ARTICLE IN PRESS
SEARES-01469; No of Pages 18
Journal of Sea Research xxx (2016) xxx–xxx
Contents lists available at ScienceDirect
Journal of Sea Research
journal homepage: www.elsevier.com/locate/seares

Mid- to late-Holocene environmental evolution of the Loire estuary as observed from sedimentary characteristics and benthic foraminiferal assemblages

M. Durand [a,*], M. Mojtahid [a], G.M. Maillet [a], J.-N. Proust [b], D. Lehay [c], A. Ehrhold [d], A. Barré [a], H. Howa [a]

[a] LPG-BIAF UMR-CNRS 6112, University of Angers, UFR Sciences, 2 bd Lavoisier, 49045 Angers Cedex 01, France
[b] UMR 6118 Géosciences CNRS, Université de Rennes 1, Campus de Beaulieu, 35042 Rennes Cedex, France
[c] Grand Port Maritime Nantes Saint-Nazaire, Pôle Environnement, 18 quai Ernest Renaud BP 18609, 44186 NANTES Cedex 4, France
[d] IFREMER Brest, Pointe du Diable, 29280 Plouzané, France

ARTICLE INFO

Article history:
Received 23 March 2016
Received in revised form 21 July 2016
Accepted 5 August 2016
Available online xxxx

Keywords:
Macrotidal estuary
Mid-latitude estuary
Holocene paleoenvironment
Estuarine facies
Benthic foraminifera
Sea-level change

ABSTRACT

We used sedimentological and foraminiferal characteristics of four sedimentary cores, supported by paleogeographical and historical data, to reconstruct the depositional history of the inner Loire estuary (Near Saint-Nazaire, France) and the response of benthic foraminifera to the mid- to late-Holocene marine flooding of the incised valley. These were further used to evaluate the consequent changes in estuarine morphological and hydro-sedimentary patterns during this time period. Our results described significant changes in hydro-sedimentary dynamics over the past ~6 kyrs BP. At our location, these changes expressed the combined influence of marine (e.g., tide, storm waves) and fluvial dynamics (e.g., floods), which are linked, on a broader scale, to sea-level variations and the regional climate regime. Three main periods stand out: (1) from ~6.0 to ~2.5 kyrs BP, when the sea-level rise slowed down, a large brackish bay extended over and around the study area. The fine-grained tidal rythmites recorded north of the Bilho bank (the main tidal bar located in our study area) indicated a calm depositional environment, protected from the main riverine influence. The presence of thick flood deposits from ~5.4 to ~4.0 kyrs BP near the Bilho bank indicates further the dominance of humid conditions. (2) From ~2.5 kyrs BP to ~1850 CE (pre-industrial state), sea-level stabilized at its present value, and the pre-existing bay was progressively infilled. North of the Bilho bank, near a major mudflat (Méan), the generally homogenous sedimentation composed of silty muds rich in organic matter indicated a sheltered environment; the main water flow channel being located south of the Bilho bank. Within this overall homogenous sedimentation, foraminiferal assemblages described rather accurately the progressive infilling of the valley (indicated by a decrease in the proportions of outer estuarine species), accompanied with the channelization of the main entering marine currents (tide, storm waves) (indicated by an increase in the proportions of transported species from the adjacent upper continental shelf), and finally the buildup of the Méan mudflat and the stabilization of the environment to its present day configuration (indicated by the dominance of autochthonous inner estuarine species). (3) Since 1850 CE, the human impact progressively modified the general landscape of our study area with the construction of the Saint-Nazaire shipyard, the digging of the northern navigation channel and the polderization of the northern Bay. The southern channel was progressively abandoned by the main water flow in favor of the newly dug northern channel, causing the southern migration of the Bilho sandbank and the progressive filling of the southern channel.

1. Introduction

Estuaries are dynamic and sensitive physical and ecological systems that occur at the interface between terrestrial and marine environments. As such, they respond considerably to both natural climatic and geomorphologic changes, and to anthropogenic pressure; the latter started thousands of years ago (e.g., drainage and agriculture, grazing, saltpans), and increased in modern times (e.g., dredging, dyking up, damming, harbor management, heavy industries, urban settlement, intensive agriculture) (e.g. Colman et al., 2002; Borja et al., 2010; Moreno et al., 2014; Traini et al., 2015). Improving our knowledge of past environmental changes that influenced estuarine systems, whether triggered by natural internal processes (e.g., sediment supply, tidal regime, marine vs riverine influence), external forcing (e.g., solar irradiance, atmospheric circulation patterns) and/or by persistent human

* Corresponding author.
E-mail address: matthieu.durand@univ-angers.fr (M. Durand).

http://dx.doi.org/10.1016/j.seares.2016.08.003
1385-1101/© 2016 Published by Elsevier B.V.

impact, is essential to understand recent and future regional environmental variability (Moreno et al., 2014; Kotilainen et al., 2014). Late Quaternary sediments deposited in estuaries have a good potential as archives for paleoenvironmental reconstructions. Estuaries tend to act as traps for both fluvial and marine sediments bearing expanded sedimentary successions and retaining both continental and marine environmental signals at high time resolution through high sedimentation rates (e.g., Colman et al., 2002; Leorri et al., 2006; Ghosh et al., 2009). Nevertheless, many problems arise from the reverse sides of these advantages because of the complexity of hydro-sedimentary processes (e.g., transport, erosion, discontinuous sedimentation) making estuarine sediments poorly used for paleoenvironmental reconstructions in comparison with lacustrine and marine sediments. For instance, the mixed source of sediments from marine and continental origins makes their interpretation complex. This complexity is further found in the use of several sediment contents to trace back environmental changes, including most paleo-proxies (e.g., bio-indicators; Elliott and Quintino, 2007) or materials for chronological studies. For instance, radiocarbon dating of the sediments is difficult because of multiple sources of carbon in estuaries and reworking processes (Colman et al., 2002; Lougheed et al., 2013).

Sea-level changes strongly control the evolution of coastal environments during the late Quaternary (Clavé, 2001; Traini et al., 2013; McGowan and Baker, 2014). In particular, eustatic changes mainly control the accommodation space and therefore the morphology of estuarine systems (e.g. Jervey, 1988). In northwestern Europe, many modern estuaries, such as the Loire estuary, originate from the flooding and the filling of the Late Glacial Maximum (LGM) incised valleys during Holocene transgression (e.g. Dalrymple et al., 1994; Zaitlin, 1994; Chaumillon et al., 2010; Proust et al., 2010). Several studies targeted the reconstruction of Holocene relative sea-level (RSL) along the French Channel and Atlantic coasts (e.g., Ters, 1973; Morzadec-Kerfourn, 1974; Ters, 1986; Van de Plassche, 1991; Lambeck, 1997; Leorri et al., 2012; Goslin et al., 2013; Stéphan and Goslin, 2014; Goslin et al., 2015). More recently, Goslin et al. (2015) compiled RSL data from the western Brittany and the southern UK coasts. In general, all these studies agree about three main phases characterizing Holocene transgression along the western French coast: 1) From ~10 kyrs BP to ~6 kyrs BP, sea level rose rapidly from ~ − 30 m to ~ − 4 m, resulting in an increase in estuarine accommodation space and therefore an increase in sedimentation rates. In estuarine stratigraphical sequences, this phase is recorded as a transgressive system tract (TST) (e.g., Dalrymple et al., 1994; Zaitlin et al., 1994; Proust et al., 2010; Goslin et al., 2015); 2) From ~6 kyrs to ~3 kyrs, there was a pronounced slowdown in the rate of sea-level rise (Goslin et al., 2015), explained by a decrease in meltwater production from the global ice-sheets (Vink et al., 2007). This led to the reduction of estuarine accommodation space and the development of a part of European costal marshes and peatlands (Spencer et al., 1998; Allen, 2000; Clavé, 2001). This phase is recorded in estuarine sediment deposits as a high stand system tract (HST) (e.g., Dalrymple et al., 1994; Zaitlin et al., 1994; Proust et al., 2010; Goslin et al., 2015); 3) from ~3 kyrs to present, sea-level rose slowly from −2 m to the present RSL, reaching a near stabilization from ~2 kyrs onwards (Ters, 1973; Stéphan and Goslin, 2014; Goslin et al., 2015). During this phase, the estuarine infilling was controlled by complex interactions between climate variability (e.g., Bond et al., 1997) and the consequent hydro-sedimentary dynamics, and more recently by human activity.

In estuarine systems, sediment characteristics and benthic foraminiferal assemblages are routinely used to reconstruct past environments in relation to Quaternary sea-level fluctuations (e.g., Scott and Medioli, 1980; Hayward et al., 1999; Fatela et al., 2009, Proust et al., 2010; Leorri et al., 2011; Delaine et al., 2014; Goslin et al., 2015). The succession of various estuarine sedimentary facies combined with the distribution of estuarine foraminiferal species reflect the morphodynamics of the system, water circulation patterns, river runoff and tidal dynamics, and the interplay between marine and freshwater inflow (e.g., Moreno et al., 2014). All of these processes are to be discussed as resulting from the mixture of natural internal forcing, regional climate, and human impact. However, for the same reasons as for the dating, interpretations drawn from sedimentary deposits and benthic foraminiferal faunas in estuaries remain somehow hampered by intrinsic processes such as transport and reworking.

In this context, the Loire estuarine ecosystem has been poorly studied to date. As regards to Holocene hydrological, sedimentary and microfaunal variability, only a few studies attempted to answer this problematic via a multiproxy approach combining biological and sedimentary proxies (Ters et al., 1968; Visset and Barbaroux, 1972; Visset, 1973; Delaine et al., 2014). And yet, the Loire estuary, by being 1) one of the three major estuaries in France, 2) located at mid-latitude between two major atmospheric systems (Island low and Azores high) controlling the European Climate, and 3) under a macrotidal regime, is likely to be a sediment depot center able to record at high time resolution Holocene climate variability and sea-level fluctuations, and their impact on hydro-sedimentary and ecological processes.In this paper, we present a paleoenvironmental study from the lower inner Loire estuary near Saint-Nazaire (Fig. 1), including a detailed description of sedimentary facies successions of four sediment cores, and benthic foraminiferal content in one core located close to a mudflat. Our interpretations are supported by paleogegraphical reconstructions and historical data. Paleoenvironmental interpretations of benthic foraminiferal data are based on the results of two extensive programs describing the modern ecology of benthic foraminifera in the Loire estuary (SEMHABEL[5] and RS2E[6] projects). The main objectives of this work are: 1) to reconstruct the depositional history of the inner Loire estuary, and the response of benthic foraminifera to the mid- to late-Holocene marine flooding of the incised valley, and 2) to evaluate the consequent changes in estuarine morphological and hydro-sedimentary patterns.

2. Study area

2.1. Hydrology and geology

The Loire is the longest river in France draining a catchment area of about 117,480 km^2, and flowing into the Atlantic Ocean (northern Bay of Biscay). The Loire estuary covers an area of ~217 km^2 and extends for ~80 km long (Ciffroy et al., 2003). At the gauging station of Saint-Nazaire, the annual flow of the Loire River is on average 900 m^3/s, fluctuating between low water periods during summer and autumn (250 m^3/s) and flood periods during winter (>1800 m^3/s) (http://www.hydro.eaufrance.fr). At Saint-Nazaire, the maximum tidal range is 6.4 m. In averaged conditions, the salinity front (upper limit of the mesohaline domain) is located upstream from Cordemais, ~39 kms from the river mouth (Fig. 1A). From Nantes to Saint-Nazaire, the Loire River flows through the crystalline rocks of the Armorican Massif. Its valley is constrained by two main geological structures: The Brittany belt (SE-NW) to the north and The Pays de Retz arching to the south (Fig. 1B). The valley widens gradually from Nantes to Saint-Nazaire forming a final bottleneck (Mindin / Saint Nazaire) which marks the limit of the inner estuary (Figs. 1A, B). The outer estuary is defined as the area between Saint-Nazaire-Mindin and Préfailles-Penchâteau headlands (Gallenne, 1974) (Fig. 1A). This specific morphology originates from 1) the successive Quaternary regressions leading to the incision of the Loire valley, and 2) the sedimentary infilling occurring mainly during the last transgression (Ottmann et al., 1968; Ters et al., 1968). The same architecture is observed for most northwestern European estuaries (e.g. Dalrymple et al., 1992, 1994; Zaitlin et al., 1994; Perillo, 1995).

2.2. The Holocene sedimentary infilling

Sediments deposited in the Loire estuary are sourced from both continental and marine origins:

Please cite this article as: Durand, M., et al., Mid- to late-Holocene environmental evolution of the Loire estuary as observed from sedimentary characteristics and benthic forami..., J. Sea Res. (2016), http://dx.doi.org/10.1016/j.seares.2016.08.003