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Geomorphological records of a 'flood-dominated regime' in the Rhône Delta (France) between the 1st century BC and the 2nd century AD. What correlations with the catchment paleohydrology?

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Abstract

In the Rhône Delta, numerous paleoenvironmental indicators coming from geomorphology, sedimentology, paleoecology and archeology provide evidences of remarkable hydrological regime change at the beginning of the Roman Antiquity. A significant reinforcement in the Rhône River's competence is indicated by the increase in grain size of the sediments deposited in the floodplain, within the immediate proximity of the channel. Increase in the fluvial sediment yield is indicated by the increase in rate of sedimentation in the floodplain. Increase in water levels is indicated by the deposition of hydromorphous facies, the development of hydrophytic species, and the decrease in activity of terrestrial lombricoids in the floodplain. Numerous crevasse splays were formed by short-term avulsions of the Rhône River between the first century BC and the AD first century. Their frequency is related to an increase of Rhône River paleodischarge, which makes the channel network incapable of evacuating large volumes of water brought in by the river. The littoral zone experienced a phase of progradation between the AD 1st and the 3rd centuries, in relation to the increase of terrigenous deposits coming from the Rhône of Ulmet. The increase in solid discharge, in the flood-dominated regime (FDR) context, can be related to the overall increase in detrital output from the catchment. The Rhône Delta rather appears in phase with the northern Alps and Massif Central from the 1st century BC to the AD 1st century. The FDR at the beginning of the Christian era contrasts with the drought-dominated regime (DDR) and the reduction of torrential rainfall in the Mediterranean and south Alpine areas. These observations allow to confirm the hydroclimatic limit which could distinguish the southern part of the catchment (Provence, Durancian Alps) from the rest of the Rhône basin.

Keywords: Continental paleohydrology; Flood-dominated regime; Late Holocene; Rhône Delta; France

1. Introduction

From the early 1980s, increasing numbers of works were carried out on the changes to the Rhône fluvial hydrosystem. The first studies were commenced on the upper French Rhône River [1]. A transdisciplinary study involving geomorphology, ecology, and archeology allowed a step-by-step record to be established for the variations in water and hydrological levels recorded in the alluvial plains and measurement of the potential impact of these levels on fluvial societies, settled in the valleys since the Neolithic. The study was mainly focused on major rivers, such as the Rhône River [2,3,4,5], also Alpine tributaries like the Arve and the Isère rivers [6,7], and small catchments located in hilly massifs that drain into major river systems [8]. Parallel to the research carried out in the upper Rhône valley, and benefitting from construction of a French TGV line by the SNCF, a study of the middle Rhône valley was carried out to investigate the fluvial sediments dynamics of small tributaries on the right bank of the Rhône River [9].

All of these studies, from Lake Geneva to Montélimar, allowed several hypotheses to be proposed concerning the paleohydrological dynamics of the upper and middle Rhône River. They lead to the conclusion that a "flood-dominated regime" (FDR) occurred in the Rhône fluvial hydrosystem during the Late Holocene [10]. FDRs consist of multi-decadal periods of persistent flood activity, in agreement with significant increases in annual rainfall, rainfall inten

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sities and rainfall frequencies [11]. Points evidence of a FDR have been clearly demonstrated in the upper Rhône River at the beginning of the Roman Antiquity. It is interpreted as a climatic deterioration, intensified by anthropogenic disturbances in the Rhône catchment [3].

Until recently, the hydrological processes of the Rhône River at the beginning of the Roman Antiquity were poorly understood in the lower part of the hydrosystem. From the early 1990s, there have been numerous geomorphological studies carried out in the delta plain and the surrounding area [12,13,14,15,16]. These studies, together with regional archeological institutions and paleoecologists in Mediterranean universities, lead to greater knowledge of the major steps in human occupation within its environmental context. In addition, they give an overall view of paleohydrology that takes into account the cycles of FDRs and drought-dominated regimes (DDRs) in the lower Rhône River and provide evidence for hypotheses that have been suggested for the fluvial sediments dynamics of the upper Rhône River.

The aims of this paper are (1) to investigate the paleohydrology of the Rhône Delta between the 1st century BC and the AD 2nd century, using environmental data from many geoarcheological sites and (2) to link three centuries of fluvial sediments characteristics with the dynamics of the Rhône catchment at the beginning of the Roman Antiquity.

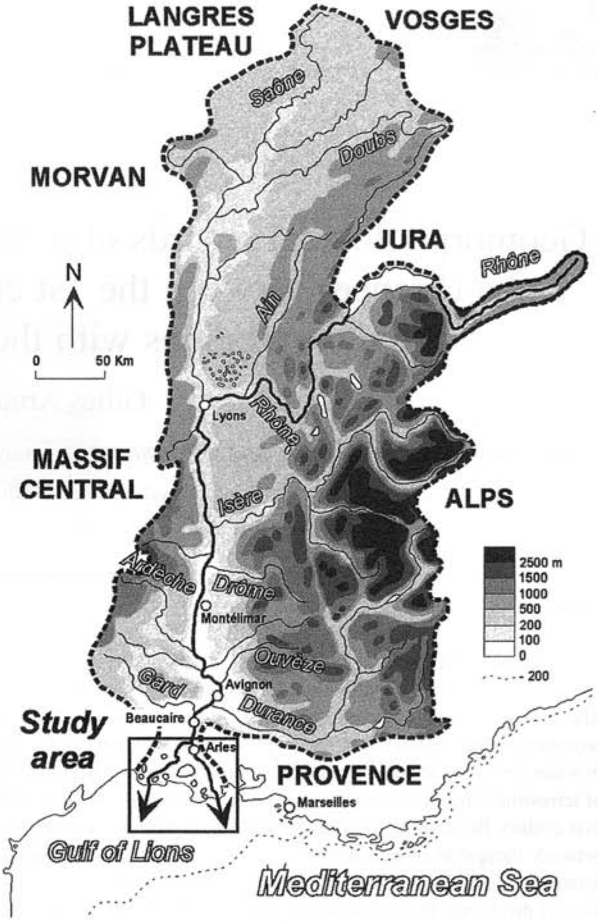

Fig. 1. The Rhône catchment.

2. Physical setting

The Rhône catchment is one of the largest in Europe, with a drainage area of ~ 97800 Km^2 [17] (Fig. 1). From the Furka Glacier (Swiss Alps) to the Mediterranean Sea, the Rhône River and its tributaries drain regions characterized by a highly diverse geology and hydroclimatology. The influence of Alpine discharge is predominant, contributing to about 80% of the solid-liquid annual discharge of the Rhône River [18].

In its lower part, the Rhône River crosses a succession of resistant spurs, upon which the urban sites of Avignon, Beaucaire-Tarascon and Arles have been situated since Antiquity. The numerous ruptures of concave slopes of the longitudinal profile, controlled by the widening of the Rhône River trough, are favourable to sediment deposition and to the widening of the alluvial plain, built-up by sediments transported by numerous tributaries. For example, on the right bank, the Ardèche and the Gard rivers drain a part of the crystalline massifs of the Cévennes and their carbonate foreland basin. On the left bank, the tributaries are the Ouvèze, the Aygues, the Lez, but above all the Durance, a Mediterranean Alpine river that drains a vast catchment etched in varied morphostructural units. The very low slope (< 0.1%) of the Rhône River as it nears sea level results in a shallow water table with swamps common in the lowest areas of the floodplain.

At the head of the delta, the fluvial regime of the Rhône River doesn't exhibit a true low water level [600 $m^3\ s^{-1}$ (1920-1997)] because it is affected by the complementary influences of sub-catchments. It has a high load capacity and stream power with an average discharge at the Beaucaire station estimated at 1701 $m^3\ s^{-1}$ (1961-1996). The contribution of these latter tributaries are decisive in the hydrological regime of the Rhône River. The Durance and the Gard rivers are subject to major autumn and spring floods, which supply an abundant sediment load. For example, the Ardèche is a right bank tributary that is particularly turbulent because it can flow at 6000 $m^3\ s^{-1}$ in a period of major flooding. It carried a large amount of bedload sediment, which has blocked off the flow of the Rhône River many times by accumulating alluvium on the opposite riverbank [19]. The overall discharge from the catchment can be the source of exceptional floods covering a vast area, which is susceptible to reshaping and/or displacing the river bed. Such an event occurred in 1993/94, a remarkable hydrological period, in which the discharge during flooding (9800 $m^3\ s^{-1}$ to 10981 $m^3\ s^{-1}$) was very similar to the 100-year flood of 1856 during which discharge reached

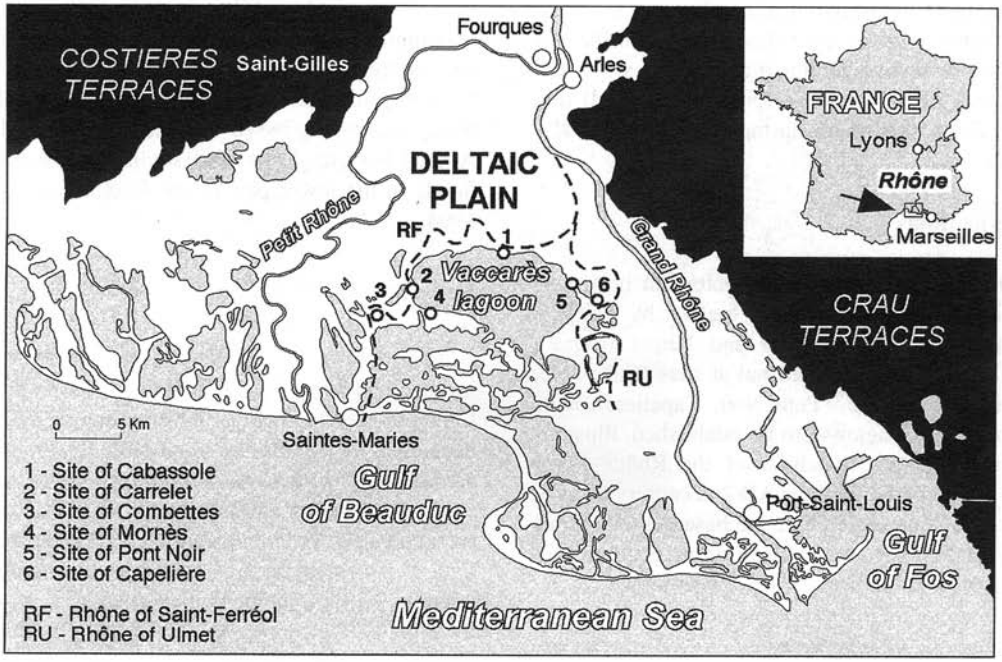

Fig. 2. Location of the study area.

11640 $m^3\ s^{-1}$ at Beaucaire [20]. The present-day high water level of the floodplain is marked by the 100-year flood of 1856.

The Rhône Delta extends from about 43 °20'N to 43 °35'N, 4 °5'E to 4 °50'E and faces to the French Mediterranean coast about 40 Km west of Marseilles. Today, it is considered as a wave-dominated delta with low tidal range (~ 30 cm) and relatively low wave conditions. It is subject to a north-Mediterranean climate, with average temperatures varying from 5-10 °C in winter to 20-30 °C in summer. Average precipitations are ~ 600 mm yr^{-1}, with maximum value (80-100 mm yr^{-1}) in autumn and minimum value (20-50 mm yr^{-1}) in summer, and the mean potential evapotranspiration is about 1200 mm yr^{-1}. The area is dominated by north-westerly (the "Mistral") and south-esterly winds. The Rhône Delta is a vast subhorizontal plain of 1740 Km^2, bordered to the northwest by the "Costières" of Nîmes and of Génerac, to the northeast by the calcareous massif of the 'Alpilles', and to the east by the stoney alluvial cone of the "Crau" (Fig. 2). The north part of the delta is marked by the presence of fossil alluvial levees [21]. Between these levees, paleochannels plugged by silty-sand sediments are juxtaposed to paleobanks (traceable by the presence of large hygrophilous trees) and fossil floodplains (still occupied by freshwater swamps in their distal part). The central part of the delta is characterized by the presence of shallow brackish lagoons, separated by fossil coastal spit bars and alluvial levees. The largest lagoon is the 'Vaccarès', whose present-day area of 65 Km^2, has considerably increased from 1950s due to the development of rice growing [22]. To the south stretch fossil coastal spit bars, covered by typical Mediterranean vegetation formed by *Pinus pinea* and *Juniperus phoenicia*. These fossil coastal spit bars, alternating with lagoons and brackish ponds, are connected to the sea by inlets.

The Rhône Delta is the result of the geodynamic interaction between the Rhône River and the Mediterranean Sea [23,24]. The delta landscape is highly dependent on its geomorphological development during the last seven millenia. Changes to the landscape during the Holocene took place in two major stages [25,26,27]. From 18000 BP, late- and post-glacial eustatic uplift of the Mediterranean Sea favoured the formation of a transgressive silty-sand prism whose apex migrates north. This lagoon-marine assemblage, composed of retrograding parasequences, limited by flood surfaces, composes most of the infilling, which sometimes exceeds 40 m in thickness south of the delta. It culminates around 6500 BC, with a maximum on lap identified at -19 m asl, north of the Vaccarès lagoon. The decreasing rate of sea level rise of the Mediterranean from 4500 BC facilitates the deposition of a high level prism, generally prograding southwards. Its geometry and its extent are linked to continental sediment input by the Rhône River, which pushed back the coastline and the brackish environments southward, and displaced the position of the relative sea level downstream [28]. Today, this prism constitutes a complex mosaic in the landscape because of its superposition and interstratification of many types of paleoenvironments: (1) saltwater to brackish swamps that occupied the present-day location of the Vaccarès lagoon during the second part of the Holocene, (2) freshwater marshes, especially those north of the delta, (3) fluvial channels belonging to many paleochannels whose numerous meanders, in particular the most recent, still strongly characterize the present-day delta landscape. The number and the position of paleochannels fluctuated many times since the last 3000 years, notably in the central part of the delta where the Saint-Ferréol and Ulmet branches (presently infilled) discharged most of the river water during Antiquity [22,29].

3. Analytical methods

The paleohydrology of the Rhône Delta can be reconstructed on each side of the Vaccarès lagoon, by studying the paleochannels of Saint-Ferréol and Ulmet (Fig. 2). Multidisciplinary fieldwork carried out at sites (Cabassole, Carrelet, Combettes, Mornès, Pont Noir, Capelière), have allowed the alluvial stratigraphy to be established, illustrating the fluvial sediments dynamics of the Rhône River between the 1st century BC and the AD 2nd century (Figs 3, 4 and 5). The results presented here are based on numerous paleoenvironmental indicators coming from geomorphology, sedimentology, paleoecology and archeology.

3.1. Geometry of the alluvial plain

Its surface area can be reconstructed using old maps and aerial photos. The geometry of its infill can be interpreted using electric survey coupled with sedimentological studies [30]. At archeological sites, alluvial sediment infillings have been studied at naturally-occurring stratigraphic sections or at cuts exposed using a back hoe. In order to gain a larger view of the fluvial paleoenvironments, and when it was possible, deep cores were drilled in the periphery of ancient settled areas. The study identifies channel deposits, i.e. their nature and geometry, providing information on periods of infilling or incision of the river bed, which reflect variations in hydrological levels and the fluvial sediment yield. The characterization of fluvial systems and their course in time and space, lead to the study of the transformations which are the expression of the changes in discharge and suspended load [31,32,33].

3.2. Sedimentology of fluvial deposits

The sedimentology of fluvial deposits allows the variation of the alluvial dynamics to be determined, in terms of the magnitude of flooding and their frequency at the decaded to centennial scale [34]. The fluvial sediment yield can be measured by the sediment volume accumulated in the channel and on the floodplain. The fluvial competence can be approximated by the grain size transported in its channel. The grain size and the thickness of the deposits are proportional to the energy of the water flow. In the Rhône Delta, the sediments deposited on the alluvial plain are fine-grained, silty-sands close to the channel and clayey silts on the banks. The use of Passega's method, which takes into consideration the median grain size (M) and the maximum grain size (C), allows a deposit to be associated with the mode of transport (rolling, saltation, suspension) and the maximum competence of the river to be determined [35,36]. An interpretation of the deposit in terms of sedimentary environment specific to the Rhône Delta (floodplain, riverbank, channel) is based on the works of Roditis [37] and Arnaud-Fassetta [38], who studied the sedimentology of floods in the lower part of the Rhône River from 1992 to 1994.

3.3. Groundwater indicators

The variation in water levels on the floodplain has been investigated using pedological and archeological indicators [39]. The development of bioturbation on the floodplain is dependent on the alluvial water table. Hydromorphous soils are associated with a rise in average level of the water table, well-drained soils are associated with a deepening of the river channel, even though an artificial lowering of the water table could be obtained by a network of drainage ditches. In addition, certain archeological vestiges, associated with dwellings situated in the immediate proximity of fluvial channels and/or lagoons can provide information on the position of sea levels and water tables. Reinforcement of the banks (Arles, Carrelet) and drainage system may indicate a greater risk of flooding in relation to an increase in water level. However, the dwellings within the immediate proximity of the bank are the worst indicators because they are not necessarily correlated to less frequent and devastating floods [12]. Therefore, not too much importance should be placed on the effect of the floods on site location close to the Rhône River. Riverbank societies can endure repeated but small scale flooding, or flooding which is violent but rare, without putting in question the occupation of the riverbanks.

3.4. Chronological markers

The chronology of sedimentary units is based on two types of data. Numerous dates were obtained from the remains of a settlement on the riverbank. Certain shards or coins were identified, which allowed the stratigraphy to be precisely dated with a margin of error of 25 to 50 years [40,41,42]. In addition, ^{14}C dates were obtained from the Centre de Datation par le Radiocarbone of Lyons on peat bogs or macro-remains of plants trapped in Rhône River sediments. All the radiocarbon dates were calibrated according to Stuiver et al. [43].

4. Paleohydrological results

A period of alluvial deposition in the Rhône Delta was identified during the 1st century BC and the AD 2nd century, indicating the convergence of paleoenvironmental indicators of a FDR.

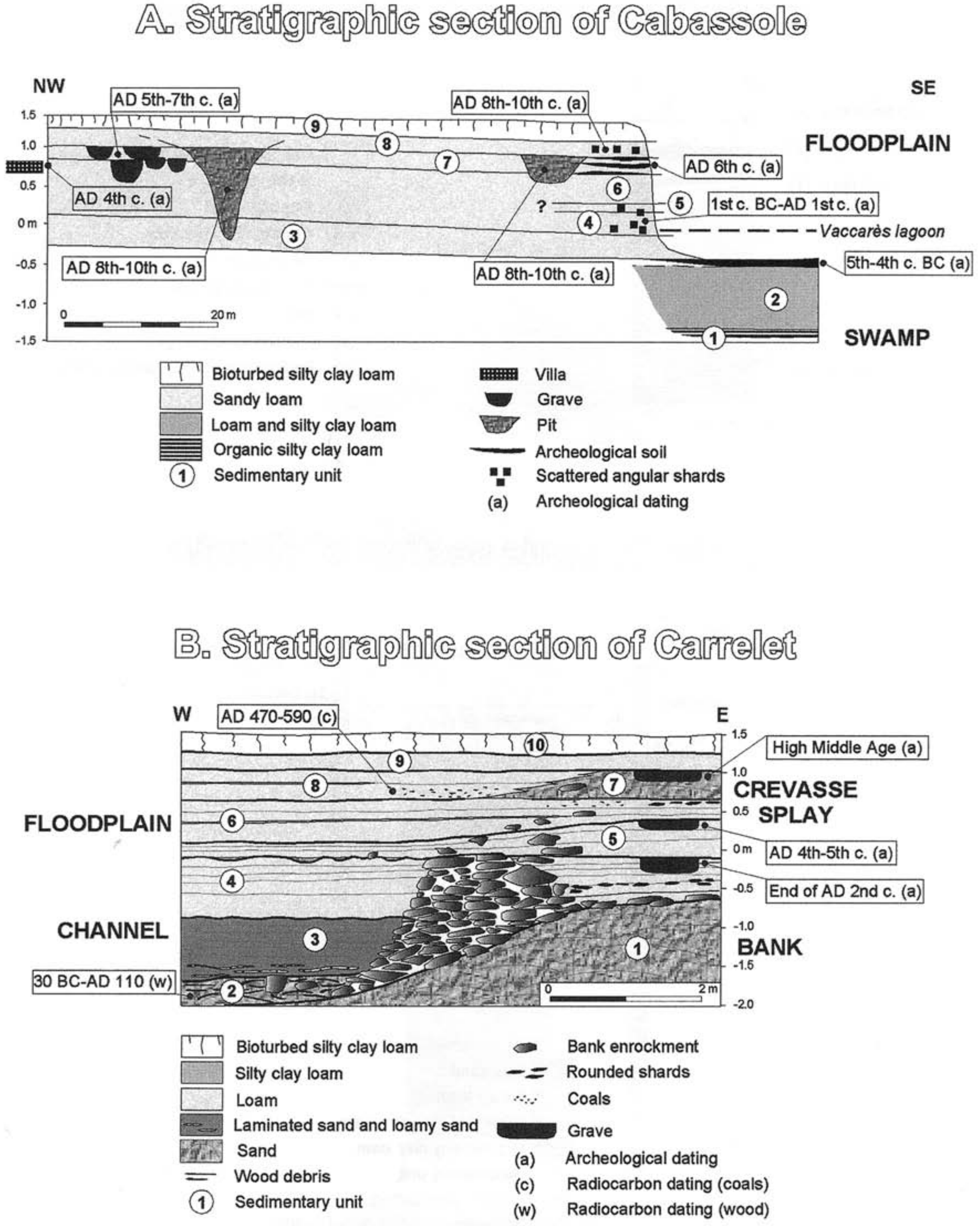

Fig. 3. Stratigraphic sections of the sites of Cabassole (A) and Carrelet (B). A. The stratigraphic section (3 m thick) shows the succession of four types of paleoenvironment, from the base to the top: organic silty clay loam corresponding to a swamp (unit 1) and loam/silty clay loam of a low-dynamic floodplain (unit 2) deposited prior to the 5th-4th centuries BC; a high-dynamic floodplain composed of six distinct sedimentary units (3 to 8) dated between the 5th-4th centuries BC and the AD 8th-10th centuries; a low-dynamic floodplain (unit 9) deposited essentially during the Low Middle Age. Please note that unit 4, dated 1st century BC-AD 1st century, highlights a significant reinforcement of the sedimentation rate in the floodplain. B. Sedimentological interpretation of the stratigraphic section (3.5 m thick) indicates four distinct paleoenvironments, from the base to the top: cross-stratified fluvial sand corresponding to a river bank (unit 1) which the top is recovered by an enrockment; channel in-filling deposits (units 2 and 3); floodplain deposits (units 4 to 6; 8 to 10); cross-stratified sand deposit corresponding to a minor crevasse splay (unit 7) dated to the High Middle Age. Please note the thickness of the unit 4 (~ 85 cm), highlighting a high sedimentation rate in the floodplain between 30 BC-AD 110 and the end of the AD 2nd century.

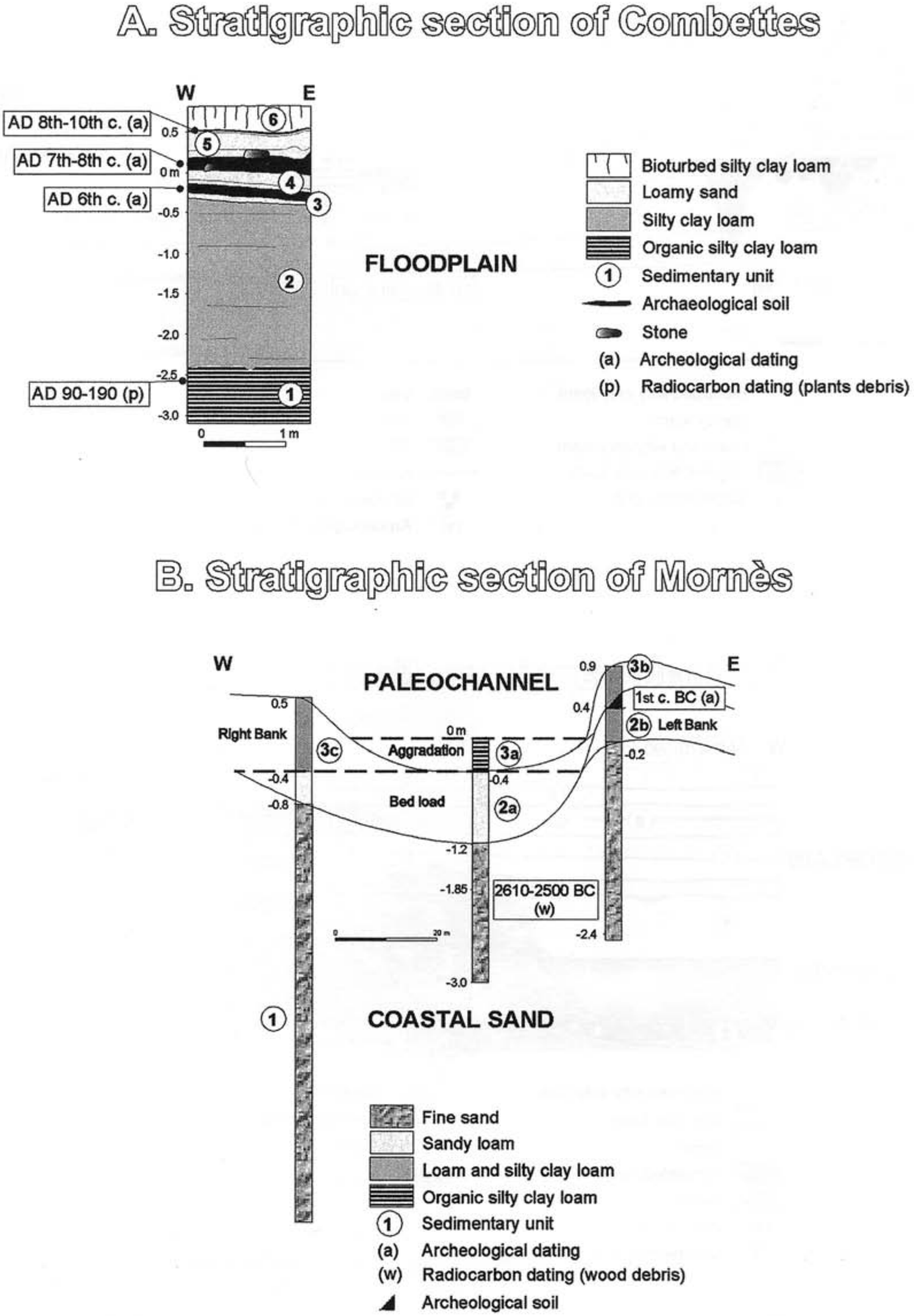

Fig. 4. Stratigraphic and logged sections of the sites of Combettes (A) and Mornès (B), respectively. A. Four lithofacies can be defined from the stratigraphic section (3.8 m thick), from the base to the top: organic silty clay loam associated to a swamp (unit 1) dated near the top AD 90-190; a low-dynamic floodplain (unit 2) composed of silty clay loam; archeological soils sandwiched within high-dynamic floodplain deposits (units 3 to 5), dated between the AD 6th century and the 10th century; a low-dynamic floodplain (unit 6) deposited essentially during the Low Middle Age. B. The facies assemblage as defined from the three cores comprises four distinct lithofacies: at the base, coastal sand deposits (unit 1) dated near the top 2610-2500 BC; fluvial sand corresponding to the bed material load of a paleochannel (unit 2a), associated to loam and silty clay loam of a bank (unit 2b) dated around the 1st century BC (unit 2); terminal paleochannel in-filling associated to the both banks (units 3b and 3c).

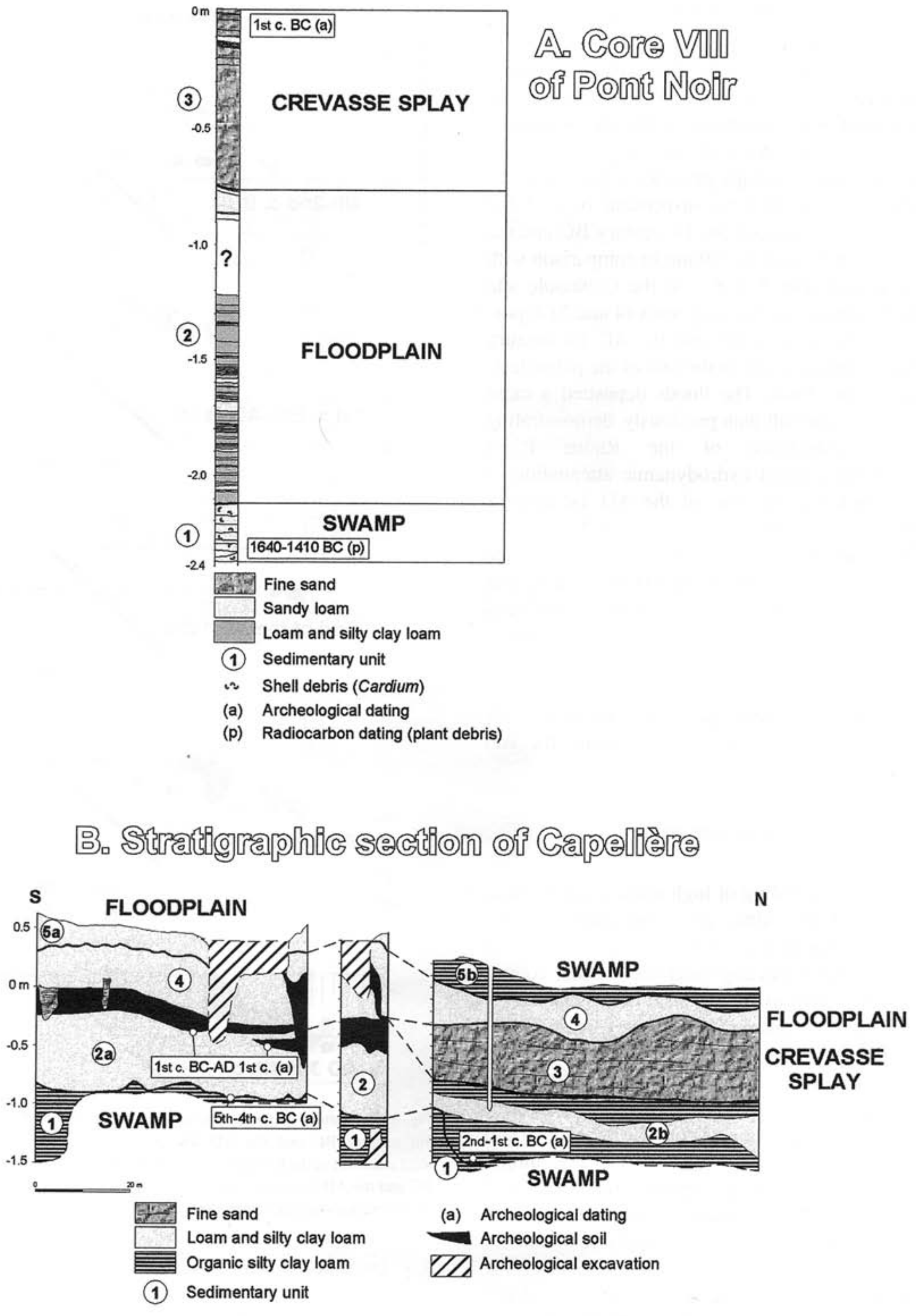

Fig. 5. Stratigraphic sections of the sites of Pont Noir (A) and Capelière (B). A. The sedimentological analysis of the core VIII (upper 2.4 m) of Pont Noir shows the succession of three types of paleoenvironment: at the base, a swamp (unit 1), episodically supplied by fluvial and/or marine deposits, radiocarbon dated 1640-1410 BC; a fluvial floodplain (unit 2), at varying distances to the river channel, whose low-dynamic sedimentation is interrupted, near the top, by the influx of coarse sandy deposits of a crevasse splay dated around the 1st century BC (unit 3) [15]. B. The stratigraphic section (2m thick) highlights the succession of five types of paleoenvironment, from the base to the top: a swamp (unit 1) near a brackish lagoon anterior to 5th-4th centuries BC; a floodplain (unit 2) connected to the north with a palustrine depression, deposited between the 5th-4th centuries and the 1st century BC; fine sand corrresponding to a crevasse splay (unit 3) dated 1st century BC-AD 1st century; a high-dynamic floodplain (unit 4) dated post AD 1st century; a low-dynamic floodplain associated to the present-day with an episodic swamp (unit 5).

4.1. Increase in the Rhône River's competence

A significant augmentation in the Rhône River's competence is indicated by the increase in grain size of the sediments deposited in the floodplain, within the immediate proximity of the channel. As with the sites of the upper Rhône River [44], the cm image provides a good illustration: the upper limit of uniform suspension (C_u) of the Rhône River increases between the 1st century BC and the AD 1st century from 240 μm to 310 μm in comparison with the preceding period (Fig. 6 A-B). At the Cabassole site (Fig. 3A), the floodplain sedimentary units (4 and 5) deposited between the 1st century BC and the AD 1st century were examined perpendicularly to the axis of the paleochannel and dated by pot finds. The floods deposited a more homogenous and coarser silt than previously, demonstrating the increased competence of the Rhône River (C_u = 250 μm). Only a short hydrodynamic attenuation of discharge is recorded at the end of the AD 1st century (C_u = 120 μm) (Fig. 6C). On the Carrelet site (Fig. 3B), it is followed by another increase in the competence (C_u = 200 μm) during the course of the AD 2nd century, but the energy of the discharge remains inferior to that produced between the 1st century BC and the AD 1st century (Fig. 6D). At the Pont Noir site (Fig. 5A), an increase in grain size of flood deposits is also observed towards the 1st century BC. Moreover, a decrease of the Rhône River's competence (C_u = 190 μm) is confirmed during the AD 3rd-4th centuries (Fig. 6E).

4.2. Increase in the fluvial sediment yield

The simultaneous recording of high sedimentation rates, at several sites on the delta, gives preference to the hypothesis of an overall increase in the sediment yield of the Rhône River, without neglecting other factors that control sedimentation rates, such as the distance of the channel or trapping by riverbank vegetation. Thus, the Cabassole site records rapid rates of sedimentation (2.3 mm yr^{-1}) in the floodplain between the 1st century BC and the AD 1st century (Fig. 7). At the Carrelet site, the rates of sedimentation (4 mm yr^{-1}) are very high between 30 BC and the end of the AD 2nd century, suggesting that the river acquired sufficient energy to transport and deposit large volumes of sediment on a regular basis. There is also the increased possibility of upstream catchments to supply sediments in greater and greater quantities, due to (1) abundant and/or harder rainfall and/or (2) lesser stabilization of fine material on the slopes. Micromorphological data show the presence of numerous gas bubbles trapped during the sedimentation, indicating a rapid burial of flood deposits (a sign of more frequent flooding) [45]. A rapid rate of sedimentation (4 mm yr^{-1}) is also observed at the Capelière site between the second half of the 1st century BC and the beginning of AD 1st century.

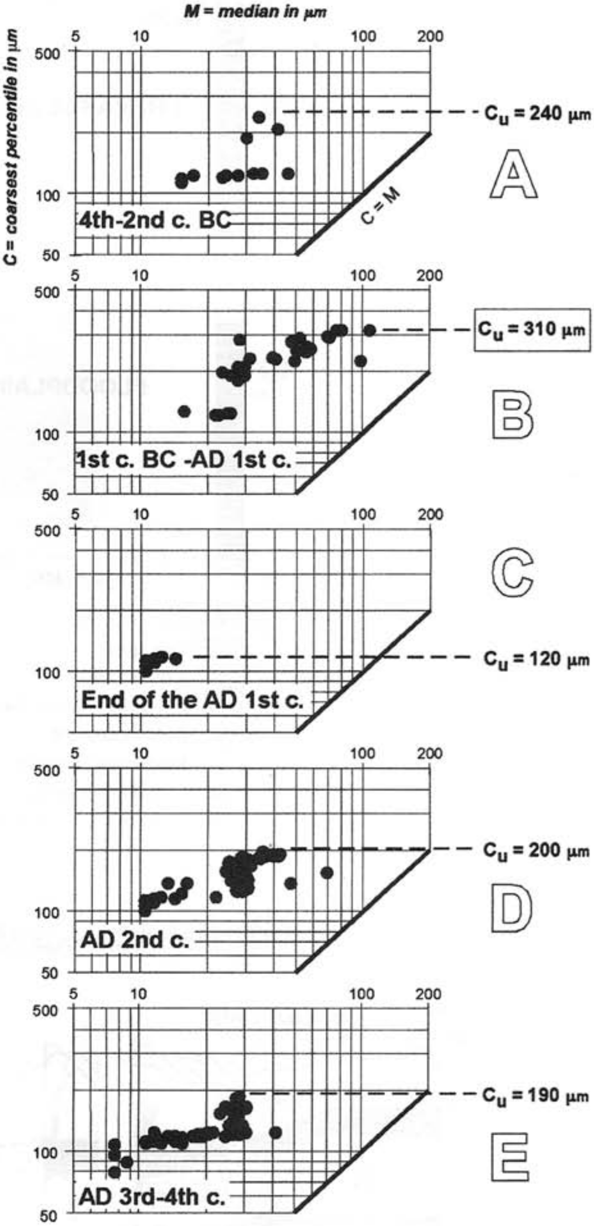

Fig. 6. Cm pattern of floodplain deposits in the Rhône Delta between the 4th century BC and the AD 4th century. Please note the significant reinforcement in the Rhône River's competence (1) between the 1st century BC and the AD 1st century and (2) during the AD 2nd century, highlighted by the increase of the upper limit of the uniform suspension (C_u).

4.3. Increase in water levels

It is indicated by the deposition of hydromorphous facies, the development of hydrophytic species (*Phragmites australis*), and the decrease in activity of terrestrial lombricoids in the floodplain [46,47]. At the Carrelet site, 85 cm of greenish silts almost completely absent of bioturbation are deposited between 30 BC and the end of the AD 2nd century by the Rhône of Saint-Ferréol (Fig. 8). At the Capelière site,

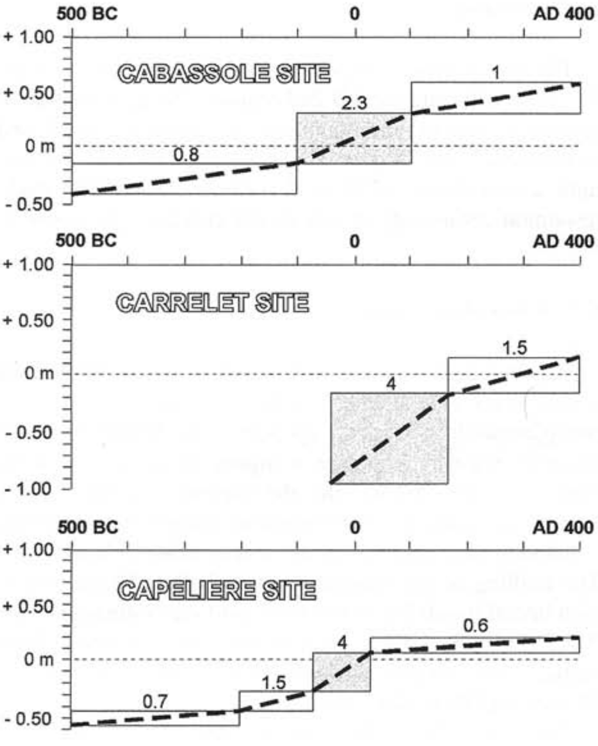

Fig. 7. Sedimentation rates in the floodplain of the Rhône Delta between the 5th century BC and the AD 4th century. The three sites studied provide evidences of remarkable increase in the sedimentation rates between the 1st century BC and the AD 2nd century.

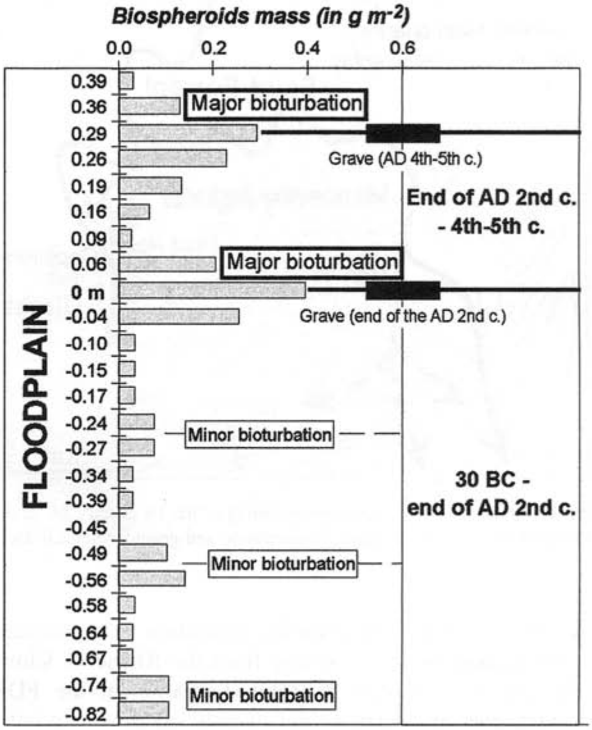

Fig. 8. Pedological evolution in the floodplain of the Rhône de Saint-Ferréol, indicating by biospheroids mass in the sediments. Between 30 BC and the end of the AD 2nd century, the high sedimentation rates limit the development of major pedogenesis. Between the end of the AD 2nd century and the late Antiquity, the decrease in the sedimentation rates and major flood events allows the development of two phases of major bioturbation, which are correlated with the major phases of land settlement (end of the AD 2nd century, AD 4th-5th centuries).

near the fossil Rhône of Ulmet, hydromorphous silty sequences were identified between the 2nd century BC and the AD 1st century. In addition, the continuation of hydromorphous environments at the Combettes site between AD 90 and 190 confirms the importance of high water levels on the floodplain downstream of the Rhône of Saint-Ferréol. During the same period, the plain at Arles undergoes a pronounced hydromorphy, in relation to the rise in the groundwater system [14].

4.4. Development of avulsions and crevasse splays

Numerous crevasse splays were formed by short-term (of durations from several hours to several days) avulsions of the Rhône River. During the 1st century BC, development of crevasse channels occurred at the Mornès, Capelière and Pont Noir sites (Fig. 9). Their frequency is related to an increase of Rhône River paleodischarge, which makes the channel network incapable of evacuating large volumes of water brought in by the river. In addition, an assumed channel infilling contributes to the increase in frequency of avulsions. One of these avulsions has been recorded at the Carrelet site between 30 BC and AD 110 (Fig. 3B; units 2 and 3), where the Rhône of Saint-Ferréol, plugged with silty-sand sediments, begin a gradual phase of infilling whereas the principal axis is displaced towards the west by many hundreds of meters. Moreover, several crevasse splays have been recorded at the sites of Capelière and Pont Noir between the 1st century BC and the AD 1st century (Fig. 5 A-B). At the end of the 1st century BC, the level of the perennial marsh transgresses on the inhabited fringe. The organic silts deposited by decantation are inter-stratified with the arrival of episodic flood deposits (sandy silts) and moving laterally to a proximal flooplain. These deposits are interrupted by several sequences of coarser flood deposits (fine sand), 50 to 70 cm thick, interpreted as crevasse splay deposited in an inundated environment. At the AD 1st century, settlement is built over this level.

4.5. Distributaries channels and rapid progradation of the deltaic coastline

Recent work by Vella [28] has shown that it is possible to trace the shoreline evolution situated along the eastern margin of the delta and to evaluate the amplitude of Rhône River's detrital input using the position of archeological structures and sedimentary facies. Thus, the littoral zone experienced a remarkable phase of progradation between

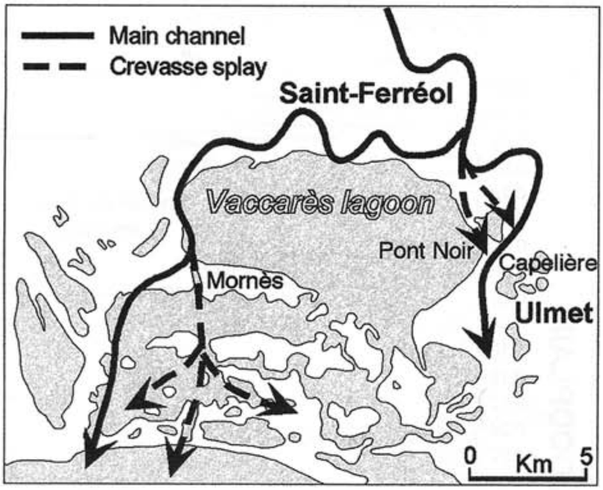

Fig. 9. Cartography of crevasse splays dating of the 1st century BC in the Rhône Delta obtained by photo-interpretation and geoarcheological data.

the AD 1st and the 3rd centuries, in relation to the increase of terrigenous deposits coming from the Rhône of Ulmet (Fig. 10). The increase in solid discharge, in the FDR context, can be related to the overall increase in detrital output from the catchment. In addition, a relative increase in the number of channels of the Rhône River at the beginning of the Antiquity is recorded in ancient scriptures [48]. During the 4th century BC, the river had five channels (Pytheas). Towards 125 BC, Polybe only found evidence of two channels. Between 100 BC and the AD 5th century, Artémidore, Strabon, Pline and Martianus Capella note the presence of three channels. Sedimentary deposits indicate that they are the branches of Peccais, Saint-Ferréol and Ulmet [22,29].

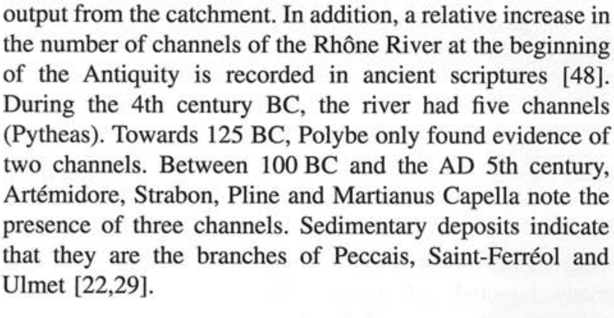

Fig. 10. Lateral changes of the coastline in the eastern part of the Rhône Delta (from Vella, 1999).

5. Discussion

The Rhône River's fluvial regime changed between the 1st century BC and the AD 2nd century. The combination of geomorphological, sedimentological, paleoecological and archeological data acquired at many sites allowed to highlight a remarkable FDR in the Rhône Delta. The high-resolution chronology of this fluvial change is presented in this paper.

5.1. A two-phase Rhône River FDR

Between the 1st century BC and the AD 2nd century, the Rhône River's floodplain undergoes a rapid sedimentation rate (Cabassole, Carrelet, Capelière). The fluvial discharge becomes regular, implying a higher frequency of flood events. At the Carrelet site, the channel records a major increase in water levels that possibly coerced the riverbank population into reinforcing the levees using enbankments. The infilling of the channel, starting before 30 BC, led to high lateral instability of the river until the beginning of the AD 2nd century, which favoured the multiplication of bank ruptures and crevasse channels, such as those discovered at Mornès and Pont Noir sites.

The Rhône River FDR in the delta is recorded in a hydrological cycle, which lasted several centuries (Fig. 11). Before the first phase of the FDR, an instable hydrological regime is observed in the Rhône Delta as early as the 5th to 4th centuries BC, with the highest energy flooding at the Cabassole and the Capelière sites. Evidence of an increase in water levels is also perceptible at Arles, with the advent of a major flood around 175 BC, which arose unexpectedly during a period of low discharge [14].

But the fluvial change (i.e. the first phase of the FDR) is clearly recorded in the Rhône Delta from the 1st century BC, with the appearance of numerous crevasse splays, more frequent flooding and higher energy discharge. Bank protection (the stone revetment at Carrelet), the sudden abandonment of several sites (Cabassole, Mornès) and the halt in cultivation of cereals (Pont Noir) possibly indicates the difficulty in managing the water and hydrological levels in the delta at this time. However, fluvial constraints do not stop the development of *villae* (Cabassole) and the extension of sites on the border of paleochannels (Albaron, Saint-Ferréol, Ulmet). This first phase in the FDR persists until the end of the AD 1st century. The competence of the Rhône River during this time reached its maximum intensity (cf. Cm pattern: C_u = 310 µm).

One brief period of quiet occurred at the end of the AD 1st century. It is characterized by the decrease of competence (C_u) and the development of soils which represent a decrease in alluviation. It is followed by a new phase of major floods between the end of the AD 1st century and the end of the 2nd century (Carrelet) during which the time phreatic levels continue to increase (Combettes). This second phase of the FDR appears less intense than the first

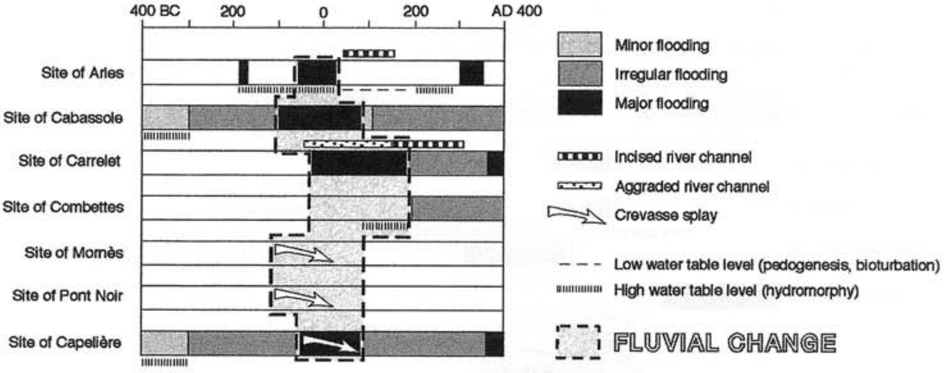

Fig. 11. Paleohydrological fluctuations in the Rhône Delta between the 4th century BC and the AD 4th century.

phase (cf. Cm pattern: C_u = 200 µm). Thus, the power of the Rhône River becomes lower and more irregular overall, from the end of the 2nd century to the beginning of the AD 3rd century. However, the low rates of sedimentation recorded in the floodplain during this period (i.e. after the fluvial change) are not necessarily related to a decrease in the fluvial sediment yield, because of the degradation of the alluvial floor that reached -12 m at the Carrelet site. Nevertheless, the floodplain becomes more favourable to soil formation.

5.2. *Impact of the Rhône River FDR on land settlement*

Geoarcheological research carried out in the Rhône Delta confirms the richness of the archeological sites between the 5th century BC to the AD 10th century [49]. The majority of the sites recorded correspond to groups of small dwellings, generally associated with agricultural or artisanal activities. They are located along the length of the paleochannels and preferentially situated at the inside margin of the floodplain close to the Rhône River, several tens of meters from the river bank.

The impact of the FDR trend on land settlement will now be discussed. Certain dwellings are perched on high points and very briefly occupied. This is the case at the Mornès site, situated on the border of a secondary channel of the Rhône of Saint-Ferréol during the 1st century BC and abandoned several decades later at the beginning of the Roman Antiquity [50]. Other archeological vestiges also indicate a rapid abandonment of the dwelling. For example, the Capelière site is suddenly abandonned in the second half of the 1st century BC (40-30 BC?), following the floods that entirely fossilize the dwellings under 40 cm of sandy silt. The site is not reoccupied until the beginning of the Christian era [51]. In addition, settled lands reworked by high-energy floods were identified at the Cabassole site between the 1st century BC and the AD 1st century, by the presence of randomly distributed shards in thick silt units [52]. They indicate the occurrence of violent floods, capable of completely eroding the anthropogenic soils on the proximal floodplain. In addition, the riverbanks are known to be reinforced during this period. At the Carrelet site, a bank enrockment is put in place between 30 BC and AD 110 on the concave bank of the Rhône of Saint-Ferréol [53].

But what kind of information can be gained from this type of data? It may indicate an important increase in water levels that obliged riverbank populations to reinforce its bank or it is the sign of a lateral instability of the channel, in the context of channel reworking attested to by sedimentological data. In contrast, does it correspond to a construction destined to limit recurrent erosion of the concave bank of the Rhône River, a phenomena that was not out of the ordinary? It is difficult to answer with certainty, even if it appears that the fluvial hydrology and its constraints are managed from early on in the Rhône Delta. Finally, abandonment of cultivation of cereals around the Pont Noir site occurs before the 1st century BC or it contemporaneous to it. It is related to the extension of hydromorphous environments and the displacement of a branch nearer to the Rhône River, but also perhaps to the brief abandonment of the Capelière site, which occurred during the 1st century BC [15]. Thus, archeological data provide support for a hydrological and groundwater impact that affected locally in the deltaic plain the type or the duration of land settlement. However, this impact is commonly ambiguous and must be put into perspective. If not, how is the development of *villae* from the AD 1st century (north of the Cabassole site) to be interpreted? How can the multiplication of fluvial sites along the length of the Rhône River between the 1st century BC and the AD 1st century to be explained?

6. Conclusion: comparison to the catchment paleohydrology

Taken together, the paleoenvironmental data obtained on five fluvial sites allow a detailed reconstruction of the paleohydrology of the Rhône Delta at the beginning of the Roman Antiquity. The morphological signs of the Rhône River FDR are found at precisely between the 1st century BC and the AD 2nd century. It should be noted that this Rhône River FDR was not a continuous event over three

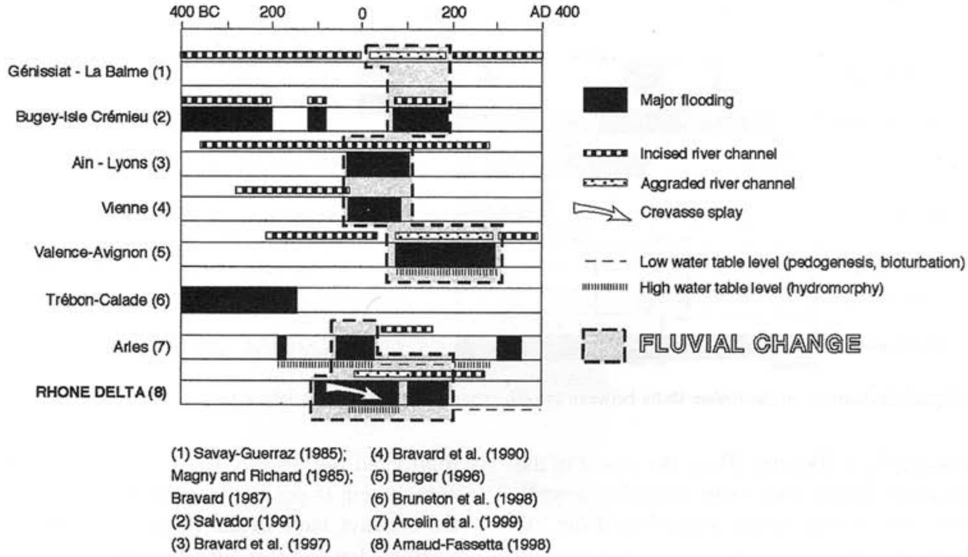

Fig. 12. Paleohydrological synthesis at the Rhône catchment scale between the 4th century BC and the AD 4th century.

centuries. It takes place in two phases of abundant water supply (1st century BC to the end of the AD 1st century; AD 2nd century), interspaced by a brief lull (end of the 1st century to the beginning of the AD 2nd century). I hypothezise that the Rhône River FDR shown in the Rhône Delta could be induced by the more instable climatic conditions (i.e. large rainfall events more frequent) of the beginning of the Roman Antiquity, intensified by human disturbances at the Rhône catchment scale [3].

The Rhône River FDR of the early Roman Antiquity has been identified on numerous sites of the Rhône fluvial hydrosystem (Fig. 12). However, the paleogeographic expression of the event is complex at the scale of the catchment. In general, the increase in flow recorded between the 1st century BC and the AD 2nd century in the Rhône Delta was in-phased with the paleohydrological functioning of the upper-middle Rhône River [4] and its Alpine tributaries [6], but also downstream of the catchment [10,16]. However, it seems that hydrological regime of the Rhône River in its delta varied out-of-phased with rivers of the Durancian Alps and Provence during the same period [54,55,56].

From these relationships, it might be envisaged that the Rhône River, which functions like an allochthonous river in the most southern regions of the catchment, was capable of imposing its rhythm of floods on the lower Provence area between the 1st century BC and the AD 2nd century, although this area underwent an important water deficit and climatic stability between the 2nd century BC and the AD 4th century [56]. At the beginning of the Roman Antiquity, the Rhône River remained largely influenced by the upstream part of its catchment and the border of the Cévennes part of the Massif Central, whose the main rivers (Gard, Vidourle) show a significant rise in number and intensity of floods. Finally, the hydroclimatic paleogeography at the beginning of the Roman Antiquity would confirm the isolation of the lower Provence from the rest of the Rhône catchment, the limit being situated at the latitude of the Drôme région.

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