ELSEVIER

Marine Geology 222–223 (2005) 235–265

MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

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Evolution of the Rhône delta plain in the Holocene

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Received 8 June 2004; received in revised form 20 January 2005; accepted 15 June 2005

Abstract

The delta plain of the Rhone shows many sandy beach ridges cropping out at the surface. We propose here a radiocarbon chronology for the accumulation of the sedimentary bodies and an interpretation of the morphology of the mouth lobes that they form. Morphologies of the lobes depend on four principal factors: (1) the variation of the relative sea level, which constitutes the morphogenic base level, (2) the fluvial input (volume of water discharge and sedimentary input, number and position of the mouths), (3) marine dynamics (volume and direction of the longshore drift, dominant wave direction) (4) the accommodation space created by the rise of relative sea level, along with the paleobathymetry onto which the lobe will prograde immediately in front of the delta and at sea.

Our conclusions are: the main Holocene paleo-delta lobes of Ulmet and Saint Ferréol were contemporaneous, being deposited from 4000 to 2000 yr BP. However, the fluvial style of their downstream channel (meandering for Ulmet channel and linear for Saint-Ferréol) and the lobe morphologies of both channels are contrasted: rounded in the case of Ulmet and elongated for Saint-Ferréol. The role of the accommodation space is confirmed by two recent drillholes traversing the entire Holocene succession, which reveal a prior stage of sedimentary filling in the case of the Saint-Ferréol lobe, thus limiting the accommodation space and favouring a rapid and pointed progradation of this lobe.

The decoupling between hydrological activity and progradation of lobe indicates the complexity of mechanisms in the large catchment basin of Rhône. However, the high rate of progradation of Saint-Ferréol lobe after 2900 BP is probably a consequence of the increase of human activity after this date.

The variation of relative sea level remains an important factor controlling the evolution of the Rhone delta after 6000 BP. The local (?) stabilization of the relative sea level between 4585 BP and 3520 BP played an important role in the triggering of coastal progradation (Saint-Ferréol lobe, eastern margin Rhône delta).
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Keywords: Holocene; beach ridge; sea-level; accommodation space; sedimentary input; progradation

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doi:10.1016/j.margeo.2005.06.028

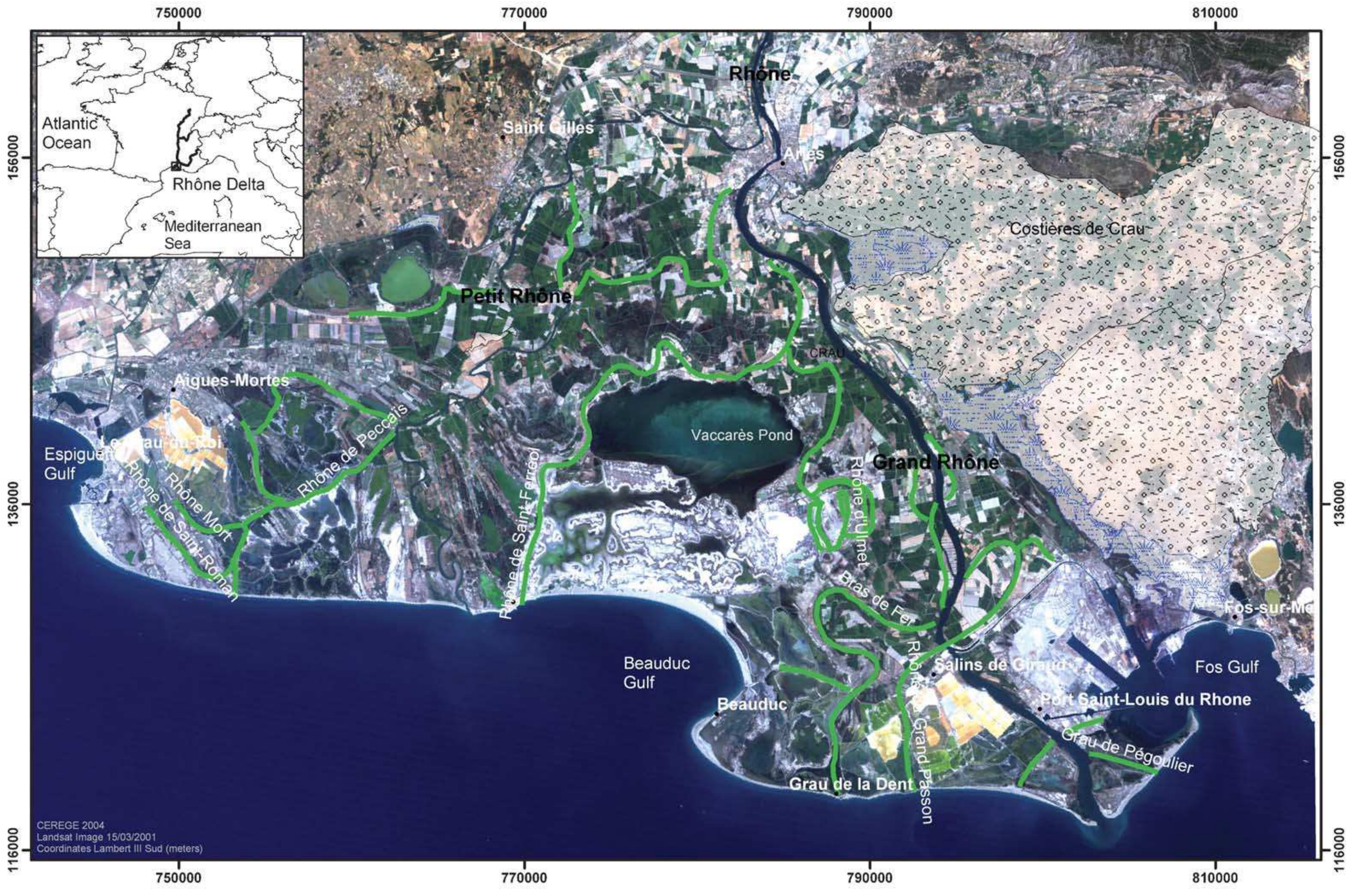


Fig. 1. Geographical position of the studied area: the Rhône delta. The green lines represent palaeo-channels of the Rhône. Pleistocene gravel of Crau and fresh water marsh on the eastern margin of the delta are superimposed on the landsat image.

1. Introduction

The build up of deltas is influenced by various factors controlling their evolution through time. From 10,000 to 7000 BP sea level variations were very rapid and induce a retrogradation (back-stepping) and then a vertical build up (aggradation) of the sedimentary bodies. From 7000 yr BP onwards, the deceleration in the rise of sea level favoured progradation under the influence of sedimentary fluxes. Dynamics of avulsion then becomes the morphogenic factor determining the geographical distribution of fluxes. The delta plains actually start building up from this time onwards (Stanley and Warne, 1994).

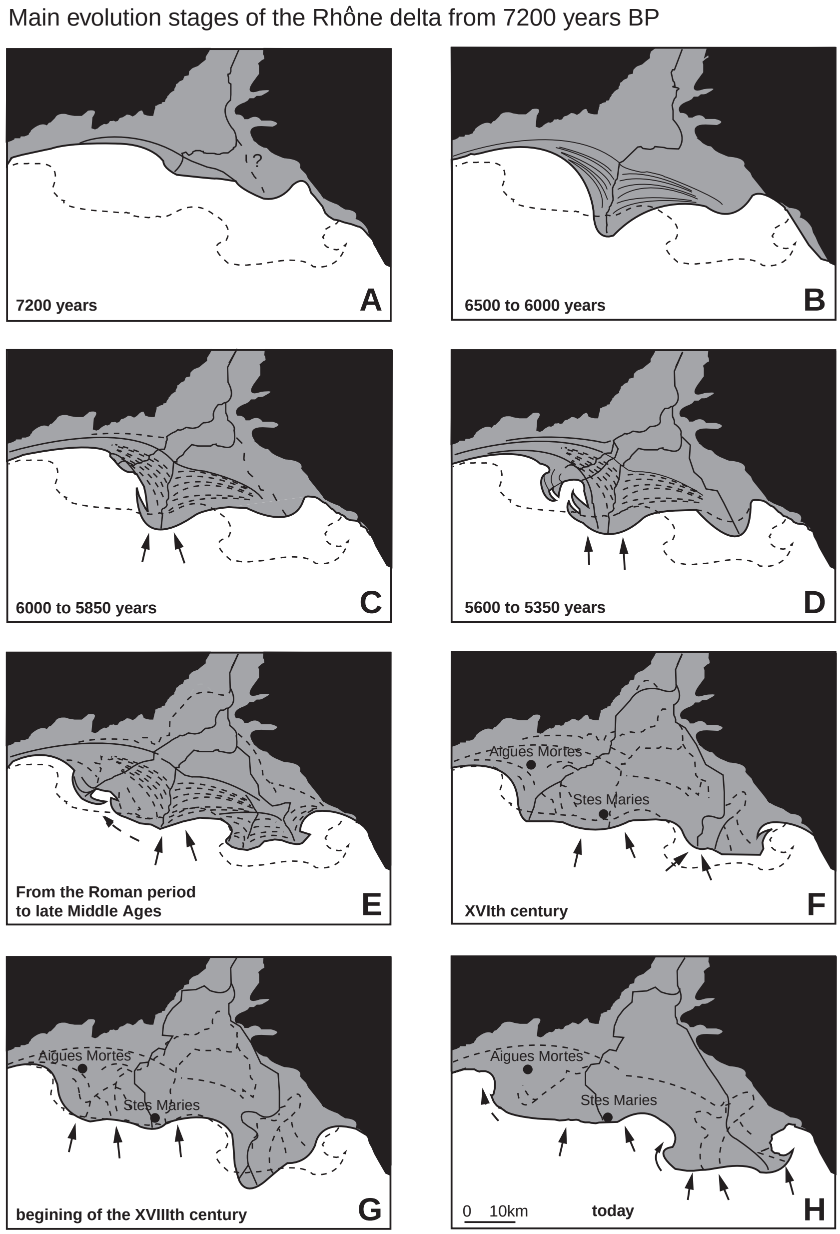


Fig. 2. Main evolution stages of the Rhône delta since 7200 yr BP from L'Homer et al., 1981.

As we approach the historical period, human activities had an increasing influence on the modification of sedimentary fluxes and the mechanisms of avulsion (Berendsen and Stouthamer, 2000; Stouthamer, 2001).

In the case of the Rhone delta, few data are available on the Holocene sedimentary bodies concealed under the deltaic plain since only a small number of boreholes have attained the Pleistocene substrate. These boreholes were drilled in the 1950s and 1960s (Kruit and Van Andel, 1955; Oomkens, 1970; Pons et al., 1979), leading to an interpretation of the Holocene stratigraphy of the plain in terms of a schematic sequence stratigraphy, thus establishing a map of the Pleistocene surface underlying the postglacial delta. The wells have recently been re-interpreted by BRGM, Boyer et al. (this volume). On the inner continental shelf, the data collected by seismic reflection supports these interpretations, but the lack of radiocarbon dating makes difficult to establish any chronostratigraphy for the sedimentary sequences.

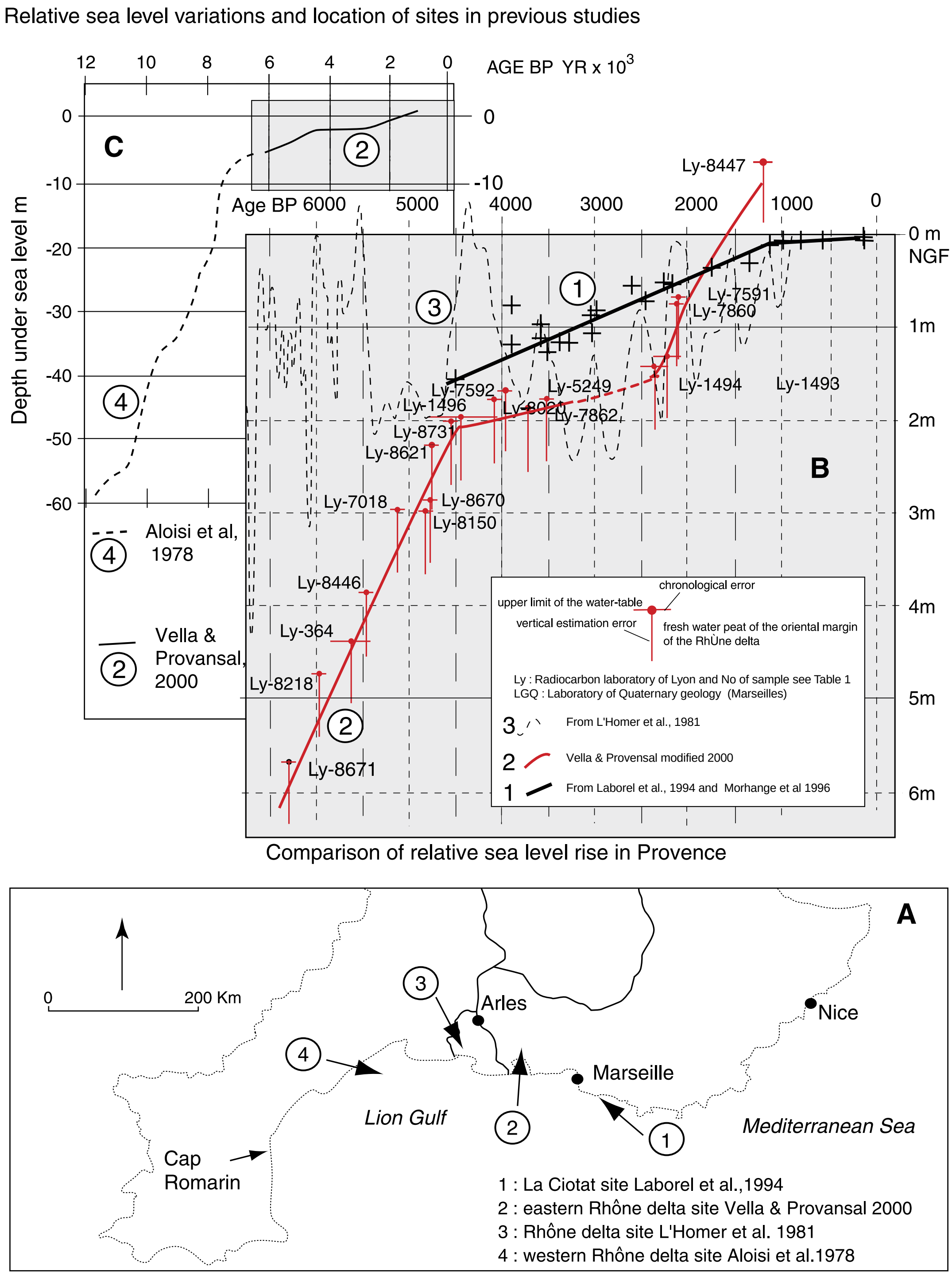
Gensous and Tesson (2003) proposed a link between sedimentary bodies on the shelf and stratigraphic data acquired in the plain by Oomkens (1970). These authors describe retrograding transgressive wedges deposited during the slowing down of the sea level rise. For Holocene deposits, Marsset and Bellec (2002) proposed a correlation with seismic profiles collected in the delta and well as with previous studies at sea (Aloisi, 1986) and on land (L'Homer et al., 1981). On the other hand, the sedimentary bodies of the subsurface have been studied and mapped in detail (Kruit and Van Andel, 1955; Colomb et al., 1975; L'Homer, 1975, 1993; L'Homer et al., 1981). The beach ridges and fossil alluvial channels are particularly visible south of Vaccarès pond on aerial photographs and satellite images (Fig. 1). North of Vaccarès, only a few alluvial channels are visible because of agricultural activities during the 19th and 20th centuries have obliterated most of the traces of these "fossilized" features.

The aim of the present study is to propose a new chronology for the outcropping beach ridges associated with the main river mouths, using the radiocarbon dating of subsurface core samples and the large amount of recently acquired archaeological data. These features are associated with clearly visible lobes (Saint-Ferréol, Ulmet and Peccaïs). The dating of beach ridges should therefore provide a new and detailed 14C chronology for delta lobe activity. In this study, we attempt to explain the variability of observed morphologies and define the dominant factors influencing the morphology. While some of these factors are classical (Galloway, 1975), such as hydrodynamics (waves) and sediment supply (rivers), we also propose to integrate the influence of accommodation space. The tide is minimal in the case of the Rhône delta.

2. Previous scheme of the Rhone delta plain edification

L'Homer et al. (1981) put forward the previous overall model for the build up the Rhone delta plain (Fig. 2). This model takes account of the variation of the relative sea level established from the morphology of the mouths, the dating of offshore bars, and from the alluvial activity (avulsion, crevassing/overbank flows, meander formation, etc.). These authors obtained a curve of the variation in relative sea level from 7000 yr BP, which shows many fluctuations (Fig. 3B). The current sea level is reached at 6000 yr BP, followed by many regressions and transgressions. These authors consider that fluctuations in the rates of relative sea level rise are entirely responsible for the changes in morphology of sedimentary systems. However, according to other authors, the Rhone delta plain evolution is controlled by two factors: eustatic effects and variations of alluvial sediment supply (Oomkens, 1970; Pons et al., 1979; Provansal et al., 2003).

Fig. 3. Relative sea level variations and location of sites in previous studies. 3A Location of relative sea level studies around the Lion Gulf. 3B Comparison of the relative sea level variation around the Lion Gulf during the last 6000 yr 1: black crosses represent the data gained by 14C datations of algal rims (*Lithophyllum lichenoïdes*) from rocky cliffs at La Ciotat by Laborel et al., 1994. 2: red crosses represent data gained by 14C dating of the fresh water peat from the eastern part of Rhône delta by Vella and Provansal, 2000. The curve shows clearly a stabilisation during almost one millennial. 3: the pecked line represents data gained from 14C dating of shells in beach ridges. 3C Curve of the relative sea level rise during the Holocene. 4: the first part of the curve, before 6000 BP, (4) is plotted from 14C dating of shells in high stand deposit by Aloisi et al., 1978, the second part (1) is plotted from the fresh water peat curve of Vella and Provansal, 2000.


Relative sea level variations and location of sites in previous studies
AGE BP YR x 10^3
Depth under sea level m
C
Age BP 6000
5000
4000
3000
2000
1000
0 m NGF
1m
2m
3m
4m
5m
6m
B
Aloisi et al, 1978
Vella & Provansal, 2000
Ly-8447
Ly-7591
Ly-7860
Ly-1494
Ly-1493
Ly-7592
Ly-1496
Ly-5249
Ly-8020
Ly-7862
Ly-8731
Ly-8621
Ly-7018
Ly-8670
Ly-8150
Ly-8446
Ly-364
Ly-8218
Ly-8671
chronological error
upper limit of the water-table
vertical estimation error
fresh water peat of the oriental margin of the RhÙne delta
Ly : Radiocarbon laboratory of Lyon and No of sample see Table 1
LGQ : Laboratory of Quaternary geology (Marseilles)
From L'Homer et al., 1981
Vella & Provansal modified 2000
From Laborel et al., 1994 and Morhange et al 1996
Comparison of relative sea level rise in Provence
A
0
200 Km
Arles
Nice
Marseille
Lion Gulf
Mediterranean Sea
Cap Romarin
1 : La Ciotat site Laborel et al.,1994
2 : eastern Rhône delta site Vella & Provansal 2000
3 : Rhône delta site L'Homer et al. 1981
4 : western Rhône delta site Aloisi et al.1978

The schematic model of L'Homer et al. (1981) sets the beginning of the construction of the Rhone delta plain at 7200 yr BP (Fig. 2A). According to these authors, the coast corresponding to this date is concealed beneath 2 m of muddy marsh deposits to the west of the delta. The second stage, after this onlap maximum, leads to coastal progradation between 7200 and 6500 yr BP and the onset of symmetrical lobe construction starting from the Saint Ferréol channel (Fig. 2B). The growth of this lobe takes place, according to these authors, between 6500 and 6000 yr BP owing to the development of single channel and a period of stability of relative sea level associated with a general regressive tendency from 6000 yr (Figs. 2C and 3B). Although the two tendencies nowadays appear contradictory, they are clearly expressed on the curve of relative sea level variation by a fall to approximately −3 m after having reached a level ranging between −1 m and the present-day level. From 6000 to 5350 yr BP, the sea level goes through two new phases of highstand inferred from the erosion of the Saint Ferréol lobe and the multiplication of distributaries (west of the Peccais Rhone and east of the Ulmet Rhone, L'Homer, 1975), with an intervening fall in relative sea level. The delta plain at that time develops a multilobate form (Fig. 2D).

From 5400 to 4350 yr BP, the sea level is regarded as stabilized at around −2 m below the archaeological sites to the west of the delta plain (Fig. 2E). From 4350 yr BP to the Roman period, the initially symmetrical Peccaïs lobe becomes asymmetrical or deviated, taking into account the change of the principal alluvial channel towards a "tangential" direction and the major sedimentary inputs from longshore drift typical of the "spit process of Beauduc" (Fig. 2F). During these periods, the eastern part of the delta itself is also prograding, even though no radiocarbon dating is available for this zone. While the sea level is regarded as slightly lower than at present (between −2 m and −1 m), sudden slight fluctuations occur, including a rise that reaches the present-day level between 4350 and 4100 and again towards 2200 BP. The first high level is attributed to a highstand observed at Cap Romarin on the Languedoc–Roussillon coast (Fig. 3A), about 100 km to the west of the Rhone delta (Aloisi et al., 1978). The second high level could be followed by a slight regression explaining the presence of Roman remains located below the present-day sea level. The first reliable charts appearing in the modern period (since the 16th century) allow a faithful reconstruction of the evolution of the delta, dominated by progradation of the eastern part of the plain (Fig. 2E, G, H).

The Holocene sea levels higher or equal to the present level were derived in the Rhone delta by L'Homer et al. (1981) based on littoral coastal erosion processes, bibliographical data outside the delta, in particular for the Cap Romarin (Aloisi et al., 1978), as well as from the presence of submerged archeological sites and the dating of offshore bars.

Today, these hypotheses are no longer accepted, since it has been shown that the mobility of the shoreline in the Rhone delta depends above all on the action of waves and the longshore drift currents (Sabatier, 2001) as well as the sedimentary flux in relation to the position of the river mouths. The precise position of the marine highstand at Cap Romarin–based on a fossil notch in the cliff–is nowadays invalidated by the isotopic dating of the 5e stage (Laborel et al., 1998). As observed off the Rhone delta, the construction of the offshore bars associated with the Cap Romarin notch depends especially on wave action. The differences in level between the bars probably reflect exceptional storm episodes rather than eustatic changes (Pirazzoli, 1991). On the other hand, on the coast of Provence in particular, results based on the analysis of archaeological remains (Pirazzoli, 1976; Delano-Smith, 1979; Flemming and Webb, 1986) indicate a weak tectonic mobility since Antiquity and a progressive rise in sea level. Morhange et al. (1996, 2001, 2003) arrived at closely similar results using numerous recent studies around the Old Port in Marseilles (Fig. 4 and Table 1), using a combination of archaeological and biological markers fixed on the structures. By dating biological indicators on archaeological structures from the old port in Marseilles, this author obtained a series of positions yielding an estimated variation of sea level since the end of the Neolithic era: an elevation of 1.6 m is recorded at 4420 ± 45 BP (Ly-8423), 2463–2215 Cal BC, whereas, during the ancient Greek period, the sea level is established at 0.67 and 0.63 m NGF, and at the end of Roman Antiquity, between 400 and 500 A.D, the level is −0.25 m NGF. For

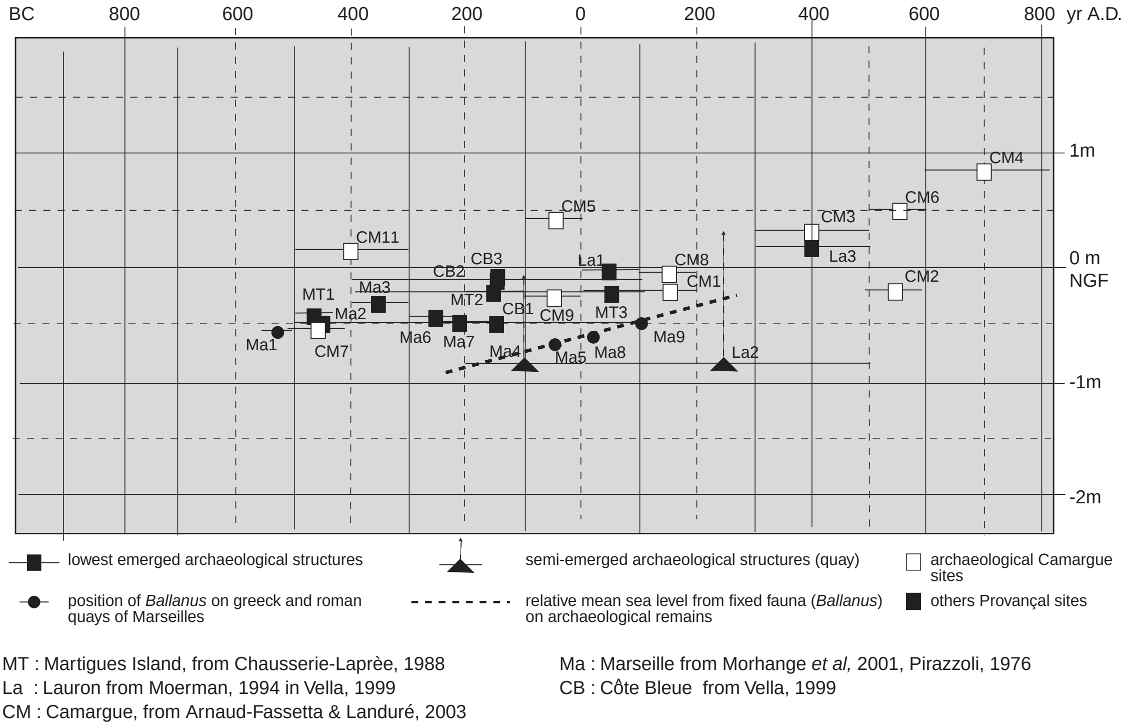


Fig. 4. Age-depth diagram : data from emerged archaeological remains compared with data gained from fixed fauna on archaeological structures.

the modern period, the position of the sea level is established at -0.12 m NGF.

These elevations are consistent with the sea-level variation curve established at La Ciotat close to Marseilles (Fig. 3A) (Laborel et al., 1994) from biological markers fixed on cliffs (Fig. 3B). The archaeological sites localized from the Rhone delta to Marseilles have allowed an approach of the same type (Fig. 4 and Table 1). Apart from the vestiges from the Gulf of Fos, which are poorly preserved and not easily dated, the positions of the base level were reconstructed from reliable archaeological indicators (hearths, occupation floors, bases of grave pits, quarry floors without convincing traces of a sea wall protecting them during extraction, fish ponds, pottery kilns). These indicators validate the coherence of the observations on the vertical position of sea level on the coasts of Provence since Greek Antiquity (Chausserie-Laprée, 1988; Vella, 2002). Lastly, the preservation of the cave paintings in the Cosquer cave, located on the rock coast of Marseilles, confirms that sea level did not rise higher than the present level since the last glacial maximum in this region. Indeed, while the lower part of several of these paintings are erased by the rise in sea level, the higher part of these same patterns is preserved up to nearly 0.5 m above the current level. The effaced part above sea level corresponds to the maximum value of the current fluctuations in sea level due to meteorological forcing and tides (Morhange et al., 2001; Pirazzoli, 1998; Lambeck and Bard, 2000).

However, the overall model of L'Homer et al. is still being used (Marsset and Bellec, 2002) in spite of new results obtained from the dating of alluvial channels (Arnaud-Fassetta, 2000) associated with the lobes. These results allow us to date the phases of alluvial filling, which can take place at a late stage, but do not date the entire period of activity of the river channel. We therefore need to review the previous model, in order to establish: (i) a local curve of the variation of relative sea level independent of the position of the offshore bars of the Rhone delta, which are subject to variations in hydrodynamic intensity and erosional processes (Pirazzoli, 1991), and (ii) a radiocarbon chronology for the develop-

Table 1
Lowest position of emerged archaeological structures in Provence

Site	Type of structure	Years BC/AD	Level in m NGF	Level interpretation	References	N° in the Fig. 3
Marseille César	Fauna on quay	575/550 BC	−0.63	Midlittoral zone	Morhange et al., 1996, 2001	Ma1
Marseille César	Wall out of water	Vth century BC	−0.56	Maximal level of the sea	Morhange et al., 1996, 2001	Ma2
Marseille César	Wall out of water	IVth century BC	−0.39	Maximal level of the sea	Morhange et al., 1996, 2001	Ma3
Marseille J. Vernes	Slipway	II/IIIth century BC	−0.85	Semi-emerged	Morhange et al., 1996, 2001	Ma4
Marseille J. Vernes	Fauna on quay	50 BC	−0.72	Midlittoral zone	Morhange et al., 1996, 2001	Ma5
Marseille César	Wall out of water	IIIth century BC	−0.46	Maximal level of the sea	Morhange et al., 1996, 2001	Ma6
Marseille César	Slipway	300/100 BC	−0.48	Maximal level of the water table	Morhange et al., 1996, 2001	Ma7
Marseille J. Vernes	Fauna on quay	1/50 AD	−0.65	Midlittoral zone	Morhange et al., 1996, 2001	Ma8
Marseille Bourse	Fauna on quay	100 AD	−0.60/−0.4	Midlittoral zone	Pirazzoli, 1976	Ma9
MartiguesVillage 1	Level of life occupation	450/430 BC	−0.50	Maximal level of the sea	Vella, 2002	MT1
MartiguesVillage 1	Level of life occupation	IIth century BC	−0.20	Maximal level of the sea	Vella, 2002	MT2
MartiguesVillage 3	Fireplace	1st century AD	−0.20/−0.5	Maximal level of the sea	Vella, 2002	MT3
Martigues Laurons	Wall out of water	1st century AD	−0.05	Maximal level of the sea	Vella, 2002	La1
Martigues Laurons	Dike	I/IVth century AD	−0.90/+0.27	Maximal level of the sea	Vella, 2002	La2
Martigues Laurons	Bottom of grave	IV/Vth century AD	+0.15	Maximal level of the sea	Vella, 2002	La3
Martigues Lavéra	Littoral quarry	IV BC/1st century AD	−0.48	Maximal level of the sea	Vella, 2002	CB1
Martigues Couronne	Littoral quarry	IV BC/1st century AD	−0.18	Maximal level of the sea	Guéry et al., 1981	CB2
Martigues L'Arquet	Littoral quarry	IV BC/1st century AD	−0.13	Maximal level of the sea	Guéry et al., 1981	CB3
Camargue Combettes	Fireplace	IIth century AD	−0.20	Maximal level of the water table	Arnaud-Fassetta and Landuré, 2003	CM1
Camargue Carrelet	Bottom of grave	VIth century AD	−0.20	Maximal level of the water table	Arnaud-Fassetta and Landuré, 2003	CM2
Camargue Carrelet	Bottom of grave	IV/Vth century AD	−0.25	Maximal level of the water table	Arnaud-Fassetta and Landuré, 2003	CM3
Camargue Carrelet	Bottom of grave	Middle Age	+0.85	Maximal level of the water table	Arnaud-Fassetta and Landuré, 2003	CM4
Camargue Mornès	Level of life occupation	1st century AD	+0.4	Maximal level of the water table	Arnaud-Fassetta and Landuré, 2003	CM5
Camargue Cabassole	Bottom of grave	V/VIth century AD	+0.5	Maximal level of the water table	Arnaud-Fassetta and Landuré, 2003	CM6
Camargue Capellière	Level of life occupation	Vth century AD	−0.61	Maximal level of the water table	Arnaud-Fassetta and Landuré, 2003	CM7
Camargue Capellière	Level of life occupation	IIth century AD	−0.13	Maximal level of the water table	Arnaud-Fassetta and Landuré, 2003	CM8
Camargue Capellière	Level of life occupation	1st century AD	−0.3	Maximal level of the water table	Arnaud-Fassetta and Landuré, 2003	CM9
Camargue Capellière	Level of life occupation	V/VIth century AD	−0.07	Maximal level of the water table	Arnaud-Fassetta and Landuré, 2003	CM10
Camargue Capellière	Level of life occupation	I/IIth century AD	+0.12	Maximal level of the water table	Arnaud-Fassetta and Landuré, 2003	CM11

ment of the offshore bars forming the lobes of the prograding mouths.

3. Methods

This study depends on the radiocarbon dating of sedimentary bodies, while first establishing a curve of the variation in relative sea level, acquiring knowledge of river activity based on bibliographical data and the interpretation of the rates of progradation of the lobes or river activity.

The dating of sedimentary bodies presented here was carried using three approaches:

(1) based on stratigraphic cross-sections extending from the marine to the lagoonal domain, by dating each of the bodies formed in these environments;
(2) dating of beach ridges of equivalent elevation in order to determine the horizontal chronology of the successive deposits collected by short cores (1 or 2 m);
(3) studying longer cores (30/40 m), in order to compare the vertical coherence of the dating of each sedimentary body.

The depositional environments are determined from the study of surface features, the granulometry of the sediments, as well as the micro- and macrofossils (macrobenthos, ostracods and pollen) contained in the sediments. The coherence of the dating is checked by obtaining results on adjacent sedimentary units that are laterally or vertically juxtaposed. We used this method to avoid the difficulties concerning radiocarbon dates pointed out by Stanley (2001). This author indicated possible reworking near the channels and the recent low sedimentation rates over the greater part of the deltaic plain. Some radiocarbon dates from the surface are older than expected and inverted, but most dates (14 out of 18) indicated a modern age. This recent sedimentation on the surface depends on fluvial inputs favouring the total submergence of the plain, which was still frequent up to the 18th century, or local near the active channels and in environments with strong biological production such as marshes, lagoons and peat bogs. In this study, we attempt to identify the recent episodes of sediment reworking/redeposition or recent organic carbon production, and check the coherence of the suggested chronology.

The acquisition of a reliable curve for the local relative sea level (Vella and Provansal, 2000) provides a reference base level (Powell, 1875; Davis, 1902; Schumm, 1977, 1993; Blum and Tornqvist, 2000). This curve (Fig. 3B and Table 2) is established from the dating of freshwater peats deposited at the immediate contact with the Pleistocene substrate, which is considered as being incompressible. The eastern margin of the delta is characterized by an important influx of groundwater circulating through Pleistocene gravels and emerging along the Coustière de Crau between Fos and Arles (Fig. 1). This groundwater body gives rise to an almost continuous peat bog between Arles and Fos. The level of emplacement of the peat bog depends on the level of resurgence of the groundwater, which is a function of the sea level. The penetration of seawater into the permeable Pleistocene formations of the Crau plain, which forms the substrate of the sandy and muddy deposits of the Rhone delta, blocks off the influx of fresh water emerging between 0 and 70 cm above the marine base level. This bracket of uncertainty is related to two other principal factors: the thickness of overlying impermeable silts and the variations in groundwater fluxes. Nowadays, these flows are considerably increased (40% to 50%) by irrigation of the Crau plain (water meadows and orchards), while currently active peat bogs develop only 50 or 60 cm above the current mean sea level located at approximately +0.10 m NGF. The variations in elevation of active peat development are thus strictly limited by the variation of base level. Peats can thus represent an indicator of sea level and have been used for this purpose for many years (Jelgersma, 1966; Pirazzoli, 1976; Van de Plassche, 1982; Denys and Baetman, 1995). On the other hand, the high compressibility of the peats, lower than or equal to 90%, and their slow rate of accommodation, higher than or equal to 1 cm per century, means that we can only date peats in contact with the Pleistocene gravel and consider thickness intervals of 1 cm or less. Core sampling carried out between Mas Thibert and Fos, on the eastern margin of the delta, and excavations with the mechanical shovel, have allowed us to access many peaty deposits that meet the paleo-ecological and positional criteria

Table 2
Radiocarbon dates of fresh water peat used to plot the curve of relative sea level (from Vella and Provansal, 2000) Ly-code laboratory: Centre de datation par le radiocarbone de Lyon France

Sample	^{14}C Age	Years BC/AD	δ^{13}C	Upper limit	Lower limit	Cross sections	Lat. N	Long. E
Ly-8447	1200 ± 55	700/965 AD	−28.44	0.73	0.03	A–B	43°26′300	4°56′400
Ly-7591	2100 ± 45	305 BC/2 AD	−27.3	−0.7	−1.4	A–B	43°26′180	4°56′500
Ly-7860	2120 ± 55	342 BC/ 0	−28.36	−0.9	−1.6	A–B	43°26′100	4°56′500
Ly-1493	2240 ± 140	733 BC/43 AD	estimated −25	−1.35	−2.05	C–D	43°28′800	4°52′200
Ly-1494	2260 ± 150	747 BC/46 AD	estimated −25	−1.43	−2.13	C–D	43°28′800	4°52′200
Ly-7862	3520 ± 55	1964/1702 BC	−26.73	−1.8	−2.5	A–B	43°25′900	4°56′240
Ly-5249	3735 ± 75	2385/1928 BC	estimated −25	−2.5	−3.2	C–D	43°25′920	4°56′
LGQ-1059	3750 ± 190	2853/1674 BC	estimated −25	−2.15	−2.85	A–B	43°25′900	4°56′
LGQ-1055	3760 ± 170	2615/1689 BC	estimated −25	−2.13	−2.83	A–B	43°25′880	4°56′
LGQ-1057	3780 ± 180	2856/1689 BC	estimated −25	−2.24	−2.94	A–B	43°25′860	4°56′
Ly-8020	3975 ± 60	2617/2297 BC	27.57	−1.89	−2.59	E–F	43°30′500	4°48′400
LGQ-1064	3990 ± 210	3033/1891 BC	estimated −25	−2.13	−2.83	A–B	43°25′860	4°56′
Ly-7592	4085 ± 60	2858/2483 BC	−27.67	−1.8	−2.5	A–B	43°26′	4°56′
Ly-1496	4450 ± 300	3807/2294 BC	estimated −25	−2	−2.7	C–D	43°26′860	4°52′450
Ly-8731	4585 ± 45	3488/3112 BC	−27.73	−2.05	−2.75	E–F	43°28′650	4°52′200
Ly-8621	4755 ± 50	3635/3383 BC	−27.21	−2.3	−3	E–F	43°30′450	4°48′380
Ly-8670	4770 ± 45	3638/3388 BC	−26.71	−2.88	−3.58	E–F	43°31′	4°48′200
Ly-8150	4825 ± 45	3690/3414 BC	−27.6	−3	−3.7	A–B	43°25′900	4°56′300
Ly-7018	5135 ± 75	4138/3767 BC	−27.25	−3	−3.7	A–B	43°26′080	4°55′860
Ly-8446	5450 ± 65	4452/4106 BC	−27.42	−3.9	−4.6	A–B	43°26′300	4°54′
Ly-364	5600 ± 150	4774/4094 BC	estimated −25	−4.37	−5.07	C–D	26′800	4°52′450
Ly-8218	5986 ± 55	5005/4763 BC	−27.09	−4.76	−5.46	A–B	43°27′	4°54′300
Ly-8671	6295 ± 50	5315/5089 BC	−27.49	−5.68	−6.38	E–F	43°30′	4°47′800

Peats radiocarbon datation on the eastern Rhône delta and limits of the sea-level in meters NGF. Datations by *Centre de datation par le radiocarbone de Lyon*, J. Evin and C. Oberlin. Calibrations according to Stuiver and Braziunas, 1993.

(freshwater peats of water meadows with swamp saw-grass: *Cladium mariscus*). Radiocarbon dating of these samples has made it possible to reconstruct a curve of variation of the fresh water table of the Crau plain as a function of the relative sea level.

4. Results

4.1. Position of sea level since 6000 yr BP

The sedimentary bodies currently at or near the surface were emplaced in relation to a base level close to its present-day elevation. These bodies correspond to the highstand system tract developed after the slowing down of sea-level rise around 6000 yr BP. However, the new local sea-level (relative sea level) curve proposed here allows us to identify precisely the onset of downlap movement (Fig. 3 and Table 2).

Indeed, the current deltaic landforms rise generally only slightly above the base level. The highest features located on the plain are the riverbank levees and the beach ridges. At present, the plain is at a height of 1 to 2 m above mean sea level. However, this is caused by present-day aeolian processes (Sabatier et al., 2002). The elevation of the dune ridges ranges between 1 and 3 m. In exceptional cases, for the highest and most recent dunes at the Pointe de l'Espiguette, their elevation ranges between 6 and 12 m above sea level. It is thus difficult to envisage the accommodation of fossil sedimentary bodies at elevations of more than 12 m compared with their corresponding base level. The fossil sedimentary bodies in the subsurface were thus emplaced at a level close to the present-day elevation.

Fig. 3B shows an age vs. elevation plot for the fresh water table, representing the evolution of relative sea level based on the dating of peats. This diagram indicates that sea level has always remained in a position lower than that of the present-day. Such a result is in agreement with recent observations carried out on the coasts of Provence and Languedoc (Laborel

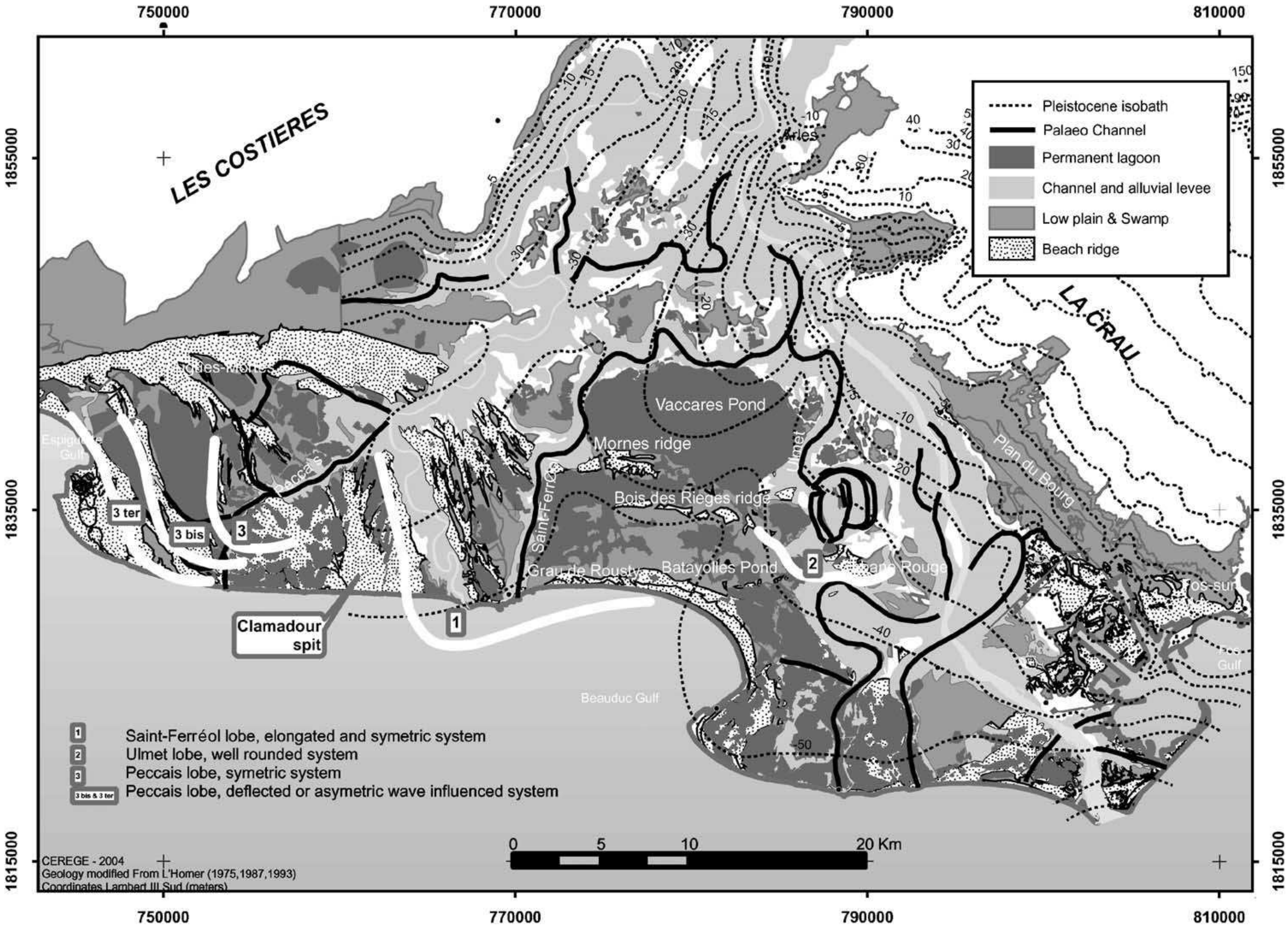


Fig. 5. Location and relative chronology of the main lobe delta on the geomorphologic map of the Rhône delta. Beach ridges and palaeo channels are particularly visible on the south of the delta plain.

et al., 1998). Before 6000 BP, Aloisi et al. (1974), proposed a local sea level curve using radiometric data of marine shells during the last deglacial period. This curve showed a regular rise in sea level up to about 6000 yr BP followed by a slowing down of sea level rise. The precision of this local sea level curve is not sufficient and global sea level (Bard et al., 1990, 1996; Blanchon and Shaw, 1995) showed the alternating periods of increase and decrease rates of sea level rise during the last deglaciation. Sedimentary bodies and seismic profile on the inner continental shelf suggest that stillstands or even sea-level drops occurred (Gensous and Tesson, 2003; Berné et al., 2003).

The measurements carried out on the eastern part of the Rhone delta allow us to highlight two major facts:

(1) the rise of relative sea level since approximately 6300 yr (Ly-8671) defines a plateau between approximately 4585 yr BP (Ly-8731) and 2120 yr BP (Ly-7860);
(2) a comparison of this curve with the data collected by Laborel et al. (1994) on the rock substrates of eastern Provence indicates a discrepancy between the two sites (Vella and Provansal, 2000). This discrepancy ranges between 0.5 and 1.5 m at a maximum, and is consistent with the archaeological quarry floors from the Gulf of Fos (Vella, 2002).

4.2. Beach ridges

The Rhone delta shows many sandy beach ridges cropping out at the surface (S. Figs. 1 and 5). We propose here a relative chronology for the accommodation of successive sedimentary bodies. The Saint-Ferréol lobe occupies the central part of the delta, bounded to the west by a thick barrier beach that

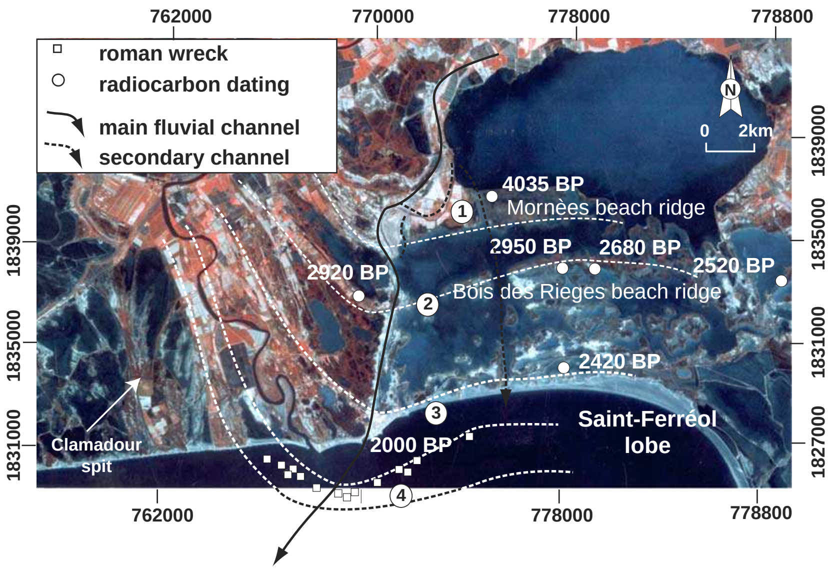


Fig. 6. The prograding beach ridges of Saint Ferreol lobe delta. The wave symmetrical lobe delta of Saint Ferréol. Pecked line underlines the main beach ridge. Core site and radiocarbon ages are indicated by white points, white squares indicate the position of Roman wrecks. Dark arrows underline main palaeo channel and secondary channel is underlined by dark picked line. Note the slight dissymmetry between the eastern beach ridge, separated by large lagoonal zone to the amalgamated beach ridge plain in the western area. (1) Mornès beach ridge is dated by one radiocarbon date from Arnaud-Fassetta, 2000. (2) The Bois des Rièges beach Ridge is dated by two radiocarbon dates and the symmetric beach ridge on the right bank of the palaeochannel is dated by another date. The dates are obtained on vegetal remains in tide marks for the Bois des Rièges and on vegetal remain in life position in the SF core on the right bank. (3) The third beach ridge is dated in the internal part on the Batayolles site (Ly-8683 see Table 2) by one 14C date on vegetal remains in a tide mark. The external part is dated by archaeological remains (Roman wrecks) identified and dated by Long, 1997. The boats carried iron ingots by the Rhône but stranded before on the coastal barrier. All the wrecks are dated around the first century BC. The wreck are concealed and preserved by progradation of a Fourth beach ridge. Later the erosion of the pointed lobe and the dominant drift constructed to the west le Clamadour spit.

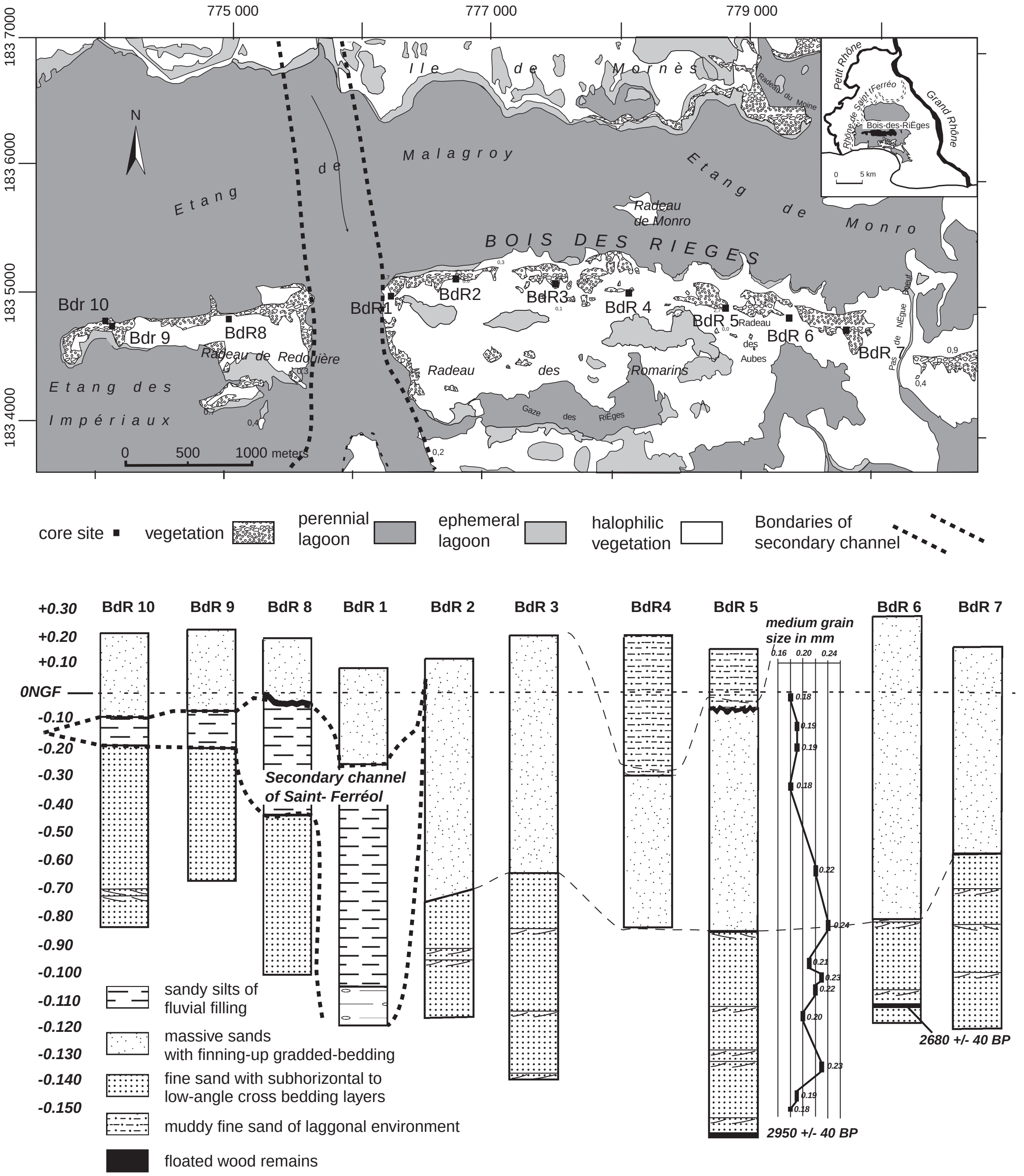


Fig. 7. Map of the core position on the Bois des Rièges beach ridge and stratigraphy simplified of cores. The sandy beach ridge is cut by a secondary channel of Saint Ferreol filling by muddy deposit without lagoonal or marine fauna. The secondary channel cut the fourth beach ridges on the east part of the lobe.

joins up with the sandy coast of Languedoc. Eastwards, the contact between the beach ridges of Saint Ferréol and the river mouth/distributary system of the Ulmet arm is partly buried by surface fluvial deposits. However, we can observe a slight change of direction towards the SSE of the Bois des Rièges beach ridge (Figs. 5 and 6), which would appear compatible with the existence of a rivermouth/distributary system during the build up of Saint-Ferréol lobe. On the other hand, two paleogulfs occupy the western and eastern parts of the delta plain. The Saint-Ferréol lobe is a typical wave influenced symmetrical lobe (Bhattacharya and Giosan, 2003). However, we note a slight difference of morphology between sandy barrier bar complexes of the left bank (east) separated by large lagoonal deposits and the more or less amalgamated beach-ridge plains of the right bank (west). This difference is more marked for the 2nd and the 3rd beach ridges. The dissymmetry of the beach ridges between the right and left banks of the Saint-Ferréol lobe is probably related to the prevailing direction of the swell (fetch). The influence of the direction of swell on the delta mouths has again been demonstrated recently (Pranzini, 2001). However, the Saint Ferréol lobe is characterised by a pointed lobe with a single fluvial elongated channel during the formation of the first three beach ridges. After this period, the rate of mouth shift to the west and the fluvial activity seems to decline if we consider the map of the mouth reconstructed from archaeological data, which shows a channel deflection to the west (Long, 2002), emerged sedimentary features and an increase of inlet channels. The prograding movement continued to build up the 4th beach ridge, but progressive filling of the Saint-Ferréol channel, upstream of the first beach ridge, between the 1st century BC and the 6th century AD (Arnaud-Fassetta, 2002) is due to more difficult evacuation of a greater solid discharge under the constraint of a renewed sea level rise. A crevasse splay occurred near the Mornès beach ridge during the 1st century BC (Arnaud-Fassetta, 2002), and this secondary channel almost crossed the three fossils beach ridges to the east of the lobe, extending from the Mornès beach ridge in the north to the Grau de Rousty in the south (Figs. 6 and 7).

The Peccaïs lobe, which fills the western gulf, post-dates the erosion of the Saint Ferréol lobe, since they are bounded by sand-spit hooks resulting from the erosion of the 4th beach ridge. The Peccaïs system lobe underwent a radical transformation from a more or less symmetric delta lobe to an asymmetric or deflected wave-influenced delta lobe. It is difficult to resolve this question in the absence of dating on the fluvial channel associated with the barrier beaches. According to certain definitions of delta morphology (Bhattacharya and Giosan, 2003), this evolution shows an important decrease of the fluvial discharge and a strong unidirectional longshore drift relative to wave activity. In the eastern paleogulf, the present-day channel of the main Rhone and recent fluvial deposits mask the morphological evolution as well as the contact between the beach ridges of Saint-Ferréol and the central part of the delta.

This relative chronology agrees with the sequence of events suggested by previous authors (Russell, 1942; Kruit and Van Andel, 1955; L'Homer et al., 1981). However, recent radiocarbon dates carried out on beach ridges of the Saint Ferréol Rhone and south of the Ulmet lobe makes it possible to propose a new absolute chronology for these sedimentary systems and associated channels (Table 3).

Two sectors were studied in particular: the central part related to the fossil arms known as Saint Ferréol and Ulmet and the eastern margin of the delta. The beach ridges of the central part were built up starting from the paleo-mouth of the Rhone de Saint Ferréol. On either side of this mouth, there are series of broad beach ridges consisting of several more or less coalescent beach ridges defining a pointed lobe advancing towards the SSW (S. Fig. 6). Only the beach ridges on the left (east) bank have been dated. This zone belongs to the Camargue national reserve and has been protected since 1927, being only affected by extensive pasture. Cores collected at 1.5-to 2-m depth do not show any effects of anthropic reworking. All the east beach ridges are cut by a fossil fluvial channel dating back to the 1st century B.C. based on archaeological levels located on the levees (Arnaud-Fassetta, 2002).

The 1st beach ridge (Mornès beach ridge) is located the farthest north and is dated (S. Table 3) 4035 ± 55 yr BP (Ly-7761) (Arnaud-Fassetta, 2000) on the internal part of the beach ridge. Described from a deep core sample (Bouteyre et al., 1970) and two shallower boreholes (approximately 3 m), this beach ridge overlies fine deposits of probable prodeltaic

Table 3
Radiocarbon datations of beach ridges and various sedimentary environments in the Rhône Delta

Sample	Conventional ^{14}C Age	Years BC/AD	$\delta^{13}C$	Material	Core name	Depth in meter	Lat. N WGS 84	Long. E WGS 84	Site name
Poz-3938	9760 ± 50	9280–9170 BC		Peat	FG	41.65	43°26.772	4°36.933	Fangassier
Poz-3936	2920 ± 35	1259–1001 BC		Vegetal remains	SF	3	43°29.571	4°26.296	Cacharel
Poz-3937	9580 ± 50	9213–8742 BC		Peat	SF	39.10	43°29.571	4°26.296	Cacharel
Ly-7761	4035 ± 55	2845–2420 BC		Wood	Mornès	1.85	43°31.545	4°29.989	Mornès ridge
MC-2014	5730 ± 170	4970–4240 BC	− 25	Peat	Frignants	7.4	43°31.357	4°29.358	Mornès ridge
MC-2015	5910 ± 170	5195–4415 BC		Organic clay	Frignants	11	43°31.357	4°29.358	Mornès ridge
MC-2016	6140 ± 120	5285–4795 BC		Peat	Frignants	26	43°31.357	4°29.358	Mornès ridge
MC-2017	9260 ± 130	8790–8055 BC		Peat	Frignants	29.5	43°31.357	4°29.358	Mornès ridge
MC-1168	10230 ± 130	10530–9055 BC		Peat	Frignants	36	43°31.357	4°29.358	Mornès ridge
MC-1170	11100 ± 130	11310–10830		Wood	Frignants	40	43°31.357	4°29.358	Mornès ridge
beta-167163	2950 ± 40	1290–1020 BC	− 26.4	Wood	Bdr5	1	43°29.800	4°32.687	Bois des Rièges ridge
beta-164694	2680 ± 40	900–800 BC	− 27	Wood	Bdr6	1.7	43°29.700	4°32.701	Bois des Rièges ridge
Ly-8683	2420 ± 55	752–400 BC		Wood	Beauduc	1.2	43°27.598	4°30.484	Batayolles
LYON-1314OXA	2620 ± 45	832–764 BC	− 24.26	Wood	Cab	1.63	43°27.762	4°39.606	Cabane rouge
Ly-11309	2280 ± 65	409–180 BC		Vegetal remains	SD11	1.5	43°30.202	4°39.831	Grand Parc
Poz-2723	1435 ± 30	560–660 AD		Vegetal remains	ACC01	6.7	43°30.656	4°40.007	Tour du Valat
Poz-2721	5780 ± 40	4770–4502 BC		Vegetal remains	BES01	5.6	43°29.816	4°38.544	Tour du Valat
Poz-2720	1975 ± 60	111BC–132AD		Vegetal remains	BES01	3.2	43°29.816	4°38.544	Tour du Valat
Poz-2722	1600 ± 25	407–535 AD		Vegetal remains	RDV01	8.8	43°29.913	4°41.006	Tour du Valat
Ly-7020	6590 ± 105	5314–4893 BC	− 22.71	Organic clay	C3.1	5..55			Cavaou
Ly-8027	6415 ± 45	5039–4805 BC	1.18	*Mesophyllum bisoïdes*	Cora	6.60	43°25.329	4°55.820	Cavaou
Ly-7018	5135 ± 75	4138–/767 BC	− 27.25	Peat	L100S0n	2	43°26.08	4°55.860	Cavaou
Ly-7592	4085 ± 60	2858–2483 BC	− 27.67	Peat	ES1.4	2.2	43°26.180	4°56.500	Marais de Fos
Ly-7862	3520 ± 55	1964–1702 BC	− 26.73	Peat	SGV1	1.8	43°25.900	4°56.240	Saint Gervais
Ly-8679	3870 ± 45	2452–2195 BC	− 27.21	Wood	Rad	2.30	43°28.534	4°48.828	Grand Radeau
Ly-7591	2100 ± 45	305 BC–2AD	− 27.3	Peat	ES1.3	2.20	43°26.180	4°56.500	Marais de Fos
Ly-8681	6580 ± 50	5569–5423 BC	− 19.88	Peat	MC150	7	43°26.314	4°54.102	Marais du Cavaou
Ly-8447	1220 ± 55	700–965 AD	− 28.44	Peat	ES3.2	1.2	43°26.300	4°56.400	Marais de Fos
Ly-8020	3975 ± 50	5315–5089 BC	− 27.49	Peat	Vig.1	2.6	43°29..981	4°47.745	Vigueirat
Ly-8023	2886 ± 40	787–549 BC	− 1.82	Marine shell	Vig. CF	1.55	43°27.598	4°30.484	Vigueirat beach ridge
LGQ-1056	2330 ± 180	823 BC–60AD		Organic clay	H2	3.5	43°27.716	4°54.102	Pont Clapet beach ridge

Datations with MC code datings come from Pons et al., 1979. Ly-code laboratory: Centre de datation par le radiocarbone de Lyon France, Poz-code laboratory: Poznan radiocarbon laboratory Poland, Beta-code laboratory Beta analytic laboratory of Miami USA.

origin dated 5730 ± 170 yr BP (MC-2014). The sedimentary beach ridge cut by the fluvial channel is essentially sandy, and fossilized by approximately 1 m of fluvial deposits. The age of 4035 yr BP (Cal BC 2845-2420) is thus consistent with the other chronological markers, as well as with the dating of the underlying body and the archaeological site. Kruit and Van Andel (1955) correlates this left (east) bank beach ridge with the Sylve Godesque beach ridge on the right (west) bank. This latter feature is very broad (3.5 km), joining the Languedoc coast and passing 2.5 km to the south of Aigues-Mortes. It is probably made up of several coalescent beach ridges, and is dated in its inner part between approximately 7000 and 5000 yr BP (Bazile, 1976).

The 2nd beach ridge (Bois des Rièges) is situated farther south, where it is described from 10 cores varying in depth from 0.9 to 1.8 m sampled along the whole length on the external part. Sandy beach ridge complexes partly submerged to the south form the rest of the 2nd offshore ridge (Fig. 7). These cores provide evidence for a prograding sedimentary sequence:

(1) fine sands at the base with subhorizontal to low-angle cross-bedding layers containing floated wood debris, interpreted as lower beach facies deposited up to the high-water mark;
(2) massive fine sands with fining-up units, containing floated wood and interpreted as upper beach facies;
(3) these facies are cut by the filling of a fluvial channel with sandy silts very rich in plant remains;
(4) towards the top, the sedimentary sequence passes up into oxidized and bioturbated muddy fine sands with a marine-lagoonal fauna (*Cerastoderma lamarckii* and *Cyprideis torosa*) of euryhaline and eurythermal type.

The base of the sequence is dated on the both sides of the palaeo-mouth: between 2950 $\pm$ 40 yr BP(Cal BC 1290 to 1020-beta-167163) and 2680 $\pm$ 40 yr BP (Cal BC 900 to 800-beta-164694) on the eastern beach bar and dated 2920 $\pm$ 35 BP (Cal BC 1260 to 1000-Poz-3936) on the western beach ridge.

The internal part of the 3rd beach ridge is located 500 m back from the present-day coastline (S. Fig. 6). A 2.70-m-deep borehole located between Grau de Rousty and Etang de Batayolles reveals a stratigraphic sequence similar to the preceding one. Massive medium sands at the base, formed near the high-water mark, are overlain by sandy-silt and silty deposits representing a prograding type of sequence. The wood debris in the massive sand is dated at 2420 $\pm$ 50 yr BP (Cal BC 750 to 400-Ly-8683). On the right (west) bank of the palaeo-mouth, all the beach ridge is preserved.

On the left (east) bank, the presence of an offshore bar is attested by the alignment of 14 Roman wrecks on a sub-marine beach bar according to the stranding hypothesis developed by archaeologists (Illouze, 1988; Long, 1997) and sedimentologists (Barusseau et al., 1994, 1996). The external bar would be positioned at about the level of the current -10-m isobath, approximately 2 km south of the present-day coastline of the Gulf of Beauduc. Most of the wrecks are located farther south, between 12 and 14 m water deep and 4 km south from the present day coast line. The large width of the beach ridge is coherent with the width observed on the left bank of the mouth where the coalescent sandy beach ridges forms a 2.5 km wide beach ridge plain.

The wrecks were stranded on a sub-marine beach bar, and then subsided approximately 6–10 m following erosion of the coast. The beach ridge is dated from the age of the shipwrecks between 50 B.C. and 50 A.D. (Long, 1997). Long (2002) proposed a map of the palaeo-mouth from the position of the wrecks and anchors. The mouth, with several inlet channels and probably submerged sedimentary features, is shifted to the west (Fig. 8). The prograding movement of the 4th beach ridge, post-dating the wrecks, would have been located even further offshore in an unknown position. Its advance led to the fossilization of the Roman wrecks and their preservation up to the present day (Fig. 6). Recent erosion of this part of the coast (Sabatier, 2001) progressively uncovers the wrecks preserved in this manner.

On the left bank, the 4th beach ridge disappears under the effect of present-day erosion of the coast (Long, 1997). The destruction of this ridge and its reworking/redeposition towards the west allowed the accommodation of a major sand spit (Clamadour spit) with an open headland (Figs. 1 and 5). Many hooks are visible exposed on the western part of the delta. A vast paleo-gulf thus occupied the western part of the delta throughout the build-up of the Saint-Ferréol lobe and even at the beginning of its retreat. The later distributary systems were based on these sandy hooks.

The sedimentary bodies outcropping south of the Etang de Vaccarès belong to a beach and lagoon

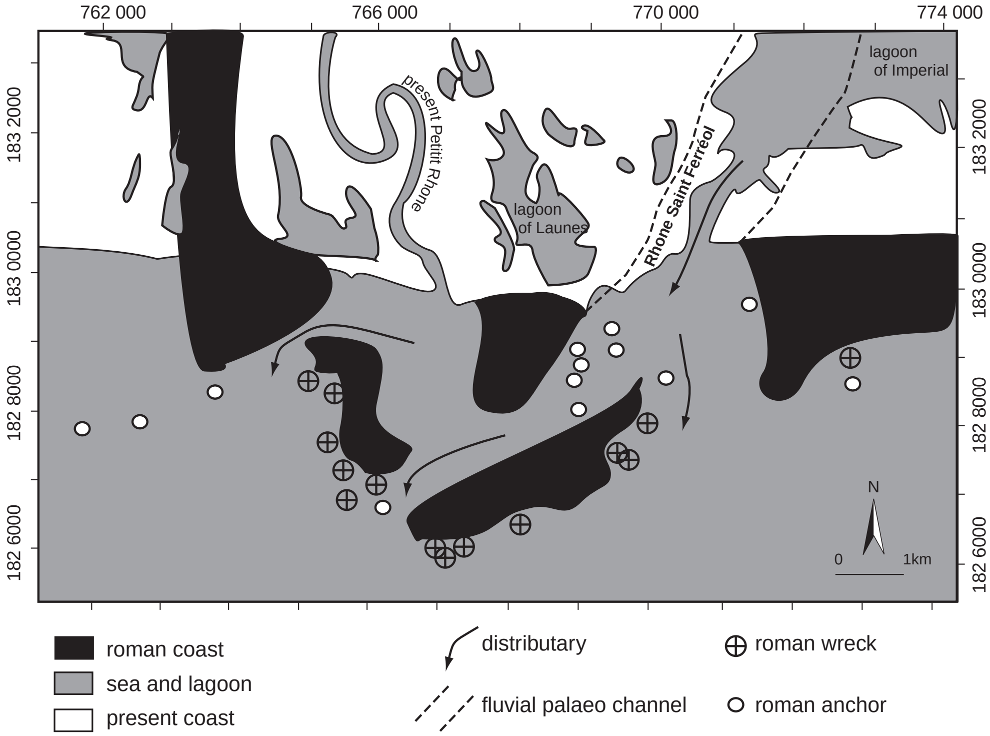


Fig. 8. Hypothetical map of the Saint Ferréol mouth from archaeological data (modified from Long, 2002). The Roman boats were stranded on submarine beach bar. The alignment of wrecks defines the palaeo coastline obliterated by subsequent erosion. Roman anchor indicate probably area in open water where boats were lying at anchor.

deposits environment (Figs. 5 and 6). The elevation of these bodies is consistent with the sea level position of at the time of their deposition, assuming a rise of a few metres for the deposits above their respective base levels. The oldest beach ridge (Mornès beach ridge, n°1) is concealed beneath 1.10 m of fluvial deposits. For beach ridges 2 and 3, the uppermost parts of the paleobeach ridges are exposed at the current surface of the plain, but their backshore is covered with lagoonal-marine deposits with thicknesses of 0.6 and 0.4 m, respectively.

Farther east, the Ulmet lobe is still poorly dated. The Bois des Rièges beach ridge nevertheless seems to be connected towards the east with a pre-existing paleo-lobe. However, ancient and recent fluvial deposits cover the beach ridges associated with the lobe. There is only one sandy outcrop, interpreted as a beach ridge (L'Homer, 1975), that limits the southern part of the lobe at the site of Cabane Rouge. It is dated 2620 ± 45 yr BP (LYON-1314OXA) (Vella, 1999). This age is consistent with the archaeological dating of the Ulmet channel and its activity is linked to the origin of the lobe (Pasqualini et al., 2004). The Ulmet Rhône channel presents a predominant meandering river style in its downstream part. Seven channels are identified and localised on the aerial photography (Fig. 9). A photo-interpretation study, carried out by Pasqualini et al. (2004), established the relative ages of channels by cross cutting relationships (Berendsen and Stouthamer, 2000). Four cores in different channels show frequent avulsions in the meander between 2280 ± 65 yr BP (Ly-11309) and 1435 ± 30 BP and permitted to identify a 8th channel buried under a more recent channel deposit. The 8th channel dated 5780 ± 40 BP is the oldest channel identified in the Ulmet system and shows that the Ulmet system is contemporaneous to the Saint Ferréol system. The evolution of the sedimentation rate of the Ulmet channel is probably similar to the Saint-Ferréol one and favours avulsions after the 1st century BC. Meanwhile, the fluvial style of the downstream part of channels is very different (meandering for the Ulmet

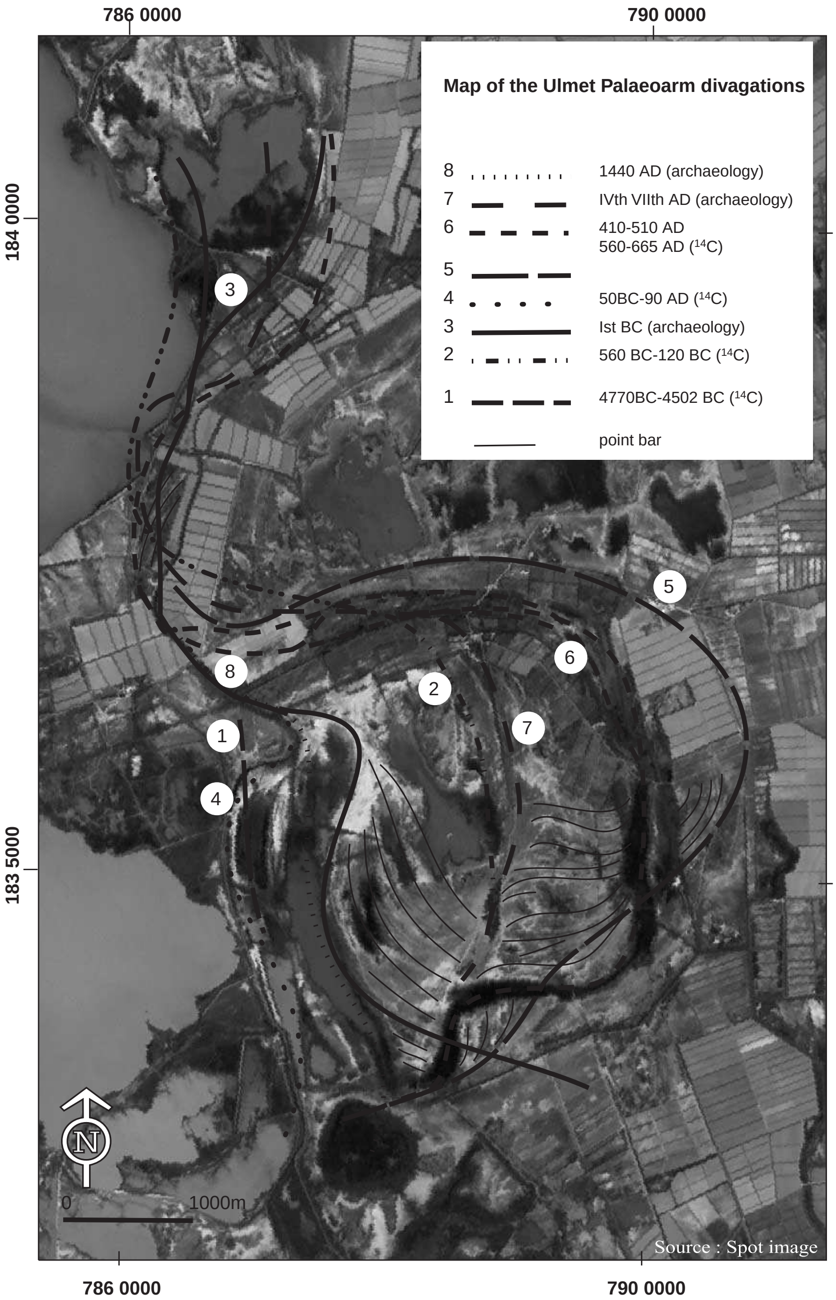


Fig. 9. Map of the Ulmet palaeo arm divagations. Seven channels are identified on the photography, an eighth channel is identified by drilling (n°1). Channels 1, 2, 4, 6 are dated by 14C (cf. Table 2), channels 3, 8, 7 are dated by archeological remains. Channel 3 is dated by Roman site studied Arnaud-Fassetta, 2000 and Landuré 2003. Channel 7 by the archaeological site of Montille du Saint Serein. Channel 8 by the medieval tower of Tour du Valat. Channel 5 is "dated" by relative chronology by cross cutting relation ship from the methodology of Berendsen and Stouthamer, 2000.

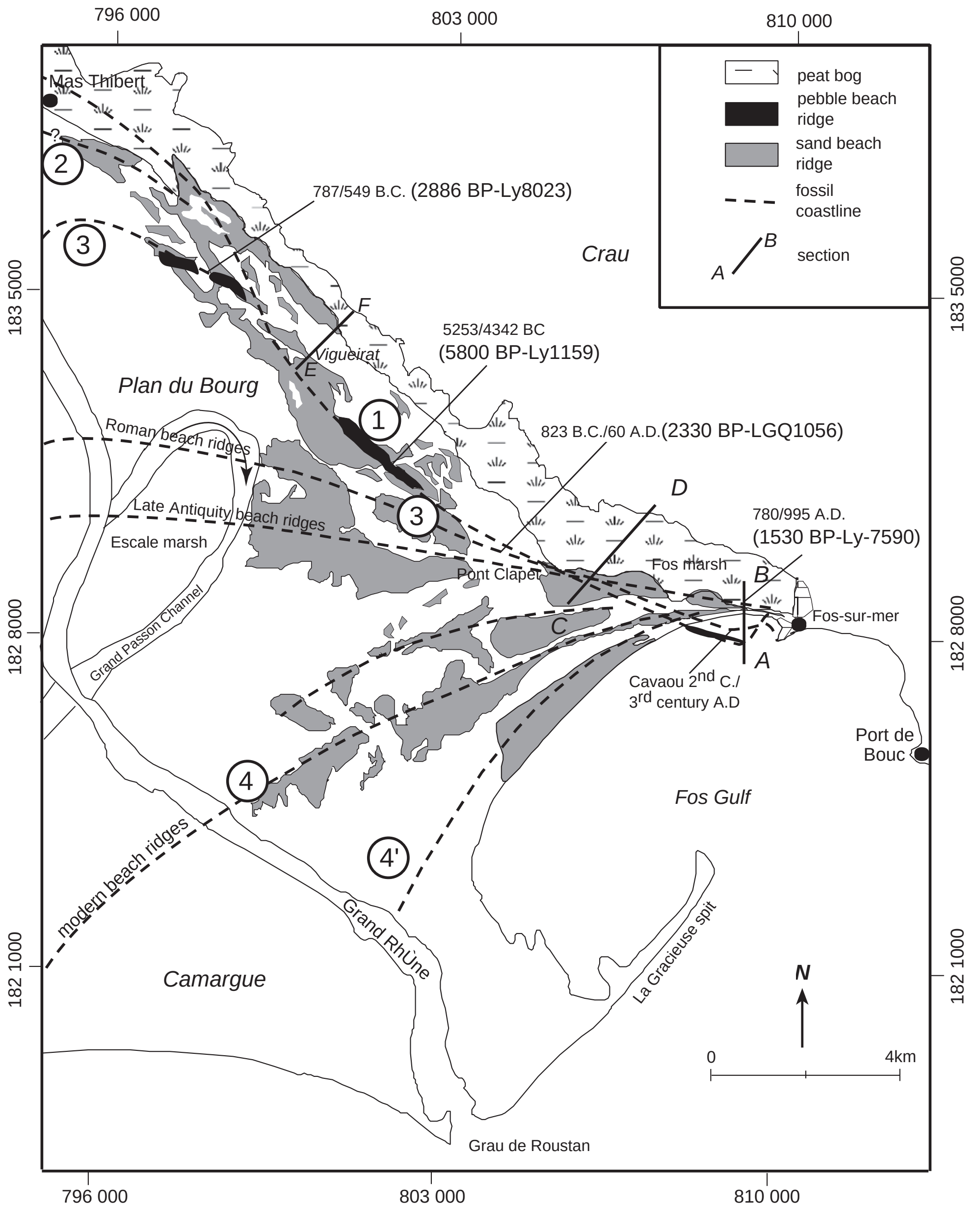


Fig. 10. Palaeoshore line on the eastern margin of the Rhône delta and location of the cores cross sections. Beach ridge radiocarbon datings indicate a progressive filling of the palaeo-gulf from 2886 ± 40 BP up to the modern period. The first coastline (1) is dated from Fos sur mer between 6560 ± 85 and 6120 ± 55 BP (Vella, 1999) and 5800 BP from Cordon du Relai (Colomb et al., 1975). The pebble beach ridge follows probably the boundary of the Crau plain. The second (2) coastline is visible to the outcrop but not dated. The third is a pebble beach ridge dated 2 886 ± 40 yr BP on shells of *Mytilus galloprovincialis* (3). The Roman beach ridge (4) is dated to the Pont Clapet site on organic clay (see Table 2). The important mobility observed on the Fos Roman archaeological site explain probably the wide morphology of the beach ridge and the relative stabilisation of the filling of the palaeogulf during Roman times. The other beach ridges (5 and 5′) are posterior to XVIth century.

arm, linear for the Saint-Ferréol) and the lobe morphologies of both channels are very different: rounded for Ulmet and pointed for Saint-Ferréol.

On the eastern margin of the delta, in the area around Fos and Plan du Bourg, the oldest shorelines are not outcropping (Fig. 10). They are buried beneath a few metres of sediments. Several sections (Fig. 10) along the eastern part of the delta show evidence for pebbly or sandy beach ridges in coastal onlap separating lagoonal-marine or boggy environments.

Near Fos-sur-mer (Fig. 11 section A–B), lagoonal deposits dated at 6590 ± 105 yr BP were accumulated

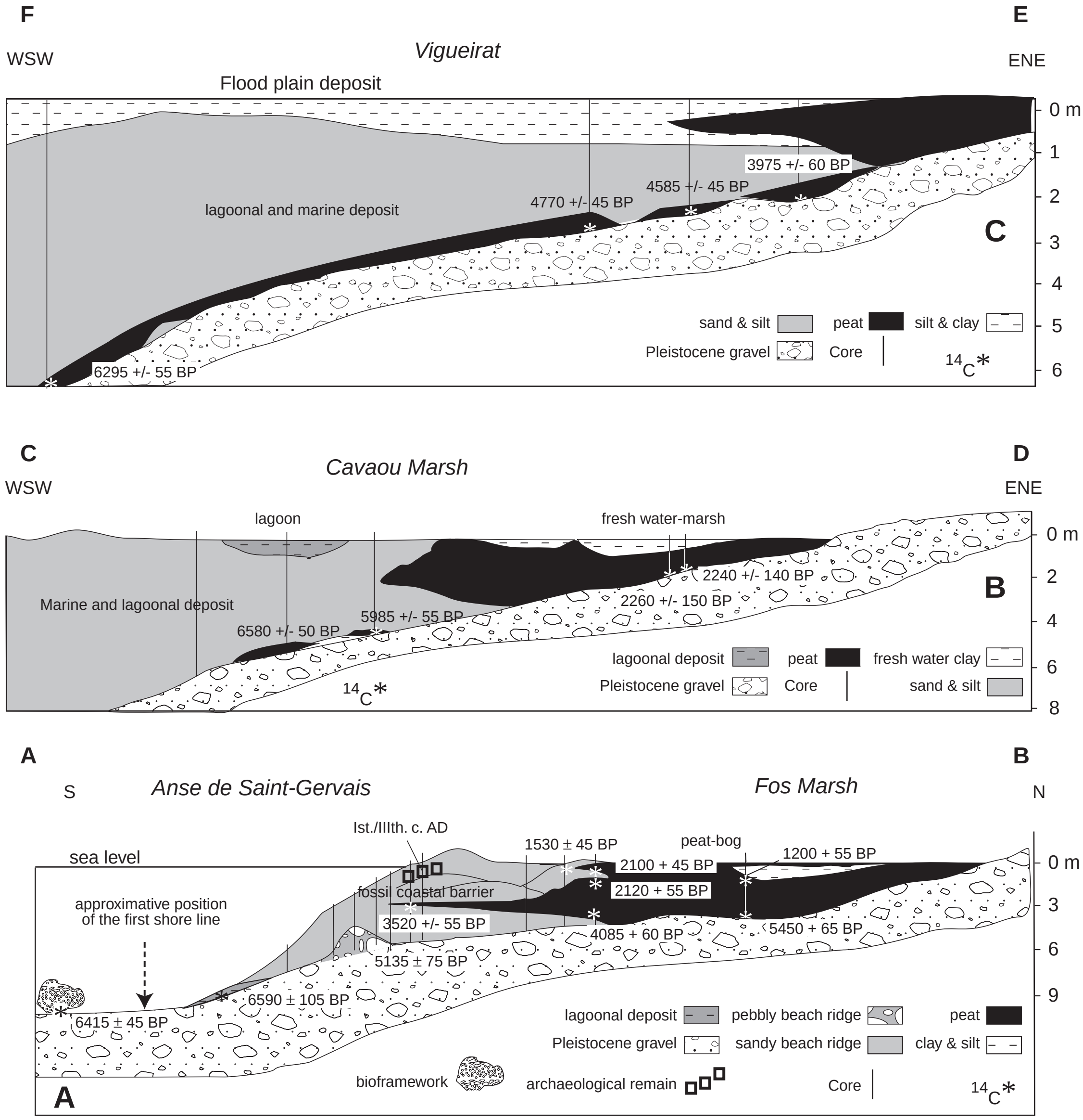


Fig. 11. Cross section over the eastern part of the Rhone delta after core observations by the authors and technical report of the Port Autonome de Marseille (1970). At the bottom, peat deposits are in back-stepping position on the Pleistocene gravel (cross section 11B and 11C). Regressive fresh water peat took place between 6580 ± 55 and 3975 ± 60 yr BP and during the following period fresh water peat deposits prograded on the marine sedimentary environment (3520 ± 55 yr BP 11A). After, fresh water peat aggraded slowly at the boundary of the Pleistocene gravel and Holocene Rhône delta deposit till today.

while bioconstructions (*Mesophyllum lichenoïdes*) dated at 6415 ± 45 yr BP developed in the open sea to the south (Fig. 11A). Although an early shoreline separates these two formations and is eroded by the successive transgressive movements, the existence of this beach ridge is supported by the presence of a lagoonal deposit. A second regressive beach ridge dated at 5135 ± 75 yr BP is identified on the same cross-section. Behind these beach ridges, aggrading boggy facies lie directly on the Pleistocene gravels surface (Fig. 11A). Freshwater peats prograde onto the preceding coastal environment, between 4085 ± 60 yr BP and 3520 ± 55 yr BP. Then, accretion-fill deposits typical of marine or lagoonal-marine environments (2) and back-stepping beach ridges (3) were emplaced between 3870 ± 45 yr BP (Ly-8679) and 2100 ± 45 yr BP (Ly-7591). Finally, beach ridges of overall prograding character form barriers between the lagoonal environments and the peat bogs (4).

To the NW (Fig. 11 section C–D and E–F), regressive boggy facies lie directly in on lap relationship on the surface of Pleistocene gravel. Freshwater peats back-steps between 6580 ± 50 BP and 3975 ± 60 BP (Fig. 11B and C). Behind the marine deposits, freshwater peats were built up, which then prograded onto the coastal environments. The top of the deltaic plain near the principal channels is draped by overbank deposits.

On the surface of the plain between Fos and Mas Thibert, we can see a series of sandy beach ridges. Their morphology points to the existence of a palaeo-gulf in the eastern part of the delta. The dating of these beach ridges indicates a progressive filling before 2886 ± 40 yr BP (Ly-8023) up to the modern period. For the Plan du Bourg sector, the interpretation of aerial photographs makes it possible to pick out four shorelines in the sub-surface from north to south (S. Fig. 10). The northernmost shoreline is not dated. The next ridge, identified on the surface and in boreholes, is dated 2886 ± 40 yr BP on shells of *Mytilus galloprovincialis*. The third beach ridge is exposed at the surface in the area of the Escale marsh and identified in boreholes farther east (Pont Clapet). Organic matter in this deposit is dated 2330 ± 180 (LGQ-1056). The final beach ridge is considered as modern based on a comparison of old maps and an illustrated view of 1585 (municipal files of Arles).

5. Discussion

The build-up of the highstand deposits of the Rhone delta is the result of combined influence of base level and volume of sedimentary input during the later part of the Holocene (Fig. 12). However, other factors seem to control the morphology of the deltaic lobes and associated beach ridges, in particular the inheritance of earlier fluvial inputs that fill the accommodation space.

5.1. Role of sea level

The curve of relative sea-level variation established locally (Vella and Provansal, 2000) starts with an overall slowing down in the rise of relative sea level (Lighty et al., 1982; Fairbanks, 1989; Bard et al., 1990, 1996). The earliest identified peaty beds are dated at about 6500 yr BP. This could be related to the decreasing rate of sea-level rise, leaving sufficient time for the accommodation of a marsh, and then its filling by a peat bog containing *Cyperaceous* plants. Indeed, peaty sequences commonly begin with a clayey organic deposit a few centimeters thick, becoming more organic-rich and then boggy upwards with well-preserved macro-remains. The lack of peat older than 6500 yr BP on the eastern margin of the delta could thus be due to an excessively rapid sea-level rise. Indeed, the rate of overall sea-level rise over the period 8500–6500 yr BP is estimated at approximately 10 mm/yr (Chappel and Polach, 1991; Bard et al., 1996), and catastrophic sea-level rise could have occurred until 7600 BP (Blanchon and Shaw, 1995). The not linear rise of sea level leads a curve in two periods of rapid sea-level rise (about 2 mm/yr): the first one between 6295 ± 50 BP and 4585 ± 45 BP and the second one between 2120 ± 55 BP and 1200 ± 55 BP (S. Fig. 3B and Table 2). These two periods are separated by a period of relative stability (Vella and Provansal, 2000).

Contrary to the commonly held view, subsidence in the Rhone delta was of limited magnitude at least over the last 6000 yr. A tectonic effect localised in the Gulf of Fos could account for the shift in the curves of relative sea level compared with the rock substrate in Provence (Vella and Provansal, 2000) as well as the sinking, in the same proportions, of certain archaeological structures (Vella, 1999). In addition, the posi-

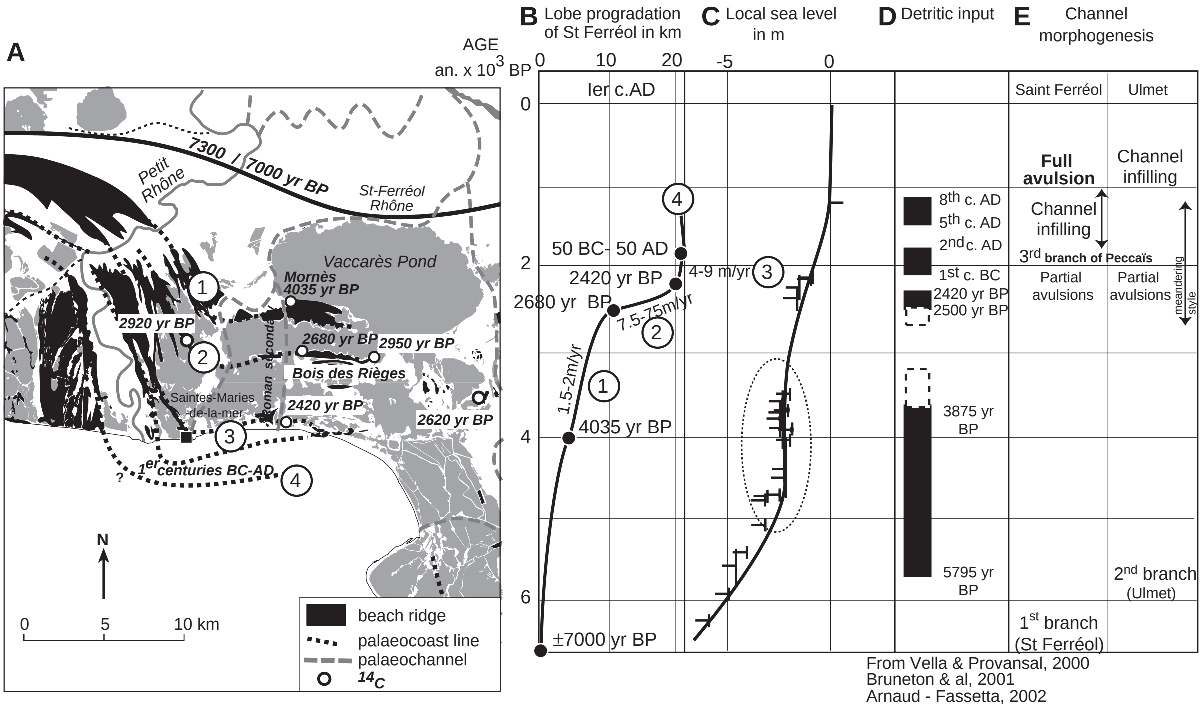


Fig. 12. Progradation rate of the Saint Ferréol lobe and sea level/fluvial input control. A: lobe map. B: Coastal progradation and rate calculated on cal BC chronology. C: local sea level curve. The symbols indicate the error bars of time and level. D and E: detritic input and channel morphogenesis are qualitative factors observed in different zones of the downstream Rhône area (from Provansal et al., 2003).

tion of the archaeological structures located on dry land (hearths, occupation soils) in the Camargue, have an elevation that is consistent with other coastal archaeological sites of Provence from Martigues to Marseille (Vella, 2002).

The position of the sea level established on the Rhone delta is a relative position because it is unrealistic to seek to reconstruct a global curve for the rise in sea level. To draw up a global sea level curve for the world ocean would require the integration of eustatic, hydro-isostatic and local tectonic data into geophysical models. At present, these models remain imperfect (Pirazzoli, 1998; Morhange et al., 2001), including that of Peltier (1998), since the data constraining the models are discontinuous, scattered or incomplete. The tectonic or hydro-isostatic constraints are often integrated as if they were continuous, although they function essentially in an irregular way. However, it should be noted that the curve established for the delta of the Rhone is of some value at the scale of the Provence region and can even be applied to the northwestern Mediterranean. We should point out that, firstly, the curve established by Vella and Provansal is in continuity with the curve proposed by Aloisi et al. (1974) (See Fig. 3C), and, secondly, there is a moderate and constant deviation of sea levels at Marseilles as established from biological markers on archaeological remains and from biological rims with *Lithophyllum lichenoïdes* at La Ciotat. Therefore, these sea levels all correspond to a single event occurring around Fos before the beginning of the Christian era, which shifts the recorded levels by approximately 50 cm. This event has been interpreted as a phase of tectonic activity localised within the gulf of Fos, showing a moderate vertical amplitude. In addition, this event is reflected by a retreat of the shoreline that considerably modified the paleogeography and led to a marine incursion of the freshwater peat bog located behind the shore in the Fos marshes (Vella et al., 1999; Vella and Provansal, 2000; Vella, 2002). Lastly, the summarized results of investigations on the archaeological remains (Pirazzoli, 1976; Delano-Smith, 1979; Flemming and Webb, 1986) show a weak tectonic mobility from the period of Greek Antiquity to the present day. Morhange et al. (1996, 2001, 2003) arrived at similar results, based on the numerous recent studies carried out around the Old Port in Marseilles.

This relative sea level rise is however sufficiently rapid to create some potential accommodation, variable both in time and space (Muto and Steel, 2000). The pattern of sea-level rise generates a probable maximum sedimentation rate along the axis of the river channels. The weak sedimentary inputs on the eastern margin favour the penetration of the transgressive surface and the maximum flooding surface. This leads to the development of a wide paleogulf of shallow water depth, taking into account the pre-Holocene topography (Pleistocene alluvial formation of the Crau plain). The peaty deposits are emplaced behind beach ridges or paleorelief in the Pleistocene substrate. In the absence of seismic data, the internal structure of the transgressive deposits cannot be characterized, but the geometry of the beach ridges (Fig. 11 section A) and the distribution of the boggy facies clearly indicate an onlap relationship. This phase is well dated on two sections from the eastern margin and the stratigraphic arrangement is visible on many sections. On sections 11B and 11C, the retrogradation of the peats is backstepping and dated between 6580 ± 50 and 3975 ± 60 BP. On section A, the retrogradation of the beach ridge is dated between 6590 ± 105 yr BP and 5135 ± 75 BP (Ly-7018).

The outcropping of the beachridge in Camargue, the dynamics of progradation Saint-Ferréol lobe and the transition to a highstand deposit regime starts around 4035 yr BP, while the fresh water peats of the eastern margin Rhône delta are formed at 4085 yr BP onto marine sediments in a very different sedimentary context. This indicates the role played by local (?) stabilization of relative sea level in the triggering of progradation (Figs. 3B, 11A, and Fig. 12). After this phase, the progradation and erosion of the coast is primarily controlled by sedimentary inputs, but sea level continues to have an influence on the mechanisms of creation sediment accommodation space on the delta plain and for avulsion process. Effectively on the floodplain the sedimentation rates increase between the 1st century and the AD 2nd century (Arnaud-Fassetta, 2002) after the end of the period of stability shown by the local sea-level curve (Vella and Provansal, 2000). Consecutively, on the Ulmet and Saint-Ferréol lobes, we note avulsion process and high sedimentation rate on the plain and in channels after 2100 BP and the renewed sea-level rise. The avulsions resulted from a combination of eustatic forcing and sediment flux.

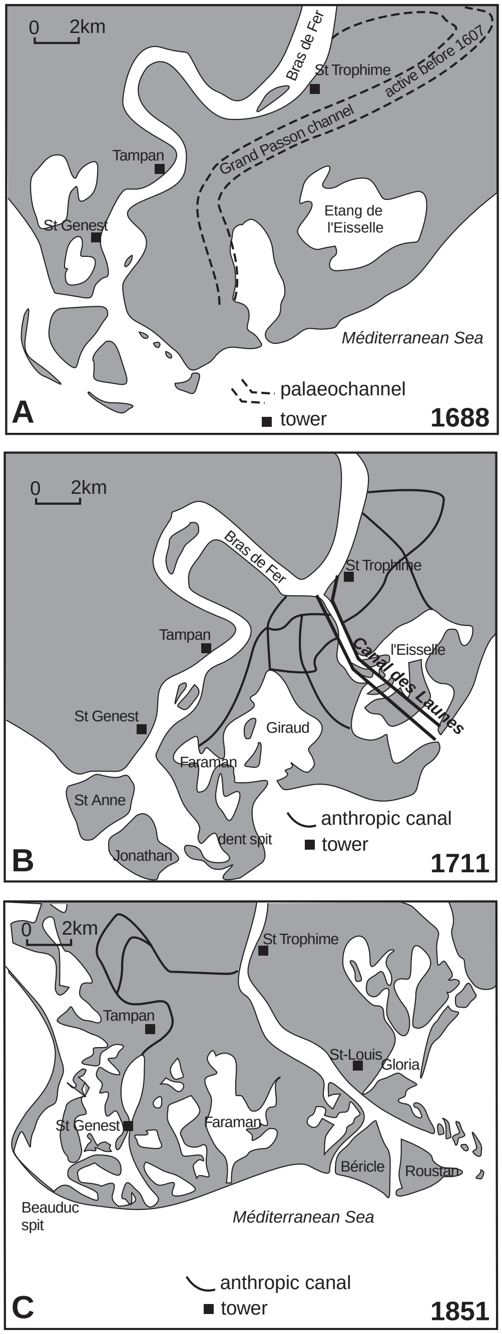
5.2. *Role of sediment input on the rate of lobe progradation*

In the eastern part of the delta, the chronology of the most recent channels is relatively well known (Fig. 3F, G, H). The Grand Passon arm appears to have been active in the 14th century (Rossiaud, 1994), even as early as the 13th century and continued up to 1607 (Colomb et al., 1975). The Bras de Fer was apparently active between 1587 and 1711 (Colomb et al., 1975; Rossiaud, 1994), while the downstream channel of the Grand Rhone would have become active from 1711 or 1713 (Russell, 1942) up to the present day. The activity of these channels explains the strong progradation that can be observed on modern maps of the delta in this sector (Fig. 13). For the older fluvial deposits, now buried beneath the deltaic plain, the lack of boreholes and chronological markers throughout the Holocene succession limits our hypotheses to the central part of the Camargue and the eastern margin. Because of the lack of deep boreholes on the Ulmet lobe, the sedimentary inputs prior to the emplacement of the lobe are not known. However, the morphology of Pleistocene surface argues in favour of late-stage fluvial inputs in the eastern sector (Fig. 14).

The Rhone d'Ulmet appears to be active between 5780 ± 40 BP and the medieval period, being closed artificially in 1440 (Rossiaud, 1994). In previous study (Provansal et al., 2003) the beginning of the fluvial activity was not established and the beach ridge of Cabane Rouge at the fluvial mouth was the oldest trace dated (2620 ± 45 BP). The single 1-km wide beach ridge of Cabane Rouge is interpreted as a stabilisation of the coastline, associated with a slight tendency to progradation of the delta plain.

In the centre of the delta, the Saint Ferréol arm was active between 4000 yr BP and 1440 AD, when it was closed off artificially from the Grand Rhone (Russell, 1942). There are sufficient dating results on the Saint-

Ferréol lobe to establish a true chronology of progradation. For at least three phases of progradation took place between 4000 yr BP and 50 A.D. The beach ridges correspond to phases of coastal stabilization, whereas the spaces between the beach ridges are currently occupied by ponds representing phases of variable rate of progradation. The progradation rates calculated from the minimum and maximum time-intervals of the calibrated radiocarbon dates are initially relatively slow (1.5 to 2 m/yr), becoming very fast between the 2nd and 3rd beach ridges (7.5 to 75 m/yr) and again a little slower for the construction (stabilization) to the 3rd beach ridge (4 to 9.3 m/yr). The average progradation rate between the construction of the 1st beach ridge and the 3rd beach ridge is 3.5 to 4.4 m/yr (Fig. 12). Using historical maps of the mouth of Bras de Fer during the Little Age Ice, we can calculate an advance of the emerged lobe of 160 m/yr for the period 1665/1688, and a rate of progradation of 60 m/yr between 1895 and 1952 for the present mouth of the Grand Rhône (Provansal et al., 2003). In this way, the values obtained for the progradation of the Saint-Ferréol lobe are of the same order of magnitude as the data for a more recent period based on precise mapping surveys and field measurements.



Four phases of more abundant sediment supply were determined (Fig. 12) on the basis of hydrosedimentological data (rate of sedimentation, alluvial changes, grain-size changes) collected on the deltaic plain (Arnaud-Fassetta, 2000, 2002), as well as from the alluvial plain of the lower Rhone (Bruneton et al., 2001; Provansal et al., 2003). These phases are dated between 5800–3800 yr BP, 2500–2400 yr BP, 1st century BC to 2nd century AD and 5th–8th centuries AD (Provansal et al., 1999, 2003). The first one period is not well characterised and the data set (hydrological and radiocarbon dating) is not collected at the same resolution scale by different authors (Arnaud-Fassetta, 2000; Bruneton et al., 2001; Provansal et al., 2003).

Between 4035 ± 55 yr BP and 2680 ± 40 yr BP (beach ridges 1 and 2) the relative slow construction of the lobe prevents the matching of hydrosedimentary activity with coastal evolution. However, the building of the initial most massive offshore beach

Fig. 13. Modern evolution of the eastern Rhône delta plain after historic maps (from Provansal et al., 2003, modified) 12A Before the Bras de fer active since 1585, the Grand Passon channel was active from the medieval period until 1607 (L'Homer, 1975; Rossiaud, 1994). 12B Avulsion occurred in the Canal des Launes that drained fresh water of Rhône toward littoral salt marsh. 12C The Grand Rhône channel flowed definitely to the southeast, but only an evolution of the mouths will occur during the following 50 yr.

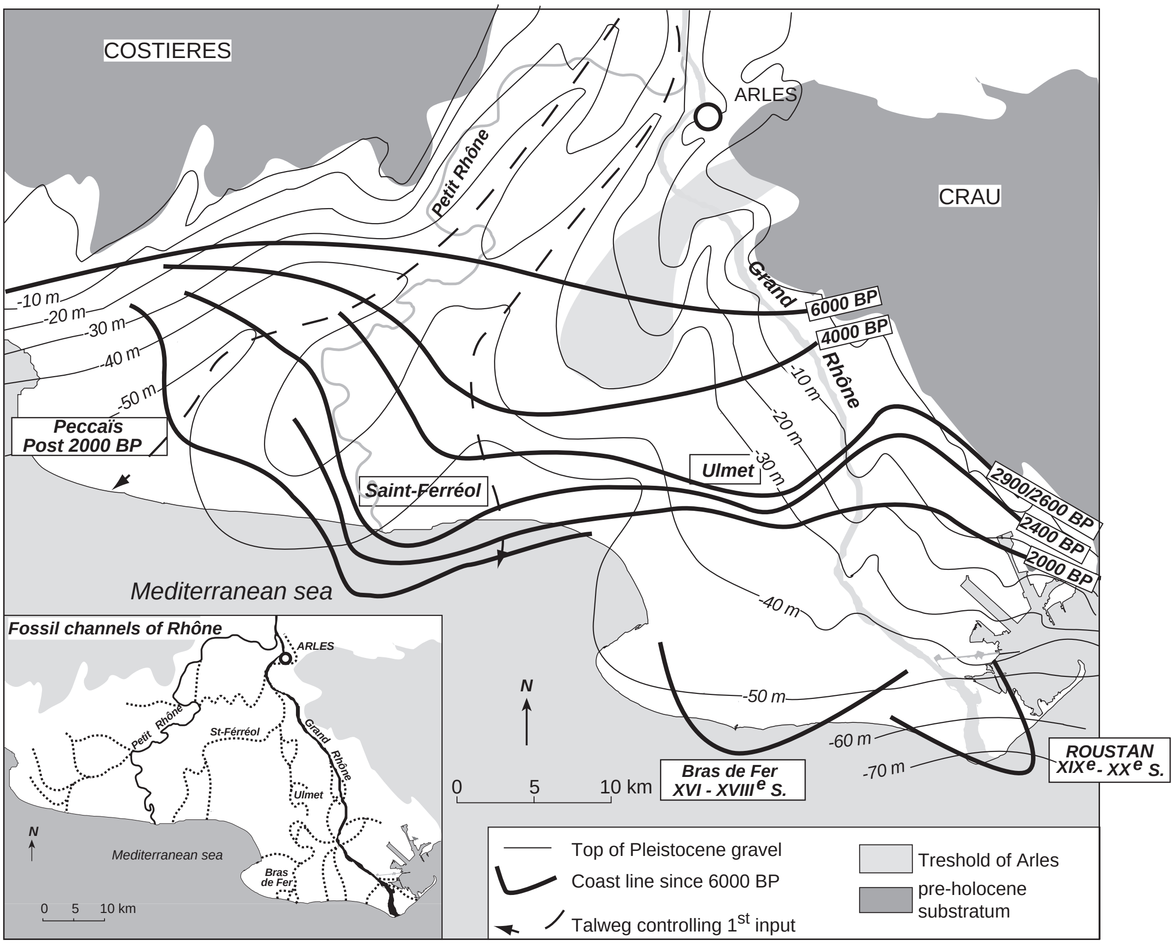


Fig. 14. Comparison of the delta lobes progradation and the Pleistocene gravel isobaths. Palaeothalweg on the Pleistocene gravels and the threshold to the south of Arles guided the first fluvial input to the center of the delta plain. Later lobes progradation is controlled by the position of palaeochannel and avulsions.

ridge (Mornès) could begin after a delay of one millennium in comparison with the longest sedimentary phase at Arles (5800–3800 BP). The slower progradation is related to a larger volume of space to fill.

The following stages, associated with narrower ridges, prograde rapidly. Their formation is favoured by the flood dominated regime indicated by Arnaud-Fassetta (2002).

During the faster progradation from the construction of the 2nd beach ridge (2680 ± 40 yr BP—Cal BC 900 to 800) to the beginning of 3rd beach ridge's construction dated 2420 ± 55 yr BP (Cal BC 752 to 400), we note a large hydrological activity in the delta. An intense alluvial activity characterises this period in the upper Rhone valley (Salvador et al., 1993), but the tendency to downcutting appears to be related to a reduction in river discharge (Bravard et al., 1992). In small river basins and in the Southern Alpine zone, the beginning of the Iron Age is characterised by a tendency to strong torrential activity (Jorda, 1992; Provansal and Morhange, 1994; Provansal, 1995). The progradation of the Saint-Ferréol lobe is consistent with the erosive activity of the upstream part of the catchment area but is in contradiction with a reduction of discharge over the whole catchment as inferred on the delta.

Beach ridge 3 was accumulated between 2420 ± 55 yr BP (Cal BC 752 to 400) and 50 BC-50 AD. It forms a boundary to the coastal progradation of the Saint-Ferréol lobe taking place between the emplacement of beach ridges 2 and 3, and corresponds partially to a period of strong hydrological activity recognized between 1st century BC to 2nd century AD on the lower alluvial plain near Arles and on the delta (Provansal et al., 1999). During the Roman period, sediment-load discharge seems relatively important and led to the aggradation/accretion of the channel beds, with overbank flooding and high water-table levels. Several crevasse splays and secondary arms appeared, and the hydromorphological activity obstructed the navigation of ships, thus justifying the dredging of Marius channel during the 1st century B.C (Vella et al., 1999).

The progressive filling of the Saint-Ferréol channel took place between the 2nd and 6th centuries AD (Arnaud-Fassetta, 2000). Thus, the decline of Saint-Ferréol channel favoured the activity of Ulmet and Peccaïs channels, which can be linked to an avulsion (Fig. 12). The Saint-Ferréol channel occupied a stable position for almost 2000 yr, which resembles to the duration of the "cycle" evoked by Roberts in the Mississippi river (Roberts, 1997). However, it is impossible to ignore the importance of rhythmic sedimentary fluvial inputs in the progradation, the instability and finally, the avulsion.

The emplacement of the 4th beach ridge took place after the 1st century B.C., but a hydrological crisis characterized by major sediment influx is recognized at Arles and on the deltaic plain (Arnaud-Fassetta, 2002) during the Late Antiquity (5th–8th centuries AD). This crisis appears to have led to the latest progradation.

The absence of data on the evolution of the Ulmet lobe prevents us from determining the role of this distributary in relaying the pattern of discharge. However, the southernmost position established for the Ulmet lobe is dated at 2620 ± 45 yr BP (Cal BC 832 to 764), which could thus indicate its progradation during the previous period. On the downstream Ulmet channel partial avulsions and full avulsions have occurred since 2280 ± 65 yr BP (Ly-11309) and increased during the Late Antiquity (Fig. 12). In lower Provence, however, this period is characterised by a reduction in flows (Provansal, 1995). Again, progradation of the delta reflects the hydro-sedimentary activity of the Atlantic catchment area rather than its Mediterranean part.

The relationships observed between the different discharges are not easily comparable with the global climatic evolution. Indeed, the late Holocene is characterised by a climatic decoupling between the Atlantic and the Mediterranean zones. Warmer and drier conditions in the Mediterranean zone coincided with cool and wet conditions on the Atlantic coast (Mc Dermott et al., 1999). Since the catchment area of the Rhone is subject to these two climatic zones, it is difficult to establish the proportion of one compared to the other. Moreover, from the later part of the Holocene onwards, the effects of human activities on erosion becomes important and then probably determinant during the historical period. On the other hand, a local factor must have controlled progradation on the delta between the lobes of the Rhone d'Ulmet and Saint Ferréol.

5.3. Role of accommodation space

The progradation of the highstand deposit was facilitated around Saint-Ferréol by the existence of a prior surface river channels in the topography on Pleistocene gravel (Fig. 14). On the continental shelf, postglacial deposits are organised into a set of four transgressive units or parasequences backstepping from the outer shelf towards the delta plain (Gensous and Tesson, 2003). These parasequences are correlated with postglacial deposits drilled on the delta plain (Lagaaij and Kopstein, 1964; Oomkens, 1970; Bouteyre et al., 1970). Others steps are identified in the morphology of the inner shelf, fluvial input slows down of retrogradation the coastline and favours delta plain aggradation. A new core (SF01) crosses an emerged palaeodelta plain between 30 and 40 m of depth under the recent plain surface and is dated 8850 ± 82 BP (Ly-12097) and 9580 ± 50 BP (Poz-3937) and confirm the radiocarbon dating of Frignants (Bouteyre et al., 1970).

Thus, at the Frignant borehole (Fig. 15), we note an aggradation of 20 m between 6140 ± 120 yr BP (MC-2016) and 5730 ± 170 yr BP (MC-2014) (Bouteyre et al., 1970), which corresponds to an accommodation rate ranging between 1.7 and 10 cm/yr. These values are closely comparable with the current accommodation rates observed in the sector of the present Rhone mouth. Present rates ranged between 20 and 48 cm/yr (Charmasson et al., 1998; Radakovitch et al., 1998)

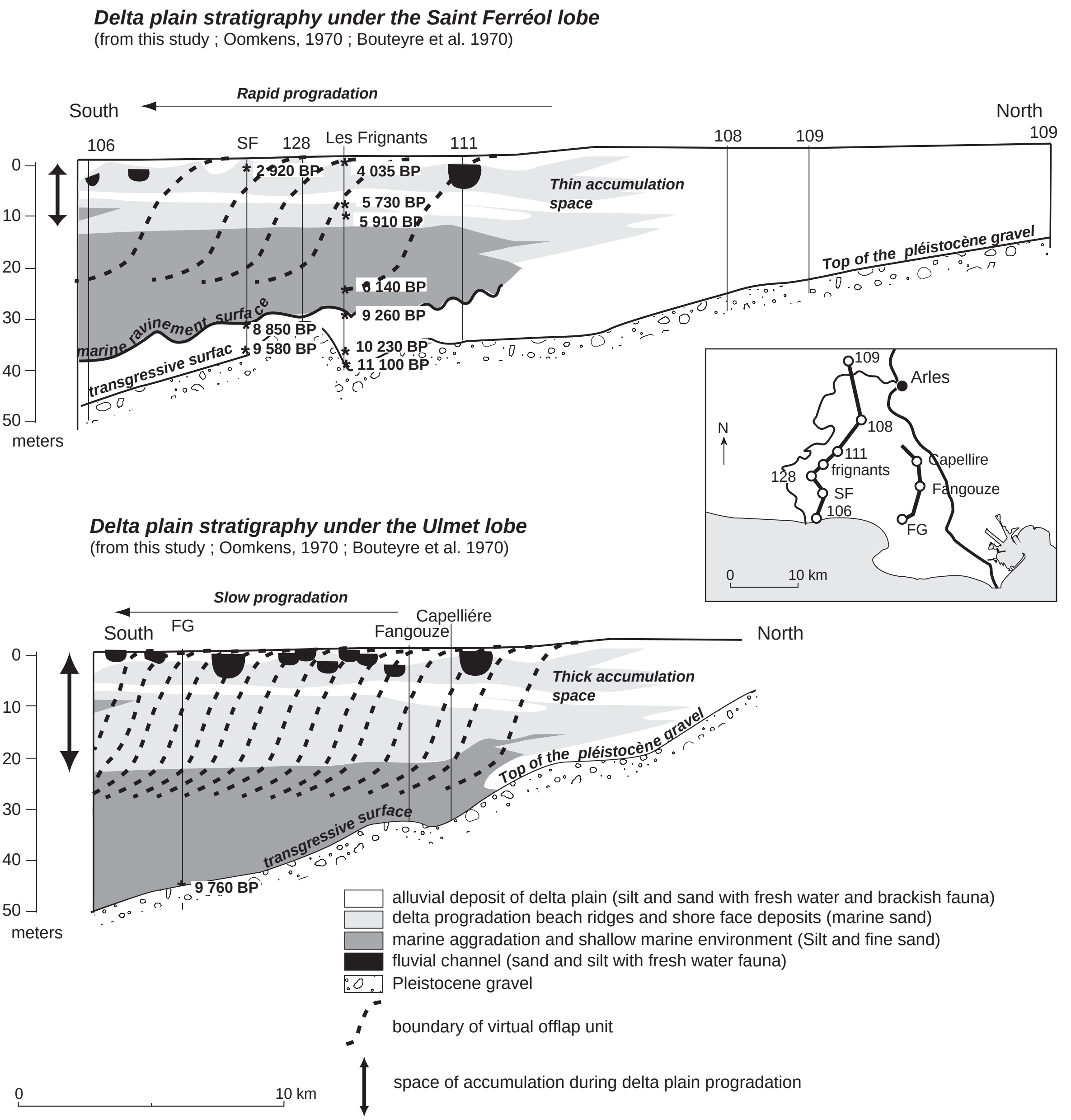


Fig. 15. Comparison between delta plain stratigraphy under the both lobes of Saint Ferréol and Ulmet. The stratigraphy is partly conceptual (offlap boundaries). Sedimentation environments are interpreted from Oomkens, 1970, Bouteyre et al., 1970, and Pons et al., 1979. Radiocarbon dating from Pons et al., 1979 and GDR marge. The presence of predelta plain deposits at the bottom of the Saint-Ferréol stratigraphy reduced the potential accommodation space and favoured infilling by marine deposits. A thinner accommodation space resulted in the case of the Saint-Ferréol lobe and favoured the rapid progradation.

near the river mouth, and between 0.20 and 0.63 cm/yr on the inner shelf (Zuo et al., 1990; Radakovitch et al., 1998). The large space of potential accommodation did not lead initially to a progradation of the coast, despite the high sediment-load discharge. On the contrary, it favoured the aggradation and build-up of a very thick prodelta required for the future progradation of the 1st beach ridge (Fig. 15).

The thick morphology of the 1st beach ridge and the long interval of time before the start of the first phase of progradation between 4035 and 2600 yr BP appear to reflect the important potential accommodation downstream of the paleomouth. Subsequently, progradation would be facilitated by the small amount of potential space to be filled and the gentle submarine slope. The lobe then acquires an increasingly pointed shape (S. Figs. 6 and 12).

On the contrary, the Ulmet lobe displays a well-rounded morphology, and a multiplicity of fossil channels indicating frequent avulsions in the downstream part of the watercourse (Figs. 9 and 15) and a predominant meandering river style (S. Fig. 9). Moreover, the width of the Cabane Rouge beach ridge and the absence of prograding bars after 2620 ± 45 yr BP is interpreted as indicating a stabilisation of the coastline. Global factors, whether climatic or eustatic, cannot explain this difference in morphology. It could originate from local geomorphological or hydrological factors related to the prior filling of the marine zone. Indeed, although the Pleistocene substrate around the paleo-mouths of Saint-Ferréol and Ulmet lies at a depth of approximately -40 m, a major channel cut into the roof of the Pleistocene formation guides the early-stage Holocene inputs towards the central part of the delta under the lobe of Saint-Ferréol. To supply the thalweg under the Ulmet lobe, the watercourse would have passed over a threshold located south of Arles between -10 and -20 m (Fig. 14). Lastly, the lobe-related channels exposed on the surface of the plain show a diametrically opposite morphology. The influence of these channels is greater than the inherited Pleistocene features controlling the pattern of aggrading and pre-prograding sedimentation. The Saint-Ferréol lobe is in the form of a highly elongated single channel with little bifurcation. Only one secondary channel, dating back to the 1st century B.C. (Arnaud-Fassetta, 2000), cuts the beach ridge of Mornès, Bois des Rièges and probably the third beach ridge as well. It seems to play a subordinate role in the construction of the lobe. On the other hand, the Ulmet channel displays a highly complex form composed of many channels with very marked meanders showing cutoffs, and exhibiting various river styles ranging from sinuous channel to braided. The filling of these channels was dated between 2280 ± 65 yr BP (Ly-11309) and 1435 ± 30 yr BP (Poz-2723). The presence of many sites along these channels and the radiocarbon dating makes it possible to date the main activity extending from the 5th or 6th century B.C. to the Medieval period. An important part of Ulmet activity corresponds to the Saint Ferréol progradation. However, the morphology of these lobes is completely different. This disparity in behaviour could be related to the space available for sediment accommodation. The Saint Ferréol Rhone progrades onto a space already largely filled by pre-Holocene and earliest Holocene units (Fig. 15) deposited from the inner shelf (Gensous and Tesson, 2003) to the sedimentary plain (Oomkens, 1970; Bouteyre et al., 1970). By contrast, the vast accumulation space available downstream of the Rhone d'Ulmet is not filled by coastal and fluvial inputs during the early part of the Holocene. In this eastern part of the delta the transgressive surface lays directly on the top of the Pleistocene gravel of Crau (Fig. 15). Marine clay sedimentation took place directly at the base of the Holocene delta succession (Capelière and Fangouze cores) and the lack of sediment leads to the formation of a regressive pebble beach ridge by reworking of the Pleistocene gravel surface (Colomb et al., 1975; L'Homer, 1975). The important accumulation space led to a slow progradation of the Ulmet lobe and the creation of thick beach ridge, favouring avulsions downstream of the deltaic plain (S. Figs. 9 and 15).

6. Conclusion

The variation of relative sea level remains an important factor controlling the evolution of the Rhone delta after 6000 BP. Even during periods of slow sea level rise, this variation plays a major role in the emplacement of the highstand deposits and the triggering of progradation. Moreover, the accommodation space created by even a slight sea level rise leads to filling of the emergent deltaic plain. The mode of progradation of the coastline, as well as the morphologies of the associated beach ridges and channels, is always controlled by the accommodation space available in front of the river mouth. This space is a function of the Pleistocene surface topography and features inherited from the sedimentary filling during the earlier part of the Holocene.

The role of sedimentary fluxes cannot be outlined in detail because of a lack of high-resolution chronology for the development of beach ridges and distributaries over the entire delta and a 3D knowledge of the overall geometries of the delta. However, we note that progradation of the delta between 4000 and 2400 yr BP is relatively in good agreement with the hydrological activity over the whole catchment area. From 2400 yr BP onwards, the decoupling between progradation of the Saint-Ferréol lobe and the hydrological activity indicates that the influence of sediment-load input and/or river discharge was able to compensate for the regional climatic effects.

Acknowledgements

This work is a contribution to the "GDR marges" and Eurodelta programme (EVK3-2001-00200 EVK3-2001-00200), supported by the French Government and the EU, respectively. We thank the national reserve of the Camargue, in particular Eric Coulet and François Lescuyer who authorized our access to a highly protected zone and provided us with material and personnel assistance during core sampling on the Bois des Rièges beach ridge. We are much obliged to Christine Oberlin and the staff of the radiocarbon dating laboratory at Lyons, Tomasz Goslard of Poznan Laboratory, and our thanks to Beta Analytic laboratory for their patience. Field assistance by French Coastal Conservatory (Domaine de la Palissade), Compagnie des Salins du Midi and Mr. Boudet (Company Director) provided generous access to the Fangassier site, Mme. and Mr. Flandrin provided generous access to the Cacharel site.

Dr. M.S.N. Carpenter (Rennes) was responsible for the translation and post-editing of the article in English. The Authors would like to thank sincerely M. Rabineau and L. Giosan for their helpful comments on the manuscript.

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