Extreme storms during the last 6,500 years from lagoonal sedimentary archives in Mar Menor (SE SPAIN)

Dezileau L. *[,1], Pérez-Ruzafa A.[2], Blanchemanche P.[3], Degeai J.P.[3], Raji O.[1,4], Martinez P.[5], Marcos C.[2] and Von Grafenstein U.[6]

[1]{Université de Montpellier, Geosciences Montpellier, CNRS, UMR 5243}

[2]{Universidad de Murcia, Departamento de Ecologia e Hidrologia, Regional Campus of International Excellence Campus Mare Nostrum, Murcia 30100, Spain}

[3]{Université Montpellier 3, Laboratoire d'Archéologie des Sociétés Méditerranéennes, CNRS, UMR 5140}

[4]{Department of Earth Sciences, Université MohammedV-Agdal, Rabat, Morocco}

[5]{Université Bordeaux 1, EPOC, CNRS, UMR 5805}

[6]{Laboratoire des Sciences du Climat et de l'Environnement, CNRS/CEA, Saclay}

* Correspondence to : laurent.dezileau@gm.univ-montp2.fr

Abstract

Amongst the most devastating marine catastrophes that can occur in coastal areas, are storms and tsunamis, which may seriously endanger human society. Many such events are known and have been reported for the Mediterranean, a region where high-frequency occurrences of these extreme events coincides with some of the most densely populated coastal areas in the world. In a sediment core from Mar Menor Lagoon (SE Spain), we discovered eight coarse grained layers which document marine incursions during periods of intense storm activity or tsunami events. Based on radiocarbon dating, these extreme events occurred around 5250, 4000, 3600, 3010, 2300, 1350, 650 and 80 years cal BP. No comparable events have been observed during the 20th and 21th centuries. The results indicate little likehood of a tsunami origin for these coarse grained layers, although historical tsunami events are recorded in this region. These periods of surge events seem to coincide with the coldest periods in Europe during the late Holocene, suggesting a control by a climatic mechanism for periods of increased storm activity. Spectral analyses performed on the sand % revealed four major periodicities of 1228 ±327, 732 ±80, 562 ±58, and 319 ±16 yr. Amongst the well-known proxies that have revealed a millennial-scale climate variability during the Holocene, the ice-rafted debris (IRD) indices in North Atlantic developed by Bond et al. (1997, 2001) present a cyclicity of 1470 ±500 yr, which matches the 1228 ±327 yr periodicity evidenced in the Mar Menor lagoon, considering the respective uncertainties on the periodicities. Thus, an in-phase storm activity in Western Mediterranean is found with the coldest periods in Europe and to the North Atlantic thermohaline circulation. However, further investigations, such as additional coring, high-resolution coastal imagery, are needed to better

constrain the main cause of these multiple-events.

Keywords: coastal lagoons, storm, tsunami, Mediterranean Sea, Late Holocene.

1. Introduction

In the last century the Mediterranean coastal zones have undergone a considerable development and the coastal disasters incidence has significantly increased. The coastal zones are exposed to flooding and coastal erosion processes, and are highly vulnerable to extreme events, such as storms, cyclones or tsunamis, that can cause significant losses (Seisdedos et al., 2013).

Mediterranean intense storms and cyclones are rare meteorological phenomena observed in the Mediterranean Sea. Different climatological and meteorological works in the western Mediterranean area show that extreme storms and cyclones show a complex variability in the sense of non-uniform spatial and temporal patterns (Trigo et al., 2000; Lionello et al., 2006; Gaertner et al., 2007). This is in partly due to the lack of a clear large scale pattern which may be expected when dealing with intense events, as the number of events is low with irregular intensity and intervals. More long-term observations or palaeo-reconstructions in different areas of the western Mediterranean are needed. Tsunamis are known to occur in the Mediterranean Sea where all types of sources earthquakes, volcanic eruptions and landslides from the continental margins are active. There are evidences of large tsunamis during the historical and pre-historical period, especially in the tectonically more active eastern Mediterranean (e.g., Kelletat and Schellmann, 2002; Morhange et al., 2006). The western part of the basin has also been reported as tsunami-exposed. Historic events have been reported from the Algerian coast and tsunami propagation has been modelled (Alvarez-Gomez et al., 2011). Geomorphic evidence of ancient tsunami impacts has also been documented (Maouche et al., 2009). A long-term record of tsunami and storm activity on time scales of centuries to millennia is especially important in understanding the temporal variability of these extreme events.

This study focuses mainly on the Murcia province in Spain (Figure 1). This lowland Mediterranean coast is sensitive to risks of submersion during extreme events. We propose to use a high-resolution geochemical and sedimentogical approach to reconstruct past surge events in the Mar Menor lagoon, and then confront our results with extreme historical coastal events in the western Mediterranean.

2. Study site

The Mar Menor lagoon is the largest lagoon on the Spanish Mediterranean coast, located at the SE of the Iberian Peninsula, in the region of Murcia in the area called Campo de Cartagena basin (Lat. 37.786129, Lon. 0.810450, Figure 1). This coastal lagoon occupies an area of approximately 135 km^2 with an average depth of 3.6 m. This lagoon is separated from the Mediterranean sea by La Manga, which is a sandy barrier of 20 km long, between 30 and 500 m wide and less than 3 m above sea level. This sandy barrier is crossed by five, more or less functional, channels or “golas”. The Campo de Cartagena Basin represent 1,440 km^2, with an elevations ranging from the sea level to 1065 m, surrounded by the Mediterranean Sea to the

East, the anticline of Torrevieja to the North and the Cartagena-La Unión mountain range to the south. This basin is filled by sediments from early Miocene to Quaternary. The major lithologies are composed of sand, silt, clay conglomerate, caliche and sandstone of the Quaternary period; marl, conglomerate and gypsum for the Miocene and Pliocene periods (Jiménez-Martinez et al, 2012). The lagoon and the northern salt marshes of San Pedro are protected for their ecological importance (Special Protected Area of Mediterranean Interest, Natura 2000 network and Ramsar). The area is impacted by residual past mining activity, agricultural activities (intensive fruits and vegetable production), and urban growth coupled with touristic development since 1956 (Pérez-Ruzafa et al., 1987; 1991; 2005). Most of La Manga area is urbanized, a population of 10,000 inhabitants live here all year long, and growing to ~ 200,000 habitants during summer. High population density and low level topography makes the area very sensitive to the impact of climate change and sea level rise. Mar Menor lagoon is considered as one of the Spanish coast most threatened site by the mean sea level rise and possible increase of extreme climatic events.

3. Materials and methods

3.1 Core material

A 4-m-long piston core (MM2) was collected in the Mar Menor lagoon in September 2011 (Figure 1) with the UWITEC© gravity coring platform (Laboratoire des Sciences du Climat et de l'Environnement and University of Chambery) using a simplified piston corer of 2 m length and 83 mm inner diameter. Two consecutive sections (0 to 2 m and 2 to 4m sediment depth, respectively, were cored from a first position followed by a third section (1 to 3m) from a position ca 1 m apart to cover the technical hiatus between the first two sections. MM2 core was collected at 4 m below sea level.

3.2 Physical measures

Back to the laboratory, the structure of the sediment was studied using the Scopix X-ray scanning (EPOC, University of Bordeaux 1) and photographed. This was complemented by granulometric analyses on contiguous 1-cm samples using a Beckman-Coulter LS13320 laser diffraction particle-size analyser (Géosciences Montpellier). XRF analysis were performed on the surface of split sediment core MM2 every 0.5 cm using a non-destructive Avaatech core-scanner (EPOC, Université Bordeaux 1). The split core was covered with a 4 μm thin Ultralene to avoid contamination. Geochemical data was obtained at different tube voltage, 10 kV for Al, Si, S, Cl, K, Ca, Ti, Mn, Fe and 30 kV for Zn, Br, Sr, Rb, Zr (Richter et al., 2006).

3.3 Macro-fauna

To study mollusc shells, samples were taken every 2 cm and sieved at 1mm. Macro-fauna samples were taken at fixed volume (100 cm^3). Individuals were determined to the lower taxonomic level possible (species or genera) and counted. Assemblage structure was estimated by mean of species richness (S), taxon abundance (n_i) and total abundance (N).

3.4 Geochronology

The chronology of core MM2 was carried out using ^{137}Cs and ^{210}Pb method on a centennial time-scale by gamma spectrometry at the Géosciences Montpellier Laboratory (Montpellier, France). ^{14}C analyses were realized on mollusk shells at the Laboratoire de Mesure on ARTEMIS in CEA institute at Saclay. These measurements were obtained from monospecific samples of *Cerastoderma glaucum* at each level. ^{14}C ages were corrected for reservoir age (see Sabatier et al., 2010 for method) and converted to calendar years using the computer program OxCal v4.2 (Bronk Ramsey, 2001, 2008) at two standard deviations (see chapter 4.3).

3.5 Spectral analyses

Cyclic patterns in the Mar Menor lagoonal sequence were studied from spectral analyses by using two methods in order to reduce possible biases of a single method (Desprat et al., 2003). We used the maximum entropy method (MEM) and the multi-taper method (MTM). The MEM selects the spectrum with the highest entropy, which represents the least biased estimate for the given information, or put in other terms, the maximally noncommittal with regard to missing information (Harremoës and Topsoe, 2001). The spectrum obtained by this method shows an excellent frequency resolution with sharp spectral features (Berger et al., 1991; Dubar, 2006; Pardo-Iguzquiza and Rodriguez-Tovar, 2006). The MTM is a non-parametric method that (1) reduces the variance of spectral estimates by combining multiple orthogonal windows in the time domain before Fourier transforming, and (2) provides a narrowband F-test useful to assess the significance of periodic components (Thomson, 1982, 1990; Percival and Walden, 1993).

4. Results

4.1 Core description

Photo, X-ray images, X-ray fluorescence and high-resolution grain-size analysis for MM2 indicate several thin, coarse-grained layers preserved within mud sediments. These coarse layers are constituted by a mixture of shell debris and siliciclastic sand and have basal boundaries easily identified from a change to coarser grain size and darker colour on X-ray images (Figure 2a). Theses coarser grain size layers indicate “energetic” events, relative to the background sedimentation (i.e mud facies) and are probably link to washover events (storm or tsunami).

4.2 Sediment source

The terrigenous fraction in Mar Menor lagoon is mainly controlled by terrestrial and marine inputs. The core (MM2) was collected at 800 m from the sandy barrier and more than 8,500 m from the different river mouths. On our study site, watercourses are the source of fine fraction dispersed in the lagoon and marine inputs are characterized by coarse sands. The lagoon barrier beach sand samples show unimodal distribution with a mean grain population ranging between 160 and 653 μm. The percentages of this grain population decrease from the sea to the lagoon in surface samples (Figure 2b). The evolution with depth of this population displays eight main changes in MM2 core revealed by the grey bands on Figure 3. The main peaks of coarse sands occur around 290, 255, 210, 170, 150, 60, 40 and 5 cm (Figure 3).

Major chemical elements using the ITRAX core scanner provide high-resolution palaeoenvironmental information in a variety of sedimentary environments. In the present study we chose the ratio Si/Al and Zr/Al that better discriminate between the two source areas, marine vs drainage basin (Dezileau et al., 2011, Sabatier et al., 2012; Raji et al., 2015). The high Zr/Al ratio value is probably explained by the presence of heavy minerals (like zircon) from marine sand and the high Si/Al ratio is due to Quartz minerals in marine sand. Si/Al and Zr/Al ratios have the same evolution with depth, especially in the first three meters of the sediment core (Figure 4, shaded bands).

A fundamental step in the core analysis is to establish criteria to correctly identify overwash layers. We systematically used grain size variation and geochemical signatures (i.e. Si/Al and Zr/Al ratios). As the background sedimentation shows a fine silt facies, we consider values higher than 20% of the $63\mu m$ fraction as outlining "high energy" events (Figure 3). Positive anomalies of the Si/Al and Zr/Al ratios above 12 and 2.5 respectively (Figure 4), indicate a higher relative contribution of marine sand. The marine origin of these "high energy" events was also highlighting through molluscs identification (*Bittium recticulatum* and *Rissoa ventricosa*) (see chapter 4.3, Figure 6).

4.3. Faunal variations

Macro-fauna analyses are a good indicator of a lagoon palaeo-isolation state. While total abundance and relative abundance of individuals of the different species is a good indicator of environmental stress and lagoon productivity, species richnes is a good indicator of marine influence because species develop in different ranges of salinity, temperature and oxygenation and colonization of marine species into the lagoon environments depends of the isolation degree and connectivity between both systems (Pérez-Ruzafa and Marcos, 1992; Pérez-Ruzafa et al., 2005). Figure 5 shows the variation of the number of species and total abundance (number of individuals in 100 cm^3) along the studied time series. Taxon richness ranges between 0, at depths higher than 365 cm, and 18 reached at a 260 cm depth. The impoverished depths, after the earlier azoic one, corresponds to 302-362 cm with a mean of 4.76 taxons, 72-78 cm with a mean of 5 taxons and 30-36 cm with a mean of 5.7 taxons. The depths with highest species richness are from 192 to 266 cm and from 81 to 186 cm. These depths would correspond to a higher marine influence. Above 150 cm takes place a progressive impoverishment in the number of species reflecting a progressive isolation of the Mar Menor from the Mediterranean Sea, with punctual peacks in species richness, probably related to episodes of rupture of the sandbar (Figure 5). The total abundance confirm

The most frequent species, present in more than 50% of the samples, excluding the azoic depths, are *Corbula gibba* (Olivi, 1792) (92.4%), *Bittium reticulatum* (da Costa, 1778) (84.9%), *Tellina* sp (78.9%), *Pusillina* (=Rissoa) *lineolata* (Michaud, 1830) (78.2%), *Acanthocardia paucicostata* (G. B. Sowerby II, 1834) (77.3%), *Cerastoderma glaucum* (Bruguière, 1789) (71.4%), *Anthalis* sp (63.9%), Abra sp (74.8%), *Loripes lacteus* (Linnaeus, 1758) (61.3%) and *Philine aperta* (Linnaeus, 1767) (59.7%). Hydrobiidae sp appear in 47.9 % of the samples, but is restricted to the upper 150 cm, constituting 61.5% of the assemblage at 15 cm depth section. This specie is a typical lagoon inhabitant. *Conus ventricosus* (Gmelin, 1791) appears only in the 13.5% of the samples, comprised between 162 and 293 cm depth, reaching dominance up to 7% of the assemblage, but characterizes typical marine conditions, reinforced with the presence of abundant seaurchin spines.

Data of Figure 6 show a main change in mollusc population at around 150-130 cm characterized by an increase of the most typical lagoonal specie *Hydrobia acuta*, whereas the abundance of species with marine affinity like *Pusillina* (=Rissoa) *lineolata* and *Conus ventricosus* decrease (Figure 6). This main change in mollusc population also reveals a major palaeoenvironmental change around 150 cm, this faunal variation is probably due to a change in environmental context from a lagoonal environment, with a marine influence to a more isolated environment.

4.4 Age model

The chronology of core MM2 has been established for the last 6,500 years BP using ^{137}Cs, ^{210}Pb and (AMS) ^{14}C dates on monospecific shell samples, geochemical analysis of mining-contaminated lagoonal sediments and palaeomagnetism (Dezileau et al., in prep). Radiocarbon age of lagoonal and marine organisms is usually older than the atmospheric ^{14}C age and has to be corrected by substraction of the “reservoir age” (Siani et al., 2001; Reimer and McCormac 2002; Zoppi et al., 2001; Sabatier et al., 2010; Dezileau et al., 2015). We evaluated the modern reservoir ^{14}C age by comparing an age derived from ^{137}Cs, ^{210}Pb data and geochemical analysis of mining-contaminated lagoonal sediments with an AMS ^{14}C age of a pre-bomb mollusc shell (see Sabatier et al., 2010 for method). The reservoir age (R(t)) with a value of 1003 ± 62 ^{14}C yr is 600 yr higher than the mean marine reservoir age (around 400 yr) and may be explained by an isolation of the lagoon from the Mediterranean Sea. This high reservoir age value is similar to other estimates in different Mediterranean lagoons (Zoppi et al., 2001; Sabatier et al., 2010).

^{14}C ages were also obtained on a series of Holocene mollusc shells sampled at different depths of the ~2-m-long core MM2 (Figure 7, Dezileau et al., in prep). Comparing palaeomagnetic ages and ^{14}C ages versus depth, we show that the reservoir age has changed in the past and was lower (505 yr) than the modern value (1003 yr, Dezileau et al., in prep). This change was also observed in another Mediterranean lagoons (Sabatier et al., 2010). In the Mar Menor lagoon, Linear Sedimentation Rate (LSR) obtained for the core MM2 suggest a low mean accumulation rate of 0.6 $mm.yr^{-1}$, from the base to the top of the core.

5. Discussion

5. 1 Site sensitivity to overwash deposits

Site sensitivity to overwash deposits may result from different factors such as barrier-elevation, sediment supply, inlet, and change in sea level (Donnelly and Webb, 2004; Scileppi and Donnelly, 2007, Dezileau et al., 2011). An increase of sea level induces a shift of the barrier landward. Therefore, an increase of sand layers in a sediment core may be due to a sea level change. In the Mediterranean Sea, the sea level has remained more or less constant during the last 5000 yrs (< 2m, Pirazzoli, 1991; Lambeck and Bard, 2000). Before this period, a significant change in sea level occurred. During the first phase of lagoonal sediment deposit (between 6500 and 5000 years Cal BP), the number of sand layers is low. The sandy barrier was probably at more than 1 km from the present position and may probably explain why sand layers are not observed. The strong increase in coarse grain layer frequency after ca 5400 years Cal BP can be explained by a migration of the barrier up to a position, which is not far away from the present position.

Fauna content reveals a major palaeoenvironmental change around 150 cm (i.e. 2400 yr cal BP, Figure 6). Such change is probably due to a shift from a leaky lagoon to a restricted and choked lagoon environment, sensu Kjerfve (1996). Thus, after this date (i.e 2400 yr cal BP) the barrier was continuous with sometimes inlet formation in relation to intense overwash events. To conclude, between 2400 yr cal BP and today, the lagoon is isolated from the sea. During this period the general morphology of the lagoon and the barrier have not changed drastically. Between 5400 yr cal BP and 2400 yr cal BP the lagoon was less isolated from the Mediterranean Sea, typical from a leaky lagoon environment. During this period, fine sediments were accumulated. The lagoon experienced quiescent sedimentation probably protected behind a sandy barrier more or less continuous. The presence of sand layers may be interpreted by intense overwash events. Between 6500-5400 yrs BP, the morphology of the lagoon and the barrier is different. The position of the sandy barrier was far away from the present position. In that case, the number and the intensity of surge events recorded are not comparable to the upper part of the core (Figures 3 and 8). During this period, the lack of sand layers does not mean no surge events but simply they are not recorded.

5. 2 Storms or tsunamis?

The Zr/Al and Si/Al ratios of sandy layers are above 12 and 2.5 respectively (Figure 8), indicating a higher relative contribution of marine sand. The marine origin of these “high energy” events was also highlighted through molluscs identification (*Bittium recticulatum* and *Rissoa ventricosa*, Figure 8). This multiproxy approach suggests the occurrence of eight periods of increase of overwash events reflecting perturbations of coastal hydrodynamic due to palaeostorm or palaeotsunami events (grey band on Figure 8).

Both tsunamis and storms induce coastal flooding. It is difficult to discriminate storm and tsunami deposits (Kortekaas and Dawson, 2007; Morton et al., 2007; Engel and Brückner, 2011). The coarse-grained layers observed in the core MM2 could be a signature of tsunamis or storms. Records of historic and contempory coastal hazards (storms and tsunamis) may help us to determine which historical events left a sedimentological signature in the Mar Menor lagoon.

In textual archives, extreme storm events were described due to the strong economic and societal impact of these events (Seisdedos et al., 2013). For the last 200 years, 27 storms affected the coast of Murcia. Among all of these storms, some seems to be more catastrophic. The storm of November first, 1869 produced the wreckage of a numerous ships in the Torrevieja harbour. Between Isla Grosa and San Pedro del Pinatar more than thirty-five ships sank and crashed. In the Mar Menor lagoon, fifty fishing boats were destroyed and thrown to the ground. Wave heights associated with this storm were estimated higher than 8 m off the La Manga sandbar. This severe storm also affected La Union and Cartagena cities destroying houses and paralyzing it for many days. From the hydrological and ecological point of view, the 1869 storm led to drastic and persistent changes in the salinity of the lagoon and to the colonization of new species of marine origin (Navarro, 1927), affecting also the fisheries in the lagoon (Pérez-Ruzafa et al., 1991). There are historical references to some other storms that led to the breaking of the sandbar in the Mar Menor (in 1526, 1676, 1687, 1690, 1692, 1694, 1706, 1762, 1765, 1787, 1795) (Jiménez de Gregorio, 1957; Pérez-Ruzafa et al., 1987), although there is no information about their magnitude, the extent and exact location of the breaks and their impact on the lagoon environment. Some ups and downs in the number of species observed in Figure 5 could be related to these events, but an extensive and detailed study would be required for understanding the relationship between the frequency, duration and intensity of the storms and the spatial and temporal scales of their effects and their impact on the fossil record.

Different tsunamis occurred on the Spanish coasts, they are more catastrophic and intense on the Atlantic than on the Mediterranean side (Alvarez-Gomez et al., 2011). In the occidental part of the Mediterranean area, there are historical disastrous tsunami events recorded. In Northern Algeria, in addition to the 2003 tsunami, the first well documented event remains the tsunami in the Djijelli Area associated with the seismic event of August 1856, which was also recorded in the Balearic Islands (Maouche et al., 2009). In the Alboran Sea area some reports mention tsunamis that affected the African and Spanish coasts in 1790, 1804 and 1522 (IGN, 2009). For an earthquake magnitude 6.8 (2003 Boumerdes earthquake) with its epicenter calculated at 15 km offshore of Zemmouri, Wang and Liu (2005) show a regional character of the tsunami phenomenon from a numerical simulation. The tsunami propagating from the Algerian coast to the Murcia Province has a lesser amplitude and the tsunami wave height is low (< 25 cm). The Boumerdes-Zemmouri tsunami did not induce any damage along the province of Murcia and the La Manga sandbar. Alvarez-Gomez et al. (2011) identified the hazardous sources and the areas where the impact of tsunamis is greater from numerical simulations. From a set of 22 seismic tsunamigenic sources, the Maximum Wave Elevation was estimated between 0.5 and 1 m along the South-Eastern Spanish coast. All these historical events have been classified as a magnitude between 1 and 3 in the Tsunami Intensity Scale (on a scale of 6 for a maximum intensity, Maramai et al., 2014). Since these different historical events have a magnitude equal or lower than the Boumerdes-Zemmouri tsunami (3 in the Tsunami Intensity Scale), and that this event did not affect significantly La Manga sandbar and the Province of Murcia, considering the available data, historical tsunami events do not seems to be associated to the different sand layers in the

Mar Menor lagoon for the last 500 years. From the "Catálogo de Tsunamis en las Costas Españolas", no tsunamis are recorded along the South Eastern coast of Spain from -218 BC to 1756 AD. No information on the existence of tsunamis is recorded over longer periods of time. However, more than 100 boulders were identified along the coastal zone of Algiers and Maouche et al. (2009) suggested that the deposition of the biggest boulders could be attributed to tsunami events. The radiocarbon results highlight two groups of boulders dated to around 419 AD and 1700 AD. Although no historical accounts report these events, tsunami events are extremely rare and mainly of low magnitude and cannot be at the origin of the different sand layers in the Mar Menor lagoon.

To determine which historical events may let sandy layers, we compared our high-resolution record of past extreme sea events from the core MM2 to the catalogue of historical storm and tsunami events in the area. The first coarse-grained event layer has been dated at 80 cal. BP (i.e. 1880 A.D+/-30 years). This sandy deposit could be associated to the storm of November first, 1869, recorded in many city archives between Cartagena and Torrevieja and in the Mar Menor, and considered as the most catastrophic storm event in the Province of Murcia for the last 200 years. In the core MM2, no sand layers are consistent with the Algerian tsunamis dated to around 419 AD and 1700 AD (Figure 8). There is evidence that this sand layer is compatible with large storm waves.

5.3 Storm activity in the context of past climatic changes

Based on our ^{14}C age model, marine coarse grained event layers occurred around 5250, 4000, 3600, 3010, 2300, 1350, 650 and 80 years cal BP. Except one period dated at 3600 years cal BP, the seven other periods of most frequent surge events in the Mar Menor lagoon seem to coincide with the coldest periods in Europe during the late Holocene, taking into account chronological uncertainty (Figure 8, Bond et al., 2001). A spectral analysis was performed on the ca 6.5-kyr time series of the sand percentage from the MM2 sequence. The results show four major frequencies with high spectral power densities and significant F-test values at ca $8x10^{-4}$, $1.4x10^{-3}$, $1.8x10^{-3}$, and $3.1x10^{-3}$ yr^{-1} (Figure 9A). Considering the full width at half maximum (FWHM) of these peaks on the MTM spectrum, this yields respective periodicities of 1228 ±327, 732 ±80, 562 ±58, and 319 ±16 yr for the MM2 sand % proxy. Multi-centennial to millennial timescale climate variabilities similar to these periodicities have been reported in the literature for the Holocene (Bond et al., 1997, 2001; Langdon et al., 2003; Debret et al., 2007, 2009; Wanner et al., 2011; Kravchinsky et al., 2013; Soon et al., 2014). Amongst the well-known proxies that have revealed a millennial-scale climate variability during the Holocene, the ice-rafted debris (IRD) indices in North Atlantic developed by Bond et al. (1997, 2001) present a cyclicity of 1470 ±500 yr, which matches the 1228 ±327 yr periodicity evidenced in the Mar Menor lagoon, considering the respective uncertainties on the periodicities. When filtering the raw data of the Mar Menor sand % record by a Gaussian filter with a frequency of $8x10^{-4}$ yr^{-1} (1228 years), six cycles appear with a noteworthy enhancement of the cyclic amplitude after 5500 cal yr BP (Figure 9B). The five ascending phases occurring on the 1228-yr filtered curve at ca 5715/5115, 4525/3945, 3365/2775, 2145/1215, and 575/-35 cal yr BP approximate the high storm activity periods evidenced in the French Mediterranean lagoon of Pierre-Blanche for the last 7000 years (Sabatier et al., 2012).

The origin of the storminess periods evidenced by the spectral analysis in the Mar Menor lagoon can be discussed in the light of previous works mentioning analogous climate variabilities during the Holocene. Bond et al. (1997, 2001) associated the 1470 ±500 yr IRD cycle to a solar forcing, amplified by a change of North Atlantic Deep Water production. Langdon et al. (2003) found a sub-millennial climate oscillation in Scotland possibly related to the North Atlantic thermohaline circulation (THC). Moreover, Debret et al. (2007, 2009) showed a cyclicity of 1500 yr since the Mid-Holocene probably link to an internal forcing due to the THC.

Concerning the multi-centennial periodicities, Soon et al. (2014) used global proxies to evidence a 500-yr fundamental solar mode and to identify intermediate derived cycles at 700 and 300-yr which could be rectified responses of the Atlantic THC to external solar modulation and pacing. Kravchinsky et al. (2013) found also a 500-yr climate cycle in the southern Siberia presumed to be derived by increased solar insolation and possibly amplified by other mechanisms. Some authors found a relationship between the ca 700-yr period and the monsoonal/ITCZ regimes in equatorial Africa (Russell et al., 2003; Russell and Johnson, 2005), southern Asian (Staubwasser et al., 2003), and eastern Arabian Sea (Sarkar et al., 2000), while other authors suggested that the ca 700-800 yr period could be a subharmonic mode derived from the fundamental 1500-year cycle of the THC (Von Rad et al., 1999; Wang et al., 1999). Besides, Rimbu et al. (2004) mentioned a 700 yr variability from sea-surface temperature (SST) records in the tropical and North Atlantic. Hence, our results seem to indicate that the Late Holocene multi-centennial variability of the cyclogenesis in Western Mediterranean was steered by both, external (solar) and internal (THC/ITCZ) forcings. Further investigations of additional sequences and high-resolution coastal imagery will be required to assert reliably the origin of these multi-centennial periods in the Mediterranean area.

7. Conclusion

This study provides a 6500-yr high-resolution record of past overwash events using a multi-proxy approach of a sediment core from the Mar Menor lagoon in Spain in the Western Mediterranean Sea. Eight sandy layers are preserved in the core and seems to be associated to periods of increased extreme sea events. The results indicate little likehood of a tsunami origin for these coarse grained layers, although historical tsunami events are recorded in this area. These surge events seem to coincide with climatic cold periods in Europe during the late Holocene, suggesting a control by a climatic mechanism for periods of increased storm activity. From the available data, we have identified seven periods of high storm activity at around 5250, 4000, 3600, 3010, 2300, 1350, 650 and 80 years cal BP. Except one period dated at 3600 years cal BP, the seven other periods of most frequent surge events in the Mar Menor lagoon seem to coincide with the coldest periods in Europe during the late Holocene, taking into account chronological uncertainty. Spectral analyses performed on the sand % revealed four major periodicities of 1228 ±327, 732 ±80, 562 ±58, and 319±16 yr. The origin of the storminess periods evidenced by the spectral analysis in the Mar Menor lagoon can be discussed in the light of previous works mentioning analogous climate variabilities during the Holocene. Our results seem to indicate that the Late Holocene multi-centennial variability of the cyclogenesis in Western Mediterranean was steered by both, external (solar) and internal (THC/ITCZ) forcings. However, further investigations, such as additional coring, high-resolution coastal imagery, are needed to better constrain the main cause of these multiple-events.

Acknowledgments

The authors would like to thank all participants in the coring expedition, particularly E. Regnier (Technician, LSCE - IPSL, Paris) for his collaboration in the various stages of this study. This study is funded by the MISTRALS PALEOMEX project. We thank the Laboratoire de Mesure ^{14}C (LMC14) ARTEMIS in the CEA Institute at Saclay (French Atomic Energy Commission) for the ^{14}C analyses. This article benefited through constructive reviews by Stella Kortekaas and Suzanne Leroy.

References

Álvarez-Gómez, J. A., González, M., and Otero, L.: Tsunami hazard at the Western Mediterranean Spanish coast from seismic sources, Natural Hazards and Earth System Science, 11, 227-240, 2011.

Berger, A., Melice, J.-L., Hinnov, L.: A strategy for frequency spectra of Quaternary climate records. Climate Dynamics 5, 227-240, 1991.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M. N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G.: Persistent solar influence on North Atlantic climate during the Holocene, Science, 294, 2130-2136, 2001.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., DeMenocal, P., Priore, P., Cullen, H., Hajdas, I., Bonani, G.: A pervasive millennial-scale cycle in North Atlantic Holocene and Glacial climates. Science 278, 1257-1266, 1997.

Bronk Ramsey, C., Development of the Radiocarbon calibration program OxCal, Radiocarbon, 43, 355-363, Proceedings of 17th International 14C Conference, 2001.

Bronk Ramsey, C., Deposition models for chronological records, Quaternary Science reviews, 27, 42-60, 2008.

Debret, M., Bout-Roumazeilles, V., Grousset, F., Desmet, M., McManus, J.F., Massei, N., Sebag, D., Petit, J.-R., Copard, Y., Trentesaux, A.: The origin of the 1500-year climate cycles in Holocene North-Atlantic records. Climate of the Past 3, 569-575, 2007.

Debret, M., Sebag, D., Crosta, X., Massei, N., Petit, J.-R., Chapron, E., Bout-Roumazeilles, V.: Evidence from wavelet analysis for a mid-Holocene transition in global climate forcing. Quaternary Science Reviews 28, 2675-2688, 2009.

Desprat, S., Sanchez-Goni, M.F., Loutre, M.-F.: Revealing climatic variability of the last three millennia in northwestern Iberia using pollen influx data. Earth and Planetary Science Letters 213, 63-78, 2003.

Dezileau, L., Pérez-Ruzafa, A., Camps P., Blanchemanche P., Grafenstein U., Holocene variations of radiocarbon reservoir ages in the Mar Menor lagoon system, Radiocarbon, in prep.

Dezileau, L., Sabatier, P., Blanchemanche, P., Joly, B., Swingedouw, D., Cassou, C., Castaings, J., Martinez, P., and Von Grafenstein, U.: Intense storm activity during the Little Ice Age on the French Mediterranean coast, Palaeogeography, Palaeoclimatology, Palaeoecology, 299, 289-297, 2011.

Dezileau L., Lehu R., Lallemand S., Hsu S-K., Babonneau N., Ratzov G., Lin A.T., Dominguez S., Historical reconstruction of submarine eartquakes using 210Pb, 137Cs and 241Am turbidite chronology and radiocarbon reservoir age estimation off East Taiwan. Radiocarbon. doi:10.1017/RDC.2015.3, 2016.

Donnelly, J. P., Webb III, T., Murnane, R., and Liu, K.: Backbarrier sedimentary records of intense hurricane landfalls in the northeastern United States, Hurricanes and Typhoons: Past, Present, and Future, 58-95, 2004.

Dubar, M.: Approche climatique de la période romaine dans l'est du Var : recherche et analyse des composantes périodiques sur un concrétionnement centennal (Ier-IIe siècle apr. J.-C.) de l'aqueduc de Fréjus. ArchéoSciences 30, 163-171, 2006.

Engel, M., and Brückner, H.: The identification of palaeo-tsunami deposits–a major challenge in coastal sedimentary research, Dynamische Küsten–Grundlagen, Zusammenhänge und Auswirkungen im Spiegel angewandter Küstenforschung. Proceedings of the 28th Annual Meeting of the German Working Group on Geography of Oceans and Coasts, 2011, 22-25,

Gaertner, M.A., Jacob, D., Gil, V., Domínguez, M., Padorno, E., Sánchez, E., Castro, M. : Tropical cyclones over the Mediterranean Sea in climate change simulations. Geophysical Research Letters 34. doi:10.1029/2007GL029977, 1-5, 2007.

Harremoës, P., Topsoe, F.: Maximum entropy fundamentals. Entropy 3, 191-226, 2001.

IGN: Catalogo de Tsunamis en las Costas Espanolas. Instituto Geografico Nacional, www.ign.es, 2009.

Jimenez de Gregorio, F.: *El Municipio de San Javier en la historia del Mar Menor y su ribera*. Ayuntamiento de San Javier, Murcia, 1957.

Kelletat, D., and Schellmann, G.: Tsunamis on Cyprus: field evidences and 14C dating results, Zeitschrift für Geomorphologie, NF, 19-34, 2002.

Kjerfve, B.: Coastal lagoons. In Kjerfve B (ed). *Coastal lagoon processes*. Elsevier Oceanography Series 60: 1-8, 1994.

Kortekaas, S., and Dawson, A.: Distinguishing tsunami and storm deposits: an example from Martinhal, SW Portugal, Sedimentary Geology, 200, 208-221, 2007.

Kravchinsky, V.A., Langereis, C.G., Walker, S.D., Dlusskiy, K.G., White, D.: Discovery of Holocene millennial climate cycles in the Asian continental interior: Has the sun been governing the continental climate? Global and Planetary Change 110, 386-396, 2013.

Lambeck, K., and Bard, E.: Sea-level change along the French Mediterranean coast for the past 30 000 years, Earth and Planetary Science Letters, 175, 203-222, 2000.

Langdon, P.G., Barber, K.E., Hugues, P.D.M.: A 7500-year peat-based palaeoclimatic reconstruction and evidence for an 1100-year cyclicity in bog surface wetness from Temple Hill Moss, Pentland Hills, southeast Scotland. Quaternary Science Reviews 22, 259-274, 2003.

Lionello, P., Bhend, J., Buzzi, A., Della-Marta, P.M., Krichak, S., Jansá, A., Maheras, P., Sanna, A., Trigo, I.F., Trigo, R. : Cyclones in the Mediterranean region: climatology and effects on the environment, in Mediterranean Climate Variability. In: Lionello, P., Malanotte-Rizzoli, P., Boscolo, R. (Eds.), Mediterranean Climate Variability. : Developments in Earth and Environmental Sciences, 4. Elseviered., 324–372, 2006.

Maouche, S., Morhange, C., and Meghraoui, M.: Large boulder accumulation on the Algerian coast evidence tsunami events in the western Mediterranean, Marine Geology, 262, 96-104, 2009.

Maramai, A., Brizuela, B., and Graziani, L.: The Euro-Mediterranean Tsunami Catalogue, Annals of Geophysics, 57, S0435, 2014.

Morhange, C., Marriner, N., and Pirazzoli, P. A.: Evidence of Late-Holocene Tsunami Events in Lebanon Z. Geomorphol NFSuppl.-Bd., 146, 81-95, 2006.

Morton, R. A., Gelfenbaum, G., and Jaffe, B. E.: Physical criteria for distinguishing sandy tsunami and storm deposits using modern examples, Sedimentary Geology, 200, 184-207, 2007.

Navarro, F.: Observaciones sobre el Mar Menor (Murcia). Notas y resúmenes del Instituto Español de Oceanografía, Ser. II, 16:1-63, 1927.

Paillard, D., Labeyrie, L., Yiou, P.: Macintosh program performs time-series analysis. EOS Transactions AGU 77(39), 379-379, 1996.

Pardo-Iguzquiza, E., Rodriguez-Tovar, F.J.: Maximum entropy spectral analysis of climatic time series revisited: Assessing the statistical significance of estimated spectral peaks. Journal of Geophysical Research 111, D10102, 2006.

Percival, D.B., Walden, A.T.: Spectral analysis for physical applications: multitaper and conventional univariate techniques. Cambridge University Press, New York, 583 p, 1993.

Pérez-Ruzafa, A., Marcos, C., Pérez-Ruzafa, I., and Ros, J.: Evolución de las características ambientales y de los poblamientos del Mar Menor (Murcia, SE de España), Anales de Biología, 1987, 53-65,

Pérez-Ruzafa, A., Marcos-Diego, C., and Ros, J.: Environmental and biological changes related to recent human activities in the Mar Menor (SE of Spain), Marine Pollution Bulletin, 23, 747-751, 1991.

Pérez-Ruzafa, A., Marcos-Diego, C.: Colonization rates and dispersal as essential parameters in the confinement theory to explain the structure and horizontal zonation of lagoon benthic assemblages. Rapp. Comm. int. Mer Médit. 33: 100, 1992.

Pérez-Ruzafa, A., Marcos, C., and Gilabert, J.: The ecology of the Mar Menor coastal lagoon: a fast-changing ecosystem under human pressure, Coastal Lagoons. CRC Press, Boca Racon, 392-421, 2005.

Pirazzoli, P. A.: World atlas of Holocene sea-level changes, Elsevier Oceanography Series, 58, 1-280, 1991.

Raji, O., Dezileau L., Snoussi M., and Niazi, S.: Extreme sea events during the last millennium in North-East of Morocco. Natural Hazards and Earth System Sciences, 15,203-211, 2015.

Reimer P.J., McCormac F.G.: Marine radiocarbon reservoir corrections for the Mediterranean and Aegean seas. Radiocarbon 44(1):159–66, 2002.

Rimbu, N., Lohmann, G., Lorenz, S.J., Kim, J.H., Schneider, R.R.: Holocene climate variability as derived from alkenone sea surface temperature and coupled ocean-atmosphere model experiments. Climate Dynamics 23, 215-227, 2004.

Russell, J.M., Johnson, T.C.: Late Holocene climate change in the North Atlantic and equatorial Africa: Millennial-scale ITCZ migration. Geophysical Research Letters 32, L17705, 2005.

Russell, J.M., Johnson, T.C., Talbot, M.R.: A 725 yr cycle in the climate of central Africa during the late Holocene. Geology 31(8), 677-680, 2003.

Sabatier, P., Dezileau, L**.,** Blanchemanche, P., Siani, J., Condomines, M., Bentaleb, I., Piques, G.: Holocene variations of radiocarbon reservoir ages in a Mediterranean lagoonal system. Radiocarbon, 52, (1), 91-102, 2010.

Sabatier, P., Dezileau, L., Colin, C., Briqueu, L., Bouchette, F., Martinez, P., Siani, G., Raynal, O., Von Grafenstein, U.: 7000 years of paleostorm activity in the NW Mediterranean Sea in response to Holocene climate events. Quaternary Research 2012, 1-11, 2012.

Sarkar, A., Ramesh, R., Somayajulu, B.L.K., Agnihotri, R., Jull, A.J.T., Burr, G.S.: High resolution Holocene monsoon record from the eastern Arabian Sea. Earth and Planetary Science Letters 177, 209-218, 2000.

Scileppi, E., Donnelly, J.P. : Sedimentary evidence of hurricane strikes inwestern Long Island, NY. Geochemistry, Geophysics and Geosystems 8, Q06011. doi:10.1029/ 2006GC001463, 2007.

Seisdedos, J., Mulas, J., González de Vallejo, L. I., Rodríguez Franco, J. A., Gracia, F. J., Del Río, L., y Garrote, J. :Estudio y cartografía de los peligros naturales costeros de la región de Murcia. Boletín Geológico y Minero, 124 (3): 505-520, 2013.

Siani G., Paterne M., Michel E., Sulpizio R., Sbrana A., Arnold M., Haddad G. : Mediterranean sea surface radiocarbon age changes since the last glacial maximum. Science 294(5548):1917–20, 2001.

Soon, W., Velasco Herrera, V.M., Selvaraj, K., Traversi, R., Usoskin, I., Arthur Chen, C.-T., Lou, J.-Y., Kao, S.-J., Carter, R.M., Pipin, V., Severi, M., Becagli, S.: A review of Holocene solar-linked climatic variation on centennial to millennial timescales: Physical processes, interpretative frameworks and a new multiple cross-wavelet transform algorithm. Earth-Science Reviews 134, 1-15, 2014.

Staubwasser, M., Sirocko, F., Grootes, P.M., Segl, M.: Climate change at the 4.2 ka BP termination of the Indus valley civilization and Holocene south Asian monsoon variability. Geophysical Research Letters 30(8), 1425, 2003.

Thomson, D.J.: Spectrum estimation and harmonic analysis. Proceedings of the IEEE 70(9), 1055-1096, 1982.

Thomson, D.J.: Time series analysis of Holocene climate data. Philosophical Transactions of the Royal Society of London, Series A, Mathematical and Physical Sciences 330, 601-616, 1990.

Trigo, I.F., Davies, T.D., Bigg, G.R., : Decline in Mediterranean rainfall caused by weakening of Mediterranean cyclones. Geophysical Research Letters 27, 2913–2916, 2000.

Von Rad, U., Schaaf, M., Michels, K.H., Schulz, H., Berger, W.H., Sirocko, F. A 5000-yr Record of Climate Change in Varved Sediments from the Oxygen Minimum Zone off Pakistan, Northeastern Arabian Sea. Quaternary Research 51, 39-53, 1999.

Wang, L., Sarnthein, M., Erlenkeuser, H., Grimalt, J., Grootes, P., Heilig, S., Ivanova, E., Kienast, M., Pelejero, C., Pflaumann, U.: East Asian monsoon climate during the Late Pleistocene: high-resolution sediment records from the South China Sea. Marine Geology 156, 245-284, 1999.

Wang, X., Liu, P.L.-F., : A numerical investigation of Boumerdes-Zemmouri (Algeria) earthquake and tsunami. Computer Modeling in Engineering Science 10 (2), 171–184, 2005.

Wanner, H., Solomina, O., Grosjean, M., Ritz, S.P., Jetel, M.: Structure and origin of Holocene cold events. Quaternary Science Reviews 30, 3109-3123, 2011.

Zoppi U., Albani A., Ammerman A.J., Hua Q., Lawson E.M., Serandrei Barbero R. :Preliminary estimate of the reservoir age in the Lagoon of Venice. Radiocarbon 43(2A):489–94, 2001.

Figures captions

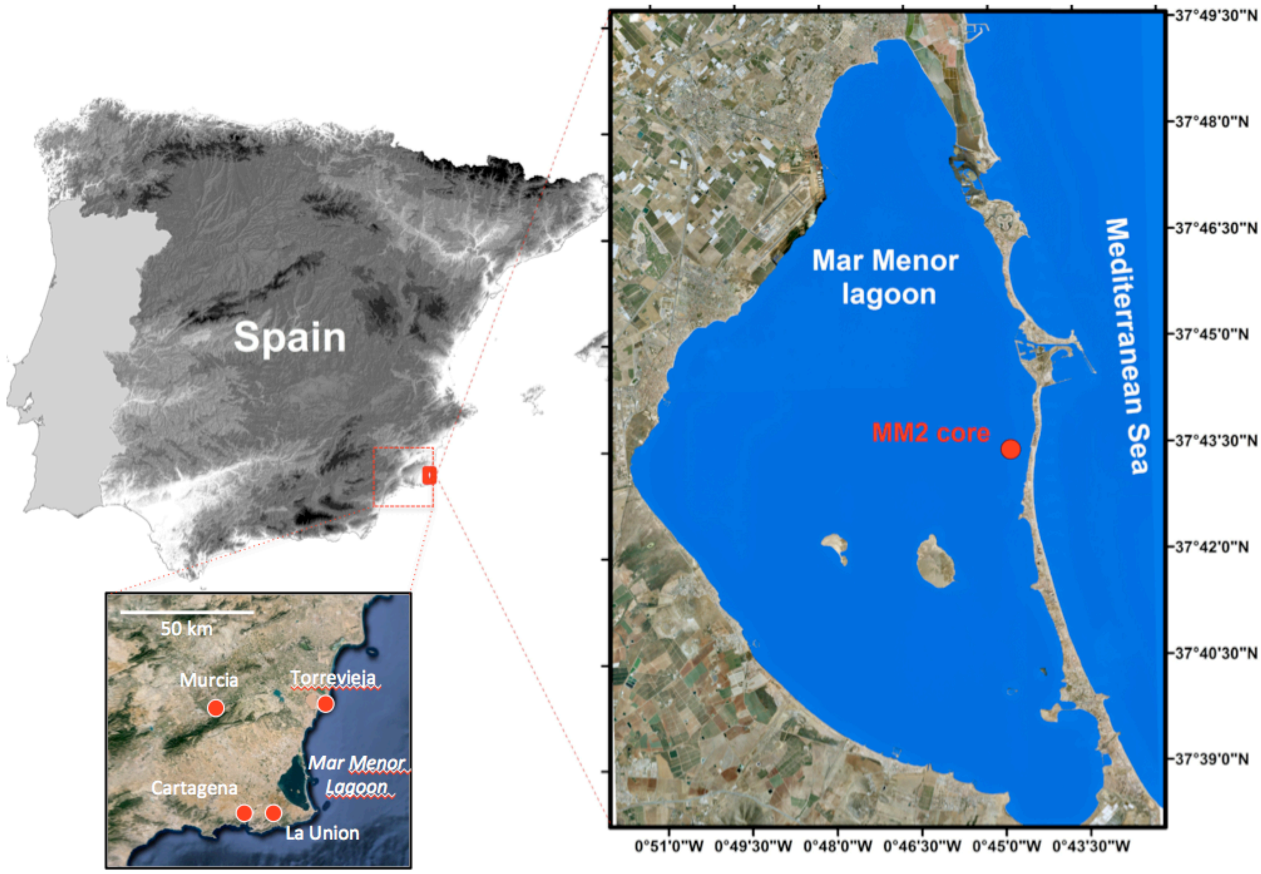

Figure 1. Map of the Mar Menor lagoon with localisation of the core MM2.

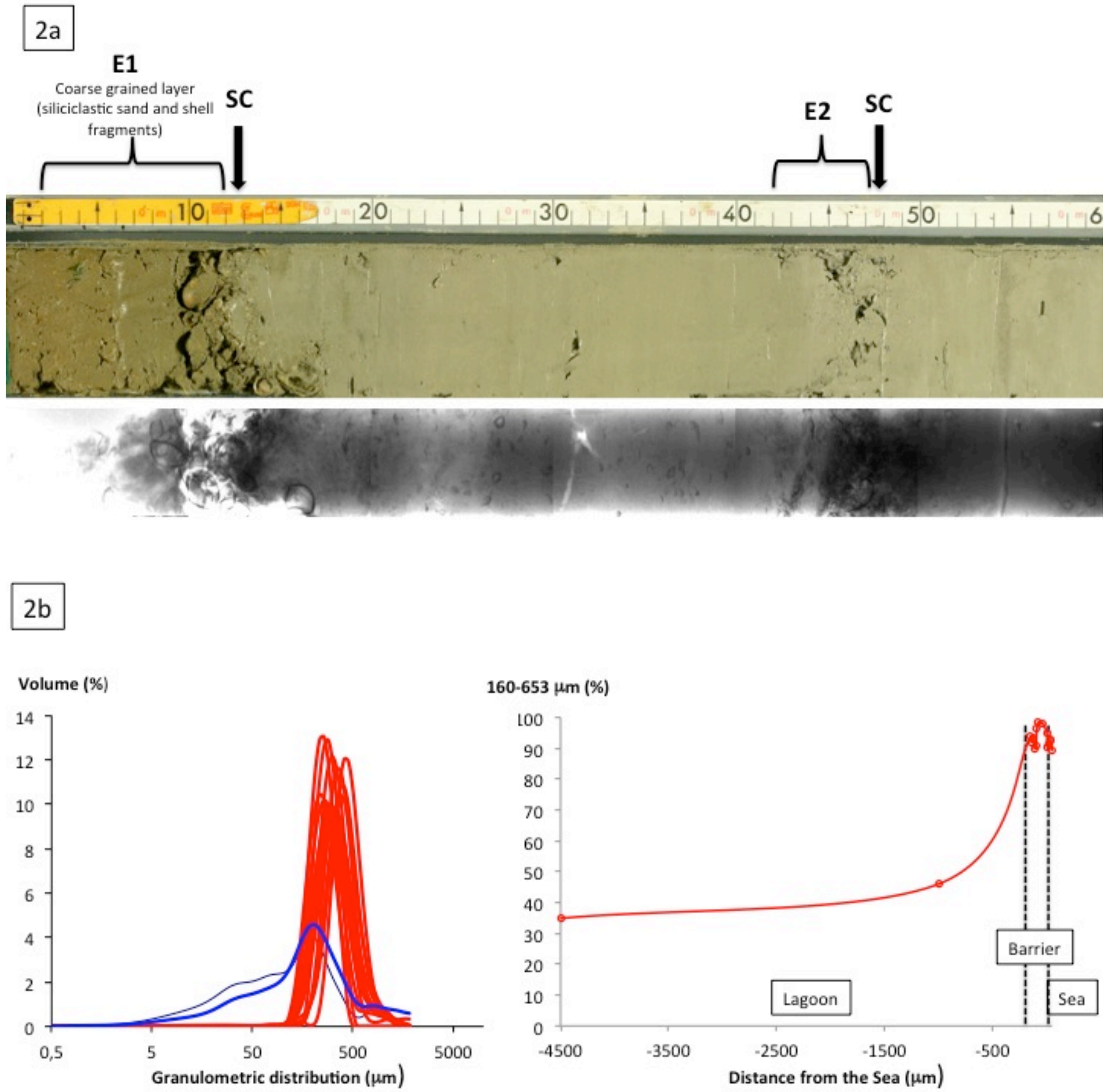

Figure 2. a) Photography and X-ray of the core MM2 (0 and 60 cm). Coarse grained layers are a mixture of siliciclastic sand and shell fragments. These layers have often sharp contacts (SC) with the clay and silt sediments below. **b)** Granulometric distribution of surface samples collected

on a E-W transect from the Sea and the Barrier (red) to the lagoon (blue). Evolution of the 160-653 μm population from the sea to the lagoon in surface samples.

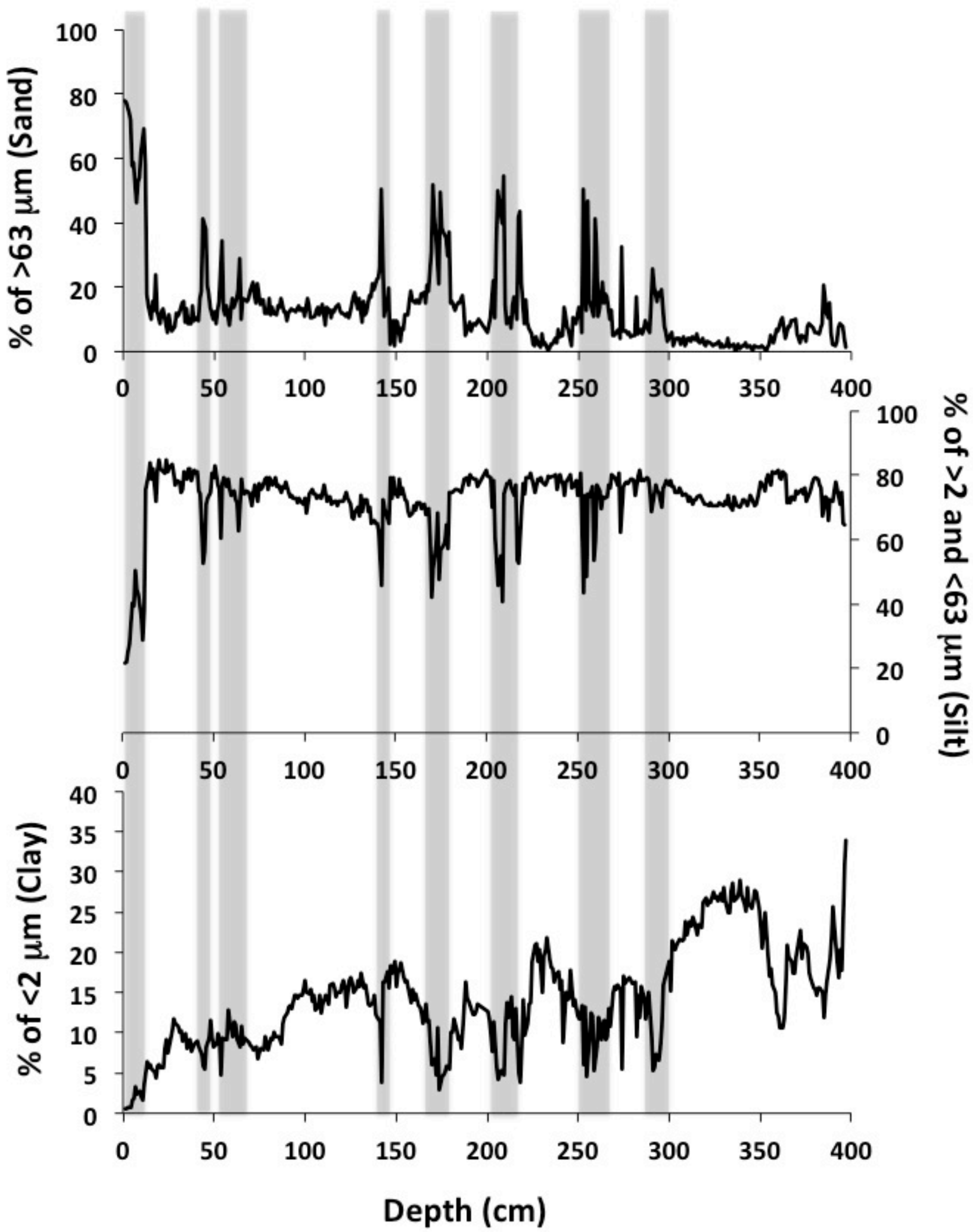

Figure 3. Grain size population from the Mar Menor MM2 record with clay (<2 μm), silt (>2 and

<63 μm) and sand fraction (>63μm). Shaded areas mark the main variations of the sand fraction.

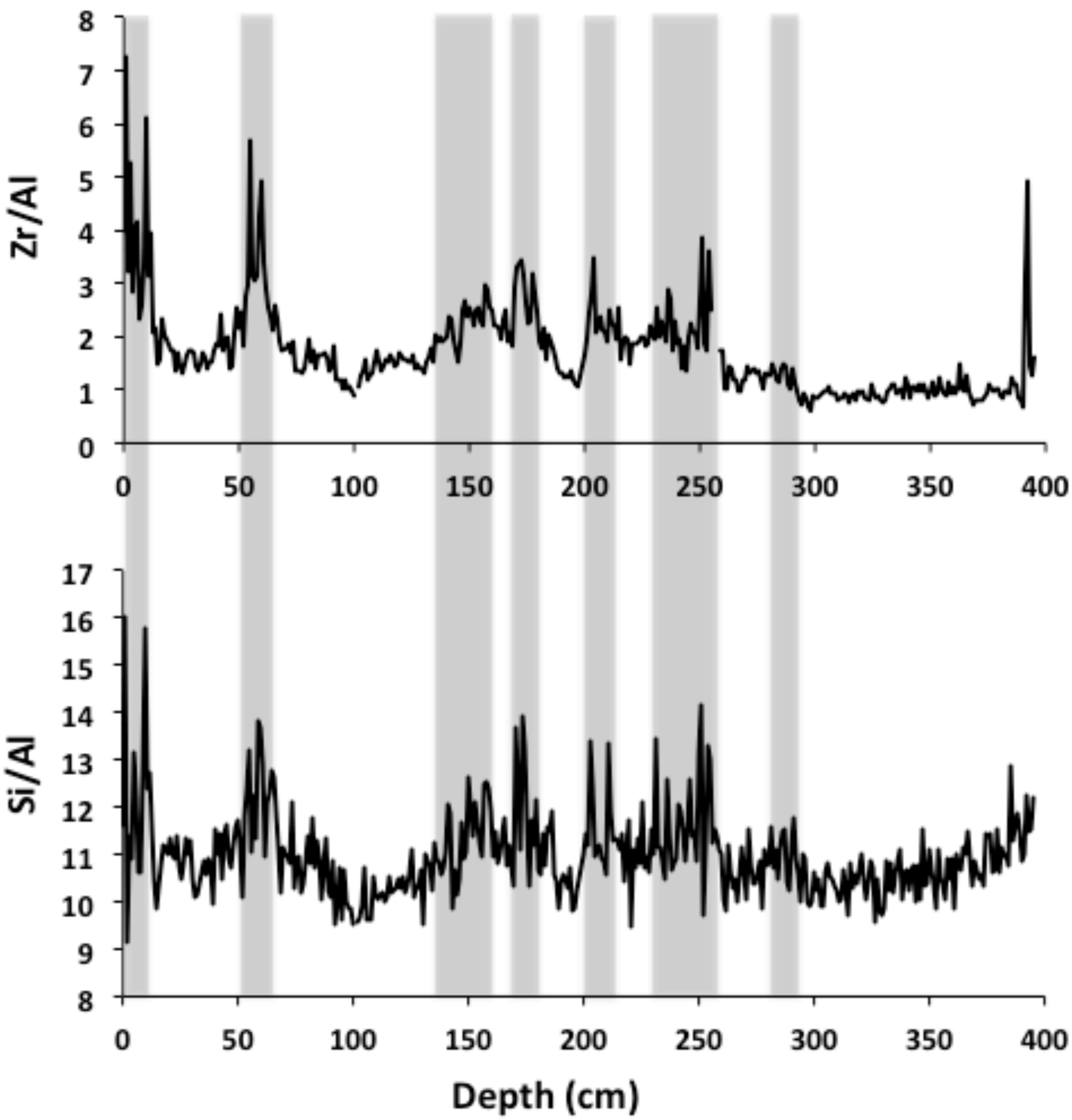

Figure 4. XRF records from the core MM2 with down-core variations of ratio Zr/Al and Si/Al. Shaded areas mark the main variations of Zr/Al and Si/Al.

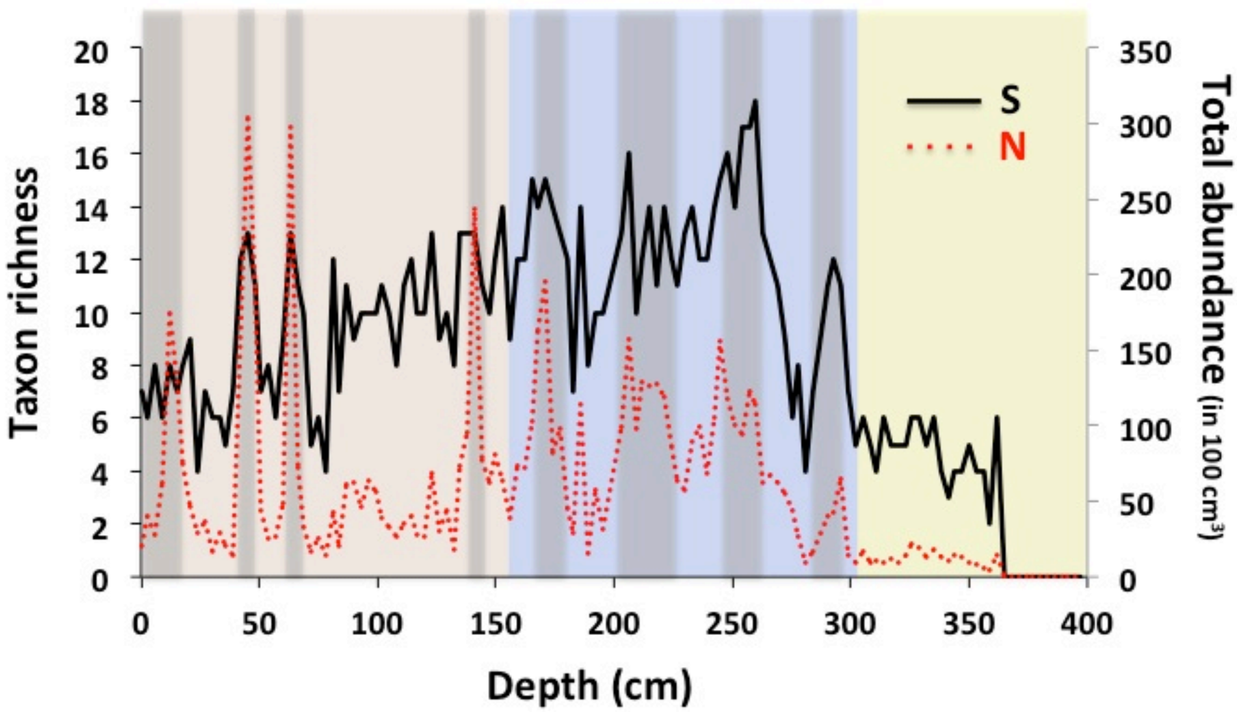

Figure 5. Taxon richness (S) and total number of individuals (N) with depth from the core MM2. Macro-fauna samples were taken at fixed volume (100 cm^3). The different colour bands correspond to depths: azoic (yellow), under higher marine influence (blue) and under a progressive isolation of the Mar Menor from the Mediterranean Sea (brown). The grey bands correspond to punctual peacks in species richness, probably related to episodes of rupture of the sandbar.

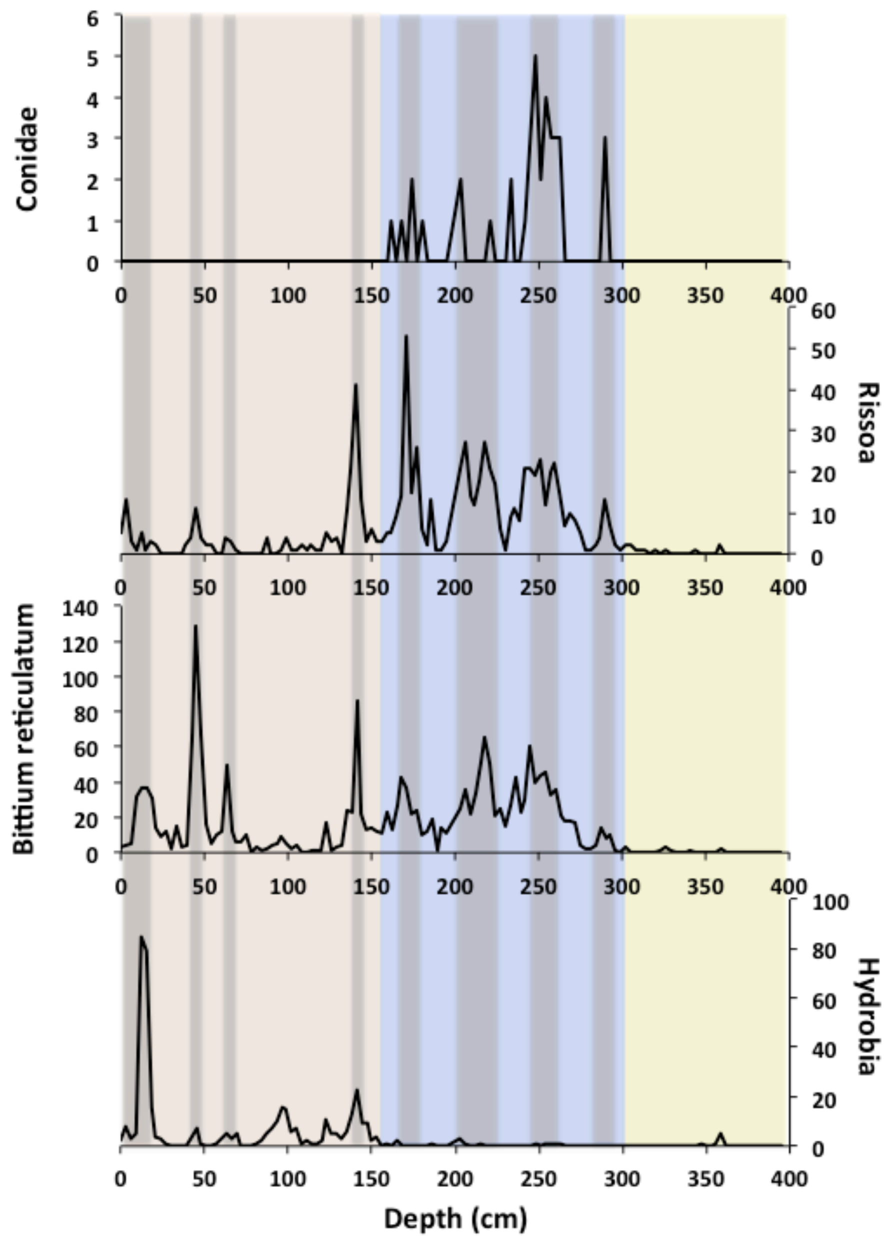

Figure 6. Evolution of the abundance in mollusc population (number of individuals in 100 cm^3) with depth: lagoonal specie (*Hydrobia acuta*); typical marine specie (*Conus ventricosus*: Conidae), marine influence (*Bittium Reticulatum* and *Pusillina lineolata:* Rissoa).

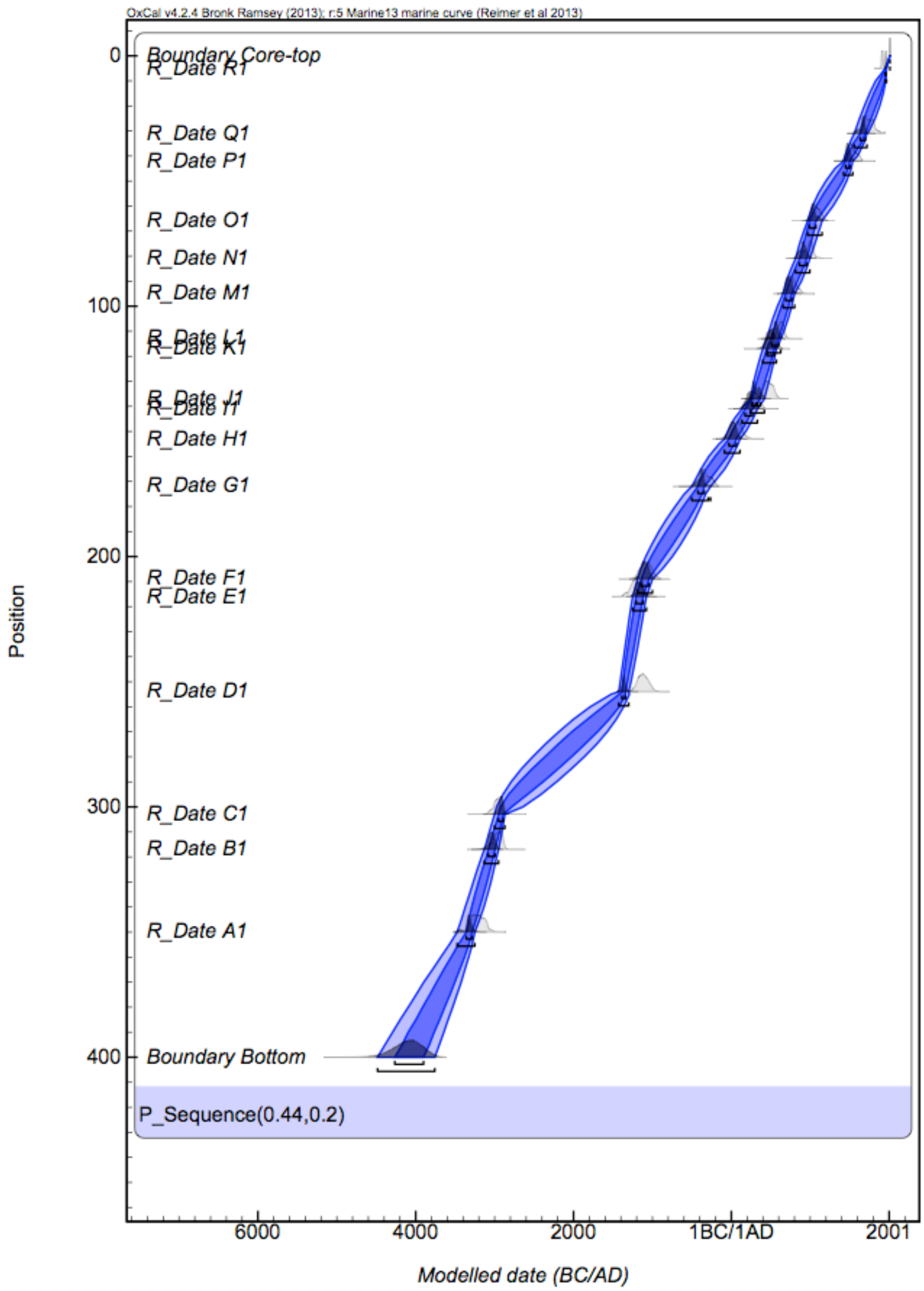

Figure 7. Age vs Depth for the core MM2. The Age model was calculated using OxCal 4 with 17 ^{14}C dates.

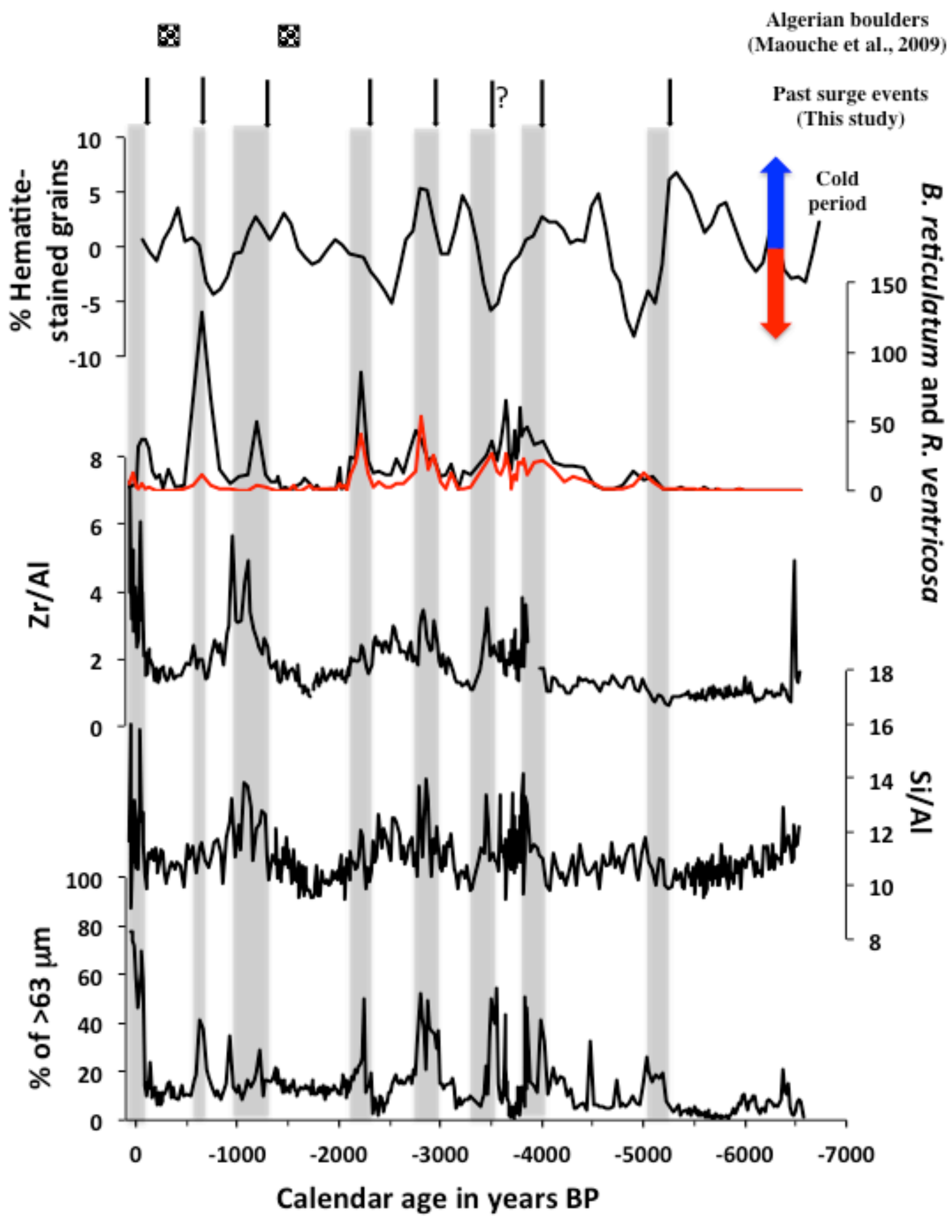

Figure 8. Core MM2 with from bottom to top: Grain size (sand fraction); Si/Al and Zr/Al XRF ratio; number of B. reticulatum (Black line) and R. Ventricosa (Red line), % Hematite-stained grains (Bond et al., 1997, 2001), ages of Algerian boulders (Maouche et al., 2009). Grey bands are the past surge events.

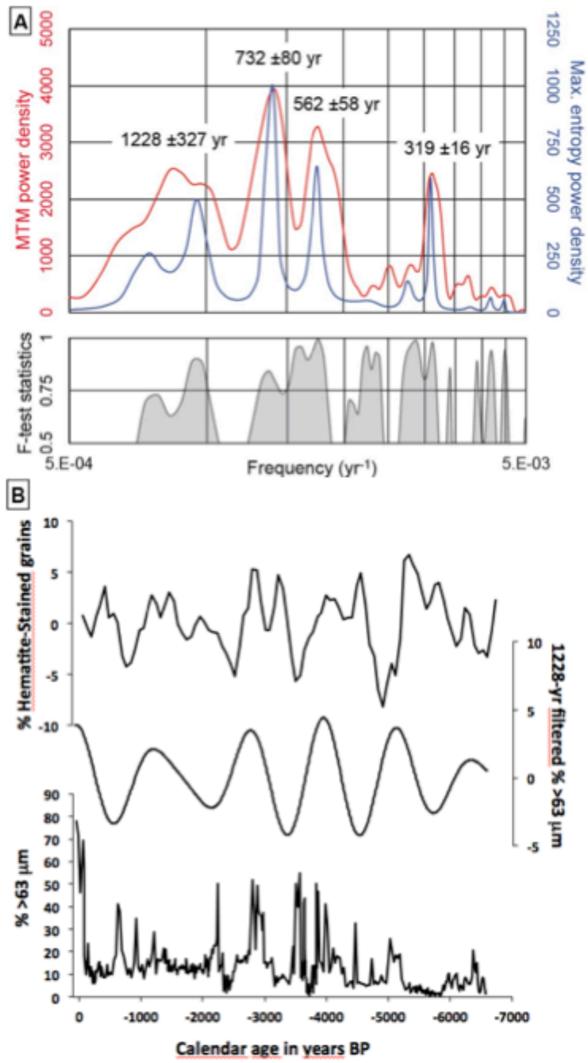

Figure 9. Time series analysis from the Mar Menor MM2 record. (A) Spectral analyses of the % of sand with AnalySeries v.2.0.8 (Paillard et al., 1996) by using the Multi-Taper method (linear trend removed, width.ndata product: 1.3; number of windows: 2) and the Maximum entropy method (linear trend removed, % of series: 40, number of lags: 133). (B) Comparison between the % Hematite-stained grains (Bond et al., 1997, 2001), the Gaussian filter on the % of sand for the 1228-yr period (frequency: 0.0008, bandwidth: 0.0002) and the sand fraction of the core MM2.