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Sediment budget of the Rhône delta shoreface since the middle of the 19th century

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Abstract

This study analyses long-term (1841–1872–1895–1974) changes in the Grand Rhône prodeltaic lobe to (1) quantify the accumulation, (2) determine the evolution of relict prodeltaic lobes and (3) establish long-term relationships between river sediment discharge, the shoreface and the continental shelf. Our results show a reduction of the sedimentation of the prodeltaic lobe at the main river mouth, since 150 yr by a factor of 3.7 (12.63 to 3.41×10^6 m^3 yr^{-1}). At the minor mouth of the river, erosion dominates and speeds up during the same period (-0.53 to -1.34×10^6 m^3 yr^{-1}). These changes are found to directly result from the river sediment input decrease related to the natural decreasing of the frequency of major floods (end of the Little Ice Age), the reforestation in the catchment area, the dam construction and the dredging activities (since the 1950s). Our results indicate that while there is large sediment accumulation in the area around a growing prodeltaic lobe, there is also a reduced contribution of the river sediments to the non-adjacent beaches of the mouth. Following a shift in the river channel and mouth, the relict prodeltaic lobes (Petit Rhône–St Férreol, Bras de Fer and Pégoulier) are reworked by waves and their sediments contribute partially to the growth of the spits (Espiguette, Beauduc and Gracieuse). This suggests that there is a "time-shift" between the input of river sediment to the sea and the build up of a beach. The chronic erosion of the coastline is likely to continue in the future since (1) a river shift is not possible, because the river channels are controlled by dykes and human intervention, (2) the decrease of river sediment input and (3) the relict prodeltaic lobes constitute sedimentary reservoirs that are gradually being used up.

Keywords: bathymetry; river sediments input; prodeltaic lobe; large scale coastal behaviour

1. Introduction

When a river discharges into the sea, delta building will occur if the input of sediment exceeds the marine erosion able to remove the deposited material. Understanding and assessing the input of river sediment to the sea, as well as its littoral distribution, represent

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important challenges since major deltas all around the world are undergoing an erosional regime (Stone and Donley, 1998). In microtidal Mediterranean environments, previous studies have already tried to establish a relationship between fluvial input and sediment redistribution in the littoral zone, e.g. the deltas of the Danube (Giosan et al., 1999), Ebro (Jiménez and Sánchez-Arcilla, 1993; Guillen and Palanques, 1997), Nile (Stanley and Warne, 1998), Pô (Cencini, 1998) and Rhône (Blanc, 1977; Suanez and Provansal, 1998, 1999; Sabatier and Suanez, 2003). By using old maps, bathymetric profiles, aerial photographs, longshore sediment transport equations and box models, these studies have led towards establishing shoreline changes and the quantification of littoral cells. If river sediment input decreases or if the river mouth changes its location, the prodeltaic lobe starts to be destroyed by wave action and the shoreline migrates landwards (Kolb and Van Lopik, 1966; Wells and Coleman, 1987; Li et al., 2000; Pranzini, 2001). The reworked material from the pre-existing prodeltaic lobe is re-distributed over the shoreface according to wave action and sediment grain size (Stive and de Vriend, 1995). However, studies have seldom addressed the relationships and interactions between fluvial sediment input and the building of associated prodeltaic lobes. In any case, even though the decreasing river sediment discharge to the sea in relation to climatic change, reforestation and dams are often described as responsible for coastal erosion (Guillen and Palanques, 1993; Milliman, 1997; Pont et al., 2002). The connection between the fluvial sediment inputs, the deltaic lobes and the shoreface is not well established.

At the present, the Rhône delta is a “wave-dominated delta” according to Galloway’s (1975) terminology. Nevertheless, the river sediment load may play an important role in controlling shoreline location and coastal sediment budget (Suanez and Simon, 1997; Suanez and Provansal, 1998; Sabatier and Suanez, 2003). Since the middle of the 19th century, in relation with climatic changes (end of the Little Ice Age), the frequency of major floods has been consistently decreasing on the Rhône, as on the other main European rivers (Probst, 1989; Pichard, 1995; Arnaud-Fassetta and Provansal, 1999). At the same time, land-use changes and reforestation in the catchment are reducing the solid discharge, notably the bedload (Bravard, 1989; Miramont and Guilbert, 1997; Warner, 2000). This trend has been reinforced since the 1950s by dam construction and dredging activities (Poinsard, 1992; Klingeman et al., 1994; Gautier, 1994; IRS, 2000). Previous works (Arnaud-Fassetta, 1997; Antonelli et al., 2004) have shown that the deltaic response of the river channel is a general incision of the bed between the end of the 19th century and the end of 20th century. However, the effects of decreasing fluvial sediment discharge on the evolution of the prodeltaic lobes and the shoreface are poorly understood on this time scale. In this study, we analyse long-term (150 yr) shoreline and bathymetric changes to (1) quantify the accumulation of the Rhône prodeltaic lobe, (2) determine the evolution of relict prodeltaic lobes and (3) establish long-term relationships between river sediment discharge, the shoreface and the continental shelf.

2. Environmental settings

2.1. The Rhône river

The present Rhône river is divided in two main arms: the eastern branch (Grand Rhône, 50 km in length) and the western branch (Petit Rhône, 70 km in length), both discharging into the Mediterranean Sea by the Roustan and the Orgon mouths, respectively (Fig. 1). The breakdown of the river discharge is 10–15% for the Petit Rhône and 85–90% for the Grand Rhône (Surell, 1847). The mean annual water discharge (measurements from 1960 to 1996) is 1710 $m^3\ s^{-1}$ without any general trend during the 20th century (Antonelli et al., 2004), but the frequency of major floods has been decreasing since the beginning of the 19th century (Pichard, 1995) (Fig. 2). Return period discharges for 2, 10 and 100 yr are 6000, 8300 and 11,200 $m^3\ s^{-1}$, respectively (Pont et al., 2002). 80% of the solid discharge is related to liquid discharge when the flood is higher than 3000 $m^3\ s^{-1}$ (Pont and Bardin, 1996).

Several authors have estimated the Bedload Sediment Transport (BST) and/or the Suspended Sediment Transport (SST) of the Rhône river (Surell, 1847; Pardé, 1925; Van Straaten, 1959; Savey and Deleglise, 1967; Pauc, 1976; Aloisi et al., 1977; Blanc, 1977; Milliman and Meade, 1983; El Habr and Golterman, 1987; Dugas, 1989; Roditis and Pont, 1993; Pont and Blombed, 1995; Antonelli and Provansal, 2002a,b; Pont et al., 2002). Studies carried out since the end of the 19th century have used different methodologies and especially focus on the SST, but they all indicate a general decreasing trend (Pichard, 1995) in good correlation with the tributaries (Fig. 2). From the beginning of the 19th century to the first part of the 20th century, before the construction of dams, the mean SST is estimated to range between 27.2 to 31.0×10^6 t yr^{-1}. Sogreah (1999) re-evaluated previous measurements between 1956 to 1958 and argued for a mean SST value of about

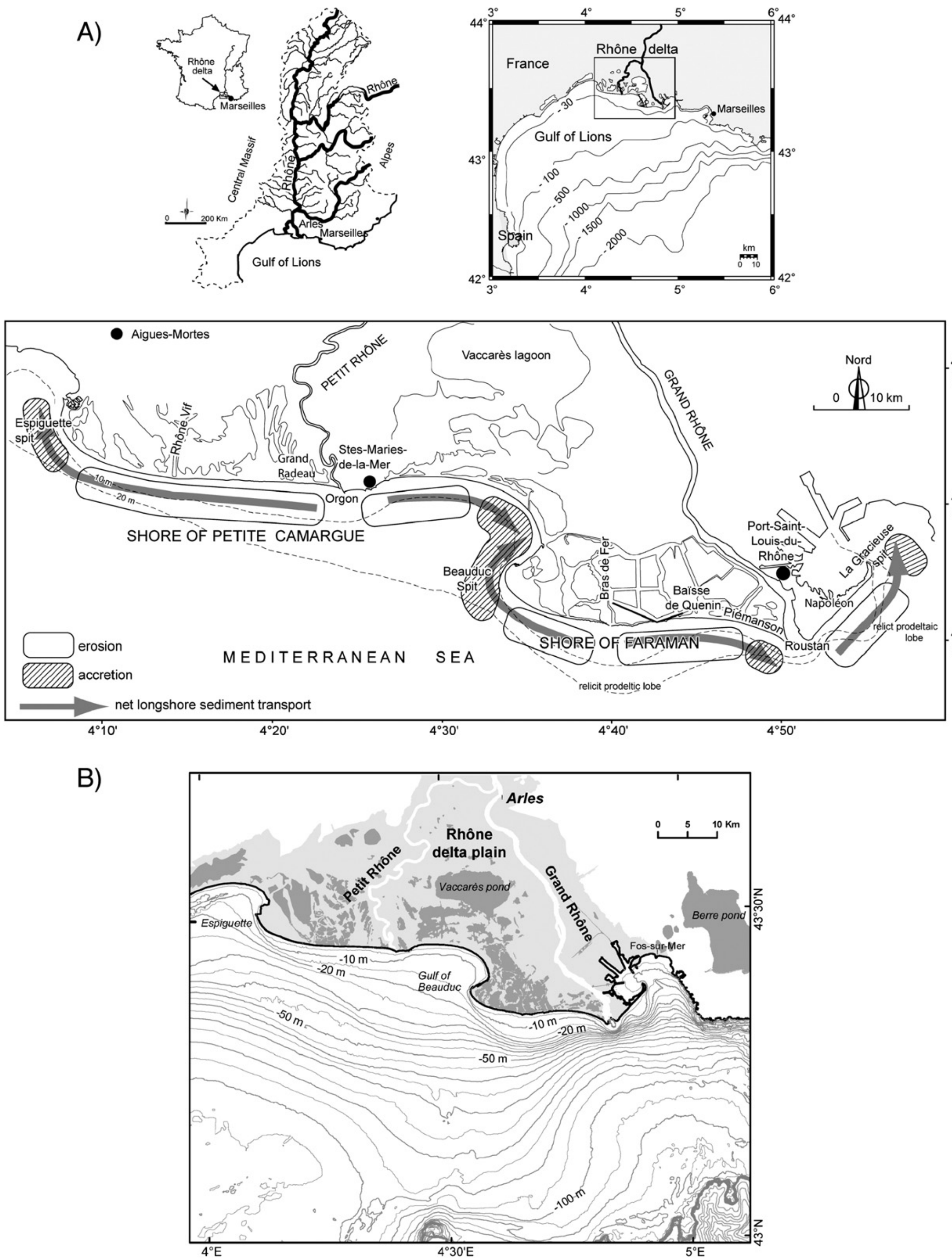

Fig. 1. A: location map and littoral drift cell pattern (modified from Sabatier and Suanez, 2003); B: bathymetric map (end of 20th century) of the investigated site.

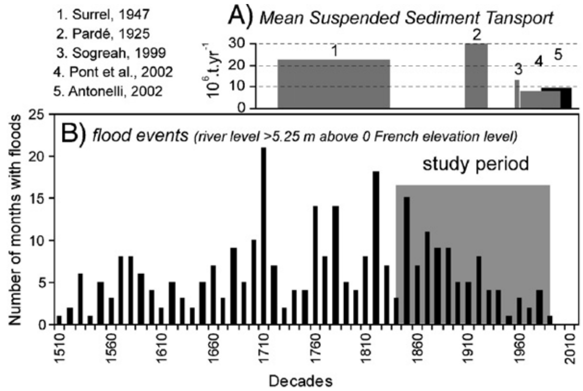

Fig. 2. Decrease in river floods and suspended sediment input to the sea. A: mean SST from different authors.; B: frequency of floods at Arles (modified from Pichard, 1995).

13.0×10^{6} t yr^{-1} for the middle part of the 20th century. While Pont et al. (2002) proposed a mean SST value of about 7.4×10^{6} t yr^{-1} for the period 1962–1996, Antonelli and Provansal (2002a) demonstrated that the field measurements of Pont et al. (2002) underestimated sediment transport and the authors proposed a mean value of 9.6×10^{6} t yr^{-1} between 1980 to 2000.

2.2. Successive river mouths and construction of Rhône prodeltaic lobes

Although the present Rhône is divided into two main arms, the river and mouths had different locations during the construction of the Holocene Rhône delta (Russell, 1942; Kruit, 1955; Oomkens, 1970; L'Homer et al., 1981; Arnaud-Fassetta, 1998; Vella and Provansal, 2000; Vella et al., 2005). At this time scale, all these authors provide evidence that the shoreline advance is connected to the river mouth position and river sediment input. Since 4000 yr BP, the Rhône river has developed several successive arms and mouths, and the present deltaic plain displays remnants of these relict structures that have been re-examined by Vella et al. (2005), who give a new chronology for the sub-surface sedimentary ridge of the Rhône deltaic plain. Successive displacements of the river mouths have thus given rise to the offshore abandonment of relict prodeltaic lobes: St Ferreol (Cal. 2845–2420 BC to 1st Century AD.), Grand Passon-Bras de Fer (12th century to 1711) and Pégoulier (1711 to 1892). These latter can be identified at the present day through the lobe-type pattern of their bathymetry, such as exhibited by the prodeltaic lobes at the Roustan and Orgon mouths (Fig. 1). However, there remain some uncertainties on the existence of the relict prodeltaic lobe of the Rhône Vif (1532 to 1552), identified according to L'Homer (1993) from the sedimentology and morphology. This artificial mouth with low discharge remained open for only 20 yr, which seems very short to build up a prodeltaic lobe. Since 1552, the location of the Petit Rhône mouth (Orgon) has been fixed on the west side of Saintes-Maries-de-la-Mer (L'Homer et al., 1981). The current shoreline began to take its present shape from the beginning of the 18th century. Following an important flood in 1711, the Rhône of the Bras de Fer channel changed course towards the east and assumed its present-day configuration as the Grand Rhône (Fig. 3). Since 1711, although the location of the Grand Rhône channel has remained the same, the number and location of the local main mouths has changed (Fig. 4). Between 1711 and 1852, the Grand Rhône had three separate and concomitant mouths: Piémanson, Roustan and Pégoulier. In 1855, the Piémanson and Roustan mouths were closed by dykes in order to concentrate water and sediment discharge into the Pégoulier. In 1892, engineering works re-opened the Roustan mouth for navigation. The re-opening of the Roustan mouth and the subsequent shifting of the sediment discharge through it led to the start of the filling in of the Pégoulier channel. Meanwhile, the Pégoulier mouth was closed off by longshore sediment transport deposits. However, since 1892, the Grand Rhône has continued to discharge at the same mouth (Roustan).

2.3. The nearshore and shelf domain

The wave regime is divided into three dominant directions: SW (30% calm waves generated by offshore winds), SSE (16%) and SE (11% storm waves generated by onshore winds). The modal, annual and decennial recurrence significant wave heights (Hsig) are 0.6 m, 3.3 m and 4.6 m, with a significant period (Tsig) of 4 s,

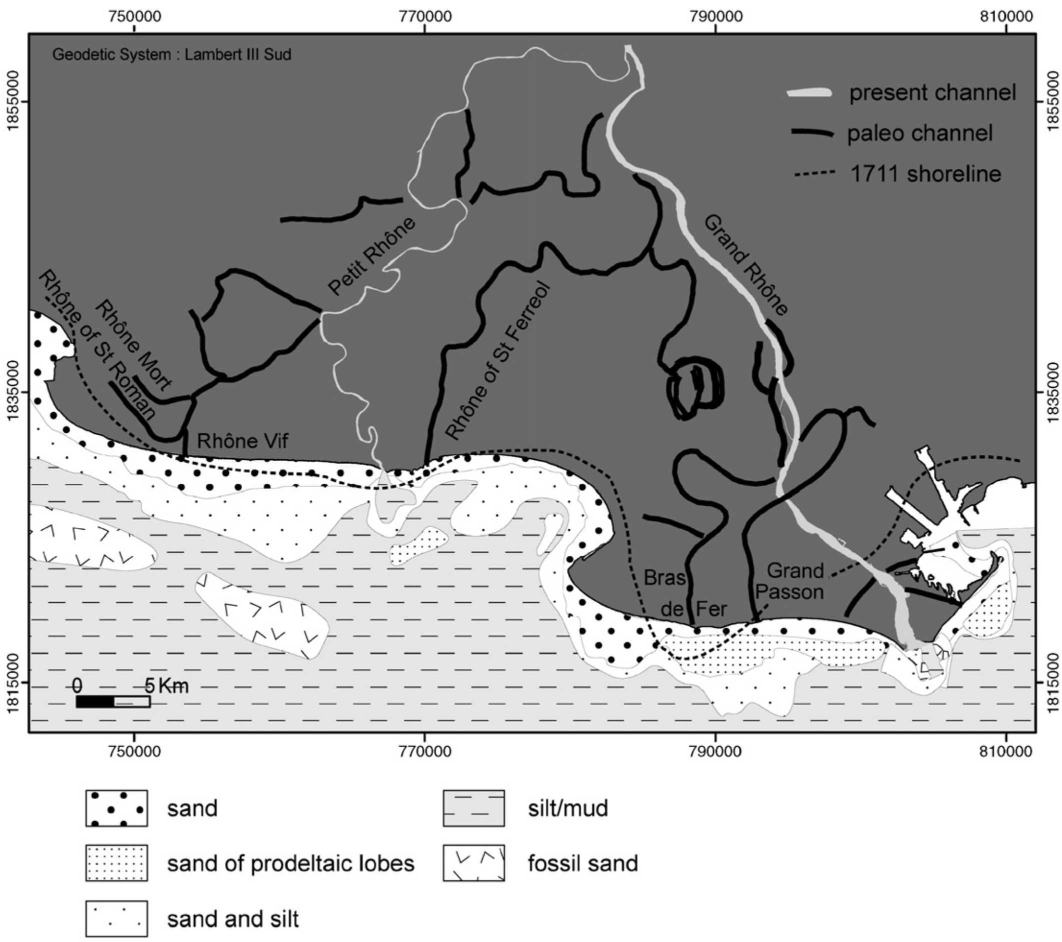

Fig. 3. Shifts in the mouths of the Rhône (modified from Vella et al., 2005) and sedimentology of the seabed (modified from Blanc, 1977).

6.5 s and 7.5 s respectively. The tidal range, +/−0.30 m, is considered negligible in our study.

The nearshore zone is generally characterised by the presence of two or three bars. Beaches of the surf zone are of the “Dissipative” and “Longshore-Bar-Trough” types, according to the classification of Wright and Short (1984). The coast of the Rhône delta can be considered as a closed box for longshore sediment transport since the Gracieuse and Espiguette spits (on the eastern and western sides, respectively) act as sediment traps. Between these two boundaries, the Rhône delta shoreline shows a littoral drift cell pattern (Blanc, 1977; Sabatier and Suanez, 2003) in which accretional areas (Gracieuse spit, Beauduc spit and gulf and Espiguette spit) are supplied by sand from erosional areas (Napoleon, Faraman and Petite Camargue beaches) (Fig. 1). This littoral drift cell pattern is caused by strong longshore sediment transport in relation to oblique waves (SE and SW sectors). Both present and relict prodeltaic lobes have caused orthogonal wave concentration and divergent longshore sediment transport. While some authors have proposed a quantification of local medium-term longshore sediment transport (Blanc, 1977; Suanez and Bruzzi, 1999), the overall long-term sediment budget has never been estimated. The shelf domain extends from 40 to 150 m water depth, with a mean slope of 0.5% and a mean width of 40 km. The water circulation across the shelf takes place via the Liguro-Provencal current, which is oriented NE–SW.

Fig. 3 represents the marine sedimentology of the Rhône delta, for which Blanc (1977) proposes a synthesis taken up again by L’Homer (1993). The mean grain size of the beachface sediment is about 0.2 mm (Masselink, 1992; Sabatier, 2001) and decreases seaward (Aloisi et al., 1977; Blanc, 1977). Silts dominate at depths greater than approximately −20 m, except in the gulf of Beauduc where they are observed at shallower depths. This latter sector corresponds to a

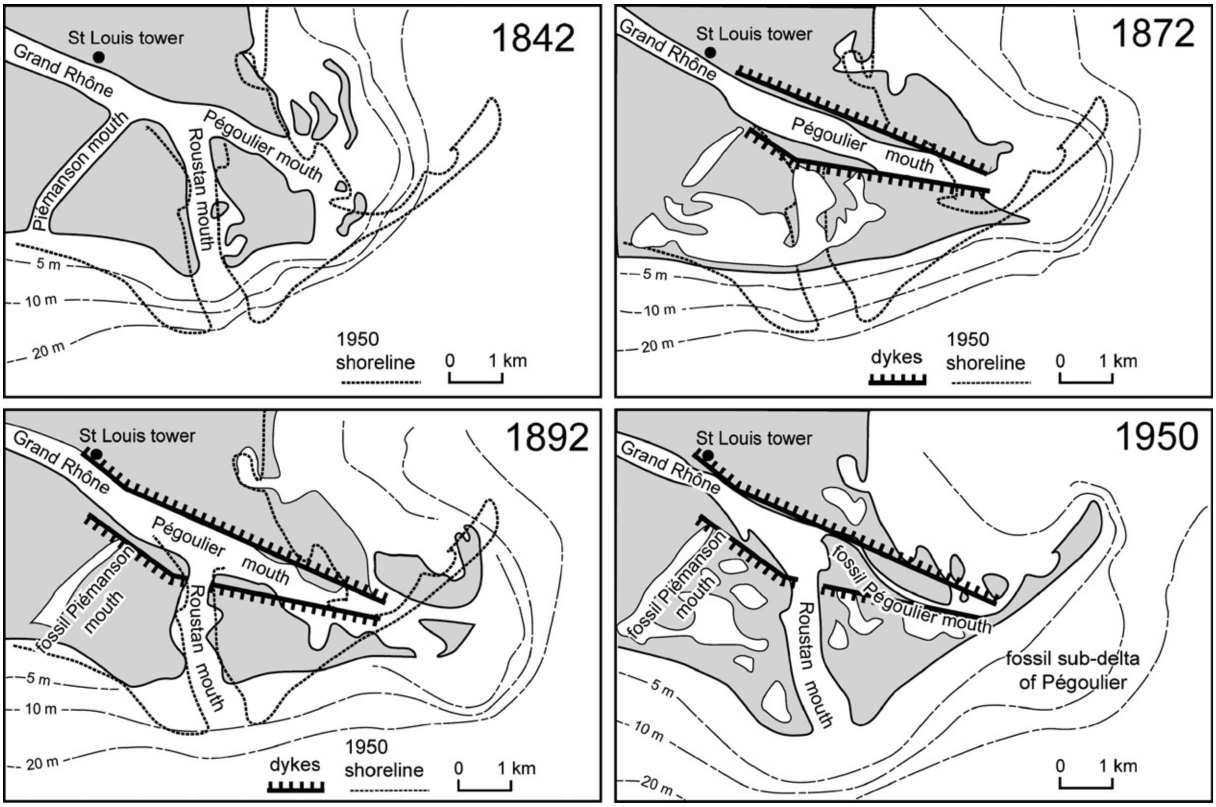

Fig. 4. Qualitative evolution of the mouth of the Grand Rhône between 1842 and 1950 (from Vernier, 1976).

sheltered zone where the fine material can form a deposit. An outstanding feature concerning the relict prodelta lobes of Pégoulier, Piémanson and Bras de Fer, which are identifiable by their sedimentology, is that they are composed of coarse sands (Fig. 3). In the Petite Camargue, however, Blanc (1977) suggests the existence of relict prodeltaic sands, even though no mouth is known in the sector, apart from the poorly established mouth of the Rhône Vif. The continental shelf is composed of muds, except in some sectors where relict sands crop out at around −80 m water depth (Aloisi et al., 1977).

3. Background on sedimentary connections between the river and marine domains

In the area around the Grand Rhône mouth, Suanez and Bruzzi (1999) used a box model based on converting shoreline change into volumes by a closure depth integration methodology (Jiménez and Sánchez-Arcilla, 1993) to quantify the sedimentary connections between the river and the shoreface. According to this method, the sand input of the Rhône to the eastern part of the littoral zone (Gracieuse spit) averaged about 0.016×10^{6} m^{3} yr^{-1} between 1944 and 1995. Suanez and Bruzzi (1999) argue for a complex relationship between river sediment input and shoreline changes because no linear connections were evidenced. However, these preliminary conclusions are principally based on the mass conservation equation (Pelnard Considere, 1956) to convert shoreline movements into submarine volume changes, which is usually defined for long straight beaches and not for river mouth areas. Moreover, while the mass conservation equation is useful for simple evaluations, it does not clearly take account of beach and shoreface processes and can give erroneous results (Thieler et al., 2000). Between 1988 to 1995, Suanez et al. (1998) calculated the accumulation of the Roustan prodelta lobe at between 2.6 to 4.6×10^{6} m^{3} yr^{-1} using bathymetric comparisons (0 to −20 m depths). These values are particular because the time period concerned is marked by exceptional floods with a 100-yr return period (1993–1994), which prevents us from interpreting the results from the viewpoint of large-scale coastal behaviour. Nevertheless, the amounts of prodeltaic lobe sedimentation and sand input from the river to the littoral budget are very different, suggesting there is little active fluvial sediment contribution to the beach system. In contrast, Blanc (1977), Masselink (1992) and Suanez and Bruzzi (1999) suggested that relict prodeltaic lobes are crucial in coastal sediment transport processes because they can feed the surf zone and contribute to the littoral sediment budget, at least for the coarse-grained fraction. Consequently, the Rhône river sand contribution to the beach is not yet clearly evaluated.

On the shelf, offshore deposition of fluvial sediment is demonstrated by Zuo et al. (1997), Radakovitch et al. (1998), Durrieu de Madron et al. (2000) and Touzani and Giresse (2002), who used ^{210}Pb and ^{137}Cs dating methods on cores between −20 to −100 m water depth. The analysis of cores indicates rapid sedimentation in the proximal part of the prodelta (average rate of 40 g cm^{-2} y^{-1}), with values between 0.2 and 0.6 g cm^{-2} y^{-1} at depths ranging between −20 to −50 m in the more distal parts. Sedimentation rates fall to 0.1–0.25 g cm^{-2} y^{-1} in the deeper areas (Radakovitch et al., 1998; Durrieu de Madron et al., 2000). Authors studying the shelf argue for three different sediment sources, i.e.: Rhône sediment input, biogenic productivity and atmospheric input. Previous studies have linked particulate matter and organic carbon budget between the shelf and the slope (Durrieu de Madron et al., 2000), but no relationship has been investigated between the shoreface and the shelf.

In summary, previous studies evaluating the contribution of the Rhône in the sediment supply to the littoral zone are based on a rather imprecise methodology (mass conservation equation) and concern only the middle of the 20th century. On the other hand, studies quantifying sedimentation around the mouth (prodeltaic lobe) of the Grand Rhône are based on the comparison of bathymetric surveys relating to only one limited period of 8 yr. Moreover, the sedimentation rates measured by geochemistry only relate to the continental shelf. Lastly, none of these previous studies allows us to appreciate and to quantify the long-term impact of the Rhône sedimentary input reduction to the sea. In order to implement these spatial, temporal and methodological shortcomings, the present study analyses the variations recorded in bathymetric surveys between 1841 and 1974. The objective is to characterise the long-term prodeltaic lobe behaviour as well as the sediment budget of the shoreface and the river–shoreface–shelf system of the Rhône delta.

4. Methodology

In order to determine and quantify the long-term bathymetric changes of the Rhône delta, we analysed bathymetric data from four time intervals. All data were collected by the Etablissement Principal du Service Hydrographique et Océanographique de la Marine (EP SHOM), except for the data from near the Roustan mouth collected in 1988 by the Port Autonome de Marseille (PAM). The data sets span from the middle of the 19th century to the end of the 20th century (1841–1872–1895 and 1974–1982–1988 (Table 1). The set from 1841 covers the littoral zone between the Grand Rhône and the Petit Rhône, so it cannot be used in evaluating the littoral budget for the whole Rhône delta. The other data sets cover the whole Rhône delta nearshore zone. The last bathymetric survey is a compilation of several dates to obtain a more complete bathymetric morphology of the Rhône delta shoreface in 1974–1982 and 1988. For simplification, we refer to all the 20th century data as “1974” in the text. All soundings are digitized and corrected to the common French horizontal and vertical reference system (Lambert III Sud and 0 National Elevation Level) using GIS and image processing software. The secular vertical evolution of the sea level, +2.01 mm/yr during the 20th century (Suanez et al., 1997) is corrected on all data sets. The X and Y coordinates errors are estimated at ±10 m. The vertical errors integrating error measurements, tides and waves are estimated at +0.76 and −0.56 m for the 19th century data set and +/−0.20 for the 20th century data set (Sabatier, 2001). For each period, we computed a Digital Terrain Modelling (DTM). A common bathymetric contour of 20 m is taken as a deeper boundary because this contour is common to the sets of bathymetric data. This depth is also consistent with the theoretical significant wave base estimated at −21.9 m depth by the common rule Lo/4 of Komar (1998) using a decennial storm return period (where Lo is the deep wave length). Moreover, this depth is close to the sand/

Table 1
Data used for the shoreline and bathymetric changes analysis

Date	Type of data	Source	Area
1841	Bathymetric map	Etat Major	Grand Radeau to Grand Rhône mouth
1872	Bathymetric sounding	EPSHOM (Brest)	Espiguette to la Gracieuse
1895	Bathymetric sounding	EPSHOM (Brest)	Espiguette to la Gracieuse
1974	Bathymetric sounding	EPSHOM (Brest)	Rhône Vif to Piémanson
1982	Bathymetric sounding	EPSHOM (Brest)	Espiguette to Rhône Vif
1988	Bathymetric sounding	EPSHOM (Brest)	Piémanson to la Gracieuse

mud limit observed between −20 and −30 m depth (Fig. 3). Thus, we can assume that we include the major part of the shoreface influenced by waves. The amount of erosion or sedimentation between two periods is determined by DTM comparison. The sediment budget is obtained by the difference between the accretional and erosional volumes: net positive and negative values suggest sediment input and output, respectively. Overwash and aeolian sediment transport were not taken into account into the sediment budget because previous studies have shown that these processes are negligible in comparison to submarine processes in a long-term sediment budget (Sabatier, 2001). We calculated a breakdown by depth of the budget at around −10 m in order to investigate the behaviour of the shoreface between the upper part, where longshore drift in the surf zone is prevalent, and the lower part, where longshore processes decrease and cross-shore processes increase (Wright et al., 1991; Stive and de Vriend, 1995; Zeiler et al., 2000; Hequette et al., 2002). Thus, we can compare the behaviours of the upper shoreface (0 to −10 m depth) and the lower shoreface (−10 to −20 m depth).

5. Results

5.1. Global sediment budget

Our bathymetric data display areas which are undergoing depositional and erosional processes (Fig. 5). After a mouth location change, the remainder river mouths and prodeltaic lobes are systematically undergoing erosion. At the contrary, the Petit Rhône prodeltaic lobe is eroding all over the investigated period while the presence of the river. Since 1841, areas undergoing sediment accumulation are the Beauduc Gulf and the littoral spits of Espiguette and of Beauduc. The Gracieuse spit appeared in 1895. The Grand Rhône mouths spatial distribution display a sedimentary accumulation belt of 1.5 km.

Since bathymetric data for the whole littoral zone are just available for the periods 1872–1895 and 1895–1974, we can only estimate two overall sedimentary budgets. For both the time intervals 1872–1895 and 1895–1974, the overall sediment budget is positive, but it decreases by a factor of 7.4 when the two periods are compared (from $+11.10$ to $+1.47\times10^6$ m^3 yr^{-1}, respectively).

5.2. Quantification of changes in prodeltaic lobes

The long-term bathymetric changes (Fig. 5) show that the net accumulation at the Grand Rhône prodeltaic lobes decreases consistently with time, yielding values of 12.63; 8.37 and 3.40×10^6 m^3 yr^{-1} for the periods 1841–1872, 1872–1895 and 1895–1974, respectively. In contrast to the Grand Rhône, the offshore areas of the Petit Rhône mouth and prodeltaic lobe are being increasingly eroded, with values of −0.53; −1.07 and -1.34×10^6 m^3 yr^{-1} for the same respective periods. This erosion combines the Petit Rhône and St Férréol relict prodeltaic lobe, without any eventual distinction between them.

All relict prodeltaic lobes show the same trend: when the river is no longer discharging at their mouth, after a natural or anthropic river shift, they all become subject to erosion (Fig. 5). The erosion of the Bras de Fer relict prodeltaic lobe is slowly decreasing with time (e.g.: −1.30; −1.14 and -1.02×10^6 m^3 yr^{-1} for 1841–1872, 1872–1895 and 1895–1974 respectively). Between 1841 and 1895, the erosion of the prodeltaic lobes of Piémanson and Roustan started after the artificial closure of their mouth, and only ceased after the re-opening of the Roustan mouth in 1892. Since then, the mouth location changed towards the west induces erosion of the Pégoulier relict prodeltaic lobe.

5.3. Quantification of changes in the shoreface

In order to evaluate sediment budgets for areas dominated by waves and less influenced by the river, we calculated sediment volumes located at the western part of the Grand Rhône accumulation zone (around the sector Baïsse de Quenin). This area is called “shoreface” in this study. The eastern part sediment processes are dominated by the Rhône inputs (Fig. 5 and Sabatier and Suanez, 2003) and then not integrated in the analysis of the shoreface because we try to focus on the wave dominated part of the delta. The Petit Rhône prodeltaic lobe remains in the shoreface budget quantification as it is under an erosional regime and as it is not possible to establish the sediment input to the sea by the Orgon mouth. The sediment budget of the shoreface zone remains positive ($+2.73\times10^6$ m^3 yr^{-1}) during the first time interval but become negative (-1.94×10^6 m^3 yr^{-1}) for the second time interval in relation to an increase of erosion (−3.04 to -4.21×10^6 m^3 yr^{-1}) and a decrease in accumulation (+5.77 to $+2.27\times10^6$ m^3 yr^{-1}). In detail, the upper shoreface (0–10 m), between 1872 and 1895, shows fairly similar values between accumulative and erosional regimes, yielding a slightly net positive budget ($+0.34\times10^6$ m^3 yr^{-1}) (Fig. 6). In contrast, the lower shoreface gained more sediment during the same period and the net sedimentary budget is significantly positive ($+2.39\times10^6$ m^3 yr^{-1}). Between 1895 and 1974, the opposite trend is observed (Fig. 6). The net sedimentary budget of the upper shoreface is slightly in erosion

(-0.28×10^{6} m^{3} yr^{-1}) meanwhile the net lower shoreface displays strong erosional regime (-1.66×10^{6} m^{3} yr^{-1}).

5.4. River sediment contribution to the non-adjacent beaches of the mouth

To the east of the Roustan mouth, it is possible to quantify the sedimentary contribution of the Grand Rhône river to the Gracieuse spit which is a non-adjacent beach of the mouth. The sedimentary budget of this littoral cell (Fig. 1) between 0 to −20 m depth, shows an erosion of the relict Pégoulier prodeltaic lobe of about -0.54×10^{6} m^{3} yr^{-1} and an accumulation of the spit of about $+0.59\times10^{6}$ m^{3} yr^{-1} between 1895 to 1974. Thus, assuming that the eroded area feeds the area under accumulation by longshore sediment transport processes (littoral drift cell), we can infer that the mean long-term sediment contribution of Grand Rhône river to the littoral drift is equal to 0.05×10^{6} m^{3} yr^{-1} between 1895 to 1974. In comparison with the sedimentation in the Roustan prodeltaic lobe during the same time interval ($+3.41\times10^{6}$ m^{3} yr^{-1}), this value represents merely 1.5% of the lobe sedimentation. However, this value is to be considered as a minimum limit as we are

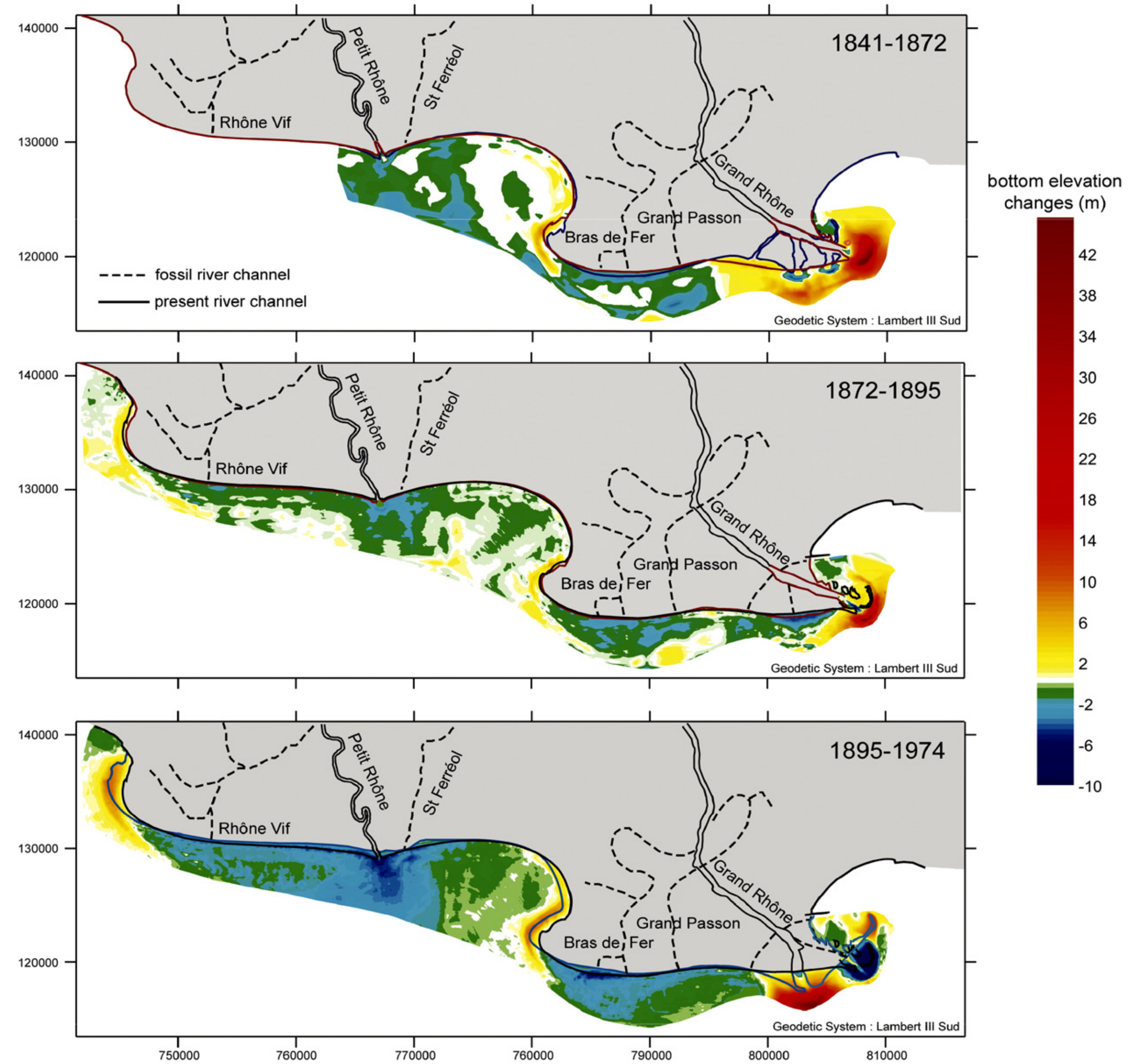

Fig. 5. Bathymetric measurements superposition results at three time periods between 1841 and 1974.

hypothezising a global sedimentary input from the relict prodeltaic lobe of Pégoulier to the Gracieuse spit. Moreover, offshore outputs can occur which would enhance sedimentary inputs from the river to the littoral spit. This method could not be applied to determine the contribution of the Grand Rhône to the littoral budget in the eastern sector between 1872 and 1895 because the net longshore sediment transport around the Piémanson, Pégoulier and Roustan mouths is unclear during this period.

6. Discussion

6.1. The littoral cell organisation

The net upper shoreface budget, between 1872–1895 and 1895–1974 on the area dominated by the waves and less influenced by the river (without the Grand Rhône prodeltaic lobes), appears slightly positive or negative and can be considered in equilibrium without significant inputs into the system. It is well known that the upper shoreface, defined in our study between the shoreline and the −10 m depth contour, is strongly affected by waves action and longshore sediment transport (Komar, 1998) when the waves are oblique which is the case along the Rhône delta shoreline during the SE storm waves and during the SW modal conditions waves. The equilibrium budget implies longshore sediment redistribution between erosional and accretional area. The relict sediments of the prodeltaic lobe of Petit Rhône–St Férreol, Bras de Fer and Pégoulier are moved alongshore to build the Espiguette, Beauduc and Gracieuse spits according to the littoral cell organisation

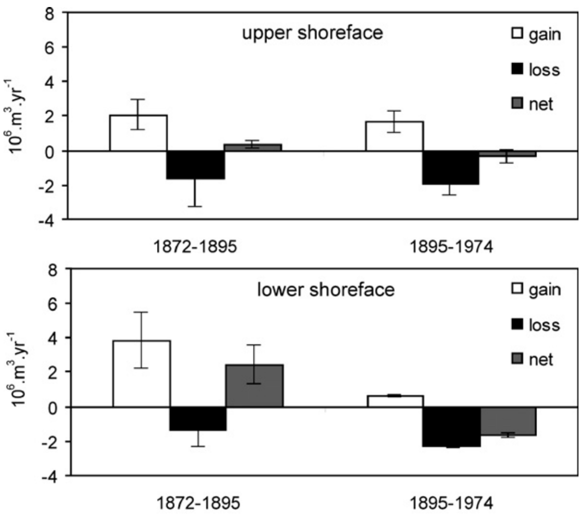

Fig. 6. Sediment budget of the upper and lower shoreface.

(Suanez and Provansal, 1998; Sabatier and Suanez, 2003). The pattern of the accretion of the Beauduc and Espiguette spits takes the same form (Fig. 5). The maximum accumulation takes place where the shore is advancing more rapidly (top of the spit). However, the comparison of bathymetric data indicates as well that the accumulation of the spit is taking place upstream of the longshore drift and also extends offshore down to approximately −20 m by forming a bathymetric profile with a marked slope (around 6% meanwhile the slope of the shoreface is around 1–2%, see arrow Fig. 7). In the case of the Espiguette spit (Fig. 7), this slope morphology was used as an argument to identify a hypothetical relict prodeltaic lobe of the Rhône Vif (L'Homer, 1993; Berné et al., 2002) that we call into question here. In reality, it appears that this morphology corresponds to the accumulation of the spit and not to a relict prodeltaic lobe (Fig. 7).

6.2. The morphological adjustment of a deltaic system to the external forces

The decrease in Grand Rhône prodelta accumulation and the increasing of erosion on the Petit Rhône prodeltaic lobe is related to the reduced frequency of floods (Fig. 2). Our analysis points out that the decrease of river sediment input to the sea had started before the construction of dams. Firstly, this decrease is related to climatic change (end of Little Ice Age) demonstrated by the reduction in the occurrence of major floods (Pichard, 1995; Pont et al., 2002). Secondly, the changes in soil management in the catchment area (reforestation of alpine hill slopes, decline in agricultural population) have reduced the amount of river sediment. This early slowing down in river sediment transport is combined with increasing stream power and boundary shear stress caused by engineering works (bank revetment, groynes, hydraulic deflectors), leading to channel adjustments (channel incision) downstream of Arles since 1860 (Antonelli and Provansal, 2002b; Arnaud-Fassetta, 2003; Antonelli et al., 2004). After 1950, dam construction and dredging activities halted or dramatically reduced the coarse bed load transport, producing channel incision and morphological changes in the upstream Rhône and its tributaries (Bravard and Peiry, 1993). However, these works did not trap all the suspended sediment transport (SST) (IRS, 2000), suggesting a limited effect due to hydroelectric plants on the lower Rhône River, where a slowing-down in the incision rate has been detected ever since the 1960s (Antonelli et al., 2004). On the relicts prodeltaic lobes, such as the Bras de Fer, slowly decreasing erosion rates

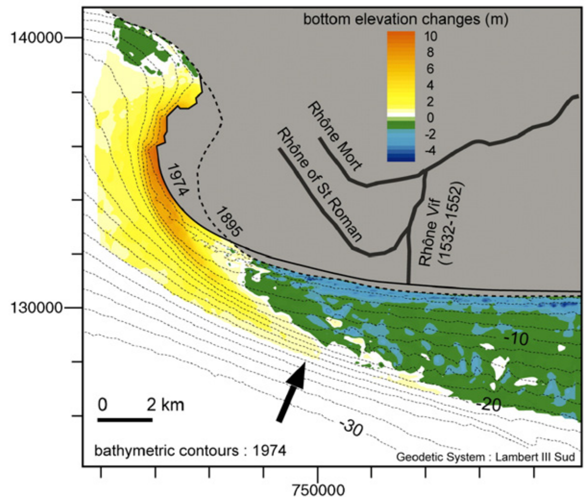

Fig. 7. Sub-marine accumulation of the Espiguette as far as the Rhône Vif between 1895 and 1974.

suggest that they are adapting to the forcing agents reaching an equilibrium profile. Thus, relict prodeltaic lobes can be considered as time-limited sediment sources, depending on there size and waves exposures. At secular time scale, we probably observe a morphological readjustment of the deltaic bodies with climatic and anthropic forcing factors.

6.3. Connections between the river, active prodeltaic lobe, shoreface and shelf of the Rhône system

Based on our results and previous studies on deltaic river channel incision and estimation of sediment transport, an overall long-term sediment budget can be proposed for the river-mouth–shoreface–shelf of the Rhône system (Fig. 8). We first need to determine and quantify the river sediment input to the marine domain, which then can be compared with the bathymetric shoreface changes. Previous studies have generally estimated the amount of the Rhône river SST (cf site presentation) but to estimate the sedimentary budget, the whole Rhône river transport is needed (BST and SST). On large rivers, the distribution of BST and SST is usually considered as 10% and 90%, respectively, of the total sediment transport (Milliman and Meade, 1983). This approximation is of the same order of magnitude if we base our estimations on the exceptional floods of 1993 and 1994 (Arnaud-Fassetta, 1997; Antonelli and Provansal, 2002b), which indicate values of about 13% and 87% for BST and SST, respectively. Thus, we used this ratio to estimate the total sediment load transported by the river but we kept in mind that these values should be considered as an order of magnitude. We converted the weight (ton) into volumes (m^3) by using the 1.59 ratio based on the sediment grain density (2.65 t m^3) and sediment porosity (1–0.4). In the marine domain, we used bathymetric comparison results. They were obtained in separating the Rhône prodeltaic lobes accumulations from areas under waves influence (shoreface).

From the middle of the 19th to the first part of the 20th century, before the construction of dams, the estimated total sediment transport of the Rhône (calculated on the methodology described before and based on the SST estimations from Surell, 1847; Pardé, 1925) (Fig. 2) probably lies around 20×10^6 m^3 yr^{-1} (19.10 to 21.66×10^6 m^3 yr^{-1}). Moreover, we do not have any information on the evolution of the bed river,

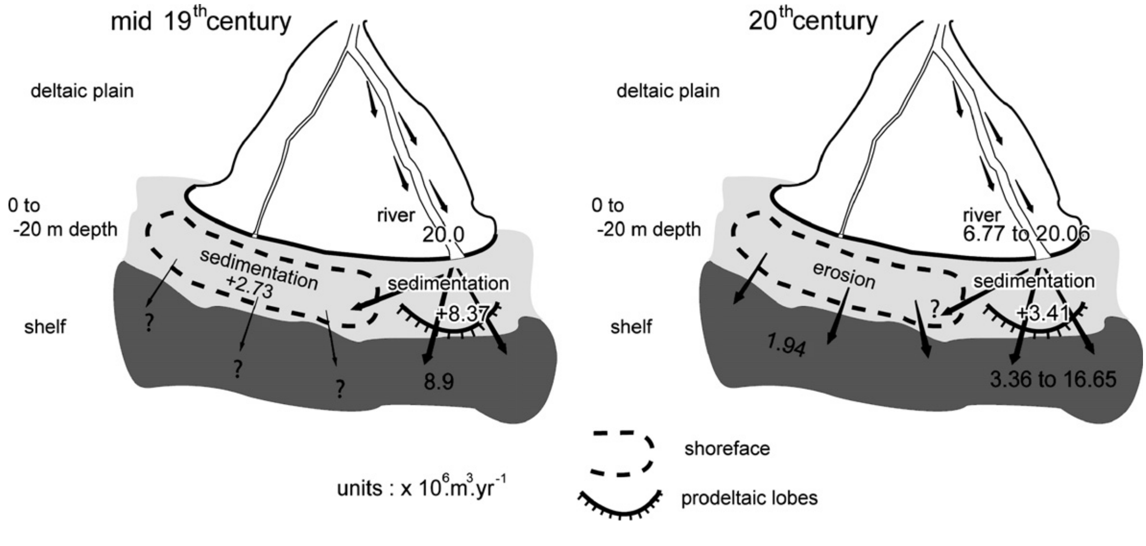

Fig. 8. River-mouth–shoreface–shelf sediment budget for the mid-19th century and during the 20th century.

which can either traps sediments in transit (by accretion) or, on the contrary, supplies sediments (by incision) which then move towards the sea. Thus, as the net sedimentation of the Grand Rhône prodeltaic lobe is about 8.37×10^6 m^3 yr^{-1} during the period 1872–1895, we estimate the river sediment by-pass via the prodeltaic lobe at around 11.63×10^6 m^3 yr^{-1}. In the lower shoreface area (−10 to −20 m), the sediment budget is positive for the period 1872–1895. Since the net upper shoreface budget is in equilibrium, the sediments in the lower shoreface cannot come from the upper zone. Onshore sediment transport from zones deeper than −20 m can hardly be expected, so we consider that the net accumulation of the lower shoreface is derived from the Rhône river sediment input. The lower shoreface of the Rhône delta can receive river sediment discharge (Zuo et al., 1997; Radakovitch et al., 1998; Durrieu de Madron et al., 2000; Touzani and Giresse, 2002) extending out to sea via plumes as observed in other comparable deltaic environments (Jiménez et al., 1999). By deducing the Rhône inputs from the prodeltaic lobe and from the shoreface, the supplies of the Rhône river to the shelf (deeper than −20 m depth) is thus estimated to be around 8.90 M m^3 yr^{-1} (Fig. 8).

It is difficult to propose a mean value of the river sediment input for the 20th century because of decreasing river floods during this period and the lack of reliable data. In consequence, based on maximum (Surell, 1847; Pardé, 1925) and minimum (Antonelli and Provansal, 2002a) SST evaluation during the 20th century, we calculated the total river sediment transport ranging between 6.71 and 20×10^6 m^3 yr^{-1}. Based on bathymetric profile line comparisons (1907 and 1991), Arnaud-Fassetta (1998) estimated a negative sediment budget for the Grand Rhône of about 0.06×10^6 m^3 yr^{-1}. Since the Grand Rhône channel is under an erosional regime, we may assume that it can supply sediment to the coastal zone. Arnaud-Fassetta (2003) suggested that sediment transport was facilitated by channelization of the Rhône during the 20th century. While we do not take into account bank morphology and narrowing, field measurements indicate that these features are partially artificial and that their influence is negligible at the considered time scale (Arnaud-Fassetta, 2003). Moreover, civil engineering works since 1867 along the two arms have limited the extent of flooding, and sedimentation on the deltaic plain has been significantly reduced. It therefore appears reasonable to consider that the incised bed-material is transported downstream and acts as source of sediment supply to the sea. Because there are no long-term river bathymetric profile lines available for the Petit Rhône, the sediment budget of this arm is not evaluated. Nevertheless, it should not have any strong influence on the overall sediment budget at this time scale because the Petit Rhône is a minor arm and its sinuous morphology probably favours accumulation in the channel (Arnaud-Fassetta, 1998; Antonelli et al., 2004). By subtracting the river sediment input to the sea (total sediment transport added to the channel erosion) from the prodeltaic lobe accumulation ($+3.41 \times 10^6$ m^3 yr^{-1}), we can estimate a maximum prodeltaic lobe by-pass between 3.36 and 16.65×10^6 m^3 yr^{-1}. Between 1895 and 1974, the shoreface sediment budget suggests net equilibrium of the upper part and net offshore loss on the lower part (1.66×10^6 m^3 yr^{-1}) (Fig. 7), probably caused by undertow and downwelling as observed on other sites (Hequette and Hill, 1993; Jiménez et al., 1999; Hequette et al., 2002). During the 20th century, with decreasing river sediment discharge, the sediment input to the sea was insufficient to compensate for the loss of sediment farther offshore. We cannot infer that, while offshore sediment transport occurred during 1895–1974, no such transport would have occurred during 1872–1895. Indeed, our results are based on bathymetric comparisons, which indicate the net evolution. We thus consider that offshore sediment transport would have occurred during both periods, but during the 19th century this movement was counterbalanced by considerable river discharge of suspended sediment during plumes. River sediments are also being deposited offshore, on the shelf, where a positive sedimentation rate has been demonstrated (Zuo et al., 1997; Radakovitch et al., 1998; Durrieu de Madron et al., 2000; Touzani and Giresse, 2002). These authors argue for an important contribution of the Rhône River to shelf sedimentation. However, the offshore loss of sediment from the shoreface, estimated in this study from bathymetric comparisons, will also contribute to the shelf sedimentation (Fig. 8).

To conclude, we point out that our analysis and interpretations are based on a comparison of bathymetric sounding over the long term and only yield orders of magnitude. Field measurements during storms and floods most probably reflect sedimentary exchanges between the mouth zone and the shoreface, as well as between the upper and lower shoreface, as already observed in the Ebro delta (Jiménez et al., 1999) in a comparable environment with the delta of the Rhône. It is also well known that coarse sediments move onshore and fine sediments off-shore during storms (Stive and de Vriend, 1995). While this segregation probably occurs on the shoreface of the Rhône delta, such processes have never yet been measured on this site.

7. Conclusion

The present analysis is based on the evolution of the long-term bathymetry (150 yr), leading to some novel insights into the relations between the river, active and relict prodeltaic lobes, shoreface and continental shelf. First of all, we show that the reduction in the sedimentary inputs of the Rhône to the sea over the last 150 yr has resulted in a reduction in sedimentation at the mouth. We also clearly show that this reduction began before the construction of dams. Our results indicate that there is a large accumulation of sediment in the area around a growing prodeltaic lobe, associated with a reduced contribution to longshore sediment transport. Following a shift in the river channel and mouth, the prodeltaic lobe is reworked by waves and its sediment contributes partially to the growth of spits. This suggests that there is a “time-shift” between the input of river sediment to the sea and the build up of a beach. In an initial stage, the sediments are trapped in the prodeltaic lobe, and later, when the mouth location has shifted, they are reworked to build spits. During the Holocene and up to the modern period, the river channel has shifted many times through natural and anthropic processes to build up the present deltaic plain and shoreface morphology. Nowadays, as the river channels are controlled by dykes and human intervention, a river shift is not possible (assuming that the dykes can resist the strongest flood events). Under these conditions, and with the decreased input of fluvial load into the sea, it thus appears unlikely that river sediments can significantly contribute to the beaches of the Rhône delta coast. Moreover, the relict prodeltaic lobes constitute sedimentary reservoirs that are gradually being used up. The chronic erosion of the coastline, which is caused by a deficit in sediment, a very weak supply and the redistribution of the river sediments, is thus likely to continue in the future.

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