Sedimentary balance and sand stock availability along a littoral system. The case of the western Gulf of Lions littoral prism (France) investigated by very high resolution seismic

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Abstract

Very high-resolution seismic data was acquired along the microtidal wave-dominated littoral zone of the western Gulf of Lions (SE France) with a view to estimate the volume of sand present in the upper shoreface under conditions of stable high sea level. An upper sand unit is thus identified at the top of the shoreface, bound at its base by a hard floor made of beach-rock layers or geological substrate. This upper sand unit (USU) is mobile and represents the available sand stock used for internal exchanges and beach supply. Estimate of the USU volume takes place within each sedimentary compartment and cell defined along the littoral zone. Two main results are obtained from this quantification. (1) The distribution of the sand stock fits with the littoral drift pattern, updrift source zones being characterized by low volume USU, while downdrift sink areas are characterized by much larger sand reservoirs. This distribution pattern is verified at all scales, the regional, the compartment and the cell scales; (2) the volume of the upper shoreface sand reservoir seems to match the adjacent beach behaviour. Wherever the beach evolution trend is negative, the stock is depleted and, on the contrary, the beaches associated to voluminous reservoirs do not suffer erosion.

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1. Introduction

Beach and shoreface sedimentary systems are commonly preserved in rock records and are known as potential reservoirs with good properties (e.g. Cant, 1984; Plint, 1988; Morris et al., 2003; Walker and Plint, 1992 for a review). They have been and still are extensively described and characterized in terms of lithology, sedimentary facies, geometry, and sequential organization. Part of the information and understanding, especially on sediment dynamics and facies, are provided through our knowledge of modern analogues (e.g. Héquette and Hill, 1995; Swift et al., 1991 for a review). Data on geometry and sequence stratigraphy are mainly provided through sub-surface investigations and outcrop studies in sedimentary basins (e.g. Hart and Long, 1996; Proust et al., 2001; Gensous and Tesson, 2003; Hampton and Storms, 2003; Swift et al., 1991 for a review). They rarely come from present-day systems (Swift et al., 2003) since appropriate sub-surface studies (very high resolution seismic investigations) are not yet commonly performed along modern very shallow littoral areas, especially beach and shoreface environments in open marine areas.

At regional scale, when studying a modern beach/shoreface system and its general wave climate, two hydrodynamic and transport components have to be considered: the residual longshore component which induces littoral drift direction, and the alternating cross-shore component. These two processes should be regarded as key processes that govern the sand stock distribution along and across the system, and thus would partly control reservoir geometry.

This paper presents the results of seismic surveys performed along the littoral zone of the western Gulf of Lions (or ‘Languedoc-Roussillon’ littoral) (Mediterranean sea, SE France). The wave-dominated beaches of the
western Gulf of Lions locally experience severe recessions that alternate in space and time with more stable states or even constructional phases. These changes point out to the existence of noticeable longshore and cross-shore processes described along many other littoral systems (e.g., Aaggard and Masselink, 1999; Larson and Kraus, 1992, 1994; Lippmann et al., 1993; Birkemeier, 1984; Mason et al., 1984; Bowen and Huntley, 1984; Holman and Bowen, 1982; Bowen and Inman, 1971).

In terms of longshore component, the Languedoc-Roussillon littoral system could be divided into different sedimentary compartments (Schuster, 1966; Barusseau and Saint-Guily, 1981; Barusseau et al., 1991, 1994, 1996; Akouango, 1997; Durand, 1999; Agence de l’eau, 2001). Their existence is confirmed by studies of the shoreline migration trends since the middle of the XXth century, on the basis of aerial photography comparison (CETE and IPSEAU, 1997). Each compartment is identified by acrretional or erosional evidence, and is generally separated from the adjacent compartments by physical barriers such as river mouths or rocky capes that totally or partially interrupt the longshore transport, due to the protrusion size.

In a cross-shore direction, a littoral system extends down to the modal closure depth, defined as a transition zone between the shoreface and the inner shelf (Hallermeier, 1981; Niedoroda and Swift, 1991; Cowell et al., 1999), below which seabed changes are not practically detectable. In the Languedoc-Roussillon littoral case, the mean closure depth is about 8 m and the inner geomorphic unit of the upper shoreface/lower foreshore is represented by a highly variable position and shape bar-and-trough system. Many studies recently focused on the morphodynamics behaviour of these bar-and-trough systems (Zenkovitch, 1967; Holman and Sallenger, 1993; Levoy et al., 1998; Michel and Howa, 1999; Konicki and Holman, 2000; Rueßi, 2000; Certain et al., 2002; Stepanian and Levoy, 2002; Dawson et al., 2002; Shand, 2003; Van Enckevort and Rueßi, 2003) that play a key role in focusing and dissipating wave energy (Short, 1999) in addition to constituting the main active sand stock.

The aim of the present paper is to characterize, based on seismic data, a present-day shoreface system in terms of sand stock distribution and volume. We will explain how these features can be related to the regional hydrodynamic conditions, and why they should be carefully considered for a better understanding of beach evolution, and more generally of beach/shoreface system functioning during a stage of sea-level stillstand.

2. General presentation of the study area

2.1. Geological context

The investigated area is part of the ‘Languedoc-Roussillon’ coast, located in the western Gulf of Lions, between the towns of Frontignan in the north and Argelès (Le Racou) in the south, close to the border between France and Spain (Fig. 1).

Except on the outer shelf and the shelfbreak where Pleistocene sediments are preserved (Aloiisi and Monaco, 1977), most of the shelf is covered by a Holocene formation named the ‘epicontinental prism’ (Ausseil, 1978; Aloiisi, 1986). This Holocene prism is commonly divided into two units from the coastline to the middle shelf: (1) the inner coastal unit (down to −20/−30 m) includes the littoral area and the inner shelf sand prism made of sands grading to sandy muds; (2) the middle shelf unit is wholly composed of mud. The littoral sands that comprise the dunes, beaches, upper-shoreface bar-and-trough system and lower-shoreface (Fig. 2), generally overly a rocky substratum, the age of which ranges from Pliocene in the south (Martin, 1978; Martin et al., 1981) to Mesozoic in the north (Aloiisi, 1986).

In addition, or less continuous beach rock layers are frequently observed by coring in the sandy unit (Barusseau et al., 1996; Akouango, 1997). They locally outcrop directly on the sea floor, especially in troughs between bars when the superficial sand layer has been removed by waves. Their age ranges from about 6000 years B.P. (Barusseau et al., 1996; Akouango, 1997) to about 1700 years B.P. (off Leucate, this study, cf. Table 3). Beach rock layers are very common in the Mediterranean shelf domain with strong age variability in the Gulf of Lions due to the local conditions of beach barrier formation. In the inner shelf and thus in the upper-shoreface, they are generally associated with the last stage of the Holocene transgression when sea level began to stabilize and littoral prisms were built (Tessier et al., 2000).

In the outer shelf, beach rock layers were found in the same conditions of sea-level stabilization, and are associated to the last low stand littoral prism construction (Berné et al., 1998).

2.2. Sediment supply and characteristics

The sediment of the Holocene unit mainly originates from seven main rivers (Fig. 1): in the south, the rivers Tech, Têt and Agly, in the north, the rivers Aude, Orb, Hérault and, in the east, the Rhône river. Because of the violent and abundant episodic rainstorms during spring and fall and the vicinity of mountains, all these rivers supplied large quantities of sediment (several millions of tons) to the shore until recent times (Parde, 1941). In 1940 for instance, catastrophic floods in the south part of the Gulf of Lions lead to the construction of large deltaic and prodeltaic bodies in front of the Têt and Tech river mouths (Parde, 1941). Since the Second World War, river sizing, reforestation and hydroelectric dam constructions resulted in a drastic decrease of sediment supply to these deltas that are now progressively reworked and destroyed (Durand, 1999).

In the whole area, superficial sediments are represented in average by fine to medium sands (125–320 μm), generally well sorted. However, significant cross-shore
variations are observed with a general seaward decrease of grain size (Jago and Barusseau, 1981). Longshore variations exist as well. The coarsest sediments are generally found in the vicinity of deltaic mouths and a downdrift decrease in grain-size is observed.

2.3. Climatic and hydrodynamic conditions

The Gulf of Lions is a typical wave-dominated microtidal environment according to Hayes’s classification (1979). Tidal range is lower than 0.25 m (SHOM, 2003).

Two wind orientations prevail in the western part of Gulf of Lions: offshore NW winds and onshore winds (E-SE) (Casanobe, 1961; Person, 1973, in Cattaliotti-Valdina, 1978; Mayencón, 1992). They can, respectively, induce set-down and set-up of the sea level, reaching +1 m at the coast during storms. The significant height ($H_s$) of waves generated by the offshore NW winds is generally low ($H_s < 0.3$ m) while the wave peak period varies between 3 and 4 s. $H_s$ for dominant SE swells (L.C.H.F, 1984) can be as high as

Fig. 1. The coastline of the western Gulf of Lions with the different littoral compartments. Arrows indicate the littoral drift direction. The nature of the limit between compartments is explained in the text.
3.5 m with periods between 5 and 9 s during storms, i.e. about a dozen times per year. The rest of the time, 80% of the waves are lower than 1 m (Durand, 1999; Certain, 1999, 2002).

E-SE storms induce a dominant residual longshore current in the study area, while the opposite littoral drift due to low offshore wind waves is weak. Sediment volumes transported by the longshore currents have been estimated from 10 to 40,000 m$^3$ per year (L.C.H.F, 1984; SOGREAH, 1983; Monaco, 1971). Because of the curved orientation of the coast (Fig. 1), the residual littoral drift is directed northward along the southern portion of the shoreline (oriented NS), and towards the southwest along the northern portion of the study area (oriented SW–NE). To the east of Frontignan, a change in the drift direction (towards the NE) is due to the wave refraction induced by the Rhône delta promontory and rocky banks. This segment, noted 1 in the Fig. 1, is not included in the study.

3. Longshore partitioning and cross-shore morphodynamics

3.1. Compartment description and general trends of evolution

As mentioned in Section 1, the Languedoc-Roussillon littoral system can be divided into different sedimentary compartments. A sedimentary compartment is defined by specific patterns of hydrodynamic circulation and longshore transport (Coastal Engineering, 1992). A sedimentary compartment is usually identified with an erosion zone updrift (longshore direction) and an accretion zone down-drift. Limits between compartments can thus be defined by changes in hydrodynamic conditions or interruption of sedimentary longshore flux, like rocky cape for example. In those stretches of coast, the physical processes are relatively independent of those operating in adjacent portions of the littoral and the sediment budget could be evaluated (Motyka and Brampton, 1993).

At a regional scale, both southern and north-eastern ends of the study area (Fig. 1) are subject to erosion, whereas the central portion where the littoral transport converges is a stable or accretional area. The general hydrodynamics can explain this pattern dominated by the longshore currents (Fig. 1) and the present-day decrease of deltaic-origin sediment supply (Arnaud-Fassetta, 1998).

On the basis of (i) the littoral drift direction, (ii) the natural physical barriers existing along the coast and (iii) the coastline evolution observed from the middle of the XXth century (CETE and IPSEAU, 1997) showing updrift erosion and downdrift accretion, five main compartments from the Rhône area to Argelès can be distinguished (Fig. 1): (1) L’Espiguette-Frontignan; (2) Frontignan-Cap d’Agde; (3) Cap d’Agde-Narbonne; (4) Narbonne-Leucate cape; (5) Leucate cape-Argelès.

Table 1
Percentage of erosional, accretional and stable beach areas along the western Gulf of Lions littoral

<table>
<thead>
<tr>
<th>Compartments</th>
<th>Erosion (%)</th>
<th>Accretion (%)</th>
<th>Stability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) L’Espiguette—Frontignan</td>
<td>41</td>
<td>26</td>
<td>32</td>
</tr>
<tr>
<td>(2) Frontignan—Cap d’Agde</td>
<td>36</td>
<td>12</td>
<td>52</td>
</tr>
<tr>
<td>(3) and (4) Cap d’Agde—Narbonne—Leucate Cape</td>
<td>15</td>
<td>44</td>
<td>41</td>
</tr>
<tr>
<td>(5) Leucate Cape—Argelès</td>
<td>49</td>
<td>40</td>
<td>11</td>
</tr>
<tr>
<td>Global</td>
<td>32</td>
<td>35</td>
<td>32</td>
</tr>
</tbody>
</table>

The limits between these compartments are of three types (Agence de l’eau, 2001), representing either (1) a zone of convergent littoral drift like the limit between Compartment 3 and Compartment 4 (Narbonne), (2) a zone of divergent littoral drift like the limit between Compartment 1 and Compartment 2 (Frontignan) and (3) a zone of full or partial interruption of littoral drift by capes such as the limits between Compartment 2 and Compartment 3 (Cap d’Agde), and Compartment 4 and Compartment 5 (Leucate cape) (Fig. 1).

This partitioning reflects the opposition between the central zone from Leucate cape to Cap d’Agde (Compartment 3 and Compartment 4) where erosion is less important than accretion, and the lateral zones (Compartments 1 and 2 in the north, Compartment 5 in the south) where erosion exceeds accretion (Table 1; Agence de l’eau, 2001).

3.2. Cell description

From a management perspective, it is necessary to consider a smaller spatial scale and each main compartment can itself be divided into cells, their borders corresponding to river mouths or harbour jetties that trap part of the drift as well. Along the study area, in addition to seven river mouths, a total of 23 harbours and nine minor structures are found (CEPREL, 1995), dividing the coast into 31 cells with an average length of 7 km. Among them, eight cells and 11 sites (Fig. 3), representative of the majority of the compartments, were investigated using the seismic approach. They are listed in Table 2 with an indication of their beach evolution trend (CETE and IPSEAU, 1997; Durand, 1999; Agence de l’eau, 2001).

3.3. Bar-and-trough system description and dynamics

For each site listed in Table 2 the seismic investigation was performed on the lower and the upper-shoreface, i.e. the sub-marine beach, typically shaped, as mentioned in Section 1, by a succession of 1–3 bars and troughs (Fig. 2). The first trough, named the ‘inner trough’, separates the aerial beach from the sub-marine beach. The number of bars and troughs (Table 3), their dimension and depth vary from one site to another. The lower shoreface, offshore the outer bar, is characterized by a very gentle and uniform slope (≪1%) (Fig. 2).
The bar morphology along the study area illustrates the different terms of the traditional classifications of wave-dominated beach types (Short, 1999; Short and Aagard, 1993), in correlation with the Gourlay parameter (1968). The bars are linear in the north (Frontignan to Cap d’Agde) in association with dissipative beaches, while they are crescentic in the south (Argelès to Leucate) where beaches are reflective. In the central area (Cap d’Agde to Leucate), the bars exhibit both characteristics and beaches are of intermediate type (Barusseau and Saint-Guily, 1981).

Evolution of cross-shore profiles shows at medium term, i.e. decades, that the littoral system reacts to marine climate variability according to two successive modes of evolution (Certain, 2002). The first mode is an equilibrium-oscillating model which corresponds to the ordinary mode of back and forth bar migration, depending of hydrodynamic energy. Bars migrate seaward during storms and shoreward when energy decreases. The second mode, which was described for other areas (Ruessink and Kroon, 1994; Wijnberg, 1995; Lippmann et al., 1993; Shand, 2003) is a ‘net offshore migration’ model. The latter points out the receding trend of the bars under the effect of paroxystic events (storms of rare occurrence—from 20 to 50 years) as a prelude to their degeneration.

Table 2
Beach evolution trend in studied cells (cf. Fig. 3 for location)

<table>
<thead>
<tr>
<th>Compartment considered</th>
<th>Cell number</th>
<th>Names of sites investigated by VHR seismic</th>
<th>Beach evolution trend (+ accretion, − erosion, ± stability)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1</td>
<td>Frontignan</td>
<td>−</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Sète north lido</td>
<td>−</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Sète intermediate lido</td>
<td>±</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Sète south lido</td>
<td>±</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>Fleury (north of the harbour)</td>
<td>+</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>Leucate (south of the harbour)</td>
<td>+</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>Saint-Marie</td>
<td>−</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>Canet (north of the harbour)</td>
<td>−</td>
</tr>
<tr>
<td>5</td>
<td>7</td>
<td>Canet (south of the harbour)</td>
<td>+</td>
</tr>
<tr>
<td>5</td>
<td>7</td>
<td>Saint-Cyprien (north of the harbour)</td>
<td>−</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>Le Racou (Argelès)</td>
<td>−</td>
</tr>
</tbody>
</table>
Table 3
Main characteristics of the upper sand unit identified by seismic in the shoreface prism (cf. Figs. 4 and 6 for seismic profiles)

<table>
<thead>
<tr>
<th>Sites</th>
<th>Upper sand unit (USU) characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frontignan Fig. 4A</td>
<td>No bar or one very smoothed bar. The upper sand unit (USU) is relatively thin (max 1.5 m), with no internal reflectors. It rests directly on the geological substratum and disappears offshore at about 4.5 m depth.</td>
</tr>
<tr>
<td>Sète—North lido Fig. 4B</td>
<td>Two bars are developed. The USU, 0.25 m thick, rests on a relatively irregular and continuous reflector identified by coring as a palaeosol dated 6000 ± 60 years BP and a beach rock layer (Akouango, 1997; Tessier et al., 2000). Underlying units are interpreted as Holocene deposits infilling irregularities incised in the Pleistocene substratum. The USU thins very progressively offshore and reaches a minimum thickness (a few 10 cm) at about 7–8 m depth.</td>
</tr>
<tr>
<td>Sète—Intermediate lido Fig. 4C</td>
<td>The USU, lightly thicker (3 m max.) than in the north, rests as well on a high amplitude reflector assumed to be a beach rock layer. It thins progressively offshore to get a minimum thickness (a few 10 cm) at about 6–7 m depth. No internal reflector is observed.</td>
</tr>
<tr>
<td>Sète—South lido Fig. 4D</td>
<td>Two well developed bars are shaped. The USU, reaching about 4 m thick, rests on an irregular and continuous reflector similar to that observed in the north lido part and also assumed to be a beach rock layer. It thins offshore, reaching a minimum thickness (a few 10 cm) at about 7–8 m depth. No visible internal reflector.</td>
</tr>
<tr>
<td>Fleury Fig. 4E</td>
<td>Two bars are very well developed. The USU is thick (3.6 m), with no internal reflector. It overlies a relatively irregular reflector corresponding probably to the top of the geological substratum. The USU reaches its minimum thickness offshore at about 9–10 m depth.</td>
</tr>
<tr>
<td>Leucate Fig. 4F</td>
<td>Three bars clearly appear, the inner most one, however, being quite flat. The USU is thick (5 m max) and thins slowly offshore, with still a thickness of 1.5 m at a 10 m depth. It rests on well defined reflector identified as a beach rock layer core. North dipping internal reflectors appears in the outer bar (cf. Fig. 6A).</td>
</tr>
<tr>
<td>Sainte Marie Fig. 4G</td>
<td>Three bars, as in Leucate, are clearly shaped, the inner most one being also a very flat feature. The USU is relatively thin compared with Leucate (3.5 m max) and lies on a very well marked reflector assumed to represent a beach rock layer. The USU disappears quite rapidly offshore reaching a minimum thickness at about 6 m depth. No internal reflector is visible in the bars.</td>
</tr>
<tr>
<td>Canet-north of the harbour Fig. 4H</td>
<td>The USU reaches a maximum thickness of about 3 m and rests on a quite well defined reflector (beach rock layer?). At about 10 m depth, its thickness is &lt;0.5 m. Two bars are well developed. No internal reflector is visible inside.</td>
</tr>
<tr>
<td>Canet-south of the harbour Fig. 4I</td>
<td>Similar to the north part. The maximum thickness is about 3 m and reaches a minimum (a few 10 cm) at about 9–10 m depth. The underlying reflector displays locally some channel-like features. Two bars are present. The inner bar is not visible in the seismic profile due to too shallow water above.</td>
</tr>
<tr>
<td>Saint Cyprien Fig. 4J</td>
<td>Two bars are present, the outer bar appearing as a very smoothed relief. The USU is relatively thin (lower than 3 m max) and rests on a flat reflector typical of a beach rock layer signature. The maximum thickness (a few 10 cm) is reached at 7–8 m depth. North dipping internal reflectors appears in the latter (cf. Fig. 6D).</td>
</tr>
<tr>
<td>Le Racou (Argelès) Fig. 4K</td>
<td>Only one bar is developed. The pattern is similar to that observed at Frontignan. The USU is very narrow and thin (1.5 m max) with no internal reflector, and rests directly on the geological substratum. It disappears offshore at about 6–7 m depth.</td>
</tr>
</tbody>
</table>

4. Methods of seismic investigation

The seismic device used for the study is a boomer IKB-Seistec (Simpkin and Davis, 1993). It is characterized by a line-in-cone receiver located close to the boomer plate (70 cm). Its frequency band is 1–10 kHz. During the surveys carried out on a small open boat (5 m), a SIG Energos power supply was used on board with a power of 100 J and a shooting rate of 2 shots/s. The seismic data were recorded with Delph system, and position was determined by a differential GPS directly connected to the Delph. Post-survey seismic data processing with Delph software included frequency bandpass filtering, automatic gain correction (usually TVG), trace stacking, swell filtering if necessary. The IKB-Seistec boomer is particularly well adapted to very shallow water surveys (Simpkin and Davis, 1993) and, with a vertical resolution of some decimetres, to the study of superficial sediments and present-day evolutions. It has already been used successfully to prospect the upper shoreface off of Sète (Tessier et al., 2000).

The available seismic data for this study cover a total of 11 sites surveyed from Frontignan to Le Racou (Fig. 3) and represent about 100 profiles 1 km long in average. The location of the sites was chosen to review the cells (Table 2) deemed representative of all the cell types and compartments. Consequently, longshore and cross-shore profiles were shot with varying density depending on the site. All the surveys occurred during the same period, without any storm event.
5. Results of the very high-resolution seismic investigation

On most seismic profiles it was possible to identify an upper sand unit (USU) isolated from the rest of the underlying deposits by a high amplitude reflector. Thanks to available core data (Barusseau et al., 1996; Akouango, 1997) and outcrop information provided by diving (this study), the high amplitude reflector at the base of the USU was identified as a resistant layer corresponding to a beach rock layer or to the top of the bedrock. The top of the USU corresponds to the sea floor, generally shaped by the bar-and-trough system. The thickness of the USU rapidly decreased offshore down to the mean closure depth.

Since each prospected site displays a relatively good homogeneity, only the most representative cross-shore profile is shown to illustrate a study zone (Fig. 4). For each prospected zone, the geometry, thickness, bar-and-trough system morphology of the USU was defined. All these characteristics, in addition to information on internal reflectors geometry, and on beach rock layer age, are summarized in Table 3.

For each zone the volume of the USU was determined from the seismic data (Fig. 5). This quantification clearly shows very significant differences (up to a factor 20) between the northern (Frontignan) and southern (Argelès-Le Racou) ends, where it is less than a few 100 m$^3$ per linear meter alongshore (lm), to the central area (Fleury) where it reaches 2000 m$^3$/lm.

Shore-parallel seismic profiles were also investigated (Fig. 6) to see whether a longshore component of sediment movement is recorded in the USU. Internal reflectors dipping northward, albeit rare, were identified in the external bars at Leucate and Saint-Cyprien. North dipping reflectors are also visible in the prodeltaic bodies off the Têt and Tech rivers (Fig. 6C and E).

6. Interpretation and discussion

Few models of shoreline response incorporate the regional impact of changes in sediment availability. Cowell and Thom (1994) addressed this shortcoming by incorporating sea-level changes in the case of sandy barrier–dune complexes. Today during an episode of sea-level highstand, only changes in bathymetric contours are used in order to decipher the shoreface changes and the storage of sediment input (Norton et al., 2003; Sabatier, 2001).

The very high-resolution seismic data presented herein addresses three points:

1. the upper part of the shoreface, identified as the USU, located above indurate layers or the underlying floor, constitutes a sand stock;
2. the USU is mobile under regional conditions of circulation, matching the longshore littoral partitioning at both compartment and cell scales;
3. a good correlation exists between the beach evolution trend and the USU volume, pointing to significant beach/upper-shoreface exchanges.

Fig. 4. Examples of shore-perpendicular seismic profiles, with interpretation, from Frontignan (A) to Le Racou (K) (cf. Fig. 3 for location). USU, upper sand unit; BRL, beach rock layer; RS, rocky substratum.
The USU generally lies over a beach rock layer. Such beach rock layer acts as a hard floor isolating the USU from the underlying packed sands that consequently become useless in the coastal sediment budget. Thus the USU represents in the present-day shoreface, the sand stock that is potentially mobile and thus available for the system operation.

Two arguments demonstrate that the USU is actually mobile: (i) its distribution in terms of volume, in accordance with the general pattern of longshore transport in the gulf and (ii) the occurrence of internal migration forms.

The regional distribution of sand stocks is a consequence of the convergent pattern of the longshore sediment transport towards the central area of the western Gulf of

![Fig. 4 (continued)](image)

![Fig. 5](image)

*Fig. 5. Volume of sand per linear metre involved in the USU with indication of the evolution trend of the beach associated to the investigated site.*
Lions littoral. It displays a strong contrast between source zones where the USU volume is low (Frontignan in the north, Argelès—Le Racou in the south) and sink zones where the USU volume is high (Fleury, Leucate) (Fig. 5).

However, gradients are not regular and the regional trend is disrupted each time a natural (or anthropogenic) obstacle intercepts part of the longshore transport. Each obstacle then generates the formation of an occasional limit with a sink and a source zone in the updrift and downdrift sides of the limit. This architecture of source-and-sink zones exists at the scale of the compartments and cells too. For example, in Compartment 2 (Frontignan—Sète south lido) (Table 2), available sand volume increases from 200 m³/lm in the updrift zone (Frontignan) to 1240 m³/lm at the downdrift end (Sète south lido). So in one compartment, the available sand stock may be increased by a factor 6. In Compartment
5 (Argeles—Leucate cape), a downdrift increase is observed as well, from 140 to 1930 m$^3$/lm. This pattern is also reproduced at cell scale in the two cases that were investigated (cells 2—Sète lido- and 7—Canet to Saint-Cyprien—, Table 2) with an increase in the drift direction of the USU volume between Sète north lido (330 m$^3$/lm) to Sète south lido (1240 m$^3$/lm), and Saint-Cyprien (550 m$^3$/lm) to Canet-South of the harbour (990 m$^3$/lm). The physical limit between compartments or between cells may disturb the regional trend observed. Due to capes or anthropogenic constructions on the coast, the sediment balance is deeply modified locally. Depending on the nature and size of the obstacle, a total or partial reduction of transmitted sediment flux is observed.

The longshore mobility of the USU is in addition confirmed by the presence in the outer bar of internal reflectors, the dip of which is consistent with the littoral drift direction. It is especially the case in the southern part of the gulf, because of the strong incidence of waves, where north-dipping reflectors are common features.

Most studies dealing with the morphodynamical evolution of bar-and-trough systems focus on the cross-shore component of transport, either in the western Gulf of Lions area (Akouango, 1997; Certain, 1999) or in other areas (e.g. Michel and Howa, 1999; Levoy et al., 1998; Lippmann et al., 1993; Birkemeier, 2001; Shand, 2003). In the Gulf of Lions, our seismic data clearly evidence a cross-shore component of transport. For instance, onshore dipping internal reflectors are present in the outer bar of Sète north lido (Fig. 4B). This result is consistent with numerous morphological observations showing a complete reworking of the bars during main storm events (Certain, 1999; Tessier et al., 2000), causing occasionally the underlying beach-rock layer to outcrop.

The cross-shore component is also clearly seen in the good correlation, at regional scale, between the volume of the USU, i.e. of the available sand stock, and the beach evolution trend (Table 2; CETE, 1997; Durand, 1999; Agence de l’eau, 2001). Wherever the volume of available sand is small, an erosional trend is observed; on the contrary, beach accretion occurs where large quantities of sands are stocked in the corresponding upper-shoreface (Fig. 5). The causal link involved in this relation is probably the role of well developed shoreface body. In case of a large incoming sand flux, a complete sequence of bars can develop, thus attenuating wave energy and diminishing longshore currents, not strong enough to transport large quantities of sand out of the sink zone. On the other hand, the coastline is eroded when the shoreface system is incomplete and not enough sediment can feed the beach. Lions was to examine the distribution and estimate the volume of the sand reservoirs stocked in the shoreface, and potentially available for beach supply. A very high-resolution seismic methodological approach was chosen and applied on selected sites of the coast. The following conclusions can be drawn from this study:

(1) From a technical point of view, very high-resolution seismic investigations performed with tools and boats adapted to very shallow water (from 1 to 10 m), constitutes a powerful approach to investigate present-day littoral prism geometry and dynamics.

(2) In the case of the western Gulf of Lions, the seismic data allowed us to identify in the upper-shoreface body the mobile sand layer that could be considered as active and directly available for foreshore/upper-shoreface exchanges, and to estimate the volume of this mobile sand stock. Seismic data also provided accurate indications about sediment transport directions, emphasizing both cross-shore and longshore components.

(3) The distribution and size of mobile sand reservoirs is closely related to the littoral drift pattern. The volume of the reservoirs increases in the downdrift direction, at all scales: at the regional scale ($\approx 100$ km), at the littoral compartment scale ($\approx 10$ km) and finally at the cell scale ($\approx$ a few kilometres). The seismic approach demonstrates that this longshore transport component should be regarded as a general mechanism by which the whole sand body is regularly displaced alongshore.

This conclusion arising from the study of a topical case could be used to better understand ancient shoreface preservation. It highlights that a shoreface sand reservoir volume close to the sediment source is not necessarily larger, but depends also on the longshore sediment redistribution under the action of the regional littoral drift dynamics.

(4) The volume of the upper shoreface sand reservoir is consistent with the behaviour of the adjacent beach. Whenever the reservoir is depleted, the beach evolution trend is negative. On the contrary, the beaches associated to voluminous reservoirs do not suffer erosion. From a general point of view, this conclusion makes it possible to acquire better knowledge about the evolution of the littoral prism of the western Gulf of Lions. Because fluvial sediment inputs are nowadays extremely reduced, it is expected that more and more beaches will suffer severe recession, except in the littoral drift convergence central area where large amounts of sand can accumulate in the shoreface.

7. Conclusion

The main objective of this regional scale study performed along the littoral prism of the western Gulf of

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