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Large Scale Evolution of the Littoral of the Rhone Delta (Southeast France)

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ABSTRACT

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A study of changes to the Rhone delta littoral at the mouth of the Rhone delta was made using diachronic analysis of aerial photographs and satellite images. The evolution of the coastline shows that the littoral has been prograding over the last fifty years. The evolution by different sectors shows that the sectors located to the east of the mouth of the Rhone have prograded while the western part has eroded. The whole of the littoral is being displaced towards the east because of the action of littoral drift currents, oriented west-east, and the western waves.

ADDITIONAL INDEX WORDS: *Coastal evolution, aerial photointerpretation, image analysis, coastal erosion, deltaic environments.*

INTRODUCTION

Coastal deltaic environments are extremely changeable. The use of photo-interpretation and analysis of satellite images allows an understanding of the changes, which is essential to the management of the littoral. These methods of analysis have been applied to a part of the littoral of the Rhone delta situated on either side of the mouth of the Rhone river.

This study is part of continuing research on the evolution of the Rhone delta (BLANC, 1975, 1977, 1982, 1993; VERNIER, 1976; L'HOMER, 1992; SUANEZ and PROVANSAL, 1993). First, morphosedimentary changes to the littoral over the last fifty years will be investigated. The evolution of these modifications by homogeneous sectors will be the object of the second part of this paper. Finally, the analysis of forms of erosion and accretion will lead to several hypotheses on the impact of morphodynamic factors that dominate the littoral.

THE STUDY AREA

The study area is located on either side of the mouth of the Rhone (Figure 1). It encompasses La Gracieuse spit and Napoléon beach to the east and Piémanson beach to the west. The present-day morphogenetic factors are:

(1) The fluvial dynamic : characterized by sedimentary influxes from the river to the sea, principally during floods. The bottom load, mainly sandy (CARRIO, 1988) plays a major role in the sediment supply to beaches. It is estimated from *(i)* known data on material in suspension (RODITIS and PONT, 1993; PONT, 1993).

(2) The marine dynamic : represented by swells and currents. Swells come from three main directions : SW (30% of the total regime), SSE (16%), and SE (11%). The dominant currents are *(i)* the Ligurian-Provence current flowing from east to west. It does not influence the morphogenesis of the littoral very much because it is located in the open sea (DUBOUL-RAZAVET, 1956), *(ii)* the drift currents flows from west to east close to the coast. It plays an important role in the sediment transport.

(3) The aeolian dynamic : represented by continental winds (the Mistral and the Tramontane, oriented N–NW, 31% of total regime) and the sea winds, mostly oriented E to SE (27% of the total regime). The latter is principally related to storms.

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EVOLUTION OF THE LITTORAL OVER A FIFTY YEAR PERIOD

The diachronic analysis, based on the study of aerial photographs and satellite images, shows the change in coastline over the last fifty years. The method consists of superposing the layers of information date by date (Figure 2).

Method

Acquistion and analysis of the image data were made at the Computer Resource Centre of St. Jerome University (Marseille), using software called PERICOLOR (MATRA), and IAX software installed on the IBM 3090 system. It is based on methods used in previous work on changes to the littoral using image analysis (GUILLEMOT and THOMAS, 1985; WANG and VERGER, 1985; VERGER *et al.,* 1987; GRENIER and DUBOIS, 1990; SHOSHANY and DEGANI, 1992; CROWELL *et al.,* 1991, 1993; KUNTE, 1994; DOLAN *et al.,* 1991).

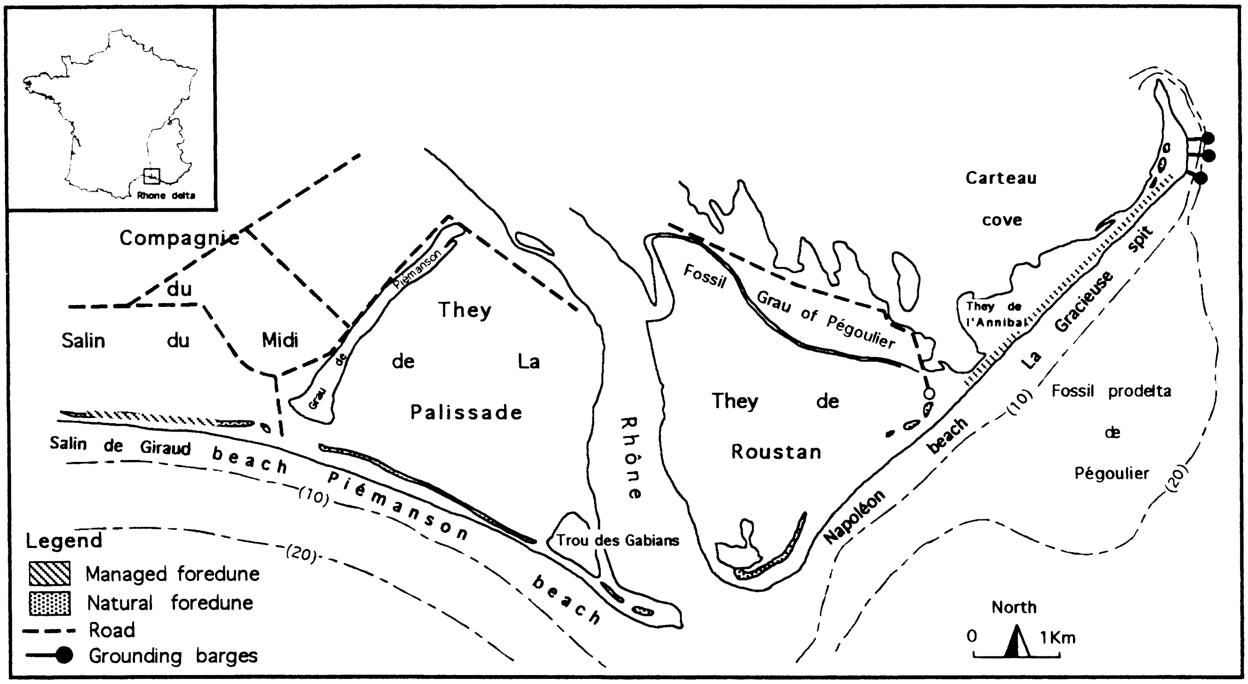

Figure 1. Location map.

Data Acquisition

Aerial photographs from 1944 were taken during the last world war by allied forces. These photographs will be compared to four sets (1955–1960–1971–1979–1989) taken later on by IGN (Institut Géographique National) and private compagny (Aerial). The use of satellite imageries (Landsat TM) concern the two last periods : 1984 and 1993.

These data constitute sampling at the scale of one decade and allow the evolution of the coastline to be studied over the last fifty years.

Data Acquisition and Geometric Correction

Photo-interpretive zoning was made of the images after the assemblage of a mosaic covering the whole of the sector studied. The mosaic was then captured by video camera with a resolution of about 3 m from the ground. Digitalization was done from the screen.

Geometrical corrections were made using a landmark system. For each of the dates, many landmarks (ruins, buildings, road intersections, etc.) have been taken as topographic references. These landmarks have been carefully located on the IGN topographic map at 1/25,000. This grid of points has been digitized in the same way as the mosaic obtained for photo-interpretation and used as a reference document.

Analysis of satellite data uses the traditional methods of classification. Discrimination of the emerged part of the littoral was made by classifying wet zones, using the infrared TM5 channel. Skeletization of the coastline was made using contours.

Diachronic Analysis

The studed area extends from west to east, from Piémanson beach to La Gracieuse spit and from north to south (changes recorded in Carteau cove being considered). The superposition of data allowed the changes in the coastline to be observed over the last fifty years. Quantification of sectors undergoing accretion and erosion was made using a morphometric module installed under the PERICOLOR system. This software allows calculation of coded surfaces and measurement of different parameters corresponding to these surfaces (large and small diameter, lengthening and cuvature coefficients, perimeter, barycenter, *etc.*).

Results

The morphologic evolution of the littoral is expressed in m^2 (Figure 3). The sum of the surfaces undergoing erosion and accretion is calculated for each period. Four trends appear:

(1) During the 40s and 50s, the morphologic evolution is very slow, indicated by a relative stability of the system.

(2) Starting in the 60s and until the end of the 70s, there is a progradation of the littoral system.

(3) The 80s are characterized by a phase of erosion.

(4) The beginning of the 90s shows a new prograding system.

A variation coefficient of the littoral was calculated for each period, taking into account all of the central values (Table 1):

$$\textit{Variation coefficient: } \kappa_{xi} = [(\sigma_{Sxi} / \sigma_S) * 100] / \delta_t$$

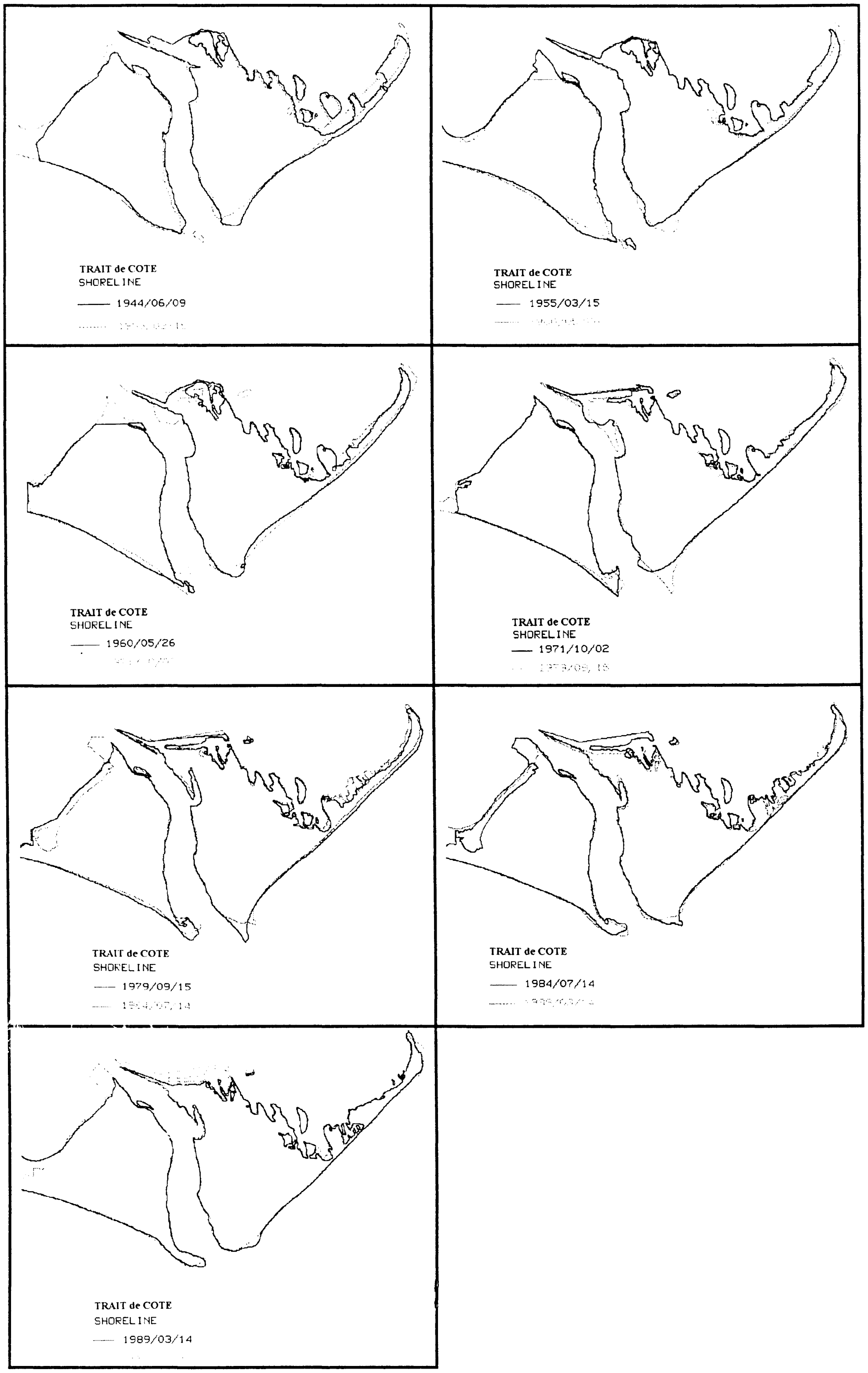

Figure 2. Mi-secular shoreline changes of the Rhone delta at the mouth area.

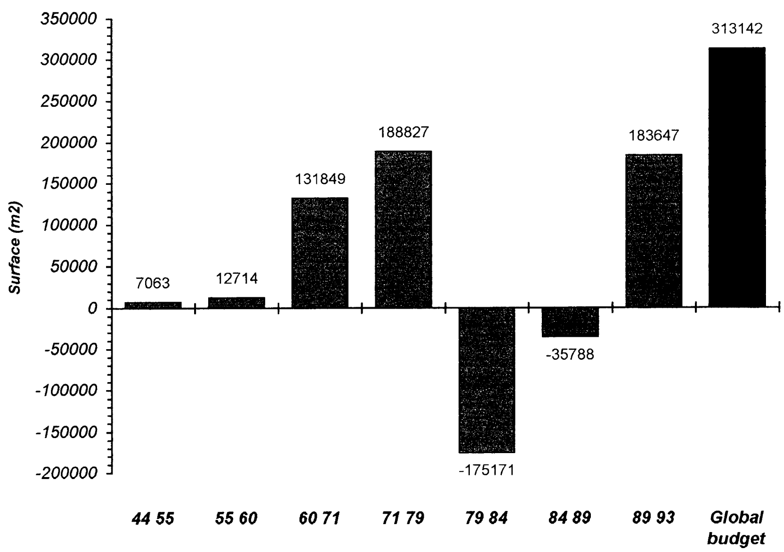

Figure 3. Morphological evolution of the littoral over the last 50 years (in m²).

σ_{Sxi} = budget for the period considered
σ_S = global budget (over the whole period)
δ_t = nb of years

Conclusion

Two main conclusions can be made from the first part of the analysis:

(1) The littoral in this sector is prograding overall. The budget over the last fifty years is positive : +313142 m2 (Figure 4). This gain is mainly concentrated during the period going from 1960 to 1979. To transform shoreline displacement into volume changes, a closure depht of 8 m has been adopted. This is based on the method described by JIMENEZ and SANCHEZ-ARCILLA, 1993; JIMENEZ *et al.,* 1993. A volumetric gain of about 50,000m3/year is obtained. However, it possible that the zone is directly influenced by sediment influx from the Rhone, due to its location close to the river mouth. Comparison with other sectors of the Camargue is necessary.

(2) Modification of the coastline over the last fifty years was not uniform over time. The dispersion obtained by the variation coefficient indicates an erratic evolution. It is probable that the frequency distribution and the intensity of the main morphogenetic factors, which are floods and storms, play an important role in this evolution.

EVOLUTION OF THE COASTLINE BY SECTOR

Method

Five homogeneous sectors have been defined in function of their dominant morphodynamic factors (Figure 5):

Table 1. *Evolution of variation coefficients of the littoral over the last fifty years.*

1944–55	1955–60	1960–71	1971–79	1979–84	1984–89	1989–93
0, 2	0, 8	3, 8	7, 5	−11, 2	−2, 3	14, 7

(1) Piémanson beach, oriented NW-SE, is a sector that is very vulnerable to SW swells, which are the most frequent type during the year.

(2) The zone situated at the mouth of the Rhone is directly related to the sediment supplied by the Rhone.

(3) Napoléon beach is vulnerable to SE swells and is also supplied by Rhone sediments transported by drift currents currents, flowing west to east.

(4) La Gracieuse spit is characterized by a double evolution. Since the end of the 19th century, it has evolved naturally. Due to the rehabilitation program at La Gracieuse spit, started by the *Port Autonome de Marseille* in 1988, all of the morphosedimentary processes have become entirely artificial.

(5) The evolution of the tip of La Gracieuse spit, is also completely controlled by human intervention since the 1970s. The grounding of barges on the tip of the spit has greatly influenced the evolution of the littoral in this sector.

The aim is to evaluate the role of each sector in the global evolution for each period.

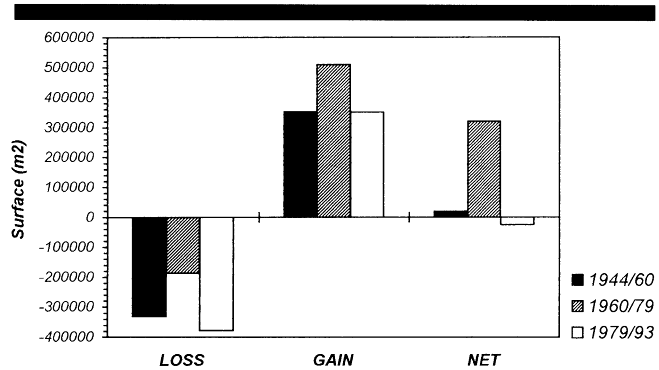

Figure 4. Rates of deltaïc area changes (in m²).

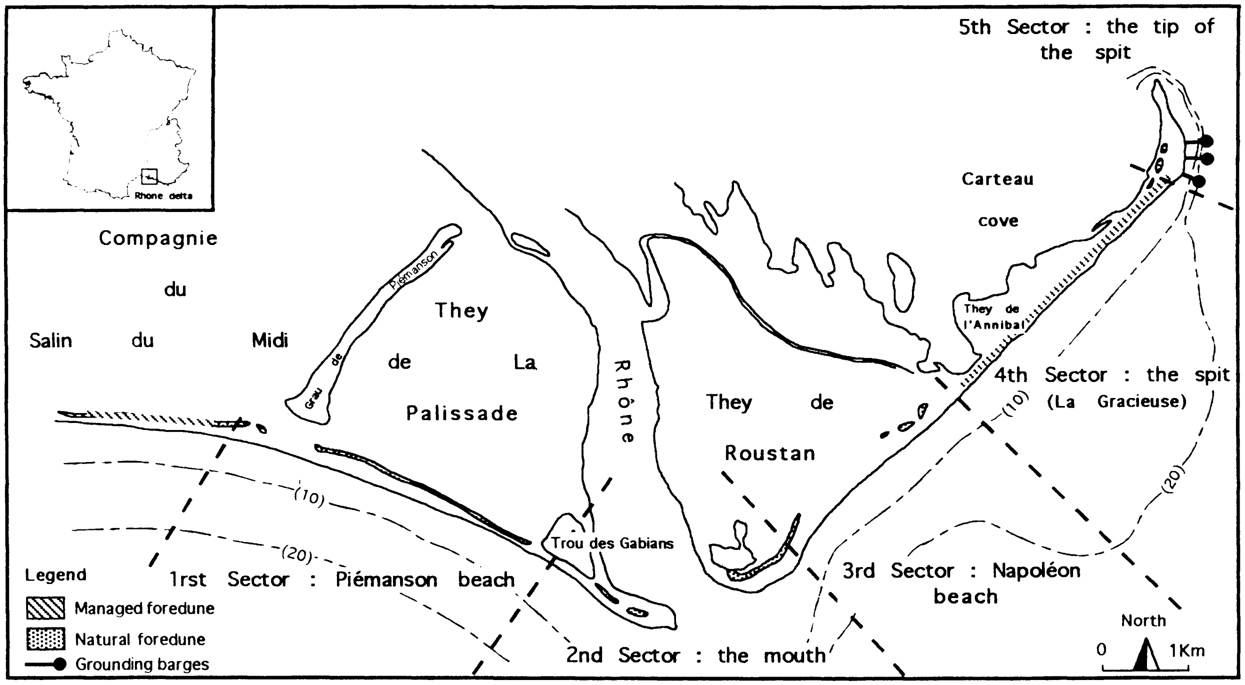

Figure 5. Division of the littoral into five homogeneous sectors according to the dominant driving agents.

Observations (Figure 6)

The first period (1944–60) is characterized by very low changes. The whole coast has not recorded significant variations. Important changes appear for the second period (1960–79). The Piémanson beach is characterised by a loss of sediment while the other sectors were prograded. The recent period (1979–93) shows a different situation : the mouth of the Rhone has eroded, the Piémanson beach is still characterized by a loss of sediment while La Gracieuse spit has strongly prograded.

Commentary

(1) The evolution of the river mouth is complex. It is marked by alternating periods of accretion and erosion, which may correspond to flood periods of the Rhone. There is a continuous displacement of the river mouth towards the east, which is indicated by the accumulation of sediments related to the drift currents. Two statements can be made : *(i)* the question of the origin of this material is posed, *(ii)* it seems that the river fluxes are not sufficient enough to allow the progradation of the littoral perpendicular to the coastline.

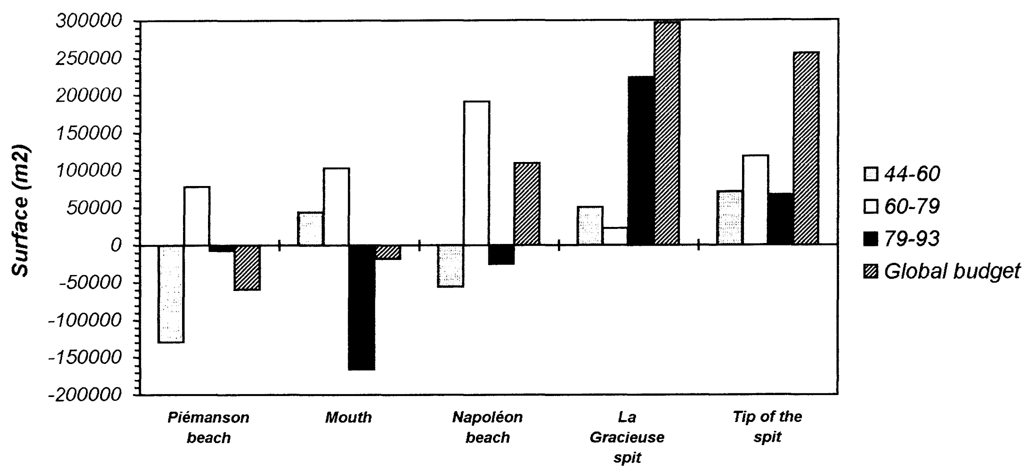

Figure 6. Rates of deltaïc area changes by different sectors (in m²).

(2) Piémanson beach is characterized by a slow but continuous evolution over time. Starting from the 40s, its profile tends to become more regular in the ESE direction. The retreat of the littoral is particularly important at Le Trou des Gabians. It seems that the sedimentary material lost at Piémanson beach in this area is transported and deposited, forming the spit that partially closes the outlet of the Rhone. This sediment transfer is facilitated by the drift currents, flowing from west to east.

(3) The changes recorded at Napoléon beach are very small, the coastline evolves very little in this sector and the periods of progradation coincide with those occurring when the river mouth records a loss of material. This process is highly visible between 1960 and 1971, indicated by the effects of a reworking of Rhone sediments. Napoléon beach is considered as a transit zone where sedimentary transfers indicate a time lag between the flood sediments of the Rhone and their redistribution in the littoral, situated to the east of the river mouth.

(4) The evolution of La Gracieuse spit until the 80's is a prolongation of the morphological and sedimentary history of this sector since the end of the 19th century. The closure of Pégoulier inlet and the artificial opening of Roustan inlet in 1896 have resulted in the progressive construction of the spit under the effect of a dominant SW beach drift that connects the islets (or *theys*) to the pro-delta of Pégoulier. In 1944, Annibal *they* was not connected to the emerged sandy part. The two were not connected until 1955. From 1944 to the 80's, the coastal retreat at La Gracieuse spit did not result in the rupture or the partial disappearance of this buildup. The central part of the sand deposit was displaced towards the NW. The present-day equilibrium profile was made in the mid–80s. Since this period, the buildup as a whole seems to have stabilized, and since the beginning of the 90s there has been an enlargement of its tip that is linked to the development by the *Port Autonome de Marseille* since 1988. The rehabilitation of coastal dunes and the immersion of barges has stopped the NW displacement of sediment and the enlargement of the beach from the reconstituted dunes and the drift currents.

(5) The evolution of the tip of La Gracieuse spit is marked by two steps. Up until the mid–60s, it is characterized by a lengthening of its tip. This progradation is oriented towards the NE. Starting from the 70s, the development by the *Port Autonome de Marseille* modified all of these changes. Repeated grounding of barges perpendicular to the littoral resulted in a disturbance of the train of SW swells. The refraction phenonmena that follow modify the sedimentation of the sector, facilitating buildup in the NNW direction.

Conclusion

There are three main changes to the coastline:

(1) Evolution of the littoral over the past fifty years is characterized by a general displacement of the whole of the system to the east. The changes are particularly visible in the area of the river mouth. They are the result of the action of two morphodynamic factors : dominant SW swells and drift currents, flowing from east to west. This observation tends to minimize the impact that the SE swells can have, which is particularly efficient during autumn storms.

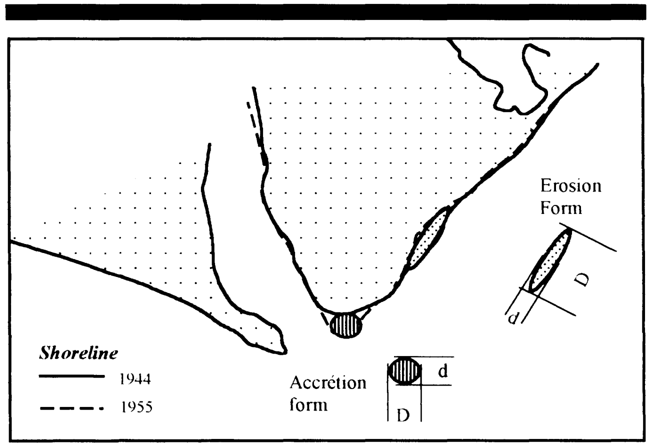

Figure 7. The use of erosion and accretion form parameters to calculate the morphometric parameters (d) and (e).

(2) The progressive displacement of the sedimentary masses from one sector to another is shifted in time. This out of phase evolution of the littoral shows that the sedimentary transfer from the river mouth is characterized by a response time that is more or less rapid, depending on the sector. This process can be explained by damming phenomena encountered by dominant flows, oriented from east to west : *(i)* the first can be explained by the arrival of fluvial currents at the sea, it favors the accumulation of a sediment load in the area of the river mouth, *(ii)* the second is formed by the submarine topography of the fossil promontory of Pégoulier, facilitating sediment accumulation on Napoléon beach, *(iii)* the last is constituted by the grounding of barges at the tip of the spit, inhibiting a part of the sedimentary transit.

(3) The intermittent progradation of the river mouth has a SSE to SE direction : the temporary construction of sandy fans could correspond to periods of high activity of the Rhone. This brings into question the role of floods in terms of frequency, intensity and the nature of sedimentary material in suspension.

MORPHODYNAMIC PROCESSES AND SEDIMENTARY TRANSPORT

Method

The morphometric parameters (lengthening coefficient (e) and the length of the small diameter (d) have been calculated from image analysis. Forms of erosion and accretion can be characterized using this method (Figure 7).

The length of the small diameter corresponds to the distance (d) generally perpendicular to the coast. It allows the quantification of changes to the coast in terms of retreat or progradation. A high value of (d) indicates the intervention of rapid morphodynamic processes where forcing phenomena (floods, storms) may have played an important role.

The lengthening coefficient ($e = D/d$) allows the evaluation of changes to the littoral parallel to the coastline. A high val-

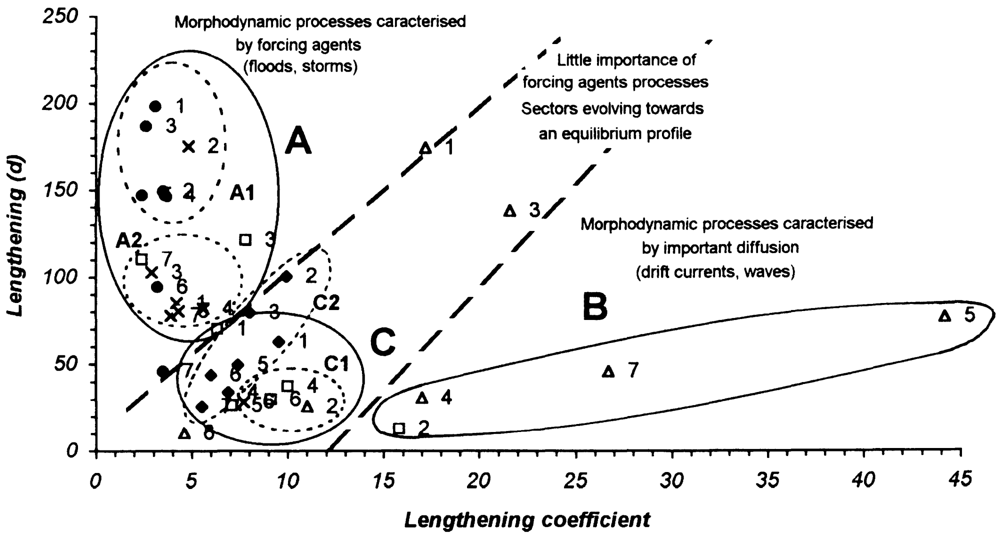

Figure 8. Crossing of morphometric parameters (d) and (e) by sectors and periods. ● The mouth, □ Napoléon beach, ◆ Piémanson beach, × La Gracieuse spit, and △ The tip of the spit, *1*—1944–55, *2*—1955–60, *3*—1960–71, *4*—1971–79, *5*—1979–84, *6*—1984–89, and *7*—1989–93.

ue of (e) can be explained by the domination of drift currents facilitating redistribution or lateral transfer.

Observations

Figure 8 shows the distribution in time and space of the relationship between parameters (e) and (d). The following observations can be made :

(1) An initial group (A) is subdivided into two groups (A1) and (A2). The sub-group (A1) is characterized by high values of (d), between 150m and 200m, and a very low lengthening coefficient (< to 5). It mostly includes the data corresponding to the river mouth sector. The sub-group (A2) is also characterized by a very low lengthening coefficient (< to 5), whereas the values of (d) are between 70m and 120m. For the most part, it includes data corresponding to the tip of La Gracieuse spit and several data corresponding to Napoléon beach (1960–71) and 1989–93).

(2) The second group (B) is defined by a high lengthening coefficient (between 15 and 45), whereas the value of (d) is small (< to 60m). It includes sectors of the littoral situated to the east of the river mouth : Napoléon beach and La Gracieuse spit.

(3) The last group (C) is subdivided into two sub-groups (C1) and (C2). Its homogenity is due to values expressed by lengthening coefficients between 5 and 10. Conversely, a distinction can be made using the parameter (d). The sub-group (C1) includes the sectors situated to the east of the river mouth : Napoléon beach and La Gracieuse spit. It is characterized by values of (d) lower than 30m. The sub-group (C2) can be explained by values of (d) between 30m and 70m. It is mainly represented by Piémanson beach.

Commentary

The first group (A) shows that the morphosedimentary processes respond to rapid dynamics of accretion or erosion where forcing is a decisive factor. Periods of very high progradation could correspond to "repeated" periods of flooding. Periods of erosion would be the result of an increase in the frequency of storms. These dynamics mainly influence the river mouth sector and Napoléon beach (depending on the period). The modal functionning of Napoléon beach is comparable to the La Gracieuse spit sector. During a flood period, it records a part of the sedimentary influx as well as the river mouth sector. This difference in magnitude of energy explains the high values of (d) recorded for the periods 1960–71 and 1989–93. The presence of the tip sector shows that the "anthropic forcing" (grounding of barges at the tip of La Gracieuse spit) plays an important role in the morphosedimentary evolution of this sector.

The second group (B) corresponds to the sectors where sedimentary transport related to the swells and drift currents are dominant. It mainly includes sectors situated to the east of the river mouth (La Gracieuse spit).

The last group (C), mainly composed of Piémanson and Napoléon beaches, is characterized by slow morphosedimentary processes of little importance, indicated by a relatively stable situation. These two sectors evolved towards an equilibrium profile. The most representative example is Piémanson beach : the spatial distribution of the parameters (d) and (e) trend towards zero from the earliest to the most recent periods. Today there is almost no change recorded in this sector.

Conclusion

These results show that the Camargue littoral can be divided into three areas, according to their evolution through time :

(1) The river mouth, Napoléon beach (episodically), as well as the tip of the spit sector are characterized by exceptional morphodynamic processes where the forcing factors (natural or artificial) play an essential role.

(2) Piémanson and Napoléon beaches evolve more regularly, under the effects of swells and drift currents. The change in coastline is continuous and the trend is towards an equilibrium profile.

(3) The morphosedimentary processes at La Gracieuse spit are characterized by a slow displacement of a wide band of mid- and infra-littoral sandy material. The SW swell and the drift currents influence the evolution of the littoral in this sector.

DISCUSSION

Aerial photographs and satellite images facilitate the study of displacement of the coastline over time. Photo-interpretation is much more precise than satellite images for the changes observed (GRENIER and DUBOIS, 1990; CROWELL *et al.*, 1990). The study had the following results :

The evolution of the littoral area as a whole is characterized by a progradation, and therefore probably by a positive sedimentary budget over the last fifty years. This result confirms the importance of Rhone sediment influxes and poses the question of the true impacts of recent managements along the Rhone on the transit of suspended sediment. Input of sandy material (bottom load) seems sufficient to supply this part of the Camargue littoral. This being so, a comparison of these results with the data obtained on the Petite Camargue sector (BLANC, 1975, 1977, 1982, 1993), makes it necessary to interpret the data carefully. The author shows that the western part of the Camargue (Faraman, Beauduc and Stes. Maries de la Mer) is characterized by a retreat of the littoral over the last several decades. Progradation of the littoral in the eastern sector (Piémanson, Napoléon and La Gracieuse spit) can be explained by the proximity of the mouth of the Rhone.

The evolution of the coastline over the last fifty years shows that the whole area was displaced eastward, following the orientation of the drift currents currents. Fluvial currents flowing southward only play a minor secondary role. The managements along the length of the Rhone have undoubtedly reduced water flow of the river, decreasing the effects of floods at the outlet. Today, there is a partial closure of the river mouth, which is oriented towards the east. The possiblility of the infilling of Roustan Inlet could have resulted in the opening of a new outlet at Gabians Inlet.

The observations made on the dominant morphodynamic processes for each sector of the delta shows the probable importance of floods and storms in the evolution of the littoral. Analysis of these data was made by constructing a model of the flooding of the Rhone and its tributaries, and the study of a correlation between the liquid debit and solid debit (PONT, 1993). Research is in progress on the correlation be tween the liquid and solid debits of the Rhone and the evolution of the sedimentary budget over the last fifty years. Similar observations can be made for storms. The analysis, compared to several storms and morphosedimentary responses of the littoral (BRUZZI, 1995), has shown the complexity of the processes whose effects should be considered for the study of development of the littoral.

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