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Reconstruction of paleostorm events in a coastal lagoon (Hérault, South of France)

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ABSTRACT

Finding records of past catastrophic storm events is essential to evaluate the long term climatic evolution in a given coastal area. This question has been addressed by the study of sediment cores sampled in a small coastal lagoon of the French Mediterranean coast (Pierre Blanche lagoon). Two cores were studied in detail and revealed the presence of three main storm events.
The sedimentation rates calculated using the CFCS ^{210}Pb model, in agreement with ^{137}Cs data, are 3±0.4 and 4.2±0.7 mm y^{-1} near the border and in the center of the lagoon respectively. This suggests that the 0.6 m deep lagoon could be filled with sediments over the next 150 yr. Our study shows that storm events can be characterized in sedimentary sequences identified by facies, grain size and faunal assemblages (lagoonal and marine species). Comparison of ^{210}Pb, ^{14}C chronology and historical accounts suggest that the three identified storm events took place in 1742, 1839 and 1893 A.D. (i.e. about one catastrophic event per century).

1. Introduction

Storms are one of the most alarming natural hazard due to the recent concentration of resources and population in coastal areas (Pielke et al., 2005; Turner et al., 2006). In view of the last winter storm events having affected the south of France like in 1982 with 46 m/s wind (category 2 in Saffir–Simpson scale), this storm caused the death of 15 people and economic losses estimated at 400 million euros. It is necessary to examine the past decadal- to millennial-scale variability of storm activity in order to determine the frequency of the most extreme events in relation to the climate evolution (Goldenberg et al., 2001; Webster et al., 2005). General circulation models have been used to investigate the variations of the cyclonic activity in the Mediterranean region. Anagnostopoulou et al. (2006) clearly show a decrease of the frequency and an increase of intensity of the severe cyclones for the future (2071–2100). On the opposite, Lionello et al. (2002) do not show a large change in the regime of the cyclone in the same region in relation to the doubling of the CO2 atmospheric content. Both models, based on meteorological data, do not give the same conclusion. This is probably due to a calibration problem because of a lack of instrumental long time series.

In north-western part of the Mediterranean Sea instrumental records are only available since the last 20 yr for surge and waves (wave buoy in Sète) and 50 yr for wind speed and direction (meteorological station), we used sediment cores to record the past washover events. Recent studies of some lagoons worldwide have shown that this environment could be a good area to record past climate and environmental changes, like flood and storm events (Liu and Fearn, 1993; Goff et al., 2000; Liu and Fearn, 2000; Donnelly et al., 2001a,b; Scott et al., 2003; Andrade et al., 2004; Donnelly, 2005; Donnelly and Woodruff, 2007). But, despite the importance of this subject, this type of study is still scarce.

The Languedoc-Roussillon shoreline is characterized by many coastal wetlands that resulted from the interaction between a process of shore line regularization by migrations of littoral barriers and a slow filling of these areas by the rivers (Certain et al., 2004). Coastal wetlands of north-western of the Mediterranean Sea are mainly characterized by sedimentary system with a fairly high accumulation rate (Monna et al., 1995; Schmidt et al., 2007). This study focused on the wetland complex of the Aigues-Mortes gulf (central part of the Golfe du Lion), more particularly on the Pierre Blanche lagoon (about 10 km south of the city of Montpellier) to identify and characterize the record of environmental changes due to these winter storm (Dezileau et al., 2005). To understand the sediment dynamics, we considered the main sediment sources, i.e. the riverine particulate input, the marine sediment input during storm events, and the organic production resulting from biological activity inside the lagoon. In order to trace the origin of detritic materials, we followed a multi-proxy

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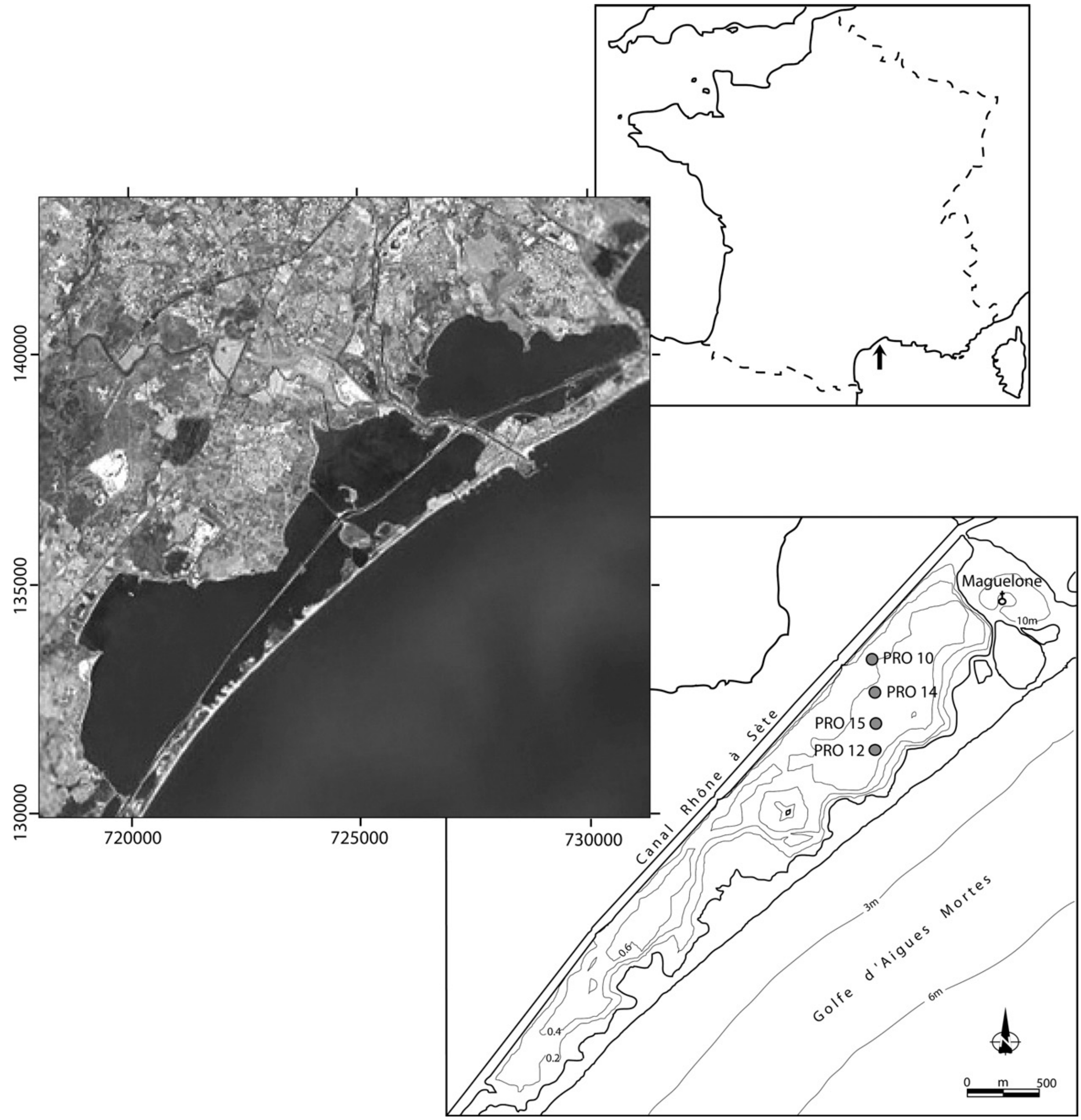


Fig. 1. Map of Pierre Blanche lagoon with localisation of the four short cores along a N–S transect (PRO 10, PRO 14, PRO 12 and PRO 15).

approach associating sedimentological, granulometric and faunistic data. On the other hand, a chronology is needed to be established. Usually, on centennial timescales, the sedimentation rate is calculated through ^{210}Pb radiochronology (Krishnaswami et al., 1971; Noller, 2000). In this study, to date recent paleostorm events, we have compared historical data, from communal archives, and radiochronological data obtained from both ^{210}Pb models (Golberg, 1963; Krishnaswami et al., 1971; Pennington et al., 1976) and ^{137}Cs activity-depth distributions (Robbins and Edgington, 1975).

2. Study area

Pierre Blanche is an elongated lagoon (Fig. 1), 267 ha large and 60 cm water deep. Its northern part is limited by the Rhône-Sète navigation channel (construction started in 1666). The south-east boundary is a 5 km long and ~200 m wide sandy barrier (Fig. 2a). Even if there is no direct connection with the sea, in some places the barrier is less than 60 m wide and 3 m high above the mean sea level. This implies a strong marine influence during storm events, as evidenced by the traces of ancient inlets. Languedoc displays a classical microtidal littoral with a maximal tide excursion lower than 50 cm.

In the western part of Gulf of Aigues-Mortes, north-western wind (Tramontane) blows 60% of the days involved with stronger winds than 5 m/s. Mean velocities recorded since the sixteen are about 10 m/s. Maximal velocities exceed 44 m/s. North-eastern wind (Mistral) occurs lesser (20%) and the mean and maximal velocities observed are slightly the same. South-eastern to south-western winds are not so important (20%) and rarely exceeding 20 m/s. However some rare (1 to 5 events a year) strong winds can exceed this value. The strongest one ever recorded by instrumental stations at Sète was about 46 m/s during the storm of 6–8 November 1982 (category 2 in Saffir–Simpson scale). This value may be compared to that recorded during usual years like 2002 and 2003, when maximal south-eastern winds recorded were 32 m/s and 25 m/s respectively (Bouchette et al., 2007). These strong winds occurred during winter storms and enhanced along the coastline the effect of the swell generated seaward. In the present day, the coastline

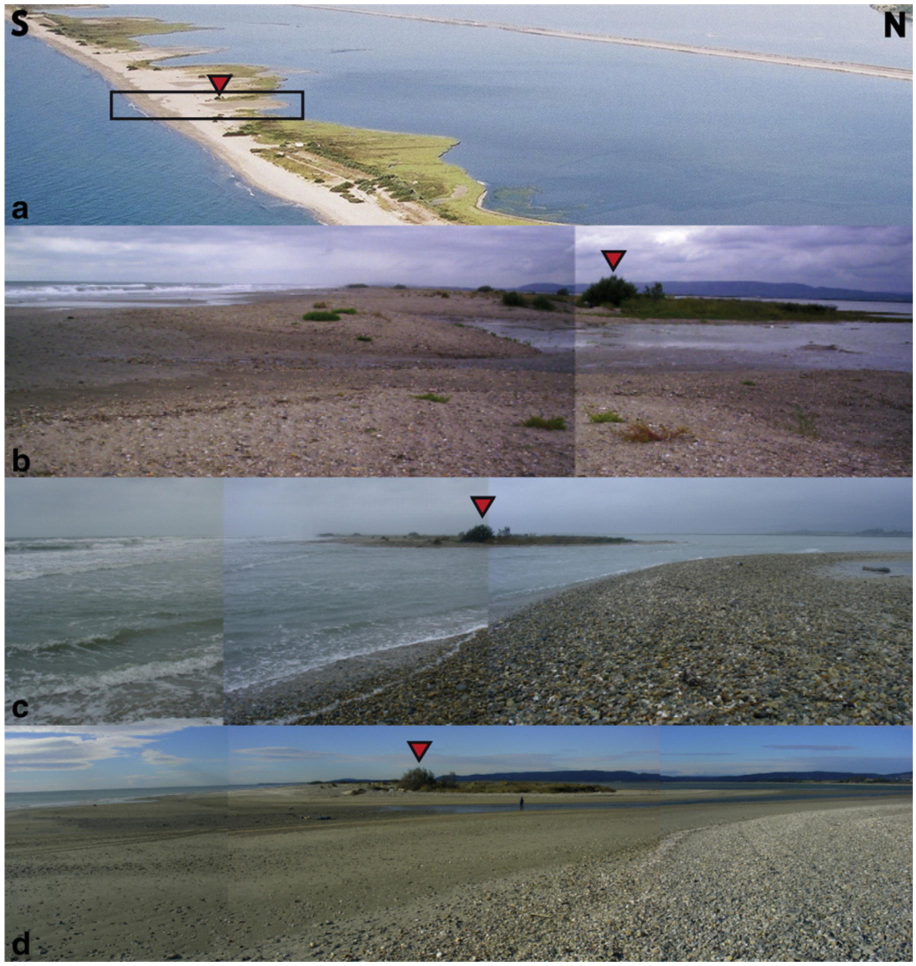


Fig. 2. Pictures of a coastal line where an inlet was created, during the 18–19 October 2006 storm. (a) is an air photography taken before the storm where we can see the width of the barrier appears, (b) picture taken in 2005 after a small event which weakened the barrier. (c) shows the inlet created at the same place by the 18–19 October 2006 storm with a strong landward tidal flow. (d) picture taken ten days after this event, where the inlet was covered up again with sand and pebbles. The red triangle shows a landmark present on all photographies. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

is mostly impacted by such a combination of south-eastern winds and winter swells. The coastal waves are strongly influenced by height period due to east to south-eastern winds. Usual wave period in the Gulf of Aigues-Mortes ranges from 3 s and 7 s. Wave directions are parted in three main types of climate. South-eastern waves correspond to 69% of the observed waves, southern waves to 17% and south-western to 14%. The annual significant wave height (Hs) and period (Tm), measured at Sète station under 32 m water depth (10 km far from the studied zone) are fair weather waves during 88% of the year (Hs = 0.84 m; Tm = 4.2 s, Guizien K. personal communication). However, this fair weather wave climate is occasionally disturbed by east to south-eastern storms, like that occurred in 1982. The annual proportion of waves higher than 4 m was around 1% and the return period of a 6 m high wave was every 10 yr (Guizien K. personal communication). However, this wave buoy installed since 1988 does not allow to get back in time far enough to evaluate the decennial to centennial wave climate.

On October 18–19 2006, a storm with 7 m high waves occurred and resulted in the opening of an ephemeral inlet (Fig. 2c), where an inlet had almost been opened during a previous storm (Fig. 2b). During this event shoreward flow transported material (sandy sediment and small shells) to the lagoon through the inlet (Fig. 2c). Two days after, the water flow was reversed and the lagoon was drained, due to the sea set down. Two weeks later, the inlet was closed and the breach was covered up again with sand and pebbles (Fig. 2d). Aerial photographs analysis demonstrates that influence of this storm on lagoonal sedimentation was almost negligible, except maybe in the direct vicinity of the inlet, where a small washover fan containing some marine shells (small *Bittium reticulatum* and *Rissoa ventricosa* transported by flow) was created. In principle, if cores were collected in more distal area of the lagoon, far enough from this inlet (a few hundred meters), likely contain sedimentological evidence of stronger storms (with low return period), powerful enough to affect the whole lagoonal system.

3. Sampling and analytical methods

Four short cores (<1 m) separated by about 200 m (Fig. 1), were collected on a N–S transect in Pierre Blanche lagoon in September 2005 by manually inserting a PVC tube (inner diameter of 8.5 cm) from a small vessel. Back to the laboratory, cores were X-radiographed (imagery department in "Clinique du Millénaire"), sliced opened, photographed, logged and divided into 1 cm sections prior to analysis. The two northernmost cores (PRO 10 and PRO 14) were analysed every 3 cm for malacofauna. The two other cores (PRO 12 and PRO 15), closer to the barrier, were analysed in more detail (every centimeters) with the same methods. Their grain size distribution was also determined using a Malvern Mastersizer Hydro 2000G in the laboratory of Interactions and Dynamic of Surface Environment (IDES) at Orsay. In addition, geochemical data were obtained by gamma spectrometry for U, Th series nuclides and ^{137}Cs by Geosciences Montpellier (GM). To study macrofaunal organisms, samples were sieved at 1 mm and the number of individuals of all species were counted. Grain size distribution measurements were made on the less than 1 mm sediment fraction without decarbonatation. Bulk sediments were first suspended in deionized water and gently shaken to achieve disaggregation. After introduction of sediment into

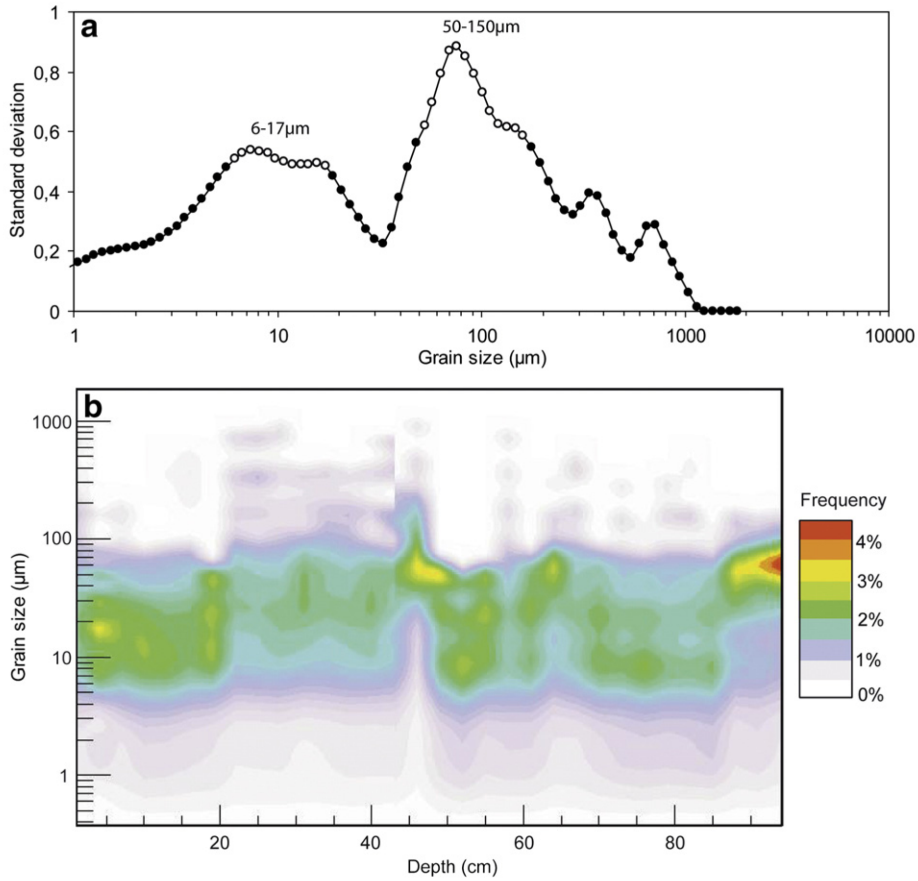


Fig. 3. (a) Standard deviation values *vs.* grain size class diagram of core PRO 15. Open circles are the most important granulometric populations, with one (thin silt) between 6 and 17 µm, and the other (thin sand) between 50 and 150 µm. (b) Contour plot of the grain size distribution of the core PRO 15.

the fluid module of the granulometer, ultrasounds were used to avoid particles flocculation. In the laboratory, sediment samples were weighted, washed (three times) with deionized water and dried at 70 °C, for four days. Later, samples for gamma spectrometry were crushed and transferred into small polystyrene cylindrical boxes of known volume. Radionuclide activities were calculated by comparison with the known activities of an in-house standard (volcanic rock) filling the same boxes (Condomines et al., 1995). Since ^{137}Cs is absent in the standard, its activity was calculated from the efficiency curve of the BEGe detector (CANBERRA BEGe 3825). As polystyrene boxes are not gas-tight, ^{222}Rn can be lost through the walls and thus ^{226}Ra activities were determined only from the 186 keV peak of ^{226}Ra (after correction of the interfering 185.7 keV peak of ^{235}U) and not from the peaks of the ^{222}Rn daughters (^{214}Pb, ^{214}Bi). In each sample, the ^{210}Pb (unsupported) excess activities were determined by subtracting the ^{226}Ra (supported) activity from the total ^{210}Pb activity. A self-absorption correction based on major element composition and sample density was systematically applied for all photopeaks. For low-energy gamma rays, such as the 46.5 keV of ^{210}Pb, this correction can be relatively large (around 6%).

Four shell samples were selected for ^{14}C age determinations. ^{14}C analyses were conducted at the Laboratoire de Mesure ^{14}C (LMC14) on ARTEMIS in CEA institute at Saclay (Atomic Energy Commission). ^{14}C ages were converted to calendar years using the Calib 5.0.2 calibration program (Hughen et al., 2004) at two standard deviations.

4. Results and interpretations

4.1. Identification of storm deposits

The lagoon is mostly filled by clay and silt with shell fragments alternating with layers of fine sandy material. This succession accounts for different transport and sedimentation processes: one is the transport of small sized particles carried in suspension then decanted; the other one correspond to coarser sand transport, carried either by wind or by water during a high energy event (e.g., a storm event). Cores PRO 12 and PRO 15 show significant grain size variations with some sand layers. These layers are characterized by few shell fragments. The color of the sediment was rather dark, grading from olive grey to grey and black. Color also gives information on the amount of organic matter in the sediment and on anoxic conditions in the lagoon. Grain size data are generally displayed in a spectrum where the percentages of the populations are plotted *vs.* grain size fraction. They show a combination of different populations of particles. Nevertheless, few methods can discriminate the different populations. Boulay et al. (2003) used a simple method to identify the grain size intervals with the highest variability. Standard deviation quantifies the variability of different measures around the mean values. Using this method, we can determine the grain size classes having the most important variation through time. Standard deviation values *vs.* grain size classes of core PRO 15 are displayed on Fig. 3. Two mean grain populations, presenting the highest variability, can be identified. One between 6 and 17 µm (fine silt) and the other coarser, between 50 and 150 µm (fine sand). The evolution with depth of the 50–150 µm population in PRO 15 core shows several peaks (Figs. 3 and 4).

On the other hand malacofauna is a good indicator of lagoon isolation state because it develops in different ranges of salinity, temperature and oxygenation. In fact, three species develop typically in a lagoon environment (*Hydrobia acuta*, *Cerastoderma glaucum* and *Abra ovata*) whereas two other are typical of a marine environment (*B. reticulatum* and *R. ventricosa*). The presence of marine species within the lagoon indicates either their transport during a storm event or a change in environmental conditions. Fig. 4 shows three peaks of 50–150 µm sandy

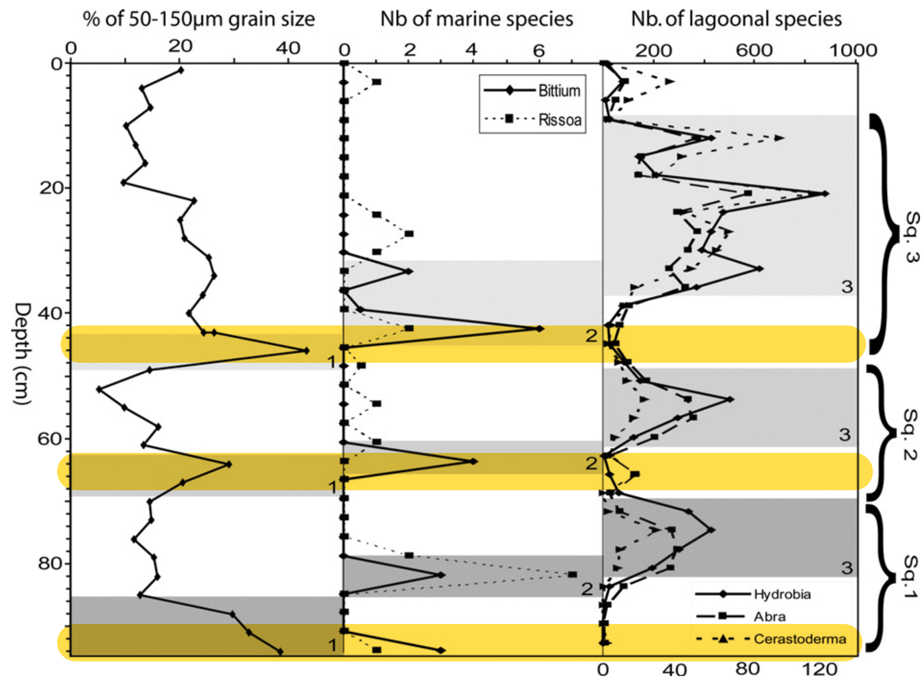


Fig. 4. Storm event sequences succession in core PRO 15. From left to right: 50–150 µm grain size population, marine species (*Bittium reticulatum* and *Rissoa ventricosa*), lagoonal species (*Hydrobia acuta*, *Cerastoderma glaucum* and *Abra ovata*). Bands shaded in gray were the three main sequences registered in PRO 15 sediment. The different greys correspond to different sequences. The numbers (1, 2 and 3) correspond to facies types described in Fig. 5.

population at 45, 65 and 90 cm, followed, just a few centimeters above, by three peaks of marine species while the lagoonal fauna almost disappears. Data of Fig. 4 show a strong anti-correlation between species living in lagoon conditions (*H. acuta*) and that representative of the marine environment (*B. reticulatum*). The close association of sandy layers, marine species and the disappearance of lagoonal fauna suggest that the observed sequences can be interpreted by a succession of marine invasions of the lagoon during storm events, followed by closure of the barrier and return to typical lagoon conditions.

Through the multi-proxy analysis of a core, based on grain size and fauna composition, it is possible to recognize typical facies whose succession identifies a storm event (Figs. 4 and 5):

- type 1 facies shows fine sand with some marine species probably carried with this sand.
- type 2 facies, found just above the same fine sand layer. The grey silt contains typical marine fauna (*B. reticulatum* and *R. ventricosa*), then grain size becomes finer upwards with the apparition of some lagoonal species.

Sequence

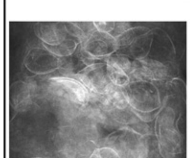
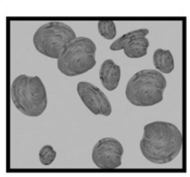
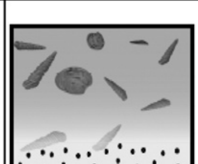
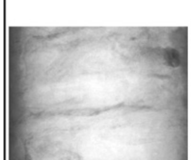
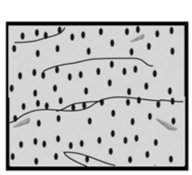
RX observation	Schematic interp.	Facies	Fauna	Grain size	Interpretations
		3 Thin gray silt	Lagoonal (Cerastoderma, Abra, Hydrobia)	6 - 17 µm	Lagoon conditions get over by lido closure. So typical species develop again with a strong expansion before a new storm event.
		2 Grey silt just above a sandy layer	Marine (Bittium, Rissoa, and any lagoonal species)	15 - 35 µm	Marines species develop on a sandy substrate with high salinity. Then marines conditions disappear slowly when sandy lido is closed.
		1 Thin sand	Marine (Bittium, Rissoa)	50 - 150 µm	A layer of sand is deposited instantaneously transporting some marine species, when a storm event occurs.

Fig. 5. Facies and characteristic sequences for storm layers in the lagoon environment.

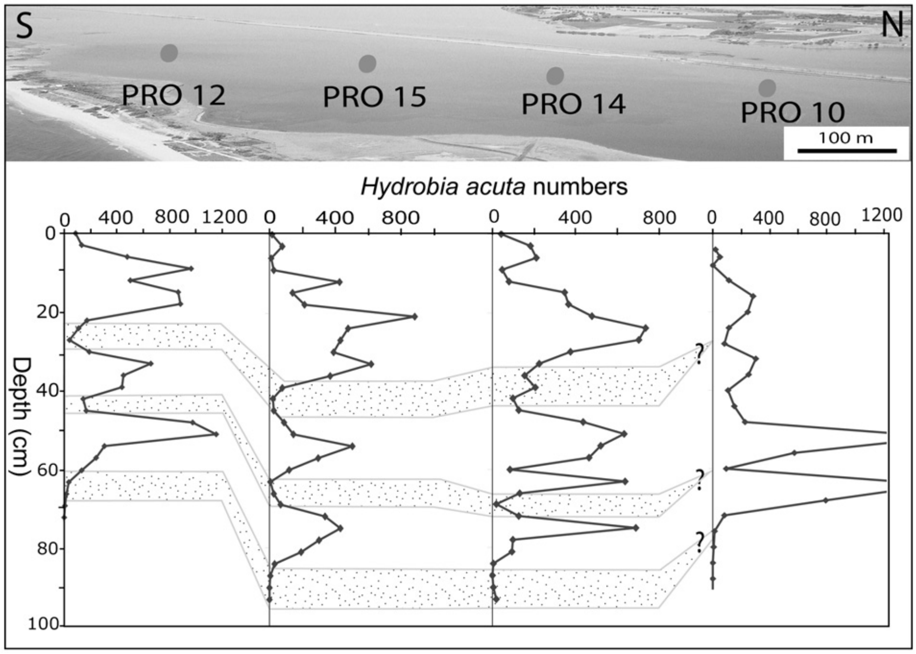


Fig. 6. *Hydrobia acuta* repartition in Pierre Blanche lagoon along a N–S transect. The three *Hydrobia acuta* minima, corresponding to marine inputs during storm events have been correlated between cores (dotted bands). The same layers are deeper in the center of the lagoon, with a maximum depth between PRO 15 and PRO 14 cores.

- type 3 facies is made of fine grey silt with typical lagoonal fauna (*H. acuta*, *C. glaucum* and *A. ovata*).

Malacofauna contents were studied in all four cores. Three periods with very low abundances of the lagoonal species (*H. acuta*) in Pierre Blanche lagoon were observed (Fig. 6). A clear link can be made between all four cores, with the exception of core PRO 10. These lateral correlations, along a 600 m transect, indicate a good preservation of these events in the whole study area and suggest higher accumulation rates in the central part of the lagoon. When a storm occurs, wind and wave energy break up the barrier and trigger a landward material transfer, from the barrier to the lagoon. Transported material is mainly sand with some marine fauna and almost instantaneously sinks to the bottom. If the inlet remains open for a sufficiently long time, then the salinity in the lagoon increases and marine species can develop on the sandy substrate to the detriment of lagoonal fauna. When the sandy barrier closes, the lagoon becomes isolated once again, hence environmental conditions change with consequent reappearance of lagoonal species at the expense of marine fauna for which environmental conditions are unfavourable. In all four sediment cores (Fig. 6) we observed three sequences that probably correspond to three main storm events (Fig. 4), with an impact on the whole of the lagoon.

4.2. Accumulation rates and age model

The basic methodology of ^{210}Pb dating was established in a seminal paper by Golberg (1963). ^{210}Pb precipitates from the atmosphere through ^{222}Rn decay and accumulates in surface soils, glaciers or lakes, lagoons, where successive layers of material are buried by later deposits. Many ^{210}Pb models were proposed, allowing to calculate sedimentation rates (Appleby and Oldfield, 1992; Noller, 2000). In the simplest model, the initial (^{210}Pbex), [$(^{210}Pb)_{ex} = (^{210}Pb) - (^{226}Ra)$] is assumed constant and thus ^{210}Pbex at any time is given by the decay law [$(^{210}Pb)_{ex} = (^{210}Pb)_{0,ex}\ \exp - \lambda_{210} \cdot t$]. The CFCS model (Golberg, 1963; Krishnaswami et al., 1971) supposes a constant ^{210}Pb flux and a constant sedimentation rate. Although the sedimentation rate in the lagoon is clearly variable due to the near-instantaneous sedimentation of sandy storm deposits, the CFCS model can still be applied when typical lagoonal conditions prevail. It is the case of core PRO 12 and PRO 15 above depths of 23 cm and 37 cm respectively. In a logarithmic diagram, ^{210}Pbex should define a straight regression line whose slope allows to calculate an average sedimentation rate (Fig. 7, values in Table 1). Using the average sedimentation rate W (mm y^{-1}), the age T_m of the sediment layer can be calculated, for each depth Z_m (cm).

$$\ln\left(\left(^{210}\mathrm{Pb}_{ex}^{m}\right)\right) = \ln\left(\left(^{210}\mathrm{Pb}_{ex}^{0}\right)\right) - \left(\frac{\lambda_{210}}{W}\right) \times Z_m, \quad \text{with:} \quad T_m = \frac{W}{Z_m}$$

This simple model only gives an estimation of the average sedimentation rate and does not take into account possible variations of sediment accumulation rate and/or ^{210}Pb supply. It is thus impossible to precisely date a sedimentologic event. However, any major modification in the sedimentation rate should result in a change of slope in the logarithmic diagram. The post-depositional mixing, by biologic activity (bioturbation) can also affect ^{210}Pb data

Table 1
Activities of radionuclides in cores PRO 15 and PRO 12

Cores	Depth	^{210}Pb	^{226}Ra	^{210}Pb$_{ex}$	^{137}Cs
	(cm)	(mBq/g)	(mBq/g)	(mBq/g)	(mBq/g)
PRO 15	0–1	138.6±4.2	25.4±3.9	113.2±5.8	18.1±0.8
	3–4	116.1±2.5	27.3±2.8	88.8±3.7	20.2±0.5
	9–10	100.8±2.8	21.6±3.1	79.3±4.2	24.6±0.8
	12–13	92.2±2.1	20.3±2.3	71.9±3.1	23.4±0.6
	15–16	79.2±1.9	23.7±2.3	55.6±3.0	41.0±0.9
	18–19	78.8±2.0	20.6±2.5	58.2±3.2	45.9±1.0
	24–25	42.7±1.8	17.4±2.8	25.3±3.4	10.5±0.4
	30–31	31.9±1.6	22.3±2.6	9.6±3.0	2.9±0.3
	36–37	25.4±1.7	22.6±3.1	2.8±3.6	0.8±0.2
	39–40	23.8±1.4	27.0±2.8	0	0
PRO 12	0–1	112.8±2.8	25.1±2.9	87.7±4.0	18.9±0.6
	3–4	93.5±2.6	24.2±2.9	69.3±3.9	16.8±0.6
	6–7	84.2±2.8	22.0±3.3	62.2±4.3	17.5±0.7
	9–10	65.5±2.5	24.8±3.1	40.8±4.0	20.1±0.7
	12–13	56.6±2.2	22.8±3.6	33.8±4.2	20.0±0.7
	15–16	48.0±3.0	22.9±4.3	25.1±5.2	11.0±0.6
	18–19	32.6±2.1	21.4±3.5	11.3±4.1	4.6±0.4
	22–23	25.9±1.0	23.9±1.5	1.9±1.8	0
	27–28	22.2±0.9	22.2±1.4	0	0

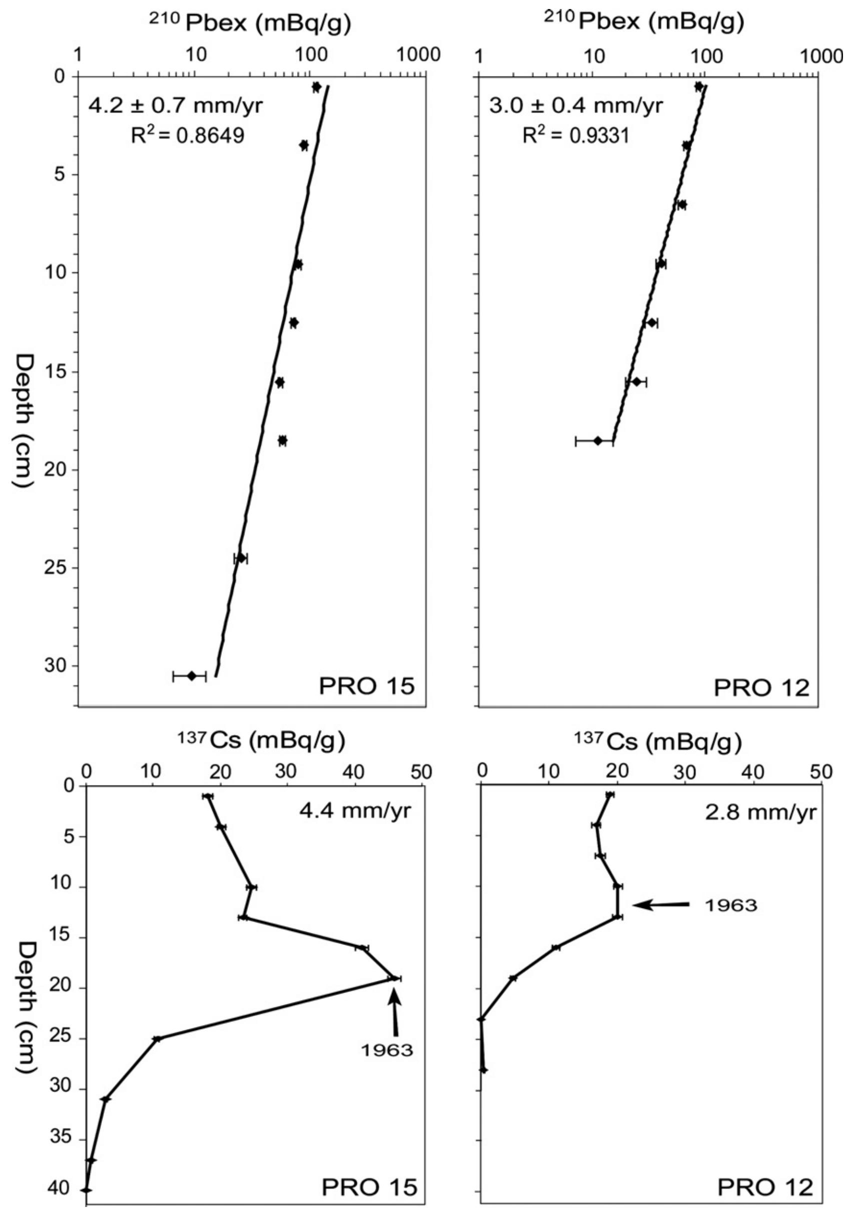


Fig. 7. ^{210}Pbex and ^{137}Cs activity-depth profiles in cores PRO 15 (left) and PRO 12 (right) from Pierre Blanche lagoon. ^{210}Pb excess disappears at around 25 cm for PRO 12 and 37 cm for PRO 15. The deepest ^{210}Pbex values were not considered to calculate the sedimentation rate, because of their large associated errors.

interpretation. This effect is difficult to estimate because there is no typical mixing surface layer with the same ^{210}Pb activity. This potential problem is currently being evaluated, by implantation of luminophores, in order to understand the effect of physical and biological mixing on the ^{210}Pb depth distribution (Gerino et al., 1998; François et al., 2002).

Fig. 7 shows that the sedimentation rates vary from 3.0 ± 0.4 to 4.2 ± 0.7 mm y^{-1} between the border (PRO 12) and center (PRO 15) of the lagoon. These sedimentation rates are in agreement with those previously obtained from another lagoon (Thau) in the same area by Monna et al. (1995), Schmidt et al. (2007). Both radiochronological dating and faunistic correlation (Fig. 6) indicate that the sedimentation rate is higher in the center of the lagoon. These rates are relatively high in this wetland area where water depth varies between 0.4 and 0.8 m. Extrapolating the present-day sedimentation rate would result in a filling of this lagoon in the next 150 yr, without taking account neither the sea level rise nor the littoral antropic impact.

The most usual dating method based on ^{137}Cs data (Robbins and Edgington, 1975) assumes that the depth of the maximum ^{137}Cs activity in the sediment corresponds to the 1963 maximum atmospheric production. A ^{137}Cs peak is well identified in PRO 15 core at 19 cm deep and suggests an average accumulation rate of 4.4 mm y^{-1} similar to the value derived from ^{210}Pbex data. Differently, in core PRO 12 there is no real peak but rather an enlarged maximum at around 12 cm depths which gives a sedimentation rate of 2.8 mm y^{-1}, again in agreement with ^{210}Pbex data. However ^{137}Cs is still present at depths of more than 30 cm, whereas this radionuclide has been shown to appear in this area in 1958, a date corresponding to the first high altitude atmospheric tests (Radakovitch et al., 1999). This paradox could be explained by the important mobility of Cs in sea water. Indeed, one of the Cs properties is its high mobility in marine sediments, with a preferential downward diffusive transport in porewater (Charmasson et al., 1998; Radakovitch et al., 1999). In spite of this mobility, ^{137}Cs can be used to date sediment because the diffusive transport will result in the spreading of the Cs peak and not in its downward move. On both cores the ^{137}Cs activity-depth distributions do not show the Chernobyl signal, it is probably due to the low-resolution analysis on these cores (every 3 cm) or to its too low concentration in surface soil on the small watershed.

^{14}C data give a sedimentation rate of 3.15 mm y^{-1}, this rate was in good agreement with ^{210}Pb and ^{137}Cs depth distributions. Reservoir age in lagoon environment of Mediterranean region is high, due to a strong continental Carbon contribution (Siani et al., 2000; Zoppi et al., 2001). In this study, we have estimated the reservoir age at around 950±75 yr (Table 2) by both extrapolating to the surface of sediment and by correlation with ^{210}Pb data (Sabatier et al. in preparation).

The agreement between average sedimentation rates derived from ^{210}Pb, ^{137}Cs and ^{14}C data suggests that the various disturbing processes like bioturbation (Cochran, 1985), grain size effects (Chanton et al., 1983) or instantaneous events (Smith and Walton, 1980; Arnaud et al., 2002) did not play a major role in the studied parts of the cores.

5. Identification of paleostorms

In the last 400 yr, the stronger storm occurred in south of France was in 1666, 1669, 1738, 1742, 1766, 1771, 1790, 1839, 1893, 1956 (historical account) and 1982, 1999 (MétéoFrance data). In communal account, storm events were mentioned because they make damage in the vicinity of the studied city. Sedimentological and paleoecological results described above allow us to identify the most powerful storm events as historical period (i.e. paleostorm) with the presence of sand layer (50–150 μm) together with marine species (*B. reticulatum*) and the disappearance of lagoonal species (Fig. 8).

Based on our age model the last three catastrophic storm events recorded in this cores-transect occurred in 1742 (with the inlet closing in 1761), 1839, and 1893. These dates were obtained by comparison between ^{210}Pb, ^{14}C data and historical accounts.

- The storm of September 4th, 1742, recorded in many city archives around the Aigues-Mortes gulf, is considered as the most catastrophic event. This storm, probably due to S to SE winds, submerged some local cultivated lands which had been obtained at the expense of old lagoonal parts. This event was not accompanied by coastal river floods. One of the main consequences was the creation of a large inlet, near Maguelone, which remained open until 1761.
- The 1839 tropical storm has for consequence the wreckage of a few ships, like a trading vessel (more than 20 m long) off the Frontignan village (Serra, 2004). The violence of winds during this storm, associated with the shallow water in this area, explains this shipwreck.
- The most recent event recorded in the PRO 15 core could correspond to the storm of September 21, 1893 which affected the north of France and the Mediterranean region, causing devastations in the Sète area as certified by many engraving illustrations.

Table 2
Radiocarbon ages from Pierre Blanche lagoon (core PRO 15)

Depth (cm)	^{14}C (yr BP)	^{14}Ccal BP (2σ, Hughen et al. 2004)	^{14}Ccal BP (ΔR = 550 yr)
3–4	Post A.	Post A.	Post A.
20–21	1055±30	610±60	60±60
60–61	1095±30	660±65	110±65
83–84	1285±30	825±80	275±80

Soft-sediment deformation at the contact between overwash sand and underlying mud in all cores indicates that little sediment may have been removed by the storm deposit inside the lagoon. This was supported by the good agreement between ^{210}Pb extrapolation and ^{14}C data.

It should be noted that the most recent catastrophic event, the 1982 storm, was not registered in the studied sediment cores. One could argue that the storm events described above were of similar intensity as the 1982 event, and that they were recorded in the lagoon sediments because of a thinner barrier in the past centuries. However, examination of old geographical maps shows that the location and width of the barrier have not changed significantly. It thus appears that the past storm events registered in our cores were stronger than the 1982 event. Although we have not studied a multi-transect cores, the record analysis

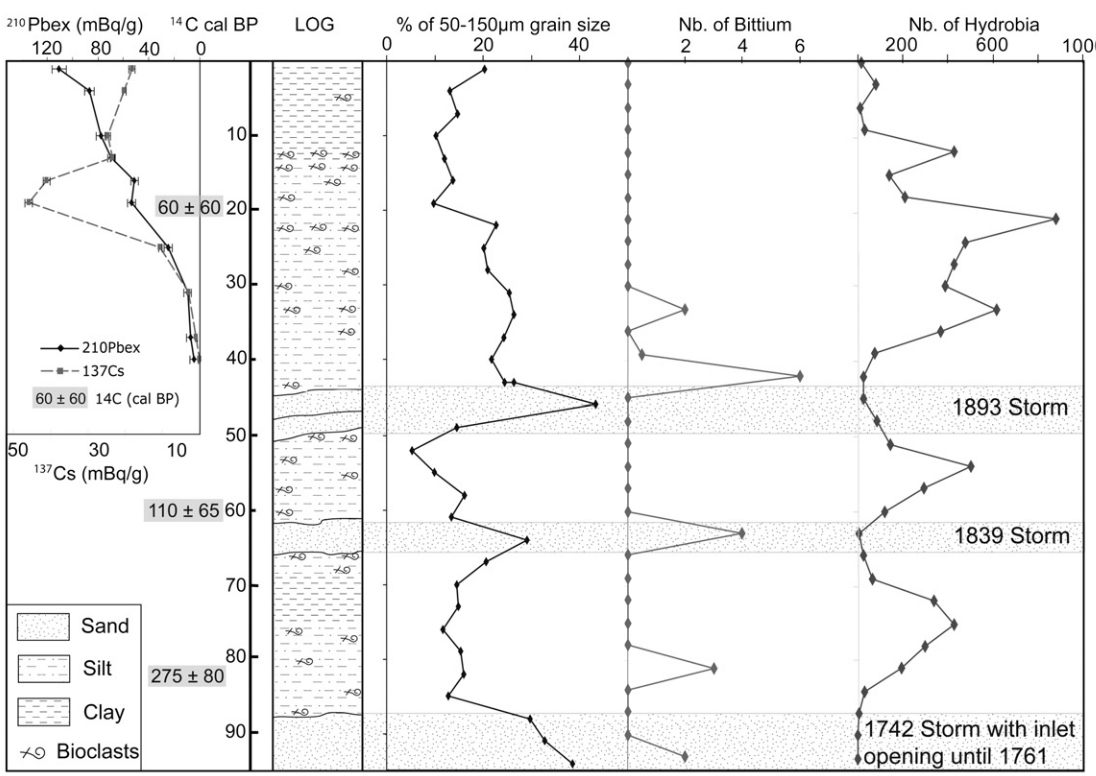


Fig. 8. Storm event characterization in core PRO 15. From left to right: ^{210}Pbex and ^{137}Cs activity-depth profiles, ^{14}C date (grey band), sediment description, 50–150 μm grain size population, lagoonal species (*Hydrobia acuta*). Dotted bands correspond to the main paleostorms events registered in historical accounts corresponding to different events described in Fig. 4.

of washover deposit from a backbarrier marsh provided evidence of three main storms in the past 300 yr in Gulf of Aigue-Mortes. If this observation is confirmed, the frequency of such paleostorms, seems to be about one each century.

6. Conclusions

This study of Pierre Blanche lagoon demonstrates that an analysis associating sedimentology, granulometry and faunistic data allows to identify the strongest storms in the Mediterranean area. The record of such events on lagoonal sedimentation is characterized by typical successions (silt with typical lagoonal species, with intercalations of fine sand and marine species). Average sedimentation rates calculated by ^{210}Pbex CFCS model are high and vary from 3.0 ± 0.4 mm y^{-1} near the border to 4.2 ± 0.7 mm y^{-1} in the center of the lagoon, where water depth is between 0.4 and 0.8 m. We thus expect a complete filling of this lagoon in the next 150 yr. Moreover, radiochronological dating (^{210}Pbex and ^{137}Cs) together with historical accounts allows to date the record of past main storms. Three distinct catastrophic events were identified in 1742, 1839 and 1893 over nearly 3 centuries. Therefore, from the presently available and limited data, the recurrence of historic events more powerful than that of 1982, is around one main storm per century. Paleoclimatic recording of Mediterranean storm thus appears clearly possible in lagoonal systems.

The methodology proposed can thereafter be applied over longer time scales, allowing a paleostorm record over the Late Holocene period. To this aim, two long cores have been sampled, in March 2006, in the same lagoon. These cores cross the whole Late Holocene lagoon sediment filling and will allow to identify catastrophic events for at least 6000 yr.

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