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Review

Deltaic plain development and environmental changes in the Petite Camargue, Rhone Delta, France, in the past 2000 years

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ABSTRACT

The deltaic plain of the Petite Camargue which constitutes the western part of the Rhone Delta, began its main progradation around 2000 yr ago. Several delta lobes follow each other and have participated in the deltaic evolution. The deltaic lobes have distinct morphologies which reflect the dynamic fluvial and marine processes under the influence of climatic and human controls. Two delta lobe systems were built by the Daladel and Peccaïs channels, after which a deflected wave-influenced delta lobe was formed by the La Ville and Saint-Roman channels. The latest channel, the Rhone Vif channel, is skewed because this channel was completely canalized and engineered up to its mouth in the beginning of the 16th century. Since the avulsion of this channel about 1550 A.D., the coastline of the Petite Camargue has been especially affected by the influence of waves and currents. The spits replaced the beach ridges which juxtaposed themselves and have migrated westward since the 16th century. The formation of the western part of the delta in the last 2000 yr is affected by not only the fluvial sedimentary fluxes and the coastal dynamics to the mouth but also climatic change and human influence.

Introduction

Much recent literature emphasizes that the evolution of large Mediterranean deltas have been driven in particular by the rates of postglacial sea-level rise and the rates of fluvial sediment supply. There is considerable variation, and the importance of individual sedimentary processes (fluvial, marine, and aeolian) is not clear. Although the chronology and amplitude of Holocene sea-level variations differ according to different authors (Labeyrie et al., 1976; Aloisi et al., 1978; L'Homer et al., 1981; Aloisi, 2001; Vella et al., 2005), the general shape of all interpreted relative sea-level curves have one common characteristic, the decrease in the rate of rise from 7000 yr ago (Fig. 1), which conforms with the global model established for stable oceanic margins (Bard et al., 1993; Montaggioni and Faure, 1997). This phenomenon helps to explain the formation of most large deltas throughout the world (Stanley and Warne, 1994). Some authors consider fluctuations in relative sea level to be entirely responsible for the progradation of deltaic lobes (Collectif Camargue, 1970; L'Homer et al., 1981). But according to Arnaud-Fassetta (1998), the construction and evolution of the Rhone delta are fundamentally controlled by eustacy and variation in sediment supply.

Rhone delta deposits began to agrade and prograde on the Mediterranean coast about 6000 yr ago, after the high stand of sea level and due to the influence of sedimentary fluxes. More recent studies established a working chronology for the Rhone paleochannels (Saint-Ferreol, Albaron-Peccaïs, Ulmet and others) and the deltaic lobes (Arnaud-Fassetta, 1998; Vella et al., 2005; Rey et al., 2005; Rey, 2006). Themobility of Rhone delta coastlines has been a product of the influence of fluvial sediments, climate and anthropogenic forces. 5 periods have been marked by more abundant sediment supply, as has been determined in the Arles plain (Bruneton et al., 2001) and along the palaeochannels in the delta (Arnaud-Fassetta, 2002). Most of the very fast progradation and avulsion (river bed instability) appears to be coeval with stable sea-level and abundant sediment input (Provansal et al., 2003).

The purpose of this study is to present a summary of the progradational phases recognized in the deltaic plain of Petite Camargue. To understand the stages of accretion and to determine a regional chronology for Holocene beach ridges and rivers, Paleochannels and relict Holocene dunes have been investigated and cored to determine the depositional environments and have been dated by ^{14}C. We examine the evolution of the Petite Camargue delta plain to evaluate the effect of changes in climate, sediment discharge, and anthropogenic influences in controlling the morphology and avulsion history of the associated distributary channels. We also discuss the implications of erosion and beach replenishment along the Petite Camargue.

Geographical setting

The Rhone delta is located in the northern part of the western Mediterranean basin, at the north of the Golfe du Lion. The plain of the Rhone Delta forms a 50 km long, 70 km wide complex of Holocene

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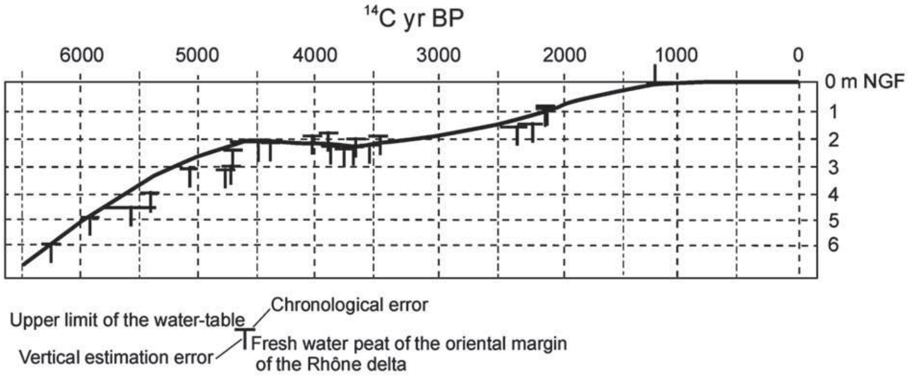

Figure 1. Sea-level on the Rhône Delta (from Vella and Provansal, 2000). Radiocarbon dates of fresh water peat used to plot the curve of relative sea level in meters NGF (means French Standard Levelling). Datations by Centre de datation par le radiocarbone de Lyon France. Calibrations according to Stuiver and Braziunas, 1993.

sediments deposited by the Rhone River in lagoon or marine basins. The distance between the delta apex near Arles and the coast is ≈40 km (Fig. 2). The Rhone Delta is usually identified as a wave-dominated delta (Galloway and Hobday, 1996). Its morphology and size depend on the fluvial (stream power, sediment discharge) and marine processes (waves, currents, deeper plate form) which shape it.

The Rhone coast is microtidal. The dominant wind directions are to the NW, N and NE, which drive coastal currents to the west or east. The only long-period waves come from the east to south-east and give rise to a dominant westward littoral drift. The combination of wave dynamics and lateral migration of the distributary mouths give rise to a rapid shoreline evolution. Winds not only control coastal currents but also transport significant quantities of sand, which broaden strandplain and coastal dunes along the Rhone. Holocene deposits are close to the coastline and are eroded by waves in several locations. They are found along the entire coast and, at present, nourish beaches which generally show a negative sedimentary budget. Actually, most of the coastline is eroding, except the Espiguette and Beauduc spits which advance very quickly due to longshore drift confluences.

The exposed plain of the Rhone Delta covers an area of over 1740 km^2. The Grand Rhone and Petit Rhone channels drain its plain. The plain is characterized by various types of both freshwater and saltwater lagoons, marshes and swamps, ponds, crevasse splays with foreshores and emerging sandy banks. Paleochannel and paleodunes are also recognized in the deltaic plain. Paleodunes are significant in analysing ancient relationships between river input and wave energy, as wave dominated deltas produce lobate deltas, or extreme wave dominance produces deflected deltas (Bhattacharya and Giosan, 2003). All of them allow us to follow the main stages of deltaic progradation.

Methods

The alluvial plain of the Petite Camargue has been mapped from aerial photographs and satellite images, as well as from ancient maps. Two areas appear clearly: fluvial and palustrine deposits between the Pre-Holocene Costières terraces and the wide Holocene beach ridge called "Les Sables," and fluvio-marine deposits from Les Sables to the present shoreline. Therefore, the deltaic plain is characterized by numerous beach ridges and associated channels, crevasse splays, lagoons, ponds and swamps produced by the progradation (Fig. 3). All these features allow the reconstitution of the Petite Camargue paleogeography.

Two methods have been used

Old maps, historical text and archeological findings

To identify the Petite Camargue shorelines from the Modern period until today, old cartographic documents are a valuable source. As a matter of course, the maps from the 18th and 19th centuries are more exact. In recent decades, a significant contribution to the identification of old coastlines has emerged from aerial photography and satellite imagery. All maps are digitized with MapInfo software. The precision is less than 10 m for the 20th century documents, 10–15 m for the 19th and 18th century documents, and 15–20 m for the 17th and 16th century documents. These documents date the modern and recent beach ridges. Paleoenvironments have also been dated using archaeological findings and historical records. The archaeological findings or relict structures are mostly located on the paleodunes on "Les Sables" and are principally from the Roman period, the 2nd century BC to the 1st century AD (Raynaud, 2005). Some Roman shipwrecks dated between the 1st century BC and the 1st century AD are on fossil submarine beach bars formed by the Saint-Ferreol river positioned as far as 2.5 km off the current coast (Long, 2002). These elements confirm that the deltaic lobes of Daladel and Peccaïs are younger than the 1st century AD.

Sedimentologic and stratigraphic analyzes of the fluvial and marine deposits over the deltaic plain

Recent information has been obtained by cores in the paleo-channels (Photo 1) and relict Holocene dunes (Photo 2). Sediment cores were taken with a mechanized Russian corer (Jowsey, 1966) positioned in the abandoned channels and on the fossil beach ridges. In order to determine the past channel hydrodynamics and the means of its infilling, sediment samples were taken along the core depending upon the appearance of sedimentary units; samples were analyzed with a laser granulometre. Abandoned channel fills located in the Petite Camargue consist of scarce pebbles and gravels and medium and fine sands which grade upward into fine silts and organic deposits. These deposits filled the last remaining spaces in the channel when it was abandoned. Sediment facies of the fossil beach ridges give more information about their nature, their formation and evolution. Chronological control is based on six radiocarbon dates (Table 1) taken from published studies (L'Homer, 1993; Rey, 2006). Radiocarbon ages were calibrated with the CALIB4.4 program (Stuiver et al., 1998). The dates contribute to dating the channel activity and their abandonment and the beach ridge formation.

Daladel delta lobe

The Aigues-Mortes paleogulf infilling accelerated around 2000 yr ago when the Daladel channel cut the wide beach ridge of the "Les Sables." This old gulf attained its maximum size around this time, when the delta lobe of the Saint-Ferreol channel separated two adjacent gulfs (Aigues-Mortes and Fos) of the Rhone delta (Fig. 4).

The Daladel's channel was active before the 3rd century AD (Table 1). A sample of wood collected inside the abandoned channel facies,

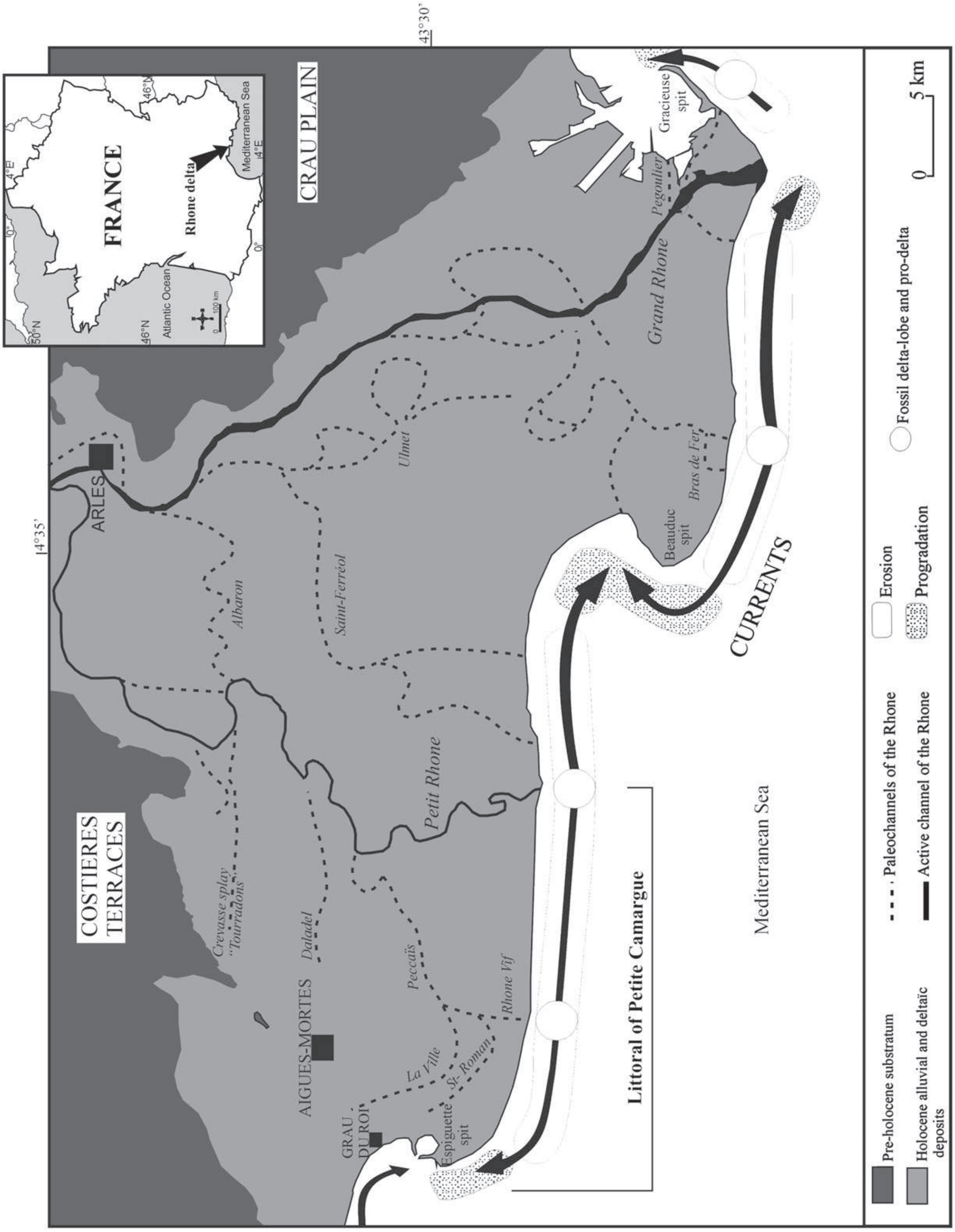

Figure 2. Erosion and progradation along the coast of the Rhone Delta.

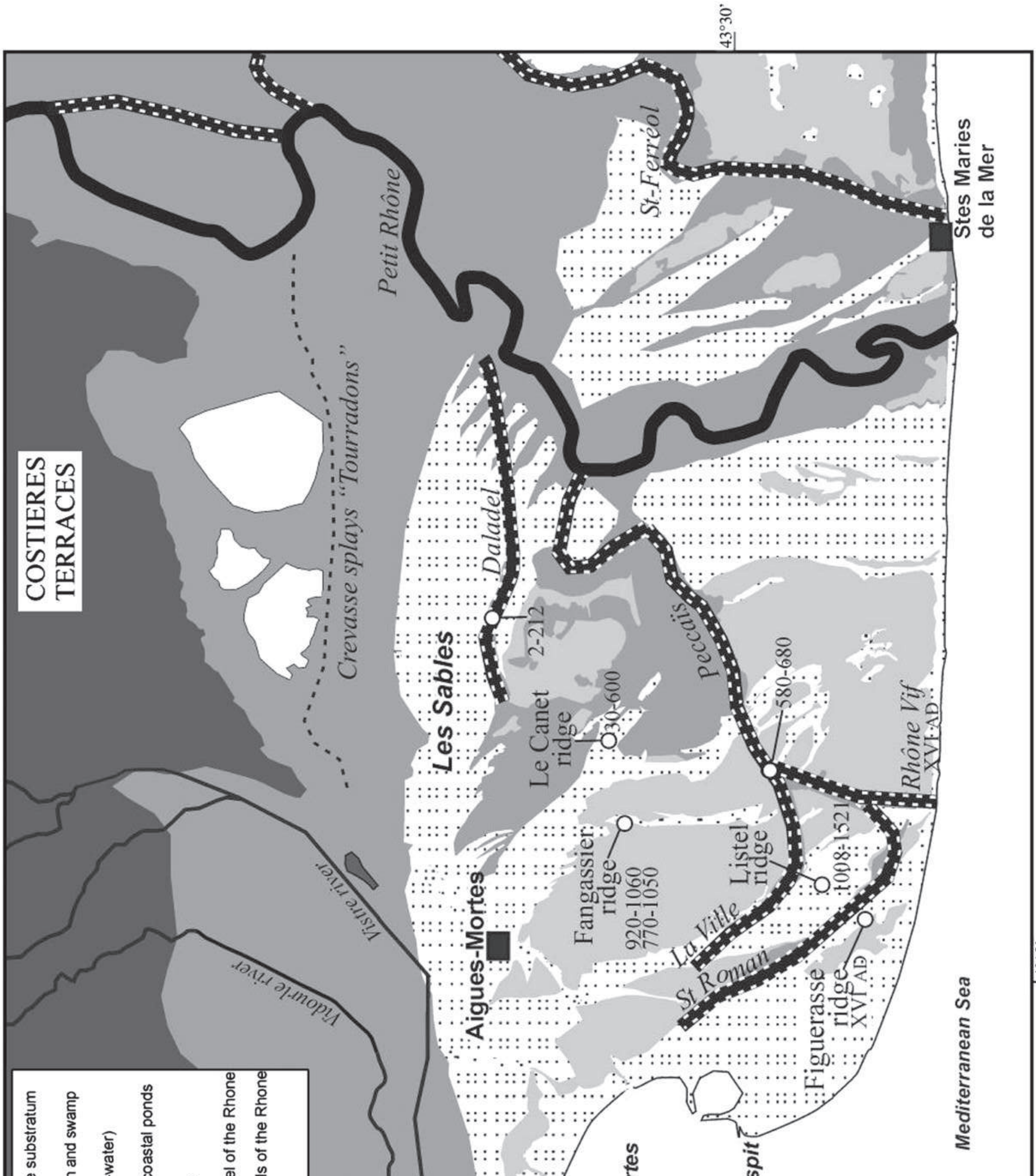

Figure 3. Geomorphological map of the study area with the modern and ancient delta lobes of the Rhone river. Location of the cores and ^{14}C analyses.

Table 1
Radiocarbon age determination collected in several localities of deltaic plain of the Petite Camargue

Laboratory code	^{14}C age (^{14}C yr BP)	Calibrated age Cal AD	Dated materials	Level, m NGF	Site name
GdA 578	1065 ± 30	920–106	Wood	−0.48	Fangassier ridge
GdA 15750	1085 ± 60	770–1050	Wood	−0.86	Fangassier ridge
Ly 1764	1090 ± 150	1008–1521	Shell	≈ +1	Listel ridge
GdA 456	1410 ± 30	580–680	Wood	−4.64	Peccaïs
Ly 1264	1720 ± 130	30–600	Shell	≈ +1	Le Canet ridge
Saclay 1381	1920 ± 35	2–212	Wood	−5.2	Vernède

Ly-code laboratory: Centre de datation par le radiocarbone de Lyon France; Saclay-code laboratory: Centre de datation par le radiocarbone de Saclay France; GdA: Gliwice Radiocarbon Laboratory Poland.

which consists of persistent beds of fine-grained homogeneous clay and silty clay, gave a date of 1929 ± 35 ^{14}C yr BP. These deposits overlay the active sand-bed channel characterized by low to moderate specific mean annual flood and high to very high flood variability. These dates point to the period of channel abandonment (probably because of an avulsion) and the beginning of its sedimentary infilling.

The channel has built several prograding beach ridges (Fig. 5A), forming sandy morpho-sedimentary units. The last beach ridge of the Daladel delta lobe leans on the beach ridge of the Saint-Ferreol which had already formed by the 1st century BC–1st century AD. This chronology was obtained by the Roman shipwreck position located near the fossil submarine beach bars of Saint-Ferreol river (Long, 2002). The Daladel system lobe seems to be a wave-influenced delta lobe. Some of the paleodunes were eroded. However, making it difficult to determine if the system was an asymmetric or symmetric lobe. However, according to Bhattacharya and Giosan (2003), this delta lobe morphology is characteristic of important fluvial sedimentary fluxes and a light bi-directional longshore drift relative to fluvial activity. The Daladel system lobe attains its maximal progradation around the 1st to 3rd century AD. The average progradation rate between the construction of the first beach ridge and the last beach ridge was 10 m/yr. The absence of dating on the paleodunes precludes a more exact date.

Peccaïs delta lobe

The period between Late Antiquity and the Middle Ages saw the expansion of the new Peccaïs's lobe system. A sample of wood collected inside the sedimentary facies of the active channel gave 1410 ± 30 ^{14}C yr BP (Table 1). Therefore, the Rhone Peccaïs was an active channel between 580 and 680 AD. The sedimentary facies of the active channel are characterized by rare pebbles and gravels, medium and fine sands. The small thickness of these units (≈50 cm) shows that fluvial deposits in this active channel are not well-preserved, and that most of the sand has been move from the Peccaïs river mouth. Then, the sand has been remobilized on the beach ridges.

The Peccaïs system lobe constitutes a wave-influenced delta lobe that is more or less symmetric (Fig. 5B). The morphology of this delta lobe shows an important fluvial sediment supply and a light bi-directional longshore drift relative to fluvial activity (Bhattacharya and Giosan, 2003) similar to the Daladel system lobe. The result is the rapid growth of the delta lobe. In fact, this rapid progradation has produced the formation of at least four identifiable beach ridges. Lagoons and marshes are located behind each of the beach ridges because of the rapid advance. Two paleodunes have been dated by radiocarbon. The dune of Le Canet is made of sand and is characterized by high angle cross-lamination. The marine shell collected to the surface of the ridge, dated 1720 ± 130 ^{14}C yr BP (Table 1), dates the dune of Le Canet between 30 and 600 AD. The dune of Fangassier is also made of sand and is characterized by high angle cross-lamination. The aeolian unit, dated at 1065 ± 30 ^{14}C yr BP by means of radiocarbon age determination on wood (Table 1), covers a thick organic deposit which corresponds to an accumulation of wood from the foreshore. A sample of wood collected inside the organic deposit gave 1085 ± 60 ^{14}C yr BP (Table 1). The Fangasier ridge formed since the VIIIe century and finished its formation between 920 and 1060 AD. The progradation rate

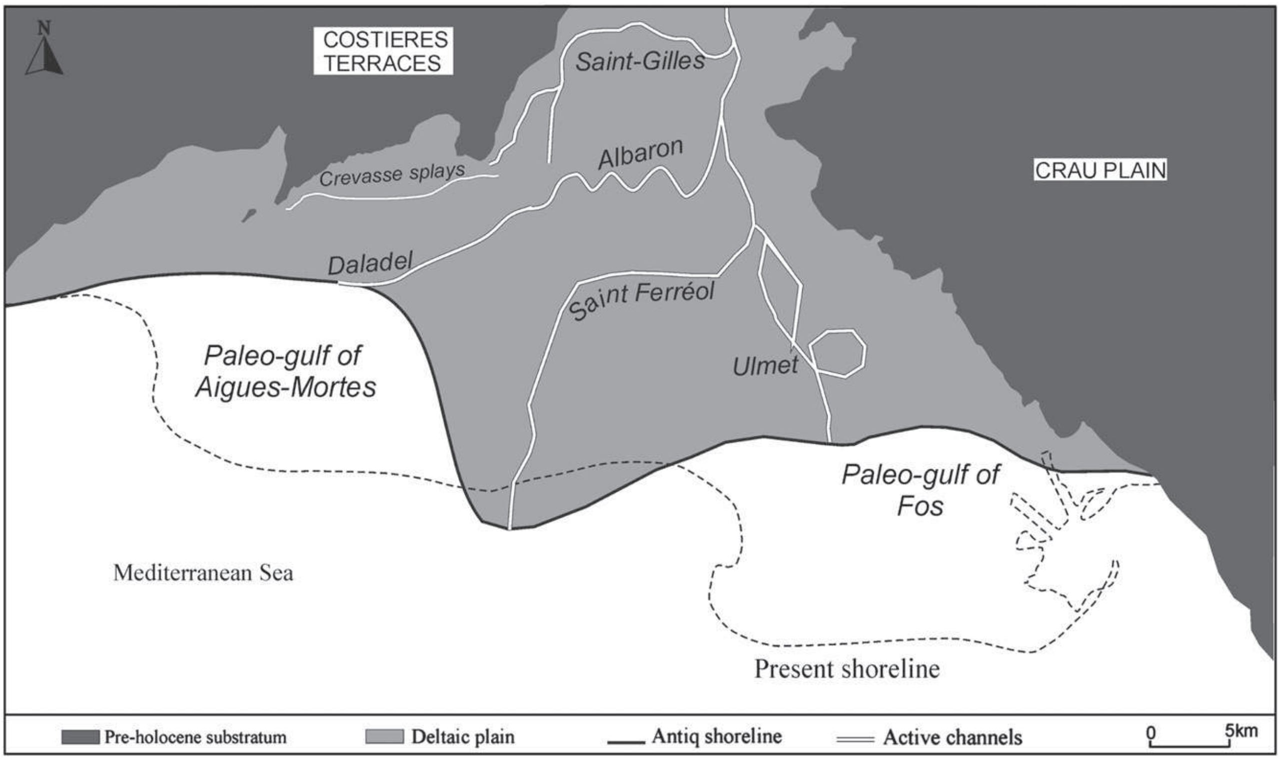

Figure 4. Shoreline position of the Rhone Delta between the 1st century BC and the 1st century AD.

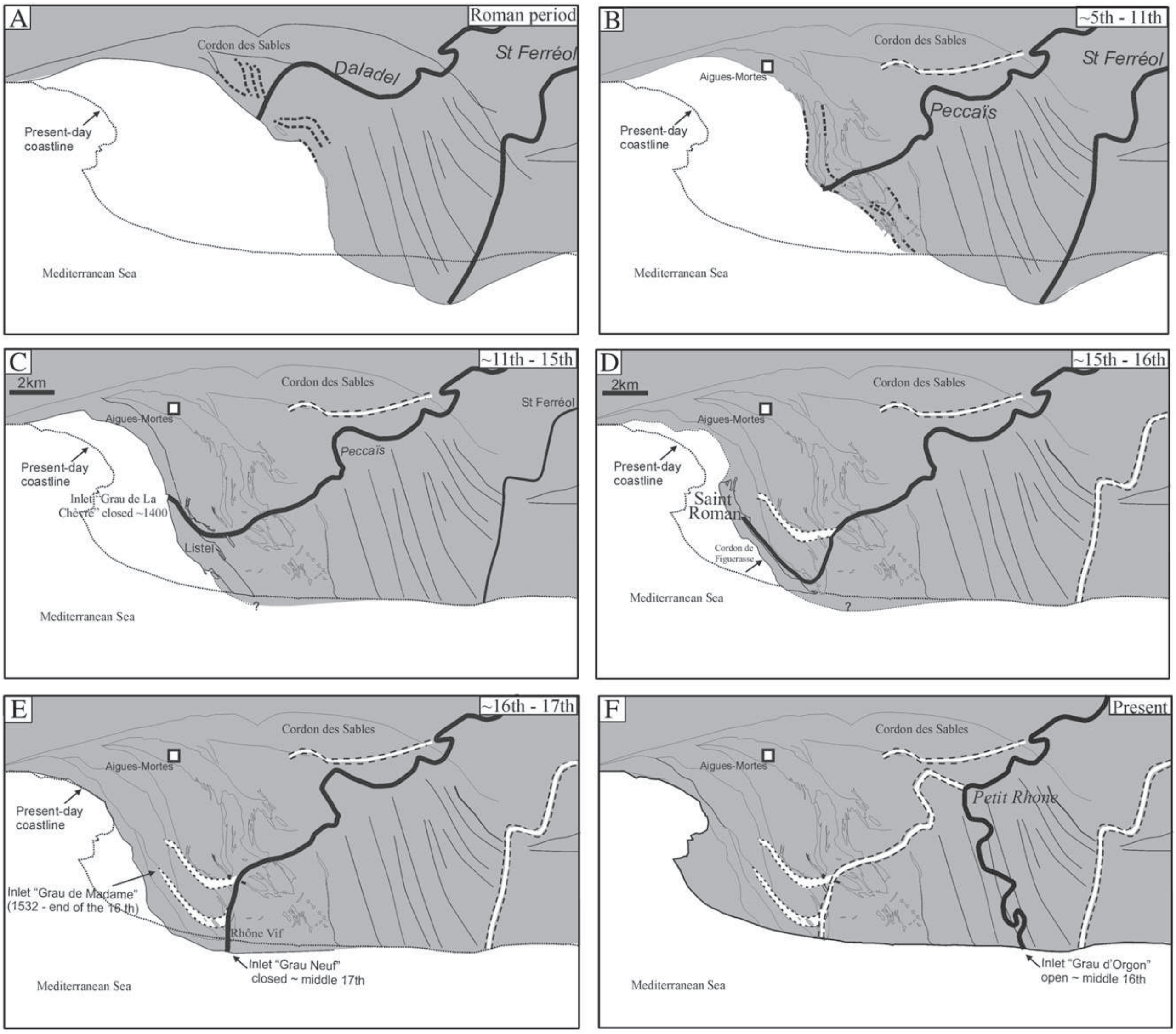

Figure 5. Time-slice paleogeographic maps detailing evolution of the deltaic plain of Petite Camargue from 2 ka to ~ present.

calculated is relatively high between the first and the last beach ridge (Le Canet and Fangassier ridge): globally, river-mouth progradation reached approximately 8 m/yr. This delta lobe attained its maximum progradation around 920–1060 AD.

La Ville delta lobe

It is likely that in the middle of the 11th century, a major event formed a new branch called La Ville channel. This new branch connects the Saint-Gilles's channel to Peccaïs's channel while Albaron-Peccaïs's channel is abandoned (Fig. 6). The formation of the La Ville channel produced a new hydro-sedimentary dynamic. This period records the transition from a wave-dominated delta lobe to an extreme wave-dominated deflected delta (Fig. 5C). The mouth of the La Ville channel has become downdrift-oriented and runs parallel to the coast, because the waves closed the outlet via a beach ridge, named Listel, connected to the updrift beach. The river mouth has been forced by the dominant wave to migrate. The terminal river course orientation gives information on the processes: an important unidirectional longshore drift and a relatively light fluvial sedimentary flux. According to Bhattacharya and Giosan (2003), these processes result in a deflected wave-influenced delta lobe as Senegal delta type (Ausseil-Badie et al., 1991; Barusseau et al., 1995) or Mahanadi delta type (Mohanti, 1993).

The beach ridge of Listel was dated by means of radiocarbon age determination on a marine shell collected from the surface, dated 1090 ± 150 ^{14}C yr BP (Table 1). This data has been corrected by the marine calibration with a δ^{13}C estimated as 0‰ (Rey, 2006). Finally, the beach ridge is believed to have developed between the 11th and 16th century AD. The progradation rate attains 4 m/yr but the growth speed is slow because of the delta lobe morphology. However the Listel beach ridge is wide and very long, which demonstrates the important sedimentary fluxes. The important marine discharge could arise from a unidirectional longshore current fed by the erosion of the downdrift Saint-Ferreol delta lobe and/or because the hydrographic organization of the deltaic plain has changed during this period.

The channel of La Ville was abandoned around 1350–1400 AD. Its abandonment was probably accelerated by the lengthening of the beach ridge and the longitudinal profile of the channel of La Ville. In fact, these elements have decreased the channel hydraulic gradient and therefore have produced sedimentary deposits inside the channel and its mouth (Rey, 2006). These processes generated a river-bed instability and caused an avulsion of the bed around 1350–1400 AD. The new channel formed a new deltaic lobe. This process is fundamental to the shifting of river mouths and the construction of deltas.

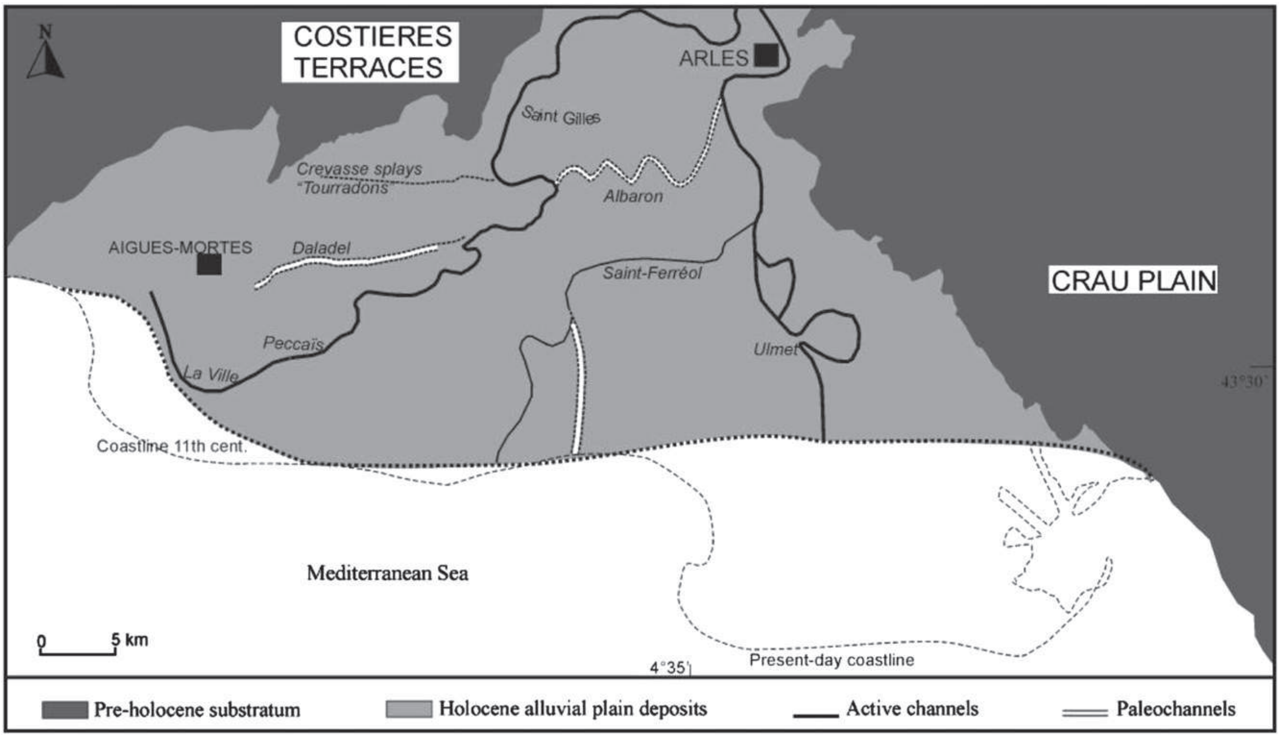

Figure 6. Coastline position of the Rhone Delta around the 11th century.

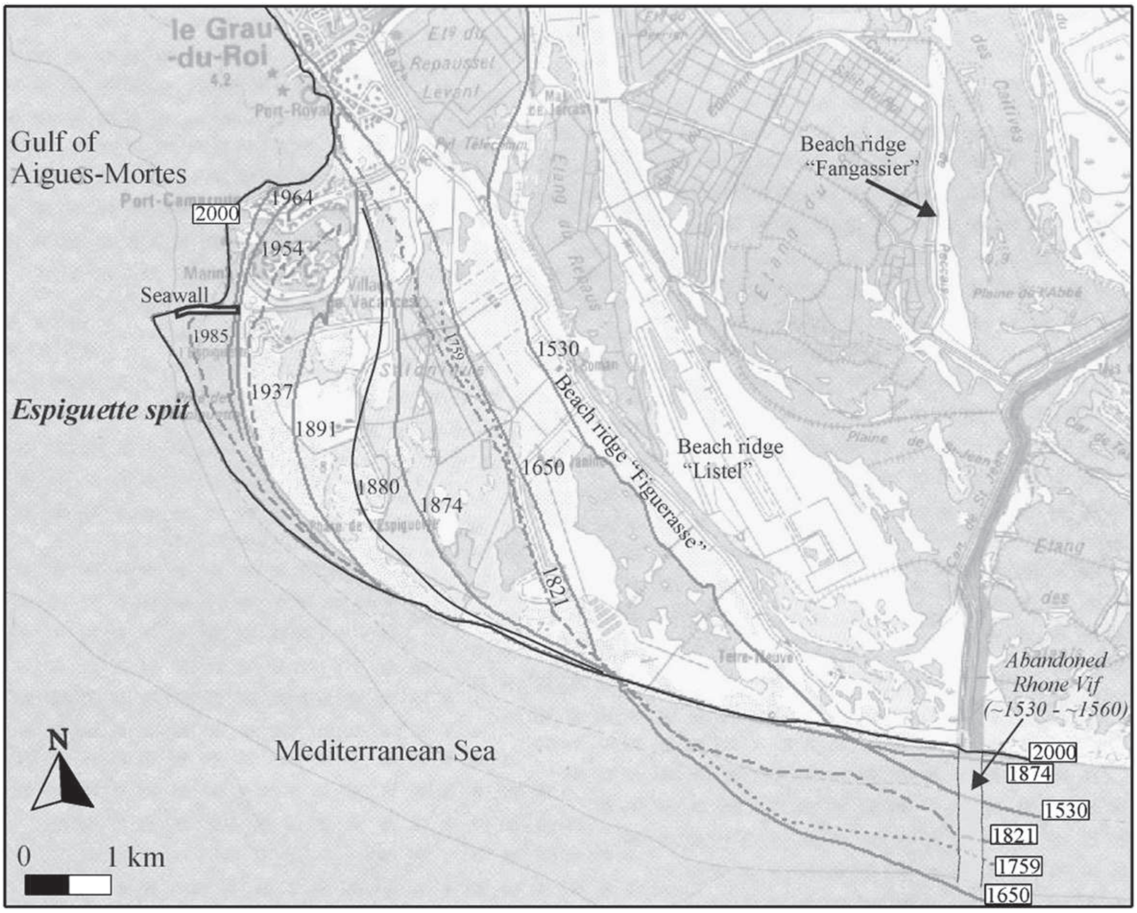

Figure 7. Evolution of the beach ridges from 1530 AD to 2000 AD.

Saint-Roman delta lobe

Around 1350–1400 AD (L'Homer, 1993; Florençon, 1996) a new branch called the Saint-Roman was formed by a breach through the Listel's beach ridge. Until the early 16th century, the Saint-Roman channel formed a wave-deflected delta (Fig. 5D) like La Ville system. The terminal river course ran parallel to the Figuerasse beach ridge. This morphology is characteristic of an important unidirectional longshore drift and a relative light fluvial sedimentary flux (Bhattacharya and Giosan, 2003). Figuerasse's beach ridge is wide (>300 m) and long as well as having very high dunes (15 to 17 m). This shows very important sedimentary fluxes. In fact, in spite of the delta lobe morphology, the progradation rate is fast (8 m/yr). Like the Rhone La Ville, the Saint-Roman channel and its mouth are filled during their activity period. According to Fitzgerald (1982), the hydraulic gradient declines because of the beach ridge and channel lengthening. The hydraulic gradient limits the discharge of the sediments out of the pass, therefore, the sediments deposit inside the channel and near the mouth. The outlet of the Saint-Roman channel is progressively closing and, at the same time, the bottom of the Saint-Roman channel's bed is rising (channel sedimentary infilling). Progressively, coastal shipping became dangerous and finally, the solution was to form a new branch.

In the early 16th century, the outlet and Saint-Roman channel were filled by fine sands (Rey, 2006). To resolve these threats to coastal shipping, a new branch called Rhone Vif was formed (Fig. 5E) and artificially embanked around 1532 AD (Ménard, 1753). The new channelling produced a very fast progradation between 1530 and 1650 AD and we calculate an advance of the emerged delta lobe of 983 m (8.2 m/yr).

The Petite Camargue after the 16th century

Around 1550 AD a major flood caused a bed avulsion. The Rhone Vif was abandoned and the Petit Rhone channel, located to the east, was formed (Fig. 5F). Since then, the channel has drained the deltaic plain of the Rhone delta. Since the avulsion, the Petite Camargue littoral has not been directly subject to fluvial activity. The coastline evolution depends on waves and currents which build up several beach ridges. The beach ridges are located successively behind each other, and are elongated and parallel to the present coastline.

From the mid-17th century, the littoral of the Petite Camargue is divided into two sections, one in accretion and the other in severe erosion (Fig. 7). Globally, more than half of the Petite Camargue littoral suffers severe erosion. In front of the old river mouth of Rhone Vif, approximately 1695 m of coast was eroded between 1650 and 2000 AD. The current maximum erosion rate is 9 m/yr, therefore higher than maximum accretion rates. The sands from eroded beaches feed the western beaches, and so the erosion has been moving toward the west since 1530 AD.

Between the 18th and early 19th centuries, the coastline advance decreased (<5 m/yr) despite achieving a maximum rate of 15 m/yr between 1759 and 1777 AD. The progradation has mainly been by the coalescence of beach ridges. The beach-ridge morphology shows an important sedimentary flux by longshore drift even if the progradation rate does not particularly reflect this.

From the end of 19th century to today, the progradation rate calculated was rapid (10 m/yr). Maximal rates of 30 to 90 m/yr were attained between 1874 and 1891 AD. The advance of the coastline was achieved by spit coalescence. This kind of littoral formation explains

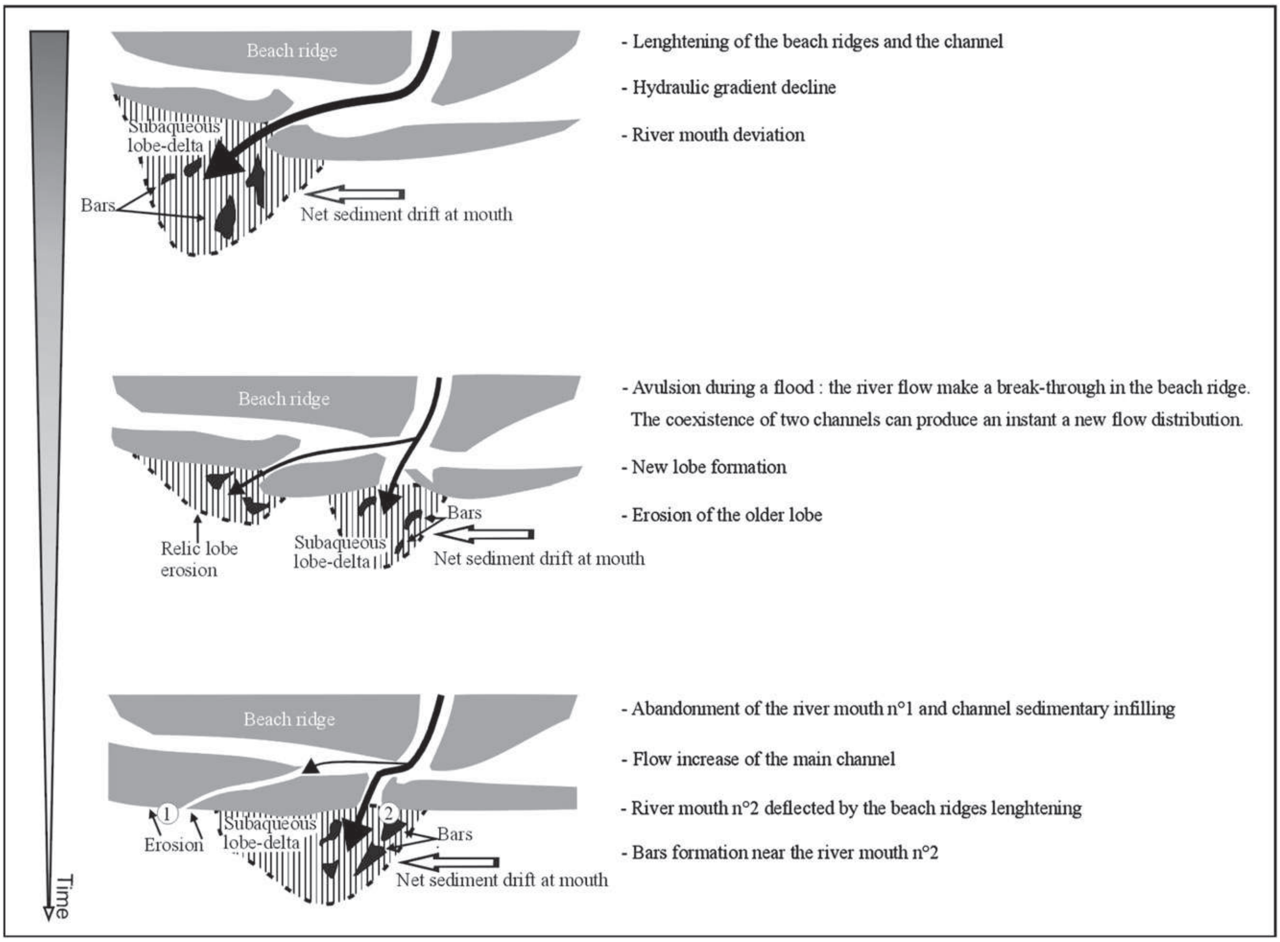

Figure 8. Outlet evolution under an extreme wave dominated and deflected delta formation.

the rapid progradation. The spit formations, such as Espiguette spit, are linked to the confluence of two longshore drift systems (Fig. 7).

During the 20th century, the shoreline of the Petite Camargue was mainly influenced by the coastal defence structures that protected over 60% of the coastline, resulting in its almost complete artificial stabilization. Dune degradation and beach erosion were protected by structures oriented perpendicular to the prevailing wind. Today, the wider portions of the littoral of the Petite Camargue are protected by heavy and light structures on the coastal area, but the results are not sufficient. In fact, the beach erosion is severe in several sites. The efficacy of artificial coastal defence is variable with lifespans ranging from 3 to 10 yr. Locally, the artificial coastal defence have stopped or decreased the coastline erosion.

A seawall has been situated on the Espiguette spit extremity since around the 1960's in order to protect the Port Camargue harbour inlet and marina. The seawall stops the longshore drift and traps the sands as a breakwater. In consequence, the Espiguette spit advanced very quickly, 172 m between 1964 and 1985 (9 m/yr) and 168 m (11.2 m/yr) between 1985 and 2000. Now, the sands pass behind the seawall and move from the Port Camargue harbour and the inlet named Grau du Roi.

Discussion

The western part of the Rhone delta is young, as it was built over the last 2000 yr. Previously, the Rhone channel and crevasse splays emptied into lagoons formed at the end of the Flandrian transgression and closed by several convergent beach ridges. These events are also important on the Ombrone and Arno deltas (Pranzini, 2001) and on the Danube delta (Panin, 1997). In reference to Panin (2003), Rey (2006) call it the "Blocked Petite Camargue deltaic plain". Finally, around the Roman period, the deltaic plain of the Petite Camargue was limited by a broad beach ridge called "Les Sables" which limited the vast Aigues-Mortes gulf. Paleochannels and relict Holocene dunes help define the main phases of coastal modifications related to fluvial, marine and aeolian sediment supply, sea-level changes, climatic conditions and anthropogenic influence.

The first two system lobes constitute a wave-influenced delta lobe more or less symmetric to the Peccaïs's lobe. Wave-influenced delta-lobe symmetry suggests important fluvial sedimentary fluxes. The delta lobe of Daladel was the first delta lobe build-up on the Aigues-Mortes's paleogulf. Its advance began in the Roman period. The second delta lobe was the Peccaïs delta lobe, which developed between Late Antiquity and the Middle Ages (11th century). Channel materials moving eastward and westward by littoral drift fed well-nourished beach ridges, which were formed without significant breaks (evident in the lack of soils).

Progradation of these delta lobes occurred during deceleration in rate of sea-level and rapid influx of sediment. In fact, the conditions favourable to beach progradation in a wave-dominated coast occur only when the sea-level rises, slows or stabilizes (Roy et al., 1994). Moreover, climatic and human forces have also influenced the advance of delta lobes. This situation could have permitted a high discharge of fluvial sedimentary fluxes, as seen with the delta lobe of Saint-Ferreol channel which attained a progradation rate of 15 m/yr between 1290–1020 BC and the 1st century AD (Provansal et al., 2003). The fluvial sediment supply has generated a very fast growth of the delta lobes and the gradient of the delta plain has probably diminished. The strengthening of liquid and solid flows has occurred during active hydro-sedimentary periods (recurring and high-powered floods, fast progradation) and due to the pressure of human activities on the landscape (Bruneton et al., 2001; Arnaud-Fassetta, 2002; Berger et al., 2002, 2003; Provansal et al., 2002; Van der Leeuw, 2005). The widespread agricultural use of the plain and deforestation would have caused a significant increase in soil erosion and therefore a high transport load by the channels. These impacts were observed on the other Rhone channels and on the river-basin around Late Antiquity (Arnaud-Fassetta, 1998; Berger and Jung, 1996; Bravard, 1995; Provansal et al., 1999; Salvador, 1991; Vella, 1999) but not over the whole river-basin around the Roman period (Salvador et al., 1993).

Moreover, the Rhone delta is characterized by a new flow distribution because of the decline of the Saint-Ferreol channel between the 2nd and 6th century AD (Arnaud-Fassetta, 1998). In the end, all these factors have been influenced by the power stream and the sedimentary fluxes of the Daladel and Peccaïs channels.

The formation of La Ville and Saint-Roman are made up of a deflected wave-influenced delta lobes. Theses morphologies are linked to multiple factors:

—flow redistribution due to new branch formation about the 11th century,
—the fluvial sedimentary steady-stream in response to climatic change (LIA) and human influence(the reforestation of the river-basin, river damming and river bed quarrying)
—unidirectional and high-powered longshore drift,
—an important marine and aeolian sediment supply (because of emerged delta lobe erosion of the Saint-Ferreol, during the Little Ice).
—the Little Ice Age, characterized by an increase in rainfall and recurring floods followed by an increase in discharge and sediment supply of Mediterranean streams (Camuffo and Enzi, 1994; Belotti et al., 2004). Little Ice Age effects have been observed on the Rhone delta (Provansal et al., 2003) even if the periods of channel

Photo 1. Abandoned channel of Peccaïs. The sedimentary infilling is not finished, the water stagnates in the deeper areas (Rey, 2006).

Photo 2. Middle Age dune of Fangassier. This beach ridge represents the last stage of the delta lobe progradation of Peccaïs (Rey, 2006).

activities (16th–19th) located on the Eastern part of the deltaic plain do not correspond to La Ville, Saint-Roman and Rhone Vif channel activities (11th–16th centuries).

Longshore drift current, fluvial discharge and also the hydraulic gradient decline (because of channel lengthening) have largely influenced the channel activity, including infilling, abandonment and bed avulsion. When the distributary channel is highly deflected by development of a downdrift elongated spit, it loses its hydraulic efficiency, begins to backfill and later avulses by breaching the updrift margin of the spit (Fig. 8). These processes can generate breaches through the beach ridges (as Listel ridge) and cause avulsions (as with Saint-Roman channel) or lead up to anthropogenic avulsion (as with Rhone Vif channel).

Between the 1530's and the end of the 16th century, the embankment of the Rhone Vif produced a strong fluvial discharge which were responsible for the rapid advance of the shoreline. It is difficult to know if the advance was linked to Little Ice Age impacts, erosion of the delta lobe of Saint-Ferreol or if the artificial embankment (and outlet) produced a self-dredging phenomenon leading to rapid progradation.

Since the 16th century, the littoral of the Petite Camargue split into two parts. The widespread erosion of the shoreline is linked to erosion of fossilized emergent and submarine delta lobes (Rhone Vif, Petit Rhone and Saint-Ferreol) as well as the fluvial sedimentary decrease of the Rhone river caused by the end of the Little Ice Age, the reforestation of the river basin, river damming and river bed quarrying (Pichard, 1995; Jorda and Provansal, 1996; Institut Rhône Saône, 2000; Warner, 2000; Descroix and Gautier, 2002; Kondolf et al., 2002; Liébault and Piégay, 2002; Sabatier and Suanez, 2003). In the western area, the advance of the Espiguette spit benefited from updrift erosion and longshore drift confluences.

Principal consequences affecting the human-induced delta destruction phase include: marine incursion onto low-lying northern delta plain sectors, increased salinization of cultivated land (rice growing) and salinization of fresh water, ponds and lagoons, decline of the biodiversity (disappearance of wetlands), coastal erosion, and a decreased capacity to regenerate itself.

Conclusion

Five important generations of delta lobes and beach ridges have characterized the deltaic plain of the Petite Camargue over the past 2000 yr. The older wave-influenced delta lobe formed during a sea-level rise and under anthropogenic pressure, which occurred during the Roman period. The symmetric wave-influenced delta lobe of Peccaïs developed during a sea-level rise but climatic and human pressures have produced high fluvial sedimentary fluxes which occurred during Late Antiquity. The changes from symmetric to deflected deltas are primarily a function of climate and anthropogenic changes in fluvial sediment discharge. From the 11th century, this hydro-sedimentary dynamic has generated two deflected delta lobes. These asynchronous formations were influenced by several factors: the delta lobe erosion of the Saint-Ferreol, avulsions of beds and channel abandonment, and the Little Ice Age effects. Finally, we can observe the process responsible in the shifting of the river mouths and in the construction of deltas. Old channels are progressively infilling. Therefore the high floods caused breaches and avulsion of river beds. The new channel formed a new deltaic lobe and determined the position of the new mouth. The old channel became a spread salt pond. The construction of the Rhone delta depends on internal control of fluvial sedimentary dynamics (Roberts, 1997) and allocyclic forces external to the alluvial system of the delta.

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