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Geomorphological evidence for fluvial change during the Roman period in the lower Rhone valley (southern France)

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Abstract

The hydrological and geomorphological dynamics of the lower Rhone river (southern France) are studied during the Roman period (2nd–1st centuries BC, 2nd–3rd centuries AD). The crossing of archaeological and radiocarbon dating methods allow to study events at a pluridecadal to centennial scale. From the Avignon town to the delta, the 15 sites where Roman fluvial dynamics were recorded show higher flooding frequencies, higher energy levels during floods, rises in the marshes or groundwater levels, and/or active morphological dynamics such as channel migrations from 1st century BC to 1st–2nd centuries AD, with respect to the encircling periods. Although this fluvial change does not reach the amplitude of great climatic events such as the Little Ice Age in the Rhone valley, we show that it is also perceived in other parts of the catchment and could have a climatic origin. However, this event is not recorded in the immediate Mediterranean environment of the lower Rhone, so that the Rhone appears to efficiently transmit a foreign climatic change.

Keywords: Fluvial geomorphology; Floods; Geoarchaeology; Holocene; Roman period; Rhône; France

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1. Introduction

Changes to the Rhone fluvial system in the Holocene have been investigated in the upper and middle Rhone (Bravard et al., 1986, 1992; Salvador et al., 1993; Berger 1996), as well as in the river systems adjacent to the main fluvial axis. This study, which brings together research in the fields of geomorphology, palaeoecology and archaeology, has demonstrated the presence of hydrological variations and of mutations to the fluvial system during the Holocene that have been interpreted as indications of climatic change in the river system, which effects may well be increased by increased human activity (Marston 1993; Provansal et al., 1999). The Roman period, from the end of the 2nd century BC to the beginning of the 2nd century AD, was characterized by higher and more frequent floods as well as greater increases in water level.

Geomorphological research undertaken within a multi-disciplinary team has shown that in the last 3000 years, the river has undergone synchronous mutations in the lower Rhone valley (and its tributaries), in the middle and upper river basin (Arnaud-Fassetta and Provansal, 1999; Provansal et al., 1999; Leveau, 1999). The objective of this paper is to analyse the palaeohydrological functioning of the lower Rhone valley between the 2nd century BC and the 2nd century AD as well as to discuss its palaeoclimatic significance in relation to the upper and middle river valley.

2. The environmental context

The lower Rhone valley is marked by several rocky outcroppings upon which the towns of Avignon, Beaucaire-Tarascon and Arles developed in Antiquity. Between these “hard points”, the alluvial plain widens, particularly at the confluence of rivers carrying an abundant sediment load (Figs. 1 and 2): on the right bank, the Ardèche and Gardon rivers, which drain the crystalline massifs of the Cévennes and their limestone foothills; on the left bank, the Durance river is fed by a vast river system in the southern Alps. The river gradient reduces upstream from the delta ($< 0.1\%$), allowing for the accumulation of sediment and the widening of the floodplain. This also tends to maintain the water table at a high level with marshes forming in the lowest parts of the floodplain.

Supplied by several differing climatic zones, the lower Rhone is not subject to severe low discharge (low discharge at 600 $m^3 s^{-1}$ (1920–1997)). The Rhone’s complex regime is characterised by high levels from November to May, setting the seasonal cycle for the marshes of the floodplain. The mean flow (1709 $m^3 s^{-1}$ at Beaucaire 1992–1997) generates a high grain shear stress and increased transport capacities. Floods carry an abundant sediment load (Pont, 1997). They are related to exceptional meteorological events. They can be on a regional scale, in connection with Mediterranean autumn disturbances causing intense thunderstorms, especially in the river basins of the Ardèche and the Gardon. In the spring, these disturbances are combined with the melting of snow in the Durance river basin, resulting in considerable increases in water levels. Generalised flooding on a supra-regional scale appears in winter or spring, fed by the

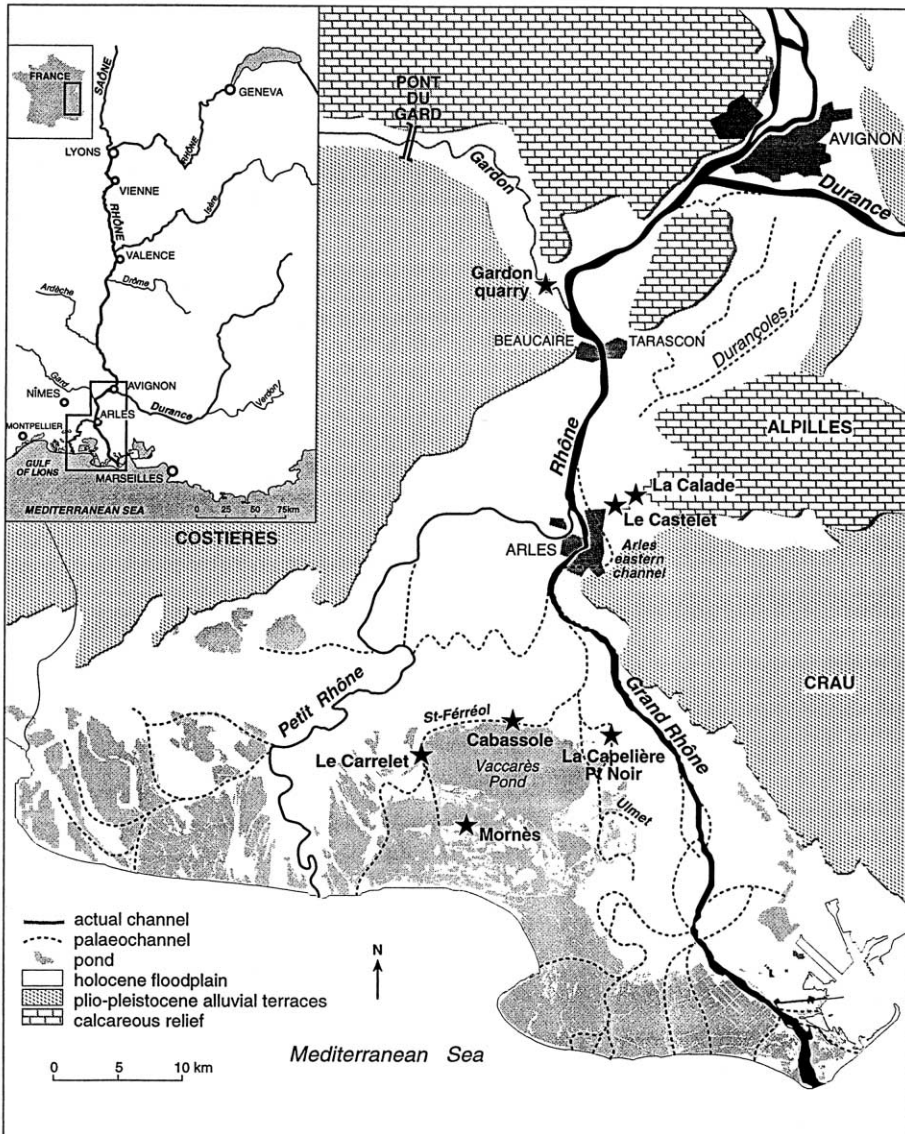

Fig. 1. Location of the study area in the Rhone catchment.

Fig. 2. The lower Rhône valley and delta geomorphological context, location of the main studied sites.

rain–snow regime of the middle Rhone. This can generate centennial floods over large areas, capable of remodelling or moving the riverbed: this happened in 1993–1994 (9400–10,600 m^3 s^{-1}), in 1840 and 1856 (11,640 m^3 s^{-1}, Pardé, 1925) when an historic limit to the floodplain was reached.

3. Methods of investigation

The 15 sites where Roman deposits could be dated are here presented. Sedimentological and geomorphological data, datings arguments and hydrological interpretations are summarized in Table 1. At archaeological places, alluvial stratigraphic sequences were studied in natural or archaeological sections. Cores were sampled near these sites. Palaeohydrological interpretations and study of fluvial palaeoenvironments are based on sedimentary and geomorphological analysis (Bravard and Salvador, 1999; Brown 1997).

3.1. Analysis of morphogenic changes

The shape of the river channel and of the alluvial plain is reconstructed horizontally by pointing the extension of flood deposits, vertically by the stratigraphical study of sedimentary units. The nature and the disposition of these deposits as well as the filling in or cutting phases of the fluvial bed inform as to the depth and the caliber of the channel and allow for the identification of the fluvial type. Following these elements through time and space enlightens the morpho-sedimentary adjustments to modifications in flow and charge (fluvial metamorphoses: Schumm, 1977; Starkel, 1983). The shape and number of branches determine the capacity of the flow, the frequency and the amplitude of flooding.

3.2. Analysis of flood deposits

The granulometry of flood deposits describes the variation in the grain shear stress, linked to the magnitude of the floods. It decreases with distance from the channel. It is expressed here by the main grain size (Mgs, Folk and Ward, 1957). The C/M pattern (Passega, 1957; Bravard, 1983) allows to relate the deposits to the transport mode (suspension, saltation, rolling) and makes it possible to define the maximum grain size of the uniform suspension (Cu) and graded suspension (Cs) (Peiry, 1994). Arnaud-Fassetta (1997) collected modern sedimentary data from the 1992–1994 floods in the lower Rhone, allowing for the interpretation of former deposits in terms of sedimentation environments (floodplain, banks). Soil erosion in the catchment can be reconstructed in an invariant environment from the sedimentation rate depending on the suspended sediment load concentration. The sorting of the whole sediment (sands to clays) is also described using Folk and Ward (1957).

Archaeological data introduces a bias in sedimentary interpretations. The use of alluvial matter in ancient construction requires specific argumentation in order to identify natural deposits (Brochier, 1994). The erosion or collapse of a building during flooding, obstructions and the resulting flush effects increase the grain-size, degrade the sorting, and sometimes prevent hydrologic interpretations. The elevation asl of the top of the sediments indicates the minimum height of the flooding water, highly dependent on urban topography.

3.3. Interpretation of marsh, groundwater and flood levels

The hydrological fluctuations of the marshes in the floodplain inform of the variations in the floodplain water table level according to the transversal geometry of the riverbeds and, in particular, the respective elevation asls of the water level in the channel and of the floor of the alluvial plain.

In wetland environments, the ostracofauna and the sedimentary facies characterise the vegetal colonisation, annual regime and mineral content of the water body. Ostracode species are grouped according to their tolerance to salinity changes (Neale 1988; Curry, 1999) (high for the brackish *Cyprideis torrosa*, moderate to low for other, mostly freshwater species), their resistance to drying (Holmes and Horne, 1999) (high for Candoninae, Cypridinae, Ilyocypridinae and *Cyclocypris laevis*, low for *Metacypris cordata*, *Limnocythere sancti-patricii*, *Paralimnocythere psammophila* and *Darwinula stevensoni*) and their biotope (Scharf, 1997) (*C. compressa* is a pioneer species, able to dwell in running waters, and appears to be overrepresented in flood deposits; *D. stevensoni* is characteristic of clear waters; Ilyocypridinae, on the other hand, are associated with the biotopes of littoral macrophytes). Marsh sediments are differentiated by their $CaCO_3$ and organic content and by the micromorphology of the sand fractions, in order to differentiate between flood deposits (no macroremains, 25–35% $CaCO_3$, low organic content), authigenic organic-carbonated sediments (40–50% $CaCO_3$, high organic content, carbonated concretions in the sand fraction), and shallow marshland peat (absence of carbonates, abundant organic macroremains).

In terrestrial hydromorphic alluvions, the rise of water tables is perceptible in the reduction in the number of biospheroids secreted by land *lombricidae* (Jeanson, 1964; Wiecek and Messenger, 1972).

The frequency of overflowing is evaluated by the development of bio-disturbances and the presence of archaeological layers. The biosoils are identified by the abundance of biospheroids and the disturbance of sedimentary structures by roots and by the activity of *lombricidae*. Pedological-induced chemical changes are, on the other hand, insufficiently differentiated from the background noise of the sedimentary deposits.

Drainage systems and the backing up of sewage drains can be signs of higher flood risks and/or a rise in the average water levels. In most cases, however, archaeological sites in immediate proximity to the river channel were occupied continually from the 5th–4th centuries BC to the 4th–5th centuries AD, despite indications of recurrent flooding. They are, therefore, poor indicators of fluvial hydrological fluctuations (Arnaud-Fassetta and Landuré, 1997). One must be wary not to adopt an overly determinist approach to the relationship between risk factors and land settlement, quite variable according to the function and importance of a site.

3.4. Datings

The most precise dating was obtained from archaeological sites, generally based on pottery. Eleven ^{14}C datings (Table 2) were obtained from the 'Centre de Datation par le Radiocarbone, Université Lyon 1' on peat, charcoal fragments or organic macroremains. All of the datings were calibrated using the INTCAL98 calibration curve (Stuiver et al.,

Table 1
Sedimentological and morphological data collected on the lower Rhône sites

Site	Location	#	Morphological and/or sedimentary event	Sedimentation rate (mm/year)	MGS (μ)	Cu–Cs	Dating arguments	Interpretation	Nature and time of Roman fluvial change
Blanchissage	Avignon city	1	silt deposits				between a 1st century BC and a 1st century AD floor	one flood or more	At least seven floods between 50 BC and the end of 1st century AD
		2	silt deposits				interstratified with four 1st century AD floor levels	three floods or more	
		3	destruction levels				post-1st century AD	no flood; ploughing	
N–D la Principale	Avignon city	1	silt deposits		4 to 50		interstratified with five 50–0 BC floor levels	four floods or more	Mgs inferior to the little Ice Age ones (150 to 250 μm); frequency of floods superior to the present one
		2	silt deposits				interstratified with three 1st century AD archaeological levels	two floods or more	
Gardon quarry	lower Gardon river	1	17 silty and sandy flood sequences		100 to 225	Cu = 600, Cs = 800	flooding associated with the opening of an early 1st century AD quarry; deposits cut into by early 2nd century tombs	17 floods	17 floods during 1st century AD; rare floods or no floods afterwards
Piton core	Arles city, Trinquetaille (right bank)	1	silt deposits	1.7 to 2.1			^{14}C datings: between 4170 ± 45 BP, [2900–2503]cal. BC, and 2035 ± 50 cal. BP, [171 cal BC; 74 cal. AD]	rare and low energy floods on the site floodplain environment	widening of the main Rhone channel, 1st century BC; some floods on urban sites, 1st and 2nd century BC

		2	stratified sand and silt deposits	for all the Roman period, 5.0 to 8.7		between the 2035 ± 50 BP 14C dating and a villa floor (probably last decade of 1st century BC)	natural levee environment	
		3	silt deposits			interstratified with archaeological Roman levels, under the 270 AD destruction levels	two floods or more on the site	
		4	burnt and heterogeneous ploughed levels	post-270 AD, 1.3		historical sources: destruction of the quarter, 270 AD; medieval potteries	no flood clearly identified in the destruction levels	
RG trenches	Arles city, Trinquetaille (right bank)	1	sandy silts levels		50 to 150	interstratified with end of 1st century BC and later Roman structures before 270 AD	two floods or more connection between levee and floodplain environments	floods on urban sites; thickening of the levee up to 5.3 m elevation asl
AdC trench	Arles city, Trinquetaille (right bank)	1	biodisturbed silts			6th–4th century BC potteries inside	low frequency and low energy floods	More numerous floods with a higher energy level between 1st century BC and 2nd century AD
		2	sandy silts			over a 2nd–1st century BC walking structure; contains an in situ dolium; under a 1st century AD	at least two flood of higher energy during a short period	
		3	silts deposits			floor interstratified with three 1st and 2nd AD floor levels	two floods or more	
		4	ploughed heterogeneous silts			270 AD destruction of the quarter; medieval potteries	probable floods during medieval and modern times	

Table 2
^{14}C datings

Accepted dating (BP)	Lab. reference	Site	95% confidence interval	AMS	Nature of dated element
4170 ± 45	Lyon-1039 (OXA)	Arles-Piton	[2900; 2503] cal. BC	Y	fragments of leaves
2035 ± 50	Lyon-1038 (OXA)	Arles-Piton	[171 cal. BC; 74 cal. AD]	Y	coal fragments
2420 ± 35	Ly-9387	Castelet	[759; 400] cal. BC	N	peat without carbonates
1895 ± 50	Ly-9386	Castelet	[3; 238] cal. AD	N	peat
1570 ± 45	Ly-9386	Castelet	[421; 601] cal. AD	N	organic macroremains
1510 ± 30	Ly-9384	Castelet	[441; 644] cal. AD	N	peat without carbonates
930 ± 30	Ly-9383	Castelet	[1021; 1209] cal. AD	N	peat without carbonates
2145 ± 65	Ly-8152	Calade	[335; 16] cal. BC	N	organic macroremains
1580 ± 40	Ly-8153	Calade	[419; 588] cal. AD	N	organic macroremains
1920 ± 40	Ly-7320	Carrelet	[15; 210 cal. AD]	N	wood fragments
4035 ± 55	Ly-7761	Mornes	[2845; 2420] cal. BC	N	wood fragments

1998) and are shown in calendar years (BC or AD) in order to simplify comparison with archaeological datings.

The combination of geomorphological, sedimentological, pedological and archaeological indicators on several sites helps to eliminate local phenomena and to propose a palaeohydrological synthesis representative of the lower Rhone.

4. Sedimentary and stratigraphic data collection

4.1. The site of Avignon

The two studied archaeological excavations lie on the left bank approximately 1000 m from the supposed location of the channel (Fig. 3, Table 1). They reveal Roman (50 BC–end of 1st century AD) suburban sites, consisting of floor and wall structures, stratified with silty homogenous sediments with terrestrial mollusc shells interpreted as flood deposits. Four of these flood levels were deposited between 15.5- and 16.5-m elevation asl in the second half of the 1st century BC, while three or four such levels were deposited in the 1st century AD. Despite disturbances in the granularity, induced by anthropisation, the sediment is fine ($4\ \mu m < Mgs < 50\ \mu m$), with the exception of one sandy level ($Mgs = 127\ \mu m$) deposited towards the end of the 1st century BC. The global sedimentation rate ranges from 5 to 10 mm/year. On the C/M Passega diagram, these deposits are connected to the nearby flooplain. The pre-Roman deposits could not be seen.

The upper alluvial deposits show plough disturbances, archeologically dated from early Middle Ages (6th century AD) and obliterated by only one flood level (Mgs 50 μm, artificially raised by anthropisation) within the present day town. Outside the town walls, from the 14th century on, 1 to 1.5 m of alluvial silt were deposited in the floodplain. Their coarseness (Mgs 150 to 250 μm) testifies to a powerful hydrology.

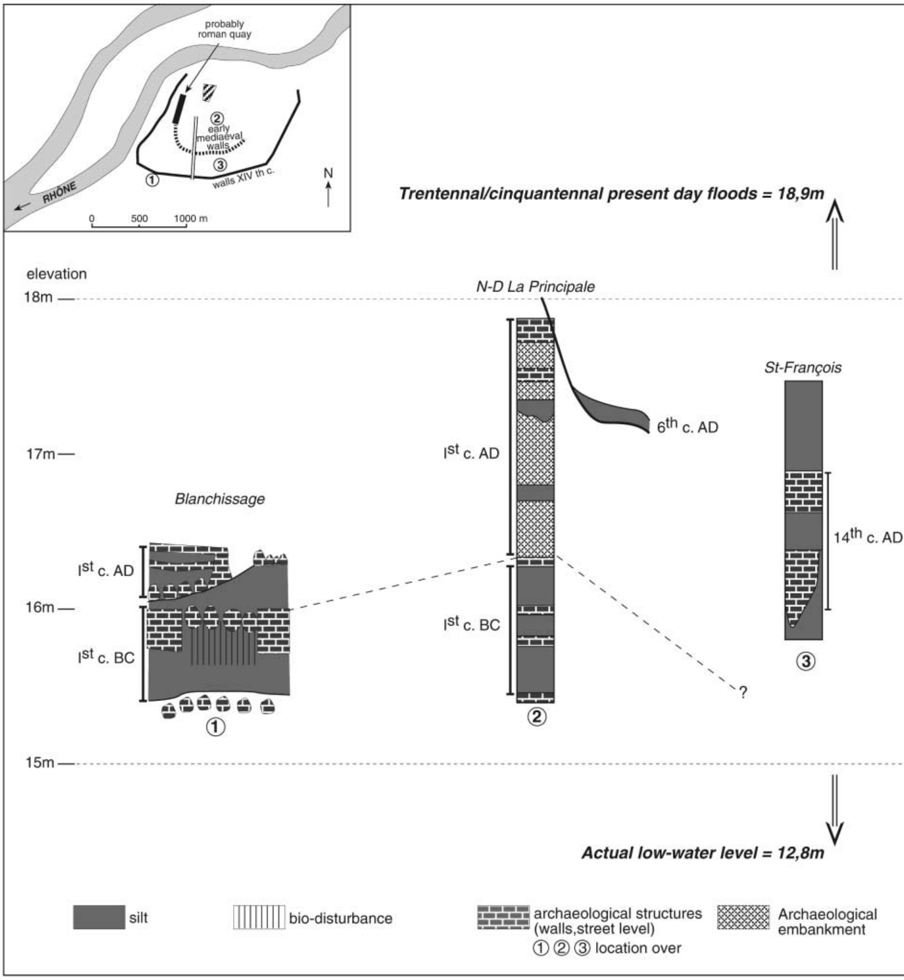

Fig. 3. The site of Avignon.

4.2. The lower Gardon river

The archaeological excavations on the quarry of the Pont du Gard demonstrated the existence of 17 superimposed flood sequences (Fig. 4, Table 1). They lie on the quarry extraction floor, dated to the first decades of the 1st century AD, and are cut into by tombs dating to the early 2nd century AD. The four basal sequences are contemporary to the functioning of the quarry as they are inter-stratified with quarry debris.

The C/M Passega diagram of these deposits shows that they are connected to the nearby floodplain or to the riverbanks. They indicate a strong competence ($Cu = 600$ μm, $Cs > 800$ μm), due to the river gradient and a local factor, the opening out of the gorges. Changes in thickness and coarseness underline an increasing flood energy: the first 12 sequences are 5–15 cm thick ($Mgs < 100–150$ μm). Each sequence is bio-dis-

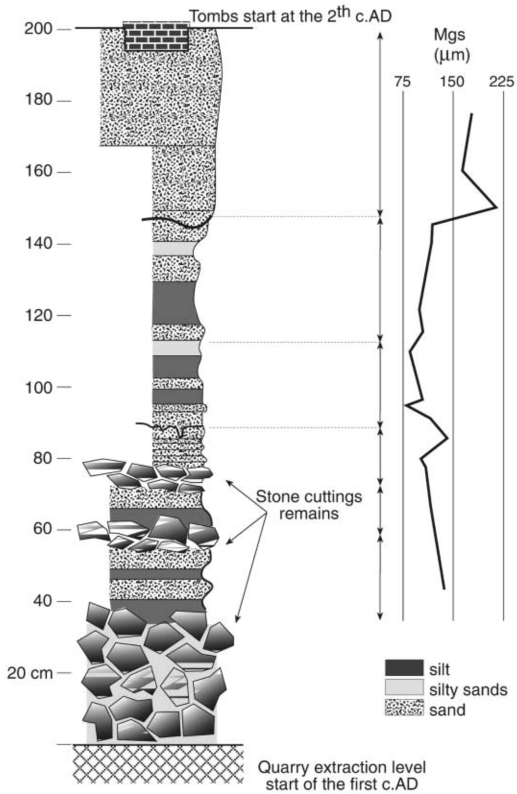

Fig. 4. Lower Gardon river (Pont du Gard Quarry).

turbed, indicating plant growth between flooding. The five most recent deposits are thicker (13–25 cm), and not bio-disturbed, with a high coarseness (150 μm < Mgs < 225 μm).

The hydrological activity of the Gardon was therefore increased in the course of the 1st century AD. It is difficult, however, to determine the hydraulic effects induced by the opening of the quarry, which probably attracted floodwaters and amplified their effect. The thicker upper sequences could indicate the immediate proximity of a secondary channel intruding into the low-lying zone of the quarry. The tombs at the summit of this sequence suggest that this sector is out of reach of the frequent flooding from the early 2nd century AD.

4.3. Arles: the Roman urban site

Flood deposits have been observed on the convex right bank (Trinquetaille) and on the concave left bank. The differing contexts influence the sediment recordings.

On the right bank, which is the most exposed to flooding, one core (Piton, Fig. 5) and two archaeological excavations (Fig. 6, AdC and RG) were studied. Archaeological data give here performant boundaries between the foundation of the Roman town (46 BC)

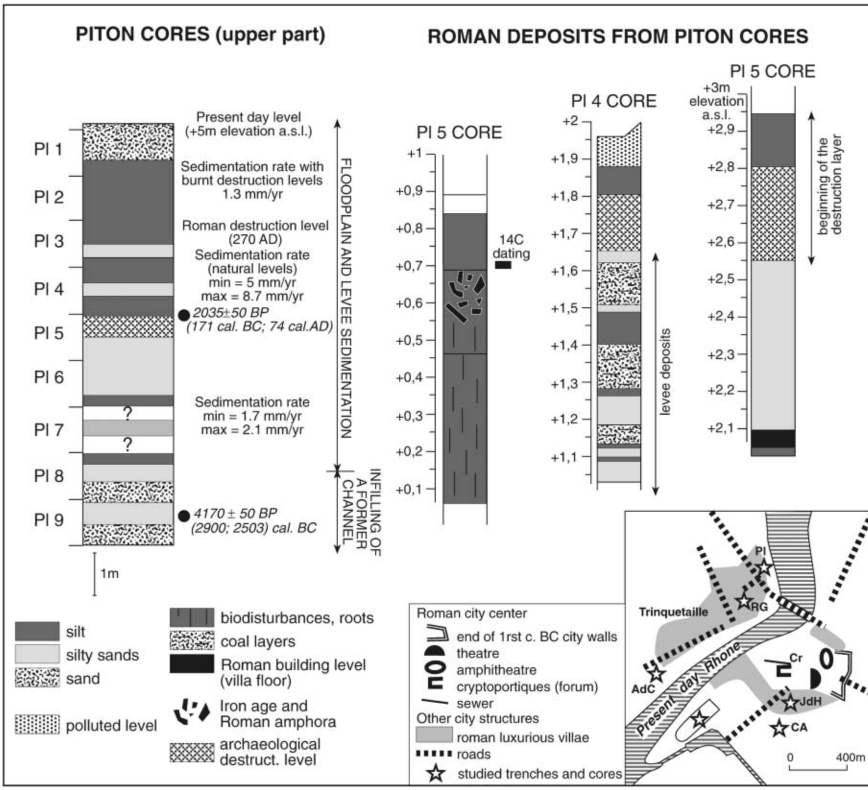

Fig. 5. Piton core (Arles right bank).

and the destruction of the Roman quarter in 270 AD. Radiocarbon datings were obtained in Piton core, where the upper 5 m of 19 m range from the Roman period to the present day. The Pleistocene pebble bottom was not reached in this core, but is supposed to lie 25 m under the surface (L'Homer et al., 1981). The Piton core shows a clear rise in the sedimentation rate during the Roman period in comparison with the former and latter periods (Table 1). Moreover, immediately after the 171 cal. BC–74 cal. AD radiocarbon dating and under a Roman *villa* floor, 50 cm of stratified silty sands testify to the presence of a levee on the site, briefly replacing the floodplain silts. Because the archaeological data give evidence of the fixation of the left bank at the Arles crossing for the Roman period (remains of a quay and of the rampart, Heijmans and Sintes, 1994), this deposit is interpreted as a widening of the main Rhone channel during 1st century BC and not as a lateral moving. To the south, the RG trench shows sandy silts interstratified with Roman buildings; the natural deposits suggest the transition between levee and floodplain environments. Their elevation, grain-size and statigraphy allow to replace the thickening of the massive natural levee up to 5.3 m elevation asl, and reveal

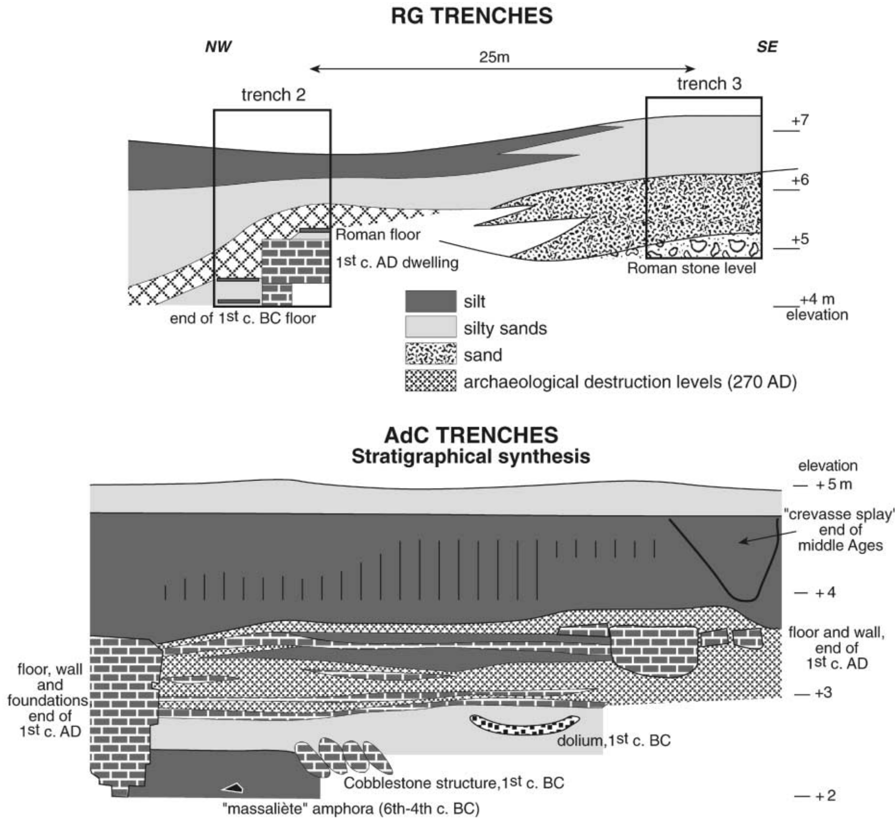

Fig. 6. Archaeological trenches of the Arles right bank.

two or more flooding episodes. At the southern limit of the Roman town, the AdC trench also shows flood deposits associated with Roman structures. At least two flooding phases are archaeologically dated from 1st century BC. They consist of massive sandy silts contrasting with the former very biodisturbed silts, archaeologically dated around 4th century BC. Two more sandy flood levels are interstratified between 1st and 2nd century AD floors. For the whole quarter of Trinquetaille, the general abandonment of dwellings in the 3rd century AD is shown by destruction layers (heterogeneous burnt sediments) without any flood levels.

On the left bank two, archaeological excavations were studied and added to the former studies of Iron Age archaeological sites (JdH and Cryptoportiques, Fig. 5, both revealing an isolated flood dated to 175 BC). The stratigraphy of the Roman circus track illustrates the fluvial activity in the adjacent floodplain (Fig. 7). The base of the track is situated at 2.5 m elevation asl. It is dated to the 2nd century AD by dendrochronological analysis of the wood piles that serve as its foundation (Frédéric Guibal, personal communication). It covers 1.5 m of dense hydromorphic silt, which contains a few 1st centuries BC and AD potteries (deposition rate 7.5 mm/year). Their main grain size varies between 25 and 35 μm, with their position in the C/M Passega diagram

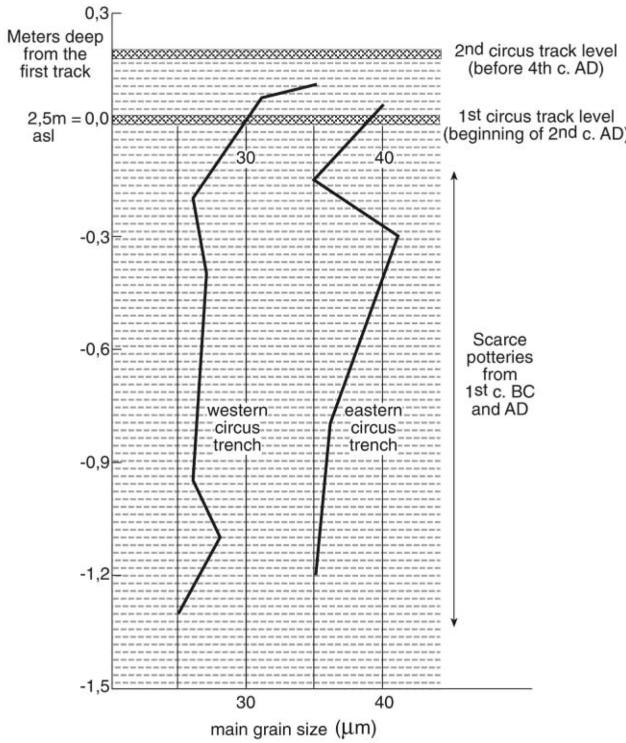

Fig. 7. Granulometry of flood deposits in Circus trenches (Arles left bank).

characterising deposits from overflow near to the channel. The average coarseness becomes higher on moving away from the channel of the present day Grand Rhone, which indicates the probable presence of a secondary channel to the East.

The filling of the Roman sewers, built in the 1st century AD in the center of the ancient town, indirectly registers variations in the water levels of the Rhone (Lopez-Saez et al., in press). The reconstituted main outlet of these sewers, 2.5 m^2 wide, opens into the fluvial channel at 1.5 m elevation asl, at the low water level of the present Rhone. The secondary branches of the sewer, situated between 3.4 and 5 m elevation asl, show no signs of deposits before the 3rd century AD, probably due to regular maintenance. The two-thirds of their filling are archeologically dated to 3rd century AD, a time of political decline in Arles. They consist of coarse well-sorted sands, which testify to the persistence of a dynamic hydrology, implying that the river levels remained fairly low. The last third, undated, consists of fine silty deposits with occasional ostracodes and terrestrial molluscs suggesting problems in evacuation (bottlenecking, inversion of the flow marked by the presence of microfauna).

4.4. The Arles floodplain

Three coring sites revealed marshland deposits, one 600 m east of the left bank of the Grand Rhone (core CA) and two on the eastern edge of the floodplain some 5 km from the river (La Calade and Castelet). They demonstrate the persistence of an irregular floodplain topography during the Roman period.

To the South of the ancient town, some hundred meters from the actual main channel, the CA core (Fig. 8, Table 1) describes the paludal infilling of a secondary channel (oxbow marsh). The bottom of the sequence could not be reached. Deposits are dated by pottery finds and archaeological layers. Before the Roman period, ostracofauna dominated by *M. cordata* testifies to a permanent water body. High organic matter rates and the presence of a freshwater "marl" of authigenic carbonates illustrate the dense plant population. It is permitted by rare and low energy floodwaters, which decanted silty clay (6 μm < Mgs < 9 μm). At their summit, the disappearance of fauna in a level of framboidal pyrite indicates an anoxia phase. During the Roman period from the Roman settlement (second half of 1st century BC), the sedimentation suggests the episodic

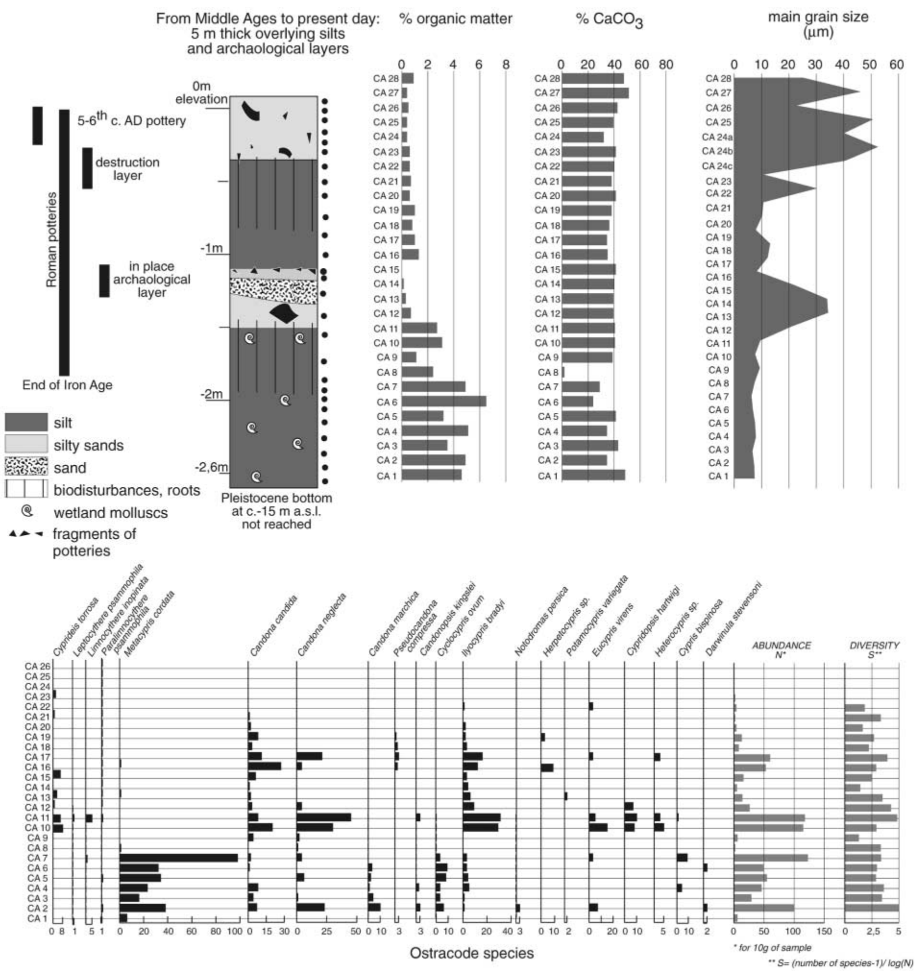

Fig. 8. Sediments of ostracofauna from CA core (Arles floodplain).

functioning of a secondary channel: 1.5 m of alluvium (Mgs increasing from 10 to 20 μm, excepted archaeological layers) are deposited between −1.5 m elevation asl and −0.25 m. The functioning of this channel can be correlated to the flooding coming from the East at the circus in Arles. The lowering organic content and the disappearance of permanent- and clear-water ostracode species (*M. cordata*, *D. stevensoni*) with respect to the increasing of *Candoninae*, *Ilyocypridinae* and *Cypridinae* appear to be associated with higher sedimentation rates which lead to a temporary water body. The elevation asl of the deposits cannot therefore be seen as a marker of the low water levels in the Roman period. Disappearance of fauna from −0.75 m is associated with increased marks of bio-disturbance and drying. These latter levels contain artefacts suggesting the destruction of settlements, and may hence be dated around 3rd century AD. A final phase dating to Late Antiquity (5th–4th centuries AD) corresponds to sandy deposits between −0.25 and +0.10 m elevation asl (Fig. 8).

At the eastern limit of the floodplain, on the marshy sites of la Calade and Castelet (Figs. 2 and 9, Table 1), the stretch of marshland fluctuates in relation to the level of the floodplain groundwater, the Rhone floods, and the discharge of springs from the nearby hills. The two logs that were cored rested on the Pleistocene bottom (Bruneton, 1999). Five radiocarbon datings on bulk peat sediment range between beginning of Roman period (2nd–1st centuries BC) and beginning of Middle Ages (4th–6th centuries AD). Two of them are confirmed by pollen analysis in la Calade (Andrieu-Ponel et al., 2000). In the Castelet core, the last 2.5 m of 6 m correspond to Roman and later deposits (−4.1 to −1.3 m elevation asl). In la Calade, the first sediments were deposited in the marsh at 0.5 m elevation, 25 cm under peats, which were radiocarbon dated to 355–16 cal. BC, and the marsh persisted until the beginning of the modern era, with 2.4 m thick deposits. The same stratigraphy could be identified in both sites, with alternation of decantation clay (Mgs < 7 μm) from Rhone flooding, chalk and peat.

Between 759–400 cal. BC and 355–16 cal. BC (Iron Age) flood deposits reached a low marsh (temporary water ostracodes such as *candoninae* in la Calade, low ostracode abundance in Castelet). Between 35–16 cal. BC and 3–238 cal. AD, a rise in the groundwater level is recorded by a facies of chalky peat and by an abundant perennial water ostracofauna in both areas. Starting in the 2nd century AD and for the following 200 years after sedimentation rates, disappearance of authigenic calcite and ostracode associations testify to a seasonal drying with a rise in salinity, indicating a drop in the groundwater level. Flood sediments enter the marsh once again afterwhile, dated in la Calade and Castelet to between cal. AD 421–558 and cal. AD 419–588 (late Antiquity/low Middle Ages).

4.5. The Rhone river in the delta complex

In the Rhone delta (Fig. 2), geo-archaeological excavations related to Roman sites were studied along the Saint Ferréol and Ulmet palaeo-channels and in their paludal floodplain, allowing for a chronology of the Rhone sedimentation and hydrological activity.

Along the palaeo-branch of Saint-Ferréol (Fig. 10, Table 1), three sites were excavated for this period from up- to downstream.

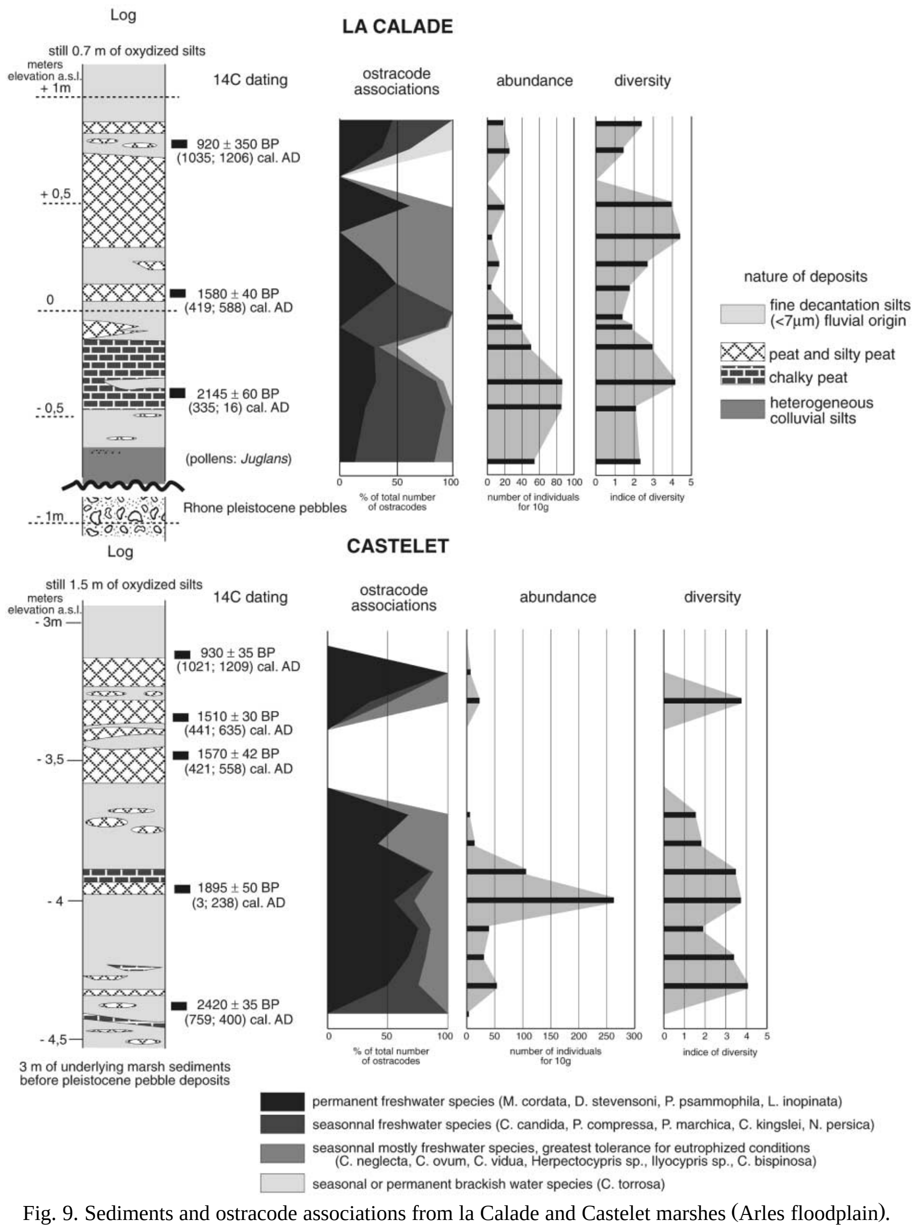

Fig. 9. Sediments and ostracode associations from la Calade and Castelet marshes (Arles floodplain).

• At the 'Cabassole' site, the floodplain sedimentary units deposited between the 1st century BC and the 1st century AD were examined perpendicularly to the axis of the palaeo-channel and dated by pot finds. The floods deposited a more homogenous and coarser silt than previously, demonstrating the increased competence of the river (20

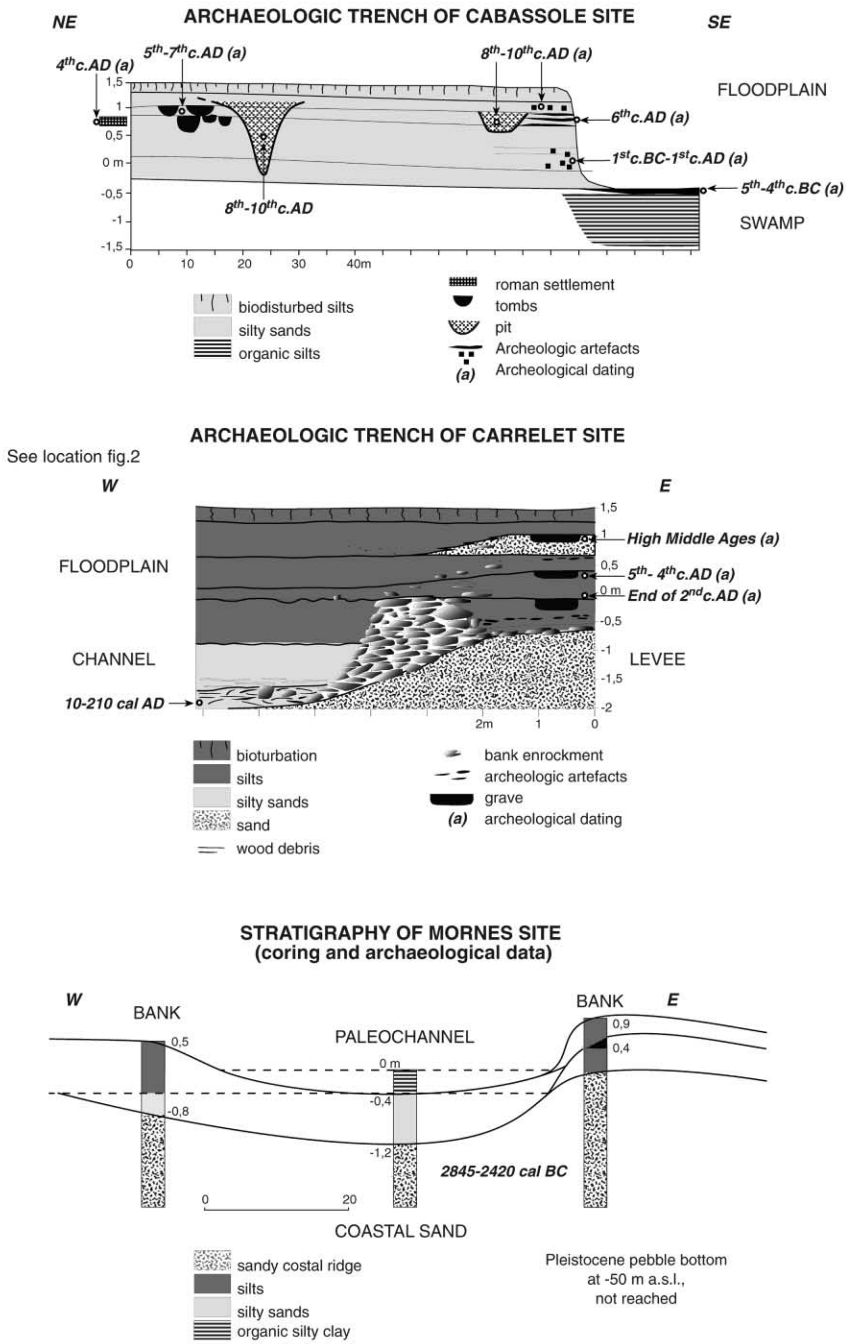

Fig. 10. St. Ferreol paleobranch morphological evolution.

μm < Mgs < 30 μm; Cu = 250 μm). The sedimentation rate increases (2–4 mm/year, vs. 0.6–1.2 mm/year between 4th and 2nd centuries BC, and vs. 0.8–1.0 mm/year between end of 1st and 5th centuries AD). The energy of the flow starts to abate from the end of the 1st century AD (10 μm < Mgs < 15 μm; Cu = 120 μm) until the arrival of coarser deposits dated by a 5–7th centuries archaeological layer.

• On the 'Carrelet' site, excavations in the floodplain were associated with cores 13 m deep in the palaeo-channel. Between 15 cal BC–210 cal. AD and the end of the 2nd century AD (archaeological dating), 85 cm of sediments (10 μm < Mgs < 20 μm; Cu = 200 μm) accumulated on the external side of the levee, whereas 2 m of silty sand (55 μm < Mgs < 115 μm; Cs = 350 μm) fill in the internal side of the bank, pushing the main axis of the channel several hundred meters to the West. The absence or the weakness of bio-disturbance and the presence of numerous gas bubbles trapped during the sedimentation indicate frequent and successive flooding. A Roman bank enrockment may be interpreted as a defence work against floods. At their summit, a bio-soil and tombs dating to the 2nd century AD show a decrease in the flood frequency.

• On the 'Mornès' site, a sandy coastal ridge, dated to 2845–2420 cal. BC, is cut by a palaeo-channel and its levees. They correspond to a secondary divergence East of the main Saint Ferréol branch. The 90-cm-thick deposits of the levee contain an archaeological level dated between 75 and 25 BC. The levee is characterised by silty sand (75 μm < Mgs < 165 μm) deposited by uniform suspension (Cu = 310 μm). The channel reveals first silty sand deposited by uniform suspension (75 μm < Mgs < 170 μm, Cu = 315 μm), then a filling in by decantation of fine fluvio-lagoon sediments (10 μ < Mgs < 20 μ).

On the 'Ulmet' palaeo-branch (Fig. 12, Table 1), about 4 km upstream from the Roman coastline, the stratigraphies of the 'Capelière' and 'Pont Noir' sites (Fig. 11) are

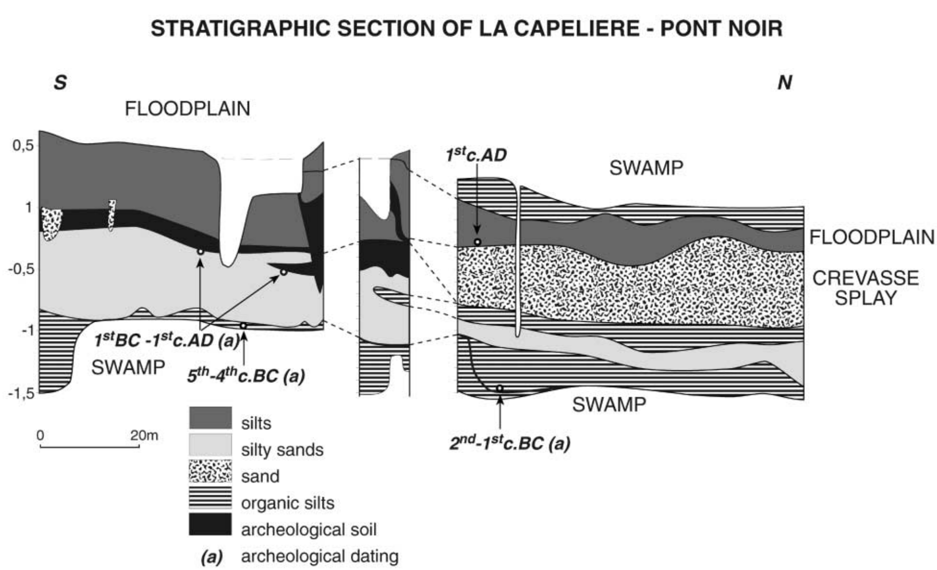

Fig. 11. Ulmet paleobranch morphological evolution.

indicative of either freshwater or brackish lagoon environments, episodically flooded by the river since the 2nd millennium BC (Arnaud-Fassetta et al., in press). Several settlements have been identified on its edges, dated by the pot finds to the 5th–4th centuries BC, 1st century BC and 1st century AD.

In the 1st century BC, flood silts and silty sand indicate the development of a high energy emerged floodplain and the aggradation of a levee up to 0.2 m elevation asl. At the end of the 1st century BC, the level of the perennial marsh transgresses on the inhabited fringe (la Capelière). The organic silts deposited by decantation are interstratified with the arrival of episodic flood deposits (sandy silt) and moving laterally to a proximal floodplain. These deposits are interrupted in la Capelière by several sequences of coarser flood deposits (fine sand), 1 to 10 cm thick, interpreted as crevasse splays deposited in an inundated environment. A 1st century AD settlement is built over this level.

5. Palaeohydrological characterisation and interpretation

The characterisation of high waters (flooding), the geomorphology of fluvial environments and the altimetry of the hydrological and ground water levels on the different sites, allow to build a schema for the Rhone palaeohydrological functioning around Roman times.

5.1. High water characterisation

Only flooding waters, as they deposit alluvions outside the channel, can be here studied through their frequency, their extension and their sediment load.

The enumeration of the flood sequences shows that during 1st century BC and 1st century AD, high waters overflowing the channel occurred 17 times on the Gardon and 7 times in Avignon. In Arles and the delta, only a minimum number was obtained, four or more in Arles, because of the lack of stratigraphical limits between the flood sequences and of the very changing topography. These counts are slightly higher than at the 20th century, where floods flowed only twice over the banks, this frequency probably being artificially lowered by the 19th century large scale dyking up. Moreover, the pedological indicators suggest shorter intervals between the floods in comparison to the times encircling the studied period. The extreme flooding levels are less frequent, however, than during the Little Ice Age, during which historical sources indicate intervals between flood sequences of as little as 5 years to annual (Pichard 1995). Neither do they reach the flood levels of the end of Roman times (5th–7th centuries AD), such as the ones recorded in la Calade.

In comparison to the periods encircling the 1st centuries BC and AD, the increase in the sediment coarseness (main grain size, Cu/Cs, textural field evaluations) on sites where former and later deposits were observed (Gardon, Arles-AdC, -CA, Cabassole) testifies to the increase in floods energy (Table 1, Fig. 11). These values equal the present ones for the proximal floodplain (Roditis and Pont, 1993; Arnaud-Fassetta, 1996). They are inferior to those from the Little Ice Age at Avignon and in the delta.

The sedimentation rates are generally higher than before and after, showing an increase in the river transport capacity. These values, of 4 to 10 mm/year, reach those from the Little Ice Age in the distal floodplain and in the delta.

5.2. Fluvial geomorphology

It is characterised by the lateral instability of the channel and of its edges, documented in Arles and in the delta. This contrasts with the morphogenic stability of the preceding and succeeding centuries.

The mobility of the river channel is showed by the widening of the main channel (transition from floodplain to levee deposits in Piton core, Arles); the aggradation of the levee (Arles right bank, delta sites); the lateral displacement of the main channel (Le Carrelet); the re-activation of secondary channels (Arles left bank, in the delta at Mornès) and the appearance of crevasses (La Capelière). The sites of the Saint Ferréol branch show that the general riverbed aggradation trend is interrupted from the beginning of the 2nd century AD, and moves into a trend of strong channel incision.

These characteristics convey an adjustment in the fluvial style towards braiding, indicating an aggradation trend in the channel during 1st centuries BC and AD. The metamorphosis is less acute, however, than during 5th to 6th centuries AD and the Little Ice Age, when a river morphology with migrating multiple branches appears in the delta (Arnaud-Fassetta and Provansal, 1999). These difficulties in evacuating the sediment load are not attributable to a downstream control as the slope of the banks in the delta conveys a connection with a relative sea level lower than at present (Vella et al., 1998). It indicates, therefore, an increase in the solid and liquid flow of the river (Galloway, 1975; Starkel, 1983; Bravard, 1989).

5.3. Hydrological and ground water levels (Fig. 12)

The marshes in the floodplain expanded and deepened (Calade–Castelet, la Capelière) despite the increase in sedimentary deposits. The rise in ground water levels equally resulted in the development of hydromorphic facies in the delta. This trend was inverted during the course of the 2nd century AD (Fig. 12).

Water-levels in the ancient river channel are still poorly defined. In Arles, the facies of CA core allows situating the low water level between −1 and 0 m elevation asl. This along with the elevation of the sewer outlet corresponds to an average water level of less than 2 m elevation asl. These figures are close to present levels (low water 0.9 m elevation; average water level 1.5 m elevation). In the context of the underlying rise in the alluvial plain in association with that of the sea level in the course of the Holocene, the closeness of the ancient and present hydrological levels implies greater liquid flow at the beginning of Roman times.

The rise in hydrological levels can be partly imputed to a trend towards the infilling noted in the channel in the course of the 1st century AD (Carrelet).

5.4. Chronological boundaries

These interpretations underline a change in fluvial dynamics for a short period. Because of this briefness, strong chronological arguments are needed to ascertain its

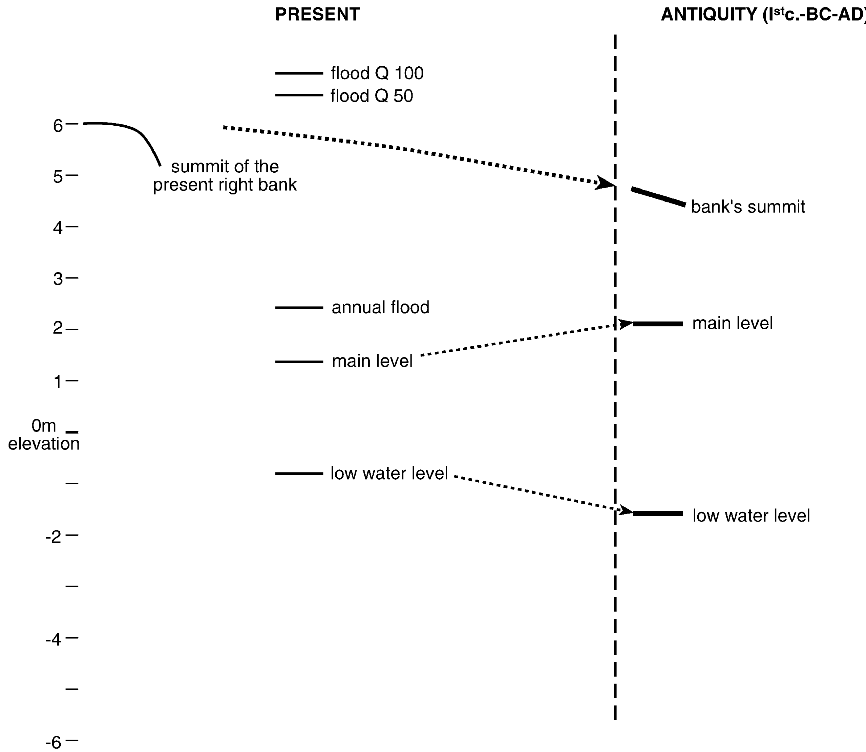

Fig. 12. Altimetry of present and Roman hydrological levels in Arles city.

hydrological significance. Table 1 summarizes the chronological and sedimentological data for each site.

- In three sites (Arles-Piton, Calade–Castelet marsh), the beginning of the change is radiocarbon dated to 1st century BC and these increased dynamics still last during the 1st century AD.
- In seven sites, sediments which characterise a strengthening in fluvial dynamics contain potteries and/or archaeological occupation levels dated to 1st century BC and contrast with former sediments conveying calmer conditions, not precisely dated (Circus, CA core, Carrelet, Mornès, la Capelière) or archaeologically dated to between 5th and 2nd centuries BC (Arles-AdC, Cabassole, Pont Noir). This contrast does not preclude some former exceptional floods, such as the 175 BC one in Arles (JdH, Crypto.)
- Four sites (Avignon, Gardon, Arles-Cirque, Arles-RG) reveal sediments from 1st centuries BC–AD conveying stronger fluvial conditions than today, without allowing a comparison with the former deposits.
- The abatement of the fluvial dynamics is strictly dated to 2nd century AD by archaeological settlements or radiocarbon datings in two sites (Gardon, Carrelet). In six sites (Arles-AdC, -Piton, -Circus, -RG, CA), it looks more progressive, with still some

floodings during 2nd century AD and very low dynamics during 3rd century AD (Arles-sewers).

- In three sites, the strong fluvial dynamics of 1st centuries BC–AD and of 5–7th centuries AD are separated by a calmer period which is not precisely dated (Avignon, Calade–Castelet, Cabassole).

6. Discussion

6.1. A palaeohydrological fluctuation

These items enlighten a change in the fluvial dynamics during 1st centuries BC and AD, characterised by (1) more frequent floods with stronger water discharge and sediment load, (2) higher groundwater levels in the floodplain and (3) an accelerated riverbed morphogenesis corresponding to an aggradational trend in the channel, with respect to the former and latter conditions. However, the Rhone did not enter a crisis period such as the Late Antiquity and Little Ice Age ones. So we must discuss whether this specific functioning was only linked to a few exceptional events occurring at random or whether it was in relation to an average rise of the Rhone discharge.

Starkel (1983, p. 223, lines 17 to 24) underlines that a single very exceptional flood is able to cause a morphogenic change of the channel such as a rapid widening. Many decades are subsequently needed for the river to evacuate the sedimented load. During this readjustment time, the over-elevated water-level in the channel might cause a rise in the floodplain groundwater. Anyway, he insists on this event to be really exceptional, with a recurrence interval of hundreds to thousands years. There are no proofs of such an event, and an important flood is not likely to explain the Rhone functioning, because isolated great floods such as the 175 BC and the 2nd century AD ones, or even as the 1993–1994 ones, did not break the tendency to low groundwater levels and morphological stability.

So the fluvial changes in the Roman period are more easily explained by the clustering of many events (Starkel, 1983, 1991) through a “flood-dominated regime” (Erskine et al., 1992). In this case, a disequilibrium threshold in the fluvial dynamics could have been attained because of the decreasing period between great flooding events. Many sedimentary signs ascertain this hypothesis for the studied period. It is probable, but not certain, that this increased flooding frequency is associated with an increase in the average abundance of the Rhone, which could directly explain the undelayed rise in the floodplain water-levels. Such a relationship between the highest frequency of flooding and the increase in the mean flow has been shown during the Little Ice Age in the lower Rhone (Pichard, 1999).

6.2. Towards a palaeoclimatic interpretation?

As shown by Knox (2000), a flood-dominated regime, eventually associated with a higher mean flow, would imply a more irregular climate in the Rhone catchment, with numerous extreme precipitation events, and maybe an increased total volume of precipitations.

Morpho-sedimentary traces of an increase in flow related to an increase in precipitation are unevenly reported over the Rhone river system throughout the Roman period. They are clearly attested in the middle Rhone and its tributaries (Bravard et al., 1992; Berger, 1996). Some indicators are disputed in the Languedoc (Provansal et al., 1999), but they are not found in either the southern Alps (Jorda, 1992; Miramont, 1998), or in the small rivers of lower Provence (Provansal, 1995; Jorda and Provansal, 1996; Bruneton, 1999). The functioning, therefore, of the lower Rhone in Antiquity is tied to that of the western (Gardon) and to the northern regions more than it is to its immediate Mediterranean environment from the left subcatchment (Arnaud-Fassetta, 1998).

This spatial pattern is not similar to the geography of Roman settlement and land use: deforestation and agriculture, susceptible to cause rises in sediment charge, are no less important in Provence on the eastern bank than in Languedoc on the western bank, and the Roman occupation began earlier and lasted longer in the lower Rhône than in the upper catchment. Thus, an anthropogenic explanation cannot be invoked. It appears more likely that the different parts of the Rhone basin reacted differently to a modest climate change, the sheltered regions being the most eastern and mediterranean ones. This limit could directly rely on climatic parameters, such as the seasonal position and activity of the polar front, or depend on the adjustment capacity of the morphological and hydrological systems in response to the variation in water discharge.

The supposed climatic oscillation does not have, however, the importance of the major humid fluctuation from the Subboreal and Subatlantic chronozones, namely the circa 2800 BP–Iron Age (Van Geel et al., 1998), the Late Antiquity (Burga, 1988) and the Little Ice Age ones (Le Roy Ladurie, 1967; Pfister, 1992; Serre-Bachet et al., 1992). Its morpho-sedimentological consequences are not so acute in the lower Rhone and in the whole Rhone basin (Salvador et al., 1993; Pichard, 1995; Jorda, 1985; Provansal, 1995; Arnaud-Fassetta, 1998; Arnaud-Fassetta and Provansal, 1999). Moreover, only these strong morpho-climatic crises are clearly recorded in the Western Europe proxy data. The 1st BC and AD centuries are rarely extracted from the context of a "thousand-year-long dry tendency" (Harrison and Digerfeldt, 1993) or from the irregular climatic oscillations of the Subboreal–Subatlantic chronozone. There are nonetheless some contemporary events located around the alpine part of the Rhône: the high lake-level phase of "Petit Maclu 1" in the Jura (Magny 1994), the Zürich lake floods moving 1st AD archaeological material (Schindler, 1981; Schneider et al., 1982). We suggest that the briefness of this fluctuation helps to explain this scarceness. What's more, the amount of European sites available for climatic reconstruction is lowered for that period by the frequent anthropisation, which alters the representativity of some data, especially the palaeobotanic ones (Brown and Barber, 1985). The identification of a minor fluctuation towards wetter or more irregular climate was possible in the lower Rhone because of the sequence dilatation in the floodplain, of the crossing of several palaeoenvironmental methods and of the numerous archaeological and ^{14}C datings.

7. Conclusion

The diversity of morphological and hydrological changes covered by this study during 1st centuries BC and AD shows the ability of a major river system to react to even small climate oscillations. We suggest that the major factor is the crossing over of a threshold in great floods frequency. Therefore, important environmental events in the Rhone floodplain, such as reactivation or widening of river channels, marshes transgressions, and general rises in groundwater levels, could be registered at a human timescale (less than two centuries) during Roman times.

As shown by recent works, this Roman oscillation is widely perceived in the Rhone valley, but not in the immediate neighborhood of the lower Rhone region. Here appears a limit in the use of fluvial systems for palaeoclimatic reconstruction: the Rhone river acts during this period as the very efficient vehicle of an external hydrological event.

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