Last millennia sedimentary record on a micro-tidal, low-accumulation prodelta (Têt NW Mediterranean)

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Abstract

Statistical sequential analysis was performed on a series of sediment cores collected from the Têt prodelta in the Gulf of Lions, northwestern Mediterranean Sea, between October 2003 and October 2004. Seabed changes during that period were correlated to hydrodynamic conditions (waves and currents) and river discharge. Low sediment supply prevents full preservation of new sediment strata on this low-accumulation prodelta located on a microtidal, storm-dominated inner shelf. Severe meteorological events caused a rapid succession of erosion and deposition phases. For example, the December 2003 flood and storm produced a flood layer deposit that persisted for 2 months with only slight transformations due to early diagenesis and/or bioturbation, until a new storm event eroded this layer. A typical sedimentary sequence was observed for the secular deposits composed of a 10-cm-thick sandy layer overlaying silty-clayey layers. These characteristic features were used to analyse the last millennia sedimentary record of the Têt prodelta. The low preservation of freshly deposited sediments and variable sedimentation rates during the last millennia period yield a sedimentary sequence formed by the outcropping of muddy prodeltaic units intersected by heterogeneous silty-sandy units similar to those formed under present day hydrodynamic conditions. No flood layer was found related to catastrophic flooding of the last century in the sedimentary record. The Little Ice Age (~1550–1850 AD) probably favoured the formation of a well-developed muddy prodelta in the mouth of the Têt River. Later on, the decrease of sediment supply by rivers due to climate change and/or human activities (damming, irrigation), and the increase of the number of high-energy storms reaching the coast, induced a coarsening of the top sediment layer on this prodelta. This modern change of the substrate is also observed in the composition of benthic biota found in the substrate.

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1. Introduction

Small rivers contribute a significant amount of the total sediment load to the global marine systems (Milliman and Syvitski, 1992; Mulder and Syvitski, 1995) and most of the sediment entering shallow coastal areas is entrapped in deltas. Prodelta corresponds to preferential depositional areas of riverborne and organic material. They are composed of fine grained deposits (clays and silts) (Aloisi and Monaco, 1975), and are commonly found off river mouths at depths range from 20 to 50 m, where wave and current energy decrease and flocculation by purely physico-chemical processes may cause nearshore mud accumulation on the shelf (Drake, 1976). Nevertheless, it has been demonstrated that waves and currents energy remain occasionally strong enough to induce a part of resuspension and transport prodeltaic material seawards (Smith and Hopkins, 1972). For these reasons, prodeltas do not constitute static reservoir of fine sediment, but are temporal deposit areas of clays and silts located in the sediment transport pathway between the turbid near-shore zone and the middle and outer shelf mud deposits.

Whatever the amount of sediment input from the nearby river, the prodelta records a trace of hydrological and biological changes, notably meteorological events such as floods and storms (Nittrouer and Wright, 1994). It is now well understood that in prodeltas of flood-prone rivers, well-preserved sedimentary strata are rather easy to identify, e.g. offshore of the Eel River, northern California (Sommerfield and Nittrouer, 1999), the Mississippi–Atchafalaya deltaic system (Allison et al., 2005); the Rhône River in the Gulf of Lions (Beaudouin et al., 2005), or the Po River (Trincardi et al., 2004). Conversely, sedimentary features of small flood-prone prodeltas are presumed to be more complex, due to slow accumulation rates and the low preservation potential of deposits. To date, only a limited number of studies round the world have addressed the modern to last millennia (century to millennial time-scale) sedimentary record in such small prodeltaic environments (Ingram et al., 1996), which are common in the Mediterranean. However, none of these studies addressed the sedimentary record itself, nor estimated the shelf mass accumulation rates over longer timescales. Are the conditions in small prodeltaic environments favourable to the formation of new sediment strata? Is there an identifiable sedimentary record and what is the structure of the record in small prodeltas from the last century to the last millennia period?

As part of the Eurostrataform project, which investigated the transfer of sediment from sources (catchment areas) to sinks (deep basins), this study aims at better understanding the formation and evolution of new sediment strata on continental shelves under the influence of meteorological events (floods, storms). Starting with the relationship between hydrodynamic forcing and resulting sedimentological and geochemical characteristics, an attempt is made to define the last millennia record on a prodelta located on a microtidal continental shelf influenced by small rivers and dominated by storms.

2. Regional setting

The Gulf of Lions, in the northwestern part of the Mediterranean Sea, is a large continental margin incised by numerous canyons. Its modern sedimentation is largely controlled by sedimentary inputs from several river systems (Fig. 1a): the Rhône River, the largest Mediterranean river in terms of liquid (≈56×10⁶ m³ yr⁻¹) and solid discharges (10±3×10⁶ t yr⁻¹), and several small torrential rivers (the Vidourle, Lez, Hérault, Orb, Aude, Agly, Têt and Tech rivers). The Rhône contributes to more than 90% of the total annual liquid and solid discharges of the rivers to the Gulf of Lions (Bourrin et al., 2006). But small torrential rivers can discharge large amount of material to the coastal area in few days during flash flood events (Serrat et al., 2001). This sediment amount can play a significant role in the sedimentation of the Gulf of Lions.

The predominant northwesterly (“Tramontane” and “Mistral”) and southeasterly winds (“Marin”) control variable mesoscale eddy circulations on the continental shelf (Estournel et al., 2003). The Tramontane as well as the Marin winds generally induce cyclonic circulation in the western part of the continental margin (Millot, 1990). Flood events are frequently associated with SE storms, which advect humid air inland and promote strong rains over the coast. Floods follow these storms a few hours later (Puig et al., 2001; Palanques et al., 2002; Ferré et al., 2005).

The location of continental sources and hydrodynamic processes control sediment distribution on this continental shelf. A decrease in grain-size is observed from the inner shelf to the outer shelf (Fig. 1a). The coastal area is sandy and the sand–mud transition overlaps the average wave action limit at around 30 m water depth (Jago and Barusseau, 1981). Numerous rocky formations are found in the study area and present various mixed facies. A well-developed mid-shelf mud deposit follows the mean shelf circulation pattern from...
Fig. 1. (a) Sedimentary map of the continental margin of the Gulf of Lions (adapted from Monaco and Aloïsi, 2000, Observatoire Régional de l’Environnement Méditerranéen, http://medias.obs-mip.fr/orme/). The general and mesoscale circulations (black arrows) as well as the dominant winds (big arrows) are shown; (b) detailed sedimentary map of the Têt prodelta (redrawn from the Geological Map of Perpignan, 1/50,000e).
The outer-shelf is characterized by lowstand sandy shoreface deposits (Jouet et al., 2006). The late-Holocene deposits form an alongshore muddy wedge (Fig. 1a). This geometry predominantly reflects the dispersal of the Rhône River inputs by coastal circulation. The main depocentre is located directly front to the mouth of the Rhône and decrease further west (Aloïsi, 1986). The thickness of the late-Holocene deposit diminishes towards the southwestern part of the Gulf, confirming that the western torrential rivers are less important sediment sources. Seismic profiles off the Têt River (Roussillon area) (Labaune et al., 2005) have shown that, at 30 m water depth, the entire Holocene (the last 10,000 yrs) is found in a sediment layer a few meters thick (Fig. 2). However, the thickness of these deposits is highly variable and depends on the underlying morphology of the Transgressive Ravinement Surface (TRS) corresponding to the last Holocene transgression. The late-Holocene prodeltaic system, corresponding to the Highstand Systems Tract (HST), is wedge-shaped and pinches out seaward around 30 m depth where beach rocks are located (Fig. 2a). These rocky formations are composed of gravels and pebbles as well as aeolian sandstones. Dating in these sandstones gives an age of 27,200±1000 cal yrs BP, but these formations were reworked during slight standstill during the Holocene transgression around 6000 and 8000 cal yrs BP (Monaco et al., 1972). Sediment cores sampled at >40 m water depth (F116 and S13) showed a homogeneous muddy facies of several meters (Fig. 2b) characterizing the midshelf mud belt (Mear, 1984). At the base of these cores, gravels and coarse sand layers characterize the surface of marine transgression from the last glacial period, and allow dating of the different stages of relative sea level

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Fig. 2. (a) Dip-oriented seismic profile (see the location on the Têt prodelta map, Fig. 1b) showing the architecture of the sedimentary deposits on the inner shelf (modified from Labaune et al., 2005). In dark grey colour, the Highstand Systems Tract Prism (HSTP) characterized by gently steeping foresets, where beach rocks outcrop locally. (b) Lithology of cores sampled close to this seismic profile are also shown in Fig. 1 [F119, S13 and F116 (Monaco, 1971; Mear, 1984); XDM05 (Bourrin, unpubl. data; DC1, this study)]. The dotted line represents the possible Transgressive Ravinement Surface (TRS) and shows the different stages of the last marine transgression.
rise during this period. Other sediment cores (XDM05, Bourrin, unpubl. data and F119, Monaco, 1971) sampled at 28 m and 35 m water depth show alternations of fine sandy layers and siltyclayey layers and characterize a more complex organisation of the late-Holocene to last millennia sedimentary record (Fig. 2b).

The detailed map of the study site (Fig. 1b) shows an increase of the fine particle fraction (<63 μm) in the sediment from the coastline (5%) to the mid-shelf mud belt (>75%) (Aloisi and Monaco, 1975). As a result of the predominance of along-shore southward currents in this area, the highest content of muddy sediment is not directly found in front of the river mouth but south-eastward, at a water depth >30 m, and between the beach rocks. Mineralogical analysis demonstrated that despite their bathymetric location, the prodeltas are enriched with the finest clays (smectite). This mineral is commonly observed in the Pliocene formations of the western drainage basins of the Gulf of Lions and often forms aggregates with organic compounds and pollutants (Roussiez et al., 2005).

3. Materials and methods

3.1. “Source” to “sink” approach

River fluxes, meteorological forcing, currents, waves and near-bed total suspended solids (TSS) were monitored between October 2003 and October 2004 by a multi-instrumented system (“Plateforme d’Observation de l’Environnement Méditerranéen — Littoral Languedoc-Roussillon”, POEM-L2R) (Fig. 1b). This system includes an automatic river sampler that collects 2 km upstream of the Têt River mouth (42°42.831’N, 002°59.615’E) and a meteo-oceanic buoy moored at 28 m water depth in the prodelta, at about 1.5 nm off the river mouth (42°42.210’N, 003°04.012’E), sheltering an area on the seabed to deploy instruments.

3.1.1. River fluxes

The river sampler was programmed to collect 1 L of water at 80 cm below the surface, once a day during normal periods, and automatically switch to hourly sampling during flood events. The water samples were filtered through 0.45 μm Nuclepore filters and dry-weighted in the laboratory to estimate the TSS concentration. The hourly liquid discharge was measured by the “Agence de l’eau de l’Aude” at the hydrological station of Pont Joffre in Perpignan (code Y0474030, data available on the website http://www.hydro.eauffrance.fr/accueil.html) located 10 km upstream from the mouth (42°42.205’N 02°53.583’E). Estimations of flood return periods were done from long term measurements of river discharge (1977–2004) following the momentum adjustments method of the Gumbel law. A rating curve was established based on long-term measurements (1980–1999 period from Serrat et al., 2001) combined with new data (this study) of instantaneous TSS concentration and river discharge measurements (Fig. 3). The following equation:

\[
\log TSS = 0.29 \log(Q)^2 + 0.0951 \times \log(Q) + 0.9839(R^2 = 0.5553, n = 1400)
\]

was applied to mean daily river discharges to obtain mean annual fluxes corrected with Fergusson method (Fergusson, 1987).

3.1.2. Meteorological forcing

An anemometer (Young Wind Monitor Model 05106, Campbell Scientific) mounted at 4 m above the sea surface on the buoy measured wind speed and direction. A bottom-mounted RDI ADCP 600 kHz equipped with a wave gauge was deployed at 28 m depth beneath the buoy. It recorded current profiles (magnitude and direction) over the entire water column along 1-m depth-cells, as well as wave orbital velocity below the surface and pressure. Surface height and directional spectrum of waves were derived from the combination of these measurements (RD Instruments, 2001). Estimations of storm return periods were done from long term measurements of wave characteristics in the whole Gulf of Lions (1996–2005) and following the momentum adjustments method of the Gumbel law. Near-bed currents and wave’s characteristics were used to estimate the total shear stress at the bottom due to both mean current and waves, following Grant and Madsen (1986). Results were used to estimate sediment resuspension events.

3.1.3. Prodelta seabed monitoring

One NKE ALTUS sonic altimeter (2 MHz), mounted on small tripod, was deployed on the seabed by SCUBA divers to monitor erosion/deposition events by measuring the seabed position every 15 min from 26 November to 12 December 2003, and from 4 February to 18 March 2004. Factory instrument accuracy is ±0.5 cm. Water turbidity was measured using a D&A Instruments Optical Back-scatter Sensors (OBS-3) mounted on a frame at 0.15 mab, collecting data every 3 h in 20 min bursts logging at 2 Hz. OBS sensors were calibrated in the laboratory using bottom sediment collected at the tripod location prior to the deployments,
and signals from these instruments were converted into TSS concentrations.

### 3.2. Sediment sampling and analysis

From October 2003 to October 2004, 2 sediment cores at 28 m water depth were collected by SCUBA divers once a month using transparent Perspex tubes (20 cm length, 4 cm diameter) at the buoy site (Fig. 1). A longer sediment core (1 m length, 8 cm diameter) was also collected using the same method at this site in May 2005. A small core was also sampled in May 2005 to check the integrity of the surface layer in the long core. Each core was sectioned into 1-cm-thick slices, except for the first cm which was sectioned into two 0.5 cm layers. Grain-size analyses were performed on sonicated samples during 5 min with MilliQ-filtered water using a Malvern Mastersizer 2000 particle size analyser equipped with a sample dispersion unit. Total carbon (TC) and organic carbon (OC) contents (% sediment dry weight) were obtained by combustion in a LECO CN 2000 analyser after acidification with HCl 2N to remove carbonates in the case of OC analysis.

The size spectra obtained from the different sediment samples were analysed following the Entropy method, which classifies the spectra on the basis of their morphology (Johnston and Semple, 1983). This classification has been used to describe grain-size changes in sediment cores and explain sediment erosion, transport and deposition by assuming that spectra with the same shape characterize sediments exposed to the same forcing conditions (Woolfe and Michibayashi, 1995; Woolfe et al., 2000). Entropy analysis, a statistical sequential analysis, classifies the size spectra into groups based on a measure of variance between groups relative to the total variance of the whole set of size spectra. The number of groups is empirically determined and its optimal value is reached when the variance explained by the distribution of the spectra into the different groups is minimum. The grouping is more effective when the inter-group variance relative to the intra-group variance is larger. In this study, an optimal effectiveness of the spectral group classification of up to 70% was reached for 4 groups. The spectra were thus grouped into classes with similar grain-size properties. Each spectral group characterizes a typical sediment unit defined by a mean spectrum, a median grain-size ($D_{50}$) and a pelitic index (% <63 μm).

### 3.3. Geochronology

#### 3.3.1. $^{210}$Pb

Fine fraction of sediment samples (<63 μm) were freeze-dried, homogenized using a mortar and pestle, and totally dissolved according to a wet ashing technique using various mineral acids [HNO3 65%; HNO3/HClO4 mixed (v/v); HF 48%, HCl 32%]. The following methodology was taken from Radakovitch (1995). After solubilisation in 250 mL of 0.3 M HCl, 0.1g ascorbic acid was added to reduce Fe (III) to Fe (II).
at 90 °C. Polonium from the resulting solution was spontaneously deposited onto polished silver discs at 60–65 °C for about 16 h while stirring. After autoplating, the disk was rinsed with water and dried at room temperature. Chemical recoveries of \(^{210}\)Po ranged from 97% to 99%. \(^{210}\)Po activities deposited on each side of the silver disc were determined in a photomultiplier counter by measuring photons produced on a photosphere screen by alpha emission. Activities were corrected for the decay of \(^{210}\)Po between plating and counting, and the decay of \(^{210}\)Pb between sampling and plating. Corrected \(^{210}\)Po activities were assumed to be equal to \(^{210}\)Pb activities. Excess \(^{210}\)Pb (\(^{210}\)Pb\(_{xs}\)) activity was determined by subtracting from the total activity the supported \(^{210}\)Pb activity, determined as the mean \(^{210}\)Pb concentration at the base of the sediment core. Mean mass-accumulation rates (\(R\) in g cm\(^{-2}\) yr\(^{-1}\)) were calculated using the Constant Rate of Supply (CRS) model of Goldberg (1963):

\[
R = \frac{\dot{S}}{A_{exces}} \quad \text{with} \quad S = \int_z^Z \rho A_{exces} dz
\]

where \(S\) is the cumulative concentration of \(^{210}\)Pb\(_{xs}\) (Bq m\(^{-2}\)) in a sedimentary layer of thickness \(z\), and \(A_{exces}\) is the \(^{210}\)Pb\(_{xs}\) activity (Bq kg\(^{-1}\)). This method takes into account down-core variations of sediment density, and constant supply of \(^{210}\)Pb through time is assumed. Mean sediment accumulation rates (cm yr\(^{-1}\)) were determined by normalizing the sediment profile to the density measured for each sediment sample.

3.3.2. Radiocarbon dating

Shells of the gastropod \(Turitella\ communis\) sampled from sediment cores were used to perform radiocarbon dating in order to estimate \(^{14}\)C based sediment accumulation rates and ages in the modern sedimentary record (small cores) and the paleo-sequence (long core) on the Têt prodelta. Kershaw and co-workers (1988) showed that dating shells of \(T.\ communis\) is a more reliable method to estimate sediment accumulation rates than dating the carbonate fraction of bulk sediment. In each shell we performed two sections perpendicular to the shell axis with a circular diamond-coated saw in order to obtain an aliquot of circa 100 mg. Each aliquot was first sonicated during 5 min with H\(_2\)O\(_2\) 30% v/v and then etched with 0.1 M HCl during 3 min. Samples were then carefully rinsed with distilled water, dried overnight at 60 °C and stored in an inert atmosphere. The samples, ranging from 25 to 68 mg, were then sent to the Woods Hole Oceanographic Institution’s NOSAMS Facility for radiocarbon analysis. Special care was taken to obtain the calendar age of each sample. Siani and co-workers (2000) report for the Gulf of Lions a regional correction of the marine reservoir effect (400 yrs) of 118±30 yrs (database available at http://calib.qub.ac.uk/marine/). This reservoir correction was used in the CALIB 5.0 code (Stuiver and Reimer, 1993; Stuiver et al., 2005) to convert radiocarbon ages to calibrated ages using the calibration data set marine 04.14c (Hughen et al., 2004). Age intervals with maximum probabilities were used as best age estimators (Table 1).

4. Results

4.1. River inputs

During the study period, the mean daily Têt River discharge was 18 m\(^3\) s\(^{-1}\) (mean pluri-annual daily discharge = 10 m\(^3\) s\(^{-1}\)) with a mean TSS concentration of 30 mg L\(^{-1}\). From long-term based rating curve and daily river discharge measurements, the total solid discharge between October 2003 and October 2004 was estimated to be 88,000 t (mean annual ∼61,000 t). On the basis of the annual discharges between 1980 and 2004, the period analysed during this study can be considered as one of the wettest of the last 25 yrs.

### Table 1

<table>
<thead>
<tr>
<th>Core</th>
<th>Depth (cm)</th>
<th>Sediment unit</th>
<th>NOSAMS code</th>
<th>Radiocarbon age (yr)</th>
<th>Calendar age interval (AD)</th>
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</thead>
<tbody>
<tr>
<td>DC1</td>
<td>3–4</td>
<td>Unit III</td>
<td>OS-53715</td>
<td>455±35</td>
<td>[1896 :1953*]</td>
</tr>
<tr>
<td>DC1</td>
<td>8–9</td>
<td>Unit II</td>
<td>OS-53716</td>
<td>535±35</td>
<td>[1871 :1951*]</td>
</tr>
<tr>
<td>DC1</td>
<td>13–14</td>
<td>Unit II</td>
<td>OS-53717</td>
<td>550±30</td>
<td>[1866 :1951*]</td>
</tr>
<tr>
<td>DC1</td>
<td>38–39</td>
<td>Unit II</td>
<td>OS-53718</td>
<td>815±35</td>
<td>[1555 :1658]</td>
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<tr>
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<td>11–12</td>
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<td>560±30</td>
<td>[1858 :1950*]</td>
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<td>Unit III</td>
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<td>560±30</td>
<td>[1858 :1950*]</td>
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<td>Unit III</td>
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<td>[1836 :1950*]</td>
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<td>Unit I</td>
<td>OS-53722</td>
<td>640±30</td>
<td>[1710 :1852]</td>
</tr>
</tbody>
</table>

* The year 1950 is considered as the modern limit of the radiocarbon dating method.
Fig. 4. Time-series of (a) Wind speed (in m s\(^{-1}\)) measured at the Meteo France meteorological station of Torreilles (code 66212001) located near the Têt River mouth (42°45.379′N 02°58.781′E), (b) Daily river discharge of the Têt River (\(Q_d\) in m\(^3\) s\(^{-1}\)), (c) Daily discharge of Total Solids in Suspension (TSS discharge in t d\(^{-1}\)) of the Têt River estimated from Serrat et al. (2001) and measured at the POEM station 1.5 km upstream to the river mouth, (d) Significant wave height (\(H_{\text{SIG}}\) in m) measured at the POEM site 1.5 nm off the Têt River mouth, from October 2003 to October 2004. The dark grey areas correspond to the south-eastern storm events.
Between October 2003 and October 2004 three major floods of the Têt River, related to southeasterly winds, occurred with daily discharge exceeding 200 m$^3$ s$^{-1}$ (2-yr recurrence interval flood). During these three floods, which lasted 8 days, 85% of the annual solid discharge of the Têt River was exported to the coastal zone. The largest flood, in April 2004, had an estimated return period of 5 yrs ($Q_d > 280$ m$^3$ s$^{-1}$, Fig. 4b), and delivered about 35,000 t of sediments in 3 days, i.e. 40% of the annual discharge (Fig. 4c).

Fig. 5. (a) Time-series of bottom shear-stress due to current and waves estimated from GM 86 model (Grant and Madsen, 1986) from October 2003 to October 2004, and (b) Detailed stick plot of bottom currents (m s$^{-1}$), time-series of near-bed orbital velocities (in m s$^{-1}$), suspended solids concentration at 0.15 mab (in g L$^{-1}$) and seabed changes (cm) during December 2003 and February 2004, in the POEM site off the Têt River mouth. The black arrows indicate the date when sediment cores were sampled from the prodelta.
4.2. Hydrodynamics on the inner shelf

The observation period was also particularly energetic and characterized by several SE storms (Fig. 4d). Three SE events had significant wave height ($H_{SIG} > 5 \text{ m}$ (2-yr recurrence interval) and 4 SE annual events with $H_{SIG} > 3 \text{ m}$. The largest storm in December 2003 ($H_{SIG} > 8.5 \text{ m}$) had a >20 yr return period. The calculated mean bed orbital velocity, was 3 cm s$^{-1}$ during the whole experiment, and reached maximum >80 cm s$^{-1}$ during the December 2003 and February 2004 storms (Fig. 5a). Orbital velocities >35 cm s$^{-1}$ (corresponding shear stress 0.12 Pa) were sufficient to erode at least unconsolidated silts or fine sands ($D_{50} = 80 \mu \text{m}$). Such conditions occurred about 5% of the time, mainly in winter during SE storms. Typical bottom shear stresses were measured in laboratory with an annular Mini Flume (Amos et al., 2000) from sediment of the Têt inner shelf. Threshold values of 0.03 and 0.12 Pa were obtained, which correspond to the resuspension threshold for clays and fine sands, respectively (Bourrin et al., 2004). Effective bottom shear stress during these major storms reached respective values of 3 and 1.5 Pa (Fig. 5a), and near-bed suspended solids concentrations reached values of 2 and 4 g L$^{-1}$ during the storm peaks in December 2003 and February 2004 (Fig. 5b). Currents measured 2 m above the bottom ranged between 2 and 50 cm s$^{-1}$ and were mainly directed southwards.

4.3. Sediment dynamics

Storms associated with floods were qualified as “wet” storms (October and December 2003, and April 2004) and storms without floods were qualified as “dry” storms (February 2004). Such a distinction was established on the difference of their impact on sediment transport in the inner shelf of the Roussillon shelf (Guillén et al., 2006). Altimetric measurements of the seabed in this area at 28 m water depth showed that a sediment layer of 4 to 6 cm was eroded by wave resuspension during the most severe storms (the 4th December 2003 and the 21st February 2004, Fig. 5b). Few hours after the peak of the wet storm, a 1-cm-thick flood layer was immediately deposited in the Têt inner shelf. A second moderate storm (8th December 2003) provokes 3 days after, the accretion of ~4 cm of sediment. After the dry storm, no flood layer was deposited in the inner shelf. Contrariwise, continuous accretion of ~3 cm of sediment was observed several days after the dry storm (from 2nd to 9th March 2004). A second moderate event (15th March 2004) finally occurred enhancing sediment erosion until 1 cm depth.

4.4. Sediment core analysis

4.4.1. Statistical sequential analysis

The sediment monitoring of the Têt prodelta provided a series of eight 20-cm-long sediment cores (Fig. 6). Based on, facies analysis and grain-size characteristics, the sedimentary logs revealed 4 sediment types. We used the Entropy analysis method to confirm this observation. The first three distinct sediment units were labelled I, II and III from bottom to top of the core (Fig. 7). Unit I (below 14 cm depth, Fig. 7b) contains principally clays (mode=15 $\mu \text{m}$) and silts (mode=60 $\mu \text{m}$). The average median grain size ($D_{50}$) of this unit is 30 $\mu \text{m}$ and has up to 60% pelitic fraction. Unit II (9 to 14 cm depth, Fig. 7b) is composed of clays (mode=15 $\mu \text{m}$) and silts or very-fine sands (mode=70 $\mu \text{m}$). The $D_{50}$ of this unit is about 50 $\mu \text{m}$ and its pelitic fraction is comprised between 50% and 60%. The gastropod T. communis is often found in this unit. Unit III (0 to 9 cm depth, Fig. 7b) is formed by very-fine, well-sorted sands, with $D_{50}=80 \mu \text{m}$, and <40% pelitic fraction. The same granulometric modes of silts, around 20 $\mu \text{m}$, and fine sands, around 70 $\mu \text{m}$, were found in these three units but with various proportions. The 4th unit, labelled I0, was observed at the top of Unit III in two cores collected in December 2003 and February 2004. This unit, less than 3 cm thick, is composed of fluffy sediments corresponding to a mixture of mud (mode=15 $\mu \text{m}$) and organic material (2.96% and 1.49% organic carbon for December and February respectively) and has a high water content (70.5% and 49.6% respectively). The $D_{50}$ of this unit is about 50 $\mu \text{m}$ and has a pelitic fraction ~60%.

4.4.2. Annual evolution

The thickness of the units described above changed throughout the experimental year because of the impact of the different storm events. Erosion/deposition sequences directly affected the thickness of Unit III, which varied between 6 and 15 cm, and it is thus qualified as an active unit (Fig. 6). The 2-cm-thick fluffy layer (Unit I0) was first observed at the top of the core sampled in December 2003 and it was still present in February 2004. Its persistence is probably linked low waves activity during this period, whereby speeds were <15 cm s$^{-1}$ recorded between mid-December and mid-February. This flood-related layer disappeared after the dry storm event of 21st February 2004 when maximum
Fig. 6. Sedimentary logs of high-frequency monitoring cores sampled from October 2003 to October 2004 showing down-core profiles of the pelitic index (fraction of particles $< 63 \, \mu m$) and $^{210}Pb_{as}$ activities.
bottom orbital velocities reached 80 cm s$^{-1}$. No significant changes were noticed in the thickness of the other units. After that storm, the sedimentary sequences from March to September 2004 did not show any perceptible difference in grain size despite a period of high river discharge in April–May 2004 linked to spring snow melting. Only small changes were observed in the thickness of these units, probably related small-scale spatial variability. Grain-size analysis on replicate cores (10th October 2003 and 28th April 2004, Fig. 6) sampled few meters from each others show weak variability in the grain-size profiles. This variability can nevertheless affect the determination of the different units by the statistical sequential analysis over few centimetres.

4.4.3. Ecological patterns

The gastropod *T. communis* preferentially lives in terrigenous muddy environments such as prodeltas, where frequent inputs of fine sediment and fresh organic matter occur (Sartenaer, 1958). During the sampling period, SCUBA divers observed accumulations of *T. communis* on the seabed surface (28 m water depth), and especially in the depressions formed by bottom currents or by
biological activity. Several T. communis shells were found at different depths in the cores. Based on the light salmon colour of their shells, living or recently dead gastropods were commonly observed at the surface of the sediment or within the first cm of the top unit (Unit III). Also dead gastropods, characterized by dark colours (Sartenaer, 1958), were found between 3–4 cm and 15–16 cm depths.

In the 2 cores sampled after the December and February severe storms, accumulations of T. communis were found at the base of the reworked layer (Unit III) from 6 to 12 cm depth (Fig. 6).

4.4.4. Age of the sequence

The radioisotope 210Pb (T1/2 = 22.3 yrs) provides important information both about the degree of reworking of the top sediment layer (Unit III) on a century time scale, and about the input of fresh continental material in the same time. In all short cores except for the first one (10th October 2003), the top sediment layer is characterized by higher and rather homogeneous 210Pbxs activities down to ∼10 cm, corresponding approximately to the thickness of the reworked layer (Unit III) during extreme storms (Fig. 6). Mixing can be produced by physical processes such as near-bed currents or biological processes such as burrowing or feeding activities by benthic organisms (Nittrouer and Sternberg, 1981). The four sedimentary units identified in the small cores (Fig. 6) are also distinguishable in the 210Pb profiles. The mean value of 210Pbxs activity in the top unit (Unit III) was 25 Bq kg⁻¹. The intermediate Unit II presented an almost linear decrease of 210Pbxs activities from 25 to 5 Bq kg⁻¹, activity found in the Unit I. The flood layer (Unit I0, Fig. 6) was characterized by high 210Pbxs activities reaching 80 Bq kg⁻¹ in December 2003.

Radiocarbon dating of T. communis shells was performed on Units III, II, I in small cores collected in April 2004 and June 2004 (Table 1). All the shells in Unit III located from surface to 8 cm depth showed similar recent ages from 1836 to 1950* AD (modern). We obtained the same interval of ages for the shells in Unit II located between 8 and 14 cm depth (Fig. 6). Radiocarbon dating at the base of Unit I gives an age of 1710–1852 AD. Radiocarbon and 210Pb dating thus suggest that the top sequence of about 10 cm thick was formed during a period of about one century.

4.5. Long-term sedimentary signal

The 85-cm-long sediment core (DC1) was also analysed using the Entropy method (Fig. 9b). Based on the characteristics of Units I, II, III of the small cores, three larger sedimentary sequences can be identified. The uppermost sequence, from 0 to 20 cm deep, consists of a succession of the three units described above and identical to the units of the small cores and represents the modern sedimentary sequence. Indeed, radiocarbon dating in the top unit (Unit III) of this sequence yielded ages ranging from 1866 to 1953 AD (modern) (Fig. 9a and Table 1). The next sequence, from 20 to 45 cm deep, is formed by the succession of Units III, II, I and constitutes a fining-up sequence. Shell fragments, mud clasts and organic debris were observed at around 30 cm in the Unit II. Radiocarbon dating at the base of this unit (38–39 cm) showed an age of 1555–1658 AD. The lowest sequence extends from 45 cm deep to the bottom of the core. It is formed by a coarsening-up sedimentary sequence and lies on a gravel and pebble layer containing mollusc shells. Grain-size trends of the small core and the long core show similar increase of the % of <63 μm sediment fraction from the surface (Fig. 9d).

As in the short cores, the top of DC1 is characterized by higher 210Pbxs activities (Fig. 9c). No surface mixed layer was found in the long core. Below that layer, the linear decrease of 210Pbxs activities are the same until supported 210Pb is reached at around 12 cm depth, corresponding to the secular limit of the sedimentary sequence. Based on 210Pbxs profile and from CRS model, mean sedimentation rate of 0.085 cm yr⁻¹ was found for the long core. Radiocarbon ages provided mean accumulation rates of 0.035 cm yr⁻¹ at 3–4 cm depth and 0.123 cm yr⁻¹ at 39 cm depth, thus confirming the slow and variable accumulation rate on the Têt prodelta during the last millenia period.

5. Discussion

5.1. Modern strata formation in inner-shelf environments

5.1.1. Preservation of flood layers

The main mechanisms leading to the formation of new sediment layers front to river mouths were recently investigated in the Gulf of Lions (Pauc, 2005; Guillén et al., 2006; Maillet et al., 2006) and in other continental shelves (Wheatcroft and Borgeld, 2000; Curran et al., 2002; Wheatcroft et al., 2006). The larger fraction of riverborne particles (silts and very-fine sands) is first deposited during flood in the vicinity of the mouth. The finer fraction flowing in surface hypopycnal plume settled after electro-chemical flocculation processes and can reach few tens of kilometres in the case of small rivers (Drake, 1976). The resulting bottom flood layer is
then composed of a thin layer of silts and very-fine sands, overlaid by a fine particle layer enriched in organic matter. Time-series observations of cores clearly showed the presence a few cm-thick fluffy deposit (Unit I₀) at the top of the core the 12th December 2003, on the Têt prodelta after the wet storm (4th December 2003) and the consecutive moderate storm event (8th December 2003) (Fig. 8a). But sediment core only give information on the record of past events and the sequence of the events is difficult to analyse with such information. Details are provided by altimetric measurements (Fig 8b) and showed that a 1-cm flood layer was previously deposited following the flood event of the 4th December 2003. Then a moderate second storm induced sediment accretion at least back to the pre-storm seabed level. This storm, non-associated with significant river discharge, promoted the advection of shallower material previously deposited in the nearshore during the flood to the inner-shelf on the Têt prodelta. This flood layer persisted only 2 months before a new storm event totally swept this freshly deposited and non-consolidated sediment material. During the second event (dry storm), no flood occurred and few material was available in the nearshore zone to be advected to the inner-shelf. The conditions to observe the deposit of a flood layer on the Têt inner-shelf thus depend strongly to the pre-flood conditions and the succession of the events (flood and storm) (Guillén et al., 2006). The adjustment of each sediment cores at base of the Unit II, where a drop in sediment grain-size is observed, clearly shows the similarity between high-frequency altimetric measurements and core sampling (Fig. 8). This sequence of events confirms previous observations on the inner shelf of the Têt River, which showed the presence of an ephemeral fluid mud layer that persisted for only 1 month (Courp and Monaco, 1990). The only way modern sediment strata can be created on this type of inner shelf characterized by energetic wave conditions would be by an increase in flood events over very short time periods. Deposition of a new flood layer on top of a recently deposited layer could prevent the latter from being eroded and/or bioturbated in the surface mixed layer (Wheatcroft and Drake, 2003).

5.1.2. Storm bed thickness

Another important topic to discuss in the Têt River inner-shelf is the storm bed thickness. Preferential accumulation of dead gastropods was observed in Unit III (Fig. 8a) and can be explained by the reworking of the upper sediment layer during the most severe storms (i.e. 8th December 2003 and 21st February 2004). While fine sediment particles were rapidly winnowed during the onset of the storms, coarser sandy particles and shells could be remobilised during the peak of the storm with maximum orbital speeds of up to 80 cm s⁻¹. During the declining phase of the storm, coarse particles and shells settle first, and were thus found at the base of the reworked layer (Unit III). These shells were
subsequently covered by a mixture of sediment advected from shallower areas and from the Têt River. Accumulation of gastropod shells at the base of Unit III seems therefore to be a good marker for estimating the depth at which sediment was reworked by bottom currents. As other have noted (Wiberg, 2000), storm bed thickness depend on current and waves conditions. For the conditions occurred in December 2003 ($u_b>1$ m/s and $u>0.4$ m/s towards the southeast) and February 2004 ($u_b>0.9$ m/s and $u>0.4$ m/s towards the southeast) on the Têt prodelta, the model of Wiberg (2000) predicts a storm bed thickness of about 1–2 cm at 50 m depth. Measured storm bed thickness in this study is significantly higher. These values depend on in-situ altimetric measurements at a shallower site (28 m), and show sediment erosion of ~5 cm during severe storm events. Furthermore, there is no net deposition immediately during the declining phase of the storm. Only deposition of a thin flood layer was observed with a time lag of a few hours after the dry storm. Winnowing of the fines and advection toward the southeast, few fresh materials available for advection from the nearshore, was explained for the sediment divergence creating such erosion levels at the study site.

5.2. Multi-scale sedimentary record

5.2.1. Secular sediment budget

Prodeltas of the northwestern Mediterranean Sea characterized by a high content of clay minerals were extensively mapped in the 1980s (Aloïsi and Monaco, 1975) and more recently, on the basis of trace metals at the seabed surface (Roussiez et al., 2005). Prodeltas surface areas in the western Gulf of Lions were thus calculated from the integration of such data in GIS software (Bourrin et al., 2006). The depth where supported $^{210}$Pb activities are reached corresponds approximately to the lower limit of the sedimentary record of these prodeltas of the last century (~12 cm depth on the Têt prodelta, Fig. 8a). Bourrin et al. (2006) have estimated that only a small fraction (~20%) of the fine sediment freshly deposited on the prodelta area remained in place. In a nearby similar prodelta influenced by sediment supply from three coastal rivers (the Aude, Orb and Hérault), sediment retention was estimated to be ~40% using the same method based on $^{210}$Pb mass accumulation rates. The mean $^{210}$Pb mass accumulation and sedimentation rates calculated from the whole series of small cores is 0.11 g cm$^{-2}$ yr$^{-1}$ (min=0.09, max=0.16) and 0.07 cm yr$^{-1}$, respectively. $^{210}$Pb mass accumulation rates from others cores sampled in this area give similar values (Roussiez, 2006; Table 2) and thus comfort the estimated retained sediment fraction in these prodeltas. Thus, under present day conditions, most of the sediment entering the western Gulf of Lions by small coastal rivers, bypasses prodelta areas and is advected southward and seaward on century time scales. In this type of prodelta, the secular sedimentation rate results from the predominance of hydrodynamic forcing over the discontinuous and weak sediment supply, and only a limited fraction (~20%) of sediment is trapped in the proximal portion of the dispersal system.

The balance between the total amount of fresh sedimentary material introduced into the coastal area and the frequency and strength of resuspension events in the inner shelf of continental margins can lead to various sedimentary records in prodeltaic environments. In prodeltas where large inputs of fresh material occur, the sediment accumulation rate is greater than the erosion rate and a sedimentary signal can be preserved (Fernandez, 1984; Aloïsi, 1986; Wheatcroft et al., 2006). It has been shown using high-resolution pollen analyses that proximal to the mouths of large rivers (e.g. the Rhône), entire sedimentary sequences representing seasonal variations can be retained (Touzani and Giresse, 2002; Beaudouin et al., 2005). Nevertheless, the number of disturbed or incomplete sequences showed that about 50% of the total amount of sediment freshly deposited in the Rhône prodelta is subsequently resuspended by nearbed orbital currents. Also, off the flood-prone mountainous Eel River, a maximum of 20% of sediment introduced into the coastal area is generally retained on event and century time scales (Wheatcroft et al., 1997; Sommerfield and Nittrouer, 1999). However, geochronology reveals that catastrophic flash-floods can generate long-term accumulation layers of fine-grain sediment near river mouths. In the case of small event-dominated prodeltas influenced by flash floods, such as the Têt prodelta, the sedimentary record seems to be more complex. A large number of meteorological

<table>
<thead>
<tr>
<th>Core Location (degrees)</th>
<th>Depth (m)</th>
<th>$^{210}$Pb mass accumulation rate (g/cm$^2$/an)</th>
</tr>
</thead>
<tbody>
<tr>
<td>35 42.716N, 3.065E</td>
<td>26</td>
<td>0.14</td>
</tr>
<tr>
<td>POEM 42.704N, 3.067E</td>
<td>28</td>
<td>0.11 (0.09–0.16)</td>
</tr>
<tr>
<td>351 bis 42.699N, 3.090E</td>
<td>33</td>
<td>0.182</td>
</tr>
<tr>
<td>353 42.712N, 3.152E</td>
<td>51</td>
<td>0.21</td>
</tr>
<tr>
<td>37 bis 42.582N, 3.206E</td>
<td>81</td>
<td>0.15</td>
</tr>
</tbody>
</table>
events can rework the same active, few-cm-thick layer. As an example, during the last century, the biggest flood event ever described in this area, “the Aïguat” of 1940 (Desailly, 1990), provided such a huge quantity of sediment to the inner shelf that the aerial delta prograded by more than 250 m into the sea. A comparison of aerial photographs before and after this catastrophic flood event clearly showed that the delta had been eroded since then by the littoral drift and, in fact, in the prodeltaic sedimentary record there is no evidence of such an event. The flood layer deposited on the prodelta has probably been levelled, eroded by wave resuspension and redistributed southward (Delpont and Motti, 1994). In present day conditions, the low inputs of sediment to the coastal area are not sufficient to counterbalance enhanced erosion during storms, reducing the preservation potential. In this case, the sedimentary record is assumed to be merely a low frequency signal of the meteorological events affecting the system. The variation of sediment characteristics with depth is then the expression of long-term variations of the prodelta dynamics due to climatic changes and/or changes in mean sea level.

5.2.2. Secular to late-Holocene sedimentary record

The high-frequency analysis of Têt prodelta modern sequence has been extrapolated to analyse the long-term sedimentary record in the same environment (DC1 core, Fig. 9). Sediments exposed to the same hydrodynamic conditions in modern or geological timescales have the same grain-size characteristics (Fig. 9c). The modern (upper) sequence of the Têt prodelta is expressed by the succession of Units III, II, I overlapped by a flood layer (Unit I0). Unit I is found several times in the Têt prodelta long-term sedimentary record. Unit I is found between 14 and 20 cm depth and shows a radiocarbon age of 1710–1852 AD (Fig. 6). This unit is interpreted as the expression of more continuous sedimentation in the coastal zone compared to the present day. It appears from the literature (Benech, 1993) and archives (Desailly, 1990) that the period of the Little Ice Age (~1550–1850 AD) was characterized by an increase in the number of severe flooding events in the catchment area of the Roussillon rivers area linked to the Pyrenees mountains. The same events were recorded for the Rhône during the same period (Sabatier et al., 2006). This period of enhanced precipitation was also accompanied by human deforestation activities in the catchment area inducing higher continental sediment inputs to the coastal area (Vella et al., 2005). This period was thus favourable to the progression of the sandy coast and the build-up and conservation of a muddy prodelta on the Roussillon inner shelf. It is suggested that Units II and III, at the top of the modern sediment sequence, were formed from the muddy Unit I by mechanical transformation and winnowing of the fine fraction during successive storm events, at a time of limited sediment supply from rivers and increased number of storms. Unit II was then formed from Unit I and Unit III from Unit II by the same mechanism. The bottom units would be progressively isolated from surface hydodynamics as sedimentation develops.

In fact, the top sediment layer becomes coarser as it is depleted of its fine fraction during successive storms reaching the coastal zone. The low sediment accumulation rate on the Têt prodelta would then result from a build up of mixed and sorted sediment within a frequently reworked layer of about 10 cm thick. The coarsening of the surface layer was also observed by biologists who have observed a generalized change in the benthic macrofaunal populations in the coastal zone since the 1960s (Grémare et al., 1998). They hypothesized that this modification could have been caused by temporal changes of the sediment inputs from the Rhône and the small coastal rivers and by the frequency of easterly storms. Durand (1999) found evidence of an increase in the number and strength of storms in the Gulf of Lions from the 1980s onwards. Furthermore, river bed mining and the construction of flood-control dams (Ludwig and Probst, 1998) has substantially decreased continental inputs from rivers. The preservation of a muddy layer would then be the expression of the close juxtaposition of two flood events (Wheatcroft and Drake, 2003), and/or a long-term predominance of strong sediment supply by rivers over hydrodynamic conditions, like during the Little Ice Age.

Two other sequences composed by the succession of Units III, II, and I are found in the long-term record of the Têt prodelta and could have been formed under similar conditions to those of the present day. The sedimentary sequence found under the modern sequence (between 20 and 45 cm depth) is formed by heterogeneous layers of silts and clays. This median sequence, with an age ranging between 1555 and 1658 AD, is a coarsening-up sequence and suggest dynamic conditions different to those prevailing during the formation of the modern and basal sequences. This could be due to a change in sediment river supply due to climatic conditions, or to local variations in coastal morphology related to a change in the mean sea level. If present-day dynamic processes are extrapolated to this sequence, Units III and II at 45 and 60 cm depth, respectively, could have been formed by the reworking of the underlying prodeltaic unit (Unit I). The lowest
prodeltaic unit (Unit I), located at the base of the lower sequence (at ~ 70 cm depth), could be the expression of a high sedimentation period between the higher than present sea-level stand (+2 m at 4,500 cal yrs BP) in western Mediterranean sea and the present day sea-level, stabilized some 2,000 cal yrs BP in the Roussillon.
coastal zone (Aloïsi et al., 1978). The bottom layer, formed by sands and gravels, at the base of core DC1, is similar to an old beach facies described at other locations in the Gulf of Lions, the base layer of part of the Holocene sedimentary record in this region (Monaco, 1971; Tesson et al., 2005). The coarsening of the basal sequence could be related to a deceleration of sediment inputs from local rivers and/or to a period of upsurge in the number of storms in the area as under present day conditions. If we assume an age of ∼2000 cal yrs BP for this base layer and a mean sedimentation rate of ∼0.1 cm yr⁻¹ for the whole sedimentary record of the Têt prodelta, we certainly have some lacks of sedimentation. This sedimentary record of a small prodelta thus renders a complex signal of the last millennia to the late-Holocene period. Others sediment cores sampled in the Têt inner-shelf also have a complex organisation (Fig. 2), and the base of these cores could correspond to a base layer of the Holocene period. Others cores sampled seaward (Fig. 2) have a more continuous record and can be used to analyse the sedimentation of the continental margin during the whole Holocene period. The interpretation of the sedimentary record of such small coastal systems to analyse past conditions must then be done very carefully because of the presence of discontinuity in the signal of the last millennia.

6. Conclusions

Deposition of fine riverborne particles after extreme floods appears to be the main mechanism governing the formation of new sediment strata on the Têt prodelta. Their preservation is conditioned by the intensity of post-depositional reworking by wave events. On the Têt prodelta, flood layers were often observed after flood events and their residence time was less than 2 months due to waves resuspension during SE marine storms, showing that present day hydrodynamic conditions do not allow the preservation of intact sediment strata on the Têt inner shelf. The secular ²¹⁰Pb sedimentation rate is very low (0.07 cm yr⁻¹), and only ∼20% of the continental material entering the coastal zone is retained in the inner shelf. The modern sedimentary record of the Têt prodelta is a complex signal resulting from the balance between few sedimentary inputs and the frequency and strength of storm events. This record builds up as mixed and sorted sediments within a frequently reworked layer about 10 cm thick. In present day conditions, sediment in the top sediment layer of the Têt prodelta is characterized by a grain-size coarsening due both to the decrease of solid river discharge since the end of the XIXth century and the winnowing of fine particles during severe storm events.

Older preserved muddy prodeltaic units were observed in the Têt prodelta last-millennia sedimentary signal. These phases are interpreted as periods of river sediment load increase or by extreme flash-flood events, and thus as periods of higher potential for the preservation of muddy sediment on the prodelta area. As an example, the Little Ice Age (∼1550–1850 AD) as a period during which human activities in the mountainous catchment areas led to deforestation and more easily erodible lands. This period, also observed in similar Mediterranean environments, was favourable to the increase of suspended solid river discharges and the formation of a muddy prodelta on the Têt inner shelf.

The last-millennia sedimentary record of the Têt prodelta is characterized by preserved prodeltaic units during phases of high sedimentation intersected by heterogeneous sedimentation phases during energetic periods as under present day conditions. The formation mechanisms of such environments, and thus their sedimentary record, should be the same for prodeltas located in microtidal seas influenced by meteorological events such as floods and storms. Thus, small prodeltas record the long-term succession of meteorological events as a low frequency signal. But we have to be very careful when analysing and interpreting this signal in terms of long-term variations of climate change and/or human impact. If no complete signal is available elsewhere in front of large systems, then it can be interesting to analyse sedimentary records in front of small-size systems. Independently of the river size, deltaic/prodeltaic environments on inner shelves, lagoons or lakes, develop sedimentary records that can be used to analyse the variability of past environmental conditions.

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