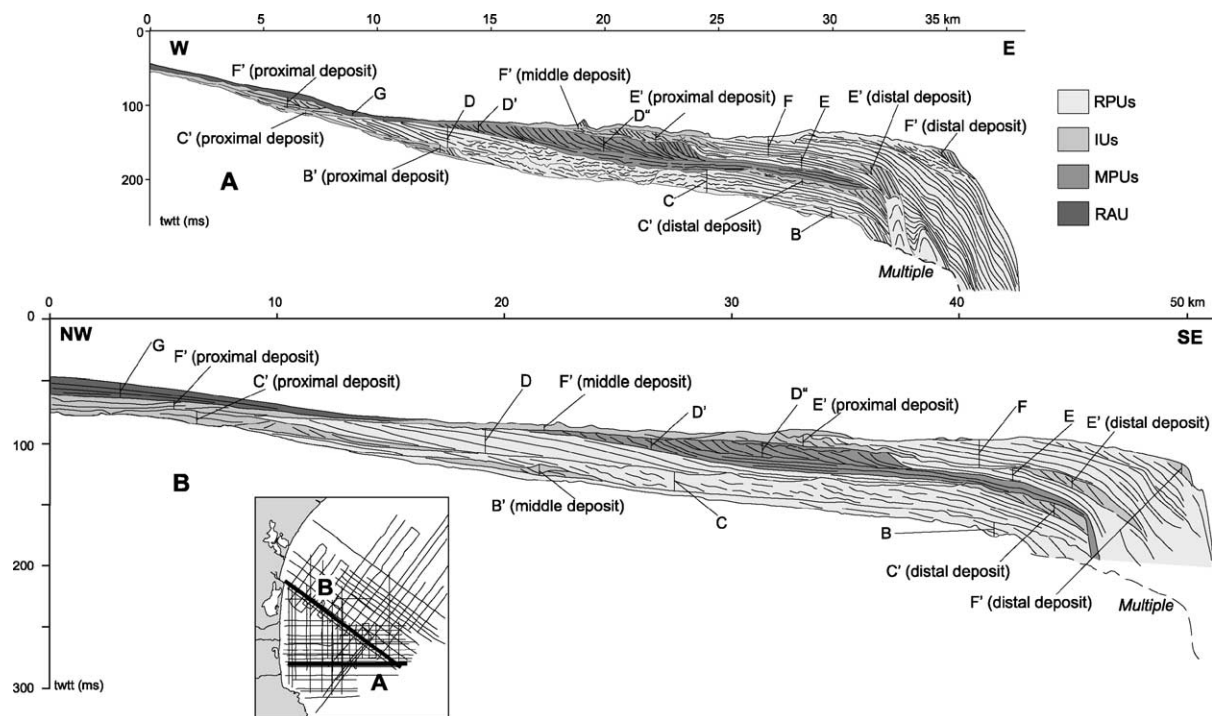


Fig. 4. Cross-shelf stratigraphic sections of the Roussillon Shelf, showing interpretation of seismic units. RPU, regional prograding units; IUs, intercalated units; MPUs, mid-shelf progradational units; RAU, regional aggrading unit. RPU, control the basinward development of the shelf during prolonged regressions. IUs represent the record of rapid transgressions between major regressions. The identification of MPUs is particularly remarkable, as they have not been previously defined in other shelf sectors of the Gulf of Lions margin. MPUs show well-preserved high-energy proximal facies encased within two RPU (D and E). Finally, the RAU represents recent shelf sedimentation.

gradients ($> 1\text{--}2^\circ$) where the units are distributed over the upper slope (Fig. 5C). Wavy reflection patterns locally occur within prograding facies, generally in the vicinity of submarine canyon heads (Fig. 5B). Other seismic facies are also reported in different units, i.e. inner shelf sub-parallel facies (RPU C) and limited preservation of high-angle ($2\text{--}3^\circ$) proximal facies (RPU F). Internally, minor downlap surfaces within low-angle prograding configurations are locally observed.

4.2. Intercalated units (IUs): B', C', E' and F'

These units show patchy distributions in cross-shelf sections, as they may be made up of several unconnected shelf deposits, or they may be connected through thin veneers. However, three main types of deposits with distinct seismic facies are distinguished according to the location of depocenters: distal, middle and inner deposits (Figs. 7 and 8).

4.2.1. Distal deposits

Distal deposits occur over a steep outer shelf, where gradients higher than $0.2\text{--}0.3^\circ$ are common. There, distal deposits are several kilometers wide (Fig. 7A). They show erosive upper boundaries with local occurrence of small channels, whereas lower boundaries are downlap surfaces. Depocenters show elongated, NNE–SSW oriented distributions. Maximum thickness usually ranges between 10 and 35 ms (Fig. 8). The deposits show wedge to lenticular

external shapes in cross-shelf sections with high-angle ($3\text{--}4^\circ$) progradational reflector configurations. The configurations are highly reflective, and they may be parallel-oblique, tangential-oblique or sigmoid (Fig. 7A).

4.2.2. Middle deposits

Middle deposits occur on the gentle middle shelf, where gradients are generally lower than 0.2° . Middle deposits exhibit poor lateral continuity and variable orientations (Fig. 8). They show toplap/erosional upper boundaries which in places may show an undulating pattern, whereas lower boundaries are smooth downlap surfaces. Thickness is usually less than 10 ms. Middle deposits are characterised by a two-member internal structure (Fig. 7B and C). Both lower and upper members show high-angle ($> 2^\circ$) progradational reflectors and high reflectivity. Besides, the upper member is usually characterised by the occurrence of bedforms at the top (Fig. 7B). IU E' does not show a middle deposit.

4.2.3. Proximal deposits

Proximal deposits occur over a physiographic ramp ($0.4\text{--}1^\circ$) which defines the inner to middle shelf transition. Those deposits occur in elongated depocenters parallel to the present-day coastline. The only exception to this general trend is the proximal deposit of IU E', which occurs on the mid-outer shelf (Fig. 8). Inner deposits show smooth boundaries, with variable reflector terminations ranging

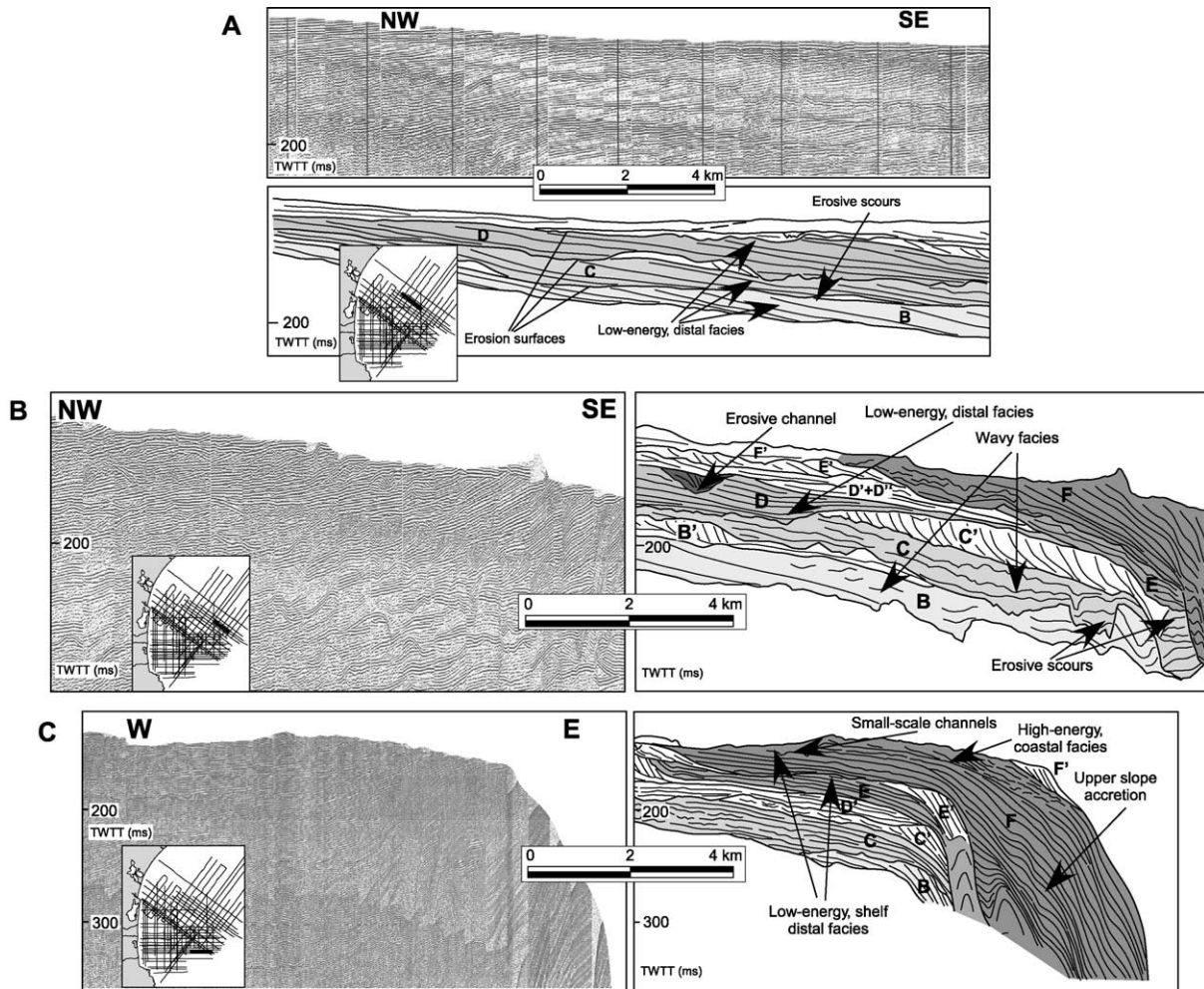


Fig. 5. Seismic sections and interpretations showing stratigraphic features of RPUs: (A) low-energy facies and erosive boundaries are dominant in middle shelf settings; (B) the older RPUs (B–D) tend to pinch out distally, and they frequently show wavy facies on the outer shelf; (C) the younger RPUs (E and F) show a well-defined wedge external shape, with thickness increasing basinward and pinching out landward on the outer shelf.

from erosional truncation to concordance at the top and downlap/onlap at the bottom. Thickness is generally less than 10 ms but in places it may reach 15 ms (Fig. 8). Seismic unit E' does not show this inner deposit. A two-member structure separated by an erosional surface similar to middle deposits is also found (Fig. 7C).

4.3. Mid-shelf prograding units (MPUs): D' and D''

Seismic unit D' had not been identified in the Rhône shelf, and in the Languedoc shelf it was considered an IU. Seismic unit D'' had not been recognised previously in other shelf areas of the Gulf of Lions. These two seismic units show distinct seismic features which are intermediate between RPUs and IUs. In contrast to IUs, MPUs are constituted by a single main deposit. MPUs are distributed on the mid-outer shelf and locally on the upper slope. Their upper boundaries are smooth to gently undulating, and erosional truncation to toplap terminations are common. Small-scale erosive channels can be found along the upper

boundary. Downlap to concordance occurs at the lower boundaries (Fig. 9). The units show lenticular external shapes, with thickness of more than 10 ms and frequently ranging between 20 and 30 ms. Main depocenters display NNE–SSW orientations (Fig. 10).

In contrast to RPUs, MPUs are dominated by high-angle (1–2°), high reflectivity progradational facies. These facies may evolve seaward to sub-parallel, highly continuous reflectors (Fig. 9). Wavy facies locally occur within sub-parallel reflectors, generally close to submarine canyon heads. Internal downlap surfaces are observed in places.

4.4. Regional aggradational unit (RAU)

The most recent seismic unit (G) shows concordance at the top and concordance to gentle downlap at the bottom (Fig. 11). However, there is clear evidence of onlapping basal deposits north of the study area, probably in relation with inner deposits of underlying IU F'. Our data are not

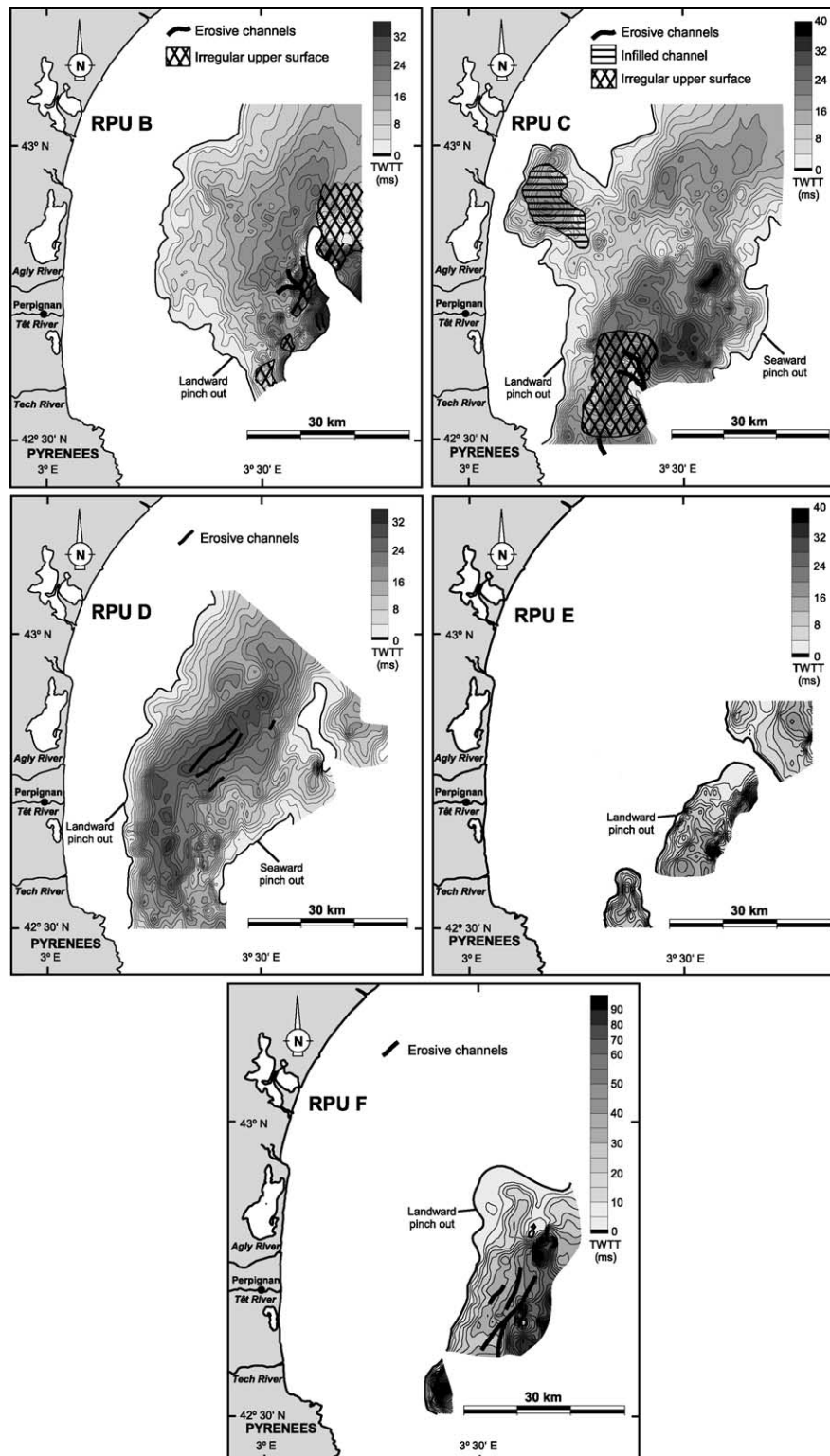


Fig. 6. Isopach maps of RPUs. The three older RPUs (B–D) show widespread distributions, developing laterally continuous depocenters on the shelf. In contrast, the two younger RPUs (E and F) are not distributed on the inner and middle shelf, and they have the maximum thickness on the upper slope. Highly irregular upper surfaces are particularly developed on top of RPUs B and C, and erosive channels occur on top of most of RPUs.

sufficient to clarify the relation between both deposits, and a specific study is being undertaken at present.

This unit is wedge-shaped and is distributed on the inner-middle shelf. Main depocenters overlie the inner shelf

paralleling the present-day coastline. Thickness usually reaches more than 10 ms and in places even more than 25 ms (Fig. 12). It is characterised by a sub-parallel to prograding configuration (Fig. 11).

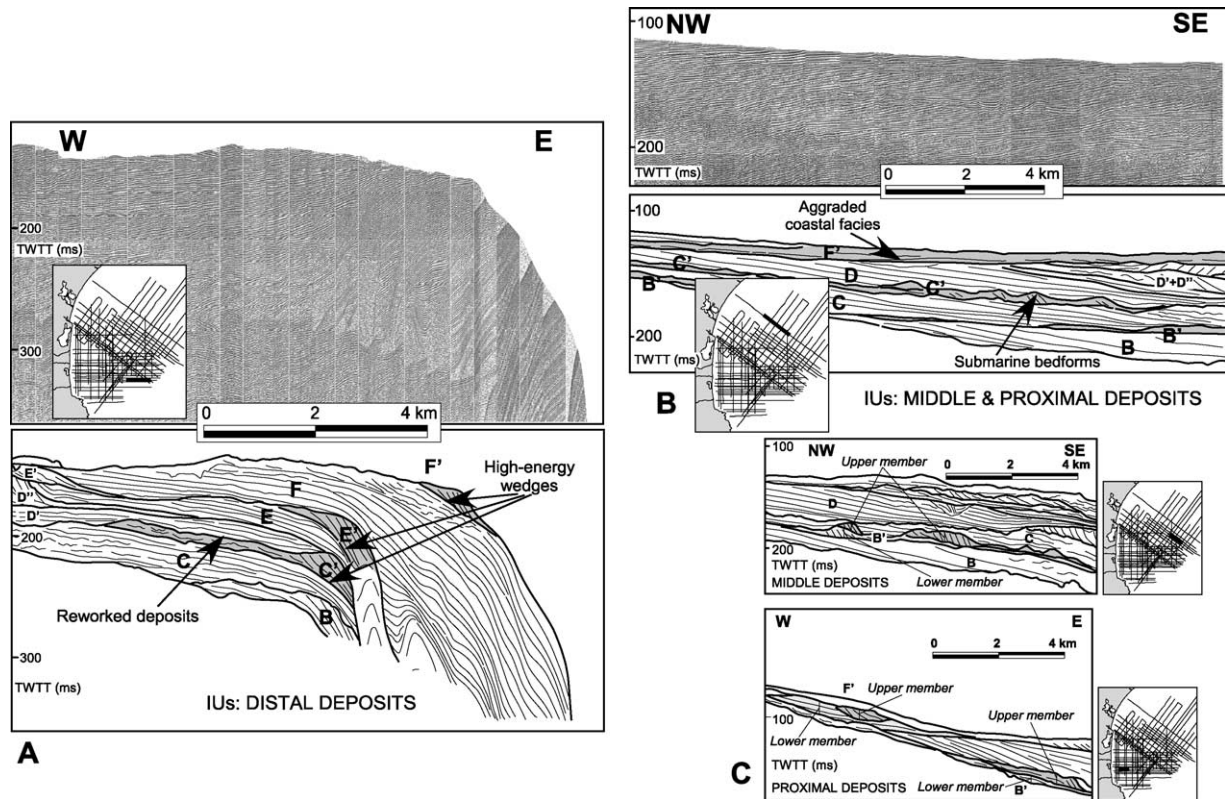


Fig. 7. Seismic sections and interpretations showing distribution and stratigraphic features of IUs: (A) distal deposits are wedge-shaped, high-angle progradational bodies; (B) middle and proximal deposits are coastal sedimentary bodies with moderate development; (C) two-member internal structure characterises middle and proximal deposits of IUs.

5. Interpretation of seismic units: sedimentary environments

Seismic units were interpreted in terms of sedimentary environments and paleoceanographic conditions, by considering the distribution of seismic units, seismic facies and character of bounding discontinuities. Piston cores collected in the Languedoc Shelf provided information about the sedimentary facies of upper parts of RPU F and IU F', thus improving the interpretation of sedimentary environments (Tesson et al., 2000).

5.1. RPUs: B, C, D, E and F

Correlation with sediment core data indicates that the top of RPU F comprises layers of fine sands to silt intercalated in silty clays and/or clayey silts (Berné, Lericolais, Marsset, Bourillet, & De Batist, 1998; Gensous & Tesson, 1996; Rabineau, Berné, Ledrezen, Lericolais, Marsset, & Rotunno, 1998). Those sediment facies, together with the dominance of low-angle prograding configurations within RPUs, were the basis for interpreting RPUs in the Rhône and eastern part of Languedoc Shelves as distal portions of coastal sediments deposited in a moderate-to-low energy marine environment, either mid to lower shoreface deposits (Gensous & Tesson 1996; Tesson, Allen, & Ravenne, 1993;

Tesson et al., 2000), or lower shoreface to prodeltaic deposits (Berné et al., 1998; Rabineau et al., 1998). Considering the apparent poor representation of fluvial incision on the Roussillon Shelf, the hypothesis of coastal progradation through beach deposits seems more reasonable (Suter & Berryhill, 1985; Yoo, Park, Shin, & Kim, 1996). The high lateral continuity shown by these units suggests linear sources (Chiocci et al., 1997), which also favours the hypothesis of beach deposits.

Wavy configurations are related with enhanced wave activity on the shelf (Tesson et al., 2000) and with gravitational processes on the upper slope, as a result of combined high sediment supply and high slopes. Southward progradations can be attributed to the dominance of southward-directed shelf currents, which would transport the sediment supplied by the northern rivers, such as the Orb and the Hérault.

5.2. IUs: B', C', E' and F'

IUs have a trend parallel to paleo-bathymetric lines, which generally indicates coastal deposits (Saito, 1994) of various origins (Tesson, 1996; Tesson et al., 2000).

High-angle units equivalent to distal deposits and cored in the adjacent Rhône and Languedoc Shelves are dominated by medium to coarse sands (Berné et al., 1998;

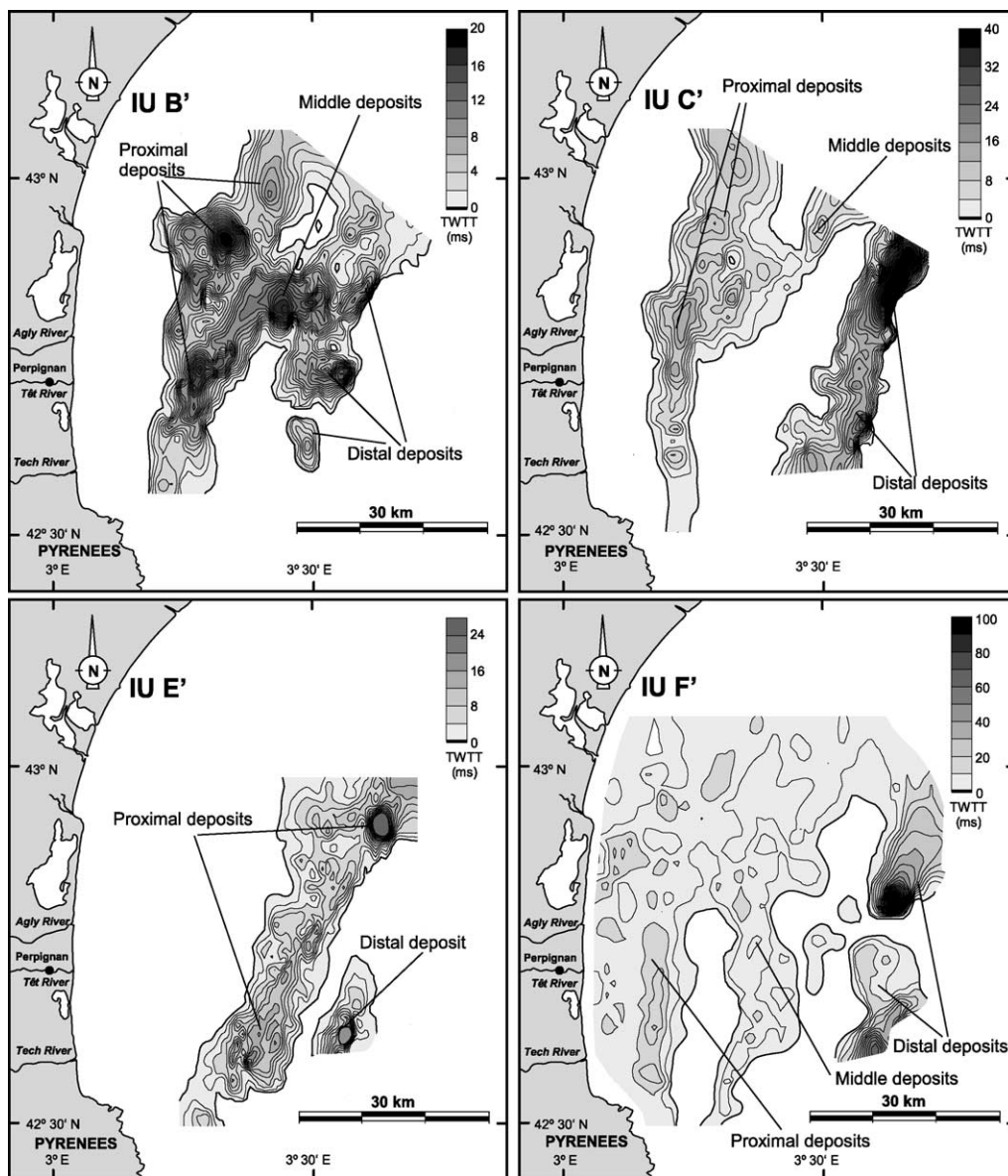


Fig. 8. Isopach maps of IUs. Distal deposits usually show NNE–SSW oriented, elongated depocenters on the outer shelf. Middle deposits usually occur northwards of Perpignan, and they show moderate development. IU E' does not show a middle deposit. Proximal are highly continuous depocenters showing NNE–SSW orientations and locally significant thickness.

Gensous & Tesson, 1996; Rabineau et al., 1998). They have been interpreted as a large variety of high-energy sedimentary environments, such as river mouth deltas, sand spits/semi-enclosed bays, littoral and offshore bars (Tesson, 1996; Tesson et al., 2000), or as shoreface sand bodies (Berné et al., 1998). An alternative hypothesis for similar high-energy, distal wedges, would consider them infra-littoral wedges. These wedges are related with the erosive action of storm waves in the shoreface, and cross-shore sediment flux led by downwelling currents (Chiocci & Orlando, 1996; Hernández-Molina, Fernández-Salas, Lobo, Somoza, Díaz del Río, & Alveirinho Dias, 2000b).

The internal structure of middle deposits is indicative of lower coastal deposits and upper marine deposits, as similar architectures have been documented in the Japanese Shelf

(Saito, 1994). The lower member would be attributed to lagoon or shoreface systems. The upper member would be constituted by marine-derived sediments formed through the reworking of coastal lithosomes. Depositional morphologies interpreted as sandy bedforms were generated due to the interaction of current flows with the sea floor. Southward bedform orientation suggests the dominance of southward-directed flows.

The moderately developed sedimentary wedges composing the lower member of proximal deposits can be considered as prograding beach/barrier deposits or coastal sedimentary wedges (Chiocci, Orlando, & Tortora, 1991), whereas sub-parallel facies probably indicate back-barrier deposits preserved in topographic depressions (Browne, 1994). The upper member can be interpreted as reworked

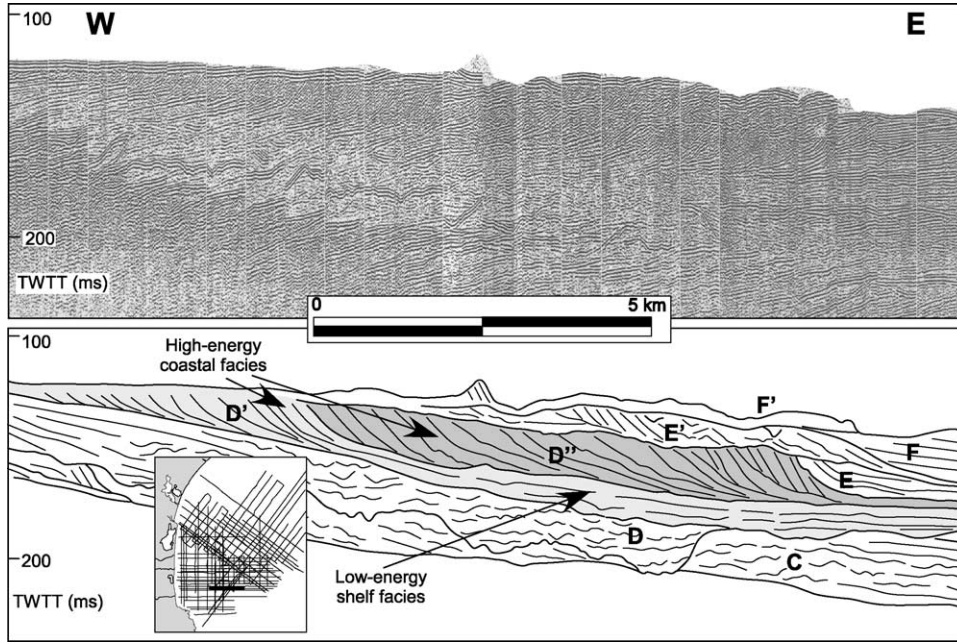


Fig. 9. Seismic section and interpretation showing stratigraphic characteristics of MPUs. MPUs are characterised by the dominance of high-angle, progradational facies with a highly reflective acoustic response. In the case of MPU D', proximal facies evolve distally to low-energy shelf facies.

deposits, and particularly low-angle configurations could represent healing phases.

5.3. MPUs: D' and D''

The correlation between high- and low-angle seismic facies with sediment facies reported in the Gulf of Lions provides some clues for the sedimentary interpretation of MPUs. Thus, high-angle facies evolving seaward to

sub-parallel facies could be interpreted as sandy coastal deposits, typically beach deposits evolving seaward to shelf muds, deposited below storm wave base level.

5.4. RAU: G

It is interpreted as fine-grained sediments deposited in a marine environment, probably of prodeltaic origin, suggested by the identification of high amplitude, high

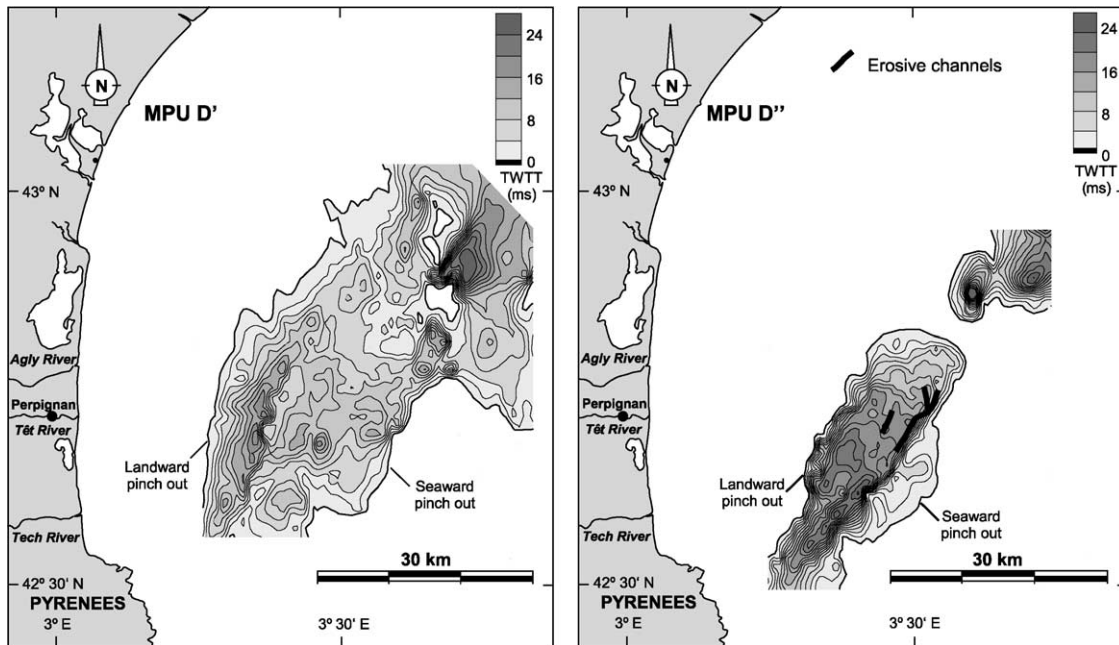


Fig. 10. Isopach maps of MPUs. They show a main elongated depocenter on the middle shelf with a NNE–SSW orientation and moderate thickness. In cross-shelf sections, MPU D' shows a wider distribution due to the presence of low-angle distal facies. MPUs are not distributed on the upper slope.

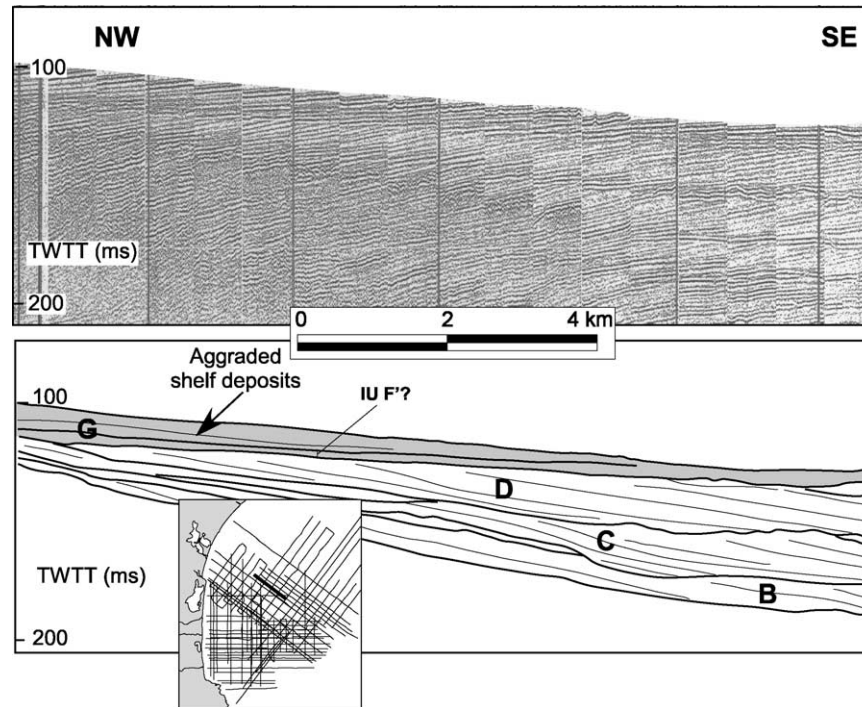


Fig. 11. Seismic section and interpretation showing main stratigraphic features of RAU. It is characterised by wedge external shape and by an aggradational to progradational internal configuration.

continuity reflectors (Aloisi, 1986; Gensous, Williamson & Tesson, 1993; Gensous & Tesson, 2003). The southward thickness decrease suggests the contributions of northern rivers, such as the Hérault and Orb. The contribution of the Roussillon streams does not seem to be significant, as depocenters are lower than 8 ms.

6. The sedimentary record of regressive periods

6.1. Deposition during sea-level fall-lowstand: evidences of forced regressions

RPUs are the primary component of the Roussillon Shelf. Large-scale regressive wedges equivalent to RPUs are generally associated with relative sea-level falls and lowstands and have been interpreted from a sequence stratigraphy point of view in other shelf settings as:

- Forced regressive wedge systems tract (FRWST) plus lowstand systems tract (LST) separated by a sequence boundary (Kolla et al., 2000; Proust, Mahieux, & Tessier, 2001).
- HST plus FRWST placed below the sequence boundary (Trincardi & Correggiari, 2000). They are interpreted as FRWSTs where proximal facies of the HST and FRWST have been eroded and are only preserved distally (Chiocci, 2000).
- LSTs when no subdivision between regressive and truly lowstand deposition is made (Chiocci et al., 1997; Ercilla & Alonso, 1996; Trincardi & Field, 1991).

RPUs recognised in the Roussillon Shelf (B–F) have also been documented in nearby sectors of the Gulf of Lions, such as the Languedoc Shelf (Tesson et al., 2000). In general, they show similar distribution patterns. They are interpreted as LSTs because RPUs are absent on the inner

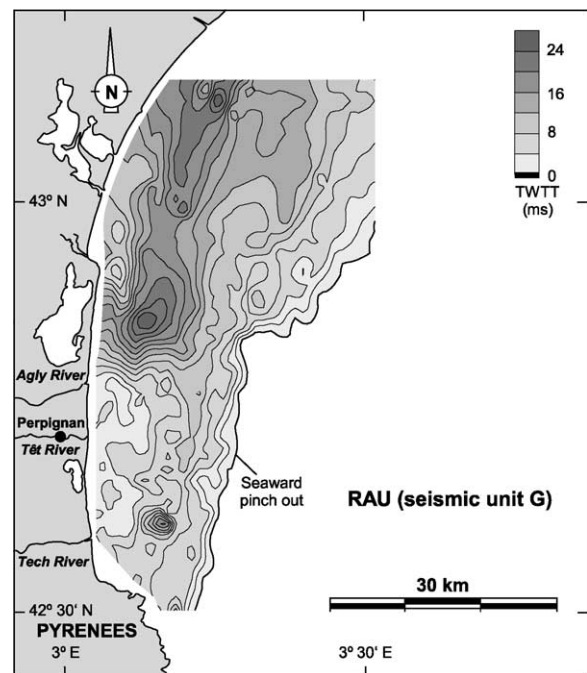


Fig. 12. Isopach map of RAU (seismic unit G). It shows a N–S oriented depocenter on the inner shelf, with a southward thickness decrease.

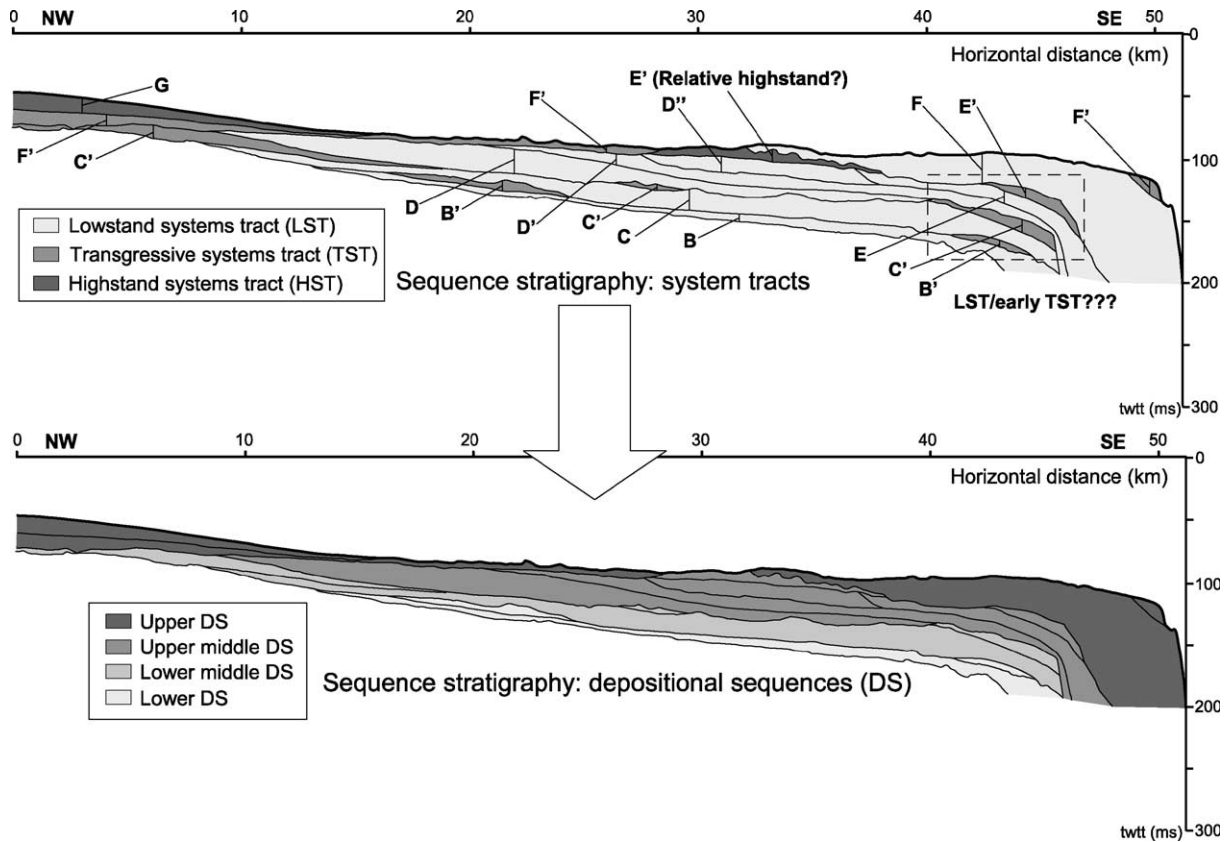


Fig. 13. Sequence stratigraphy interpretation of the Roussillon Shelf, in terms of systems tracts (LST, TST and HST) and depositional sequences. Distal deposits of IUs could be interpreted as lowstand or early transgressive in origin. Four depositional sequences related with regressive–transgressive cycles were recognised.

shelf and therefore are detached from the recent HST, as it was observed in the Rhône Shelf (Tesson et al., 1993). Besides, a distinct stratigraphic boundary that could establish the limit between different systems tracts (HST-FWRST-LST) is not identified within RPUs (Fig. 13).

Some stratigraphic criteria used to identify forced regressions (Posamentier & Morris, 2000) are identified in the study area, such as the recognition of long-distance regressions. Most of the regressive wedges show wide cross-shelf distributions, and the upper boundaries exhibit a widespread erosional character, which suggests erosion during subaerial exposure of the shelf (Sager, Schroeder, Davis, & Rezak, 1999). In the Roussillon Shelf, a complex stratigraphic pattern identified in the interval between RPUs D and E may also provide significant clues for the recognition of forced regression in continental shelves (Fig. 13A). In the adjacent Languedoc Shelf, the interval was interpreted as the result of two regressive periods (deposition of RPUs D and E) separated by a transgressive period represented by unit D' (Tesson et al., 2000). Besides, seismic unit D'' was not recognised in the Languedoc Shelf. In this paper, an alternative explanation is proposed on the basis of the architecture observed on the Roussillon Shelf. Thus, evidences of the existence of

a significant transgression occurring between deposition of RPUs D and E are not found. In contrast, the stratigraphic pattern suggests the existence of forced regression (Fig. 14A).

RPU D is characterised by a main depocenter on the middle shelf (Fig. 6); basinward, there is no evidence of erosion on its upper boundary, as distal clinofolds show very low angles, being concordant in relation to the upper boundary. Instead, the transition from RPU D to MPU D' is characterised by progressively shallower clinofolds going from proximal to distal. High-energy clinofolds of MPU D' are observed seaward of low-energy distal deposits of RPU D (Fig. 14B), indicating that the progradational depositional system is building into progressively shallower water. Therefore, this stratigraphic pattern suggests base level lowering and the occurrence of forced regression (Posamentier & Morris, 2000).

MPU D' changes downward to MPU D'', which presents similar high-energy clinofolds downlapping abruptly against the lower boundary. Besides, the offlap break of MPU D'' is down-stepped with respect to the updip unit. This architecture formed by MPU D' and downstepped MPU D'' (Fig. 14B) is very similar to that observed in the Lagniappe delta, and was associated with a forced

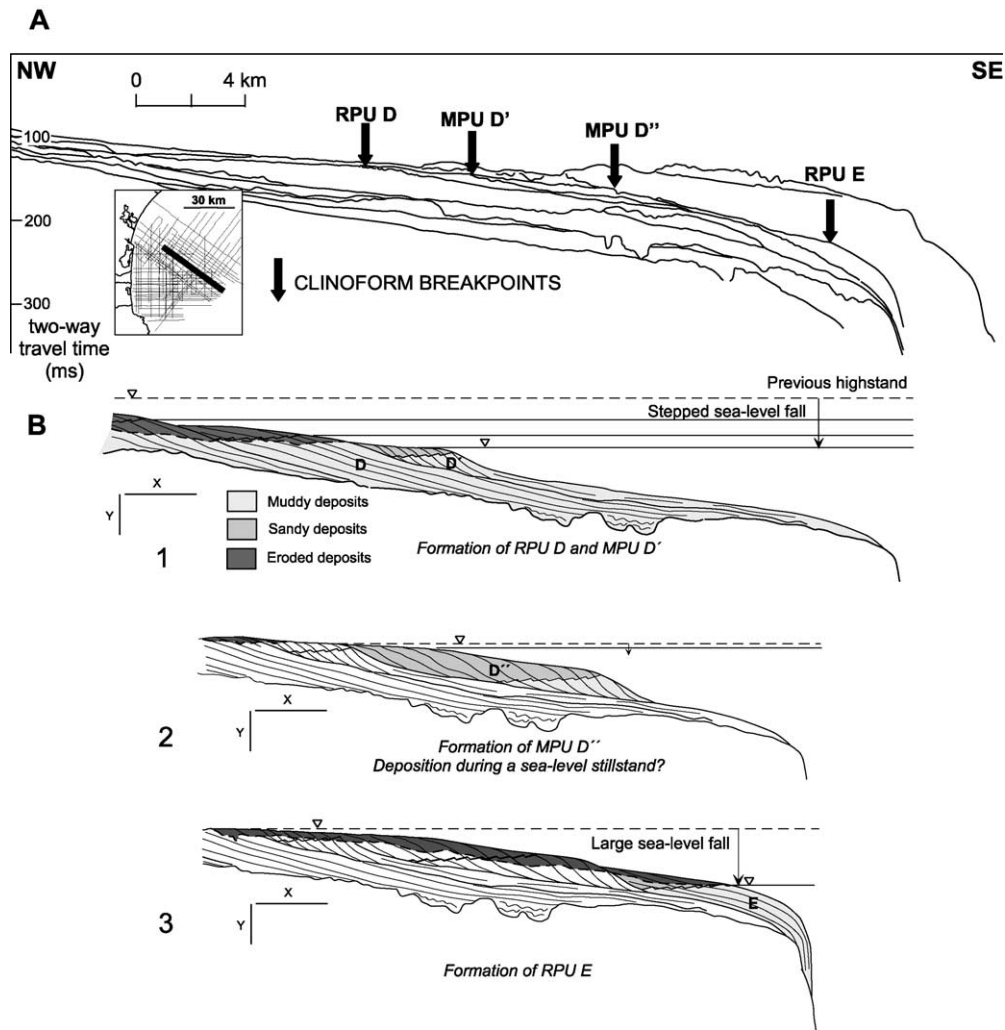


Fig. 14. Evidences of forced regressions in the Roussillon Shelf: (A) seaward migration of clinoform breakpoints from RPU D to RPU E; (B) proposed model to explain the formation and preservation of MPUs encased within RPUs (seismic unit D landward and seismic unit E seaward) through a forced regression mechanism. The occurrence of progressively shallower clinoforms going from proximal to distal is considered a strong indicator of forced regression.

regression process (Kolla et al., 2000). Basinward, MPU D'' is substituted by RPU E, which show low-angle seismic facies very different of dominant seismic facies in MPUs D' and D''. We propose that the drastic change of seismic facies between MPUs and RPU E is probably associated with changes of the rate of sea-level fall. Thus, deposition of MPUs would be linked to stillstand conditions after forced regressions, in contrast to deposition of RPU E that would be linked to a relative sea-level fall (Fig. 14B). Consequently, the interval between RPUs D and E does not show evidences of the occurrence of significant transgressions, and apparently this interval should be included in the same DS.

6.2. Implications for sand-prone reservoirs

The identification on the Roussillon Shelf of MPUs has implications for the emplacement of sand-prone reservoirs.

Shelf-perched sandy reservoir are mostly referred to as incised valley fills and high-energy coastal sandy bars with sharp basal contact with underlying muddy deposits. Recent studies of Quaternary shelf deposits around the Mediterranean Sea have little documented these models. The main exception is provided in the central part of the Gulf of Lions or Languedoc Shelf (Rabineau et al., 1998; Tesson, 1996; Tesson et al., 2000), where thick sandy and regressive coastal deposits have been deposited near the shelf break in relation with the regressive–transgressive turnaround of fourth/fifth order glacio-eustatic cycles, and thin and patchy sandy features have punctuated the following transgressive episodes on the mid and inner shelf. In the Roussillon Shelf, sand-prone deposits encased within widespread regressive wedges have been significantly preserved. MPUs of the Roussillon Shelf, with high-energy deposits (coastal sands) evolving seaward to low energy deposits (mostly silt and marine mud) show an example of potential reservoir directly

connected with organic matter rich muds, as distally there is no sharp basal contact between the two. This is an alternative play type which could be exported to sub-surface analysis and may improve field development strategies.

7. Shelf transgressions: influence of physiographic and oceanographic factors

In the Gulf of Lions, IUs have been interpreted as the record of transgressive periods (Tesson, 1996; Tesson et al., 2000). Proximal deposits of discontinuous IUs are recognised in the entire Gulf of Lions (Tesson & Gensous, 1998). In contrast, a distal deposit characterised by high-angle progradations is recognised on the Languedoc Shelf (Berné et al., 1998; Rabineau et al., 1998; Tesson, 1996; Tesson, & Gensous, 1998; Tesson et al., 2000), but middle deposits were not identified (Tesson et al., 2000). Their relatively high preservation seems to be quite unusual. Several explanations account for the poor representation of pre-LGM transgressive deposits, including:

- (a) Low generation potential by shoreface erosion, especially favoured with low wave energy and with low shelf gradients (Trincardi & Correggiari, 2000).
- (b) Erosion during subsequent sea-level falls and lowstands (Chiocci, 2000; Chiocci et al., 1997).
- (c) Rapid sea-level rises in contrast to more prolonged sea-level falls (Okamura & Blum, 1993; Yoo & Park, 1997).

In the study area, wave energy and shelf physiography (a) should have played a significant role, as (b) and (c) are ultimately dependant on glacio-eustatic sea-level changes and should be observed elsewhere.

7.1. Distal deposits

There is controversy concerning the nature and related sea-level position of distal deposits, as two main hypothesis have been proposed. One interpretation considers formation of distal deposits during maximum relative sea-level lowstands (Berné et al., 1998; Rabineau et al., 1998; Tesson, 1996; Tesson & Gensous, 1998; Tesson et al., 2000). In contrast, the other alternative claims for deposition during the early stages of sea-level rises (Tesson, 1996; Tesson & Gensous, 1998; Tesson et al., 2000). Under the light of existing stratigraphic database, it appears very difficult to discern if they were generated during lowstands or during early transgressions (Figs. 13 and 15A). Age control is needed to interpret those deposits in relation with distinct trends of sea-level change. Independently of the sea-level trend, these outer deposits could be related to shoreface/prodeltaic or to infralittoral deposits (Fig. 15A).

In some cases, particularly in relation with formation of distal deposit of IU F', the observed stratigraphic patterns

suggest that its generation was probably linked to the action of storm events that eroded previous regressive deposits and led to deposition below wave base level (Fig. 15B). Those systems would be similar to storm terraces (Chiocci & Orlando, 1996), or to infralittoral wedges (Hernández-Molina et al., 2000b). The following facts support this interpretation:

- (a) High-angle clinofolds of distal deposits clearly downlap the lower boundary, as physical continuity with low-angle clinofolds is not observed. The absence of seaward transition to low-energy facies characteristic of regressive deposits suggests higher energetic conditions.
- (b) Contrasting preservation observed between high-energy proximal facies within RPU and high-angle distal deposits of IUs. The most common stratigraphic pattern observed in the Roussillon Shelf shows well-developed distal deposits of IUs seaward from low-angle facies of RPU. However, in some locations high-angle proximal facies evolving downward to low-angle distal facies are observed within RPU F. Seaward, distal deposits of IU F' are poorly developed. These contrasting geometries would suggest that distal deposits of IUs developed after erosion of proximal facies of RPU (Fig. 15B).
- (c) High gradients characterise the different palaeo-shelf-breaks over which distal deposits of IUs are generally located. Increased influence of high-energy storm events would have been favoured by steep littoral domains when the shoreline was located in an outer shelf position.

7.2. Middle deposits

The identification of an internal two-member structure supports the existence of monotonous transgressions, during which coastal deposits were subsequently reworked to form a wave ravinement surface, which was overlain by marine deposits (Saito, 1994). Shelf physiography seems to have played a major role for the formation and preservation of those deposits (Fig. 16A). First, their low representation indicates an origin linked to enhanced and continued transgressions, probably due to low and uniform mid-shelf gradients. Secondly, reduced action of waves and storm events is implied, as the low gradients of the middle shelf favoured energy dissipation and the occurrence of low-energy coastal processes (Fig. 16A).

7.3. Inner deposits

These deposits show a higher preservation than middle deposits. In other shelves, the preservation of transgressive lithosomes is enhanced by underlying topography (Tortora, 1996). In the study area, the steep transition between

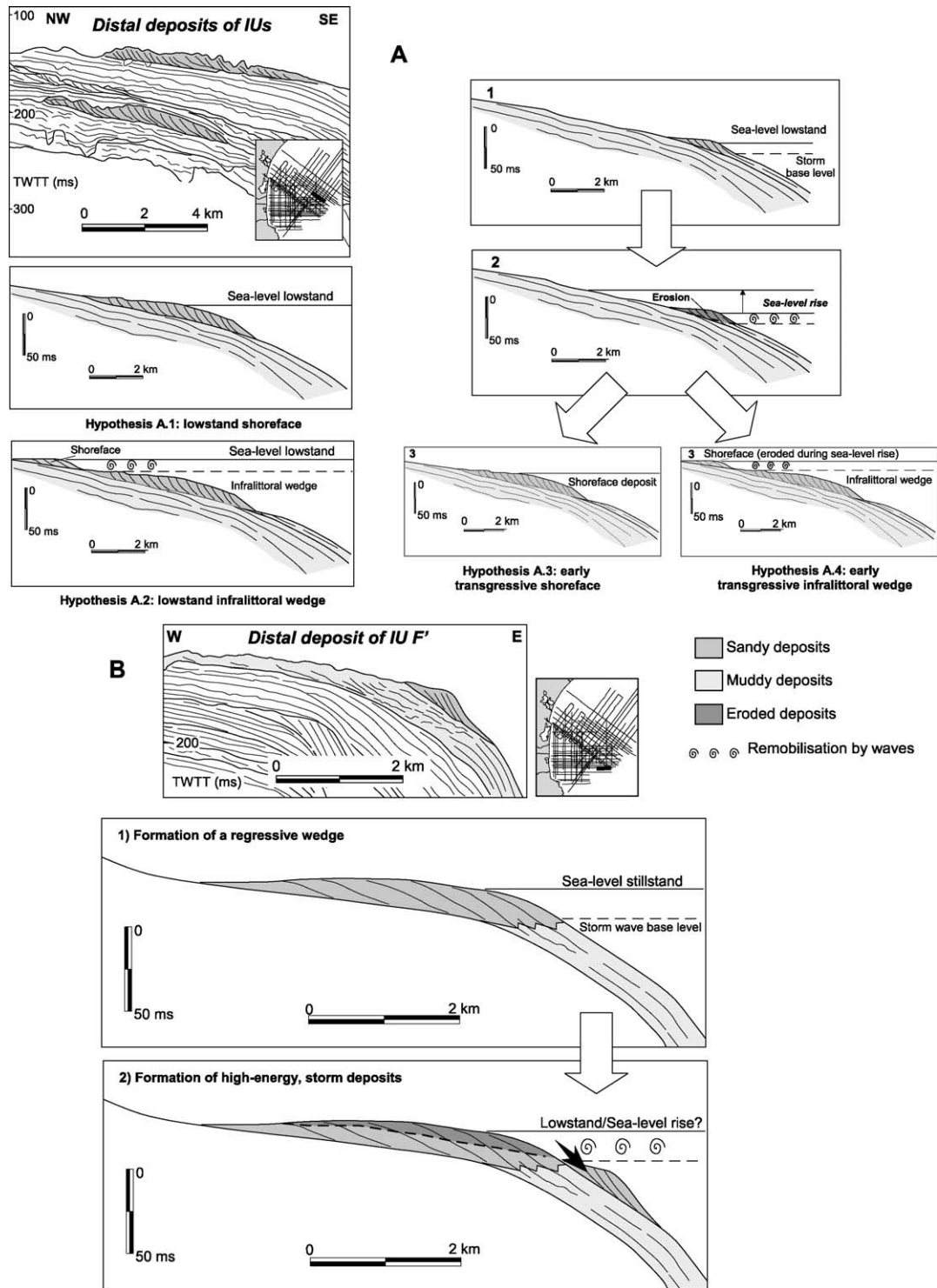


Fig. 15. Origin of distal deposits of IUUs: (A) genetic hypothesis of distal wedges, considering a lowstand (A.1 and A.2) or an early transgressive (A.3 and A.4) origin; (B) the local preservation of high-energy proximal facies within RPU F' suggests that distal deposit of IU F' was generated through the erosion of previous regressive wedges.

the inner and middle shelf probably led to slower transgression and therefore to the generation of coastal lithosomes (Fig. 16B). The identification of healing phases in specific locations suggests erosion during the subsequent rise, which probably occurred at a higher speed due to the low gradients of the inner shelf (Fig. 16B).

8. Regressive–transgressive cycles in the Roussillon Shelf

8.1. The regressive–transgressive motif: spatial changes

The repetition of a regressive–transgressive motif corresponding to high-frequency DSs marks the sedimentary

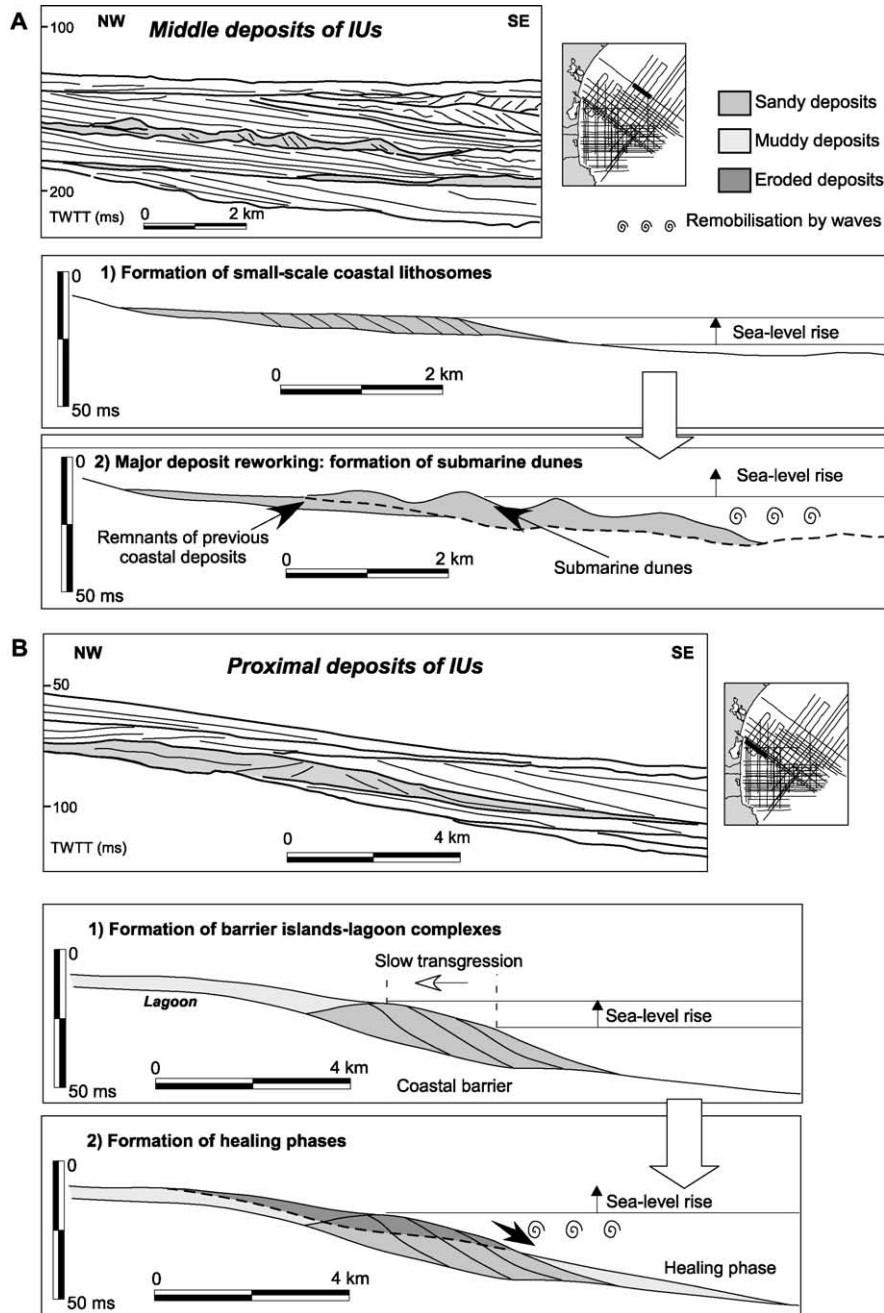


Fig. 16. Genetic models to explain the formation of middle and proximal deposits of IUs: (A) middle deposits developed during shelf flooding and reworking of previously deposited coastal lithosomes; (B) proximal deposits developed during slow transgressions over the inner-middle shelf transition. Coastal barriers were generated and partially removed during subsequent transgression.

succession in the Roussillon Shelf (Fig. 13). Changes of spatial distribution of each motif were deduced from (Fig. 17):

- (a) Identification of landward pinch outs and clinofrom breakpoints of RPU and MPU. Total lengths between both lines provide minimum estimates of the magnitudes of shelf progradation during regressive intervals.
- (b) Identification of landward pinch outs of IUs, providing an estimation of the magnitude of transgressive intervals.

Similar spatial analysis have been used for determining mechanisms of continental margin build-up (Fulthorpe & Austin, 1998). Spatial changes within the four DSs (lower, lower middle, upper middle and upper) show distinct patterns in the Roussillon Shelf:

- (a) Lower DS (RPU B+IU B'). The regressive interval represented by RPU B was characterised by increased northward progradation. RPU B was not preserved in the south of the study area, and northwards the amount of shelf progradation ranged between 20 and 25 km.

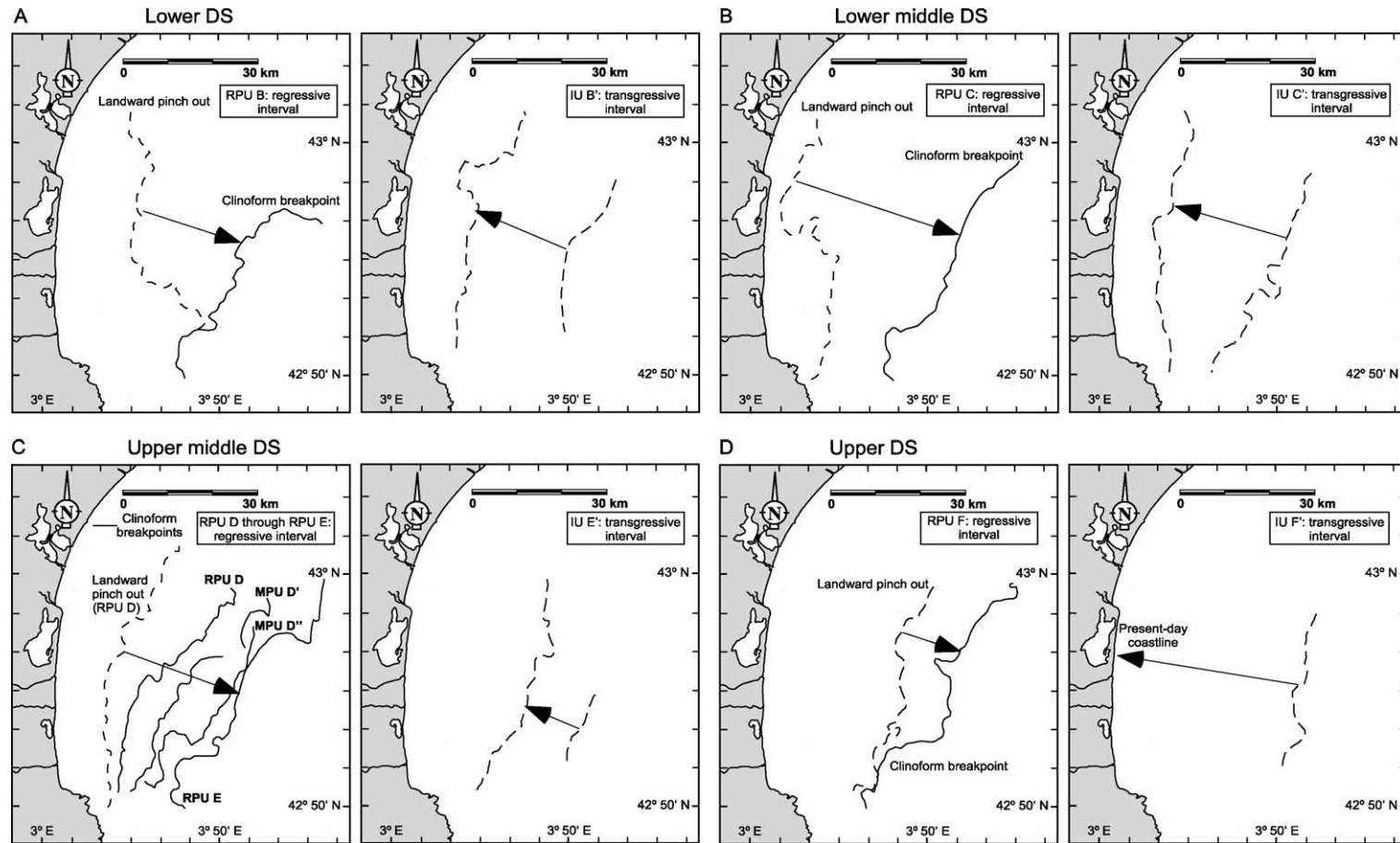


Fig. 17. Spatial architecture of regressive–transgressive cycles representing high-frequency depositional sequences (DSs) in the Roussillon Shelf: (A) lower DS was characterised by regression and transgression of similar magnitude; (B) lower middle DS was characterised by regression and transgression of similar magnitude; (C) upper middle DS was characterised by the dominance of the regressive interval; (D) upper DS was characterised by the dominance of the transgressive interval.

The cliniform breakpoint of RPU B acquired a NNE–SSW orientation (Fig. 17A). The transgressive interval represented by IU B' was more uniform in the study area (about 20 km), as the orientations of distal and proximal deposits were subparallel (N–S evolving northward to NNE–SSW) (Fig. 17A).

- (b) Lower middle DS (RPU C+IU C'). The regressive interval represented by RPU C was characterised by significant progradation along the study area. Thus, shelf progradation ranged between 10 and 15 km in the south and about 40 km in the north of the study area (Fig. 17B). The transgressive interval represented by IU C' was more uniform, although transgression length increased northwards, from 15 km in the south to 25 km in the north of the study area (Fig. 17B).
- (c) Upper middle (RPU D+MPU D'+MPU D''+RPU E+IU E'). The regressive interval of this DS includes two MPUs encased between two RPUs, as explained in Section 6.1. The overall length of regression increases northwards, ranging between 12 km in the south to more than 30 km in the north of the study area (Fig. 17C). Considering each progradational step, it seems that a similar northward increase of progradation occurred during RPU D deposition. However, the progradation induced by the interval between MPU D' and RPU E was more uniform. The transgressive interval is represented by IU E'. Apparently, the length of transgression was fairly reduced (12–13 km) and occurred uniformly (Fig. 17C).
- (d) Upper DS (RPU F+IU F'). The regressive interval is represented by RPU F, which caused a moderate regression, ranging from zero in the south to more than 10 km in the north of the study area. The transgressive interval represented by IU F' was apparently very uniform in the study area. Assuming that the coastline evolved from distal deposit of IU F' to the present-day coastline, the length of transgression ranged between 35 and 40 km (Fig. 17D).

Some general trend can be observed considering the magnitudes and patterns of regressive–transgressive cycles associated with DSs. Regressive intervals were not uniform, as progradation was very reduced to the south and increased significantly northwards (Fig. 17). The reduction of sediment supply to the south would partially explain this general trend. In contrast, transgressive intervals seem to have occurred more or less uniformly along the study area, suggesting a lower significance of sediment supply and the occurrence of rapid sea-level rises. The comparison between lengths of regression and transgression within each DS suggests three types of cycles:

- (a) Cycles where regression and transgression were of similar magnitude. This is the case of lower and lower middle DSs. Lengths of regression (20–25 km and

occasionally over 30 km) are comparable to lengths of transgression (up to 25 km).

- (b) Cycle where the amount of regression was more significant. This is the case of upper middle DS, where the magnitude of transgression was about 40% of the magnitude of regression.
- (c) Cycle where the amount of transgression was more significant. This is the case of upper DS, where the magnitude of regression was approximately 25% of the magnitude of transgression.

8.2. Cyclicity of depositional sequences

A major unresolved question in this margin is the leading cyclicity of recent shelf sequences (Lobo, 2000; Rabineau, 2001; Tesson et al., 1993, 2000). The following information is available to propose chronostratigraphic scenarios to explain the generation of high-frequency DSs:

- (a) Dating of shallow deposits. ¹⁴C dating of the upper part of RPU F gave an estimated age of 40 ka BP, and a coarse-grained shelly layer dated 12–10 ka BP was identified above (Gensous & Tesson, 1996).
- (b) Thickness of Quaternary sediments. Information from exploratory wells (Cravatte et al., 1974) suggests that Quaternary thickness ranges between 300 and 400 m, although the Quaternary lower limit is still unknown on the Gulf of Lions Shelf (Lofi, Rabineau, Gorini, Berné, Clauzon, De Clarens, 2003). According to our data, maximum thickness of the studied DSs ranges on the outer shelf between 90 and 120 ms (75–100 m by applying a velocity of 1650 m/s).
- (c) Magnitude of sea-level rises between major regressions. The difference in water depths between distal and proximal deposits of IUs B', C' and E' provided an indication of the magnitude of associated sea-level rises. It was assumed that IU F' was related with the post-glacial transgression (Gensous & Tesson, 1996). Sea-level rises associated to IUs B' and C' are broadly comparable, with average values of 50 m. In contrast, the sea-level rise associated with IU E' was considerably lower, with an average value of 35 m.

According to age dating and to previous observations (Monaco, 1973), RPU F could be related to the MIS 2 sea-level fall and lowstand. Two main hypothesis can be considered concerning the timing of older regressive–transgressive cycles:

- (a) Major regressions would be related to pre-MIS 3 sea-level cycles, mainly led by a fourth-order periodicity (~100 ka) (Imbrine, Hays, Martinson, McIntyre, Mix, Morley et al., 1984; Williams, 1988). Those cycles are supposed to control the sedimentary build-up of several western Mediterranean margins (Chiocci, 2000; Ercilla & Alonso, 1996; Trincardi & Correggiari,

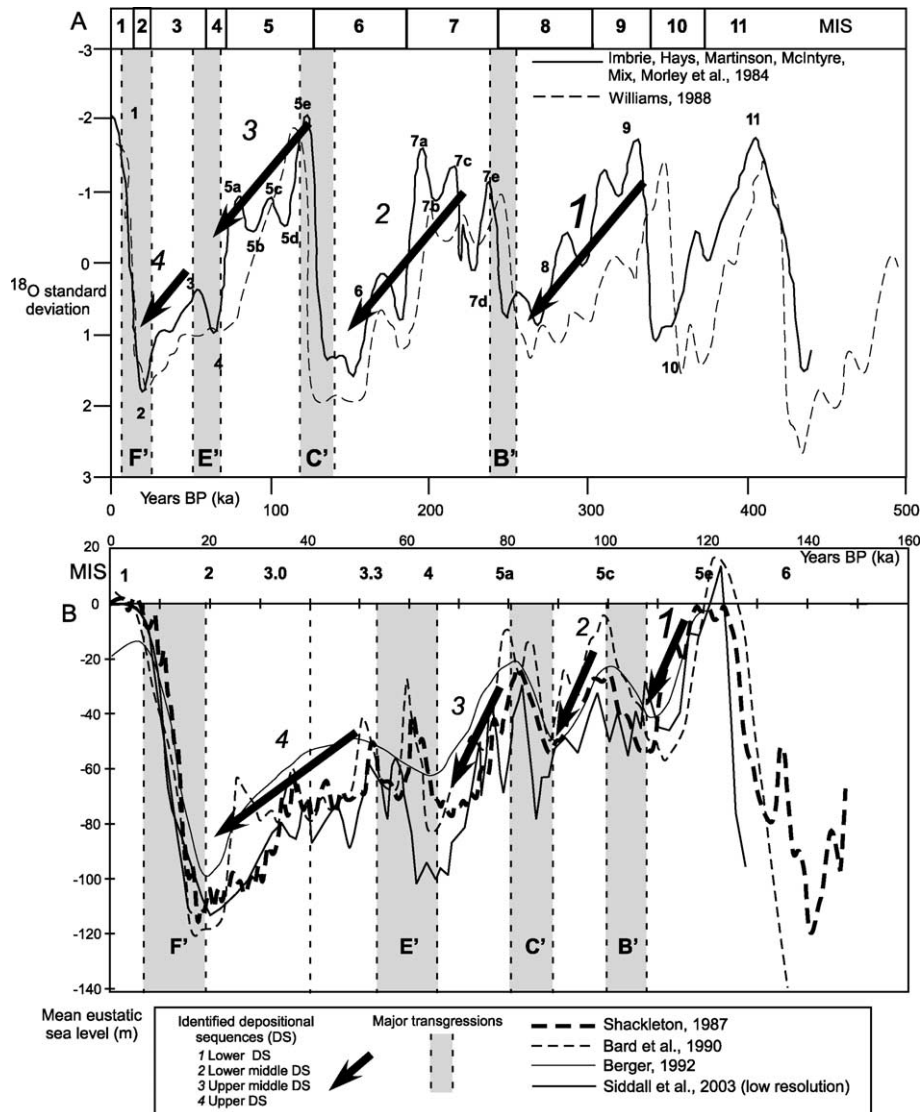


Fig. 18. Tentative correlations between identified depositional sequences (DSs) and late Quaternary high-frequency sea-level changes. It was assumed that upper DS was formed since MIS (marine isotopic stage) 3. Hypothesis A relates IUs to late Quaternary glacial/interglacial transitions. Hypothesis B relates IUs to stadial/interstadial transitions during the last 130 ka.

2000). This leading cyclicity has been also proposed for the Gulf of Lions margin (Rabineau, 2001). If IUs are interpreted as TSTs, IUs B' and C' would be related to major glacial–interglacial sea-level rises. Consequently, major regressions would have occurred during intermediate sea-level falls (Fig. 18A). This correlation implies that IUs only record part of the major sea-level rises, because these were higher than 100 m, whereas the estimated values in the study area are about 50 m.

- (b) Major regressions would be related to late Quaternary falling sea-levels and lowstands occurring before MIS 3 and after the last interglacial period, due to a higher significance of fifth-order cycles (~ 20 ka) (Shackleton, 1987; Bard, Hamelin & Fairbanks, 1990; Berger, 1992). The influence of those sea-level cycles on shelf sedimentation is particularly documented in the Gulf of Mexico (Anderson et al., 1996; Kolla et al., 2000;

Morton & Suter, 1996; Sydow & Roberts, 1994; Thomas & Anderson, 1991). This hypothesis would consider that SU B' and C' were related to stadial–interstadial transitions sea-level rises, and therefore the identified DSs would constitute a fourth order sequence (Fig. 18B). In general, reported values of those minor sea-level rises are lower than our estimations, as sea-level changes up to 35 m have been reported (Siddall, Rohling, Almogi-Labin, Hemleben, Meischner, Schmelzer et al., 2003). In any case, very high subsidence rates should be assumed. However, the apparent limited amount of Quaternary deposits on the shelf, about 300–400 m according to Lofi et al. (2003), does not favour this hypothesis, as it would imply that the last glacial cycle DS would account for about 25% of the total estimations of Quaternary thickness.

9. Conclusions

A seismic stratigraphic study conducted in the Roussillon Shelf reveals that the recent sedimentary record is composed of at least four high-frequency DSs represented by regressive–transgressive cycles.

Regressive intervals are represented by RPU, which are interpreted as LSTs deposited during periods of sea-level fall and/or lowstand. The occasional preservation of high-energy coastal facies attributed to MPU encased within an overall regressive interval is particularly remarkable. The identification of progressively shallower clinofolds going from proximal to distal is considered a reliable indicator of the existence of a forced regression process. This stratigraphic pattern is rare, as high-energy proximal facies are not usually preserved, because they tend to be eroded by subaerial exposure and transgressive ravinement. MPU of the Roussillon Shelf encased within widespread regressive wedges show an example of potential reservoir directly connected with organic matter rich muds.

Transgressive intervals are recorded by IU. The relatively high preservation of pre-LGM transgressive deposits is a consequence of the combined influence of previous shelf physiography and enhanced wave activity. Relatively steep slopes on the outer shelf and on the inner-middle shelf transition led to reduced transgressions and favoured the generation of wave-dominated coastal deposits. The identification of locally thick high-energy deposits close to the paleo-shelfbreak is especially significant. It is suggested that they were probably generated through the erosion of previous regressive deposits.

The analysis of spatial changes of seismic units composing the DSs provided useful insights concerning the nature of regressive–transgressive cycles. In general, regressive intervals were not uniform, as progradation increased northwards. In contrast, transgressive intervals occurred more homogeneously. The two older sequences were characterised by regressive and transgressive intervals of similar magnitude. In contrast, the two younger were characterised by the clear dominance of one interval, either the regressive or the transgressive.

The generation of DSs was attributed to the influence of high-frequency sea-level cycles. The dominance of fourth order cycles (~120 ka) would imply that IUs represent a partial record of major glacial–interglacial transgressions. The apparent limited preservation of Quaternary sediments on the shelf does not favour the dominance of higher order cycles (~20 ka).

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