Hydroclimatic hazards, vulnerability of societies and fluvial risk in the Rhone Delta (Mediterranean France) from the Greek period to the Early Middle Ages

G. Arnaud-Fassetta, C. Landuré

1. Introduction

The Rhone Delta is a large coastal plain whose Holocene elaboration results from the combination of several physical factors (alluviation, eustatism, soil movements). The variability of hydro-sedimentary discharges played an important role in the delta's evolution. From the genetic point of view, the Rhone Delta is meant to support inundation of the flood plain, avulsions and conflicts between salt water and fresh water. Therefore, the Rhone Delta constitutes an unstable physical environment with strong natural constraints (Arnaud-Fassetta, 1998). Moreover, its land development and its occupation during the Antiquity and the Early Middle Ages show that societies took place in the delta before the complete construction of river embankments and sea defences during the 19th century (Pasqualini and Landuré, in press). Therefore, antique and mediaeval communities might have been more or less exposed (physically and materially) to flood hazards, in the context of variations of river stage through time.

Current scientific research poses the question about the relations between societies installed along great fluvial systems and flood risk. The concept of risk is related to a mathematical function which integrates (1) the physical and material danger for human beings faced with a natural hazard and (2) the potential damages, that is to say the percentage of population and/or the value of material things apt to be destroyed (Bourrelier et al., 2000; Smith and Ward, 1998). All these depend on social, economical, political, technical and cultural factors. Therefore, the risk is linked to a natural hazard whose frequency and magnitude are variable at temporal and spatial scales; in addition, the risk is linked to the vulnerability of the societies who adapt their behaviour and resistance/resilience capacity faced with the hazard (Dauphiné, 2001; Thouret, 1996).

In this study, the hazard is represented by the river floods in the Rhone Delta. In this regard, flood events are strongly dependent on climatic factors; this is why they are referred to hydroclimatic hazards. Concerning vulnerability, it is that of the societies who settled and spread along the palaeo-Rhone alluvial ridges. Therefore, the question deals with the notion of fluvial risk in the last 2000 years from 800 BC to AD 1000. Which role has played the flood risk in economical and rural delta development? Was it permanent? Has the social group always taken the risk into account?

Since 1995, two scientific projects supported by the French Ministry of Culture ["Delta du Rhône" (1995–1998) and "Rhône d'Ulmet" (1999–2001)], coordinated, respectively, by Michel Pasqualini and Corinne Landuré (Archaeological Regional Service DRAC/PACA) have enabled the clarification of some questions, especially about development of societies in the Rhone Delta and their interactions with the functioning and the regime of the river (Delta du Rhône, 1995, 1996, 1997, 1998; Landuré, 2000a). In this article, we present the results of 7 years of scientific studies, especially: (1) the characterisation and the periodisation of hydroclimatic hazards in the Rhone Delta, (2) the type of settlements, the forms of occupation and the vulnerability of the sites and (3) the evolution of the fluvial risk between the Greek period and the Early Middle Ages.

Geodynamical and palaeo-hydrological contexts of the study

The Rhone originates in the Swiss Alps at an elevation of ~1735 m above sea level (asl) and flows 812 km to the Mediterranean Sea. The Rhone and its tributaries flow across a large drainage area of ~97,800 km^2, characterised by various geological units (Alps, Massif Central, Jura). The lowest part of the Rhone valley is one of the largest Mediterranean deltas.

The present-day Rhone Delta is drained by two sandy-silt-dominated distributaries (Arnaud-Fassetta, 2003; Arnaud-Fassetta et al., 2003), namely the Grand Rhone (9/10 of total discharge) and the Petit Rhone (1/10) (*Fig. 1*). It corresponds to a low-relief surface of ~1700 km^2, whose physiographical setting results mainly from the evolution of fluvial palaeo-hydrology and glacio-eustatic variations during the Late Glacial and Holocene periods (Gensous and Tesson, 1997; Gensous et al., 1993; Tesson et al., 1990). The evolution of the Rhone Delta can be divided into two stages: aggradational and progradational. The aggradational system developed from ~16,000 to 4500 BC, whereas the progradational system developed after 4500 BC when sea level approximated its present-day position.

The palaeo-hydrological evolution of the Saint-Ferréol (SF) palaeo-Rhone (Arnaud-Fassetta, 1998) and related river-mouth sandy bars (Vella, 1999) was an important process of delta progradation from 3700 to 2000 BC. Then, the delta progradation decreased because of the division of the fluvial system into three distributaries, namely the Albaron-Peccaïs (AL) palaeo-Rhone to the west, the SF palaeo-Rhone in the middle and the Ulmet (UL) palaeo-Rhone to the east. These three distributaries constitute the hydrographical network and the setting for the hydroclimatic hazards during the studied period.

2. The hydroclimatic hazard in the Rhone Delta: characterisation, geomorphological impact and 100–10-year variability

2.1. The hydroclimatic hazard: a natural phenomenon

Here, the so-called "natural hazard" is supported by floods of the Rhone River. In the Lower Rhone, floods causes are mainly of Mediterranean origin. But floods can be generalised to the whole drainage basin and they can be responsible for huge overflows. These events generally occur every 30–100 years. Less abrupt than flash floods that characterise Rhodanian, Mediterranean tributaries like the Ouvèze and Ardèche rivers, the consequences of fluvial floods in the delta are slow flooding. The reason for this is the necessary delay for the concentration of the water in the whole drainage basin. The velocity of the stream flow is slow but the hydro-geomorphological effects of floods can produce important damages in the deltaic plain.

In the Rhone Delta, the occurrence and the impact of hydroclimatic hazard depend on several factors as the frequency of extreme flows, the channel geometry, the possibilities of floodplain submersion and the speed of evacuation of the flood flows in the deltaic plain. The floodplain submersion can be exacerbated and the speed of evacuation of the flood flows to be reduced when high sea levels are increased above normal by storm-surge conditions.

The geomorphological features of hydroclimatic hazard are based on the isolated or the combinated occurrence of three main phenomena: floodplain deposition, crevassing and avulsion (Arnaud-Fassetta, 2000; Crichton and Siboni, 2001). They present different types of constraints for rural societies living in the Rhone deltaic plain. Floodplain deposits do not only represent high fluvial constraint, but also an agricultural advantage. What is restrictive is less the result of river alluviation than the height, the power and the time of submersion of flood flows. Crevasse splays and avulsions represent a hard fluvial constraint because of (1) the energy that is liberated by the hazard in this form, (2) spatial and geomorphological transformations caused by the hazard and (3) the unpredictability of this event. Traces of ancient floodplain deposits, crevasse splays and avulsions are numerous; they allowed the characterisation of the palaeo-Rhone hydrological regime.

2.2. The complex hydrological regime of the palaeo-Rhone in its delta

A multi-criteria analysis, based on the combination of several types of data obtained by core sampling, bore sounding and stratigraphic sections, enabled the definition of the palaeo-hydrographic and palaeo-hydrological contexts of numerous complementary

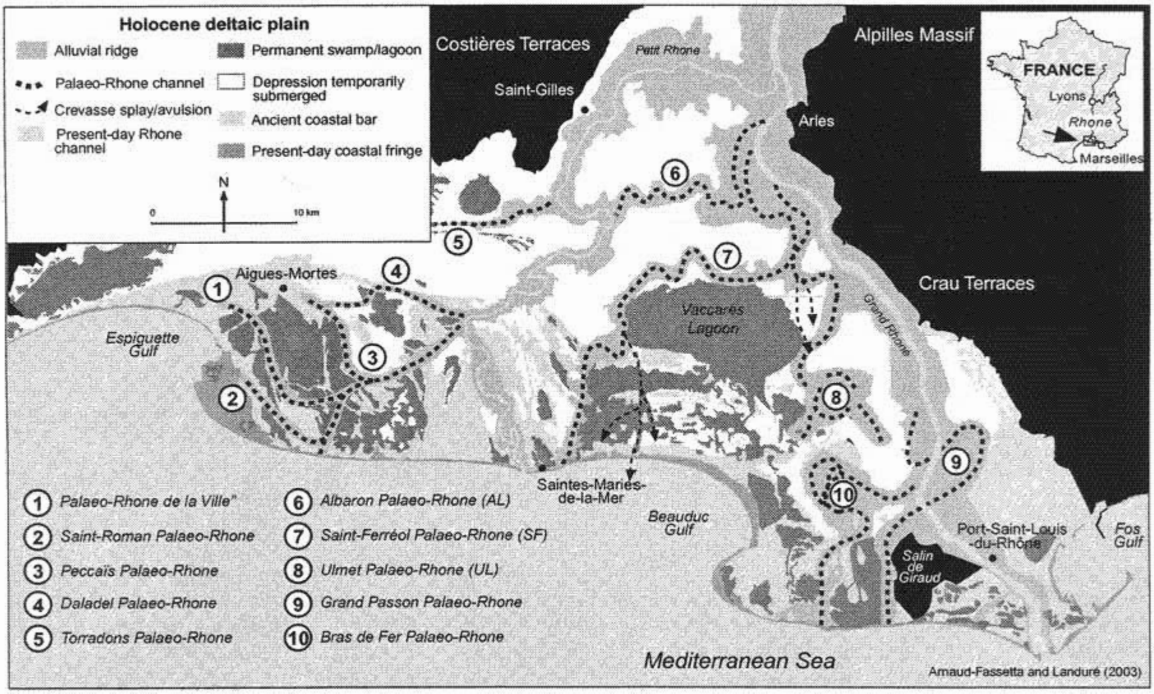

Fig. 1. Geomorphological map of the Holocene Rhone deltaic plain showing fluvial palaeochannels of the Rhone, and crevasse splays which were active between the Greek period and the Early Middle Ages.

archaeological sites. Identification criteria of the hydrological system were based on numerous key parameters like competence, transport capacity and channel pattern (*Table 1*). Thanks to this analysis, we have characterised the hydro-sedimentary regime of the palaeo-Rhone in its channel and in its adjacent flood plain. This study partly makes use of typology of the hydrological regime proposed by Erskine and Warner (1988). These authors challenged the existence of alternating periods of "flood-dominated regime" (FDR) and "drought-dominated regime" (DDR). In fact, we have adapted Erskine and Warner's typology to the palaeo-hydrological context of the Rhone Delta, with the objective to bring out much better the hydrological complexity of the Lower Rhone. The final points of our study show that the hydrological regime of the Lower Rhone, which results from glacier-melting, snow-melting and rains with mixed oceanic and Mediterranean influences, exhibit three alternating periods of FDR, "irregular flood-dominated regime" (IFDR) and DDR (Arnaud-Fassetta, 1998).

2.2.1. The FDRs

FDRs are linked to high hydrodynamic activity (*Fig. 2a*). The Rhone's hydrological regime is characterised by high mean discharge combined with frequent high-energy flood events. In the channel, aggradation processes are powerful when associated with frequent and abundant sedimentary deposits (*Fig. 2b*). They allow the development of typical deltaic braiding ($Q^{+}_{l} < Q^{+}_{s}$; Schumm, 1977; Starkel, 1983), which is characterised by several shallow river channels that enclose quite a few sandy bars. The sands of which they are made have a medium to fine grain-size distribution, and involve a high Rhone competence, which can reach 0.61 mm. The in-filled channels allow the development of avulsions and crevasse splays. In the flood plain, FDR periods are favourable to the extension of swamps and to the general rise of the water table, related to a shallow channel and a high mean discharge. The frequent waterlogging of the soils hinders the development of pedogenesis. Alluvial units are characterised by a large homogeneous grain-size distribution. Coarse granular

Table 1
Palaeo-environmental performance indicators highlighting methods and variables used to describe the functioning and the evolution of the Rhone fluvio-deltaic plain (from Arnaud-Fassetta, 1998, completed)

Physical and biological indicators of the fluvio-deltaic palaeoenvironment functioning	*Methods and procedures of the multidisciplinary approach*	*References*	*Studied sites in the Rhone Delta*
Flood frequences of the Rhone River	Relations between alluvial sedimentation rates, sedimentary structures preservations and the density of artifacts in the vertical sequence of the floodplain	Brown (1997)	Cabassole, Le Carrelet, Les Combettes, La Capelière
Water table in the deltaic plain	(1)Geochimical analysis of alluvial deposits; (2)Fauna analysis; (3)Micropalaeontology; (4)Micromorphology	Plaziat et al. (1987)	Cabassole(1, 2), Le Carrelet(1, 2, 4), Les Combettes(1, 2), Mornès(1, 2), Le Pont Noir(1, 2), La Capelière(1, 2, 3, 4), Fumemorte(1, 2)
Pedogenetic activity in the floodplain	(1)Geochimical analysis of alluvial deposits (organic matter, calcium carbonate); (2)Fauna analysis; (3)Soil micromorphology (number of biospheroids in relation with earthworms activity)	(1, 2)Duchaufour (1984); (3)Wiecek and Messenger (1972); Arnaud-Fassetta (1998)	Cabassole(1, 2), Le Carrelet(1, 2, 3), Les Combettes(1, 2), Mornès(1, 2), Le Pont Noir(1, 2), La Capelière(1, 2, 3), Fumemorte(1, 2), La Tour du Valat(1, 2), L'Abbaye d'Ulmet(1, 2)
Competence of the Rhone River	Bedmaterial grain-size analysis; CM diagrams interpretation	Folk and Ward (1957); Passega (1957); Bravard and Peiry (1999)	Le Carrelet, Les Combettes, Mornès, Le Pont Noir, La Capelière, La Tour du Valat, L'Abbaye d'Ulmet
Lateral stability of the channel	Sediment facies analysis of riverbank and proximal floodplain environments	Macaire (1990), Miall (1996)	Cabassole, Le Carrelet, Les Combettes, Mornès, Le Pont Noir, La Capelière, Fumemorte, La Tour du Valat, L'Abbaye d'Ulmet
Channel in-filling/Channel incision	Sedimentation rates and sedimentary structures analysis of the stratigraphic channel cross-sections	Plaziat et al. (1987); Ashley and Hamilton (1993)	Le Carrelet, Mornès, La Capelière, La Tour du Valat
Avulsions/Crevasse splays development	Combination of photo-interpretation and alluvial stratigraphic analysis (sediment facies, channel geometry)	Bridge (1984); Aslan and Autin (1999); Pérez-Arluca and Smith (1999)	Le Carrelet, Les Combettes, Mornès, Le Pont Noir, La Capelière, La Tour du Valat

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Physical and biological indicators of the fluvio-deltaic palaeoenvironment functioning	*Methods and procedures of the multidisciplinary approach*	*References*	*Studied sites in the Rhone Delta*
Channel pattern/Channel change	Combination of photo–interpretation and alluvial stratigraphic analysis (sediment facies, channel geometry)	Schumm (1969)	Le Carrelet, La Capelière
Source–areas of fluvial sands	Heavy mineral analysis	Parfenoff et al. (1970); Tourenq (1986); Arnaud-Fassetta (1998)	Le Carrelet

Arnaud-Fassetta and Landuré (2003).

particles (fine sand and sandy silt) are well represented, involving for flood flows high maximum competence (0.2–0.27 mm) and invariability. High sedimentation rates (2–5 mm · year^{-1}) are linked to high transport capacity and/or to frequent overflows due to in-filled channel.

2.2.2. The IFDRs

During IFDRs, the Rhone's hydrological regime is characterised by a relatively low mean discharge with a few large flood events that temporarily involve the rise of the hydrological levels (*Fig. 3a*). In the channel, alluvial deposits are characterised by sand units (high-energy flood events) or silty-sand units (low-energy flood events). The Rhone's maximum competence never reaches more than 0.5 mm. Moreover, flood deposits are insufficient to fill in the channel for a long time, which is why vertical incision still occurs here ($Q_1^- < Q_s^-$ or $Q_1^+ > Q_s^+$). In the flood plain, the high inter-annual variability of the overflows is proved by very important oscillations of grain-size distribution between two flood periods (*Fig. 3b*). Coarse deposits (silty sand) are alternatively laid down with fine deposits (clayey silt). The maximum competence of the floods has been measured at 0.19–0.26 mm. Channel incision (1) restricts overflows which can be proved by low sedimentation rates (0.6–1.6 mm/year) and (2) involves the lowering of the water table, so that good draining of the flood plain allows the activity of burrowing animals and the development of biosoils.

2.2.3. The DDRs

During DDRs, the hydrological regime is regular and large events are very rare, nearly non-existent (*Fig. 4a*). In the channel, sediments are finer and they are composed of fine sand, enriched with an abundant silt fraction: the Rhone maximum competence is low (0.4–0.46 mm). The mean discharge is low because of reduced water arrivals in the drainage basin and/or channel incision. Insufficient sediment yield is responsible for the lack of sandy bars; channel pattern seems to evolve towards meandering or anastomosing ($Q_1^- < Q_s^-$). In the flood plain, the setting of very fine deposits (clayey silt) is linked to prevailing decantation processes. The competence of maximum overflows is low (0.12–0.2 mm): it is related to the low Rhone hydraulicity. Sedimentation rates are very low (0.5–0.6 mm/year) because overflowing is exceptional and transport capacity is reduced. Weak alluviation processes and a low water table allow the development of pedogenesis (*Fig. 4b*).

2.3. Periodisation of hydroclimatic hazards from 800 BC to AD 1000

From 800 BC to AD 1000, the periodisation of hydroclimatic hazards shows a typical hydrological behaviour characterised by three FDRs, interrupted by periods of lower hydrological activity, typically IFDR or DDR (*Fig. 5*). Results from the deltaic plain sensu stricto (Arnaud-Fassetta, 1998) are given with those of ARL (Arcelin et al., 1999).

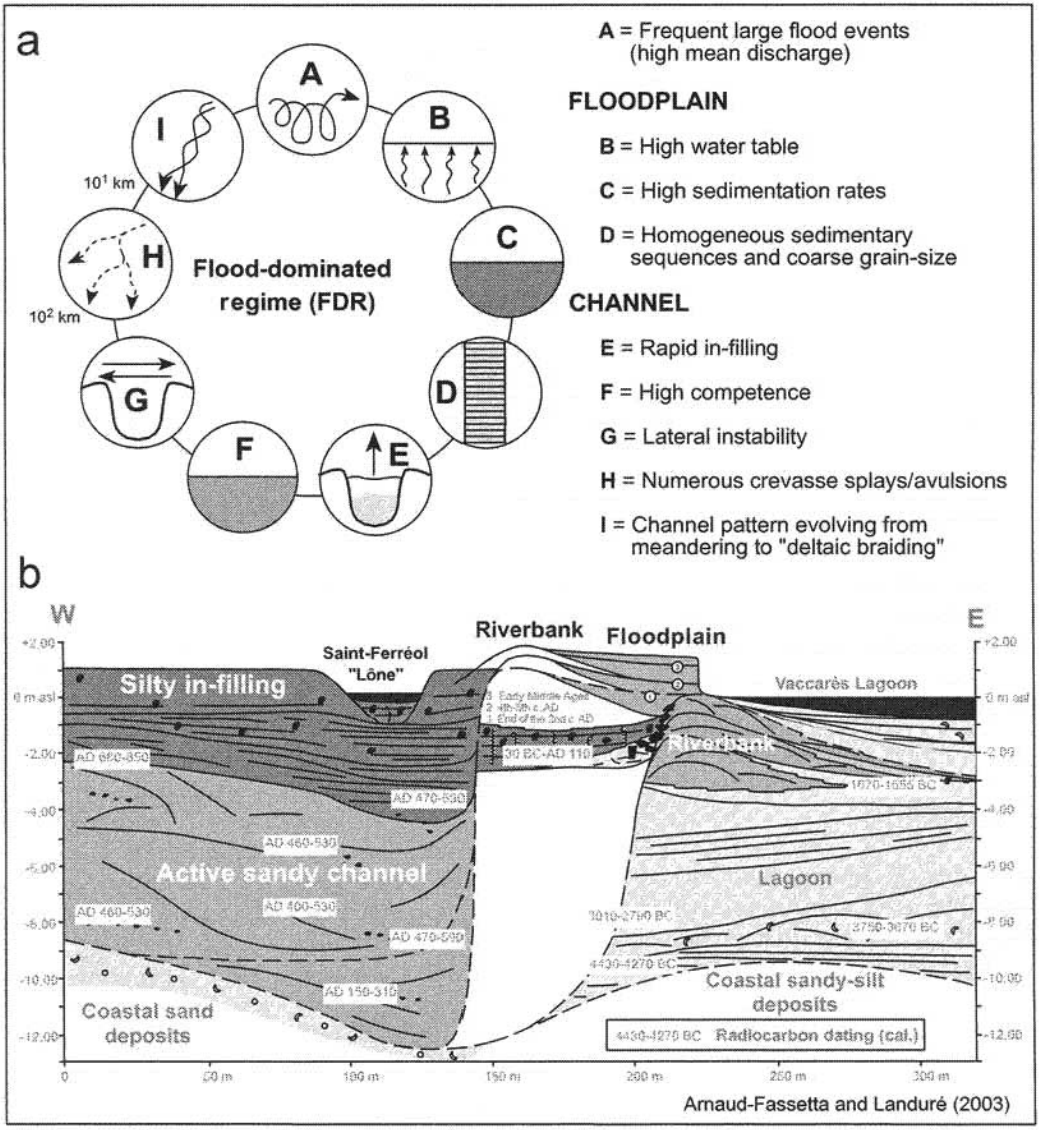

Fig. 2a. Hydro-sedimentary functioning of the Rhone deltaic plain during the periods of FDR.
Fig. 2b. Stratigraphic cross section in LCR showing the rapid in-filling by sand deposits of the Rhone channel between AD 400 and 590, in a context of the FDR 3 (from Arnaud-Fassetta, 1998, modified).

FDR 1 (800–500 BC): It can be seen at La Capelière (LCP) by the great lateral instability of the UL palaeo-Rhone; the channels are affected by avulsions, crevasse splays and formations of large sandy deposits in the proximal flood plain ($Q_l^+ < Q_s^+$). The high water table favours the extension of swamps from the north to the south of the delta [Cabassole (CAB), LCP)].

DDR 1 (500–400 BC): It happens when the Rhone alluvial activity slows down ($Q_l^- < Q_s^-$). In ARL, the Rhone overflows and reaches the low level of 2 m in Le Jardin d'hiver (JAR) around 475 BC. At the same time, a farm and routes are built on the riverbank at the level of 2–3 m in the La Roquette district. This may prove that the Rhone's mean discharge is

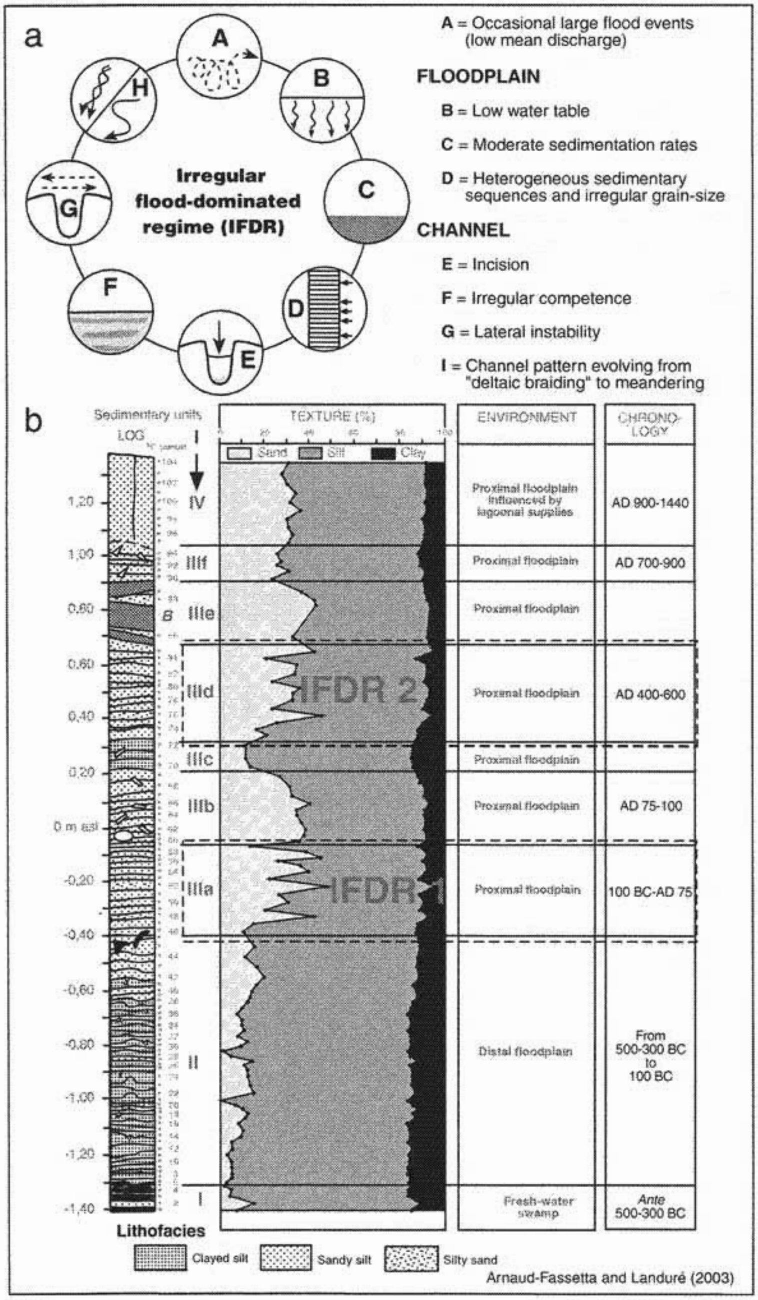

Fig. 3a. Hydro-sedimentary functioning of the Rhone deltaic plain during the periods of IFDR.

Fig. 3b. Summary logged section of the site of CAB. The succession of four main sedimentary units involves an environmental change from freshwater swamp to proximal flood plain. Strong and rapid grain-size variations in units IIIa and IIId illustrate the contexts of IFDR 1 and IFDR 2, respectively (from Arnaud-Fassetta, 1998, modified).

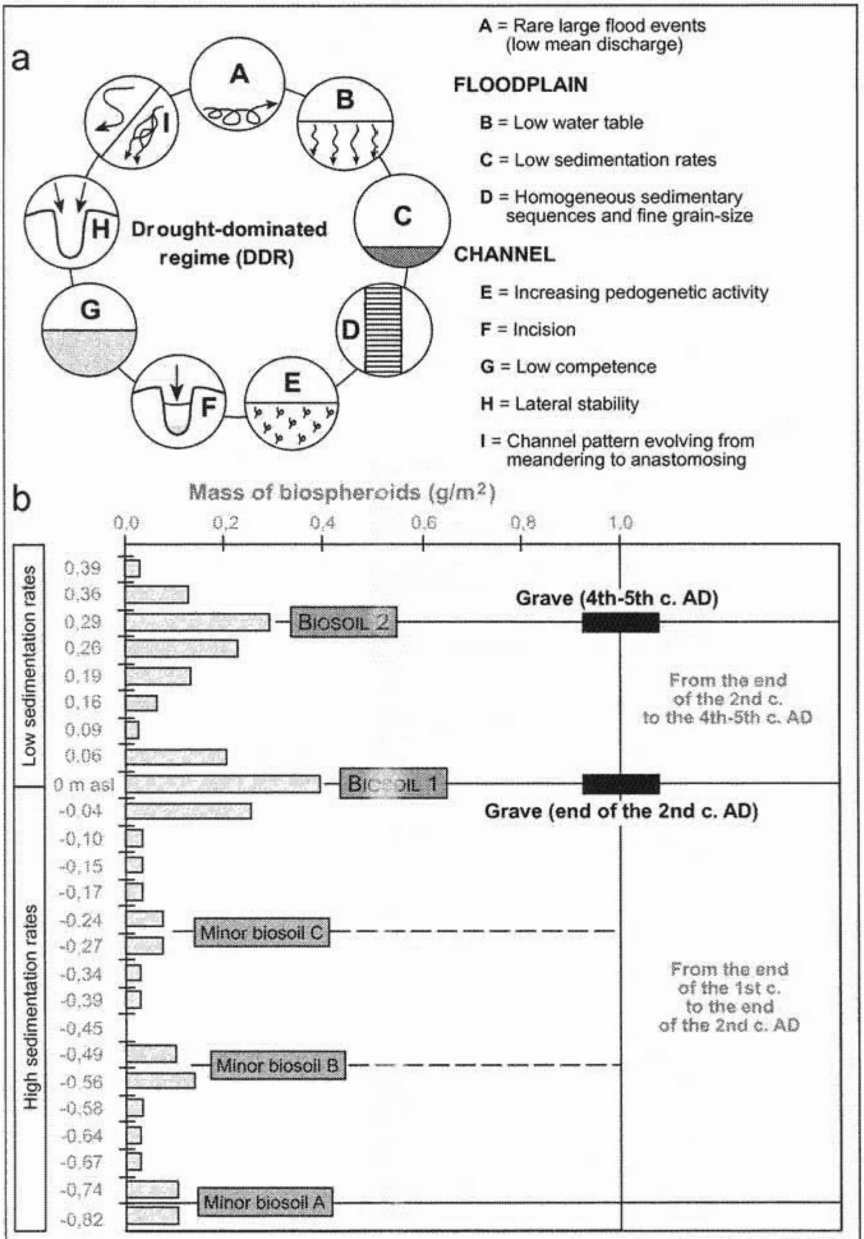

Fig. 4a. Hydro-sedimentary functioning of the Rhone deltaic plain during the periods of DDR.

Fig. 4b. Quantitative analysis of the evolution of pedogenetic activity in the Rhone flood plain from the end of the 1st century AD to the 4–5th century AD (LCR). Pedogenetic activity is expressed by the mass (per unit of surface) of biopheroids that were counted every 5 cm on a column of forty thin sections. Two well-developed biosoils (1,2) are correlated with a phase of low sedimentation rates and land occupation. Three minor biosoils (A–C) are associated to a phase of high sedimentation rates that limited the activity of burrowing animals (from Arnaud-Fassetta, 1998, modified).

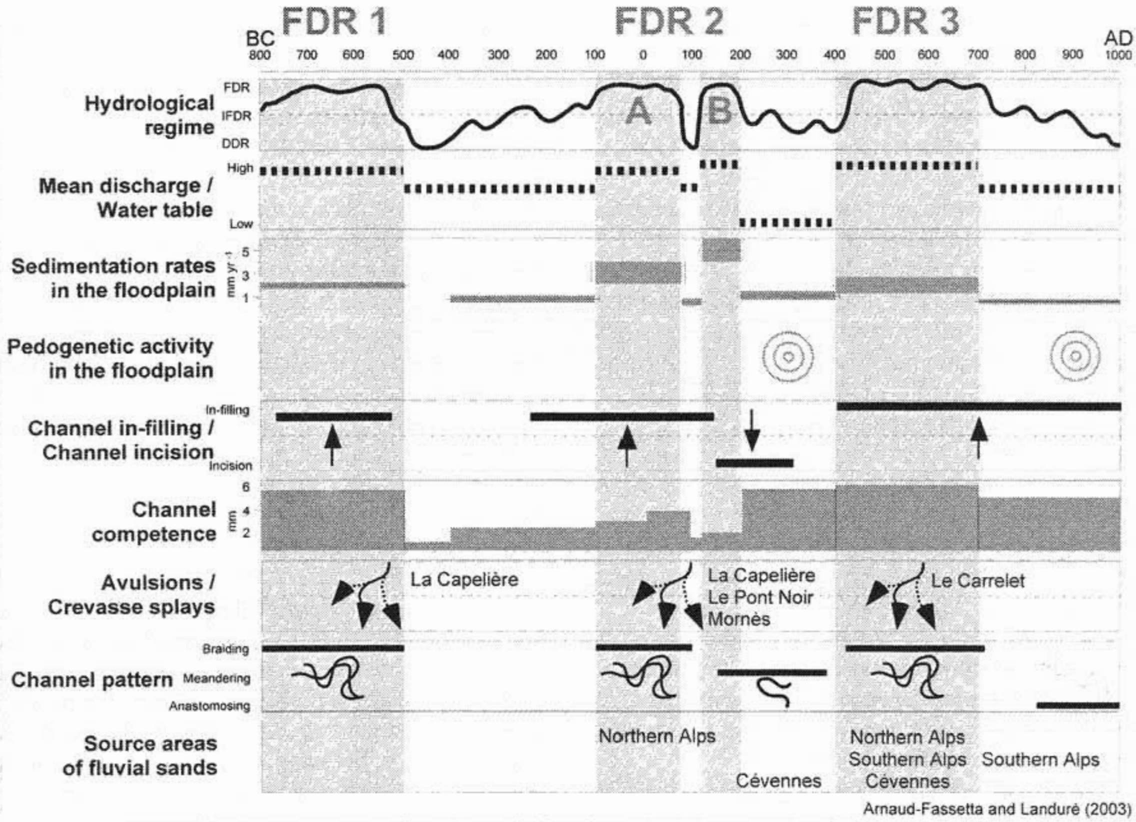

Fig. 5. Outcome of the palaeo-hydrological functioning of the Rhone in its delta, showing the existence of three periods of FDR from 800 BC to AD 1000.

relatively low at this time. In the floodplain, sedimentary deposits of the SF palaeo-Rhone are very fine at CAB: the maximum competence does not exceed 0.12 mm.

IFDR 1 (400–100 BC): The Rhone hydraulicity becomes more contrasted and powerful ($Q_l^+ > Q_s^+$). Around 175 BC, two sites in ARL [Les Cryptoportiques (CRY), JAR] are affected by flood events with a high level (respectively, 5.5 and 4.2 m). In the flood plain (CAB), the heterogeneity of sedimentary deposits is the sign of a calm hydrological regime with only a few violent flood events. Maximum competence (0.24 mm) rises but the sedimentation rates still stay reasonable (0.6–1.2 mm/year). This fact involves a relatively low transport capacity and/or rare overflows.

A second FDR takes place between 100 BC and AD 200 (Arnaud-Fassetta, 2002). It presents two periods (FDR2a and FDR2b) which are separated by a short period (a few decades) of DDR2 between AD 75 and 125.

FDR 2a (100 BC–AD 75): Around 100 BC, the development of crevasse splays in Mornès (MOR) and LCP highlights an important channel instability of the Rhone ($Q_l^+ < Q_s^+$). Between 30 BC and AD 110, the Rhone's mean discharge rises and involves lateral aggradation of the SF channel in Le Carrelet (LCR). On the SF channel, steep riverbanks must be elevated and strengthened by a boulder armouring (cf. infra). Between 100 BC and AD 75, the maximum competence of the flood flows rises, which can be seen in CAB. Important sedimentation rates (2–4 mm/year) are the sign of frequent overflows and/or high transport capacity in relation with an abundant sediment yield. The development of hygrophilic species shows that the Rhone Delta is more humid and freshwater dominated at this time. At the end of the 1st century BC, the sites of Sainte-Luce, Truchet and Trinquetaille reveal that the flood level reached 4 m (Bruneton et al., 2001). Consequently, riverbank constructions have been built to protect societies against overflows. On the site of Le Cirque (CIR), we note traces of important hydromorphy in overbank deposits. On the sites of Brossolette (BRO) and CRY, the settlements are all located on elevated points (1.5–4 m); at the same time, the site of JAR is abandoned.

DDR 2 (AD 75–125): A brief period of weak fluvial activity ($Q_{l-} < Q_{s-}$) involves a decrease of the maximum competence (0.16 mm) of Rhone's overflows in CAB and Les Combettes (LCO). The site of ARL confirms this result; during the second half of the 1st century AD, flood levels reach 2–3 m and the maximum competence of overflows waves does not exceed 0.19–0.2 mm; at the same time, the channel's maximum competence does not exceed 0.38 mm. At the end of the 1st century AD and at the beginning of the 2nd century AD, vertical soil development at the height of 1.7 m on the site of CIR is the sign of the decrease of overflows and/or the lowering of the water table. A network for the evacuation of wastewater and a settlement are built at a height of 0 m or slightly less on the site of Le Crédit Agricole.

FDR 2b (AD 125–200): During this period, alluvial activity rises in LCR. At the same time, very thick silty deposits (0.85 m) are being laid in the flood plain of the SF palaeo-Rhone. The maximum competence of the overflow waves is constant but does not exceed 0.2 mm; therefore, it remains beneath the competence level reached during the FDR 2b. The very high sedimentation rates (6–13 mm/year) indicate either the importance of the sediment supply ($Q_l^+ < Q_s^+$) or the rapidity of the aggradation in the flood plain, which responds to the rapid creation of accommodation space. In ARL, an alluvial flood deposit appears around AD 150 between the two track levels of the Roman circus (CIR).

IFDR 2 (AD 200–450): The Rhone sediment yield is not sufficient in comparison with the water inputs ($Q_l^- < Q_s^-$ or $Q_l^+ > Q_s^+$). In this context, between AD 150 and 310, the SF palaeochannel is affected by a strong incision of the alluvial floor: it reaches –12 m in LCR. However, the Rhone's maximum competence stays high (0.6 mm). In the flood plain (CAB, LCR, LCO), maximum competence does not exceed 0.19 mm; moreover sedimentary deposits are mainly composed of fine particles, in spite of some layers with coarser particles, which indicate higher floods. Decantation facies are very rare because of rare overflows. This situation corresponds to an IFDR with only a few violent floods. Sedimentation rates are generally low (0.8–1.6 mm/year) in association with the incised channel, which overflows less. Between the middle of the 4th century AD and the beginning of the 5th century AD, a rural construction in CAB seems to be the sign of an efficient drainage of the lowest part of the flood plain. During the 4th century AD, the water table is low in ARL, thereby favouring the settlement and the construction of routes at 0–1 m, on the site of CIR. Nevertheless, the Rhone overflows from time to time. For example, a flood level is recorded at 4.5–5.5 m in BRO from the end of the 3rd century AD to the 6th century AD.

FDR 3 (AD 450–700): In most of the sites of Camargue, hydrological conditions worsen, in connection with the increase of solid and liquid discharges ($Q_l^+ < Q_s^+$). The SF palaeochannel undergoes an important in-filling of more than 6 m in LCR, that involves the development of crevasse splays (LCR, LCO). Maximum Rhone competence reaches 0.61 mm. Thanks to the analysis of heavy minerals, it is proved that sediments carried by the Lower Rhone originated from the whole river basin, i.e. from the Alps and Massif Central (Arnaud-Fassetta, 1998). In the floodplain, fluvial deposits become coarser in relation with maximum competence rising up to 0.24 mm. Sedimentation rates are high (1.3–2.7 mm/year) in connection with a channel with greater overflows. The important growing of riparian forest shows that more fresh water arrives in the flood plain. In ARL, floods reach high levels; in BRO, a flood level takes place between 5.5 and 6.3 m, probably during an exceptional flood. On the site of Suarez, flow networks only appear from 5.5 m.

IFDR 3 (AD 700–1000): During this period, the Rhone hydraulicity slows down irregularly but surely in the whole of Camargue. This however reflects a situation typical for the delta, as the result of the gradual reduction in activity of the SF and UL palaeochannels ($Q_l^- < Q_s^-$). In the channel, maximum competence is reduced to 0.5 mm. In CAB and LCR, the maximum competence of overflow waves raises down to 0.2 mm. Sedimentation rates too decrease (0.5–0.7 mm/year).

In conclusion, three FDRs characterise the palaeohydrology of the Rhone Delta from 800 BC to AD 1000. They are associated with phases of degradation of climatic conditions, emphasised by human activities. Intensive swamp extension, which is characteristic of the FDR 1 (800–500 BC), could be the sign of an excessive pluviometric balance; this fact is present in almost the whole river basin (Bravard et al., 1997; Bruneton, 1999; Jorda and Provansal, 1996; Magny, 1992). It is also associated with a fresh climatic oscillation on a Western European scale (Van Geel et al., 1996). The two phases of FDR 2 (100 BC–AD 75 and AD 125–200) could be induced by the more unstable climatic conditions (i.e. more frequent events of large rainfall). Note that it was in-phased with the palaeo-hydrological functioning of the Upper–Middle Rhone (Bravard et al., 1997) and its Alpine tributaries (Peiry, 1988), but also downstream of the river basin (Bruneton et al., 2001; Provansal et al., 1999). However, it varied out-of-phased with rivers of the Durancian Alps and Provence (Jorda and Provansal, 1996; Provansal, 1995a,b). The FDR 3 (AD 450–700) could be put in relation with a pluviometric growth, maybe associated with a cold period, in the whole Rhone river basin (Arnaud-Fassetta, 1998; Magny, 1992; Patzelt, 1994; Zoller, 1977). During worsening climatic conditions, hydroclimatic hazard occurs more intensively and more frequently. It can potentially reinforce the vulnerability of societies.

3. The vulnerability of societies faced with hydroclimatic hazard

The inventory of many archaeological sites of Camargue has enabled the examination of their nature and function and of the vulnerability of the antique and mediaeval societies in relation to the river, its floods, its crevasse splays and its avulsions.

3.1. The archaeological sites of in the delta: their localisation, evolution and nature/function

The inventory of the archaeological sites, realised thanks to on-foot prospecting, came to a sum of 155 sites, created between the 6th century BC and the 10th century AD (*Fig. 6a,b*). In reality, the number of sites may have been underestimated if we take into account the fact that some are probably still buried, considering the deltaic context where the processes of alluviation remain very active. This problem with the burying of the sites was also brought up during the geo-archaeological excavations conducted in the Middle Rhone (Berger and Jung, 1996). Despite the supposed deficiency of the inventory, the superposition of the archaeological sites with the map of the palaeochannels of the Rhone shows a human occupation whose mode of distribution is essentially turned towards the river.

3.1.1. Sites essentially established along the distributaries of the palaeo-Rhone

Throughout the concerned period, most of the sites are situated along the three distributaries of the Rhone that were active during the Antiquity and the Early Middle Ages. Sixty-three sites (i.e. 40% of the total) were located in the area under direct influence of the SF palaeo-Rhone, which was probably the most active distributary during the first part of the Antiquity, 29 (19%) were close to the AL palaeo-Rhone and 26 (17%) were close to the UL palaeo-Rhone (*Fig. 6c*). We shall also mention four sites established in the zone of diffluence SF palaeo-Rhone/UL palaeo-Rhone (Delta du Rhône, 1998). Among the remaining sites, 13 (8%) are situated alongside the palaeocoast, and the last 20 (13%) seem to be far from both the palaeocoast and the three above-mentioned palaeochannels of the Rhone. If we add up this data, the proportion of sites established in immediate proximity to the palaeochannels of the Rhone amounts to 79%, thereby confirming that the nearness to the palaeo-Rhone was indeed the main factor to have determined the choice made by the communities when establishing their sites in the delta. This result obviously brings up the question of the vulnerability of these sites, settled in the zone liable to flooding.

3.1.2. A more or less continuous occupation during nearly 1600 years

The earliest traces of occupation in Camargue may date from the 6th century BC, with the (ancient) discovery of fragments of Attic ceramics (Gantès, in press). However, recent excavations have never dated back further than the 5th century BC. Five sites on the side of the lagoons of Vaccarès and of Le Fournelet illustrate the Greek occupation in the Rhone Delta. The study of their palaeo-environmental context shows that these sites were established in the flood

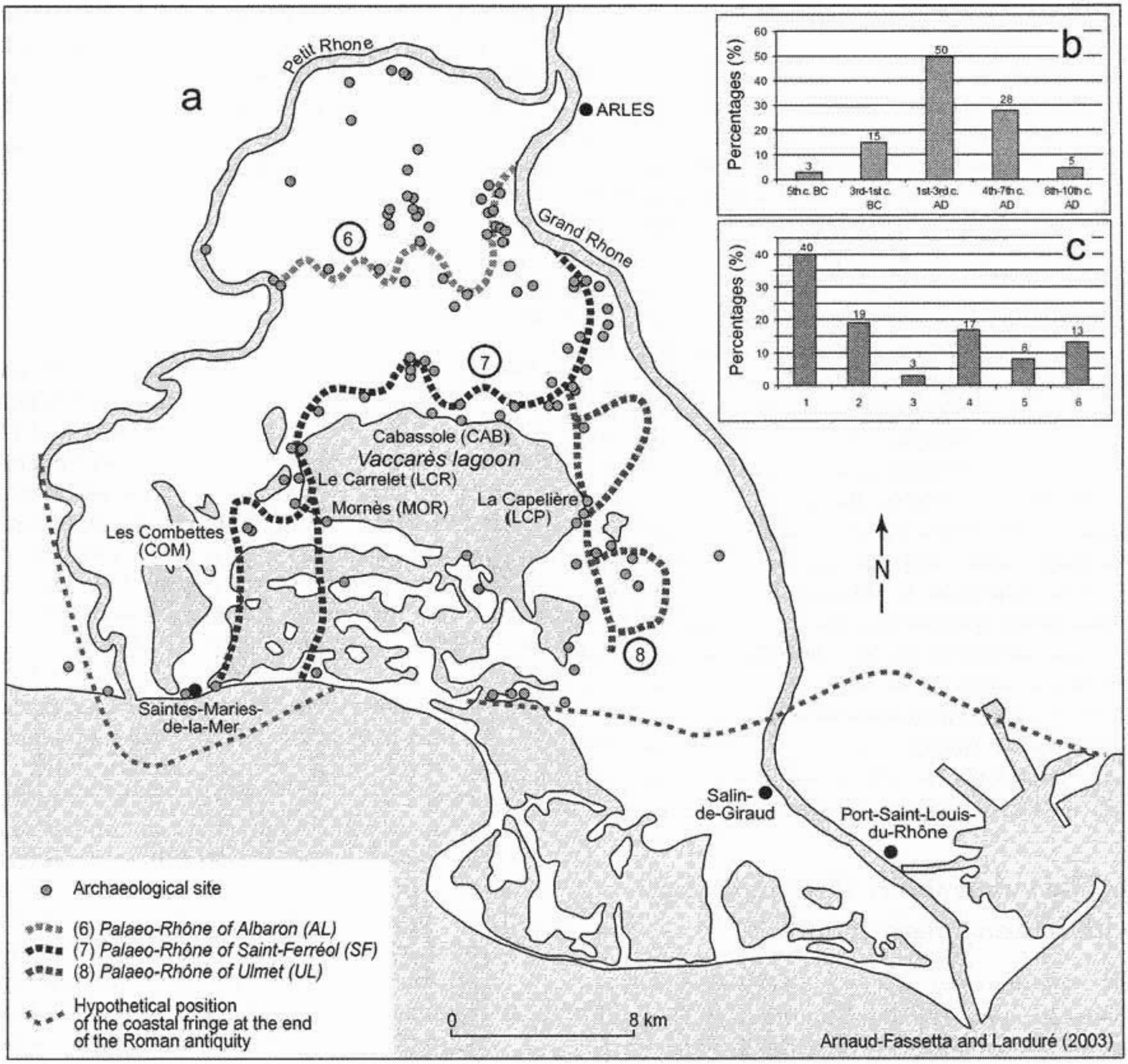

Fig. 6a. General view of Camargue showing location of archaeological sites for the period 5th century BC–10th century AD.

62

Fig. 6b. Evolution of the number (expressed as percentages) of archaeological sites from the 5th century BC to the 10th century AD.

Fig. 6c. (Location of archaeological sites in the deltaic plain; 1: sites near the SF palaeo-Rhone; 2: sites near the UL palaeo-Rhone; 3: sites in the zone of diffluence SF palaeo-Rhone/UL palaeo-Rhone; 4: sites near the AL palaeo-Rhone; 5: sites alongside the palaeocoast; 6: sites to be far from both the palaeocoast and the three above-mentioned palaeochannels of the Rhone.

plain of the SF palaeo-Rhone and the UL palaeo-Rhone.

With 26 located sites, the period between the 3rd and the 1st century BC appears as the beginning of a populating dynamics. This tendency is confirmed during the period between the 1st and the 3rd century AD, with a strong increase in the number of sites (86 sites). Some can certainly be interpreted as important villae. Built in the flood plain, these villae seem in particular to be situated in Upper Camargue, at a time when this region benefits from agricultural development in connection with the expansion of the Roman colony of ARL (Leveau, 1993a,b, 1999).

The number of located sites dating from between the 4th and the 7th century AD is lesser (48 sites). The most important settlements of the previous period are still inhabited while new settlements are created in the zones of the flood plain which were till then unoccupied. These observations could confirm the continuity of the populating – moreover, also strongly evidenced in the west of Lower Provence – which it would be tempting to interpret as related to the importance of the city of ARL (Trément, 2001).

Concerning the 8–10th century AD, the number of sites is still decreasing, with only eight sites located on the alluvial ridges of the palaeo-Rhone. The paucity of sources may be due to the forms of construction emerging during this period, which, by favouring the use of earth and perishable material, leave little traces in the ground (Kotarba, 1988). One could also attribute the decrease in the number of sites to a phenomenon of restructuring of the population (groupings of population). What is more, this phenomenon, which would have been initiated in Camargue as from the 8–10th century AD, is evidenced in Provence and Languedoc around the year 1000 (Fossier, 1992; Schneider and Paya, 1995).

3.1.3. Which forms of occupation for which economic resources/activities?

The forms of occupation and the nature of the economic activities of Camargue from 600 BC to AD 1000 were specified thanks to geo-archaeological excavations on five sites situated on the riverbanks of two palaeochannels of the Rhone: the SF palaeo-Rhone [LCR (Martin, 1995, 1998), CAB (Richier, 1996), LCO (Landuré, 1996a), MOR (Landuré, 1996b)] and the UL palaeo-Rhone [LCP (Landuré, 1997, 2000a,b)] (*Fig. 6a*).

As regards the ground occupation, the sites of LCO, LCR and LCP have been interpreted as grouped settlements; the site of MOR may be a temporary settlement, whereas CAB seems to correspond to a small rural settlement. They were only chosen because of the possibilities they offered for intervening on site, yet are not in any way representative of a form of occupation that can be generalised to the whole of the delta. The results of prospecting and recent research conducted on a Gallo-Roman site in south Camargue revealed the existence of a mosaic of large villae and agricultural settlements during the antique period (Excoffon et al., in press; Pasqualini, 1999).

Concerning the economic activities, the societies settled in the delta first practised agriculture. The Rhone flood plain enabled (1) cereal growing, as evidenced by palynological analyses (Arnaud-Fassetta et al., 2000) and the discovery of millstones and (2) the development of viticulture; in LCR was discovered a boundary stone marking the limits of a property mentioning the presence of vines and gardens (Gayraud, 1989). As a complement to agriculture, the populations also practised breeding, as from the 5th century BC, as shown by the first results of the excavations of LCP (Forest, 2001). Other economic activities have been identified, and first of all, handicraft. In LCR, traces of metallurgy have been dated from the end of the 4th century – beginning of 5th century AD (Martin, 1995). An activity linked to the manufacturing of soda or glass seems to have developed in CAB in the 9–10th century AD (Amouric and Foy, 1991; Richier, 1996). Furthermore, the exploitation of salt and fish was revealed in LCR, thanks to the discovery of salting basins dating from the 5th century AD (Martin, 1995). This salting industry was most probably favoured by the geography of the site. LCR was a vast vicus situated between the Vaccarès lagoon and the Rhone, and was therefore close to the fishing areas, to the lands favourable to salt farming and to a navigable fluvial way (i.e. the SF palaeo-Rhone) which ensured the distribution of the production. Moreover, the presence of salterns as from the 5th century AD is conceivable, considering that some are mentioned in the texts, although with no precise localisation (Benoit, 1959). The hypothesis of Stouff (1986), which states that the mediaeval salt works mentioned on the banks of the Vaccarès lagoon were probably exploited before the 13th century AD, goes along the same lines.

Finally, the Rhone probably facilitated the contacts between the sites of the delta and their possibilities in supplying themselves with construction materials, namely the stones that were transported from ARL, and with various goods. Its role as an interface between the sites is also revealed by the variety and abundance of ceramic material found, which reflect the privileged exchange currents between the sea and the continent via the ports of Marseilles and ARL (Hirbec, 1998).

3.2. About the vulnerability of societies

3.2.1. A strong vulnerability, lessened by settling on the highest points of the flood plain

The proximity of the Rhone, privileged for economic reasons, made the societies vulnerable insofar as, situated in the zones liable to flooding, they were exposed to devastating rises in water levels and to the unpredictable avulsions. The societal vulnerability was however lessened by settlements chosen on the higher points of the flood plain, from the moment that the topography (i.e. the relief sensu stricto) allowed it. Four sites evidence this logic of settlement.

In LCP, traces of a swamp with fresh to brackish water, dating from the 8th to 5th century BC (Lyon-1497/1498) were found between –1.5 and –1 m. Then, during a phase when the UL palaeo-Rhone came closer (avulsion?), the swamp was covered up with sandy-silt flood deposits. The latter contributed towards giving strong relief to the flood plain and little by little formed a dominant point between the main channel situated to the west of the site and a secondary channel situated to the north. At the top of this knoll, at an altitude of –0.5 m some buildings on sand deposited soil and load-bearing posts were installed around 500–475 BC, forming the first traces of occupation of the site (*Fig. 7a,b*). In CAB, the results of the geo-archaeological investigations illustrate comparable settlement conditions. The settling of men on this site dates from the Greek period (5–4th century BC). It is represented by a layer of ceramics of approximately 300 m spread on floodplain deposits whose summit is situated at –0.4 m. Again, two factors favoured human settlement: (1) the transition from a paludal environment to a better-drained flood plain and (2) the raising of the topographical surface of the flood plain as the result of the 0.2 m deposit of silt.

In LCO, the arrival of communities in the 6th century AD is favoured by the same palaeo-environmental conditions. Around AD 90–190 (Lyon-7760), the site was occupied by a swamp situated between –3.1 and –2.4 m. Then, the setting up of a flood plain combined with a riverbank raises the topographical surface by 2.3 to –0.1 m. This raising of the lands, linked with a better-drained environment, brought favourable conditions to the installation of a settlement. The site of MOR is also on a height (0.6 m), i.e. on the floodplain deposits topping one of the ancient bars of the river-mouth of the SF palaeo-Rhone. Like the other sites, the settlement is very close to the Rhone, present here as a secondary distributary. However, despite being situated at an important altitude, which is superior to other contemporary sites, the site is occupied during only a couple of decades in the 1st century BC, maybe due to the abandonment of the secondary channel.

In the light of these four examples, it seems the proximity of the river, that was looked for by man probably mainly for economic reasons, imposed building on zones of altitude, which limited the duration and the height of inundation on the sites, and therefore their vulnerability. The privileged sectors were riverbanks (LCP, LCO, LCR), the higher zones of the flood plain (CAB) and secondarily, the fossils bars of the river mouth topped by floodplain deposits (MOR).

3.2.2. The other preventive measures for minimising the vulnerability of the sites: boulder armouring on the riverbanks and drainage ditches in the flood plain

Other measures were taken for the protection against floods, or at least, to minimise their destructive consequences. The most current were the erection of boulder armouring on the riverbanks and the digging of drainage ditches in the flood plain.

Boulder armouring: Probably very discontinuous in this period, they were made up of decimetric, unattached blocks of stone, disposed on the inner face of the riverbanks so as to limit their erosion during high fluvial flows. We are going to detail here the one discovered in LCR (Martin, 1995). On this site, a survey with a mechanical shovel realised on the (concave) left riverbank of the SF palaeo-Rhone, revealed a boulder armouring made of blocks whose size varied from 0.3 to 0.6 m (*Fig. 8a,b,c*). Followed over a length of 6 m, it has a width of 2.5 m for a height of 1.5 m, and its top reaches the spot height of –0.6 m. It seals the upper part of the riverbank which was dated by radiocarbon from between 30 BC and AD 110 (Lyon-360). This hydraulic equipment, probably installed between the FDR2a and the FDR2b (cf. supra), had two functions: the obvious one, which was protecting the concave riverbank from the phenomenon of sapping, and the more

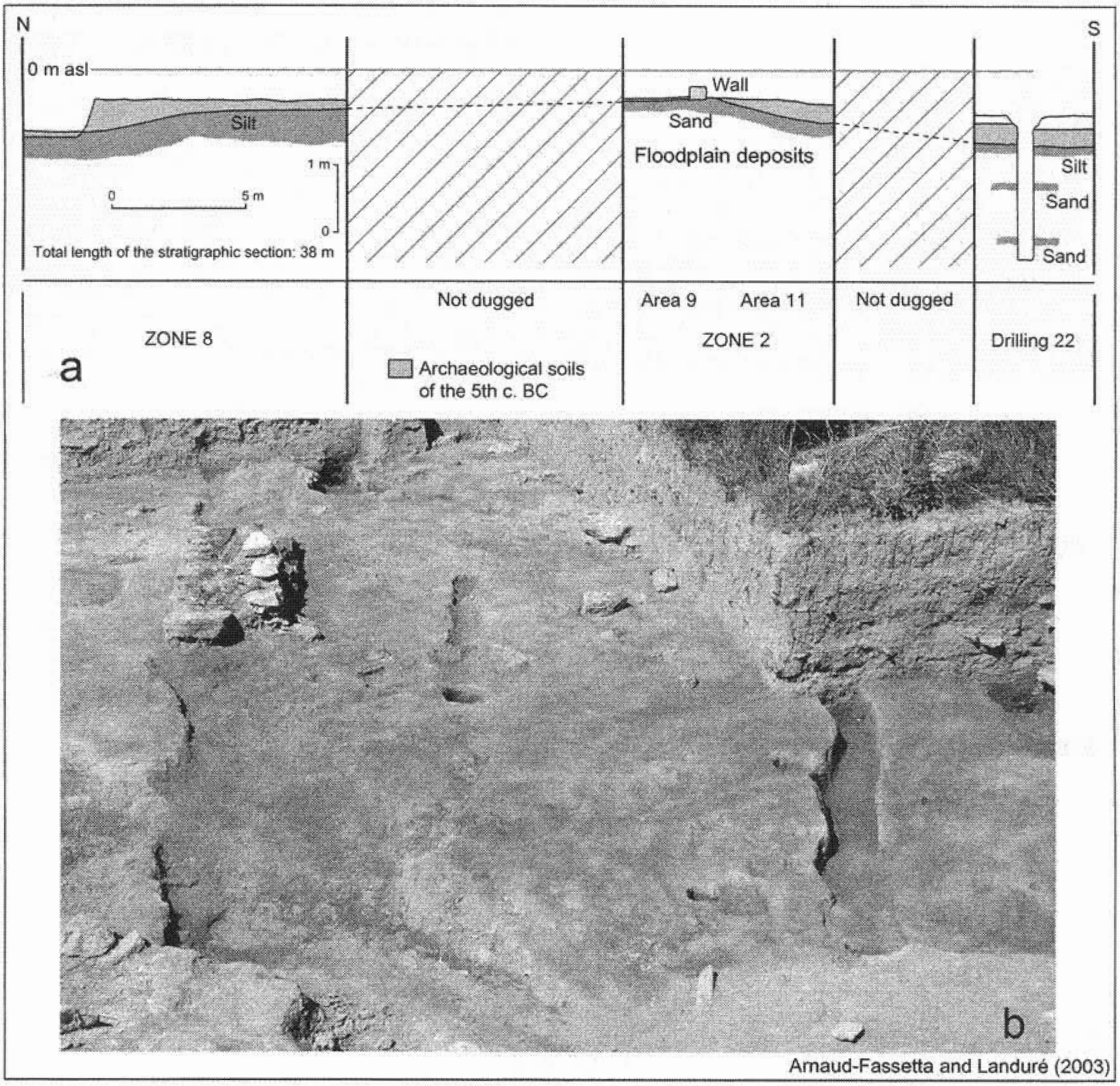

Fig. 7a. Schematic stratigraphic cross section in LCP, showing the general topography on which human settlement was installed during the Greek period.

Fig. 7b. Details of occupation levels of the 5th century BC. Note the presence of sand deposited soil (in low position) and the tracks of load-bearing posts installed on the flood deposits.

hypothetical one of protecting zones of settlement (which we have however not managed to localise).

Drainage ditches: Dug at the periphery of the settlements, most of the time they lowered the water table and reinforced the permanent or temporary emersion of the high zones of the flood plain. Some examples of ditches have been revealed in the excavated sites.

In CAB, a ditch (FO 2011) was unearthed over a length of 5 m. It was 3.5 m large and 0.5 m deep, with oblique inner walls and a flat bottom. Its in-filling, dating from the 8th and 10th century AD, was made of silt mixed with tiles, scoria and animal bones. These characteristics did not enable the identification of its precise function. During the same period, another

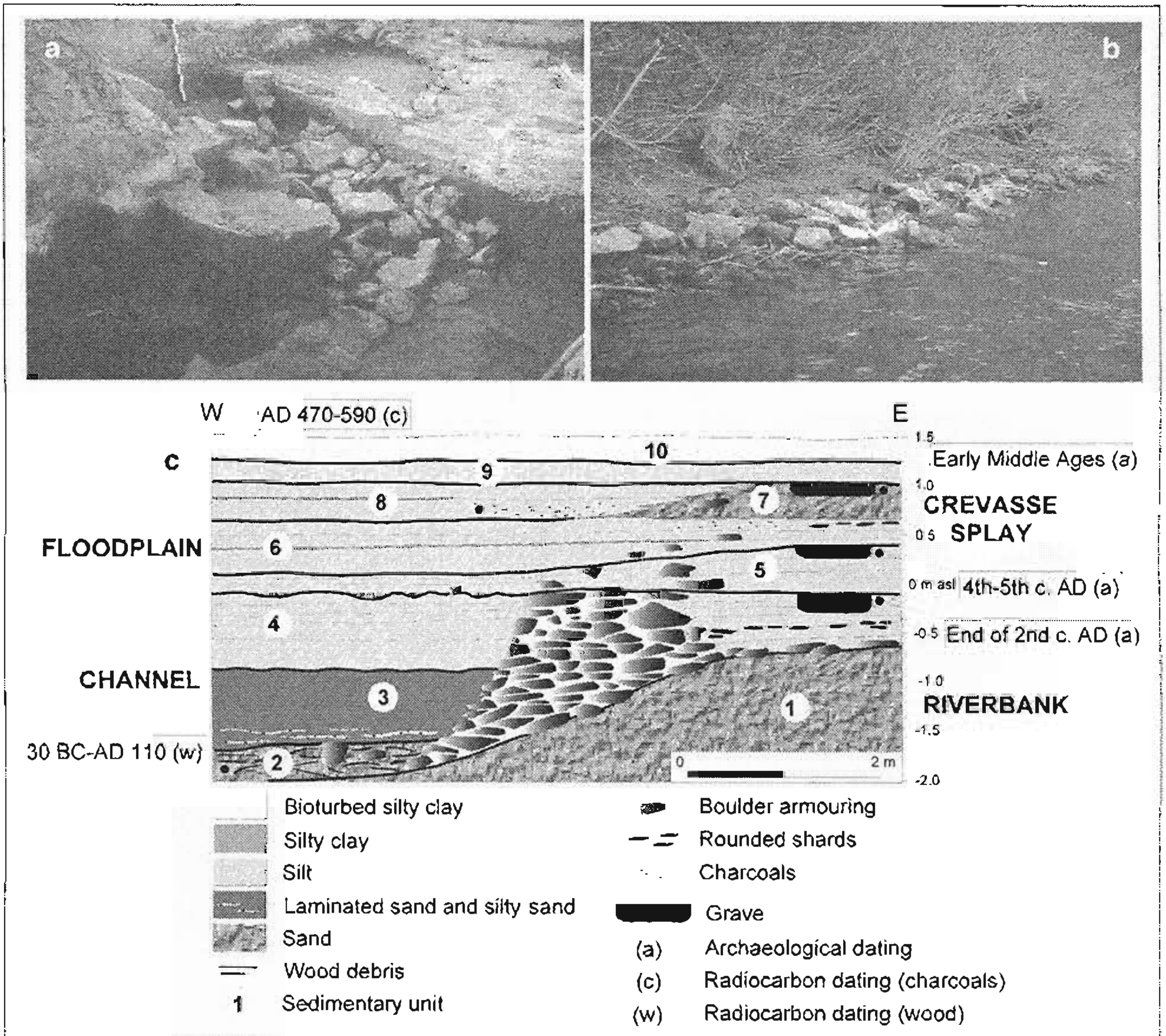

Fig. 8a. View of boulder armouring (30 BC–AD 110) discovered in LCR.
Fig. 8b. View of present-day boulder armouring on the riverbank of the Petit Rhone showing some similarities with the one of LCR.
Fig. 8c. Stratigraphic cross section in LCR showing the succession of four fluvial palaeo-environments: a riverbank supporting a boulder armouring dated 30 BC–AD 110; the channel of the SF palaeo-Rhone which was in-filled (on the cross section) before the end of the 2nd century AD; a flood plain occupied from the end of the 2nd century AD and the Early Middle Ages; and a crevasse splay dated from AD 470–590.

ditch (FO 2077), similar to the previous one, was filled. 3.5 m large and 0.6 m deep, its base was composed of layers of ashes that came from the emptying of nearby ovens. This level was sealed by a 0.5-m-thick filling up, which shows an alternation of sandy units (eight out of all) and carbonated clayey layers, which evidence a hydraulic functioning and show that the ditch was regularly filled with water. The phases with water and of rapid flow are materialised by sandy layers, whereas the carbonated clayey layers are associated with phases of decantation then evaporation. This ditch, orientated N5, was probably used for evacuating the water of the SF palaeo-Rhone (to the north) towards the Vaccarès lagoon (to the south). The grain-size of the sedimentary in-filling shows how powerful the overflowing water of the Rhone was, capable of moving sands from the inhabited flood plain. The importance of the deposit and the number of sandy units evidence the repetition of this phenomenon.

On the site of LCP, a ditch (FO 7026) demarcates the settlement of the 1st century BC (*Fig. 8d*). Orientated N45, it prolongs towards the west (i.e. in the swampy depressions situated at –1 m) the evacuation of the water of the UL palaeo-Rhone situated to the east of the site. It is 1.7 m wide on the top, 1 m deep and is U shaped. It was in-filled with homogeneous, massive alluvia, which can be interpreted as a very rapid in-filling, probably following a phase of flooding.

4. The fluvial risk from the Greek period to the Early Middle Ages: a Rhone Delta perspective

4.1. Most of the time, the sites were occupied whatever the rhythm of the floods

In general, the variability of the flood rhythm in the Rhone flood plain did not have a direct impact on the duration of the settlements (Arnaud-Fassetta and Landuré, 1997).

For example, the settlement in CAB, located in the flood plain of the SF palaeo-Rhone, was exposed to more or less frequent floods at any time of the occupation (5–4th century BC, 1st century BC–1st century AD, 4–5th century AD, 5–6th century AD, 8–10th century AD). Relative variable sedimentation rates show that overflows are irregular: high rates during the FDR 2 (2–4 mm · year^{-1}) and the FDR 3 (1.3–2.5 mm · year^{-1}) or low rates during the IFDR 1 (0.6–1.2 mm · year^{-1}), the IFDR 2 (0.8–1 mm · year^{-1}) and the IFDR 3 (0.5 mm · year^{-1}). On the whole, we cannot establish any relationship between flood rhythms and length in time of human occupation. During the 5–4th century BC, the 4–5th century AD and the 8–10th century AD, human occupation of the site might have been favoured by the rarity of the overflows (DDR 1, IFDR 2, IFDR 3). During the 5–4th century BC and the 1st century BC–1st century AD, the occupation phases remained diffuse and/or temporary although hydrological context was completely different: an FDR context for the first period and a DDR context for the second one. Finally, any trace of human occupation was identified during the FDR 2 (1st century BC to 1st century AD) although occupation levels of the 5–6th century AD are well preserved during the FDR 3.

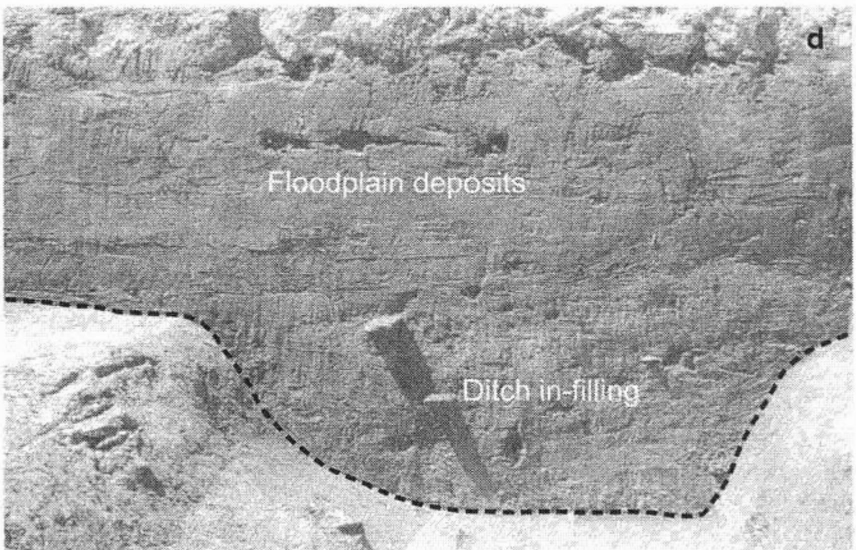

Fig. 8d. View of a drainage ditch (1st century BC) discovered in LCP.

Furthermore, the settlement of LCO, located on a steep riverbank, must have been faced with the floods of the SF palaeo-Rhone during the whole period of occupation (6–10th century AD). However, the study of ceramic material of the archaeological levels sandwiched between flood deposits from –0.1 to 0.6 m shows that floods did not interrupt human occupation. Like in CAB, the site was abandoned when aggradation of the flood plain slowed down, in relation with the decrease in hydraulicity of the SF palaeo-Rhone.

In conclusion, the environmental determinism seems to be relatively weak. When the hazard is only represented by Rhone's overflows, whatever its frequency, it does not hinder long-term human occupation in the flood plain. On the contrary, when the hazard involves overflows with crevasse splays and avulsions, it can imply that sites were abandoned or unoccupied for several decades.

4.2. Some examples of abandoned or unoccupied sites during the FDRs

FDR periods were locally characterised by violent floods, followed by crevasse splays and avulsions and the complete or partial abandonment of the settlements, as illustrated by the sites of LCP or LCR.

On the site of LCP, human occupation was discontinuous from the 5th century BC to the 7th century AD. A small rural settlement was built on the bumpy sandy-silt flood deposits right from the beginning (cf. supra). As regards its geographical situation (i.e. to the west of the main channel of UL palaeo-Rhone and down to the confluence between the two of its secondary distributaries), the site can easily suffer from floods and crevasse splays (*Fig. 9*). That is why human occupation levels of the 1st century BC are completely recovered by sandy-silts deposits which are 0.1 m thick to the centre of the habitat and 0.4 m thick on its borders (*Fig. 10*). These flood deposits are connected to sands (crevasse splays) to the north of the site and have covered a spot, interpreted as a warehouse in which two amphoras were found. After these catastrophic floods, which probably appear in the second half of the 1st century BC, the settlement is abandoned and reoccupied some decades later (~AD 30).

In LCR, sandy-silts (flood deposits), whose thickness reaches 0.8 m, fossilised a boulder armouring laid on a steep riverbank which was elaborated between 30 BC and AD 110. No traces of a settlement have been evidenced during this FDR 2 period, although a settlement was probably there at the same time as the boulder armouring. Only a tomb dating from the end of the 2nd century AD was discovered at the top of the flood deposit (Martin, 1995). In fact, the main phase of human occupation was the 4th century AD, i.e. during the IFDR 2: during this period, flood events and crevasse splays were rare. The 4th century AD was marked by the implantation of a settlement, interpreted as an important vicus, with a ground surface estimate of 1–2 ha wide (Martin, 1995). From the 5th century AD, the channel of the Rhone was characterised by an in-filling because of numerous floods and an important sediment yield (FDR 3). This hydro-geomorphological context is favourable for the increase in the rhythm of overflows and the formation of crevasse splays. Constructions of the 4th century AD are fossilised below 1 m of sandy-silts (flood deposits) and silty-sands (crevasse splays) (*Fig. 8c*). At the end of the FDR 3 (around the 7–8th century AD), no more houses exist on the site and the only remains found were two graves, which only reflect a sporadic human presence.

4.3. Conclusions on the fluvial risk

The afore-mentioned examples show a very complex situation. Sometimes, Rhone floods hindered a continuous rural settlement. That was the case of the site of LCP, where a crevasse splay was followed by the abandonment of the settlement during a few decades, from the end of the 1st century BC to AD 30. In LCR, numerous overflows covered up the ancient settlement by 1 m of sandy silts. But floods always did not have the same impact on the whole delta. For example, on the sites of LCO and CAB, the habitat developed and grew in FDR contexts; frequent overflows occurred but without major consequences on the continuity of the settlement.

In fact, the continuity of the rural settlements depends mainly on the types of hazard in the flood plain. The phenomenon of flood submersion in the alluvial plain can be considered as a secondary factor in the abandonment of sites or changes in relevant economic activities, even if the hazard occurs very frequently, like during the FDRs or IFDRs. In fact, three mains physical factors can involve the abandonment of a site:

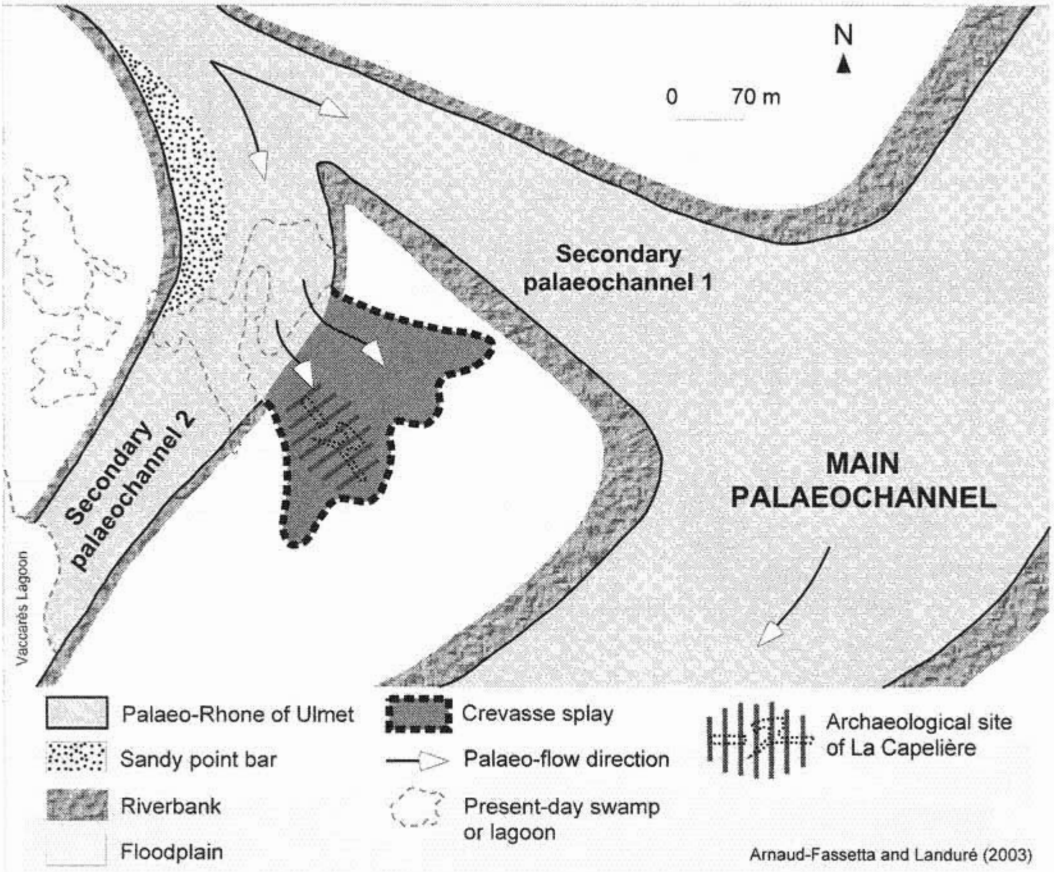

Fig. 9. Map showing the palaeo-hydrological network of the UL palaeo-Rhone in LCP from the 1st century BC to the 1st century AD. Note the presence of a crevasse splay whose silty-sand deposits completely recovered the archaeological site at the end of the 1st century BC. This catastrophic event involved the abandonment of settlement during several decades (from Crichton and Siboni, 2001).

(1) Hydroclimatic hazard when it combines overflows, crevasse splays and avulsions during the FDR: The frequency of huge floods is decisive for the in-filling of fluvial channels (which can be very fast: from a few decades to 200 years) and the development of crevasse splays and avulsions. In this context, the hazard (i) liberates a strong energy that is very dangerous for human life and (ii) can destroy land functions that predominated before the flood event.

(2) Hydromorphy in the flood plain: It is a constraint as big as the fluvial one, as presented in (1), because an outcropped water table disturbs the viability of a settlement and the possibilities of floodplain land use. For example, Arnaud-Fassetta et al. (2000) have shown that cereal agriculture in Le Pont Noir (LPN) stopped just after the extension of the hydromorphy in the flood plain of the UL palaeo-Rhone around the 1st century BC. Another study (see Arnaud-Fassetta, 2000) explains that human occupation on the sites of CAB, LCP and LPN followed the change of environment from hydromorphous environments (swamp) to well-drained environments (flood plain).

(3) Hydraulicity and channel morphology: In the delta, economic activities were partly supported by the fluvial network. As regards navigation, deep and wide channels, low stream power or the possibility to navigate on secondary channels were very important. We however do not know how concept of risk was taken into account, because the abandonment of sites could occur in different and opposed hydrological

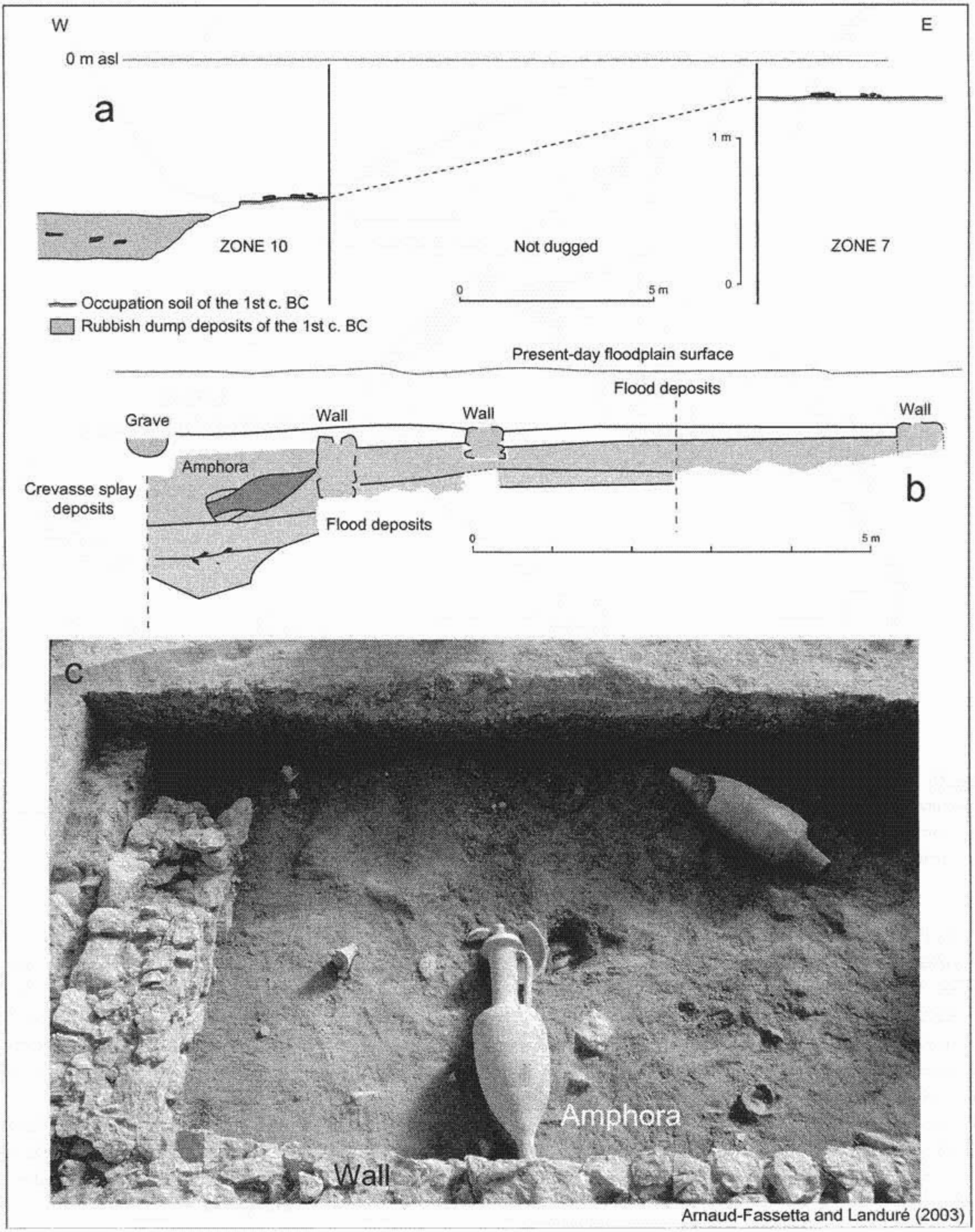

Fig. 10a. General view of topography in LCP of the 1st century BC. The presence of an intact amphora closed by a cap is a sign that the site has been rapidly abandoned, probably after the large flood event of the end of the 1st century BC.

contexts, either (i) a too low channel hydraulicity (LCO, CAB) or (ii) a too high channel hydraulicity with the development of crevasse splays (LCP) and/or channel in-filling, which encouraged the use or digging of secondary channels (e.g. the excavation of the Marius canal).

Therefore, this study highlights a paradoxical result: when fluvial risk was high, the communities established on the alluvial ridges of the palaeo-Rhone (SF, UL), which were then very vulnerable to floods (*Fig. 11*). The abandonment of sites and the decrease in economic activities occurred (i) suddenly, but not for a long time, when crevasse splays and avulsions appeared or (ii) gradually, but for a long time, when the water table rose. On the contrary, when the risk was low, moribund palaeochannels favoured a retreat in the occupation and the abandonment of sites, although the strength of the hazard and the risk were greatly weakened.

At this stage, it is important to introduce the concepts of threshold/vulnerability/resilience of societal and environmental systems (Bailly et al., 1996; Smith and Ward, 1998). Threshold concept is linked to the evolution of natural constraints (climate, hydrology) and their environmental expressions (channel hydraulicity, crevasse splays and avulsions, water table). The impact of these constraints can be overcome by societies if their resilience is high, that means if social groups are able to come back to their initial situation immediately after the event. If fluvial constraints are greater than the capacity of resilience of societies (which includes its degree of vulnerability), an irreversible threshold is attained, and societies must find a new balance.

On the site of LCP, hazard represented a big constraint on goods and probably on human beings only when hazard exceeded a certain limit (i.e. when it combined frequent overflows, crevasse splays, avulsions). Environmental pressure and risk became so unbearable for local population that the site was abandoned and restored a few decades later. In this case, the threshold was reached very suddenly and the vulnerability of the population was high. Moreover,

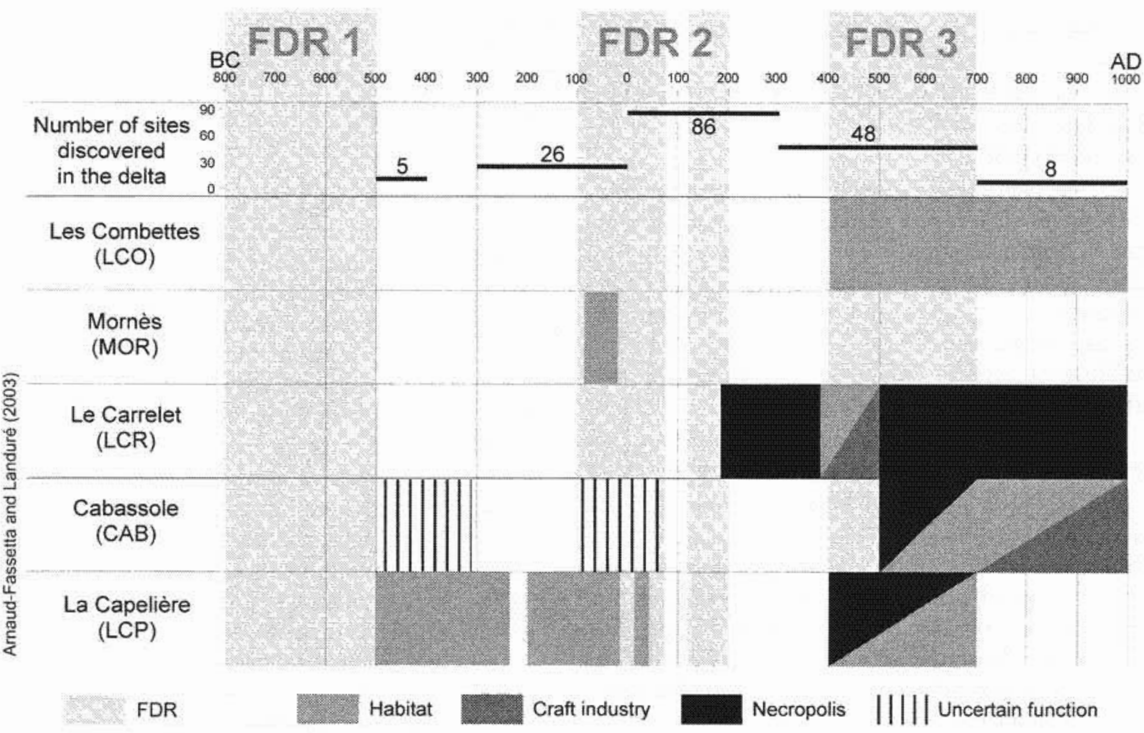

Fig. 11. Correlations between the Rhone's hydrological regime and ground occupation in the deltaic plain from 800 BC to AD 1000.

the resilience of the societal system might have been weakened because several decades were necessary to restore and inhabit this site, whereas it only took several days to a couple of years to react to the recent Rhone floods of 1993–1994.

In other cases, the resilience of the societal system might have been stronger, pushing the threshold that makes the environmental system go from acceptable to unacceptable, higher. For example, we showed that the hydraulicity of the SF palaeo-Rhone decreased which involved channel in-filling from the 8th century AD. However, its riverbanks were occupied at least until the 10th century AD. That means that during two centuries, populations were confronted with different problems: (1) the discontinuity of the fluvial network and difficulties in navigating in this part of the delta (and certainly the necessary maintenance and cleaning it implied) and (2) still water [bad smell, diseases, etc. (see Rossiaud, 1994)] and (3) the rise of saltwater levels and the freshwater supplies, due to an insufficient supply of fluvial water.

5. Summary and concluding remarks

The outcome of this research can be summarised as follows:

(1) The palaeo-Rhone appears as a major element that has structured the development of human settlements in the delta.

(2) The vulnerability of societies was strong because 79% of the sites were situated along the Rhone palaeochannels, in the zone liable to flooding of the alluvial plain. However, vulnerability was lessened by settling on the highest points of the flood plain, digging of drainage ditches in the flood plain and building of boulder armouring for minimising the effects of fluvial erosion.

(3) The time of occupation of a site depends on the time of functioning of a Rhone palaeochannel.

(4) The permanence of the habitats appears less conditioned by flooding sensu stricto than (i) the abrupt events like crevasse splays or avulsions, (ii) the raise of water table and the hydromorphy in the flood plain and (iii) the channel morphology and channel hydraulicity. Nevertheless, an hydraulicity too low or too strong can produce the same effects and involve the abandonment of the habitats.

(5) The fluvial risk was strong when from the hydroclimatic hazard point of view, (i) the repetitive flood events, in a context of FDR, involve a channel in-filling and crevasse splays/avulsions development and (ii) the increase of mean discharges involves the general raising of water table levels and the hydromorphy of the flood plain. From the societal vulnerability point of view, (i) the settlements are installed near the Rhone or in the zones of possible chute cut-offs and (ii) the preventive measures against floodplain submersion or fluvial erosion are ineffective.

(6) The fluvial risk was low when from the hydroclimatic hazard point of view, (i) in a context of DDR or IFDR, the incised channel has a sufficient capacity to contain most of the flood flows, reducing crevasse splays/avulsions development, (ii) the hydraulicity of the channel is too low and (iii) low mean discharges of the river involve the lowering of the water table, enough to allow the good draining of the deltaic plain, but not too much either, to limit the soils salinization. From the societal vulnerability point of view, settlements are (i) rare near the Rhone or (ii) present in a context where the preventive measures against floodplain submersion or fluvial erosion are effective and (iii) the socio-political context is (supposed) favourable.

(7) This study has allowed to precise the status of the fluvial risk, which could have been:

- Relatively slight: In certain cases, the fluvial risk could have been absolutely managed by the social groups installed near the Rhone. In fact, the environmental determinism seems to be relatively weak and henceforth we can rule out a relation of cause and systematic effect between the development/abandonment of the habitats and the hydrological regime of the Rhone. The diversity of fluvio-deltaic environments has probably given the human society the choice in the installation of the habitats and allowed some geographical adjustments faced with flood events. Moreover, except in the contexts of abrupt flood events (crevasse splay, avulsion), the slow rise in the Rhone's flood overflows probably gave the social groups time to react faced with the flood events in the delta.
- Suffered: Even if the fluvial risk was real, in fact very few preventive measures were taken for minimising the vulnerability of the sites. Only some sporadic boulder armouring has been found, but any remain of hydraulic equipment really efficient against floods, like levees, has

been discovered. Furthermore, we must lay stress on the absence of a consistent flood management system along the whole fluvial system. The only preventive measures against floods have focused on (i) the digging of drainage ditches and (ii) the protection of the riverbanks by boulder armouring. With the first ones, the protection against floods was relatively slight. With the second ones, the erosion of the riverbanks was weakened but they did not deprive the Rhone to overflow: therefore the sites have been kept vulnerable faced with the flood plain submersion, despite the undeniable will to weak its effects.

- Accepted: The question still remains insofar as the economic interest can be considered as the main reason of the installation of the societies in the alluvial plain of the Rhone. This fact leads us to ask three other questions:

(i) How did the societies appreciate the fluvial risk?

(ii) Did they look at the flood risk objectively?

(iii)Did they have sufficient technological means/ social organisation to analyse the risk in order to have other choices that accept it?

Similarly, did the management of the fluvial risk in the countryside has really been a priority (and if yes, on what scale) during the two studied millenia?

(8) Finally, the parameters that control the dynamics of ground occupation depend on complex processes and causal relations between the hydroclimatic hazard and the societal vulnerability have not been always strictly linear. If the channel changes, like between the 1st century BC and the 2nd century AD, had a strong impact on the ground occupation (rapid abandonment, hiatus in the frequenting sites), it seems that during other periods, the sites (i) were continuously occupied despite the flooding context or (ii) abandoned without the flood risk being the main cause. At this stage, the research could be detailed involving more historians and sociologists, so that we can access "objectively" of the influence of socio-economic and political factors in the evolution of the fluvial risk.

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