Holocene evolution of a Languedocian lagoonal environment controlled by inherited coastal morphology (northern Gulf of Lions, France)

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Abstract. – The Maguelone shore extends along the northern coast of the Gulf of Lions margin, West of the Rhône delta and East of some high gradient coastal streams that have been providing most of the clastic sediments to the Gulf of Lions margin since the early Miocene. This 10 km wide area comprises an onshore small coastal watershed (15 km long) in low-lying carbonate hills, kilometer wide marshes, sandy beach and shoreline featuring local low sedimentation. Deposit architecture in such a coastal zone records dynamics of incised valley fill under the influence of rivers and wave/current hydrodynamics in a microtidal environment during an eustatic cycle.

A detailed analysis of about 250 km of very high resolution seismic profiles, tens of cores and outcrops data revealed the evolution of the Maguelone coastal system from Late-Quaternary to present-day. It highlighted also dominant denudation processes in the upstream catchments associated to the formation of incised valley seaward during Quaternary. Combination of this inherited morphology together with hydrodynamics controlled the lagoonal environment evolution since the last transgression. In particular, the Maguelone shore is characterized by the formation of built-over-rias lagoonal systems and records an evolution from partially protected lagoon to isolated lagoon environment. These two stages of lagoon evolution correspond to distinct deposit environments. Correlation of fauna contents with deposit geometry improves lagoonal environment models.

INTRODUCTION

As for most sedimentary environments, climatic cycles control sedimentary architecture and morphology of coastal zones at the geological time scale [Thorne and Swift, 1991; Cattaneo and Steel, 2003; Vella et al., 2005 and Jouet et al., 2006]. Conversely, detailed stratigraphic analyses of littoral deposits can reveal sea level changes, history of erosion/deposition and records of other processes under partial climatic control. In this general context, many studies deal with
the reconstruction of coastal architectures during the last post-glacial transgression and highstand to characterize the recent morphological and depositional dynamics [Vella et al., 2005; Storms et al., 2008]. To meet this objective, some studies focus on coastal incised valleys formed during previous lowstand. Such inherited morphologies are privileged areas of sedimentation during sea-level rise [e.g. Clauzon et al., 1987; Clauzon, 1990; Boyd et al., 1998; Weber et al., 2004; Duvail et al., 2005 and Chaumillon et al., 2008]. They display high sedimentation rates and good preservation of deposits, and record also combined effects of river-controlled processes and of wave/wind-driven hydrodynamics.

The littoral of Gulf of Lions (northern Mediterranean Sea) is characterized by kilometre-wide lagoons separated from the sea by emerged sandy barriers a few tens of metres wide. This peculiar morphology results from a well-known process of shore construction by waves and currents in a microtidal environment [Barusseau et al., 1996; Certain et al., 2005b; Short, 1999]. The Maguelone shore extends between the Rhône delta to the East and high gradient coastal streams to the West. One striking feature of the Maguelone shore is the fact that a mosaic of numerous outcrops of rocks ranging from Late Pliocene to Holocene occurs onshore [Alabouvette et al., 2003]. This shows that erosion processes dominated the pre-Holocene landscape formation, with possible formation of incised valleys; it suggests that thicknesses of Holocene deposits are small.

In this paper, we analyse the architecture of Holocene coastal deposits of the Maguelone shore thanks to very high resolution seismic profiles, together with short cores and outcrop data. From this reconstruction, we determine the evolution of the Maguelone shore from Late Quaternary to present-day. This paper highlights the existence of incised valleys under the present littoral zone and their role in the preservation of Holocene deposits. The emphasis of this topographic inheritance on the Holocene sediment dynamics is discussed. It is also highlighted how lagoons can form on the long term time scale.

**GENERAL SETTING**

**Morphological setting**

The Maguelone shore is a 10 km long littoral segment located along the Languedocian coast in the Gulf of Lions, closed to Montpellier city (fig. 1). Basically, the Maguelone shore is a wind/wave-dominated microtidal sandy system, characterized by several km wide lagoons isolated from the open sea by a narrow beach barrier. Existing inlets between lagoons and open sea are artificial. At present time, lagoons are less than 2 metres deep. At sea, the shoreface is an association of unconsolidated sand deposits and rocky plateaus (fig. 1). These plateaus are made of continental, lacustrine or marine Pliocene formations, and continental conglomeratic Pleistocene series [Alabouvette et al., 2003]. The Maguelone shore includes also a small coastal watershed onshore, in low-lying carbonate hills made of Mesozoic limestone, Cenozoic detritic deposits (conglomerate, carbonate sandstone and clay), partly covered by a patchwork of discontinuous decametre-thick sedimentary formations ranging from Pliocene to Holocene in age [Alabouvette et al., 2003].

**Hydrodynamics and sediment fluxes**

The Maguelone shore is microtidal, with a maximal tide range of about 40 cm. Typical wave climate can be derived from real-time wave measurements at Sète buoy station (located 6 km seaward Sète harbour, at a water depth of 50 m) since 1988. Major wave incidences are from southeast and south, with rare but highly energetic waves from southwest. Fair weather waves occur 88% a year (Hₐ=0.84 m; Tₘ=4.2 s) and storm conditions may result in waves of the order of several metres in height. Wind forcing is extracted from Sète harbour and Montpellier airport wind stations. The major wind forcing on the Maguelone shore is Mistral (northeasterly wind) and Tramontane (northwesterly wind). Storm wave conditions are usually associated to southeasterly or southerly winds. At the continental shelf scale, water circulation is driven by wind/buoyancy and north-westernmost Mediterranean circulation (locally termed Northern Current), well evidenced by measurements and simulations [Millot, 1990; and subsequent litterature]. To the nearshore, wave incidence with respect to coastline orientation defines a mean alongshore drift oriented southwestward, that inverts...
during storms from south or southwest. In addition, wave-driven currents and classical wind/buoyancy-driven circulation interact at the inner shelf scale [Denamiel, 2006] and may generate at the coast alongshore drifts oriented southwestward alternately with northeastward ones, depending on the wave and wind combined forcing conditions. The Maguelone shore shows typical morphological sand features (sand deposition and erosion in the lee of coastal defence structures) that demonstrate that the net longshore sediment drift is southwestwards, except in the eastern Maguelone shore where some morphological structures argue for a northeastward drift. The change in orientation of the alongshore drift is not well located.

The river Mosson (15 km long) drains a small catchment area (370 km²), and supplies fine sediment (silt and clay) to the Maguelone lagoons during flash flood events mainly. Mosson River average flow is 1.2 m³/s but has reached 258 m³/s during the December 3rd 2003 flash flood event [DIREN, 2009]. Additionally, a longer coastal river named Lez (~30 km long) supplies sediment to the shoreface, eastern Maguelone shore. The main sediment flux [Certain, 2002; Pont et al., 2002] comes from the Rhône river located 50 km to the East.

**Gulf of Lions geological background**

In the Gulf of Lions, the Pliocene began with the flooding of the Mediterranean basin at the end of the Messinian salinity crisis [Hsü et al., 1973], termed the Zanclean transgression. Messinian canyons, formed during fall of sea level that started around 5-6 Ma [Gautier et al., 1994; Krijgsman et al., 1999 and Lofi, 2002], were flooded and formed the Early Pliocene rias. Several studies show that the sedimentary filling of incised valleys correspond to Gilbert delta [Clauzon et al., 1987; Clauzon, 1990 and Duval et al., 2005]. At the top of these formations Early Pliocene in age, prograding sedimentary wedges quickly migrated seaward and covered the Messinian erosion surface. Thanks to seismic profile analysis, Lofi et al. [2003] proposed a model of three distinct prograding wedges Early Pliocene, Middle Pliocene and Late Pliocene/Quaternary in age. The most recent wedge is more than 1000 m thick in the outer-shelf. At a higher resolution, the upper part of this wedge contains several regional scale prograding units, separated by erosion surfaces [Tesson et al., 1990; Tesson and Gensous, 1998 and Rabineau et al., 2006]. These units were interpreted as lowstand prograding wedges that took place during successive sea-level falls of Pleistocene glacio-eustatic cycles [Posamentier et al., 1992; Jouet et al., 2006]. Onshore, Duval et al. [2001] and Alabouvette et al. [2003] observed imbricated terrace systems along the main Roussillon and Languedocian rivers. Their formation is linked to Pleistocene glaciation cycles. During the last deglacial stage, a Rhône subaqueous delta occurred in the middle/inner shelf, precisely from 15000 to 10500 cal. yr B.P. These deposits correspond to a major transgressive tract on the shelf [Berné et al., 2007]. The present study area corresponds to the coastal zone and links onshore environments to the continental shelf.

**METHODS AND DATA**

Datasets acquired for the present study are presented in figure 1B. They consist of: 1) 250 km of very high resolution (VHR) seismic data acquired from 2003 to 2007 offshore and in lagoons during CALAMARS and BEACHMED-e European cruises, 2) 1 to 15 m long cores collected in the framework of the projects PROGELAC, ECLICA and ALLIANCE (2003). Numerous samples were extracted for ^14C dating.

**Coastal and lagoonal VHR seismic profiles**

At sea and in lagoons, seismic profiles were acquired with an IKB-Seistec boomer (CALAMARS Survey). In addition, a surface tow boomer from applied acoustics was used at sea exclusively (BEACHMED-e, IX-Survey). The IKB-Seistec boomer device is a 2 m long catamaran characterized by a horizontal offset of 0.5 m between the source (boomer plate) and a line-in-cone receiver. It is well adapted to shallow water environments. It was used with frequencies ranging from 4 kHz to 9 kHz and a signal energy from 50 to 200 J. Seismic data were acquired with the Delph 2.3 software. The applied acoustic device is composed of a 1500 J source mounted on a catamaran and of a single-channel streamer. Seismic data were acquired with an Octopus 360 signal processor and a Coda DA200 digital recording system.

The seismic data were converted in SEG-Y format and processed with Bash scripts (www.gladys-littoral.org) on the basis of Seismic Unix tools [Cohen and Stockwell, 2001] together with GMT [Akima, 1979; Wessel and Smith, 1998].

Lack of seismic data in Arnel lagoon, north Maguelone Cathedrale (fig. 1B) is due to a water depth less than 20 cm.

Identification of seismic units and their boundaries relies on the analysis of seismic data following a classical seismic stratigraphic method (in terms of reflector terminations and configurations) [Mitchum and Vail, 1977].

**Cores and datations**

Numerous cores were acquired in the present-day Maguelone shore. Six cores were used in this study: MAG-1, TOTH-1, M5-1, M5-2, AR06, PB06 (fig. 1B). The longest cores (MAG-1 and TOTH-1) were collected from the beach barrier and the Mosson delta by a Triplex method. This method requires a steel corer tube including two distinct sleeves. During coring, the rotation of the outer sleeve is dissociated from that of the internal sleeve. This drastically reduces the deformation of the sediment contained in the inner sleeve and maximizes the amount of retrieved material (about 97%). Cores AR06 and PB06, about 3 m and 7.80 m long respectively, was extracted with the hammer coring platform of University of Savoie (Chambery). Short cores M5-1 and M5-2 were extracted manually with PVC tubes.

In the laboratory, cores were split, photographed, logged in details (measurement of physical proxies, determination of biogenic sedimentary structures and of vertical facies succession with a resolution of one centimetre). In core PB06, macro-fauna content analyses were performed on 2 cm long sections. To study mollusc shells, samples were sieved at 1 mm and the number of individuals of all
species was counted (every 2 cm). The most representative molluscs of lagoonal environments are *Hydrobia acuta*, *Abra ovata*, *Cerastoderma glaucum* and *Rissoa ventricosa* [Dezileau et al., 2005; Sabatier et al., 2008].

$^{14}$C analyses in the cores MAG-1, TOTH-1 and AR06 (table I) were conducted at the “Laboratoire de Mesure $^{14}$C” at Saclay (LM14C) in the framework of the ARTEMIS project. The dating $M_{5.1}$-45 in the core $M_{5.1}$-1 was conducted at the Beta Analytic Radiocarbon Dating Laboratory at Miami in 2004. $^{14}$C age calibrations were computed with the Calib 5.0.2 software [Hughen et al., 2004] at two standard deviations. Reservoir age in lagoon environments of the Mediterranean region is high due to a strong continental carbon contribution [Siani et al., 2000 and Zoppi et al., 2001]. The reservoir age used in this study has been estimated by Sabatier et al. [2009] at about 943 +/- 25 years, by extrapolating the reservoir age measured at the seabed and by correlation with Pb$^{210}$ data. In marine facies, reservoir age used for calibration is 618 +/- 30 years.

RESULTS

Seismic units

Basement Upl and regional erosional surface

Acoustic basement Upl is the deepest unit that was observed in the study area. The base of this unit is not observed, neither on seismic data (fig. 2 and fig. 3) nor in the deepest core. Where the seismic signal is good, Upl displays thick seismic facies including continuous and very high-amplitude reflections (fig. 4C). These reflections present a southward gentle dip on cross-shore sections and a low-amplitude folding on alongshore sections (fig. 3B). In some cases, Upl consists of transparent or chaotic reflections, with some undulating sub-parallel discontinuous high-amplitude reflections (fig. 3A). These facies characterize seismic zones where there is no major reflection (fig. 4D) and where seismic signal is blurred (fig. 4E) respectively. Upl is separated from overlying formation U1 by an erosional surface, illustrated by significant seismic facies changes and truncated reflections. Where Upl unit is overlaid by any other units (U2, U3L, U3F), its top corresponds to a Regional Erosional Surface (= RES), as testified by truncated reflections (fig. 3). The RES forms a highly uneven surface that fits locally with the present-day seafloor (fig. 3B). To the east, the RES passes to the marine Palavas plateau and to the marine Maguelone plateau (fig. 3A). To the west, it coincides with the Aresquiers marine plateau. The RES displays two major incisions 10 to 15 m deep and 200 m long. The main directions of these incisions are roughly perpendicular to the present-day coastline. One of the incisions is located off the city of Palavas, and the other is off the Vic lagoon (fig. 3B).

Unit U1

In this paper, the seismic unit U1 groups all sub-units flanked by Upl and the RES (fig. 2 and fig. 3A). Unit U1 fills the highly irregular top of Upl (fig. 2A and fig. 3A). It forms hundreds of meters long and meters thick bodies of limited lateral extension. These deposits display chaotic seismic facies mainly with some low-amplitude reflections. This facies corresponds to disorganized and discontinuous reflections (fig. 4E). Figures 2B and 2C show that, in lagoon area, unit U1 is composed of three distinct sub-units termed U1-1, U1-2 and U1-3. These sub-units display different seismic facies and are separated by erosional surfaces. The first sub-unit, U1-1, is characterized by transparent or chaotic reflections with some irregular and discontinuous high-amplitude reflections which form trough. The top of U1-1 is an uneven erosional surface as illustrated by truncated reflections. U1-2 consists of parallel facies (fig. 4A). It fills depressions and presents some draping reflections at the base. The top of U1-2 corresponds to a plane surface at the seismic profile scale. U1-3 consists of sigmoid cliniform seismic facies as illustrated by downlap reflections on the base surface. A 3D detailed analysis of U1-3 on all seismic profiles gives evidence of a fan delta-like geometry prograding south-westward (fig. 5A). U1-3 is exclusively located in the north of Vic lagoon. In the same area, another smaller fan delta progrades south-eastward. The top of unit U1 corresponds to the RES surface. The RES surface is diachronic and corresponds to the top of U1 and Upl.

Unit U2

The base of unit U2 corresponds to the RES everywhere it was observed. U2 fills paleo-topographic depressions of the RES. Raynal et al. [2009] show that U2 consists in stacked prograding sets (U2-1, U2-2 and U2-3, fig. 3B) that display

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**Table I.** $^{14}$C datations from sediment cores in marine and lagoonal domain. $^{14}$C age calibrations were computed with the Calib 5.0.2 software [Hughen et al., 2004] at two standard deviations. In marine facies, reservoir age (R) used for calibration is 618 +/- 30 yr. In lagoonal facies, reservoir age used is 943 +/- 25 yr (Sabatier et al., 2008). Depth WRT present-day s.l = Depth with respect to present-day mean sea-level.

<table>
<thead>
<tr>
<th>Core</th>
<th>Position</th>
<th>Name</th>
<th>Depth WRT present-day s.l.</th>
<th>Material</th>
<th>Lithological facies</th>
<th>Age BP</th>
<th>Age cal. BP</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAG-1</td>
<td>sandy</td>
<td>M377</td>
<td>377 cm</td>
<td>Abra ovata</td>
<td>sand</td>
<td>2405 +/- 30</td>
<td>1745 +/- 120</td>
</tr>
<tr>
<td></td>
<td>barrier</td>
<td>M370</td>
<td>730 cm</td>
<td>Cerastoderma glaucum</td>
<td>lagoonal sand</td>
<td>5470 +/- 35</td>
<td>5590 +/- 110</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M580</td>
<td>880 cm</td>
<td>Rissoa ventricosa</td>
<td>biodiastic sand</td>
<td>5405 +/- 40</td>
<td>5525 +/- 115</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M1250</td>
<td>1150 cm</td>
<td>Oyster</td>
<td>brood</td>
<td>245600</td>
<td>&gt;= 45500</td>
</tr>
<tr>
<td>TOTH-1</td>
<td>Moscou</td>
<td>T600</td>
<td>600 cm</td>
<td>Cerastoderma glaucum</td>
<td>lagoonal sand</td>
<td>3320 +/- 70</td>
<td>2850 +/- 145</td>
</tr>
<tr>
<td></td>
<td>river delta</td>
<td>T1520</td>
<td>1520 cm</td>
<td>Rissoa ventricosa</td>
<td>biodiastic sand</td>
<td>6200 +/- 40</td>
<td>6430 +/- 130</td>
</tr>
<tr>
<td></td>
<td></td>
<td>T2000</td>
<td>2000 cm</td>
<td>Abra ovata</td>
<td>brood</td>
<td>7400 +/- 40</td>
<td>7650 +/- 110</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MS-15</td>
<td>15 cm</td>
<td>Organic sediment</td>
<td>lagoonal sand</td>
<td>9620 +/- 170</td>
<td>9650 +/- 160</td>
</tr>
<tr>
<td>A108</td>
<td>lagoon</td>
<td>A108-332</td>
<td>332 cm</td>
<td>Cerastoderma glaucum</td>
<td>lagoonal sand</td>
<td>4995 +/- 30</td>
<td>5095 +/- 145</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A108-335</td>
<td>335 cm</td>
<td>Cerastoderma glaucum</td>
<td>maris sand</td>
<td>5753 +/- 30</td>
<td>5850 +/- 140</td>
</tr>
<tr>
<td></td>
<td></td>
<td>P108-170</td>
<td>170 cm</td>
<td>Cerastoderma glaucum</td>
<td>lagoonal sand</td>
<td>1780 +/- 30</td>
<td>1740 +/- 30</td>
</tr>
</tbody>
</table>

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internal erosion surfaces arguing for alternated episodes of erosion and progradation. The southwestward kilometer long progradation is roughly consistent with that of the present day coastline. The top of U2 corresponds to a smooth erosional surface, which fits to the present day seafloor.

**Unit U3F**

The base of this seismic unit corresponds to the RES. U3F is located exclusively on the main incision in Vic lagoon (fig. 2B). This incision is tens of m wide (up to 200 m) and displays meanders (fig. 5). This incised valley presents a mean southwestward orientation. To the base, U3F is mainly aggradational with draping parallel facies. The upper part of U3F displays sigmoidal clinof orm reflections in opposite directions (fig. 2B). The top of this seismic unit is globally flat.

**Unit U3L**

Unit U3L was observed both at sea and in the present-day lagoons. It occurs on the RES surface and was not observed on U2. However, seismic profiles do not provide data below the present-day emerged barred beach where such geometry may have occurred. The thickness of unit U3L is highly variable, as testified by the important vertical shifts of the RES surface. U3L shows draping parallel seismic facies (fig. 4A) characterized by parallel and roughly horizontal high-amplitude reflections. Where the underlying RES surface is uneven, basal reflections in U3L present onlap geometry (fig. 2A and 2C). In the lagoon, the top of unit U3L is the water/sediment interface. The centre of Vic lagoon presents a large area of biogenic gas release that prevents seismic imaging of the lagoon-fill in that place (fig. 2). At sea, the top of U3L is truncated by a smooth erosion surface displaying a seaward dipping. Locally, this erosion surface merges with the seafloor.

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**FIG. 2.** Interpreted VHR seismic profiles CAII VIC-07 (A), CAII VIC-35 (B) and CAII VIC-36 (C), showing global units architecture in the lagoons. RES (Regional Erosional Surface) corresponds to the top of Upl or U1. Seismic data in the centre of lagoons shows biogenic gas release.

**FIG. 2.** Profils sismiques THR interprétés, CAII VIC-07 (A), CAII VIC-35 (B) et CAII VIC-36 (C), montrant l'ensemble des unités observées en lagune. La RES (Regional Erosional Surface) correspond au toit de l'unité Upl ou U1. Le centre deslagunes est caractérisé par la présence de gaz biogé- nique.
Unit U4

The base of unit U4 is observed seaward and corresponds either to a smooth erosion surface on U3L or locally to the RES surface. U4 is characterized by transparent or chaotic facies with few low-amplitude reflections (fig. 4D and 4E). Cross-shore profiles such as Maguelone-5 (fig. 3A) show that the seaward extension of U4 is limited to the present-day shoreface, about one kilometer away from the shoreline. The reflections within U4 show a moderate dipping oriented seaward, roughly parallel to the present-day mean nearshore slope. The top of U4 corresponds to the present-day seabottom.

Cores

Three main facies successions are distinguished in the cores, corresponding to the main sub-environments that compose the study area, i.e. from North to South, the lagoon, the beach-barrier and the shoreface (fig. 6).

Back-barrier facies succession

The typical succession observed in back-barrier areas begins at the base with a coarse polygenic conglomerate composed of rounded elements of carbonate lime mud, quartz and yellow silt (fig. 6). In core TOTH-1, this conglomerate is older than 7665 yr. In core AR06, from 3.32 to 3.40 m, this coarse deposit consists of limestone and quartz clasts and some marine bioclasts like Bittium reticulatum and Rissoa sp., dated at 5800 +/- 105 cal yr B.P. This deposit is also observed at the base of PB06. Above the coarse conglomerate or marine bioclastic sand, grey uniform lagoonal mud with thin silty and sandy intervals occurs. Thickness of the lagoonal mud intervals is variable. Maximum thickness is observed in core TOTH-1, reaching 17 m (fig. 6).
Radiocarbon data testify that lagoonal deposits are Holocene in age. The base of those deposits was dated at 7665 +/− 110 cal yr B.P. at 20 m of depth in TOTH-1 and at 5695 +/− 145 cal yr B.P. at 3.32 m of depth in AR06. Consequently, the base of lagoonal deposits is not isochron. The top of lagoonal deposits corresponds to the present lagoon floor. In core TOTH-1, located in the Maugnon delta (fig. 1B), lagoonal deposits are overlain by deltaic deposits (from 1.20 to 3 m of depth). The top of this core corresponds to an embankment.

**Present beach barrier facies succession**

The typical facies succession observed in the present beach barrier area is described in core MAG-1. This core is located on the sandy beach barrier close to Maugnone Cathedrale (fig. 1A). From the base at 12.20 m, the core displays sand mixed with coarse polygenic conglomerate. This conglomerate is the same as that observed at the base of cores TOTH-1, AR06 and PB06. According to radiocarbon data, these deposits are older than 45600 years (fig. 6). From 12.20 to 9 m of depth, green, grey or yellow ochre mud and silt, with carbonate concretion occur. All these layers are poor in organic matter. The top of the carbonate level corresponds to an erosional surface. A bioclastic marine sand bed, dated at 5520 +/− 115 cal yr B.P., takes place on this surface. At 8.50 m, the first lagoonal deposits appear. From 8.50 to 5 m, lagoonal facies are intercalated with marine sands. At 7.30 m, this deposit is dated at 5590 +/− 110 cal yr B.P. At 5 m, lagoonal muds are topped by an erosional surface covered by sands. This sand is composed of quartz, chlorite, biotite and includes up to 15% of bioclastic content. At the base of this uppermost sandy interval, sediments are dated at 1745 +/− 120 cal yr B.P.

**Shoreface**

The shoreface area is limited by the present sandy barrier to the North and by marine plateaus to the South (fig. 1A). At the base, short cores M5-1 and M5-2 display a grey homogeneous mud rich in organic matter. Presence of 5 to 10% of bioclastic content argues for lagoonal deposits with marine influence. Most of these sediments consist of mud, mixed with silt or fine sand, and present marine bioclasts such as *Bittium reticulatum*, *Rissoa sp.* and *Cerastoderma glaucum*. Usually, these deposits are interbedded with marine sand including open sea bioclasts like *Turritella*, *Pecten sp.* and *Bittium reticulatum* (e.g. from 116 to 118 cm, and from 129 to 136 cm in core M5-1). In core M5-1, lagoonal deposits were dated at 9450 +/− 460 cal yr B.P. This 14C dating of lagoonal deposits with marine influence shows contamination, according to the depth of the dated level and the global eustatic curve. Contamination is in agreement with marine silt and sand supply in the lagoon. This dating gives a maximal age but indicates that these lagoonal deposits, located off the present-day sandy barrier, are older. A layer of fine-grained detritic sand covers the top of the lagoonal muds. Locally, this layer is mixed (M5-1) or interbedded (M5-2) with cm-long rolled pebbles. This sandy material originates from the present-day barrier.

**Fauna contents**

Lithostratigraphy and macropaleontology are powerful approaches to highlight the complexity of wetland environments [Mazzini et al., 1999; Amorosi et al., 2005; Ricci Lucchi et al., 2006]. By this way, paleoenvironmental evolution of lagoons in relation to their closure by sandy barrier can be determined.

From a sedimentological point of view, the study of core PB06 (fig. 6) suggests a relative homogeneous lagoonal depositional environment from 744 cm of depth to the top. This deposit is characterized by grey clays and silts with intercalated sand layers (less than 10% of the total sediment) interpreted as paleostorm events [Sabatier et al., 2008]. However, the high-resolution analysis performed on fauna indicates a significant change (fig. 7), marked by a clear shift in mollusc population at around 190-170 cm (i.e. about 731 +/− 87 cal yr B.P.). This shift corresponds to an increase of typical lagoonal species (*Hydrobia acuta*) whereas the number of marine species (*Bittium recticulatum*) decreases. This argues that a change in environmental conditions (salinity, temperature, nutrients, and oxygenation) occurred at about 700 cal yr B.P.: the depositional environment evolved from a lagoonal with marine influence to an isolated lagoon. This change dates the closure of the lagoon by the sandy barrier.

**Sedimentary units**

**Substrate of Holocene deposits**

In this paper, the substrate of Holocene deposits groups the seismic units located below the RES (Upl and U1; fig. 8). To the west of Vic lagoon, the top of Upl is directly correlated with Pliocene onshore outcrops, as testified by Alalouvette et al. [2003] (fig. 1A). These Pliocene outcrops are represented by lacustrine white chalky limestone or altered white chalky limestone nodules in an ocher to red silt
matrix. The gentle southeastward dip of Upl (fig. 3A) is consistent with the Pliocene strata dip in outcrops. A differential subsidence induced by the sedimentary and hydrostatic loading of the shelf [Tesson and Allen, 1995] can explain this regional dip. Where unit U1 can be extended onshore, to the north of Vic lagoon, a comparison with the outcrops demonstrates that U1 is made of terrigenous silts and conglomerates with clasts of Mesozoic and Cenozoic limestones as well as quartz and biotites. This facies is in agreement with observation of the marine Maguelone plateau, where U1 is composed of conglomerates and sandstones. Unit U1 is interpreted as Pleistocene continental deposits.

Prograding sand bodies

Detailed study of geometries and facies in Unit U2 (fig. 3) shows that this unit consists in several stacked bodies of marine sandy deposits [Raynal et al., 2009]. In addition, U2-1, U2-2 and U2-3 bodies reveal the existence of 10 m high sets that fill up former depressions and prograde toward the southwest over several kilometres. U2 consists of stacked prograding sets that display internal erosional surfaces, arguing for alternated episodes of erosion and progradation. Raynal et al. [2009] interpret this formation as paleo-sand spit prograding alongshore (i.e. southwestwards). To explain the sand spit formation, the authors refer to a sediment transfer from the Rhône delta by alongshore hydrodynamics during the last stage of Holocene transgression.

Alluvial meander filling

Unit U3F, observed in the northern Vic lagoon, corresponds to the filling of an incised valley (fig. 8). Two kinds of
filing were distinguished. At the base, the filling is characterized by a regular aggradation. Where the incision enlarges, in the upper part, the filling consists of lateral accretion, perpendicular to the main direction of the incision (fig. 2B). The isopach map of U3F (fig. 5B) shows meander geometry in this unit interpreted as the filling of an alluvial incised valley. The incision is located southward a depression oriented South-North between Vic lagoon and the Mosson river.

Lagoonal deposits

Correlations of seismic profiles and cores show that U3L unit consists of clays accumulated in a low energy environment and interpreted as lagoonal deposits. These lagoonal deposits display a highly variable thickness (fig. 8). The oldest lagoonal muds were dated at 7500 yr B.P. (table I). Two types of lagoonal deposits are distinguished, (1) lagoonal deposits formed of grey uniform muds with thin silty and sandy intervals (cores TOTH-1, AR06, PB06 and MAG-1, fig. 6). They correspond to a lagoon environment with intermittent connexion to marine environment during paleostorms events [Sabatier et al., 2008]; (2) lagoonal sediments made of mud mixed with silt or fine grained sand and including some marine bioclasts such as Bittium reticulatum, Cerastoderma glaucum and Rissoa sp. (M5-1 and M5-2, fig. 6). These deposits reflect a lagoon environment with important marine influence. At the edge of present-day lagoons, deposits are characterized by mixed facies composed of lagoonal muds, lithoclasts from the local substrate facies, bioclasts and vegetal fragments.

Sand barrier

Seismic unit U4, characterized by transparent or chaotic facies with few low-amplitude reflections, is correlated with the last littoral sand bar. These deposits show an external meter high and 10 m wide sand bar that forms one of the main morphological features of the present-day nearshore zone.

DISCUSSION

Sand barrier retrogradation

The geometrical study of the Maguelone shore highlights the evolution of the barrier, which closes the lagoonal environment. During an early stage, the barrier corresponds to sand spits evolving as a narrow sandy beach retrograding barrier. This change and more specifically the retrogradation are the result of balance between sea-level rise, hydodynamics and sediment supply. The destabilization of the sand spit system and the retrogradation of the sandy barrier were controlled by accommodation space during sea-level rise [Cattaneo and Steel, 2003]. This accommodation depends on sediment supply and sea-level rising rate (with no tectonic and subsidence). From about 7500 to 5500 yr B.P., the rate of eustatic rise is considered as constant, with a value of 3.3 mm/yr in average. During this period, creation of accommodation is counterbalanced by the formation and growth of sand spits, as testified by the deposition of lagoonal facies (fig. 9). From 5500 yr B.P., the rate of sea-level rise has decreased to 2.4 mm/yr. Accommodation becoming lower, alongshore-transported sediments migrated to the spit head preferentially. As a result, the sand spit, except at its head, corresponds since that moment to a by-pass or erosional zone [Ollerhead and Davidson-Arnott, 1995]. The low to non-existent direct sediment supply from local rivers, combined with important wave erosion, induce the retrogradation of the sand barrier. This retrogradation occurs on previously lagoonal deposits and the subsequent construction of unit U4 (fig. 8), as testified by the base of the sandy barrier, which corresponds to a wave ravinement surface (fig. 9) [Cattaneo and Steel, 2003]. The sandy barrier retrogradation has been facilitated by the presence of flat and smooth lagoonal deposits. With such conditions, the sandy barrier retrogradation is enhanced, in spite of lower sea-level rising rate [Roy et al., 1994]. This process of sandy barrier retrogradation during a low rate of sea-level rise is in agreement with other regional studies such as in the Thau lagoon [Barusseau et al., 1996; Ferrer et al., 2010].
At present, a landward displacement of the sand barrier is observed, induced by wave erosion of the beach barrier and sediment transport by overwash processes toward the lagoon [Honeycutt and Krantz, 2002; Buynevich et al., 2004; Certain et al., 2005a; Certain et al., 2005b; Buynevich et al., 2007 and Sabatier et al., 2008].

Holocene systems tract

The Holocene sedimentary succession is differently preserved into the incised valleys and outside of the valleys (fig. 10), highlighting the influence of incised valleys on the geometry and chronology of coastal systems tracts. The RES (Regional Erosional Surface) topography is inherited from sea-level fall during successive glacial periods when the coastal rivers of Maguelone shore (Mossun and Lez rivers) formed coastal incised valleys (fig. 3B and fig. 8B). The RES corresponds as well to the base of the Holocene coastal system tracts, and thus is the Holocene transgressive surface. Therefore the RES is a polygenic erosional surface, the last stage of erosion corresponding to wave action during the Holocene transgression.

Transgressive System Tract (TST)

The TST is composed of deposits that give evidence for various environments.

The first transgressive deposit corresponds to a 10 cm thick discontinuous marine sand interval onto the RES (cores TOTH-1, AR06, PB06 and MAG-1, fig. 6).
northermost places where such marine deposits are observed, on the RES, at the base of unit U3L, are located along the northern edge of the present-day lagoons, below the Mosson delta (core TOTH-1). Comparison between sea-level curves (fig. 8A) and $^{14}$C dating of bioclastic marine sand (table I) is in agreement with this interpretation. The dating fits with Mediterranean [Labeyrie et al., 1976; Aloisi et al., 1978; Dubar and Anthony, 1995] and global sea-level curves [Fairbanks, 1989; Bard et al., 1990; Chappell and Polach, 1991; Edwards et al., 1993; Bard et al., 1996; Hanebuth et al., 2000 and Cutler et al., 2003]. Sabatier et al. [2008] described as well in another palavasian lagoon, at 8 m depth below present sea-level, this transgressive sand interval dated it at 7850 +/– 125 cal yr B.P.. This age demonstrates that sea-level was at this moment at 8 m maximum below the present level. Due to the topography of the RES, the sea invaded the studied zone, reaching the location of the present Mosson delta. During the Holocene transgression, the Mosson and Lez incised valleys formed rias, and the coastline was very irregular, with successive gulls and rocky headlands made of Pliocene or Pleistocene material.

The next transgressive deposits consist of a tract of synchronous deposits observed in incised valley filling (fig. 10). They are composed of marine sand spit (unit U2), lagoonal deposits (unit U3L) and retrograding fluvial deposits (unit U3F). This incised valley fill is in agreement with the model of Zaitlin et al. [1994]. The progradation toward the southwest of sand spits induces the infill of depressions, including the incised valleys, and the closure of the coastal environment that transformed progressively as a lagoon. The early lagoon muds were observed in the valleys. They are dated at 7665 +/- 110 cal yr B.P. (core TOTH-1). The alluvial channel filling (unit U3F) was observed exclusively in the Mosson incised valley (fig. 2B and fig. 8).

**Highstand System Tract (HST)**

As previously explained, during the highstand the combination between high-energy hydrodynamics and low sediment supply, causes the retrogradation of the sandy barrier (unit U4). During the retrogradation, lagoonal deposits continued to fill the back-barrier area. The retrogradation surface of the sandy barrier corresponds to a wave ravinement surface (wRs) after Cattaneo and Steel [2003]. During this stage, wave action erodes the sand spits so that rocky plateau (Pliocene and Pleistocene) and previously deposited lagoonal muds outcrop off the present-day barrier (fig. 3A and fig. 10). In the landward edges of the lagoon, fluvial deposits prograde on lagoonal mud (fig. 6 and fig. 10). As a consequence of the barrier retrogradation and deltaic progradation, the size of the lagoon has decreased continuously from the early highstand.

Because the transition between the TST and the HST appears to be very progressive, no maximum flooding surface (MFS) was identified.

**Isolated and protected lagoon**

This study questions the basic definition of a lagoonal environment. The mechanisms for the formation of a lagoonal environment have long been discussed, on the basis of conceptual studies mainly [De Beaumont, 1845; Gilbert, 1885; McGee, 1890; Johnson, 1919; Hoyt, 1967; Fisher, 1968; Davis and Fitzgerald, 2003]. All these theories hinge on a basic idea: a lagoon occurs as soon as a topographic trough is filled of water with some connections with the open sea. This results in a brackish environment.

This study has revealed the existence of a Holocene lagoon thanks to geometrical and sedimentological criteria, the lagoon fill being characterized by typical seismic facies and units (e.g. U3L) and the presence of sediment distinct from that of open sea (e.g. that found in TOTH-1). It was demonstrated that the lagoon exists as soon as a topographic high occurs. In the Maguelone lagoon case, this high was formed by the sand spits that migrated alongshore around 7500 yr B.P. [Raynal et al., 2009]. On the lee-side of the sand spit, wave and wind energy became very low, and lagoonal conditions could start to develop. Indeed, a lagoon is defined as a protected environment with respect to the hydrodynamical action of the open sea. However, in this study, macrofauna analysis shows the complexity of lagoonal environment (fig. 7). Lagoonal species development depends on water temperature, salinity, water chemical composition. All these parameters are controlled partly by the existence of connections with the open sea. The drastic change that is observed in mollusc population probably reflects the construction of a continuous sandy barrier with no
permanent inlet and thus no continuous inflow of marine water into the Palavasian lagoon system. The sediment fill mainly records temporary connections during storms that provoke the deposition of over-wash sands into the lagoon [Sabatier et al., 2008]. We assume that the final closure of the environment, leading to an isolated lagoon, occurred at about 731 +/- 87 cal yr B.P. when lagoonal species became significantly dominant and simultaneously the number of marine species decreased drastically.

CONCLUSION

This study based on very high resolution seismic profiles, cores and field observations, has revealed the three-dimensional architecture of the Maguelone coastal system tract. The sedimentary dynamics evolution from the Late Quaternary to present-day has been determined. Before the Holocene deglacial eustatic rise (fig. 8A), the Maguelone shore is characterized by an uneven topography (RES in this paper; fig. 10), inherited from the Pleistocene glacio-eustatic cycles. In this context, rivers like the Mosson and Lez have incised valleys. During the Holocene, while sea-level rises, the sea invades this topography and delineates successive uneven shorelines that migrates northward. Inherited incised valleys form rias. The trangression is recorded by the deposition of thin and discontinuous marine sand intervals. At the end of the transgression (around 7500 yr B.P.), alongshore sand supplied from the Rhône delta nourishes nearshore spits, which protect back-barrier domain. At the same time, lagoonal sedimentation occurs in the deeper part inherited topography formed by the Lez River. At around 5500 yr B.P., the decrease in rate of sea-level rise destabilizes the sand spit depositional system, allowing erosion and reworking of sands. The combination between the low rate of sea-level rise, relatively high energy hydrodynamics and low sediment supply induces the retrogradation of the sandy barrier [Barusseau et al., 1996]. Dating of sand on the present-day barrier demonstrates that it almost reached its present-day position around 1800 yr B.P.

The presence of incised valleys plays a decisive role in the depositional evolution. In the Maguelone shore, cross-shore section in the Holocene fill of the incised valleys shows a succession from marine to continental deposits.

Comparison of geometrical contents and fauna analysis of lagoonal deposits highlights the difference between a protected lagoon and an isolated lagoon. In the Maguelone shore, sedimentary geometries indicate that lagoonal sedimentation began around 7500 yr B.P. However, the large increase of lagoonal species, simultaneous with a significant decrease of marine species at 731 +/- 87 cal yr B.P., demonstrate that the lagoons became isolated since that period. Between 7500 yr B.P. and about 700 yr B.P., the lagoons of the Maguelone shore have kept an important marine connection, due to the instability of beach barriers.

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