20th century sediment budget trends on the Western Gulf of Lions shoreface (France): An application of an integrated method for the study of sediment coastal reservoirs

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A B S T R A C T
This paper presents a shoreface sediment budget established for the 20th century (1895–1984–2009) along the microtidal wave-dominated coast of the western Gulf of Lions (Languedoc-Roussillon, Mediterranean Sea, SE France). The implementation of a diachronic bathymetric approach, coupled with the definition of sand reservoirs (upper sand unit—USU) by very high-resolution seismic surveys and the results of LiDAR investigations, offers a new means of defining precisely the magnitude and change trends of the sediment budget. The aim of this study is to link the Large Scale Coastal Behaviour (LSCB) of the littoral prism (expressed in terms of shoreface sediment budget, shoreface sediment volume and spatial distribution pattern of cells) to climatic change, river sediment input to the coast, longshore sediment transport distribution, impact of hard coastal defence structures and artificial beach nourishment. The results show a significant reduction of the volume of the western Gulf of Lions littoral prism over 114 years (−26.1 ± 4.6 × 106 m³). From 1895 to 1984, the overall budget is slightly positive, with a volume estimated at 4.2 ± 3.5 × 106 m³. For 1984–2009, however, the estimated sediment budgets clearly indicate that erosion is dominant over the last 25 years, with a volume loss of −30.2 ± 4.2 × 106 m³. In relation to the long-term sediment budget and longshore drift pattern, the long-term trend of the USU volume distribution displays strong spatio-temporal contrasts linked to longshore sediment drift, spatial distribution of fluvial sediment inputs and hard engineering structures. Locally, the sedimentary reservoir is significantly eroded within a century (−80% of USU), since the initial amount present was low and not sustainable. The emphasis is on the importance of considering the volume changes of available sediment reservoirs rather than their losses and gains. Erosion of the Languedoc-Roussillon shoreface is likely to continue in the future due to the “natural” decrease of river sediment input and the sand removal for human purposes. Consequently the littoral sand prism results in sedimentary reservoirs that are gradually being used up.

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1. Introduction

The coastal system is highly dynamic at different scales in time and space, which can have potentially significant impacts upon both ecological and human environments (Pilkey and Hume, 2001). Indeed, the morphological unit located between the beach and the shelf, most commonly referred to as the shoreface (Wright and Short, 1984; van Rijn, 1998), represents a “buffer zone” between the land and the sea, where waves have a significant impact on sediment transport and distribution. Consequently, the shoreface contributes in a major way to the coastal sediment budget by acting as either a sink or a source of sediment and represents an important control on shoreline movement (McNinch and Wells, 1999; Aagaard et al., 2004; Héquette and Aernouts, 2010; Aagaard, 2011). Unfortunately, it is extremely difficult to establish shoreface sediment budgets accurately (Pilkey et al., 1993; Kana, 1995). The shoreface behaviour remains poorly understood (Cowell and Thom, 1994; Masselink and Hughes, 2003; Hinton and Nicholls, 2007), especially at the longest (secular) timescales because: (1) the lack of a good-quality long-term data means that it is necessary to observe coastal behaviour on a sufficiently large spatial scale (100 km) (Stive et al., 1990, 2002), (2) there is limited understanding of interactions between numerous forcings in time and space, and (3) the difficulties of upscaling knowledge of short-term processes on a longer timescale (de Vriend, 1991). As a result, many approaches for studying coastal systems often focus on detailed processes or small spatio-temporal scales rather than considering Large Scale Coastal Behaviour (LSCB) that describes coastal evolution taking place over decades or centuries.

Hence, due to the increasing natural and anthropic pressures on the coastal environment (Hinton and Nicholls, 2007), many examples worldwide show the importance of grasping the long-term response of the coastal zone to different forcings. Indeed, the spatial and temporal behaviour of the shoreface has direct applications in coastal engineering projects involving beach nourishment (van Duin et al., 2004), the siting of coastal structures (Larson and Kraus, 1994), or more generally, the preservation of towns and touristic complexes on the sandy shoreface.
over the next decades (Sabatier et al., 2006). Furthermore, according to Stern (2007), it is cheaper to prevent erosional problems than to be faced with their consequences.

In this paper we propose an integrated approach to provide a meaningful assessment of the availability of sediment in the littoral zone at a regional scale and its evolution throughout the last century.

This study, based on bathymetry and high-resolution seismic data for determining the volumes of the nearshore sediment prism (McNinch, 2004; Miselis and McNinch, 2006; McNinch and Miselis, 2012), concerns the Languedoc-Roussillon shoreface (western Gulf of Lions, Mediterranean Sea, SE France). Many coastal studies have been conducted in this region, including several quantitative approaches (Barusseau and Saint-Guily, 1981; Barusseau et al., 1994, 1996; Durand, 1999; Certain et al., 2004, 2005). However, most of these studies have concentrated on shoreline evolution on meso- to macro-scales (month to year or decametre to kilometre), with the result that issues such as overall sediment budget and shoreface evolution at hyper-scales (>100 km and decade to century scale) remain poorly understood.

The overall aim of the present study is to illustrate how an integrated method putting together extensive bathymetric datasets, seismic and LiDAR investigations, and a sound knowledge of the morphodynamic context allows quantifying the evolution of a shoreface sediment budget over a period of more than a century (1895–2009) at the regional scale (>100 km).

2. Environmental setting

2.1. The geological context and morphology of beaches

The investigated area corresponds to the “Languedoc-Roussillon” coast, located in the western part of the Gulf of Lions, forming about 200 km of coastline between Argelès in the south, close to the border between France and Spain, and Le Grau du Roi in the north (Fig. 1), close to the Western limit of the Rhône delta.

The coast is mainly made up of sand beach barriers interrupted by rocky capes (Cap Leucate, Cap d’Agde, Sète) delimiting four main sedimentary compartments (Fig. 1) (Barusseau and Saint-Guily, 1981; Barusseau et al., 1994, 1996). Beach states are mainly intermediate to dissipative and rarely reflective according to Wright and Short’s classification (1984). The upper shoreface is generally characterized by a succession of 1–3 bars and troughs and a mean slope of 1 to 3% (Aleman et al., 2011). The lower shoreface, located offshore from the outer bar, is characterized by a very gentle and uniform slope (<1%). In the case of the Languedoc-Roussillon coast, the mean closure depth (Hallermeier, 1981) is around −6 and −8 m (Sabatier et al., 2004).

The superficial sediments of the shoreface are represented on average by generally well sorted fine to medium sands (125–320 μm). However, significant cross-shore variations are observed with a general seaward decrease of grain size (Jago and Barusseau, 1981). Longshore variations are also seen in the grain size distribution. The coarsest sediments are generally found in the vicinity of river mouths and a downdrift decrease in grain-size is observed along the coast. The littoral sands generally overlie a rocky substratum or older sedimentary formations ranging from the Quaternary to the Pliocene in age (Martin et al., 1981; Barusseau et al., 1996; Raynal et al., 2009).

2.2. Marine dynamics

The Gulf of Lions is a typical wave-dominated microtidal environment according to the classification of Hayes (1979). Two wind orientations prevail in the study area: NW offshore winds (60% of the time) and...
E-SE onshore winds (30% of the time) (Mayençon, 1992). At the coast, the significant wave height (Hs) generated by the offshore winds is generally low. For SE swells generated by the onshore winds, the wave height is lower than 1 m for 80% of the time (LCHF, 1984), but during storms (i.e. about a dozen times per year) it can exceed 3.5 m, reaching 7 m during exceptional storms (1997, 2003). The maximum swell at Sète is 5, 7.8 and 9 m, for return periods of 1, 10 and 100 years, respectively (LCHF, 1984). Although tidal range is lower than 0.25 m (SHOM, 2008), onshore winds during storms induce a set-up of the sea level that reaches +1 m NGF at the coast during storms (Gervais et al., 2012). Temporal analysis of mean sea level shows a rise of 11 cm during the 20th century at Marseilles, corresponding to a trend of +1.1 mm/year (Pirazzoli, 1986; Brunel and Sabatier, 2009).

Onshore winds and the associated wave climate induce several residual longshore currents of different directions along the coast. Sediment volumes transported by the longshore currents have been estimated as ranging from 10,000 to 40,000 m$^3$ per year (LCHF, 1984; Durand, 1999). Because of the curved orientation of the studied coastline (Fig. 1), the residual littoral drift is directed northward in compartment 1, towards the southwest in compartment 2, inducing a zone of convergent longshore drifts at Port-La-Nouvelle. Between compartments 1 and 2, wave refraction due to rocky banks at Frontignan leads to divergent longshore drift directed towards the SW in compartment 3 and 4, towards the NE in compartment 2. At a regional scale, this partitioning reflects a contrast between the central part, where the longshore transport converges towards a stable or accretional area, and the southern and north-eastern ends of the study area are subject to erosion (CETE Méditerranée and IPSEAU, 1997; Durand, 1999; CETE, 2002).

2.3. Fluvial inputs

In compartments 1 and 2, beach shoreface sediment is supplied by six rivers (Fig. 1), the Roussillon rivers (Tech, Têt and Agly) in the south (compartment 1), and the Narbonnais rivers (Aude, Orb and Hérault) in the centre (compartment 2). Compartments 3 and 4 are devoid of any rivers but during the final stages of the Holocene, the Rhône and Hérault rivers supplied large amounts of sediments to this eastern part of the gulf (Dubouy-Razavet, 1956; L’Homme et al., 1981). The reworked material of the prodeltaic lobes built by these rivers was re-distributed over the shoreface, being transported downdrift of these compartments by wave action (Sabatier et al., 2006, 2009; Ferrer et al., 2010). However, due to the eastward avulsion of the Rhône 5000 years ago, the mouth is situated too far east and, as a result, no natural sand input is able to balance the erosion of the beaches in the eastern part of the Gulf of Lions.

The Mediterranean climate (annual rainfall 700 mm) is characterized by generally long-lasting dry periods, separated by short storm events. These events cause occurrences of recurrent heavy floods (Serrat et al., 1996); catastrophic flash-floods of only a few hours are well known in the region (Pardé, 1941). Because of the vicinity of the mountains, all these rivers supplied large quantities of sediment (several millions of m$^3$) to the shore until recent times. In 1940, for instance, catastrophic floods of the Tech, Têt and Agly rivers discharged into the sea between 9 and 13.5 × 10$^6$ m$^3$ (Pardé, 1941) (Table 1). Since the middle of the 20th century, river management, reforestation and dam constructions have resulted in a drastic decrease of sediment supply to the coast (DDAF et Service RTM des Pyrénées Orientales, 1990; Durand, 1999). From 1978, the maximum river discharge has been interrupted by 20 due to dams (Têt example: Fig. 2) and a sediment volume of 370 000 m$^3$ appears trapped in dams on the Agly and Têt rivers (DDAF et Service RTM des Pyrénées Orientales, 1990). Furthermore, from 1971 to 1992, at least 7 × 10$^6$ m$^3$ of sands and pebbles were extracted from river beds in the Languedoc-Roussillon region (Durand, 1999). This practice has been forbidden since 1992.

According to DDAF (1990), Koulinsky (1998), Serrat et al. (1996, 2001), IRS (2000) and Bourrin et al. (2006), particulate sediment flux of the rivers (sands, gravels and pebbles) has become limited in recent decades (Table 1). The total annual sediment flux can be estimated at between 260,500 and 357,700 m$^3$, corresponding to a sediment volume of 6.5 to 8.9 × 10$^6$ m$^3$ supplied by the rivers from 1984 to 2009 in the southern part of the Gulf of Lions.

2.4. Engineering works for coastal development and defence

The Languedoc-Roussillon coast has been transformed since the 1960s by the construction ex nihilo of 12 seaside and yachting resorts (Mission Racine). Today, more than 30% of the Languedoc-Roussillon coastline is equipped with hard coastal defence structures (IFEN, 2007; Anthony and Sabatier, 2012) aimed at protection from disturbances in longshore drift induced by the harbour jetties. Rip-rap operations have been undertaken all along the coast, except in the south of compartment 2 and in the central parts of compartments 3 and 4.

Since 1980–90, sand beach nourishment has also been implemented. In compartment 1, 1.5 × 10$^6$ m$^3$ of sediment has been bypassed from the updrift to the downdrift part of the harbours. In compartment 4, a unique beach nourishment operation involving a volume of 1.1 × 10$^6$ m$^3$ was carried out in 2008 by transferring sand trapped in the Espiguette spit towards the beaches of the Gulf of Aigues Mortes.

Finally, in compartment 2, dredging in the harbour channel of Port-La-Nouvelle has led to the removal of 1.5 × 10$^6$ m$^3$ of sands between 1984 and 2009, which were then released at a disposal site at a water depth of 20 m.

<table>
<thead>
<tr>
<th>River</th>
<th>Catch-ment size (km$^2$)</th>
<th>River length (km)</th>
<th>Mean flow (m$^3$/s)</th>
<th>Bedload transport (m$^3$/year)</th>
<th>1940 Flood Solide charge (M m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tech</td>
<td>726</td>
<td>82</td>
<td>9</td>
<td>1000/18,000</td>
<td>57.5</td>
</tr>
<tr>
<td>Têt</td>
<td>1300</td>
<td>114</td>
<td>13</td>
<td>18,500/34,500</td>
<td>2.5/3.5</td>
</tr>
<tr>
<td>Agly</td>
<td>1040</td>
<td>80</td>
<td>7</td>
<td>1000/5200</td>
<td>1.5/2.5</td>
</tr>
<tr>
<td>Aude</td>
<td>830</td>
<td>150</td>
<td>45</td>
<td>80,000/100,000</td>
<td>No flood</td>
</tr>
<tr>
<td>Orb</td>
<td>4374</td>
<td>115</td>
<td>22</td>
<td>80,000/100,000</td>
<td>No flood</td>
</tr>
<tr>
<td>Hérault</td>
<td>2250</td>
<td>135</td>
<td>52</td>
<td>80,000/100,000</td>
<td>No flood</td>
</tr>
</tbody>
</table>
3. Methods

3.1. Bathymetric data

Three high-quality bathymetric datasets (1895, 1984 and 2009) were analysed (Table 2) to determine and quantify the long-term bathymetric changes of the Languedoc-Roussillon shoreface.

Bathymetric data from 1895 (oldest accurate sounding data available for the whole study area) were collected by the SHOM (Service Hydrographique de la Marine) by means of theodolite triangulation and then compiled on nautical charts. Most of these charts had never been scientifically analysed in Languedoc-Roussillon before Brunel (2012). Their treatment was based on classical methods (Dolan et al., 1980), applied in similar long-term sediment budget studies on other parts of the French coast: Rhône delta, eastward of Languedoc-Roussillon (Sabatier et al., 2006, 2009) and Marennes-Oléron Bay, Maumusson Inlet, on the French Atlantic coast (Bertin et al., 2004, 2005). The charts were scanned (600 dpi), digitised and georeferenced in French metric Lambert 93 coordinates. The geometrical correction was carried out with ER Mapper© software, from a reference document consisting of the BD-ortho 1998©, a highly accurate georeferenced aerial photograph mosaic produced by the IGN (Institut Géographique National). Then, sounding points were manually digitised using the Geographic Information System Map Info 7.5®. Bathymetric data from 1984 (closest to the Mission Racine sounding data points available for the whole study area) collected by the SHOM were extracted from the HistoLitt® data base, a very accurate georeferenced data base of soundings points. A common isobath of 8 m was directly connected to the recorder. Post-survey seismic data processing was used with a power of 100 J and a shooting rate of 2 shots/s. The very high-resolution (VHR) seismic data were recorded with a small open boat (5 m), a SIG Energos onboard power supply and a line-in-cone receiver located close to the boomer plate (70 cm), using a frequency band of 1–10 kHz. During the surveys carried out with a small open boat (5 m), a SIG Energos onboard power supply was used with a power of 100 J and a shooting rate of 2 shots/s. The very high-resolution (VHR) seismic data were recorded with a Delph system and position was determined by a differential GPS directly connected to the recorder. Post-survey seismic data processing with Delph software included frequency bandpass filtering, automatic gain correction (usually TVG), trace stacking and 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 several centimetres (±0.06 m), to the study of the upper sand unit (USU) and superficial sediments (Tessier et al., 2000; Certain et al., 2005).

The available seismic data for this study cover a total of 18 sites surveyed from Grau du Roi to Le Racou (Fig. 3). The location of the sites was chosen to include cells considered representative of all compartment types as well as cells associated with significant erosion and management issues (i.e., Roussillon harbours, lidos at Sète and in the Gulf of Aigues Mortes). A common isobath of 12 m is taken as the lower depth limit for the whole set of seismic data. For each site (around 500 m coastline length), an average of 10 cross-shore profiles were surveyed on the lower- and upper shoreface, i.e. the submerged beach (500 m average length). Three longshore seismic profiles per box were also investigated for each site to determine whether a longshore component of sediment volume is recorded in the USU between cross-

<table>
<thead>
<tr>
<th>Date</th>
<th>Type of data</th>
<th>Source</th>
<th>Area</th>
<th>Density</th>
<th>Vertical Margin of error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1895</td>
<td>Bathymetric map</td>
<td>SHOM</td>
<td>Whole zone</td>
<td>1 pt/50 m</td>
<td>±0.30</td>
</tr>
<tr>
<td>1984</td>
<td>Sounding data set</td>
<td>SHOM</td>
<td>Whole zone</td>
<td>1 pt/50 m</td>
<td>±0.20</td>
</tr>
<tr>
<td>2009</td>
<td>LiDAR</td>
<td>FUGRO/DREAL LR</td>
<td>Whole zone</td>
<td>1 pt/10 m</td>
<td>±0.30</td>
</tr>
</tbody>
</table>
shore profiles. All the surveys (total of 160 km seismic profiles) were undertaken during the summer period, without any storm event before the surveys. To assess the volume of sand and then compare it to the long-term sediment variations, we measured average USU thickness in terms of volume for each site (m$^3$/m$^2$).

The results presented here summarize around 10 years of seismic surveying of the sand shoreface prism of the Gulf of Lions (Barusseau et al., 1996; Certain et al., 2004, 2005; Raynal et al., 2009; Ferrer et al., 2010). On most seismic profiles, it was possible to identify USU isolated from the rest of the underlying deposits by a high-amplitude reflector. The USU generally overlie the surface of a rocky substratum, the age of which ranges from Mesozoic in the north (Aloisi, 1986) to Pliocene in the south (Martin et al., 1981). But more or less continuous Quaternary beach rock layers are also frequently observed by coring in the sandy unit (50 cores). They locally outcrop directly on the seafloor, especially in troughs between bars when the superficial sand layer has been removed by waves (information provided by diving). Their age ranges from about 6000 year BP (Barusseau et al., 1996) to about 1700 year BP (Certain et al., 2005). 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. Since each prospected zone is relatively homogeneous on both cross-shore and shore-parallel seismic profiles, we assume that the estimated USU cell volume calculated here is representative of the whole region.

3.3. Long-term USU volume trends

The long-term USU volume trend ($\text{Lgt USU Vt}$) is calculated in % by dividing the long-term sediment budget over the three studied periods (1895–1984; 1984–2009; 1895–2009) by the total upper sand unit volume (USU volume in 1895) (Eq. (1)), for the 18 cells for which seismic data are available (cf. paragraph 3.2).

$$\text{Lgt USU Vt} = \frac{\text{SB (by period)}}{\text{USU volume 1895}} \times 100$$

where $\text{Lgt USU Vt}$ is the long-term upper sand unit volume trend (in %), SB is the sediment budget (in m$^3$/m$^2$) by period (1895–1984; 1984–2009; 1895–2009) and USU volume 1895 is the reference upper sand unit volume (in m$^3$/m$^2$), measured between the instantaneous sea bottom in 1895 and the lower limit of the USU. Negative values imply a reduction of the shoreface volume and long-term sediment output, whereas positive values suggest an accretion of the shoreface volume and sediment input. The variation in upper sand unit volume allows us to estimate beach trend in relation to the long-term sediment budget. This method evaluates the variations in sand volume over the shoreface and underlines the importance of considering the changes in the actual volume of sand available in the nearshore zone rather than just looking at the changes in bathymetry for estimating shoreface sediment budgets.

3.4. Limitations of bathymetric analysis and seismic surveys

The accuracy of the bathymetric comparison depends on the errors associated with the various sounding measurements: ±0.3 m for the first survey (1895), ±0.2 m for the second survey (1984) and ±0.3 m for the LiDAR data (2009). For this reason, changes cannot be shown when they are less than 50 cm (for 1895–1984) or 60 cm (for 1895–2009). However, the changes observed are generally greater than the error ranges.

Another source of error is due to the fact that changes in emerged beach volume are not taken into account. However, these beaches
are relatively narrow and 1/3 of them have been equipped with coastal defence structures. According to Durand (1999), emerged beaches form only a small part of the total sand volume of the littoral prism.

Unfortunately, according to the SHOM, bathymetric data are not available at this large scale between 1895 and 1984, which would allow for examining the changes in sediment budget during the 20th Century.

Finally, bathymetric and LiDAR surveys provide a snapshot view of the seabed, whereas the USU seismic surveys were performed over a period of nearly ten years. Discrepancies can arise from using these non-contemporaneous sources of data. However, considering the involved scale, we consider that the discrepancy between data sets is insufficient to distort the general trends that are highlighted. Furthermore, for the most evident changes in USU (compartment 4) both kinds of data were gathered the same year (2009).

4. Results

4.1. Regional-scale sediment budget

For the overall period from 1895 to 2009, the residual shoreface budget for Languedoc-Roussillon is $-26.1 \pm 4.6 \times 10^6$ m$^3$ ($-0.23 \pm 0.04 \times 10^6$ m$^3$/year) (Fig. 4).

From 1895 to 1984, the overall sediment budget is slightly positive, with $4.1 \pm 3.5 \times 10^6$ m$^3$, which corresponds to $0.05 \pm 0.04 \times 10^6$ m$^3$/year. However, for the period from 1984 to 2009, the volume estimation clearly indicates that erosion is dominant over the last 25 years, with a budget of $-30.2 \pm 4.2 \times 10^6$ m$^3$ corresponding to $-1.2 \pm 0.16 \times 10^6$ m$^3$/year. Fig. 4 shows a shift from equilibrium (1895–1984) to an erosional regime (1984–2009).

In terms of spatial distribution, a comparison of the bathymetric maps reveals a contrasted pattern of bathymetric erosion and accretion by compartments (Fig. 4). For 1895–1984, compartments undergoing accretion correspond to the southern part of the study area, with values of $9.4 \pm 0.6 \times 10^6$ m$^3$, or $0.1 \pm 0.01 \times 10^6$ m$^3$/year, in compartment 1, and $8.7 \pm 1.4 \times 10^6$ m$^3$, or $0.10 \pm 0.02 \times 10^6$ m$^3$/year, in compartment 2. Otherwise, sectors undergoing erosion correspond to the northern part of the study area, with values of $-1.1 \pm 0.6 \times 10^6$ m$^3$, or $-0.01 \pm 0.006 \times 10^6$ m$^3$/year, in compartment 3, and $-12.8 \pm 0.8 \times 10^6$ m$^3$, or $-0.14 \pm 0.01 \times 10^6$ m$^3$/year, in compartment 4.

For the period 1984–2009, all compartments are subject to erosion, with values of $-6.3 \pm 1.6 \times 10^6$ m$^3$ or $-0.25 \pm 0.06 \times 10^6$ m$^3$/year; $-15.7 \pm 1.5 \times 10^6$ m$^3$ or $-0.62 \pm 0.06 \times 10^6$ m$^3$/year; $-3.2 \pm 0.2 \times 10^6$ m$^3$ or $-0.12 \pm 0.008 \times 10^6$ m$^3$/year and $-4.8 \pm 0.8 \times 10^6$ m$^3$ or $-0.19 \pm 0.008 \times 10^6$ m$^3$/year for compartments 1, 3, 4 and 4, respectively. Erosion increases in the northern part of the region, while the positive trend changes to negative in the southern part. The sand volumes involved are strongly contrasted, since erosion during the last 25 years has been 7 times greater than accretion over the preceding 89 years.

4.2. Cell-scale sediment budget

Long-term bathymetric changes are quite complex and do not uniformly affect the whole set of compartments. The direction of longshore sediment transport and constraints due to rocky headlands, river mouths or harbour jetties leads to the development of a pattern of sedimentary cells (Certain et al., 2005).

Compartment 1 is divided into 12 cells (Fig. 5). Between 1895 and 1984, the accretional sector of each cell downdrift of the river mouth (Tech, Têt and Agly river: cells 3, 7, 8 and 9) or updrift of harbour jetty (south Saint-Cyprien, north Saint-Cyprien, south Canet and Port Leucate: cells 4, 5, 6 and 11) records the largest gain in this compartment. Other cells located in between accretional cells show stable or slightly erosional trends (cells 2, 10), while cells at either extremity of the compartment are erosional (cells 1 and 12). During the period 1984–2009, all the cells underwent erosion, with maximum values measured in cells near the Têt river mouth (cell 7) and the Tech river mouth (cell 3). An inversion of the sedimentary budget is then observed...
during the 20th Century, except for cells at the border of the compartment where erosion continued.

Compartment 2 is divided into 13 cells (Fig. 5). For the period 1895–1984, the sediment budget in the south (cells 14 to 21) was stable or positive, whereas cells father north at the Orb river mouth (22 to 24) were generally erosional. For the period 1984–2009, the entire compartment underwent erosion, with erosion being more marked updrift in the north of the compartment (cells 18 to 25).

Compartment 3 is divided into 3 cells (Fig. 5). Between 1895 and 1984, only the north (cell 28) was undergoing erosion, while the rest of the compartment (cells 26 and 27) was accretional. Between 1984 and 2009 the entire compartment was undergoing erosion, with maximum loss in the north (cell 28).

Compartment 4 is divided into 7 cells (Fig. 5). Almost all the cells were undergoing erosion during both periods. However, erosion was more intense towards the south and the centre (cells 29 to 33), whereas the northern cells 34 and 35 were relatively protected.

4.3. Sediment availability

On most seismic profiles, it is possible to identify USU isolated from the rest of the underlying deposits by a high-amplitude reflector (Fig. 6). The top of the USU corresponds to the seabed, with a morphology generally characterized by a bar-and-trough system. The thickness of the USU decreases rapidly offshore down to the mean closure depth. The USU generally overlies a rocky substratum or, more often, a beach rock layer, forming a hard floor separating the USU from the underlying packed sands, which consequently become isolated from the coastal sediment budget. In the present-day shoreface, the USU represents a reservoir of sand that is potentially mobile and thus available for sedimentary exchanges. Since each surveyed site is relatively homogeneous, we only consider three representative cross-shore profiles here to illustrate three of the studied zones (cells 8, 20 and 27, Fig. 6).

The volume of the USU (Fig. 7) shows highly significant differences (up to a factor of 10) between maximum values in the south and central area (compartments 1 and 2), where they can reach 5.2 m$^3$/m$^2$ (cell 18) and minimum values in the northern part of the Gulf of Lions (compartments 3 and 4), where the values range from 0.5 to 1.0 m$^3$/m$^2$.

Differences also exist at the compartment scale. In compartment 4, the USU volume increases from south (cell 29: 0.5 m$^3$/m$^2$) to north (cell 33: 0.8 m$^3$/m$^2$). In compartment 3, the mean USU volume is around 1 m$^3$/m$^2$ but available sand volume increases from 0.5 m$^3$/m$^2$ in the updrift zone (cell 28) to 1.8 m$^3$/m$^2$ at the downdrift end (cell 26). In compartment 2, the USU volume reaches 1.7 m$^3$/m$^2$ (cell 20) and 5.2 m$^3$/m$^2$ (cell 18). In compartment 1, the mean USU volume exceeds 1.5 m$^3$/m$^2$, with USU values ranging between 1.3 (cell 5) and 3.2 m$^3$/m$^2$ (cell 12).

This distribution and size of sand reservoirs (Fig. 7) is closely related to the littoral drift pattern architecture of source and sink. The volume of the sand reservoirs increases downdrift, both at the regional scale (>100 km) and at the compartment scale (>10 km). There is a strong contrast between source zones, where the USU volume is low (cell 29; cell 28), and sink zones where the USU volume is high (cell 12; cell 18) (Fig. 7).

4.4. Long-term USU volume trends

Long-term USU volume changes display large spatio-temporal variations (Fig. 8). In terms of spatial distribution, the alternating positive
and negative values in compartment 1 express a strong contrast between adjacent cells, even though the overall volume of USU in the compartment remains positive between 1895 and 2009. The rate of change depends on the location of the cells in relation to the presence of river mouths and harbour jetties, and correlates with the sediment budget variations by cells (Fig. 5). In compartment 2, the USU volume trend is stable in the south but more than 20% of the initial USU volume has been eroded farther north, even though this compartment is located in the central zone of converging longshore drifts. In the north of compartment 3 and in compartment 4, especially since the initial amount was low (Fig. 7) and not sustainable (cf. Section 2.3), almost 2/3 of the sedimentary reservoir has been significantly eroded within a century.
with maximum of 80% of the initial USU volume has been eroded for cells 28 and 30.

5. Discussion

The general interest of this study to assess its applicability to other coastal areas depends on its ability to reflect the influence of the main factors responsible for the observed changes, since they are also in action in other regions of the world.

5.1. Longshore transport, USU volume and sediment budget distribution

The general pattern of fluvial inputs at the scale of the gulf parallels the regional distribution of USU volume, which is itself correlated with the shoreface sediment budget (Certain et al., 2005). Generally, the greater the depletion of the USU reservoir, the more negative the sediment budget trend and vice versa, but there are local exceptions that can provide some valuable information. This spatial distribution is a consequence of the diverging pattern of longshore sediment transport between compartments 3 and 4, and converging drifts towards the central part of the Languedoc-Roussillon coast from compartments 1 and 2.

In the south (compartment 1), variations in USU volume and longshore sediment budget are more varied than in the north (compartment 3 and 4). Indeed, the USU is segmented by natural boundaries at river mouths (Tech, Tête and Agly), where fluvial sediment supply resulted in the development of prodeltaic lobes which form sedimentary reservoirs that were gradually used up during the recent period. Then, the reworked material is re-distributed over the downdrift beaches and shoreface.

Between compartments 1 and 2, the sediment is relatively abundant owing to the converging pattern of longshore sediment transport towards the central sector of the Languedoc-Roussillon coast (Durand, 1999). However, at the centennial scale, beaches associated with voluminous reservoirs do not necessarily avoid being affected by shoreface erosion (Certain et al., 2005). For example, at Cap Leucate (cell 12), even though the USU makes up a large volume of sediment along the Languedoc-Roussillon coast (3.2 m$^3$/m$^2$) (Fig. 7), erosion is recorded at the secular scale (more than 20% of USU volume eroded during the century) (Fig. 8). This contrast between large USU volume and secular erosion (1895–2009) appears to reflect a significant shift between an earlier period of deposition by longshore drift (before 1895) and a reduction of longshore sediment inputs (1895–2009). At present, even the intense erosion in the updrift parts of the compartments is insufficient to provide sufficient quantities of sediment downdrift.

Towards the north (compartments 3 and 4), the distribution and size of sand reservoirs (Fig. 7) is closely related to the longshore drift pattern. The volume of the reservoirs increases in the downdrift direction (Certain et al., 2005). For example, in compartment 3 (Sète lido), the available sand reservoir increased sixfold between the updrift zone (north Sète lido, cell 28) and the downdrift side (south Sète lido, cell 26). For compartment 4, the available sand reservoir increased fourfold between the updrift zone (Frontignan, cell 29) and the downdrift side (Carnon, cell 33). The total volume of USU on the north Languedoc-Roussillon coast is low, and has decreased by 50% on average during the last century. Both compartments are currently deprived of any fluvial sediment supply and this significant reduction of the sand shoreface prism could lead to its rapid disappearance.

5.2. Influence of storm climate changes on secular sediment budget

In the context of the marine climate in the northern part of the Western Mediterranean, according to Ullmann and Moron (2008) and Sabatier et al. (2009), the analysis of the wave climate does not reveal any increase in the force of storm waves. Over the long term, the temporal analysis of storm surges reveals only very weak increasing trends (Sabatier et al., 2009). Between 1905 and 2003, Sabatier et al. (2009) point out that a slow increase can be observed in the height of the annual maximum surge (+3.0 mm/year ± 0.6 mm; p > 99%) and the annual frequency of the number of surges (+0.07 day/year ± 0.02 day/year; p > 99%). Although these trends are weak, they are statistically significant, suggesting a very slow increase in the number and intensity of storms surges during the 20th century due to the slow rise in sea level.

Even when taking these very weak trends into account, the proposed values cannot be directly correlated with the shift from an equilibrium situation (1895–1984) to a major sedimentary deficit (1984–2009). From another point of view, it is unlikely that the regional impact of storms (Ullmann and Moron, 2008; Sabatier et al., 2009) could induce strong spatial contrasts between compartments 3 and 4 (significant erosion since 1895), or the observed shift in compartments 1 and 2 from sediment accretion (1895–1984) to an dominantly
erosional state (1984–2009). Consequently, we propose that the slow regional climatic changes at the present-day represent a secondary factor influencing LSCB changes. However, forecasts for 2100 (around +0.18 to 0.59 m of global sea-level rise, IPCC, 2007) imply an increased impact of climate change on the shoreface.

5.3. Influence of river sand input on secular sediment budget

To understand the long-term evolution of the Languedoc–Roussillon shoreface, it is necessary to estimate the influence of river sand inputs on secular sediment budget, especially since these inputs contribute to the formation of the upper sand unit (Barusseau et al., 1994, 1996). Owing to the decrease in sediment input since the end of the Little Ice Age and the development of infrastructures to control river channels, fluvial sediment supply at the present-day appears limited compared to the beginning of the 20th century (Surell, 1847; Pardè, 1925; SOGREAH, 1999; IRS, 2000; Antonelli, 2002; Pont et al., 2002; Lique et al., 2009). This overall behaviour is also reflected in the Languedoc–Roussillon data, since the last major flood event dates back to 1940 and the discharge of rivers partly controlled by human infrastructures has dropped sharply from the early 1970s onwards (Fig. 2). Indeed, during the period 1984–2009, all river mouths and adjacent cells systematically underwent strong erosion (Fig. 5).

From 1984 to 2009, sediment discharge from rivers, estimated at between 6.5 and 8.9 × 10⁶ m³ (cf. Table 1), is 2.5 to 3.5 times lower than the loss of sediment in compartments 1 and 2 (−22.1 ± 3.1 × 10⁶ m³). More precisely, the ratio of sediment volume loss to sediment discharge is 2.5 for compartment 2 (Aude, Orb and Hérault rivers), 3 to 5 for compartment 1 (Têt, Té,t and Agly rivers). Thus, even though the rivers continue to supply sediment, their inputs are insufficient to counteract marine erosion.

Our analysis points out that the decrease of river sediment input is locally recent in compartments 1 and 2. For example, during the period 1895–1984, bathymetric changes in cells adjacent to the mouths in compartment 1 show a systematically positive budget, indicating that river sand input re-distributed in areas near the river mouth favours shoreface accretion (Tech, Têt and Agly) (Fig. 5). Consequently, during the period 1895–1984, we assume that rivers discharged enough sediment to feed the lidos and shoreface morphology of the southern compartment (Barusseau et al., 1994, 1996; Durand, 1999). However, in the absence of sufficient fluvial supply to the sea, prodelta lobes and more generally littoral prism sand bodies now form sedimentary reservoirs that are gradually being used up.

This trend reflects the present context of a general “climatic” and anthropogenic decline of river sediment transport and discharge to the sea (Lique et al., 2009; Lespinas et al., 2010; Serrat et al., 2001; Pont et al., 2002; Walling and Fang, 2003). It is very difficult to distinguish between natural and artificial effects on fluvial discharge, but decrease of river sediment supply has been clearly reinforced by human activities with dam construction and dredging often being described as responsible for coastal erosion (Guillén and Palanques, 1993; Milliman, 1997; Pont et al., 2002; Poulos and Collins, 2002). In the Languedoc–Roussillon region, dams built on rivers to control flooding have led to a drastic reduction (−80%) of fluvial discharge (Têt example: Fig. 2) (Ludwig et al., 2004; Bourrin, 2007). Consequently, very few floods are able to transport sediment because of the limitation of competence upstream from the dams. Moreover, sediment extraction in the lower river valley (around 7 × 10⁶ m³ between 1971 and 1992) represents 1/3 of the sedimentary deficit in the Roussillon and Narbonnais sectors (compartments 1 and 2) between 1984 and 2009 (−22.1 ± 3.1 × 10⁶ m³). This estimate is probably lower than the volume actually involved since it does not take into account extractions before 1971 and illegal extractions after 1992. In this way, the sediment that should normally be distributed within the coastal zone is finally diverted due to human activities. Lastly, the persistent erosion recorded in compartments 3 and 4 should probably be attributed to the lack of any fluvial input since 5000 year BP (Sabatier and Suanez, 2003; Sabatier et al., 2006; Ferrer et al., 2010).

5.4. Influence of coastal engineering

The impact of harbours on the long-term shoreface budget is complex (Short, 1992) and non-uniform. Natural longshore sediment re-distribution was strongly disturbed by coastal management after the 1960s (Argelèes, Saint-Cyprien, Canet, Port Barcarès and Port Leucate). Each harbour jetty generates the formation of an artificial boundary with a sink on the updift side and a source zone on the downdrift side. In the Gulf of Lions, harbours account for 2/3 of the cell boundaries, exceeding the number of natural boundaries ever since the 1960s.

In Languedoc–Roussillon, the balance between accretion in cells updift and erosion downdrift of harbours jetties can be locally positive, as shown between 1895 and 1984 (Fig. 5: cells 6, 7, 11 and 12). For these sites, even though the trend is negative during the period from 1984 to 2009, a relative equilibrium state is maintained at the secular scale (1895–2009). This long-term morphological evolution is probably linked to the adaptation of the lower shoreface to the installation of harbour jetties under favourable sedimentological conditions (cf. Section 5.3). As negative secondary effects of harbours on sediment budget only appeared during the 1984–2009 period, this long-term morphological evolution suggests that there is a “time-lag” between the construction of the hard engineering structures (1960) and negative secondary effects (visible since 1984). This time-lag, which is about 25 years in the case of the Roussillon coast, increases the difficulty of differentiating the impact of natural forcings and anthropic activities when analysing the coastal system.

However, in the recent period (1984–2009) characterized by an overall negative budget, offshore sediment transport is enhanced mainly by the presence of groynes and jetties in coastal sectors where cross-shore and rip currents (Short, 1992; Kraus et al., 1994) have already been observed (Durand, 1999). For example, cells 4, 5, 9 and 10 (Fig. 5) show evidence of intense erosion. The volume of sediment eroded in the downdrift cells is higher than the volume deposited in the updift cells (Fig. 5). In the Gulf of Aigues Mortes, the overall deficit is so large at the secular scale that the impact of the harbour is integrated within this dominant trend without leading to any improvement in the situation.

Since the 1980s, coastal managers have addressed the problem of erosion by carrying out beach nourishment. However, at the scale of the Languedoc–Roussillon coast, the ratio between the volumes of eroded sediment and beach nourishment is extremely disturbed since the sediment budget from 1984 to 2009 is −30.2 ± 4.2 × 10⁶ m³, while the artificial re-nourishment is only 2.6 × 10⁶ m³ over the same period, which is 12 times smaller than the losses of sand.

Lastly, dredging practices can increase the deficit as shown in the case of Port-La-Nouvelle (compartment 2, cell 15). Over a period of 25 years (1984 to 2009), 1.5 × 10⁶ m³ of sand was dredged for harbour access, representing 10% of the sediment losses in this compartment between 1984 and 2009. As the disposal site is located at a water depth of −20 m, it is unlikely that this material can contribute to the shoreface nourishment in a natural way.

5.5. Offshore sediment transport deduced by the sediment budget

The assessment of long-term negative sediment budgets raises the question of sediment losses and it should be borne in mind that the estimated volumes are largely greater than the error margins. When applying the sediment budget concept, losses of sediment can be considered in various ways, either cross-shore or alongshore.

Although landward migration of sands towards the beach and the beach barrier has been observed in a few places, no significant natural onshore beach movements are recorded (Durand, 1999). Similarly, the limited amount of sediment deposition by washover, which occurred
locally during the Little Ice Age (Dezileau et al., 2011), can be regarded as negligible at the present day (Sabatier et al., 2008). Consequently, the negative sediment budget of the shoreface cannot be explained by landward sediment transport.

Longshore losses are difficult to envisage at the northern and southern extremities of the study area. In fact, it would be necessary to assume contrary longshore drift directions, which would cast doubt on the whole pattern of cells along the Languedoc-Roussillon coast (Fig. 1). These cells are based on geomorphological indicators (Durand, 1999; Sabatier et al., 2009) such as sedimentary accumulations against groynes and harbour jetties (in the south) and the Espiguette sand spit (in the north). Moreover, there is no evidence for a progressive migration of sands towards the compartment extremities. For instance, in compartments 3 and 4, the significant masses of sediment eroded in the divergence zone (cell 28 to 33) do not contribute to the downward drift and the sediment budget in the south (cells 27 to 26) and north (cells 34 to 35) is declining, or stable at best (Fig. 5). Even in the central convergence zone between compartments 1 and 2, the volume of deposits accumulated is lower than the volume of sediments eroded in both the south (cells 1 to 11) and the north (cells 18 to 25). Centrifugal movement is only observed in the Gulf of Aigues Mortes, where the amount of sediment is strongly reduced and the littoral drift pattern is dominantly conservative with a converging movement towards the northern part of the gulf at the Espiguette spit, between the Languedoc-Roussillon and Camargue coasts (Fig. 1).

Finally, the only conceivable outlet for sediment losses is represented by the offshore zone at ≤ 12 m depth, as already theoretically considered by Jago and Barusseau (1981). We suppose that important sediment removal is mostly due to downwelling during storms or dense water cascading (Palanques et al., 2006). Moreover, field measurements along the shore at Sète and Leucate at around 6 m water depth display offshore currents during storms (Gervais et al., 2012), such as observed at 28 m depth on the Têt inner shelf (Guillén et al., 2006). It is thus highly probable that a large part of the negative sediment budget of the Languedoc-Roussillon shoreface is explained by offshore losses such as observed along other sandy coasts (Backstrom et al., 2009; Sabatier et al., 2009). The negative global sediment budget computed down to −8/−12 m depth implies considerable loss of sediment beyond the closure depth (−6 to −8 m, Sabatier et al., 2004). These movements of fine sand escape the detection on this temporal and spatial scale, despite the fact that this information is essential for coastal management. This bias does not prevent us from regarding the provided estimates as indicative of the sediment budget on the shoreface. Although the general negative sediment budget of the compartments between 1984 and 2009 suggests offshore sediment loss, this mechanism was probably also present between 1895 and 1984, as well as in compartments fed by river inputs. In such cases, the large sedimentary load carried by rivers would offset the offshore sediment transport.

6. Conclusion

In this study, we analyse the sediment budget and the variations of USU volume over a period of more than a century on the Languedoc-Roussillon shoreface (Gulf of Lion, France). Our objective is to relate the large-scale behaviour of a shoreface to the distribution of longshore sediment transport, climatic change, river sediment input to the coast and impact of human activities (hard engineering structures, sand dicing and beach nourishment).

The methodology is based on an original approach using long-term bathymetric analysis (1895–1974–2009) combined with seismic and LiDAR surveys and a thorough knowledge of the mechanisms in action.

Firstly, our results show an erosion of the Languedoc-Roussillon shoreface over a period of 114 year. For the period 1895–1984, the overall sediment budget is slightly positive. By contrast, the sediment budget for 1984–2009 clearly indicates that erosion is dominant over the last 25 years. Secondly, since the initial amount is low and locally not sustainable, the secular-scale evolution of USU volume shows that the shoreface sand reservoir is significantly eroded within a century. As observed on other major beaches worldwide, the Languedoc-Roussillon coast has been subject to the erosion of its shoreface for more than half of the 20th century.

The main factors proposed to explain the decrease of shoreface sediment budget include (1) the weak redistribution of sandy inputs from rivers towards the beaches, (2) the gradient of longshore transport, (3) considerable losses towards the offshore zone and (4) sand dredging practices.

Indeed, it appears that present-day rivers cannot nourish the beaches of the Languedoc-Roussillon coast, due to decreased sediment input since the end of the LIA and artificial control of river channels. Even an exceptional flood, such as the 1940 event, hardly amounts to half of the erosional loss of sediment over a century. Not only was the 1940 flood an exceptional event, but also the artificial management subsequently carried out on the catchment prevents the re-occurrence of such an episode. Under these conditions, the sediment budget of prodeltaic lobes and adjacent beaches will continue to be negative, since these bodies are destroyed by wave action, and the shoreline will migrate landwards.

Furthermore, it is expected that more and more beaches will suffer severe recession, especially in littoral downdrift zones where smaller amounts of sand are available to accumulate on the shoreface. For example, this sediment deficit affects particularly the sector between compartments 3 and 4, but could spread to the whole coastal zone of those compartments within the next century if the observed decline in sediment supply persists.

Lastly, the shoreface sediment deficit has been clearly reinforced by dredging practices. Indeed, the total volume of sand dredged in the Languedoc-Roussillon rivers and Port-La-Nouvelle harbour from 1970 to 2009 represents 1/3 of the total sediment losses between 1895 and 2009.

In the case of a depleted prism, only an input from a new source of sediment could offset the lack of sediment supply. Such a process is currently observed locally, where reworked pebbles from Quaternary fluvial deposits are derived from outcrops located at −5/−10 m depth, but this has no impact on the input nourishing the adjacent beaches.

A strategic retreat may be envisaged to cope with erosion in cases where beach nourishment cannot be carried out due to the excessive volumes of sandy material required, since our results clearly show a chronic sedimentary deficit that will not be resolved under the marine, fluvial and anthropic conditions prevailing at the present day.

In conclusion, we may emphasize the advantage of pooling results about datasets of depth changes and seismic and morphological definition of the sandy unit involved in the sediment exchange between the beach and the shoreface. The relationship between LSCB on one hand and initial USU volume on the other is complex and must be evaluated in each case study. This method is likely to provide better estimates of coastal sediment budget and should enable politicians and environmental managers to make decisions in full knowledge of the coastal processes.

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