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## Sedimentary record of environmental changes and human interferences in a macrotidal bay for the last millenaries: the Marennes-Oléron Bay (SW France)

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*Key-words.* – Estuary, Tidal channel, Mud drape, Holocene, Sea level rise, Bedrock control, Tides, Human impact, Bathymetry, Very high resolution seismic.

*Abstract.* – This synthesis of the morphological and stratigraphical evolutions of the Marennes-Oléron Bay (west coast of France) combines bathymetric data (1824 and 2003) and very high-resolution seismic profiling groundtruthed by vibracore samples. The Marennes-Oléron Bay is characterised by a very high sedimentation rate and appears to be an ideal place to investigate the sedimentary record of the major environmental changes that occurred since the last several millennia.

The sediment budget of the Marennes-Oléron Bay, between 1824 and 2003, is clearly positive. The flood-dominated northern Marennes-Oléron Bay displays sediment gain in both intertidal and subtidal areas whereas the ebb-dominated southern Marennes-Oléron Bay displays sediment gain restricted to the intertidal area and deepening of subtidal channels. In addition, human influences such as oyster farming may play a role in the sediment gain of the bay.

The sediment-fill of the northern Marennes-Oléron Bay consists of five main phases: (1) lenticular units and flooded intertidal flats recording lower sea level periods before 7500 yr B.P.; (2) tidal channel-fills recording changes in tidal drainage pattern from 7500 to 5000 yr B.P.; (3) a subtidal unit which constitutes the main phase of sediment fill in the northern part of the bay from 5000 to 1500 yr B.P.; (4) a major channelized erosional surface related to huge coastline changes from 1500 to 1000 yr B.P.; and (5) a mud drape emplaced during the last millennia and potentially recording historical human impact (deforestation and land reclamation). The sediment fill of the southern Marennes-Oléron consists of sandbanks, mixed sand-and-mud flats and tidal channels, mainly emplaced under wave-and-tide processes since the last centuries.

Despite its relatively thin (20 m at the maximum), recent and rapid sediment fill, the stratigraphic organization and morphological evolution of the Marennes-Oléron Bay is very complex and spatially variable. Like in many other estuaries, sediment fill of the Marennes-Oléron Bay was successively controlled by relative sea level changes, and then by sediment supply driven by hydrodynamic changes related to huge coastline migrations, and finally by human activities. Moreover, this kind of “rocky coast” estuary, where the sediment-fill is very thin and discontinuous, is characterised by a bedrock control at each phases of the sediment fill both in terms of preservation in topographic lows and in terms of control on hydrodynamics and related sediment input.

### Enregistrement sédimentaire des changements environnementaux et des interférences humaines dans une baie macrotidale au cours des derniers millénaires : la baie de Marennes-Oléron (SW France)

*Mots-clés.* – Estuaire, Chenal de marée, Drapage vaseux, Holocène, Remonté du niveau de la mer, Contrôle par le socle rocheux, Marée, Activité anthropique, Bathymétrie, Sismique très haute résolution.

*Résumé.* – Cette synthèse sur les évolutions morphologiques et stratigraphiques de la baie de Marennes-Oléron (côte ouest de la France) repose sur des données bathymétriques (1824 et 2003), des enregistrements sismiques à très haute résolution et des carottages. La baie de Marennes-Oléron qui se caractérise par de très forts taux de sédimentation représente un site idéal pour étudier l’enregistrement sédimentaire des changements environnementaux qui se sont produits lors des derniers millénaires.

Le budget sédimentaire de la baie de Marennes-Oléron, entre 1824 et 2003 est clairement positif. Dans la partie nord de la baie, dominée par le flot, le gain sédimentaire se situe à la fois dans les zones inter- et subtidales, alors que dans la partie sud de la baie, dominée par le jusant, le gain sédimentaire se limite aux zones intertidales avec un creusement des chenaux subtidales. L’activité ostréicole semble jouer un rôle dans le gain sédimentaire au niveau des zones intertidales.

Le comblement sédimentaire de la partie nord de la baie de Marennes-Oléron comprend cinq phases principales, de la base vers le sommet : (1) des unités lenticulaires et des estrans enregistrant des périodes de plus bas niveau marin avant 7 500 B.P. ; (2) des complements de chenaux témoignant de réorientations dans le drainage de la baie entre 7 500 et 5 500 B.P. ; (3) une unité subtidale mise en place entre 5 500 et 1 500 B.P. et qui constitue la plus grande partie du comblement ; (4) une surface d’érosion majeure liée à une mobilité drastique du trait de côte entre 1 500 et 1 000 B.P. ; (5) un drapage vaseux déposé depuis le dernier millénaire et enregistrant probablement l’impact anthropique de la déforestation et de la poldérisation. Dans la partie sud de la baie de Marennes-Oléron des bancs de sable, des estrans mixtes

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sablo-vaseux et des chenaux tidaux constituent un comblement rapide depuis les derniers siècles principalement.

L'ensemble des données montre que malgré un comblement sédimentaire peu épais (20 m au maximum), récent et rapide, les évolutions morphologiques et l'organisation stratigraphique de la baie de Marennes-Oléron sont très complexes et variables dans l'espace. Comme dans la plupart des estuaires, le comblement sédimentaire de cette baie a successivement été contrôlé par les changements relatifs du niveau de la mer, puis par les apports sédimentaires gouvernés par des changements hydrodynamiques en relation avec des migrations importantes du trait de côte et enfin par les activités humaines. Une originalité de ce type d'estuaire de côte rocheuse, caractérisé par une couverture sédimentaire très fine et discontinue, est le contrôle par la morphologie du socle rocheux à toutes les étapes du comblement, tant du point de vue de la préservation des sédiments dans les creux topographiques, que du point de vue de la modification des paramètres hydrodynamiques et des apports sédimentaires qui leurs sont associés.

## INTRODUCTION

Present-day estuaries are natural sediment sinks and are rapidly filled with sediments at both geological (millennia) and historical time scale (decades to centuries). The main processes governing their sediment-fill include [Zaitlin *et al.*, 1994] relative sea level rise, hydrodynamics (waves and tidal currents), bedrock shape and sediment supply (marine and continental). Previously, studies reported that modern estuarine environments in Europe allow the distinction of four main phases of sediment infilling. From 10000 to 6500 years B.P. (phase 1), rapid relative sea level rise (about 7 mm.yr<sup>-1</sup>) [Lambeck, 1997] was the main parameter controlling sedimentation [Dias *et al.*, 2000; Long *et al.*, 2000; Freitas *et al.*, 2002]. During this first period, sedimentation rate was high and reached few millimeters per year [Dabrio *et al.*, 2000; Dias *et al.*, 2000; Boski *et al.*, 2002; Lario *et al.*, 2002]. From 6000 to 3000 years B.P. (phase 2), deposition of extensive peat levels [Devoy, 1979; Delanay and Devoy, 1995; Regnaud *et al.*, 1996; Spencer *et al.*, 1998; Waller *et al.*, 1999; Allen, 2000a and b; Clavé *et al.*, 2001], development of barrier islands and sand spits and closure of estuaries [Boski *et al.*, 2002; Freitas *et al.*, 2002] have been related to a relative sea level stillstand. From 3000 to 2000 years B.P. (phase 3), deposition of marine sediments occurred during an episode of renewed sea level rise [Mary *et al.*, 1975; Visset, 1988; Breton *et al.*, 1991; Cearetta, 1993; Delanay and Devoy, 1995; Cearetta and Murray, 1996; Regnaud *et al.*, 1996; Sánchez Goñi, 1996; Spencer *et al.*, 1998; Waller *et al.*, 1999; Allen, 2000a]. From 2000 years B.P. to present (phase 4), sedimentation within estuaries was mainly controlled by both climate changes and increasing human activities. Human activities since 2000 years have mainly included extensive land reclamation and deforestation [Pontee *et al.*, 1998; Pawlowski, 1998]. The former leads to a decrease of tidal prism and an increase of sedimentation following a positive feedback loop mechanism [Van der Wal *et al.*, 2002; Bertin *et al.*, 2005]. The latter leads to soil erosion and an increase of sedimentation [Pitte, 1983; Higounet, 1985; Dabrio *et al.*, 2000]. Hence it appears that sedimentation of modern European estuaries was initially controlled by the early Holocene rapid sea-level rise and later by the complex interactions between human activities, climate, sediment supply and long-term morphodynamic behaviour.

Characterised by a very high sedimentation rate [Gouleau *et al.*, 2000; Bertin *et al.*, 2005], the Marennes-Oléron bay (MOB, figs 1 b and c) appears to be an ideal place to investigate the sedimentary record of the major environmental changes that occurred since the last

several millenia [Chaumillon *et al.*, 2004; Billeaud *et al.*, 2005], in order to help us understand the relative importance of the various parameters controlling estuarine infilling. In this study, the sedimentary record of the MOB is investigated using a dense grid of new very high-resolution seismic data combined with historical bathymetric data and core analysis.

## SETTING AND PREVIOUS WORK IN THE STUDIED AREA

### General setting

The MOB is located in the Bay of Biscay about 20 km to the north of the Gironde estuary (fig. 1a). The MOB is a 190 km<sup>2</sup> wide semi-enclosed environment connected to the Atlantic Ocean through the Pertuis d'Antioche to the North, and the Maumusson Inlet to the South (figs 1 and 2). It is bounded seaward by Oléron Island and mainland whose NW-SE elongated rocky outcrops are fringed by extensive marshes (fig. 2). Intertidal flats represent about 60% of the total surface area of the bay and are cut by sandy tidal channels (fig. 2b). The Marennes-Oléron Bay can be subdivided into four geomorphologic domains : (1) the Longe de Boyard, a 8 km long elongated sandbank located between two tidal channels in the northern entrance [Chaumillon *et al.*, 2002, 2008a; Bertin and Chaumillon, 2005a], (2) the northern MOB (NMOB, fig. 2b) with the "Rade des Trousses Channel" [Bertin *et al.*, 2005; Bertin and Chaumillon, 2005a] that is bounded to the south by the "Coureau d'Oléron Strait" (COS, fig. 2b), (3) the southern MOB (SMOB, fig. 2b) consisting of mixed sand-and-mud flats cut by tidal channels, and (4) the southern "Maumusson" tidal inlet [Bertin *et al.*, 2004, 2005].

### Hydrodynamic setting

Tides affecting the study area are semi diurnal. MOB is a macrotidal coastal environment with tidal ranges ranging from less than 2 m during neap tides to more than 6 m during spring tides. Tides and the associated tidal currents are the dominant forcing in the sedimentary dynamic of MOB, which has already been investigated using numerical models. Tidal currents control the transport and redistribution of sediments, resulting in a flood-dominated residual sand flux within both the northern entrance and Rade des Trousses channel [Bertin, 2005], an ebb-dominated residual sand flux in the southern Maumusson Inlet [Bertin, 2005], and a pronounced onshore residual flux on the eastern mud flat of the Marennes-Oléron Bay [Bassoulet *et al.*, 2000].

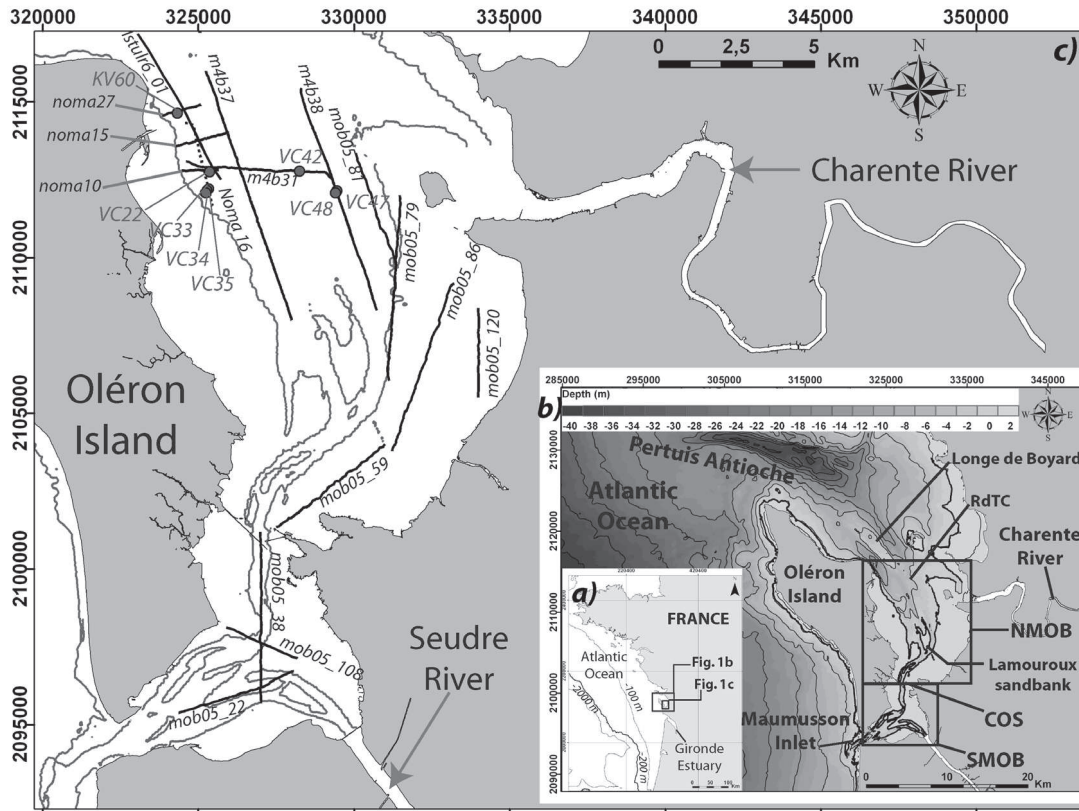


FIG. 1. – Location maps of the study area (NTF geodetic system, Lambert IIe, coordinates in meters). The 0 m isobath line is in reference to the marine chart-sounding datum at La Rochelle Harbor, that is -3.504 with reference to the Nivellement General de France. (a) Location of the Marennes-Oléron Bay on the West Coast of France. (b) Bathymetric map of the study area with a bathymetric contour of 5 m. NMOB and SMOB represent the northern and the southern Marennes-Oléron Bay, respectively. The Rade des Trousses Channel (RdTC) and the Coureau d'Oléron Strait (COS) are also indicated. (c) Simplified bathymetric map of the Marennes-Oléron Bay, showing the VHR seismic tracks used in this study (bold lines). Circles indicate the location of the vibracores discussed in this study. Seismic profile Noma 16 discussed in Chaumillon *et al.* [2004] is indicated with a bold dashed line.

FIG. 1. – Cartes de localisation de la zone d'étude (système géodésique NTF, Lambert IIe, coordonnées en m). La courbe isobathe du 0 correspond au niveau de référence hydrographique au port de La Rochelle, soit -3.504 m par rapport au 0 du Nivellement Général de France. (a) Localisation de la baie de Marennes-Oléron (MOB) sur la côte ouest de la France. (b) Carte bathymétrique de la zone d'étude avec un intervalle bathymétrique de 5 m. NMOB correspond à la partie nord de la baie de Marennes-Oléron et SMOB correspond à la partie sud de la baie de Marennes-Oléron. Le chenal de la Rade des Trousses (RdTC) et le Coureau d'Oléron (COS) sont également indiqués. (c) Carte bathymétrique simplifiée montrant les routes sismiques utilisées dans cette étude (traits gras). Les cercles indiquent la position des carottes utilisées dans cette étude. Le profil sismique Noma16 discuté dans Chaumillon *et al.* [2004] est représenté en trait pointillé gras.

Mean annual significant offshore wave height is about 1.5 m, but winter storms can episodically produce waves larger than 9 m [Bertin *et al.*, 2008]. Peak wave periods ranging from 8 to 12 s represent more than 60% of the annual wave climate while periods larger than 15 s occur more than 2% of the time. Wave directions are predominantly W to NW, which represent more than 60% of the annual wave climate and induce a southward net littoral drift along the southwestern coast of Oléron island [Bertin *et al.*, 2008]. Within the MOB, swells are strongly attenuated but their strong obliquity with respect to the shoreline induces a significant longshore transport, which results in the building of up to hectometer to kilometer long sand spits close to the two entrances of the bay [Bertin *et al.*, 2005]. Wind waves induce mud resuspension during the high-water slack period [Bassoulet *et al.*, 2000].

Two small rivers flow into the MOB, the Charente and the Seudre rivers (fig. 1b and c). The volumes of freshwater introduced by these rivers are respectively 65 and 0.55 m<sup>3</sup>.s<sup>-1</sup> [Tesson, 1973; Bry and Hoflack, 2004], which is

more than two orders of magnitude less than those moved by the tide during each tidal cycle [Tesson, 1973; Bertin *et al.*, 2005]. The mean annual solid discharge of the Charente River is about 41000 t [Gonzalez *et al.*, 1991]. Sediment discharge from the Seudre River was not measured but it is likely much lower than those of the Charente River.

### Morphological evolution of the Marennes-Oléron Bay

A synthesis of historical data and maps [Pawlowski, 1998] was used by Bertin [2005] to show the qualitative evolution of the Marennes-Oléron Bay area (fig. 3). This synthesis allowed showing huge changes of the coastline since the last centuries and evidenced the communication between MOB and the Gironde estuary during the Middle Age (fig. 3). Comparison of bathymetric maps produced in 1824 and 1995 has allowed computation of the sediment budget of the MOB [Bertin *et al.*, 2005]. Calculated sediment budget is clearly positive (106 x 10<sup>6</sup> m<sup>3</sup> added over the last 171



years). Sediment accretion occurred mainly in four types of areas: (1) close to the connections with the open ocean; (2) in the lower parts of intertidal flats; (3) in the Rade des

Trousses Channel; and (4) in areas where land reclamation has occurred. Sediment erosion occurred mainly within channels of the southern part of the bay. The recent and

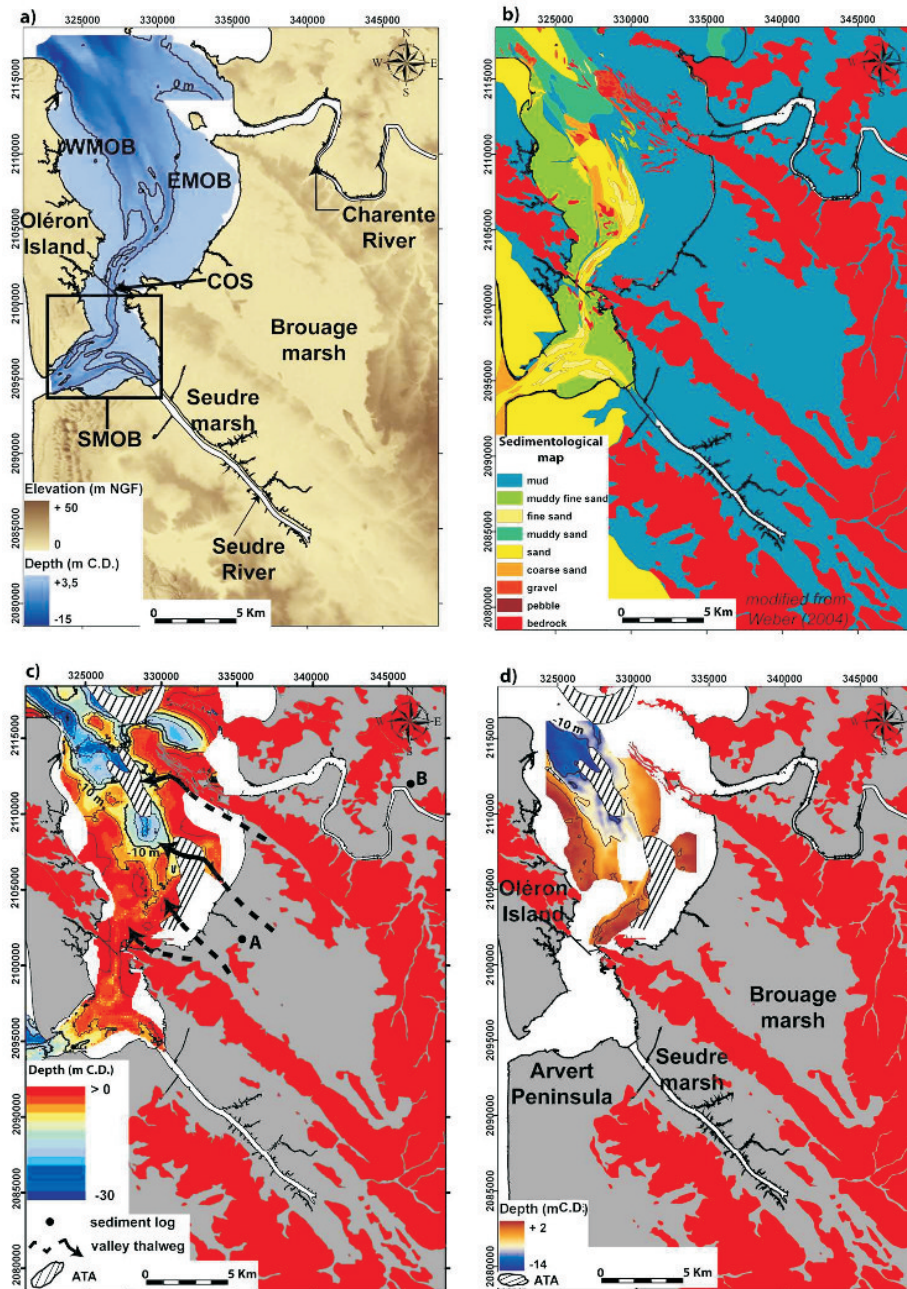


FIG. 2. – (a) Bathymetric (in reference to the marine chart-sounding datum at La Rochelle Harbor) and topographic (in reference to the Nivellement General de France) map of the Marennes-Oléron Bay and surrounding areas. WMOB, EMOB, SMOB and COS represent the western, the eastern, the southern Marennes-Oléron Bay, and the Coureau d'Oléron Strait, respectively. (b) Simplified sedimentological map of the Marennes-Oléron Bay and surrounding areas [modified from Weber, 2004]. (c) Bedrock isobath map of the Marennes-Oléron Bay and location of the continental bedrock outcrops within surrounding areas (in red colour). The Acoustic Turbidity Area (ATA) is indicated by the hatched polygons. -10 m bedrock isobath is indicated in bold. Black arrows indicate the location of the thalweg incised valley of the EMOB. Circles and letters A and B indicate the location of sediment log already described in Gabet [1969] and Carbonel *et al.* [1998] respectively. (d) Isobath map of the erosional unconformity EU1 observed within the northern MOB. The Acoustic Turbidity Area (ATA) is indicated with hatched polygons.

FIG. 2. – (a) Carte bathymétrique (niveau de référence : 0 hydrographique) et topographique (niveau de référence : 0 du Nivellement générale de France) de la baie de Marennes-Oléron et régions adjacentes. WMOB, EMOB, SMOB correspondent aux parties ouest, est, sud et de la baie de Marennes-Oléron et COS indique le Coureau d'Oléron. (b) Carte sédimentologique simplifiée de la baie de Marennes-Oléron et régions adjacentes [d'après Weber, 2004]. (c) Carte isobathe du socle rocheux et localisation des affleurements rocheux (en rouge). La zone de turbidité acoustique est représentée en hachuré. La courbe isobathe du socle rocheux à -10 m est indiquée en gras. Les flèches indiquent les thalwegs des vallées dans la partie orientale de la baie de Marennes-Oléron. Les cercles et lettres A et B indiquent la position des carottes respectivement décrites dans Gabet [1969] and Carbonel *et al.* [1998]. (d) Carte isobathe de la discordance érosionnelle EU1 identifiée dans la partie nord de la baie de Marennes-Oléron. La zone de turbidité acoustique est représentée en hachuré.

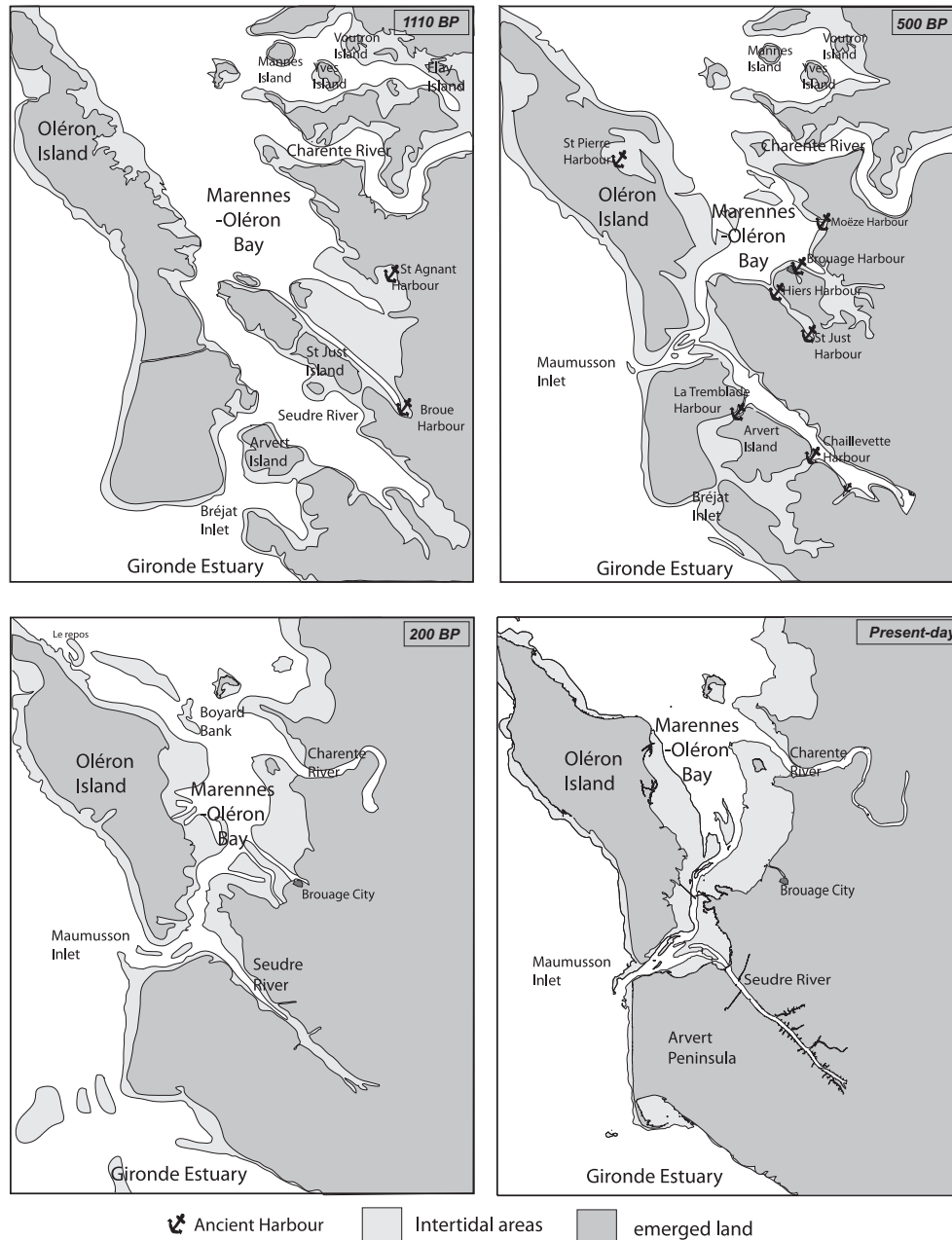


FIG. 3. – Historical evolution of the coastline in the vicinity of the Marennes-Oléron Bay [modified from Bertin, 2005].

FIG. 3. – Evolution historique du trait de côte dans la région de la baie de Marennes-Oléron [modifié d'après Bertin, 2005].

rapid sediment infilling of the bay has been attributed to both natural processes and human activities [Bertin *et al.*, 2005; Bertin and Chaumillon, 2006].

### Stratigraphy of the Marennes-Oléron Bay

Previously published seismic profiles were obtained for the northern entrance of the bay [Chaumillon *et al.*, 2002, 2008a], at Maumusson Inlet [Bertin *et al.*, 2004] and in the Rade des Trousses Channel [Chaumillon *et al.*, 2004; Billeaud *et al.*, 2005; Bertin and Chaumillon, 2006]. Within the Rade des Trousses Channel, those previous workers have identified four main seismic units and three of them were cored. The uppermost unit is a mud drape that can be

related to three concomitant main causes: (1) natural infilling process that leads to a decrease in the tidal prism and, in turn, to positive feedback and an increase in sedimentation [Pendon *et al.*, 1998; van der Wal *et al.*, 2002]; (2) climate changes resulting in an increase in suspended matter input [Bourrin *et al.*, 2007]; (3) human activities, including land reclamation and deforestation leading to the expulsion of suspended-matter which induced the increased sedimentation and deposition of muddier sediments within the estuary.

It is the aim of this study to make a synthesis of both seismic and bathymetric results to understand better the sediment-infilling history of the MOB and the related forcing parameters.



## METHODOLOGY

### Bathymetric data

A set of historical (1824) and recent (2003) bathymetric data was extracted from the database of the “Service Hydrographique et Océanographique de la Marine” (SHOM) and of the local hydrographic service (“Direction Départementale de l’Équipement”, DDE 17), respectively. The historical bathymetric data set was collected using lead line, positioned using horizontal sextant and was georeferenced using ArcView software (ESRI) and extensions developed by the SHOM. The local geodesic system New Triangulation of France (NTF) was chosen, with Clarke 1880 as the reference ellipsoid. Planar Lambert II co-ordinates were calculated for a geomorphological description together with surface and volume computations. The reference level of sounding reduction was defined as the marine chart-sounding datum at La Rochelle Harbour, that is  $-3.504$  m with reference to Institut Géographique National 1969 [SHOM, 2003]. Digital elevation models (DEM) were developed using ArcView 9.1 software and the 3-D Analyst extension (ESRI), using a kriging interpolation technique and a grid spacing of 50 m (fig. 4). Depth errors for the 1824 bathymetric data were checked by assuming stability of rocky outcrops between the two surveys [Bertin *et al.*, 2005] and were estimated to be  $\pm 0.35$  m at the maximum. According to SHOM, the relative error does not exceed  $\pm 10$  m in position and  $\pm 0.5$  m in depth for 1824 data. According to the DDE 17, the maximum relative error does not exceed 1 m horizontally and 0.1 m vertically for the 2003 bathymetric data. The random component included in these errors is significantly reduced for volume and sedimentation-rate estimations due to the fact that these computations utilize a large number (45000 for 2003 data) of sounding points [Thomas *et al.*, 2002]. Consequently, it can be argued that the uncertainties of the values derived from the bathymetric data are significantly overestimated. The secular volume computations were calculated using the difference between the 2003 and the 1824 DEMs. A conservative approach was adopted where only elevation changes greater than  $\pm 0.5$  m between subsequent surveys were considered to be significant [Van der Wal *et al.*, 2002; Bertin *et al.*, 2005].

### Seismic profiling and stratigraphy

The stratigraphy was investigated using more than 600 km of seismic profiles recorded during the number of seismic surveys NOMADE (2000) and MOB05 (2005), on “Les Deux Mouettes” vessel, and MOBIDYC 4 (2004) and LSTULR6 (2006) on CNRS/INSU R/V “Côte d’Aquitaine” (fig. 1c). A boomer plate associated with a line in cone receiver (vertical resolution of 0.25 m) [Simpkin and Davis, 1993] was used to image the detailed internal architecture of the MOB. The shot interval was 250 or 500 ms, which corresponds to the average distances between adjacent seismic traces of 0.4 and 0.8 m respectively. Processing of seismic data was carried out using Seismic Unix software, consisting of noise mute in the water column, automatic gain correction, band-pass filtering and swell filtering using a methodology developed at La Rochelle University [Chaumillon *et al.*, 2008a]. A P-wave velocity of  $1600 \text{ m s}^{-1}$  was chosen for time-to-depth conversion (figs 5 to 13).

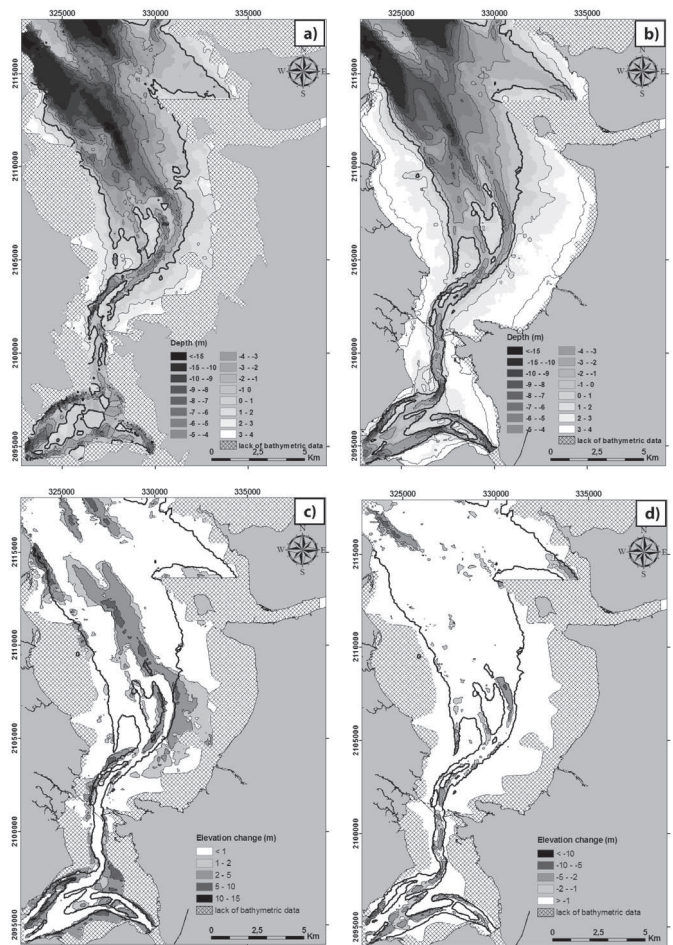


FIG. 4. – Bathymetric and differential maps of the Marennes-Oléron Bay. The bold line indicates the 0 m isobath. (a) Digital elevation models of the bathymetry of 1824 and coastline of 1824. (b) Digital elevation models of the bathymetry of 2003 and coastline of 1997. (c) Positive sediment gain (net deposition) map between 1824 and 2003. (d) Negative sediment gain (erosion) map between 1824 and 2003.

FIG. 4. – Cartes bathymétriques et de différences bathymétriques de la baie de Marennes-Oléron. La courbe en gras indique le 0 hydrographique (marine chart-sounding datum). (a) Modèle numérique de terrain bathymétrique et trait de côte en 1824. (b) Modèle numérique de terrain bathymétrique et trait de côte en 2003. (c) Carte de gain sédimentaire entre 1824 et 2003. (d) Carte d’érosion sédimentaire entre 1824 et 2003.

Cores VC22, VC42 and VC47, collected during MOBIDYC 5 CNRS/INSU cruise (2006, R/V Côte de la Manche, fig. 1c) were sectioned longitudinally, lithologically described, photographed, X-radiographed [SCOPIX, Migeon *et al.*, 1999], and sampled for grain-size analyses. Samples for grain-size analyses were collected from intervals where X-ray images and grey-level curves showed noticeable changes. Grain size analysis was conducted using a microgranulometer (Mastersizer S instrument, Malvern Instruments). Inman’s [1952] classification was used to define the various grain-size fractions: clay and fine silt ( $< 15 \mu\text{m}$ ), medium silt ( $15\text{--}30 \mu\text{m}$ ), coarse silt ( $30\text{--}63 \mu\text{m}$ ) and very fine sand ( $> 63 \mu\text{m}$ ). Description of cores KV60 and VC48 are available in Weber [2004] and Allard *et al.* [2008], respectively.

The radiochronology is based on ten uncalibrated radiocarbon dates, obtained on shells of the bivalves *Abra* sp.

(Poz-20105, Poz-20106, Poz-20121, Poz-20122, Poz-23454), *Ostrea edulis* (Poz-23455, Poz-23457), *Cerastoderma edule* (Poz-26304, Poz-26303) and *Pandora inaequalis* (Poz-26302). The AMS method was conducted in the Poznan Radiocarbon Laboratory, Poland. Samples were intact and thin shells of the bivalves.

## RESULTS

For the description of the results obtained, the MOB is subdivided into two parts, namely, northern part (NMOB, fig. 1b) and southern part (SMOB, fig. 1b), which are developed on both sides of the narrow “Coureau d’Oléron” Strait (COS, fig. 1b). The NMOB is subdivided in a western (WMOB, fig. 2a) and an eastern part (EMOB, fig. 2a).

### Bathymetric results

The net volume change between the 1824 and 2003 DEM was estimated over 70% of the total area of the MOB, which is 44% of the intertidal area and 100% of the subtidal area (figs 4a and b). The sediment budget between 1824 and 2003 (179 years) was  $+77 \pm 48 \times 10^6 \text{ m}^3$  (table I). The corresponding average sedimentation rate was about  $+3 \pm 1.9 \text{ mm.yr}^{-1}$  (table I). Sediment gain occurred mainly on tidal flats on both sides of the whole MOB and tidal channels of the NMOB (fig. 4c) whereas erosion was mainly restricted to the tidal channels of the SMOB (fig. 4d).

The net change in sediment volume on the intertidal zone of the MOB between 1824 and 2003 was about  $+38 \pm 15 \times 10^6 \text{ m}^3$  ( $4.8 \pm 1.9 \text{ mm.yr}^{-1}$ ; table I). Sedimentation volumes and rates increase toward the head of the Bay: in the NMOB sediment accretion within intertidal zone was about  $+17 \pm 12 \times 10^6 \text{ m}^3$  ( $2.7 \pm 1.9 \text{ mm.yr}^{-1}$ ; table I), whereas in the SMOB it was about  $+21 \pm 3.5 \times 10^6 \text{ m}^3$  ( $12 \pm 1.9 \text{ mm.yr}^{-1}$ ; table I). Maximum vertical accretion reached more than 10 m in a mixed flat within the western part of the NMOB and nearly 6 m in the mixed flat of the SMOB (fig. 4c).

The net change in sediment volume on the subtidal zone of the MOB between 1824 and 2003 was about  $+39 \pm 33 \times 10^6 \text{ m}^3$  ( $2.3 \pm 1.9 \text{ mm.yr}^{-1}$ ; table I). In the NMOB, sediment accretion within subtidal zone was

restricted to the main tidal channel (fig. 4c) and was about  $+43 \pm 28 \times 10^6 \text{ m}^3$  ( $+3 \pm 1.9 \text{ mm.yr}^{-1}$ ; table I). Maximum vertical accretion could reach more than 8 m in the Rade des Trousses Channel. Sediments mainly consisted of mixed very fine sand and fine silts (figs. 1b, 2b and 4c). The subtidal zone of the NMOB displays widely scattered areas of erosion, which are mainly located adjacent to accretion areas that correspond to channel migrations [Bertin *et al.*, 2005]. At the scale of whole subtidal area of the SMOB, the sediment budget is almost in equilibrium:  $-4 \pm 4.5 \times 10^6 \text{ m}^3$  (table I). Nevertheless, the channel bottoms locally show deepening of a few meters that could reach more than 8 m eastward of the Maumusson tidal inlet (fig. 4d).

### Seismic and core results

Seismic profiles recorded within the different parts of the MOB provide evidence for the presence of twelve main seismic units overlying the Mesozoic bedrock (U0) that is locally exposed on the seafloor (fig. 2b). The structural contour map of the upper surface of Mesozoic bedrock EU0 (fig. 2c) [Chaumillon *et al.*, 2008b] displays incisions that can be considered as small to intermediate valleys [cf. Ashley and Sheridan, 1994] ranging from few hundred of meters to more than 5 km in width and from few meters to more than 20 m in depth. The major valley axis lies in a north-south orientation. The valley tapers southward and has width of less than 1 km in the Coureau d’Oléron Strait (fig. 2a and c).

### The western Marennes-Oléron Bay (WMOB)

Seismic profiles indicate that four major seismic units overlie the Mesozoic bedrock in the WMOB (figs 5, 6 and 7). From base to top, these units are UT1, UT2, UT3 and UT4 [Chaumillon *et al.*, 2004; Billeaud *et al.*, 2005; Bertin and Chaumillon, 2005b]; the equivalent units were labelled Uaid1, Uaid2, Uaid3 and Uaid4sd in Chaumillon and Weber [2006].

Unit UT1 is composed of lense-shaped seismic sub-units with small lateral extent (figs 5 and 6). These sub-units are isolated from each other and typically present in the depression on the surface of the Mesozoic bedrock. They are characterised by high-angle oblique parallel reflectors (fig. 6). Northward of the MOB, basal progradational units, similar to those observed in the WMOB, are believed to consist of medium to coarse sand and are dated to  $6105 \pm 35 \text{ }^{14}\text{C yr B.P.}$  [Chaumillon and Weber, 2006].

Unit UT2 consists of a valley-fill, lying upon both the incised Mesozoic bedrock and Unit UT1 (figs 5, 6 and 7) and extends to the Rade des Trousses Channel (figs 8, 9). Its thickness varies from about 2 to 15 m. The seismic facies is characterised by moderate to high-amplitude reflectors. Internal configuration consists of subhorizontal reflectors that dip gently toward the northwest or northeast in the north-western part of the WMOB. Upper boundary of UT2 is an erosional unconformity (EU1; figs 6 and 7). Unit UT2 is correlated with shelly bioturbated very fine to fine sand (figs 6 and 7) that alternates with a few thin planar beds made of clay to fine silt (fig. 6). Two shells of *Abra* sp., collected in core M3VC60 at 3.58 m and M5VC22 at 3.02 m bsf (below seafloor), yielded ages of  $3095 \pm 35 \text{ }^{14}\text{C yr B.P.}$

TABLE. 1. – Sediment budgets and average sedimentation rates, calculated from difference bathymetric maps (1824-2003), of the whole, the subtidal and the intertidal zones of the MOB and of the whole, the sub-tidal and the intertidal zones of the northern and southern parts of the MOB. The boundaries of the northern and southern parts of the Mob are shown in figure 1. TABL. 1. – Budgets sédimentaires et taux de sédimentation moyens, calculés à partir des différences de bathymétrie entre 1824 et 2003, pour la totalité et les zones inter et subtidales de la baie de Marennes-Oléron ainsi que pour la totalité et les zones inter- et subtidales des parties nord et sud de la baie de Marennes-Oléron (les limites des parties nord et sud de la baie de Marennes sont montrées dans la figure 1.

Location	Net change in sediment volume ( $\times 10^6 \text{ m}^3$ )		Sedimentation rate ( $\text{mm.yr}^{-1}$ )	
	Intertidal	Subtidal	Intertidal	Subtidal
MOB	77± 48		3 ± 1.9	
	38 ± 15	39 ± 33	4.8± 1.9	2.3± 1.9
North MOB	60± 40		3± 1.9	
	17 ± 12	43 ± 28	2.7± 1.9	3 ± 1.9
South MOB	17± 8		4.3± 1.9	
	21 ± 3.5	-4 ± 4.5	12± 1.9	-1.7± 1.9



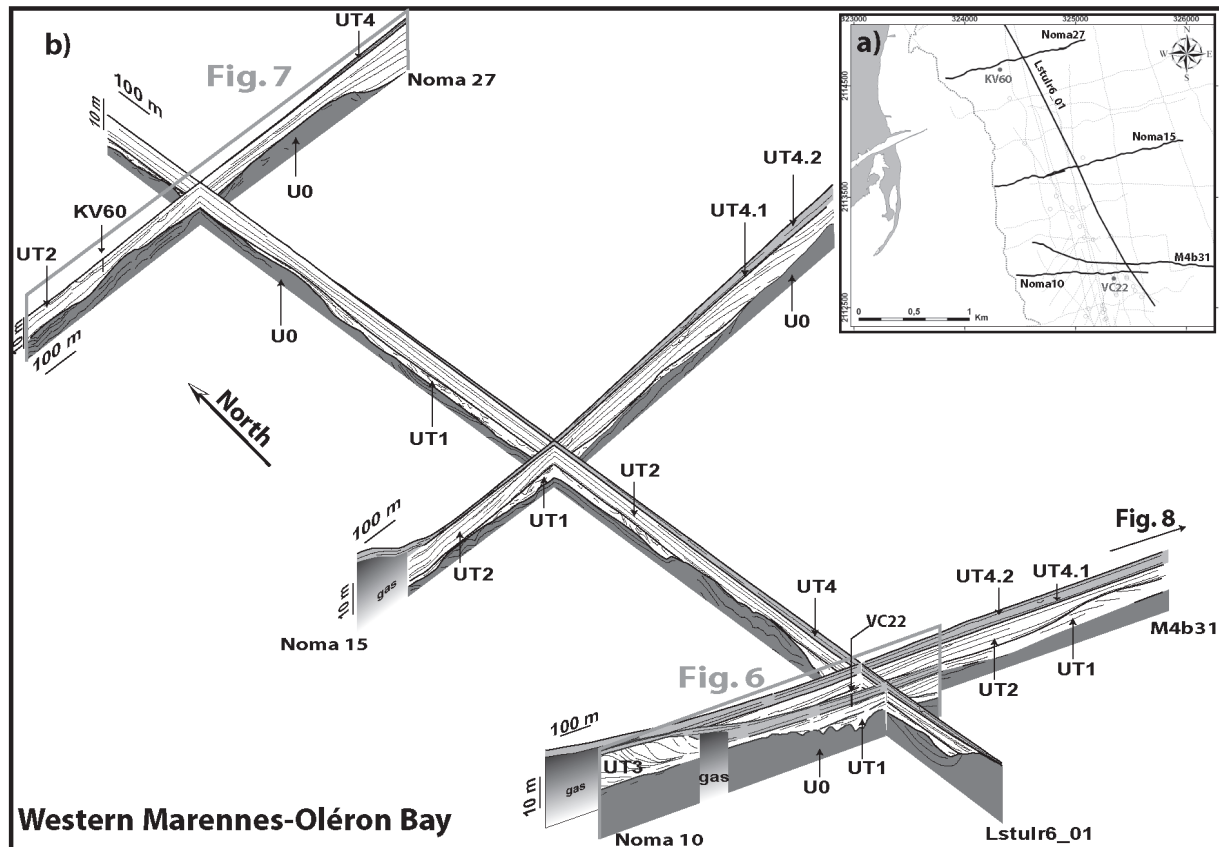


FIG. 5. – (a) Carte de localisation des profils sismiques et des carottes dans la partie ouest de la baie de Marennes-Oléron. Les traits gras et les cercles noirs indiquent les profils et carottages montrés dans la figure 5b. (b) Montage 3D des profils Noma27, Noma15, Noma10, M4b31 et Lstulr6\_01, illustrant l'architecture interne du comblement sédimentaire dans la partie ouest de la baie de Marennes-Oléron. L'unité sismique U0 correspond au socle rocheux et les unités UT1, UT2, UT3 and UT4 (UT4.1 and UT4.2) correspondent à la couverture sédimentaire meuble.

FIG. 5. – (a) Carte de localisation des profils sismiques et des carottes dans la partie ouest de la baie de Marennes-Oléron. Les traits gras et les cercles noirs indiquent les profils et carottages montrés dans la figure 5b. (b) Montage 3D des profils Noma27, Noma15, Noma10, M4b31 et Lstulr6\_01, illustrant l'architecture interne du comblement sédimentaire dans la partie ouest de la baie de Marennes-Oléron. L'unité sismique U0 correspond au socle rocheux et les unités UT1, UT2, UT3 and UT4 (UT4.1 and UT4.2) correspondent à la couverture sédimentaire meuble.

(Poz-23454) and  $1695 \pm 30$   $^{14}\text{C}$  yr B.P. (Poz-20106), respectively (figs 6 and 7).

UT3 consists of a bank lying upon unit UT2 (figs 5 and 6). The maximum thickness of unit UT3 reaches 12 m. The internal configuration is progradational. This unit is composed of mixed of gravel, medium and fine sand and silt [Chaumillon *et al.*, 2004]. Shells of *Cerastoderma edule* and *Pandora inaequalis* collected at the top of UT3 unit from three cores, M5VC33, 34 and 35 respectively located at 10, 50 and 100 m of the previously published seismic profile NOMA16 [Chaumillon *et al.*, 2004] yielded ages of  $1235 \pm 30$   $^{14}\text{C}$  yr B.P. (49 cm bsf in M5VC33, Poz-26304),  $1165 \pm 30$   $^{14}\text{C}$  yr B.P. (57 cm bsf in M5VC34, Poz-26302) and  $1245 \pm 30$   $^{14}\text{C}$  yr B.P. (104 cm in M5VC35, Poz-26303).

Unit UT4 consists of a sheet drape, lying upon both units UT2 and UT3 (figs 5, 6, 7) and extends to the EMOB (figs 8, 9, 10 and 11).

The base of UT4 corresponds to the erosional unconformity "EU1", which is correlated with a shell-bed and a sharp decrease of grain size upward [Chaumillon *et al.*, 2004; Billeaud *et al.*, 2005]. The maximum thickness of unit UT4 reaches up to 5 m and this unit thins progressively towards both the northwest and the southwest of the NMOB. Seismic facies consists of high-frequency and

moderate-amplitude reflectors with a sub-parallel and sub-horizontal internal configuration. Upper surface of UT4 corresponds to the present-day seafloor. Unit UT4 is correlated with planar bedded fine silt and clay that alternate with bioturbated and shelly fine sand layers (figs 6, 9). UT4 is associated with methane-rich sediment within the Rade des Trousses Channel (fig. 9) [Bertin and Chaumillon, 2005b; Roussel *et al.*, 2009]. UT4 is subdivided into two sub-units, namely, UT4.1 and UT4.2 that are separated by a high-amplitude sub-horizontal reflector correlated with a shelly sand layer at 1.45 m bsf (fig. 6), where an *Abra* sp. yielded an age of  $570 \pm 30$   $^{14}\text{C}$  yr B.P. (Poz-20121). Another shell of *Abra* sp., collected in UT4.1 at 2.75 m bsf yielded an age of  $910 \pm 30$   $^{14}\text{C}$  yr B.P. (Poz-20122).

#### The eastern Marennes-Oléron Bay

Seismic profiles indicate five major seismic units overlying the Mesozoic bedrock (fig. 10). From base to top, these units are Ue1.1, Ue1.2, Ue2, Ue3 and UT4. In particular, Ue1.1, Ue1.2 and Ue3 correspond to U1.1, U1.2 and U3, respectively in Allard *et al.* [2008].

Ue1.1 and Ue1.2 consist of a valley-fill. Reflectors of unit Ue1.1 onlap the incised Mesozoic bedrock (U0). Unit

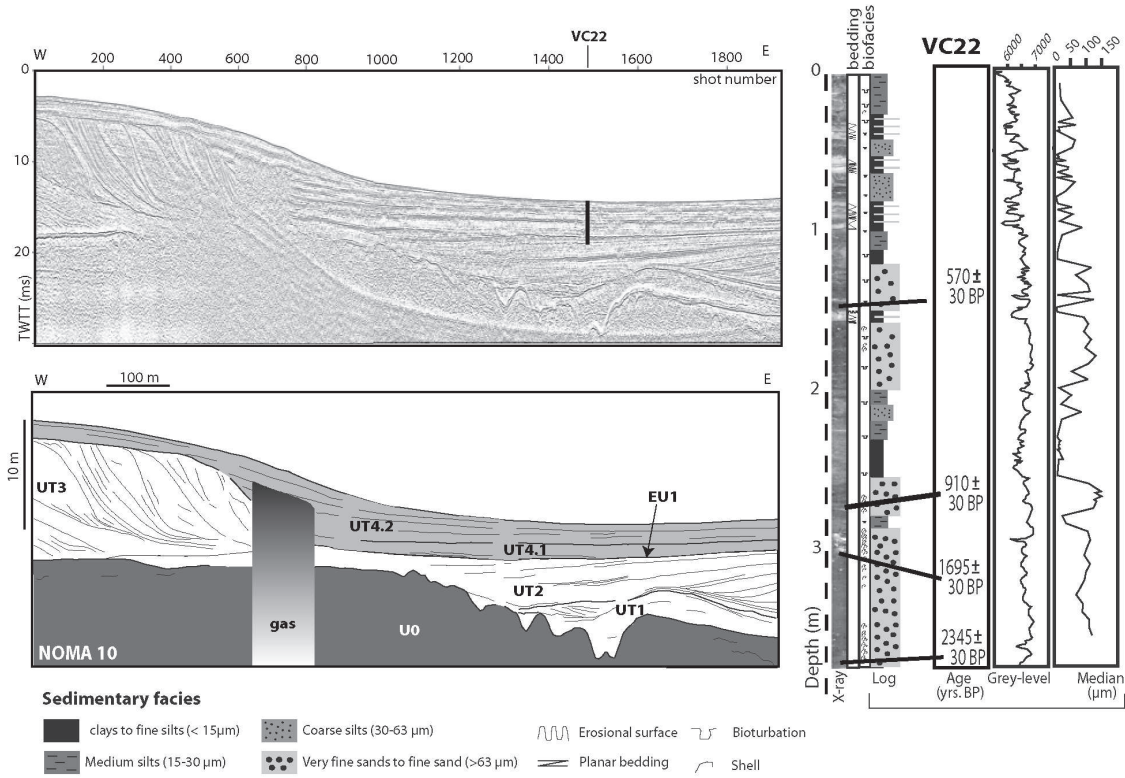


FIG. 6. – VHR seismic profile Noma10 and its interpretation showing the internal architecture of the sediment infilling within the western part of Marennes-Oléron Bay. Detailed description of vibracore VC22 include, from left to right: depth (m below seafloor: bsf), X-ray image, bedding and biofacies, grain size, <sup>14</sup>C uncalibrated dates, grey-level curve and median grain-size in micrometers.

FIG. 6. – Profil sismique Noma10 et son interprétation montrant l'architecture interne du comblement sédimentaire de la partie ouest de la baie de Marennes-Oléron. La description de la carotte VC22 comprend de gauche à droite : la profondeur (en m par rapport au fond marin), l'image RX, le litage et le biofaciès, la granularité, les âges non calibrés, la courbe de niveau de gris et la médiane de granularité en micromètres.

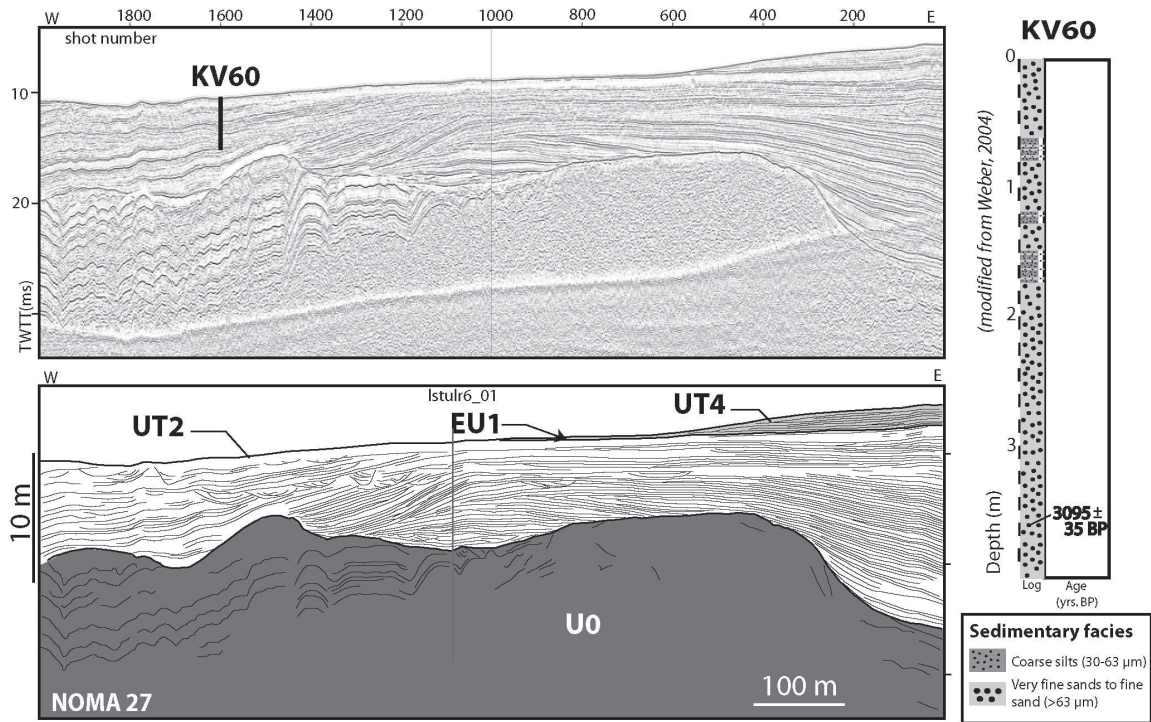


FIG. 7. – VHR seismic profile Noma27 and its interpretation showing the internal architecture of the sediment infilling within the western part of Marennes-Oléron Bay. Simplified description of vibracore KV60 [modified from Weber, 2004] is indicated, including from left to right: depth (m bsf), grain size, <sup>14</sup>C uncalibrated dates.

FIG. 7. – Profil sismique Noma27 et son interprétation montrant l'architecture interne du comblement sédimentaire de la partie ouest de la baie de Marennes-Oléron. Description simplifiée de la carotte KV60 [modifié d'après Weber, 2004] avec de gauche à droite : la profondeur (en m par rapport au fond marin), la granularité, les âges non calibrés.

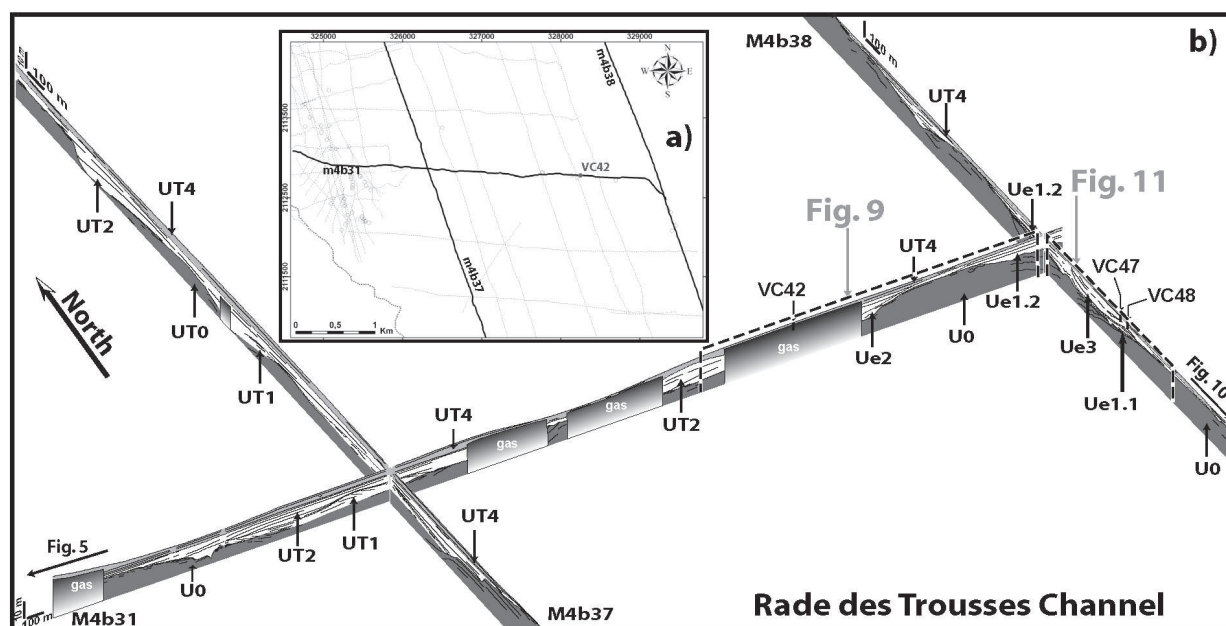


FIG. 8. – (a) Location map of seismic profiles (Bold dark lines indicate the seismic profiles shown in this study) and vibracore (circles) within the Rade des Trousses Channel. (b) Fence diagram of seismic profiles M4b31, M4b37 and M4b38, showing the internal architecture of the Rade des Trousses Channel at the transition between the WMOB and the EMOB. Seismic unit U0 corresponds to the bedrock and seismic units UT1, Ue1.1, Ue1.2, Ue2, Ue3, UT2, and UT4 (UT4.1 and UT4.2) correspond to the soft sedimentary cover.

FIG. 8. – (a) Carte de localisation des profils sismiques (les profils montrés dans cette étude sont représentés en gras) et des carottes (cercles) dans la rade des Trousses. (b) Montage 3D des profils M4b31, M4b37 et M4b38, illustrant l'architecture interne du comblement sédimentaire dans la rade des Trousses. L'unité sismique U0 correspond au socle rocheux et les unités UT1, Ue1.1, Ue1.2, Ue2, Ue3, UT2, and UT4 (UT4.1 and UT4.2) correspondent à la couverture sédimentaire meuble.

Ue1.1 thickness varies from 2 to 5 m. Seismic facies is characterised by low amplitude reflectors. Internal geometry consists of a divergent valley-fill (fig. 11).

Unit Ue1.2 overlies U1.1 and onlap the Mesozoic bedrock (U0, fig. 11). Ue1.2 thickness varies from 1.5 to 4.5 m. The seismic facies is characterised by low-to-middle amplitude reflectors. Internal geometry consists of gently undulating and sub-parallel reflectors. Ue1.2 is correlated with clay and fine silt including intertidal mudflat species. Two shells of *Scrobicularia plana* (-4.1 m bsf) and *Loripes lacteus* (-2.3 m bsf) yielded ages of  $8030 \pm 50$   $^{14}\text{C}$  yr B.P. and  $7610 \pm 40$   $^{14}\text{C}$  yr B.P. respectively [Allard *et al.*, 2008] (fig. 11).

Unit Ue2 consists of a drape lying on Ue1.2 unit and on the slope of the Mesozoic bedrock. Seismic facies is transparent (fig. 9).

Unit Ue3 consists of a channel-fill downcutting Ue1.1 and Ue1.2. The maximum thickness of Ue3 is about 8 m (fig. 11). Seismic facies is characterised by high frequency, middle to high amplitude reflectors. Internal geometry is a complex channel-fill. Unit Ue3 is correlated with shell beds dominated by *Ostrea edulis* associated with medium to coarse silt (fig. 11). Two shells of *O. edulis* (-2.3 m and -3.5 m bsf) yielded ages of  $5130 \pm 35$   $^{14}\text{C}$  yr B.P. (Poz-23455) and  $5560 \pm 40$   $^{14}\text{C}$  yr B.P. (Poz-23457).

The upper UT4 unit (fig. 11) has been already described in section 4.2.1. In the EMOB, UT4 lies upon the erosional unconformity, "EU1", located at the top of Ue1.2, Ue2 and Ue3 (fig. 9 and 11) and is correlated with a 0.5 m-thick bed composed of shelly very fine sand deposit [Allard *et al.*, 2008]. A shell of *Abra* sp. located within UT4.1 at 0.84 m

bsf yielded an age of  $630 \pm 30$  years  $^{14}\text{C}$  yr B.P. [Poz-20250; Allard *et al.*, 2008].

### The southern Marennes-Oléron Bay

Seismic profiles indicate four major seismic units overlying the Mesozoic bedrock (fig. 12). From base to top, these units are Us1, Us2, Us3 and Us4.

Unit Us1 consists of a 10 m-thick progradational body with moderate lateral extent (about 1500 m wide), which partly fills a major incision within the Mesozoic bedrock (fig. 12). Internal configuration of Us1 is oblique tangential. Seismic facies is characterised by low frequency and low amplitude reflectors with moderate continuity (fig. 13).

Unit Us2 consists of banks with few m to 10 m thickness and 200 to 1000 m width, lying upon both the Mesozoic bedrock and unit Us1 (fig. 12). Internal configuration of Us2 is oblique parallel. Seismic facies is characterised by small amplitude and high frequency with reflectors of low continuity. Locally the upper part of Us2 and its top surface is correlated with medium sand (fig. 13).

Us3 consists of banks with few m to 10-12 m thickness and few hundred of meters to few kilometres width, lying upon the Mesozoic bedrock and units Us1 and Us2. Internal configuration of Us3 is mainly oblique parallel and locally includes small channel-fills. Seismic facies is characterised by small amplitude and high frequency reflectors with low continuity (fig. 13). The top of those banks corresponds to the present-day seafloor and is correlated with medium sand and locally with mixed sand and mud (fig. 2b). Superimposition of 1824 bathymetric cross-sections on seismic



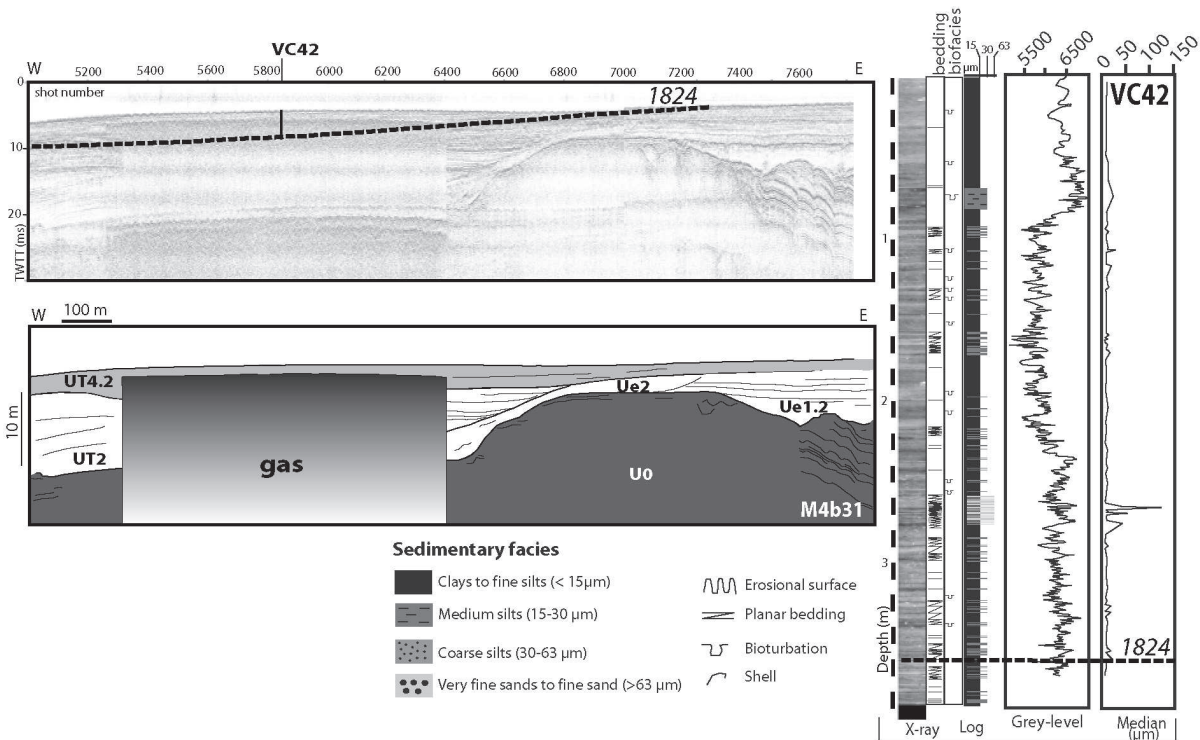


FIG. 9. – VHR seismic profile M4b31 and its interpretation showing the internal architecture of the sediment infilling within the Rade des Trousses Channel. Detailed description of vibracore VC42 includes from left to right: depth (m bsf), X-ray image, bedding and biofacies, grain size, grey-level curve and median grain-size in micrometers. Seabottom of 1824 is indicated thanks to a dashed line on both seismic profile and VC42 core description.

FIG. 9. – Profil sismique M4b31 et son interprétation montrant l'architecture interne du comblement sédimentaire dans la rade des Trousses. La description de la carotte VC42 comprend de gauche à droite : la profondeur (en m par rapport au fond marin), l'image RX, le litage et le biofaciès, la granularité, la courbe de niveau de gris et la médiane de granularité en micromètres. Le fond marin en 1824 est indiqué par une ligne pointillée à la fois sur le profil sismique et sur la carotte VC42.

profiles (figs 12 and 13) shows that a large part of those banks was deposited since the onset of the 19th century.

Unit Us4 consists of a complex channel-fill that is 10 m thick and more than 1 km wide. Individual channel-fills observed within Us4 are a few meters deep and 100 to 300 m wide. Seismic facies is characterised by small amplitude and high frequency reflectors with low continuity (fig. 13). The top of Us4 corresponds to the present-day seafloor and can be correlated with mixed fine sand and mud (fig. 2b). Superimposition of 1824 bathymetric cross-sections on the seismic profile (fig. 13) shows this unit mainly arose after the beginning of the 19th century.

## DISCUSSION

### Secular evolution

Volume computations based on careful comparison of recent bathymetric chart of 2003 with that of 1824 in the MOB indicate that there has been a positive sediment budget between 1824 and 2003. The computed volume difference is  $+77 \pm 48 \times 10^6 \text{ m}^3$  which differs from the  $+106 \times 10^6 \text{ m}^3$  value estimated by Bertin *et al.* [2005]. This difference is due to the choice of the mask analysis contour (fig. 4), which excludes the Maumusson Inlet, the Seudre River, the upper tidal flats and land areas reclaimed since 1824 (fig. 4).

The morphological evolution of the NMOB is different from that of the SMOB. The NMOB displays sediment gain in both intertidal and subtidal areas whereas the SMOB displays sediment gain only in the intertidal area. Sediment loss is inferred in the subtidal channels of SMOB, where channel depth increased.

Contrasting style of morphologic evolution between NMOB and SMOB can be related to the hydrodynamics of the MOB. It has been shown theoretically that flood-dominated estuaries become shallower and that ebb-dominated estuaries maintained with time due to tidal distortion [Friedrichs and Aubrey, 1988]. Due to the connection of the MOB with the ocean at both north and south of Oléron Island (fig. 1), there is an asymmetry between the ebb and flood tidal prisms and tidal durations at the entrances of the bay. Flood dominance is observed at the northern entrance [Tesson, 1973; Bertin *et al.*, 2005] while ebb dominance is observed at the southern Maumusson Inlet [Bertin *et al.*, 2004 and 2005]. The former is supported by the presence of flood-dominated sandbanks, the Longe de Boyard [Chaumillon *et al.*, 2008a] and the Lamouroux sandbank (fig. 1b) [Bertin, 2005] in the NMOB, whereas the latter is supported by the occurrence of an ebb-dominated tidal Inlet in the SMOB [Bertin *et al.*, 2004]. Nevertheless, unlike in Friedrichs and Aubrey [1988], ebb-dominance in the SMOB is related to disequilibrium in tidal prisms and does not result from tidal distortion. By analogy with Friedrichs and Aubrey [1988], sediment gain within the whole NMOB can

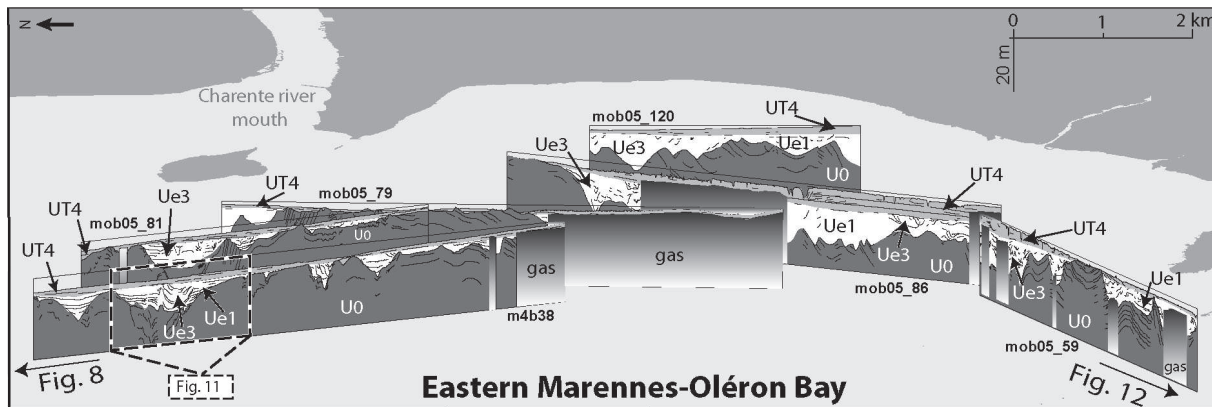


FIG. 10. – Fence diagram of seismic profiles M4b38, Mob05\_59, Mob05\_79, Mob05\_81, Mob05\_86 and Mob05\_120, showing the internal architecture of the EMOB. Seismic unit U0 corresponds to the bedrock and seismic units Ue1.1, Ue1.2, Ue3 and UT4 correspond to the soft sedimentary cover.  
 FIG. 10. – Montage 3D des profils M4b38, Mob05\_59, Mob05\_79, Mob05\_81, Mob05\_86 et Mob05\_120, illustrant l'architecture interne du comblement sédimentaire dans la partie est de la baie de Marennes-Oléron. L'unité sismique U0 correspond au socle rocheux et les unités Ue1.1, Ue1.2, Ue3 and UT4 correspondent à la couverture sédimentaire meuble.

be explained by its flood-dominance. On the contrary, channel deepening in SMOB may result from a dynamic response to aggradation of intertidal flats, thus maintaining hydraulic efficiency.

A strong correlation between areas of sediment gain in the intertidal areas since 1824 and the position of oyster farms has been already pointed out by Bertin and Chaumillon [2006]. Those areas have been estimated to be

$35 \times 10^6 \text{ m}^3$  that is close to the net changes of  $+ 38 \pm 15 \times 10^6 \text{ m}^3$  within the whole intertidal zone of the MOB. This correlation together with the work of Sornin [1981], which showed that oysters directly contribute to sedimentation of fine particles, by creating obstacles to currents favouring their decantation, indicate that, at a secular time scale, oyster farming may contribute significantly to the positive sediment budget of the bay.

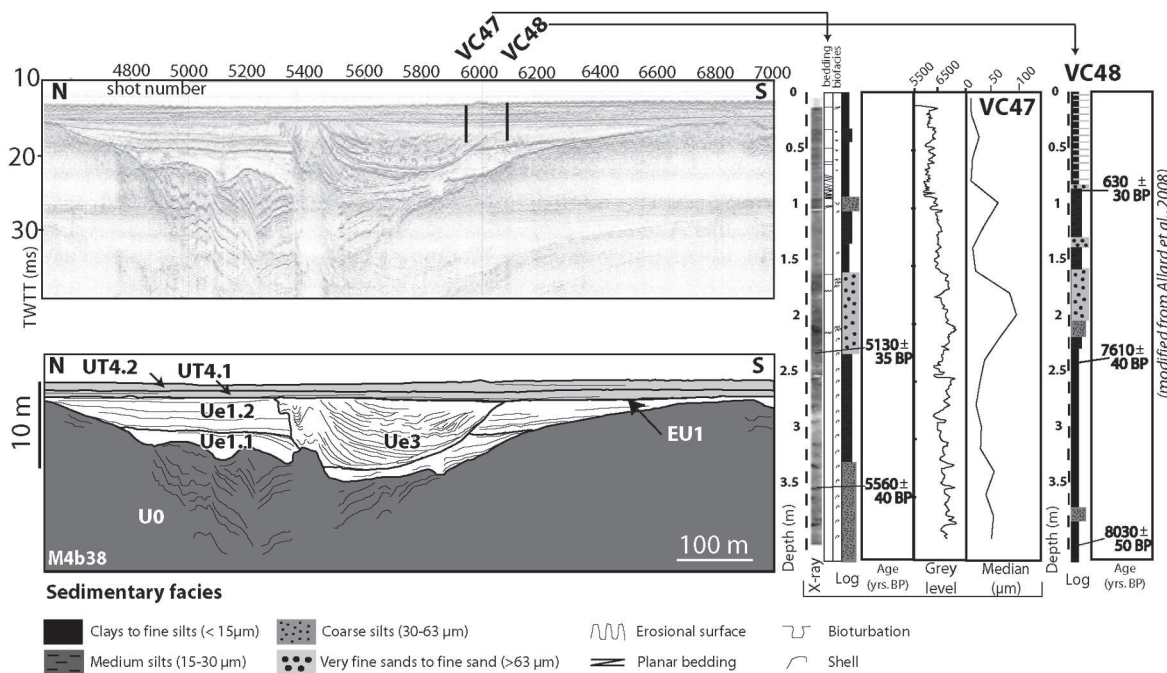


FIG. 11. – VHR seismic profile M4b38 and its interpretation showing the internal architecture of the sediment infilling within the EMOB. Detailed description of vibracores VC48 [modified from Allard et al., 2008] and VC47 includes from left to right: depth (m bsf), X-ray image, bedding and biofacies, grain size,  $^{14}\text{C}$  uncalibrated dates, grey-level curve and median grain-size in micrometers.  
 FIG. 11. – Profil sismique M4b38 et son interprétation montrant l'architecture interne du comblement sédimentaire dans la partie est de la baie de Marennes-Oléron. La description des carottes VC48 [modifié d'après Allard et al., 2008] et VC47 comprend de gauche à droite : la profondeur (en m par rapport au fond marin), l'image RX, le litage et le biofaciès, la granularité, les âges  $^{14}\text{C}$  non calibrés, la courbe de niveau de gris et la médiane de granularité en micromètres.

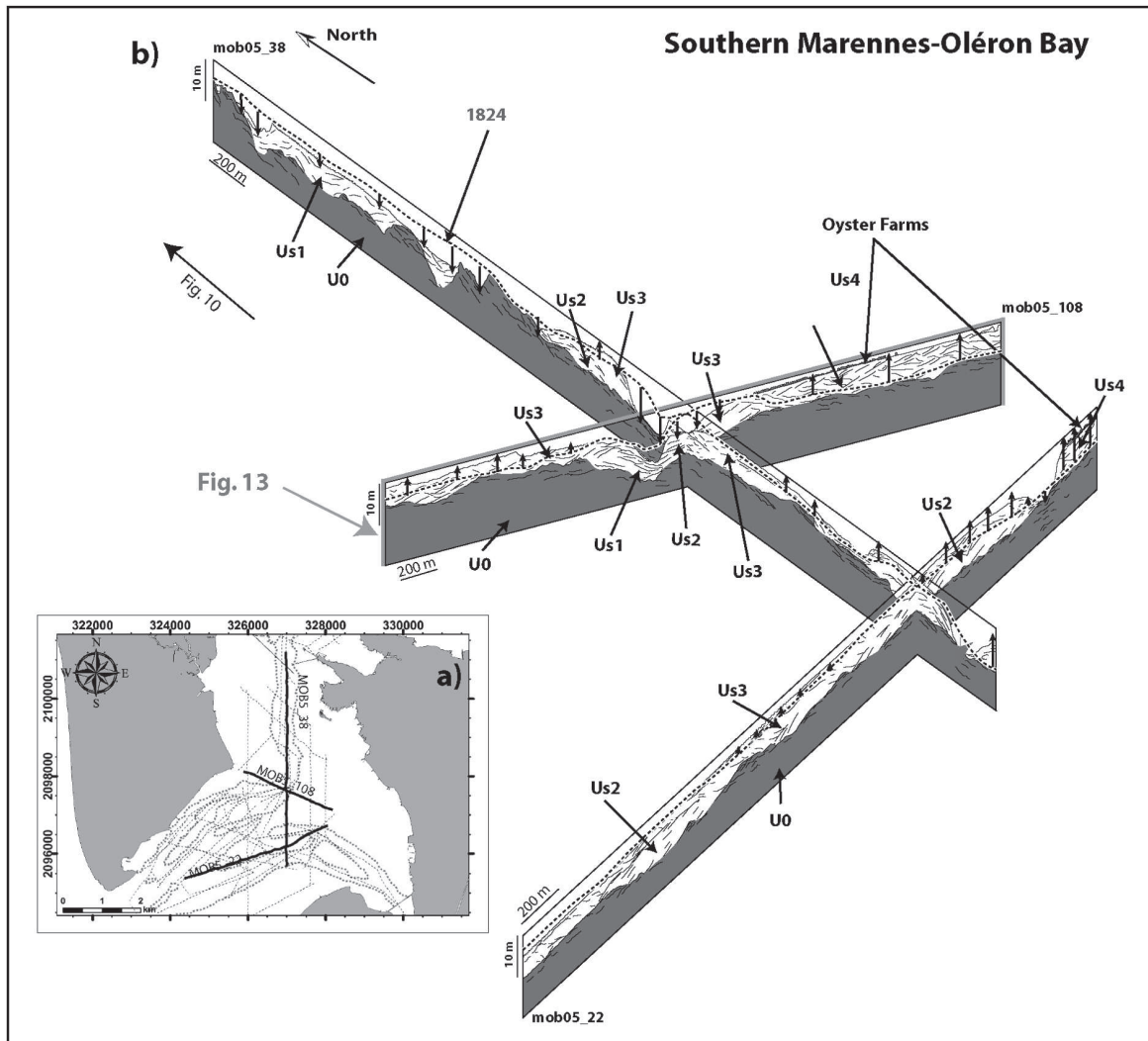


FIG. 12. – (a) Location map of the seismic profiles within the SMOB (bold dark lines indicate the seismic tracks discussed in this study). (b) Fence diagram of seismic profiles Mob05\_22, 38 and 108, showing the internal architecture of the SMOB. Seismic unit U0 corresponds to the bedrock and seismic units Us1, Us2, Us3 and Us4 correspond to the soft sedimentary cover. Seabottom of 1824 is indicated thanks to a dashed line and show that the main seismic units of the SMOB have been deposited over the last two centuries.

FIG. 12. – (a) Carte de localisation des profils sismiques dans la partie sud de la baie de Marennes-Oléron (les profils utilisés dans cette étude sont représentés en gras). (b) Montage 3D des profils Mob05\_22, 38 et 108, illustrant l'architecture interne du comblement sédimentaire de la partie sud de la baie de Marennes-Oléron. L'unité sismique U0 correspond au socle rocheux et les unités Us1, Us2, Us3 et Us4 correspondent à la couverture sédimentaire meuble. Le fond marin en 1824 (ligne pointillée) montre les dépôts mis en place depuis cette époque.

### Millennial evolution of the Marennes-Oléron Bay

Combined analysis of seismic profiles and sedimentary core results allows distinguishing five sediment infilling stages within the MOB (fig. 14).

#### *Stage 1: Early Holocene phase (before 7500 years B.P.)*

Given that occurrence of modern mudflats between  $-3.5$  m and  $+2.5$  m NGF, both its intertidal-flat origin and occurrence depth of around  $-11$  m NGF ( $-7.5$  m with reference to the marine chart-sounding datum at La Rochelle Harbour) are suggestive of that seismic unit Ue1.2 belongs to the transgressive systems tract (TST) [Allard *et al.*, 2008]. Underlying seismic unit Ue1.2 has similar seismic characters and is also interpreted to belong to the TST. Basal lense-shaped sub-units UT1 have not been dated but may

belong to either the lowstand or transgressive systems tracts.

#### *Stage 2: About 7500 to 5000 years B.P.*

Seismic unit Ue3 is interpreted as tidal channel-fills belonging to a former E-W tidal channel network related to the drainage of the Brouage Marsh area (figs 2b and 10). Given the available radiocarbon dates of the channel-fill and underlying units, both the incision and infilling of this channel have occurred between around 7500 years  $^{14}\text{C}$  yr B.P. to 5500 years  $^{14}\text{C}$  yr B.P. In the surrounding marshes, this period of time corresponds to a succession including marine sand at the base and intertidal silt at the top [Carbonel *et al.*, 1998; Decker *et al.*, 2001; Weber *et al.*, 2004a], representing the end of the transgression and the beginning of the regression respectively. Given their orientation (fig. 2c) and



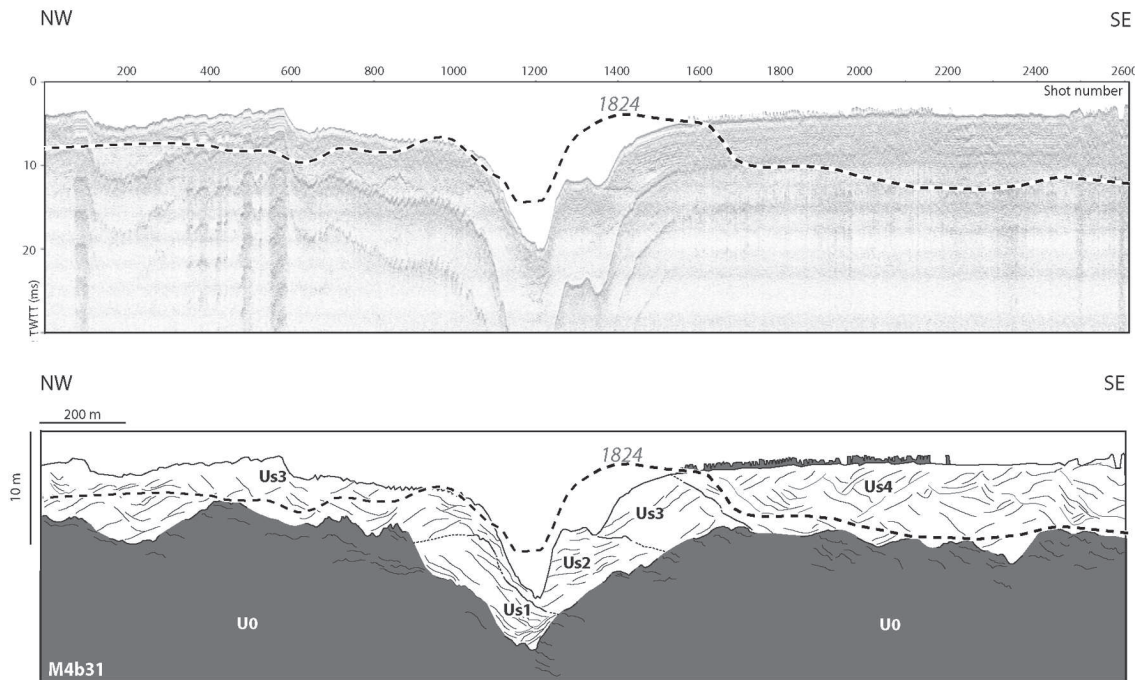


FIG. 13. – VHR seismic profile Mob05\_108 and its interpretation showing the internal architecture of the sediment infilling within the SMOB. Seabottom of 1824 is indicated with a dashed line. Oyster farm installations (in grey) are observed on top of Us4 unit.

FIG. 13. – Profil sismique Mob05\_108 et son interprétation montrant l'architecture interne du comblement sédimentaire dans la partie sud de la baie de Marennes-Oléron. Le fond marin en 1824 est indiqué par une ligne pointillée. Les installations ostréicoles (en gris) sont localisées au sommet de l'unité Us4.

the age of their sediment-fill, tidal channels corresponding to seismic units Ue3 may have been filled following a decrease in the tidal prism and current speeds in response to the sediment-fill of the Brouage marsh (fig. 2a) and associated coastline progradation. As Ue3 is synchronous with a regressive phase in the marshes, it is interpreted as the early highstand systems tract (HST).

### Stage 3: About 5000 to 1500 years B.P.

In the WMOB, seismic unit UT2 consists of the bulk of the valley-fill in the WMOB. Internal configuration of UT2 is aggradational. Considering that the inferred age of UT2 is younger than the regressive channel-fill of Ue3 (stage 2), UT2 can be interpreted as regressive subtidal deposits belonging to the HST. This interpretation differs from that of Chaumillon and Weber [2006], which interpreted UT2 as the TST, based on the fact that the stepped morphology of time-equivalent the Pertuis Breton sediment-fill (few kilometers north of the MOB) was formed in response to sea-level rise [Weber *et al.*, 2004b]. However the application of the Vail model [Vail *et al.*, 1991], which locates the TST/HST contact at the change from onlapping reflectors to seaward prograding reflectors, at the scale of very high resolution seismic (less than 1 m of vertical resolution) lead to great complexity as progradational parasequences may occur in both the TST and HST [Carter *et al.*, 1998] and as simultaneous progradation and retrogradation may occur simultaneously in different parts of the same estuarine system [Allen and Posamentier, 1994; Dalrymple and Zaitlin, 1994]. Therefore, the end of onlap is not a correct criterion for the TST-HST boundary in very high-resolution seismic studies.

### Stage 4: From 1500 to 1000 years B.P.

The seismic boundary EU1 is an erosional unconformity correlated with a shell bed and a marked grain-size change. Meanwhile, although EU1 is almost flat at a kilometer-scale (fig. 6, 7, 9, 11) [Chaumillon *et al.*, 2004; Billeaud *et al.*, 2005], it appears as a channelized erosional unconformity at the scale of the entire NMOB (fig. 2d). There was a communication between the Gironde estuary and the SMOB (fig. 3) around 1100 yr B.P., and it is assumed that in this palaeogeographical setting, tidal ravinement was more intense and may have induced EU1. This communication between the Gironde estuary and the SMOB was filled and the Maumusson Inlet opened since around 500 yr B.P.

### Stage 5: From about 1000 years B.P. to present-day

In the NMOB, the uppermost seismic unit UT4 corresponds to a sheet drape composed of silt, the base of which is dated to 910 yr B.P. This drape shows a sharp grain size decrease relative to underlying units and has been interpreted as recording an increase in mud supply mainly in response to deforestation and suspended matter migration related to land reclamation during the middle age [Chaumillon *et al.*, 2004; Billeaud *et al.*, 2005; Chaumillon and Weber, 2006].

In the SMOB and in the Coureau d'Oléron area (fig. 2a), the UT4 mud drape is absent. Seismic units Us1, 2, 3 and 4 are not correlated with cores but superimposition of bathymetric cross sections of 1824 on seismic profiles shows that a large part of the SMOB infill (Us3 and 4) has been emplaced during the last two centuries (figs 12 and 13). Units Us 1, 2 and 3 are considered as sandbanks. Given that Us1 and 2 are deposited before 1824, they are

interpreted as sandbank cores similar to the core of the Longe de Boyard at the northern entrance of the MOB [Chaumillon *et al.*, 2008a]. Us3 represents active modern sandbanks, associated with the tidal flux through the Maumusson Inlet. Unit Us4 consists of a channel fill mainly emplaced after the beginning of the 19th century and is interpreted as recording tidal channel abandonment because its orientation made it hydraulically inefficient (figs. 4a and c and 13). This abandoned channel may be related to the old drainage network associated with the communication between the MOB and the Gironde during the Middle Age (fig. 3).

**Controlling factors of a tidal bay-fill**

From this study it appears that the sediment-fill of the MOB is thin and complex and has been controlled by several factors through time.

The basal eastern bay-fill consists of drowned intertidal flats, which was thus partly controlled by the last sea-level rise [Allard *et al.*, 2008].

Those drowned flats are located in intermediate-sized valleys that are filled with sediment because they are sub perpendicular to the main valley where lies the present-day main tidal channel and where scour may have removed some or all of the transgressive sediment. The location of

preserved transgressive deposits in those intermediate valleys indicates that the bedrock morphology (including the depth of incision and the valley orientation) has played a role in sediment preservation after the sea level rose. Bedrock control on sediment dynamic and stratigraphy is also evidenced in the SMOB where some present-day tidal channels are anchored in bedrock incisions (fig. 12), as has already been shown for the Maumusson Inlet [Bertin *et al.* 2004].

The location of preserved drowned flats in the EMOB can also be related to tidal drainage reorientation (from a West-East orientation to a present-day North-South orientation), which was induced by the infilling of surrounding marshes (fig. 2) that have prevented tidal ravinement in this area. Tidal currents also control the secular infilling of the bay as the NMOB morphological evolution can be explained by its flood dominance whereas channel deepening and aggradation of intertidal flats in the SMOB can be explained by its ebb dominance. Secular infilling of the bay is also controlled by waves near the entrances of the Bay as attested by the formation of several sandspits during the last two centuries [Bertin *et al.*, 2005].

The suspended matter that have filled the MOB does not only originate from the Charente River (mean annual solid discharge: 41000 t.yr<sup>-1</sup>, Gonzalez *et al.*, 1991], but also

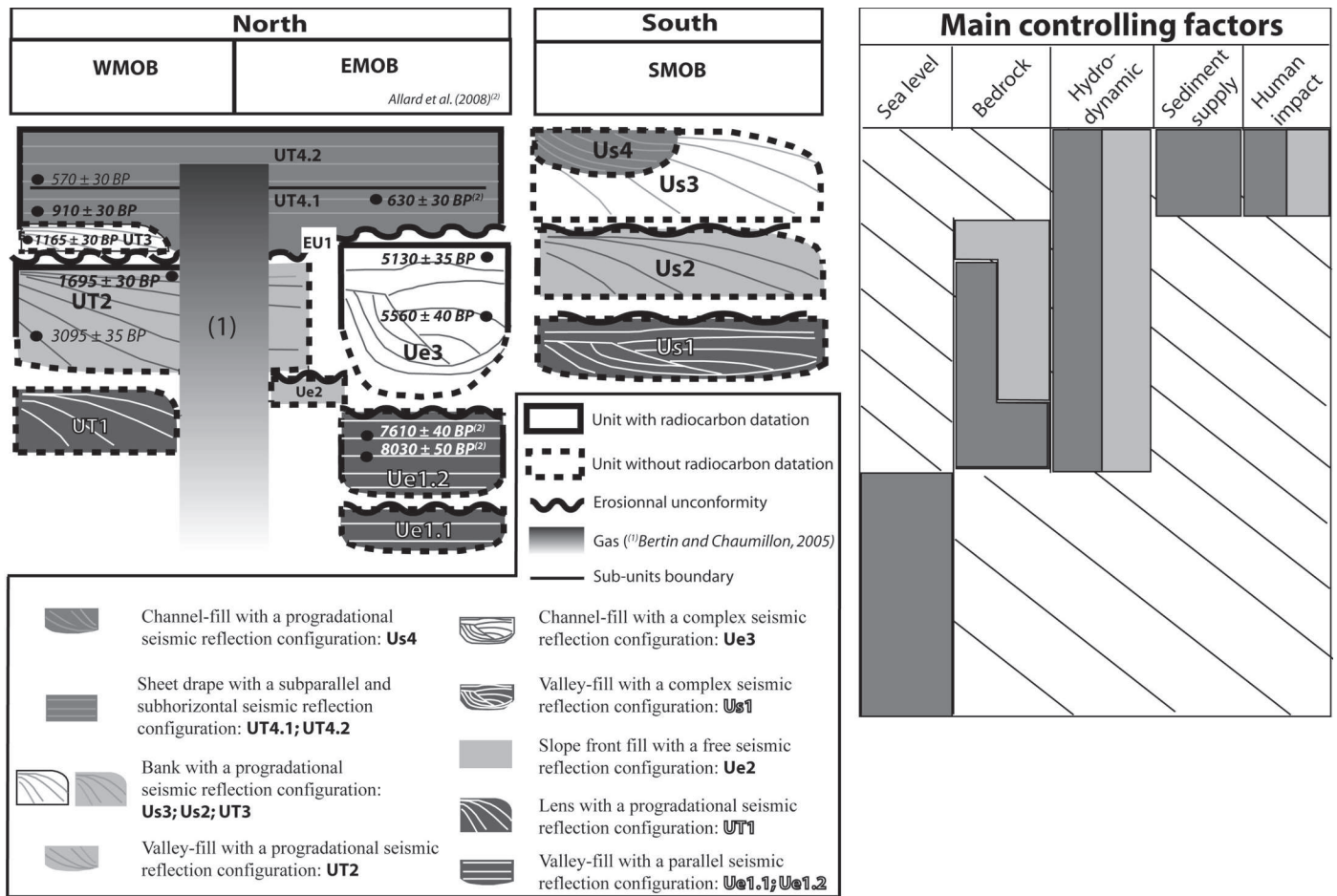


FIG. 14. – Synthetic stratigraphic logs showing the lateral variations of the Holocene-fill within the Marennes-Oléron Bay.  
 FIG. 14. – Logs synthétiques montrant les variations latérales du comblement sédimentaire holocène dans la baie de Marennes-Oléron.

from the Gironde estuary, which is one of the most important sources of continental sediment supply within the Bay of Biscay (flux of suspended matter:  $1.2 - 1.5 \times 10^6 \text{ t.yr}^{-1}$ ) [Castaing and Jouanneau, 1987]. Actually, under certain oceanographic conditions, the Gironde plume is deviated clockwise at the end of the ebb and faces the two entrances of the MOB at the beginning of the flood [Froidefond *et al.*, 1998], so that flood current can advect it into the MOB. This latter phenomenon can explain the relatively large amount of mud sedimentation in the NMOB and surrounding areas [Chaumillon *et al.*, 2008b].

Mud-fill of the NMOB corresponds mainly to the mud drape (UT4), which has recorded an increase in mud supply since around 1000 years B.P., as observed elsewhere in Europe [Lesueur *et al.*, 1996; Freitas *et al.*, 2002; Leorri and Cearreta, 2004; Garcia-Garcia *et al.*, 2005; Dinis *et al.*, 2006]. Such major mud supply, which occurred during the middle age, may be related to soil erosion in response to extensive deforestation of Europe during this period [Lesueur *et al.*, 1996; Freitas *et al.*, 2002; Billeaud *et al.*, 2005; Dinis *et al.*, 2006]. Human influence on the MOB sediment-fill can be also inferred from the correlation of the position of oyster farms with sediment gain within intertidal areas during the last two centuries [Bertin and Chaumillon, 2006] and from the role of oyster farms, which create obstacles to currents favouring decantation [Sornin, 1981].

The fourth forcing parameters, namely eustasy, sediment supply, bedrock morphology and anthropogenic activities that have controlled the secular morphological evolutions and Holocene stratigraphy of the MOB have been also pointed out in many over semi-enclosed coastal environments. During the early Holocene, eustasy was the dominating element controlling the sedimentation of estuaries of Europe [Allen and Posamentier, 1994; Dias *et al.*, 2000; Long *et al.*, 2000; Freitas *et al.*, 2002], Africa [Lang *et al.*, 1995], North America [Knebel and Circé, 1988; Mallinson *et al.*, 2005], South America [Gómez *et al.*, 2005], Australia and New Zealand [Roy, 1994; Heap and Nichol, 1997]. During the middle Holocene, following the decrease in mean sea-level rise rate, sediment supply and climate changes became dominant in the control of sedimentation [Pendon *et al.*, 1998; Moura *et al.*, 2007]. Since then, anthropogenic activities, namely deforestation and increase in agriculture [Dabrio *et al.*, 2000; Cronin and Vann, 2003; Vella *et al.*, 2005; Bourrin *et al.*, 2007; Dinis *et al.*, 2006; Hubeny *et al.*, 2008], land reclamation [Pontee *et al.*, 1998], damming [Dias *et al.*, 2000], mining [Jaffe *et al.*, 2007], contributed decisively to the sediment balance in estuarine systems but also at a global scale [Hooke, 2000]. It can be concluded that the patterns observed in the MOB are not unique and reinforce the idea that estuarine-fills during Holocene were primarily controlled by eustasy and latter by autogenic factors and anthropogenic activities. In addition to these forcing parameters, the bedrock morphology plays a major role because the soft sedimentary cover is

thin. Such control of antecedent topography was also evidence at the scale of the Bay of Biscay [Chaumillon *et al.*, 2008b] and in similar coastal setting [Belknap and Kraft, 1985; Heap and Nichol, 1997; Lobo *et al.*, 2003].

## CONCLUSION

Analyses of bathymetric maps and very high-resolution seismic reflection profiles correlated with core samples have allowed us to make a synthesis of the morphological and stratigraphical evolutions of the Marennes-Oléron Bay. This study has provided a better knowledge concerning the sediment-fill of this tidal bay and related forcing parameters.

The Marennes-Oléron Bay sediment-fill is thin (20 m at the maximum) and has displayed a positive sediment budget between 1824 and 2003. Two main depositional systems, namely, the southern and northern Marennes-Oléron Bay have been identified on the basis of both their morphological and stratigraphical evolutions.

The morphological evolution of the southern ebb dominated Marennes-Oléron Bay is characterised by sediment accretion on the tidal flats and the deepening of the main channels and the main part of its sediment-fill has been emplaced during the last centuries.

The northern flood-dominated Marennes-Oléron Bay is characterised by an increase in the elevation of both the tidal flats and channels bases, and five main stages have been distinguished in its sediment fill. The earliest filling stage (before 7500  $^{14}\text{C}$  yr B.P.) was controlled mainly by the last sea level variations whereas the remaining stages (from 7500-5000  $^{14}\text{C}$  yr B.P. to present-day) were successively controlled by autogenic factors, including hydrodynamic changes related to coastal evolutions, and by anthropogenic activities. In addition to these forcing parameters, the MOB represents an example of "rocky coast" estuary, where the sediment fill is very thin and discontinuous, and is characterised by a bedrock control at each phases of the sediment fill both in terms of preservation in topographic lows and in terms of control on hydrodynamics and related sediment input.

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