THE UPPER RHÔNE DELTA SEDIMENTARY RECORD IN THE ARLES–PITON CORE: ANALYSIS OF DELTA-PLAIN SUBENVIRONMENTS, AVULSION FREQUENCY, AGGRADATION RATE AND ORIGIN OF SEDIMENT YIELD

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ABSTRACT. Results from analyses of the Arles–Piton sediment core, retrieved from the apex of the Rhône Delta, highlight processes of Holocene deltaic construction controlled mainly by hydrosedimentary variability and channel avulsions. The alluvial suite was investigated for grain size, sedimentary structures, $CaCO_3$, organic matter, heavy minerals and chrono-stratigraphy (^{14}C and archaeological/historical dates). The study shows the succession of six facies associations: a distributary channel (before 6157–5843 BC), a swamp (5719–5530/4796–4463 BC), a distal flood plain (5719–5530/4796–4463 BC), a distributary channel (4796–4463/2900–2503 BC), a proximal flood plain (2900–2503 BC/AD 270–290), and a crevasse splay (after AD 270–290). Substantial changes in hydrodynamics are strongly linked to three channel avulsions (before 6157–5843 BC, after 4796–4463 BC and after 2900–2503 BC). A correlation with the whole channel avulsion history of the Rhône Delta allowed us to propose an average rhythm of channel avulsion of *c.* 1450 years. From 5719–5530 BC to AD 270–290, the flood plain aggraded at the average rate of 2.5 mm/a. The aggradation rates were higher both in the proximal and distal flood plains, where sedimentation process is continuous. They were lower both in the active distributary channels, because of frequent truncation of the alluvial suite, and the abandoned channels where detritic inputs are minimum. The sediment supply arriving to the upper Rhône Delta was derived mainly from proximal source areas (Massif Central, Southern Alps) during the last 8000 years, except during the hydrological changes of Roman antiquity during which detritic inputs were derived firstly from the Northern Alps and Southern Alps, and secondly from the Massif Central.

Introduction

According to models based on the concepts and principles of high-resolution sequence stratigraphy (Vail *et al.* 1977; Emery and Myers 1996), the sedimentary bodies of a delta generally present three distinct sequence sets: (1) the bottom set, constituted by deep-water deposits of the basin margin, (2) the fore set, characterised by prodeltaic and distal delta-front facies, and (3) the top set where the alluvial or shallow-marine sedimentary facies are associated with the delta plain and proximal delta front (Galloway and Hobday 1996). Upstream of the coastal onlap, the delta plain does not present strictly 'marine' influences, and the sedimentary facies correspond to fluviatile or palustrine depositional subenvironments. The processes of construction of the upper delta plain lead to the development of several superimposed, juxtaposed or cut-and-fill alluvial ridges. The following depositional subenvironments (distributary channel, riverbank/crevasse splay) generally characterise the latter.

The lateral instability of alluvial ridges is chiefly dependent on several key parameters, including relief of the delta plain, longitudinal and lateral gradients, degree of sinuosity, variations of discharge/sediment yield ratio, hydrological change to an increase of flood peaks, channel avulsion (i.e. the relatively sudden displacement of a distributary channel to a new course in the deltaic plain) thresholds, crevassing process, and rates of floodplain aggradation (Jones and Schumm 1999). Oomkens (1970) and others have reconstituted the geometry of the Holocene delta plain of the Rhône River, and have shown evidence of several juxtaposed, superimposed or cut-and-fill palaeochannels. Unfortu-

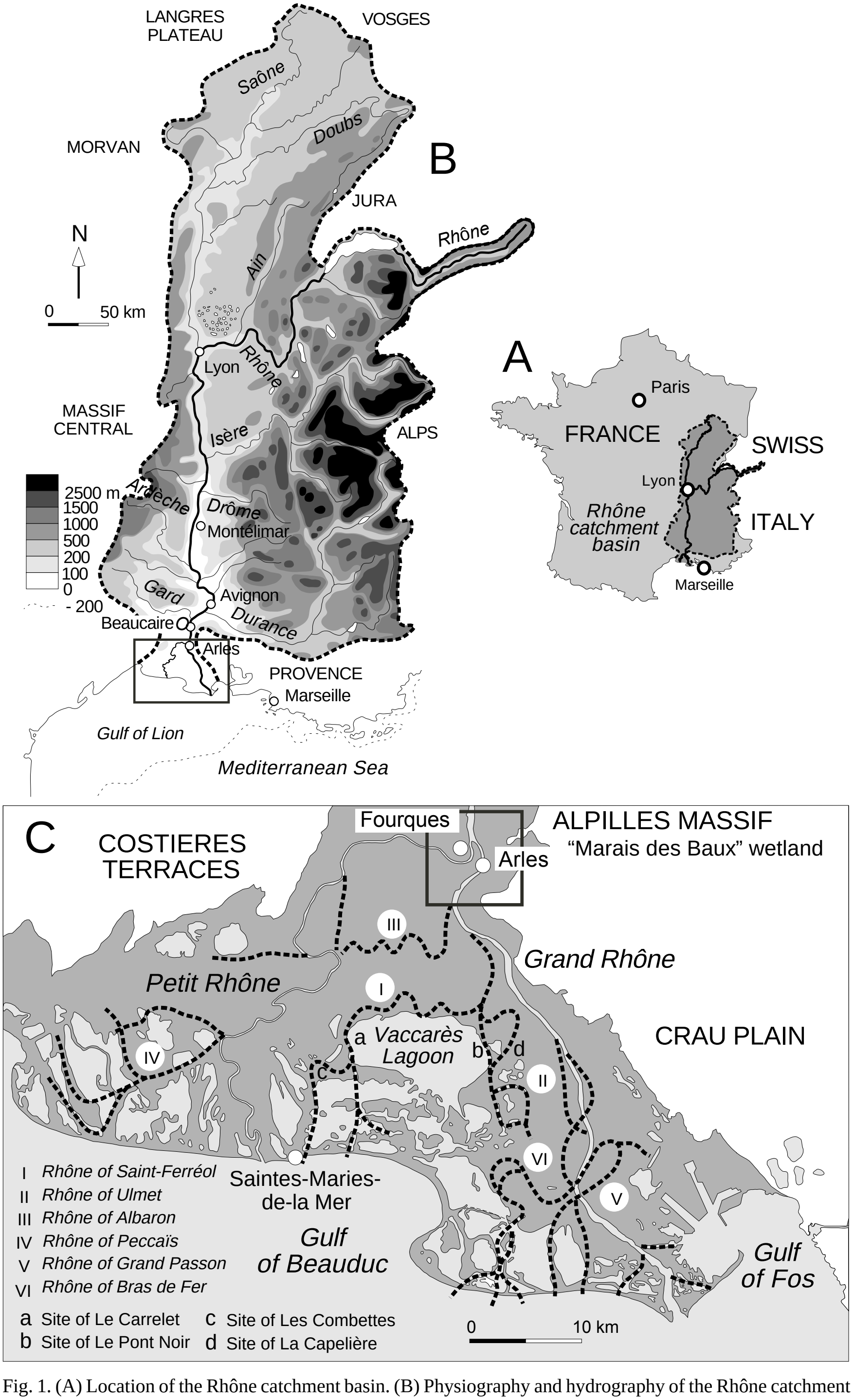


Fig. 1. (A) Location of the Rhône catchment basin. (B) Physiography and hydrography of the Rhône catchment basin. (C) Map showing the geometry and the (palaeo)hydrography of the Rhône Delta

nately, these reconstructions are not detailed for the upstream part of the delta plain. L'Homer (1975a, 1975b, 1987, 1993) identified the palaeo-hydrographic network of the Rhône Delta. However his work only concerned the visible channels in the surface. Consequently, analysis of the Arles–Piton core, situated at the delta apex, should allow for an improved definition of the succession of the alluvial ridges and the dynamics of the Rhône River, and demonstrate the fundamental role played by channel-avulsion processes in the construction of the Holocene delta plain.

This paper identifies, using sedimentological, mineralogical and chronostratigraphic data, the succession of the depositional subenvironments, the frequency of channel avulsions, the speed of delta-plain aggradation and the origin of detritic inputs yielded in the upper Rhône Delta during the Holocene.

Hydrogeomorphological background

The Rhône Delta (1740 km^2) forms a 55-km long, 70-km wide complex of Holocene sediments deposited by the Rhône River in lagoonal or marine basins (Fig. 1). The main part of the Holocene delta plain is located in an incised-valley system formed during the late Pleistocene sea-level lowstand of the Mediterranean (Tesson *et al.* 1990). It is constituted by several overlapping sedimentary sequences that began to develop following the last post-glacial eustatic sea-level rise (Gensous and Tesson 1997). The thickness of Holocene sedimentary bodies increases southward, reaching more than 50 m in the delta-plain margin. During the Holocene, the dynamics of this complex river/shelf hydrosystem were driven by a number of different factors, including variations in the river regime, the characteristics of the detritic inputs, the vertical and lateral evolutions of the coastline, and the negative movements of the ground (sediment compaction and subsidence). The first three parameters are strictly dependent on climate variability and on the increasing effects of human activities along the Rhône River and its valley (Provansal *et al.* 1999; Arnaud-Fassetta 2003).

Immediately upstream of the delta, the present Rhône River has a mean annual water discharge of 1710 m^3/s and its hydrological regime is characterised by intra- and interannual variability, due to various glacial, nival and pluvial influences in the catchment basin (Pardé 1925). Today, two main distributary channels (Grand Rhône and Petit Rhône) carry the bulk of the water through the delta (Compagnie Nationale du Rhône 1982). A hydrodynamic threshold exists in the lower Rhône Valley where the river passes from a high gradient (0.00025 m/m) in the Beaucaire alluvial plain to a low gradient (0.00004 m/m) in the delta plain. The present Grand Rhône in Arles (near Trinquetaille district) has a channel width of 180–290 m, a maximum channel depth of 17 m and an average discharge of 1500 m^3/s. Flood levels have never exceeded 7 m on both riverbanks (Pichard 1995). The washload (fine sands and silts), moved by suspension, constitutes the main part of the sediment yield of the Rhône River, estimated at an average of *c.* 8–9 million t/a (Pont *et al.* 2002; Antonelli 2002). The bed-material load consists essentially of cobbles–pebbles (D_{50} *c.* 34 mm) and coarse to medium sands (D_{50} = 0.65–0.4 mm; Arnaud-Fassetta *et al.* 2003a).

Materials and methods

The 'Arles–Piton' sediment core, retrieved from the Trinquetaille district, 2 km downstream of the diffluence of the Rhône River, was obtained in July 1998. The coring site is located in the proximal flood plain, just to the south of the apex of the present Rhône delta plain, at 25 km north-northeast of the actual coastal fringe (Gulf of Beauduc) (Figs 1C and 2A). The sediment core was taken using an 8-cm-diameter stationary piston corer that recovers up to 1-m-long sediment segments. Coring of overlapping sediments from defined depths, and their correlation on the basis of core description and analytical data, yielded a total of 18.3 m of more or less continuous sediment sequences with a core recovery of more than 82%. The bottom of the Holocene deposits, situated between –20 m and –30 m depth (L'Homer 1987; Fig. 2B), was not reached. Once the core was opened, it was described and photographed for structural analysis. It was then subject to sampling for grain-size, geochemical, heavy-mineral and dating (^{14}C, archaeology; Table 1) analyses. The archaeological chronology was based on the unreworked archaeological layers crossed by the core and identified as such by archaeologists. All measurements presented both in the text and the figures are expressed in metres above or below present **mean sea level** (**m.s.l.**) of the Mediterranean.

For the grain-size analysis, 226 samples were collected in intervals of *c.* 5 cm. The granulometry was measured by a laser particle analyser (Coulter

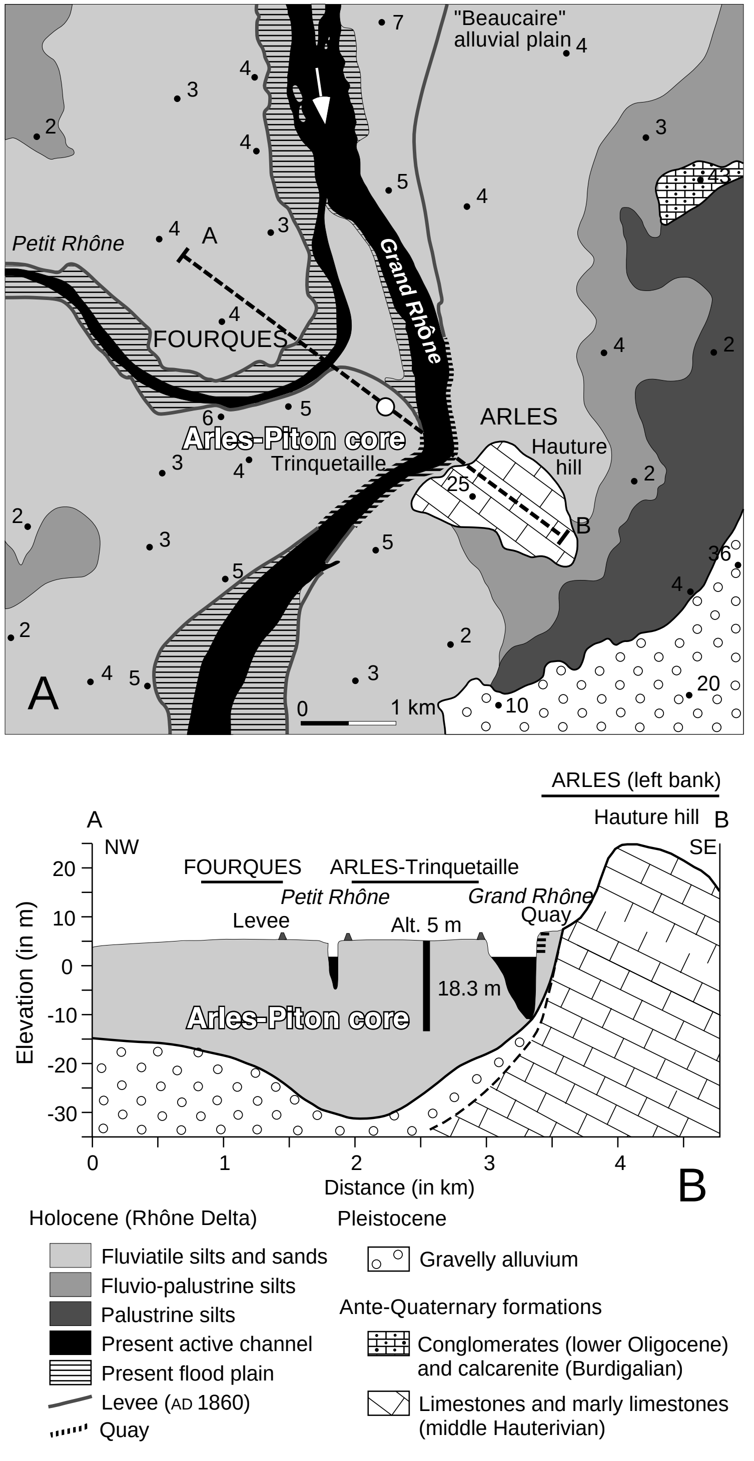


Fig. 2. Location of the Arles–Piton sediment core in the Rhône Delta. (A) Geomorphological map of the Rhône flood plain around the city of Arles. (B) Stratigraphic cross-section of the Holocene alluvial infilling at Arles

Table 1. List of conventional/AMS ^{14}C ages and archaeological/historical data used for chronology of the sections of Arles–Piton core, upper Rhône Delta. Rejected dates are noted in italic

Elevation (in m) relative to present m.s.l.	Laboratory no.	Material dated	Dating method	$\delta^{13/12}$C (‰)	Age (^{14}C yr BP)	Cal. yr BC/AD (2σ)
3.17/3.88	IRPA Arles	Rubefied silt (fire)	Historical data	–	–	AD 270
2.55/2.8	SRA DRAC-PACA	Italic amphora (reworked)	Archeology	–	–	Post 1st c. BC?
1.65/1.82	SRA DRAC-PACA	Italic amphora	Archeology	–	–	1st c. BC
0.46/0.84	SRA DRAC-PACA	Italic amphora	Archeology	–	–	2nd-1st c. BC
0.69/0.7	LYON-1038 (OXA)	Charcoal	^{14}C (AMS)	–26.65	2035 ± 50	171 BC-AD 74
–3,46/–3.47	LYON-1039 (OXA)	Peat	^{14}C (AMS)	–28.03	4170 ± 65	2900–2503 BC
–6.67/–6.68	LYON-1040 (OXA)	Peat	^{14}C (AMS)	–27.67	5795 ± 70	4796–4463 BC
–10.79/–10.8	LY-9559	Peat	^{14}C (conventional)	–27.62	6715 ± 60	5719–5530 BC
–10.94/–10.95	LY-9558	Peat	^{14}C (conventional)	–27.76	7130 ± 65	6157–5843 BC
–12.33/–12.45	–	Organic silt	^{14}C (AMS)	Not dated		
–12.45/–12.55	–	Organic silt	^{14}C (AMS)	Not dated		
–13.26/–13.27	*LY-1952 (Poz-1572)*	*Charcoal*	*^{14}C (AMS)*	*–27.38*	*6820 ± 60*	*5835–5624 BC*

Counter LS100) that was adjusted for high-resolution measurements on the fraction <2 mm. Occasional coarse material was removed using a 2-mm sieve. Grain-size parameters (Folk and Ward 1957) have been estimated. Sediment transport types were identified by the *CM* Passega (1957) method, modified by Arnaud-Fassetta (1998). Furthermore, geochemical analyses were conducted in intervals of 5–10 cm. Calcium carbonate content of 244 samples was measured using a Bernard calcimeter. The analyses were carried out on the fraction <0.1 mm. Total organic matter (TOM) content of 168 samples was determined by loss on ignition (NF ISO 10694).

For the heavy-mineral analysis, a total of 25 sand units were subsampled in intervals of 30 cm. Analysis was made for the fine sand fraction (0.16–0.05 mm). Usually 200 non-opaque grains were studied per sample. Forty-one translucent heavy-mineral types were identified. They consisted mainly of zircon, garnet and green hornblende. Tourmaline, zoisite, epidote and chlorite are less abundant. Two heavy-mineral associations can be used as indicators of two distinct sediment-source areas. The first, (green hornblende-epidote-glaucophane-chloritoid-piemontite) is indicative of Alpine sources (left bank of Rhône River). In this association, glaucophane and piemontite originate from the Southern Alps (Durance basin) and the Northern Alps (Isère basin), respectively (Van Andel 1955). The second (hypersthene-augite-brown hornblende-andalusite-diopside-hedenbergite) indicates Massif Central origins (right bank of Rhône River). Moreover, high amounts contained in fragile or easily alterable minerals (garnet-amphibole-epidote) reflect short redeposition whereas the presence of resistant or more stable minerals (rutile-staurolite-tourmaline-zircon) reflects reworking (Petit *et al. 1996).*

Results

From facies associations to depositional subenvironments

Five fundamental facies associations were identified in the 18.3 m section of Arles–Piton core (Figs 3 and 4): distributary channel deposits (51% of the 18.3 m section of Arles–Piton core), crevasse splay deposits (5%), proximal flood plain deposits (25%), distal flood plain deposits (11%), and swamp deposits (8%).

Facies association 1: distributary channel deposits

Channel fill in distributaries of the upper Rhône Delta consists of gravels and medium sands which grade upward into fine silts and organic deposits. These fining-upward sequences reflect the change from active to abandoned conditions. Maximum thickness of channel fills is *c.* 6 m. Distributary channel deposits are classified into two sedimentary facies.

Sedimentary facies 1a: active distributary channel. Sedimentary facies 1a is characterised by abundant medium-sand matrix with rare fine gravels (10–20 mm). Basal contact is erosional. Sand and gravel show small-scale cross-bedding or massive structure. Medium sands and fine gravels (Fig. 5A, B, D and E) are transported respectively by

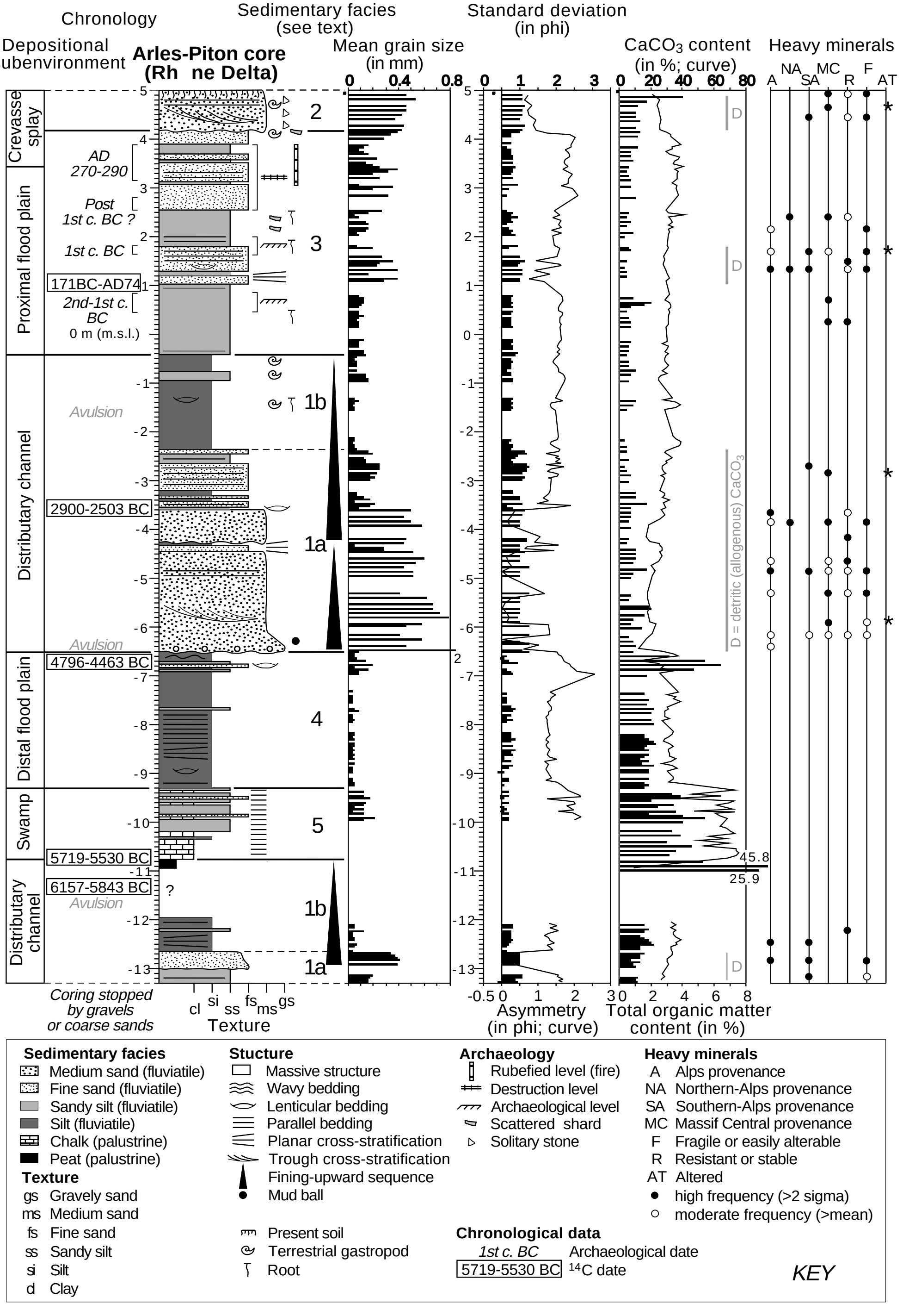


Fig. 3. Sedimentological, geochemical and mineralogical analyses of Arles-Piton core, upper Rhône Delta

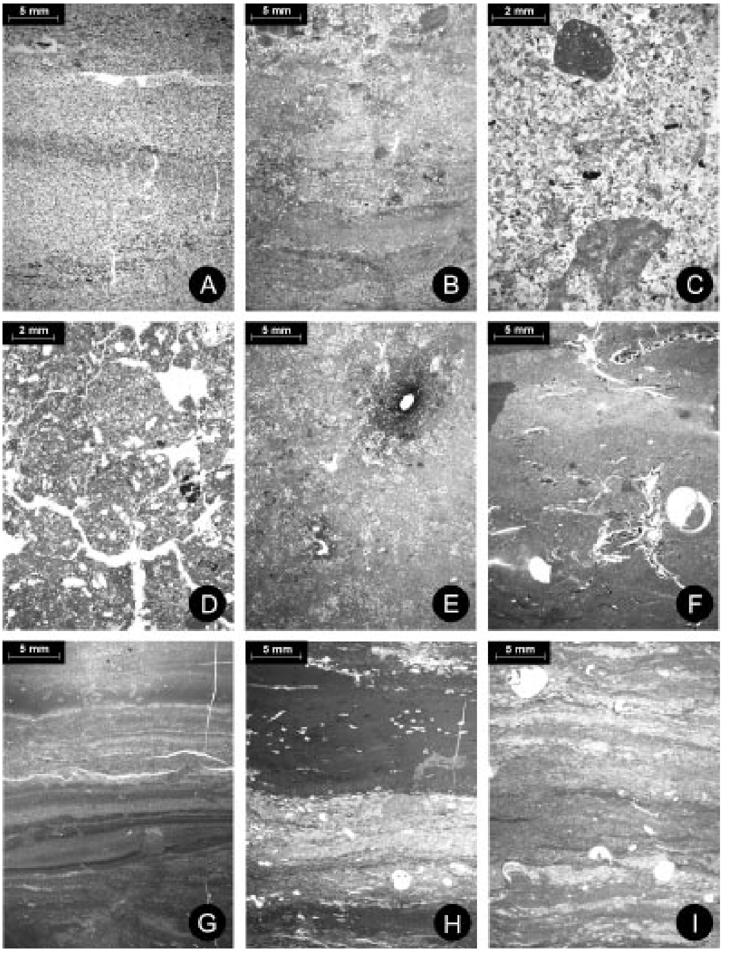


Fig. 4. Thin section photomicrographs (J.-F. Berger) courtesy of some sedimentary facies of the Arles–Piton core, upper Rhône Delta. (A) Sedimentary facies 1a (moderate-energy distributary channel): subparallel-laminated interbedded micro-vegetal debris and very moderately sorted fine sands. (B) Sedimentary facies 1a (abandoning distributary channel): at the bottom, subparallel-laminated interbedded fine silts and fine sands; at the top, traces of erosion and redistribution of old alluvial beds under the shape of small, soft balls. (C) Sedimentary facies 2 (crevasse splay): deposits with massive structure including poorly sorted fine to medium sands with subrounded charcoal, burnt mudbrick and calcareous stone fragments. (D) Sedimentary facies 3 (proximal flood plain dominated by mixed flooding and crevassing processes): fine-grained sand showing a subangular blocky structure associated with a pedological evolution. (E) Sedimentary facies 3 (proximal flood plain influenced by dominant flooding process): massive coarse silts and very fine sands with few micro-channels, reorganisation by earthworm activity and precipitation of a lot of iron oxides in soil porosity (hypocoatings). (F) Sedimentary facies 4 (distal flood plain dominated by flooding process): organo-mineral deposit consisting of massive or finely laminated fine silt interbedded with organic/shell debris laminations. Traces of roots and aquatic plants are abundant. (G) Sedimentary facies 4 (swampy distal flood plain influenced by flooding process): subparallel fine-laminated interbedded fine silts and very fine sands with more or less bioturbation. Good conservation of primary sedimentary structures is due to high burying ratio. (H) Sedimentary facies 5 (swamp with frequent flood supplies): subparallel-finely laminated chalk deposits with abundant gastropod shells (white levels on the photo), interbedded with fine silt to fine sand laminations (dark levels). (I) Sedimentary facies 5 (swamp with occasional flood supplies): subparallel-laminated chalk deposits (white levels) with abundant *limnaea* shells interbedded with rare fine silt laminae (dark levels)

mixed saltation-suspension and rolling processes (Fig. 6). High sand content (95%) involves the presence of currents with a high content of saltation-suspension matter. The standard deviation values are very diverse (Fig. 5A) because of fluctuating hydrodynamic conditions. The presence of mud balls supposes channel currents sufficiently high to erode cohesive material of riverbanks or alluvial floor. The abandoning of distributary channels is characterised by dominant planar cross-stratification, lenticular bedding, massive structure (occasional) or horizontal lamination (Fig. 4B) developed in interbedded silt (suspension) and fine sand (saltation or rolling; Fig. 6), with a bed thickness of *c.* 0.02–0.05 m (Fig. 5A, B, D and E). Diversified low to moderate values of predominantly allogenous $CaCO_3$ (Fig. 5C and D), and very low to moderate TOM contents (Fig. 5C and E) are the other characteristics of this depositional subenvironment.

*Sedimentary facies 1b: abandoned distributary channe*l. Sedimentary facies 1b, associated with unconnected distributary channels (due to avulsion), is similar to that of the flood plain (see below, facies association 3). It is generally represented by dominantly massive fine silts moved as suspension (Fig. 6), and solitary, very fine-sand laminae (Fig. 5A, B, D and E) deposited in a still pool. Rare lenticular bedding, parallel laminations and tabular-planar cross-stratifications can occur. Thickness (up to 1.9 m) of fine deposits is sometimes important, suggesting, in certain cases, sudden channel abandonment. Standard deviation values are high (Fig. 5A). Contents of mixed $CaCO_3$ (Fig. 5C and D) and TOM (Fig. 5C and E) are highly variable. On the top of the abandoned channel infill, humified peat with very low proportions of $CaCO_3$ is observed (Fig. 3).

Facies association 2: crevasse splay deposits

This facies association is rare in the upper part of the Rhône Delta, but more characteristic in the lower part of the present delta plain where riverbank height is lower (Arnaud-Fassetta 2002; Arnaud-Fassetta and Landuré 2003). Maximum thickness of the deposits is *c.* 0.8 m. Dominant grain size is fine to medium sands (Fig. 5A, B, D and E) moved by saltation or rolling. Typical structures include small-scale cross-bedding (thickness of cross-stratified sets of *c.* 0.1–0.2 m) with low-angle (<10°) cross-strata, parallel lamination or massive structure. Poor sorting (Fig. 5A) indicates rapid deposition. Percentages of allogenous $CaCO_3$ (Fig. 5C and D) are low and TOM contents (Fig. 5C and E) are low to moderate.

Facies association 3: proximal flood plain deposits

Grain-size lies mostly in the coarse-grained silt range, with a few beds of fine-grained sand (Fig. 5A, B, D and E). Structures include well-developed regular millimetre- to centimetre-scale coarse silt laminae with interbedded fine sand laminations. This diversified structural succession indicates extreme variation in flow regime. Fine-sand laminations are interpreted as 'flood event' beds in the coarse silt-dominated flood plain. A positive asymmetry suggests a possible enrichment in fine particles at the end of flood events. The sorting is poor to very poor (Fig. 5A). $CaCO_3$ contents are variable and of mixed origin (allogenous and authigenous); coarser deposits (i.e. flood or crevasse deposits) generally present lower $CaCO_3$ values. TOM contents (Fig. 5C and E) are very low to moderate. Traces of roots, terrestrial malacofauna and the remains of human occupation (occupation level, abandonment layer, burnt layer, scattered shard; Arcelin *et al.* 1999) are abundant (Fig. 4D). Anthropogenic material provokes abnormally high coarsest percentile (*C*) values (Fig. 6).

Facies association 4: distal flood plain deposits

Structures are massive (Fig. 4F) or parallel-laminated, with irregular millimetre- to centimetre-scale fine silt laminae with interbedded coarse silt/very fine sand laminations (Fig. 5A, B, D and E). Wavy or lenticular structures are rare. One of the differences from abandoned channel deposits (sedimentary facies 1b) is the absence of fine sand laminations. Deposition processes are dominated by decantation (Fig. 6) and the absence of tractive/selective currents leads to poor to very poor sorting (Fig. 5A). Grain-size distribution presents perfect symmetry or rarely positive/strong positive asymmetry (Fig. 5B), suggesting that enrichment in fine particles is rare. Contents of mixed allogenous and authigenous $CaCO_3$ (Fig. 5C and D) are variable (very low to high) and TOM contents (Fig. 5C and E) are low to very high. The sediment is thoroughly bioturbed by the activity of earthworms. It contains abundant terrestrial malacofauna and a large suite of pervasive root traces (Fig. 4F).

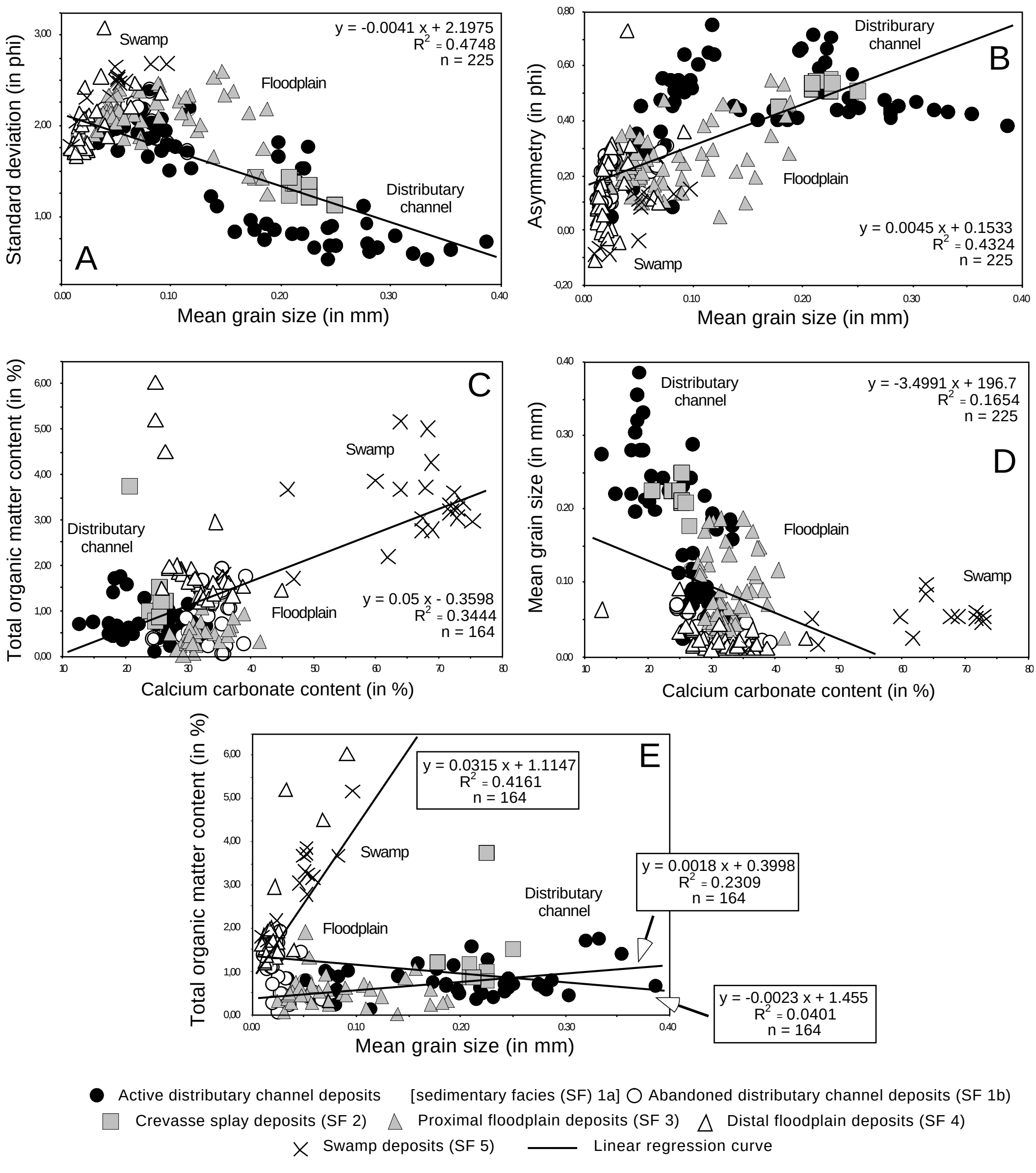
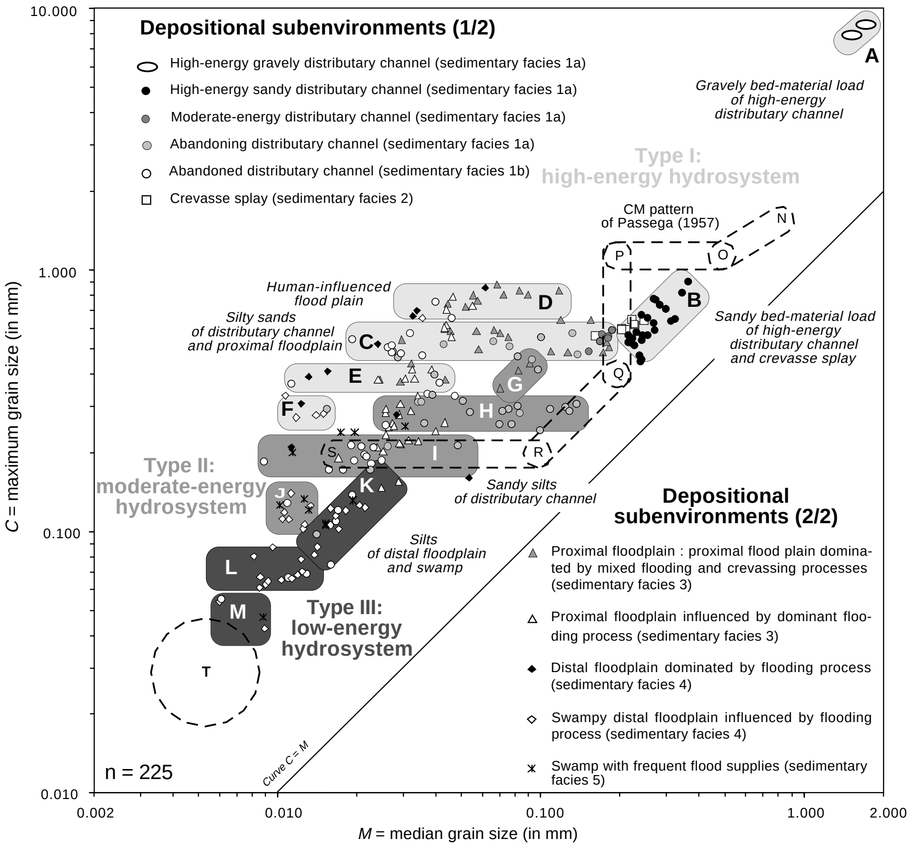


Fig. 5. Relationships between grain size, geochemical parameters and depositional subenvironments deduced from the Arles–Piton core, upper Rhône Delta. (A) Plot of mean grain size *(μ_Z)* against standard deviation (σi). (B) Plot of mean grain size (μ_Z*)* against asymmetry (*sk_i*). (C) Plot of calcium carbonate content against total organic matter content. (D) Plot of calcium carbonate content against mean grain size *(μ_Z)*. (E) Plot of mean grain size (μ_Z) against total organic matter content

Facies association 5: swamp deposits

Swamp with frequent flood supplies presents finely laminated chalk deposits interbedded with fine silt to fine sand (Fig. 5A, B, D and E) laminations, indicating deposition in a quiet-water environment (Fig. 4H). Decantation is the dominant process (Fig. 6), but ‘coarse’ (i.e. coarse silts and fine silts) deposits from suspension are frequently introduced into the swamp during flood events. Non-selective currents generate poor to very poor sorting (Fig. 5A) and grain-size distribution presents perfect



		High-energy hydrosystem						Moderate-energy hydrosystem				Low-energy hydrosystem		
CM pattern types		I						II				III		
Modes of sediment transport		A	B	D	C	E	F	G	H	I	J	K	L	M
Depositional subenvironments (in %)	⬭	**100**												
	●		**100**											
	● (dark grey)				**100**									
	● (light grey)				25	3		3	6	**53**	7	3		
	○			6	25	3	3		3	9	**31**	11	6	3
	□		**88**		12									
	▲ (grey)			29	**48**	13		**10**						
	△			8	8	18				**39**	21	6		
	◆			**30**	10		**30**			10	20			
	◇			3			13		22			22	**34**	6
	⋇								**28**	**28**	8	**28**		8

Modes of sediment transport

[**A**] Rolling [**B**] Rolling and saltation

[**C**] Saltation and graded/uniform suspension

[**E**] Graded and uniform suspension

[**D**] Uniform suspension (abnormally high *C* values are due to anthropogenic effect)

[**G**, **K**] Graded suspension (decreasing energy from G to K)

[**H**, **I**, **L**] Uniform suspension (decreasing energy from H to L)

[**F**] Uniform suspension and decantation [**J**, **M**] Decantation

Fig. 6. CM pattern showing relationship between grain size parameters (D_{50} and D_{99}), mode of sediment transport and depositional subenvironments deduced from the Arles–Piton core, upper Rhône Delta.

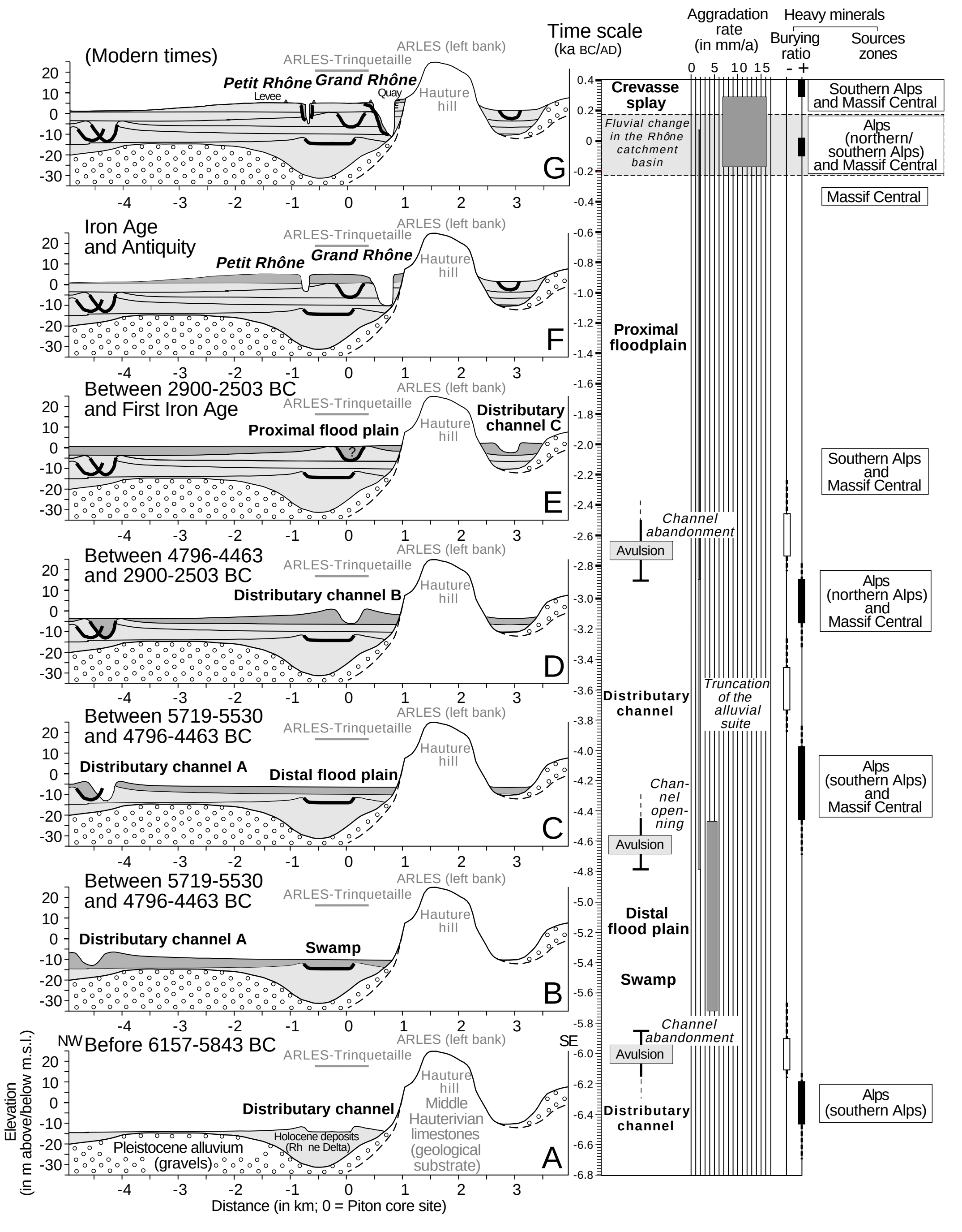


Fig. 7. Hypothetical sequence of upper Rhône Delta evolution during the last 8000 years

symmetry or rarely positive asymmetry (Fig. 5B). Contents of predominantly authigenous $CaCO_3$ (Fig. 5C and D) and TOM contents (Fig. 5C and E) are moderate to very high. When flood supplies are occasional, sedimentary facies consists of subparallel-laminated chalk deposits with abundant *limnaea* shells interbedded with rare fine silt laminae (Fig. 4I). Authigenous $CaCO_3$ contents (Fig. 5C and D) are very high and TOM contents (Fig. 5C and E) are high to very high.

Succession of depositional subenvironments and origin of sediment yield

Figure 7 presents the succession of depositional subenvironments in the present upper Rhône Delta plain at Arles–Trinquetaille, on the basis of the analysis of sediment origin (Fig. 3).

An upward-fining sequence (sedimentary facies 1a to 1b) indicates the presence of a distributary palaeochannel of the Rhône River (between –13 m and –10.76 m). It was active prior to 6157–5843 BC and it is characterised by a fine sand-dominated alluvium in the basal part of channel infill. Heavy-mineral analysis shows that sediment supplies were mainly from the Alps. Sedimentation rate was not high because 'channel' sand is only 0.5 m thick. Subsequently, this distributary channel disconnected gradually from –12.65 m to –10.56 m (sedimentary facies 1b). The increase of resistant minerals, reflecting the reworking of old sediments, is correlated to the reduction of Alpine supplies. The palaeochannel is then abandoned, as a result of an avulsion which occurs before 6157–5843 BC.

A swamp (facies association 5) develops between 5719–5530 BC and 4796–4463 BC (between –10.76 m and –9.3 m). A distal flood plain (facies association 4) is dated to between 5719–5530 and 4796–4463 BC (between –9.3 m and –6.51 m).

A second distributary palaeochannel, which is characterised by two upward-fining sequences, occurs between 4796–4463 BC and the 2nd-1st centuries BC (between –6.51 m and –0.42 m). (1) The first (represented by the –6.51/–4.27 m depth interval) was deposited between 4796–4463 BC and 2900–2503 BC. It is associated with an active alluvial channel identified between –6.51 m and –4.45 m (sedimentary facies 1a), characterised by a sand-gravel bed-material load. Heavy-minerals composition reveals that sediment supplies are from the Alps (the Southern Alps in particular) and Massif Central. There is a close correlation between the presence of Massif Central sediments and high percentages of fragile minerals. (2) The second, from –4.27 m to –0.41 m, occurs prior to 2900–2503 BC. The reactivation of the channel between –4.27 m and –3.6 m is correlated with the supply from the Alps and sedimentary contributions of the Massif Central. A channel infilling by fine-grained sediments began at 2900–2503 BC (between –3.6 m and –2.37 m). The sediment supplies alternately came from the Southern Alps and Massif Central. Very fine-grained sediments from –2.37 m to –0.42 m (sedimentary facies 1b) indicate that the distributary channel was suddenly abandoned after 2900–2503 BC, most likely as a result of an avulsion.

A proximal flood plain (facies association 3) is dated from 2900–2503 BC to AD 270–290 (between –0.42 m and 4.17 m). At the base (from –0.41 m to 0.98 m; *c.* 2nd-1st centuries BC), sediment supplies are dominated by those originating from the Massif Central. This confirms again the importance of the sedimentary contributions of the Massif Central to the Rhône Delta. The low percentages of fragile minerals indicate low burying ratio. In certain cases, we note an evolution in antiphase concerning the supplies of resistant (old sediments) and fragile (sedimentary material quickly constituted) minerals. The dominant sediment supplies are those resulting from both the Southern and Northern Alps. From 1.8 m to 2.55 m (end of the 1st century BC?), the slowing down of the sedimentation rates observed in the fine-grained deposits of the proximal flood plain is synchronous with the increase of resistant minerals. We observe the decrease of the Southern Alpine supplies. At the top (from 2.55 m to 4.17 m), a reinforcement of the hydrodynamics is shown by the formation of a proximal flood plain influenced by crevassing process.

A crevasse-splay deposit (facies association 2) covers the flood-plain surface after AD 290 (between 4.17 m and 5 m). Heavy-mineral analysis shows that dominant supplies were from the Massif Central and Southern Alps (at the base). High percentages of fragile minerals reflect relatively short redeposition.

Discussion

Channel-avulsions frequency

The sedimentary-facies succession deduced from Arles–Piton core allowed us to characterise of hydrosedimentary dynamics and the degree of lateral instability of the alluvial system in the upper part of the Rhône Delta. The succession therefore constitutes a stratigraphic model of sedimentation for the upper part of the Holocene delta plain. The results from the study confirm that channel avulsion is a very important process in the deltaic plain construction. These results indicate an abrupt sedimentary facies superposition (channel infilling before 6157–5843 BC avulsion/channel abandonment before 6157–5843 BC wamp and distal flood plain development from 5719–5530 BC to 4796–4463 BC avulsion/channel opening after 4796–4463 BC alluvial infilling avulsion/channel abandonment after 2900–2503 BC proximal flood plain and crevasse splay development from 2900–2503 BC to present) and clearly reveal that several substantial changes in hydrodynamics linked to channel avulsions have occurred. Avulsion sediments represent a significant proportion (*c.* 43%) of the uppermost 18.3 m of the alluvial fill in the North Rhône Delta (Arles–Trinquetaille).

In the upper Rhône Delta, avulsion of distributary palaeochannels can be due to several interacting causes such as: an increase of alluvial ridge relief (between the riverbanks and the distal flood basin); a decrease in channel slope by extension (progradation) of the deltaic plain, which causes a reduction in the capacity of the channel to evacuate all the water and sediment; and a hydrological change to an increase of flood peaks. There is clearly a relation between the Rhodanian flood-plain palaeohydrology, the channel avulsions and the geomorphological evolution of the Rhône Delta. Indeed, the important humid phase recorded in the upper Rhône Valley at Lyon (4400–3800 BC; Bravard *et al.* 1997) and in the site of Le Castelet at 4500–3500 BC (Bruneton 1999), derived from geomorphological and sedimentological data, is contemporary with the channel-avulsion occurring after 4796–4463 BC at Arles–Trinquetaille (Arles–Piton core; this study). At the same time, a significant progradation of the deltaic plain (i.e. decrease of channel slope) is demonstrated by the covering of marine or saline lagoon deposits by freshwater to euryhaline environments in the site of Les Frignants (4970–4240 BC; Pons *et al.* 1979) and in the site of Le Carrelet (4430–4270 BC; Arnaud-Fassetta 1998). The progressive rise of the Rhône watertable after 2200 BC (Bruneton 1999) is related to extensive floods and channel avulsions in the Rhône Delta, in the sites of Le Carrelet (after 3030–2775 BC and after 1730–1500 BC; Arnaud-Fassetta 1998), Le Pont Noir (after 1640–1410 BC; Arnaud-Fassetta *et al.* 2000) and Arles (after 2900–2503 BC; this study). These post-2200 BC episodes contribute to the forwarding of the deltaic lobe of the Rhône of Saint-Ferréol, which the progradation is maximal at 750–400 BC (Vella 1999).

Finally, the inventory of all the major avulsions (i.e. those that preceded the construction of large deltaic lobes) recorded in the alluvial infills of the Rhône Delta shows the following succession: (1) avulsion before 6157–5843 BC of the former Rhône channel in Arles–Trinquetaille (Arles–Piton core; this study); (2) avulsion after 4796–4463 BC of the Rhône channel in Arles–Trinquetaille (Arles–Piton core; this study); (3) avulsions after 2900–2503 BC of the Rhône channel in Arles–Trinquetaille (Arles–Piton core; this study), and after 3030–2775 BC of the former channel of the Rhône of Saint-Ferréol; (4) avulsion after 1640–1410 BC of the channel of the Rhône of Ulmet (Arnaud-Fassetta *et al.* 2000); (5) avulsion of the Rhône of Albaron-Peccaïs at the beginning of Roman antiquity (L'Homer 1987); (6) avulsion at *c.* AD 1000–1200 of the channel of the Grand Passon (Arnaud-Fassetta 2000). A rhythm of channel avulsions is observed in the Rhône Delta over the last 8000 years; it is on average close to 1450 years (min. 850 years; max. 2300 years; $n = 32$). The rhythm of avulsions in the Rhône Delta during the Holocene conforms closely to Bridge's (1984) proposition, which considers that avulsions occur every 1000 years on average. It is also comparable to that recorded for the Mississippi Delta (*c.* 1000–2000 years; Roberts 1997), suggesting that certain generic factors (rapid delta progradation decreasing delta plain slope loss of flow efficiency and sediment dispersal) control the thresholds of channel avulsion and delta switching. To conclude, assuming that the average rates of aggradation of the delta plain are close to 1.4–2.5 mm/a (see below), channel avulsion phenomena were able to occur since the relief of alluvial ridges exceeded *c.* 3.6 m (min. 2.2 m; max. 5.7 m) in the upper part of the delta, and *c.* 2 m (min. 1.2 m; max. 3.2 m) in the lower part. These values are very close to those (*c.* 3 m) proposed by Bridge (1984).

Rates of delta-plain aggradation

From a general point of view, the present study indicates that the aggradation rate of the Rhône Delta plain in Arles was *c.* 2.5 mm/a between 5719–5530 BC and AD 270–290. This rate is comparable with observations of Holocene deposition rates (*c.* 3 mm/a) made by Bridge and Leeder (1979). At the site of Le Carrelet (cores SF00 and SF10; Arnaud-Fassetta 1998), in the lower Rhône Delta, delta plain aggradation occurs at a rate of 2.3–2.5 mm/a between 4430–4270 BC and 1670–1555 BC, which is comparable to values measured for the Arles–Piton core, but in a context where the sedimentary supplies participating in the aggradation come not only from the Rhône River and the swamps but also from the sea and the lagoons. The aggradation rates in Le Carrelet were lower (1.6–1.7 mm/a) between 1670–1555 BC and AD 200, in a palaeoenvironmental context similar to that described by Arles–Piton core, namely a strong influence of the river and the swamps. Similar values were obtained at the site of Le Pont Noir, with aggradation rates of 1.4–1.7 mm/a between 1640–1410 BC and 100 BC (Arnaud-Fassetta *et al.* 2000). Lower sedimentation rates in the distal part of the delta plain could be explained by the sedimentary fluxes being able to disperse over a wider delta plain. Therefore, they explain why altitudes are higher in the upper deltaic plain (alt. 3–6 m) than in the lower one (alt. 0.5–2 m). This phenomenon has been clearly demonstrated in other Mediterranean deltas (Arnaud-Fassetta *et al.* 2003b).

Concerning the active distributary palaeochannel, dated between 4796–4463 BC and 2900–2503 BC, the calculated sedimentation rates are 1.3–1.9 mm/a. The aggradation rates in other distributary palaeochannels of the Rhône Delta were 14.1–41.7 mm/a between AD 400 and AD 850 (Arnaud-Fassetta 1998).

The deposits dated between 2900–2503 BC and 171 BC-AD 74, associated with the abandoned distributary palaeochannel, indicate sedimentation rates of 0.6–0.8 mm/a. The abandoning channel of the Rhône of Saint-Ferréol infilled in a rhythm of 2.4–3.1 mm/a between AD 680–850 and AD 1500 (Arnaud-Fassetta 1998), while that of the Bras de Fer infilled at a rate of 2.2–11.1 mm/a between AD 1725 and AD 1850 (Arnaud-Fassetta and Provansal 1999).

The proximal flood plain dated between 171 BC-AD 74 and AD 270–290 aggraded at a rate of 3.6–8.4 mm/a, which is high compared to values generally obtained in the proximal flood plains of the delta (0.6–1.6 mm/a; Arnaud-Fassetta 2000). These high sedimentation rates correlate with the hydrological change that occurred in the Rhône Valley during Roman antiquity. From Avignon to Arles, this period of 'flood-dominated regime' was characterised by more powerful flood events, higher flooding frequencies, higher sedimentation rates and rises in groundwater levels in the flood plain (Arcelin *et al.* 1999; Bruneton *et al.* 2001). At the same time, avulsion, major crevassing and coastal progradation occurred in the delta plain (Arnaud-Fassetta 1998, 2002).

The distal flood plain dated between 5719–5530 BC and 4796–4463 BC records sedimentation rates of 2.1–3.5 mm/a. In the distal flood plain of the Rhône of Saint-Ferréol, the site of Les Combettes presents higher sedimentation rates (3.8–11.6 mm/a) between AD 20–310 and AD 500–600 (Arnaud-Fassetta 1998).

Finally, the swamp which developed between 5719–5530 BC and 4796–4463 BC aggraded at a rate of 1.2–2.0 mm/a. Sedimentation rates in the swamps of La Capelière were estimated to be 0.7–1.2 mm/a between 760–395 BC and 100 BC (Arnaud-Fassetta and Landuré 2003).

Long-term sediment sources variability

The heavy-mineral analysis confirms that the sedimentary fluxes arriving in the Rhône Delta during the last 8000 years were derived from several possible source areas. The sediment supplies of the Massif Central were the most frequent (52% of sediment occurrence; Fig. 3), followed by those from the Alps (48% of occurrences). Among the Alpine contributions, those resulting from the Southern Alps dominated (36% of occurrences).

However, these values varied through time following the climatic–anthropogenic changes in the catchment basin. Firstly, the sedimentary yield was most commonly derived from a single subcatchment. Although there were occasions when two subcatchments participated in the sedimentary yield, it was rare for the entire catchment to do so. The participation of the whole catchment basin occurred during periods of strong fluvial dynamic activity (between 4796–4463 BC and 2900–2503 BC). However, the proximal flood plain of Roman antiquity (2nd century BC-2nd century AD) seems to have been regularly affected by the Alpine sediments. The contributions of the Massif Central, although not unimportant, were irregular, especially at the beginning of the hydrological change.

Finally, in the Arles–Piton core, large proportions of iron-stained quartz (ISQ; Stanley and Jorstad 2002) correlate well with high percentages of fragile easily alterable minerals. The presence of these in the rivers is explained by high burying ratios linked to important transport capacity or very active erosion processes on hillsides. Strong soil erosion can occur only in a context of periodically increasing hydrological fluxes (i.e. wetter climatic conditions) and strong anthropogenic activity in the Rhône catchment basin. Heavy-mineral and ISQ analyses shows that the subcatchments concerned would be those that are closest to the delta, especially Massif Central tributaries (according to the analysis of the ISQ), and Massif Central and Southern Alpine tributaries (according to the analysis of heavy minerals).

Conclusions

(1) The detailed study of the 18.3-m-long Arles–Piton core reveals the depositional history and hydrological functioning of the upper Rhône Delta over the past 8000 years. The results obtained in this study complete the chronostratigraphic models established in the upper Rhône Delta, in particular the Oomkens (1970) model proposed 34 years ago.

(2) The reconstruction of the deltaic palaeoenvironment is derived from description of the facies associations and from their interpretation in terms of depositional subenvironments. In particular, the *CM* pattern (Passega 1957) was used to distinguish the depositional subenvironments by the criteria of competence and mode of sediment transport. There are significant differences between the former *CM* pattern of Passega (1957) and that obtained in the upper Rhône Delta. In particular, it seems that the vertical energy gradients both in the channel and the flood plain have an influence on the 'uniform suspension', which is contradictory to Passega's theory. Furthermore, several subpatterns appear to exist according to the degree of energy of the depositional subenvironments. These contradictions with respect to the initial model were identified in previous work on the dynamics of the Rhône River in its delta (Arnaud-Fassetta 1998).

(3) Sedimentological analysis of the alluvial suite shows that fluvial deposits, and distributary channel deposits in particular, are the dominant facies associations in the upper part of the Rhône Delta. In particular, the alluvial infilling shows the succession of six distinct depositional subenvironments: a first distributary channel (before 6157–5843 BC), a swamp (from 5719–5530 BC to 4796–4463 BC), a distal flood plain (from 5719–5530 BC to 4796–4463 BC), a second distributary channel (from 4796–4463 BC to 2900–2503 BC), a proximal flood plain (from 2900–2503 BC to AD 270–290), and a crevasse splay (after AD 270–290). The abrupt change of environmental conditions indicates several substantial variations in hydrodynamics and lateral channel instability.

(4) It is presumed that one of the most important factors of lateral channel instability in the Rhône Delta is avulsion. In the upper Rhône Delta, the mean channel-avulsion frequency during the last 8000 years is close to 1450 years (min. 850 years; max. 2300 years).

(5) Heavy minerals are good indicators of the origins of alluvium of the Rhône River through the time. During the last 8000 years, the sediment yield arriving in the upper Rhône Delta was derived mainly from proximal source areas (Massif Central, Southern Alps), except for the hydrological changes during Roman antiquity during which detritic inputs were derived firstly from the Northern Alps and Southern Alps, and secondly from the Massif Central.

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