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Fluviatile palaeoenvironments in archaeological context: Geographical position, methodological approach and global change – Hydrological risk issues

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ABSTRACT

Under the perspective of fluvial risk analysis in urban and rural areas, three large catchments of the Western Europe (Loire, Rhône, Isonzo/Frioul-Italy) have been studied to demonstrate the relevance of combining the three hydrogeomorphological approaches (hydrography, hydrology, hydraulics). This combination allows better characterisation of both Holocene hydroclimatic variability and flooding hazard. The hydroclimatic hazard has been quantified in the three studied catchments, highlighting several phases of flood-dominated regime (FDR) since the end of Late Glacial. Impacts of FDRs were aggravated at sometimes by human actions over the last 5000 years. Combining hydrogeomorphological data with land use data allows an analysis of fluvial risk in each catchment studied. In a general way, fluvial risk has been significantly analysed since the construction of anthroposystems (e.g., since the Roman time). The fluvial risk evolved differently in cities (Tours, Vienna, Lyons, Aquileia) and rural zones (Varennes de Tours, Rhône Delta).

1. Introduction

Research led by hydrogeomorphologists has lead to numerous applications in the vast field of geoarchaeological sciences (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 Prestreau, 1997; Brown, 1997; Carcaud et al., 1998; Macklin, 1999; Provansal et al., 1999; Arnaud-Fassetta, 2000; Vermeulen and De Dapper, 2000; Bruneton et al., 2001; Coulthard and Macklin, 2001; Cubizolle and Georges, 2001; Fouache et al., 2001; Bintliff, 2002; Lespez, 2003; Lewin and Macklin, 2003; Schimmelmann et al., 2003; Meier, 2004; Salvador et al., 2004; Deckers, 2005; Arco et al., 2006). Hydrogeomorphology provides data on the environmental characteristics around the historical locations of human settlement in river valleys.

Studies in fluvial geoarchaeology aim at defining specific environmental conditions surrounding and within archaeological sites. Taking a long term perspective, the influences of the geologic and climatic factors are paramount. During the last post-glacial, the factors controlling fluvial dynamics are essentially the climate and human action, both of which directly or indirectly influence vegetation cover and soil development. Thus, the current state of valleys, and the rivers which drain them, is a complex product, inherited both from social practices and dynamics of physical environments. Valley history enables the study of fluvial dynamic adjustments resulting from climate and social changes over several millennia. The aim is not only to define the causes of global environmental changes, but also to explore in greater detail the links between river dynamics and human societies in terms of fluvial risk.

Thus, fluvial geoarchaeology necessitates a thorough knowledge of key parameters which allow researchers to describe palaeoenvironments, to explain the causes (climate, autocyclicity, human action) of their evolution and to quantify societal vulnerability facing hydroclimatic constraints. This type of palaeoenvironmental research, necessarily multi- or trans-disciplinary, has expanded on an international scale in recent years, leading to a significant broadening of the knowledge base concerning the linkages among societies, environment and climate. Such an expansion has taken place in France (Bravard and Prestreau, 1997; Arnaud-Fassetta and Landuré, 2003; Burnouf and Leveau, 2004) as

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in the rest of the Mediterranean basin (Raban and Holum, 1996; Vermeulen and De Dapper, 2000; Arnaud-Fassetta et al., 2003; Fouache, 2003; Morhange and Provansal, 2007), to quote only a short, not exhaustive list of publications dealing with river systems and fluvial harbours. The approach is based on palaeoenvironmental investigation methods (field data, sedimentary and palaeoecological analyses, photo-interpretation) integrated with Geographical Information Systems (GIS) and associated with modelling tools (Berger et al., 2005). It ultimately provides spatio-temporal reconstructions highlighting the modifications of drainage networks and river patterns, control factors (global forcing, channel avulsion, channelisation, etc.), and the timing of events.

Hydrogeomorphologists working on fluviatile palaeoenvironments generally find a possible outcome for their research, which concern the geomorphology, fluvial dynamics and palaeohydrology. In particular, geographers generally emphasise two specific points: (i) to establish palaeoenvironmental reconstructions in space and time, and (ii) to clarify the links between river dynamics and human societies in terms of landscape evolution and fluvial risk. Three different approaches (hydrography, hydrology, hydraulics), with specific methods for each one, constitute source data for arguing and discussing flood risk in the past. Literature, however, shows that hydrogeomorphological studies in geo-archaeological context rarely reconstitute these three parameters simultaneously.

The aim of this paper is to demonstrate the relevance of combining these three hydrogeomorphological approaches to better characterise flood hazard in the perspective of fluvial risk analysis. Three large European catchments are used to support this analysis: the catchments Loire and Rhône (France), and the Isonzo catchment (Northern Italy).

2. Regional setting

Three case studies centred on mid-latitude, north-western, European catchments are presented below (Fig. 1). Climatic influences (mountain, as Alps, "Massif Central" and Jura; oceanic or Mediterranean concerning plains and plateaus) are various. The history of these three catchments is characterised by centuries of battles against hydrological hazards, the impact of which varied according to the climato-anthropogenic context. The societal vulnerability was also able to evolve for multiple, interrelated reasons linked to economic, technical, social, cultural, demographic, political and hydroclimatic evolution. The three studied catchments have distinct physical and human histories.

2.1. Loire catchment

The Loire River is 1020 km length with a 115,000 km^2 catchment area (1/5 of the French territory). Between Nevers and Nantes cities, the middle and lower Loire River floodplain includes several vales (Dion, 1961; Babonaux, 1970; Fig. 2A). Some vales have significant dimensions, such as Orléans vale (300 km^2, 8 km wide) and Authion vale (470 km^2, 10 km wide). The current Loire River is dyked and displays abundant evidence of the dense human occupation pressure in the Loire valley.

Hydrological characteristics of the middle and lower Loire River are due to geological, morphological and climatic heterogeneities and the uneven distribution of confluences. Sediment yields come from a catchment area extending to three main geological domains: the "Massif Central", the "Bassin de Paris" (Paris basin) and the "Massif Armoricain". Topographical, structural and lithological characteristics of these three domains control the hydrographical network. The upstream catchment is developed in endogenous formations to the "Massif Central", the middle catchment is almost entirely developed in sedimentary formations to the "Bassin de Paris", while the lower catchment is associated with endogenous formations to the "Massif Armoricain". This catchment area is geologically heterogeneous including Proterozoic and Paleozoic deformed crystalline and sedimentary rocks covered by Mesozoic and Cenozoic marine and continental deposits (Joly, 1984). High terrain of the Loire basin (1800–1900 m a.s.l.) is situated in the Massif Central where some minor glaciers were developed during

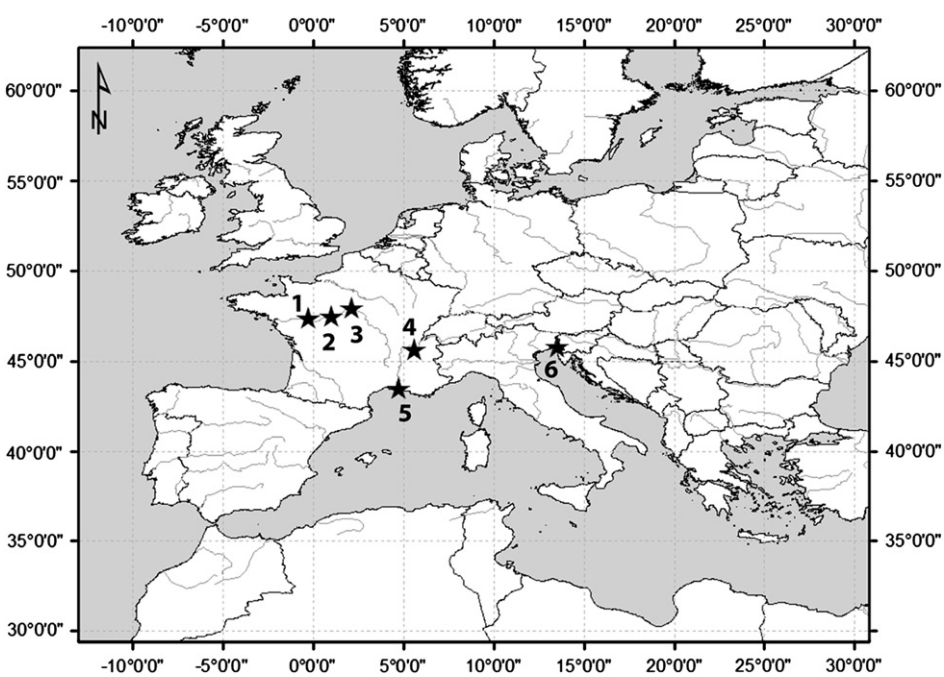


Fig. 1. Location of studied sites in the mid-latitudes Western Europe. From west to east: (1, 2, 3) the Loire River (France), (4, 5) the Rhône River (France) and (6) the Isonzo River (Italy).

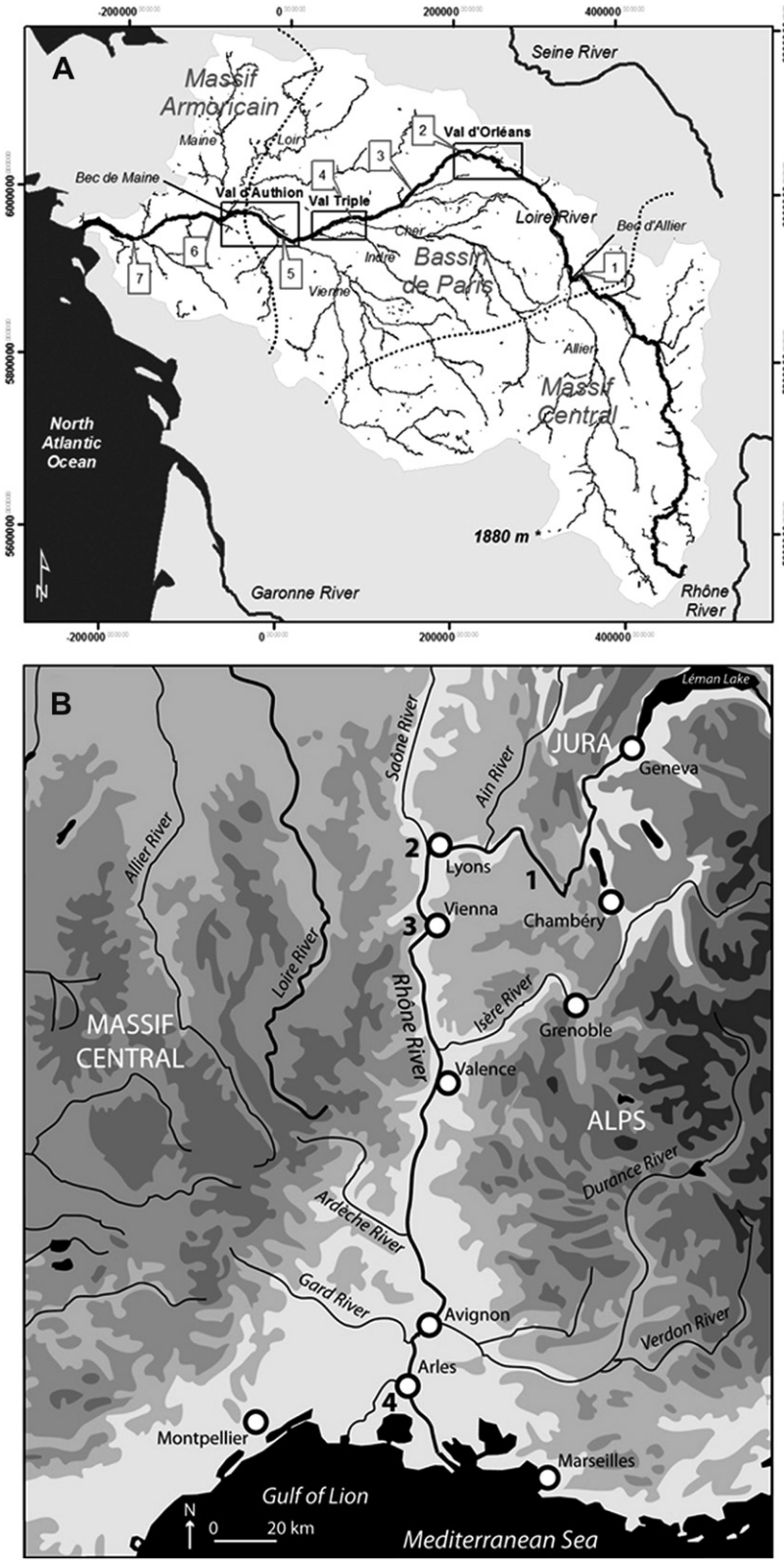


Fig. 2. Maps of studied sites in the catchments of the rivers Loire and Rhône. (A) The studied sectors (Orléans vale; Triple vale; Authion vale) in the Loire catchment. Endogenous rocks of the Massif Central and of the Massif Armoricain are, respectively, drained by the upper and lower Loire hydrographical networks, while sedimentary rocks of the Bassin de Paris are essentially drained by the middle Loire river hydrosystem. Cities of the current Loire alluvial plain: 1, Nevers; 2, Orléans; 3, Blois; 4, Tours; 5, Saumur; 6, Montjean-sur-Loire; 7, Nantes. (B). The studied sites in the Rhône catchment. 1, Basses Terres; 2, Lyons; 3, Vienna-Saint-Romain-en-Gal; 4, Rhône Delta (Camargue).

the Last Glacial Maximum (Buoncristiani and Campy, 2004). The discharge of the Loire River (mean discharge at Saint-Nazaire: 931 m^3/s) doubles downstream of the Cher, Indre and Vienne river confluences. These confluences give the Loire River a complex flow regime characterised by three main influences [Mediterranean influence, low mountain oceanic influence and lowland and plateau oceanic influence] and weighted but irregular discharges (Schulé, in press). In the upstream basin, the Loire River flow regime is pluvial–nival Mediterranean type. The middle Loire River flow regime is pluvial, influenced by snow melt (Dacharry, 1974). Large floods (3500–4500 m^3/s) and low flows (to 100 m^3/s) generally occur in January–February and during summer, respectively. Societies settled more or less continuously in the Loire River valley from the Palaeolithic period (Epipaleolithic) and during the Holocene. The Loire River was then dyked from the Middle Ages (Burnouf et al., 2003b).

2.2. Rhône catchment

The Rhône River (812 km long) is characterised by a complex hydrological regime with intra- and interannual variability because of various influences (glacial, nival, pluvial, Mediterranean) in the basin. It drains a large catchment (97,800 km^2) characterised by various hydromorphostructural units (Alps, "Massif Central", Jura; Fig. 2B).

In the upper part of the basin, the Rhône valley has been overdeepened by glaciers and appears as a succession of glacier basins which are filled by glacio-lacustrine and fluvio-glacial deposits (Salvador et al., 2004). These Quaternary formations are covered by the Holocene sandy-gravel alluvium of the Rhône River, which have prograded downstream from one basin to another to the Basses Terres basin. In this basin, located at the junction of the southern calcareous Jura Mountains (Bugey) and French Pre-alps (Chartreuse), the Rhône River alluvial deposits are about 10 m thick. The slope of the floodplain averages 0.7% upstream, with occurrence of a braided fluvial pattern, but declines to 0.1% downstream, partly due to a downstream local base-level control, a calcareous rock bar, and to the progradation of the gravel bedload, still entrapped today in the glacier basin. Thus, in this area, the Rhône was a dominantly meandering river which shifted freely on the floodplain from the Boreal period as illustrated by a set of former wandering meanders preserved on its surface. Archaeological evidence indicates remains of human activity dating from the Neolithic period but a significant fall in rural settlement along with an intensification of land use took place during the Roman period (Berger, 2005; Gaucher et al., in press).

Further downstream, near Lyons and Vienna, hydrosedimentary processes are strongly influenced by the local reworking of an abundant, inherited fluvio-glacial stock and by the Ain River bedload input which determined a strong, long profile after its confluence, almost 1%, and lead to high energy fluvial environments and hydrogeomorphic adjustments from the Late Glacial period (terraces, fluvial pattern metamorphosis; Bravard et al., 1997). Conversely, on the other side of the valley, the major tributary of the Rhône, the Saône River, does not display the same dynamic due to a finer load input and more stability during the Holocene. Lyons and Vienna are two urban major sites of Roman period, one (*Lugdunum*) established in the Rhône-Saône confluence and the other (*Colonia Julia Vienna*) in the Rhône riverside. The present-day mean annual discharge of the Rhône River in the Basses Terres area is 454 m^3/s, 634 m^3/s in Lyons, and 1030 m^3/s near Vienna, 30 km downstream of the Saône-Rhône confluence.

The lower part of the basin constituted of a large deltaic plain (1740 km^2) which developed during the Late Glacial and Holocene periods (Gensous and Tesson, 1997). The evolution of the Rhône Delta can be divided into two stages: retrogradational–aggradational and subsequently progradational–aggradational. The first developed from 18,000 to 7500 BP, whereas the second developed after 7500 BP when sea level approximated its present-day position. The palaeohydrological evolution both of the Saint-Ferréol palaeochannel and related river-mouth sandy bars contributed to delta progradation between 5500 and 4000 BP (Vella et al., 2005). From this period, the delta progradation decreased because of division of the hydrographical network, and the construction of deltaic lobes in deeper marine zones (Arnaud-Fassetta, 2007). The present-day Rhône Delta is drained by two sandy-silt-dominated distributaries: the Grand Rhône River (1500 m^3/s; 90% of total water discharge) and the Petit Rhône River (Antonelli, 2002). Archaeological data (Landuré et al., 2004) revealed the establishment of numerous human settlements in the deltaic plain from the 6th century BC. Essentially built 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.

2.3. Isonzo catchment

The Isonzo catchment ($\sim$3400 km^2; Fig. 3) is influenced by mixed climatic conditions (temperate, oceanic with Mediterranean influence). Rainfall is distributed with a NE–SW gradient (>3200 mm/a on the east slope of the Triglav and in the Ucja valley, 1500 mm/a at Gradisca and 1000 mm/a at Aquileia). Annual rainfall regime is characterised by minima (winter and summer) leading to drought-dominated regime and maxima (autumn and spring) leading to flash floods. The catchment includes the massive limestones of the Karst plateaus and massifs from the east, and the Alpine massifs and their piedmont from the north (Carulli et al., 1980). The Alpine massifs are composed of the Carnic Alps to the northwest, constituted mainly of limestone, and the Julian Alps to the northeast, where compact limestone is associated with dolomite. Elevations range from 950 m to 2780 m. Geomorphological features linked to Quaternary glaciations have been preserved within the landscapes of the two massifs. This mountainous unit produces a large amount of debris that accumulates further downstream. On the piedmont, the substrate is characterised by calcareous marl, marly limestone and marly calcareous flysch. Most of the piedmont surface is covered by alluvial megafans formed during late Quaternary. Steep river-channel gradients and high sediment loads have caused many avulsions of the rivers Torre, Natisone and Judrio on the fans.

Situated in the eastern part of the Frioulian coastal plain, the Isonzo Delta (400 km^2) is strictly linked to four main control factors: alluviation, eustatic fluctuations, subsidence process, and anthropogenic actions (Arnaud-Fassetta et al., 2003). During the last Glacial Maximum (23,000–18,000 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 (Marocco, 1991). During the post-glacial transgression, the sea first submerged the Istrian coast (10,000 BP), followed by the Karst coastline of Trieste (7000 BP), and finally the Frioulian coastal plain. The Holocene Aquileia plain was affected by generally continuous channel-avulsion process (Siché, 2008). Today, two types of rivers drain the deltaic plain: (i) several minor rivers which lie downstream of a karstic spring boundary on the piedmont, and (ii) the sandy-gravel-dominated Isonzo River (230 m^3/s), an allochtonous river which starts in the mountainous area (Julian Alps).

The first settlement phase in the deltaic plain dates between the 9th and 8th century BC (Carre and Maselli Scotti, 2001). The area was occupied for a short period in the 2nd century BC by

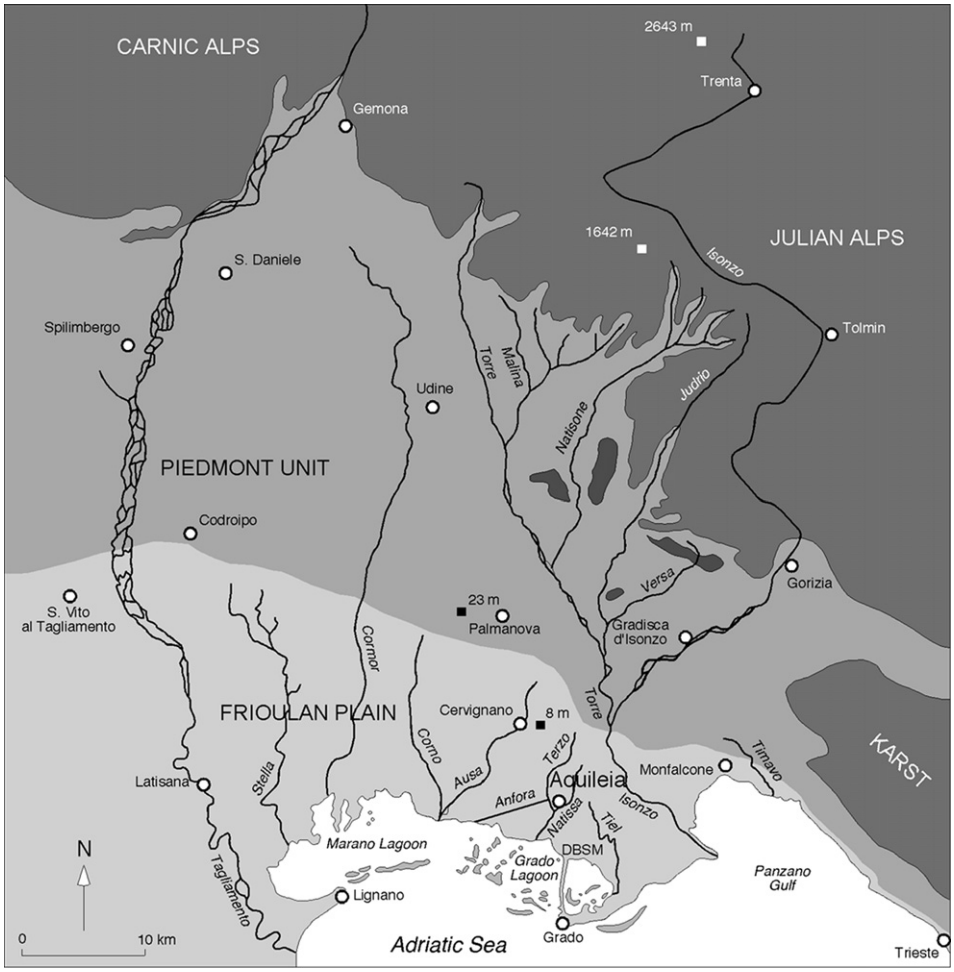


Fig. 3. Map of Aquileia deltaic plain in the Isonzo catchment.

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.

While there are many differences, these three catchments have a common feature: recurring fluctuations in the river regime and channel pattern (floods and channel avulsions), which could be equated with flood hazards (evolution of their frequency and magnitude in time) and spatio-temporal fluctuations of societal vulnerability in the floodplains.

3. Materials and methods

During the last few decades, fluvial geomorphology was used to reconstruct the hydrological functioning of floodplains, and to analyse the interactions between societies and their environment (Vita-Finzi, 1969; Butzer, 1982; Needham and Macklin, 1992; Bravard and Prestreau, 1997; Brown, 1997; Vermeulen and De Dapper, 2000; Burnouf and Leveau, 2004). Numerous common points emerged from these studies, in particular the use of three hydromorphometric approaches common to fluvial geomorphology (hydrography, hydrology, hydraulics). However, review of the literature shows that these three approaches were rarely employed simultaneously in fluvial geoarchaeology. The methodology developed here proposes the application of an integrated method taking into account all the facets of the fluvial hydrogeomorphology via reconstructions of palaeohydrography, palaeohydrology and palaeohydraulics. Source data consists of textual archives, aerial and field photos, remote sensing data, maps, and field surveys (topography, geomorphology, stratigraphy, hydraulics).

3.1. Palaeohydrography as a basic tool for defining river patterns

Palaeohydrographical studies aim to identify and map old hydrographical networks, and to finally reconstruct the drainage network to the scale of the alluvial floodplain. In the Loire River, fluviatile palaeochannels were identified from an integrated approach which combined analysis of a Light Detection and Ranging Digital Elevation Model (LiDAR DEM), morphostratigraphical and geophysical investigations, and the use of a Geographical Information System (GIS). In the Basses Terres floodplain, Rhône palaeochannels were integrated into a GIS which contribute to geoarchaeological investigations (Fig. 4). Palaeohydrographical maps of the Rhône Delta (Arnaud-Fassetta, 2000) and Aquileia plain (Arnaud-Fassetta et al., 2003) were extracted from geomorphological, stratigraphic and geoarchaeological data. The geomorphology of deltaic plains was based mainly on detailed analysis of topographical/geological maps (scale from 1:25,000 to 1:50,000) and photo-interpretation. Following Siché et al. (2006), fluviatile palaeochannels were extracted using digital elevation models computed using digital photogrammetry and GIS. Drainage density (D_d; in km/km^2) of deltaic areas was calculated using the equation of Horton (1945); Eq. (1).

Dynamics of the drainage network (by avulsion or lateral migration) were based on photo-interpretation and stratigraphic data. Most of the stratigraphic information was obtained from borehole data (5–25 m deep) collected along transects at 90° 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. Ages of alluvial units were determined from radiocarbon analysis of bulk organic carbon in the sediments, from Optically Stimulated Luminescence (OSL) age determinations on sediments, from archaeological material (Carre and Maselli Scotti, 2001; Landuré et al., 2004), and from age-depth models. Furthermore, some archaeological vestiges (bridge, fluvial quay, wreck) can be considered as good palaeohydrographical indicators.

3.2. Palaeohydrology as a tool for characterising river dynamics

Palaeohydrology aims to characterise fluvial dynamics from the hydrological regime. This study adapted the typology to Erskine and Warner (1988) to the palaeohydrological context of the Rhône and Isonzo regimes. Regime-based palaeoflow estimates were supported by three types of hydrological regime (Arnaud-Fassetta, 2007): 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 given by 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). Frequency and magnitude of floods of the middle Loire River were characterised on the basis of sedimentary records (sedimentary analysis) and textual sources (development of historical floods database). Within sedimentary sequences with overbank deposits lithofacies (organo-mineral deposits), the mass accumulation rates of mineral matter (for protocol, see Macaire et al., 2005, 2006) and the flows' competence (grain-size: D_{50} and D_{90}) were correlated with the frequency and magnitude of floods. In order to bring to light regional changes in fluvial dynamics, sedimentary sequences studied were located in several transverse profiles of the alluvial plain.

3.3. Palaeohydraulics as an additional tool for quantifying erosion and transport processes

Hydraulic reconstructions serve to estimate both the erosion and transport capacities of old rivers. In the studied catchments, and in particular those situated in the Mediterranean area, the floods can be very unpredictable and powerful. The reconstruction of their hydraulic characteristics supplied information about their occurrence in the past. The first step requires a set of stratigraphic cross-sections deduced from analysis of alluvial infillings. Palaeohydraulic reconstructions required acquisition of several transverse cross-sections, the geometry of which was deduced from the transverse sections reconstituted by topographic maps, electric soundings, Ground Penetrating Radar (GPR) surveys and sedimentary boreholes.

Several key parameters calculated at bankfull stage were then derived from the reconstituted hydraulic geometry: cross-section area, wetted perimeter, roughness and energy slope (deduced from the straight-line passing by the top of palaeo-riverbanks). These enabled quantification of several hydraulic parameters such as the channel capacity (C; in m^2; Eq. (2)), the specific stream power (ω; in W/m^2; Eq. (3)), derived from the formula of Bagnold (1966) which allowed quantification of the capacity both of vertical and lateral erosion of the streams (Nanson and Croke, 1992), and the river discharge (Q; in m^3/s) estimated from the average of results obtained with three equations, those of Manning (1891); Eq. (5), Williams (1978); Eq. (6) and Rotnicki (1991); Eq. (7). Estimation of the roughness coefficient of Manning (n; non-dimensional) was necessary to resolve the last equation. Values for n were determined by the formula of Strickler (1923); Eq. (8) for the Rhône River, by the average of results obtained by the equation of Strickler (1923); Eq. (8), the table of Chow (1959) and the formula of Limerinos (1970); Eq. (9) for the Isonzo River, and by the table of Chow (1959) for the middle Loire River.

As indicated above, every set of hydrogeomorphological data (hydrography, hydrology and hydraulics) has its own aims and methods. The objective of this paper is to show that their combined use in a unified framework can help to better understand fluvial dynamics both in the physical and human context of the studied catchments.

4. Results

4.1. Palaeoenvironments and hydrogeomorphology of the middle and lower Loire valley since the Weichselian

In the middle Loire River (Orléans vale), fluvial environments responded to climate changes acting at different scales: that of changes relative to MIS 3, 2 and 1, and that of rapid, strong changes as in those operating during the Late Glacial (Castanet et al., 2008). Thus, many Weichselian geomorphological inheritances are present within the alluvial plain of middle Loire River during the Holocene, as indicated by the presence of very low terrace and pleniglacial deposits underlying Holocene units (Castanet et al., 2007). In the current alluvial plain, the Holocene active channel is narrow, which suggests relatively reduced geomorphological work by the Loire River during the last 12 millennia. This is the result of the framework imposed by the Weichselian inheritances (reducing Holocene channel mobility) and from the relatively weak specific stream power (ω) of the Loire River. The high ω values of the Holocene Loire River generated some meanders cut-off and avulsions. An incision occurred during the Preboreal, reaching the maximal incision level of the Holocene. Two hypotheses concerning the evolution of the fluvial pattern are proposed: (i) a single channel as early as the Preboreal, (ii) a pattern with two or three main stable channels and its evolution to a single sinuous to meandering channel pattern between Preboreal and Atlantic periods. The main controlling factors of this evolution are an increasing liquid discharge/solid discharge ratio and the evolution from a periglacial to a pluvial (pluvio-evaporal) flow regime, influenced by brutal smelting during spring, as indicated in the western part of the Massif Central, with large discharges (J.-N. Salomon, personal communication). These changes are a consequence of the rapid climate warming during the Preboreal and the associated vegetation cover changes (development of the forest; Reille and Beaulieu, 1988; Cyprien et al., 2004; Visset et al., 2005).

From 11,500 to 4500 cal. BP (Fig. 5), decreasing fluvial activity is observed. The decrease in the mass accumulation rates of mineral matter and the reduced grain size of overbank deposits suggest a decrease in the magnitude and frequency of floods. This tendency is related to the stabilisation of slopes, a decrease in sediment yield (Sifeddine et al., 1996; Macaire et al., 1997; Fourmont, 2005), and a decrease in the solid flux between slopes and alluvial plains. A decrease in the bankfull discharge (Q_b) and ω values of the middle Loire River between the Preboreal and the Atlantic period is identified, within limits of the methodology (Q_b decrease estimated

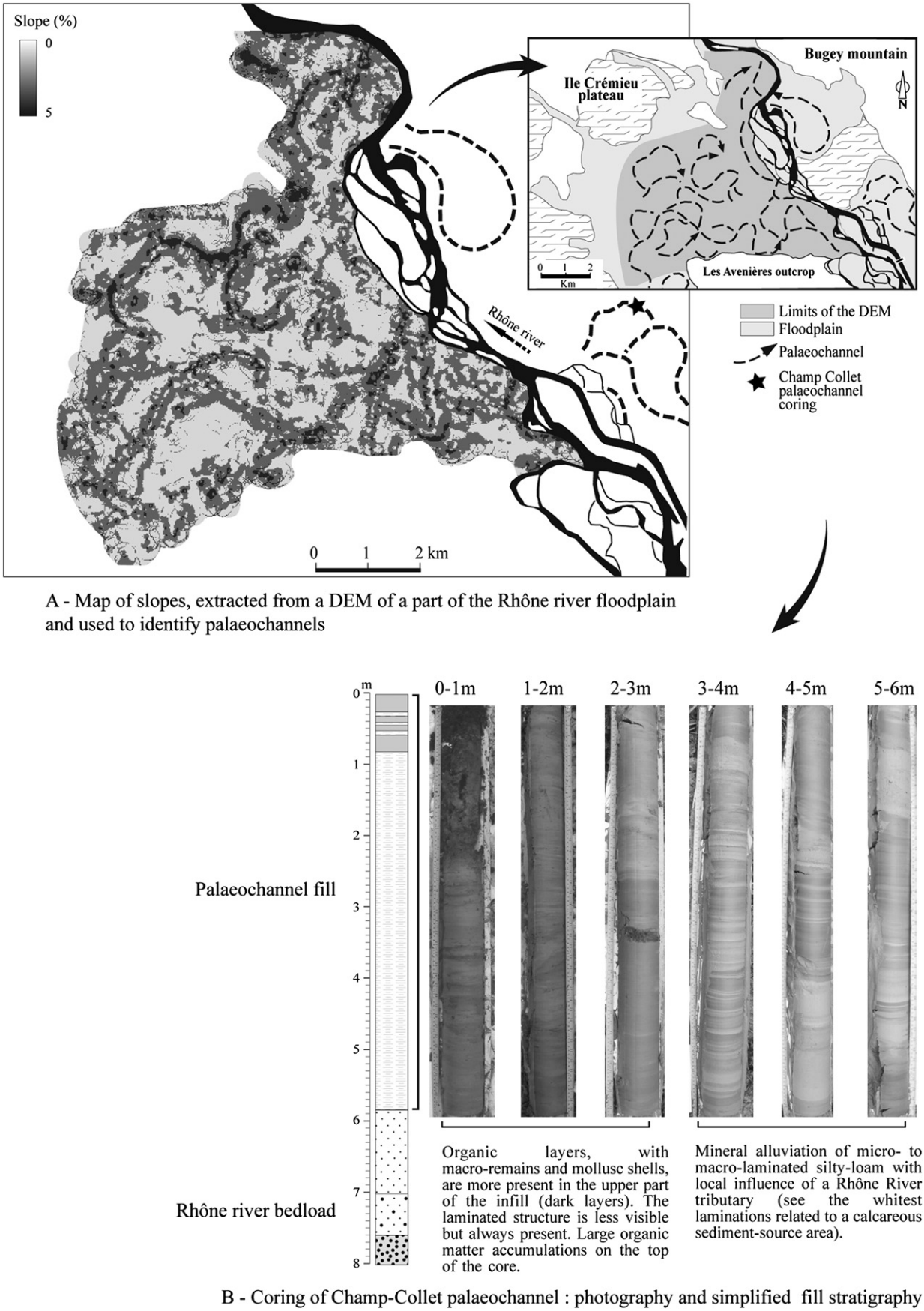


Fig. 4. Illustration of palaeohydrological investigations in the Basses Terres floodplain, upper Rhône River, using DEM, GIS and stratigraphic data.

around 40–60%). From 4500 cal. BP to current times, a transformation of the fluvial sedimentary environments is observed. The increase in mass accumulation rates of mineral matter and in grain size of overbank deposits suggests increased fluvial activity. Palaeohydraulic estimations indicate increased Q_b and ω values. Between Atlantic and Subatlantic periods (Early Middle Ages), estimated Q_b increase between 20 and 90% (within limits of the methodology). This change of fluvial activity around 4500 cal. BP arose (i) one millennium after the first evidence of temporary clearings and cultivations and the reactivation of slope processes such as sheetwash, rilling, and gullying, (ii) more than one or two millennia before the uninterrupted indications of cultivation and pasture (Reille and Beaulieu, 1988; Miras et al., 2004; Argant and Cubizolle, 2005) and the reactivation of the morphogenetic activity of slopes (Sifeddine et al., 1996; Ballut, 2000; Cubizolle et al., 2001; Fourmont, 2005; Négrel et al., 2004), and (iii) during a rise of precipitations observed at the catchment scale (Guiot et al., 1989). The fluvial change observed in the Middle Loire River around 4500 cal. BP seems to be due to an external climatic control. Anthropogenic factors modifying slopes could have intensified the fluvial response.

This long-term evolution of fluvial dynamics (multi-millennium scale) is punctuated by a variability characterised by seven multi-centennial to millennium scale episodes of increased fluvial activity (Castanet, 2008): episodes E7 [10250–9350], E6 [8700–7700], E5 [6800–5900], E4 [4450–3550], E3 [3000–1650], (E3B [2900–2700]; E3A [2250–1900]), E2 [1100–900], and E1 [550–100] (cal. BP). They are characterised by (i) an increase in frequency and or magnitude

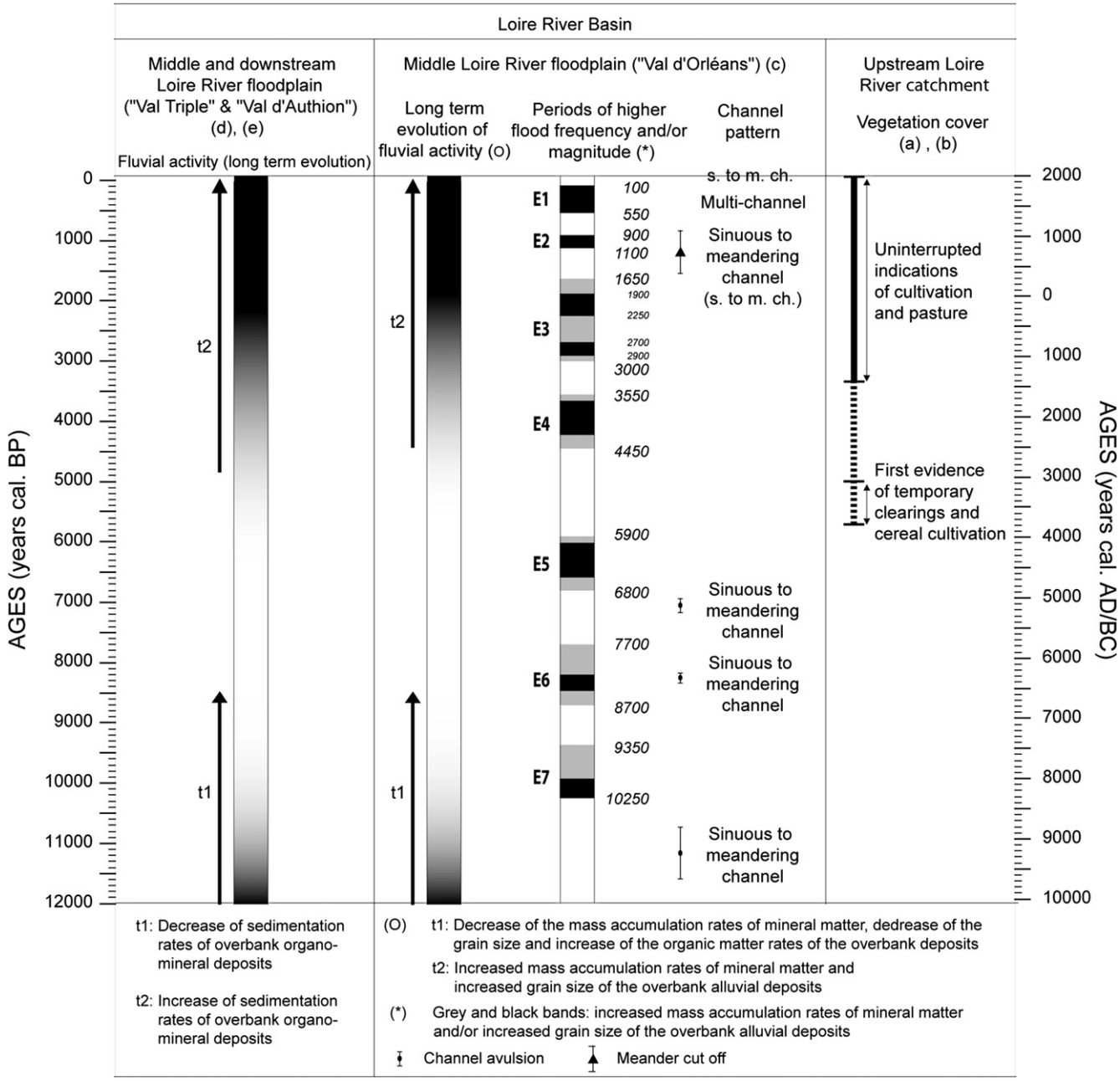


Fig. 5. Holocene fluvial activity of the middle and lower Loire River. Studied sites: Orléans vale (c, Castanet, 2008), Triple vale, and Authion vale (d, Carcaud et al., 2002; e, Carcaud, 2004). Correlation with the upper Loire River vegetation cover (Reille and Beaulieu, 1988; Argant and Cubizolle, 2005). Note that in the Orleans vale, Holocene fluvial dynamics are characterised by multi-centennial to millennium scales episodes.

of floods, and (ii) sometimes by a change of the fluvial pattern. This variability does not seem to be controlled by an autogenic, a tectonic or a volcanic evolution but by external climatic parameters.

Evolution of the lower Loire River fluvial landscapes (downstream of Tours) shows four main stages (Carcaud and Garcin, 2001; Carcaud et al., 2002; Burnouf et al., 2003a,b; Carcaud, 2004; Fig. 6). Two sectors are distinguished. The middle Loire River near Tours shows early fluvial metamorphosis, whereas the lower Loire River shows a late fluvial metamorphosis, directly depending on sea-level change.

The first stage took place during the Late Pleniglacial and the beginning of the Late Glacial. Pleniglacial and Late Glacial evolutions are not yet well indicated (mineral deposits). The Late Pleniglacial is interpreted as an incision phase characterised by maximal erosion near the estuary. The end of the late Pleniglacial and the beginning of the Late Glacial was an aggradation phase with a braided fluvial pattern on the scale of the entire plain.

The second stage took place during the Late Glacial/Holocene transition. A fundamental fluvial metamorphosis characterised the middle Loire River near Tours. A transition system from a braided to a single channel fluvial pattern is observed. The current mosaic of the Loire vales appeared during this stage: low flow channel fixed near a side of the valley, natural levees and back swamp development. In the alluvial plain, abandoned channel, isolated from the active channel, experienced several evolutions: filling, flood axes and/or tributary development.

The third stage took place during the first half of the Holocene. The fundamental fluvial metamorphosis was a slow multi-millennia transition. Near Tours, Loire River secondary channels were abandoned during this first part of the Holocene. In the middle Loire River back swamps, organo-mineral sedimentation and very low sedimentation rates are identified. In the lower part of the Loire valley, the sea-level rise during the Atlantic caused clayey peat deposition at the level of Loire vales and all lower tributary valleys.

The fourth stage took place during the second part of the Holocene. From the middle Neolithic period, all studied sites were characterised by hydrodynamic contrasts. Increased fluvial activity marked the middle Neolithic period and the Bronze Age. It is characterised by increasing sedimentation rates, peat bog disappearance and abandoned channel reactivation. Less fluvial activity was observed during the Iron Age and the Roman period (peaty swamp development and decreasing sedimentation rates). From the Middle Ages, organic deposits disappeared and the sedimentation was widely controlled by human intervention in the catchment.

4.2. Holocene palaeoenvironments and hydrogeomorphology of the Rhône valley

In the upper Rhône valley (Fig. 7), 70 km upstream of Lyons, a multi-disciplinary team (Salvador et al., 2004; Berger, 2005; Salvador et al., 2005), following previous studies (Bravard, 1983, 1987; Roberts et al., 1997), found evidence for several palaeochannels which contribute to identify the spatio-temporal fluctuations of the Rhône River and their origin from Neolithic to Modern times. Palaeohydrography investigations using photo-interpretation, old maps and floodplain morphology survey enabled the location of several palaeochannels distributed on the Basses Terres floodplain. Chronology of their activity was deduced from radiocarbon dates derived as much as possible from charcoal and organic macro-remains contained within the base of the palaeochannel infills. Several generations of palaeomeanders were identified which traced the migration of the Rhône River toward the floodplain until the Roman period, from which a 10 km palaeomeander belt is preserved. These palaeochannels spread on a southern part of the floodplain, the central part of which is occupied by a molassic outcrop. More recent palaeomeanders are recognised only on the northern branch and are dated by historical/radiocarbon data from the Middle Ages. These investigations demonstrate firstly the dominance of a meandering fluvial pattern from the Atlantic period, and secondly the avulsion of the Rhône River on the other side of the floodplain during Roman times. Historic maps indicate the occurrence of a braiding fluvial pattern from the 17th century, which indicates the progradation of a coarse bedload formation into the floodplain, associated with the Little Ice Age climatic degradation (Bravard, 1987).

The partial reconstruction of palaeohydrological regime of the Rhône River is based on the detailed examination of floodplain and palaoemeander cross-section stratigraphy, sedimentological and biological analysis of the trapped deposits. Mineral sequences are characterised by their granularity (D_{50}, D_{99}), thickness and carbonate content (autogenic processes). The texture of the deposits and the alluvial sequence types are linked to the magnitude of the floods. The prevalence of mineral or organic sedimentation phases demonstrates the occurrence of flooding on the site and the degree of connection with the river. The succession of several flood sequences has been studied using a micro-morphological approach on laminated deposits. Four periods of increased fluvial activity with higher intensity of floods are identified during the middle Bronze Age, Roman (High Empire), late antiquity and Modern periods (Little Ice Age). This higher activity is manifested according to periods (i) in the coarsening of material in palaeochannel fills and in the increase of the rate of deposition; (ii) channel lateral instability and river avulsion; (iii) the aggradation of coarse bedload formations sometimes according to the shift from a meandering to a braided pattern. Beginnings of the river discharge increase during Little Ice Age and are deduced from the size of a medieval-modern paleochannel; this is the largest recorded on the floodplain and contained a paludification phase in several palaeochannels and floodplain areas (which are respectively related to higher river discharge and high water levels).

In the Rhône deltaic plain, the palaeohydrographical data were acquired by numerous deep-core samplings coupled with photo-interpretation of recent fluvial forms (Arnaud-Fassetta and Provansal, 1999). The hydrographical network was placed in its environmental context (strictly continental or deltaic; Fig. 8). For the last ten millennia, palaeohydrographical maps show the speed at which the hydrographical network evolved before the completion of embankment works at the end of the nineteenth century (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., the number and length of fluviatile distributaries) evolved, which modified the effect of flood events on riverine communities. The flood impact on societies was estimated by frequency–magnitude analysis of flood events.

In the lower Rhône valley, the evolution of the river regime between 800 BC and the present was defined by studying flood frequencies, aggradation rates, channel avulsion and fluvial metamorphosis. Environmental databases (Arnaud-Fassetta et al., 2000, 2005) succeeded in compiling a robust, palaeohydrological synthesis from the Iron Age (Arnaud-Fassetta and Landuré, 2003), revealing four phases of FDR (first Iron Age, late Iron Age–beginning of Roman antiquity, late antiquity–early Medieval, Little Ice Age) correlated to the whole catchment (Fig. 9A). 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

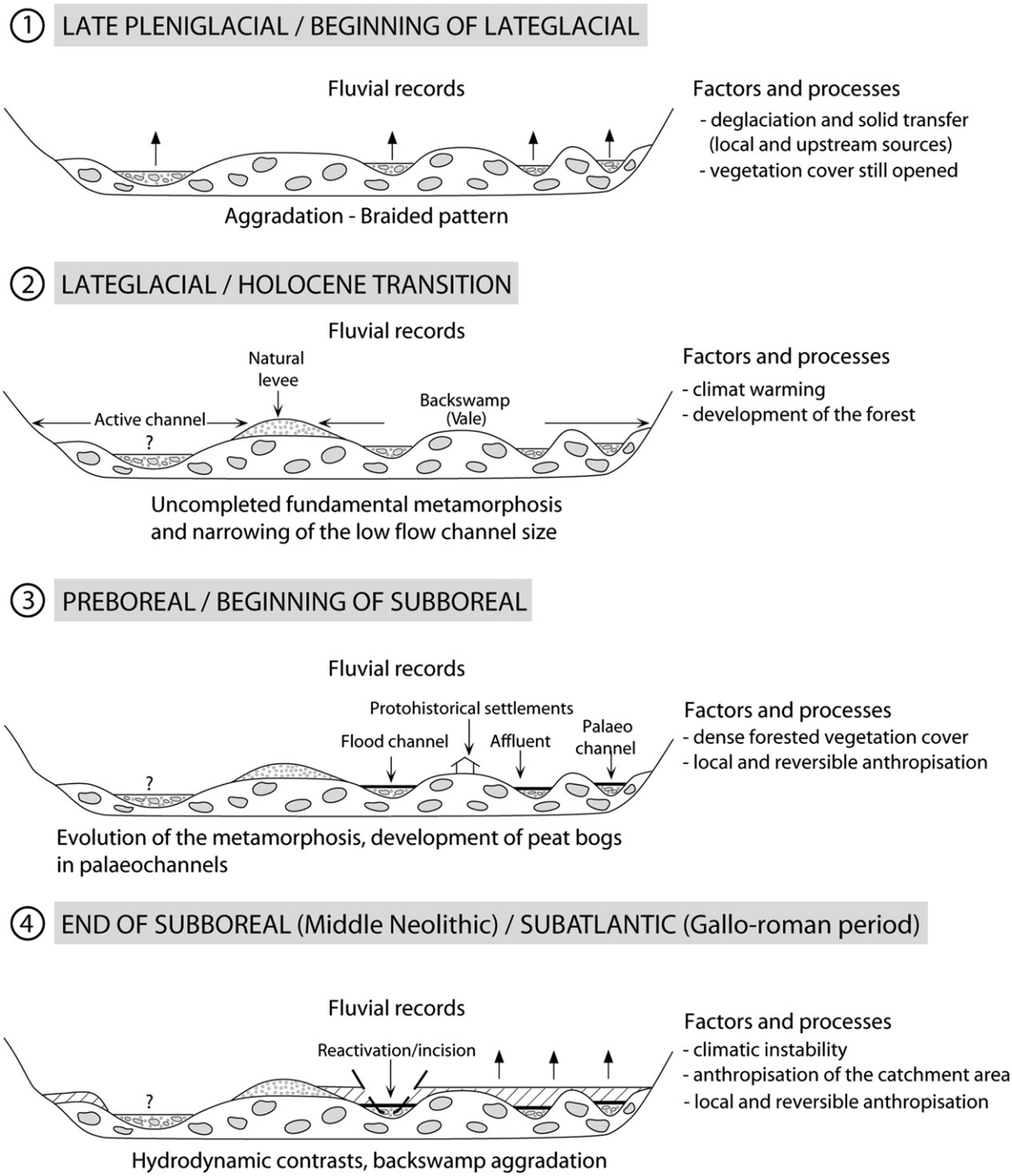


Fig. 6. Main phases of fluvial landscapes evolution in the vales Triple and Authion, upstream part of the Loire alluvial plain (Carcaud and Garcin, 2001, Carcaud et al., 2002; Burnouf et al., 2003a,b; Carcaud, 2004).

avulsions and metamorphoses of palaeochannels (Arnaud-Fassetta, 2002, 2004). Hydraulic calculations quantified channel capacity, Q and ω, related to these flood events.

Evolution at bankfull stage of channel capacity, Q and ω, for the late antiquity and Middle Ages periods, was compared to the present-day (Fig. 9B). Hydraulic characteristics of antic and mediaeval fluviatile palaeochannels were deduced from an analysis integrating bed geometry, hydraulic slope and grain size of 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 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 Ages, the bankfull-channel capacity of the Rhône River was only 3887 m^2. 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 ω

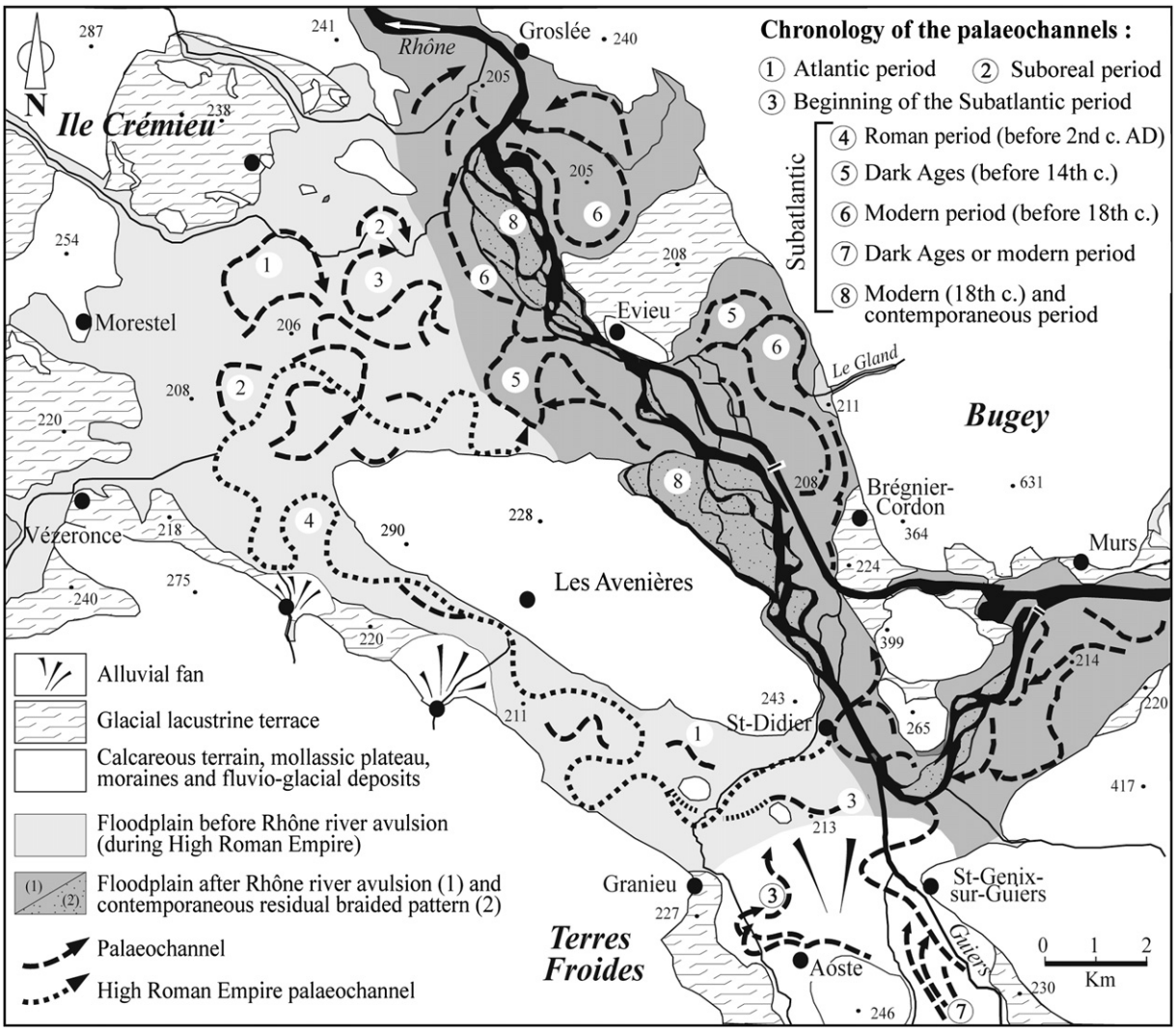


Fig. 7. Chronological succession of the palaeochannels in the Basses Terres floodplain, upper Rhône River.

values shows that in the late antiquity, they were distributed well on the whole deltaic plain. In the Late Middle Ages, ω increased and concentrated in the east part of the Rhône Delta, thereby increasing both the impact of fluvial hazards, and the induced hydrological risk.

4.3. Palaeoenvironments and hydrogeomorphology of the lower Isonzo valley during the Holocene

In the lower part of the Isonzo catchment, reconstruction of the drainage network was deduced from the analysis of inherited forms (palaeo-alluvial ridges) by stratigraphic investigations, photo-interpretation and exaggeration of the relief on digital ground model (Marocco, 1991; Siché, 2008). In the deltaic plain, these works led to small-scale, palaeohydrographical maps showing the gradual migration of the hydrographical network towards the East. Mapping was refined around the antic site of Aquileia by numerous sediment cores collected into the fluviatile palaeochannels. The Aquileia site was connected to the Torre-Isonzo catchments by a high-energy distributary channel coming from the northeast (Fig. 10A). The width of the palaeo-alluvial 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 illustrates that the Roman city was situated on one of these palaeo-alluvial 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 is divided into two fluvial branches. The first came from the north and was directly connected to the site via the Roman bridge. The second, now a spring-fed river, came from the northeast. Geo-archaeological investigations improved the evolution scenario of the channel geometry of the latter, in particular its narrowing throught time.

Recent palaeohydrological work confirms the presence of important waterways at least since the Bronze Age. During antiquity, the Aquileia deltaic plain was crossed by rivers flowing on alluvial ridges. Flooding and regular sediment supply led to aggradation and progradation of the deltaic plain. Several cores were retrieved from the subsoil located around the ancient Roman fluvial harbour. The core deposits record the presence of high-energy, braided-type river channels. The S1 core is representative of this sequence (Fig. 10C): channel activity (torrential FDR, strong competence) was at a maximum between the end of the Iron Age and the early antiquity, and then decreased until the Early Middle Ages. This change in hydrological dynamics is shown by the CM pattern.

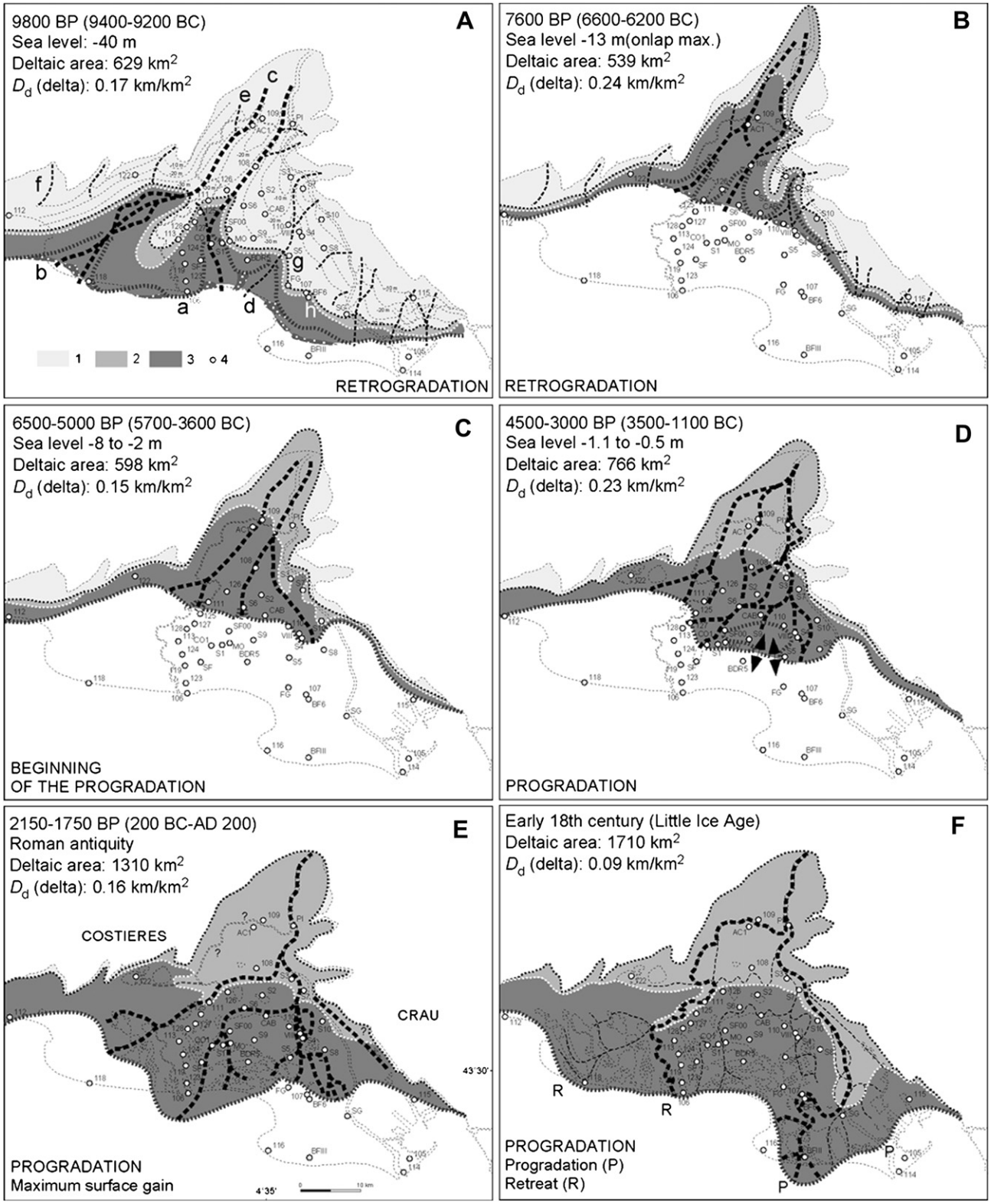


Fig. 8. Hydrogeomorphological and palaeohydrographical changes in the Rhône Delta during the last 10,000 years. 1, Freshwater, continental environment; 2, freshwater, deltaic environment; 3, brackish-salted, deltaic environment; 4, borehole. a, Coastal fringe; b, sandy bar; c, Rhône palaeochannel; d, e, f, minor coastal river, tributary, other river; g, deltaic area boundary; h, hypothetical "fresh-water/brackish-salted" environments boundary. Note the maximum rate of deltaic progradation between 4500–3000 and 2150–1750 BP, and the decrease of the drainage density during Modern times of anthropogenic origin.

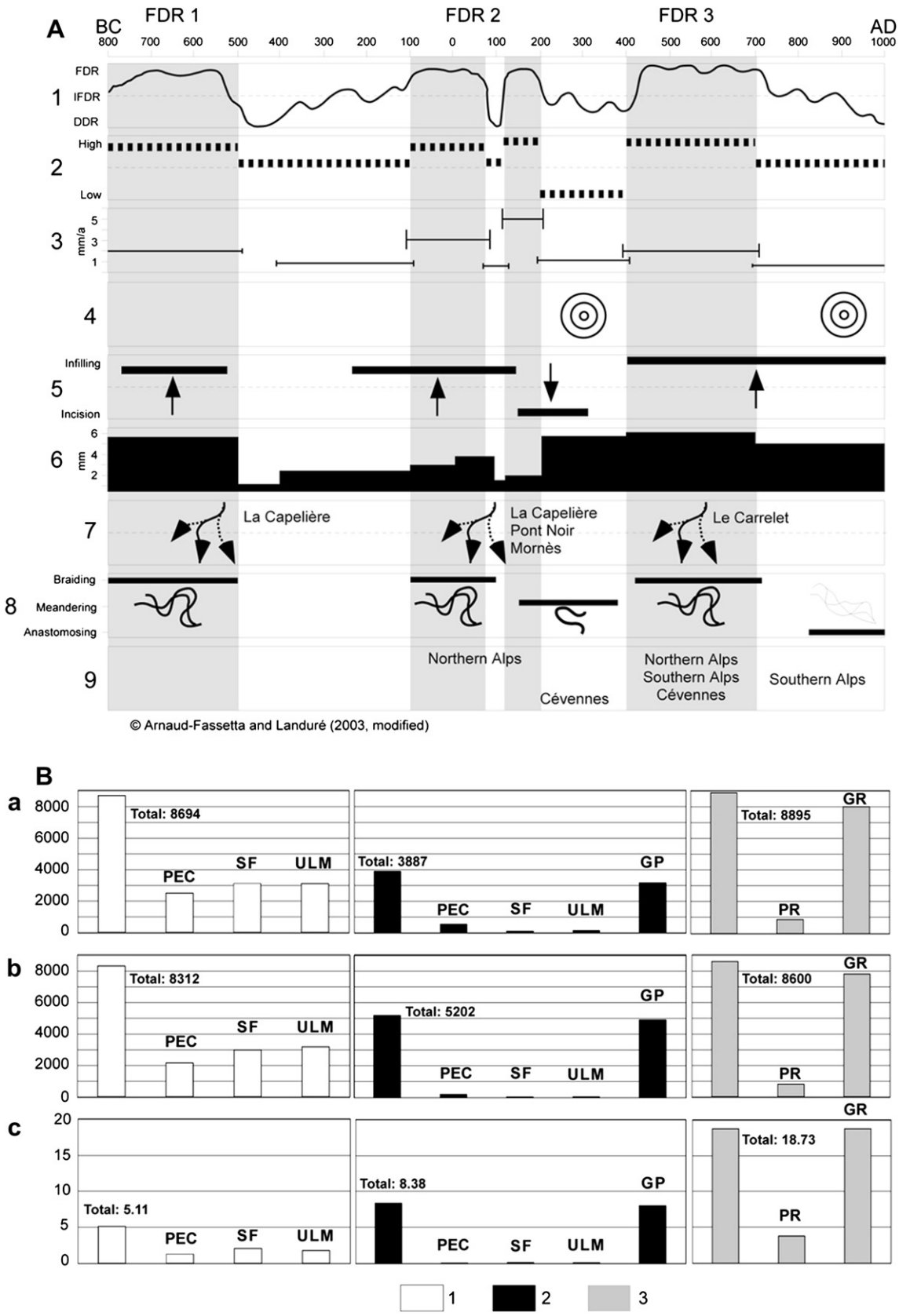


Fig. 9. Palaeohydrology and palaeohydraulics of the Rhône River in the delta plain. (A) Palaeohydrological synthesis from 800 BC to AD 1000. 1, Hydrological regime; 2, mean river discharge and phreatic level; 3, sedimentation rates in the floodplain; 4, pedogenesis in the floodplain; 5, channel geometry; 6, channel competence; 7, avulsions and crevasse splays; 8, channel pattern; 9, source zones of channel sands. (B) Palaeohydraulic evolution at bankfull stage from antiquity to present. a, Channel capacity (in m^2); b, Q values (in m^3/s); c, ω values (in W/m^2). 1, Late antiquity; 2, Late Middle Ages; 3, present-day. SF, Rhône of Saint-Ferréol; ULM, Rhône of Ulmet; PEC, Rhône of Peccaïs; GP, Rhône of Grand Passon (Escale meander); GR, Grand Rhône; PR, Petit Rhône.

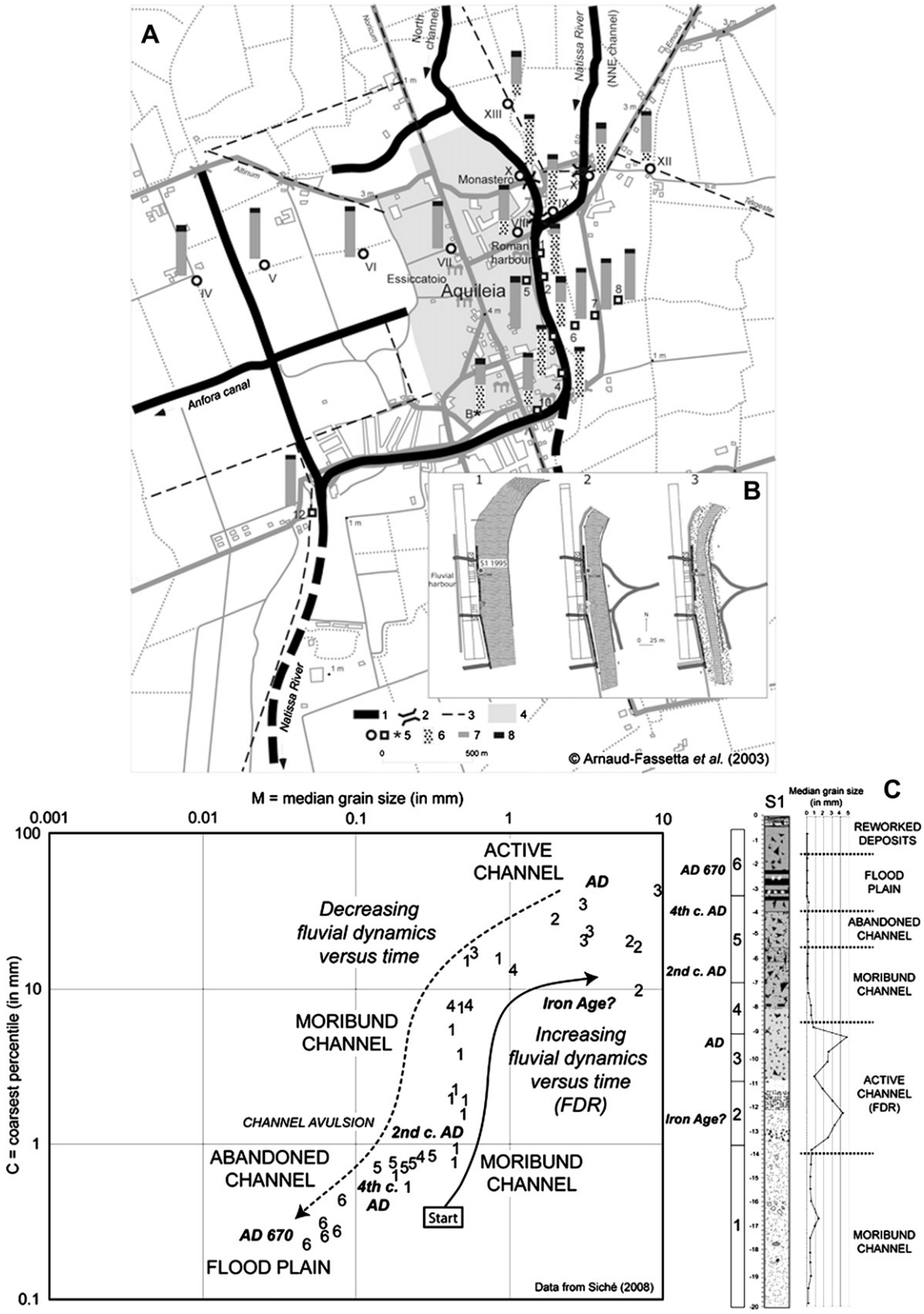
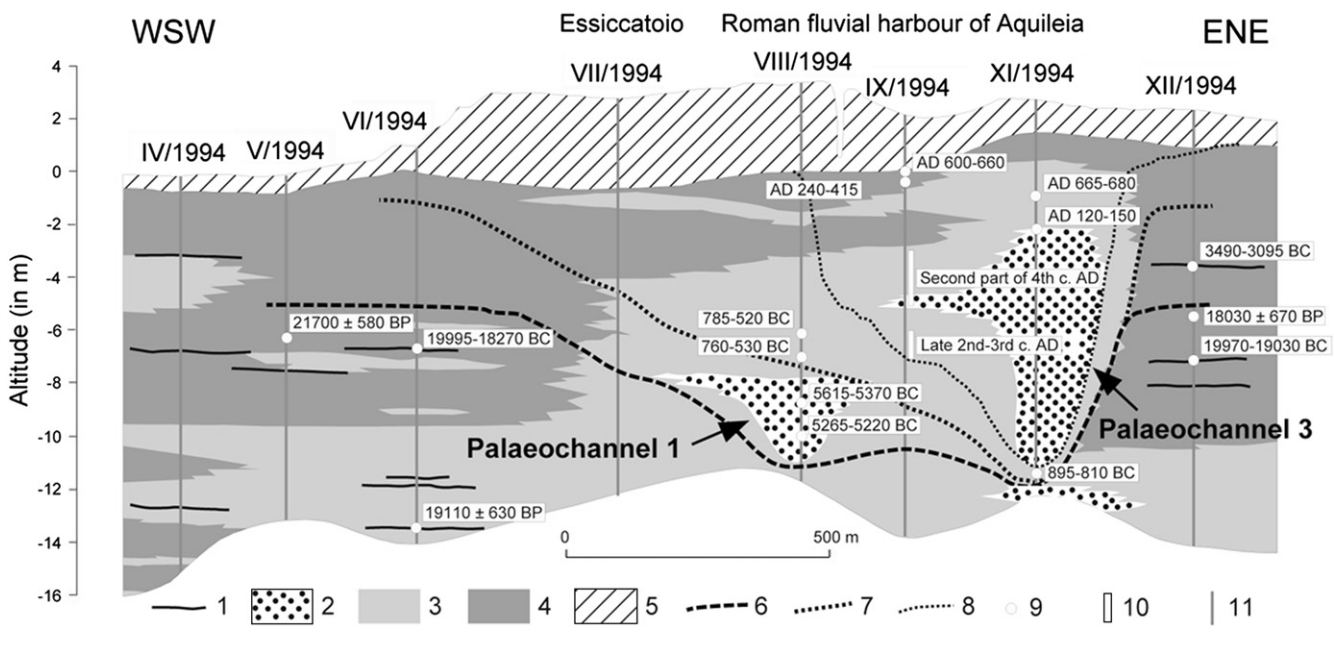


Fig. 10. Palaeohydrography and palaeohydrology of the Aquileia site, Isonzo Delta. (A) Palaeohydrographical interpretation near Aquileia during antiquity. 1, Roman palaeochannel; 2, Roman bridge; 3, Roman road; 4, Roman city; 5, boreholes; 6, channel deposits; 7, floodplain deposits; 8, reworked deposits. Note that the antic city is lined in the north and in the east by high-energy rivers. (B) Evolution of palaeochannel width in the Roman fluvial harbour between the end of the 1st century AD and the Middle Ages (data from Siché, 2008). 1, End of the 1st century AD; 2, 4th century AD; 3, Early Middle Ages. (C) Palaeohydrological evolution in the Aquileia site between the Iron Age and Early Middle Ages, deduced from chronostratigraphical data (S1 core) and the use of CM pattern of Passega (1957). Note the maximum competence of fluviatile palaeochannels around the turn of era, e.g. after Aquileia's foundation in 181 BC.

Hydraulic calculations, derived from chronostratigraphic data, confirm the hypothesis of a high-energy regime. The alluvial sequence (Fig. 11) 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, can be compared to the present-day, braided Isonzo downstream to the confluence with Torre. Values of ω confirm this hypothesis, showing the existence, at the beginning of the antiquity, of an alluvial plain with multiple channels, on which river avulsions are explained both by the progradation of channel bars and aggradation of the alluvial floor. Indeed, ω has been estimated to have a maximal value of 200 W/m^2, typical of a braided river floodplain, where the dominant process is lateral point-bar or braid-channel accretion (Nanson and Croke, 1992). This ω value is close to ω values estimated on the present-day Isonzo River (to the east) at 17 km upstream from its mouth (Fig. 11). The position of the palaeocoastline contemporary of the Roman site was probably situated at this distance, according to historical data.

4.4. Palaeohydrological synthesis, from studied cases to European perspective

Between the beginning of the Holocene and ~ 5 cal. ka BP, episodes of increased fluvial activity of the middle Loire River, Durance River (Jorda and Provansal, 1996; Jorda et al., 2002), South Alps rivers (Miramont, 1998; Miramont et al., 1999) and middle



Stratigraphic data from Marroco (1991) and Arnaud-Fassetta *et al.* (2003)

Hydrogeomorphological variables

	Palaeochannel 1	Palaeochannel 3	Present Isonzo River (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 m^2);
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 m^3/s);
ω	130	201	258	ω: specific stream power (in W/m^2).

Fig. 11. Palaeohydraulic reconstruction 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). See text for the equations of the used hydraulic parameters.

Rhône and pre-Alps rivers (Berger and Brochier, 2000; Berger, 2003), are contemporary with episodes of relatively low fluvial activity in North Europe [Great Britain (Macklin et al., 2005), Poland (Starkel, 2003a)] and in Mediterranean Europe [Spain and Italy (Benito, 2003)]. This does not include the increased fluvial activity episode contemporary with the high lake level "Joux 2" in the Jura and North Alps (Magny, 2004). For example, increased fluvial activity episodes recorded in the French hydrosystems show a significant alternation with episodes both of the Tagus River (Benito, 2003) and Vistula River (Starkel, 2003b) which are relatively synchronous (Fig. 12). Recent collective work (Macklin et al., 2006) identified five major flooding episodes in two or more regions of both Northern Europe (Great Britain, Poland) and Southern Europe (Spain) between 11.65 and ~5 cal. ka BP. Only one is contemporary with increased fluvial activity episodes recorded in the French hydrosystems previously described (Fig. 12). As well, the 8.2 cal. ka BP cold event (Alley et al., 1997) is not recorded at the level of north and south European fluvial hydrosystems (Macklin et al., 2006) although increased fluvial activity episodes of mid-latitude European hydrosystems arose during this event (this study, Jorda and Provansal, 1996; Miramont et al., 1999; Pastre et al., 2002, 2003). This anti-correlation of the fluvial activity intensity between, on one hand, the northern and southern European hydrosystem and on the other hand, the mid-latitude European hydrosystem could be correlated with the Holocene hydrological tripartition of Europe (Castanet, 2008).

From ~5 cal. ka BP, the Loire River and French hydrosystems, the Mediterranean Europe [Spain (Gutiérrez-Elorza and Pena-Monné, 1998; Benito, 2003; Macklin et al., 2006; Thorndycraft and Benito, 2006)], mid-latitude Europe [France (Bravard et al., 1992; Arnaud-Fassetta, 1998, 2007; Carcaud et al., 2002; Pastre et al., 2003; Carcaud, 2004; Arnaud et al., 2005; Salvador, 2005; Sheffer et al., 2007) and North Europe [Poland (Starkel, 2003a), Great Britain (Macklin et al., 2005)] were simultaneously affected by major floods. For example, during the last five millennia, each common episode of increased fluvial activity of the rivers Loire and Rhône included one to three major flooding events recorded in northern and southern Europe (that is six or seven events relative to ten events identified; Macklin et al., 2006; Fig. 12). The age and length of the Loire and Rhône Rivers, and of the French and European hydrosystems (Macklin et al., 2006), present several similitudes. Furthermore, the beginning of the common episode E3 (Fig. 12) was simultaneous with the climatic change characterised in North-Western Europe between 900 and 810 cal. a. BC (Van Geel et al., 1996). Also, hydrogeomorphological changes of the latest increased fluvial activity (E1) are interpreted as a response to the climatic changes of the Little Ice Age [as recorded in the upstream Loire River basin (Chuine et al., 2004; Stebich et al., 2005)]. This suggests an external climatic control of many increased fluvial activity episodes (colder and wetter conditions; Magny et al., 2003; Macklin et al., 2006). These observations on the last five millennia reinforce the hypothesis of hydrological change timing relatively synchronously in Europe for latitudes from 36°N to 59°N (Macklin et al., 2006). This suggests a change in the external climatic forcing of the European fluvial hydrosystems (northern, mid-latitude and southern European hydrosystems) around 5 cal. ka BP (Castanet, 2008) contemporary with the mid-Holocene hydroclimate system switch (Steig, 1999).

However, disparities are identified between the Loire River, the Rhône River and the European fluvial hydrosystems analysed in this study during the last 5000 years. This could be related to the spatio-temporal variability of the response time of the hydrosystems, by

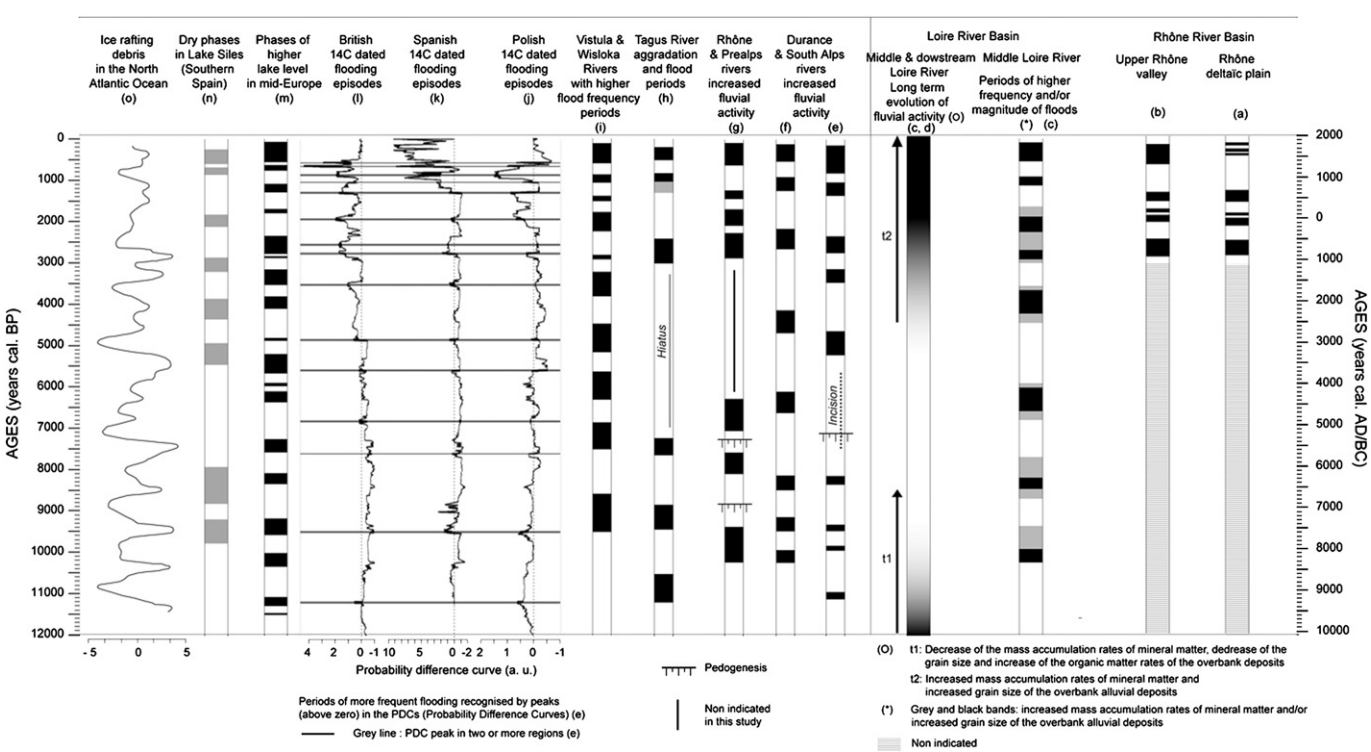


Fig. 12. Holocene evolution of the relative flood-frequency and magnitude of the Rhône River [(a) Arnaud-Fassetta, 2007; (b) Salvador, 2005] and the Loire River [(c) Castanet, 2008; (d) Carcaud et al., 2002; Carcaud, 2004]. Comparison with the fluvial activity records established for mid-latitude Europe [(e) Miramont, 1998; (f) Jorda and Provansal, 1996; Jorda et al., 2002; (g) Berger and Brochier, 2000; Berger, 2003] and south and north Europe [(h) Benito, 2003; (i) Starkel, 2003a; (j, k, l) Macklin et al., 2006], with the lake-level records established for west-central Europe [(m) Magny, 2004] and for west-south Europe [(n) (Carrion, 2002)] and with the North Atlantic IRD record [(o) (Bond et al., 2001)].

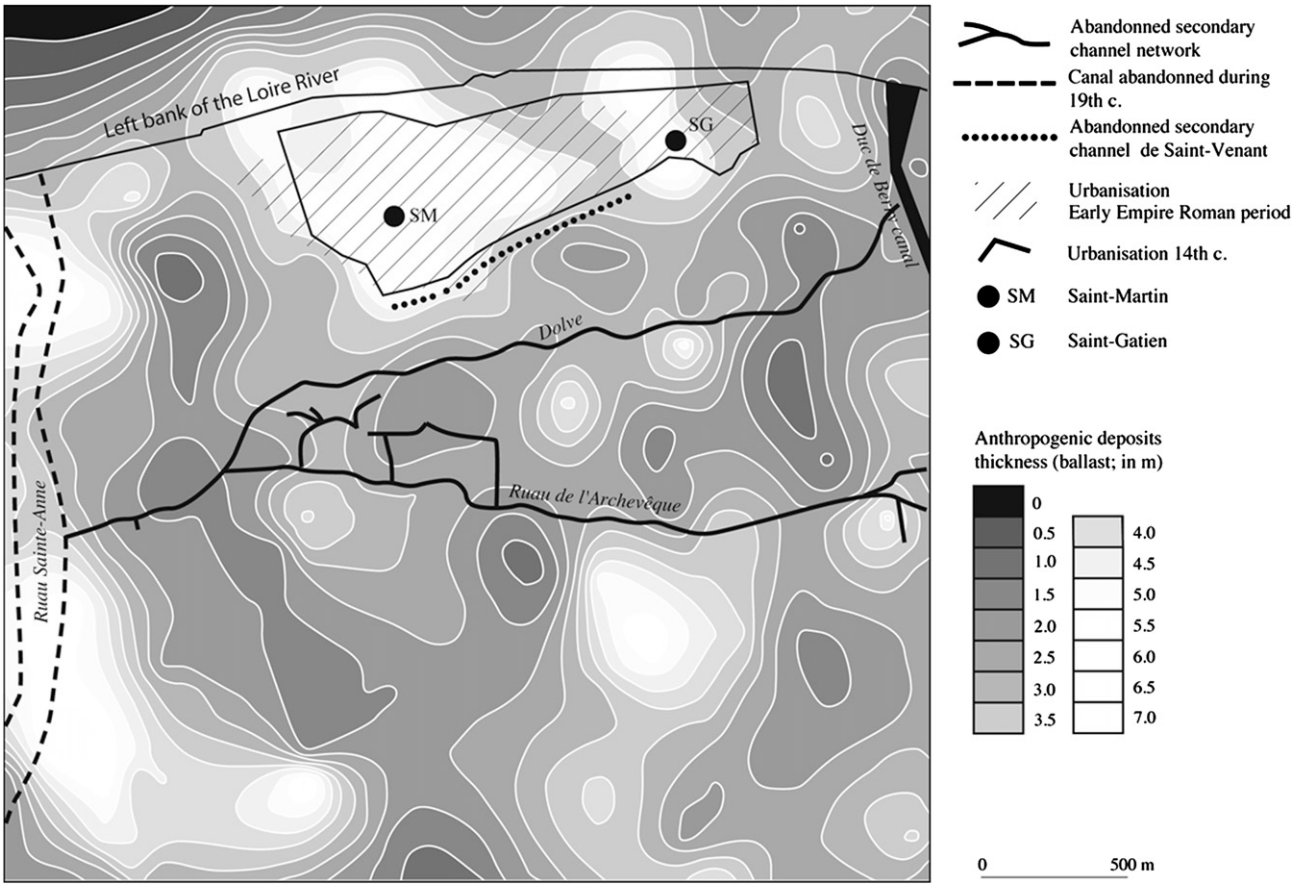


Fig. 13. Urban occupation in the middle Loire alluvial plain: example of Tours from the Iron Age, its hydraulic structures and anthropogenic deposits (Burnouf and Carcaud, 2000). Aggradation of the alluvial plain is estimated around 5 m under the Saint-Gatien cathedral and 6 m under the Saint-Martin abbey (anthropogenic deposits associated with permanence of urban occupation in the historical center).

anthropogenic factors at the level of the catchment areas and/or by methodological limits related to the determination of increased fluvial activity episodes.

5. Discussion

Having established the dynamics of these fluvial systems on multiple temporal and spatial scales, discussion now turns to the relations between the hydromorphological evolution of river hydrosystems and fluvial risk.

The concept of risk is related to a mathematical function which integrates: (i) the physical and material danger for human beings faced with a natural hazard and (ii) the potential damages, that is to say the percentage of population and/or the value of material things apt to be destroyed (Smith and Ward, 1998). All this depends 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). The risk approach not only concerns the management of the crises. It is more complex because it results from a large number of physical and human factors, and requires the knowledge of both hazards and the vulnerability components (Alexander, 2000).

The fluvial risk is the integration of all risks linked to the action of superficial water flows: flood (overflowing), erosion and sedimentation (lateral and/or vertical) in the channel and the riverbanks, channel avulsion in the floodplain, pollution and severe low flows. Research in fluvial hydrogeomorphology is centred on global approaches aiming at improving the actions of management and prevention of these risks (Arnaud-Fassetta et al., in press). In this study, the hazard is represented by the river floods in three catchments (Loire, Rhône, Isonzo). 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-alluvial ridges or near the fluviatile distributaries in the bottom valley.

The question of the correlations between the river floods and the risk was addressed in the three studied areas. The question deals with the notion of fluvial risk in the last 2000 years. Which role has flood risk played in economical and rural/urban development? Was it permanent? Has the social group always taken the risk into account? As indicated below, it seems that managing the impacts of hydrological hazards and induced fluvial risk was different in rural and urban areas.

5.1. Societies and fluvial risk in alluvial plains

From the Roman period, the fluvial hydrosystem can be classified as an anthroposystem (sensu Lévêque et al., 2003). An integrated approach to analysing the uses, installations and hydrosedimentary dynamics of the rivers is useful, for example, the work in the Loire alluvial plain which focuses on the Triple vale (Figs. 2 and 13), a confluence space including uses, urban (Tours city) and rural (Varennes de Tours) installations.

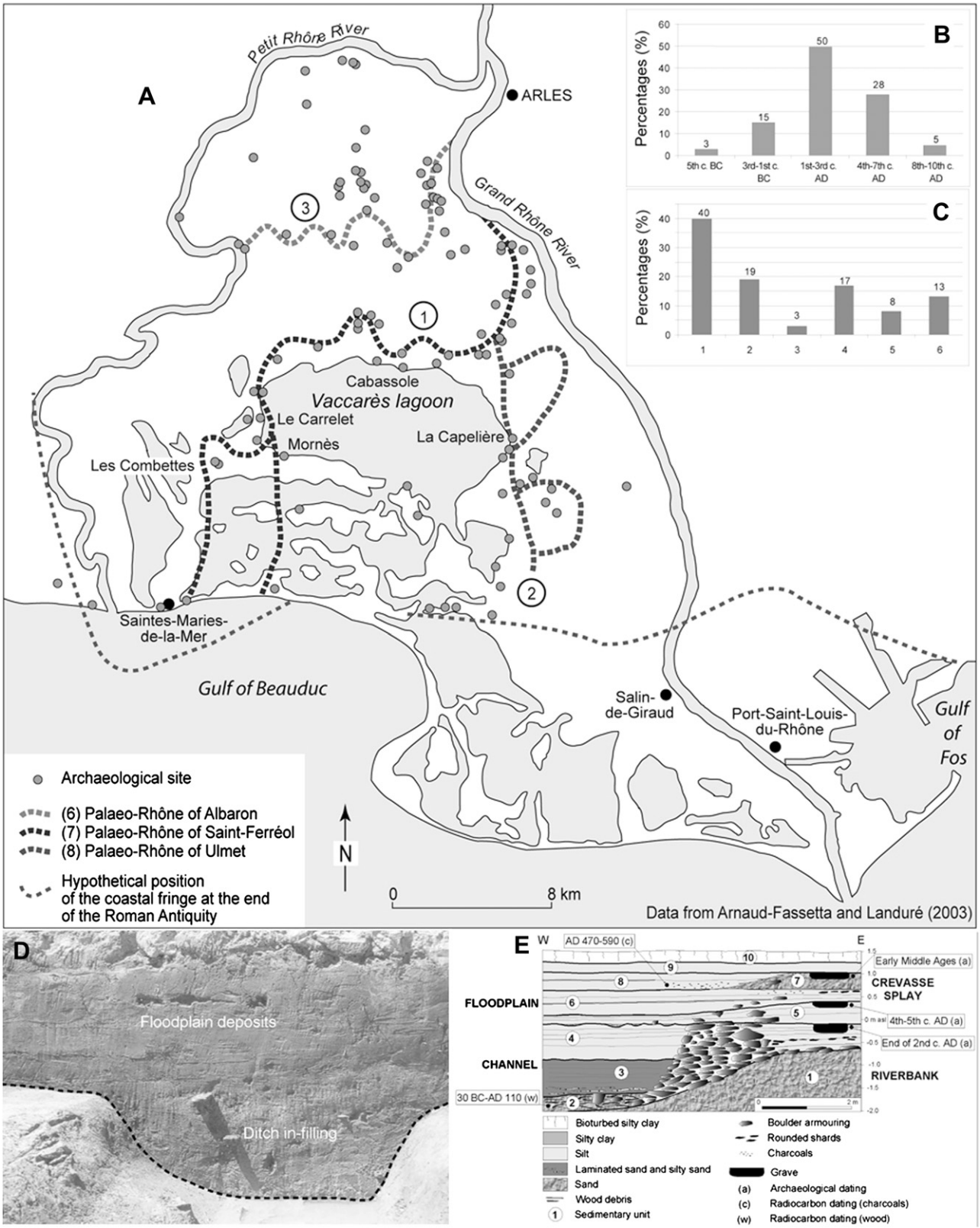


Fig. 14. Relations between flood hazard, societal vulnerability and fluvial risk in the Rhône Delta. (A) Location of archaeological sites in Camargue for the period 5th century BC–10th century AD. (B) Evolution of the number (expressed as percentages) of archaeological sites from the 5th century BC to the 10th century AD. (C) Palaeogeographic and palaehydrographical context of archaeological sites in the delta plain; 1, sites near the palaeo-Rhône of Saint-Ferréol; 2, sites near the palaeo-Rhône of Ulmet; 3, sites in the zone of diffluence of the Saint-Ferréol and Ulmet palaeochannels; 4, sites near the palaeo-Rhône of Albaron; 5, sites alongside the palaeocoast; 6, sites to be far from both the palaeocoast and the three above-mentioned palaeochannels of the Rhône River. (D). Stratigraphic cross section on the site of Le Carrelet (west bank of Vaccarès Lagoon) showing the riverbank of the palaeo-Rhône of Saint-Ferréol supporting a boulder armouring dated 30 BC–AD 110. (E) View of a drainage ditch (1st century BC) discovered on the site of La Capelière (east bank of the Vaccarès Lagoon).

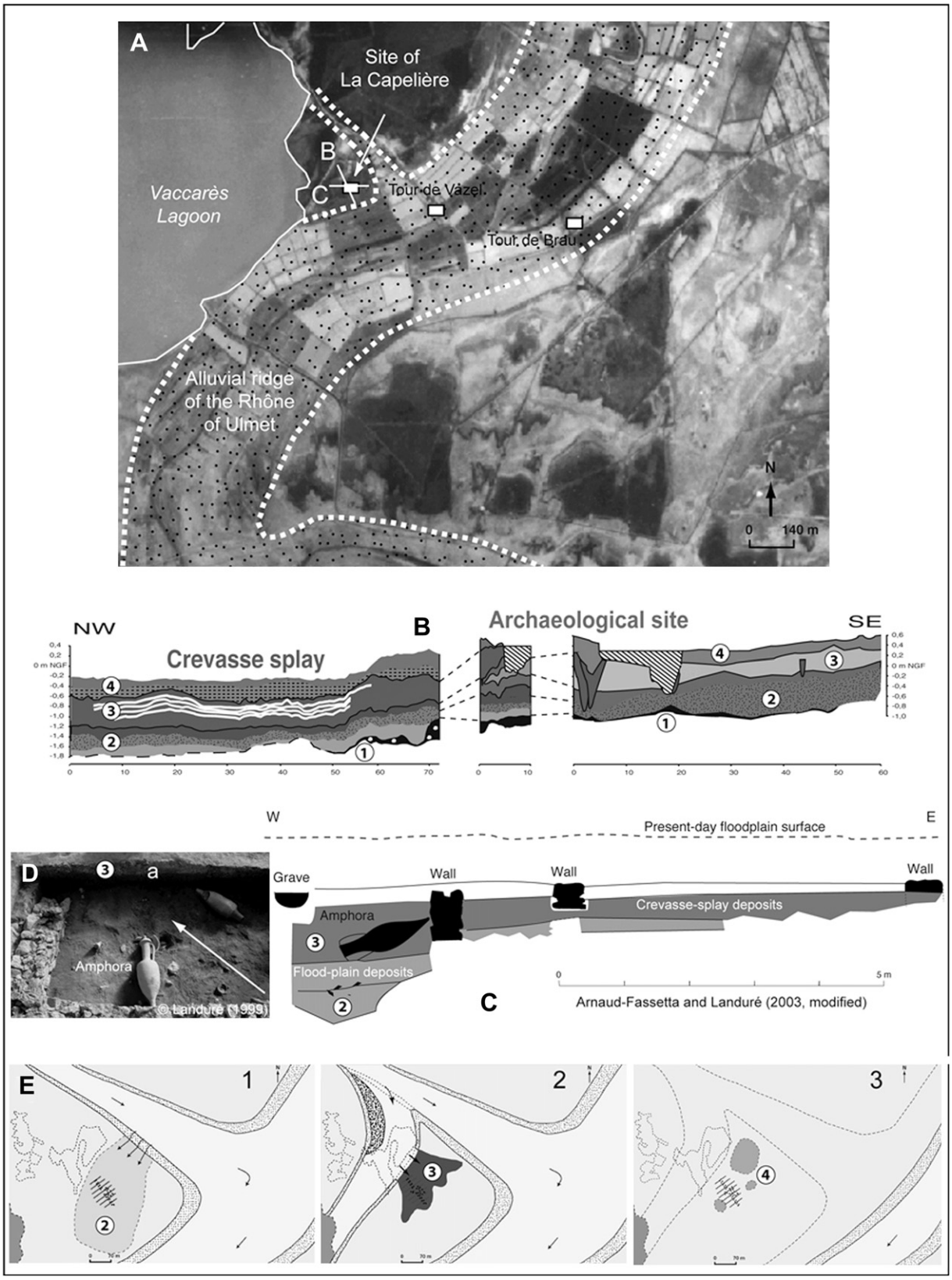


Fig. 15. Fluvial risk at La Capelière, Rhône Delta, at the beginning of Roman antiquity. Geoarchaeological results highlight the phenomenon of converging factors enable to lead to the abandonment of an inhabited site situated near to a Rhône palaeochannel. (A) Location of the archaeological site on the alluvial ridge of the Rhône of Ulmet. (B) General stratigraphic section, showing the evolution of depositional environments [1, palustrine, fluviatile; (2, 4, floodplain, 3, crevasse splay; correspondence with C, D and E)]. (C) Detail of the stratigraphic section showing the burying of the archaeological vestiges (end of 1st century BC) by crevasse splay deposits. (D). Photograph showing two amphora and walls (end of 1st century BC) recovered by (a) crevasse splay and floodplain deposits. Arrow indicates the direction of flood palaeoflux. (E) Maps showing the hydrographical evolution around the site. 1, 5th–1st Century BC; 2, end of the 1st century BC; 3, 5th 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 flood event led to the abandonment of settlement until AD 40.

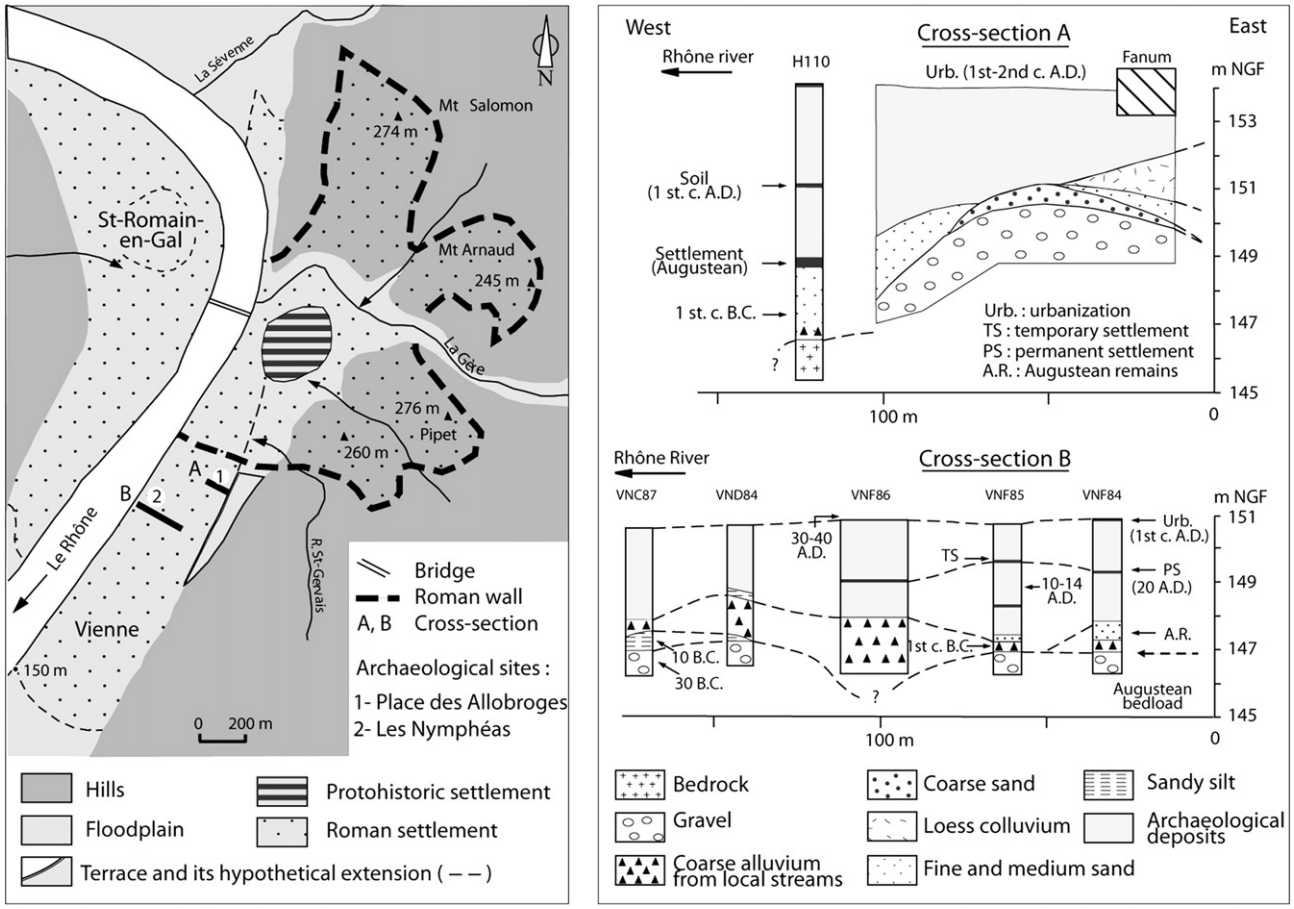


Fig. 16. Evidence of the coercive character of flooding which led to a rise from 1 to 3 m of the settlement in the city of Vienna, upper Rhône River, during the 1st century AD (after Bravard et al., 1990).

The city of Tours has been located at the confluence of the rivers Loire and Cher (Fig. 2) at least since the Iron Age. Three periods of interrelations are identified (Carcaud, 2004):

(i) Until the 11th century, urban populations attempted to appropriate fluvial space but these actions were local. For example, at Tours, the riverbank was modified creating a territorial increase estimated to be around 150–250 m (Galinié et al., 2004). During the same period, permanence of the urban occupation at the level of the historical center induced a change of the micro-topography and an aggradation estimated around 5 m under the Saint-Gatien cathedral and 6 m under the Saint-Martin abbey (Burnouf and Carcaud, 2000; Fig. 13).

(ii) Several mediaeval hydraulic installations had a regional dimension. Some aimed at reducing the width of the Loire River channel and at protecting the vale from floods. Others, such as those observed at Tours at the end of the 14th century, served to divert the course of the river towards the bulwarks with defensive, sanitary and economic motives (Noizet et al., 2004). However, there was no real anthropogenic river control. The difficulty of managing the higher fluvial activity during the Little Ice Age and the increased flood risk in the last part of the 14th century illustrates this (Burnouf and Maillard, 2003).

(iii) During early Modern times, the installations became widespread in the catchment area. In the Triple vale, at the end of the 18th century, the flood risk management became more radical. It consisted of a complete anthropogenic reorganization of the confluence Loire-Cher (Bec du Cher), from three junctions to just one (Villandry; Burnouf et al., 2004).

This local study confirmed the benefit of an approach crossing several spatio-temporal scales. In a regional framework, the river mosaics were built in a long temporal scale with a multi-millennial response time. However, systematic installations observed in the Triple vale and the climatic change of the Little Ice Age produced almost immediate records (Garcin et al., 2006).

5.2. Specific fluvial risk in rural areas

In rural areas such as the Rhône Delta, no significant correlation is highlighted between fluvial dynamics such as Flood-Dominated Regimes (FDR) and archaeological sites. However, a strong correlation is observed during antiquity and the Middle Ages between the hydrographical evolution and the development of human settlements (archaeological sites) along the fluviatile palaeochannels (Fig. 14 A, B and C). Due to the location of 79% of sites along the Rhône palaeochannels, in the proximal floodplain, the vulnerability of antique and medieval societies was high (Arnaud-Fassetta and Landuré, 2003).

However, vulnerability was mitigated by local, human actions. During the antiquity and Early Middle Ages, the hydraulic management of the delta plain was made through the use of "soft techniques", only modifying the environment at a minimal level and working in harmony with the "natural", physical environment. The more serious modifications to the hydrographical network were only made later, from the Late Middle Ages. Most of time, sites were built on the highest points of the floodplain. Thus, locations to build the sites were chosen according to their proximity to the alluvial ridges and palaeo-riverbanks, which enabled sufficient

gains in altitude (from tens of centimetres to a few metres) to avoid any potential flooding. In order to control and exploit natural resources (water, salt, wood, fishing, etc.) as efficiently as possible, riverine societies thus installed habitations near the river. Anthropogenic actions consisted of improvement of drainage conditions in the floodplain, including the digging of drainage ditches (Fig. 14D) in order to reduce the time and extension of flooding, and to consolidate palaeochannels' riverbanks (Fig. 14E) flowing near villages and places where it was possible to cross the river or approach the bank by boat. The building of boulder armouring to minimise effects of fluvial erosion in the channels was certainly set up for this reason. Whatever protective actions against the floods, societal vulnerability was strong when the hydroclimatic hazard became more frequent and more morphogeneous.

Nevertheless, there was no strict or permanent determinism exerted by the physical environment, even if some disasters (e.g., flashy inundation by riverbank breaking and crevassing) could have affected inhabited sites during periods of FDR. The evolution of land use, particularly along riverbanks of historical channels, seems to have been globally independent from the variability of the flood hazard. 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 periods, the magnitude of fluvial risk mainly depended 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: (i) many fluviatile distributaries with low channel capacity, e.g. shallow, infilled channels; (ii) repetitiveness of overflows, crevasse splays and avulsions during periods of FDR; (iii) high ω values; (iv) fragile riverbanks (low bank, easily erodible lithology, little vegetated); and (v) hydromorphy in the floodplain. When all these physical conditions were combined, they generated hydrological disasters and the abandonment of sites, as demonstrated on the site of La Capelière during the beginning of Roman antiquity (Fig. 15).

5.3. Specific fluvial risk in urban areas

In urban areas, fluvial dynamics influenced land use. Downstream of the Saône-Rhône confluence, in Vienna, J.-P. Bravard demonstrated the influence of hydrological and geomorphological changes on the Roman settlement in the floodplain (Bravard et al., 1990; Salvador et al., 2002). A succession of fluvial activity phases was identified, from a period of aggradation and braiding during the Iron Age to a period of river incision and low discharges during the end of La Tène period. The Iron Age floodplain became a low terrace and was no longer flooded on a regular basis. Therefore during a period of Drought-Dominated Regime (DDR) in the 1st century BC, Roman settlement could spread in lower zones of the previously flooded area. Since the end of the 1st century BC and during the 1st century AD, increased fluvial activity (FDR) occurred as attested by large volumes of overbank deposits. Various works identified in the urban sectors (drainage, successive artificial heightening) indicate the coercive character of flooding which led to a rise from 1 to 3 m of the settlement in the town (Fig. 16).

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

Land use, on the other hand, had some influence on fluvial dynamics. In Lyons, as in Vienna, A. Vérot-Bourrély and J.-P. Bravard highlighted the reconstruction of Roman settlement over artificial deposits, in response to the increasing fluvial activity recorded during the 1st century AD (Vérot et al., 1989; Bravard et al., 1997; Salvador et al., 2002). This response was generalised at the Rhône-Saône confluence during Claude's reign (AD 37–54) and was related to an elevation of 50 cm in height. Just before this period, evidence of drainage measures was identified through the partial infilling with amphora and local traces of embankments of several palaeochannels.

In the Roman city of Aquileia, measures taken to limit flood impacts were often more premature than the ones taken in rural areas, but also more radical and sometimes irreversible regarding hydrosedimentary functioning and environmental impacts. In particular, several active palaeochannels were artificially infilled to increase the urbanised area (Arnaud-Fassetta et al., 2003). Hydraulic works led to river channelisation, as demonstrated in the sector of the Roman fluvial harbour (Figs. 10B and 17). In the towns, the stakes were obviously different than in the country, and the

Fig. 17. Portion of the quay discovered along the Roman fluvial harbour of Aquileia (photo by Arnaud-Fassetta, 2006). The structure (1) is situated on the right bank of the Natissa palaeochannel, which crosses the Roman city flowing towards the south (2); the artificial infilling (3) dates from Modern Times.

measures implemented were more important, to assure the survival of buildings, infrastructures and people. The fluvial risk was considered to be secondary to the profits (economic, strategic, political) that societies made from the exploitation and the use of the Natisso River. This point of view is also shared by historians–archaeologists (Alline, 2007).

6. Conclusions

A combination of hydrography, hydrology and hydraulics is an essential part of investigating and characterising the interrelationships between river behaviour and human settlement. The alluvial analogues are useful for linking the functioning of present river systems with the past, within limits of the "actualist" method. Fluvial risk cannot be 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 (section in recurrent erosion; human-modified section); (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.

Considering the fluvial risk, relations between societies and rivers are generally complex. Sometimes, a physical determinism prevails, as Magny (1995) showed for the Jurassian lakes during the second part of the Holocene. In the Rhône Delta, because of catastrophic floods (e.g. the site of La Capelière at the end of 1st century BC), some phases of FDR also led to a brutal but temporary abandonment of sites. However, in most cases, research did not demonstrate a strict determinism due to either the physical environment or hydrosedimentary functioning of hydrosystems on societal behaviour. During antiquity and the Middle Ages, active channels of the Rhône River (Saint-Ferréol, Ulmet) were very attractive and fixed riverine societies when the fluvial risk was at its highest level. Inhabited sites moved when the fluvial risk was minimal. In the Isonzo Delta (site of Aquileia), Roman settlements emerged and developed the fluvial harbour whatever the hydrosedimentary conditions of rivers. Furthermore, the site was founded during the maximal fluvial hydrodynamics, and the development of the Roman city went on in spite of recurring flood events. In this context, Aquileia became one of the biggest Mediterranean fluvial harbours of antiquity. Also, in the middle Loire floodplain, several important cities as Orléans, Blois and Tours had an important development during historical times (i.e., Roman and early Modern Times), mainly during episodes of higher fluvial activity (FDR).

Causal relations between the hydroclimatic hazard and societal vulnerability result from complex, multi-factorial processes which were not still strictly linear. In the Rhône Delta, the permanence of rural habitats depended on whether the hazard occurred in the floodplain (crevasse splay, avulsion, water-table rise, river regime, channel geometry). If the impact of hydrological change between the 1st century BC and the 2nd century AD had strong repercussions on land occupation (brutal abandonment and hiatus in the attendance of sites), because of a too strong hydrological constraint (FDR), it was not an obstacle for the extension of land occupation in the delta plain. At the same time, this latter recorded a significant increase of inhabited areas (e.g., more large number of created sites), in a context of large progradation (e.g., maximal gain of surface) of the delta plain. Also during other periods, the occupation of rural sites went on in spite of recurrent floods, or contracted for reasons other than fluvial risk. In the Aquileia site, we showed that Roman society was finally able to manage the river system whatever the hydrological state of rivers (i.e., active or moribound channels). However, the absence of a strict physical determinism should be moderated. Indeed, the channel change (e.g., channel contraction and confinement) that appeared during antiquity and the general shifting of rivers towards the East had an impact on the functioning of a big harbour, even if this site function also depended on historic and political events.

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Appendix

Palaeodrainage density (D_d; in km/km^2) in the Rhône Delta:

$$D_d = \frac{\sum L}{A_d} \tag{1}$$

where L is palaeochannel length (in km) in a delta of palaeoarea A_d (in km^2).

Channel capacity (C; in m^2):

$$C = Wd \tag{2}$$

where W is channel width (in m) and d is mean channel depth (in m).

Specific stream power (ω; in W/m^2):

$$\omega = \frac{\Omega}{W} \tag{3}$$

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

$$\Omega = \rho g Q S \tag{4}$$

where ρ is density of floodwaters (1500 kg/m^3), g is acceleration due to gravity (9.81 m/s^2) and S is gradient of the water energy surface (in m/m) derived here from elevation of riverbanks.

River discharge (Q; in m^3/s; Manning, 1891):

$$Q = \frac{AR^{0.67}S^{0.5}}{n} \tag{5}$$

where A is cross-sectional area (in m^2), R is hydraulic radius (in m) and n is Manning's resistance coefficient (dimensionless; cf. infra, Eqs. (8) and (9)).

River discharge (Q; in m^3/s; Williams, 1978):

$$Q = 4A^{1.21}S^{0.28} \tag{6}$$

River discharge (Q; in m^3/s; Rotnicki, 1991):

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

Roughness coefficient of Manning (n; dimensionless; Strickler, 1923):

$$n = 0.0151 D_{50}^{0.17} \quad (8)$$

where D_{50} is median bed material grain size (in mm).

Roughness coefficient of Manning (n; dimensionless; Limerinos, 1970):

$$n = \frac{0.113 R^{0.17}}{1.09 + 2.2\log(R/D_{84})} \quad (9)$$

where D_{84} is particle diameter for which 84% are finer (in mm).

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