The Late Holocene sediment infilling and beach barrier dynamics of the Thau lagoon (Gulf of Lions, Mediterranean sea, SE France)

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Abstract. – A study combining very high resolution seismic and sediment core data has been carried out on the Thau lagoon (Mediterranean coast, microtidal setting, SE France) in order to understand more clearly the dynamics and Holocene chronology of its closure through the different stages of its filling. One main seismic unit (U2) has been defined into the infill, above the rocky basement (U0) and a composite unit U1, which is interpreted as remnants of Pleistocene fluvial terraces or/and to early marine Holocene deposits. Unit U2, that reaches locally 9 m in thickness, rests conformably on U1 in the central part of the lagoon and onlaps U0 or U1 close to the edge of the lagoon. It is divided in two sub-units, U2-1 and U2-2. U2-2 rests paraconformably on U2-1 in the central part of the lagoon where the infill is the thickest, while a marked erosional unconformity is observed between U2-1 and U2-2 on topographic highs of the basement and on the seaward edge of the lagoon. A total of seven elementary sequences have been observed in U2-1 and U2-2.

According to core data, U2 consists in a series of mud-dominated sequences, with shell fragments dispersed at the base. The vertical distribution of the fauna into U2-1 and U2-2 reveals a lagoonal environment. However in U2-1, marine species are more abundant in the south of the lagoon. 14C AMS dating provides three ages: ~ 6000 cal yr B.P. in the lower part of U2-1 on CAL1, ~ 5400 cal yr B.P. just above the boundary between U2-1 and U2-2 on CAL4, ~ 3000 cal yr B.P. in the middle of U2-2 on CAL4.

A scenario to explain the lagoon infill stratigraphy and geometry is proposed. The beginning of the lagoon infill occurred with the initiation of the barrier construction, as soon as the sea-level rise slowed down significantly, i.e. between 7000-6000 yr B.P. The sediment-fill began into the back-barrier system, with a high rate of sedimentation for U2-1, according to the radiocarbon data. At 5400 yr B.P., the barrier is assumed to be totally closed leading to the deposition of the fully lagoonal U2-2 succession. The unconformity between U2-1 and U2-2 is interpreted as the result of a rapid landward retreat of the barrier. This severe retreat could be related to climate forcing and/or brutal change in sediment discharge driven by the Rhône River, which is the main sediment source of the longshore drift. In this scenario, the last sub-unit, U2-2, represents most of the late Holocene infill. In this framework, the elementary sequences observed in U2-2 could be related to high frequency climate changes of about 1000-1500 years periodicity according to 14C dates.

Remplissage sédimentaire tardi-holocène et dynamique du lido de la lagune de Thau (golfe du Lion, mer Méditerranée, SE France)

Mots-clés. – Lido, Flèche sableuse, Apports sédimentaires

Résumé. – Une étude combinant des données de sismique très haute résolution et de carottes sédimentaires a été menée sur la lagune de Thau (SE France) dans le but de clarifier la dynamique et la chronologie Holocène de sa fermeture grâce au remplissage sédimentaire. Une unité sédimentaire principale (U2) a été définie dans le remplissage de la lagune qui repose sur le substratum rocheux (U0) et sur une unité composite U1 qui correspond à des restes de terrasses fluviales ou/et à des dépôts marins pré-holocènes. L’unité U2, avec une épaisseur maximale de 9 m, repose en concordance sur U1 au centre de la lagune, et en onlap sur U0 ou U1 en bordure de la lagune. U2 consiste en une alternance de réflecteurs parallèles continus de haute amplitude et de réflecteurs peu continus de faible amplitude. Cette unité est divisée en deux sous-unités U2-1 et U2-2. U2-2 repose en discordance sur U2-1 au centre de la lagune là où l’épaisseur du comblement sédimentaire est maximale, tandis qu’une discordance marquée existe entre les deux sous-unités à l’approche des hauts-fonds et sur la bordure orientale de la lagune. Au total, sept séquences élémentaires ont été observées dans U2-1 et U2-2.

D’après l’interprétation des données sédimentologiques des carottes, U2 est constituée de séries à dominante argileuse avec des fragments de coquilles à sa base. La distribution verticale de la faune dans U2-1 et U2-2 révèle un environnement de dépôt lagunaire. Cependant, dans U2-1, des espèces marines sont plus abondantes dans la partie sud de la lagune. Des datations AMS au 14C ont fourni trois âges: ~ 6 000 cal B.P. dans la partie inférieure de U2-1, ~ 5 400 cal B.P. juste au-dessus de la limite entre U2-1 et U2-2, ~ 3 000 cal B.P. au milieu de U2-2.

Un scénario est proposé afin d’expliquer la stratigraphie et la géométrie du remplissage sédimentaire. Le début du remplissage a commencé avec l’initiation de la construction du lido dès que le niveau marin s’est stabilisé, vers 7 000-6 000 B.P. Le remplissage débute par le dépôt rapide de U2-1. A partir 5 400 B.P., la lagune est totalement isolée par le lido.
permettant le dépôt de U2-2. La discordance entre U2-1 et U2-2 est interprétée comme le résultat d’une migration rapide du lido vers le continent. Ce recul brutal peut être relié à une variation climatique et/ou à un changement brutal des apports sédimentaires du Rhône, principale source alimentant la dérive littorale. Dans ce scénario, la sous-unité U2-2 représente la majeure partie du remplissage tardi-holocène. Dans ce contexte chronologique, les séquences élémentaires observées dans U2-2 pourraient être liées à des changements climatiques de périodicité de l’ordre de 1 000 à 1 500 ans, en accord avec les datations 14C.

INTRODUCTION

Along wave-dominated coastal systems, as soon as coastal barriers begin to be created, lagoons could isolate progressively [Zecchin et al., 2008]. These lagoons can be considered as closed or partially closed wave-dominated estuaries [Reinson, 1992] described by Dalrymple et al. [1992]. Lagoonal systems are appropriate fields to understand the influence of the sea level rise [Sorrel et al., 2009], sediment availability Fitzgerald et al. [2000], hydrodynamic forcing and the inherited bedrock morphology [Bertin et al., 2004] on coastal sediment body construction [Ricci-Lucchi et al., 2006; Allard et al., 2009]. We propose here to study the different stages of the barrier construction and evolution by analyzing the sedimentary record preserved into the lagoon.

In the Gulf of Lions, where the Languedoc-Roussillon coast is characterized by many coastal lagoons, the Holocene evolution has been controlled by a rapid sea level rise reaching 10.6 mm/year before 7000 yr B.P. [Aloisi et al., 1978], followed by a much slower rise, i.e. 1 mm/year [Vella et Provansal, 2000]. Each lagoon is separated from the sea by an emerged beach barrier which is the result of the combined activity of waves and currents, longshore littoral drift, transport and sand accumulation [Barusseau et al., 1996; Certain et al., 2005b]. As it is generally the case, lagoon sediments are characterized by mixed silty clay and organic matter, locally interbedded with marine sand layers (wash-over fans) preserved close to the sand barrier [Hesp and Short, 1999]. The accumulation rates are relatively high, about 2.5 mm/year in the Thau lagoon on the last century timescale [Schmidt et al., 2007], up to 4 mm/year in the Pierre Blanche lagoon located East of the Thau lagoon [Sabatier et al., 2008].

The Languedoc-Roussillon lagoons have been the subject of various studies such as life conditions and shellfish production [Gangnery et al., 2001; Sneathkin et al., 2002], biogeochemistry and heavy metal distribution or pollution [Schmidt et al., 2007]. Geological studies focused mainly on the sedimentary infill and the paleogeographical evolution [Certain et al., 2004; Tesson et al., 2005]. In other Mediterranean areas, stratigraphic and paleontological approaches have revealed that sedimentary sequences contained in the lagoon infill are correlated with Holocene climate changes [Massari et al., 2004; Ricci-Lucchi et al., 2006]. Some studies focused specifically on lagoon closure in relation to sand spit evolution [Simeoni et al., 2007], and more generally on the evolution of adjacent systems such as alluvial plain [Amorosi et al., 2004], delta [Bellotti et al., 1994] and embayment [Soursar et al., 2008].

The aim of the present work, based on a combination of new high resolution seismic, sediment core and radiocarbon dates, is to reconstruct the history of the sedimentary infill of the Thau lagoon in order to define the role of factors that have controlled the sand barrier dynamics and associated closure of the lagoon. Such as other works performed along the Languedoc-Roussillon coasts [Planchais et al., 1984, Canet-St Nazaire lagoon; Certain et al., 2004, Leucate lagoon; Raynal et al., 2010; Sabatier et al., 2010, Palavasian lagoons], this study shows the influence of the Rhône River on the sandy barrier dynamics. This allows comparing regional responses and thus deciphering the role of global factors from local factors.

THE STUDY AREA

The study area is the Thau lagoon, located on the French Mediterranean coast (fig. 1) and more precisely in the gulf of Lion where the general hydrodynamic circulation on the continental shelf flows westward [Millot, 1990]. This circulation induces fine westward sediment transport originating from the Rhône [Ulses et al., 2008]. This littoral was under the influence of a westward longshore drift during the Holocene [Akouango, 1997; Raynal, 2008]. The Thau lagoon is the largest lagoon along the Languedoc-Roussillon coast. It covers an area of 75 km² with a maximum length of 19 km and maximum width of 1.3 km. The average water depth is 4 m; 35% of the lagoon water depth is more than 5.5 m, and locally reaches 10 m.

The lagoon catchment area (280 km²) consists of Jurassic karstified limestones and Miocene and Eocene marly limestones (fig. 1). It is limited by the Quaternary volcanic mountain of Agde in the south, the Upper Jurassic limestone of the Moure Mountains in the west, and the Jurassic (Callovian and Sequanian) limestone of the Gardiole Mountains in the north. Along the northern coast of the lagoon, Pliocene lacustrine limestone outcrops are found. Between the Quaternary volcanic mountain and the Moure Mountains, Quaternary marls constitute the alluvial plain of the Hérault River. The catchment is drained by small intermittent rivers characterised by a long dry period between May and September, and flush flash floods during the wet season in autumn. All the rivers are located in the Moure Mountains. The hydrological regime is dominated by two main rivers, the Vène River (67 km²), fed by karstic springs, and the Pallas River (52 km²).

Previous work on the Thau lagoon sediment infilling performed by Chassefière [1968] has shown that during the Early Holocene transgression, the lagoon area formed a wide embayment. During the transgression, small shelly shoals formed in the embayment before the definitive closure by the beach barrier. These shoals were then isolated to form the "cadoules", a local name that designates mounds (circular bioherms and/or shelly shoal), a few hundred metres in diameter, scattered in the northern part of the lagoon [Chassefière, 1968]. Today, the lagoon is connected to the sea by three inlets. Two of them, the Pissesauemes and Quilles inlets, crossing through the sandy barrier (fig. 1),

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are almost closed. An artificial inlet, the Sète harbour inlet, provides the main connection. No active washover dynamics occurs at present, although the northern part of the sandy barrier, near Sète, is subject to severe erosion [Certain et al., 2005b].

The prevailing winds blow from the northwest (the Tramontane wind, 23%) and west (18%) [Certain, 2002; Certain et al., 2005a]. The hydrodynamic circulation in the Thau lagoon is not well known but modelling under different wind conditions shows vortex occurrence around the oyster beds [Millet, 1989]. In the northern part of the lagoon, the Vise spring, close to Balaruc, surges after a complex circulation within the Jurassic karst [Aquilina et al., 2003; Pinault et al., 2004]. Most sea waves in the area have a mean significant height ($H_s$) 2 m, 30% of the values being 1 m, predominantly in summer. The wave directions are 140-220°N associated with sea breeze. Only 2% of waves have $H_s$ 4 m with periods from 5 to 10 s and a SE to E direction and occur during storms that typically last only 24 h. Tidal range does not exceed 0.30 cm [Akouango, 1997; S.H.O.M., 2003]. Nevertheless, higher water level variations are observed in response to set-ups and set-downs under the influence of wind and atmospheric pressure fluctuations. In extreme cases, set-ups can reach 0.50 m in the shoaling zone during storms [Akouango, 1997] and 1 m on the beach under the action of breaking waves [Certain, 2002]. The Thau lagoon is an important shellfish breeding area [Soletchnik et al., 2002] leading to a strong biological production. About 15000 tons of oysters per year are produced in the lagoon, i.e. roughly 10% of the French total production [Gangnery et al., 2001].

**METHODS**

The seismic device used for the study is a boomer IKB-Seistec, specifically designed for shallow water investigations [Simpkin and Davis, 1993]. It is characterised by a line-in-cone receiver located close to the boomer plate (5 m), a SIG Energos power supply was used with a power of 100 J and a shooting rate of 2 shots/s. The seismic data and DGPS positioning were simultaneously recorded on a PC with Delph-Seismic. Post-survey processing was made by using Delph-Seismic and Seismic Unix software, including frequency bandpass filtering, trace stacking, and swell filtering when necessary. The available seismic data almost cover the total area of the Thau lagoon. 46 profiles were shot, representing a total length of 57 km [Benabdellouahed, 2005]. The profiles are oriented both longshore (NE-SW) and cross-shore (NW-SE) (fig. 1).

In order to ground-truth part of the seismic data, four gravity cores, from 1 to 2 m long, have been collected in the Thau lagoon during the CALAMAR2 campaign in November 2005 (fig. 1). The cores were simply analysed for sedimentary facies interpretation and macrofauna determination.
In addition, three samples (organic matter in bulk sediment) were collected along the cores for radiocarbon dating (performed by Beta Analytics). Ages have been calibrated using IntCal04 [Reimer et al., 2004].

RESULTS

Seismic units

The seismic profiles have been analyzed on the basis of the conventional principles of seismic stratigraphy [Mitchum and Vail, 1977]. Above the substrate (named U0) two main seismic units, named U1 and U2, have been recognized in the sedimentary infilling according to their geometry, upper and lower boundaries (onlap, toplap, downlap, conformable and unconformable) and acoustic facies (amplitude, continuity, frequency and configuration of the internal reflectors). Seven acoustic facies have been distinguished. Their characteristics are listed in the table I. Since the infill is mainly made of soft muds, a P-wave velocity of 1600 m/s was chosen for time-to-depth conversion [Hamilton, 1972; Billeaud et al., 2005].

Unit U0

(fig. 2) represents the rocky substrate at the bottom of the lagoon basin. Its upper boundary is an erosional surface. Depending on the substrate nature, acoustic facies in U0 are variable but they mainly show an oblique parallel internal configuration dipping to SE consistent with the bedrock strata observed onshore [Denizot et al., 1967; Barrière and Berger, 1978; Berger et al., 1981].

Unit U1

rests on U0 (fig. 2). Its lower limit displays an angular unconformity. In most of the lagoon, its upper limit is conformable. Its outer shape is a drape smoothing the underlying bedrock morphology. U1 has a maximum thickness of about 5 m. U1 is not present everywhere. It is characterized by a transparent facies (T1) sometimes masked by gas (C) showing a chaotic facies [e.g. Garcia-Gil et al., 2002; Bertin and Chaumillon, 2005]. It disappears toward the inner edge of the lagoon and locally on the substrate highs (fig. 2, 4, 7). On the barrier edge, the seismic interpretation is more difficult and does not allow concluding on the presence of U1.

Unit U2

is the main unit of the lagoon sediment fill (fig. 2). It is present everywhere. It rests on U1 or directly on U0 (fig. 3). It is conformable on U1 or on onlap on U0. It comprises two major acoustic facies, P2 and P3, associated to minor acoustic facies (S1, S2 and C), and shows an overall aggradational configuration in the central part of the lagoon. The thickness of U2 varies from 1.5 to 9 m. On the basis of acoustic facies and internal surface geometry, U2 can be divided into two sub-units, named U2-1 and U2-2. In most of the lagoon, the boundary between U2-1 and U2-2 is a conformable surface. However, on the seaward edge of the lagoon, the basal surface of U2-2 corresponds to an onlap surface or, close to the sandy barrier, to a downlap surface (fig. 6).

U2-1, 0 to 4.5 m thick, shows parallel reflectors with generally lower amplitude than the reflectors observed in U2-2. In the north of the lagoon, U2-1 displays higher amplitude reflectors than in the south. Locally on some substrate highs, U2-1 displays oblique reflectors and numerous acoustic hyperboles, indicating probably very coarse material (fig. 2). On the basis of its internal configuration, U2-1 can be subdivided into three elementary acoustic sequences (named s1, s2, s3) made of a succession of low amplitude/low continuity reflectors and high continuity/high amplitude reflectors (fig. 2). The elementary sequences of U2-1 present an aggradational configuration (conformable surface) in the central part of the lagoon and onlap terminations (fig. 3A) on the substratum (discordant surface) northwestward and in front of the substrate highs on U1.
U2-2 is 1.5 to 4.5 m thick. On the basis of the same seismic facies variations than those identified in U2-1, U2-2 comprises four elementary acoustic sequences, from s4 to s7. The boundaries between these elementary sequences are draping surfaces. Each reflector of the elementary sequence onlaps the substratum close to the lagoon edges. However, around substrate highs, the top of s5, characterized by oblique to sigmoid reflectors, is locally truncated (erosional surface) by s6 (fig. 3B, tabl. II). Close to the sandy barrier, the aggradational sequences of U2-2 display sigmoid internal configuration and a downlap surface on the limit of U2-1/U2-2 (fig. 7).

In the northern part of the lagoon, the sedimentary infilling cannot be clearly divided into seismic units and subunits. Acoustic facies are mostly made of wavy parallel reflectors defining more or less regularly spaced mounds (tabl. I), corresponding to the so-called “Cadoules” defined by Chassefière [1968]. The origin of these bodies is still a matter of debate (bioherm development or hydrothermal circulation?) and will not be discussed in the present paper.

Acoustic masks appear on most of the profiles. On the landward edges of the lagoon, acoustic mask is due to the presence of dense grass (or seaweed?) beds. In the central part of the lagoon, acoustic masks are located in the area

### Table I. – Characteristics of the acoustic facies observed on the seismic profiles shot in the Thau lagoon.

<table>
<thead>
<tr>
<th>Acoustic facies</th>
<th>Amplitude</th>
<th>Continuity</th>
<th>Frequency</th>
<th>Configuration</th>
<th>Units</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>High</td>
<td>Low to medium</td>
<td>High</td>
<td>Parallel to sub parallel</td>
<td>U0</td>
<td>Rocky substrate</td>
</tr>
<tr>
<td>T1</td>
<td>null</td>
<td>Transparent</td>
<td>Transparent</td>
<td>Transparent</td>
<td>U1</td>
<td>Fluvial terraces, colluvions, transgressive sands</td>
</tr>
<tr>
<td>P2</td>
<td>Low to null</td>
<td>Low to medium</td>
<td>Low to medium</td>
<td>Oblique sigmoid</td>
<td>U0</td>
<td>Rocky substrate</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>U2-1, U2-2</td>
<td>Sand, silt</td>
</tr>
<tr>
<td>S1</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Parallel</td>
<td>U2-1, U2-2</td>
<td>Fine grained sediments (clay)</td>
</tr>
<tr>
<td>S2</td>
<td>Medium to High</td>
<td>Low to medium</td>
<td>High</td>
<td>Symetric sigmoid</td>
<td>U2-1, U2-2</td>
<td>“Cadoules” (bioclastic mounds)</td>
</tr>
<tr>
<td>C</td>
<td>High</td>
<td>Weak</td>
<td>High</td>
<td>Chaotic</td>
<td>U1, U2-1, U2-2</td>
<td>Gas, seaweeds</td>
</tr>
</tbody>
</table>

### Table II. – Characteristics of the acoustic facies observed on the seismic profiles shot in the Thau lagoon.

TABL. II. – Caractéristiques des facies acoustiques observés sur les profils sismiques de la lagune de Thau.

In the northern part of the lagoon, the sedimentary infilling cannot be clearly divided into seismic units and subunits. Acoustic facies are mostly made of wavy parallel reflectors defining more or less regularly spaced mounds (tabl. I), corresponding to the so-called “Cadoules” defined by Chassefière [1968]. The origin of these bodies is still a matter of debate (bioherm development or hydrothermal circulation?) and will not be discussed in the present paper.

Acoustic masks appear on most of the profiles. On the landward edges of the lagoon, acoustic mask is due to the presence of dense grass (or seaweed?) beds. In the central part of the lagoon, acoustic masks are located in the area...
where sedimentary infilling is the thickest and are interpreted to be due to the presence of gas (biomethane) generated by the degradation of the organic matter contained in the lagoonal deposits.

In addition to the detailed analysis of the lagoon infill, seismic data allowed us to reconstruct a bathymetric map of the lagoon, the isopach map of the infill, and an isohyp map of the rocky substrate upper boundary (fig. 5). The deepest part of the lagoon is in its central part (fig. 5a) with a water depth close to 12 m. The substrate upper boundary (fig. 5b) is characterized by two heights in the north of the lagoon, and one height in the south. In the centre of the lagoon, a palaeovalley is evidenced, reaching up to 22 m deep bmsl. The sedimentary infill is the thickest in the palaeovalley, close to 12 m (fig. 5c).

**Sedimentological data and chronology**

In order to determine the lithology and the age of the different seismic units, four cores (1 to 2 m long, fig. 6) have been collected in the lagoon, three along the northern (inland) edge and one close to the barrier (fig. 1). The cores allow sampling mainly U2-2, the base of CAL1 reaching however U2-1 (fig. 4A). They demonstrate that the main lagoon infill unit, U2, is essentially made of clay-rich muds. In all cores, shell-rich intervals alternate with organic clay-rich intervals containing few shell debris (fig. 6). This alternation of sedimentary facies is correlated to elementary seismic sequences identified in U2-1 and U2-2. In CAL2 core, fine sand layers are intercalated in the clay-rich succession (figs 4B and 6) at the proximity of the beach barrier.

**Table II.** – Internal configuration of the reflectors of the elementary sequences observed on the seismic profiles shot in the Thau lagoon.

<table>
<thead>
<tr>
<th>Elementary sequence name</th>
<th>Lagoon centre</th>
<th>Lagoon edges</th>
<th>Substrate highs</th>
</tr>
</thead>
<tbody>
<tr>
<td>s1</td>
<td>Parallel</td>
<td>Onlap on U0</td>
<td>Onlap on U0</td>
</tr>
<tr>
<td>s2</td>
<td>Parallel</td>
<td>Onlap on U0 and on the limit of s1/s2</td>
<td>Onlap on U0</td>
</tr>
<tr>
<td>s3</td>
<td>Parallel</td>
<td>Onlap on U0 and on the limit of s2/s3</td>
<td>Onlap on U0</td>
</tr>
<tr>
<td>s4</td>
<td>Parallel</td>
<td>Onlap on U0 and on the limit of U2-1/U2-2</td>
<td>Onlap on the limit of U2-1/U2-2</td>
</tr>
<tr>
<td>s5</td>
<td>Parallel</td>
<td>Onlap on U0 and on the limit of s4/s5</td>
<td>Toplap on s6</td>
</tr>
<tr>
<td>s6</td>
<td>Parallel</td>
<td>Onlap on U0 and the limit of s5/s6</td>
<td>Parallel, draping the sedimentary infill</td>
</tr>
<tr>
<td>s7</td>
<td>Parallel</td>
<td>Onlap on U0 and the limit of s6/s7</td>
<td>Parallel, draping the sedimentary infill</td>
</tr>
</tbody>
</table>

**FIG. 3.** – (A) Sample of seismic profile P32 (cf. fig. 1 for location) and its interpretation. (B) Sample of seismic profile P27 (cf. fig. 1 for location) and its interpretation. The seismic terminations of elementary sequences reflectors present an onlap surface on the substratum at the edge of the lagoon (A). U2-1 reflectors finish on an onlap surface on U1 around the substrate highs (B) while the reflectors of s4 and s5 form a toplap surface truncated by s6.

**FIG. 3.** – (A) Extrait du profil sismique P32 (cf. fig. 1 pour la position) et son interprétation. (B) Extrait du profil sismique P27 (cf. fig. 1 pour la position) et son interprétation. Les terminaisons des réflecteurs sismiques des séquences élémentaires forment des onlaps sur le substratum au niveau des bordures de la lagune (A). Les réflecteurs de U2-1 se biseautent en onlap sur U1 autour des points hauts du substratum (B) pendant que les réflecteurs de s4 et s5 sont tronqués en toplap par s6.

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Two macrofauna assemblages are present in the core CAL4: a marine assemblage, dominated by Bittium reticulatum, and a lagoonal assemblage dominated by Hydrobia ulvae [Sabatier et al., 2008]. The lagoonal assemblage is prevalent all along the cores but at the base of CAL4, located in the south part of the lagoon and reaching the base of U2-2, the marine assemblage is dominant.

Three radiocarbon ages have been obtained along the cores. At the base of CAL1, the sample D1, located in the basal part of U2-1 (in the seismic elementary sequence s2), provides an age of 6290-6010 cal yr B.P. (fig. 6). In the CAL4 core, the sample D2, located at the limit between U2-1 and U2-2, provides an age of 5600-5320 cal yr B.P. D3, located in the middle of U2-2 (at the limit between s5 and s6), provides an age of 3230-2850 cal yr B.P.

**INTERPRETATION OF SEISMIC AND CORE DATA**

Seismic data collected into the Thau lagoon allow two main stages of sediment fill to be distinguished: 1) the first stage corresponds to the basal draping unit U1, which lies on the substratum (U0) and smooths the irregularities of the latter; 2) the second stage corresponds to a fine grained, aggradational unit (U2), and constitutes the bulk of the lagoon-fill.

The substratum U0 of the lagoon is mainly Pliocene in age according to the available data on the regional geology [Denizot et al., 1967; Barrière et Berger, 1978; Berger et al., 1981; Tessier et al., 2000; Tesson et al., 2005; Raynal et al., 2010], and the strata dip angle observed on the seismic profiles. Its very irregular upper unconformity is interpreted as the result of incision that occurred during the successive Pleistocene sea-level drops [Zecchin et al., 2009] topping substratum highs (fig. 8A). These formations could have been reworked during the transgression. In the troughs, the transparent acoustic facies of U1 could locally correspond to a transgressive sand sheet [e.g. Cattaneo and Steel, 2003]. Sand layers have been cored in the bottom of other lagoons along the Gulf of Lions coastal zone [Raynal et al., 2010; Martin et al., 1981]. They have been interpreted as shoreface sands that were deposited during the first stage of the transgression, prior to the forthcoming closure of the lagoons (fig. 8B, C). This configuration could explain that no wave-cut surface is observed is the Languedocian lagoons [Raynal et al., 2010; Martin et al., 1981]. However, some substrate highs could have been reworked by wind wave into the lagoon (fig. 3B).

The bulk of the lagoon sedimentary fill corresponds to unit U2. According to sedimentological data, U2 has been deposited in a low energy environment. This means that U2 could represent the lagoon fill since the barrier started to be created. The boundaries between the elementary sequences can be interpreted as a change in sedimentation linked to a stop in the sedimentation or a high productivity shells period [Sabatier et al., 2010]. Radiocarbon dating indicates that U2 is Holocene in age and more precisely post-6500 cal yr B.P.

Two sub-units are distinguished (U2-1, U2-2) within U2. In the southern part of the lagoon, U2-1 is characterised by more transparent seismic facies compared to the northern part. This is interpreted as the result of higher energy depositional conditions. Moreover, macrofauna analysis indicates a more marine influence in the south. Thus it is assumed that the sandy barrier already existed and was rapidly formed at the time of U2-1 deposition in an offshore location, since U2-1 is preserved below the present beach barrier (fig. 4B) and is identified in cores collected on the shoreface [Akouango, 1997; Tessier et al., 2000]. As indicated by the abundance of marine fauna, the lagoon was still largely open in the south through wide inlets. This partial closure allows the fast deposition of U2-1 up to 5600-5320 cal yr B.P. (fig. 8D).

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Fig. 5. – The Thau lagoon. (A) Bathymetric map, (B) isohyps map of the substrate top (U0) and (C) isopach map of the sedimentary infill (U1 + U2), reconstructed from the seismic data.

Fig. 5. – Cartes de la lagune de Thau représentant (A) la bathymétrie, (B) les isohypses du toit du substratum (U0) et (C) les isopaques du remplissage sédimentaire (U1 + U2), reconstruites à partir des données sismiques.

Fig. 6. – Sedimentological log of the CALAMAR cores. CAL1, CAL3 and CAL4 can be well correlated since they are located inside the lagoon. CAL2 is closer to the sandy barrier. It exhibits a homogeneous distribution of sediment with some sandy layers. Dated samples are indicated. s2 to s7: elementary sequences defined on the seismic profiles.

Fig. 6. – Logs sédimentologiques des carottes CALAMAR. CAL1, CAL3 et CAL4 peuvent être corréllées de manière satisfaisante car elles sont positionnées dans la lagune. CAL2 est plus proche du lido. Elle montre une distribution plus homogène du sédiment avec quelques lits sableux intercalés. Les échantillons datés sont indiqués. Les séquences élémentaires de s2 à s7 décrites sur les profiles sismiques sont indiquées.
An important change occurred between the deposition of U2-1 and U2-2 sub-units. On the seismic data, U2-2 shows in the seaward edge of the lagoon, landward dipping strata interpreted as washover fans. No washover fans have been observed in U2-1. Similar geometries have been recently imaged in a gravel barrier [Bennett et al., 2009]. This configuration of U2-2 indicates that an important landward migration of the sandy barrier occurred after the deposition of U2-1 (fig. 8E). Migration of the barrier and washover fans evidenced by seismic data, are not observed today probably because of the large size of the present-day barrier, compared to the barriers of the palavasian lagoons located eastward [Raynal et al., 2010; Sabatier et al., 2008].

Around 5600-5320 cal yr B.P. U2-2 deposited conformably on U2-1 in the central part of the lagoon, testifying a relative continuity in the infilling. As described previously, in the thickest aggradational part of the infill, U2-1 and U2-2 comprise elementary seismic sequences, 0.5 to 1 m in thickness. The base of each sequence is marked by a shell-rich interval. This interval can be interpreted as a period of high mortality of lagoonal fauna itself resulting from marine incursion in the lagoon, or, on the contrary, as a period of high productivity of lagoonal species.

The age of 5600-5320 cal yr B.P. for the U2-1/U2-2 boundary allows to estimate an average sedimentation rate for U2-2 of 0.37 mm/y at the scale of the late Holocene. Based on this sedimentation rate, the time of deposition of the elementary sequences comprised in U2-2, varies from about 1080 to 1620 years. In addition, the age of the boundary between s5 and s6, i.e. 3230-2850 cal yr B.P., is consistent with this estimated sedimentation rate.

DISCUSSION

The new results obtained on the Thau lagoon allow discussion of the main factors that have controlled its sedimentary infilling, such as the basement morphology, sediment supply and climate variations.

The inherited bedrock morphology

The substrate was deeply carved before and during the last glacial maximum regression, acting as sediment traps for early to mid-Holocene deposits in the incised valleys of the inner shelf [Tesson et al., 2005] and in some sheltered areas in the lagoon (i.e. CAL 1 core). This substrate is supposed to be Pliocene in age. The reflector dip of the substrate is coherent with the dip of Pliocene strata outcropping onshore and, in the western part, the Pliocene passes through the bank from the emerged domain to the lagoon. Such a pattern is found in other Languedocien lagoons as the Vic lagoon [Raynal et al., 2010] where the sedimentary infill lies on the underlying Pliocene strata.

In the Thau lagoon area, unit U1 covering the Pliocene substratum shows maximum thickness in the trough, located between the two topographic highs of the substrate (fig. 5b). At the beginning of the deposition of U2-1, the lagoon was quickly isolated from the sea by a south-westward oriented sand spit, which constitutes today the barrier, using the Saint-Clair mount as an anchor point. Hence, the position of the outcrops of the Saint-Clair mount and Agde volcanic mound has clearly influenced the position of the barrier. Many authors have already demonstrated that the bedrock has a significant influence on barrier dynamics [e.g. Belknap and Kraft, 1985; Riggs et al., 1995; Heap and Nichol, 1997; Fitzgerald et al., 2000; Bertin et al., 2004; Browder and McNinch, 2006; Burningham, 2008].

As already evidenced in other studies [Cooper, 2001; Regnauld et al., 2004], the inherited bedrock has finally exerted a direct influence on wave action and, as a consequence, on the geometry of the lagoonal deposits.

Sediment supply

Thanks to a general westward littoral drift, the Rhone delta, located at about 100 km to the east of the Thau lagoon, is the main provider of sediment, since the late Holocene, to the shoreface and adjacent coastal zones in the northern part of the Gulf of Lions. Relative sea-level rise and fluvial sediment discharge are assumed to be the main controlling factors of the delta evolution [L’Homé et al., 1981; Oomkens, 1970; Pons et al., 1979; Provansal et al., 2003]. The edification of the Rhone delta started 7200 years ago, using the Saint Ferréol channel located in the central western part of the present-day deltaic system. Between 7200 and 6000 yr B.P., a first deltaic lobe (St Ferréol lobe) developed thanks to large sediment supply. Relative sea level rise is frequently proposed as the factor responsible for barrier construction [Hesp and Short, 1999; Davis and Fitzgerald, 2004]. The early construction of the sandy barrier of the Thau lagoon could also be linked to this first stage of construction of the Rhône delta. Sediment supply from adjacent fluvial source and the exportation of sediment to the shelf has been evidenced on the Atlantic coast [Chauillon and Weber, 2006; Fitzgerald et al., 2000 and 2005], in the Mediterranean Sea [Certain et al., 2005] and in Africa [Anthony et al., 1999]. The first main avulsion of the Rhône outlet occurred 6000 years ago, leading to the construction, between 6000 and 5350 yr B.P., of a new lobe west of the first one. This period corresponds to the main construction of the Thau sandy barrier and the coeval deposition of U2-1. Shortly after, the delta plain developed a multilobe shape with the construction of a new lobe, the Ulmet lobe, in the
eastern part of the delta [L’Homer, 1975]. According to Vella et al. [2005], this phase could have been initiated as soon as 5780 ± 40 yr B.P. From that time, the sediment supply in the western part of the delta decreased drastically. As a consequence, sandy barriers located to the west of the delta, including the Thau lagoon barrier, probably started to retreat rapidly because of this decrease in sediment supply from the Rhône delta. As soon as the barrier started to retreat, the deposition of U2-2 started and continued until the present day.

**Climate variations**

Around 6000 yr B.P., the sea had almost reached its present-day level [Labeyrie et al., 1976; Aloisi et al., 1978; Dubar and Anthony, 1995]. From that time climate fluctuations appear to be one of the major forcing factors of coastal geomorphology evolution [Dabrio et al., 2000; Zazo et al., 2008; Allard et al., 2009; Billeaud et al., 2009]. North-Atlantic millennial-scale climate changes or RCC (rapid climate changes), including Dansgaard/Oeschger oscillations, Heinrich and Bond events, are generally evoked to describe these fluctuations [Bond et al., 1997; deMenocal et al., 2000; Zic et al., 2002; Timmermann et al., 2003; Mayewski et al., 2004; Debret et al., 2007]. Along the Atlantic – Mediterranean coasts of south Spain, Zazo et al. [2008] demonstrated how changes in coastal morphology evolution have been controlled by millennial periodicity climate crisis in relation to the Bond events. Two major RCC are generally mentioned, one around 6000-5000 yr B.P., a second around 3500-2500 yr B.P. Two minor RCC are generally mentioned at about 4200-3800 yr B.P., and at 1200-1000 yr B.P. The first main Rhône outlet avulsion, which is assumed to have influenced the construction and migration rate of the barrier, is coeval with the 6000-5000 yr B.P. RCC. Without accurate chronological control, it is however not
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CONCLUSION

The present study highlights the Holocene sedimentary infilling of the Thau lagoon, the largest lagoon of the Languedoc-Roussillon coast (SE France). The infilling is made up of one main sedimentary unit composed principally of lagoonal muds. This unit rests on a relatively thin basal formation that represents the first stage of the lagoon infilling above the eroded rocky basement. The nature of these basal deposits is unknown. We believe they correspond to remnants of Pleistocene terraces or (and) early Holocene sand sheets that were laid down during the first stages of the transgression. In the bulk of the lagoon sediment-fill, two major steps, related to the evolution of the sandy barrier, have been distinguished: (1) a first step of lagoon infilling started around 6500 yr B.P., when the lagoon was semi enclosed. The barrier development was controlled by a large amount of sediments delivered by the Rhône River and by relative sea level rise; (2) a second step that started at 5400 yr B.P. The lagoon was closed, and the barrier was retreating severely, probably in response to a decrease in sediment supplied by the Rhône delta related to the eastward shift of its main lobe. Our study points out that three main factors have controlled the evolution of the Thau lagoon area, (1) the decrease of relative sea level rise is responsible for the main phase of construction of the barrier; (2) the bedrock morphology controls the location of barrier anchor points, the lagoon fill thickness and the location of the lagoon depocentres. In addition, bedrock highs into the lagoon induce differentiated infill geometries; (3) sediment supply controls the barrier development and dynamics. The Rhône Delta is the main source of sediment in the lagoon area. We propose that the lagoon sedimentary infill has recorded the first steps of the delta construction during the late Holocene, since these steps may have a direct impact on the sandy barrier behaviour. The causes of these major stages are probably related to climate changes. However, our data do not allow us to reach a firm conclusion that climate fluctuations, such as the late Holocene millennial climate cycles, are recorded in the lagoonal mud succession.

References
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