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DYKE BREACHING AND CREVASSE-SPLAY SEDIMENTARY SEQUENCES OF THE RHÔNE DELTA, FRANCE, CAUSED BY EXTREME RIVER-FLOOD OF DECEMBER 2003

ABSTRACT: ARNAUD-FASSETTA G., *Dyke breaching and crevasse-splay sedimentary sequences of the Rhône Delta, France, caused by extreme river-flood of December 2003*. (IT ISSN 0391-9838, 2013).

Crevasse splays caused by the flood event of December 2003 in the Rhône Delta (Mediterranean France) offered the opportunity to study the «stage I» of Smith & *alii* (1989), as contemporary analogues for quantifying lateral erosion and overbank deposition in the flood plain. From two study cases («Petit Argence» and «Claire Farine»), main hydrogeomorphological impacts of December 2003 flood event and sedimentary facies associated with each crevasse-splay sub-environment (crevasse channel, crevasse-splay lobe, proximal and distal flood basin) are detailed. Fluvial landforms, sediment-body geometries and sedimentary-facies characteristics are determined using a combination of topographic maps, remote sensing data, field measurements, and laboratory analyses. Spatial distribution of hydraulic parameters such as mean flow velocity, bed shear stress, and specific stream power is derived from relationship with mean flow depth, sediment structure, sediment grain size, sediment thickness, and distance from the Petit Rhône channel/dyke breach. Sedimentological analysis highlights different gradients of downstream thickness, fining, and sorting of sediments. The 3-D geometry of crevasse splays is reconstructed with calculation of the sedimentary volume deposited or eroded in the delta-plain area. Sediment balance (674,227 ± 33,711 m^3) derived from December 2003 crevasse splays is correlated with the delta-plain sediment balance.

KEY WORDS: Rhône Delta, Rare flood, Fluvial geomorphology, Crevasse splay, Flood-plain deposition, Sediment balance, Hydrological risk.

INTRODUCTION

Many papers were published dealing with hydromorphological, sedimentological, and geochemical impacts of the flood of December 2003 in the Rhône Delta (Mediterranean France) nine years after the event. Publications have focused on the following, from upstream to downstream: (i) Variations of dissolved major and trace element concentrations in the lower Rhône River (Ollivier & *alii*, 2006); (ii) Radiological consequences in the flood plains both of the Rhône River upstream of Arles and the Petit Rhône River (Eyrolle & *alii*, 2006); (iii) Suspended sediment and ^{137}Cs fluxes in the Grand Rhône River (Antonelli & *alii*, 2008); (iv) Morphological changes and sedimentary processes at the mouth of the Grand Rhône River (Maillet & *alii*, 2006); (v) Stratigraphic signatures due to flood deposition near the Grand Rhône mouth (Drexler & Nittrouer, 2008); (vi) Radionuclide deposition in the Grand Rhône prodelta (Miralles & *alii*, 2006); and (vi) Dilution zone of the Rhône River in the Mediterranean (Gatti & *alii*, 2006). Only the thematic focal point (ii) focused on «crevasse splays» but little has been said about the sedimentation processes, and protocols based both on field measurement and mapping methods were different.

Crevasse splays are recognised to have an important impact in the sedimentary construction (*i.e.*, by aggradation and/or progradation processes; Galloway & Hobday, 1996, p. 74) of both alluvial plains (Allen, 1964; Coleman, 1969; Bridge, 1984; O'Brien & Wells, 1986; Smith, 1986; Smith & *alii*, 1989; Mjos & *alii*, 1993; Smith & Pérez-Arlucea, 1994; Gomez & *alii*, 1997; Kraus & Gwinn, 1997; Bristow & *alii*, 1999; Ethridge & *alii*, 1999; Krauss & Wells, 1999; Pérez-Arlucea & Smith, 1999; Davies-Vollum & Kraus, 2001; Farrell, 2001; Makaske & *alii*, 2002; Kraus & Davies-Vollum, 2004; Slingerland & Smith, 2004; Sihna & *alii*, 2005; Stouthamer & Berendsen, 2007) and delta/

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This study would not have been possible without the sustained effort of all my family members whom I forced to take time for fieldwork during the Christmas holidays in 2003. I particularly thank my father Guy Arnaud-Fassetta (Istres) for lending me a cross-country vehicle for the field excursions, P. Freytet (University Paris-Diderot) for a discussion of the results, and M. Laromanière (University Paris-Diderot) for his help in the Laboratory of Sedimentology. I finally thank the Editor in Chief of the journal, P.R. Federici, A. Ribolini, assistant (University of Pisa) and M. Soldati (University of Modena e Reggio Emilia), and D.-J. Stanley (Smithsonian Institution of Washington), C. Esposito (University of New Orleans) and T. Brown (University of Southampton) whose suggestions are greatly appreciated. This paper is a tribute to Prof. Monique Fort, the colleague with whom I shared twelve years at the University Paris-Diderot and in the field.

coastal plains (Fisk & *alii*, 1954; Coleman & Gagliano, 1964; Arndorfer, 1973; Elliott, 1974; Kezel & *alii*, 1974; Van Gelder & *alii*, 1994; Chen & *alii*, 1996; Boyer & *alii*, 1997; Ten Brinke & *alii*, 1998; Aslan & Autin, 1999; Baeteman & *alii*, 1999; Berendsen & Stouthamer, 2000; Stouthamer, 2001; Törnqvist & Bridge, 2002; Hesselink & *alii*, 2003; Cahoon & *alii*, 2011; Esposito, 2011; Stouthamer & *alii*, 2011). Nevertheless, the development of crevasse splays has become a less common phenomenon since most of the fluvial-deltaic hydrosystems have been affected by major anthropogenic activity (Hesselink & *alii*, 2003) as the implementation of dykes and other structures, intended to fix the river-channel and to limit in both space and time overbank events in flood basins, necessarily modified the hydrological-sedimentary functioning of a river, and reduced the occurrence and the development of crevasse splays. Therefore, the crevasse splays caused by the flood event of December 2003, when waters of the lower Rhône River breached the dykes, offered the opportunity to study a phenomenon that has become uncommon, and that, in the case of the Rhône Delta, had not occurred since 1993-1994 (Arnaud-Fassetta, 1996; Siché, 1997).

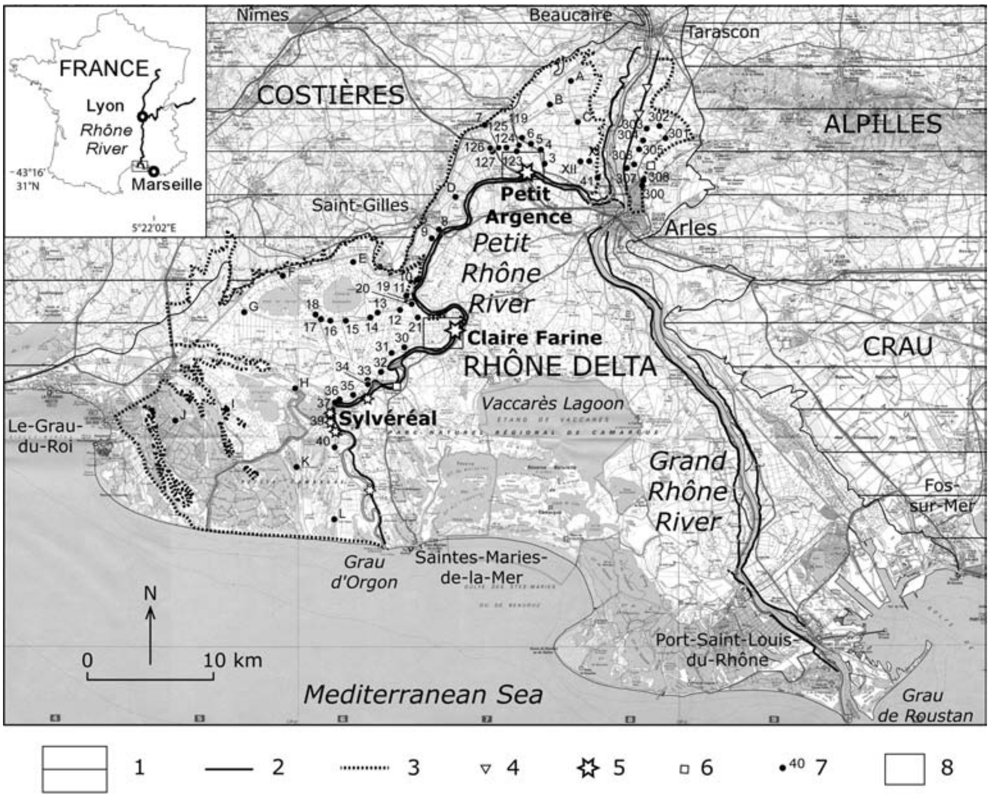
Crevasse splays are sedimentary fluvial deposits that form when a main channel breaks its natural or artificial levees and erodes/deposits sediment on a floodplain (Coleman, 1969). They develop during flood events as water and sediment (*e.g.*, from coarse sand to silty clay; Stouthamer, 2001) pour through breaches in the riverbank of a main channel (Galloway & Hobday, 1996, p. 63). This breach can cause large deposits that spread in a pattern similar to that of a river delta, with a relationship between the development of sedimentary bodies and the flooded basin, but differ with that of an alluvial fan deposit. Lateral erosion results in a crevasse channel, and overbank deposition in a crevasse splay *stricto sensu* (Arndorfer, 1973, p. 269). Despite that crevasse-splay deposits are lithologically similar to avulsion deposits, they differ in temporal and spatial scales. Crevasse-splays have short life spans (*i.e.*, days to years); they correspond to channel margin deposits and interchannel flood-basin depositional environments, which cover limited areas, generally less than several tens of square kilometres (Kraus & Wells, 1999, p. 252). On the basis of genetic processes and facies architecture, Galloway & Hobday (1996, p. 74, fig. 4.9) distinguish (i) crevasse splays, for which aggradation and progradation processes participate in the same proportions (but with a little difference in favour of progradation) in the deposition of sediments both on the sub-aerial floodplain and the levees that flank fluvial channels, from (ii) crevasse deltas that predominantly prograde into flooded backswamps and interchannel lakes. Furthermore, different scenarios have been proposed in the literature concerning the construction stages of crevasse-splay lobes. A good knowledge of these stages is necessary for the recognition of crevasse splays in the ancient stratigraphic record (Kraus & Gwinn, 1997; Kraus & Wells, 1999), to demonstrate lateral instability of palaeochannels (Van Gelder & *alii*, 1994, p. 300), and, in a more general way, to understand the processes leading to the avulsion of fluvial channels (Pérez-Arlucea & Smith, 1999; Stouthamer, 2001; Makaske & *alii*, 2002). According to Smith & *alii* (1989, p. 21), there exists three intergradational types of crevasse splay that form during the avulsion cycle: «stage I» splays are relatively small, lobate in plan with shallow unstable distributary channels and wedge-shaped sand sheets that overlie finer-grained, wetland deposits; «stage II» splays are larger, contain dense networks of anastomosing channels, and form disconnected tabular sand bodies or continuous sand sheets, some of which incise underlying wetland sediments; and «stage III» splays, with low-density, stable anastomosing channels, that form isolated stringer sands encased in fine-grained floodplain sediments. However, some crevasse-splay developments differ from kinematics proposed by Smith & *alii* (1989). Recently, Farrell (2001) enhanced the modalities of the «stage I» crevasse splay of Smith & *alii* (1989) by including facies and geometries consistent with a bay-fill model. The present study suggests a more particularly detailing of «stage I» deposition/erosion processes by analysing the characteristics of crevasse splays in the Rhône Delta. The working hypothesis is that the development of a channel avulsion by crevasse splay is now improbable because the dykes of the Rhône River had been repaired just after the December 2003 flood event.

Finally, as Mjos & *alii* (1993) indicated nineteen years ago, crevasse-splay sediments and their quantitative geometry [*i.e.*, three dimensional (3-D) properties] are not well known and studies are rare (Kesel & *alii*, 1974; O'Brien & Wells, 1986; Gomez & *alii*, 1997; Ten Brinke & *alii*, 1998). This also applies to the case of the Rhône Delta in which crevasse-splay deposits have not been detailed. Consequently, from two examples of 2003 crevasse splays in the Rhône Delta, the aims of this paper are (i) to characterise the main hydrogeomorphological features and sedimentary facies associated to each crevasse-splay sub-environment, (ii) to quantify the 3-D geometry of the crevasse splays, with a calculation of sedimentary volume deposited or eroded in the delta-plain area, and (iii) to estimate the spatial distribution of hydraulic parameters such as mean flow velocity, bed shear stress, and specific stream power and their relationship to mean flow depth, sediment structure, sediment grain size, sediment thickness, and distance from the Petit Rhône channel/dyke breach.

THE LOWER RHÔNE VALLEY AND THE DECEMBER 2003 FLOODING

The Rhône Delta is positioned downstream of a wide catchment (97,800 km^2), one of the largest in Europe. From its glacier in Switzerland to the Mediterranean off southern France, the Rhône River and its tributaries drain several geological and hydroclimatic units (Alps, Jura, Massif Central). The apex of the Rhône Delta is located upstream of Arles (fig. 1). In Fourques, the river splits into two branches. The Grand Rhône River (length: 50 km; mean gradient: 0.00009) has the greatest (85-90%) discharge. Its sub-straight/slightly sinuous channel, almost completely embanked, flows into the sea by the *Grau de*

FIG. 1 - Examined areas in the Rhône Delta. 1: margins beyond the Holocene delta plain; 2: dyke; 3: boundaries of areas flooded (outside the dykes) by December 2003 flood event; 4: tunnel flooded by December 2003 flood event; 5: dyke breaches; 6: dyke overtopping; 7: sample; 8: location of fig. 4A and 4B.



Roustan. The average channel depth is 9 m for an average channel width of 335 m. The Petit Rhône River (10-15% of the discharge; mean gradient: 0.00005) is most embanked all the way to the sea and joins the Mediterranean *via* the *Grau d'Orgon* after a sinuous/meandering course of 60 km. Its average channel depth is 6.5 m for an average width of 135 m. Despite low maximum specific stream power (9.4 W/m^2; Arnaud-Fassetta, 2003), the Petit Rhône River is prone to the occurrence of crevasse splays for two reasons, hydrographical (sinuous/meandering pattern) and human (non-concerted dyke management by two different governance structures, the SYMADREM on the left bank and the Gard «Department» on the right bank). Since the 2003 flood, dyke management has been coordinated by the interregional organisation SYMADREM/SMIADDRM. The bed material of the deltaic Rhône River is characterised by four types of sediments (cobbles-pebbles, sand, compact silt, mouth mud; Arnaud-Fassetta & *alii*, 2003; Brousse & Arnaud-Fassetta, 2011). However, sand is predominant, with a median grain size of 0.40-0.55 mm. This fraction moves by both saltation and suspension at practically all flows, and the bed material is thus continuously being reworked during floods.

During the last century, the annual sediment load of the lower Rhône River was estimated at 21 Mt. Since the volume of sediment carried to the Mediterranean would have been greatly reduced (–70 to –80%) at the end of the Little Ice Age crisis associated to the effects of river-regulation works and hydropower equipment. Today in the delta plain, the solid discharge of the Rhône River is estimated to 8 Mt/a, with variations from 2 to 26 Mt/a depending on the frequency and magnitude of floods during that year (Antonelli, 2002). Most of sediment load (64%) would transit into the river during floods exceeding 3000 m^3/s, within 36 days (Pont & *alii*, 2002). Because of the embankments, only 30,000 t/a would deposit in Camargue as the result of pumping for irrigation (Heurteaux & *alii*, 1992). The dykes, constructed between 1849 and 1869 (Joanny, 1993), significantly reduced the occurrence of crevasse splays that were a common phenomenon in the past before dyke construction (L'Homer, 1987; Arnaud-Fassetta, 2009).

The hydrological regime of the lower Rhône River, of Mediterranean-type (attenuated), is characterised by high waters from November to May. Thus, no period of severe low flows (average of 600 m^3/s) affects the Rhône River and mean discharge is 1700-1710 m^3/s upstream of the delta plain. Downstream, torrential tributaries draining the Alps (Durance River) and the Cévennes (Ardèche River, Gard River) play an important role in the hydrological and sediment regime of the lower Rhône River. Rainfall generalised to the whole Rhône catchment may be the source of exceptional [≥100-year recurrence interval (RI)] hydroclimatic events that cause large flooded areas and trigger significant changes in the riverbed. In the lower Rhône River, such flood hazards occurred during the 19th century in May 1856 (12,000-12,500 m^3/s) and November 1840 (12,500-13,000 m^3/s), during which tine floods affected the very edge of the historic floodplain. Today, the accepted threshold values for the reference Rhône discharges, estimated during the period 1920-2000 in Beaucaire-Tarascon, are as follows: 8400 m^3/s (10-year RI flood), 11,300 m^3/s (RI 100-year flood), 13,300 m^3/s (RI 500-year flood), and 14,200 m^3/s (RI 1000-year flood). Since 1993, the Rhône River has experienced six major flood events: October 1993 (9800 m^3/s in Beaucaire-Tarascon), January 1994 (10,980 m^3/s), November 1994 (9750 m^3/s), November 1996 (8990 m^3/s), September 2002 (10,500 m^3/s), November 2002 (10,200 m^3/s), and December 2003 (11,500 ±5% m^3/s).

The latest flood, that of December 2003, is the most important since the «reference» event of 1856. From 03/11/30 to 03/12/04, heavy rainfall fell on the Mediterranean basin, associated with exceptionally strong winds at sea and on shore during 03/12/03 and the night of the 03/12/04. The flood of December 2003, of «extensive Mediterranean» type, was due to exceptional meteorological conditions: (i) high cumulative rainfall (maximum: 500 mm); (ii) duration of the event (more than 48 h); (iii) its geographical extension affecting 24 «departments» alerted by Météo-France, *i.e.*, the whole valley of the Rhône River downstream of Lyon); (iv) occurrence of the event during the end of the fall marked by «high» temperatures both on the continent and the Mediterranean in early December; (v) soil saturated by important rainfall recorded in the Languedoc since the beginning of the fall; and (vi) exceptional strong sea wind that slowed the drainage of floodwaters towards the river mouths. In response to significant rainfall in previous days (maximum: 393 mm in the Cevennes from 03/11/30 to 03/12/02; 100 mm in the Rhône plain from 03/12/01 to 03/12/02), all tributaries of the Rhône River downstream of Lyon were affected by floods, gradually amplifying the discharges downstream. On the Rhône River, the height of floodwaters increased very quickly. Between the 03/12/01 and the 03/12/02, the Rhône discharge increased from 1800 m^3/s to 8000 m^3/s in Viviers, and from 2400 m^3/s to 10,000 m^3/s in Beaucaire-Tarascon in less than 30 h. The maximum peak discharge reached in the night of the 03/12/03 was not easy to estimate on the Rhône River. The «consensus conference» organised in Lyon in July 2005 finally allowed to retain the value of 11,500 (±5%) m^3/s reached in Beaucaire-Tarascon the 03/12/03 at 9:00 p.m., which corresponds to a RI just over 100-year but lower than that achieved during the «reference» flood of 1856 (RI 100- to 150-year). The peak discharge was estimated at 1450-1500 m^3/s on the Petit Rhône River. In the lower valley, the Rhône River burst its banks, flooded an alluvial plain surface of about 500 km^2, and broke several dykes. The worst affected areas were located (i) between Beaucaire-Tarascon and Arles, inundated by 16 to 18 Mm^3 of water that passed through three tunnels crossing the dykes, and (ii) on the right bank of the Petit Rhône River, affected by two major dyke breaks in the areas of the farmhouses (so-called «mas» in the local idiom) of «Petit Argence» and «Claire Farine» (fig. 1).

Both human and material consequences of the December 2003 flood event were severe, particularly in the downstream part of the Rhône Valley. In Aramon, 2000 people (60% of the population of the city), whose homes were flooded in September 2002, were evacuated at the height of the event. The villages of Comps and Vallabrègues, located a few kilometres near Aramon, were completely inundated. In Arles, nearly 6,000 people living in the northern part of the city were evacuated and ten days of pumping were necessary to dry the damaged neighbourhoods with mega-pumps sent from Italy and Germany. For the city of Arles, the damage was estimated at between 150 and 200 million Euros by the Chamber of Commerce in 2003. About a thousand companies, including three hundred in the industrial area, were affected and 2,500 employees were laid off. In the Petite Camargue (West Rhône Delta), nearly 3,000 people were evacuated on 03/12/03 after dyke breaches on the right bank of the Petit Rhône River. About 2600 inhabitants of the village of Fourques were also evacuated as well as 300 to 400 people living in Le Cailar. Finally, for the 24 «Departments» affected by the flood of December 2003, the overall damage cost was estimated at 1.130 billion Euros by the French Ministry of Ecology, Sustainable Development, Transport and Housing.

FIELD SURVEY, REMOTE SENSING AND DATA ANALYSIS

Fluvial landforms, sediment-body geometries and sedimentary-facies characteristics were determined using a combination of topographic maps, remote sensing data, field measurements, and laboratory analyses.

Before the fieldwork, preparation at the University Paris-Diderot had consisted in the acquisition of a SPOT 4 (7 December 2003; resolution: 20 m) image, photos of the flooded zones taken from the surface or by helicopter by local agencies, and several IGN topographic maps at 1:25000 and BRGM geologic maps at 1:50000 of the Lower Rhône Valley. After pre-selection of the studied sites, the original topographical maps had been enlarged so as to be able to make a land survey at a scale of 1:5000. Fieldwork was carried out in the Rhône Delta for several days (*i.e.*, from 17 to 31 December 2003) after the flood event, accounting for over a hundred hours. Geomorphological and sedimentological surveys were made at the same time as of the field prospecting. For both studied sites («Petit Argence» and «Claire Farine»), compilation of a geomorphological map was proposed, focusing on the general features of crevasse-splay sub-environments, and on the geometry of the depositional bodies and their main sedimentological characteristics, focused on sediment texture and structure. Hydraulic observations (direction of the main water fluxes) and land-use data (detached houses and «mas», orchards, cereals, meadows, riparian forest, etc.) were also mapped. Topographic surveys were made with a laser theodolite (Leica TCRM-1101) supplemented by a laser telemeter (Leica LRF-800), and a DGPS (Trimble R7-5700).

Samples in the flood basin and near channels were spaced to highlight the true morphological and lithological variations in the sub-surface. A total of 177 sediment samples were taken on natural stratigraphic sections and in trenches, auger holes or cores (fig. 1, 4A, 4B). The coring technique involved driving 80 mm diameter PVC tube into the sediment using a 1.5 kg hammer. The PVC tube was then extracted from the sediment with a car oil filter wrench (Arnaud-Fassetta, 1996). All cores showed a grain-size homogeneity throughout the entire sediment column. The December 2003 flood deposits typically were separated from the pre-existing soil by evaluating several indicators such as sediment colour, erosional or angular discordances, pedological soils, buried grass stems and roots, organic layer corresponding to crop residue, etc. (Arnaud-Fassetta, 2000). For each sampled site, we measured the distance as the crow flies from the axis of the dyke breach, sediment thickness, and maximal water height above the deposit. The maximal water heights reached during the peak discharge were derived from flood marks (organic debris or sediments) on trees and buildings, and/or from the information supplied by local residents.

We also measured the grain size of the deposits. Particle-size distributions were determined by dry sieving and/or laser granulometry. The «Udden-Wentworth» size grade scale for detrital particules (Udden, 1914; Wentworth, 1922), and the grain-size parameters such as mean size (M_z), sorting index or inclusive graphic standard deviation (σ_I), and inclusive graphic skewness (Sk_I) used in this study are from the work of Folk & Ward (1957). We also tested the CM pattern (Passega, 1957) by plotting on a bilogarithmic diagram the coarsest 1-percentile (C) against the median (M) of a cumulative grain-size distribution, in order to interpret transport and deposition mechanisms. Sedimentary structures (Pettijohn & Potter, 1964; Blatt & *alii*, 1972; Bridge, 2003), mean grain size (M_z), and mean water depth (d) measured in the flood plain completed the analysis to determine the mean velocity (U; Allen, 1968; Harms & *alii*, 1982; Southard & Boguchwal, 1990), bed shear stress (τ; Leeder, 1982), and specific stream power (ω; Allen, 1982) of flood flows. Several parameters were also plotted with significant value such as mean grain size *vs.* distance from the dyke breach, or sediment thickness *vs.* distance from the dyke breach.

Finally, the SPOTLIGHT image was analysed to propose estimates of the flooding surface. Remote-sensing analysis was supplemented by field survey to quantify the flood limit with an accuracy of 1 m. Deneba Canvas® software was used to map and quantify the total flooding surface. Sediment balance was calculated from the areas of flood deposits derived from the remote sensing data and field observations, and from the sediment thickness or erosion zones identified in the field. Microsoft Excel® software was used to build several data matrices (erosion zones, sediment thickness, sediment grain size in surface and volume units, eroded volume, sediment volume). Each matrix was built with an accuracy of 1 x 1 m (1 m^2) for the entire flooded area in the Rhône Delta downstream to Beaucaire-Tarascon. After determining homogeneous morphological-sedimentary units (*i.e.*, deposit sub-environments) both in the field and laboratory, we reported for each area of 1 m^2 values of sediment thickness or erosion, and mean grain size, representing a total of tens of thousands of points that were all individually controlled, with a margin of error that we estimated at 5%.

RESULTS

Hydrogeomorphological impacts of the December 2003 flood event

On the left bank in the area between Beaucaire-Tarascon and Arles (fig. 1), the Rhône River overflowed in the «*ségonnaux*», *i.e.* areas of the flood plain delimited between the riverbank and the dyke - width and water level respectively reached more than 1 km and 2.5 m, respectively, in some places (fig. 2A). The floodwaters have rushed by two tunnels crossing the railway embankment that acts as a dyke in the area (fig. 1, 2A, 2B). The total discharge that passed by the tunnels was estimated to ~ 200 m^3/s. We are not dealing here with a phenomenon of «dyke breaching», one that led to the development of a crevasse splay, but with an inundation by floodwaters. However, we were required to integrate this sector to quantify both the flooded area and the sediment balance in the whole delta plain. The flood deposits (n = 9) are thin (0.05-0.7 cm), fine-grained (0.015 mm < M_z < 0.045 mm), and essentially composed of silt (50-84%). Some erosion forms (scour depression, flood-plain stripping) occurred near the tunnels related to high values of specific stream power outlet for river tunnels (fig. 2C).

In the north and western parts of the delta plain (fig. 1), two major breaches (total discharge: 200 m^3/s) were opened through the dykes located on the right bank of the Petit Rhône River, leading to the development of crevasse splays (fig. 3). Field observations recorded some characteristics common to both crevasse splays (fig. 4). Three zones can be distinguished: (i) an erosion zone near the dyke breach, divided into two parts, a deep scour depression and a platform stripped of several decimetre thick deposit on margins; (ii) a transfer zone where the processes of sedimentation and erosion are mitigated; (iii) a release zone marked by the presence of prograding and/or aggrading depositional lobes, with grain-size values decreasing towards the margin and incised by channels connected or not to the main channel. Powerful reverse currents, where direction was partially controlled by structures (agricultural dykes, rows of trees), led to the relative deformation of sedimentary bodies oriented upstream with reference to axis of the crevasse splays, and to deposition of fluviatile shell (*Corbicula fluminea*) placers. In the flood basin, *i.e.*, beyond areas of crevasse lobes, sedimentation processes led to the deposition of sandy-silt to silt bodies where grain size and thickness decrease from proximal to distal zones.

In the area of «Petit Argence», a breach opened by overtopping in the dyke of the Petit Rhône River on December 3 around 3:00 p.m. (fig. 3A, 3B, 4A). The measured width of the dyke breach is 82 m, whereas the channel width of the Petit Rhône River is 110 m in this section (fig. 5B). Part of the floodwaters of the channel entered through the dyke breach. Both bed shear stress and specific stream power near the dyke breach enabled the channel to dig a large scour depression (fig. 5D), reworking the old deposits of the delta plain up to 8-9 m deep, and releasing gravel/cobbles bedload to several tens of metres down-

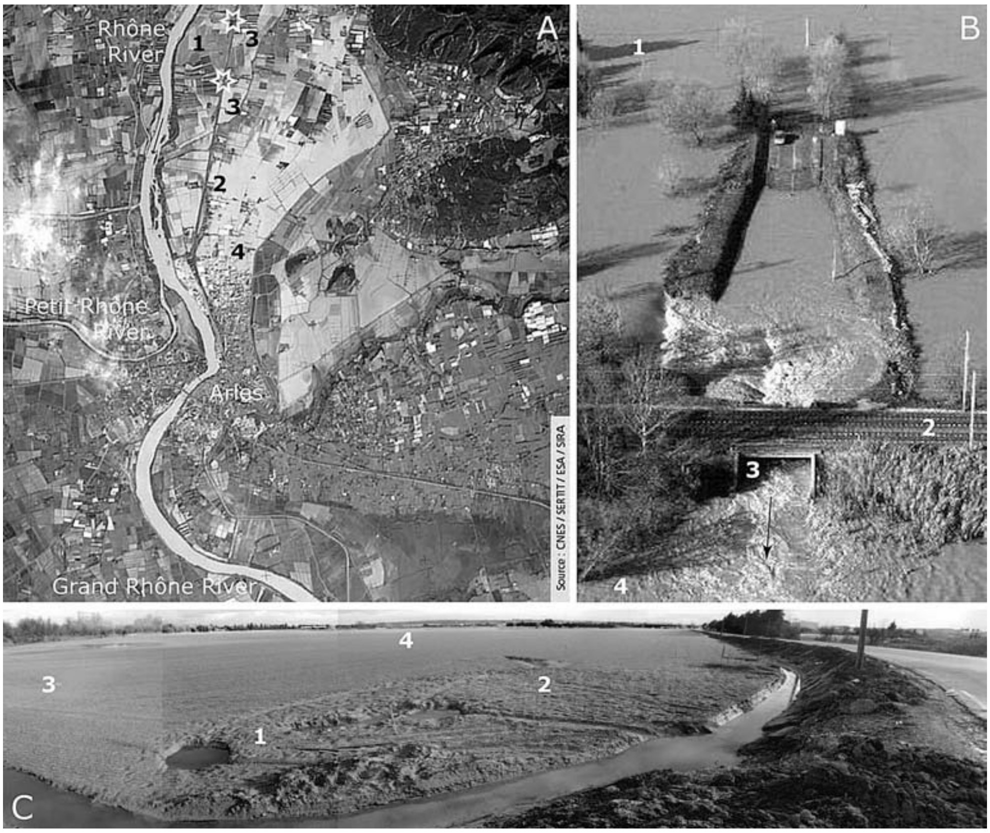


FIG. 2 - Flooded area during December 2003 flood event, on left bank of the Rhône River between Beaucaire-Tarascon and Arles. A: General view of flooded area in December 2003. 1: *ségonnal*; 2: dyke (RFF railway embankment) for flood-plain protection; 3: tunnels under railway track (Rhône River floodwaters rushed through the tunnels); 4: inundated flood plain. B: Tunnel under the RFF railway track in the site of «Mas Tessier» upstream of Arles (03/12/03; photo *in* Degoutte & Sarralde, 2008). 1: *ségonnal*; 3: tunnels built under the railway track (2) allowing Rhône River floodwaters to rush through tunnels); 4: inundated flood plain. C: Flooded area outside dyke at «La Citerne» site, upstream of Arles. After flooding of tunnel crossing the dyke (RFF railway embankment), the floodwaters that were guided by the road (to the right) invaded the flood plain. 1: scour depressions (length: 1.2 m; width: 0.8 m; depth: 0.5 m); 2: stripped zone and micro-channel cutting into surface; 3: accumulation of silts with very fine sands; 4: proximal flood basin. Photo: G. Arnaud-Fassetta (03/12/22).

stream of the dyke breach. The main channel of the crevasse splay (width up to 186 m) then took a NW-SE direction (fig. 5G). This event stripped a large area of surficial sediment 30-40 cm thick (fig. 5F) and destroyed the crops and orchards planted in the area, before depositing sandy-silt sediment in the form of lobes that prograde towards the margin of the crevasse splay. These crevasse-splay lobes locally buried the orchards under 2.5 m of sand. At the surface of these crevasse-splay lobes there developed a branched hydrographical network composed of secondary channels (width: 20 m; depth: 1.5 m) separated by sandy ridges. Tree-lined hedges played an important role in guiding flood flows, the deposition processes, and sediment distribution. Sand sheets associated to micro-scours were observed downstream of the gaps opened between the hedges (fig. 6D). The floodwaters and the geometry of the deposits were also guided by the orientation of other transverse structures, particularly the A54 motorway embankment downstream of the crevasse splay. Several farmhouses (*mas*) built in the area were flooded during many days. The maximum water depth above the sediments deposited during the flood was estimated at 1.3 m as indicated by the presence of flood marks.

In the area of «Claire Farine», located downstream of the above-cited site (fig. 3C, 3D, 4B), the floodwaters were «relatively» less morphogeneous. December 3 to 7:45 a.m., a few hours before the breach at «Petit Argence», the scouring of floodwaters in the Petit Rhône channel (width: 110 m) opened a dyke break (width: 51 m) immediately next to a pumping station, slightly downstream of where the dyke had broken in 2002 (fig. 5A). In this area, the dyke had been considerably weakened by the 2001 flood events and one of the «mas» owners interviewed in the field told us that the dyke was fractured in several places for several months. Our observations have also shown that the dyke was weakened by pipes of 60 cm in diameter buried at 1.5 m depth, and emplaced for irrigation water. The surface occupied by the crevasse splay is smaller than that of «Petit Argence», but the distribution of the sedimentary bodies is similar (*i.e.*, half-ring features around the breaking point of the dyke). The maximum water depth reached on the site was estimated at 1 m. In the proximal erosion zone, many scour depressions were dug by eddies and turbulence of waters; the most important of these was 11 m deep. Abutting on the downstream, non-destroyed part of the dyke, the flood flows divided in several channels and a part was directed upstream, *i.e.*, toward the «Claire Farine» farmhouse. This phenomenon explains the asymmetric shape of the crevasse splay, somewhat deformed towards the North, and the complexity of the flood hydrographical network and channelisation. Ultimately, the floodwaters took an E-W direction, before being guided by the general slope of the delta plain toward the SW. The subdivision of flood flows limited the extension of the crevasse splay. Unlike that of «Petit Argence», the hydrographical network of «Claire Farine» crevasse splay present a less organised hierarchical structure (*i.e.*, with only lower order channels) and most of crevasse

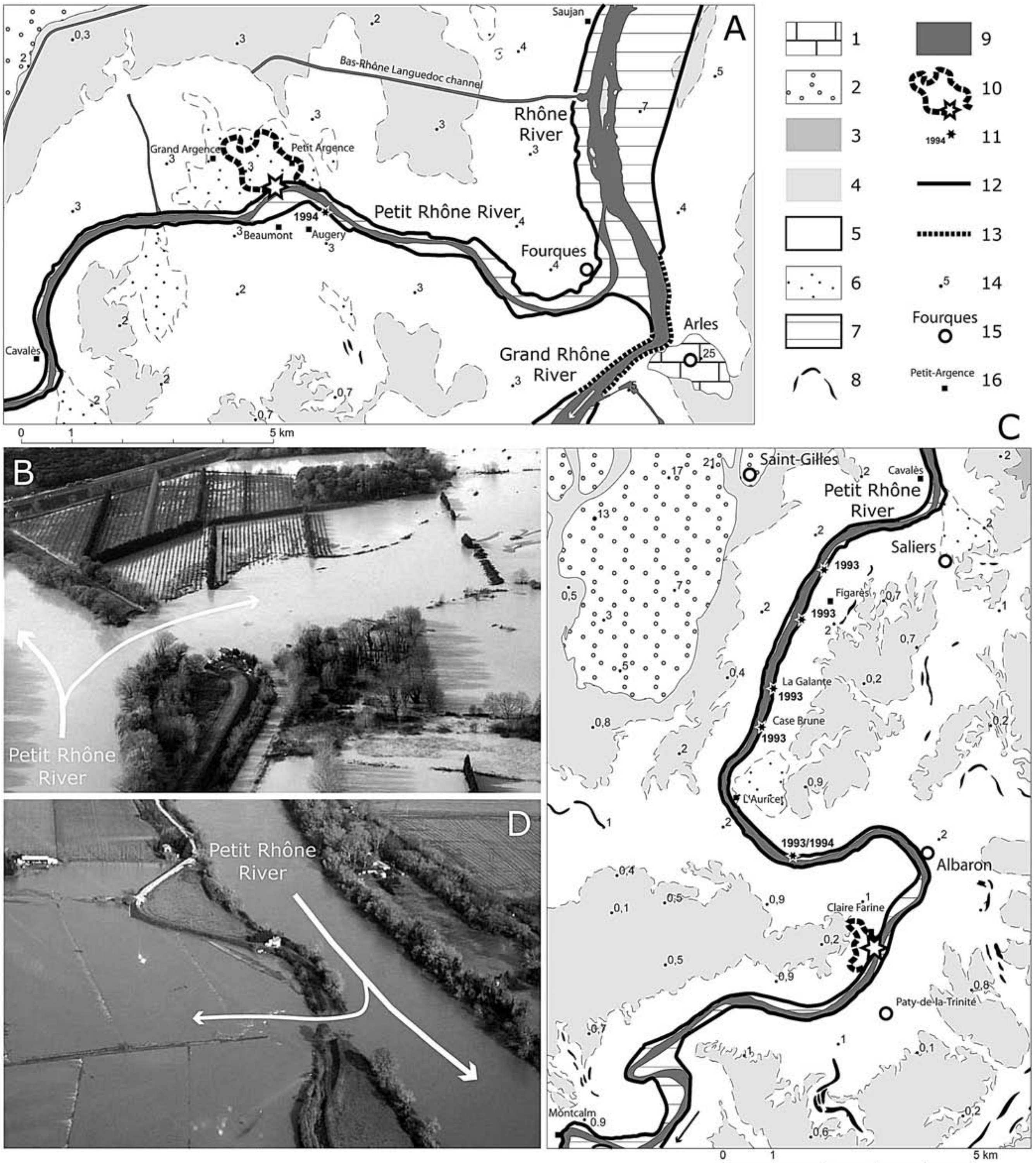


FIG. 3 - Both dyke breaches opened along Petit Rhône River during December 2003 flood event. A: Map of «Petit Argence» dyke breach. B: Photo of «Petit Argence» dyke breach (photo: Syndicat mixte de protection et de gestion de la Camargue gardoise, 03/12/05, 2:00 p.m.). C: Map of «Claire Farine» dyke breach. D: Photo of «Claire Farine» dyke breach (photo: Syndicat mixte de protection et de gestion de la Camargue gardoise, 03/12/05, 2:00 p.m.). 1: geological substrate (mesozoic limestones); 2: Pleistocene alluvial terrace; 3: proximal flood plain disconnected from present-day channel by dykes; 4: hydromorphous flood plain disconnected from present-day channel by dykes; 5: paludal flood plain disconnected from present-day channel by dykes; 6: ancient crevasse splay; 7: present-day flood plain; 8: fluviatile palaeochannel; 9: present-day channel or canal; 10: boundary of 2003 crevasse splay; 11: recent dyke breach; 12: dyke; 13: quays of Grand Rhône River at Arles; 14: altimetric point (in m NGF); 15: city; 16: *mas* (farmhouse).

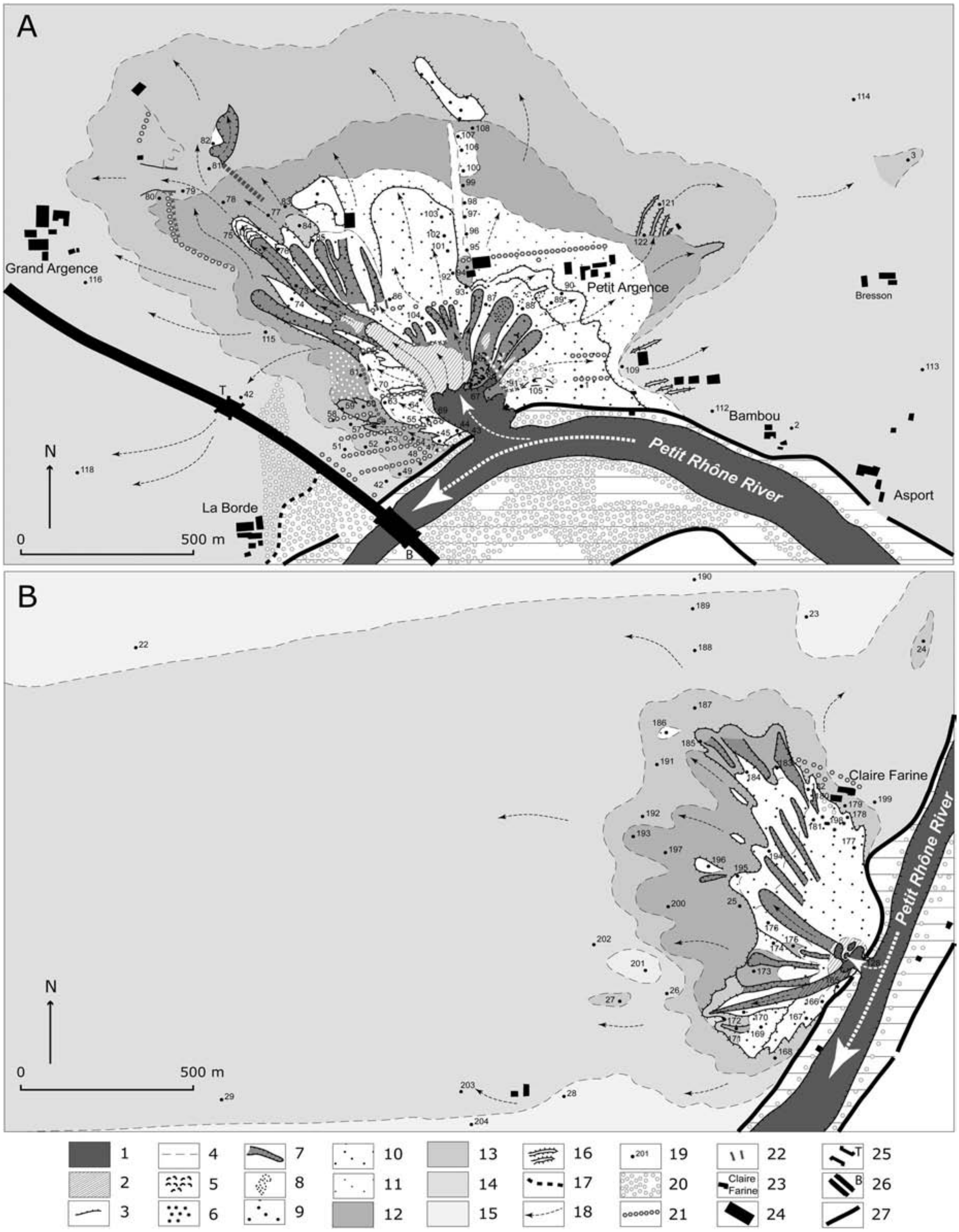


FIG. 4 - High-resolution maps of December 2003 crevasse splays on right bank of Petit Rhône River in western part of the Rhône Delta. A: Crevasse splay of «Petit Argence». B: Crevasse splay of «Claire Farine». 1: Petit Rhône channel and head of main crevasse channel; 2: flood-plain stripping; 3: scarp; 4: gradual boundary; 5: imbricated peat blocks; 6: fluviatile shells (*Corbicula fluminea*) deposited upstream of breach axis; 7: crevasse channel; 8: scour depression; 9: crevasse-splay lobe (coarse to medium sand and gravel near dyke breach; «Area 1»); 10: crevasse-splay lobe (medium to fine sand; «Area 2»); 11: crevasse-splay lobe (fine to very fine sand; «Area 3»); 12: crevasse-splay lobe (silty sand; «Area 4»); 13: proximal flood basin (sandy silt); 14: distal flood basin (coarse silt); 15: distal flood basin (fine silt); 16: isolated hydraulic dune; 17: flooding-area boundary; 18: direction of flood flows; 19: sample number; 20: riparian forest and grove; 21: hedge (cypress, poplar); 22: hedge breached by flood flows; 23: permanent settlement (*mas*) and outbuilding; 24: raised road; 25: tunnel; 26: bridge; 27: Rhône dyke.

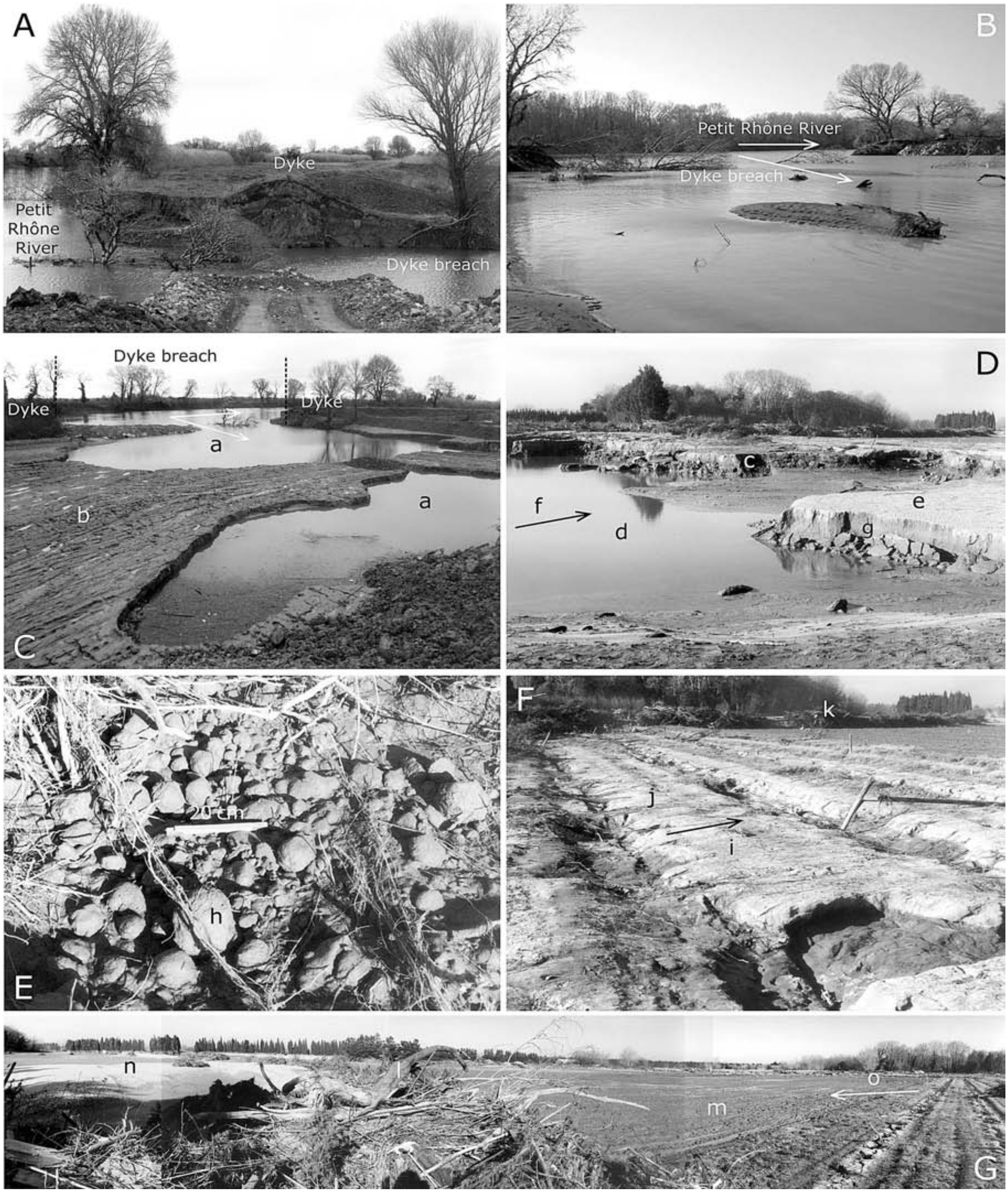


FIG. 5 - Hydromorphological impacts of crevasse splays developed on right bank of Petit Rhône River during December 2003 flood (part 1). A: Breach (width: 51 m) opened through dyke built between 1895 and 1897 along right bank of Petit Rhône River in «Claire Farine». In foreground, the upstream part of dyke breach is partially infilled by blocks of blast-furnace slag coming from Fos-sur-Mer. B: Erosion and enlargement of crevasse channel (width: 186 m; depth: 8-9 m) from dyke breach (width: 82 m) of Petit Rhône River in «Petit Argence». C: Erosion zone near dyke breach of Petit Rhône River in «Claire Farine»: (a) coalescent scour depressions (depth: 8-9 m) connected to Petit Rhône channel, and (b) flood-plain stripping (30-40 cm) that affected plowed part of the cultivated soil. D: Sinuous scarp (visible height: 1.5 m; c) separating to left (d) the erosion zone (scour depression of 8-9-m deep) connected to Petit Rhône channel (site of «Petit Argence») and to right (e) the stripped zone in axis of main crevasse channel whose flow direction is shown by arrow (f). The high degree of roundness of some collapsed blocks (g) reflects their fall while channel was still at high-water level (during or after flood). E: Mega-mudballs (maximum diameter: 10 cm; h) formed by rolling of blocks eroded from scarp (c) and then accumulated in furrows of ancient orchard (destroyed by flood). F: Flood-plain stripping (i) in the axis of the main crevasse channel where flow direction is shown by arrow (j). The orchard was destroyed by flood and fruit trees (k) accumulated along crevasse channel as log jams. G: Panoramic view of main crevasse channel in «Petit Argence». In the axis of photo, accumulation of wood debris (log jams; l) separating to right the main crevasse channel dominated by erosion processes (stripping; m) and to left a sandy, lateral bar (n). Flow direction shown by arrow (o). Photos A, C, D, E, F, G: G. Arnaud-Fassetta (03/12/26); photo B: Syndicat mixte de protection et de gestion de la Camargue gardoise.

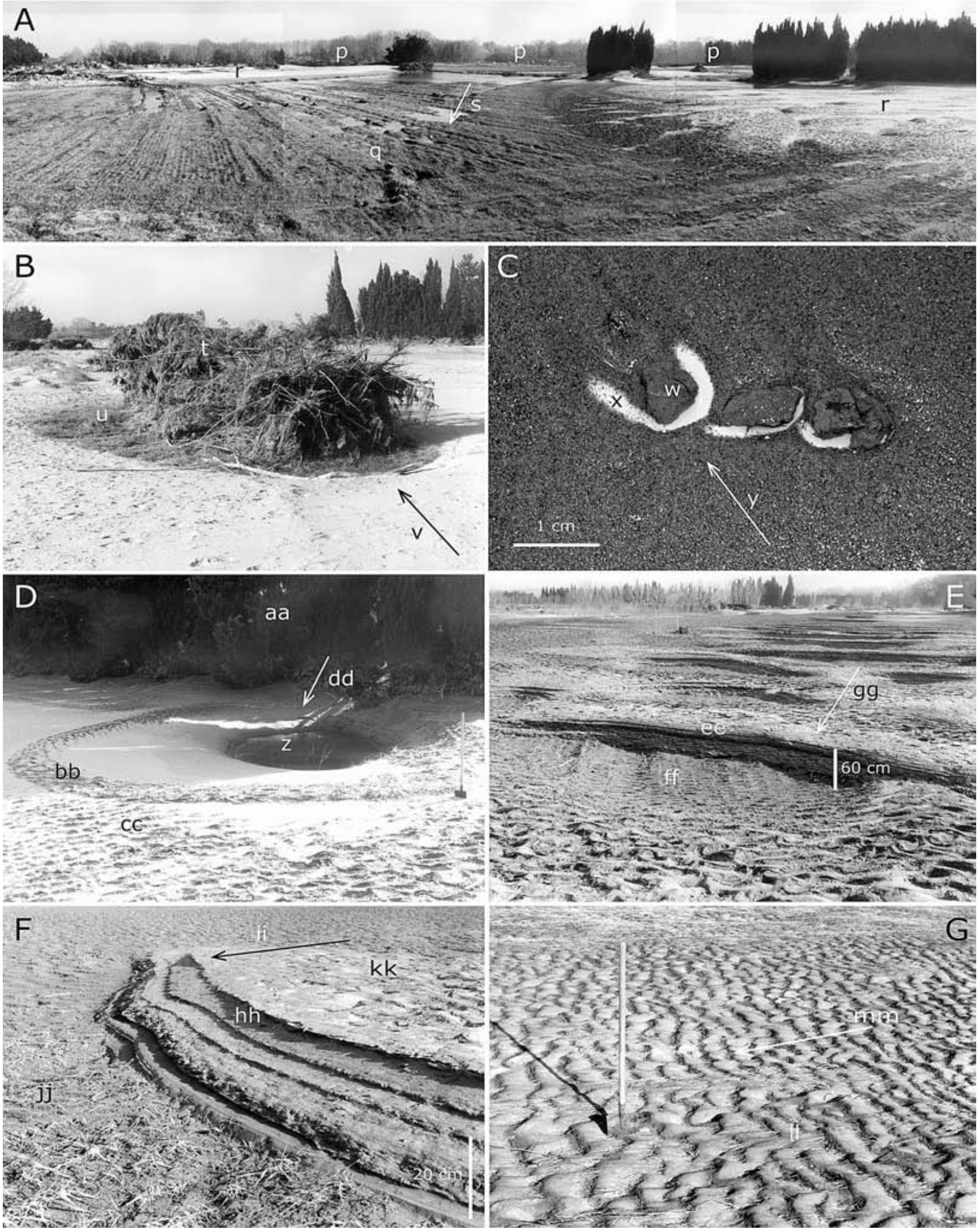


FIG. 6 - Hydromorphological impacts of crevasse splays developed on right bank of Petit Rhône River during December 2003 flood (part 2). A: Panoramic view of main crevasse channel in «Petit Argence» downstream of fig. 5G. Breakthrough of cypress hedge (p) by flood currents of main crevasse channel. Note absence of alluvium (q) in channel axis (strong currents) and sand accumulations on its margins (lateral bar; r). Flow direction shown by arrow (s). B: Effect of obstacle (wood debris) on sedimentation process in main crevasse channel in «Petit Argence». Flood currents were disturbed in contact with tree (snatched from a hedge upstream; t), and no sedimentation (u) occurred all around wood debris. Flow direction shown by arrow (v). C: Simulation in lab of «obstacle effect» described in fig. 6B. Water flow swirls around debris (here a mudball; w), creating a lack of sandy sedimentation around (x). Flow direction shown by arrow (y). D: Detail view of a scour depression (length: 10 m; width: 8 m; depth: 1.2 m; z) downstream of a cypress hedge (aa) situated at margin (left bank) of main crevasse channel of «Petit Argence». Note asymmetry (bb) of ridge bordering scour depression, and linguoid ripples marks (lower flow regime; cc). Flow direction shown by arrow (dd). E: Transverse hydraulic-dunes system (ee) alternating with scour depressions (ff) developed in axis of main crevasse channel of «Petit Argence» before its outlet in silty-sand area (Area 3) of crevasse-splay lobe. Wavelength is approximately 3-4 m and amplitude is 30-50 cm. Lower flow regime (sub-aquaeous dunes, between 2-D sand waves with straight crests and 3-D dunes with sinuous crests and troughs). Flow direction shown by arrow (gg). F: Detailed view of transverse hydraulic dune (hh) developed in axis of main crevasse channel of «Petit Argence» before its outlet in «Area 3» of crevasse-splay lobe. Amplitude is approximately 50 cm. Lower flow regime (tabular cross-stratification regime, plane beds formed by migrating 2-D dunes). Flow direction shown by arrow (ii). Note pre-flood topography (Area 3 of CSL; jj) and linguoid ripple marks (lower flow regime; kk) at top of the dune. G: Transverse asymmetrical, linguoid current ripples (lower flow regime; ll) in silty-sand area (Area 3) of crevasse-splay lobe («Petit Argence»). Wavelength is approximately 10-20 cm and amplitude is 3-6 cm. Flow direction shown by arrow (mm). Photos: G. Arnaud-Fassetta (03/12/26).

channels develop directly from the dyke break. As of the 28 December 2003, the dyke had still not repaired but simply confined within a perimeter of 50-100 m by an artificial levee (bund) several metres high. Depressions and ditches had been dug in and outside the river bund in order to lower the water table and make the floodwaters more easily reattached to the Petit Rhône River. The total cost of repairing the «Claire Farine» dyke breach is estimated at 2.5 million Euros.

From Sylvéréal (fig. 1C), the Petit Rhône River in some places (*e.g.*, «Grande Abbaye mas») exceeded the top of the dykes and flooded the delta plain by overtopping. Beyond the dykes and more distant overflow areas, the floodwaters deposited fine sediment. An increase of both the grain size and sedimentation rate was observed on delta margins, due to lateral inputs by gullying of the Costières slopes, or upstream of the transverse structures such as perched irrigation channels and road embankments.

Crevasse-splay sub-environments and facies: description, geometry and distribution

The crevasse-splay sub-environments described below are what Hasselink & *alii* (2003, p. 242) called «dyke-breach deposits», *i.e.* «*deposits formed adjacent to and outside of the margin of the embanked floodplain. These deposits have a lobate to elongated shape, conforming to the geometry of stage 1 crevasse-splay deposits described by Smith & alii (1989)*». Analysis of the resulting data indicates that both active crevasse splays are composed of several sub-environments such as crevasse channels, crevasse-splay lobes, and proximal and distal flood basins. Each crevasse-splay sub-environment exhibited a distinctive suite of sedimentary facies.

Crevasse channels. (i) *Main crevasse channels* (MCCs) develop from a dyke breach. In «Claire Farine», the MCC is 100-m wide for a dyke-breach width of 51 m (fig. 5A), and its length does not exceed 500-600 m (fig. 4B). In «Petit Argence», the MCC is wider (186 m) immediately near the dyke breach (82-m wide; fig. 5B) and extends over 1 km in length (fig. 4A). Four zones can be distinguished in the MCCs: the «scour zone», the «stripped zone», the «no deposit/no erosion zone», and the «deposition zone». In the «scour zone» located near the dyke breach, the channel entrenched the Holocene sediments of the fluvial-deltaic plain to a depth of 8-to-9 m (*i.e.*, equivalent to the channel depth of the Petit Rhône River in this section; fig. 4, 5A to 5D). The bedload (gravel and cobbles up to 15 cm diameter) released on the MCC margins downstream of the dyke breach. Flow velocity, bed shear stress and specific stream power exceeded the critical values estimated to 1.75 m/s, 9 N/m^2, and 10 W/m^2, respectively (fig. 11). Beyond the scour zone lies the «stripped zone» (etching of 30- to 40-cm thick; fig. 4, 5F). A scarp (apparent height: 1 m) denotes the contact between the two (fig. 5D). Between 0 and 200 m («Claire Farine») and between 100 and 600 m («Petit Argence») from the axis of the dyke breach (fig. 4), the stripped zone is characterised by mega-mudballs (maximum diameter: 10 cm; fig. 5E). Beyond this zone, the MCC probably records a loss of energy since scouring and evidence of erosion are not observed. Thus, the channel floor is the ante-flood topographic surface, as has been observed in «Petit Argence». The channel is bound by sand bars and/or wood debris corresponding to uprooting of both the riparian forest and hedgerows of trees (cypress and orchards; fig. 5G, 6A). Finally, the MCC accumulated sediment beyond 600-700 m from the dyke breach (fig. 6B, 6C). Mean thickness of MCC sediment is 127 cm, varying from 400 to 6 cm (fig. 9B, 9C). In general, its deposition occurred at a water depth ranging between 194 and 50 cm (mean: 128 cm). In the MCC («Petit Argence»), mean flow velocity was between 1.3 and 1.8 m/s, the specific power exceeding 6 W/m^2, and the bed shear stress greater than 3.5 N/m^2 at 138 m from the dyke (fig. 11). On average, the MCC deposits (n = 6) are composed of 79% of medium-coarse (< 1 mm) sand, with minimum and maximum values of 36-95%. They are well to poorly sorted [$0.48 < \sigma_I$ (mean value: 0.67, moderately well sorted) < 1.16] and enriched in fine grain fractions [$0.02 < Sk_I$ (mean value: 0.21, fine skewed) < 0.47], particularly in fine to very fine sand and silt (fig. 9A). Mean grain size (fig. 9B) is 0.373 mm (0.190 mm < M_z < 0.470 mm), with coarsest 1-percentile (fig. 9C) ranging from 0.512 mm to 24.5 mm. Sediment is transported by mixed rolling and saltation processes (high-energy MCC), and/or graded suspension or high-energy uniform suspension (low-energy MCC; fig. 10A). A downstream grain-size fining is observed with the decrease of M_z: 0.470 mm at 149 m (sand bar), 0.388 mm at 194 m (sand bar), 0.380 mm at 692 m (sand sheet), and 0.304 at 914 m (sand dune). Sediment structure is characterised by upper plane beds (near the dyke breach) or 3-D dunes/2-D sand waves (600-900 m from the dyke breach; fig. 6E, 6F), revealing a transition between upper flow regime (lower-upper) and lower flow regime (upper-lower/lower). (ii) *Secondary crevasse channels* (SCCs) correspond to channelisation of flood flows on sandy prograding/aggrading lobes. At least 12 SCCs (length: 200-1300 m) were identified in «Claire Farine», and 16 SCCs (length: 200-900 m) in «Petit Argence» (fig. 4). They are directly connected to the MCC («Petit Argence») or to the dyke breach («Claire Farine»). Scoured in sand sheets, their width is about 20 m for a bankfull depth of 1.5 m (fig. 7G).

Crevasse-splay lobes (CSLs). Most of sediments (n = 91) are composed of coarse-medium (48% of sediment) to fine-very fine (42%) sand or thixotropic silty sand. Mean sediment thickness is 84 cm and ranges from 300 to 7 cm (fig. 9B, 9C). Mean grain size is 0.469 mm (0.084 mm < M_z < 20.638 mm; fig. 9B), with coarsest 1-percentile varying from 0.305 mm to 49.365 mm (fig. 9C). Sediment is well to very poorly sorted [$0.44 < \sigma_I$ (mean value: 0.86, moderately sorted) < 2.03] and enriched in fine grain fractions [$-0.02 < Sk_I$ (mean value: 0.21, fine skewed) < 0.58], particularly fine to very fine sand and silt (fig. 9A). Sediment is transported by mixed rolling and saltation processes (high-energy CSL), and release from graded suspension or high-energy uniform suspension (low-energy CSL; fig. 10A). Many shells (*Corbicula fluminea*) were found upstream of the both dyke breaches (fig. 4, 7C). CSL deposits are characterised by a upstream/downstream contrast: downstream from the dyke breach, some deposits

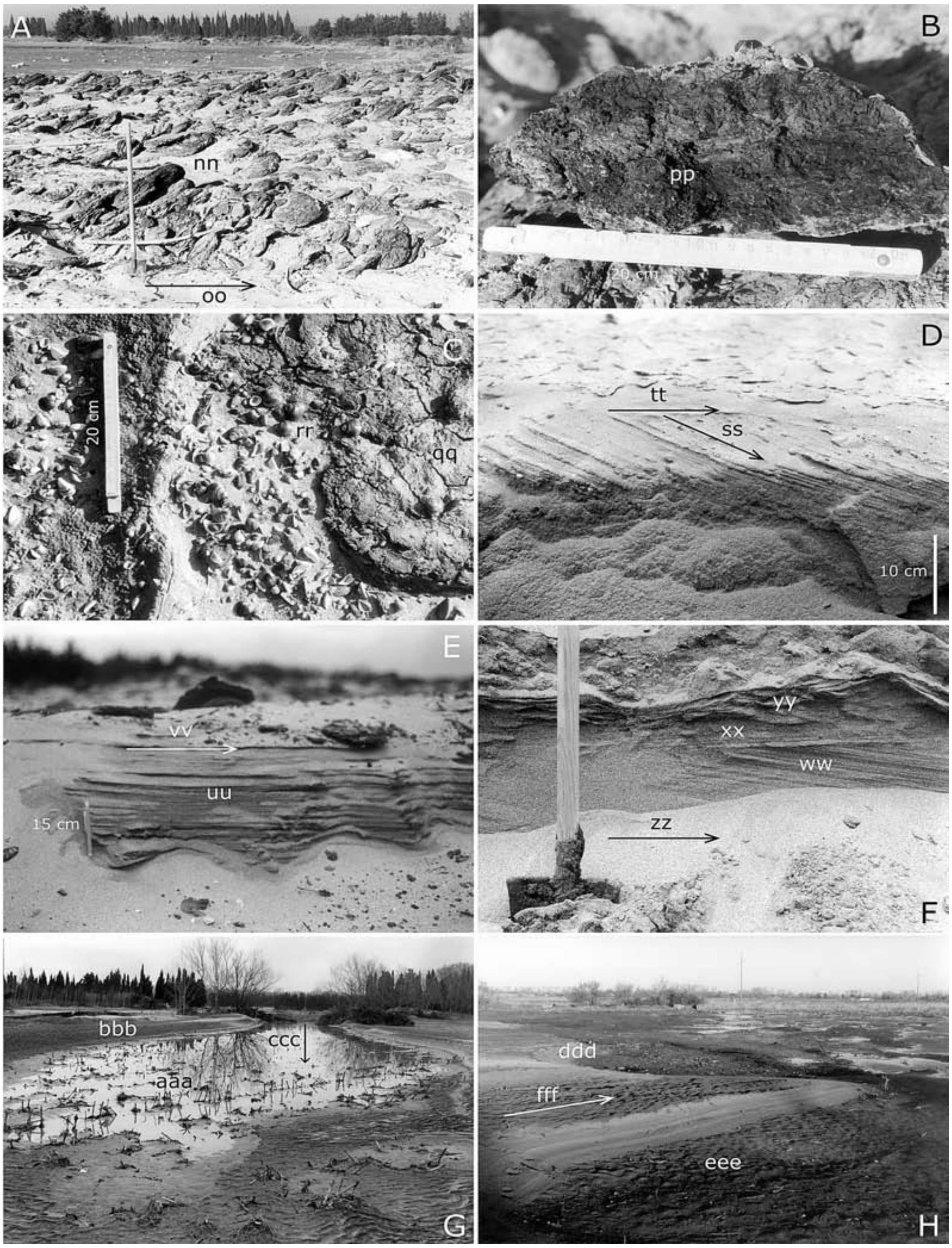


FIG. 7 - Hydromorphological impacts of crevasse splays developed on right bank of Petit Rhône River during December 2003 flood (part 3). A: Imbrication of decimetric-to-metric peat blocks (nn) forming crevasse-splay lobe («Area 1») in «Petit Argence». Current from left (SE) to right (NW; oo). This «old» peat (palaeoswamp) was reworked by floodwaters from scour depression (d) near dyke breach. It was observed «*in situ*» in channel floor of Petit Rhône River during 1999 scuba-diving campaigns (Quisserne, 2000; Arnaud-Fassetta & *alii*, 2003). Kruit (1955) also pointed this peat deposit at 4-m depth from both sides of the Petit Rhône channel. B: Detailed view of «old»-peat block (pp) of type in fig. 7A. C: Detailed view of crevasse-splay lobe («Area 1») in «Petit Argence». Peat block (qq) with matrix composed of sand and abundant fluviatile-channel shells (particularly *Corbicula fluminea*; rr). Only observed in upstream part (relative to axis of breach) of crevasse-splay lobes, these shells reflect action of low-energy reverse currents at end of flood event. D: Exposed sandy crevasse-splay lobe («Area 1») in «Petit Argence» showing moderately dipping foresets (ss) of planar cross-bedding. Flow direction shown by arrow (tt). E: Crevasse-splay lobe («Area 1») of «Petit Argence». Planar stratification produced from upper flow regime (lower-upper), sandy planebeds (uu). Flow direction shown by arrow (vv). F: Exposed crevasse-splay lobe («Area 1») in «Petit Argence» showing gently dipping foresets (ww) of dune (3-D) followed by (xx) sand waves (2-D) with flat (parallel) bedding and (yy) ripples with cross-laminations. It is characteristic display of transition from upper-lower flow regime to lower-lower regime (Singh & *alii*, 2007). Area shown is 80-cm wide and 40-cm height. Flow direction shown by arrow (zz). G: One of numerous secondary crevasse channels (bankfull width: 20 m; bankfull depth: 1.5 m) prolonging main crevasse channel (here immediately north of D179 road) in «Petit Argence». The secondary crevasse channel (aaa) is delimited by sandy levees (bbb) and flow direction shown by arrow (ccc). H: Site of «Claire Farine». Sandy dunes (2-D sand waves) with sinuous front (ddd) dominating area (Area 3) of crevasse-splay lobe characterised by current ripples (eee). Flow direction shown by arrow (fff). Photos: G. Arnaud-Fassetta (A, B, C, D, E, F, G: 03/12/26; H: 03/12/28).

are thinner and located at a greater distance from the crevasse (fig. 8A, 8B), while in the upstream area others are composed by a lower percentage of fine and very fine sand (fig. 8A). Sediment grain size depends on both the distance from the dyke breach and crevasse channels. Distribution of sediment grain size is arranged in areas as concentric half-rings around a point of origin constituted by the dyke breach. In «Petit Argence», the coarse to medium sand area («Area 1») extends up to 790 m, the medium to fine sand area («Area 2») up to 930 m, the fine to very fine sand area («Area 3») up to 1220 m, and the silty sand area («Area 4») up to 1570 m (fig. 4A). In «Claire Farine», «Areas 1 and 2» extend up to 720 m, «Area 3» to 860 m, and «Area 4» to 1000 m (fig. 4A). In «Areas 1 and 2», sediment structures are characterised by upper plane beds (fig. 7E), 3-D dunes (fig. 7F), 2-D sand waves with planar cross bedding, and current ripples with cross laminations (fig. 7F). They reveal a flow regime that varies from upper flow regime (lower-upper) to lower flow regime (upper-lower/lower/lower-lower). We also observed imbricated peat blocks that the largest ones measure 1.1 m in diameter and 30 cm in thickness (fig. 7A, 7B). The estimated mean flow velocity indicates values between 1.3 and 1.8 m/s for the CSLs closest to the dyke breach, and between 0.5 and 1.3 m/s for the more distal ones. The values of bed shear stress and specific stream power were greater than 3 W/m^2 and 0.8 N/m^2, respectively (fig. 11). The contact between «Areas 2 and 3» is abrupt, marked by a sinuous scarp of 10-50 cm of height (fig. 4, 7H). In «Area 3», sediment structures typically exhibit transverse asymmetrical, linguoid, small current ripples, indicating a lower flow regime (lower-lower). The mean flow velocity is between 0.5 and 0.9 m/s, while the specific stream power records a significant decline, with values between 0.1 and

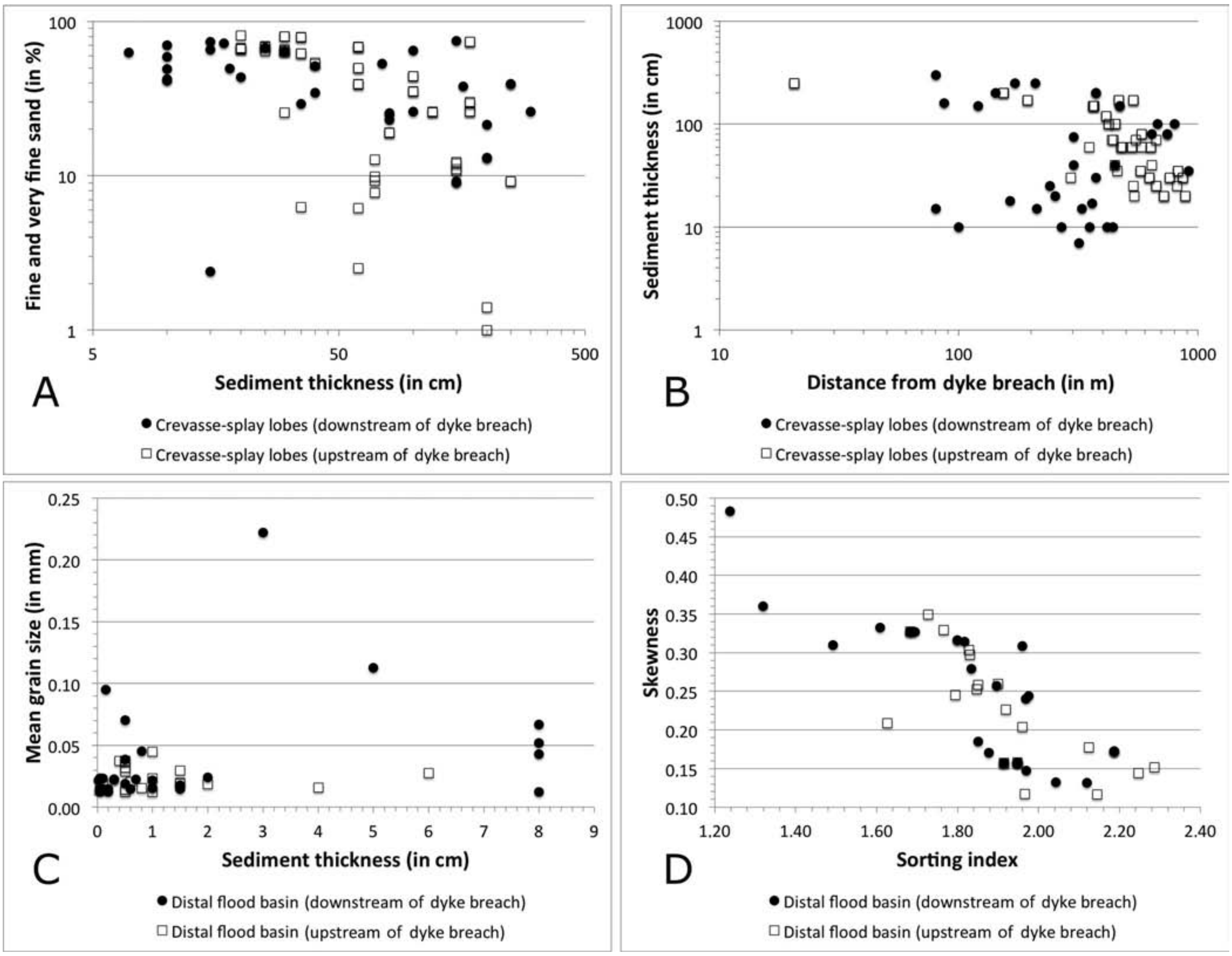


FIG. 8 - Sedimentological characteristics of crevasse-splay sub-environments (part 1). A: Regression analyses of sediment thickness *vs*. fine and very fine sand in crevasse-splay lobes downstream and upstream of dyke breach. B: Regression analyses of sediment thickness of crevasse-splay lobes (downstream and upstream) *vs*. distance as crow flies from dyke breach. C: Regression analyses of sediment thickness *vs*. mean grain size in distal flood basin downstream and upstream of dyke breach. D: Regression analyses of sorting index *vs*. skewness in distal flood basin downstream and upstream of dyke breach.

0.7 W/m^2 (fig. 11). The outer boundaries of «Areas 3 and 4» are gradual. Isolated hydraulic dunes (sediment thickness: 50 cm; M_z: 0.282 mm; σ_I: 0.70, moderately well sorted; Sk_I: 0.28, fine skewed; fig. 9) prolong «Area 3» in the axis of MCCs and SCCS (fig. 4). These features trend along the direction of water flows and therefore are a good indicator of current direction.

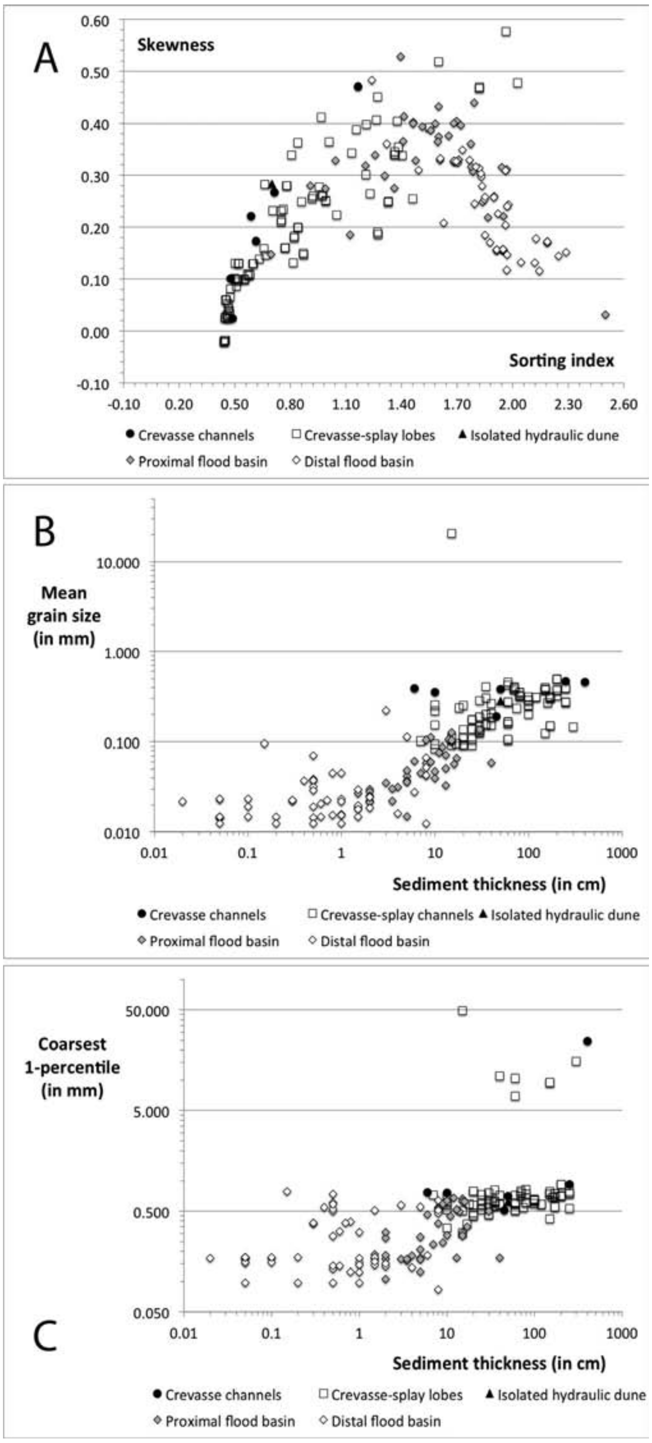


FIG. 9 - Sedimentological characteristics of crevasse-splay sub-environments (part 2). A: Regression analyses of sorting index *vs*. skewness. B: Regression analyses of sediment thickness *vs*. mean grain size. C: Regression analyses of sediment thickness *vs*. coarsest 1-percentile.

Proximal flood basin (PFB). The PFB sediment (n = 38) is characteristic of «ordinary» proximal flood-plain deposits (Arnaud-Fassetta, 1996), as they could have deposited only a few dozen metres from the riverbank if the crevasse splays had not formed. But crevasse splays tend to release such sediment between 360 to 1570 m from the riverbank. The contact between the CSLs and PFB deposits is gradual. The sediment is composed of fine to very fine sand (45 %) and silt (45 %), moderately to very poorly sorted [$0.70 < \sigma_I$ (mean value: 1.55, poorly sorted) < 2.50], and is highly enriched in fine grains [$0.03 < Sk_I$ (mean value: 0.33, very fine skewed) < 0.53], particularly in silt and clay (fig. 9A). Mean sediment thickness is 10 cm, ranging from 40 to 1.5 cm (fig. 9B, 9C). Mean grain size is 0.058 mm (0.015 mm $< M_z <$ 0.136 mm; fig. 9B), with coarsest 1-percentile varying from 0.106 mm to 0.675 mm (fig. 9C). Most sediment is transported by uniform-suspension process (fig. 10A). Sediment structure is characterised by rare, very small current ripples (wavelength: 2 cm; amplitude: 0.5 cm), but in most cases the sediment is just finely laminated (centimetric to millimetric laminae), indicating decantation of suspended load.

Distal flood basin (DFB). The DFB sediments (n = 54) are characteristic of «ordinary» distal flood-plain deposits (Arnaud-Fassetta, 1996). These are found from 700 m («Petit Argence») and 500 m («Claire Farine») up to 20 km from the dyke breach. Some sediment deposited downstream of the dyke breach are coarser and thicker; they are also better sorted and comprise larger fractions of fine particles (fig. 8C, 8D). They are composed of silt (61 %), fine to very fine sand (22 %) and clay (13 %), poorly to very poorly sorted [$1.24 < \sigma_I$ (mean value: 1.89, poorly sorted) < 2.29] and enriched in fine grains [$0.12 < Sk_I$ (mean value: 0.23, fine skewed) < 0.48], particularly in fine silt and clay (fig. 9A). Mean sediment thickness is 1 cm, with a range from 8 to 0.02 cm (fig. 9B, 9C). Mean grain size is 0.031 mm (0.012 mm $< M_z <$ 0.222 mm; fig. 9B), with coarsest 1-percentile varying from 0.083 mm to 0.784 mm (fig. 9C). Most of sediment is transported by uniform-suspension process (fig. 10A). Sediment structures are characterised by planar, fine-laminated bedding (millimetric laminae), indicating a decantation of suspended load.

Quantification of sediment balance

The flood extension is related to crossing of breached dykes by the Rhône waters in December 2003; the total flooded area was 429.117 ± 21.456 km^2. On the left bank of the Rhône River, between Beaucaire-Tarascon and Arles, the flooded area beyond dykes and strictly linked to the Rhône flood waters of 2003 was estimated at 21.753 ± 1.088 km^2. Sediment volume (25,040 ± 1,252 m^3) represents only 3 % of the total volume deposited in the floodplain outside dykes (tab. 1). The eroded volume is low (200 m^3). Both in the northern and western parts of the delta, two major breaches were opened in dykes on the

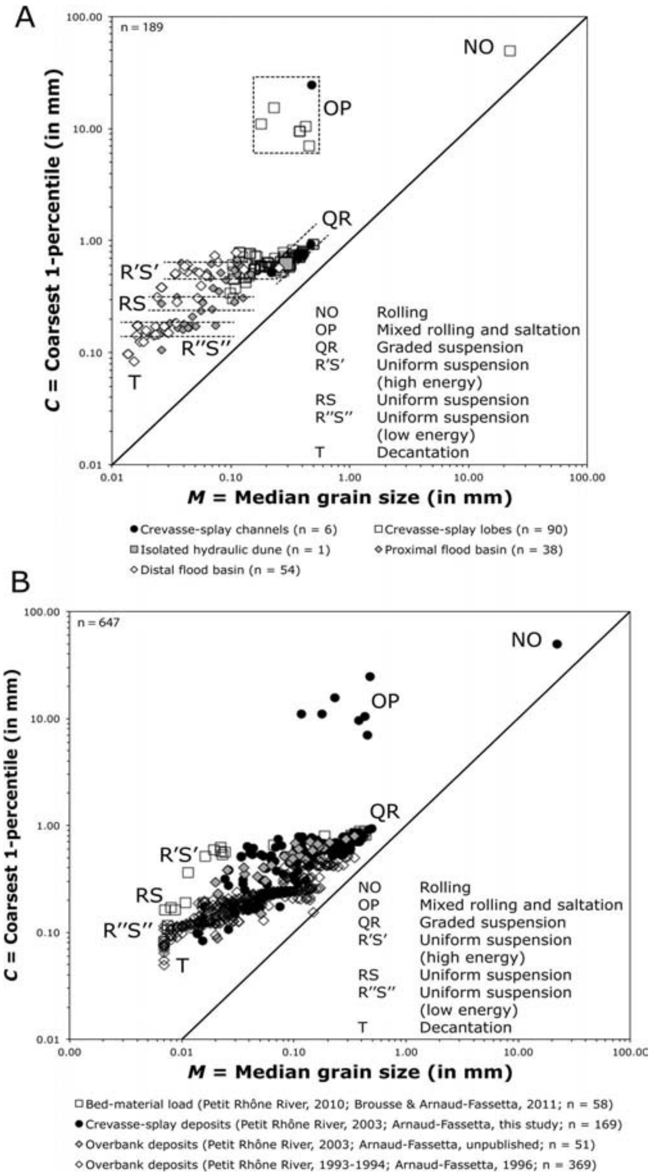


FIG. 10 - CM patterns of December 2003 crevasse-splay sub-environments (A) compared with bed-material load and overbank deposits of Petit Rhône River (B).

right bank of the Petit Rhône River, leading to the formation of crevasse splays and flooding of 414 ± 21 km^2. In the sector of «Petit Argence», the sediment volume was estimated at 469,535 ± 23,477 m^3 (sand ~ 81%), for an eroded volume of 113,804 ± 5,690 m^3: the sediment budget is very in surplus (355,731 ± 17,786 m^3). In the sector of «Claire Farine», deposition is lower than in «Petit Argence», and the sediment budget is also in surplus. Downstream of Sylvéréal, sediments accumulated in the sectors not directly influenced by crevasse splays represent a volume of 155,547 ± 7,777 m^3 (silt ~ 63%). Finally, the Rhône waters have deposited 810,429 ± 40,522 m^3 (sand ~ 67%) of sediment outside the dykes both in the flood plain downstream of Beaucaire-Tarascon and the delta plain. The sediment balance is estimated at 674,227 ± 33,711 m^3, taking into account the eroded areas that represent a volume of 136,202 ± 6,810 m^3.

DISCUSSION AND CONCLUDING REMARKS

«Crevasse-splay» phenomenon

Crevasse splays are phenomena that accompanied the last greatest flood events in the Rhône Delta, particularly along the Petit Rhône River, despite the fact that the channel has been embanked since the second part of the 19th century. In October 1993 (from 8 to 9), twelve dyke breaches were opened including that at Figarès, the largest one (width: 40-50 m; discharge: 80 m^3/s), in addition to those at Case Brune, La Galante, and L'Auricet. These quickly filled due to the lowering of water level in the Petit Rhône channel caused by the opening of the «Figarès» breach upstream (fig. 3A, 3C). In January 1994 (from 7 to 8), «only» four dyke breaches occurred, the most important at Beaumont (width: 20-30 m) and L'Auricet (width: 65-80 m; discharge: 100 m^3/s), and for the latter taking place in the same areas as in 1993. It took several days to fill and close the breaches, requiring costly human intervention. The shape of crevasse splays has varied from flood to flood and from one site to another, in relation to hydrography (hierarchical network), hydrology (flow regime), hydraulics (energy and direction of currents), flood-

TABLE 1 - Sediment balance in the delta plain derived from dyke crossing and dyke breaching by December 2003 flood in the Lower Rhône Valley downstream of Beaucaire-Tarascon. Co-Gr: cobbles and gravel; CS-MS: coarse to medium sand; FS-VFS: fine to very fine sand; Si: silt; Cl: clay. Margin of error up to 5%

Studied sites	**Accumulated sediment volume (in m³)**						**Eroded sediment volume (in m³)**	**Sediment balance (in m³)**
	Co-Gr	**CS-MS**	**FS-VFS**	**Si**	**Cl**	**Total**		
Arles	0	1,783	6,640	14,445	2,172	25,040 *3%*	-200	
Petit Argence	699	249,280	132,796	77,016	9,744	469,535 *58%*	-113,804	
Claire Farine	0	76,567	37,677	39,816	6,247	160,307 *20%*	-22,198	
Other sites	0	3,829	35,760	97,763	18,195	155,547 *19%*	0	
Total	699 *0.1%*	331,459 *41%*	212,873 *26%*	229,040 *28%*	36,358 *4%*	**810,429**	-136,202	**674,227**

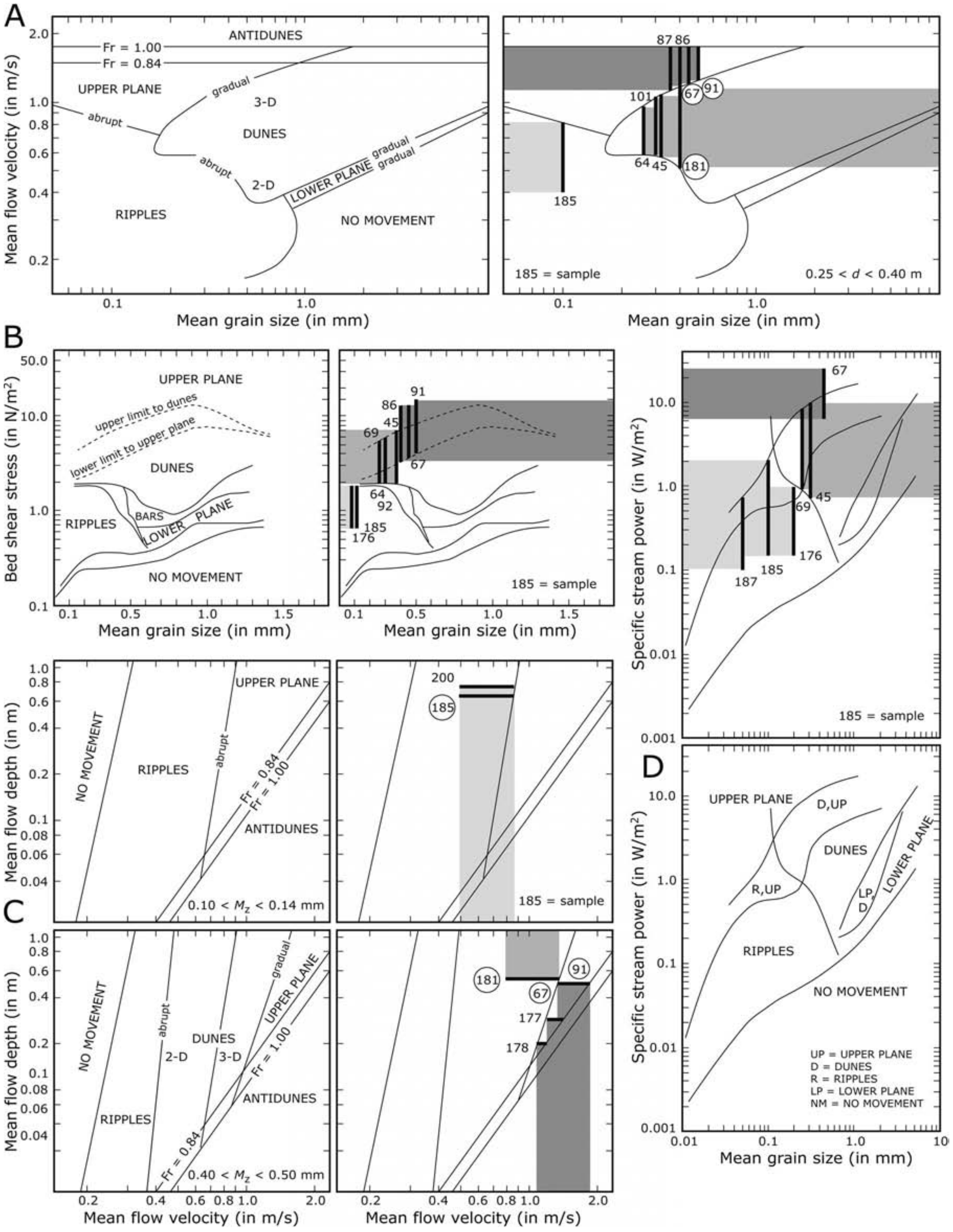


FIG. 11 - Estimation of mean flow velocity, bed shear stress, and specific stream power of flood waters on sites where crevasse splays occurred in December 2003 by plotting the sedimentary structures (modified after Harms & *alii*, 1982) with (A) mean grain size *vs*. mean flow velocity (Southard & Boguchwal, 1990), (B) mean grain size *vs*. bed shear stress (Leeder, 1982), (C) mean flow velocity *vs*. mean flow depth (Southard & Boguchwal, 1990), and (D) mean grain size *vs*. specific stream power (Allen, 1982). Distances from dyke breach: 138 m (S 67; MCC), 142 m (S 45; «Area 1» of CSL), 154 m (S 91; «Area 1» of CSL), 171 m (S 69; «Area 1» of CSL), 209 m (S 64; «Area 1» of CSL), 303 m (S 176; «Area 1» of CSL), 350 m (S 177; «Area 1» of CSL), 365 m (S 87; «Area 1» of CSL), 444 m (S 178; «Area 1» of CSL), 460 m (S 181; «Area 1» of CSL), 467 m (S 92; «Area 1» of CSL), 472 m (S 86; «Area 1» of CSL), 536 m (S 101; «Area 1» of CSL), 592 (S 200; «Area 3» of CSL), 819 m (S 185; «Area 3» of CSL), and 925 m (S 187; «Area 1» of CSL). S = sample; MCC: main crevasse channel; CSL: crevasse-splay lobe). Mean flow velocity, bed shear stress, and specific stream power values values were most likely higher between 0 and 154 m. The competence measured is 150 mm near the dyke breach, and 20.638 mm at 80 m from the dyke breach.

plain topography, sediment and human activity (land use and presence of structures). Anthropogenic forcing induces that entire crevasse splays are aborted before the «stage II» described by Smith & *alii* (1989). In this way, this study joins the conclusions reached by Hesselink & *alii* (2003), *i.e*, Smith's model cannot be fully applied to modern, embanked crevasse splays that abort at the end of «stage I». Therefore, further development of a dyke-breach splay does not occur because of dyke repair after the flood event. This distinguishes a dyke-breach splay from most natural crevasse splays that enlarge during subsequent floods (Cahoon & *alii*, 2011).

«Crevasse-splay» sub-environments and facies

This study serves to postulate an original «model» concerning the geometry and distribution of crevasse-splay sub-environments and facies. In the Rhône Delta, these topics were initially examined by Siché (1997) who reported identical observations to those presented here on the abundance of sand fraction, the considerable channel depths, and succession of hydromorphological processes/phenomena in space and time during flood events, dyke breaching, and crevassing. Our model provides a sedimentological reference database detailing the relationship between sediment thickness, grain size, and the distance from the dyke breach. Four main crevasse-splay sub-environments were identified (crevasse channels, crevasse-splay lobes, and proximal and distal flood basins). Several gradients were noted as to downstream thickness, fining and sorting of sediments, with two «thresholds» at 1150 m and 10,250 m from the dyke breach (fig. 12). From 0 to 1150 m from the dyke breach, sediment thickness ranges from 400 to 0.5 cm, with exclusive values greater than 10 cm (fig. 12A), mean grain size (M_z) varies from 20.638 (coarse pebbles) to 0.012 mm (fine silt), with exclusive values greater than 0.222 mm (fine sand; fig. 12B), and sorting indices (σ_{I}) from 0.44 (well sorted) to 2.50 (very poorly sorted), with exclusive values below 1.24 (poorly sorted; fig. 12C). From 1150 to 10,250 m from the dyke breach, sediment thickness varies from 8 to 0.02 cm (fig. 12A), M_z varies from 0.222 (fine sand) to 0.012 mm (fine silt; fig. 12B), and σ_{I} ranges from 1.24 (poorly sorted) to 2.29 (very poorly sorted; fig. 12C). Beyond 10,250 m from the dyke breach, sediment thickness is < 0.2 cm (fig. 12A), M_z is less than 0.095 mm (fig. 12B), and σ_{I} is less than 1.68 (poorly sorted; fig. 12C). Overall, the three distinct zones identified along the main crevasse channel [*i.e.*, «erosion zone» (scour zone, stripped area), «transfer zone» (no erosion/no deposit zone) and «deposition zone» (sheet sand, hydraulic dune)] complete the model proposed by Gomez & *alii* (1997) in the upper part of the Mississippi Valley. This discussion would be incomplete without pointing out the sedimentological interest (facies and sub-environments characterisation, downstream grain-size variations; fig. 12) of this work for the identification of palaeo-crevasse splays by the analogs method (Arnaud-Fassetta, 2000, 2007, 2009). In the Rhône Delta, similar crevasse-splay deposits were discovered at the sites of La Capelière, Le Carrelet and Ar-

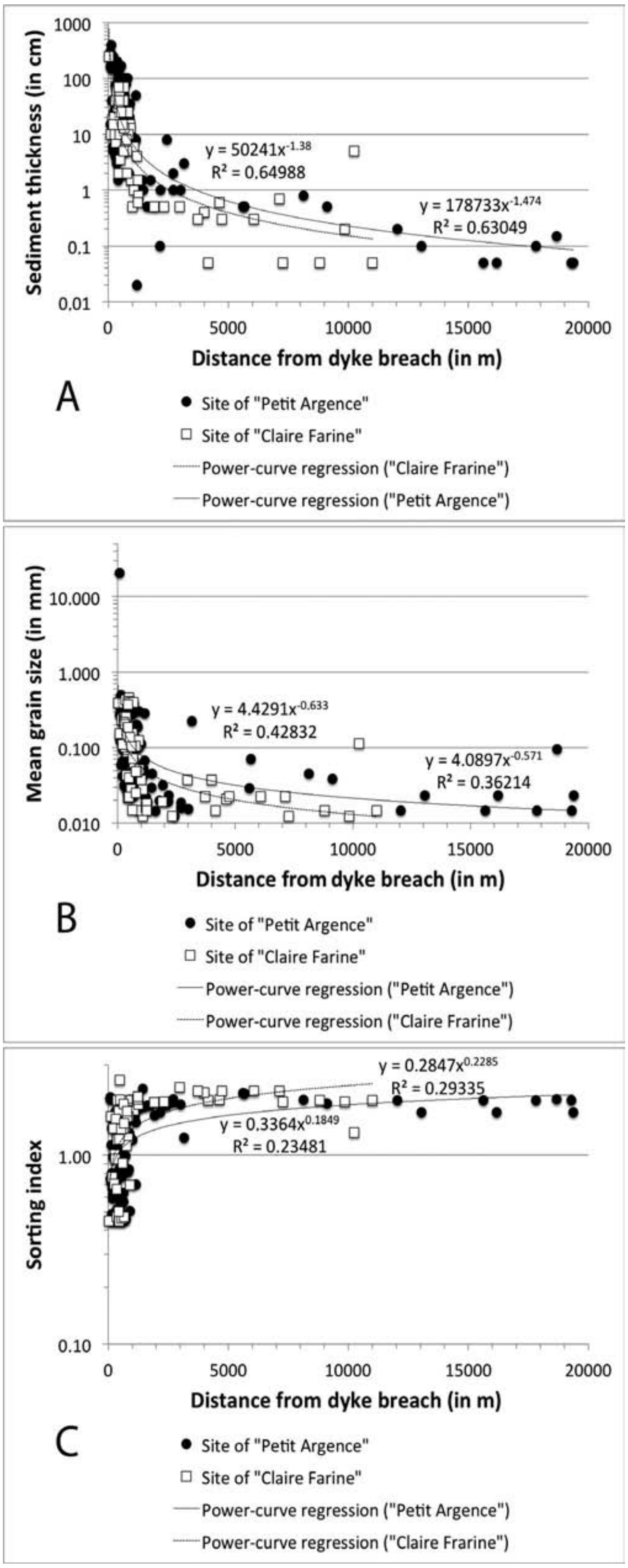


FIG. 12 - Sedimentological characteristics of crevasse-splay sub-environments (part 3). Regression analyses of sediment thickness (A), mean grain size (B), and sorting index (C) *vs*. distance from dyke breaches of «Petit Argence» and «Claire Farine».

les, and a secondary channel has been interpreted as an avulsion channel of the palaeo-Rhône of Saint-Ferréol at the site of Mornès (Arnaud-Fassetta & Landuré, 2003). Brown (1997, p. 75) also pointed out the importance of crevasse splays where deposits are easily identified because they incorporate bedload, including brick, tiles and mudballs into overbank deposits.

«Crevasse-splay» sediment volume and delta-plain sediment balance

The sediment volume derived from the 3-D quantification of December 2003 crevasse-splay deposits shows significant differences with the sedimentation of riverbanks and flood plain. Crevasse splays record more sand and a coarser load than in the flood plain. The textural disparity between crevasse-splay and other overbank sediments is shown in fig. 10B. The sand volume represents 67% (5% margin of error) of the total volume deposited by the December 2003 crevasse splays, *versus* only 48-49% of the total volume deposited both in riverbanks and flood plain (Arnaud-Fassetta, 1996). In the same manner, Siché (1997) also insisted on a predominance of sand fraction in the crevasse-splay deposits as compared to sediment deposited in the flood plain by overbank process (Arnaud-Fassetta, 1996). Therefore, crevasse-splay deposits prove to be as coarse, and coarser, than levee deposits with which they are associated. They also provide information on what the channel carries as bed-material load. In sum, crevasse-splay deposits are similar in grade to bedload and channel deposits, suggesting that the sand fraction is an important part of the sediment yield (fig. 10B; Arnaud-Fassetta & *alii*, 2003; Brousse & Arnaud-Fassetta, 2011). The proportion of channel sand may have been underestimated in quantifications proposed to date, and is one of the working hypotheses discussed by Antonelli (2002). In fact, much fluvial sand is trapped in the channel at the end of flood events without reaching the coast, at least in the Petit Rhône River, due to its transport as bedload and its possible deposition in the delta plain by crevasse splays. Consequently, this important loss of sand generates a sediment deficit in the main channel of the Petit Rhône River and at the river mouth. Therefore, a positive sediment balance of the delta plain has negative impacts on sand beaches of the deltaic fringe, which is characterised by a sediment deficit (Sabatier, 2001). The flood of December 2003 deposited 810,429 ± 40,522 m^3 of sediments in the delta plain, but 544,332 ± 27,217 m^3 of sand were lost along the deltaic coast on both sides of the Saintes-Maries-de-la-Mer.

In sum, floodwaters of December 2003 have deposited 810,429 ± 40,522 m^3 of sediment (~ 67% sand) outside the dykes in the Rhône floodplain downstream of Beaucaire-Tarascon and in the delta plain. The deposited sediment volume was very large and rapid, confirming the key role played by crevasse splays in the construction of fluvial-deltaic plains (Galloway & Hobday, 1996). The sediment balance is estimated at 674,227 ± 33,711 m^3, taking into account the eroded areas that represent a volume of 136,202 ± 6,810 m^3. These results converge with those obtained by Eyrolle & *alii* (2006) concerning the overall proportion of sand [~ 67% (this study) against 73% (Eyrolle & *alii*, 2006)] deposited in the delta plain during the 2003 flood event. However, they differ on the total amount of sediment deposited [810,429 ± 40,522 m^3 (this study) against 700,000 t (Eyrolle & *alii*, 2006)]. The underestimation of sediment balance can be explained by different methods of hydrogeomorphological mapping, sampling and thickness measurements. In addition, the quantification of the sand fraction (150,000 m^3 in Figarès, 73,000 m^3 in L'Auricet; Siché, 1997) deposited in the flood plain of the Petit Rhône River in 1993-1994 has been substancially underestimated because calculations were carried out taking into account only 45 ha and 17 ha, respectively. Finally, the sediment balance of December 2003 crevasse splays in the Petit Rhône River can be compared with that obtained in the Grand Rhône River (85-90% of total discharge in the delta). Concerning the estimation of sediment fluxes in the channel, the flood of December 2003 in the Grand Rhône River in Arles provided 5.4 Mt of sediment (suspended load) from 1 to 7 December, including 16% of sand transported as suspension (850,000 t) or suspension and bedload (1.1 Mt; Antonelli & *alii* (2008). Maillet & *alii* (2006) estimated at 4 Mt (sand: 1.2 Mt) the mass of sediment deposited between 0 and 20 m at the Grand Rhône mouth during the December 2003 flood event.

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