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Role of fluvial sediment inputs in the mobility of the Rhône delta coast (France)

Participation des apports sédimentaires fluviaux à la mobilité du littoral du delta du Rhône (France)

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Abstract

The influence of sediment input has a crucial role in the Holocene mobility of the Rhône delta coastline. Delta progradation phases are associated with more abundant and coarser sediment inputs due to anthropogenic and climatic forcing in the fluvial basin. However, the rate of sea-level rise, the sedimentation volume available in front of the mouth and the channel geomorphology modify the relationships between the fluvial input and the mobility of the delta coastline. The relation between mouth mobility and sediment input are analysed in the Rhône delta over the past 7,000 years, with particular emphasis on the interruption of progradation by fluvial avulsion and mouth shift. The present mouth and three fossil branches are studied: the Saint- Ferréol (4,000 yr BP–6th century BC), Bras de Fer and Pégoulier branches (from the 16th to the 19th century, *i.e.* during the Little Ice Age). Since the 19th century, river management has given rise to the latest stage of mouth progradation and disrupted the natural process of the avulsion.

Key words: river input, avulsion, progradation, Holocene, Rhône delta.

Résumé

Les apports solides jouent un rôle déterminant dans la mobilité holocène des littoraux du delta du Rhône. Les phases de progradation deltaïque sont associées aux apports solides abondants et grossiers qui sont liés aux forçages climatiques et anthropiques dans les bassins versants. Cette relation est cependant modulée par les variations de vitesse de montée du niveau marin, par l'amplitude de l'espace de sédimentation et par la géomorphologie du chenal fluvial. La mobilité des lobes deltaïques est analysée depuis 7000 ans, avec un intérêt particulier pour les périodes de défluviation et de déplacement des embouchures, dont les causes sont discutées. L'embouchure actuelle et trois bras fossiles sont étudiés : le bras de Saint-Ferréol (4000 ans BP-VIᵉ siècle ap. J.-C.), les Bras de Fer et de Pégoulier (XVI-XIXᵉ siècles ap. J.-C., i.e. *pendant le Petit Âge Glaciaire). À partir du XIXᵉ siècle, les aménagements favorisent les ultimes avancées du delta et perturbent le déroulement naturel des avulsions.*

***Mots clés** : apports fluviaux, défluviation, progradation, Holocène, delta du Rhône.*

Version française abrégée

Les facteurs de mobilité des littoraux deltaïques ont fait l'objet de nombreuses recherches (Galloway, 1975). Plusieurs auteurs ont souligné l'importance de phénomènes autocycliques (Schumm, 1993 ; Roberts, 1997) : la progradation des lobes, en allongeant le profil en long, induit un déséquilibre qui aboutit à l'avulsion fluviale et au déplacement des embouchures. Ce "cycle", à contrôle interne, se répèterait tous 1000 à 2000 ans dans le delta du Mississipi.

Les données nouvelles acquises depuis une dizaine d'années dans le delta du Rhône (Vella, 1999 ; Arnaud-Fassetta, 2000 ; Sabatier, 2001 ; Antonelli, 2002) permettent de proposer une synthèse des facteurs de la mobilité côtière dans ce delta (fig. 1). Parmi eux, la variabilité des apports sédimentaires fluviaux joue un rôle déterminant dans la genèse et le déplacement des lobes deltaïques. Elle est liée à des facteurs allocycliques (climat et anthropisation).

Le texte analyse d'abord les facteurs de mobilité dans le delta du Rhône : la subsidence y est négligeable à l'échelle de l'Holocène, mais les irrégularités de la topographie tardiglaciaire (Gensous et Tesson, 1997) modulent le volume de l'espace à sédimenter, favorisant ou retardant la progradation des embouchures (fig. 2). La montée du niveau

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marin, ralentie à partir de 7000 ans BP, passe par un palier entre 4800 et 2500 ans BP (Vella et Provansal, 2000), qui favorise la progradation. La variation des apports solides du fleuve est très importante. Sur la base de l'analyse sédimentaire des paléochenaux et de la plaine alluviale (carottages profonds, tranchées archéologiques), des régimes types ont été identifiés, dont le plus intense correspond à des crues plus fréquentes, chargées de sédiments abondants et grossiers (limons grossiers et sables fins). Cinq phases ont été mises en évidence dans la plaine alluviale et le delta, depuis 5800 BP (Arnaud-Fassetta, 2000). Le texte analyse le temps et le mode de réponse des lobes deltaïques à ces forçages, ainsi que le fonctionnement des avulsions successives à partir de quatre cas (bras fossiles de Saint-Ferréol, du Bras de Fer, de Pégoulier et Grand Rhône actuel).

Le bras de Saint-Ferréol (fig. 3) est caractérisé par une progradation pulsée, identifiée sur la base de quatre nouvelles dates ^{14}C, dont les étapes sont synchrones des phases d'abondance hydro-sédimentaires. Mais la vitesse d'avancée du lobe est accélérée temporairement par le palier de la montée du niveau marin et modulée par les variations du volume de l'espace de sédimentation. Les indices d'instabilité apparaissent dès l'époque romaine (bras secondaire). L'avulsion, entre le II^e et le VI^e s. ap. J.-C., est due à la conjonction d'apports solides abondants, de l'allongement excessif du profil en long et de la reprise de la montée du niveau marin.

Le Bras de Fer et le bras de Pégoulier sont contemporains du Petit Âge Glaciaire, identifié (Pichard, 1995) par une fréquence décennale élevée des crues supérieures à 5,25 m NGF à Arles (fig. 4). La progradation très rapide du Bras de Fer (fig. 5) est entravée au bout de quelques décennies par les mutations géomorphologiques de son chenal, qui piègent les sédiments (Arnaud-Fassetta et Provansal, 1999) aux dépens de l'embouchure. L'avulsion de 1711 est cependant favorisée par la présence du canal artificiel des Launes. À partir du XVIII^e siècle, en effet, l'artificialisation du milieu devient un élément essentiel des relations entre le fleuve et son littoral : l'amélioration du transit de la charge solide provoque sur le bras de Pégoulier l'avancée la plus rapide de l'histoire du delta (fig. 6), mais le risque d'avulsion y est désormais contrôlé.

Cette évolution conditionne le fonctionnement de l'embouchure au XX^e siècle, caractérisé par un important stockage sédimentaire sur le prodelta (fig. 7) (Radakovitch et al.*, 1998 ; Sabatier, 2001) : la diminution drastique des apports solides (Pont* et al.*, 2002 ; Antonelli, 2002) est aggravée par la reprise de la montée du niveau marin (Suanez, 1997). Mais l'importance de l'espace de sédimentation à l'embouchure, liée à la rapide avancée de la phase précédente, joue aussi un rôle important en piégeant les sédiments sur le prodelta. La progradation deltaïque est stoppée et la majeure partie du littoral deltaïque est soumise à l'érosion.*

Cette synthèse permet donc de montrer le rôle déterminant des apports solides sur la progradation des lobes deltaïques, dont les phases dépendent de forçages climatiques et anthropiques. Mais ces apports, en déformant le chenal, engendrent à terme son instabilité, puis l'avulsion fluviale. Des facteurs secondaires, comme l'ampleur de l'espace de sédimentation, peuvent nuancer cette relation. Enfin, depuis le XVIII^e siècle, l'anthropisation modifie les relations entre le fleuve et les lobes d'embouchure.

Introduction

The influence of fluvial sediment inputs on the mobility of delta coastlines has been the subject of many publications, including those of W.E. Galloway (1975), H.E. Reineck and I.B. Singh (1980), W.E. Galloway and D.K. Hobday (1983). These authors showed that high floods could cause an avulsion of bed, the new channel being formed from a crevasse/breach in the bank below the elevated filling of the former bed. This process, which involves shifting of the mouths, is an essential factor in the construction of deltas.

H.H. Roberts (1997) systematised the succession of avulsions, based on his work on the Mississippi delta: he envisaged a cyclic sequence lasting approximately one to two millennia, starting from an initial crevasse avulsion that determines the position of a new mouth. Each cycle is characterised firstly by abundant river input and rapid progradation, then attaining a point of disequilibrium that causes a shift of the mouth and its reworking by longshore drift. This approach depends on an internal (autocyclic) control of fluvial sedimentary dynamics, in which lengthening of the longitudinal profile is a determining factor. S.A. Schumm, (1993) and M.D. Blum and T.E. Törnqvist (2000) confirm the effects of base level proximity on the sedimentation and morphology of the channel. These authors proposed evolutionary schemes based on the lengthening of the longitudinal profile and/or variations in rate of sea-level rise, inducing channel avulsion. However, in the Rhône delta, A. L'Homer *et al.* (1981) advanced hypotheses on the combined role of varying sea-level and river inputs in controlling the channel avulsion and the rates of progradation during the Holocene.

Studies carried out over the past few decades in the Rhône delta (Arnaud-Fassetta, 2000; Vella, 1999) confirm that the rate of mouth shifting is irregular and depends on major phases of fluvial sediment input, *i.e.* on allocyclic forcing external to the alluvial system of the deltaic plain. This observation has also been made in other major deltaic systems worldwide (see Journal of Coastal Research, 1998).

The knowledge obtained on the Rhône delta over the last decade allows us to provide new answers concerning the mode and chronology of the channel avulsions. We analyse precisely the response time-lag of the prograding mouth lobe and coastline to the alluvial input and the relationships between river forcing and the shift of channel avulsion-lobes.

State of knowledge concerning the factors of lobe mobility

During the second half of the Holocene, two mouths built up two major prograding systems, one to the west (the Saint Ferréol lobe between 4,000 and 2,000 yr BP), another to the east between the 15th and 20th centuries (the lobes of Bras de Fer and Pégoulier-Roustan: fig. 1). In the gulfs created between and around these two main systems, deposition of alluvium formed the lobes and secondary fillings (Grand Passon and Plan du Bourg to the east, lobe of Ulmet in the centre, Peccais and Daladel to the west). This chronology, which was established in the deltaic plain, is now supported by the interpretation of seismic records on the continental shelf (Gensous et Tesson, 1997; Marsset and Bellec, 2002). Several factors could be involved in the processes of progradation and shifting of the mouths.

The rise in relative sea-level, at first rapid between 18,000 and 7,000 yr BP (1 cm/yr on average), created a large accommodation space. This allowed sedimentary aggradation, leading to the retreat of the coast up to a maximum flooding line (onlap stage of the delta) located to the north of the Vaccarès lagoon (L'Homer *et al.*, 1981). From 7,000 to 6,000 yr BP, the sea-level rise gradually slowed down and was characterised by a step between 4,800 and 2,500 yr BP (Vella and Provansal, 2000), that allowed the geomorphological expression of the sediment inputs, thus reversing the earlier transgressive trend and causing progradation of the coastline. The current level was reached at the end of the first millennium AD. At the Holocene time scale, subsidence has been negligible, but the space available for prodeltaic sedimentation varies according to the topography of the Pleistocene bedrock (fig. 2). The advance of the Saint-Ferréol system, localised on top of the incised channels of the postglacial Rhône is slowed down by the depth of the zone to fill in (-50 m): the delta front has advanced by about 3 m/yr between 4,500 and 2,000 yr BP. For an equivalent surface-area, the lobes of the modern system build up much more rapidly on a shallower substrate that is already partially filled in: between the 17th and 19th centuries, the delta prograded at a rate of 80 to 180 m/yr. The present-day mouth is located vertically above an abrupt gradient in Pleistocene bedrock (-70 m), which now limits its progradation.

The previous works carried out in the Rhône delta (Arnaud-Fassetta, 2000) and its immediate upstream area (Bruneton, 1999) has revealed a significant variability of the Rhône river inputs since approximately 7,000 yr BP. The longitudinal succession is well correlated with the palaeo-

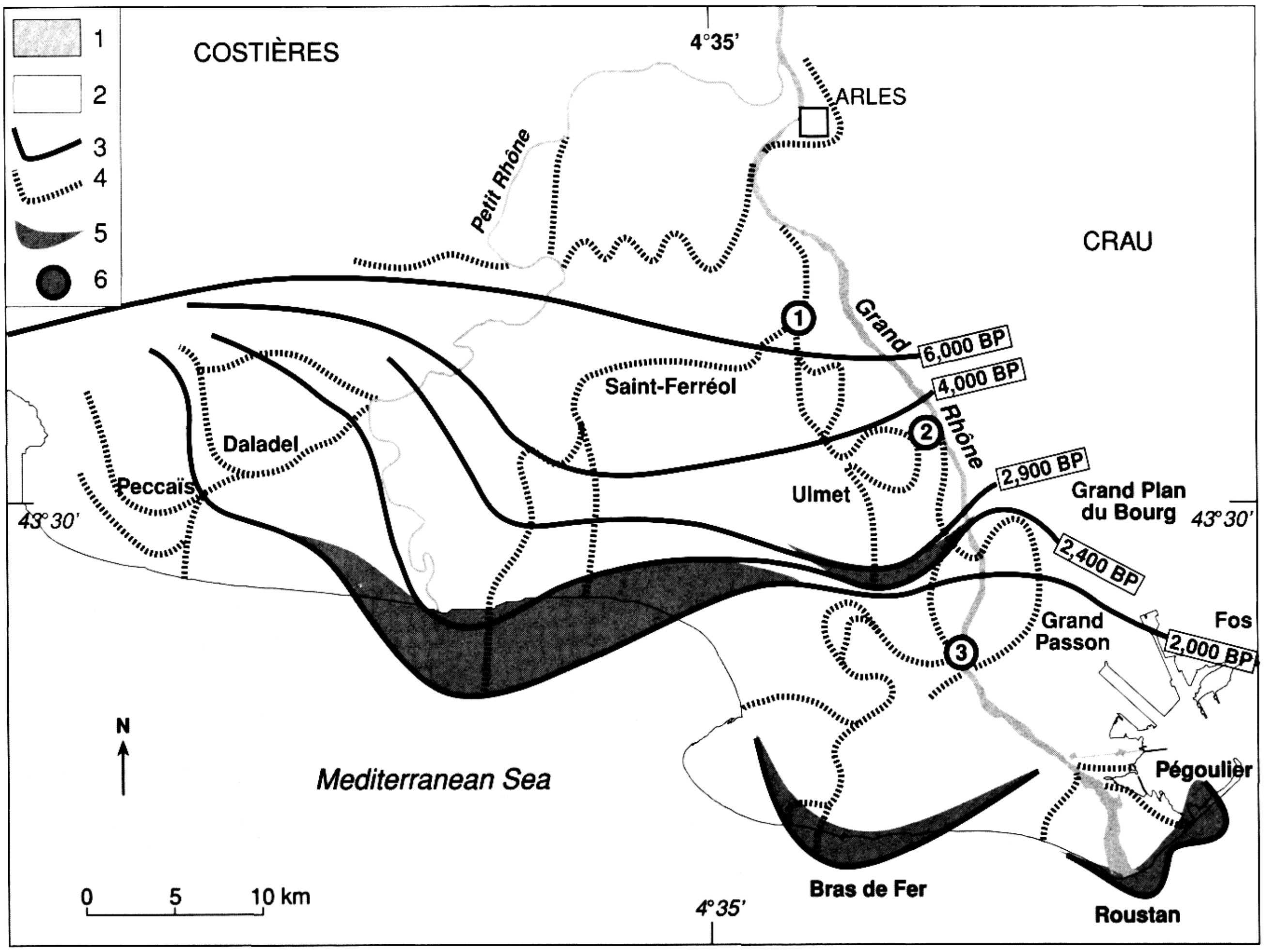


Fig. 1 – **Main fossil branches and lobe progradation since 6,000 BP**. 1: pre-Holocene bedrock; 2: Holocene alluvial and deltaic deposits; 3: successive coastlines; 4: Rhône paleochannels; 5: main Holocene deltaic lobes; 6: main avulsion points (1: from Saint-Ferréol to Ulmet channel; 2: from Ulmet to Grand Passon channel; 3: from Bras de Fer to Pégoulier channel).

*Fig. 1 – **Principaux chenaux fossiles et lobes progradants depuis 6 000 ans**. 1 : substratum pré-holocène ; 2 : dépôts holocènes alluviaux et deltaïques; 3 : lignes de côte successives; 4 : paléochenaux fluviaux ; 5 : principaux lobes holocènes ; 6 : principaux points d'avulsion (1 : du bras de Saint Ferréol vers le bras d'Ulmet ; 2 : du bras d'Ulmet vers le Grand Passon ; 3 : du Bras de Fer vers le bras de Pégoulier).*

hydrology of the upper and middle Rhône (Bravard, 1995; Provansal *et al.*, 2000). The sediment record is attributed to climatic forcing, gradually combined with increased anthropogenic influence in the catchment from the Neolithic period. The intensity of the erosion processes depends on the rate of denudation in the catchment basin: during the Holocene, except in lithologically vulnerable areas such as the black shales of the Baronnies or the Digne region, denudation of the interfluves remained primarily of anthropogenic origin, in relation to expansion of agriculture, exploitation of timber and forest fires (Jorda and Provansal, 1996). The transit of a coarse and abundant sedimentary load downstream to the mouth delta, however, depended on hydro-climatic forcing, and explains the resulting type of fluvial regime. According to the frequency and intensity of high-magnitude floods, G. Arnaud-Fassetta (2000) characterised a "flood-dominated" regime as being the most efficient in feeding the deltaic plain.

Variations between coarse sediment load and water discharge modify river morphology, which adapts itself to hydro-sedimentary constraints (Schumm, 1993; Bravard and Petit, 1997; Blum and Törnqvist, 2000). The abundant and coarse sediment discharge is partially trapped in the channel, where it leads to the development of a braided river style and to the raising of the alluvial floor. In contrast, sedimentary deficits favour river-bed adjustment against exhumation or incision of the alluvial floor, and increase the efficiency of alluvial transport. Moreover, the geomorphology of the tributary basins can induce space-time shifts of the sedimentary transport: for example, mineralogical analyses have shown that the Durance silt-sandy inputs arrived in the delta with a delay of 40–50 years after the first peak of the Little Ice Age and do not influence the Bras de Fer avulsion (Arnaud-Fassetta and Provansal, 1999). Abundant sandy inputs build up thick prograding offshore bars, whereas the fine fractions favour the development of lagoons or are evacuated towards the continental shelf.

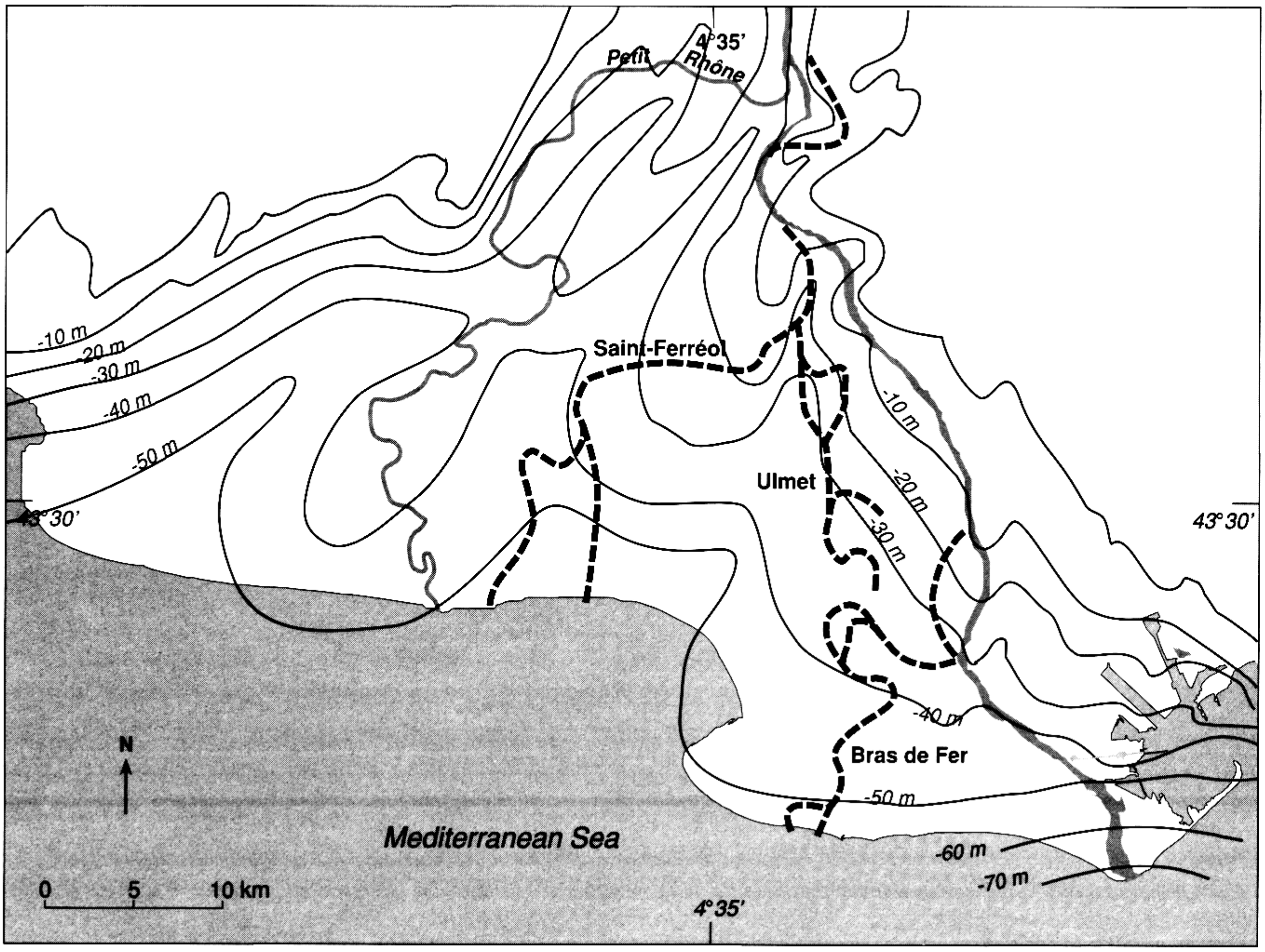
Chronology of sedimentary input in the deltaic plain

Methods of study

In the Rhône delta, the Holocene variability of the sediment input was described using several types of data collected by coring or sampling from the stratigraphic sections carried out at or near archeological sites (Arnaud-Fassetta,

Fig. 2 – **Isobaths from the top of the Pleistocene bedrock (palaeo-valleys) and main fossil branches.**

Fig. 2 – ***Isobathes du toit du substrat pleistocène (paléo-vallées) et principaux bras fossiles.***



2000). Two distinct approaches were developed in the palaeochannel and floodplain sections.

In the palaeochannels, the sedimentology of the alluvial filling is described using the median grain-size (D_{50}) and the higher percentile (D_{99}), indicative of the average and maximum competence of the flood discharges, respectively. The presence of silty-clayey mud balls indicates episodes of bank erosion, linked to widening of the channel or weakening of the banks by natural and/or anthropogenic degradation of the riverine vegetation (Arnaud-Fassetta *et al.*, 2000). The extraction of the width and depth parameters of the channel and of the competency and transport capacity variables allow us to interpret the evolution of the river style and the lateral mobility of the channel (Bruneton *et al.*, 2001). The volume of sediments that has been brought down to the mouth depends greatly on the channel morphology (cross section geometry and river style), which defines its capacity to transport flows. The sedimentary trapping is limited in the large and sub-rectilinear sections, while the massive storage of coarser alluvium (medium sand) is significant in a meandering channel, leading to the appearance of a braided river style (the "deltaic type" according to G. Arnaud-Fassetta, 2000) and to the raising of the alluvial floor. These changes reduce the sedimentary influx at the mouth and can lead to a displacement of the bed (avulsion) during major floods. The new channel is established from a crevasse in the bank, located below the old, elevated and filled bed. This process thus involves the shifting of mouths and the switching of deltaic lobes.

The floodplain is a site of storage of fine sediments (sand and silt in the proximal part, silt and clay in the distal part). This phenomenon is thus not prejudicial to the sedimentary supply to the coast, which is primarily fed by fine to medium sands. The mechanisms of aggradation vary through time depending on the accommodation space available during deposition, the number of overbank flooding events and the concentration of solid flux. The quantitative approach is based on calculating the sedimentation rates measured in mm/yr at several sites of the delta, based on archaeological and/or radiocarbon data. The identification of different periods of soil formation (frequency and thickness), based on thin section studies, has made it possible to point out breaks in the rates of sedimentation. By comparing the data from the Rhône delta data with those from the upstream basin, H. Bruneton (1999) and G. Arnaud-Fassetta (2000) showed that average sedimentation rates rather accurately reflect the magnitude and frequency of floods on the alluvial plain.

Holocene alluvial inputs

A total of five phases of more abundant sediment supply have been determined on the basis of sedimentological studies of long cores, of bank and lagoon deposits in the Arles plain (Bruneton, 1999; Bruneton *et al.*, 2001) and along the palaeochannels in the delta (Arnaud-Fassetta, 2000; Arnaud-Fassetta, 2002). The chronological resolution is better for the more recent periods, since Roman times. According to the Arles long core, these phases are dated between 5,800 and 3,800 yr BP, 2,500 and 2,400 yr BP, the 1st century BC and the 2nd century AD, and the 5th and 8th centuries AD. For the most recent phase (16th-19th centuries), field observations are corroborated by historical data recorded at Arles since 1501 (Pichard, 1995). Geomorphic and palaeohydrological data, obtained over the last decade, were not yet connected with the more recently acquired knowledge about the changing mouths and the chronology of the deltaic lobes (Vella *et al.*, 1998; Vella et Provansal, 2000; Arnaud-Fassetta et Provansal, 1999; Sabatier, 2001).

Three cases will be analysed, which illustrate the relationships between fluvial sedimentary inputs and the mobility of the mouths: 1) the Saint-Ferréol Rhône, between 7,000 yr BP and the Roman period, 2) the Bras de Fer and Pégoulier Rhône during the Little Ice Age, and 3) the Roustan mouth (present-day mouth) in the 20th century.

The role of sediment inputs to the mobility of the Saint-Ferréol lobe

The Saint-Ferréol palaeochannel advance created a pointed lobe, whose successive positions between 4,000 yr BP and the end of the 1st century AD are expressed by fossil offshore bars, clearly obvious on aerial photographs (fig. 3A). The assymmetry of these deposits, which is much less abundant to the east than in the west of the palaeomouths, is related to the strong swells from the east, generating a dominant drift towards the west–northwest. Two other branches developed during the same period (Albaron and Ulmet palaeochannel, fig. 1), but they stay back from the Saint-Ferréol lobe.

New ^{14}C ages and archaeological data indicate a pulsed progradation that accelerated between 2,600 yr BP and the Roman period. The first advance (2.5 m/yr), affecting a shoreline dated at 7,000 yr BP north of the Vaccarès lagoon (L'Homer *et al.*, 1981), built the Mornès ridge at ~ 4,035 yr BP. Then, three pulses define an advance of at least 15 m/yr between 2,950 yr BP and the first centuries AD: the first two are dated at 2,950–2,620 yr BP (Bois des Rièges ridge) and 2,420 yr BP (beneath the present-day beach); the last one, situated as far as 2.5 km off the current coast, is younger than the 1st century AD, since it buries Roman wrecks stranded on fossil submarine beach bars (Long, 1997).

The significant advance of the Saint-Ferréol lobe coincides (fig. 3B) with a deceleration in the rise of relative sea-level (Vella, 1999), which reduces the downstream constraint on the longitudinal profile of the river and allows a more efficient transit of sediments to the mouth (fig. 3C). The pulsed progradation is consistent with the chronology of the three phases of sedimentary input (fig. 3D), recently better documented by a long sedimentological core in Arles (Bruneton *et al.*, 2001) and by geomorphological studies carried out on the fluvial plain (Bruneton, 2000; Arnaud-Fassetta *et al.*, 2000; Arnaud-Fassetta, 2002). The building of the most massive offshore bar (Mornès) began, with a delay of about one millenium, during the longest detrital phase in Arles from 5,795 to 3,875 yr BP. Its slower progradation is related to the large volume of the space to fill in a deep holocene paleovalley (fig. 2). The following stages,

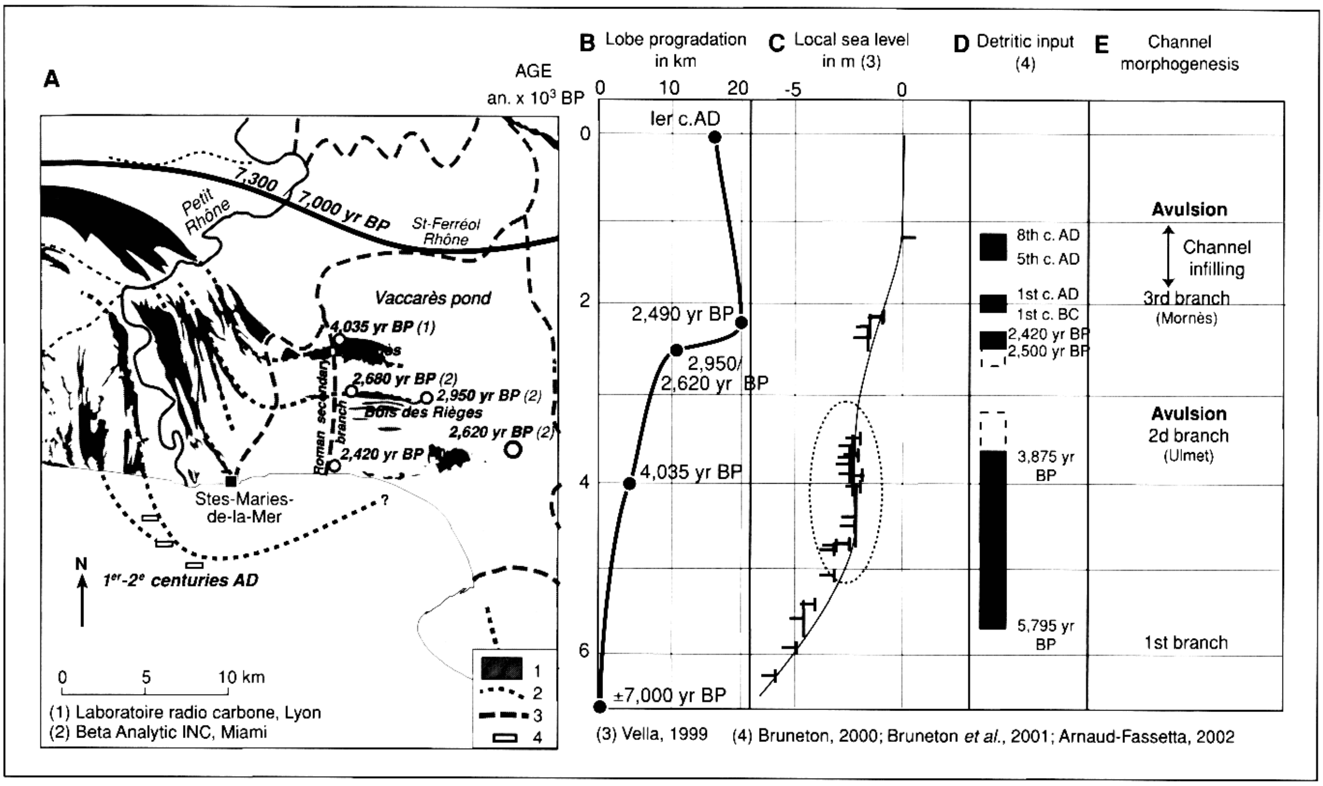


Fig. 3 – **Fluvial input, sea-level rise and progradation of the Saint-Ferréol lobe.** A: Lobe map. 1: fossil coastal ridges; 2: hypothetical positions of the successive coastlines; 3: palaeochannels; 4: Roman wrecks. B: Coastal progradation. The progradation is calculated on the basis of a photo-interpretation of the fossil coastal ridges. C: Local sea-level rise. The symbols indicate the uncertainty (or the error bars) around the ¹⁴C chronology and the vertical position data.

*Fig. 3 – **Apports fluviaux, montée du niveau de la mer et progradation du lobe de Saint-Ferréol.** A : Carte du lobe. 1 : cordons littoraux fossiles ; 2 : positions successives vraisemblables du trait de côte ; 3 : paléo-chenaux ; 4 : épaves romaines. B : Progradation du trait de côte. La progradation est calculée sur la base de la photo-interprétation des cordons fossiles. C : Montée du niveau marin. Les symboles indiquent la marge d'incertitude des dates ¹⁴C et de la position verticale.*

associated with narrower ridges, prograded rapidly between 2,500 and 2,420 yr BP, and again between the 1st century BC and the 1st century AD: on the one hand, their formation is favoured by the reduction in sedimentation space due to former prodeltaic construction, and, on the other hand, by the flood dominated context (Arnaud-Fassetta, 2002).

The very fast progradation of the Roman period appears to be contemporary with river bed instability and the emergence of several new breaches in the banks on Albaron, Saint-Ferréol and Ulmet channels (Bruneton *et al.*, 2001). On the Saint-Ferréol deltaic lobe, the appearance of a secondary arm modified the distribution of hydraulic energy and favours the filling of the channel (fig. 4E).

According to chronicles, the Rhône river may have had up to seven mouths at this time between the Grau-du-Roi and Fos (Vella *et al.*, 1998). These obstacles obstructed the navigation of ships, thus justifying the digging of the Marius canal during the 1st century BC. The progressive filling of the main channel of Saint-Ferréol took place between the 2nd and 6th centuries AD (Arnaud-Fassetta, 2000), induced by a resumption in the rise of sea-level combined with the more abundant sediment inputs (fig. 3D). From the 6th century onward, the waters of the Rhône flowed through the Ulmet channel (active since the Bronze Age), then a new eastern channel known as the Grand Passon arm (fig. 1). Linear ponds, still visible above the present ground, replaced the previous Saint-Ferréol infilled channel.

Thus, the decline of the Saint-Ferréol branch to the benefit to Ulmet and Grand Passon branches, which can be linked to an avulsion, is related here to the combination of detrital and eustatic forcings. In the context of a stable sea-level, the phases of abundant sediment input initially generate a pulsed delta advance. However, the repetition of these pulses and the lengthening of the longitudinal profile (about 5 km during the last five centuries) create morphological perturbations. At the end of Antiquity, the coincidence with the resumption of the rise in sea-level induced the infilling and the decay of the fluvial arm. The Saint-Ferréol channel occupied a stable position for about 2,000 years, which is consistent with the duration of the cycle evoked by H.H. Roberts (1997). However, we cannot ignore the importance of rythmic sedimentary fluvial inputs in the progradation, the instability and, finally, the avulsion of this channel.

The role of sediment inputs to the mobility of the delta during the Little Ice Age

Between the end of the 16th and the end of 19th centuries, the Rhône river successively built two fingered lobes. The lobe of the Bras de Fer was built up between 1586 and 1711 AD, following the avulsion of the Medieval channel of

Grand Passon, and the Pégoulier channel between 1712 and 1905 after the avulsion of the Bras de Fer channel (fig. 1). The chronology of these two systems translates the effect of two well-known forcing factors. Anthropogenic forcing corresponds to the rural demographic maximum in Western Europe. The hydro-climatic forcing of the Little Ice Age is illustrated by several major episodes of flooding recorded at Arles (fig. 4): the decadal frequency of months with floods > 4 m (equivalent to +5.25 m NGF) is significant in 1700-1710, 1750-1790, 1810-1820 and 1850-1860 (Pichard, 1995), corresponding to a flood-dominated regime.

The Bras de Fer Lobe (17-18th centuries)

The progradation of the Bras de Fer lobe, in the context of a stable sea-level, is contemporary with a first episode (more than 20 floods between 1700 and 1711), preceded by frequent floods from 1670 to 1700. The maps drawn up since 1668 (fig. 5) by the Services of the French Royal Navy for the needs of navigation describe the advance of the lobe by the emergence and accretion of small islands forming a bar in a very broad mouth, preceded by convex sand banks in 1668 (fig. 5A). The coastline advanced by at least 160 m/yr between 1668 and 1688 (fig. 5B), then became stabilized. From this date onward, the alluvium was deposited upstream of the mouth bar in 1699, while the coastline began to be eroded (fig. 5C) since the avulsion event in 1711 (fig. 5D).

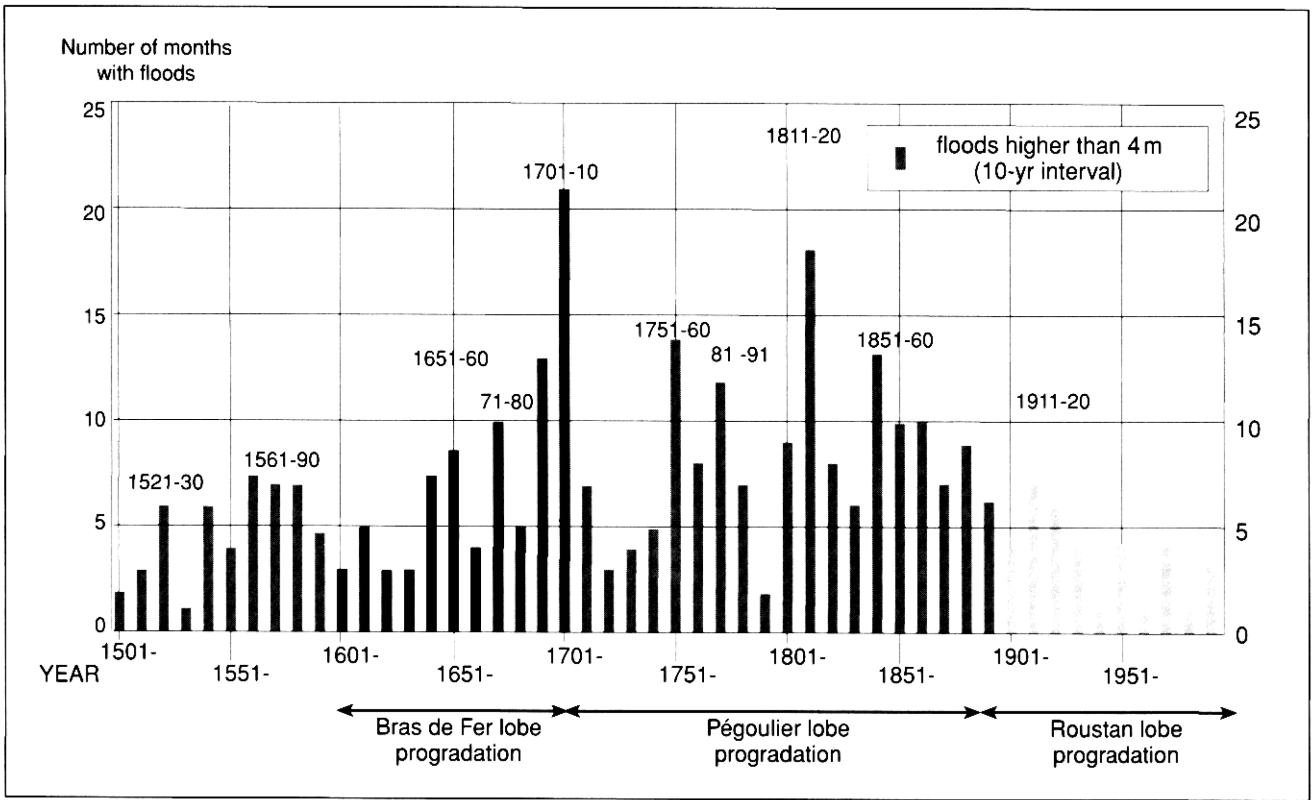
The sedimentological analyses of the cores carried out in the palaeochannel (Arnaud-Fassetta and Provansal, 1999) indicate a high hydrological competency, higher than in the ancient or present-day Rhône river, which increases towards the top of the channel fill. In addition, several chronicles report overflow of water laden with sediment in the deltaic plain. The geomorphology of the channel became unstable since the end of the 17th century, being characterised by the migration and then the re-cutting of the large meander of St. Bertrand. In contrast with an initial depth of approximately 12 m and a width of 700 m, the channel was no more than 4-7 m deep at the end of this period, with an active channel (emerged banks, flood channels, breaches fans) exceeding 2 km in width.

These observations are consistent with the increasing power of the floods during the last decades of the 17th century (fig. 4). However the sedimentary trapping in the channel and the growing instability, accounts for the decelerating progradation of the mouth, leading to the possibility of avulsion, which took place during the powerful floods of 1709 to 1712.

Thus, the Bras de Fer palaeochannel clearly shows that deltaic advance depends on the abundance and on the coarse grain size of the sediment inputs, but also on the capacity of the river channel to transport the solid load to the mouth. After 1711, the new channel followed an artificial watercourse (Launes canal), where the flow became artificially concentrated. This represents the beginning of the control of the river mouth by engineers (*i.e.*, anthropogenic forcing), who applied technical measures that became so important in the history of the Rhône delta.

Fig. 4 – **Decennal frequency of floods superior to 4 m in height (*i.e.*, 5.25 m NGF) in Arles during the Little Ice Age, after Pichard, 1995, modified.**

Fig. 4 – ***Fréquence décennale des crues supérieures à 4 m de haut (i.e. 5,25 m NGF) à Arles durant le Petit Âge Glaciaire, d'après Pichard, 1995, modifié.***



The Pégoulier lobe (18–20th centuries)

The Pégoulier arm corresponds to a segment of the present Grand Rhône (fig. 6). Its advance between 1712 and 1893 formed the Pégoulier lobe (fig. 1), whose construction coincided after 1744 (fig. 6A) with the major floods of 1750–1790, 1810–1820 and 1840–1856. The progradation of the convex banks of the mouth bar (35 to 60 m/yr), which gradually become coalescent is much more regular than in the case of the Bras de Fer arm and defines a fingered pattern from 4 to 5 km in length in 1851 (fig. 6B). The strength and the regularity of this progradation are due to embankment work and self-dredging measures (construction of the Girardon "casiers" from Arles to Lyon), which were carried out in the river since the beginning of the 19th century (Poinsard, 1992). They still allow the transit of a very abundant solid load (22 Mt at the beginning of the 19th century: Surrell, 1847) in a narrowed channel that was regularised and deepened (Antonelli, 2002; Arnaud-Fassetta, 2003). The artificial closing down of the lateral arms of the mouth

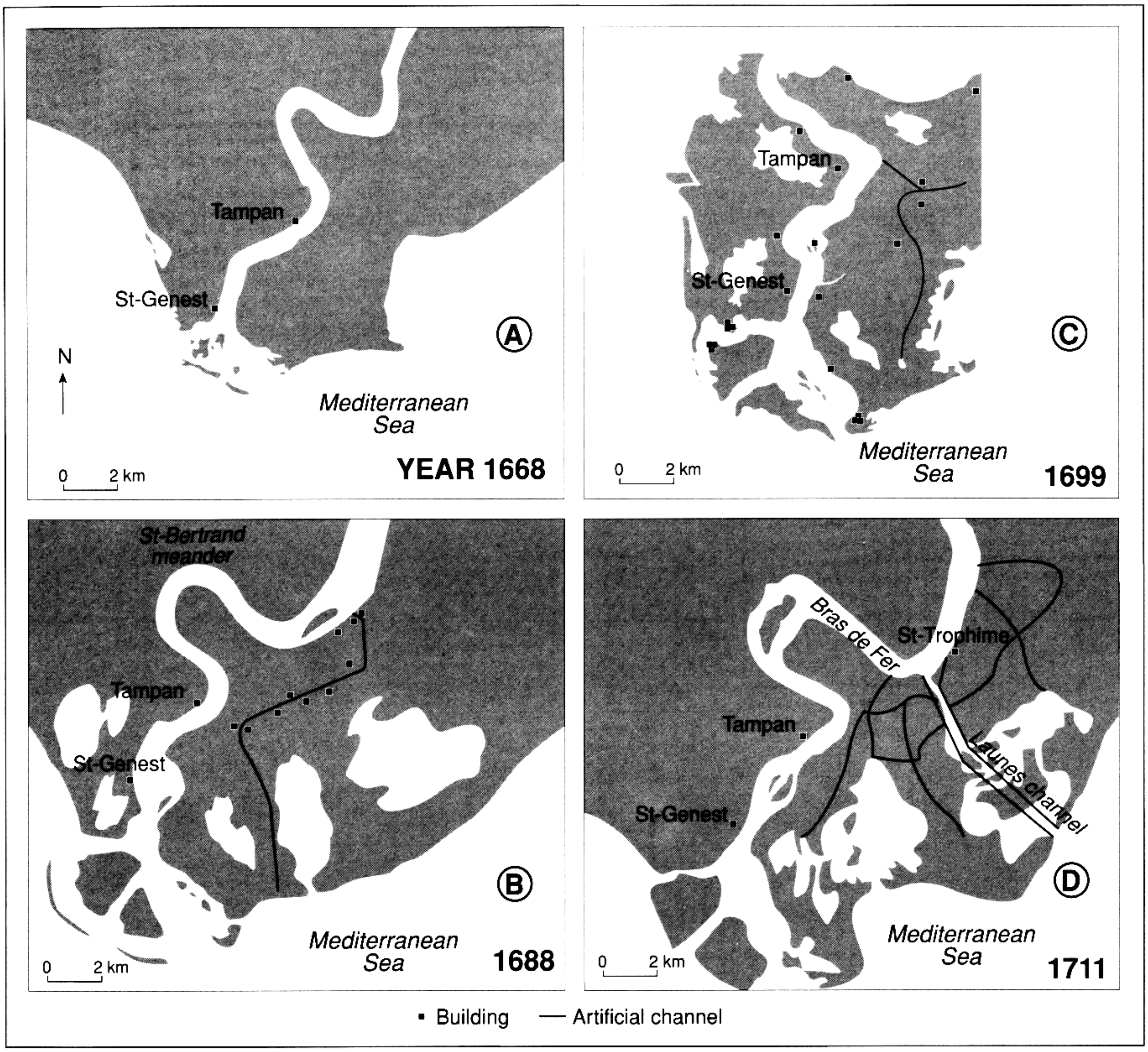


Fig. 5 – **Progradation of the Bras de Fer mouth between 1668 and 1711, date of its avulsion towards the Pégoulier arm** (after maps of the Services of the French Royal Navy. Note: precise geographic coordinates are not available). A: in 1668 the emerging islands in the mouth are preceded by convex sand banks; B: the convex sand bars advanced by at least 160 m/yr since 1668; C: in 1699 the alluvium are deposited upstream of the mouth bar, while the coastline began to be eroded; D: avulsion event during the major floods in 1711, using the artificial Launes canal.

*Fig. 5 – **Progradation de l'embouchure du Bras de Fer entre 1668 and 1711, date de son déplacement vers le bras de Pégoulier** (d'après diverses cartes des Services de la Marine Royale, dont le système de coordonnées géographique est imprécis). A : en 1668, les îles émergentes dans l'embouchure sont précédées d'une barre convexe ; B : la barre sableuse convexe a avancé d'au moins 160 m/an depuis 1668 ; C : en 1699 les alluvions se déposent en amont de la barre d'embouchure, la côte commence à s'éroder ; D : la défluviation lors des fortes crues de 1711 emprunte le canal artificiel des Launes.*

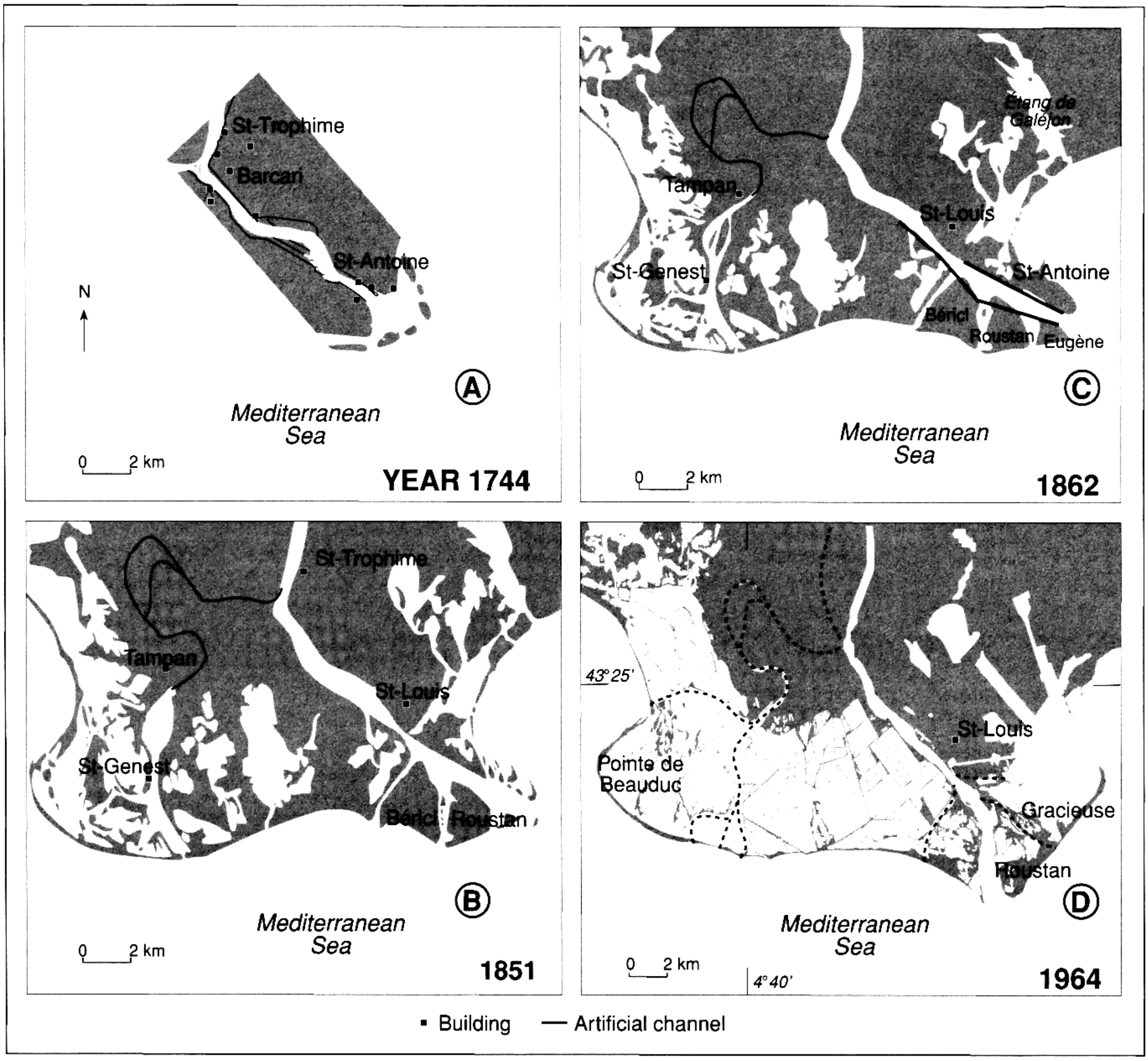


Fig. 6 – **Progradation of the Pégoulier mouth during the 19–20th centuries.** A: in 1744 beginning of the new progradation. B: in 1851 the convex coalescent banks of the mouth bar define a fingered pattern from 4 to 5 km in length. C: in 1862 the embankment works and the artificial closing down of the lateral arms of the mouth in 1856 accelerated the advance of the lobe (70 m/yr in the 1860s). D: the configuration of the mouth since 1944 results from the reopening of the western arm (Grau de Roustan) in 1893.

*Fig. 6 – **Progradation de l'embouchure de Pégoulier aux XIXe et XXe siècles.** A : en 1744 début de la progradation ; B : en 1851 les bancs sableux convexes coalescents dessinent une avancée de 4 à 5 km de long ; C : en 1862 les endiguements et la fermeture artificielle du bras latéral en 1856 accélèrent l'avancée du lobe (70 m/an dans les années 1860) ; D : la configuration de l'embouchure depuis 1944 résulte de la ré-ouverture du bras de Roustan en 1893.*

in 1856 accelerated the advance of the Pégoulier lobe (70 m/yr in the 1860s, fig. 6C). The difficulties in evacuating the sedimentary load, undoubtedly related to the lengthening of the longitudinal profile, made it necessary to reopen the western mouth (Grau de Roustan) in 1893, resulting in the present configuration since 1944 (fig. 6D).

The deltaic advance thus has taken place here under three types of forcing: hydro-climatic and anthropogenic in the catchment area, and geotechnical (*i.e.*, also anthropogenic) in the channel. The human intervention in 1893 prevented the excessive lengthening of the profile and the risk of filling, leading to the artificial opening and management of a new mouth.

The building of the two lobes (Bras de Fer and Pégoulier), occurring in comparable climatic, hydrological and sedimentary settings, confirms the important influence of the artificial river managment on the progradation. In the natural system, which dominated until the 18th century, the abundance of sedimentary input led to a paradoxical evolution, because it induced feedback, *i.e.*, the filling of the channel and the disruption of the system. The avulsion stopped the seaward advance and favoured the spreading out of the deltaic system over a wide area. In the system controlled by the engineers of the 19th century, progradation increased to a threshold level but was subsequently prevented by new operations.

The role of fluvial sedimentary inputs to the mobility of the present-day Roustan mouth

Since the reopening of the Grau de Roustan in 1893, the mobility of the delta coast falls within a very different context. The resumption of the rise in relative sea-level (2.1 mm/yr: Suanez, 1997) may have forced the sedimentary transport. The reduction in the frequency of floods > 5,25 NGF (fig. 4) and the reforestation of the principal sediment source-areas of the catchment decreased the solid load after the turn of the century. From 1945 to 1960, hydroelectric installations have worsened the retention of sands on the upstream reaches of the river. This is particularly critical on the Durance river, which represents one of principal sources of sediment supply to the downstream basin. The total solid load of the Rhône is estimated to range between 8 and 10 Mt in the second half of the 20th century (Pont *et al.*, 2002; Antonelli, 2002).

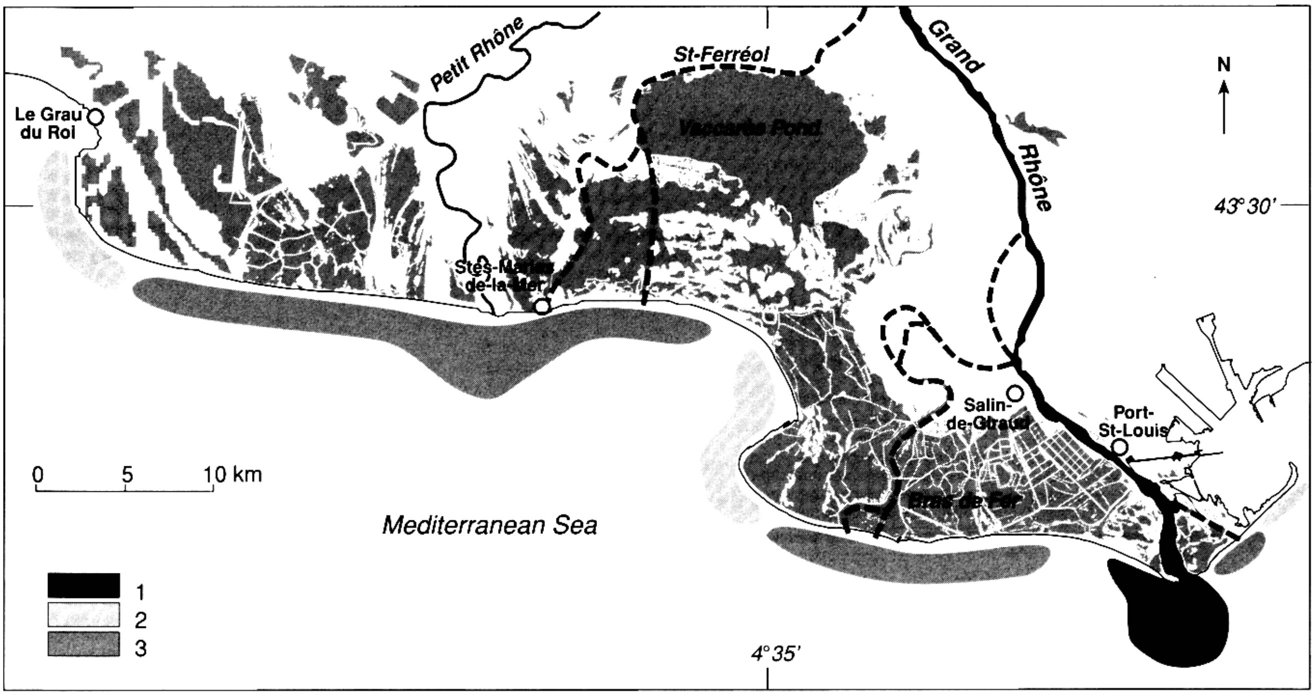
The mouth of the Rhône prograded by approximately 60 m/yr from 1895 to 1952, became stable, and then gradually deformed under the effect of longshore drift over the last few decades (Sabatier, 2001). From 1895 to 1974-1988 (fig. 7), the mouth of the Grand Rhône was the site of important sedimentary retention between 0 and -20 m (1.9 Mm^3/yr, including 500 to 700 Mm^3 of sands: Sabatier, 2001), confirmed by corings on the prodelta (Touzani, 1998; Radakovitch *et al.*, 1998). This containment implies a very weak input of river sediments supplying the deltaic coast and a long retention time on the prodelta. It induces a global destabilisation of the deltaic coast, where erosional process have prevailed. Since the rapid progradation of the mouth in the last century, the plunging of the top of the Pleistocene bedrock increases the submarine volume to be filled. In front of the present mouth, the prodelta probably acts as a sediment trap. Then the delta coast exhibits an overall negative sedimentary budget (Sabatier, 2001), characterised by an average retreat of 4 m/yr from the 1940s until the beginning of the 1980s. Since 1980, this movement has stabilised, probably reflecting the trend towards a new equilibrium of the coastal system in a context of sedimentary starvation. This trend, however, also follows the construction of rip-rap coastal defences.

Conclusion

The relationships between sediment inputs and coastal mobility are highlighted during the Holocene history of the Rhône delta: deltaic progradation is chronologically associated here with phases of more abundant and coarser sediment inputs, recognised in the upstream and middle catchment as well as on the deltaic plain itself. The study of the Saint-Ferréol lobe shows that progradation precisely reflects the pulses and relative importance of sedimentary

Fig. 7 – **Sediment trap at the present mouth and sedimentary balance in the coastal zone (1895-1974/1982), calculated on the basis of air-photo interpretation and mapping (after Sabatier, 2001)**. 1: accumulation in front of the Rhône mouth (prodelta); 2: coastal accreted zone; 3: coastal eroded zone.

*Fig. 7 – **Stockage sédimentaire devant l'embouchure actuelle et bilan sédimentaire côtier (1895-1974/1982), calculés par analyse cartographique et photo-interprétation (d'après Sabatier, 2001).** 1 : accumulation devant l'embouchure (prodelta) ; 2 : côte soumise à l'accumulation ; 3 : côte subissant une érosion.*



input. The phases of progradation are terminated by river avulsion and shifting of the mouth. This mechanism thus seems associated with a type of forcing that is closer to allocyclic, *i.e.*, climatic and anthropogenic factors, than to the autocyclic lengthening of the longitudinal profile. The same pattern is available during the Little Ice Age, while the climatic crisis, reinforced by anthropogenic degradation in the catchment area, is directly responsible for the major progradation lobes.

Nevertheless, two constraints introduce a distortion in the relationships between sediment input and coastal mobility. First, the sediment accomodation space depends on the topography of the Pleistocene bedrock and/or of the previous Holocene sedimentary aggradation: when this space is large, the river inputs are trapped at the mouth, without generating a prograding lobe. Supply to the deltaic coast in this case is limited, as observed today at the mouth of the Rhône. When accomodation space is limited, as was the case with the mouth of the Saint-Ferréol arm during the last few centuries BC, progradation becomes rapid and supplies thick offshore bars. Second, the geomorphology of the river channel is an essential factor, particularly due to its capacity to allow sedimentary transit to the coast. Due to a feedback effect, the abundant and coarse inputs, initially responsible for rapid progradation, lead to changes in the form of the river bed storing the sediments, thus facilitating avulsions. This was the case during the final episode of the Bras de Fer arm. The development of artificial banks or their weakening by the construction of channels from the 19th century onward plays a decisive role in the latest phases of advance of the Rhône delta. They enhance sedimentary transport to the mouth. However, this recent fast advance generates negative feedback by encouraging growth of the accommodation space in front of the mouth and therefore favouring aggradation over progradation.

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