SECULAR SEDIMENT BUDGET OF THE LANGUEDOC-ROUSSILLON SHOREFACE (WESTERN GULF OF LIONS)

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Abstract

This paper presents a shoreface sediment budget established for the 20[th] century (1895-1984-2009), along with the results of seismic THR surveys along the microtidal wave-dominated coast of the western Gulf of Lions (Languedoc-Roussillon, Mediterranean Sea, SE France). The aim of this study is to link the Large Scale Coastal Behaviour (LSCB) of the western Gulf of Lions 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 littoral prism over 114 yr due to (1) the "natural" decrease of river sediment input, (2) the lack of sediment supply by rivers, because the river channels are controlled by dams and human activities and (3) the littoral prism sand is composed of sedimentary reservoirs that are gradually being used up.

Key words: Shoreface, sediment budget, seismic VHR, Gulf of Lions.

1. Introduction

The coastal system is highly dynamic at different scales in time and space, which can have potentially significant impacts upon both the 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 (Vincent et al., 1983; Wright and Short, 1984), 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 (Boyd et al., 1992). Unfortunately, it is extremely difficult to establish sediment budgets accurately (Pilkey et al, 1993). Shoreface behaviour remains poorly understood (Hinton and Nicholls, 2007; Cowell and Thom, 1994), especially at the longest timescales (secular), because: (1) the lack of a good-quality long-term dataset means that it is necessary to observe coastal behaviour on a sufficiently large spatial scale (100 km) (Stive et al., 2002), (2) the 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 time scale (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 sitting 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 Stern (Stern, 2007) it is cheaper to prevent erosional problems than to be faced with their consequences.

This study is focused on the Languedoc-Roussillon shoreface (western Gulf of Lions, Mediterranean Sea,

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SE France). Understanding the evolution of this shoreface is essential because the adjacent shorelines, which have locally been subject to intense erosion over the last decades (Durand, 1999), are also affected by the high summer flux of tourists. Many coastal studies have been conducted in this region (Barusseau and Saint-Guily, 1981; Barusseau et al., 1994; Certain et al., 2005), including quantitative approaches by Durand (1999), Certain (2002) and Samat (2007). 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 global 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 quantify the evolution of the Languedoc-Roussillon shoreface sediment budget using three extensive bathymetric datasets covering a period of more than a century (1895, 1984 and 2009) at the regional scale (>100 km). This macro-scale study allows us to identify the influence of natural and anthropic parameters on shoreface evolution. The safety or vulnerability of the beach to erosion is investigated by an original approach comparing the long-term shoreface sediment budget and the upper sand unit volume (USU) measured by seismic VHR surveys. The discussion then successively treats the validity and limits of the results, the role of climatic forcings, fluvial input, longshore and cross-shore sedimentary distribution and, finally, the impact of human activities in controlling the long term shoreface budget.

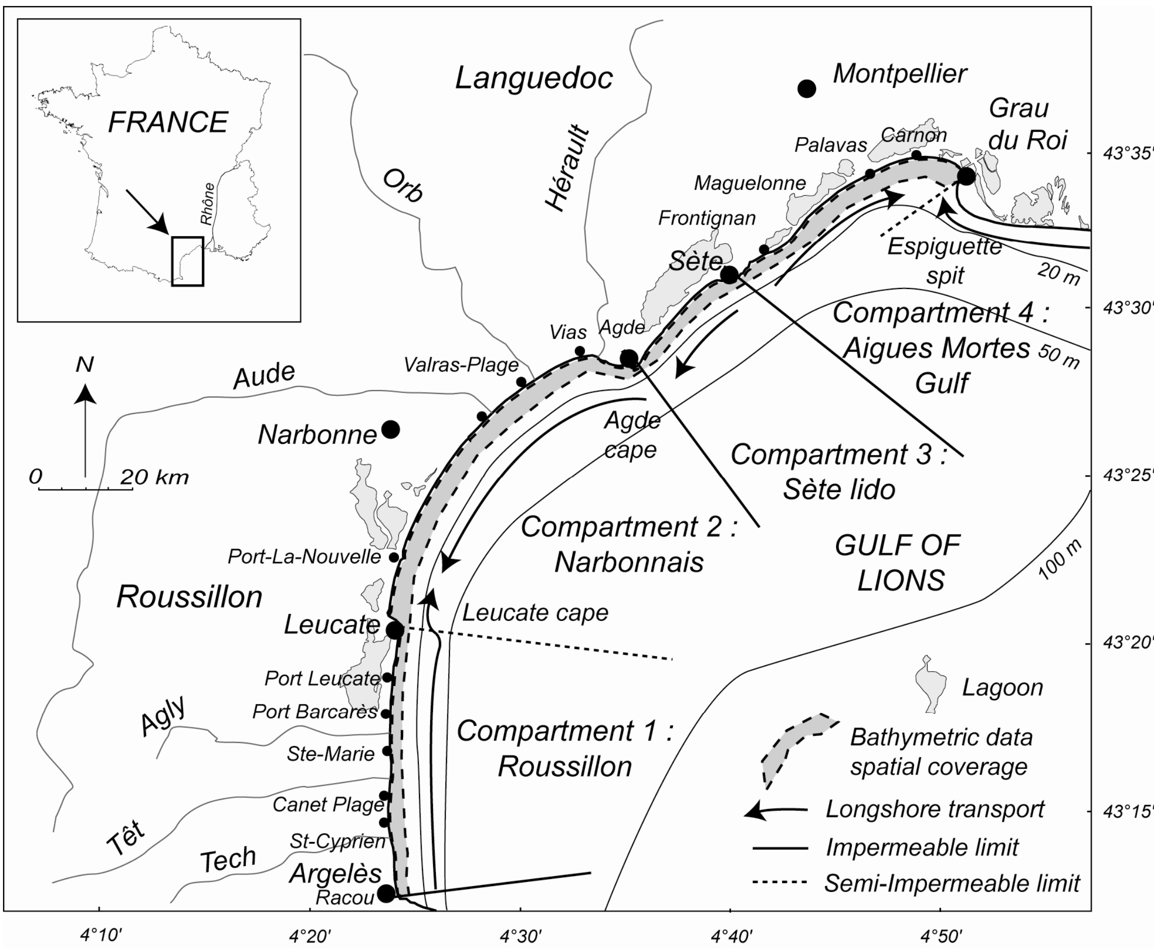

Figure 1. Coastline of the western Gulf of Lions divided into four main compartments. Arrows indicate the longshore drift direction. The nature of the limits between compartments is explained in the text.

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 and Le Grau du Roi in the north (Fig. 1). The coast is mainly made up of sand beach barriers that have isolated numerous lagoons. Beach barriers are interrupted by rocky capes (Cap Leucate, Cap d'Agde, Sète) delimiting the four main sedimentary compartments of the Languedoc-Roussillon coast: Roussillon, Narbonnais, Sète lido and Gulf of Aigues Mortes (Schuster, 1966; Barusseau and Saint-Guily, 1981; Barusseau et al., 1994; Durand, 1999). Beach states are mainly intermediate and rarely dissipative or 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%. 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 (Durand, 1999; 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). The littoral sands generally overly a rocky substratum or older sedimentary formations ranging from the Quaternary to the Pliocene in the south (Martin et al., 1981) and the north (Frontignan) (Raynal, 2008).

2.2. *Marine dynamics and sediments inputs*

The Gulf of Lions is a typical wave-dominated microtidal environment according to Hayes's classification (1979). Two wind orientations prevail in the study area: NW offshore winds and E-SE onshore (Casanobe, 1961). 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 it can exceed 3.5 m with periods of between 5 and 9 s, reaching 7 m during exceptional storms (1982, 1997, 2003) with periods around 12 s. Temporal analysis of the mean sea level shows a rise of 8 cm during the 20^{th} century at Marseilles, corresponding to a trend of +1.1 mm/year (Pirazzoli, 1986; Suanez, 1997; Brunel and Sabatier, 2009).

Sediment volumes transported by the longshore currents have been estimated as ranging from 10,000 to 40,000 m^3 per year (Durand, 1999). In compartments 1 and 2, beach shoreface sediment is mainly supplied by six main 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). Although Holocene deposits coming from the River Rhône are predominant in compartments 3 and 4 (L'Homer, 1981), no direct input from this large river is recorded at present since the net longshore drift is eastward within compartment 4 (Sabatier et al., 2006).

The Mediterranean climate is characterized by catastrophic flash-floods of only a few hours (Pardé, 1941). In 1940, for instance, catastrophic floods in the southern part of the Gulf of Lions led to the formation of large deltaic and prodeltaic bodies in front of river mouths (Pardé, 1941). The total volume of sediments discharged into the sea by the Tech, Têt and Agly rivers during this exceptional event is estimated at between 9 and 13.5 $\times 10^6$ m^3 (Pardé, 1941) (Table 1).

Since the middle of the 20^{th} century, river development works, reafforestation and dam constructions have resulted in a drastic decrease of sediment supply to the coast (Durand, 1999; Koulinsky, 1998). From 1978, the maximum river discharge has been divided by 20 due to dams and a sediment volume of 370 000 m^3 appears trapped in the Caramany and Vinça dams on the Agly and Têt rivers, respectively (DDAF 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 certain authors, from 1984 onwards, the solid discharge (sands, gravels and pebbles) is estimated as ranging between 1000 and 18 000 m^3/year, with 18 500 to 34 500 m^3/year and 1000 to 5200 m^3/year for the Tech, Têt and Agly, respectively (compartment 1), and 80 000 to 100 000 m^3/year for the Aude, Orb and Hérault rivers respectively (compartment 2) (Table 1). The total annual discharge can be estimated at between 260 500 and 357 700 m^3, corresponding to a sediment volume of 6.5 to 8.9 $\times 10^6$ m^3 supplied by the rivers from 1984 to 2009 in the southern part of the Gulf of Lions. Compartments 3 and 4 are devoid of any rivers.

River	Catchment area (km²)	River length (km)	Mean discharge (m^3/s)	Bedload transport (m^3/y)	1940 Flood Solid load (M m^3)
Tech	726	82	9	1000 / 18000	5 / 7.5
Têt	1300	114	13	18500 / 34500	2.5 / 3.5
Agly	1040	80	7	1000 / 5200	1.5 / 2.5
Aude	830	150	45	80000 / 100000	No flood
Orb	4374	115	22	80000 / 100000	No flood
Hérault	2250	135	52	80000 / 100000	No flood

Table 1. Main parameters of Languedoc-Roussillon rivers.

The Languedoc-Roussillon coast has been transformed since the 1960s by the construction of 12 yachting resorts (Mission Racine). Today, more than 30% of the Languedoc-Roussillon coastline is equipped with hard coastal defence structures. Since 1980/90, sand beach nourishment has been implemented (2.6 $\times 10^6$ m^3). In compartment 1, 1.5 $\times 10^6$ 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 $\times 10^6$ m^3 was carried out in 2008. Finally, in compartment 2, dredging in the harbour channel of Port-La Nouvelle has led to the removal of 1.5 $\times 10^6$ m^3 of sands between 1984 and 2009, which were then released at a disposal site at a water depth of 20 m.

3. Methods

3.1. *Bathymetric data*

Three high-quality bathymetric data sets were analysed to determine and quantify the long-term bathymetric changes of the Languedoc-Roussillon shoreface.
Bathymetric data from 1895 were collected by the SHOM (Service Hydrographique de la Marine). Their treatment was based on classical methods (Dolan et al., 1980), applied in similar long-term sediment budget studies on other French coast (Sabatier et al., 2006, 2009; Bertin et al., 2004). The charts were scan ned (600 dpi), digitized 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© (Institut Géographique National). Then sounding points were manually digitised. Bathymetric data from 1984 collected by the SHOM, were extracted from the HistoLitt® data base (SHOM-IGN). Bathymetric data from 2009 collected by FUGRO were extracted from an aerial “LIDAR”.
All soundings are corrected to the common French horizontal and vertical reference system (Lambert 93 and the French National Levelling vertical datum). According to the SHOM, the maximum vertical error does not exceed ± 0.3 m for the 19th century survey (1895 data) and ± 0.2 m for the 20th century survey (1984 data). According to Aleman et al., (2011) the maximum vertical errors do not exceed ± 0.3 m vertically for the Lidar bathymetric survey (2009). The X and Y coordinates errors are estimated at ±10 m for the 1895 and 1984 SHOM data, and ± 0.2 m for the 2009 FUGRO data; however, due to the very gentle mean slope, we assume horizontal errors are negligible in the volume estimation.
For each date, we computed a Digital Terrain Model (DTM) developed by numerical triangulation interpolation. The amount of erosion or sedimentation is determined by comparison of DTMs for the periods 1895-1984, 1984-2009 and 1895-2009. The sediment budget in m^3 is obtained from the difference between the accretional volume (bathymetric variations > 0.5 m for 1895-1984 and 1984-2009 and > 0.6 m for 1895-2009) and the erosional volume (bathymetric variations < 0.5 m for 1895-1984 and 1984-2009 and < 0.6 m for 1895-2009). Positive and negative values imply sediment input and output, respectively. Bathymetric variations comprised between -0.5 m and + 0.5 m (for 1895-1984 and 1984-2009) and between -0.6 m and + 0.6 m (for 1895-2009) are used to calculate the volume error margin. The results of this spatial calculation yield the overall Languedoc-Roussillon long-term sediment budget for the four main sedimentary compartments (Roussillon, Narbonnais, Lido de Sète and Gulf of Aigues Mortes). Each

sediment budget by compartment is then distributed into cells. The isobath corresponding to the lower depth limit varies between -8 m and -12 m. As the mean closure depth is around -6 and -8 m (Durand, 1999; Sabatier et al., 2004), we assume that the volume considered includes the major part of the shoreface influenced by waves. Changes in the sub-aerial beach cannot be analysed because no data are available for the foreshore in 1895 and 1984. However, previous studies have shown that sub-aerial beach volume represents only a small part of the total sediment budget of the shoreface (Durand, 1999).

3.2. *VHR seismic data and Long-term USU volume trends*

The seismic profiler system used for the present study is a IKB-Seistec boomer (Simpkin and Davis, 1993), with a Delph recorded system. Position was determined by a differential GPS directly connected to the recorder. The IKB-Seistec vertical resolution is several decimetres (± 0.06 m). The available seismic data for this study cover a total of 18 sites surveyed from Grau du Roi to Le Racou. 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 bathymetric data. For each site (500 m coastline length), an average of 10 cross-shore profiles were surveyed on the lower and the upper-shoreface, i.e. the submerged beach (500 m average length). 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 long-term USU volume trend is calculated for the 18 cells where seismic data are available 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, measured between the instantaneous sea bottom in 1895 and the lower limit of the USU) Negative values imply reduction of the shoreface volume and long-term sediment output, whereas positive values suggest accretion of the shoreface volume and sediment input.

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×$10^6$$m^3$ (± 4.6) (-0.23×$10^6$$m^3$/year (± 0.04)). From 1895 to 1984, the overall sediment budget is slightly positive, with 4.1×10^6 m^3 (± 3.5), which corresponds to 0.05×$10^6$$m^3$/year (± 0.04). However, for the period from 1984 to 2009, the volume estimation clearly indicates that erosion is dominant over the last 25 years, with a budget of -30.2×10^6 m^3 (± 4.2) corresponding to -1.2×$10^6$$m^3$/year (± 0.16). Figure 2 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. 2). For 1895-1984, compartments undergoing accretion correspond to the southern part of the study area, with values of 9.4×10^6 m^3 (± 0.6), or 0.1×$10^6$$m^3$/year (± 0.01), in compartment 1 (Roussillon), and 8.7×10^6 m^3 (± 1.4), or 0.10×$10^6$$m^3$/year (± 0.02), in compartment 2 (Narbonnais). Otherwise, sectors undergoing erosion correspond to the northern part of the study area, with values of -1.1×10^6 m^3 (± 0.6), or -0.01×$10^6$$m^3$/year (± 0.006), in compartment 3 (Sète Lido), and -12.8×10^6 m^3 (± 0.8), or -0.14×$10^6$$m^3$/year (± 0.01), in compartment 4 (Gulf of Aigues Mortes).

For the period 1984-2009, all compartments are subject to erosion, with values of -6.3×10^6 m^3 (± 1.6) or -0.25×$10^6$$m^3$/year (± 0.06); -15.7×$10^6$ m^3 (± 1.5) or -0.62×$10^6$$m^3$/year (± 0.06); -3.2×$10^6$ m^3 (± 0.2) or -0.12×$10^6$$m^3$/year (± 0.008) and -4.8×10^6 m^3 (± 0.8) or -0.19×$10^6$$m^3$/year (± 0.008) for compartments 1, 2, 3 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.

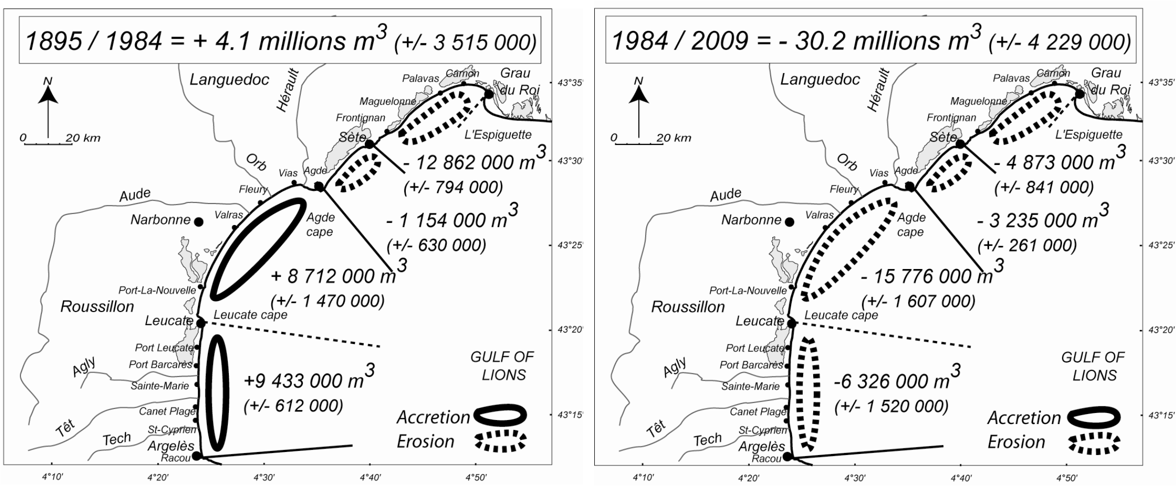

Figure 2. Sediment budget (m^3) between 1895/1984 and 1984/2009 by compartments, with margin of error (m^3).

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 lead a pattern of sedimentary cells (Fig. 3) (Durand, 1999; Certain, 2002).
Compartment 1, corresponding to the Roussillon coast, is divided into 12 cells. Between 1895 and 1984, the accretional sector of each cell in this compartment (downdrift of the river mouth or updrift of harbour jetty) records the largest gain. For instance, the gain recorded in the Tech, Têt and Agly river cells (3, 7, 8 and 9) is estimated at 2×10^6 m^3 (±0.002), 0.4×10^6 m^3 (±0.04), 2.7×10^6 m^3 (±0.02) and 0.7×10^6 m^3 (±0.16), respectively. The following gains are recorded in the south Saint-Cyprien, north Saint-Cyprien, south Canet, and Port Leucate cells (4, 5, 6 and 11, respectively): 0.4×10^6 m^3 (±0.3), 0.9×10^6 m^3 (±0.3), 1.7×10^6 m^3 (±0.1) and 2.9×10^6 m^3 (±0.07). 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): -0.37×10^6 m^3 (±0.01) and -2×10^6 m^3 (±0.03). During the period 1984-2009, all the cells underwent erosion, with maximum values measured in cells near the Têt river mouth: $-2\times10^6 m^3$ (±0.4) (cell 7) and the Tech river mouth: $-1\times10^6 m^3$ (±0.4) (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: -0.2×10^6 m^3 (±0.04) and -0.6×10^6 m^3 (±0.1), respectively. Compartment 2, corresponding to the Narbonnais coast, is divided into 13 cells. For the period 1895-1984, the sediment budget in the south (cells 14 to 21) was stable or positive (between 0.07 and 3.7×10^6 m^3), whereas cells father north at the Orb river mouth (22 to 24) were generally erosional (between -0.3 and -2.5×10^6 m^3). For the period 1984-2009, the entire compartment underwent erosion, with an average loss of -1.2×10^6 m^3 per cell, with erosion being more marked updrift, in the north of the compartment (cells 18 to 25). Compartment 3, corresponding to the Sète lido, is divided into 3 cells. Between 1895-1984, only the north (cell 28) was undergoing erosion (-2.2×10^6 m^3 (±0.7)), while the rest of the lido (cells 26 and 27) was accretional: 0.5×10^6 m^3 (±0.08) and 0.5×10^6 m^3 (±0.15), respectively. Between 1984-2009 the entire lido was undergoing erosion: -2.2×10^6 m^3 (±0.07 m^3) were lost to the north (cell 28), with budgets of -0.6×10^6 m^3 (±0.1) at the centre of the lido (cell 27) and -0.3×10^6 m^3 (±0.15) farther south (cell 26). Compartment 4, in the Gulf of Aigues Mortes, is divided into 7 cells. Almost all the cells were undergoing erosion during both periods, with an average loss per cell of -1.8×10^6 m^3 between 1895-1984 and -0.7×10^6 m^3 between 1984-2009. 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.

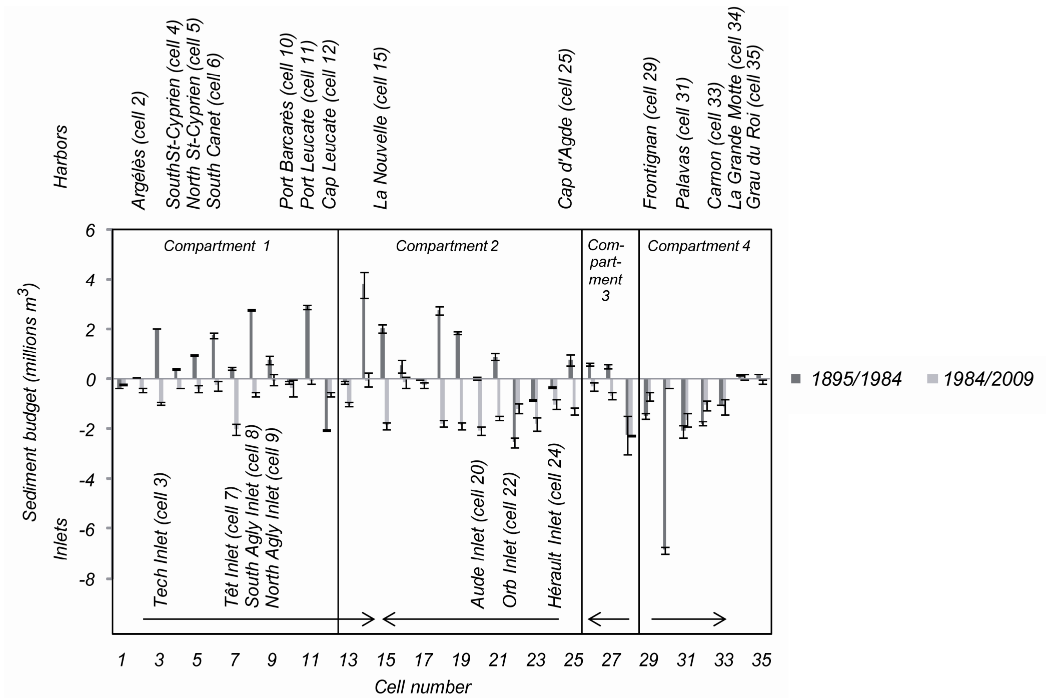

Figure 3. Comparison between sediment budgets (m^3) for 1895-1984 and 1984-2009 by cells, with error margins (m^3). Arrows indicate the net longshore drift direction. (cf. Figure 1 and 2 for location).

4.3. *Sediment availability and long-term USU volume trends*

On most seismic profiles, it is possible to identify an upper sand unit (USU) isolated from the rest of the underlying deposits by a high- amplitude reflector. The top of the USU corresponds to the sea bed, 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 beach rock layer (BRL). The volume of the USU (Fig. 4) 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: Narbonne) and minimum values in the northern part of the Gulf of Lions (compartments 3 and 4), where they remain around 0.5 m^3/m^2. Differences also exist at the compartment scale. In compartment 4 (Gulf of Aigues Mortes), the USU volume increases from south (cell 29, Frontignan: 0.5 m^3/m^2) to north (cell 33, Carnon: 0.8 m^3/m^2). In compartment 3 (Sète lido), 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: North Sète Lido) to 1.8 m^3/m^2 at the downdrift end (cell 26: Sète south lido). In compartment 2 (Narbonnais), the USU volume reaches 1.7 m^3/m^2 (cell 20: Aude inlet) and 5.2 m^3/m^2 (cell 18: Narbonne). In compartment 1 (Roussillon), the mean USU volume exceeds 1.5 m^3/m^2, with USU values ranging between 1.3 (cell 5: north Saint-Cyprien) and 3.2 m^3/m^2 (cell 12: Cape Leucate). This distribution and size of sand reservoirs 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).

Long-term USU volume changes display large spatio-temporal variations (Fig. 5). 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. 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, almost 2/3 of the sedimentary reservoir has been significantly eroded within a century, especially since the initial amount was low and not sustainable (cf. 2.2).

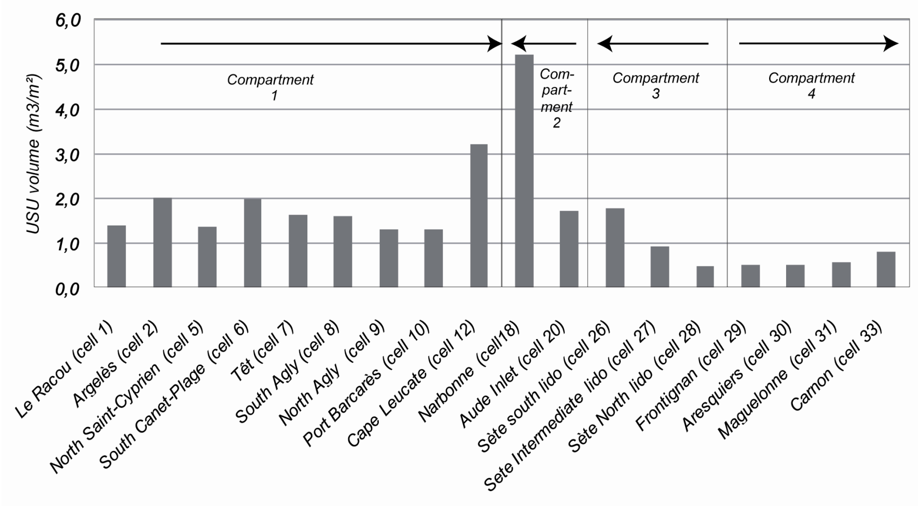

Figure 4. Present-day volume (m^3/m^2) of upper sand unit. Arrows indicate the net longshore drift direction.

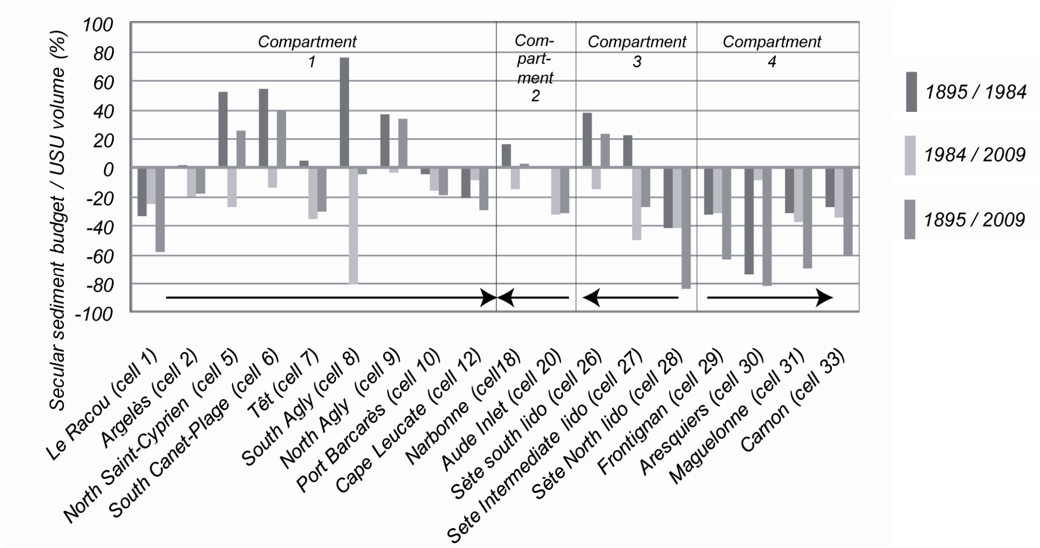

Figure 5. Time-evolution of upper sand unit for 1895-1984, 1984-2009 and 1895-2009 (in %). Arrows indicate the net longshore drift direction. (cf. Figures. 1 and 3 for locations).

5. Discussion

5.1. *Influence of storm climate changes on secular sediment budget*

In the context of the marine climate in the northern part of the West Mediterranean, according to Ullmann and Moron (2008) and Sabatier et al., (2009), analysis of the wave climate does not reveal any increase in the force of storm waves. On the long time scale, 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/yr +/−0.6 mm; p>99%) and the annual frequency of the number of surges (+0.07 day/yr +/ −0.02 day/yr; 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, which might justify a change of opinion.

5.2. ***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 (Stone and Donley, 1998), especially since these inputs contribute to the formation of the high-stand prism (Barusseau et al., 1994; Durand, 1999). 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. 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. Indeed, during the period 1984-2009, all river mouths and adjacent cells systematically underwent strong erosion (Fig. 3). From 1984 to 2009, the fluvial discharge, estimated at between 6.5 and 8.9×10^6 m^3 (cf. table 1: DDAF. des Pyrénées-Orientales, 1990; Koulinsky, 1998; Clique et al., 1984; Serrat et al., 1996, 2001; Bourrin, 2006; IRS., 2000; Pardé, 1941), is 2.5 to 3.5 times lower than the loss of sediment in compartments 1 and 2 (-22.1×10^6m^3 (±3.1)). 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, by settling out in areas near the river mouth, favours shoreface accretion (Tech, Têt and Agly) (Fig. 3). 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; 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 (Pont et al., 2002; Walling and Fang, 2003, Serrat et al., 2001). 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 (Guillen and Palanques, 1993; Milliman, 1997; Pont et al., 2002). In the Languedoc-Roussillon region, dams built on rivers to control flooding have led to a drastic reduction (-80%) of fluvial discharge (Bourrin, 2006). 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 7×10^6 m^3 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 (-22.1×10^6 m^3 ±3.1). 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 5,000 BP (Ferrer et al., 2010). However, due to the eastward avulsion of the Rhone 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 northern part of the gulf (Sète Lido, Gulf of Aigues Mortes) (Sabatier et al., 2006; Ferrer et al., 2010).

5.3. ***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*. 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 (compartments 3 and 4). Indeed, the USU is segmented by natural boundaries at rivers mouth (Tech, Têt and Agly) and by coastal management after the 1960s. In the Gulf of Lions, harbours account for 2/3 of the cell boundaries, exceeding the number of natural boundaries ever since the 1960s.
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 secular 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. 4), erosion is recorded at the secular scale (more than 20 % of USU volume eroded during the century) (Fig. 5). This contrast between large USU volume and secular erosion (1895-2009) appears to reflect a significant shift between a 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 volume of the reservoirs increases in the downdrift direction, but 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.

5.4. ***Losses towards the offshore***

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. Although landward migration of sands toward 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 (Sabatier et al., 2008), 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).
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). 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). 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).

5.5. ***Influence of coastal engineering***

The impact of harbours on the long-term shoreface budget is complex (Short, 1992) and non-uniform. In Languedoc-Roussillon, the balance between accretion in cells updrift and erosion downdrift of harbours jetties can be locally positive, as shown between 1895 and 1984 at Canet and Port Leucate. For these two 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). 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 have already been observed (Short, 1992). 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 -30.2×10^6 m^3 (± 4.2), while the artificial re-nourishment is only 2.6×10^6 m^3 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 39 years (1970 to 2009), 1.5×10^6 m^3 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.

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 Lions, France).

First, 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, the secular-scale evolution of USU volume shows that the shoreface sand reservoir is significantly eroded within a century (between 20 and 80% of USU has been eroded). 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 i) the weak redistribution of sandy inputs from rivers toward the beaches, ii) the gradient of longshore transport, iii) considerable losses towards the offshore zone and iv) 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 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 north of Sète lido and south Aigues Mortes Gulf, but could spread to the whole coastal zone of the Sète lido and Gulf of Aigues Mortes within the next century if the observed decline in sediment supply persists.

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. In conclusion, we should bear in mind the need to integrate long-term (secular) coastal morphology with the changes in sediment budget and USU volume to quantify shoreface evolution. This approach should enable politicians and environmental managers to make decisions with a fuller understanding of the coastal processes.

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