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High frequency variations of water flux and sediment discharge during the Little Ice Age (1586–1725 AD) in the Rhône Delta (Mediterranean France). Relationship to the catchment basin

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Abstract

During the 17th and 18th centuries, the Rhône delta recorded high frequency fluctuations in water and sediment influx. These variations resulted from the drastic climatic changes that took place during the Little Ice Age, which were intensified by dense land settlement in the catchment basin. The use of complementary types of information (iconographic and textual archives, photo-interpretation of traces of fluvial metamorphosis, grain size distribution and mineralogy of alluvial infillings) allows a precise study of the major change that affected the Rhône delta in the second part of the 17th and the beginning of the 18th centuries. This change corresponds to a rapid response by the fluvial system and the occurrence of floods that were higher and more frequent on the lower Rhône. It resulted in a rapid change in fluvial environments, i.e. channel infilling, raising of river banks, appearance of crevasses and secondary channels, and accelerated delta progradation. It is associated with the influx of an abundant and exceptionally coarse-grained bottom load. The provenance of these sediments is discussed, using the heavy mineral assemblages they contain, with reference to reworking of previous alluvial deposits, probably due to changes in the active band and episodic loads in the whole catchment basin. The short response time to hydrologic impulse and the importance of the metamorphosis are related to the sediment influx from the Massif Central, whose steeply inclined rivers are close to the delta. The contribution of the northern Alps and the durancian basin (southern Alps) is not as important because of their distance from the delta and the time lag affecting the bottom load transfer downstream. The aims of this study are to investigate the response time, transfer velocity of sandy deposits, and the contribution of different catchment sub-basins to the supply of the Rhône delta. The role of climatic and anthropic factors are also discussed.

Introduction

During the 17th and 18th centuries, the Rhône delta underwent a major change, characterized by the metamorphosis of fluvial environments and considerable coastal progradation. This phase, which lasted several hundred years, included many fluctuations. The first and the most important fluctuation took place during the end of the 17th and the beginning of the 18th century, concluding with the avulsion of the river that in 1712, displaced the river to its present-day location. Sedimentological and historical data corresponding to these decades are detailed enough to allow chronological analysis of its development and determine the relationship with solid influx from the catchment basin.

The hydrology and the sediment load of the Rhone's drainage basin (95 500 km^2) depend on topographical characteristics and the type of surface, the nature of the bedrock and surficial formations, and on the regional climates of each catchment sub-basin (Pardé, 1925; Bourdier, 1961). The climatic deterioration to the cool and humid Little Ice Age modified the formation of solid and liquid discharge and coincided with a dense settlement of the countryside.

There is a lot of evidence for this change in the Rhône basin, i.e. the advance of glaciers in the northern Alps (Leroy-Ladurie, 1967) and the southern Alps (Evin, 1983; Jorda, 1985; Lagier & Masson, 1997), the lowering of the upper limit of forests (Tessier et al., 1993), the increase in lacustrine levels (Magny, 1993) and the torrential nature of flooding (Brochier, 1983; Bravard, 1989; Salvador, 1991; Pfister, 1992; Miramont, 1998; Pichard, in press), the phenologic data, the archives and first instrumental measurements (Alexandre, 1987; Pfister, 1992; Roditis, 1992; Serre-Bachet et al., 1992). At this stage in the reseach, it appears that not all the regions in the catchment basin behave the same way and that the climatic parameters (temperature, precipitation) are not covariant. Jorda & Roditis (1993) and Pichard (1995) show that the hydrologic peak of the lower Rhône between 1680 and 1710 does not coincide with the most drastic periods of fluvial ice at Arles. In the durancian basin, these decades correspond to a glacial retreat (Lagier & Masson, 1997) and a less dynamic hydrology (Guilbert, 1994; Pichard, in press).

Schumm (1977), Starkel (1983) and Brown (1997) describe the modes of adjustments of rivers in terms of variations in liquid and solid discharge. Evidence of the climatic deterioration of the Little Ice Age can be found in the basin upstream of the Rhône (Bravard, 1989) and on the Durance (Guilbert, 1994; Pichard, 1995) as early as the 14th century. However, the metamorphosis of the upper Rhône and the Isère is not recorded until the 18th century (Bravard, 1989; Salvador, 1991), as is that of the Buëch and the Durance (Gautier, 1992; Miramont, 1998). The map of Cassini (1788) shows the transformation of fluvial environments at the end of the 18th century. The river is braided along its whole length, occupying a wide river bed made of coarse material. The alluvial fans of tributaries, multiple oxbow lakes, and swampy plains developed behind bank deposits, constitute major zones of sediment storage.

Downstream, the delta records the solid transfers originating in the entire catchment basin. Although the suspended sediment arrives almost instantaneously during floods, the transport of the bottom load is slower and discontinous in space and time (Roditis & Pont, 1993). It depends on the climatic geography of each drainage basin, the gradient of tributaries and their position in the drainage network, structural dams and/or intermediate sediment traps. Features of detrital influx can be misinterpreted due to chronological shifting, which makes it difficult to differentiate between the effect of climatic and anthropic forcing. Salvador (1991) estimates the displacement velocity of the bed load in Isère at 10 km/century during the 18th century. It is probable that the sandy load, which was the major component of the bottom load in the delta, was transported more rapidly.

In the delta, the major hydrosedimentary change occurs many decades earlier than those occurring upstream of the basin. Therefore, the characteristics (deformation of fluvial sediment beds) and the chronology are studied in this paper. The relationship between the upstream basin and an estimation of transfer velocities is investigated using heavy mineral assemblages to determine sediment origin.

Paleohydrology and fluvial metamorphosis of the Rhône delta from the end of the 16th century to the beginning of the 18th century

The Rhône delta is situated downstream of a catchment basin characterized by a large hydrologic and climatic diversity (Pardé, 1925; Figure 1). The alpine and mediterranean tributaries play a decisive role in the regime, abundance, and sediment load of the river. Over the last 100 km, the river receives sediment influx on its left bank from the Durance flowing from the southern Alps and on its right bank from the Ardèche, the Cèze, and the Gardon, flowing from the Massif Central. This 'torrential' regime and the sedimentary load of its tributaries appears decisive for delta morphogenesis. However, the transport of bottom load is probably more rapid for right bank tributaries with steep gradients (8–10%) than for the lower Durance (gradient: 2–3%).

Many paleochannels resulted from delta construction during the Holocene (L'Homer et al., 1981). To the east, the Bras de Fer is the most recent of these channels (Figure 2). Its period of activity is accurately determined by the iconography of texts between 1586 and 1712. Its course makes a wide loop, that cuts across many beach ridge systems. Seismic probes and offshore drill cores confirm the remnants of a large detrital cone (PNOC, 1993).

Several remarkable historical documents exist that aid in understanding the evolution of the Bras de Fer: the hydrologic chronicals of Arles, whose raw data are discussed by Pichard (1995), environmental historian,

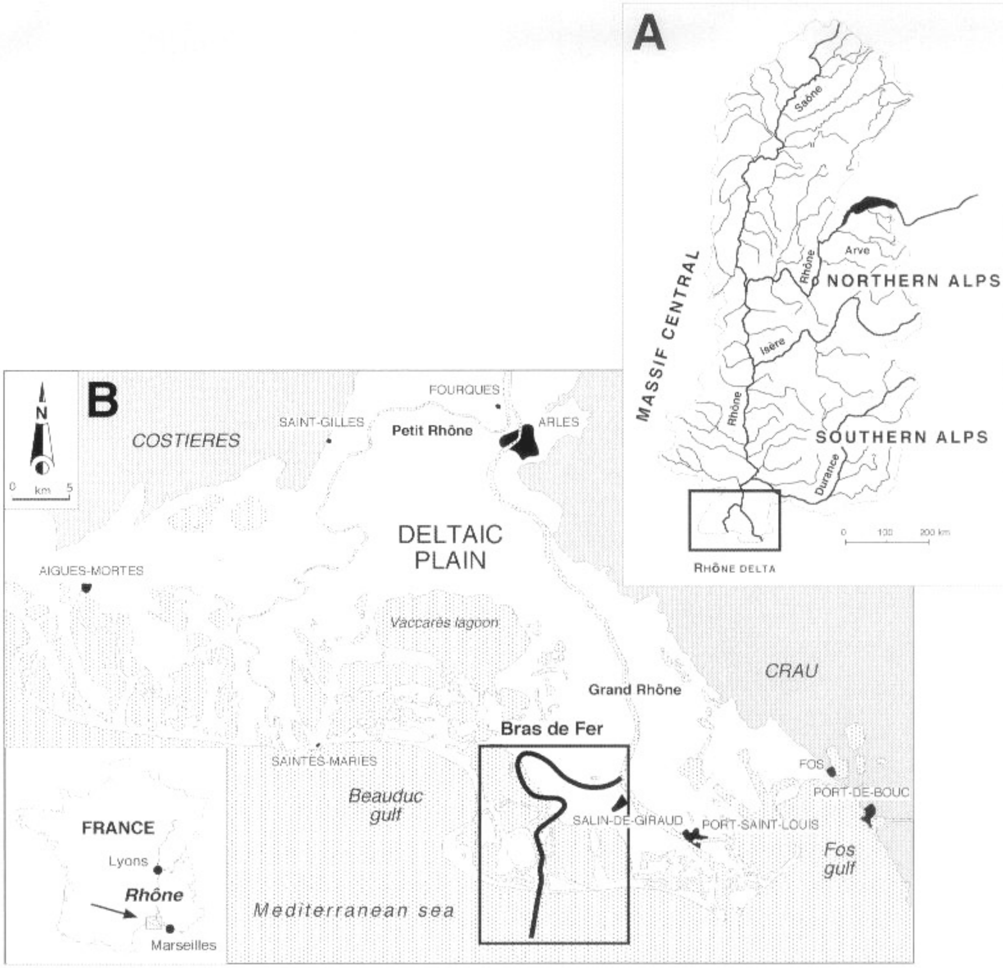

Figure 1. Location map showing the Rhône catchment basin (A) and the Bras de Fer paleostream in the Rhône delta (B).

and a continuous chronological series of very precise old maps (Caritey, 1995). The final morphology of fluvial environments were determined by topographic surveys (L'Homer, 1975a, b) and photo-interpretation. Deep cores indicate their vertical extent (Figure 3).

The periodicity of floods > 5.25 m NGF[1] is established by Pichard (1995) at Arles (Figure 4). The general increase in hydrologic flux between the middle of the 16th and the end of the 19th centuries is characterized by two distinct peak periods (1700–1710 and 1750–1810), during which high floods varied from once a year to once every decade. The first peak is preceded by a long period of instability, among which the most important floods occurred during the years 1560–1600 and 1670–1700. The period 1700–1710 corresponds to a phase of major hydrologic degradation that ends in the deflection of the Rhône into the delta.

The iconography of river mouths confirm this chronology and shows that the hydrologic change corresponds to a considerable increase in solid influx. Between 1660 and 1730, measurements made at 1- to 10-y intervals were mapped for the Royal Navy. These maps were digitalized to allow their superposition and the evaluation of the volume of sediments deposited in the channel and at its mouth (Caritey, 1995). They show the change in the fluvial landscape with the increasing emergence of islands, followed by the separation of the main channel in two subchannels between 1680 and 1710. The progradation of the Rhone's mouth at 80 m/y from 1660 to 1700 accelerates to reach 180 m/y from 1700 to 1710.

Using photo-interpretation, fluvial environments

[1] NGF: 'Nivellement Général de la France', general levelling of France.

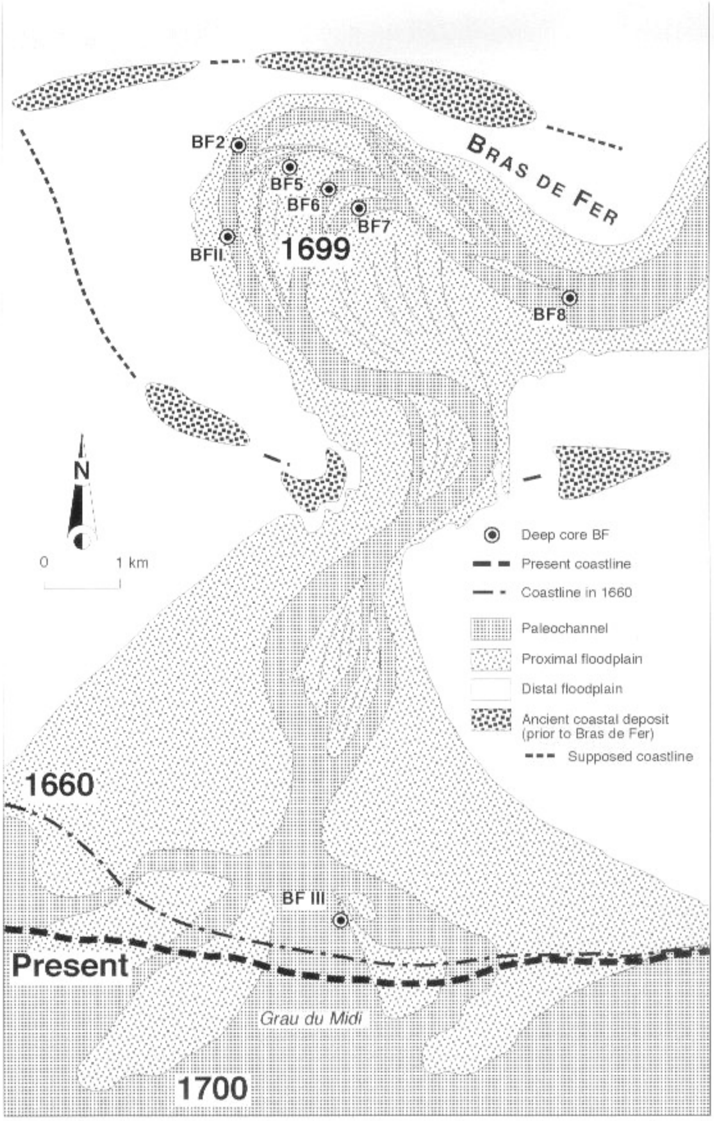

Figure 2. Paleogeography of the Bras de Fer and its mouth obtained by photo-interpretation. Location of the core sites.

before the deflection of 1712 could be reconstructed. The environments were particularly unstable: involving the multiplication of islands and crevasses and division of the river bed along the axis of meander that appears to be in the process of oxbow-lake formation. The overall structure of the beds (estimated by cores made in alluvial deposits, Figure 3), confirm the following hypothesis: the channel, a dozen meters deep and 700 m wide upstream, becomes progressively shallower in the meander and to the mouth (4 – 7 m), whereas the bank deposits multiply and thicken.

The analysis of fluvial dynamics is based on the sedimentology of seven cores (4–12 m in length) taken along the axis of the paleochannels and in bank deposits. All cores reached the marine deposits (Figure 3). Grain size analysis was performed on 200 sediment samples taken every 30 cm in the sandy layer and every 10 cm in the more silty layer. The granulometry and the C/M diagram were used to reconstruct the depositional environments (Folk & Ward, 1957; Passega, 1957; Bravard, 1983). Sediment structure, revealed by X-ray photography, was interpreted in terms of dynamics (Reineck & Singh, 1980). Based on these criteria, three types of hydrological regime (river flow) were identified (Arnaud-Fassetta, 1998): type A, characterized by a homogeneous and coarse

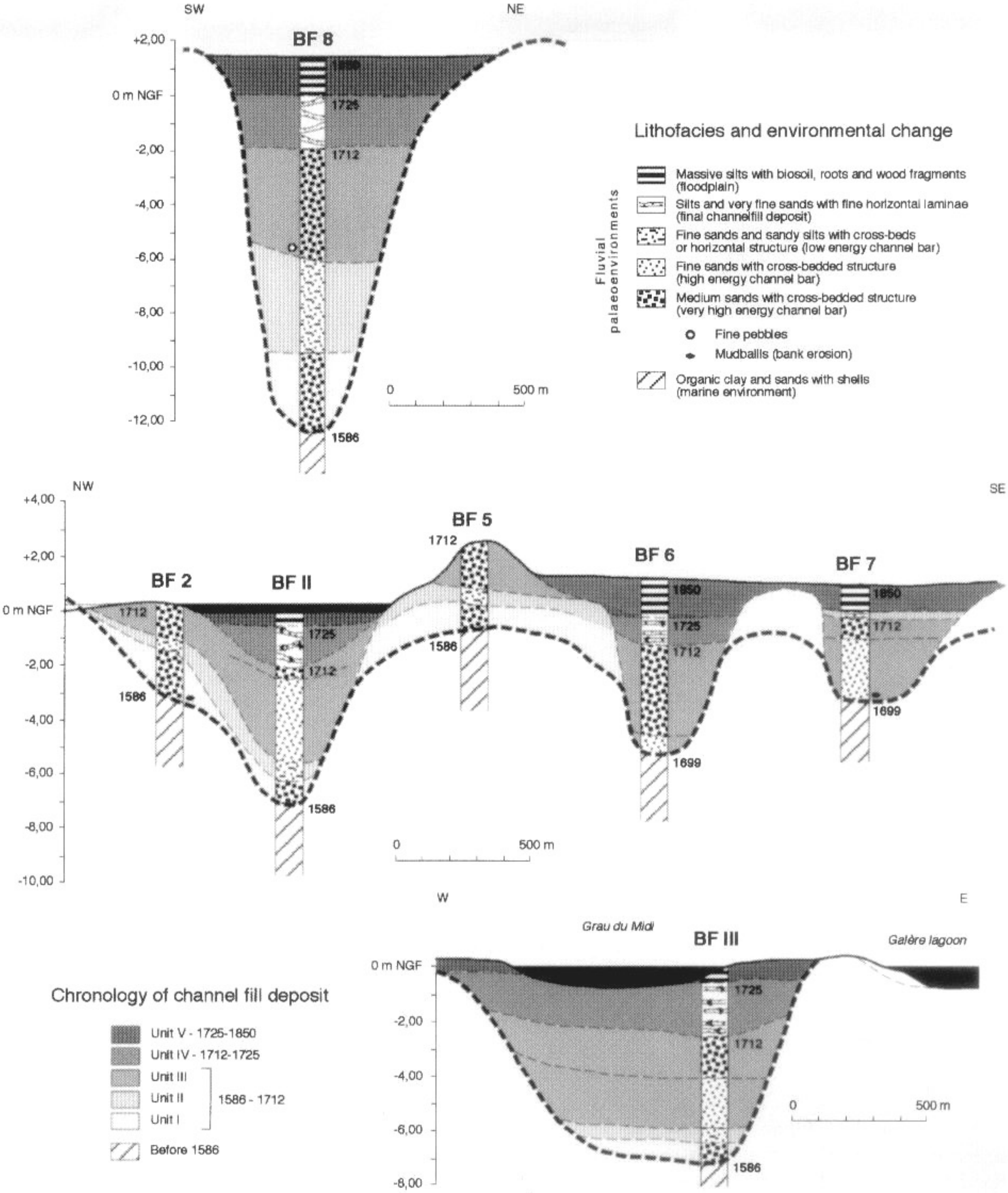

Figure 3. Bras de Fer paleostream structure and channel fill deposits.

grain size distribution (C_s: 700–800 μ), with cross-beds or oblique structures in the channel and the part of the bank close to the river, corresponds to a high and constant fluvial flows. Type B is homogeneous and has a medium grain size distribution (C_s: 400–500 μ), with a subhorizontal structure coarsely bedded in

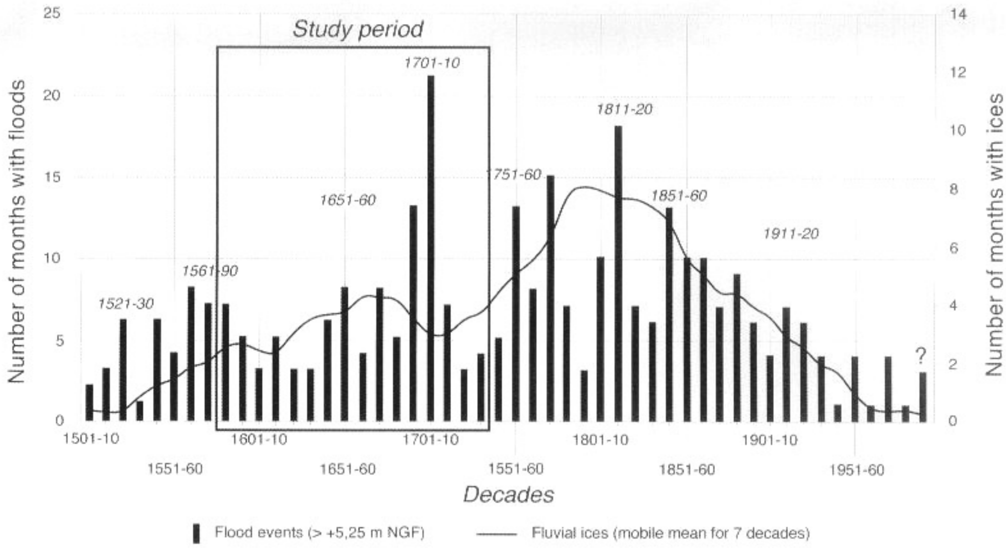

Figure 4. Flood frequency of the Rhône at Arles, since 1500 AD (after Pichard, 1995).

the channel, corresponds to a decreasing and regular fluvial flows. Type C has a heterogenous grain size distribution (C_s: 400–600 μ) with a variable structure, indicates a pluri-annual variability of fluvial flows.

The core stratigraphy differs according to the depositional environment. In the main channel, four units (types C–B–A–B) are successively superposed. In the secondary channels and on the external banks only the two upper units (A–B) are present. The chronological variablity of the dynamics, characterized by a maximum, can be compared to the hydrologic periodicity proposed by Pichard (1995). The spatial distribution of sedimentary units can be explained by the changes in fluvial landscapes and the widening of the active band, coinciding with the hydrologic maximum (Caritey, 1995). The lower unit I (type C) was deposited between 1580 and 1600. Unit II (type B) coincides with a decrease in the river's energy between 1600 and 1640. Unit III indicates a gradual increase in hydrologic activity, culminating in the peak of 1700–1710 and the lateral extension of the active band, with the creation of two new channels. Unit IV (type B) corresponds to the infilling of the Bras de Fer after deflection (1712–1725). At the top, unit V indicates floodplain deposits of the Grand Rhône, which cap the underlying units.

A rapid morpho-sedimentary response by the Rhône to hydrologic variations takes place over several years (Figure 5). The highest peak at the end of the 17th to the beginning of the 18th century is of short duration (10 years), but it is preceded by 30 – 40 years of medium to high floods, which prepares the morphologic adjustment of the river bed.

Relationship to the catchment basin: origin of the sandy bed load from the 16th–18th centuries in the Rhône delta

Numerous studies analyze the contribution of different catchment basins to the solid load transported in the hydrographic network. Some of these studies use heavy mineral as markers to determine the paleogeographic origin of solid fluxes (Hassan, 1976; Tourenq, 1986; Hamrouch & Stanley, 1990). In the Rhône catchment basin, Van Andel (1955) and Petit et al. (1996) have isolated significant assemblages whose identification is facilitated by the variety of litho-structural facies.

Heavy mineral analysis of core BF8 was made on 37 samples (Figures 3 & 6). The samples were chosen in relation to the grain size analysis. Heavy mineral analysis was only made on the fine sand fraction (160–50 μ) because it is the only fraction that is transported directly from its source, coarse sand-being frequently transported in steps (Arnaud-Fassetta, 1997). Sediment influx from the Alps are characterized by pistachite, common hornblende and glaucophane, originating in the durancian basin upstream (Dubar, 1982). Sediment influx from the Massif Central (Cévennes, Vivarais, Velay) contains augite, aegyritic augite, basaltic hornblende, hyper-

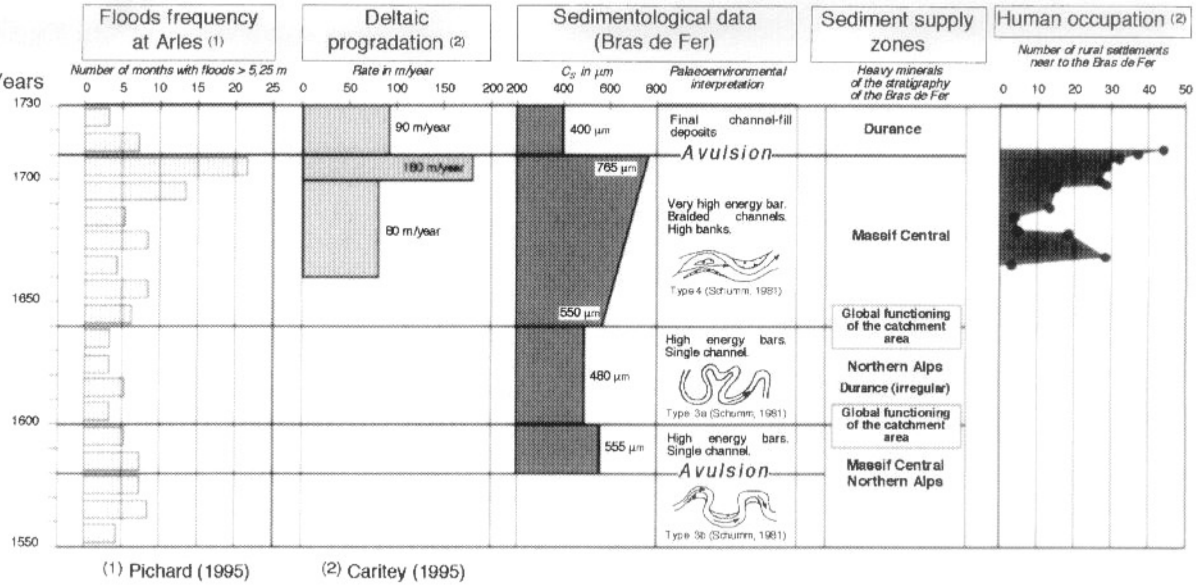

Figure 5. Table showing a compilation of water flux and sediment discharge in the Rhône delta from the 16th to 18th centuries.

stene, andalusite and titanite. In addition, two types of minerals indicate modifications in the active band of the river: the abundance of minerals resistant to weathering (zircon, tourmaline, staurolite) reflect the reworking of alluvial sediments and older detrital deposits (Gandolfi & Paganelli, 1977). Heavy minerals of high density ($d > 3.7$) include garnet, zircon and staurolite. Their transport is related to high energy currents and their deposition depends on local hydrodynamic fluctuations.

At the top of unit I and the boundary of units II and III, two short phases of sediment influx originate from the entire catchment basin. The long distance and the heterogeneity of source zones explain why these phases do not correspond to the coarser sequences. Unit II and in part, unit I, correspond to sediment influx mainly originating in the northern Alps and to a renewel of erosion of river banks, with an irregular participation of the Durance and an accessory load originating in the Massif Central. These deposits coincide with a reduction in hydrodynamics, confirmed by the presence of high density minerals, which result either from the effect of the distance of source zones or a decrease in flood energy. Unit III is unique in that its sediments originate exclusively from the Massif Central. They indicate the effect of extensive flooding due to tributaries located close to the delta and with a steep gradient. The relative absence of northern alpine and durancian sediment influx is indicative of the problem of the transfer time taken by the sandy load originating from upstream sub-basins in the Rhône catchment basin. Unit IV is associated with solid influx originating in the southern Alps (Durance). Their late arrival in the delta, compared to the beginning of change in Durance (1660–1670), indicates that the sediment was transported over a period of 40–50 years in the durancian basin before reaching the delta plain.

Discussion and conclusions

This study reveals a major change in the Rhône hydrosystem at the turn of the 17th century, which leads to a metamorphosis of the lower Rhône river bed. The river changes from meandering to 'deltaic braiding', characterized by the multiplication of channels, the deposition of numerous sandy banks, and rapid channel infilling.

The 'deltaic braiding' is a local morphosedimentary response to the major hydrologic change from 1700–1710. The rapid alteration of fluvial environments, which occurring to the peak of the change, is the result of the magnitude of fluvial activity during this period (with a frequency of many high floods occurring every year to every decade). It is also a consequence of the river bed development and the reworking of sediment load from the catchment basin during the preceding 30–40 years of hydrologic transition.

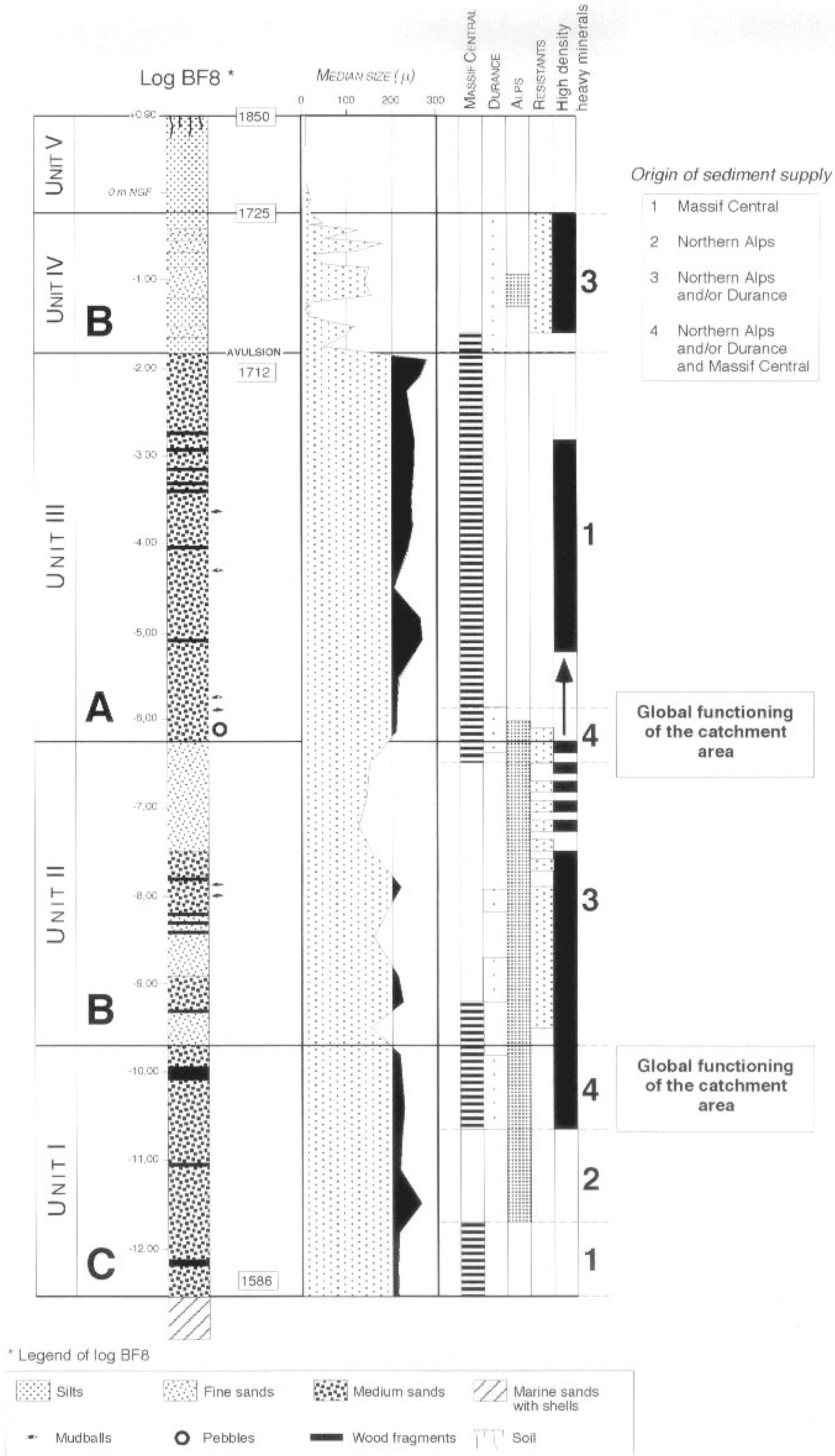

Figure 6. Heavy mineral and grain size analyses of core BF8 (Bras de Fer).

The rapid adjustment of fluvial environments also assumes the availability of abundant sediment. This is assured at the end of the 16th century by the destabilization of the hydrosystem (Little Ice Age), which starts to infill the channel during the 17th century. The hydrologic change and the metamorphosis are due to the decisive influence of the source zones in the Cévennes and the Vivarais, which are closest and have the highest hydraulic energy. Tributaries from the Cévennes and Ardèche, at a distance of only 100–150 km and with a steep gradient, have the capacity to rapidly supply the Rhône delta during hydrologic peaks. The alpine tributaries and the upstream Durance basin, because of their relatively great distance away (> 250–300 km), supply a smaller amount of sediment, whose transfer is chronologically shifted. In the durancian basin, the hydroclimatic change begins around 1660–1670, but the solid influx does not arrive in abundance at the delta until 40 – 50 years later, i.e. not before 1710. They contribute moderately to the metamorphosis of the lower Rhône at the beginning of the 18th century. Nevertheless, the effect of the possible paleoclimatic fluctuations between the Massif Central and the Alps cannot be excluded.

In light of the data, it appears that it is difficult to distinguish the effects of the climatic history and land occupation in the catchment basin. The abundance of sediment is a function of both the river's capacity of transportation and the sediment supply coming from drainage basins, in other words the effects of erosion, accelerated by settlement of the countryside beginning in the 17th century. However, the transfer of detrital sediment downstream of the fluvial system depends essentially on the hydroclimatic data (volume, intensity and seasonal distribution of precipitation, frequency and levels of floods). In the case of the lower Rhône, the exact anthropic impact and the development of fragile eastern slopes of the Massif Central, compared to those of the northern and southern Alps remains in question.

This study compares the transport velocity of sediment load in the catchment basin and the metamorphosis of the lower Rhône. Durancian sands arrive at the delta with a time lag estimated at 40–50 years. Their velocity over the distance from upstream of the basin to its mouth (250–300 km) can be evaluated at 5–8 km/y. The contribution of durancian sediment load from upstream to the metamorphosis of the lower Rhône depends on the duration of the change. In the case of a short lived change (one to many decades) the durancian deposits only contribute moderately to lower Rhône metamorphosis. The changes in fluvial landscapes is mainly due to the 'nearby' hydrogenesis, in which the Massif Central plays a decisive role. During a longer period of change (lasting one or many centuries), e.g. the First Iron Age or Late Antiquity, the overall catchment basin, including the upper Durance, contributed to the metamorphosis of the lower Rhône. Thus, the Rhône delta became the catchment basin that recorded diachronous disequilibria affecting the different catchment sub-basins, even while undergoing specific climatic constraints (Arnaud-Fassetta, 1998).

In conclusion, this metamorphosis of the delta occurs before and is chronologically disconnected from the one described by Bravard (1989) and Salvador (1991) in the northern Alps. The Isère and the Drac change from meandering to braided rivers at the end of the 18th century, whereas the Bras de Fer changes its fluvial regime at the end of the 17th century. The metamorphosis is even more rapid when the bottom load is fine-grained, and thus, more mobile. This undoubtedly explains the time lag (50–100 years) between delta metamorphosis, related to mainly sandy bottom loads that are transported rapidly (5–8 km/y) and those related to the northern Alps, associated with a slow-moving coarse bottom load (100 m/y; Salvador, 1991).

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