# PALAEOHYDROGRAPHIC, PALAEOHYDROLOGICAL AND PALAEOHYDRAULIC INVESTIGATIONS IN MEDITERRANEAN GEOARCHAEOLOGY. CASE STUDIES OF THE RHÔNE RIVER (FRANCE) AND ISONZO RIVER (ITALY) DELTAS

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## ABSTRACT

The multi-secular history of deltaic plains is strongly influenced by recurring fluctuations in the river regime. Frequency and magnitude of floods, crevasse splays and channel avulsions are considered to be important factors of the deltaic-environment evolution. The Mediterranean deltas of the Rhône River (Gulf of Lion) and Isonzo River (Gulf of Trieste) are used as case studies to support this hypothesis. Geoarchaeological investigations focusing on palaeoenvironmental reconstructions and on the links between river dynamics and human societies since Protohistory were conducted in both deltas. The links require the reconstruction of three parameters, *i.e.* hydrography, hydrology and hydraulics. This paper clearly demonstrates the need to cross these three hydrometric approaches to look at both the deltaic development and the riverine environment, and to how communities react to long- and short-term variations in fluvial dynamics. Fluvial risk cannot be reduced to, and satisfactorily assessed by, using only one of these three approaches.

## KEY WORDS

Palaeohydrography, palaeohydrology, palaeohydraulics, Mediterranean geoarchaeology, Rhône River Delta, Isonzo River Delta.

## RESUME

À l'échelle des derniers millénaites, l'histoire des plaines deltaïques est fortement marquée par la variabilité du régime hydrologique des cours d'eau qui les drainent. Les crues, les deltas de rupture de berge et les défluviations sont des aléas dont la fréquence et la magnitude conditionnent la dynamique des environnements deltaïques. Cette hypothèse a été confirmée par l'étude de deux deltas méditerranéens, celui du Rhône (Golfe du Lion) et de l'Isonzo (Golfe de Trieste). Les recherches géoarchéologiques ont focalisé sur la reconstitution des milieux depuis la Protohistoire et sur l'analyse des relations entre la dynamique fluviale et les communautés riveraines, qui passe par la détermination de trois types de paramètres (hydrographie, hydrologie, hydraulique). Cet article démontre l'intérêt de mener de front ces trois approches dans les études hydrogéomorphologiques, pour qui s'intéresse à la façon dont les sociétés réagissent aux fluctuations à plus ou moins long terme de la dynamique fluviale. Le risque hydrologique ne peut être suffisamment défini en ayant recours à l'une de ces trois approches seulement.

## MOTS CLEFS

Paléohydrographie, paléohydrologie, paléohydraulique, géaorchéologie méditerranéenne, delta du Rhône, delta de l'Isonzo.

### The hydrogeomorphological supply to face the geoarchaeological demand

One of the central points of this paper is that geoarchaeological studies should resort to all facets of fluvial hydrogeomorphology to better characterise river palaeoenvironnements and dynamics of human settlement in floodplains.

During the last decades, fluvial hydrogeomorphology has lead to numerous applications in the field of interactions between societies and their environment (Mackay, 1945; Vita-Finzi, 1969; Potter, 1976; Butzer, 1982; Limbrey, 1983; Burrin and Scaife, 1988; Waters, 1988; Gilbertson *et al.*, 1992; Needham and Macklin, 1992; Barham and Macphail, 1995; Lewin *et al.*, 1995; Bravard and Presteau, 1997; Brown, 1997; Carcaud *et al.*, 1998; Macklin, 1999; Vermeulen and De Dapper, 2000; Bruneton *et al.*, 2001; Coulthard and Macklin, 2001; Cubizolle and Georges, 2001; Fouache *et al.*, 2001; Bintliff, 2002; Fouache, 2003; Lespez, 2003; Lewin and Macklin, 2003; Schimmelmann *et al.*, 2003; Burnouf and Leveau, 2004; Meier, 2004; Salvador *et al.*, 2004; Deckers, 2005; Arco *et al.*, 2006).

There are a number of common themes that emerged from these studies, namely the need for the use of three different hydromorphometric approaches (hydrography, hydrology, hydraulics). In these studies, source data is generated using these approaches and then used to address flood risk in the past. The literature, however, shows that hydrogeomorphological studies in geoarcheological context rarely integrate simultaneously these three approaches.

The aim of this contribution is to demonstrate the relevance of combining these three hydrogeomorphological approaches to better characterise flood hazard in the perspective of fluvial risk analysis. Two deltaic plains are used to support this hypothesis: the Rhône Delta (Southern France) and the Isonzo Delta/Aquileia plain (Northern Italy).

## TWO MEDITERRANEAN STUDY CASES: THE RHÔNE RIVER AND ISONZO RIVER DELTAS

These two Mediterranean deltas have been studied in the framework of numerous research programs [Rhône Delta (Arnaud-Fassetta *et al.*, 2002; Landuré *et al.*, 2004); Isonzo Delta/Aquileia plain (Maselli Scotti *et al.*, 1994; Carre *et al.*, 2004)]. Both deltas have distinct, physical and human histories.

### The Rhône Delta

It is located downstream of a large catchment (97 800 km$^2$) characterised by various hydromorphostructural units (Alps, Massif Central, Jura). The deltaic plain (1740 km$^2$) is a product of fluvial palaeohydrology and glacio-eustatic variations, which occurred during the Late Glacial and Holocene periods. The evolution of the Rhône Delta can be divided into two stages: retrogradational-aggradational then progradational-aggradational. The first one developed from 18 000 to 7500 yrs BP, whereas the second one developed after 7500 yrs BP when sea level approximated its present-day position. The palaeohydrological evolution of the Saint-Ferréol palaeochannel and related river-mouth sandy bars was an important process of delta progradation between 5500 and 4000 yrs BP. During this period, the delta progradation decreased because of the division of the hydrographical network, and the construction of deltaic lobes in deeper marine zones. The present-day Rhône Delta is drained by two sandy-silt-dominated distributaries: the Grand Rhône (1500 m$^3$/s; 9/10 of total water discharge) and the Petit Rhône. Archaeological data revealed the establishment of numerous human settlements in the deltaic plain from the 6th c. B.C. Essentially established along the distributaries of the palaeo-Rhône River, these sites correspond to temporary or small rural settlements located on the main exchange pathways which developed between the sea and the continent via the ports of Marseilles and Arles.

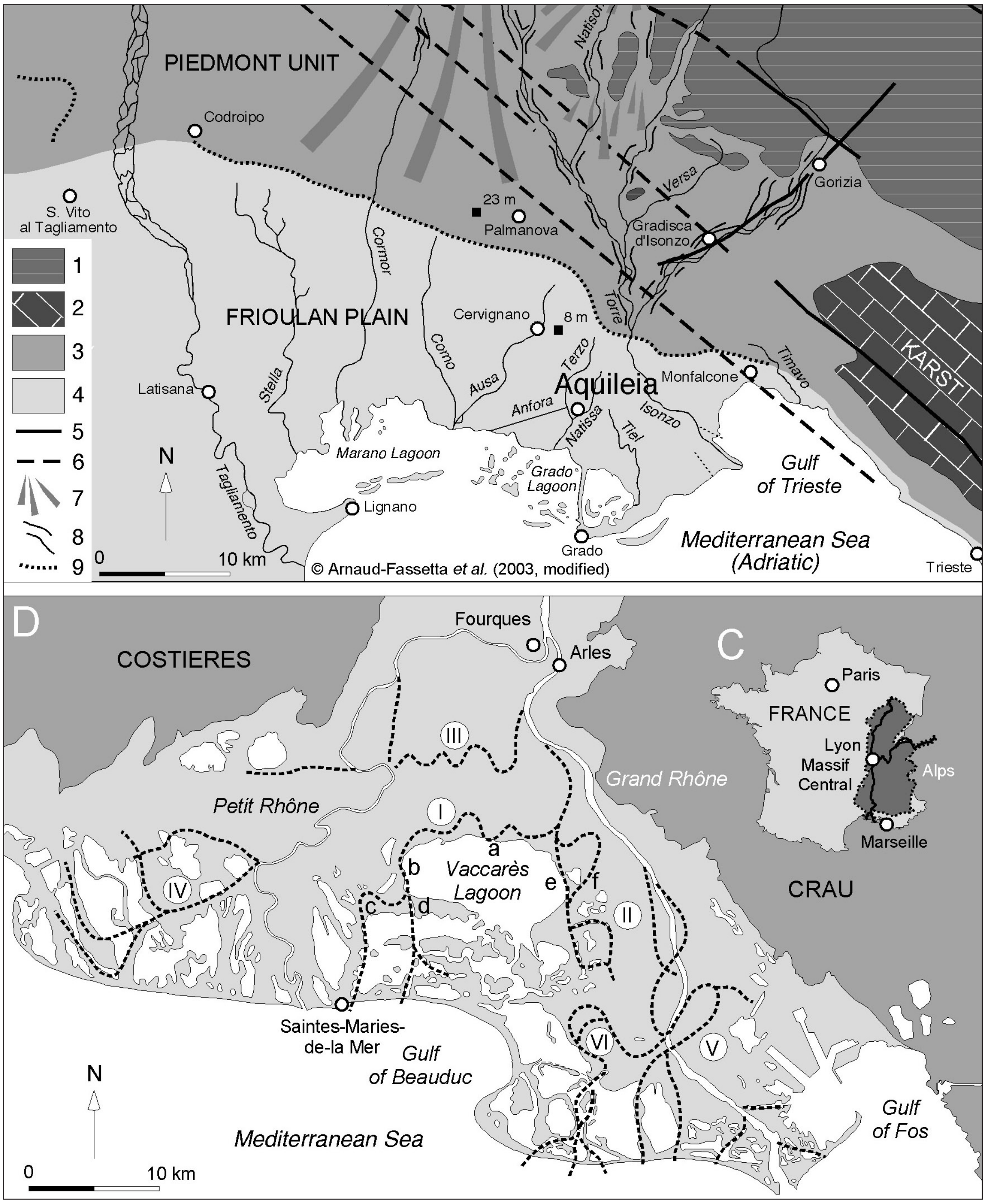



**Figure 1** Location maps of the study sites. (A) Location of the Isonzo catchment. (B) Aquileia deltaic plain and its region. 1: mountainous massifs (limestone, dolomite); 2: Karst plateau and massifs (limestone); 3: piedmont (calcareous marl, marly limestone, marly calcareous flysch); 4: plain unit (Quaternary fluvio-marine infill); 5: major fault; 6: possible fault; 7: alluvial fan; 8: enclosed valley (not represented in the mountainous units); 9: springs boundary. (C) Location of the Rhône drainage basin. (D) The Rhône Delta. I: Rhône of Saint-Ferréol; II: Rhône of Ulmet; III: Rhône of Albaron; IV: Rhône of Peccaïs; V: Rhône of Grand Passon; VI: Rhône of Bras de Fer; a: site of Cabassole; b: site of Le Carrelet; c: site of Les Combettes; d: site of Mornès; e: site of Le Pont Noir; f: site of La Capelière. Note the difference in size between the catchments, deltas and the rivers which drain them.

### The Isonzo Delta

Situated in the eastern part of the Frioulian coastal plain, this deltaic plain (400 $km^2$) is downstream of a 3400 $km^2$ catchment. It is bordered to the east by Karst plateaux and massifs, and to the north by the Alpine massifs and their piedmont. Four main factors controlled the geomorphological evolution of the deltaic area: alluviation, eustatic fluctuations, subsidence process, and anthropogenic actions. During the last Glacial Maximum (23 000-18 000 yrs BP), the Trieste Gulf was an alluvial plain drained by the palaeo-Torre-Natisone-Isonzo hydrosystem to the east and by the palaeo-Tagliamento River to the west. During the post-glacial transgression, the sea first submerged the Istrian coast (10 000 yrs BP), then the Karst coastline of Trieste (7000 yrs BP), then the Frioulian coastal plain. The Holocene Aquileia plain was affected by generally continuous channel-avulsion processes that, at least in the case of the Isonzo River, have continued until now. Today, two types of rivers drain the deltaic plain: (i) several little rivers which lie downstream of a karstic spring boundary on the piedmont, and (ii) the sandy-gravel-dominated Isonzo River (230 m3/s), an allochthonous river which starts in the mountainous area (Julian Alps). From the historical point of view, the first settlement phase in the deltaic plain is dated between the 9th and 8th c. BC The area was occupied for a short period in the 2nd c. BC by Transalpine Gauls, and then more consistently by the Romans who founded a colony in 181 BC. Located at the southernmost part of the Amber Road, Aquileia was one of the most important fluvial harbours of the Roman Empire.

In spite of specific characteristics, both deltas have at least two common features, *i.e.* recurring fluctuations in the river regime (floods and channel avulsions), and flood hazards (evolution of their frequency and magnitude in time) and vulnerability.

## HYDROGEOMORPHOLOGICAL METHODOLOGY

Recent geoarchaeological research has emphasised the links between river dynamics and human societies since Protohistory. These links require the reconstruction of three sets of data, *i.e.* hydrography, hydrology and hydraulics. Source data are textual archives, images (air photos, remote sensing data, maps) and field surveys.

### Palaeohydrography to define rivers basic patterns

Palaeohydrography's aim is to map ancient hydrographical networks. Palaeohydrographical maps of both the Rhône Delta (Arnaud-Fassetta, 2000) and Aquileia plain (Arnaud-Fassetta *et al.*, 2003) were extracted from geomorphological, stratigraphic and geoarchaeological data.


**Figure 2** (A) Acquisition of source data from the geoarchaeological excavations and sedimentological data derived from core samplings and stratigraphy (site of Abbaye d'Ulmet, Rhône Delta). (B) Use of a motorized auger belonging to the University of Paris 7 (site of Abbaye d'Ulmet, Rhône Delta). (C) View of the Rhône of Ulmet at La Capelière. (D) The Rhône of Ulmet downstream of Tout de Brau. (E) The Rhône of Saint-Ferréol at Le Carrelet. (F) The Rhône of Bras de Fer. Arrows indicate the direction of drainage.

The geomorphology of deltaic plains was based mainly on detailed analysis both of topographical/geological maps (scale from 1:25 000 to 1:50 000) and photointerpretation. Following Siché *et al.* (2006), fluviatile palaeochannels were extracted using digital elevation models computed using digital photogrammetry and GIS. Drainage density (km/km$^2$) of deltaic areas was calculated using the equation (Horton, 1945):

$$D_2 = \frac{\Sigma L}{A_d} \qquad (1)$$

where $L$ is channel length (km) in a delta of area $A_d$ (km$^2$). Most of the stratigraphic information was obtained from borehole data (5-25 m deep) collected along transects perpendicular to the palaeochannels axes. Depositional environments and lithofacies were determined using standard sedimentologic facies analysis techniques (Leopold *et al.*, 1992; Miall, 1996).

Vertical-facies changes were identified by variations in grain size, sedimentary structures, biogenic components and the abundance of organic material. The ages of alluvial units were determined from radiocarbon analysis of bulk organic carbon in the sediments, and from archaeological material (Carre and Maselli Scotti, 2001; Landuré *et al.*, 2004).

#### Palaeohydrology as a classic tool for characterising river dynamics

Palaeohydrology aims first of all at characterising fluvial dynamics from the hydrological regime. In this study, we adapted Erskine and Warner (1988)'s typology to the palaeohydrological context of Mediterranean deltas. Finally, regime-based palaeoflow estimates were supported by three types of hydrological regime: flood-dominated regime (FDR), irregular flood-dominated regime (IFDR) and drought-dominated regime (DDR). Palaeohydrological reconstructions were deduced from the analysis of floodplain stratigraphy (nature of channel and bedform migration) and competence criteria (Arnaud-Fassetta, 2006). The "maximal competence" was derived from the grain-size of palaeochannel deposits, as expressed as the median ($D_{50}$) and the coarsest percentile ($D_{99}$) of the grain-size distributions, according to Passega (1957) and Bravard and Petit (1997).

#### The palaeohydraulics as an additional tool in Mediterranean hydrosystems

Palaeohydraulic data, which are sometimes confused with the palaeohydrologic ones, are derived from the calculation of several parameters such as channel capacity, discharge, and stream power. In the Mediterranean basin, the great river floods can be extremely "flashy" and very powerful. Therefore, palaeohydraulic parameters can provide better information on the occurrence of such events in the past. We defined river hydraulics as channel capacity ($C$; in $m^2$), which was obtained using the equation:

$$C = Wd \qquad (2)$$

where $W$ is channel width (in m) and $d$ is mean channel depth (in m). Specific stream power ($\omega$; in $W/m^2$) was used in order to quantify the rate of potential energy expenditure per unit bed area of channel, which controls lateral instability of river channels (Nanson and Croke, 1992), using the equation (Bagnold, 1966):

$$\omega = \frac{\Omega}{W} \qquad (3)$$

where $\Omega$ is gross stream power (in W/m) as defined by the equation:

$$\Omega = \rho g Q S \qquad (4)$$

where $\rho$ is density of floodwaters (1500 $kg/m^3$), $g$ is acceleration due to gravity (9.81 $m/s^2$), $S$ is gradient of the water energy surface (m/m) derived here from elevation of riverbanks, and $Q$ is discharge (in $m^3/s$), which was estimated from the average of four equations (eq. 5: Manning, 1891; eq. 6: Williams, 1978; eq. 7: Rotnicki, 1991):

$$Q = \frac{AR^{0.67}S^{0.5}}{n} \quad (5)$$

$$Q = 4A^{1.21}S^{0.28} \quad (6)$$

$$Q = \frac{0.921}{n} AR^{0.67}S^{0.5} + 2.362 \quad (7)$$

$$Q = AU \quad (8)$$

where $A$ is cross-sectional area (in m$^2$), $R$ is hydraulic radius (in m), $n$ is Manning's resistance coefficient (dimensionless), and $U$ is mean velocity of palaeofloodwaters (in m/s). $U$ was calculated using the equation (Manning, 1891):

$$U = KR^{0.67}S^{0.5} \quad (9)$$

where $K$ is the so-called roughness coefficient of Strickler (dimensionless), defined as (Koulinski, 1994):

$$K = \frac{1}{2}\, 25D_{90}^{-0.17} \quad (10)$$

in which $D_{90}$ is particle diameter for which 90% are finer (in m). Seven equations (eq. 11: Strickler, 1923; eq. 12: Limerinos, 1970; eq. 13: Bray, 1979; eq. 14: Hey, 1979; eq. 15: Griffiths, 1981; eq. 16: Jarrett, 1984; eq. 17: Bathurst, 1985) were used to determine a mean value of $n$:

$$n = 0.0151D_{50}^{0.17} \quad (11)$$

$$n = \frac{0.113R^{0.17}}{1.16+2\log\left(\frac{R}{D_{84}}\right)} \quad (12)$$

$$n = \frac{0.113R^{0.17}}{1.09+2.2\log\left(\frac{R}{D_{84}}\right)} \quad (13)$$

$$n = \frac{0.113R^{0.17}}{2.03\log\left(\frac{aR}{3.5D_{84}}\right)} \quad (14)$$

$$n = \frac{0.113R^{0.17}}{0.76+1.98\log\left(\frac{R}{D_{50}}\right)} \quad (15)$$

$$n = 0.32S^{0.38}R^{-0.16} \quad (16)$$

$$n = \frac{0.32R^{0.17}}{5.62\log\left(\frac{R}{D_{84}}\right)+4} \quad (17)$$

where $D_{50}$ is median bed material grain size (in mm), $D_{84}$ is particle diameter for which 84% are finer (in mm), and $a$ varies between 11.1 and 13.46 as a function of channel cross sectional shape.

Every set of hydrogeomorphological data (hydrography, hydrology and hydraulics) has its own object and method. The objective of this paper is to show that their use in a unified framework can bring helpful results to better understand fluvial dynamics replaced in the physical and human context of both deltas.

## RESULTS

### Hydrogeomorphology of the Isonzo Delta-Aquileia Plain during the Holocene

In the Aquileia area, a palaeohydrographical map of the whole deltaic plain was produced by the analysis of small-scale multi-spectral imagery.

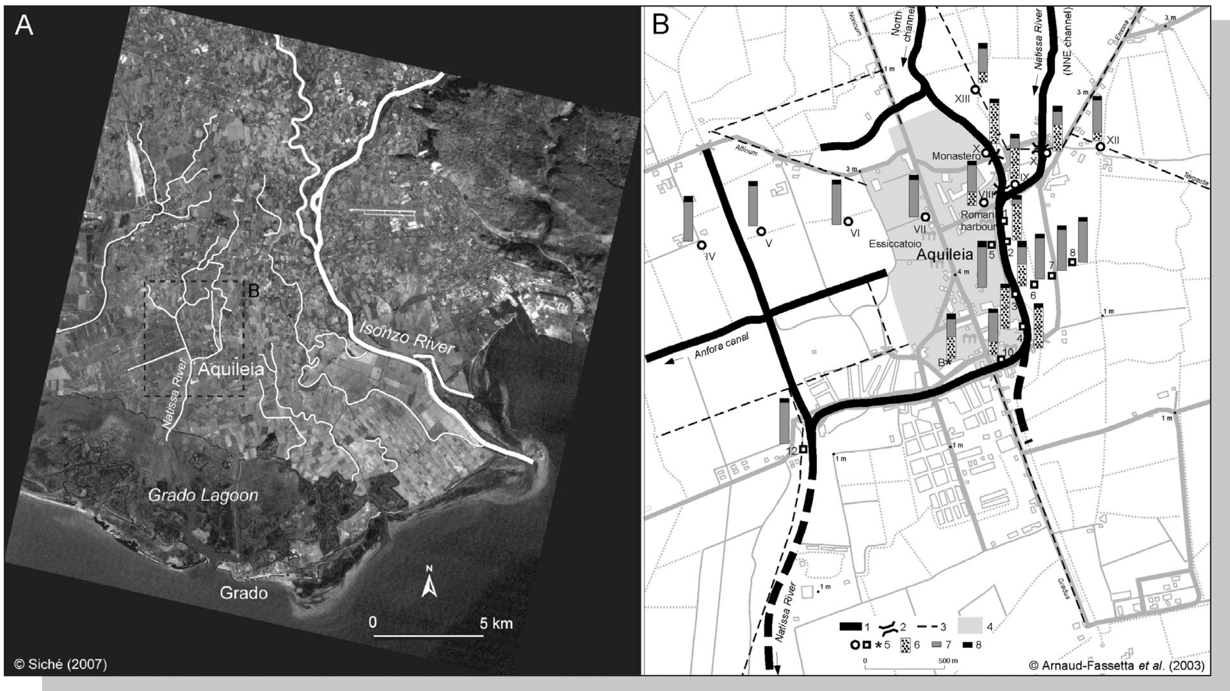



**Figure 3** (A) Hydrographical network of the Isonzo delta plain deducted from remote sensing (LandSat TM, December 1996). (B) Palaeohydrographical interpretation near Aquileia during antiquity. 1: Roman palaeochannel; 2: Roman bridge; 3: Roman road; 4: Roman city; 5: boreholes; 6: channel deposits; 7: flood-plain deposits; 8: reworked deposits. Note that the antique city is lined in the north and in the east by high-energy rivers.

Mapping was refined around the antique site by numerous sediment cores collected in the fluviatile palaeochannels. The Aquileia site was connected to the Torre-Isonzo catchments by a high-energy distributary channel coming from the northeast. The width of the palaeoalluvial ridges varies from 80 m to 300 m, which corresponds to the range of the widths observed along the active channel of the present-day Torre River. A digital elevation model highlights that the Roman city was situated on one of these palaeoalluvial ridges. Aquileia city was built on the concave riverbank of a fluvial meander near to palustrine environments, as indicated both by the historic sources and stratigraphic data. Upstream from the Aquileia site, this palaeochannel divided into two fluvial branches. The first one came from the north and was directly connected to the site *via* the Roman bridge. The second one, now a spring-fed river, came from the northeast. Geoarchaeological investigations allowed us to improve the evolution scenario of the channel geometry of the latter, in particular its narrowing in time.

Recent palaeohydrological work confirms the presence of important waterways at least since the Bronze Age. During antiquity, Aquileia deltaic plain was crossed by rivers flowing on alluvial ridges. Both flooding and regular sediment supply lead to the aggradation and progradation of the deltaic plain. Several cores were retrieved from the subsoil located around the ancient Roman fluvial harbour.

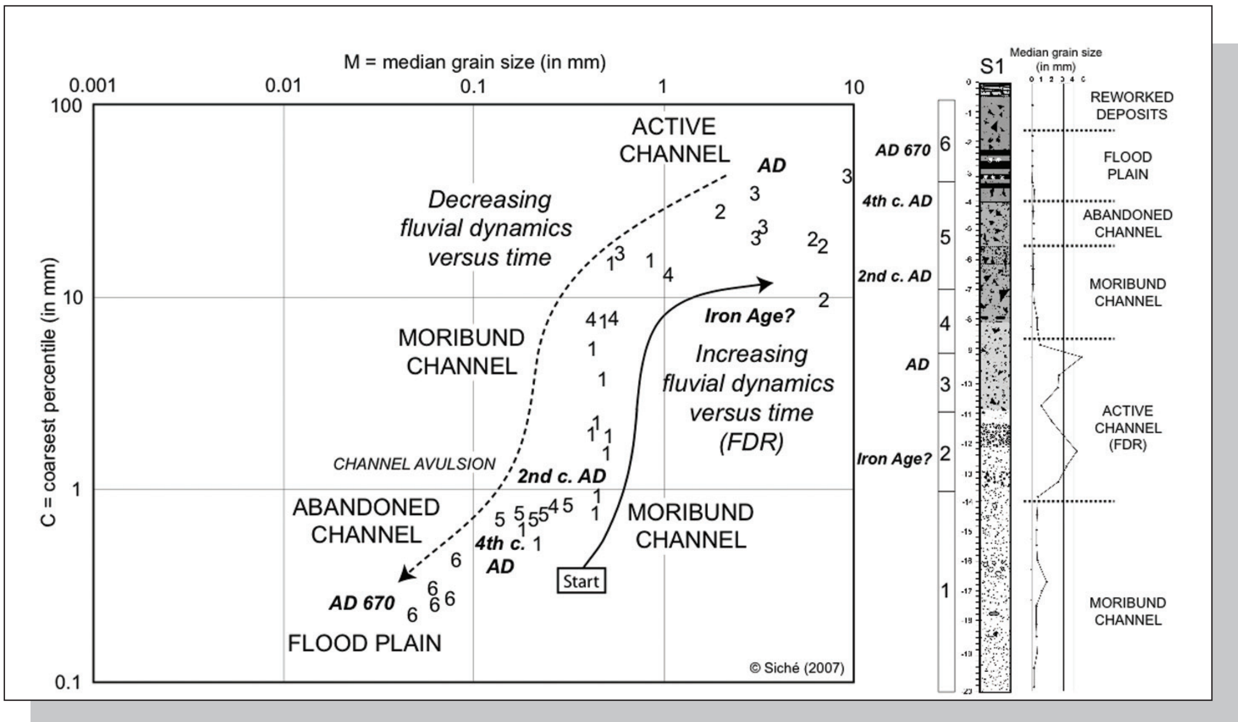
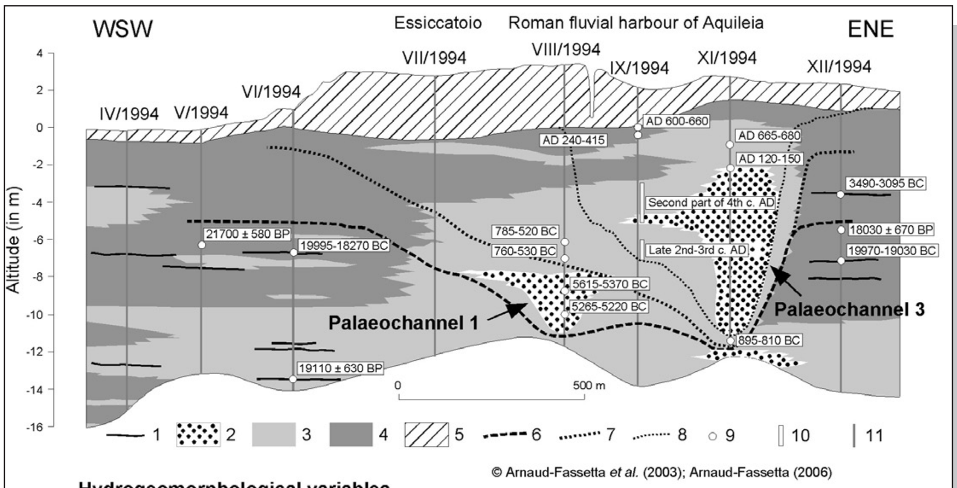



**Figure 4** Palaeohydrological evolution in the Isonzo Delta between the Iron Age and early Middle Age, deducted from chronostratigraphical data and the use of CM pattern of Passega (1957). Note the maximum competence of palaeochannels around the turn of the era, *i.e.* after Aquileia's foundation in 181 BC.

The core deposits record the presence of high-energy, braided-type river channels. The S1 core is representative of this sequence: channel activity (torrential FDR, strong competence) was maximum between the end of the Iron Age and the early Antiquity, then hydrodynamics decreased till the early Middle Age. This hydrological dynamics is shown by the CM pattern.

Hydraulic calculations, including those of stream power, confirm the hypothesis of a high-energy hydrosystem.




**Hydrogeomorphological variables**

| | Palaeochannel 1 | Palaeochannel 3 | Present Isonzo (17 km upstream of the rivermouth) | |
|---|---|---|---|---|
| $d$ | 1.5 | 2.0 | 3.6 | $d$: mean depth (in m); |
| $W$ | 420 | 423 | 287 | $W$: width (in m); |
| $s$ | 0.0025 | 0.0025 | 0.0020 | $s$: slope (in m/m); |
| $A$ | 539 | 1058 | 802 | $A$: cross-sectional area (in m²); |
| $P$ | 313 | 589 | 291 | $P$: wetted perimeter (in m); |
| $R$ | 1.72 | 1.80 | 2.76 | $R$: hydraulic radius (in m); |
| $n$ | 0.03 | 0.03 | 0.03 | $n$: roughness coefficient; |
| $D_{50}$ | 50 | 49 | 51 | $D_{50}$: median grain size (in mm); |
| $D_{84}$ | 100 | 102 | 99 | $D_{84}$: grain size 84% of particules are finer (in mm); |
| $D_{90}$ | 122 | 117 | 120 | $D_{90}$: coarsest decile (in mm); |
| $U$ | 2.4 | 2.9 | 3.5 | $U$: flow velocity (in m/s) ; |
| $Q$ | 1201 | 2441 | 2227 | $Q$ : instantaneous discharge (in m³/s); |
| $\omega$ | 130 | 201 | 258 | $\omega$: specific stream power (in W/m²). |

**Figure 5** Lithostratigraphic section and palaeohydraulics at Aquileia, Isonzo Delta.

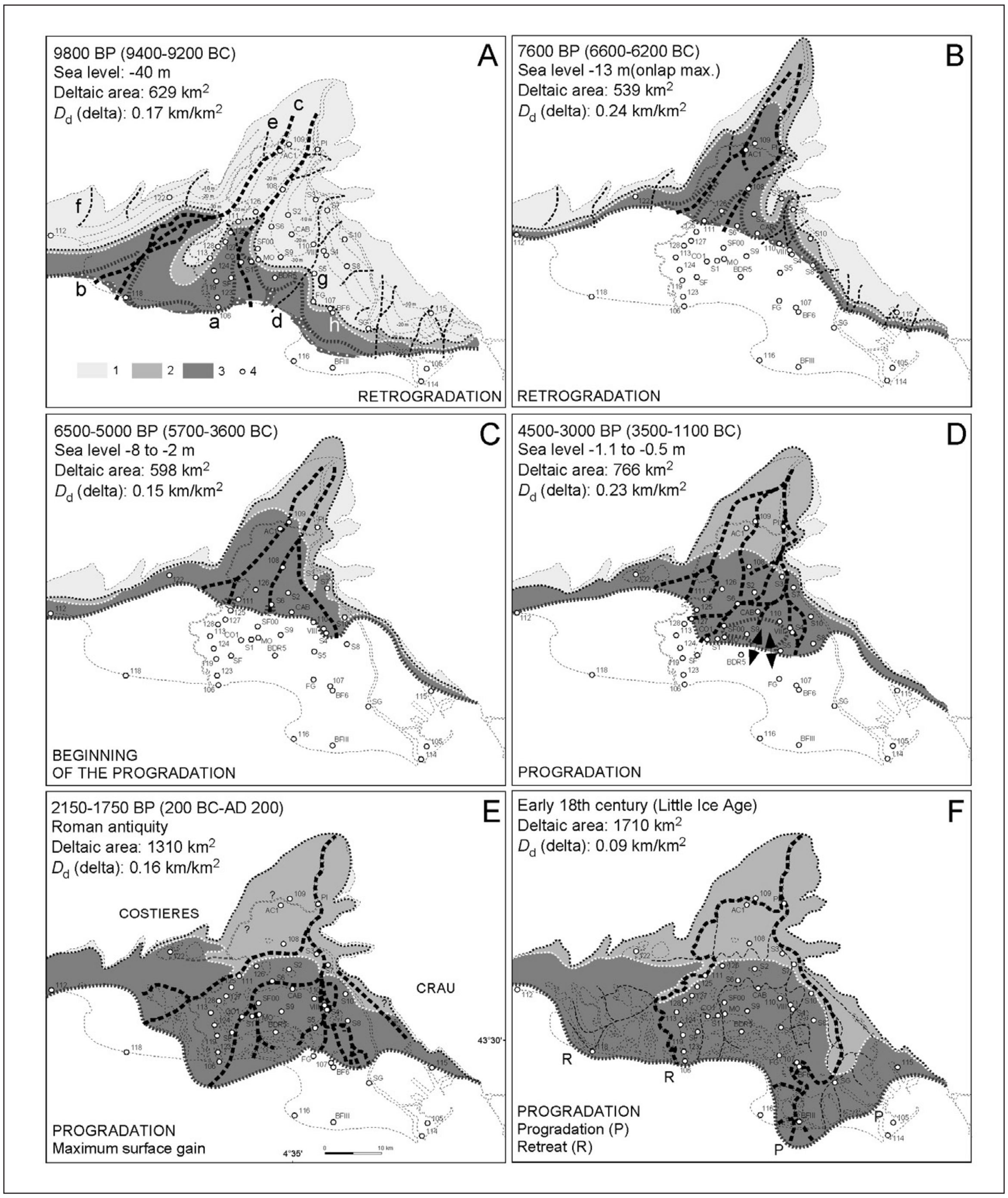
1 peat;
2 gravel;
3 sand;
4 pelite;
5 reworked material;
6 alluvial floor post 18030 ± 670 BP;
7 alluvial floor post 3490-3095 BC;
8 alluvial floor post 785-520 BC;
9 radiocarbon date (cal.);
10 archaeological date;
11 SARA borehole (1994).

The alluvial sequence reveals the presence of three cut-and-filled palaeochannels, dated from 5615 BC to AD 150. The geometric characteristics of palaeochannel 3, the most recent, allow to compare it with the present-day, braided Isonzo downstream of the confluence with the Torre. The specific stream power confirms this hypothesis, showing the existence, at the beginning of the antiquity, of the alluvial plain with multiple channels, on which river avulsions are explained both by the progradation of channel bars and aggradation of the alluvial floor. See text for the formula of the used hydraulic parameters.

The specific stream power has been estimated to have a maximal value of 200 W/m², typical of a braided river floodplain, where the dominant process is lateral point-bar or braid-channel accretion, according to Nanson and Croke (1992). This value is close to that observed on the present-day Isonzo River (to the east) at 17 km upstream from its mouth. The position of the palaeocoastline contemporary of the Roman site was probably situated at this distance, according to historical data.

### Holocene hydrogeomorphology of the Rhône Delta

In the Rhône deltaic plain, the palaeohydrographical data were acquired by numerous deep core samplings coupled with photointerpretation of recent fluvial forms (Arnaud-Fassetta and Provansal, 1999). The hydrographical network was placed in its environmental context (strictly continental or deltaic). For the last 10 millennia, palaeohydrographical maps show the speed at which the hydrographical network evolved before the completion of the embankment works at the end of the 19th c. (Arnaud-Fassetta, 2003).



The hydrographical network developed at the same time as the delta progradation, as the result of both decreasing sea-level rise and alluviation of the Rhône River. The drainage density (*i.e.* number and length of fluviatile distributaries) evolved, which modified the effect of flood events on the riverine communities. The flood impact on societies have been estimated by the "frequency-magnitude analysis" of flood events.

Environmental databases (Arnaud-Fassetta *et al.*, 2000, 2005) succeeded in compiling a robust, palaeohydrological synthesis since the Iron Age (Arnaud-Fassetta and Landuré, 2003), revealing four phases of FDR (first Iron Age, turn of the era, late Antiquity-early Middle Age, Little Ice Age). The fine-floodplain deposits were used to characterise both the frequency and magnitude of floods (event analysis). Floods greatly controlled sedimentation rates and burying ratios in the deltaic plain, and the avulsions and metamorphoses of palaeochannels (Arnaud-Fassetta, 2002; Arnaud-Fassetta, 2004). Hydraulic calculations allowed us to quantify channel capacities, discharges and specific stream powers, which relate to these flood events.

←**Figure 6** Hydrogeomorphological and palaeohydrographical changes in the Rhône Delta during the last 10 000 years.

1 freshwater, continental environment;
2 freshwater, deltaic environment;
3 brackish-salted, deltaic environment;
4 borehole;
a coastal fringe;
b sandy bar;
c Rhône palaeochannel;
d, e, f minor coastal river, tributary, other river;
g deltaic area boundary;
h hypothetical "fresh-water/brackish-salted" environments boundary.

**Note**

1 the maximum rate of deltaic progradation between 4500-3000 BP and 2150-1750 BP, and
2 the decrease of the drainage density during Modern times of anthropogenic origin.

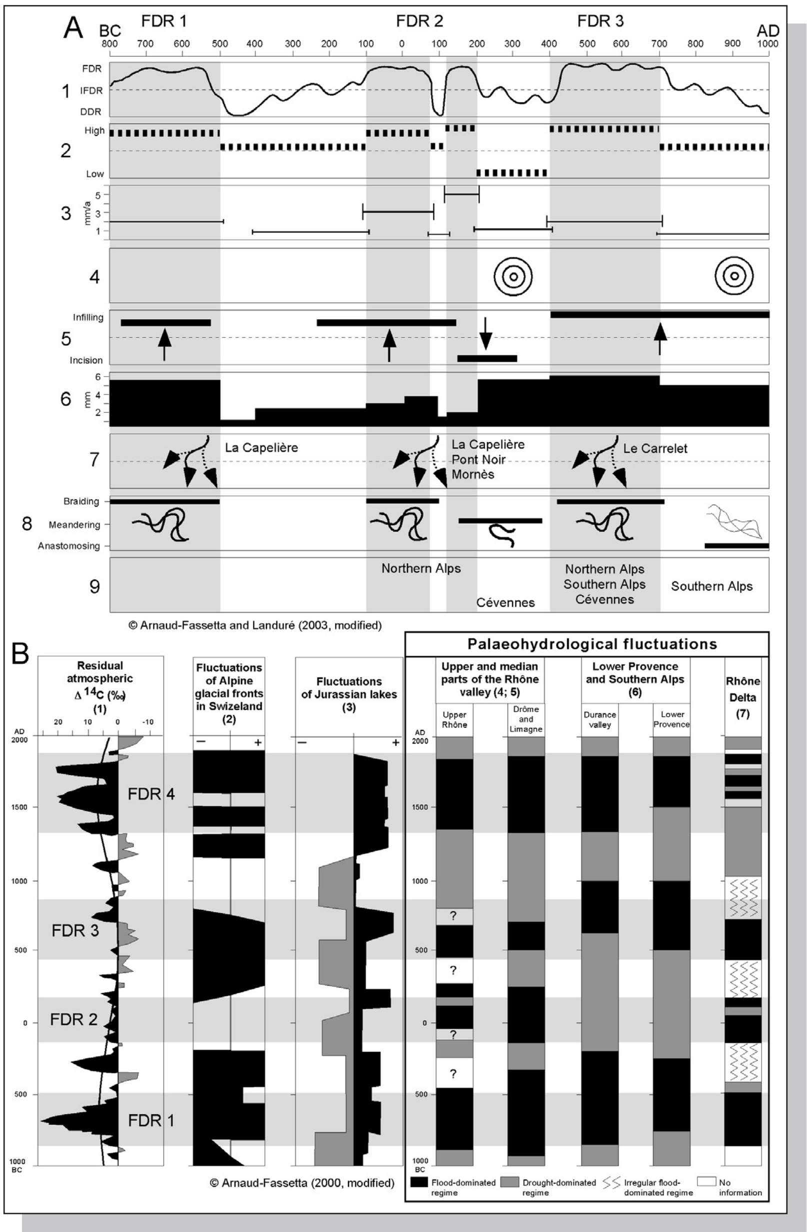



**Figure 7** Palaeohydrology of the Rhône Delta and relationship with the catchment.

(A) Palaeohydrological synthesis of the Rhône Delta from 800 BC to AD 1000.
1 hydrological regime;
2 mean river discharge and phreatic level;
3 sedimentation rates in the flood plain;
4 pedogenesis in the flood plain;
5 channel geometry;
6 channel competence;
7 defluviations and crevasse splays;
8 fluvial style;
9 source zones of channel sands.

(B) Correlations between the palaeohydrology of the Rhône Delta and the functioning of the Rhône catchment.
1 Stuiver and Braziunas (1993);
2 Patzelt (1994);
3 Magny (1992);
4 Bravard *et al.* (1992);
5 Berger (1996);
6 Jorda and Provansal (1996);
7 Arnaud-Fassetta (2000).

Note the relationship between the hydrosedimentary functioning of the Rhône Delta and that of its catchment and the West-European palaeoclimatic data. The absence of correlation between Provence and southern Alps during the early antiquity is speculative.

The hydraulic characteristics of the antique and medieval fluviatile palaeochannels were deduced from an analysis integrating bed geometry, hydraulic slope and grain size of the alluvial infillings. Calculations derived from the hydraulic geometry of the present-day Rhône Delta River serve as control. The results show that: (i) today, the bankfull capacity of both Rhône channels approximate 8895 m$^2$; (ii) during the late Antiquity, the three distributaries of the Rhône River had a bankfull-channel capacity (8694 m$^2$) very close to the present-day; (iii) during the late Middle Age, the bankfull-channel capacity of the Rhône River was only 3887 m$^2$.

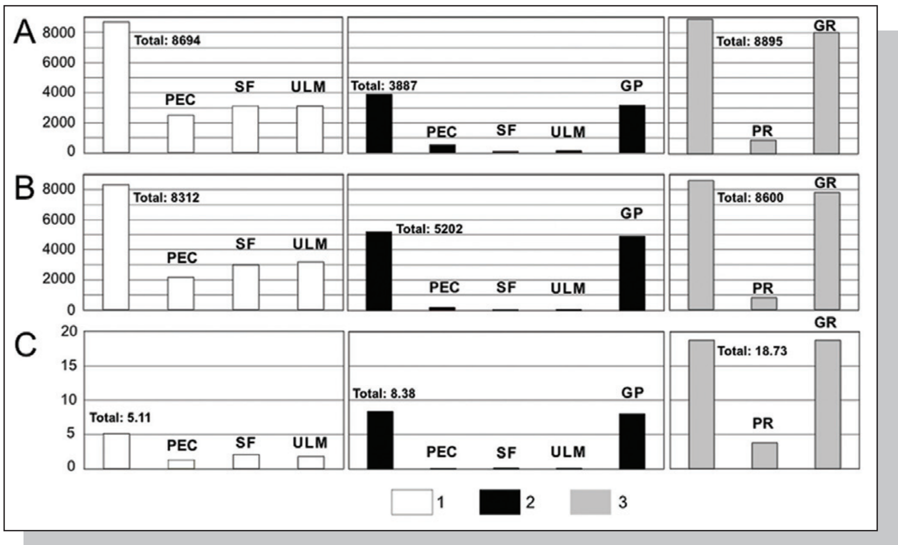



**Figure 8** Palaeohydraulics of the Rhône River in the deltaic area. (A) Bankfull channel capacity (in $m^2$); (B) Bankfull discharge (in $m^3/s$); (C) Bankfull specific stream power (in $W/m^2$); 1: late antiquity; 2: late Middle Age; 3: present-day; SF: Rhône of Saint-Ferréol; ULM: Rhône of Ulmet; PEC: Rhône of Peccaïs; GP: Rhône of Grand Passon; GR: Grand Rhône; PR: Petit Rhône.

This lower value means that a large part of the drainage in the deltaic area was made by overbank process during flood events, and not only into the main distributaries. In this case, the fluvial risk was greater for each large flood overflow. These results are confirmed by the palaeodischarge estimations. The evolution of the specific stream powers shows that in the late Antiquity, they were distributed well on the whole deltaic plain. In the late Middle Age, specific stream powers increased and concentrated in the east part of the Rhône Delta, thereby increasing both the impact of fluvial hazards, and the induced hydrological risk.

## DISCUSSION: WHAT CORRELATIONS BETWEEN HYDROGEOMORPHOLOGICAL DYNAMICS AND SOCIETIES?

The question of the correlations "river ↔ flood ↔ society ↔ risk (↵)" was addressed at both studied areas, by the recent work on fluvial risk in the Rhône Delta (Arnaud-Fassetta and Landuré, 2003), and by the PhD of Siché (2008) in the Isonzo Delta.

At Aquileia, interaction of palaeohydrology with Roman, urban development is clearly asserted. River flooding provides "natural" hydrological constraints in the deltaic plain, to which Roman communities responded by channelising rivers to ensure good navigability conditions and by implementing flood protection measures and reducing hazards in these hydromorphous environments (Arnaud-Fassetta *et al.*, 2003).

In the Rhône Delta, fluviatile palaeochannels were a major structural driver of the development of human settlements. The vulnerability of antique and medieval societies was strong because 79% of the sites were situated along the

Rhône palaeochannels, in the proximal flood plain. However, vulnerability was mitigated by settling on the highest points of the floodplain, digging of drainage ditches for reducing the time of flooding in the flood plain, and building of boulder armouring for minimising the effects of fluvial erosion in the channels. The evolution of land-use, particularly along the riverbanks of the older channels, seems to have been globally independent of the variability of the hydroclimatic hazard.

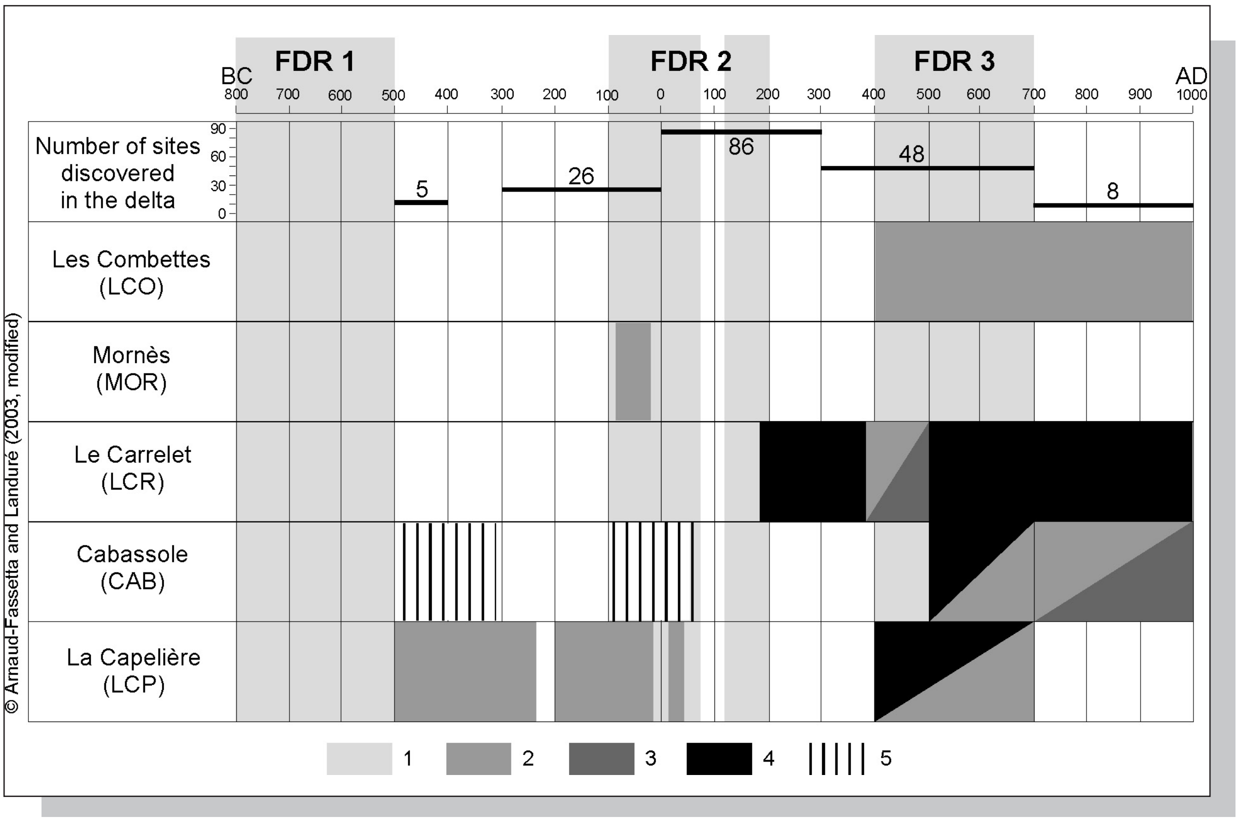



**Figure 9** Correlations between the hydrological regime of the Rhône River and human settlements in the deltaic plain from 800 BC to AD 1000. 1: flood dominated regime; 2: habitat: 3: craft industry; 4: necropolis; 5: uncertain function. Note the absence of correlation between the regime of the Rhône River and the number of sites.

A site could be occupied whatever the hydrological regime of the Rhône River was, even during periods of FDR. In fact, during Antiquity and Middle Ages, the fluvial risk depended mainly on the simultaneous occurrence of several types of hazard in the floodplain. The hydrological risk was high when there was a combination of at least five main physical factors: (ii) numerous fluviatile distributaries with low channel capacity, *i.e.* shallow, infilled channels; (ii) repetitiveness of overflows, crevasse splays and avulsions during periods of FDR; (iii) high specific stream powers; (iv) fragile river banks (low height, easily erodible lithology, little vegetated); and (v) hydromorphy in the floodplain.

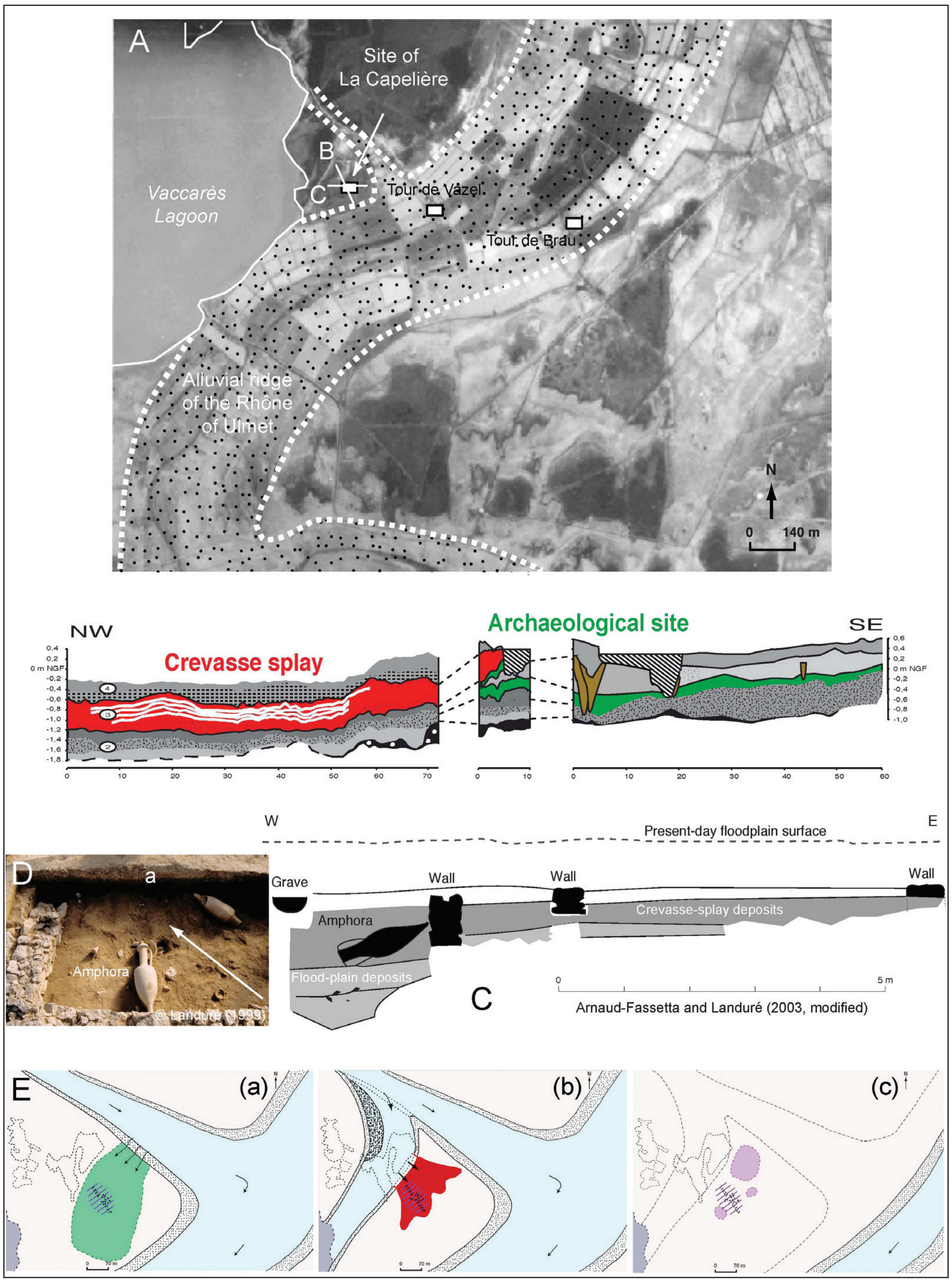



**Figure 10** Results from recent geoarchaeological investigations at La Capelière, Rhône Delta. This illustrates the phenomenon of converging factors enable to lead to the abandonment of an inhabited site situated near to the active channel of the palaeo-Rhône River. (A) Location of the archaeological site on the alluvial ridge of the Rhône of Ulmet. (B) General stratigraphic section, showing the evolution of depositional environments [palustrine, fluviatile (flood plain, crevasse splay)]. (C) Detail of the stratigraphic section showing the burying of the archaeological vestiges (end of 1st c. BC) by crevasse-splay deposits. (D) Photograph showing two amphora and walls (end of 1st c. BC) covered by crevasse-splay and flood-plain deposits (a). Arrow indicates the direction of flood palaeoflux. (E) Maps showing the hydrographical evolution around the site. a: 5th-1st c. BC; b: end of the 1st c. BC; c: 5th c. AD. Note the presence of a crevasse splay whose silty-sand deposits completely recovered the archaeological site at the end of the 1st c. BC. This catastrophic event involved the abandonment of settlement until AD 40.

## HYDROGEOMORPHOLOGICAL-GEOARCHAEOLOGICAL CONCLUSIONS AND PERSPECTIVE

From a geoarchaeological perspective, the hydrogeomorphological approach requires the concurrent use of three approaches (hydrography, hydrology, hydraulics). It is best to analyse correlations between rivers and societies, and the use of recent analogues to link the functioning of present river systems with the past, within the limits of the "actualist" method. Fluvial risk cannot be reduced to, and satisfactorily assessed by, using only one of these three approaches.

Palaeohydraulics was often neglected in former Mediterranean studies. Yet, this approach is essential when: (i) the sedimentology of channel deposits is not a discriminating parameter; (ii) sediments are lacking at the bottom of a palaeochannel; (iii) in urban context, palaeochannel widths are assessed by historical sources only.
Finally, palaeohydrography, palaeohydrology and palaeohydraulics have the potential to guide important changes in flood-frequency analysis and flood-risk assessment.

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